

Electroweak Interactions,
the Higgs Boson,
and the Search for
new heavy Bosons

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Fakultät für Mathematik und Physik
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HABILITATIONSUNTERLAGEN

vorgelegt von
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ALBERT-LUDWIGS-UNIVERSITÄT

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- [5] ATLAS Collaboration, *Measurements of the Higgs boson production cross section via Vector Boson Fusion and associated WH production in the $WW^* \rightarrow \ell\nu\ell\nu$ decay mode with the ATLAS detector at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2016-112 (CERN, Geneva, Nov. 2016), <http://cds.cern.ch/record/2231811>. 257
- [4] ATLAS Collaboration, *Measurement of the W^+W^- production cross section in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with the ATLAS experiment*, *Phys. Lett. B* **773**, 354–374 (2017) [10.1016/j.physletb.2017.08.047](https://arxiv.org/abs/1702.04519), [arXiv:1702.04519 \[hep-ex\]](https://arxiv.org/abs/1702.04519). 287
- [2] ATLAS Collaboration, *Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, submitted to JHEP (2017), [arXiv:1709.07242 \[hep-ex\]](https://arxiv.org/abs/1709.07242). 309
- [1] ATLAS Collaboration, *Search for heavy resonances decaying into WW in the $e\nu\mu\nu$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, submitted to Eur. Phys. J. C (2017), [arXiv:1710.01123 \[hep-ex\]](https://arxiv.org/abs/1710.01123). 361

1.1 Personal Information

Name **Dr. Karsten Köneke**
Born **June 5th 1978 in Hannover, Germany**
Nationality **German**
Address **Sautierstr. 44, 79104 Freiburg, Germany**
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1.2 Education

- 2003–2007 **Ph.D.**, *Massachusetts Institute of Technology*, Cambridge, MA, USA.
Thesis: “ $B \rightarrow (\rho/\omega) \gamma$ at BaBar”, [SLAC-R-891] in Mai 2007.
- 2001–2003 **Master**, *University of Massachusetts*, Amherst, MA, USA.
Participated in an exchange program with the graduate school of physics and accepted into the M.S. program in summer 2002. Graduated with thesis “Measurement of the branching fraction for the decay $B^\pm \rightarrow K^{*\pm} \gamma$, $K^{*\pm} \rightarrow K^\pm \pi^0$ with the BaBar Detector”, [SLAC-R-841] in September 2003.
- 1998–2001 **Study of Physics**, *Ruprecht-Karls-Universität Heidelberg*, Heidelberg, Germany.
Passed pre-degree (Vordiplom) with the result “very good” in August 2000.
- 1997–1998 **Community service (substitution for compulsory military service)**, *German Red Cross*, Burgdorf, Germany.
- 1990–1997 **Abitur (High School diploma)**, *Gymnasium Uetze*, Uetze, Germany.

1.3 Work and Research Projects

Since 2013 **Akademischer Rat**, *Albert-Ludwigs-Universität*, Freiburg, Germany.

Coordinator and supervisor of a local research team in the ATLAS group of Prof. Dr. K. Jakobs. Areas of research are the measurement of the properties of the Higgs boson in decays into two W bosons or into two tau leptons, the search for additional heavy Higgs bosons in these final states, the combination of all Higgs-boson measurements, studies of the electroweak symmetry breaking in WW scattering, as well as the measurement of the cross section for WW production. Further studies are performed regarding the improvement of the electron reconstruction as well as a precise measurement of the electron charge misreconstruction rate and of the identification efficiency of tau leptons. Additionally, the development and improvement of experiment-specific software is pursued.

2010–2013 **CERN Research Fellow and Marie Curie Fellow**, *CERN*, Meyrin, Switzerland.

Work on the ATLAS Higgs-boson search in the four-lepton final state. Contributions to the improvement of the electron reconstruction. Development of experiment-specific software and specialized data formats and processing steps. Development of automated data analysis software for many search and measurement channels.

2007–2010 **DESY Fellow**, *DESY*, Hamburg, Germany.

Preparations for the measurement of the cross section of the $Z \rightarrow e^+e^-$ process with first data. Determination of efficiencies of electron triggers using the Tag&Probe method. Optimization of electron triggers. Search for Supersymmetry. Evaluation of the LHC Computing Grid.

2002–2007 **Rare Decays at the BaBar Experiment**.

Measurement of branching fractions, direct CP-violations, and isospin violations in the decays $B \rightarrow K^*\gamma$, $B \rightarrow \rho\gamma$, and $B^0 \rightarrow \omega\gamma$. Extraction of $|V_{td}/V_{ts}|$ from these measurements and thus determining one side of the CKM Unitarity Triangle. Monte-Carlo studies of the inclusive process $b \rightarrow s\nu\bar{\nu}$.

2001 **Internship**, *Institut Laue-Langevin*, Grenoble, France.

Contributions to the installation of the PERKEO II experiment.

1.4 Leadership and Work within Scientific Boards

- Since 2016 **Member of the AOD Content Taskforce**, *ATLAS Collaboration*.
Taskforce to reduce the size of the most important ATLAS data formats (AOD and DAOD), while retaining the important physics information in view of the very limited resources for the ATLAS grid computing.
- 2015–2016 **Coordinator of the HWW group**, *ATLAS Collaboration*.
One of two leaders of the international ATLAS group of about 50 scientists working on all $H \rightarrow WW$ analyses. This group is performing all ATLAS analyses where the Higgs bosons decays into two W bosons. This includes the gluon-fusion, vector-boson-fusion, and W boson and Z boson associated production channels. These production channels are used to extract properties of the Higgs boson. Also, the searches for new heavy Higgs bosons decaying into two W bosons are performed within this ATLAS group.
- 2010–2013 **Coordinator of the Physics Analysis Tools group**, *ATLAS Collaboration*.
Development of software and infrastructure for data analysis. One of two coordinators of all central experiment-specific software developments for physics analysis.
- 2010 **Coordinators of the Event Management Board**, *ATLAS Collaboration*.
Definition and development of the central ATLAS data structures whilst considering the required disk space as well as the read speed. One of two coordinators.
- 2009–2010 **Leader of the Derived Physics Data Taskforce**, *ATLAS Collaboration*.
Design and development of the ATLAS “Derived Physics Data”, several data formats with detailed information close to the detector for early performance-oriented data analysis. Design and development of the required software infrastructure and organizational structure within the ATLAS Collaboration. One of two leaders.
- 2008–2011 **Coordinator of the Electron Analysis Initiative**, *ATLAS Collaboration*.
Initiative between the ATLAS groups of the University of Hamburg, University of Mainz, University of Liverpool and DESY to study the properties of W and Z boson production in the decay channel with electrons. One of two coordinators.
- 2006–2007 **Drift Chamber Operations Manager**, *BaBar Collaboration*.
Responsible for the flawless operation of the BaBar drift chamber.

1.5 Science Management

- 2014 **ATLAS Upgrade Week**, *ATLAS Collaboration*.
Local co-organizer of the ATLAS Upgrade Week in Freiburg with approximately 250 participants.
- 2011 and 2012 **Physics Analysis Tools Workshop**, *ATLAS Collaboration*.
Main organizer of two ATLAS-wide workshops on software for physics analyses and on the new design and development of the ATLAS event data model (xAOD) for the Run 2 of the LHC, each with approximately 60 participants.
- 2008 **EGamma Workshop**, *ATLAS Collaboration*.
Local co-organizer of the ATLAS “EGamma Workshop on Readiness for Data Taking” in Hamburg with approximately 100 participants.

1.6 Teaching

- WS 2017–2018 **Oberassistent “Particle Detectors”**, *Albert-Ludwigs-Universität, Freiburg, Germany*.
Lecture in the M.Sc. program by Dr. C. Weiser, organization and coordination of the homework and exercise group.
- SS 2017 **Advanced Physics Laboratory**, *Albert-Ludwigs-Universität, Freiburg, Germany*.
Supervision of the nuclear magnetic resonance and ATLAS experiments.
- WS 2016–2017 **Oberassistent “Experimentalphysik V (Kern- und Elementarteilchenphysik)”**, *Albert-Ludwigs-Universität, Freiburg, Germany*.
Lecture in the B.Sc. program by Prof. Dr. M. Schumann, organization and coordination of the homework and exercise groups.
- SS 2016 **Advanced Physics Laboratory**, *Albert-Ludwigs-Universität, Freiburg, Germany*.
Supervision of the ATLAS experiment.
- SS 2015 **Master-level Lecture “Hadron Collider Physics”**, *Albert-Ludwigs-Universität, Freiburg, Germany*.
Co-lecturer, jointly with Prof. Dr. K. Jakobs.
- WS 2014–2015 **Oberassistent “Experimentalphysik V (Kern- und Elementarteilchenphysik)”**, *Albert-Ludwigs-Universität, Freiburg, Germany*.
Lecture in the B.Sc. program by Prof. Dr. K. Jakobs, organization and coordination of the homework and exercise groups, substitute lecturer.
- SS 2013 **Introductory Lecture on Statistics for the Advanced Physics Laboratory**, *Albert-Ludwigs-Universität, Freiburg, Germany*.
Co-lecturer, jointly with Prof. Dr. K. Jakobs.

- SS 2013– SS 2014 **Oberassistent of the Advanced Physics Laboratory**, *Albert-Ludwigs-Universität*, Freiburg, Germany.
Organization and coordination.
- 2011–2015 **ATLAS Offline Software Tutorial**, *ATLAS Collaboration*.
Organization and teaching of the quarterly ATLAS Offline Software Tutorial.
- 2007–2010 **Substitute Lecturer for JProf. Dr. J. Haller**, *Universität Hamburg*, Hamburg, Germany.
Substitute lecturer in advanced particle physics.
- 2005 **Teaching Assistant for “Physics II”**, *Massachusetts Institute of Technology*, Cambridge, MA, USA.
Teaching Assistant for course in electrodynamics in the SB program using a new method: Technology Enabled Active Learning (see <http://icampus.mit.edu/teal/> for additional information regarding the TEAL project).

1.7 Co-Supervision

- Since 2013 **Albert-Ludwigs-Universität**, Freiburg, Germany.
Co-supervision of several Bachelor, Master, and Ph.D. students as well as post-doctoral researchers in the areas of Standard Model Higgs boson physics with W bosons or tau leptons, searches for new high-mass bosons with tau leptons, combination of Higgs boson measurements from several channels, development of new methods to determine parameters of effective field theories, measurement of the WW cross section, measurement of $W^\pm W^\pm$ scattering, studies regarding electron reconstruction and charge identification, identification efficiency measurements of tau leptons, validation of the missing transverse energy reconstruction, as well as work in the area of software development.
- 2010–2013 **CERN**, Meyrin, Switzerland.
Supervision of two CERN summer students. One in the area of automated fast physics analyses and the other in the area of Higgs boson physics with Z bosons.
- 2007–2010 **DESY**, Hamburg, Germany.
Supervision of two DESY summer students, and co-supervision of three diploma students and one doctoral student in the areas of the first ATLAS cross section measurement of the $Z \rightarrow e^+e^-$ process, the improvement and efficiency measurement of electron triggers, and the search for Supersymmetry.

1.8 Selected Presentations

Listed are talks at international conferences or workshops, colloquia or seminars, as well as invited talks at national conferences. Collaboration-internal talks and contributed talks at national conferences or workshops are omitted.

- 2018 *Tomographie of the Higgs boson*, DPG-Frühjahrstagung, Würzburg, Germany.
Invited main talk.
- 2016 *Search for high mass Higgs bosons using the ATLAS detector*, 38th International Conference on High Energy Physics (ICHEP2016), Chicago, USA.
Invited talk.
- 2016 *The Higgs Boson and its Properties*, DESY Seminar, Hamburg, Germany.
- 2016 *The Higgs Boson and its Properties*, Physics Colloquium, Freiburg, Germany.
Colloquium in context of Habilitation.
- 2016 *$H \rightarrow WW^*$ Decays and their Impact on Higgs Boson Parameters*, Winter Seminar of the RWTH Aachen, Saas Grund, Switzerland.
- 2015 *Measurement of $H \rightarrow WW^*$ Decays and their Impact on Higgs-Boson Parameters*, DPG-Frühjahrstagung, Wuppertal, Germany.
Invited talk.
- 2014 *Recent ATLAS Results*, 20th International Symposium on Particles, Strings and Cosmology (PASCOS2014), Warsaw, Poland.
Invited plenary talk.
- 2013 *$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ in ATLAS*, CoEPP Annual Workshop, Cairns, Australia.
- 2013 *The Higgs Boson's First Birthday*, Physics Colloquium, University of Adelaide, Adelaide, Australia.
- 2012 *Measurements of W/Z Production with the ATLAS Detector*, 11th Conference on the Intersection of Particle and Nuclear Physics (CIPANP2012), St. Petersburg, FL, USA.
Invited talk.
- 2010 *Distributing and storing required Data efficiently by means of specifically tailored Data Formats in the ATLAS Collaboration*, International Conference on Computing in High Energy and Nuclear Physics (CHEP2010), Taipei, Taiwan.

- 2009 *Early Physics Measurements at the LHC with ATLAS*, High-Energy Physics Conference in Madagascar (HEP-MAD09), Antananarivo, Madagascar.
Invited plenary talk.
- 2007 *Radiative Penguin Decays at the B Factories*, International Conference on Supersymmetry and the Unification of Interactions (SUSY07), Karlsruhe, Germany.
Invited talk.
- 2006 *$B \rightarrow (K^*/\rho/\omega)\gamma$ and Lattice QCD*, Lattice QCD Workshop, Menlo Park, CA, USA.
- 2005 *Recent Results in electroweak B Decays from the BaBar Experiment*, Particles and Nuclei International Conference (PANIC 2005), Santa Fe, NM, USA.
Invited talk.

1.9 Selected Publications

Listed are only publications where I made substantial contributions.

- [1] ATLAS Collaboration, *Search for heavy resonances decaying into WW in the $e\nu\mu\nu$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, submitted to Eur. Phys. J. C (2017), [arXiv:1710.01123 \[hep-ex\]](#).
- [2] ATLAS Collaboration, *Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, submitted to JHEP (2017), [arXiv:1709.07242 \[hep-ex\]](#).
- [3] ATLAS Collaboration, *Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2017-029 (CERN, Geneva, May 2017), <https://cds.cern.ch/record/2261772>.
- [4] ATLAS Collaboration, *Measurement of the W^+W^- production cross section in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with the ATLAS experiment*, Phys. Lett. **B773**, 354–374 (2017) [10.1016/j.physletb.2017.08.047](#), [arXiv:1702.04519 \[hep-ex\]](#).
- [5] ATLAS Collaboration, *Measurements of the Higgs boson production cross section via Vector Boson Fusion and associated WH production in the $WW^* \rightarrow \ell\nu\ell\nu$ decay mode with the ATLAS detector at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2016-112 (CERN, Geneva, Nov. 2016), <http://cds.cern.ch/record/2231811>.
- [6] LHC Higgs Cross Section Working Group, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, (2016), [arXiv:1610.07922 \[hep-ph\]](#).

- [7] ATLAS Collaboration, *Measurement of the W^+W^- production cross section in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with the ATLAS experiment*, ATLAS-CONF-2016-090 (CERN, Geneva, Aug. 2016), <http://cds.cern.ch/record/2206811>.
- [8] ATLAS Collaboration, *Search for Minimal Supersymmetric Standard Model Higgs Bosons H/A in the $\tau\tau$ final state in up to 13.3fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, ATLAS-CONF-2016-085 (CERN, Geneva, Aug. 2016), <http://cds.cern.ch/record/2206278>.
- [9] ATLAS Collaboration, *Combined measurements of the Higgs boson production and decay rates in $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ final states using pp collision data at $\sqrt{s} = 13$ TeV in the ATLAS experiment*, ATLAS-CONF-2016-081 (CERN, Geneva, Aug. 2016), <http://cds.cern.ch/record/2206272>.
- [10] ATLAS Collaboration, *Search for a high-mass Higgs boson decaying to a pair of W bosons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2016-074 (CERN, Geneva, Aug. 2016), <http://cds.cern.ch/record/2206243>.
- [11] ATLAS Collaboration, *Search for Minimal Supersymmetric Standard Model Higgs bosons H/A and for a Z' boson in the $\tau\tau$ final state produced in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, *Eur. Phys. J.* **C76**, 585 (2016) [10.1140/epjc/s10052-016-4400-6](https://doi.org/10.1140/epjc/s10052-016-4400-6), [arXiv:1608.00890](https://arxiv.org/abs/1608.00890) [hep-ex].
- [12] ATLAS Collaboration, *Searches for heavy diboson resonances in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **09**, 173 (2016) [10.1007/JHEP09\(2016\)173](https://doi.org/10.1007/JHEP09(2016)173), [arXiv:1606.04833](https://arxiv.org/abs/1606.04833) [hep-ex].
- [13] ATLAS Collaboration, *Search for a high-mass Higgs boson decaying to a pair of W bosons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2016-021 (CERN, Geneva, Apr. 2016), <http://cds.cern.ch/record/2147445>.
- [14] ATLAS Collaboration, *Search for Neutral Minimal Supersymmetric Standard Model Higgs Bosons $H/A \rightarrow \tau\tau$ produced in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, ATLAS-CONF-2015-061 (CERN, Geneva, Dec. 2015), <http://cds.cern.ch/record/2114827>.
- [15] ATLAS Collaboration, *A morphing technique for signal modelling in a multidimensional space of coupling parameters*, ATL-PHYS-PUB-2015-047 (CERN, Geneva, Nov. 2015), <http://cds.cern.ch/record/2066980>.
- [16] ATLAS Collaboration, *Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector*, *Phys. Rev.* **D92**, 012006 (2015) [10.1103/PhysRevD.92.012006](https://doi.org/10.1103/PhysRevD.92.012006), [arXiv:1412.2641](https://arxiv.org/abs/1412.2641) [hep-ex].
- [17] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, *Phys. Rev.* **D91**, 012006 (2015) [10.1103/PhysRevD.91.012006](https://doi.org/10.1103/PhysRevD.91.012006), [arXiv:1408.5191](https://arxiv.org/abs/1408.5191) [hep-ex].

- [18] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett.* **B716**, 1–29 (2012) 10.1016/j.physletb.2012.08.020, arXiv:1207.7214 [hep-ex].
- [19] ATLAS Collaboration, *Observation of an excess of events in the search for the Standard Model Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel with the ATLAS detector*. ATLAS-CONF-2012-092 (CERN, Geneva, July 2012), <http://cds.cern.ch/record/1460411>.
- [20] M. Aharrouche et al., *Double differential Z , W cross sections and their ratios in the electron channels*, ATL-COM-PHYS-2010-325 (CERN, Geneva, June 2010), <https://cds.cern.ch/record/1269075>.
- [21] ATLAS Collaboration, *Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics*, (2009), arXiv:0901.0512 [hep-ex].
- [22] K. Köneke, *$B \rightarrow (\rho/\omega)\gamma$ at BaBar*, PhD thesis (Massachusetts Institute of Technology, 2007), <http://www-public.slac.stanford.edu/sciDoc/docMeta.aspx?slacPubNumber=slac-r-891>.
- [23] BaBar Collaboration, *Branching fraction measurements of $B^+ \rightarrow \rho^+\gamma$, $B^0 \rightarrow \rho^0\gamma$, and $B^0 \rightarrow \omega\gamma$* , *Phys. Rev. Lett.* **98**, 151802 (2007) 10.1103/PhysRevLett.98.151802, arXiv:hep-ex/0612017 [hep-ex].
- [24] BaBar Collaboration, *Search for the radiative penguin decays $B^+ \rightarrow \rho^+\gamma$, $B^0 \rightarrow \rho^0\gamma$, and $B^0 \rightarrow \omega\gamma$* , *Phys. Rev. Lett.* **94**, 011801 (2005) 10.1103/PhysRevLett.94.011801, arXiv:hep-ex/0408034 [hep-ex].
- [25] BaBar Collaboration, *Measurement of branching fractions, and CP and isospin asymmetries, for $B \rightarrow K^*\gamma$* , *Phys. Rev.* **D70**, 112006 (2004) 10.1103/PhysRevD.70.112006, arXiv:hep-ex/0407003 [hep-ex].
- [26] K. Köneke, *Measurement of the Branching Fraction for the Decay $B^\pm \rightarrow K^{*\pm}\gamma$, $K^{*\pm} \rightarrow K^\pm\pi^0$ with the BaBar detector*, MA thesis (University of Massachusetts Amherst, 2003), <http://www-public.slac.stanford.edu/sciDoc/docMeta.aspx?slacPubNumber=slac-r-841>.

2.1 Introduction

The *Standard Model of Particle Physics* (SM) describes very successfully three of the four known interactions of nature: the strong interaction, the weak interaction, and electromagnetism, whereby the latter two mix into the *electroweak interaction* (EW) [27–29]. The SM is a relativistic quantum field theory and is usually formulated using a Lagrangian density. The fourth interaction, gravity, does not play any measurable role for elementary particle collider physics at the energies currently achievable due to its feeble strength.

One cornerstone of the SM is the process by which the W and Z gauge bosons acquire their mass, the process of electroweak symmetry breaking. The idea was first developed in the 1960s by several physicists [30–36] and is nowadays known as the *Brout-Englert-Higgs Mechanism* (BEH mechanism). A new complex scalar doublet field is introduced, where its potential has the particular property that its minimum is not at zero field strength, but rather at a non-vanishing *vacuum expectation value* (vev). When the interaction terms of the Higgs boson with the W and Z bosons in the Lagrangian density are developed around the minimum at this vev, terms that are identified as mass terms of these bosons appear. Of the four degrees of freedom of the complex scalar doublet, three are utilized for the longitudinal polarizations of the W and Z bosons, *i.e.*, their masses, while the fourth degree of freedom is utilized for the additional scalar particle predicted by this BEH mechanism, the Higgs boson. This theory is very predictive, as the only free parameter that remains to be determined experimentally is the mass of the Higgs boson, while all its interactions follow from this. In addition, the interaction of the Higgs boson with the SM fermions can also be utilized to describe their masses with one so-called *Yukawa coupling constant* for each fermion.

Most predictions of the SM have been experimentally verified over the last several decades to sometimes incredible precision in many measurements. One such partial summary of the agreement between SM predictions and measurements performed by the ATLAS Collaboration can be seen in Fig. 2.1. Shown are the production cross sections for many SM processes measured with proton-proton collision data taken at center-of-mass energies of $\sqrt{s} = 7, 8$, as well as 13 TeV, if available. The results are compared to the best available theory prediction for each process at each center-of-mass energy. All shown theory calculations are performed at *next-to-leading order* (NLO) in the perturbative expansion of the theory of strong interactions, *Quantumchromodynamics* (QCD), or

better. An incredible agreement, within the uncertainties of both the experimental measurements and the theory predictions, can be seen over many orders of magnitude of the production cross section. This highlights the success of both the experimental program of the LHC experiments, as well as the very detailed theory predictions that are achieved in intricate calculations. This summary also contains several measurements performed by my team and me, which will be discussed in the following sections.

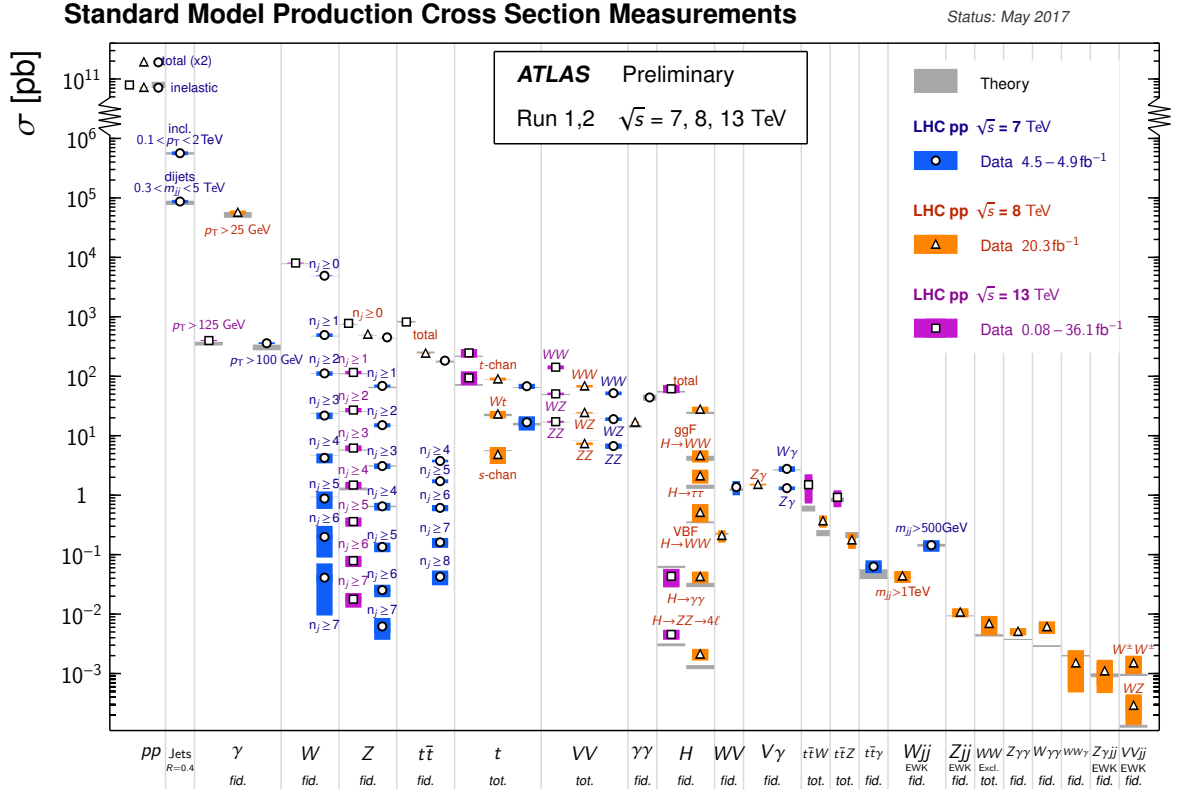


Figure 2.1: Summary of Standard Model physics results from the ATLAS Collaboration in comparison with theory predictions. The production cross sections are shown on the y-axis for the SM processes listed at the bottom. The values of the production cross section for each process are shown for proton-proton collision data taken at center-of-mass energies of $\sqrt{s} = 7, 8$, as well as 13 TeV, if available. The results are compared to the best available theory calculation for each process at each center-of-mass energy. Both measured and calculated production cross sections are shown including their uncertainties. Taken from Ref. [37].

2.2 Overview

One of the main reasons for the construction of the *Large Hadron Collider* (LHC), as well as the ATLAS and CMS experiments, was to discover the SM Higgs boson, or in the case

of its non-discovery reject the BEH mechanism as it is implemented in the SM. Before the LHC started, it was known from a fit to the electroweak precision data [38], and from direct searches for the SM Higgs boson at the experiments of the LEP-II electron-positron collider [39], that the SM Higgs boson would need to be heavier than 114.4 GeV and lighter than 285 GeV, at 95% confidence level, see Fig. 2.2. The goal was to be able to discover a SM-like Higgs boson with a mass between 100 GeV and about 1 TeV, thus covering the full mass range still allowed by the above mentioned constraints.

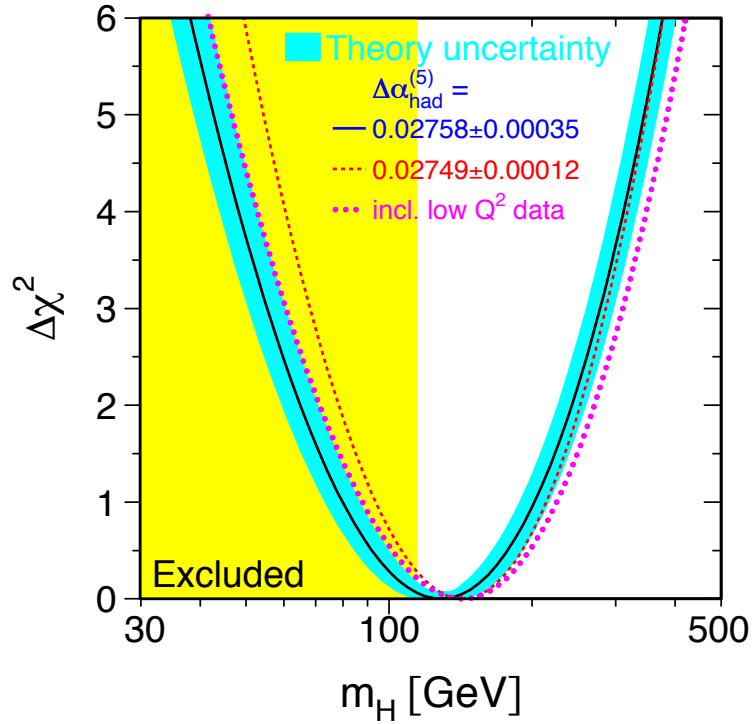


Figure 2.2: The delta-chi-square distribution as a function of the Higgs boson mass. The black line is the result of a fit to electroweak data, while the blue band represents the theory uncertainty. The vertical yellow band show the 95% confidence level exclusion limit on m_H in the direct search for the Higgs boson performed at the experiments of the LEP-II electron-positron collider. Taken from Ref. [38].

The LHC started its physics operation in November 2009 and concluded the first data-taking phase early in 2013 (Run 1). The data taken during 2010 and 2011 were recorded at a center-of-mass energy of $\sqrt{s} = 7$ TeV, while this was increased to $\sqrt{s} = 8$ TeV in 2012. The total integrated luminosity recorded by the ATLAS and CMS experiments was about 25 fb^{-1} per experiment, of which about 20 fb^{-1} was recorded at $\sqrt{s} = 8$ TeV in 2012. The second data-taking period of the LHC (Run 2) started in 2015 and is planned to conclude at the end of 2018. During this Run 2, the center-of-mass energy

was increased to $\sqrt{s} = 13$ TeV and the total integrated luminosity recorded thus far is 75 fb^{-1} . The third data-taking period (Run 3) is planned for the years 2021 until 2023 with an expected integrated luminosity of 300 fb^{-1} delivered at the design center-of-mass energy of $\sqrt{s} = 14$ TeV. The long periods between these runs are needed for maintenance and upgrade of the LHC, as well as of the experiments.

In order to achieve the goal of discovering the SM Higgs boson, or refuting its existence, a detailed strategic planning, starting even before Run 1, and a thoroughly executed research was required. This commenced within the ATLAS Collaboration with a final pre-data-taking consolidating effort, where the whole chain from the detector to the final analysis results were exercised with simulation [21]. This and following efforts included optimizing the primary lepton triggers, as well as preparations and subsequent measurements of the lepton trigger, reconstruction, identification, and isolation efficiencies using $Z \rightarrow \ell\ell$ data, a process that provides a large number of events even during the early low-luminosity phase of LHC operation due to its sizable production cross section. These studies are absolutely essential as a preparation to search for the Higgs boson in decay channels with electrons in the final state, *i.e.*, the $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ (with $\ell = e$ or μ throughout this document) as well as the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channels, especially during the early phase of LHC operations, as this is the time when one measures and calibrates how the ATLAS detector responds to actual proton-proton collision events for the first time.

These thorough preparations and subsequent data analysis in the search for the SM Higgs boson in its decay to four charged leptons led ultimately to the discovery of a Higgs boson in a combination of the results from the analyses of two other decay channels $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. As a result of the discovery of a Higgs boson by the ATLAS and CMS Collaborations [18, 40], the Nobel prize in physics was awarded in 2013 to François Englert and Peter Higgs for their original description of the BEH mechanism and the resulting Higgs boson.

However, in order to confirm that the discovered Higgs boson is indeed consistent with the predictions made by the SM, it became necessary to measure the properties of this new particle as precisely as possible. The analysis of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel played a major role in this, as this decay channel exhibits a large decay branching fraction and two isolated leptons in the final state, which provide a distinct signature in the ATLAS detector. The analysis of the full Run-1 dataset in this channel resulted in an unprecedented precision of the measurement of the ratio of the measured total production cross section times branching fraction to the in the SM expected value of $1.09^{+0.16}_{-0.15}$ (stat.) $^{+0.17}_{-0.14}$ (sys.). Thus, the observation of Higgs boson production in decays to two W bosons alone was achieved, as well as an important evidence for the Higgs boson production through *vector-boson-fusion* (VBF) with a significance of 3.2 standard deviations.

The mass of the Higgs boson was very precisely measured in a combined analysis of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ decay channels by the ATLAS and CMS Collaborations as $m_H = 125.09 \pm 0.21$ (stat) ± 0.11 (sys.) GeV [41]. As already described in the previous section, with this precise mass measurement, the interactions of the Higgs boson with

other particles are precisely predicted in the theory of the SM. Thus, in order to allow for measurement imprecisions as well as contributions to these interactions from new sources, it is required to introduce free parameters that can be used to quantify the agreement with the SM predictions. This so-called κ -framework [42] introduces a free multiplicative coupling scale parameter κ_i for every coupling of the Higgs boson with the particles of the SM in such a way that the SM is recovered when all κ_i are equal to unity. Using the Run-1 measurement of the production rates of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel, these so-called Higgs boson coupling modifiers for interactions with vector bosons (κ_V) and fermions (κ_F) were found to be in good agreement with the SM expectations of unity with best fit values of $\kappa_V = 1.04 \pm 0.11$ and $\kappa_F = 0.93^{+0.32}_{-0.23}$.

After the individual Higgs-boson analyses using all data from the LHC Run 1 were completed, a global analysis of these results from the ATLAS and CMS Collaborations was performed [43]. Amongst several more fine-grained tests, κ_V and κ_F were determined in this global analysis and found to be in excellent agreement with the SM prediction, as can be seen in Fig. 2.3. It shows the individual 68% confidence-level allowed contours resulting from the individual decay channels $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, $H \rightarrow \tau\tau$, and $H \rightarrow b\bar{b}$ in the κ_V - κ_F plane, the 68% and 95% confidence-level allowed contours for the fully-combined result, and the expected value of $\kappa_V = \kappa_F = 1$ from the SM. One can also see that the single-most-precise measurement of these quantities is using the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel, which results in this channel having the largest impact on the global result. One of the main predictions of the BEH mechanism is that the SM Higgs boson interaction with other particles of the SM is related to the mass of these particles. Figure 2.3 shows also an impressive confirmation of this relation, using the combined analysis of the same ATLAS and CMS Run-1 results as previously mentioned, and strictly assuming the full validity of the SM for this test. Also for this test, the results from the analyses of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel have a major impact, especially regarding the data points for the W boson (through the decay to two W bosons, as well as VBF production), the Z boson (through VBF production), and the top quark (through *gluon-fusion* (ggF) production). Overall, a very good consistency of the properties of the observed Higgs boson with the predictions for the SM Higgs boson were established with these measurements.

The most important background to the measurement of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decays in the ggF production channel is the SM non-resonant $WW \rightarrow \ell\nu\ell\nu$ process. As the measurement performed by the ATLAS Collaboration of the production cross section of this process in the exclusive final state with zero accompanied jets using data recorded at $\sqrt{s} = 8$ TeV revealed that the best theory predictions were low by about 5–15% [44], it became even more important for future measurements of Higgs boson properties in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel to measure the $WW \rightarrow \ell\nu\ell\nu$ production cross section at $\sqrt{s} = 13$ TeV. The measured cross section value was found to be 529 ± 20 (stat.) ± 50 (sys.) ± 11 (lumi.) fb [45], while improved theory predictions are in agreement with this result. This is an important milestone towards the finalization of the ongoing measurement of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decays using data recorded at $\sqrt{s} = 13$ TeV.

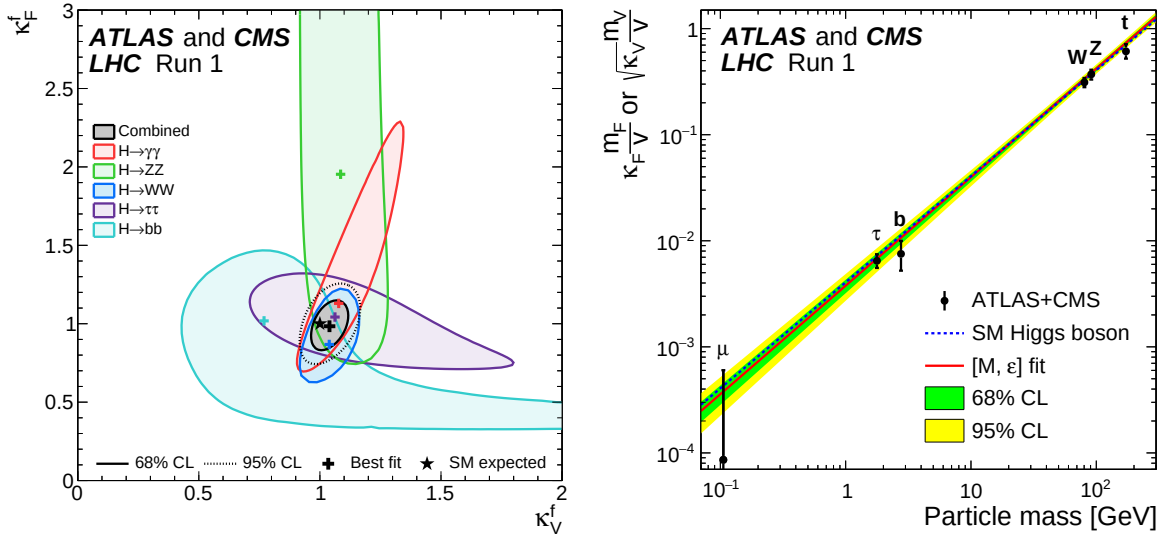


Figure 2.3: Result of the combined analysis of the ATLAS and CMS LHC Run-1 results [43]. The figure on the left shows the result of the combined measurement of the coupling-strength modifiers for the coupling of the Higgs bosons to fermions and to vector bosons, κ_F^f and κ_V^f , respectively, including also the constraints from the individual decay channels of the Higgs boson. The figure on the right shows the confirmation, within uncertainties and the assumption of the validity of the SM, of the direct correlation between the interaction strength of the Higgs boson with other particles of the SM and the mass of these particles.

One limitation of the above-mentioned κ -framework is its non-sensitivity to the tensor structure of the couplings of the Higgs boson to SM particles. One way to mitigate this is to determine the Wilson coefficients of an *Effective Field Theory* (EFT), which adds new interaction terms, while respecting the symmetries of the SM. Such an approach assumes that there are no new resonances below an energy of about 1 TeV, which seems to be a valid assumption, as the LHC has as of now not yet discovered any other new particle. However, if many Wilson coefficients are to be determined simultaneously, using also many measured distributions, the computational complexity with conventional methods becomes overwhelming. Thus, the new method of Effective Lagrangian Morphing has been developed [15] in order to prepare for measurements using the large datasets that are expected by the end of Run 2.

As thus far no significant deviations from the SM have been observed in measurements of the Higgs boson properties performed using data recorded during the LHC Run 1, an additional approach to search for new phenomena in the Higgs boson sector has been adopted at the beginning of Run 2, namely the direct search for new heavy Higgs bosons, which also included interpretations in models with new heavy vector bosons or tensor bosons. As no significant excess above the SM background expectation in any of these searches was found, upper limits on the production cross section of such new bosons as a function of their mass were measured and model-dependent exclusion limits on various model parameters were determined, as well as lower bounds on boson masses in specific

benchmark models. These new limits are a vast improvement w.r.t. the previously available limits due to the large increase of the center-of-mass energy from $\sqrt{s} = 8$ TeV to 13 TeV of the recorded proton-proton collision data used for these new analyses, and thus the resulting large increase in the effective parton luminosity for high masses.

It is an incredible scientific achievement to progress within a few years from the start of the LHC to the discovery of the Higgs boson and the subsequent measurement of its properties, which thus far are all consistent with SM predictions. No new high-mass bosonic resonances have been found as of now. However, precision measurements of properties of the Higgs boson using the very large expected datasets to be delivered by the LHC might uncover new phenomena. The following sections describe in detail several of the above mentioned results, and in particular my contributions to these.

2.3 Standard Model Vector Bosons

The weak gauge bosons W and Z play a crucial role in the breaking of the electroweak symmetry as these are the bosons that acquire mass. And experimentally, their leptonic decays leave a clean and very distinct signature in the ATLAS detector. Additionally, the production cross sections of single W or Z boson is rather large, thus, a large number of leptonically decaying weak vector bosons was available already in the early phase of LHC operations. Therefore, measuring the leptonic decays of W and Z bosons provides an excellent way to study not only electroweak physics, but also precisely determine how the ATLAS detector responds to charged leptons.

I started to study simulated $Z \rightarrow e^+e^-$ decays before the LHC delivered its first colliding protons. I used these signal events and suitable background events to optimize the primary single electron trigger that would be used later on for data taking, both in terms of efficiency and also event rate, *i.e.*, keeping the maximum number of signal events while staying within the technically allowed and very limited bandwidth of the real ATLAS trigger system. These studies are part of the final comprehensive pre-data-taking ATLAS publication [21], which was prepared to ready the collaboration and all its detector and computing systems for the actual data taking that commenced soon after.

Together with a doctoral student under my supervision, I then developed the so-called *Tag&Probe* method on $Z \rightarrow e^+e^-$ events to measure trigger and identification efficiencies of electrons in simulated events and data. These studies were embedded in a small collaboration of ATLAS researchers from the University of Mainz, the University of Liverpool, the University of Hamburg, and DESY, whose goal was to measure the double-differential cross sections of $Z \rightarrow e^+e^-$ and $W \rightarrow e\nu$ events. Within this team, my doctoral student and I focused on the analysis of $Z \rightarrow e^+e^-$ events, while others focused on the analysis of $W \rightarrow e\nu$ events. The results of this pioneering research were documented in Ref. [20], which initially led to a publication of the inclusive and differential cross sections of W and Z bosons using 36 pb⁻¹ of data collected at $\sqrt{s} = 7$ TeV [46], also shown in Fig. 2.1. A subsequent interpretation of these results, together with data from the HERA experiments, led to a measurement of the strange-quark density of the proton. It was determined to be consistent with unity ($1.00^{+0.25}_{-0.28}$) in the ratio of

the strange-to-down sea quark distribution at absolute four-momentum transfer squared $Q^2 = 1.9 \text{ GeV}^2$ and longitudinal parton-momentum fraction $Bjorken-x = 0.023$ [47].

The ATLAS Collaboration also measured the cross section of W^+W^- pair production in the fully leptonic final state using proton-proton collision data at $\sqrt{s} = 8 \text{ TeV}$ corresponding to 20.3 fb^{-1} of integrated luminosity collected during 2012 [44]. The best theory calculations available at that time predicted a cross section 5–15% lower w.r.t. the measured cross section in the exclusive 0-jet category. Additionally, also the final SM $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ measurement using data from the LHC Run 1 [16] revealed that the predicted W^+W^- cross section is smaller w.r.t. the exclusive 0-jet region measured with data, consistent with the aforementioned result. This result will be further discussed in the following section. As W^+W^- pair production is the largest background in the measurement of the ggF induced Higgs boson cross section measurement in decays to two W bosons without associated jets, as well as the source of the leading systematic uncertainty, it is important to measure this process precisely also using proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$. Thus, a postdoctoral researcher under my supervision and I performed the measurement of the cross section of W^+W^- pair production in the fully leptonic final state using proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$ corresponding to 3.16 fb^{-1} of integrated luminosity collected during 2015 [45]. Large parts of this analysis was carried out by us, including the final extraction of the cross section, and estimates of all experimental uncertainties in the analyzed samples. Agreement is found between the measured cross section of $529 \pm 20 \text{ (stat.)} \pm 50 \text{ (sys.)} \pm 11 \text{ (lumi.) fb}$ and the most accurate calculations available, which also improved considerably since the time of the above mentioned previous publication. This result, together with the results from the earlier LHC data-taking periods, is also shown in Fig. 2.1.

2.4 Standard Model Higgs Boson

Following the SM, the Higgs boson can be produced at the LHC in several different production channels. The process with the dominant production cross section is the loop-induced ggF process, see Fig. 2.4 (a), followed by the VBF process that exhibits already at leading order two jets in the final state with a characteristic rapidity separation between these two jets and a high invariant di-jet mass, see Fig. 2.4 (b). These are followed by the W and Z associated production, see Fig. 2.4 (c), the top- and bottom-quark pair associated production ($t\bar{t}H$ and $b\bar{b}H$, respectively), see Fig. 2.4 (d), as well as the single-top-quark associated production. The production cross section in proton-proton collisions of all of these processes are shown in Fig. 2.6 as a function of the center-of-mass energy of the collider for a Higgs boson mass of 125 GeV, together with the theory uncertainties for each. Given the mass of the Higgs boson, which is by now very precisely measured as $m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (sys.) GeV}$ [41], with first measurements at $\sqrt{s} = 13 \text{ TeV}$ also already being available [48, 49], and is the only free parameter in the theory, as mentioned in Section 2.1, the production cross sections can be calculated quite precisely. For example, the dominant gluon-fusion induced Higgs boson production cross section is nowadays calculated up to fourth order of the perturbative

expansion of the theory of the strong interaction ($N^3\text{LO}$ QCD) and *next-to-leading order* (NLO) EW, which leads to an unprecedented theory uncertainty due to missing higher order terms of only $\pm 3.9\%$ [6, 50]. Also the decay branching ratios of the SM Higgs boson to other SM particles are precisely calculated, given the mass of the Higgs boson. The decay branching fractions of the different SM decay modes and their theory uncertainties are also shown in Fig. 2.6 as a function of the mass of the Higgs boson.

The signature with the highest signal-to-background ratio at the LHC is the decay channel $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ as it exhibits four isolated leptons, which is a clear sign of an electroweak process at a hadron collider. However, this process is a rare process at the LHC due to the small branching ratio of the Higgs boson to two Z bosons, see Fig. 2.6, as well as the small branching ratio of a Z boson decaying to charged leptons. I was part of the analysis team where I mainly worked on the event selection. This effort led ultimately to the discovery of the Higgs boson in July 2012 [18].

Another discovery decay channel is $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, where the Higgs boson is produced in the ggF or VBF production mode. This decay channel has the advantage of a large number of produced signal events, compared to the $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ decay channel, see Fig. 2.6, but the disadvantage of no possibility to directly reconstruct the Higgs boson mass due to the neutrinos in the final state and additionally a worse signal-to-background ratio.

I got heavily involved in the analysis of this decay channel in the production through ggF or VBF when I joined the University of Freiburg and started to supervise the students and the postdoctoral researcher working on this topic. We worked on several key aspects for the final Run-1 result [16]. In the VBF production mode, we worked on providing a sufficient number of simulated background events for $Z \rightarrow \tau\tau$ events by merging a specially filtered sample that exhibits events matching the VBF topology with the standard sample. Furthermore, we did a simultaneous multidimensional selection

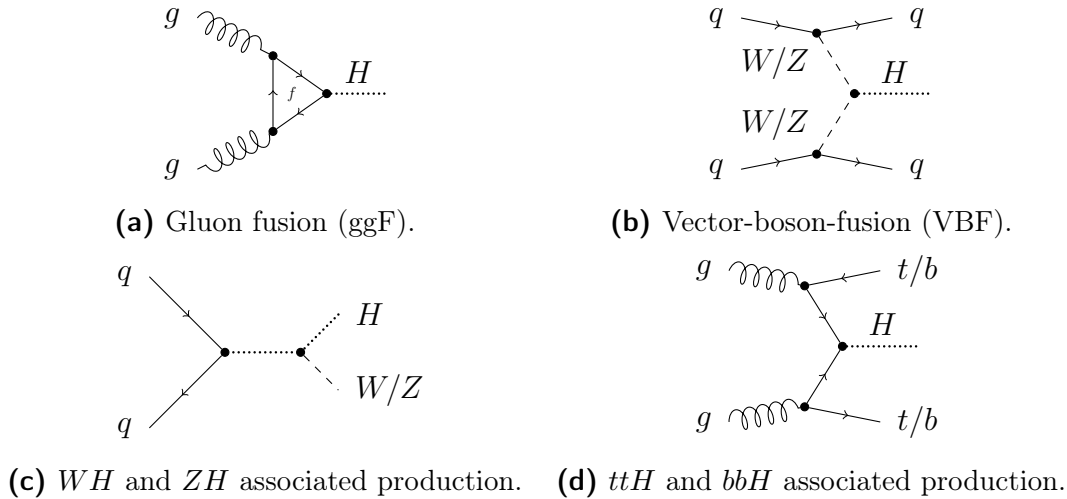


Figure 2.4: Leading-order Feynman diagrams for the production of the SM Higgs boson. Shown are (a) ggF, (b) VBF, (c) WH and ZH associated production, and (d) ttH and bbH associated production.

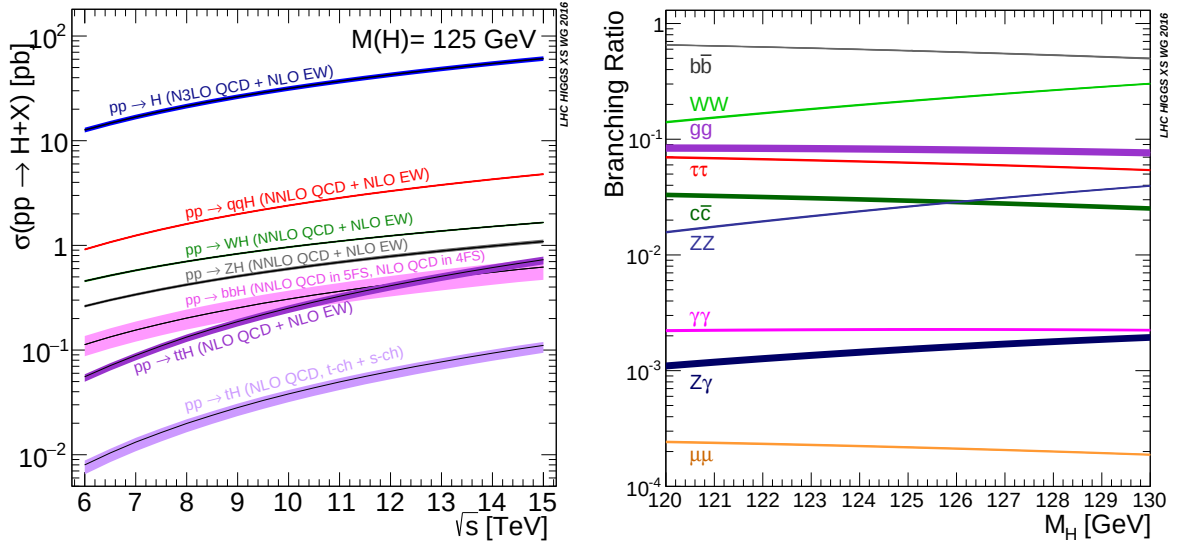


Figure 2.6: Production cross section (left) and decay branching ratios (right) of the Standard Model Higgs boson with a mass $m_H = 125$ GeV as a function of the center-of-mass energy of the LHC, and the Higgs boson mass, respectively. In both cases, the line width represents the theoretical uncertainty. Both are taken from Ref. [6].

optimization in order to maximize the final sensitivity. We also worked on the data-driven estimation of identified leptons that did not originate from a W or Z boson decay using for the first time a likelihood-based background estimation method. In addition, we provided the analysis framework that was also used by ATLAS team members from other institutes. This resulted in the direct observation of the Higgs boson in the decay mode to two W bosons on its own. The ratio of the measured total production cross section times branching fraction to the value expected in the SM is $1.09^{+0.16}_{-0.15}$ (stat.) $^{+0.17}_{-0.14}$ (sys.), which reflects the unprecedented precision of this measurement. The final combined transverse mass distribution for the categories with zero or one associated jets is shown in Fig. 2.7. Evidence for the VBF signal was found with a significance of 3.2 standard deviations, which can also be seen in Fig. 2.7.

As already alluded to in the previous section, the normalization factor of the W^+W^- background in the category without any jets in the final state w.r.t. the NLO QCD inclusive calculation from the MCFM program was found to be 1.22 ± 0.03 (stat.) ± 0.10 (sys.), which is consistent with the theoretical prediction at the level of approximately two standard deviations. This was one of my motivations to measure the W^+W^- exclusive zero-jet cross section in data recorded at $\sqrt{s} = 13$ TeV, as described in Section 2.3. I also initiated a study to reduce the impact of theory uncertainties on the W^+W^- background by using $WZ \rightarrow \ell\nu\ell\ell$ events as a data control measurement with promising results. This will likely become important for the expected very large dataset at the end of Run 3, or possibly already at the end of Run 2.

The measured value of $\mu_{\text{ggF}} = 1.02 \pm 0.19$ (stat.) $^{+0.22}_{-0.18}$ (sys.) and the measured value of $\mu_{\text{VBF}} = 1.27^{+0.44}_{-0.40}$ (stat.) $^{+0.30}_{-0.21}$ (sys.) in this $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis are used

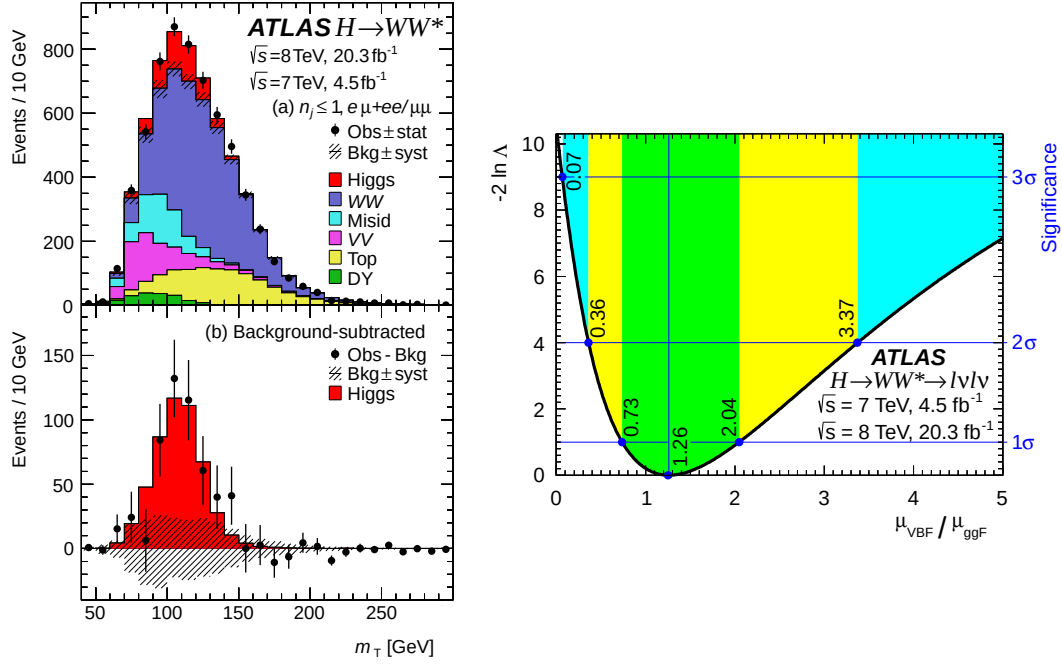


Figure 2.7: The final combined transverse mass distribution for the categories with zero or one associated jet of the $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$ analysis using data collected at $\sqrt{s} = 7$ TeV and 8 TeV (left), where the top panel shows the post-fit background and signal contributions in the filled areas, as well as the measured data points, and the bottom panel shows the same information, but with the background component subtracted. A likelihood scan as a function of $\mu_{\text{VBF}}/\mu_{\text{ggF}}$ where the value of the likelihood for this ratio at zero gives the significance of the VBF signal as 3.2 standard deviations (right). Taken from Ref. [16].

to extract the fermionic and bosonic couplings of the Higgs boson and test their compatibility with the SM prediction. The Higgs boson coupling modifiers for interactions with vector bosons (κ_V) and fermions (κ_F) were found to be in good agreement with the SM expectations of unity with best fit values of $\kappa_V = 1.04 \pm 0.11$ and $\kappa_F = 0.93^{+0.32}_{-0.23}$, which can be seen in Fig. 2.8. The ggF production is in the SM proportional to κ_F^2 , the VBF production to κ_V^2 , and the partial decay width to two W bosons to κ_V^2 . However, the total width of the Higgs boson is in the SM largely composed of fermionic partial widths, and thus largely proportional to κ_F^2 . Thus, the more precise measurement of μ_{ggF} is mostly constraining κ_V , as the sensitivity to κ_F is largely canceling in the ratio to the total width. The inverse is true for the less precise measurement of μ_{VBF} and thus the less precisely determined value of κ_F .

After the end of LHC Run 1 data taking, a combined coupling analysis of the Higgs boson results from the ATLAS and CMS Collaborations was performed and published [43]. In this analysis, the final $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$ results were the most precise amongst all studied decay channels, as can also be seen in Fig. 2.3. The $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$ results place the most stringent limits on the coupling-strength modifiers for the coupling of the Higgs bosons to fermions and to vector bosons, κ_F^f and κ_V^f , respectively. It can also be

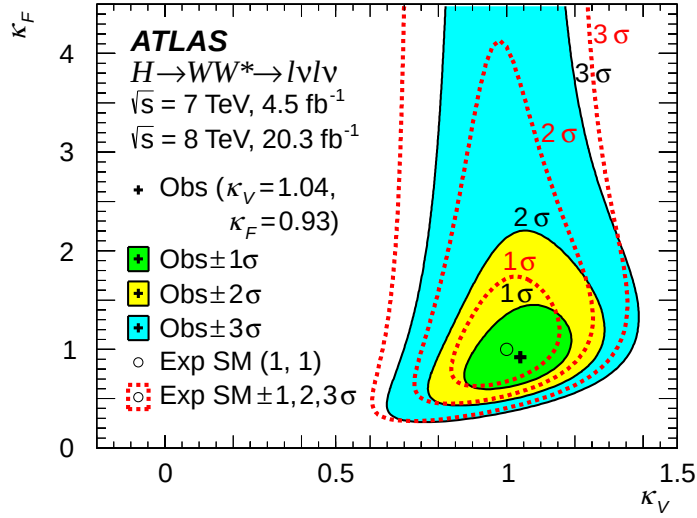


Figure 2.8: Likelihood scan as a function of the Higgs boson coupling modifiers κ_V and κ_F for the Higgs boson couplings to vector bosons and fermions, respectively, measured in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel using data collected at $\sqrt{s} = 7 \text{ TeV}$ and 8 TeV . The best-fit observed (expected SM) value is represented by the cross symbol (open circle) and its one, two, and three standard deviation contours are shown by solid lines surrounding the filled areas (dotted lines). Note that the y axis spans a wider range than the x axis. Taken from Ref. [16].

seen in Fig. 2.3 that all measurements of the interaction strengths of the Higgs boson with the other particles of the SM are consistent with being directly correlated to the mass of these SM particles. This is an excellent confirmation of the mass-generating BEH-mechanism in the SM, under the assumption of the full validity of the SM also in loop-induced processes. For this interpretation, the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ results have a large impact, especially on the measurement of the coupling strengths of the Higgs boson to W bosons, to top quarks (via ggF production), and to Z bosons (via VBF production).

In preparation for the restart of the LHC for Run 2, and thus the new analysis of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel, I wrote a new software framework to provide the required samples with the final physics object calibrations, corrections, and systematic uncertainties. At the same time, a doctoral student under my supervision improved the analysis framework. Both of these are now used by the whole ATLAS $H \rightarrow WW^*$ group and beyond, see Section 2.6.2 for more information. My contributions and expertise were recognized within ATLAS, resulting in me becoming one of the two conveners of the whole ATLAS HWW group for the standard duration of one year during the important and critical re-start phase at the beginning of Run 2. A team of up to two doctoral students and one master student under my supervision implemented and validated the full ggF analysis selection, including all data control regions to validate the simulation. We also improved the top-quark induced background suppression and determination, and evaluated theoretical uncertainties on this background and the background events originating from the $Z \rightarrow \tau\tau$ process. We implemented and validated the complex and

very sensitive final likelihood-based signal extraction. First preliminary results on the VBF and WH associated production modes, still using a limited dataset of 5.8 fb^{-1} recorded at $\sqrt{s} = 13 \text{ TeV}$ were already made public [5]. We are currently preparing a publication measuring the cross sections of the gluon-fusion and vector-boson-fusion production modes using the full proton-proton collision data taken in the years 2015 and 2016. The CMS Collaboration has also analyzed the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel using the first data recorded at $\sqrt{s} = 13 \text{ TeV}$ corresponding to an integrated luminosity of 15.2 fb^{-1} [51]. A cross section times branching fraction of 1.05 ± 0.26 times the value expected in the SM has been measured with a significance of 4.3 standard deviations, while 4.1 standard deviations were expected.

A first combination of individual production channels of the $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ and $H \rightarrow \gamma\gamma$ decay channels using up to 14.8 fb^{-1} of proton-proton data recorded at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ was performed by a doctoral student under my supervision and others [9]. The individual production and decay rates were measured. The total cross section of Higgs boson production at $\sqrt{s} = 13 \text{ TeV}$ was also determined and found to be in agreement with theory predictions, see Fig. 2.9. These results were presented at the ICHEP 2016 conference in Chicago, USA. They are a first step towards a new combination of all SM Higgs boson measurements using the full Run 2 dataset. All of the above discussed results are again summarized in Fig. 2.1.

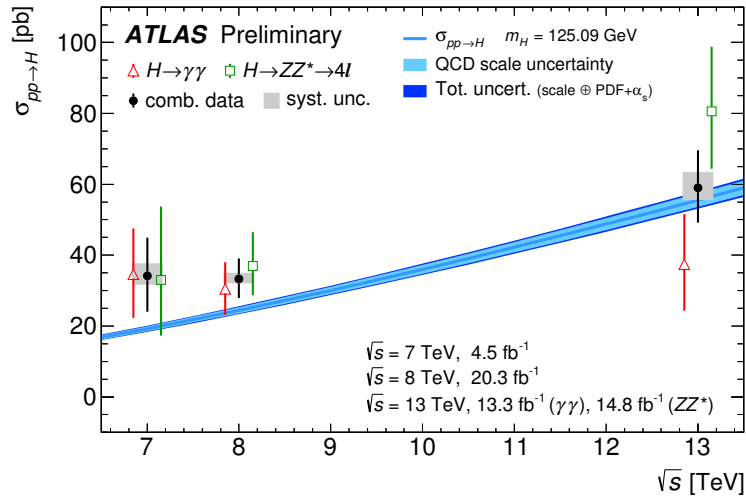


Figure 2.9: Total Higgs boson production cross section at different LHC center-of-mass energies, measured in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ decay channels and their combinations, compared to SM predictions at up to N³LO in QCD and NLO in EW [9].

From the analysis of the Run-1 data, we know that the properties of the discovered Higgs boson agree with the predictions from the SM to a precision of at best 10%, in most measurements considerably worse. Precision measurements of the Higgs boson properties will become possible with the ever increasing dataset. One rather model-independent way to quantify possible *beyond the Standard Model* (BSM) effects in the

interactions of the observed Higgs boson is to use an *Effective Field Theory* (EFT) where all heavy degrees of freedom are integrated out. Thus, the only assumption is that there are no new particles with masses below about 1 TeV, which seems to be valid, as the LHC has not yet discovered such new particles. One can then measure the individual so-called Wilson coefficients of each interaction term of such an EFT. However, as there are many such terms that can affect the physics of the observed Higgs boson, conventional methods can only measure a few such coefficients simultaneously, due to the curse of dimensionality, usually assuming the other BSM coefficient to be zero. This is where a doctoral student under my supervision and I, together with three other doctoral students from three different institutes, developed a completely new approach to allow for the simultaneous determination of many Wilson coefficients by directly measuring these coefficients in a likelihood function and allowing for a smooth interpolation, or morphing, using directly the final discriminating distributions, and thus greatly reducing the computational complexity of the established matrix element reweighting method. This new *Effective Lagrangian Morphing* method was validated using simulated events and the results were made public [15]. These studies are also part of the standard reference for Higgs boson physics, the *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector* by the *LHC Higgs Cross Section Working Group* [6], of which I am a co-author.

2.5 Search for new high-mass Bosons

One excellent way to search for new phenomena is to study the properties of the recently discovered Higgs boson precisely and accurately, as discussed in the previous section. Another way is to search directly for new resonances in the data. This is the approach that will be described in this section. It was especially interesting to search for new heavy resonances when the LHC nearly doubled its center-of-mass energy from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 13$ TeV, as the resulting parton luminosity ratio between these two center-of-mass energies rises rapidly towards high masses, as can be seen in Fig. 2.10.

New heavy resonances are motivated by many different models, be it an extended Higgs boson sector for heavy scalar particles, heavier cousins of the W and Z bosons for heavy vector particles, or new models of gravity, like bulk Randall-Sundrum models [53], for heavy tensor particles. For these types of searches, it is important to be able to analyze newly incoming data quickly and thoroughly, *i.e.*, have a good software infrastructure set up and a good team available to perform the analysis. This was the case for the high-mass $X \rightarrow WW \rightarrow \ell\nu\ell\nu$ search analysis, where I provided the infrastructure to treat systematic variations and perform the analysis. This analysis team published several preliminary results on ever increasing datasets [10, 13], while the final publication with the full dataset recorded during 2015 and 2016 was recently submitted to the European Physics Journal C [1]. As no significant excesses above the SM expectations have been observed, 95% confidence level upper limits on the cross section times branching ratio to W^+W^- have been set, see Fig. 2.11. Interpretations were performed for both ggF and VBF production modes for heavy scalar particles with a narrow or large width, heavy

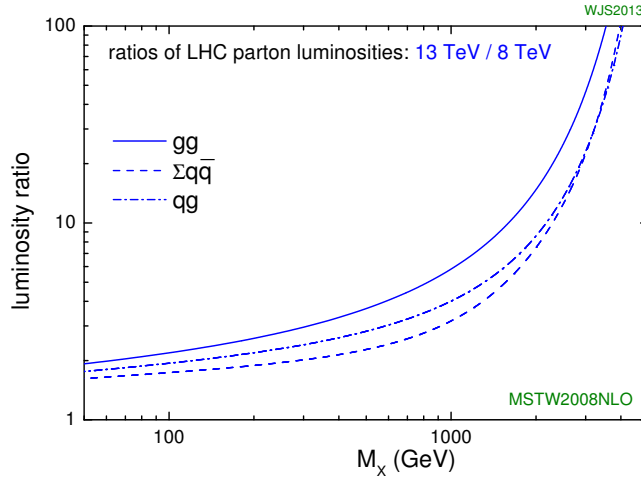


Figure 2.10: Parton luminosity ratio between the LHC operating at $\sqrt{s} = 13$ and 8 TeV as a function of the mass of the produced system [52]. The three curves represent the distinct initial states that are possible at a proton-proton collider.

vector particles, and heavy tensor particles. Parameter exclusion regions have been determined for several types of *Two-Higgs-Doublet Models* (2HDM) [54], examples of which is reproduced in Fig. 2.12. The shown Type II 2HDM model contains two Higgs doublets, one that couples to up-type quarks and another that couples to down-type quarks and charged leptons. The ratio of vacuum expectation values of these two Higgs doublets is denoted as $\tan\beta$. The model contains five physical Higgs bosons, assuming conservation of CP symmetry: one neutral CP-odd (A), two neutral CP-even (h , H), and two charged ($H^\pm$) Higgs bosons. The angle α parametrizes the mixing between the two neutral CP-even Higgs bosons. The CMS Collaboration has also searched for new high-mass Higgs bosons in the decay to two W bosons [55]. No excess above the SM expectation has been observed and the obtained limits are less stringent, as only a partial dataset recorded at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 2.3 fb^{-1} has been analyzed thus far.

Another way to search for new bosonic resonances is the decay $X \rightarrow WV \rightarrow \ell\nu q\bar{q}$, with $V = W$ or Z . This decay channel is especially sensitive at very large m_X when the two quarks hadronize so close to each other, due to the Lorentz boost, that they are reconstructed as a single jet with a large radius parameter R . This was the analysis performed, where jet substructure techniques were employed to isolate those large- R jets that are consistent with originating from a W boson (or Z boson) decay. I have supervised the analysis team in their daily work as one of the two conveners of the ATLAS HWW group, while at the same time also coordinating with analysis teams studying other related final states. The results of all di-boson final state ($\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, $\nu\nu q\bar{q}$, and $q\bar{q}q\bar{q}$) search analyses using 3.2 fb^{-1} of data recorded at $\sqrt{s} = 13$ TeV were combined. No significant excess above the SM expectation has been observed. Thus, 95%

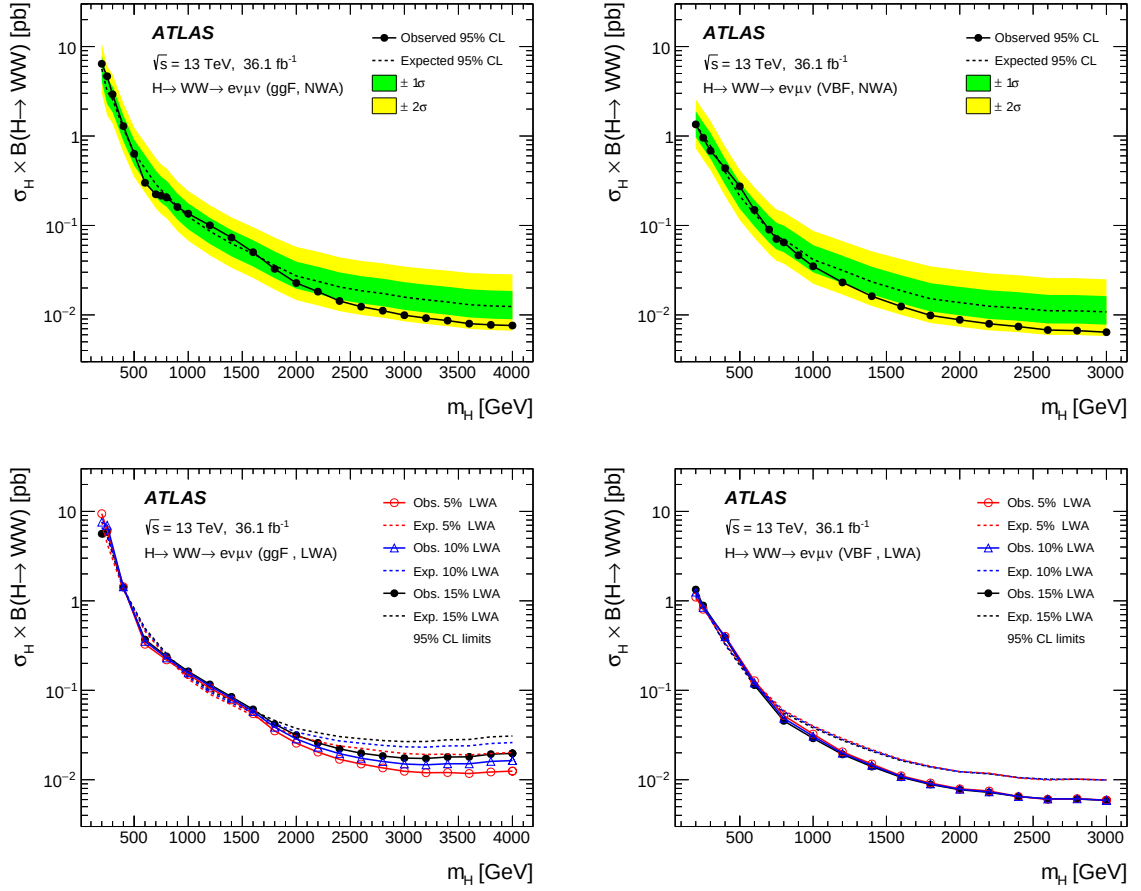


Figure 2.11: Results of the search for heavy $X \rightarrow WW \rightarrow \ell\nu\ell\nu$ decays. Shown are upper limits at 95% confidence level on the heavy Higgs boson production cross section times branching fraction into two W bosons $\sigma_H \times \mathcal{B}(H \rightarrow WW)$ in the $e\nu\mu\nu$ final state. Results for an assumed ggF (left) and VBF (right) production mode, as well as an assumed narrow width (top) and three different values for a large width, given as percentage of the mass of the heavy Higgs boson (bottom), are shown. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit. Taken from Ref. [1].

confidence level upper limits on $\sigma(pp \rightarrow X \rightarrow VV)$ have been determined as a function of m_X in several models where X is a scalar particle, a vector particle, or a tensor particle.

Finally, a search for a high-mass boson decaying into a pair of tau leptons has also been performed in several stages. This analysis was performed using the *Minimal Supersymmetric Standard Model* (MSSM) [56–58] scenario as a guideline. The Higgs boson sector of the MSSM is essentially that of the Type II 2HDM described above. The properties of this sector in the MSSM depend at leading order on only two BSM parameters, which can be chosen to be the mass of the CP-odd Higgs boson, m_A , and $\tan\beta$. In this scenario, the couplings of the MSSM heavy Higgs boson to down-type fermions are enhanced, compared to the SM Higgs boson, for large values of $\tan\beta$. This

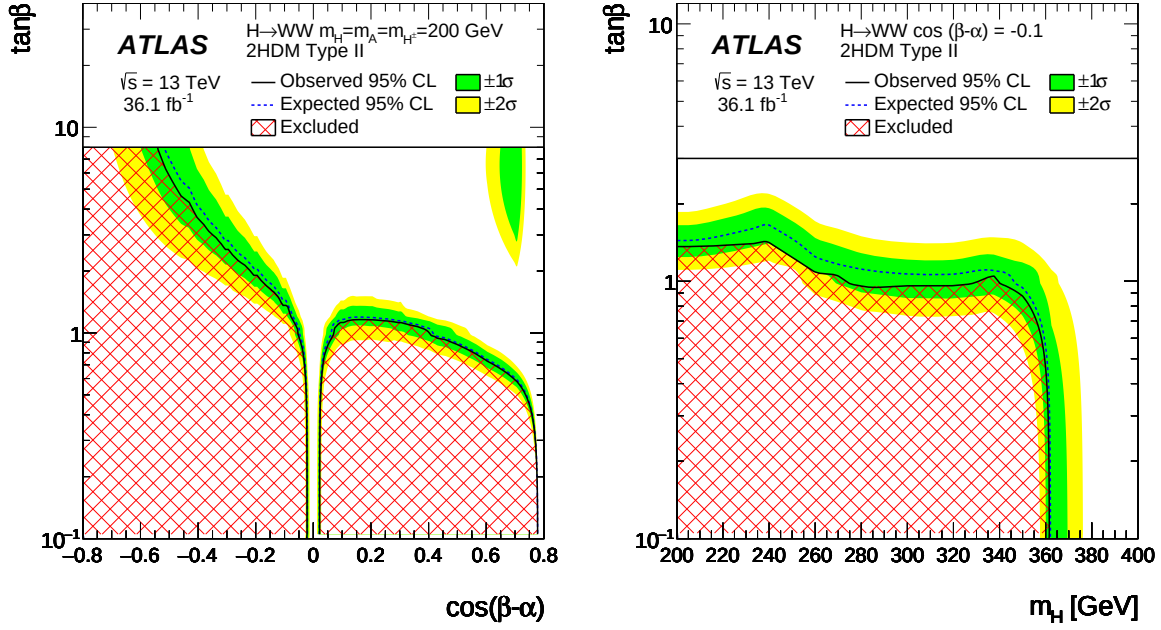


Figure 2.12: Interpretation of the results of the search for heavy $X \rightarrow WW \rightarrow \ell\nu\ell\nu$ decays in the Type II 2HDM model. Exclusion contours at 95% confidence level are shown in the $\tan\beta$ and $\cos(\beta-\alpha)$ plane, assuming a mass parameter value of 200 GeV (left), as well as in the $\tan\beta$ and m_H plane assuming $\cos(\beta-\alpha) = -0.1$ (right). The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit while the hatched regions are excluded. Taken from Ref. [1].

results in an increased branching ratio to $\tau^+\tau^-$, as well as an increased cross section for Higgs boson production in association with b -quarks. A postdoctoral researcher under my supervision was leading the analysis team. He also developed and implemented the category split into the production in association with and without b -tagged jets in order to improve the overall sensitivity, as well as the final likelihood-based limit extraction. Results have been published on the data collected in 2015 [11] and on the combined data collected in 2015 and 2016 [2]. In both cases, preliminary results were presented at important conferences [8, 14]. No significant excesses above the SM expectations have been observed in any of these results. Thus, 95% confidence level upper limits on the cross section times branching ratio to $\tau^+\tau^-$ have been set for models where the scalar particle ϕ is produced via ggF, or in associated with b -quarks, or where the resonance is a heavy vector boson, see Figs. 2.13 (a), (b), and (c), respectively. An interpretation is performed in the hMSSM scenario, in which the measured value of m_H , see Section 2.4, is used to predict the masses and couplings of the additional Higgs bosons [59, 60]. This scenario has been used to place limits on the allowed values of the $\tan\beta$ and m_A parameter space, as can be seen in Fig. 2.13 (d). In addition, the results have been interpreted using various models with a heavy Z' vector resonance. One such model is the *Sequential Standard Model* (SSM) in which the new Z'_{SSM} boson exhibits the same couplings as the SM Z boson. This model is frequently used as a benchmark model, as obtained

limits can be reinterpreted in a wide range of models. This analysis obtained observed (expected) lower limits on the mass of a Z'_{SSM} boson of 2.42 (2.47) TeV at 95% confidence level, as can be seen in Fig. 2.13 (c). The CMS Collaboration has also searched for new high-mass Higgs bosons in the decay to two τ leptons [61]. No excess above the SM expectation has been observed. The obtained limits are less stringent, as only a partial dataset recorded at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 12.9 fb^{-1} has been analyzed thus far.

2.6 Other Scientific Contributions

2.6.1 Reconstruction and Identification of Electrons and Tau Leptons

The precise and accurate electron reconstruction and identification with the ATLAS detector is an important corner stone of most analyses performed by the collaboration, and especially of those mentioned in the previous sections. Since the time of the early electron-related studies already mentioned in Section 2.3, I have been continuously active within the ATLAS group responsible for electron (and photon) reconstruction and identification.

In order to search for and measure $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$, it is important to be able to reconstruct electrons reliably also at rather low transverse momenta, *i.e.*, starting at a few GeV, in order to maximize the signal acceptance. While I was working on that analysis, I was also involved in improving the electron reconstruction by employing a new algorithm for fitting the reconstructed trajectory of the electron that allows for energy loss due to bremsstrahlung, and thereby better estimating the point of origin of the electron. This technique was adopted as the new standard for electron reconstruction in ATLAS in 2012.

In order to correct simulated electrons such that they match what is observed in data, it is necessary to apply correction factors to these for trigger, reconstruction, identification, and isolation efficiencies. A doctoral student under my supervision implemented and validated the tool that does precisely this, which is nowadays used by every ATLAS analysis with electrons in the final state.

Another doctoral student under my supervision measured the rate at which electrons are reconstructed with the wrong charge, as well as the correction factors for simulated electrons. We also provided these results to the whole ATLAS Collaboration, including all systematic uncertainties.

I am currently working with a doctoral student on another possible gain in the electron reconstruction by improving the matching of the energy deposition in the calorimeter with the correct reconstructed trajectory from the inner tracking detector. The aim is to improve the selection of the correct trajectory, especially in the light of ever increasing simultaneous proton-proton collisions per bunch crossing and thus higher charged particle multiplicities per event, and therefore also reducing the probability of reconstructing the wrong charge of electrons.

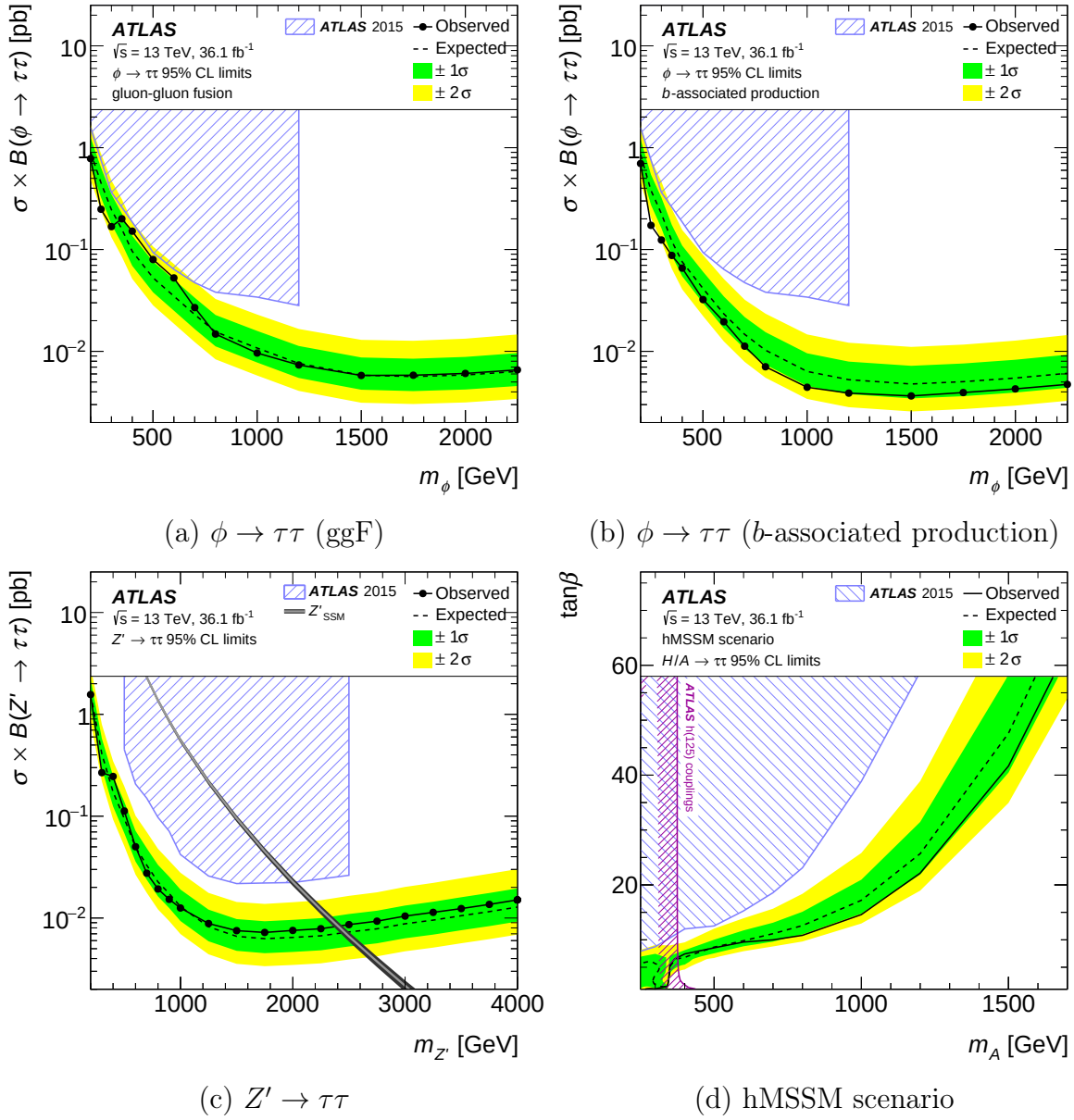


Figure 2.13: Observed and expected 95% confidence level limits in the search for new high-mass bosons in the $\tau^+\tau^-$ final state. Shown are the upper limits on the production cross section times branching fraction for a scalar boson produced via (a) ggF and (b) b -associated production, and for (c) heavy vector bosons. The hMSSM scenario has been used to determine an exclusion contour on the $\tan\beta$ vs. m_A plane (d). The inner (green) and outer (yellow) bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit, while the hatched blue regions are excluded by the previous ATLAS result [11]. Taken from Ref. [2].

Both aspects previously described are especially important for the analysis of the production of two W bosons of the same charge, produced via vector-boson-scattering,

and both decaying leptonically. This analysis is currently being worked on by a doctoral student under my supervision.

Other objects of importance in the ATLAS experiment are hadronically decaying tau leptons. These are used, *e.g.*, in the search for new bosonic resonances decaying into two tau leptons, see Section 2.5, as well as the precise measurement of SM $H \rightarrow \tau\tau$ decays in data collected at $\sqrt{s} = 13$ TeV, an analysis that I am currently performing. To correct the reconstruction and identification efficiencies in simulated events of hadronically decaying tau leptons to match what is observed in data, correction factors need to be measured and systematic uncertainties on these need to be evaluated. This has been done by a doctoral student under my supervision and the results are used by all ATLAS analyses that use these tau leptons. These results are also public [3].

2.6.2 Development of specialized ATLAS Software and Data Formats

During my early years as a postdoctoral researcher, I spent a significant amount of time on research and development that benefited the ATLAS Collaboration, and thus the scientific output, as a whole. I realized early on that the envisioned analysis strategy for ATLAS would not scale with the amount of data that was expected. Thus, I developed a new strategy, together with other colleagues, of so-called derived datasets. These are specifically tailored for an analysis, for a specific performance study, or for specific studies of our event reconstruction. This new strategy significantly improved the efficiency of the ATLAS Collaboration overall.

During the LHC Run 1, I, together with other CERN fellows and one CERN summer student under my supervision, implemented a system that would analyze newly incoming data from the ATLAS detector quickly. We implemented many physics analyses in a simplified way and produced many distributions of interest automatically on ATLAS-internal web pages. This aims at an early detection of possible anomalies, be it due to BSM physics or due to appearing issues with the detector, the data acquisition, or the reconstruction. This system is still running routinely today.

Towards the end of the LHC Run 1 and at the beginning of the first long shutdown of the LHC, I triggered the complete modernization of our entire event data model, *i.e.*, the way our data is represented and thus can be used, which is now the new standard since the beginning of Run 2. This modernization was also necessary to improve the usability and flexibility, while at the same time allowing for an overall reduced disk space usage.

In order to prepare for the LHC Run 2 analysis, I developed a software infrastructure to apply all final calibrations and corrections to our physics objects, including the propagation of all systematic uncertainties, and write out resulting files that are small enough to be used by the final analysis stages. This is used by all analyses performed at $\sqrt{s} = 13$ TeV of the channels with two W bosons in the final state that I described in previous sections, and more. Thus, I provide the basis for all of these analyses. In addition, two students under my supervision have developed and improved an analysis software package that provides ease of use, great flexibility, and a vast feature set. Due to these features, it is nowadays used by almost all analyses described above, and oth-

ers beyond that and thus improves greatly the collaboration within analysis teams and therefore contributes significantly to the excellent physics results that ATLAS publishes.

2.7 Conclusion

The LHC and the ATLAS experiment allow for new measurements and possible discoveries due to the high center-of-mass energy and the high luminosity of the proton-proton collisions. I made important contributions to $Z \rightarrow e^+e^-$ and $WW \rightarrow \ell\nu\ell\nu$ measurements, the latter especially in preparation for Higgs boson measurements in the same final state. In addition, significant contributions to the improvement and validation of the electron trigger, reconstruction, and identification were made, as well as advances regarding the essential ATLAS software infrastructure. I contributed to the discovery of the Higgs boson in the $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ channel and performed detailed studies of the properties of the Higgs boson in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel, and additionally made major advances towards a publication using the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, as well as the $H \rightarrow \tau\tau$ decay channel using proton-proton collision data recorded at $\sqrt{s} = 13$ TeV. Preparations for precision measurements of Higgs boson couplings and their interpretations are underway. A new method of Effective Lagrangian Morphing, which enables these studies in a multidimensional phase space, has been developed for this purpose. No new additional heavy bosons have been found as of now, however, the search for new phenomena goes on at an LHC that continues to deliver new collision data in a record-breaking fashion.

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Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector

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We report the observation of Higgs boson decays to WW^* based on an excess over background of 6.1 standard deviations in the dilepton final state, where the Standard Model expectation is 5.8 standard deviations. Evidence for the vector-boson fusion (VBF) production process is obtained with a significance of 3.2 standard deviations. The results are obtained from a data sample corresponding to an integrated luminosity of 25 fb^{-1} from $\sqrt{s} = 7$ and 8 TeV pp collisions recorded by the ATLAS detector at the LHC. For a Higgs boson mass of 125.36 GeV, the ratio of the measured value to the expected value of the total production cross section times branching fraction is $1.09^{+0.16}_{-0.15}(\text{stat})^{+0.17}_{-0.14}(\text{syst})$. The corresponding ratios for the gluon fusion and vector-boson fusion production mechanisms are $1.02 \pm 0.19(\text{stat})^{+0.22}_{-0.18}(\text{syst})$ and $1.27^{+0.44}_{-0.40}(\text{stat})^{+0.30}_{-0.21}(\text{syst})$, respectively. At $\sqrt{s} = 8$ TeV, the total production cross sections are measured to be $\sigma(gg \rightarrow H \rightarrow WW^*) = 4.6 \pm 0.9(\text{stat})^{+0.8}_{-0.7}(\text{syst}) \text{ pb}$ and $\sigma(\text{VBF } H \rightarrow WW^*) = 0.51^{+0.17}_{-0.15}(\text{stat})^{+0.13}_{-0.08}(\text{syst}) \text{ pb}$. The fiducial cross section is determined for the gluon-fusion process in exclusive final states with zero or one associated jet.

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I. INTRODUCTION

In the Standard Model of particle physics (SM), the Higgs boson results from the Brout-Englert-Higgs mechanism [1] that breaks the electroweak symmetry [2] and gives mass to the W and Z gauge bosons [3]. It has a spin parity of 0^+ , with couplings to massive particles that are precisely determined by their measured masses. A new particle compatible with the spin and gauge-boson couplings of the SM Higgs boson was discovered in 2012 by the ATLAS and CMS experiments at the LHC using the ZZ^* , $\gamma\gamma$, and WW^* final states [4–8]. Measurements of the particle’s mass [8,9] yield a value of approximately 125 GeV, consistent with the mass of the SM Higgs boson provided by a global fit to electroweak measurements [10]. Evidence for production of this boson at the Tevatron [11] and for its decay to fermions at the LHC [12] are also consistent with the properties of the SM Higgs boson.

The direct observation of the Higgs boson in individual decay channels provides an essential confirmation of the SM predictions. For a Higgs boson with a mass of 125 GeV, the $H \rightarrow WW^*$ decay has the second largest branching fraction (22%) and is a good candidate for observation. The sequential decay $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, where ℓ is an electron or muon, is a sensitive experimental signature. Searches for this decay produced the first direct limits on

the mass of the Higgs boson at a hadron collider [13,14], and measurements following the boson discovery are among the most precise in determining its couplings and spin [5–7].

The dominant Higgs boson production mode in high-energy pp collisions is gluon fusion (ggF), where the interacting gluons produce a Higgs boson predominantly through a top-quark loop. The next most abundant production mechanism, with a factor of 12 reduction in rate, is the fusion of vector bosons radiated by the interacting quarks into a Higgs boson (vector-boson fusion or VBF). At a further reduced rate, a Higgs boson can be produced in association with a W or Z boson (vector and Higgs boson production or VH). The leading-order production processes are depicted in Fig. 1.

This paper describes the observation and measurement of the Higgs boson in its decay to a pair of W bosons, with the Higgs boson produced by the ggF and VBF processes at center-of-mass energies of 7 and 8 TeV. The ggF production process probes Higgs boson couplings to heavy quarks, while the VBF and VH processes probe its couplings to W and Z bosons. The branching fraction $\mathcal{B}_{H \rightarrow WW^*}$ is sensitive to Higgs boson couplings to the fermions and bosons through the total width. To constrain these couplings, the rates of the ggF and VBF $H \rightarrow WW^*$ processes are measured—individually and combined—and normalized by the SM predictions for the ATLAS measured mass value of 125.36 GeV [9] to obtain the “signal strength” parameters μ , μ_{ggF} , and μ_{VBF} . The total cross section for each process is also measured, along with fiducial cross sections for the ggF process.

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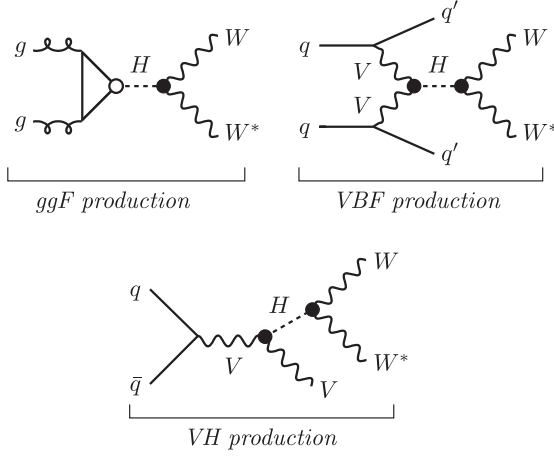
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FIG. 1. Feynman diagrams for the leading production modes (ggF, VBF, and VH), where the VVH and qqH coupling vertices are marked by $\bullet$ and $\circ$, respectively. The V represents a W or Z vector boson.

A prior measurement of these processes with the same data set yielded a combined result of $\mu = 1.0 \pm 0.3$ [5]. The results presented here supersede this measurement and contain improvements in signal acceptance, background determination and rejection, and signal yield extraction. Together, these improvements increase the expected significance of an excess of $H \rightarrow WW^*$ decays over background from 3.7 to 5.8 standard deviations, and reduce the expected relative uncertainty on the corresponding μ measurement by 30%.

The paper is organized as follows. Section II provides an overview of the signal and backgrounds, and of the data analysis strategy. Section III describes the ATLAS detector and data, and the event reconstruction. The selection of events in the different final states is given in Sec. IV. Sections V and VI discuss the modeling of the signal and the background processes, respectively. The signal yield extraction and the various sources of systematic uncertainty are described in Sec. VII. Section VIII provides the event yields and the distributions of the final discriminating variables; the differences with respect to previous ATLAS measurements in this channel [5] are given in Sec. VIII C. The results are presented in Sec. IX, and the conclusions given in Sec. X.

II. ANALYSIS OVERVIEW

The $H \rightarrow WW^*$ final state with the highest purity at the LHC occurs when each W boson decays leptonically, $W \rightarrow \ell\nu$, where ℓ is an electron or muon. The analysis therefore selects events consistent with a final state containing neutrinos and a pair of opposite-charge leptons. The pair can be an electron and a muon, two electrons, or two muons. The relevant backgrounds are shown in Table I and

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TABLE I. Backgrounds to the $H \rightarrow WW^*$ measurement in the final state with two charged leptons ($\ell = e$ or μ) and neutrinos, and no jet that contains a b -quark. Irreducible backgrounds have the same final state; other backgrounds are shown with the features that lead to this final state. Quarks from the first or second generation are denoted as q , and j represents a jet of any flavor.

Name	Process	Feature(s)
WW	WW	Irreducible
Top quarks		
$t\bar{t}$	$t\bar{t} \rightarrow WbW\bar{b}$	Unidentified b -quarks
t	tW $t\bar{b}, tq\bar{b}$	Unidentified b -quark q or b misidentified as ℓ ; unidentified b -quarks
Misidentified leptons (Misid)		
Wj	$W + \text{jet(s)}$	j misidentified as ℓ
jj	Multijet production	jj misidentified as $\ell\ell$; misidentified neutrinos
Other dibosons		
VV	$W\gamma$ $W\gamma^*, WZ, ZZ \rightarrow \ell\ell\ell\ell$ $ZZ \rightarrow \ell\ell\nu\nu$ $Z\gamma$	γ misidentified as e Unidentified lepton(s) Irreducible γ misidentified as e ; unidentified lepton
Drell-Yan (DY)		
$ee/\mu\mu$	$Z/\gamma^* \rightarrow ee, \mu\mu$	Misidentified neutrinos
$\tau\tau$	$Z/\gamma^* \rightarrow \tau\tau \rightarrow \ell\nu\ell\nu$	Irreducible

are categorized as WW, top quarks, misidentified leptons, other dibosons, and Drell-Yan. The distinguishing features of these backgrounds, discussed in detail below, motivate the definition of event categories based on lepton flavor and jet multiplicity, as illustrated in Fig. 2. In the final step of the analysis, a profile likelihood fit is simultaneously performed on all categories in order to extract the signal from the backgrounds and measure its yield.

The Drell-Yan (DY) process is the dominant source of events with two identified leptons, and contributes to the signal final state when there is a mismeasurement of the net particle momentum in the direction transverse to the beam (individual particle momentum in this direction is denoted p_T). The DY background is strongly reduced in events with different-flavor leptons ($e\mu$), as these arise through fully leptonic decays of τ -lepton pairs with a small branching fraction and reduced lepton momenta. The analysis thus separates $e\mu$ events from those with same-flavor leptons ($ee/\mu\mu$) in the event selection and the likelihood fit.

Pairs of top quarks are also a prolific source of lepton pairs, which are typically accompanied by high-momentum jets. Events are removed if they have a jet identified to contain a b -hadron decay (b -jet), but the $t\bar{t}$ background remains large due to inefficiencies in the b -jet identification algorithm. Events are therefore categorized by the number of jets. The top-quark background provides a small

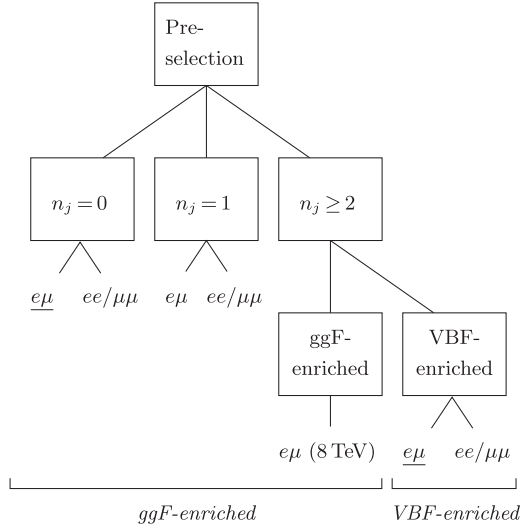


FIG. 2. Analysis divisions in categories based on jet multiplicity (n_j) and lepton-flavor samples ($e\mu$ and $ee/\mu\mu$). The most sensitive signal region for ggF production is $n_j = 0$ in $e\mu$, while for VBF production it is $n_j \geq 2$ in $e\mu$. These two samples are underlined. The $e\mu$ samples with $n_j \leq 1$ are further subdivided as described in the text.

contribution to the zero-jet category but represents a significant fraction of the total background in categories with one or more jets.

In events with two or more jets, the sample is separated by signal production process (“VBF-enriched” and “ggF-enriched”). The VBF process is characterized by two quarks scattered at a small angle, leading to two well-separated jets with a large invariant mass [15]. These and other event properties are inputs to a boosted decision tree (BDT) algorithm [16] that yields a single-valued discriminant to isolate the VBF process. A separate analysis based on a sequence of individual selection criteria provides a cross-check of the BDT analysis. The ggF-enriched sample contains all events with two or more jets that do not pass either of the VBF selections.

Due to the large Drell-Yan and top-quark backgrounds in events with same-flavor leptons or with jets, the most sensitive signal region is in the $e\mu$ zero-jet final state. The dominant background to this category is WW production, which is effectively suppressed by exploiting the properties of W boson decays and the spin-0 nature of the Higgs boson (Fig. 3). This property generally leads to a lepton pair with a small opening angle [17] and a correspondingly low invariant mass $m_{\ell\ell}$, broadly distributed in the range below $m_H/2$. The dilepton invariant mass is used to select signal events, and the signal likelihood fit is performed in two ranges of $m_{\ell\ell}$ in $e\mu$ final states with $n_j \leq 1$.

Other background components are distinguished by $p_T^{\ell\ell}$, the magnitude of the transverse momentum of the lower- p_T

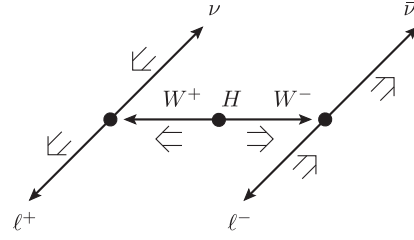


FIG. 3. Illustration of the $H \rightarrow WW$ decay. The small arrows indicate the particles’ directions of motion and the large double arrows indicate their spin projections. The spin-0 Higgs boson decays to W bosons with opposite spins, and the spin-1 W bosons decay into leptons with aligned spins. The H and W boson decays are shown in the decaying particle’s rest frame. Because of the $V - A$ decay of the W bosons, the charged leptons have a small opening angle in the laboratory frame. This feature is also present when one W boson is off shell.

lepton in the event (the “subleading” lepton). In the signal process, one of the W bosons from the Higgs boson decay is off shell, resulting in relatively low subleading lepton p_T (peaking near 22 GeV, half the difference between the Higgs and W boson masses). In the background from W bosons produced in association with a jet or photon (misreconstructed as a lepton) or an off-shell photon producing a low-mass lepton pair (where one lepton is not reconstructed), the $p_T^{\ell\ell}$ distribution falls rapidly with increasing p_T . The $e\mu$ sample is therefore subdivided into three regions of subleading lepton p_T for $n_j \leq 1$. The jet and photon misidentification rates differ for electrons and muons, so this sample is further split by subleading lepton flavor.

Because of the neutrinos produced in the signal process, it is not possible to fully reconstruct the invariant mass of the final state. However, a “transverse mass” m_T [18] can be calculated without the unknown longitudinal neutrino momenta:

$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{\nu\nu})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\nu\nu}|^2}, \quad (1)$$

where $E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$, $\mathbf{p}_T^{\nu\nu}$ ($\mathbf{p}_T^{\ell\ell}$) is the vector sum of the neutrino (lepton) transverse momenta, and $p_T^{\nu\nu}$ ($p_T^{\ell\ell}$) is its modulus. The distribution has a kinematic upper bound at the Higgs boson mass, effectively separating Higgs boson production from the dominant nonresonant WW and top-quark backgrounds. For the VBF analysis, the transverse mass is one of the inputs to the BDT distribution used to fit for the signal yield. In the ggF and cross-check VBF analyses, the signal yield is obtained from a direct fit to the m_T distribution for each category.

Most of the backgrounds are modeled using Monte Carlo samples normalized to data, and include theoretical uncertainties on the extrapolation from the normalization region

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to the signal region, and on the shape of the distribution used in the likelihood fit. For the $W + \text{jet(s)}$ and multijet backgrounds, the high rates and the uncertainties in modeling misidentified leptons motivate a model of the kinematic distributions based on data. For a few minor backgrounds, the process cross sections are taken from theoretical calculations. Details of the background modeling strategy are given in Sec. VI.

The analyses of the 7 and 8 TeV data sets are separate, but use common methods where possible; differences arise primarily because of the lower instantaneous and integrated luminosities in the 7 TeV data set. As an example, the categorization of 7 TeV data does not include a ggF-enriched category for events with at least two jets, since the expected significance of such a category is very low. Other differences are described in the text or in dedicated subsections.

III. DATA SAMPLES AND RECONSTRUCTION

This section begins with a description of the ATLAS detector, the criteria used to select events during data-taking (triggers) and the data sample used for this analysis. A description of the event reconstruction follows. The Monte Carlo simulation samples used in this analysis are described next, and then differences between the 2012 and 2011 analyses are summarized.

A. Detector and data samples

The ATLAS detector [19] is a multipurpose particle detector with approximately forward-backward symmetric cylindrical geometry. The experiment uses a right-handed coordinate system with the origin at the nominal pp interaction point at the center of the detector. The positive x axis is defined by the direction from the origin to the center of the LHC ring, the positive y axis points upwards, and the z axis is along the beam direction. Cylindrical coordinates (r, ϕ) are used in the plane transverse to the beam; ϕ is the azimuthal angle around the beam axis. Transverse components of vectors are indicated by the subscript T. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

The inner tracking detector (ID) consists of a silicon-pixel detector, which is closest to the interaction point, a silicon-microstrip detector surrounding the pixel detector—both covering $|\eta| < 2.5$ —and an outer transition-radiation straw-tube tracker (TRT) covering $|\eta| < 2$. The TRT provides substantial discriminating power between electrons and pions over a wide energy range. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field.

A highly segmented lead/liquid-argon (LAr) sampling electromagnetic calorimeter measures the energy and the position of electromagnetic showers with $|\eta| < 3.2$. The LAr calorimeter includes a presampler (for $|\eta| < 1.8$) and

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three sampling layers, longitudinal in shower depth, up to $|\eta| < 2.5$. The LAr sampling calorimeters are also used to measure hadronic showers in the endcap ($1.5 < |\eta| < 3.2$) and electromagnetic and hadronic showers in the forward regions ($3.1 < |\eta| < 4.9$), while a steel/scintillator tile calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$).

The muon spectrometer (MS) surrounds the calorimeters and is designed to detect muons in the pseudorapidity range $|\eta| < 2.7$. The MS consists of one barrel ($|\eta| < 1.05$) and two endcap regions. A system of three large superconducting air-core toroid magnets, each with eight coils, provides a magnetic field with a bending integral of about 2.5 T m in the barrel and up to 6 T m in the endcaps. Monitored drift tube chambers in both the barrel and endcap regions and cathode strip chambers covering $2.0 < |\eta| < 2.7$ are used as precision-measurement chambers, whereas resistive plate chambers in the barrel and thin gap chambers in the endcaps are used as trigger chambers, covering $|\eta| < 2.4$. The chambers are arranged in three layers, so high- p_T particles traverse at least three stations with a lever arm of several meters.

A three-level trigger system selects events to be recorded for offline analysis. The first level (level-1 trigger) is hardware based, and the second two levels (high-level trigger) are software based. This analysis uses events selected by triggers that required either a single lepton or two leptons (dilepton). The single-lepton triggers had more restrictive lepton identification requirements and higher p_T thresholds than the dilepton triggers. The specific triggers used for the 8 TeV data with the corresponding thresholds at the hardware and software levels are listed in Table II. Offline, two leptons—either ee , $\mu\mu$, or $e\mu$ —with opposite charge are required. The leading lepton (ℓ_1) is required to have $p_T \geq 22$ GeV and the subleading lepton (ℓ_2) is required to have $p_T \geq 10$ GeV.

TABLE II. Summary of the minimum lepton p_T trigger requirements (in GeV) during the 8 TeV data-taking. For single-electron triggers, the hardware and software thresholds are either 18 and 24i or 30 and 60, respectively. The “i” denotes an isolation requirement that is less restrictive than the isolation requirement imposed in the offline selection. For dilepton triggers, the pair of thresholds corresponds to the leading and subleading lepton, respectively; the “ μ, μ ” dilepton trigger requires only a single muon at level-1. The “and” and “or” are logical.

Name	Level-1 trigger	High-level trigger
Single lepton		
e	18 or 30	24i or 60
μ	15	24i or 36
Dilepton		
e, e	10 and 10	12 and 12
μ, μ	15	18 and 8
e, μ	10 and 6	12 and 8

The efficiency of the trigger selection is measured using a tag-and-probe method with a data sample of $Z/\gamma^* \rightarrow ee, \mu\mu$ candidates. For muons, the single-lepton trigger efficiency varies with η and is approximately 70% for $|\eta| < 1.05$ and 90% for $|\eta| > 1.05$. For electrons, the single-lepton trigger efficiency increases with p_T , and its average is approximately 90%. These trigger efficiencies are for leptons that satisfy the analysis selection criteria described below. Dilepton triggers increase the signal acceptance by allowing lower leading-lepton p_T thresholds to be applied offline while still remaining in the kinematic range that is in the plateau of the trigger efficiency. The trigger efficiencies for signal events satisfying the selection criteria described in Sec. IV are 95% for events with a leading electron and a subleading muon, 81% for events with a leading muon and subleading electron, 89% for $\mu\mu$ events, and 97% for ee events. These efficiencies are for the $n_j = 0$ category; the efficiencies are slightly larger for categories with higher jet multiplicity.

The data are subjected to quality requirements: events recorded when the relevant detector components were not operating correctly are rejected. The resulting integrated luminosity is 20.3 fb^{-1} taken at $\sqrt{s} = 8 \text{ TeV}$ in 2012 and 4.5 fb^{-1} at 7 TeV in 2011. The mean number of inelastic collisions per bunch crossing had an average value of 20 in 2012 and 9 in 2011. Overlapping signals in the detector due to these multiple interactions—as well as signals due to interactions occurring in other nearby bunch crossings—are referred to as “pile-up.”

B. Event reconstruction

The primary vertex of each event must have at least three tracks with $p_T \geq 400 \text{ MeV}$ and is selected as the vertex with the largest value of $\Sigma(p_T)^2$, where the sum is over all the tracks associated with that particular vertex.

Muon candidates are identified by matching a reconstructed ID track with a reconstructed MS track [20]. The MS track is required to have a track segment in at least two layers of the MS. The ID tracks are required to have at least a minimum number of associated hits in each of the ID subdetectors to ensure good track reconstruction. This analysis uses muon candidates referred to as “combined muons” in Ref. [20], in which the track parameters of the MS track and the ID track are combined statistically. Muon candidates are required to have $|\eta| < 2.50$. The efficiencies for reconstructing and identifying combined muons are provided in Ref. [20].

Electron candidates are clusters of energy deposited in the electromagnetic calorimeter that are associated with ID tracks [21]. All candidate electron tracks are fitted using a Gaussian sum filter [22] (GSF) to account for bremsstrahlung energy losses. The GSF fit reduces the difference between the energy measured in the calorimeter and the momentum measured in the ID and improves the measured electron direction and impact parameter resolutions. The

impact parameter is the lepton track’s distance of closest approach in the transverse plane to the reconstructed position of the primary vertex. The electron transverse energy is computed from the cluster energy and the track direction at the interaction point.

Electron identification is performed in the range $|\eta| < 2.47$, excluding the transition region between the barrel and endcap EM calorimeters, $1.37 < |\eta| < 1.52$. The identification is based on criteria that require the longitudinal and transverse shower profiles to be consistent with those expected for electromagnetic showers, the track and cluster positions to match in η and ϕ , and signals of transition radiation in the TRT. The electron identification has been improved relative to that described in Ref. [5] by adding a likelihood-based method in addition to the selection-based method. The likelihood allows the inclusion of discriminating variables that are difficult to use with explicit requirements without incurring significant efficiency losses. Detailed discussions of the likelihood identification and selection-based identification and the corresponding efficiency measurements can be found in Ref. [23]. Electrons with $10 < E_T < 25 \text{ GeV}$ must satisfy the “very tight” likelihood requirement, which reduces backgrounds from light-flavor jets and photon conversions by 35% relative to the selection-based identification with the same signal efficiency. For $E_T > 25 \text{ GeV}$, where misidentification backgrounds are less important, electrons must satisfy the “medium” selection-based requirement. The single-lepton trigger applies the medium selection-based requirements. Using a likelihood-based selection criterion in addition to this selection-based requirement would result in a loss of signal efficiency without sufficient compensation in background rejection. Finally, additional requirements reduce the contribution of electrons from photon conversions by rejecting electron candidates that have an ID track that is part of a conversion vertex or that do not have a hit in the innermost layer of the pixel detector.

To further reduce backgrounds from misidentified leptons, additional requirements are imposed on the lepton impact parameter and isolation. The significance of the transverse impact parameter, defined as the measured transverse impact parameter d_0 divided by its estimated uncertainty σ_{d_0} , is required to satisfy $|d_0|/\sigma_{d_0} < 3.0$; the longitudinal impact parameter z_0 must satisfy the requirement $|z_0 \sin \theta| < 0.4 \text{ mm}$ for electrons and 1.0 mm for muons.

Lepton isolation is defined using track-based and calorimeter-based quantities. Details about the definition of electron isolation can be found in Ref. [23]. The track isolation is based on the scalar sum Σp_T of all tracks with $p_T > 400 \text{ MeV}$ for electrons ($p_T > 1 \text{ GeV}$ for muons) that are found in a cone in η - ϕ space around the lepton, excluding the lepton track. Tracks used in this scalar sum are required to be consistent with coming from the primary vertex. The cone size is $\Delta R = 0.4$ for leptons with

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$p_T < 15$ GeV, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, and $\Delta R = 0.3$ for $p_T > 15$ GeV. The track isolation selection criterion uses the ratio of the Σp_T divided by the electron E_T (muon p_T). This ratio is required to be less than 0.06 for leptons with $10 < p_T < 15$ GeV, and this requirement increases monotonically to 0.10 for electrons (0.12 for muons) for $p_T > 25$ GeV.

The calorimeter isolation selection criterion—like the track isolation—is based on a ratio. The relative calorimetric isolation for electrons is computed as the sum of the cluster transverse energies ΣE_T of surrounding energy deposits in the electromagnetic and hadronic calorimeters inside a cone of $\Delta R = 0.3$ around the candidate electron cluster, divided by the electron E_T . The cells within 0.125×0.175 in $\eta \times \phi$ around the electron cluster bary-center are excluded. The pile-up and underlying-event contributions to the calorimeter isolation are estimated and subtracted event by event. The electron relative calorimetric isolation upper bound varies monotonically with electron E_T : it is 0.20 for $10 < E_T < 15$ GeV, increasing to 0.28 for $E_T > 25$ GeV. In the case of muons, the relative calorimetric isolation discriminant is defined as the ΣE_T calculated from calorimeter cells within $\Delta R = 0.3$ of the muon candidate, and with energy above a noise threshold, divided by the muon p_T . All calorimeter cells within the range $\Delta R < 0.05$ around the muon candidate are excluded from ΣE_T . A correction based on the number of reconstructed primary vertices in the event is made to ΣE_T to compensate for extra energy due to pile-up. The muon relative calorimetric isolation upper bound also varies monotonically with muon p_T ; it is 0.06 for $10 < p_T < 15$ GeV, increasing to 0.28 for $p_T > 25$ GeV. The signal efficiencies of the impact parameter and isolation requirements are measured using a tag-and-probe method with a data sample of $Z/\gamma^* \rightarrow ee, \mu\mu$ candidates. The efficiencies of the combined impact parameter and isolation requirements range from 68% (60%) for electrons (muons) with $10 < p_T < 15$ GeV to greater than 90% (96%) for electrons (muons) with $p_T > 25$ GeV.

Jets are reconstructed using the anti- k_t sequential recombination clustering algorithm [24] with a radius parameter $R = 0.4$. The inputs to the reconstruction are three-dimensional clusters of energy [25,26] in the calorimeter. The algorithm for this clustering suppresses noise by keeping only cells with a significant energy deposit and their neighboring cells. To take into account the differences in calorimeter response to electrons and photons and hadrons, each cluster is classified, prior to the jet reconstruction, as coming from an electromagnetic or hadronic shower using information from its shape. Based on this classification, the local cell signal weighting calibration method [27] applies dedicated corrections for the effects of calorimeter noncompensation, signal losses due to noise threshold effects, and energy lost in regions that are not instrumented. Jets are corrected for

contributions from in-time and out-of-time pile-up [28], and the position of the primary interaction vertex. Subsequently, the jets are calibrated to the hadronic energy scale using p_T - and η -dependent correction factors determined in a first pass from simulation and then refined in a second pass from data [26,27]. The systematic uncertainties on these correction factors are determined from the same control samples in data.

To reduce the number of jet candidates originating from pile-up vertices, a requirement is imposed on the jet vertex fraction, denoted JVf: for jets with $p_T < 50$ GeV and $|\eta| < 2.4$, more than 50% of the summed scalar p_T of tracks within $\Delta R = 0.4$ of the jet axis must be from tracks associated with the primary vertex (JVf > 0.50) [29]. No JVf selection requirement is applied to jets that have no associated tracks.

For the purposes of classifying an event in terms of jet multiplicity n_j , a jet is required to have $p_T^j > 25$ GeV for $|\eta_j| < 2.4$, and $p_T^j > 30$ GeV if $2.4 \leq |\eta_j| < 4.5$. The increased threshold in the higher- $|\eta|$ region suppresses jets from pile-up. The two highest- p_T jets (j_1, j_2 , ordered in p_T) are the “VBF jets” used to compute dijet variables in the VBF-enhanced $n_j \geq 2$ category.

Additional jets not counted in n_j have lower thresholds in three scenarios. First, those used to reject events because they lie in the η range spanned by the two leading jets in the VBF-enriched selection (see Sec. IV C) are considered if they have $p_T^j > 20$ GeV. Second, the jets for b -jet identification—described below—are required to have $p_T^j > 20$ GeV and $|\eta_j| < 2.4$. Third, the jets used for the calculation of soft hadronic recoil (see Sec. IV A and the f_{recoil} definition therein) are required to have $p_T^j > 10$ GeV and have no JVf requirement. The calibration procedure described above is applied only to jets with $p_T^j > 20$ GeV. Jets with $10 \text{ GeV} < p_T^j < 20 \text{ GeV}$ are used only in the f_{recoil} definition, and the efficiency for the requirements on this quantity are measured directly from the data, so the analysis is not sensitive to the modeling of the energy scale of these soft jets in the Monte Carlo simulation.

The identification of b -quark jets (b -jets) is limited to the acceptance of the ID ($|\eta| < 2.5$). The b -jets are identified with a multivariate technique—the MV1 algorithm [30]—that is based on quantities that separate b and c jets from “light jets” arising from light-flavor quarks and gluons. The inputs [31] to this algorithm use quantities such as the presence of secondary vertices, the impact parameters of tracks, and the topologies of weak heavy-quark decays. The efficiency for identifying b -jets is measured [32] in a large data sample of dilepton $t\bar{t}$ pair candidates. An operating point that is 85% efficient for identifying b -jets is adopted. At this operating point, the probability of misidentifying a light jet as a b -jet is 10.3%.

Two leptons or a lepton and a jet may be close in η - ϕ space. The following procedure is adopted in the case of

overlapping objects. Electron candidates that have tracks that extend to the MS are removed. If a muon candidate and an electron candidate are separated by $\Delta R < 0.1$, then the muon is retained, and the electron is removed. These cases usually indicate a muon that has undergone bremsstrahlung in the ID material or calorimeter. A high- p_T electron is always also reconstructed as a jet, so if an electron and the nearest jet are separated by less than $\Delta R = 0.3$, the jet is removed. In contrast, if a muon and a jet are separated by less than $\Delta R = 0.3$, the muon candidate is removed, as it is more likely to be a nonprompt muon from heavy-flavor decay. Finally, due to early bremsstrahlung, a prompt electron may produce more than one electron candidate in its vicinity. In the case of two electrons separated by less than $\Delta R = 0.1$, the electron candidate with larger E_T is retained.

The signature of a high-momentum neutrino is a momentum imbalance in the transverse plane. The reconstruction of this “missing” transverse momentum [33] is calculated as the negative vector sum of the momentum of objects selected according to ATLAS identification algorithms, such as leptons, photons, and jets, and of the remaining “soft” objects that typically have low values of p_T . The calculation can thus be summarized as

$$\mathbf{E}_T^{\text{miss}} = - \left(\sum_{\text{selected}} \mathbf{p}_T + \sum_{\text{soft}} \mathbf{p}_T \right), \quad (2)$$

where the reconstruction of soft objects and the choice of selected objects differ between different methods of evaluating the missing transverse momentum. Three methods of reconstruction are used in this analysis; $\mathbf{E}_T^{\text{miss}}$ is used to represent one particular method, as described below.

The large coverage in rapidity (y) of the calorimeter and its sensitivity to neutral particles motivate a calorimeter-based reconstruction of the missing transverse momentum. Selected objects are defined as the leptons selected by the analysis, and photons and jets with $E_T > 20$ GeV. The transverse momenta of these objects are added vectorially using object-specific calibrations. For the remaining soft objects, calibrated calorimeter cluster energy measurements are used to determine their net transverse momentum. The resulting missing transverse momentum is denoted $\mathbf{E}_T^{\text{miss}}$.

The significant pile-up present in the data degrades the resolution of the calorimeter-based measurement of missing transverse momentum. An $\mathcal{O}(20\%)$ improvement in resolution is obtained using a track-based measurement of the soft objects, where the tracks are required to have $p_T > 0.5$ GeV and originate from the primary vertex. Tracks associated with identified leptons or jets are not included, as these selected objects are added separately to the calculation of the missing transverse momentum. This reconstruction of missing transverse momentum, denoted $\mathbf{p}_T^{\text{miss}}$, is used in the final fit to the m_T distribution and

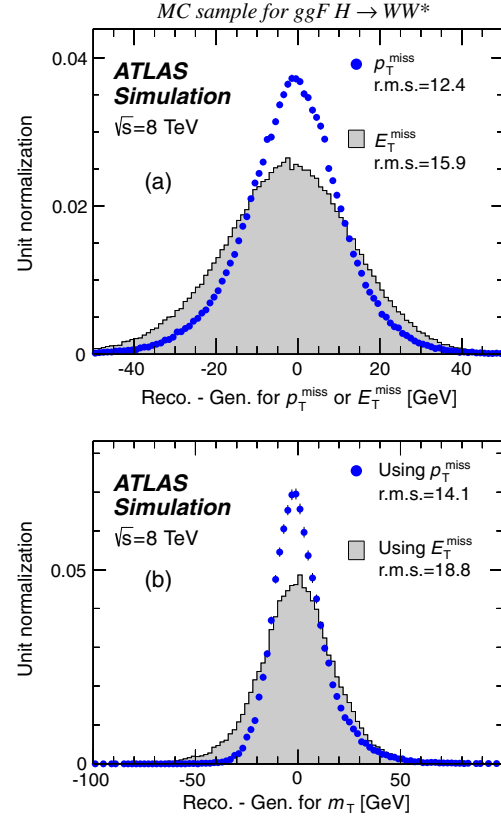


FIG. 4 (color online). Simulated resolutions of (a) missing transverse momentum and (b) m_T for the ggF signal MC in the $n_j = 0$ category. The comparisons are made between the calorimeter-based reconstruction (E_T^{miss}) and the track-based reconstruction (p_T^{miss}) of the soft objects [see Eq. (2)]. The resolution is measured as the difference of the reconstructed (Reco) and generated (Gen) quantities; the rms values of the distributions are given with the legends in units of GeV.

improves the signal resolution relative to the $\mathbf{E}_T^{\text{miss}}$ used for the previous measurement [5]. Figure 4 shows the simulated resolution for the magnitude of $\mathbf{E}_T^{\text{miss}}$ and $\mathbf{p}_T^{\text{miss}}$ (E_T^{miss} and p_T^{miss} respectively), and for m_T in the $n_j = 0$ category, all evaluated by subtracting the reconstructed quantity from the corresponding quantity obtained using generated leptons and neutrinos in $ggF H \rightarrow WW^*$ events. The rms of the m_T difference decreases from 19 to 14 GeV when using p_T^{miss} instead of E_T^{miss} in the reconstruction. The improved resolution significantly increases the discrimination between signal and certain background processes (such as $W\gamma$).

A simplified version of $\mathbf{p}_T^{\text{miss}}$ is used to suppress the Drell-Yan background in events with same-flavor leptons. This definition, denoted $\mathbf{p}_T^{\text{miss(trk)}}$, differs from $\mathbf{p}_T^{\text{miss}}$ in that

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the tracks associated with jets are also used, replacing the calorimeter-based jet measurement. This tends to align $\mathbf{p}_T^{\text{miss}(\text{trk})}$ with the jet(s) in Drell-Yan events, while in signal events $\mathbf{p}_T^{\text{miss}(\text{trk})}$ generally remains in the direction of the neutrinos. Incorporating the direction of $\mathbf{p}_T^{\text{miss}(\text{trk})}$ relative to the jet directions in the event selection thus improves Drell-Yan rejection.

The direction of $\mathbf{E}_T^{\text{miss}}$ relative to the lepton and jet directions is also used to reject Drell-Yan, particularly the case of $\tau\tau$ production where $\mathbf{E}_T^{\text{miss}}$ tends to align with a final-state lepton. A relative quantity $E_{T,\text{rel}}^{\text{miss}}$ is defined as follows:

$$E_{T,\text{rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} \sin \Delta\phi_{\text{near}} & \text{if } \Delta\phi_{\text{near}} < \pi/2 \\ E_T^{\text{miss}} & \text{otherwise,} \end{cases} \quad (3)$$

where $\Delta\phi_{\text{near}}$ is the azimuthal separation of the $\mathbf{E}_T^{\text{miss}}$ and the nearest high- p_T lepton or jet. A similar calculation defines $p_{T,\text{rel}}^{\text{miss}}$ and $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$.

C. Monte Carlo samples

Given the large number of background contributions to the signal region and the broadly peaking signal m_T distribution, Monte Carlo modeling is an important aspect of the analysis. Dedicated samples are generated to evaluate all but the W + jets and multijet backgrounds, which are estimated using data (see Sec. VI C). Most samples use the POWHEG [34] generator to include corrections at next-to-leading order (NLO) in α_s . In cases where higher parton multiplicities are important, ALPGEN [35] or SHERPA [36] provide merged calculations at tree level for up to five additional partons. In a few cases, only leading-order generators (such as ACERMC [37] or GG2VV [38]) are available. Table III shows the generator and cross section used for each process.

The matrix-element-level Monte Carlo calculations are matched to a model of the parton shower, underlying event and hadronization, using either PYTHIA6 [39], PYTHIA8 [40], HERWIG [41] (with the underlying event modeled by JIMMY [42]), or SHERPA. Input parton distribution functions (PDFs) are taken from CT10 [43] for the POWHEG and SHERPA samples and CTEQ6L1 [44] for ALPGEN + HERWIG and ACERMC samples. The Z/γ^* sample is reweighted to the MRSTmc1 PDF set [45].

Pile-up interactions are modeled with PYTHIA8, and the ATLAS detector response is simulated [46] using either GEANT4 [47] or GEANT4 combined with a parametrized GEANT4-based calorimeter simulation [48]. Events are filtered during generation where necessary, allowing up to 2 ab^{-1} of equivalent luminosity for high cross section processes such as Z/γ^* in the VBF category.

The ggF and VBF production models for the $H \rightarrow WW^*$ signal are modeled with POWHEG + PYTHIA8 [49,50] at

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$m_H = 125 \text{ GeV}$, and the corresponding cross sections are shown in Table III. A detailed description of these processes and their modeling uncertainties is given in Sec. V. The smaller contribution from the VH process, with subsequent $H \rightarrow WW^*$ decay, is also shown in Table III. Not shown are the $H \rightarrow \tau\tau$ MC samples, which have an even smaller contribution but are included in the signal modeling for completeness using the same generators as for the $H \rightarrow WW^*$ decay. The $H \rightarrow ZZ^*$ decay contributes negligibly after event selection and is not included in the analysis.

TABLE III. Monte Carlo samples used to model the signal and background processes. The corresponding cross sections times branching fractions, $\sigma \cdot \mathcal{B}$, are quoted at $\sqrt{s} = 8 \text{ TeV}$. The branching fractions include the decays $t \rightarrow Wb$, $W \rightarrow \ell\nu$, and $Z \rightarrow \ell\ell$ (except for the process $ZZ \rightarrow \ell\ell\nu\nu$). Here ℓ refers to e , μ , or τ for signal and background processes. The neutral current $Z/\gamma^* \rightarrow \ell\ell$ process is denoted Z or γ^* , depending on the mass of the produced lepton pair. Vector-boson scattering (VBS) and vector-boson fusion background processes include all leading-order diagrams with zero QCD vertices for the given final state (except for diagrams with Higgs bosons, which only appear in the signal processes).

Process	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
Signal		
ggF $H \rightarrow WW^*$	POWHEG + PYTHIA8	0.435
VBF $H \rightarrow WW^*$	POWHEG + PYTHIA8	0.0356
VH $H \rightarrow WW^*$	PYTHIA8	0.0253
WW		
$q\bar{q} \rightarrow WW$ and $qg \rightarrow WW$	POWHEG + PYTHIA6	5.68
$gg \rightarrow WW$	GG2VV + HERWIG	0.196
$(q\bar{q} \rightarrow W) + (q\bar{q} \rightarrow W)$	PYTHIA8	0.480
$q\bar{q} \rightarrow WW$	SHERPA	5.68
VBS $WW + 2 \text{ jets}$	SHERPA	0.0397
Top quarks		
$t\bar{t}$	POWHEG + PYTHIA6	26.6
Wt	POWHEG + PYTHIA6	2.35
$tq\bar{b}$	ACERMC + PYTHIA6	28.4
$t\bar{b}$	POWHEG + PYTHIA6	1.82
Other dibosons (VV)		
$W\gamma$ ($p_T^\gamma > 8 \text{ GeV}$)	ALPGEN + HERWIG	369
$W\gamma^*$ ($m_{\ell\ell} \leq 7 \text{ GeV}$)	SHERPA	12.2
WZ ($m_{\ell\ell} > 7 \text{ GeV}$)	POWHEG + PYTHIA8	12.7
VBS $WZ + 2 \text{ jets}$	SHERPA	0.0126
($m_{\ell\ell} > 7 \text{ GeV}$)		
$Z\gamma$ ($p_T^\gamma > 8 \text{ GeV}$)	SHERPA	163
$Z\gamma^*$ ($\min m_{\ell\ell} \leq 4 \text{ GeV}$)	SHERPA	7.31
ZZ ($m_{\ell\ell} > 4 \text{ GeV}$)	POWHEG + PYTHIA8	0.733
$ZZ \rightarrow \ell\ell\nu\nu$ ($m_{\ell\ell} > 4 \text{ GeV}$)	POWHEG + PYTHIA8	0.504
Drell-Yan		
Z ($m_{\ell\ell} > 10 \text{ GeV}$)	ALPGEN + HERWIG	16500
VBF $Z + 2 \text{ jets}$	SHERPA	5.36
($m_{\ell\ell} > 7 \text{ GeV}$)		

Cross sections are calculated for the dominant diboson and top-quark processes as follows: the inclusive WW cross section is calculated to NLO in α_s with MCFM [51]; nonresonant gluon fusion is calculated and modeled to leading order (LO) in α_s with GG2VV, including both WW and ZZ production and their interference; $t\bar{t}$ production is normalized to the calculation at next-to-next-to-leading order (NNLO) in α_s with resummation of higher-order terms to the next-to-next-to-leading logarithms (NNLL), evaluated with TOP++2.0 [52]; and single-top processes are normalized to NNLL following the calculations from Refs. [53–55] for the s -channel, t -channel, and Wt processes, respectively. The $t\bar{t}$, Wt , and single-top s -channel kinematics are modeled with POWHEG + PYTHIA6 [56–58], while ACERMC [37] is used for the single-top t -channel process. The WW kinematics are modeled using the POWHEG + PYTHIA6 [59] sample for the $n_j \leq 1$ categories and the merged multileg SHERPA sample for the $n_j \geq 2$ categories. Section VI A describes this modeling and the normalization of the double parton interaction process ($q\bar{q} \rightarrow W$) + ($q\bar{q} \rightarrow W$), which is modeled using the PYTHIA8 generator. For WW , WZ , and ZZ production via nonresonant vector-boson scattering, the SHERPA generator provides the LO cross section and is used for event modeling. The negligible vector-boson scattering ZZ process is not shown in the table but is included in the background modeling for completeness.

The process $W\gamma^*$ is defined as associated $W + Z/\gamma^*$ production, where there is an opposite-charge same-flavor lepton pair with invariant mass $m_{\ell\ell}$ less than 7 GeV. This process is modeled using SHERPA with up to one additional parton. The range $m_{\ell\ell} > 7$ GeV is simulated with POWHEG + PYTHIA8 [59] and normalized to the POWHEG cross section. The use of SHERPA for $W\gamma^*$ is due to the inability of POWHEG + PYTHIA8 to model invariant masses down to the dielectron production threshold. The SHERPA sample requires two leptons with $p_T > 5$ GeV and $|\eta| < 3$. The jet multiplicity is corrected using a SHERPA sample generated with $0.5 < m_{\ell\ell} < 7$ GeV and up to two additional partons, while the total cross section is corrected using the ratio of the MCFM NLO to SHERPA LO calculations in the same restricted mass range. A similar procedure is used to model $Z\gamma^*$, defined as Z/γ^* pair production with one same-flavor opposite-charge lepton pair having $m_{\ell\ell} \leq 4$ GeV and the other having $m_{\ell\ell} > 4$ GeV.

The $W\gamma$ and DY processes are modeled using ALPGEN + HERWIG with merged tree-level calculations of up to five jets. The merged samples are normalized to the NLO calculation of MCFM (for $W\gamma$) or the NNLO calculation of DYNLLO [60] (for Z/γ^*). The $W\gamma$ sample is generated with the requirements $p_T^{\gamma} > 8$ GeV and $\Delta R(\gamma, \ell) > 0.25$. A $W\gamma$ calculation at NNLO [61] finds a correction of less than 8% in the modeled phase space, which falls within the uncertainty of the NLO calculation.

A SHERPA sample is used to accurately model the $Z(\rightarrow \ell\ell)\gamma$ background. The photon is required to have $p_T^{\gamma} > 8$ GeV and $\Delta R(\gamma, \ell) > 0.1$; the lepton pair must satisfy $m_{\ell\ell} > 10$ GeV. The cross section is normalized to NLO using MCFM. Events are removed from the ALPGEN + HERWIG DY samples if they overlap with the kinematics defining the SHERPA $Z(\rightarrow \ell\ell)\gamma$ sample.

The uncertainties are discussed for each specific background in Sec. VI, and their treatment in the likelihood fit is summarized in Sec. VII.

D. Modifications for 7 TeV data

The 7 TeV data are selected using single-lepton triggers with a muon p_T threshold of 18 GeV and with varying electron p_T thresholds (20 or 22 GeV depending on the data-taking period). The identification of the electrons uses the “tight” selection-based requirement described in Ref. [62] over the entire E_T range, and the GSF fit is not used. Muons are identified with the same selection used for the analysis of the 8 TeV data. The lepton isolation requirements are tighter than in the 8 TeV analysis due to a statistically and systematically less precise estimation of the backgrounds with misidentified leptons. The jet p_T thresholds are the same as in the 8 TeV analysis, but due to less severe pile-up conditions, the requirement on the jet vertex fraction $JVF > 0.75$ can be stricter without loss in signal efficiency.

The MC samples used for the analysis of the 7 TeV data have been chosen to reflect closely the samples used for the 8 TeV data (see Table III). The same matrix-element calculations and parton-shower models are used for all samples except for the WZ and ZZ backgrounds where POWHEG + PYTHIA6 is used instead of POWHEG + PYTHIA8. The pile-up events are simulated with PYTHIA6 instead of PYTHIA8. The samples are normalized to inclusive cross sections computed following the same prescriptions described in Sec. III C.

IV. EVENT SELECTION

The initial sample of events is based on the data quality, trigger, lepton p_T threshold, and two identified leptons discussed in the previous section. Events with more than two identified leptons with $p_T > 10$ GeV are rejected.

After the leptons are required to have opposite charge and pass the p_T -threshold selections, the $e\mu$ sample of approximately 1.33×10^5 events is composed primarily of contributions from $Z/\gamma^* \rightarrow \tau\tau$ and $t\bar{t}$, with approximately 800 expected signal events. The $ee/\mu\mu$ sample of 1.6×10^7 events is dominated by $Z/\gamma^* \rightarrow ee, \mu\mu$ production, which is largely reduced (by approximately 90%) by requiring $|m_{\ell\ell} - m_Z| > 15$ GeV. Low-mass meson resonances and Z/γ^* (Drell-Yan or DY) events are removed with the $m_{\ell\ell} > 10$ GeV (12 GeV) selection for the $e\mu$ ($ee/\mu\mu$) samples. The DY, W + jets, and multijets events are further reduced

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with requirements on the missing transverse momentum distributions. Figure 5(a) shows the $E_{T,\text{rel}}^{\text{miss}}$ distribution in the $n_j \leq 1$ $ee/\mu\mu$ sample, where the dominant $Z/\gamma^* \rightarrow ee, \mu\mu$ contribution is suppressed by the $E_{T,\text{rel}}^{\text{miss}} > 40$ GeV requirement. In the $n_j \leq 1$ and $n_j \geq 2$ ggF-enriched $e\mu$ samples, a $p_T^{\text{miss}} > 20$ GeV selection is applied to significantly reduce the $Z/\gamma^* \rightarrow \tau\tau$ background and the multijet backgrounds with misidentified leptons [see Figs. 5(b) and 5(c) for the $n_j \leq 1$ categories]. The $n_j \geq 2$ VBF-enriched $e\mu$ sample requires no missing transverse momentum selection, and thus recovers signal acceptance for the statistically limited VBF measurement. In the $ee/\mu\mu$ sample, more stringent selections are applied: $E_T^{\text{miss}} > 45$ GeV and $p_T^{\text{miss}} > 40$ GeV. Table IV lists these so-called preselection criteria.

The different background composition as a function of jet multiplicity motivates the division of the data sample into the various n_j categories. Figures 6(a) and 6(b) show the jet multiplicity distributions in the $ee/\mu\mu$ and $e\mu$ samples, respectively. The $Z/\gamma^* \rightarrow ee, \mu\mu$ background dominates the $n_j \leq 1$ $ee/\mu\mu$ samples even after the above-mentioned missing transverse momentum requirements. The top-quark background becomes more significant at higher jet multiplicities. Its suppression is primarily based on the b -jet multiplicity; the distribution is shown in Fig. 6(c) for the $e\mu$ sample.

In each of the n_j and lepton-flavor categories, further criteria are applied to increase the precision of the signal measurement. Sections IVA to IV D present the discriminating distributions and the resulting event yields. The selections are also listed in Table IV along with the preselection. Section IV E details the selection modifications for the 7 TeV data analysis. Section IV F concludes with the distributions after all requirements are applied.

In this section, the background processes are normalized using control regions (see Sec. VI). The distributions in the figures and the rates in the tables for the signal contribution correspond to the expectations for an SM Higgs boson with $m_H = 125$ GeV. The VBF contribution includes the small contribution from VH production, unless stated otherwise.

A. $n_j = 0$ category

Events with a significant mismeasurement of the missing transverse momentum are suppressed by requiring p_T^{miss} to point away from the dilepton transverse momentum ($\Delta\phi_{\ell\ell, \text{MET}} > \pi/2$). In the absence of a reconstructed jet to balance the dilepton system, the magnitude of the dilepton momentum $p_T^{\ell\ell}$ is expected to be small in DY events. A requirement of $p_T^{\ell\ell} > 30$ GeV further reduces the DY contribution while retaining the majority of the signal events, as shown for the $e\mu$ sample in Fig. 7(a). At this stage, the DY background is sufficiently reduced in the $e\mu$ sample, but still dominates in the $ee/\mu\mu$ one. In this latter

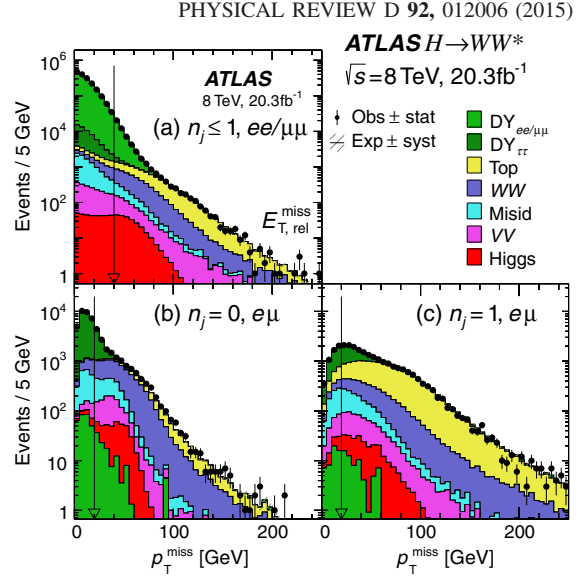


FIG. 5 (color online). Missing transverse momentum distributions. The plots for E_T^{miss} and p_T^{miss} [see Eq. (2)] are made after applying the preselection criteria common to all n_j categories (see Table IV). The observed data points (Obs, •) with their statistical uncertainty (stat) are compared with the histograms representing the cumulative expected contributions (Exp, -), for which the systematic uncertainty (syst) is represented by the shaded band. The band accounts for experimental uncertainties and for theoretical uncertainties on the acceptance for background and signal and is only visible in the tails of the distributions. Of the listed contributions (see Table I), the dominant DY backgrounds peak at low values. The legend order follows the histogram stacking order of the plots with the exception of $DY_{ee/\mu\mu}$: it is at the top for (a) and at the bottom for the others. The arrows mark the threshold of the selection requirements.

sample, a requirement of $p_{T,\text{rel}}^{\text{miss}(\text{trk})} > 40$ GeV is applied to provide further rejection against DY events.

The continuum WW production and the resonant Higgs boson production processes can be separated by exploiting the spin-0 property of the Higgs boson, which, when combined with the $V-A$ nature of the W boson decay, leads to a small opening angle between the charged leptons (see Sec. II). A requirement of $\Delta\phi_{\ell\ell} < 1.8$ reduces both the WW and DY backgrounds while retaining 90% of the signal. A related requirement of $m_{\ell\ell} < 55$ GeV combines the small lepton opening angle with the kinematics of a low-mass Higgs boson ($m_H = 125$ GeV). The $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ distributions are shown for the $e\mu$ sample in Figs. 7(b) and 7(c), respectively.

An additional discriminant, f_{recoil} , based on soft jets, is defined to reduce the remaining DY contribution in the $ee/\mu\mu$ sample. This residual DY background satisfies the event selection primarily when the measurement of the energy associated with partons from initial-state

TABLE IV. Event selection summary. Selection requirements specific to the $e\mu$ and $ee/\mu\mu$ lepton-flavor samples are noted as such (otherwise, they apply to both); a dash (-) indicates no selection. For the $n_j \geq 2$ VBF-enriched category, MET denotes all types of missing transverse momentum observables. Values are given for the analysis of 8 TeV data for $m_H = 125$ GeV; the modifications for 7 TeV are given in Sec. IV E. All energy-related values are in GeV.

Objective	ggF-enriched			VBF-enriched
	$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
Preselection	$\left\{ \begin{array}{l} p_T^{\ell_1} > 22 \text{ for the leading lepton } \ell_1 \\ p_T^{\ell_2} > 10 \text{ for the subleading lepton } \ell_2 \\ \text{Opposite-charge leptons} \\ m_{\ell\ell} > 10 \text{ for the } e\mu \text{ sample} \\ m_{\ell\ell} > 12 \text{ for the } ee/\mu\mu \text{ sample} \\ m_{\ell\ell} - m_Z > 15 \text{ for the } ee/\mu\mu \text{ sample} \end{array} \right.$			
	$p_T^{\text{miss}} > 20 \text{ for } e\mu$ $E_{T,\text{rel}}^{\text{miss}} > 40 \text{ for } ee/\mu\mu$	$p_T^{\text{miss}} > 20 \text{ for } e\mu$ $E_{T,\text{rel}}^{\text{miss}} > 40 \text{ for } ee/\mu\mu$	$p_T^{\text{miss}} > 20 \text{ for } e\mu$ -	No MET requirement for $e\mu$ -
Reject backgrounds	$\left\{ \begin{array}{l} p_{T,\text{rel}}^{\text{miss (trk)}} > 40 \text{ for } ee/\mu\mu \\ f_{\text{recoil}} < 0.1 \text{ for } ee/\mu\mu \\ p_T^{\ell\ell} > 30 \\ \Delta\phi_{\ell\ell,\text{MET}} > \pi/2 \end{array} \right.$			
		$p_{T,\text{rel}}^{\text{miss (trk)}} > 35 \text{ for } ee/\mu\mu$ $f_{\text{recoil}} < 0.1 \text{ for } ee/\mu\mu$ $m_{\tau\tau} < m_Z - 25$ -	- - $m_{\tau\tau} < m_Z - 25$ -	$p_T^{\text{miss}} > 40 \text{ for } ee/\mu\mu$ $E_{T,\text{rel}}^{\text{miss}} > 45 \text{ for } ee/\mu\mu$ $m_{\tau\tau} < m_Z - 25$ -
Misid	-	$m_T^{\ell} > 50 \text{ for } e\mu$	-	-
Top	$\left\{ \begin{array}{l} n_j = 0 \\ - \\ - \end{array} \right.$	$\left\{ \begin{array}{l} n_b = 0 \\ - \\ - \end{array} \right.$	$\left\{ \begin{array}{l} n_b = 0 \\ - \\ - \end{array} \right.$	$\left\{ \begin{array}{l} n_b = 0 \\ p_T^{\text{sum}} \text{ inputs to BDT} \\ \Sigma m_{e_j} \text{ inputs to BDT} \end{array} \right.$
VBF topology	-	-	See Sec. IV D for rejection of VBF & VH ($W, Z \rightarrow jj$), where $H \rightarrow WW^*$	m_{jj} inputs to BDT Δy_{jj} inputs to BDT ΣC_{ℓ} inputs to BDT $C_{\ell 1} < 1$ and $C_{\ell 2} < 1$ $C_{j3} > 1$ for j_3 with $p_T^{j3} > 20$ $O_{\text{BDT}} \geq -0.48$
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay topology	$m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$ No m_T requirement	$m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$ No m_T requirement	$m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$ No m_T requirement	$m_{\ell\ell}$ inputs to BDT $\Delta\phi_{\ell\ell}$ inputs to BDT m_T inputs to BDT

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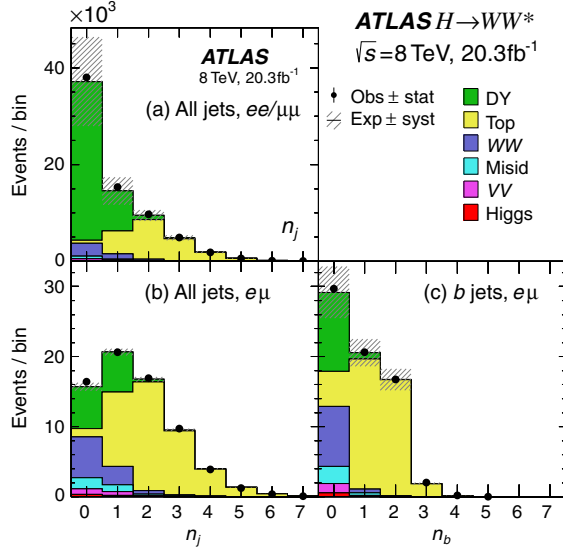
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FIG. 6 (color online). Jet multiplicity distributions for all jets (n_j) and b -tagged jets (n_b). The plots are made after applying the preselection criteria common to all n_j categories (see Table IV). See Fig. 5 for plotting details.

radiation is underestimated, resulting in an apparent imbalance of transverse momentum in the event. To further suppress such mismeasured DY events, jets with $p_T^j > 10$ GeV, within a $\pi/2$ wedge in ϕ (noted as $\wedge$) centered on $-\vec{p}_T^{\ell\ell}$, are used to define a fractional jet recoil relative to the dilepton transverse momentum:

$$f_{\text{recoil}} = \left| \sum_{\text{jets } j \text{ in } \wedge} \text{JVF}_j \cdot \vec{p}_T^j \right| / p_T^{\ell\ell}. \quad (4)$$

The jet transverse momenta are weighted by their associated JVF value to suppress the contribution from jets originating from pile-up interactions. Jets with no associated tracks are assigned a weight of 1. The f_{recoil} distribution is shown in Fig. 7(d); a requirement of $f_{\text{recoil}} < 0.1$ reduces the residual DY background in the $ee/\mu\mu$ sample by a factor of 7.

The expected signal and background yields at each stage of selection are shown in Table V, together with the observed yields. At the final stage, the table also shows the event yields in the range $\frac{3}{4}m_H < m_T < m_H$ where most of the signal resides. This m_T selection is not used to extract the final results, but nicely illustrates the expected signal-to-background ratios in the different categories.

B. $n_j = 1$ category

The one-jet requirement significantly increases the top-quark background. Since top quarks decay to Wb , events with jets with $p_T > 20$ GeV are rejected if they are

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identified as containing a b -quark [$n_b = 0$, see Fig. 6(c)]. After this requirement, the WW and the DY background processes are dominant in the sample, as shown in Table VI.

In the case of the $e\mu$ sample, a requirement is applied to the transverse mass defined for a single lepton ℓ_i :

$$m_T^{\ell_i} = \sqrt{2p_T^{\ell_i} \cdot p_T^{\text{miss}} \cdot (1 - \cos \Delta\phi)}, \quad (5)$$

where $\Delta\phi$ is the angle between the lepton transverse momentum and $\vec{p}_T^{\text{miss}}$. This quantity tends to have small values for the DY background and large values for the signal process. It also has small values for multijet production, where misidentified leptons are frequently measured with energy lower than the jets from which they originate. The m_T^{ℓ} distribution, chosen to be the larger of $m_T^{\ell_1}$ or $m_T^{\ell_2}$, is presented in Fig. 8(a), and shows a clear difference in shape between the DY and multijet backgrounds, which lie mostly at low values of m_T^{ℓ} , and the other background processes. Thus, both the DY and multijet processes are substantially reduced with a requirement of $m_T^{\ell} > 50$ GeV in the $e\mu$ sample.

The requirement of a jet allows for improved rejection of the $Z/\gamma^* \rightarrow \tau\tau$ background. Using the direction of the measured missing transverse momentum, the mass of the τ -lepton pair can be reconstructed using the so-called collinear approximation [63]. A requirement of $m_{\tau\tau} < m_Z - 25$ GeV significantly reduces the remaining DY contribution in the $e\mu$ sample, as can be seen in Fig. 8(b).

The remaining selection criteria ($p_{T,\text{rel}}^{\text{miss(trk)}}$, f_{recoil} , $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$) are the same as in the $n_j = 0$ category, except that $p_T^{\ell\ell}$ is replaced with the magnitude of $\vec{p}_T^{\ell\ell} = \vec{p}_T^{\ell_1} + \vec{p}_T^{\ell_2}$ in the calculation of f_{recoil} , and the $p_{T,\text{rel}}^{\text{miss(trk)}}$ threshold is reduced to 35 GeV. The $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ distributions are shown in Figs. 8(c) and 8(d), respectively. Differences between the shapes of the signal or WW processes and the Z/γ^* background processes are more apparent in the $\Delta\phi_{\ell\ell}$ distribution of the $e\mu + ee/\mu\mu$ events than of the $e\mu$ events.

C. VBF-enriched $n_j \geq 2$ category

The $n_j \geq 2$ sample contains signal events produced by both the VBF and ggF production mechanisms. This section focuses on the former; the next section focuses on the latter.

The sample is analyzed using a boosted decision tree multivariate method [16] that considers VBF Higgs boson production as signal and the rest of the processes as background, including ggF Higgs boson production. A cross-check analysis is performed using sequential selections on some of the variables that are used as inputs to the BDT. Table VII shows the sample composition after each of the selection requirements in the cross-check analysis. For the WW and $Z/\gamma^* \rightarrow \tau\tau$ backgrounds, the table separates contributions from events with jets from QCD vertices and

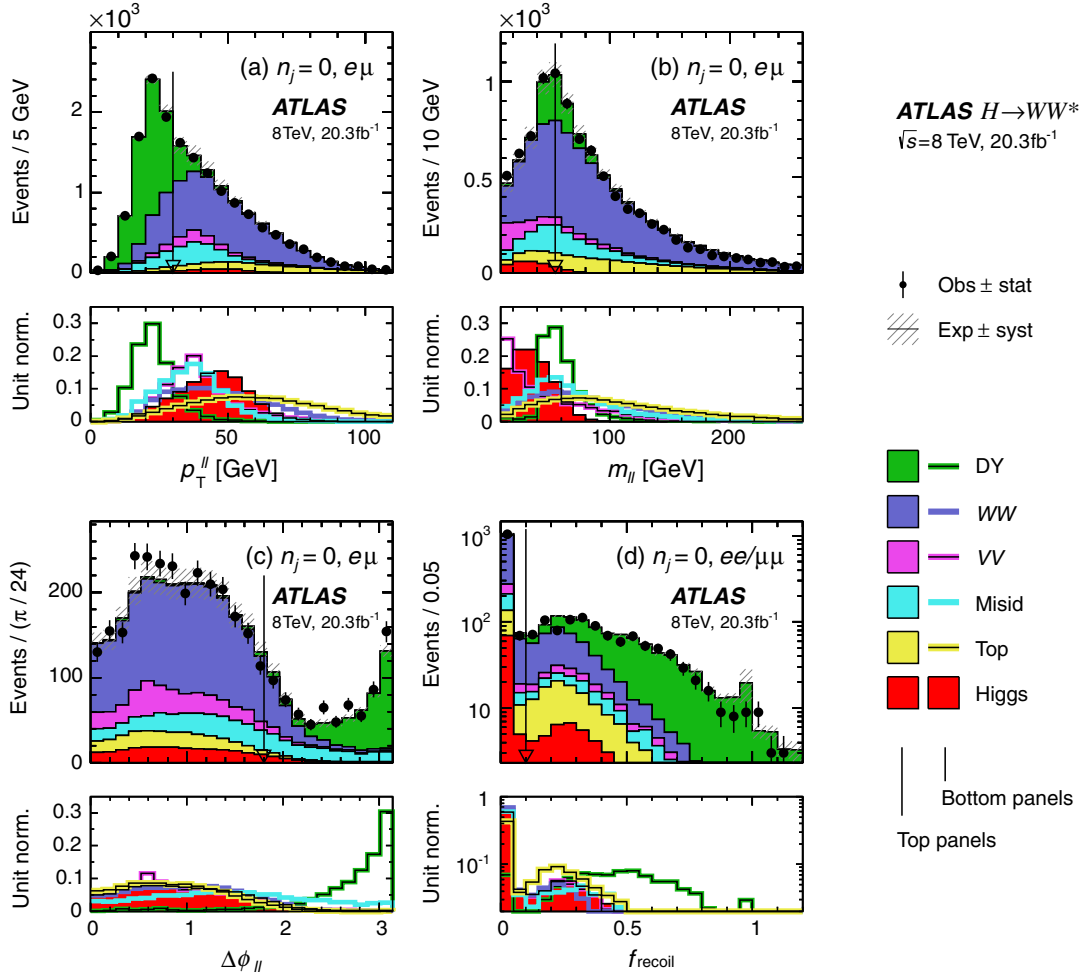


FIG. 7 (color online). Distributions of (a) $p_T^{\ell\ell}$, (b) $m_{\ell\ell}$, (c) $\Delta\phi_{\ell\ell}$, and (d) f_{recoil} , for the $n_j = 0$ category. The plot in (a) is made after requiring all selections up to $p_T^{\ell\ell}$, (b) up to $m_{\ell\ell}$, (c) up to $\Delta\phi_{\ell\ell}$, and (d) up to f_{recoil} (see Table V). For each variable, the top panel compares the observed and the cumulative expected distributions; the bottom panel shows the overlay of the distributions of the individual expected contributions, normalized to unit area, to emphasize shape differences. See Fig. 5 for plotting details.

electroweak events with VBS or VBF interactions (see Table III).

The VBF process is characterized by the kinematics of the pair of tag jets (j_1 and j_2) and the activity in the rapidity gap between them. In general, this process results in two highly energetic forward jets with $\Delta y_{jj} > 3$, where $\Delta y_{jj} = |y_{j1} - y_{j2}|$. The invariant mass of this tag-jet pair combines Δy_{jj} with p_T^j information since $m_{jj} \approx \sqrt{p_T^{j1} \cdot p_T^{j2} e^{\Delta y_{jj}/2}}$ for large values of Δy_{jj} . Both Δy_{jj} and m_{jj} are input variables to the BDT; for the cross-check analysis, $\Delta y_{jj} > 3.6$ and $m_{jj} > 600$ GeV are required [see Figs. 9(a) and 9(b)].

The Δy_{jj} gap defines a “central region,” where a relatively low level of hadronic activity is expected because the mediating weak bosons do not exchange color. The number of extra jets ($n_{\text{extra-j}}$) in the Δy_{jj} gap quantifies the activity. Requiring the absence of such jets in this region is known as a “central-jet veto” [64] and it suppresses processes where the jets are produced via QCD radiation. The central-jet veto uses jets with $p_T > 20$ GeV, and this requirement is applied in both the BDT and cross-check analyses. The selection can be expressed in terms of jet centrality, defined as

$$C_{j3} = \left| \eta_{j3} - \frac{\sum \eta_{jj}}{2} \right| / \frac{\Delta \eta_{jj}}{2}, \quad (6)$$

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TABLE V. Event selection for the $n_j = 0$ category in the 8 TeV data analysis. The selection is presented separately for the $e\mu$ and $ee/\mu\mu$ samples. The summary columns give the observed yields (N_{obs}), the expected background yields (N_{bkg}), their ratios, and the expected signal yields (N_{sig}). For the dominant backgrounds, the expected yields are normalized using control regions, as described in Sec. VI. The N_{sig} values are given for $m_H = 125$ GeV and are subdivided into the N_{ggF} and N_{VBF} contributions. The composition columns give the contributions to N_{bkg} (see Sec. VI). The requirements are imposed sequentially from top to bottom; entries are shown as 0.0 (-) if they are less than 0.1 events. The entries are rounded to a precision commensurate with the statistical uncertainties due to the random error associated with the central value of the yield ($\text{stat}_{\text{obs}} = \sqrt{N_{\text{obs}}}$) and the sampling error associated with the finite sample size used for the prediction for background type k ($\text{stat}_{\text{bkg},k}$). The errors on $N_{\text{obs}}/N_{\text{bkg}}$ are due to the combined statistical uncertainty on stat_{obs} and stat_{bkg} . Energy-related quantities are in GeV.

Selection	Summary					Composition of N_{bkg}							
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{sig}		N_{WW}	N_{top}		N_{misid}		N_{VV}	N_{DY}	
				N_{ggF}	N_{VBF}		$N_{t\bar{t}}$	N_t	N_{Wj}	N_{jj}		$N_{ee/\mu\mu}$	$N_{\tau\tau}$
<i>eμ</i> sample	1.01 ± 0.01	16423	16330	290	12.1	7110	820	407	1330	237	739	115	5570
$\Delta\phi_{\ell\ell,\text{MET}} > \pi/2$	1.00 ± 0.01	16339	16270	290	12.1	7110	812	405	1330	230	736	114	5530
$p_{\text{T}}^{\ell\ell} > 30$	1.00 ± 0.01	9339	9280	256	10.3	5690	730	363	1054	28	571	60	783
$m_{\ell\ell} < 55$	1.11 ± 0.02	3411	3060	224	6.3	1670	141	79	427	12	353	27	350
$\Delta\phi_{\ell\ell} < 1.8$	1.12 ± 0.02	2642	2350	203	5.9	1500	132	75	278	9.2	324	19	12
$\frac{3}{4}m_H < m_{\text{T}} < m_H$	1.20 ± 0.04	1129	940	131	2.2	660	40	21	133	0.8	78	4.3	2.3
<i>ee/μμ</i> sample	1.04 ± 0.01	38040	36520	163	7.2	3260	418	211	504	29	358	31060	685
$\Delta\phi_{\ell\ell,\text{MET}} > \pi/2$	1.05 ± 0.01	35445	33890	163	7.1	3250	416	211	493	26	355	28520	622
$p_{\text{T}}^{\ell\ell} > 30$	1.06 ± 0.01	11660	11040	154	6.8	3010	394	201	396	2.6	309	6700	21
$m_{\ell\ell} < 55$	1.01 ± 0.01	6786	6710	142	5.0	1260	109	64	251	2.0	179	4840	8.7
$p_{\text{T,rel}}^{\text{miss (trk)}} > 40$	1.02 ± 0.02	2197	2160	117	4.3	1097	99	59	133	0.5	106	660	0.3
$\Delta\phi_{\ell\ell} < 1.8$	1.01 ± 0.02	2127	2100	113	4.2	1068	96	57	122	0.5	104	649	0.3
$f_{\text{recoil}} < 0.1$	1.01 ± 0.03	1108	1096	72	2.7	786	41	31	79	0.0	69	91	0.1
$\frac{3}{4}m_H < m_{\text{T}} < m_H$	0.99 ± 0.05	510	517	57	1.3	349	11	8	53	-	31	64	0.1

where η_{j3} is the pseudorapidity of an extra jet, $\Sigma\eta_{jj} = \eta_{j1} + \eta_{j2}$ and $\Delta\eta_{jj} = |\eta_{j1} - \eta_{j2}|$. The value of C_{j3} increases from zero, when η_{j3} is centered between the tag jets, to unity when η_{j3} is aligned in η with either of the tag jets, and is greater than unity when $|\eta_{j3}| > |\eta_{j1}|$ or

$|\eta_{j3}| > |\eta_{j2}|$. The centrality of any extra jet in the event is required therefore to be $C_{j3} > 1$.

The Higgs boson decay products tend to be in the central rapidity region. The centrality of a given lepton, C_ℓ , with respect to the tag jets is defined similarly to that for extra

TABLE VI. Event selection for the $n_j = 1$ category in the 8 TeV data analysis (see Table V for presentation details).

Selection	Summary					Composition of N_{bkg}							
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{sig}		N_{WW}	N_{top}		N_{misid}		N_{VV}	N_{DY}	
				N_{ggF}	N_{VBF}		$N_{t\bar{t}}$	N_t	N_{Wj}	N_{jj}		$N_{ee/\mu\mu}$	$N_{\tau\tau}$
<i>eμ</i> sample	1.00 ± 0.01	20607	20700	131	32	2750	8410	2310	663	334	496	66	5660
$n_b = 0$	1.01 ± 0.01	10859	10790	114	26	2410	1610	554	535	268	423	56	4940
$m_{\text{T}}^{\ell\ell} > 50$	1.01 ± 0.01	7368	7280	103	23	2260	1540	530	477	62	366	43	1990
$m_{\tau\tau} < m_Z - 25$	1.02 ± 0.02	4574	4490	96	20	1670	1106	390	311	32	275	21	692
$m_{\ell\ell} < 55$	1.05 ± 0.02	1656	1570	84	15	486	297	111	129	19	139	6.4	383
$\Delta\phi_{\ell\ell} < 1.8$	1.10 ± 0.03	1129	1030	74	13	418	269	102	88	6.1	119	5.0	22
$\frac{3}{4}m_H < m_{\text{T}} < m_H$	1.21 ± 0.06	407	335	42	6.6	143	76	30	40	0.5	42	1.1	2
<i>ee/μμ</i> sample	1.05 ± 0.01	15344	14640	61	15	1111	3770	999	178	13	192	8100	280
$n_b = 0$	1.08 ± 0.02	9897	9140	53	12.1	972	725	245	137	10	163	6640	241
$m_{\ell\ell} < 55$	1.16 ± 0.02	5127	4410	48	9.4	351	226	85	73	7.8	79	3420	168
$p_{\text{T,rel}}^{\text{miss (trk)}} > 35$	1.14 ± 0.04	960	842	36	6.9	292	193	73	38	0.2	49	194	2
$\Delta\phi_{\ell\ell} < 1.8$	1.14 ± 0.04	889	783	32	6.3	265	179	68	30	0.2	44	194	2
$f_{\text{recoil}} < 0.1$	1.16 ± 0.05	467	404	20	3.6	188	98	44	17	-	29	26	1
$\frac{3}{4}m_H < m_{\text{T}} < m_H$	1.11 ± 0.10	143	129	14	2.0	59	23	11	11	-	11	14	-

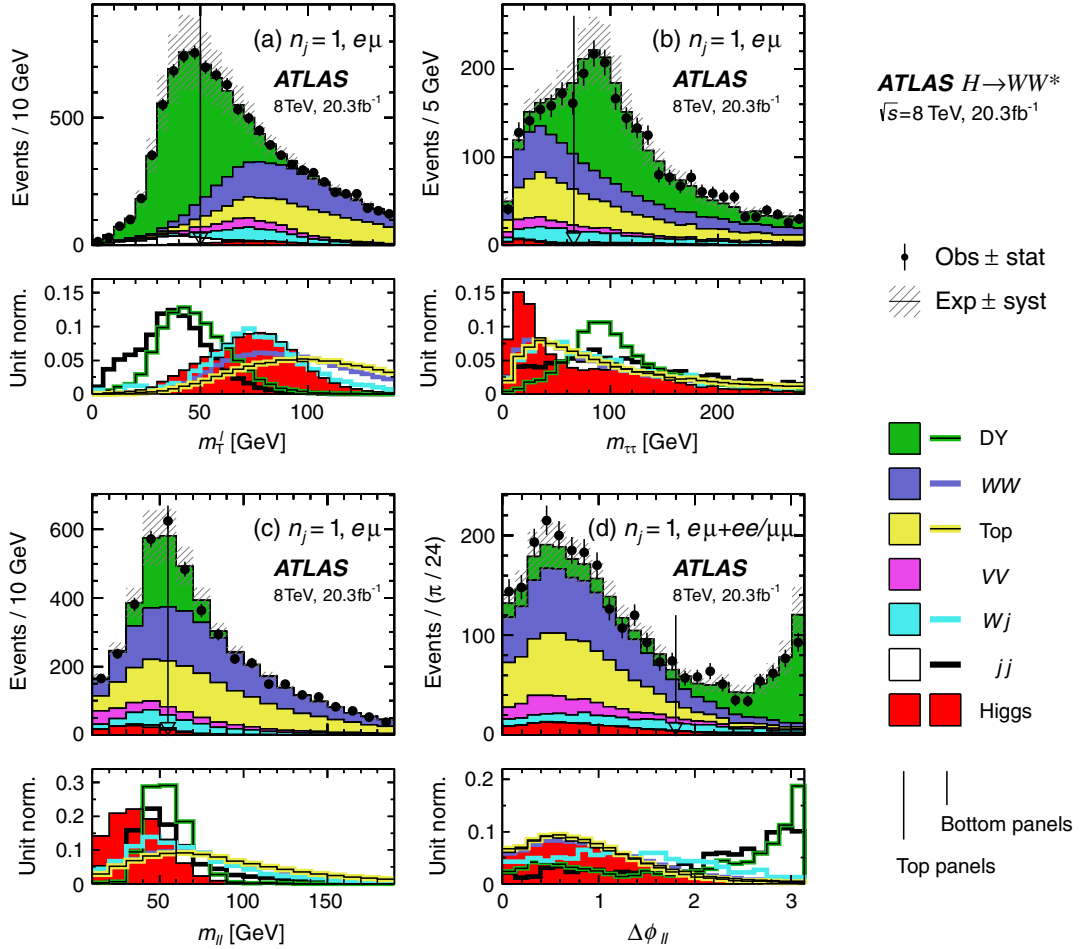


FIG. 8 (color online). Distributions of (a) m_T^ℓ , (b) $m_{\tau\tau}$, (c) $m_{\ell\ell}$, and (d) $\Delta\phi_{\ell\ell}$ for the $n_j = 1$ category. The plot in (a) is made after requiring all selections up to m_T^ℓ , (b) up to $m_{\tau\tau}$, (c) up to $m_{\ell\ell}$, and (d) up to $\Delta\phi_{\ell\ell}$ (see Table VI). See Figs. 5 and 7 for plotting details (the sum of the jj and Wj contributions corresponds to the label “Misid” in Fig. 5).

jets in Eq. (6). A requirement of $C_\ell < 1$ is applied to each lepton in the BDT and cross-check analyses. The sum of lepton centralities $\Sigma C_\ell = C_{\ell 1} + C_{\ell 2}$ is used as an input to the BDT. The $C_{\ell 1}$ distribution is shown in Fig. 9(c).

Top-quark pair production has a large cross section and the same final state as VBF Higgs boson production, with the exception that its jets result from b -quarks. A requirement of $n_b = 0$ with $p_T > 20$ GeV is made in the BDT and cross-check analyses. This requirement is made on all jets in the event regardless of classification as tag jets. Significant top-quark background still remains because of the limited η coverage of the tracker, the p_T threshold applied to the b -jets, and the inefficiency of the b -jet identification algorithm within the tracking region. Further

reductions are achieved through targeted kinematic selections and the BDT.

The pair production of top quarks occurs dominantly through gluon-gluon annihilation, and is frequently accompanied by QCD radiation. This radiation is used as a signature to further suppress top-quark backgrounds using the summed vector $\mathbf{p}_T$ of the final-state objects, $\mathbf{p}_T^{\text{sum}} = \mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\text{miss}} + \Sigma \mathbf{p}_T^j$ where the last term is a sum of the transverse momenta of all jets in the event. Its magnitude p_T^{sum} is used as input to the BDT and is required to be $p_T^{\text{sum}} < 15$ GeV in the cross-check analysis.

The sum of the four combinations of lepton-jet invariant mass, $\Sigma m_{\ell j} = m_{\ell 1, j1} + m_{\ell 1, j2} + m_{\ell 2, j1} + m_{\ell 2, j2}$, is also

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TABLE VII. Event selection for the $n_j \geq 2$ VBF-enriched category in the 8 TeV cross-check data analysis (see Table V for presentation details). The N_{ggF} , N_{VBF} , and N_{VH} expected yields are shown separately. The expected yields for WW and $Z/\gamma^* \rightarrow \tau\tau$ are divided into QCD and electroweak (EW) processes, where the latter includes VBS or VBF production.

Selection	Summary							Composition of N_{bkg}										
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{ggF}	N_{VBF}	N_{VH}	N_{signal}	$N_{\text{WW}}^{\text{QCD}}$	$N_{\text{WW}}^{\text{EW}}$	$N_{\text{t}\bar{\text{t}}}$	N_{t}	N_{misid}	N_{Vj}	N_{Vj}	N_{VV}	$N_{\text{ee}/\mu\mu}$	$N_{\text{Drell-Yan}}^{\text{QCD}}$	$N_{\text{Drell-Yan}}^{\text{EW}}$
$e\mu$ sample	1.00 ± 0.00	61434	61180	85	32	26	1350	68	51810	2970	847	308	380	51	3260	46		
$n_b = 0$	1.02 ± 0.01	7818	7700	63	26	16	993	43	3000	367	313	193	273	35	2400	29		
$p_{\text{T}}^{\text{sum}} < 15$	1.03 ± 0.01	5787	5630	46	23	13	781	38	1910	270	216	107	201	27	2010	23		
$m_{\tau\tau} < m_Z - 25$	1.05 ± 0.02	3129	2970	40	20	9.9	484	22	1270	177	141	66	132	7.6	627	5.8		
$m_{jj} > 600$	1.31 ± 0.12	131	100	2.3	8.2	-	18	8.9	40	5.3	1.8	2.4	5.1	0.1	15	1.0		
$\Delta y_{jj} > 3.6$	1.33 ± 0.13	107	80	2.1	7.9	-	11.7	6.9	35	5.0	1.6	2.3	3.3	-	11.6	0.8		
$C_{j3} > 1$	1.36 ± 0.18	58	43	1.3	6.6	-	6.9	5.6	14	3.0	1.3	1.3	2.0	-	6.8	0.6		
$C_{\ell 1} < 1, C_{\ell 2} < 1$	1.42 ± 0.20	51	36	1.2	6.4	-	5.9	5.2	10.8	2.5	1.3	1.3	1.6	-	5.7	0.6		
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\text{T}}$	2.53 ± 0.71	14	5.5	0.8	4.7	-	1.0	0.5	1.1	0.3	0.3	0.3	0.6	-	0.5	0.2		
$ee/\mu\mu$ sample	0.99 ± 0.01	26949	27190	31	14	10.1	594	37	23440	1320	230	8.6	137	690	679	16		
$n_b, p_{\text{T}}^{\text{sum}}, m_{\tau\tau}$	1.03 ± 0.03	1344	1310	13	8.0	4.0	229	12.0	633	86	26	0.9	45	187	76	1.5		
$m_{jj}, \Delta y_{jj}, C_{j3}, C_{\ell}$	1.39 ± 0.28	26	19	0.4	2.9	0.0	3.1	3.1	5.5	1.0	0.2	0.0	0.7	3.8	0.7	0.1		
$m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\text{T}}$	1.63 ± 0.69	6	3.7	0.3	2.2	0.0	0.4	0.2	0.6	0.2	0.2	0.0	0.1	1.5	0.3	0.1		

used as an input to the BDT. In the VBF topology, tag jets are more forward whereas the leptons tend to be more central. This results in differences in the shapes of the $\Sigma m_{\ell j}$ distributions for the VBF signal and the background processes, as can be seen in Fig. 9(d). This variable is not used in the cross-check analysis.

The other BDT input variables are those related to the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay topology ($m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\text{T}}$), which are also used in the $n_j \leq 1$ categories. The cross-check analysis requires $\Delta\phi_{\ell\ell} < 1.8$ and $m_{\ell\ell} < 50$ GeV.

Distributions from eight variables are input to the BDT: $\Sigma C_{\ell}, \Delta y_{jj}$, and m_{jj} for VBF selection; $p_{\text{T}}^{\text{sum}}$ and $\Sigma m_{\ell j}$ for $t\bar{t}$ rejection; and $\Delta\phi_{\ell\ell}, m_{\ell\ell}$, and m_{T} for their sensitivity to the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay topology. The BDT is trained after the common preselection criteria (as listed in Table IV) and the $n_b = 0$ requirement. This event selection stage corresponds to the $n_b = 0$ stage presented for the cross-check analysis in Table VII. Additional criteria, common to the BDT and cross-check analyses, are applied before the classification of the events based on the BDT output (described below). They include requirements on $m_{\tau\tau}, C_{j3}$, and C_{ℓ} . The observed and expected event yields after all these requirements are shown in Table VIII(a) separately for the $e\mu$ and $ee/\mu\mu$ samples. The dominant background processes include $t\bar{t}$ and Z/γ^* production. The normalization factors, described in Sec. VI, are not applied to these backgrounds at this stage.

The BDT is trained using the MC samples after the above-mentioned selections. The training starts with a single decision tree where an event is given a score of ± 1 if it satisfies particular sets of decisions (+1 leaf contains signal-like events and -1 background-like ones).

A thousand such trees are built and in each iteration the weight of miscategorized events is relatively increased, or “boosted.” The final discriminant O_{BDT} for a given event is the weighted average of the binary scores from the individual trees. The bin widths for the likelihood fit are optimized for the expected significance while keeping each bin sufficiently populated. The chosen configuration is four bins with boundaries at $[-1, -0.48, 0.3, 0.78, 1]$, and with corresponding bin numbers from 0 to 3. The lowest bin contains the majority of background events and has a very small signal-to-background ratio. It is therefore not used in the likelihood fit. The expected and observed event yields after the classification in bins of O_{BDT} are shown in Table VIII(b). Here the background yields are scaled by their corresponding normalization factors.

Appendix B documents the BDT analysis in more detail. It includes the distributions of all the input variables (showing the comparison between the VBF signal and the background processes) used in the training of the BDT as well as the data-to-MC comparison after the BDT classification. The distributions are in agreement and show that the correlations are well understood.

D. ggF-enriched $n_j \geq 2$ category

The sample of $n_j \geq 2$ events, which are neither in the VBF-enriched category for the BDT analysis nor in the cross-check analysis, are used to measure ggF production. In this category only the $e\mu$ final state is analyzed due to the relatively low expected significance in the $ee/\mu\mu$ sample. Table IX shows the signal and background yields after each selection requirement.

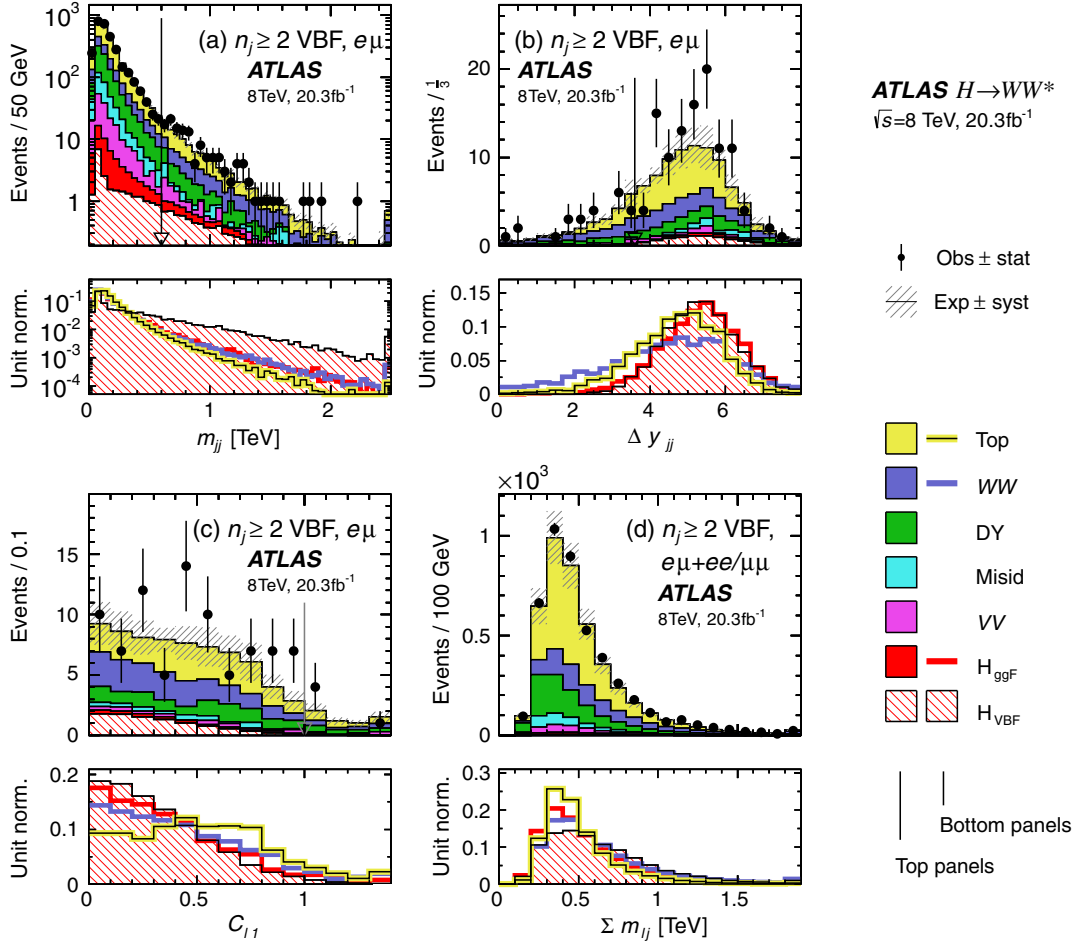


FIG. 9 (color online). Distributions of (a) m_{jj} , (b) Δy_{jj} , (c) $C_{\ell 1}$, and (d) $\Sigma m_{\ell\ell}$ for the $n_j \geq 2$ VBF-enriched category. The plot in (a) is made after requiring all selections up to m_{jj} , (b) up to Δy_{jj} , and (c) up to $C_{\ell 1}$ (see Table VII). The signal is shown separately for the ggF and VBF production processes. The arrows mark the threshold of the selection requirements for the cross-check analysis in (a)–(c). There is no selection made on the variable in (d) since it is only used as an input to the training of the BDT. See Figs. 5 and 7 for plotting details.

The initial selection, $n_b = 0$ and $m_{\tau\tau} < m_Z - 25$ GeV, is common to the other categories and reduces the top-quark and DY backgrounds. The ggF-enriched sample is forced to be mutually exclusive to the VBF-enriched sample by inverting at least one of the VBF-specific requirements: $C_{j3} > 1$, $C_\ell < 1$, or $O_{\text{BDT}} > -0.48$. A similar inversion is done for the cross-check analysis: $\Delta y_{jj} > 3.6$, $m_{jj} > 600$ GeV, $n_{\text{extra-}j} = 0$, or $C_\ell < 1$. Both sets of orthogonality requirements for the BDT and the cross-check are imposed for the $n_j \geq 2$ ggF-enriched category.

The resulting sample contains events in a region sensitive to VH production where the associated W or Z boson decays hadronically. This region is suppressed

by rejecting events in the region of $\Delta y_{jj} \leq 1.2$ and $|m_{jj} - 85| < 15$ GeV.

Figure 10 shows the $m_{\ell\ell}$ distribution after the VH orthogonality requirement. The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ topological selections, $m_{\ell\ell} < 55$ GeV and $\Delta\phi_{\ell\ell} < 1.8$, further reduce the dominant top-quark background by 70%, resulting in a signal purity of 3.3%.

E. Modifications for 7 TeV data

The 7 TeV data analysis closely follows the selection used in the 8 TeV analysis. The majority of the differences can be found in the object definitions and identifications, as described in Sec. III B. The lower average pile-up allows

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TABLE VIII. Event selection for the $n_j \geq 2$ VBF-enriched category in the 8 TeV BDT data analysis (see Table V for presentation details). The event yields in (a) are shown after the preselection and the additional requirements applied before the BDT classification (see text). The event yields in (b) are given in bins in O_{BDT} after the classification, the normalization factors are applied to the yields (see Table XX). In the specific case of (a), the normalization factors described in Sec. VI are not applied to the relevant backgrounds. The N_{ggF} , N_{VBF} , and N_{VH} expected yields are shown separately.

Selection	Summary						Composition of N_{bkg}										
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{ggF}	N_{VBF}	N_{VH}	$N_{\text{WW}}^{\text{QCD}}$	$N_{\text{WW}}^{\text{EW}}$	$N_{t\bar{t}}$	N_t	N_{top}	N_{Wj}	N_{jj}	N_{VV}	$N_{ee/\mu\mu}$	$N_{\text{Drell-Yan}}^{\text{QCD}}$	$N_{\tau\tau}^{\text{EW}}$
(a) Before the BDT classification																	
$e\mu$ sample	1.04 ± 0.04	718	689	13	15	2.0	90	11	327	42	29	23	31	2.2	130	2	
$ee/\mu\mu$ sample	1.18 ± 0.08	469	397	6.0	7.7	0.9	37	3	132	17	5.2	1.2	10.1	168	23	1	
(b) Bins in O_{BDT}																	
$e\mu$ sample																	
Bin 0 (not used)	1.02 ± 0.04	661	650	8.8	3.0	1.9	83	9	313	40	26	21	28	2.2	126	1	
Bin 1	0.99 ± 0.16	37	37	3.0	4.2	0.1	5.0	1.0	17	3.1	3.3	1.8	2.6	-	4.0	0.2	
Bin 2	2.26 ± 0.63	14	6.2	1.2	4.2	-	1.5	0.5	1.8	0.3	0.4	0.3	0.8	-	0.3	0.3	
Bin 3	5.41 ± 2.32	6	1.1	0.4	3.1	-	0.3	0.2	0.3	0.1	-	-	0.1	-	0.1	0.1	
$ee/\mu\mu$ sample																	
Bin 0 (not used)	1.91 ± 0.08	396	345	3.8	1.3	0.8	33	2	123	16	4.1	1.1	8.8	137	20.5	0.5	
Bin 1	0.82 ± 0.14	53	45	1.5	2.2	0.1	3.0	0.5	10.4	1.8	0.8	0.2	0.9	26	1.7	0.1	
Bin 2	1.77 ± 0.49	14	7.9	0.6	2.5	-	0.8	0.3	1.1	0.2	0.2	-	0.3	4.4	0.3	0.1	
Bin 3	6.52 ± 2.87	6	0.9	0.2	1.7	-	0.1	0.2	0.2	-	-	-	-	0.7	-	-	

the loosening, or removal, of requirements on several pile-up sensitive variables from the selection.

The amount of DY background in the $ee/\mu\mu$ channel depends on the missing transverse momentum resolution. This background is reduced in a lower pile-up environment, allowing lower $E_{\text{T}}^{\text{miss}}$ thresholds in the $ee/\mu\mu$ samples for the 7 TeV data analysis. The $E_{\text{T}}^{\text{miss}}$ requirement is lowered to 35 GeV, and the requirements on $p_{\text{T}}^{\text{miss(trk)}}$ are removed entirely. The effect of the reduced $E_{\text{T}}^{\text{miss}}$ thresholds is partially compensated by an increased $p_{\text{T}}^{\ell\ell}$ requirement of 40 GeV in the $n_j = 0$ category and a $p_{\text{T}}^{\ell\ell j} > 35$ GeV requirement added to the $n_j = 1$ category. The f_{recoil} criteria are loosened to 0.2 and 0.5 in the $n_j = 0$ and $n_j = 1$ categories, respectively.

In the $n_j \geq 2$ category, only the VBF-enriched analysis is considered; it follows an approach similar to the 8 TeV version. It exploits the BDT multivariate method and it uses the same BDT classification and output binning as the 8 TeV data analysis. In the $e\mu$ sample, a two-bin fit of the O_{BDT} is used (bins 2 and 3 are merged). In the $ee/\mu\mu$ sample, a one-bin fit is used (bins 1–3 are merged) due to the smaller sample size.

The background estimation, signal modeling, final observed and expected event yields, and the statistical analysis and results, are presented in the next sections.

F. Summary

This section described the event selection in the n_j and lepton-flavor categories. Each of these is treated

TABLE IX. Event selection for the $n_j \geq 2$ ggF-enriched category in the 8 TeV data analysis (see Table V for presentation details). The N_{ggF} , N_{VBF} , and N_{VH} expected yields are shown separately. The “orthogonality” requirements are given in the text.

Selection	Summary						Composition of N_{bkg}				
	$N_{\text{obs}}/N_{\text{bkg}}$	N_{obs}	N_{bkg}	N_{ggF}	N_{VBF}	N_{VH}	N_{WW}	N_{top}	N_{misid}	N_{VV}	N_{DY}
$e\mu$ category	0.99 ± 0.00	56759	57180	76	29	24	1330	52020	959	324	2550
$n_b = 0$	1.02 ± 0.01	6777	6650	56	23	15	964	3190	407	233	1850
$m_{\tau\tau} < m_Z - 25$	1.06 ± 0.02	3826	3620	49	19	12	610	2120	248	152	485
VBF orthogonality	1.05 ± 0.02	3736	3550	44	9.0	12	593	2090	241	148	477
VH orthogonality	1.04 ± 0.02	3305	3170	40	8.6	7.4	532	1870	212	132	423
$m_{\ell\ell} < 55$	1.09 ± 0.03	1310	1200	35	7.5	5.0	158	572	124	66	282
$\Delta\phi_{\ell\ell} < 1.8$	1.06 ± 0.03	1017	955	32	6.9	4.5	140	523	99	60	133
$\frac{3}{4}m_H < m_{\text{T}} < m_H$	1.05 ± 0.07	210	200	13.3	2.6	1.9	35	131	16	15	3

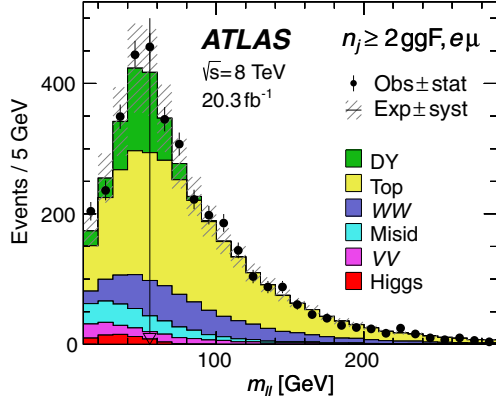


FIG. 10 (color online). Distribution of dilepton invariant mass for the $n_j \geq 2$ ggF-enriched category. The plot is made after requiring all selections up to $m_{\ell\ell}$ (see Table IX). See Fig. 5 for plotting details.

independently in the statistical analysis using a fit procedure described in Sec. VII. Inputs to the fit include the event yields and distributions at the final stage of the event selection without the m_T requirement.

The total signal efficiency for $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ events produced with $\ell = e$ and μ , including all signal categories and production modes, is 10.2% at 8 TeV for a Higgs boson mass of 125.36 GeV. The corresponding signal efficiency when considering only the VBF production mode is 7.8%.

Figure 11 shows the m_T distributions in the $n_j = 0$, $n_j = 1$, and $n_j \geq 2$ ggF-enriched categories for the 8 TeV data. The distributions for the $n_j \leq 1$ categories are shown in Fig. 12 for the 7 TeV data. The final O_{BDT} output distribution, for the VBF-enriched category, is shown in Fig. 13 for the 7 TeV and 8 TeV data samples.

Figures 14 and 15 show the p_{ℓ^2} and $m_{\ell\ell}$ distributions at the end of the event selection in the $n_j \leq 1$ $e\mu$ categories for the 8 TeV data analysis. The distributions are shown for two categories of events based on the flavor of the lepton with the higher p_T . This division is important for separating events based on the relative contribution from the backgrounds from misidentified

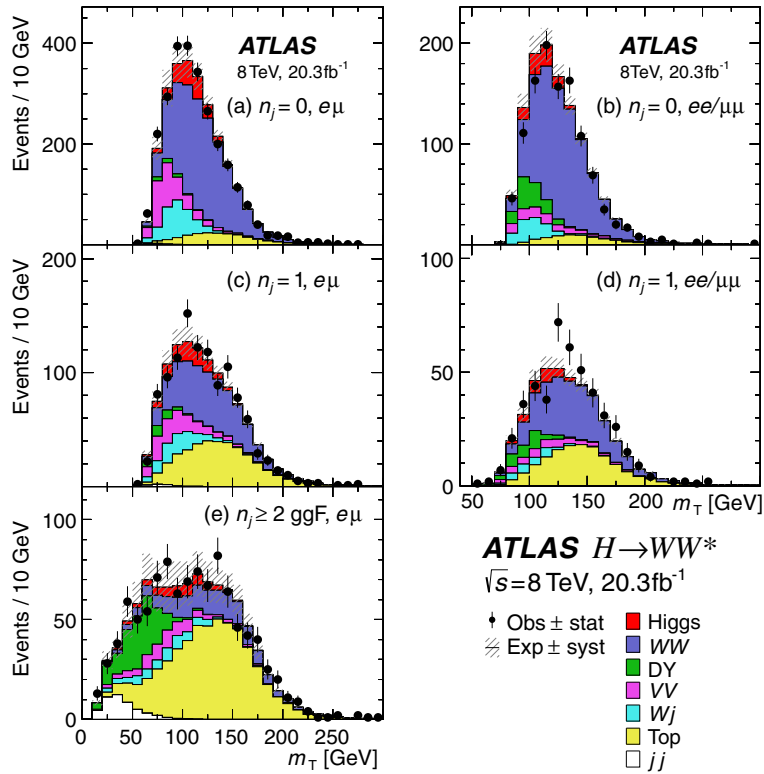


FIG. 11 (color online). Distributions of the transverse mass m_T for the $n_j \leq 1$ and $n_j \geq 2$ ggF-enriched categories in the 8 TeV data analysis. The plots are made after requiring all selections up to m_T (see Tables V, VI, and IX). See Fig. 5 for plotting details. The sum of the jj and Wj contributions corresponds to the label “Misid” in Fig. 5.

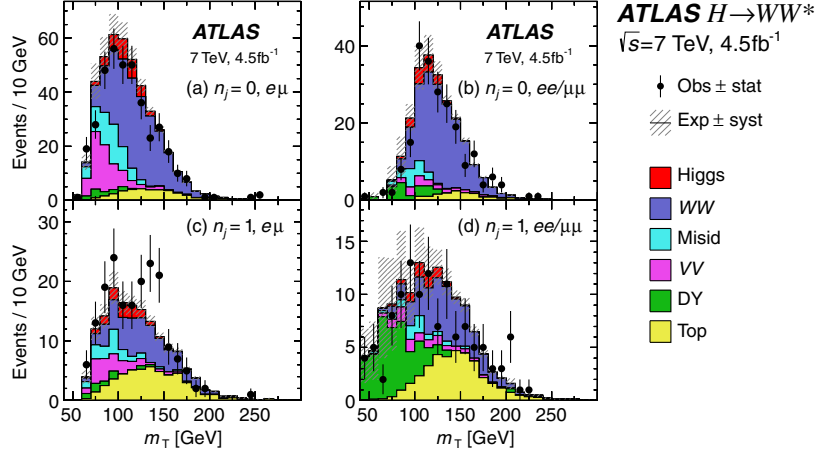
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FIG. 12 (color online). Distributions of the transverse mass m_T for the $n_j \leq 1$ categories in the 7 TeV data analysis. The plot is made after requiring all selections up to m_T (see Sec. IV E). See Fig. 5 for plotting details.

leptons (W + jets and multijets); see Sec. VIC for details. The dependence of the misidentified lepton and VV background distributions on $p_T^{\ell\ell}$ motivates the separation of the data sample into three bins of $p_T^{\ell\ell}$. The variations in the background composition across the $m_{\ell\ell}$ range motivate the division into two bins of $m_{\ell\ell}$. Figure 16 shows the corresponding distributions in the $e\mu$ $n_j \leq 1$ samples in the 7 TeV data analysis.

The event displays in Fig. 17 show examples of the detector activity for two signal candidates: one in the $n_j = 0$ $e\mu$ category for the 7 TeV data analysis, and one in the VBF-enriched $n_j \geq 2$ $e\mu$ category for the 8 TeV data analysis. Both events have a small value of $\Delta\phi_{\ell\ell}$ as is characteristic of the signal. The latter event shows

two well-separated jets that are characteristic of VBF production.

V. SIGNAL PROCESSES

The leading Higgs boson production processes are illustrated in Fig. 1. This section details the normalization and simulation of the ggF and VBF production modes. In both cases, the production cross section has been calculated to NNLO in QCD and next-to-leading order in the electroweak couplings. Resummation has been performed to NNLL in QCD for the ggF process. For the decay, the calculation of the branching fraction is computed using the $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$ partial widths from PROPHECY4f [65] and the width of all other decays from HDECAY [66].

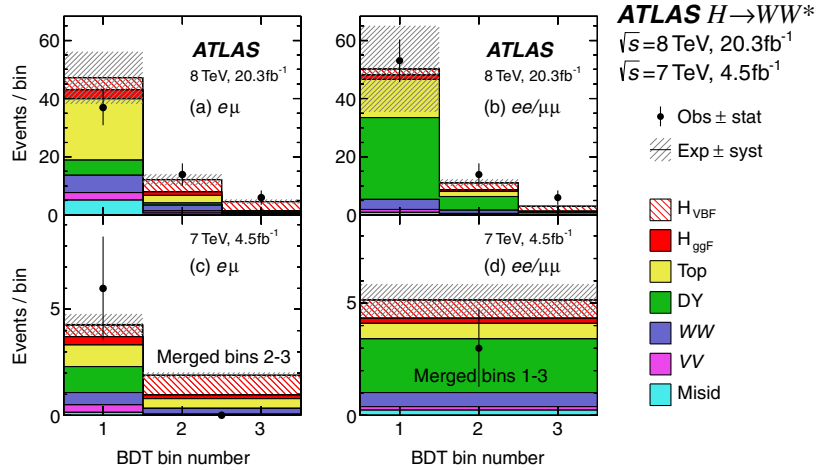


FIG. 13 (color online). Distributions of the BDT output in the $n_j \geq 2$ VBF-enriched category in the 8 and 7 TeV data analyses. The plot is made after requiring all the selections listed in Table IV and after the BDT classification. See Fig. 5 for plotting details.

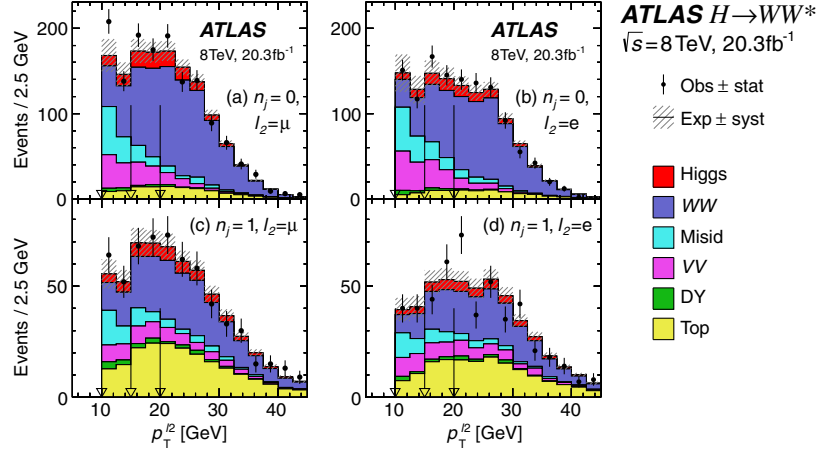


FIG. 14 (color online). Distributions of the subleading lepton p_T for the 8 TeV data analysis in the $e\mu$ sample used for the statistical analysis described in Sec. VII. The distributions are shown for two categories of events based on the flavor of the subleading lepton ℓ_2 . The plots are made after requiring all selections up to the m_T requirement, as shown in Tables V and VI. The arrows indicate the bin boundaries; see Fig. 5 for plotting details.

The $H \rightarrow WW^*$ branching fraction is 22% with a relative uncertainty of 4.2% for $m_H = 125.36$ GeV [67]. Interference with direct WW production [68] and uncertainties on VH production [69] have a negligible impact on this analysis. Uncertainties on the ggF and VBF production processes are described in the following subsections.

A. Gluon fusion

The measurement of Higgs boson production via gluon fusion, and the extraction of the associated Higgs boson couplings, relies on detailed theoretical calculations and

Monte Carlo simulation. Uncertainties on the perturbative calculations of the total production cross section and of the cross sections exclusive in jet multiplicity are among the leading uncertainties on the expected signal event yield and the extracted couplings. The POWHEG [49] generator matched to PYTHIA8 is used for event simulation and accurately models the exclusive jet multiplicities relevant to this analysis. The simulation is corrected to match higher-order calculations of the Higgs boson p_T distribution.

Production of a Higgs boson via gluon fusion proceeds dominantly through a top-quark loop (the bottom-quark

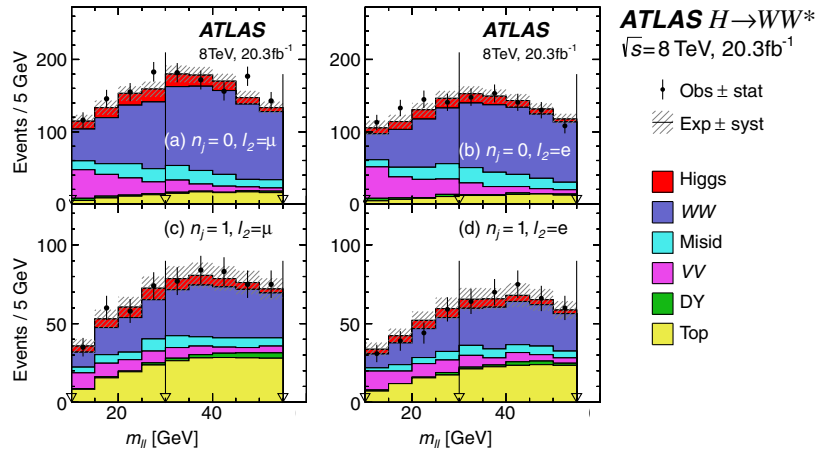


FIG. 15 (color online). Distributions of the dilepton invariant mass $m_{\ell\ell}$ for the 8 TeV data analysis in the $e\mu$ sample used for the statistical analysis described in Sec. VII. The distributions are shown for two categories of events based on the flavor of the subleading lepton ℓ_2 . The plot is made after requiring all selections up to the m_T requirement, as shown in Tables V and VI. The arrows indicate the bin boundaries; see Fig. 5 for plotting details.

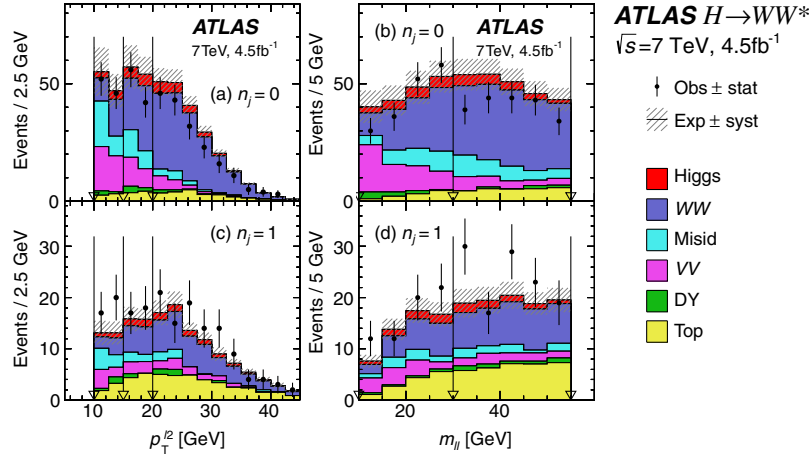
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FIG. 16 (color online). Distributions of the subleading lepton p_T and dilepton invariant mass for the 7 TeV data analysis in the $e\mu$ sample. The plots are made after requiring all selections up to m_T (see Sec. IV E). The arrows indicate the bin boundaries; see Fig. 5 for plotting details.

loop contributes 7% to the cross section). Higher-order QCD corrections include radiation from the initial-state gluons and from the quark loop. The total cross section is computed to NNLO [70] using the $m_t \rightarrow \infty$ approximation, where an effective pointlike ggH coupling is introduced. Corrections for the finite top-quark mass have been computed to NLO and found to be a few percent [71]; this difference is applied as a correction to the NNLO cross section. Resummation of the soft QCD radiation has been performed to NNLL [72] in the $m_t \rightarrow \infty$ approximation and to the next-to-leading logarithms (NLL) for finite top- and bottom-quark masses. Electroweak corrections to NLO [73] are applied using the complete factorization approximation [74]. Together, these calculations provide the total inclusive cross section for the ggF process [75], which is 19.15 pb for $m_H = 125.36$ GeV. The uncertainty on the total cross section is 10%, with approximately equal contributions from QCD scale variations (7.5%) and parton distribution functions (7.2%).

The POWHEG MC generator used to model ggF production [49] is based on an NLO calculation with finite quark masses and a running-width Breit-Wigner distribution that includes electroweak corrections at next-to-leading order [75]. The generator contains a scale for matching the resummation to the matrix-element calculation, which is chosen to reproduce the NNLO + NLL calculation of the Higgs boson p_T [76]. To improve the modeling of this distribution, a reweighting scheme is applied to reproduce the prediction of the NNLO + NNLL dynamic-scale calculation given by the HRES2.1 program [77]. The scheme separately weights the p_T spectra for events with ≤ 1 jet and events with ≥ 2 jets, since the latter include jet(s) described purely by the PYTHIA shower model, which underestimates the rate of two balancing

jets producing low Higgs boson p_T . Events with ≥ 2 jets are therefore reweighted to the p_T spectrum predicted by the NLO POWHEG simulation of Higgs boson production in association with two jets ($H + 2$ jets) [78]. The reweighting procedure preserves agreement between the generated jet-multiplicity distribution and the predictions of higher-order calculations.

The uncertainty on the jet multiplicity distribution is evaluated using the jet-veto-efficiency (JVE) method [76,79] for the ggF categories and the Stewart-Tackmann (ST) method [80] for the VBF category. The JVE method factorizes the total cross section from the acceptances of the jet vetoes in the zero-jet and one-jet channels, treating these components as uncorrelated. Three calculations of the jet-veto efficiency are defined based on ratios of cross sections with different jet multiplicities and at different orders (for example, $1 - \sigma_{n_j \geq 1}^{\text{NLO}} / \sigma_{\text{tot}}^{\text{NNLO}}$ for the veto efficiency of the first jet). The three calculations differ by next-to-next-to-leading order terms in the inclusive perturbative series, so their comparison provides an estimate of the perturbative uncertainty on the jet veto. A second estimate is obtained by individually varying the factorization, renormalization, and resummation scales by factors of 2 or 1/2, and by coherently varying the factorization and renormalization scales by these factors. These estimates are used to define an overall uncertainty, as described below.

For the efficiency ϵ_0 of the jet veto that defines the zero-jet channel, the central value is evaluated at the highest available fixed order (NNLO), with NNLL resummation. The uncertainty is taken as the maximum effect of the scale variations on the calculation, or the maximum deviation of the other calculations from this one. The results using the JETVHETO computation [81] are shown in Fig. 18, along with the reweighted POWHEG + PYTHIA8 prediction

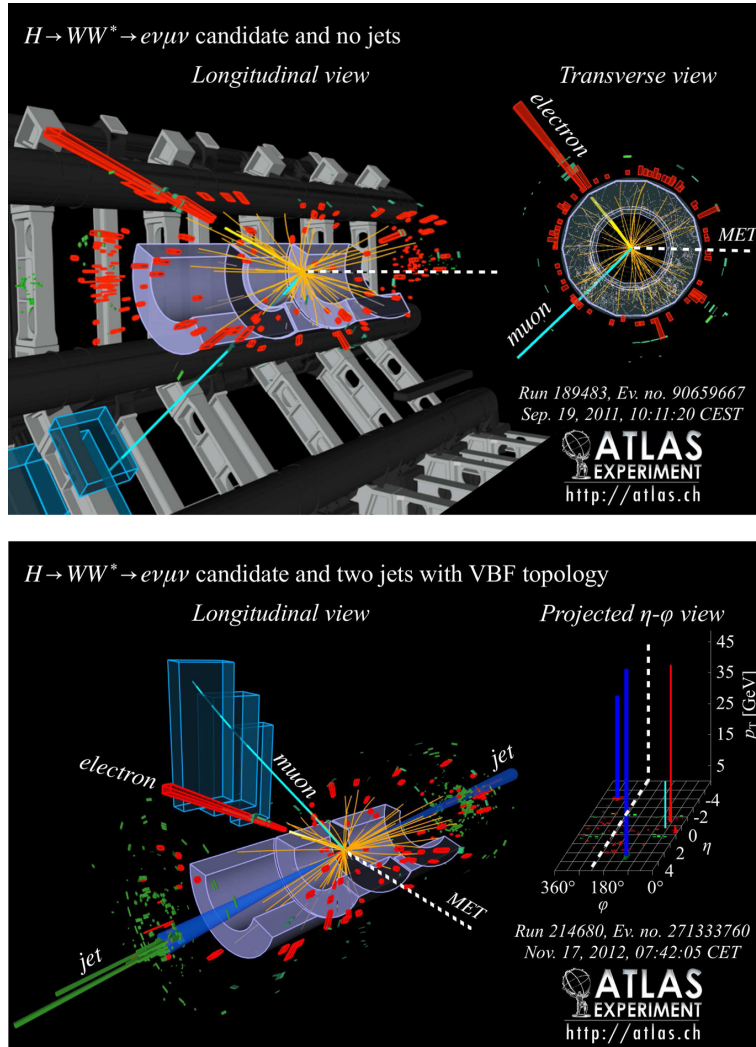


FIG. 17 (color online). Event displays of $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidates in the $n_j = 0$ (top) and $n_j \geq 2$ VBF-enriched (bottom) categories. The neutrinos are represented by missing transverse momentum (MET, dotted line) that points away from the $e\mu$ system. The properties of the first event are $p_T^e = 33$ GeV, $p_T^\mu = 24$ GeV, $m_{\ell\ell} = 48$ GeV, $\Delta\phi_{\ell\ell} = 1.7$, $p_T^{\text{miss}} = 37$ GeV, and $m_T = 98$ GeV. The properties of the second event are $p_T^e = 51$ GeV, $p_T^\mu = 15$ GeV, $m_{\ell\ell} = 21$ GeV, $\Delta\phi_{\ell\ell} = 0.1$, $p_T^{j1} = 67$ GeV, $p_T^{j2} = 41$ GeV, $m_{jj} = 1.4$ TeV, $\Delta y_{jj} = 6.6$, $p_T^{\text{miss}} = 59$ GeV, and $m_T = 127$ GeV. Both events have a small value of $\Delta\phi_{\ell\ell}$, which is characteristic of the signal. The second event shows two well-separated jets that are characteristic of VBF production.

evaluated with neither hadronization nor the underlying event. The results are consistent to within a few percent for a jet p_T threshold of 25 GeV, and the relative uncertainty at this threshold is 11%.

The efficiency of vetoing an additional jet, given the presence of a single jet, is defined as ϵ_1 . The NNLO $n_j \geq 1$ cross section needed for the highest-order calculation of the jet-veto-efficiency method is not available, though the other two calculations of the veto efficiency can be performed using the MCFM generator. The highest-order

calculation is in the range spanned by the other two calculations in both the case of ϵ_0 and in the case of ϵ_1 evaluated using a partial calculation of the NNLO $n_j \geq 1$ cross section [82]. The central value of ϵ_1 is thus estimated to be the average of the available calculations, with the uncertainty given by the maximum of the difference with respect to these calculations or the scale-varied estimate of the average. This results in a relative uncertainty of 15% on ϵ_1 , as shown in Fig. 18. The figure shows that the reweighted POWHEG + PYTHIA8 prediction for ϵ_1 agrees

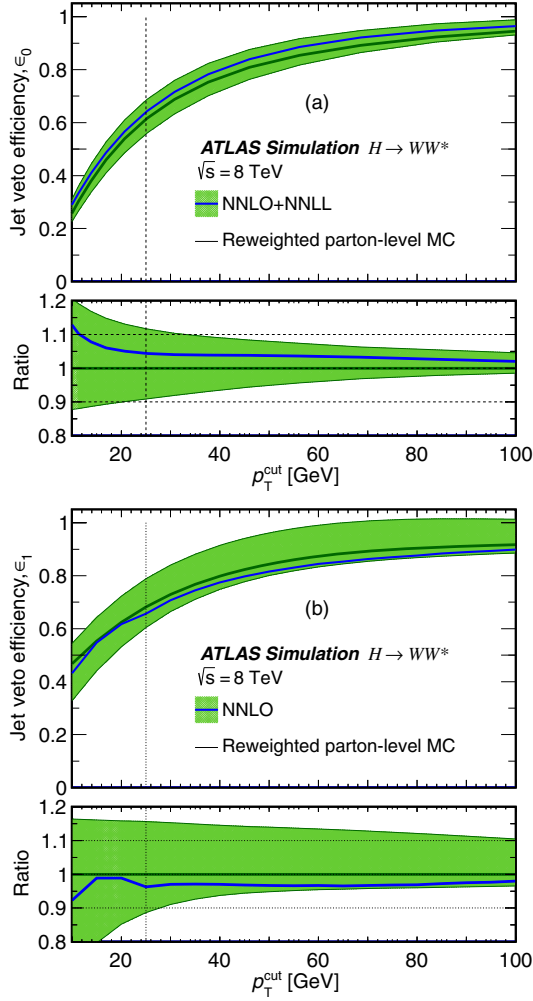
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FIG. 18 (color online). Efficiencies of the veto of the (a) first jet and (b) second jet in inclusive ggF production of the Higgs boson, as a function of the veto-threshold p_T .

with the calculation to within a few percent for a jet p_T threshold of 25 GeV.

A prior ATLAS analysis in this decay channel [5] relied on the ST procedure for all uncertainties associated with jet binning. The JVE estimation reduces uncertainties in the ggF categories by incorporating a resummation calculation (in ϵ_0) and the NLO calculation of $H + 2$ jets (in ϵ_1). The uncertainties for the ST (JVE) procedure are 18% (15%), 43% (27%), and 70% (34%) for the cross sections in the $n_j = 0$, $n_j = 1$, and $n_j \geq 2$ ggF-enriched categories, respectively. These uncertainties are reduced when the categories are combined, and contribute a total of $\approx 5\%$ to the uncertainty on the measured ggF signal strength (see Table XXVI).

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Additional uncertainties on the signal acceptance are considered in each signal category. The scale and PDF uncertainties are typically a few percent. A generator uncertainty is taken from a comparison between POWHEG + HERWIG and AMC@NLO + HERWIG [83], which differ in their implementation of the NLO matrix element and the matching of the matrix element to the parton shower. Uncertainties due to the underlying event and parton shower models (UE/PS) are generally small, though in the $n_j = 1$ category they are as large as 14% in the signal regions where $p_T^{\ell\ell} < 20$ GeV. The UE/PS uncertainties are estimated by comparing predictions from POWHEG + HERWIG and POWHEG + PYTHIA8.

The evaluation of the ggF background to the $n_j \geq 2$ VBF category includes an uncertainty on the acceptance of the central-jet veto. The uncertainty is evaluated to be 29% using the ST method, which treats the inclusive $H + 2$ -jet and $H + 3$ -jet cross sections as uncorrelated. Scale uncertainties are also evaluated in each measurement range of the BDT output, and are 3%–7% in BDT bins 1 and 2, and 48% in BDT bin 3. Other uncertainties on ggF modeling are negligible in this category, except those due to UE/PS, which are significant because the second jet in ggF $H + 2$ -jet events is modeled by the parton shower in the POWHEG + PYTHIA8 sample. A summary of the uncertainties on the gluon-fusion and vector-boson-fusion processes is given in Table X. The table shows the uncertainties for same-flavor leptons in the $n_j \leq 1$ categories, since events with different-flavor leptons

TABLE X. Signal-yield uncertainties (in %) due to the modeling of the gluon-fusion and vector-boson-fusion processes. For the $n_j = 0$ and $n_j = 1$ categories the uncertainties are shown for events with same-flavor leptons; for events with different-flavor leptons the uncertainties are evaluated in bins of $m_{\ell\ell}$ and $p_T^{\ell\ell}$. For the $n_j \geq 2$ VBF category the uncertainties are shown for the most sensitive bin of BDT output (bin 3).

Uncertainty source	$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
Gluon fusion				
Total cross section	10	10	10	7.2
Jet binning or veto	11	25	33	29
Acceptance				
Scale	1.4	1.9	3.6	48
PDF	3.2	2.8	2.2	-
Generator	2.5	1.4	4.5	-
UE/PS	6.4	2.1	1.7	15
Vector-boson fusion				
Total cross section	2.7	2.7	2.7	2.7
Acceptance				
Scale	-	-	-	3.0
PDF	-	-	-	3.0
Generator	-	-	-	4.2
UE/PS	-	-	-	14

are further subdivided according to $m_{\ell\ell}$ and $p_T^{\ell^2}$ (as described in Sec. II).

B. Vector-boson fusion

The VBF total cross section is obtained using an approximate QCD NNLO computation provided by the VBF@NNLO program [84]. The calculation is based on the structure-function approach [85] that considers the VBF process as two deep-inelastic scattering processes connected to the colorless vector-boson fusion producing the Higgs boson. Leading-order contributions violating this approximation are explicitly included in the computation; the corresponding higher-order terms are negligible [69]. Electroweak corrections are evaluated at NLO with the HAWK program [86]. The calculation has a negligible QCD scale uncertainty and a 2.7% uncertainty due to PDF modeling.

The POWHEG [50] generator is used to simulate the VBF process (see Table III). Uncertainties on the acceptance are evaluated for several sources: the impact of the QCD scale on the jet veto and on the remaining acceptance; PDFs; generator matching of the matrix element to the parton shower; and the underlying event and parton shower. Table X shows the VBF and ggF uncertainties in the most sensitive bin of the BDT output (bin 3). The other bins have the same or similar uncertainties for the VBF process, except for UE/PS, where the uncertainty is 5.2% (<1%) in bin 2 (bin 1).

VI. BACKGROUND PROCESSES

The background contamination in the various signal regions (SR) comes from several physics processes that were briefly discussed in Sec. II and listed in Table I. They are

- (i) WW : nonresonant W pair production;
- (ii) top quarks (Top): pair production ($t\bar{t}$) and single-top production (t) both followed by the decay $t \rightarrow Wb$;
- (iii) misidentified leptons (Misid): W boson production in association with a jet that is misidentified as a lepton (Wj) and dijet or multijet production with two misidentifications (jj);
- (iv) other dibosons (VV): $W\gamma$, $W\gamma^*$, WZ and ZZ ; and
- (v) Drell-Yan (DY): Z/γ^* decay to e or μ pairs ($ee/\mu\mu$) and τ pairs ($\tau\tau$);

the contamination of Higgs decays to non- WW channels is small, but considered as signal. A few background processes, such as $Z\gamma$ and WW produced by double parton interactions, are not listed because their contributions are negligible in the control and signal regions, but they are considered in the analysis for completeness. Their normalizations and acceptances are taken from Monte Carlo simulation.

For each background the event selection includes a targeted set of kinematic requirements (and sample selection) to distinguish the background from the signal. The background estimate is made with a control region (CR) that inverts some or all of these requirements and in many cases enlarges the allowed range for certain kinematic variables to increase the number of observed events in the CR. For example, the relevant selections that suppress the WW background in the $n_j = 0$ SR are $m_{\ell\ell} < 55$ GeV and $\Delta\phi_{\ell\ell} < 1.8$. The WW CR, in turn, is defined by requiring $55 < m_{\ell\ell} < 110$ GeV and $\Delta\phi_{\ell\ell} \leq 2.6$.

The most common use of a CR, like the WW example above, is to determine the normalization factor β defined by the ratio of the observed to expected yields of WW candidates in the CR, where the observed yield is obtained by subtracting the non- WW (including the Higgs signal) contributions from the data. The estimate $B_{\text{SR}}^{\text{est}}$ of the expected background in the SR under consideration can be written as

$$B_{\text{SR}}^{\text{est}} = B_{\text{SR}} \cdot \underbrace{N_{\text{CR}}/B_{\text{CR}}}_{\text{Normalization } \beta} = N_{\text{CR}} \cdot \underbrace{B_{\text{SR}}/B_{\text{CR}}}_{\text{Extrapolation } \alpha} \quad (7)$$

where N_{CR} and B_{CR} are the observed yield and the MC estimate in the CR, respectively, and B_{SR} is the MC estimate in the signal region. The first equality defines the data-to-MC normalization factor in the CR, β ; the second equality defines the extrapolation factor from the CR to the SR, α , predicted by the MC. With a sufficient number of events available in the CR, the large theoretical uncertainties associated with estimating the background directly from simulation are replaced by the combination of two significantly smaller uncertainties, the statistical uncertainty on N_{CR} and the systematic uncertainty on α .

When the SR is subdivided for reasons of increased signal sensitivity, as is the case for the $e\mu$ sample for $n_j = 0$, a corresponding α parameter is computed for each of the subdivided regions. The CR (hence the β parameter), however, is not subdivided for statistical reasons.

The uncertainties described in this section are inputs to the extraction of the signal strength parameter using the likelihood fit, which is described in Sec. VII. An extension of this method is used when it is possible to determine the extrapolation factor α from data. As described in Secs. VIC and VIE, this can be done for the misidentified lepton backgrounds and in the high-statistics categories for the $Z/\gamma^* \rightarrow ee, \mu\mu$ background. For the former, the distribution of the discriminating variable of interest is also determined from data. For completeness, one should note that the smaller background sources are estimated purely from simulation.

Table XI summarizes, for all the relevant background processes, whether data or MC is used to determine the various aspects of the method. In general, data-derived methods are preferred and MC simulation is used for a few

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TABLE XI. Background estimation methods summary. For each background process or process group, a set of three columns indicate whether data (•) or MC (◦) samples are used to normalize the SR yield (N), determine the CR-to-SR extrapolation factor (E), and obtain the SR distribution of the fit variable (V). In general, the methods vary from one row to the next for a given background process; see Sec. VI for the details.

Category	WW			Top			Misid			VV			Drell-Yan					
	N	E	V	N	E	V	N	E	V	N	E	V	N	E	V	N	E	V
$n_j = 0$																		
$e\mu$	•	◦	◦	•	◦	◦	•	•	•	•	◦	◦	◦	◦	◦	•	◦	◦
$ee/\mu\mu$	•	◦	◦	•	◦	◦	•	•	•	•	◦	◦	•	•	◦	•	◦	◦
$n_j = 1$																		
$e\mu$	•	◦	◦	•	◦	◦	•	•	•	•	◦	◦	◦	◦	◦	•	◦	◦
$ee/\mu\mu$	•	◦	◦	•	◦	◦	•	•	•	•	◦	◦	•	•	◦	•	◦	◦
$n_j \geq 2$ ggF																		
$e\mu$	◦	◦	◦	•	◦	◦	•	•	•	◦	◦	◦	◦	◦	◦	•	◦	◦
$n_j \geq 2$ VBF																		
$e\mu$	◦	◦	◦	•	◦	◦	•	•	•	◦	◦	◦	◦	◦	◦	•	◦	◦
$ee/\mu\mu$	◦	◦	◦	•	◦	◦	•	•	•	◦	◦	◦	•	•	◦	•	◦	◦

background processes that do not contribute significantly in the signal region, that have a limited number of events in the control region, or both. MC simulation is used (open circles) or a data sample is used (solid circles) for each of the three aspects of a given method: the normalization (N), the extrapolation (E), and the distribution of the discriminating variable of interest (V). The plots in this section (Figs. 19–27) show contributions that are normalized according to these methods.

This section focuses on the methodology for background predictions and their associated theoretical uncertainties. The experimental uncertainties also contribute to the total uncertainty on these background predictions and are quoted here only for the backgrounds from misidentified leptons, for which the total systematic uncertainties are discussed in Sec. VIC. Furthermore, although the section describes one background estimation technique at a time, the estimates for most background contributions are interrelated and are determined *in situ* in the statistical part of the analysis (see Sec. VII).

The section is organized as follows. Section VIA describes the WW background in the various categories. This background is the dominant one for the most sensitive $n_j = 0$ category. Section VIB describes the background from top-quark production, which is largest in the categories with one or more high- p_T jets. The data-derived estimate from misidentified leptons is described in Sec. VIC. The remaining backgrounds, VV and Z/γ^* , are discussed in Secs. VID and VIE, respectively. The similarities and modifications for the background estimation for the 7 TeV data analysis are described in Sec. VIF.

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Finally, Sec. VI G presents a summary of the background predictions in preparation for the fit procedure described in Sec. VII.

A. WW dibosons

The nonresonant WW production process, with subsequent decay $WW \rightarrow \ell\nu\ell\nu$, is characterized by two well-separated charged leptons. By contrast, the charged leptons in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ process tend to have a small opening angle (see Fig. 3). The invariant mass of the charged leptons, $m_{\ell\ell}$, combines this angular information with the kinematic information associated with the relatively low Higgs boson mass ($m_H < 2m_W$), providing a powerful discriminant between the processes (see Fig. 7). This variable is therefore used to define WW control regions in the $n_j \leq 1$ categories, where the signal is selected with the requirement $m_{\ell\ell} < 55$ GeV. For the $n_j \geq 2$ ggF and VBF categories, the WW process is modeled with a merged multiparton SHERPA sample and normalized to the NLO inclusive WW calculation from MCFM [51], since the large top-quark backgrounds make a control-region definition more challenging.

1. $m_{\ell\ell}$ extrapolation for $n_j \leq 1$

The $n_j \leq 1$ analyses use a data-based normalization for the WW background, with control regions defined by a range in $m_{\ell\ell}$ that does not overlap with the signal regions. The normalization is applied to the combined $(q\bar{q}$ or $qg) \rightarrow WW$ and $gg \rightarrow WW$ background estimate, and theoretical uncertainties on the extrapolation are evaluated.

To obtain control regions of sufficient purity, several requirements are applied. In order to suppress the Z/γ^* background, the CRs use $e\mu$ events selected after the $p_T^{\ell\ell} > 30$ GeV and $m_T^{\ell\ell} > 50$ GeV requirements in the $n_j = 0$ and $n_j = 1$ categories, respectively. The latter requirement additionally suppresses background from multijet production. A requirement of $p_T^{\ell\ell} > 15$ GeV is applied to suppress the large W + jets background below this threshold. Additional $Z/\gamma^* \rightarrow \tau\tau$ reduction is achieved by requiring $\Delta\phi_{\ell\ell} < 2.6$ for $n_j = 0$, and $|m_{\tau\tau} - m_Z| > 25$ GeV for $n_j = 1$, where $m_{\tau\tau}$ is defined in Sec. IV B. The $m_{\ell\ell}$ range is $55 < m_{\ell\ell} < 110$ GeV ($m_{\ell\ell} > 80$ GeV) for $n_j = 0$ (1), and is chosen to maximize the signal significance. Increasing the upper bound on $m_{\ell\ell}$ for $n_j = 0$ increases the theoretical uncertainty on the WW background prediction. The m_T distributions in the WW control regions are shown in Fig. 19.

The WW estimate $B_{WW,i}^{\text{est}}$ in each signal region i is given by Eq. (7). The control region is approximately 70% (45%) pure in the $n_j = 0$ (1) category. The contamination in the $n_j = 1$ category is dominated by $t\bar{t} \rightarrow WbWb$ events, where one jet is unidentified and the other is misidentified as a light-quark jet. The single-top contribution is one-third the size of this background for $n_j = 1$; for $n_j = 0$ this ratio

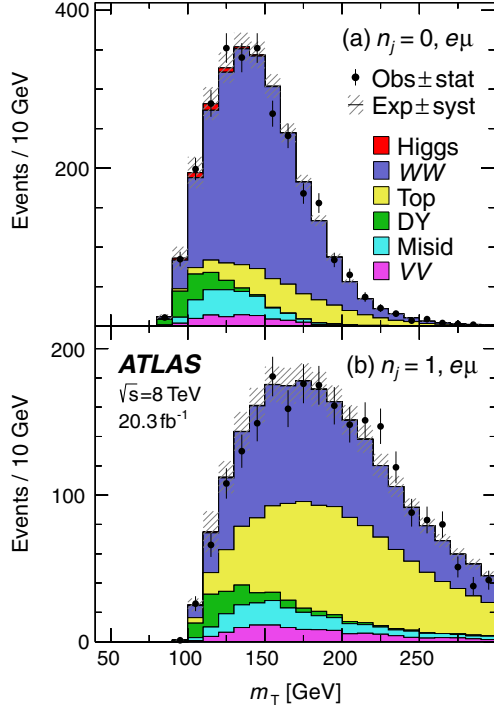


FIG. 19 (color online). WW control region distributions of transverse mass. The normalizations of all processes are as described in Sec. VI. See Fig. 5 for plotting details.

is about one-half. All backgrounds are subtracted as part of the fit for β described in Sec. VII B 1.

The CR-to-SR extrapolation factor has uncertainties due to the limited accuracy of the MC prediction. Uncertainties due to higher perturbative orders in QCD not included

in the MC simulation are estimated by varying the renormalization and factorization scales independently by factors of 1/2 and 2, keeping the ratio of scales in the range 1/2 to 2 [67]. An uncertainty due to higher-order electroweak corrections is determined by reweighting the MC simulation to the NLO electroweak calculation [87] and taking the difference with respect to the nominal sample. PDF uncertainties are evaluated by taking the largest difference between the nominal CT10 [43] PDF set and either the MSTW2008 [88] or the NNPDF2.3 [89] PDF set, and adding in quadrature the uncertainty determined using the CT10 error eigenvectors. Additional uncertainties are evaluated using the same procedures as for ggF production (Sec. VA): uncertainties due to the modeling of the underlying event, hadronization, and parton shower are evaluated by comparing predictions from POWHEG + PYTHIA6 and POWHEG + HERWIG; a generator uncertainty is estimated with a comparison of POWHEG + HERWIG and AMC@NLO + HERWIG. The detailed uncertainties in each signal subregion are given in Table XII. The corresponding uncertainties on the m_T distribution give a relative change of up to 20% between 90 and 170 GeV, depending on the signal region.

The contribution from the $gg \rightarrow WW$ process is 5.8% (6.5%) of the total WW background in the $n_j = 0$ (1) category in the signal region and 4.5% (3.7%) in the control region. Its impact on the extrapolation factor is approximately given by the ratio of $gg \rightarrow WW$ to $q\bar{q} \rightarrow WW$ events in the signal region, minus the corresponding ratio in the control region. The leading uncertainty on these ratios is the limited accuracy of the production cross section of the gluon-initiated process, for which a full NLO calculation is not available. The uncertainty evaluated using renormalization and factorization scale variations in the leading-order calculation is 26% (33%) in the $n_j = 0$

TABLE XII. WW theoretical uncertainties (in %) on the extrapolation factor α for $n_j \leq 1$. Total is the sum in quadrature of the uncertainties due to the QCD factorization and renormalization scales (Scale), the PDFs, the matching between the hard-scatter matrix element and the UE/PS model (Gen), the missing electroweak corrections (EW), and the parton shower and underlying event (UE/PS). The negative sign indicates anti-correlation with respect to the unsigned uncertainties for SR categories in the same column. Energy-related values are given in GeV.

SR category	$n_j = 0$						$n_j = 1$
	Scale	PDF	Gen	EW	UE/PS	Total	Total
SR $e\mu$, $10 < m_{\ell\ell} < 30$							
$p_T^{\ell\ell} > 20$	0.7	0.6	3.1	-0.3	-1.9	3.8	7.1
$15 < p_T^{\ell\ell} \leq 20$	1.2	0.8	0.9	0.7	1.7	2.6	3.9
$10 < p_T^{\ell\ell} \leq 15$	0.7	1.0	0.4	1.2	2.2	2.8	5.4
SR $e\mu$, $30 < m_{\ell\ell} < 55$							
$p_T^{\ell\ell} > 20$	0.8	0.7	3.9	-0.4	-2.4	4.8	7.1
$15 < p_T^{\ell\ell} \leq 20$	0.8	0.7	1.0	0.5	1.0	2.0	4.5
$10 < p_T^{\ell\ell} \leq 15$	0.7	0.8	0.5	0.8	1.5	2.1	4.5
SR $ee/\mu\mu$, $12 < m_{\ell\ell} < 55$							
$p_T^{\ell\ell} > 10$	0.8	1.1	2.4	0.1	-1.2	2.9	5.1

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(1) category [90]. An increase of the $gg \rightarrow WW$ cross section by a factor of 2 [91] increases the measured μ value by less than 3%.

Boson pairs can be produced by double parton interactions (DPI) in pp collisions. The DPI contribution is very small—0.4% of WW production in the signal regions—and is estimated using PYTHIA8 MC events normalized to the predicted cross section (rather than the β parameter from the WW CR). The cross section is computed using the NNLO $W^\pm$ production cross section and an effective multiparton interaction cross section, $\sigma_{\text{eff}} = 15$ mb, measured by ATLAS using Wjj production [92]. An uncertainty of 60% is assigned to the value of σ_{eff} —and, correspondingly, to the DPI yields—using an estimate of $\sigma_{\text{eff}} \approx 24$ mb for WW production [93]. While these estimates rely on theoretical assumptions, an increase of the DPI cross section by a factor of 10 only increases the measured μ by 1%. Background from two $pp \rightarrow W$ collisions in the same bunch crossing is negligible.

In the $n_j = 0$ SR, the ratio of signal to WW background is about 1:5, magnifying the impact of background systematic uncertainties. The definition of the CR as a neighboring $m_{\ell\ell}$ window reduces the uncertainty in the extrapolation to low $m_{\ell\ell}$. To validate the assigned uncertainties, the CR normalization is extrapolated to $m_{\ell\ell} > 110$ GeV and compared to data. The data are consistent with the prediction at the level of 1.1 standard deviations considering all systematic uncertainties.

The normalization factors determined using predicted and observed event yields are $\beta_{WW}^{0j} = 1.22 \pm 0.03(\text{stat}) \pm 0.10(\text{syst})$ and $\beta_{WW}^{1j} = 1.05 \pm 0.05(\text{stat}) \pm 0.24(\text{syst})$, which are consistent with the theoretical prediction at the level of approximately 2 standard deviations. Here the uncertainties on the predicted yields are included though they do not enter into the analysis. Other systematic uncertainties are also suppressed in the full likelihood fit described in Sec. VII B.

2. MC evaluation for $n_j \geq 2$

For the VBF and ggF $n_j \geq 2$ analyses, the WW background is estimated using SHERPA. The MC samples are generated as merged multileg samples, split between the cases where final-state jets result from QCD vertices or from electroweak vertices. The interference between these diagrams is evaluated to be less than a few percent using MADGRAPH; this is included as an uncertainty on the prediction.

For the processes with QCD vertices, uncertainties from higher orders are computed by varying the renormalization and factorization scales in MADGRAPH and are found to be 27% for the VBF category and 19% for the ggF category. Differences between SHERPA and MADGRAPH predictions after selection requirements are 8%–14% on the O_{BDT} distribution and 1%–7% on the m_T distribution, and are

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taken as uncertainties. The same procedures are used to estimate uncertainties on processes with only electroweak vertices, giving a normalization uncertainty of 10% and an uncertainty on the O_{BDT} (m_T) distribution of 10%–16% (5%–17%).

The MC prediction is validated using a kinematic selection that provides a reasonably pure sample of $WW + 2$ -jet events. Events are selected if they pass the preselection requirements on lepton p_T and $m_{\ell\ell}$, have two jets, and $n_b = 0$. An additional requirement of $m_T > 100$ GeV is applied in order to enhance the WW contribution. A final discriminant is the minimum of all possible calculations of m_{T2} [94] that use the momenta of a lepton and a neutrino, or the momenta of a lepton, a jet, and a neutrino. The possible momentum values of each neutrino, given p_T^{miss} , are scanned in order to calculate m_T ; this scan determines m_{T2} . A requirement that the minimum m_{T2} be larger than 160 GeV provides a purity of 60% for $WW + 2$ jets (see Fig. 20). The ratio of the observed to the expected number of $WW + 2$ -jet events in this region is $1.15 \pm 0.19(\text{stat})$.

B. Top quarks

At hadron colliders, top quarks are produced in pairs ($t\bar{t}$) or in association with a W boson (Wt) or quark(s) q (single- t). The leptonic decay of the W bosons leads to a final state of two leptons, missing transverse momentum and two b -jets (one b -jet) in $t\bar{t}$ (Wt) production. The single- t production mode has only one W boson in the final state and the second, misidentified, lepton is produced by a jet. The background from these events is estimated together with the $t\bar{t}$ and Wt processes in spite of the different lepton production mechanism, but the contribution from these processes to the top-quark background is small. For example, these events are 0.5% of the top-quark

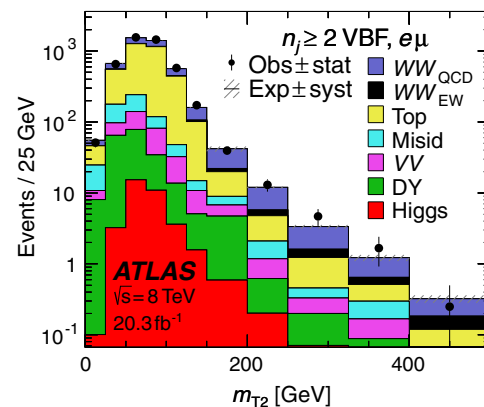


FIG. 20 (color online). WW validation region distribution of m_{T2} in the $n_j \geq 2$ VBF-enriched category. A requirement of $m_{T2} > 160$ GeV is used to define the validation region.

background in the $n_j = 0$ category. The top-quark background is estimated using the normalization method, as described in Eq. (7). In the $n_j = 0$ category, the SR definition includes a jet veto but the CR has no jet requirements. Because of this, the CR and the SR slightly overlap, but the $n_j = 0$ SR is only 3% of the CR and the expected total signal contamination is less than 1%, so the effect of the overlap on the results is negligible. In the $n_j = 1$ category, the SR definition requires $n_b = 0$ but the CR has $n_b \geq 1$. In the $n_j = 2$ VBF category, the CR is defined requiring one and only one b -tagged jet. Finally, in the $n_j = 2$ ggF category, to reduce the impact of b -tagging systematic uncertainties, the CR is defined for $n_b = 0$, and instead $m_{\ell\ell} > 80$ GeV is applied to remove overlap with the SR and minimize the signal contribution.

1. Estimation of jet-veto efficiency for $n_j = 0$

For the $n_j = 0$ category, the CR is defined after the preselection missing transverse momentum cut, using only the $e\mu$ channel, with an additional requirement of $\Delta\phi_{\ell\ell} < 2.8$ to reduce the $Z/\gamma^* \rightarrow \tau\tau$ background. The CR is inclusive in the number of jets and has a purity of 74% for top-quark events. The extrapolation parameter α is the fraction of events with zero reconstructed jets and is derived from the MC simulation.

The value of α is corrected using data in a sample containing at least one b -tagged jet. A parameter α^{1b} is defined as the fraction of events with no additional jets in this region. The ratio $(\alpha_{\text{data}}^{1b}/\alpha_{\text{MC}}^{1b})^2$ corrects systematic effects that have a similar impact on the b -tagged and inclusive regions, such as jet energy scale and resolution. The square is applied to account for the presence of two jets in the Born-level $t\bar{t}$ production. The prediction can be summarized as

$$B_{\text{top},0j}^{\text{est}} = N_{\text{CR}} \cdot \underbrace{B_{\text{SR}}/B_{\text{CR}}}_{\alpha_{\text{MC}}^{0j}} \cdot \underbrace{(\alpha_{\text{data}}^{1b}/\alpha_{\text{MC}}^{1b})^2}_{\gamma_{1b}} \quad (8)$$

where N_{CR} is the observed yield in the CR and B_{CR} and B_{SR} are the estimated yields from MC simulation in the CR and SR, respectively.

Theoretical uncertainties arise from the use of MC-simulated top-quark events in the computation of the ratio $\alpha_{\text{MC}}^{0j}/(\alpha_{\text{MC}}^{1b})^2$. These uncertainties include variations of the renormalization and factorization scales, choice of PDFs, and the parton shower model. The procedure is sensitive to the relative rates of Wt and $t\bar{t}$ production, so an uncertainty is included on this cross section ratio and on the interference between these processes. An additional theoretical uncertainty is evaluated on the efficiency ϵ_{rest} of the additional selection after the $n_j = 0$ preselection, which is estimated purely from MC simulation. Experimental uncertainties are also evaluated on the simulation-derived components of the background estimate, with the main contributions coming

from jet energy scale and resolution. The uncertainties on $\alpha_{\text{MC}}^{0j}/(\alpha_{\text{MC}}^{1b})^2$ and on ϵ_{rest} are summarized in Table XIII. The resulting normalization factor is $\beta_{\text{top}}^{0j} = 1.08 \pm 0.02(\text{stat})$, including the correction factor $(\alpha_{\text{data}}^{1b}/\alpha_{\text{MC}}^{1b})^2 = 1.006$. The total uncertainty on the background yield in the $n_j = 0$ signal region is 8%.

2. Extrapolation from $n_b = 1$ for $n_j = 1$

In the $n_j = 1$ SR, top-quark production is the second leading background, after nonresonant WW production. Summing over all signal regions with no m_T requirement applied, it is 36% of the total expected background and the ratio of signal to top-quark background is approximately 0.2. It also significantly contaminates the $n_j = 1$ WW CR with a yield as large as that of nonresonant WW in this CR. Two parameters are defined for the extrapolation from the top CR, one to the SR (α_{SR}) and one to the WW CR (α_{WW}).

The top CR is defined after the preselection in the $e\mu$ channel and requires the presence of exactly one jet, which must be b -tagged. There can be no additional b -tagged jet with $20 < p_T < 25$ GeV, following the SR requirement. The requirement $m_T^\ell > 50$ GeV is also applied to reject jj background. As in the WW case, only the $e\mu$ events are used in order to suppress the Z/γ^* contamination. The m_T distribution in this control region is shown in Fig. 21(a).

The CR requires at least one b -jet, but the SR requires zero. In the case of a simple extrapolation using the ratio of

TABLE XIII. Top-quark background uncertainties (in %) for $n_j \leq 1$. The uncertainties on the extrapolation procedure for $n_j = 0$ are given in (a); the uncertainties on the extrapolation factor α_{top} for $n_j = 1$ are given in (b). The negative sign refers to the anticorrelation between the top-quark background predicted in the signal regions and in the WW CR. Only a relative sign between rows is meaningful; columns contain uncorrelated sources of uncertainty. Invariant masses are given in GeV.

Uncertainty source	$\alpha_{\text{MC}}^{0j}/(\alpha_{\text{MC}}^{1b})^2$	ϵ_{rest}	Total		
(a) $n_j = 0$					
Experimental	4.4	1.2	4.6		
Non-top-quark subtraction	-	-	2.7		
Theoretical	3.9	4.5	4.9		
Statistical	2.2	0.7	2.3		
Total	6.8	4.7	7.6		
Regions	Scale	PDF	Gen	UE/PS	Total
(b) $n_j = 1$. See the caption of Table XII for column headings.					
Signal region					
$e\mu$ ($10 < m_{\ell\ell} < 55$)	-1.1	-0.12	-2.4	2.4	3.6
$ee/\mu\mu$ ($12 < m_{\ell\ell} < 55$)	-1.0	-0.12	-2.0	3.0	3.7
WW control region					
$e\mu$ ($m_{\ell\ell} > 80$)	0.6	0.08	2.0	1.8	2.8

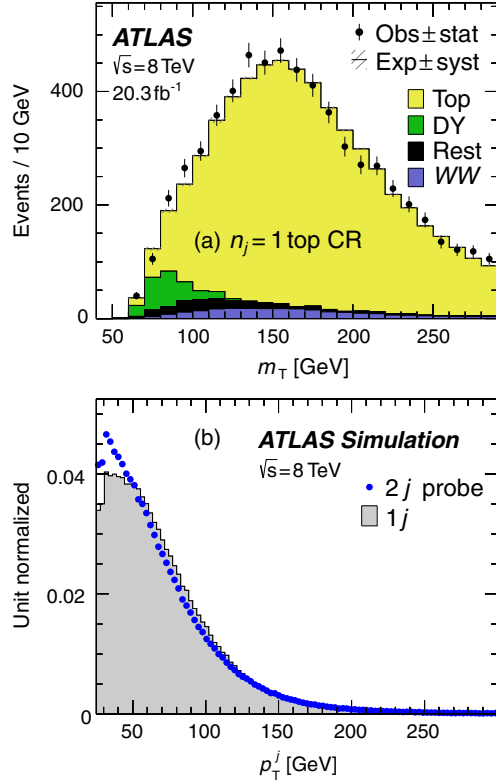
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FIG. 21 (color online). Top-quark control region distributions of (a) transverse mass and (b) jet p_T . The m_T plot in (a) scales the top-quark contributions with the normalization factor β_{top} . The p_T^j plot in (b) compares the jet p_T distribution in top-quark MC—both the $t\bar{t}$ and the Wt processes—in $n_j = 2$ ($2j$ probe) events to $n_j = 1$ ($1j$) events. For each $n_j = 2$ event, one of the two jets is chosen randomly and the p_T of that jet enters the distribution if the other jet is tagged. See Fig. 5 for plotting details.

the predicted yields in the signal and control regions, the impact of the b -tagging efficiency uncertainty on the measurement is substantial. A systematic uncertainty of 5% on the b -tagging efficiency would induce an uncertainty of about 20% on the estimated yield in the SR. In order to reduce this effect, the b -tagging efficiency $\epsilon_{1j}^{\text{est}}$ is estimated from data. The efficiency ϵ_{2j} is the probability to tag an individual jet, measured in a sample selected similarly to the SR but containing exactly two jets, at least one of which is b -tagged. It can be measured in data and MC simulation, because a high-purity top sample can be selected. Most of the events in this sample are $t\bar{t}$ events with reconstructed jets from b -quarks, although there is some contamination from light-quark jets from initial state radiation when a b -quark does not produce a reconstructed jet. Similarly, ϵ_{1j} is the efficiency to tag a jet in a sample with one jet, in events passing the signal region selection.

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The efficiency measurement $\epsilon_{2j}^{\text{data}}$ is extrapolated from the $n_j = 2$ sample to the $n_j = 1$ samples using $\gamma_{1j} = \epsilon_{1j}/\epsilon_{2j}$, which is evaluated using MC simulation. Jets in the $n_j = 2$ and jets in the $n_j = 1$ samples have similar kinematic features; one example, the jet p_T , is illustrated in Fig. 21(b). In this figure, the $n_j = 2$ distribution contains the p_T of one of the two jets, chosen at random, provided that the other jet is tagged, so that the distribution contains the same set of jets as is used in the extrapolation to $n_j = 1$. Residual disagreements between the distributions are reflected in the deviation of γ_{1j} from unity, which is small. The value of γ_{1j} is $1.079 \pm 0.002(\text{stat})$ with an experimental uncertainty of 1.4% and a theoretical uncertainty of 0.8%. The experimental uncertainty is almost entirely due to uncertainties on the b -tagging efficiency. The theoretical uncertainty is due to the PDF model, renormalization and factorization scales, matching of the matrix element to the parton shower, top-quark cross sections, and interference between top-quark single and pair production.

The estimated b -tagging efficiency in the $n_j = 1$ data is $\epsilon_{1j}^{\text{est}} = \gamma_{1j} \cdot \epsilon_{2j}^{\text{data}}$ and the top-quark background estimate in the SR is then

$$B_{\text{top},1j}^{\text{est}} = N_{\text{CR}} \cdot \underbrace{\left(\frac{1 - \epsilon_{1j}^{\text{est}}}{\epsilon_{1j}^{\text{est}}} \right)}_{\alpha_{\text{data}}^{1j}}. \quad (9)$$

The theoretical systematic uncertainties are summarized in Table XIII. The normalization factor for this background is $\beta_{\text{top}}^{1j} = 1.06 \pm 0.03(\text{stat})$, and the total uncertainty on the estimated background in the $n_j = 1$ signal region is 5%.

3. Extrapolation from $n_b = 1$ for VBF-enriched $n_j \geq 2$

The $n_j \geq 2$ categories have a large contribution from top-quark background events even after selection requirements, such as the b -jet veto, that are applied to reduce them, because of the two b quarks in $t\bar{t}$ events. The majority of the residual top-quark events have a light-quark jet from initial-state radiation and a b -quark jet that is not identified by the b -tagging algorithm. The CR requires exactly one b -tagged jet to mimic this topology, so that at first order the CR-to-SR extrapolation factor (α) is the ratio of b -jet efficiency to b -jet inefficiency. The CR includes events from $e\mu$ and $ee/\mu\mu$ final states because the Z/γ^* contamination is reduced by the jet selection.

The O_{BDT} discriminant is based on variables, such as m_{jj} , that depend on the jet kinematics, so the acceptance for top-quark events in each O_{BDT} bin is strongly dependent on the Monte Carlo generator and modeling. Motivated by the large variation of top-quark event kinematics as a function of the O_{BDT} bin, the top-quark background is normalized independently in each bin, which reduces the modeling

uncertainties. Figure 22 shows the m_{jj} and O_{BDT} distributions in the top CR used for the VBF category. The two bins with the highest O_{BDT} score are merged to improve the statistical uncertainty on the estimated background. The uncertainties on the extrapolation from the single bin in the CR to the two bins in the SR are separately evaluated.

Table XIV shows the normalization factors β_i and their uncertainties for each O_{BDT} bin, as well as the theoretical uncertainties on the extrapolation factors α_j to the corresponding SR bins.

The uncertainties on α were evaluated with the same procedure used for the WW background (see Sec. VIA 1). The only significant source is a modeling uncertainty evaluated by taking the maximum spread of predictions from POWHEG + HERWIG, ALPGEN + HERWIG, and MC@NLO + HERWIG [95]. The generators are distinguished by the merging of LO matrix-element evaluations of up to three jets produced in association with

TABLE XIV. Top-quark background uncertainties (in %) for $n_j \geq 2$ VBF on the extrapolation factor α and normalization factor β . The contributions are given in bins of O_{BDT} . The systematic uncertainty on β does not affect the measurement, but is shown to illustrate the compatibility of the normalization factor with unity. The values of β are also shown; bins 2 and 3 use a common value of β . Bin 0 is unused, but noted for completeness.

O_{BDT} bins	$\Delta\alpha/\alpha$	$\Delta\beta$ statistical	$\Delta\beta$ systematic	β
SR bin 0 (unused)	0.04	0.02	0.05	1.09
SR bin 1	0.10	0.15	0.55	1.58
SR bin 2	0.12	0.31	0.36	0.95
SR bin 3	0.21	0.31	0.36	0.95

$t\bar{t}$ (ALPGEN + HERWIG) or by differences in procedures for matching a NLO matrix-element calculation to the parton shower (MC@NLO + HERWIG and POWHEG + HERWIG). The systematic uncertainty is dominated by the ALPGEN + HERWIG–MC@NLO + HERWIG difference, and for this reason the theoretical uncertainties shown in Table XIV are fully correlated between bins.

4. Extrapolation in $m_{\ell\ell}$ for ggF-enriched $n_j \geq 2$

In the more inclusive phase space of the ggF-enriched $n_j \geq 2$ category, the $t\bar{t}$ background remains dominant after the $n_b = 0$ requirement, as is the case for the VBF-enriched category. The CR is defined with $m_{\ell\ell} > 80$ GeV to distinguish it from the signal region (see Fig. 10) and reduce signal contamination. The CR is approximately 70% pure in top-quark events, and a normalization factor of $\beta = 1.05 \pm 0.03(\text{stat})$ is obtained. The uncertainties on the extrapolation factor α to the SR are 3.2% from the comparison of MC@NLO + HERWIG, ALPGEN + HERWIG, and POWHEG + PYTHIA; 1.2% for the parton shower and underlying-event uncertainties from the comparison of POWHEG + PYTHIA6 and POWHEG + HERWIG; 1% from the missing higher-order contribution, evaluated by varying the renormalization and factorization scales; 0.3% from the PDF envelope evaluated as described in Sec. VIA 1; and 0.7% from the experimental uncertainties. The effect of the same set of variations on the predicted m_T distribution in the signal region was also checked. The variations from the nominal distribution are small, at most 4% in the tails, but they are included as a shape systematic in the fit procedure.

C. Misidentified leptons

Collisions producing W bosons in association with one or more jets—referred to here as W + jets—may enter the signal sample when a jet is misidentified as a prompt lepton. In this background, there is a prompt lepton and a transverse momentum imbalance from the leptonic decay of the W boson. Background can also arise from multijet production when two jets are misidentified

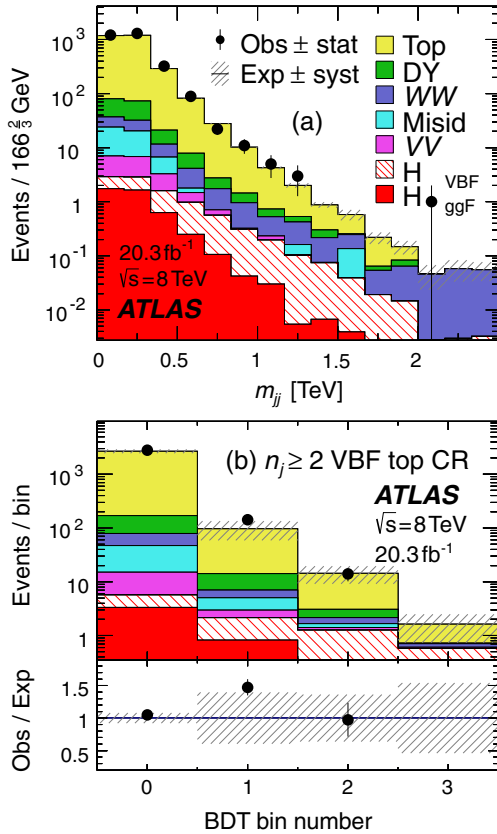


FIG. 22 (color online). Top-quark control region distributions in the VBF-enriched $n_j \geq 2$ category for (a) m_{jj} and (b) BDT output. For the plot in (b) the shaded band in the ratio shows the uncertainty on the normalization of each bin. No events are observed in bin 3. See Fig. 5 for plotting details.

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as prompt leptons and a transverse momentum imbalance is reconstructed.

1. $W + \text{jets}$

The $W + \text{jets}$ background contribution is estimated using a control sample of events where one of the two lepton candidates satisfies the identification and isolation criteria for the signal sample, and the other lepton fails to meet these criteria but satisfies less restrictive criteria (these lepton candidates are denoted “anti-identified”). Events in this sample are otherwise required to satisfy all of the signal selection requirements. The dominant component of this sample (85% to 90%) is due to $W + \text{jets}$ events in which a jet produces an object reconstructed as a lepton. This object may be either a nonprompt lepton from the decay of a hadron containing a heavy quark, or else a particle (or particles) from a jet reconstructed as a lepton candidate.

The $W + \text{jets}$ contamination in the signal region is obtained by scaling the number of events in the data control sample by an extrapolation factor. This extrapolation factor is measured in a data sample of jets produced in association with Z bosons reconstructed in either the e^+e^- or $\mu^+\mu^-$ final state (referred to as the $Z + \text{jets}$ control sample below). The factor is the ratio of the number of identified lepton candidates satisfying all lepton selection criteria to the number of anti-identified leptons measured in bins of anti-identified lepton p_T and η . Anti-identified leptons must explicitly not satisfy the signal selection criteria (so that leptons counted in the numerator of this ratio exclude the anti-identified leptons counted in the denominator of this ratio) and the signal requirements for isolation and track impact parameters are either relaxed or

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removed. In addition, for anti-identified electrons the identification criteria specifically targeting conversions are removed and the anti-identified electron is explicitly required to fail the “medium” electron identification requirement specified in Ref. [23].

Figure 23 shows the p_T distributions of identified muons [Fig. 23(a)], identified electrons [Fig. 23(b)], anti-identified muons [Fig. 23(c)], and anti-identified electrons [Fig. 23(d)] in the $Z + \text{jets}$ control sample. The extrapolation factor in a given p_T bin is the number of identified leptons divided by the number of anti-identified leptons in that particular bin. Each number is corrected for the presence of processes not due to $Z + \text{jets}$. The $Z + \text{jets}$ sample is contaminated by other production processes that produce additional prompt leptons (e.g., $WZ \rightarrow \ell\nu\ell\ell$) or nonprompt leptons not originating from jets (e.g., Z/γ^* and $Z\gamma$) that create a bias in the extrapolation factor. Kinematic criteria suppress about 80% of the contribution from these other processes in the $Z + \text{jets}$ sample. The remaining total contribution of these other processes after applying these kinematic criteria is shown in the histograms in Fig. 23. The uncertainty shown in these histograms is the 10% systematic uncertainty assigned to the contribution from these other processes, mainly due to cross section uncertainties. This remaining contribution from other processes is estimated using Monte Carlo simulation and removed from the event yields before calculating the extrapolation factor.

The composition of the associated jets—namely the fractions of jets due to the production of heavy-flavor quarks, light-flavor quarks, and gluons—in the $Z + \text{jets}$ sample and the $W + \text{jets}$ sample may be different. Any difference would lead to a systematic error in the estimate

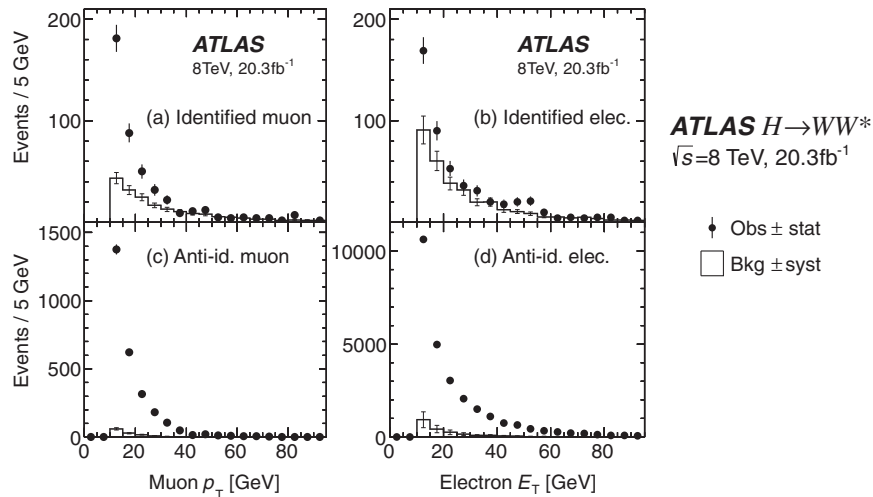


FIG. 23. Misidentified lepton sample distributions of p_T in the $Z + \text{jets}$ control sample: (a) identified muon, (b) identified electron, (c) anti-identified muon, and (d) anti-identified electron. The symbols represent the data (Obs); the histograms are the background MC estimates (Bkg) of the sum of electroweak processes other than the associated production of a Z boson and jets.

of the $W + \text{jets}$ background due to applying the extrapolation factor determined with the $Z + \text{jets}$ sample to the $W + \text{jets}$ control sample, so Monte Carlo simulation is used to determine a correction factor that is applied to the extrapolation factors determined with the $Z + \text{jets}$ data sample. A comparison of the extrapolation factors determined with the $Z + \text{jets}$ sample and the $W + \text{jets}$ sample is made for three Monte Carlo simulations: ALPGEN+PYTHIA6, ALPGEN+HERWIG, and POWHEG+PYTHIA8. For each combination of matrix-element and parton-shower simulations, a ratio of the extrapolation factors for $W + \text{jets}$ versus $Z + \text{jets}$ is calculated. These three ratios are used to determine a correction factor and an uncertainty that is applied to the extrapolation factors determined with the $Z + \text{jets}$ data sample: this correction factor is 0.99 ± 0.20 for anti-identified electrons and 1.00 ± 0.22 for anti-identified muons.

The total uncertainties on the corrected extrapolation factors are summarized in Table XV. In addition to the systematic uncertainty on the correction factor due to the sample composition, the other important uncertainties on the $Z + \text{jets}$ extrapolation factor are due to the limited number of jets that meet the lepton selection criteria in the $Z + \text{jets}$ control sample and the uncertainties on the contributions from other physics processes in the identified and anti-identified lepton samples. The total systematic uncertainty on the corrected extrapolation factors varies as a function of the p_T of the anti-identified lepton; this variation is from 29% to 61% for anti-identified electrons and 25% to 46% for anti-identified muons. The systematic uncertainty on the corrected extrapolation factor dominates the systematic uncertainty on the $W + \text{jets}$ background.

TABLE XV. Uncertainties (in %) on the extrapolation factor α_{misid} for the determination of the $W + \text{jets}$ background. Total is the quadrature sum of the uncertainties due to the correction factor determined with MC simulation (Corr. factor), the number of jets misidentified as leptons in the $Z + \text{jets}$ control sample (Stat), and the subtraction of other processes (Other bkg). As described in the text, Corr. factor is classified as theoretical and the rest as experimental. OC (SC) refers to the uncertainties in the opposite-charge (same-charge) $W + \text{jets}$ CR.

SR p_T range	Total		Corr. factor		Stat	Other bkg
	OC	SC	OC	SC		
Electrons						
10–15 GeV	29	32	20	25	18	11
15–20 GeV	44	46	20	25	34	19
20–25 GeV	61	63	20	25	52	25
≥ 25 GeV	43	45	20	25	30	23
Muons						
10–15 GeV	25	37	22	35	10	03
15–20 GeV	37	46	22	35	18	05
20–25 GeV	37	46	22	35	29	09
≥ 25 GeV	46	53	22	35	34	21

The uncertainties on the signal strength μ are classified into experimental, theoretical, and other components, as described in Sec. IX and Table XXVI. The uncertainty on μ due to the correction factor applied to the extrapolation factor is classified as theoretical because the uncertainty on the correction factor is derived from a comparison of predictions from different combinations of Monte Carlo generators and parton shower algorithms. The uncertainty on μ due to the other uncertainties on the extrapolation factor ($Z + \text{jet}$ control sample statistics and the subtraction of other processes from this control sample) is classified as experimental.

Figure 24 shows the extrapolation factor measured in the $Z + \text{jets}$ data compared to the predicted extrapolation factor determined using Monte Carlo simulated samples

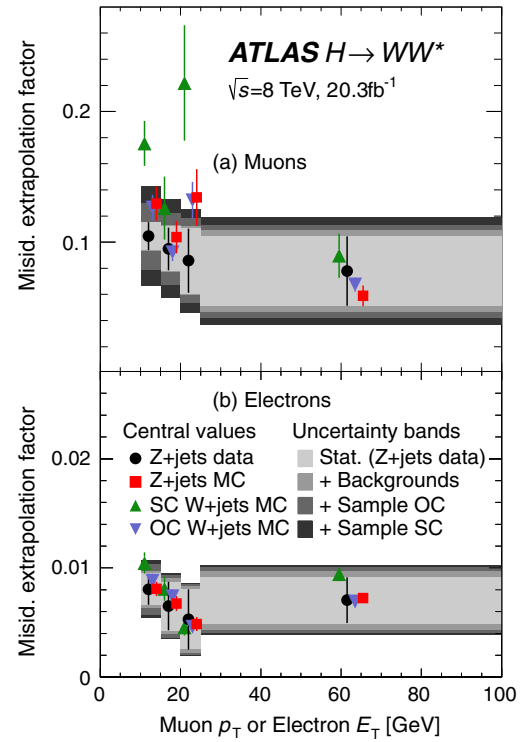


FIG. 24 (color online). Misidentified lepton extrapolation factors, α_{misid} , for anti-identified (a) muons and (b) electrons before applying the correction factor described in the text. The symbols represent the central values of the $Z + \text{jets}$ data and the three ALPGEN + PYTHIA6 MC samples: $Z + \text{jets}$, opposite-charge (OC) $W + \text{jets}$, and same-charge (SC) $W + \text{jets}$. The bands represent the uncertainties: Stat. refers to the statistical component, which is dominated by the number of jets identified as leptons in $Z + \text{jets}$ data; Background is due to the subtraction of other electroweak processes present in $Z + \text{jets}$ data; and Sample is due to the variation of the α_{misid} ratios in $Z + \text{jets}$ to OC $W + \text{jets}$ or to SC $W + \text{jets}$ in the three MC samples. The symbols are offset from each other for presentation.

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(ALPGEN + PYTHIA6) of $Z + \text{jets}$ and $W + \text{jets}$ for anti-identified muons [Fig. 24(a)] and anti-identified electrons [Fig. 24(b)]. The values of the extrapolation factors are related to the specific criteria used to select the anti-identified leptons and, as a result, the extrapolation factor for anti-identified muons is about one order of magnitude larger than the extrapolation factor for anti-identified electrons. This larger extrapolation factor does not indicate a larger probability for a jet to be misidentified as a muon compared to an electron. In fact, misidentified electrons contribute a larger portion of the $W + \text{jets}$ background in the signal region.

The $W + \text{jets}$ background in the signal region is determined using a control sample in which the lepton and the anti-identified lepton are required to have opposite charge. A prediction of the $W + \text{jets}$ background is also used for a data control sample consisting of events that satisfy all of the Higgs boson signal requirements *except* that the two lepton candidates are required to have the same charge. This same-charge control region is described in Sec. VID.

The $W + \text{jets}$ process is not expected to produce equal numbers of same-charge and opposite-charge candidates. In particular, associated production processes such as Wc , where the second lepton comes from the semileptonic decay of a charmed hadron, produce predominantly opposite-charge candidates. Therefore, a separate extrapolation factor is applied to the same-charge $W + \text{jets}$ control sample.

The procedure used to determine the same-charge extrapolation factor from the $Z + \text{jets}$ data is the same as the one used for the signal region. Because of the difference in jet composition of the same-charge $W + \text{jets}$ control sample, a different correction factor is derived from MC simulation to correct the extrapolation factor determined with the $Z + \text{jets}$ data sample for application to the same-charge $W + \text{jets}$ sample. Figure 24 compares the extrapolation factors in same-charge $W + \text{jets}$ with the ones in $Z + \text{jets}$. The correction factor is 1.25 ± 0.31 for anti-identified electrons and 1.40 ± 0.49 for anti-identified muons; as with the opposite-charge correction factors, these factors and their systematic uncertainty are determined by comparing the factors determined with the three different samples of MC simulations mentioned previously in the text (ALPGEN + PYTHIA6, ALPGEN + HERWIG, and POWHEG + PYTHIA8). The total uncertainties on the corrected extrapolation factors used to estimate the $W + \text{jets}$ background in the same-charge control region are shown in Table XV. The correlation between the systematic uncertainties on the opposite-charge and same-charge correction factors reflects the composition of the jets producing objects misidentified as leptons. These jets have a component that is charge symmetric with respect to the charge of the W boson as well as a component unique to opposite-charge $W + \text{jets}$ processes. Based on the relative rates of same- and opposite-charge $W + \text{jets}$ events, 60% of

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the opposite-charge correction factor uncertainty is correlated with 100% of the corresponding same-charge uncertainty.

2. Multijets

The background in the signal region due to multijets is determined using a control sample that has two anti-identified lepton candidates, but otherwise satisfies all of the signal region selection requirements. A separate extrapolation factor—using a multijet sample—is measured for the multijet background and applied twice to this control sample. The sample used to determine the extrapolation factor is expected to have a similar sample composition (in terms of heavy-flavor jets, light-quark jets, and gluon jets) to the control sample. Since the presence of a misidentified lepton in a multijet sample influences the sample composition—for example by increasing the fraction of heavy-flavor processes in the multijet sample—corrections to the extrapolation factor are made that take into account this correlation. The event-by-event corrections vary between 1.0 and 4.5 depending on the lepton flavor and p_T of both misidentified leptons in the event; the electron extrapolation factor corrections are larger than the muon extrapolation factor corrections.

3. Summary

Table XVI lists the estimated event counts for the multijet and $W + \text{jets}$ backgrounds in the $e\mu$ channel for the various jet multiplicities. The values are given before the m_T fit for the ggF-enriched categories and after the VBF-selection for the VBF-enriched categories. The uncertainties are the combination of the statistical and systematic uncertainties and are predominantly systematic. The dominant systematic uncertainty is from the extrapolation factors. In the case of the $W + \text{jets}$ background, these uncertainties are summarized in Table XV; in the case of the multijet background, the largest contribution is the uncertainty introduced by the correlations between extrapolation factors in an event with two misidentified leptons.

TABLE XVI. $W + \text{jets}$ and multijets estimated yields in the $e\mu$ category. For $n_j = 0$ and $n_j = 1$, yields for both the opposite-charge and same-charge leptons are given. The yields are given before the m_T fit for the ggF-enriched categories and after the VBF selection for the VBF-enriched categories. The uncertainties are from a combination of statistical and systematic sources.

Category	W + jets yield N_{Wj}		Multijets yield N_{jj}	
	OC	SC	OC	SC
$n_j = 0$	278 ± 71	174 ± 54	9.2 ± 4.2	5.5 ± 2.5
$n_j = 1$	88 ± 22	62 ± 18	6.1 ± 2.7	3.0 ± 1.3
$n_j \geq 2$ ggF	50 ± 22	-	49 ± 22	-
$n_j \geq 2$ VBF	3.7 ± 1.2	-	2.1 ± 0.8	-

For the $n_j = 0$ and $n_j = 1$ categories, the expected backgrounds are provided for both the opposite-charge signal region and the same-charge control region (described in Sec. VID), and the multijet background is expected to be less than 10% of the $W + \text{jets}$ background in these two categories. For higher jet multiplicities, the multijet background is expected to be comparable to the $W + \text{jets}$ background because there is no selection criterion applied to m_T^e . In this case, however, the multijet background has a very different m_T distribution than the Higgs boson signal, so it is not necessary to suppress this background to the same extent as in the lower jet multiplicity categories.

D. Other dibosons

There are backgrounds that originate from the production of two vector bosons other than WW . These include $W\gamma$, $W\gamma^*$, WZ , and ZZ production and are referred to here as VV . The VV processes add up to about 10% of the total estimated background in the $n_j \leq 1$ channels and are of the same magnitude as the signal. The dominant sources of these backgrounds are the production of $W\gamma$ and $W\gamma^*/WZ$, where this latter background is a combination of the associated production of a W boson with a nonresonant Z/γ^* or an on-shell Z boson.

The normalization of the VV background processes in the $e\mu$ channel is determined from the data using a same-charge control region, which is described below. The distribution of these various contributing processes in the different signal bins is determined using MC simulation. In the $ee/\mu\mu$ channels, both the normalization and the distributions of the VV processes are estimated with MC simulation. The details of these simulations are provided in Sec. IIIC.

Several specialized data sample selections are used to validate the simulation of the rate and the shape of distributions of various kinematic quantities of the $W\gamma$ and $W\gamma^*$ processes and the simulation of the efficiency for rejecting electrons from photon conversions.

The $W\gamma$ background enters the signal region when the W boson decays leptonically and the photon converts into an e^+e^- pair in the detector material. If the pair is very asymmetric in p_T , then it is possible that only the electron or positron satisfies the electron selection criteria, resulting in a Higgs boson signal candidate. This background has a prompt electron or muon and missing transverse momentum from the W boson decay and a nonprompt electron or positron. The prompt lepton and the conversion product are equally likely to have opposite electric charge (required in the signal selection) and the same electric charge, since the identification is not charge dependent.

A sample of nonprompt electrons from photon conversions can be selected by reversing two of the electron signal selection requirements: the electron track should be part of a reconstructed photon conversion vertex candidate and the track should have no associated hit on the innermost layer

of the pixel detector. Using these two reversed criteria, a sample of $e\mu$ events that otherwise satisfy all of the kinematic requirements imposed on Higgs boson signal candidates is selected; in the $n_j = 0$ category ($n_j = 1$ category), 83% (87%) of this sample originates from $W\gamma$ production. This sample is restricted to events selected online with a muon trigger to avoid biases in the electron selection introduced by the online electron trigger requirements. Figures 25(a) and 25(b) show the m_T distribution and the p_T distribution of the electron of the $n_j = 0$ category of this $W\gamma$ validation sample compared to expectations from the MC simulation. Verifying that the simulation correctly models the efficiency of detecting photon conversions is important to ensure that the $W\gamma$ background normalization and distributions are accurately modeled. To evaluate the modeling of photon conversions, a $Z \rightarrow \mu\mu\gamma$ validation sample consisting of either $Z\gamma$ or Z boson production with final-state radiation is selected. The Z boson is reconstructed in the $\mu^+\mu^-$ decay channel, and an electron (or positron) satisfying all the electron selection criteria except the two reversed criteria specified above is selected. The $\mu^+\mu^-e^\pm$ invariant mass is required to be within 15 GeV of m_Z to reduce contributions from the associated production of a Z boson and hadronic jets. The resulting data sample is more than 99% pure in the $Z \rightarrow \mu\mu\gamma$ process. A comparison between this data sample and a $Z \rightarrow \mu\mu\gamma$ MC simulation indicates some potential mismodeling of the rejection of nonprompt electrons in the simulation. Hence a p_T -dependent systematic uncertainty ranging from 25% for $10 < p_T < 15$ GeV to 5% for $p_T > 20$ GeV is assigned to the efficiency for nonprompt electrons from photon conversions to satisfy the rejection criteria.

The $W\gamma^*$ background originates from the associated production of a W boson that decays leptonically and a virtual photon γ^* that produces an e^+e^- or $\mu^+\mu^-$ pair in which only one lepton of the pair satisfies the lepton selection criteria. This background is most relevant in the $n_j = 0$ signal category, where it contributes a few percent of the total background and is equivalent to about 25% of the expected Higgs boson signal.

The modeling of the $W\gamma^*$ background is studied with a specific selection aimed at isolating a sample of $W\gamma^* \rightarrow e\nu\mu\mu$ candidates. Events with an electron and a pair of opposite-charge muons are selected with $m_{\mu\mu} < 7$ GeV, $p_T^{\text{miss}} > 20$ GeV and both muons must satisfy $\Delta\phi(e, \mu) < 2.8$. Muon pairs consistent with originating from the decay of a J/ψ meson are rejected. The electron and the highest p_T muon are required to satisfy the signal region lepton selection criteria and p_T thresholds; however, the subleading-muon p_T threshold is reduced to 3 GeV. The isolation criteria for the higher- p_T muon are modified to take into account the presence of the lower- p_T muon. The SHERPA $W\gamma^*$ simulation sample with $m_{\gamma^*} < 7$ GeV is compared to the data selected with the above criteria; the

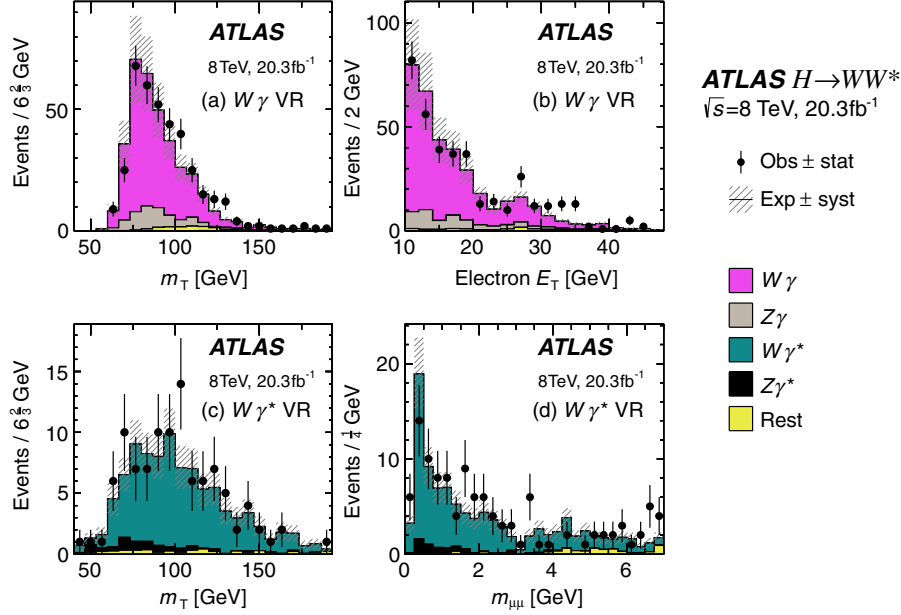
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FIG. 25 (color online). $W\gamma$ and $W\gamma^*$ validation region (VR) distributions: (a) $W\gamma$ transverse mass, (b) $W\gamma$ electron E_T , (c) $W\gamma^*$ transverse mass using the leading two leptons, and (d) $W\gamma^*$ dimuon invariant mass. The $W\gamma$ ($W\gamma^*$) plots use the data in the $n_j = 0$ (all n_j) category. “Rest” consists of contributions not listed in the legend. All processes are normalized to their theoretical cross sections. See Fig. 5 for plotting details.

distributions of the m_T calculated using the electron and the higher- p_T muon and the invariant mass of the two muons $m_{\mu\mu}$ are shown in Figs. 25(c) and 25(d).

The WZ and ZZ backgrounds are modeled with MC simulation. No special samples are selected to validate the simulation of these processes. The ZZ background arises primarily when one Z boson decays to e^+e^- and the other to $\mu^+\mu^-$ and an electron and a muon are not detected. This background is very small, amounting to less than 3% of the VV background. Background can also arise from $Z\gamma^*$ and $Z\gamma$ production if the Z boson decays to $\ell^+\ell^-$ and one of the leptons is not identified and the photon results in a second lepton. These backgrounds are also very small, and the $Z\gamma^*$ background is neglected.

The VV backgrounds arising from $W\gamma$, $W\gamma^*$, and WZ are equally likely to result in a second lepton that has the same charge or opposite charge compared to the lepton from the W boson decay. For this reason, a selection of $e\mu$ events that is identical to the Higgs boson candidate selection except that it requires the two leptons to have the same charge is used to define a same-charge control region. The same-charge control region is dominated by VV processes. The other processes that contribute significantly to the same-charge sample are the W + jets process and—to a much lesser extent—the multijet process. The same-charge data sample can be used to normalize the VV processes once the

contribution from the W + jets process is taken into account, using the method described in Sec. VIC.

Figure 26 shows the distributions of the transverse mass [26(a) and 26(c)] and the subleading lepton p_T [26(b) and 26(d)] for the same-charge data compared with the MC simulations after normalizing the sum of these MC predictions to the same-charge data. A single normalization factor is applied simultaneously to all four MC simulations of the VV backgrounds (shown separately in the figures). These normalization factors are $\beta_{0j} = 0.92 \pm 0.07(\text{stat})$ and $\beta_{1j} = 0.96 \pm 0.12(\text{stat})$ for the $e\mu$ channels in the $n_j \leq 1$ categories. The VV processes comprise about 60% of the total in both the zero-jet and one-jet same-charge data samples, with 30% coming from the W + jets process.

Theoretical uncertainties on the VV backgrounds are dominated by the scale uncertainty on the prediction for each jet bin. For the $W\gamma$ process, a relative uncertainty of 6% on the total cross section is correlated across jet categories, and the uncorrelated jet-bin uncertainties are 9%, 53%, and 100% in the $n_j = 0$, $n_j = 1$, and $n_j \geq 2$ categories, respectively. For the $W\gamma^*$ process, the corresponding uncertainties are 7% (total cross section), 7% ($n_j = 0$), 30% ($n_j = 1$), and 26% ($n_j \geq 2$). No uncertainty is applied for the extrapolation of these backgrounds from the same-charge control region to the opposite-charge signal region, since it was verified in the simulation that

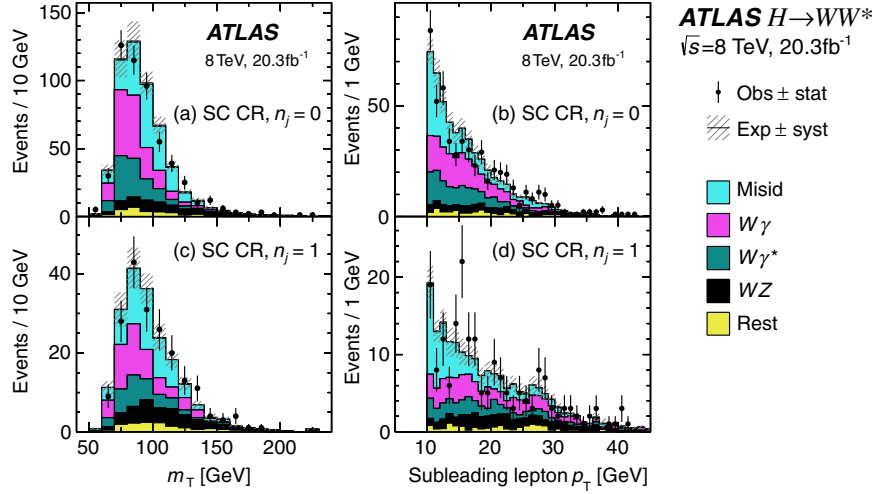


FIG. 26 (color online). Same-charge control region distributions: (a) transverse mass in the $n_j = 0$ category, (b) subleading lepton p_T in the $n_j = 0$ category, (c) transverse mass in the $n_j = 1$ category, and (d) subleading lepton p_T in the $n_j = 1$ category. “Rest” consists of contributions not listed in the legend. See Fig. 5 for plotting details.

these processes contribute equal numbers of opposite-charge and same-charge events.

E. Drell-Yan

The DY processes produce two oppositely charged leptons and some events are reconstructed with significant missing transverse momentum. This is mostly due to neutrinos produced in the Z boson decay in the case of the $Z/\gamma^* \rightarrow \tau\tau$ background to the $e\mu$ channels. In contrast, in the case of the $Z/\gamma^* \rightarrow ee, \mu\mu$ background to the $ee/\mu\mu$ channels, it is mostly due to detector resolution that is degraded at high pile-up and to neutrinos produced in b -hadron or c -hadron decays (from jets produced in association with the Z boson). Preselection requirements, such as the one on p_T^{miss} , reduce the bulk of this background, as shown in Fig. 5, but the residual background is significant in all categories, especially in the $ee/\mu\mu$ samples. The estimation of the $Z/\gamma^* \rightarrow \tau\tau$ background for the $e\mu$ samples is done using a control region, which is defined in a very similar way across all n_j categories, as described below. Since a significant contribution to the $Z/\gamma^* \rightarrow ee, \mu\mu$ background to the $ee/\mu\mu$ categories arises from mismeasurements of the missing transverse momentum, more complex data-derived approaches are used to estimate this background, as described below.

Mis modeling of p_T^{Z/γ^*} , reconstructed as $p_T^{\ell\ell}$, was observed in the Z/γ^* -enriched region in the $n_j = 0$ category. The ALPGEN + HERWIG MC generator does not adequately model the parton shower of soft jets that balance $p_T^{\ell\ell}$ when there are no selected jets in the event. A correction, based on the weights derived from a data-to-MC comparison in the Z peak, is therefore applied to MC

events in the $n_j = 0$ category, for all leptonic final states from Drell-Yan production.

1. $Z/\gamma^* \rightarrow \tau\tau$

The $Z/\gamma^* \rightarrow \tau\tau$ background prediction is normalized to the data using control regions. The contribution from this background process is negligible in the $ee/\mu\mu$ channel, and in order to remove the potentially large $Z/\gamma^* \rightarrow ee, \mu\mu$ contamination, the CR is defined using the $e\mu$ samples in all categories except the $n_j \geq 2$ VBF-enriched one.

The control region in the $n_j = 0$ category is defined by the requirements $m_{\ell\ell} < 80$ GeV and $\Delta\phi_{\ell\ell} > 2.8$, which select a 91%-pure region and result in a normalization factor $\beta_{0j} = 1.00 \pm 0.02(\text{stat})$. In the $n_j = 1$ category, the invariant mass of the $\tau\tau$ system, calculated with the collinear mass approximation, and defined in Sec. IV B, can be used since the dilepton system is boosted. An 80%-pure region is selected with $m_{\ell\ell} < 80$ GeV and $m_{\tau\tau} > (m_Z - 25 \text{ GeV})$. The latter requirement ensures that there is no overlap with the signal region selection. The resulting normalization factor is $\beta_{1j} = 1.05 \pm 0.04(\text{stat})$. The $n_j \geq 2$ ggF-enriched category uses a CR selection of $m_{\ell\ell} < 70$ GeV and $\Delta\phi_{\ell\ell} > 2.8$ providing 74% purity and a normalization factor $\beta_{2j} = 1.00 \pm 0.09(\text{stat})$. Figure 27 shows the m_T distributions in the control regions in the $n_j = 0$ and $n_j = 1$ categories. High purity and good data/MC agreement is observed.

In order to increase the available statistics in the $Z/\gamma^* \rightarrow \tau\tau$ control region in the $n_j \geq 2$ VBF-enriched category, $ee/\mu\mu$ events are also considered. The contribution from $Z/\gamma^* \rightarrow ee, \mu\mu$ decays is still negligible. The control region

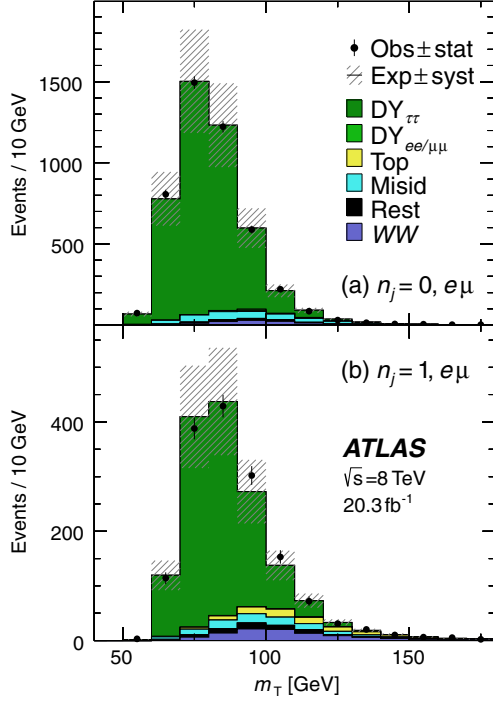
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FIG. 27 (color online). $Z/\gamma^* \rightarrow \tau\tau$ control region distributions of transverse mass. See Fig. 5 for plotting details.

is defined by the invariant mass requirements: $m_{\ell\ell} < 80$ GeV (75 GeV in $ee/\mu\mu$) and $|m_{\tau\tau} - m_Z| < 25$ GeV. The resulting normalization factor is derived after summing all three bins in O_{BDT} and yields $\beta = 0.9 \pm 0.3(\text{stat})$.

Three sources of uncertainty are considered on the extrapolation of the $Z/\gamma^* \rightarrow \tau\tau$ background from the control region: QCD scale variations, PDFs, and generator modeling. The latter are evaluated based on a comparison of ALPGEN + HERWIG and ALPGEN + PYTHIA generators. An additional uncertainty on the p_T^{Z/γ^*} reweighting procedure is applied in the $n_j = 0$ category. It is estimated by comparing the different effects of reweighting with the nominal weights and with an alternative set of weights derived with a $p_T^{\text{miss}} > 20$ GeV requirement applied in the Z-peak region. This requirement follows the event selection criteria used in the $e\mu$ samples where the $Z/\gamma^* \rightarrow \tau\tau$ background contribution is more important. Table XVII shows the uncertainties on the extrapolation factor α to the signal regions and the WW control regions in the $n_j \leq 1$ and $n_j \geq 2$ ggF-enriched categories.

2. $Z/\gamma^* \rightarrow ee, \mu\mu$ in $n_j \leq 1$

The f_{recoil} variable (see Sec. IV) shows a clear shape difference between DY and all processes with neutrinos in the final state, including signal and $Z/\gamma^* \rightarrow \tau\tau$, which are

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TABLE XVII. $Z/\gamma^* \rightarrow \tau\tau$ uncertainties (in %) on the extrapolation factor α , for the $n_j \leq 1$ and $n_j \geq 2$ ggF-enriched categories. Scale, PDF, and generator modeling (Gen) uncertainties are reported. For the $n_j = 0$ category, additional uncertainty due to p_T^{Z/γ^*} reweighting is shown. The negative sign indicates anticorrelation with respect to the unsigned uncertainties in the same column.

Regions	Scale	PDF	Gen	p_T^{Z/γ^*}
Signal regions				
$n_j = 0$	-1.6	1.4	5.7	19
$n_j = 1$	4.7	1.8	-2.0	-
$n_j \geq 2$ ggF	-10.3	1.1	10.4	-
WW control regions				
$n_j = 0$	-5.5	1.0	-8.0	16
$n_j = 1$	-7.2	2.1	3.2	-

collectively referred to as “non-DY”. A method based on a measurement of the selection efficiency of a cut on f_{recoil} from data, and an estimate of the remaining DY contribution after such a cut, is used in the $ee/\mu\mu$ category. A sample of events is divided into two bins based on whether they pass or fail the f_{recoil} requirement, and the former defines the signal region. The efficiency of this cut, $\epsilon = N_{\text{pass}}/(N_{\text{pass}} + N_{\text{fail}})$, measured separately in data for the DY and non-DY processes, is used together with the fraction of the observed events passing the f_{recoil} requirement to estimate the final DY background. It is analytically equivalent to inverting the matrix:

$$\begin{bmatrix} N_{\text{pass}} \\ N_{\text{pass}} + N_{\text{fail}} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1/\epsilon_{\text{DY}} & 1/\epsilon_{\text{non-DY}} \end{bmatrix} \cdot \begin{bmatrix} B_{\text{DY}} \\ B_{\text{non-DY}} \end{bmatrix}, \quad (10)$$

and solving for B_{DY} , which gives the fully data-derived estimate of the DY yield in the $ee/\mu\mu$ signal region. The m_T distribution for this background is taken from the Monte Carlo prediction, and the m_T shape uncertainties due to the p_T^{Z/γ^*} reweighting are found to be negligible.

The non-DY selection efficiency $\epsilon_{\text{non-DY}}$ is evaluated using the $e\mu$ sample, which is almost entirely composed of non-DY events. Since this efficiency is applied to the non-DY events in the final $ee/\mu\mu$ signal region, the event selection is modified to match the $ee/\mu\mu$ signal region selection criteria. This efficiency is used for the signal and for all non-DY backgrounds. The DY selection efficiency ϵ_{DY} is evaluated using the $ee/\mu\mu$ sample satisfying the $|m_{\ell\ell} - m_Z| < 15$ GeV requirement, which selects the Z-peak region. An additional non-DY efficiency $\epsilon'_{\text{non-DY}}$ is introduced to account for the non-negligible non-DY contribution in the Z peak, and is used in the evaluation of ϵ_{DY} . It is calculated using the same $m_{\ell\ell}$ region but in $e\mu$ events. Numerical values for these f_{recoil} selection efficiencies are shown in Table XVIII(a).

TABLE XVIII. The f_{recoil} summary for the $Z/\gamma^* \rightarrow ee, \mu\mu$ background in the $n_j \leq 1$ categories. The efficiency for Drell-Yan and non-DY processes are given in (a); the associated systematic uncertainties (in %) are given in (b). For each group in (b), the subtotal is given first. The last row gives the total uncertainty on the estimated B_{DY} yield in the SR.

Efficiency type	$n_j = 0$	$n_j = 1$
(a) f_{recoil} selection efficiencies (in %)		
$\epsilon_{\text{non-DY}}$, efficiency for non-DY events	69 ± 1	64 ± 2
ϵ_{DY} , efficiency for DY events	14 ± 5	13 ± 4
$\epsilon'_{\text{non-DY}}$, efficiency for non-DY when determining the previous row	68 ± 2	66 ± 3
Source	$n_j = 0$	$n_j = 1$
(b) Systematic uncertainties (in %) on the above efficiencies		
Uncertainty on $\epsilon_{\text{non-DY}}$	1.9	3.2
from statistical	1.8	3.0
from using $e\mu$ CR to extrapolate to the SR ($ee/\mu\mu$ category)	0.8	1.2
Uncertainty on ϵ_{DY}	38	32
from statistical	9.4	16
from using Z peak to extrapolate to the SR ($12 < m_{\ell\ell} < 55$ GeV)	32	16
Uncertainty on $\epsilon'_{\text{non-DY}}$	3.1	4.5
from statistical	1.9	3.9
from using $e\mu$ CR to extrapolate to the SR ($ee/\mu\mu$ category)	2.5	2.4
Total uncertainty on yield estimate B_{DY}	49	45

For the non-DY f_{recoil} selection efficiencies $\epsilon_{\text{non-DY}}$ and $\epsilon'_{\text{non-DY}}$, the systematic uncertainties are based on the $e\mu$ -to- $ee/\mu\mu$ extrapolation. They are evaluated with MC simulations by taking the full difference between the selection efficiencies for $e\mu$ and $ee/\mu\mu$ events in the Z peak and SR. Obtained uncertainties are validated with alternative MC samples and with data, and are added in quadrature to the statistical uncertainties on the efficiencies. The difference in the f_{recoil} selection efficiencies for the signal and the other non-DY processes is taken as an additional uncertainty on the signal, and is 9% for the $n_j = 0$ category and 7% for the $n_j = 1$ one. Systematic uncertainties on the efficiencies related to the sample composition of the non-DY background processes were found to be negligible.

The systematic uncertainties on ϵ_{DY} are based on the extrapolation from the Z peak to the SR and are evaluated with MC simulation by comparing the f_{recoil} selection efficiencies in these two regions. This procedure is checked with several generators, and the largest difference in the selection efficiency is taken as the systematic uncertainty on the efficiency. It is later added in quadrature to the statistical uncertainty. The procedure is also validated with the data. Table XVIII(b) summarizes all the uncertainties.

The largest uncertainties are on ϵ_{DY} but since the non-DY component dominates in the signal region, the uncertainties on its f_{recoil} efficiency are the dominant contribution to the total uncertainty on the estimated B_{DY} yield.

3. $Z/\gamma^* \rightarrow ee, \mu\mu$ in VBF-enriched $n_j \geq 2$

The $Z/\gamma^* \rightarrow ee, \mu\mu$ background in the VBF-enriched channel is estimated using an “ABCD” method, described below. The BDT shape for this process is taken from a high-purity data sample with low $m_{\ell\ell}$ and low $p_{\text{T}}^{\text{miss}}$ (region B). It is then normalized with a $p_{\text{T}}^{\text{miss}}$ cut efficiency, derived from the data using the Z-peak region separated into low- and high- $p_{\text{T}}^{\text{miss}}$ regions (C and D, respectively). It yields 0.43 ± 0.03 . The final estimate in the signal region (A) is corrected with a nonclosure factor derived from the MC, representing the differences in $p_{\text{T}}^{\text{miss}}$ cut efficiencies between the low- $m_{\ell\ell}$ and Z-peak regions. It yields 0.83 ± 0.22 . Bins 2 and 3 of O_{BDT} are normalized using a common factor due to the low number of events in the highest O_{BDT} bin in region B. The normalization factors, applied to the $Z/\gamma^* \rightarrow ee, \mu\mu$ background in the $ee/\mu\mu$ channel in the signal region, are $\beta_{\text{bin}1} = 1.01 \pm 0.15(\text{stat})$ and $\beta_{\text{bin}2+3} = 0.89 \pm 0.28(\text{stat})$.

The uncertainty on the nonclosure factor is 17% (taken as its deviation from unity), and is fully correlated across all O_{BDT} bins. Uncertainties are included on the O_{BDT} shape due to QCD scale variations, PDFs, and the parton shower model, and are 11% in the bin with the highest O_{BDT} score. No dependence of the BDT response on $p_{\text{T}}^{\text{miss}}$ is observed in MC, and an uncertainty is assigned based on the assumption that they are uncorrelated (4%, 10%, and 60% in the bins with increasing O_{BDT} score).

F. Modifications for 7 TeV data

The background estimation techniques in the $n_j \leq 1$ channels for 7 TeV data closely follow the ones applied to 8 TeV data. The definitions of the control regions of WW , top-quark, and $Z/\gamma^* \rightarrow \tau\tau$ are the same. The $Z/\gamma^* \rightarrow ee, \mu\mu$ background is estimated with the same method based on the f_{recoil} selection efficiencies. The f_{recoil} requirements are loosened (see Sec. IV E). The calculation of the extrapolation factor in the W + jets estimate uses a multijet sample instead of a Z + jets sample, which has a limited number of events. The VV backgrounds are estimated using Monte Carlo predictions because of the small number of events in the same-charge region. In the $n_j \geq 2$ VBF-enriched category, the background estimation techniques are the same as in the 8 TeV analysis. The normalization factors from the control regions are given in Table XX in the next section along with the values for the 8 TeV analysis.

The theoretical uncertainties on the extrapolation factors used in the WW , top-quark, and $Z/\gamma^* \rightarrow \tau\tau$ background estimation methods are assumed to be the same as in the 8 TeV analysis. Uncertainties due to experimental sources

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are unique to the 7 TeV analysis and are taken into account in the likelihood fit. The uncertainties on the f_{recoil} selection efficiencies used in the $Z/\gamma^* \rightarrow ee, \mu\mu$ background estimation were evaluated following the same technique as in the 8 TeV analysis. The dominant uncertainty on the extrapolation factor in the W + jets estimate is due to the uncertainties on the differences in the compositions of the jets in the multijet and W + jets sample and is 29% (36%) for muons (electrons).

G. Summary

This section described the control regions used to estimate, from data, the main backgrounds to the various categories in the analysis. An overview of the observed and expected event yields in these control regions is provided in Table XIX for the 8 TeV data. This shows the breakdown of each control region into its targeted physics process (in bold) and its purity, together with the other contributing physics processes. The WW CR in the $n_j = 1$ category is relatively low in WW purity but the normalization for the large contamination by N_{top} is determined by the relatively pure CR for top quarks.

The normalization factors β derived from these control regions are summarized in Table XX, for both the 7 and 8 TeV data samples. Only the statistical uncertainties are

quoted and in most of the cases the normalization factors agree with unity within the statistical uncertainties. In two cases where a large disagreement is observed, the systematic uncertainties on β are evaluated. One of them is the WW background in the $n_j = 0$ category, where adding the systematic uncertainties reduces the disagreement to about 2 standard deviations: $\beta = 1.22 \pm 0.03(\text{stat}) \pm 0.10(\text{syst})$. The systematic component includes the experimental uncertainties and additionally the theoretical uncertainties on the cross section and acceptance, and the uncertainty on the luminosity determination. Including the systematic uncertainties on the normalization factor for the top-quark background in the first bin in the $n_j \geq 2$ VBF-enriched category reduces the significance of the deviation of the normalization factor with unity: $\beta = 1.58 \pm 0.15(\text{stat}) \pm 0.55(\text{syst})$. In this case, the uncertainty on MC generator modeling is also included. The systematic uncertainties quoted here do not have an impact on the analysis since the background estimation in the signal region is based on the extrapolation factors and their associated uncertainties, as quoted in the previous subsections. In addition, the sample statistics of the control region, the MC sample statistics, and the uncertainties on the background subtraction all affect the estimation of the backgrounds normalized to data.

TABLE XIX. Control region event yields for 8 TeV data. All of the background processes are normalized with the corresponding β given in Table XX or with the data-derived methods as described in the text; each row shows the composition of one CR. The N_{sig} column includes the contributions from all signal production processes. For the VBF-enriched $n_j \geq 2$, the values for the bins in O_{BDT} are given. The entries that correspond to the target process for the CR are given in bold; this quantity corresponds to N_{bold} considered in the last column for the purity of the sample (in %). The uncertainties on N_{bkg} are due to sample size.

Control regions	Summary			Composition of N_{bkg}						Purity	
	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{top}	N_{misid}	N_{VV}	N_{DY}		$N_{\text{bold}}/N_{\text{bkg}}$ (%)	
$n_j = 0$											
CR for WW	2713	2680 ± 9	28	1950	335	184	97	8.7	106	73	
CR for top quarks	76013	75730 ± 50	618	8120	56210	2730	1330	138	7200	74	
CR for VV	533	531 ± 8	2.2	2.5	1.1	180	327	19	2.7	62	
CR for $Z/\gamma^* \rightarrow \tau\tau$	4557	4530 ± 30	23	117	16.5	239	33	28	4100	91	
$n_j = 1$											
CR for WW	2647	2640 ± 12	4.3	1148	1114	165	127	17	81	43	
CR for top quarks	6722	6680 ± 12	17	244	6070	102	50	6	204	91	
CR for VV	194	192 ± 4	1.9	1	3.1	65	117	4.7	0.8	61	
CR for $Z/\gamma^* \rightarrow \tau\tau$	1540	1520 ± 14	18	100	75	84	27	7	1220	80	
$n_j \geq 2$ ggF											
CR for top quarks	2664	2660 ± 10	4.9	561	1821	129	101	10	44	68	
CR for $Z/\gamma^* \rightarrow \tau\tau$	266	263 ± 6	2.6	13	34	18	4.1	0.1	194	74	
$n_j \geq 2$ VBF											
CR for top quarks, bin 1	143	142 ± 2	2.1	1.9	130	2.1	0.8	6.3	1.1	92	
CR for top quarks, bin 2–3	14	14.3 ± 0.5	1.8	0.6	11.6	0.2	0.2	0.9	0.2	81	
CR for $Z/\gamma^* \rightarrow \tau\tau$	24	20.7 ± 0.9	2.4	0.9	1.2	0.6	0.2	0.8	17	82	

TABLE XX. Control region normalization factors β . The β values scale the corresponding estimated yields in the signal region; those that use MC-based normalization are marked with a dash. For the VBF-enriched $n_j \geq 2$ category, the values in bins of O_{BDT} are given for top quarks; a combined value is given for $Z/\gamma^* \rightarrow \tau\tau$. The uncertainties are due to the sample size of the corresponding control regions.

Category	WW	Top quarks	VV	$Z/\gamma^* \rightarrow \tau\tau$
8 TeV sample				
$n_j = 0$	1.22 ± 0.03	1.08 ± 0.02	0.92 ± 0.07	1.00 ± 0.02
$n_j = 1$	1.05 ± 0.05	1.06 ± 0.03	0.96 ± 0.12	1.05 ± 0.04
$n_j \geq 2$, ggF	-	1.05 ± 0.03	-	1.00 ± 0.09
$n_j \geq 2$, VBF bin 1	-	1.58 ± 0.15	-	0.90 ± 0.30
$n_j \geq 2$, VBF bins 2–3	-	0.95 ± 0.31	-	
7 TeV sample				
$n_j = 0$	1.09 ± 0.08	1.12 ± 0.06	-	0.89 ± 0.04
$n_j = 1$	0.98 ± 0.12	0.99 ± 0.04	-	1.10 ± 0.09
$n_j \geq 2$, VBF bins 1–3	-	0.82 ± 0.29	-	1.52 ± 0.91

VII. FIT PROCEDURE AND UNCERTAINTIES

The signal yields and cross sections are obtained from a statistical analysis of the data samples described in Sec. IV. A likelihood function—defined to simultaneously model, or “fit” the yields of the various subsamples—is maximized.

The signal strength parameter μ , defined in Sec. I, is the ratio of the measured signal yield to the expected SM value. Its expected value (μ_{exp}) is unity by definition. A measurement of zero corresponds to no signal in the data. The observed value μ_{obs} , reported in Sec. IX, is one of the central results of this paper.

In this section, the fit regions are described in Sec. VII A followed by the details of the likelihood function and the test statistic in Sec. VII B. Section VII C summarizes the various sources of uncertainty that affect the results. A check of the results is given in Sec. VII D.

A. Fit regions

The fit is performed over data samples defined by fit regions listed in Table XXI, which consist of

- (i) signal region categories [Table XXI(a)] and
- (ii) profiled control regions [rows in Table XXI(b) marked by solid circles].

The nonprofiled control regions [rows in Table XXI(b) marked by open circles] do not have explicit terms in the likelihood, but are listed in the table for completeness.

The profiled CRs determine the normalization of the corresponding backgrounds through a Poisson term in the likelihood, which, apart from the Drell-Yan $\tau\tau$ CR, use the $e\mu$ sample. The nonprofiled CRs do not have a Poisson term and enter the fit in other ways. The details are described in the next section.

The SR categories i and fit distribution bins b that contribute to the likelihood were briefly motivated in Sec. II.

The $e\mu$ samples in the $n_j \leq 1$, the most signal sensitive of all channels, are each divided into 12 kinematic regions

($12 = 2 \cdot 3 \cdot 2$): two regions in $m_{\ell\ell}$, three regions in $p_T^{\ell^2}$, and two regions for the subleading lepton flavors. In contrast, the less sensitive $ee/\mu\mu$ samples for the $n_j \leq 1$ categories use one range of $m_{\ell\ell}$ and $p_T^{\ell^2}$.

The m_T distribution is used to fit all of the ggF-enriched categories. Its distribution for the signal process has an upper kinematic edge at m_H , but, in practice, m_T can exceed m_H because of detector resolution. There is also a kinematic suppression below a value of m_T that increases with increasing values of $m_{\ell\ell}$ and $p_T^{\ell^2}$ due to the kinematic requirements in each of the $n_j \leq 1$ categories.

The m_T distribution for the $n_j = 0$ category in the $e\mu(ee/\mu\mu)$ samples uses a variable binning scheme that is optimized for each of the 12 (one) kinematic regions. In the kinematically favored range of the $e\mu$ and $ee/\mu\mu$ samples, there are 8 bins that are approximately 6 GeV wide between a range of x to y , where x is approximately 80 GeV and y is approximately 130 GeV. A single bin at low m_T , from 0 to x , has a few events in each category; another bin at high m_T —from y to ∞ —is populated dominantly by WW and top-quark events, constraining these backgrounds in the fit.

The m_T distribution for the $n_j = 1$ category follows the above scheme with six bins. The bins are approximately 10 GeV wide in the same range as for $n_j = 0$.

The m_T distribution of the $e\mu$ events in the ggF-enriched $n_j \geq 2$ uses four bins specified by the bin boundaries $[0, 50, 80, 130, \infty]$ GeV.

The O_{BDT} distribution is used to fit the VBF-enriched $n_j \geq 2$ samples. The signal purity increases with increasing value of O_{BDT} , so the bin widths decrease accordingly. The bin boundaries are $[-1, -0.48, 0.3, 0.78, 1]$ and define four bins that are labeled 0 through 3. Only bins 1, 2, and 3 are used in the fit. The selection-based cross-check analysis uses two bins in m_{jj} $[[600, 1000, \infty]$ GeV) and four bins in the m_T distribution as defined above for the ggF-enriched $n_j \geq 2$.

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TABLE XXI. Fit region definitions for the Poisson terms in the likelihood, Eq. (11), not including the terms used for MC statistics. The signal region categories i are given in (a). The definitions for bins b are given by listing the bin edges, except for m_T and O_{BDT} , and are given in the text and noted as the fit variables on the right-most column. The background control regions are given in (b), which correspond to the ones indicated as using data in Table XI. The profiled CRs are marked by $\bullet$ and the others are marked by $\circ$. “Sample” notes the lepton flavor composition of the CR that is used for all the SR regions for a given n_j category: “ $e\mu$ ” means that a $e\mu$ CR sample is used for all SR regions; the Wj and jj CRs use the same lepton-flavor samples in the SR (same), i.e., “ $e\mu$ ” CR for “ $e\mu$ ” SR and “ $ee/\mu\mu$ ” CR for “ $ee/\mu\mu$ ” SR; the DY, $ee/\mu\mu$ sample is used only for the $ee/\mu\mu$ SR; the two rows in $n_j \geq 2$ VBF use a CR that combines the two samples (both); see text for details. Energy-related quantities are in GeV.

SR category i				
n_j , flavor	$\otimes m_{\ell\ell}$	$\otimes p_{\text{T}}^{\ell^2}$	$\otimes \ell_2$	Fit variable
(a) Signal region categories				
$n_j = 0$				
$e\mu$	$\otimes [10, 30, 55]$	$\otimes [10, 15, 20, \infty]$	$\otimes [e, \mu]$	m_{T}
$ee/\mu\mu$	$\otimes [12, 55]$	$\otimes [10, \infty]$		m_{T}
$n_j = 1$				
$e\mu$	$\otimes [10, 30, 55]$	$\otimes [10, 15, 20, \infty]$	$\otimes [e, \mu]$	m_{T}
$ee/\mu\mu$	$\otimes [12, 55]$	$\otimes [10, \infty]$		m_{T}
$n_j \geq 2$ ggF				
$e\mu$	$\otimes [10, 55]$	$\otimes [10, \infty]$		m_{T}
$n_j \geq 2$ VBF				
$e\mu$	$\otimes [10, 50]$	$\otimes [10, \infty]$		O_{BDT}
$ee/\mu\mu$	$\otimes [12, 50]$	$\otimes [10, \infty]$		O_{BDT}
CR	Profiled?	Sample	Notable differences vs. SR	
(b) Control regions that are profiled ($\bullet$) and nonprofiled ($\circ$)				
$n_j = 0$				
WW	$\bullet$	$e\mu$	$55 < m_{\ell\ell} < 110, \Delta\phi_{\ell\ell} < 2.6, p_{\text{T}}^{\ell^2} > 15$	
Top	$\circ$	$e\mu$	$n_j = 0$ after presel., $\Delta\phi_{\ell\ell} < 2.8$	
Wj	$\circ$	same	one anti-identified ℓ	
jj	$\circ$	same	two anti-identified ℓ	
VV	$\bullet$	$e\mu$	same-charge ℓ (only used in $e\mu$)	
DY, $ee/\mu\mu$	$\bullet$	$ee/\mu\mu$	$f_{\text{recoil}} > 0.1$ (only used in $ee/\mu\mu$)	
DY, $\tau\tau$	$\bullet$	$e\mu$	$m_{\ell\ell} < 80, \Delta\phi_{\ell\ell} > 2.8$	
$n_j = 1$				
WW	$\bullet$	$e\mu$	$m_{\ell\ell} > 80, m_{\tau\tau} - m_Z > 25, p_{\text{T}}^{\ell^2} > 15$	
Top	$\bullet$	$e\mu$	$n_b = 1$	
Wj	$\circ$	same	one anti-identified ℓ	
jj	$\circ$	same	two anti-identified ℓ	
VV	$\bullet$	$e\mu$	same-charge ℓ (only used in $e\mu$)	
DY, $ee/\mu\mu$	$\bullet$	$ee/\mu\mu$	$f_{\text{recoil}} > 0.1$ (only used in $ee/\mu\mu$)	
DY, $\tau\tau$	$\bullet$	$e\mu$	$m_{\ell\ell} < 80, m_{\tau\tau} > m_Z - 25$	
$n_j \geq 2$ ggF				
Top	$\bullet$	$e\mu$	$m_{\ell\ell} > 80$	
Wj	$\circ$	same	one anti-identified ℓ	
jj	$\circ$	same	two anti-identified ℓ	
DY, $\tau\tau$	$\bullet$	$e\mu$	$m_{\ell\ell} < 70, \Delta\phi_{\ell\ell} > 2.8$	
$n_j \geq 2$ VBF				
Top	$\bullet$	both	$n_b = 1$	
Wj	$\circ$	same	one anti-identified ℓ	
jj	$\circ$	same	two anti-identified ℓ	
DY, $ee/\mu\mu$	$\circ$	$ee/\mu\mu$	$E_{\text{T}}^{\text{miss}} < 45$ (only used in $ee/\mu\mu$)	
DY, $\tau\tau$	$\circ$	both	$m_{\ell\ell} < 80, m_{\tau\tau} - m_Z < 25$	

In general, the bin boundaries are chosen to maximize the expected signal significance while stabilizing the statistical fluctuations associated with the subtraction of the backgrounds. For the m_T fits, this is accomplished by maintaining an approximately constant signal yield in each of the bins. The exact values of the m_T bins are given in Appendix A 1 in Table XXIX.

The interplay of the various fit regions is illustrated for one kinematic region of the $n_j = 0$ in Fig. 28. The shape of the m_T distribution is used in the fit to discriminate between the signal and the background as shown in the top row for the SR. Three profiled CRs determine the

normalization factors (β_k) of the respective background contributions *in situ*. The variable and selections used to separate the SR from the CRs regions are given in the second row: for WW the $m_{\ell\ell}$ variable divides the SR and CR, but also the validation region (VR) used to test the WW extrapolation (see Sec. VI A); for DY the $\Delta\phi_{\ell\ell}$ variable divides the SR and CR with a region separating the two; for VV the discrete same/opposite charge variable is used. The last row shows the backgrounds whose normalizations are not profiled in the fit, but are computed prior to the fit.

The treatment of a given region as profiled or non-profiled CR depends from the complexity related to its

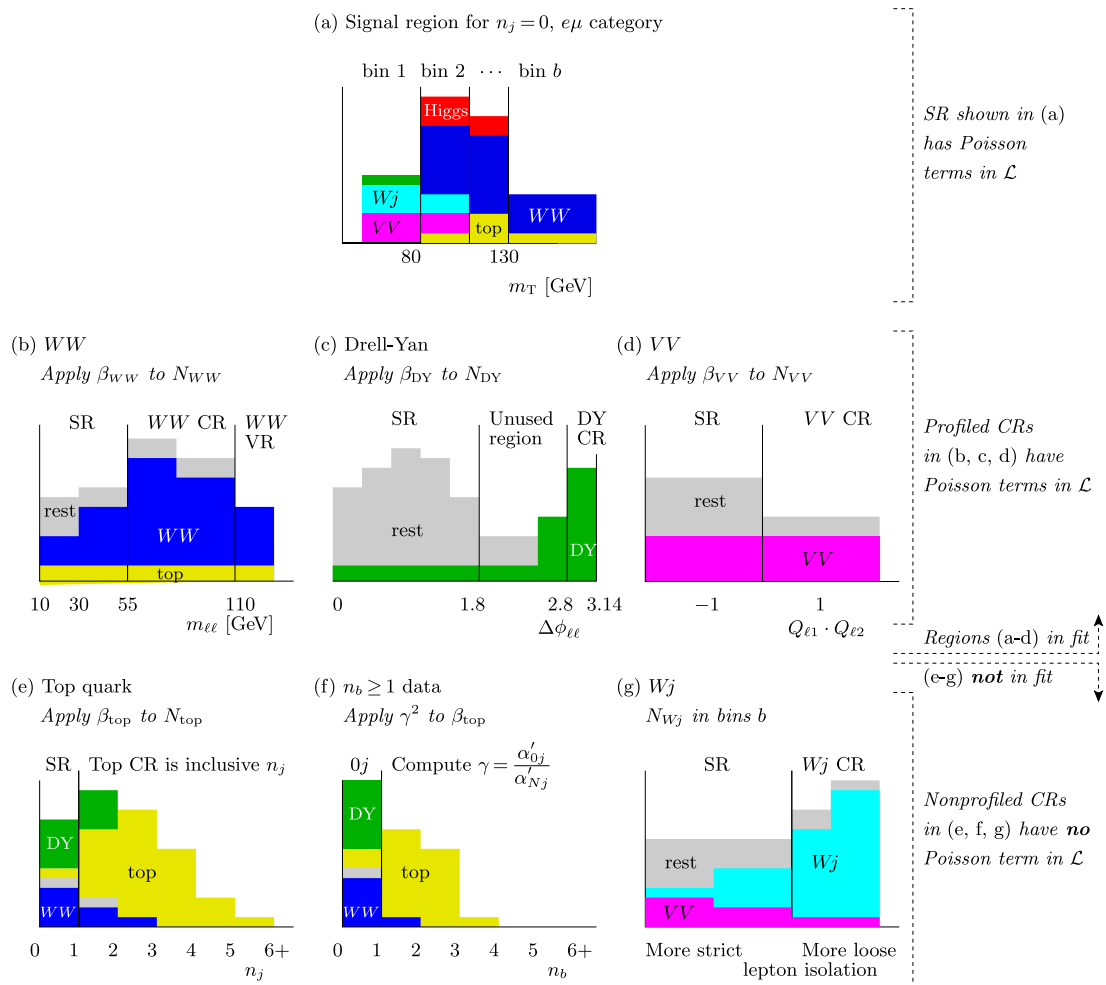


FIG. 28 (color online). Simplified illustration of the fit regions for $n_j = 0$, $e\mu$ category. The figure in (a) is the variable-binned m_T distribution in the signal region for a particular range of $m_{\ell\ell}$ and $p_T^{\ell\ell}$ specified in Table XXI; the m_T bins are labeled $b = 1, 2, \dots$; the histograms are stacked for the five principal background processes— WW , top, Misid (mostly Wj), VV , DY (unlabeled)—and the Higgs signal process. The figures in (b, c, d) represent the distributions that define the various profiled control regions used in the fit with a corresponding Poisson term in the likelihood $\mathcal{L}$. Those in (e, f, g) represent the nonprofiled control regions that do not have a Poisson term in $\mathcal{L}$, but determine parameters that modify the background yield predictions. A validation region (VR) is also defined in (b); see text.

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implementation in the fit, the impact of the estimated background in the analysis, and the level of contamination of the other process in the relative CR. Subdominant backgrounds and those whose estimation is not largely affected by the postfit yield of the other backgrounds, like Wj and multijet backgrounds, are not profiled.

B. Likelihood, exclusion, and significance

The statistical analysis involves the use of the likelihood $\mathcal{L}(\mu, \theta | N)$, which is a function of the signal strength parameter μ and a set of nuisance parameters $\theta = \{\theta_a, \theta_b, \dots\}$ given a set of the numbers of events $N = \{N_A, N_B, \dots\}$. Allowed ranges of μ are found using the distribution of a test statistic q_μ .

1. Likelihood function

The likelihood function $\mathcal{L}$ [Eq. (11) below] is the product of four groups of probability distribution functions:

- (i) Poisson function $f(N_{ib} | \dots)$ used to model the event yield in each bin b of the variable fit to extract the signal yield for each category i ;
- (ii) Poisson function $f(N_l | \sum_k \beta_k B_{kl})$ used to model the event yield in each control region l with the total background yield summed over processes k (B_{kl});
- (iii) Gaussian functions $g(\theta_t | \theta_t)$ used to model the systematic uncertainties t ; and
- (iv) Poisson functions $f(\xi_k | \dots)$ used to account for the MC statistics k .

$$\mathcal{L} = \underbrace{\prod_{i,b}^{\text{Table XXIIa}} f\left(N_{ib} \middle| \mu \cdot S_{ib} \prod_r^{\text{Syst in Sec. V}} v_{br}(\theta_r) + \sum_k \beta_k \cdot B_{kib} \prod_s^{\text{Syst in Sec. VII C}} v_{bs}(\theta_s)\right)}_{\text{Poisson for SR with signal strength } \mu; \text{ predictions } S, B} \underbrace{\prod_l^{\text{Table XXIIb}} f\left(N_l \middle| \sum_k \beta_k \cdot B_{kl}\right)}_{\text{Poisson for profiled CRs}} \underbrace{\prod_t^{\text{Syst in } \{r,s\}} g(\theta_t | \theta_t)}_{\text{Gauss. for syst}} \underbrace{\prod_k^{\text{Table I}} f(\xi_k | \xi_k \cdot \theta_k)}_{\text{Poiss. for MC stats}}. \quad (11)$$

The statistical uncertainties are considered explicitly in the first, second, and fourth terms. The first and second terms treat the random error associated with the predicted value, i.e., for a background yield estimate B the $\sqrt{B}$ error associated with it. The fourth term treats the sampling error associated with the finite sample size used for the prediction, e.g., the $\sqrt{N_{\text{MC}}}$ “MC statistical errors” when MC is used. All of the terms are described below and summarized in Eq. (11).

The first term of $\mathcal{L}$ is a Poisson function f for the probability of observing N events given λ expected events, $f(N | \lambda) = e^{-\lambda} \lambda^N / N!$. The expected value λ is the sum of event yields from signal (S) and the sum of the background contributions ($\sum_k B_k$) in a given signal region, i.e., $\lambda = \mu \cdot S + \sum_k B_k$. The parameter of interest, μ , multiplies S ; each background yield in the sum is evaluated as described in Sec. VI. In our notation, the yields are scaled by the response functions ν that parametrize the impact of the systematic uncertainties θ . The ν and θ are described in more detail below when discussing the third term of $\mathcal{L}$.

The second term constrains the background yields with Poisson components that describe the profiled control regions. Each term is of the form $f(N_l | \lambda_l)$ for a given CR labeled by l , where N_l is the number of observed events in l , i.e., $\lambda_l = \sum_k \beta_k \cdot B_{kl}$ is the predicted yield in l , β_k is the normalization factor of background k , and B_{kl} is the MC or data-derived estimate of background k in l . The β_k parameters are the same as those that appear in the first Poisson component above.

The third term constrains the systematic uncertainties with Gaussian terms. Each term is of the form $g(\theta | \theta) = e^{-(\theta - \theta)^2 / 2} / \sqrt{2\pi}$, where θ represents the central value of the measurement and θ the associated nuisance parameter for a given systematic uncertainty. The effect of the systematic uncertainty on the yields is through an exponential response function $\nu(\theta) = (1 + \epsilon)^\theta$ for normalization uncertainties that have no variations among bins b of the fit variable, where ϵ is the value of the uncertainty in question. In this case, ν follows a log-normal distribution [96]. In this notation, $\epsilon = 3\%$ is written if the uncertainty that corresponds to one standard deviation affects the associated yield by $\pm 3\%$ and corresponds to $\theta = \pm 1$, respectively.

For the cases where the systematic uncertainty affects a given distribution differently in each bin b , a different linear response function is used in each bin; this function is written as $\nu_b(\theta) = 1 + \epsilon_b \cdot \theta$. In this case, ν_b is normally distributed around unity with width ϵ_b , and is truncated by the $\nu_b > 0$ restriction to avoid unphysical values. Both types of response function impact the predicted S and B_k in the first Poisson component.

The fourth term treats the sample error due to the finite sample size [97], e.g., the sum of the number of generated MC events for all background processes, $B = \sum_k B_k$. The quantity B is constrained with a Poisson term $f(\xi | \lambda)$, where ξ represents the central value of the background estimate and $\lambda = \zeta \cdot \theta$. The $\zeta = (B/\delta)^2$ defines the quantity with the statistical uncertainty of B as δ . For instance, if a

background yield estimate B uses N_{MC} MC events that correspond to a data sample with effective luminosity L_{MC} , then for a data-to-MC luminosity ratio $r = L_{\text{data}}/L_{\text{MC}}$ the background estimate is $B = r \cdot N_{\text{MC}}$, and the uncertainty (parameter) in question is $\delta = r \cdot \sqrt{N_{\text{MC}}}$ ($\zeta = N_{\text{MC}}$). In this example, the Poisson function is evaluated at N_{MC} given $\lambda = \theta \cdot N_{\text{MC}}$. Similar to the case for the third term, a linear response function $\nu(\theta) = \theta$ impacts the predicted S and B_k in the first Poisson component.

In summary, the likelihood is the product of the four above-mentioned terms and can be written schematically as done in Eq. (11), where the ν_{br} and ν_{bs} are implicitly products over all three types of response functions—normalization, shape of the distribution, and finite MC sample size—whose parameters are constrained by the second, third, and fourth terms, respectively. In the case of finite MC sample size, θ is unique to each bin, which is not shown in Eq. (11). The statistical treatments of two quantities—the $Z/\gamma^* \rightarrow ee$, $\mu\mu$ estimate in $n_j \leq 1$ and the top-quark estimate in $n_j = 1$ —are constrained with additional multiplicative terms in the likelihood (see Appendix A).

To determine the observed value of the signal strength, μ_{obs} , the likelihood is maximized with respect to its arguments, μ and θ , and evaluated at $\vartheta = 0$ and $\xi = \zeta$.

2. Test statistic

The profiled likelihood-ratio test statistic [98] is used to test the background-only or background-and-signal hypotheses. It is defined as

$$q(\mu) = -2 \ln \frac{\mathcal{L}(\mu, \theta)}{\mathcal{L}_{\text{max}}} \Big|_{\theta=\hat{\theta}_\mu}, \quad (12)$$

and it is also written as q_μ ; the argument of the logarithm is written as Λ in later plots. The denominator of Eq. (12) is unconditionally maximized over all possible values of μ and θ , while the numerator is maximized over θ for a conditional value of μ . The latter takes the values $\hat{\theta}_\mu$, which are θ values that maximize $\mathcal{L}$ for a given value of μ . When the denominator is maximized, μ takes the value of $\hat{\mu}$.

The p_0 value is computed for the test statistic q_0 , Eq. (12), evaluated at $\mu = 0$, and is defined to be the probability to obtain a value of q_0 larger than the observed value under the background-only hypothesis. There are no boundaries on $\hat{\mu}$, although q_0 is defined to be negative if $\hat{\mu} \leq 0$. All p_0 values are computed using the asymptotic approximation that $-2 \ln \Lambda(\mu)$ follows a χ^2 distribution [98].

Local significance is defined as the one-sided tail of a Gaussian distribution, $Z_0 = \sqrt{2} \text{erf}^{-1}(1 - 2p_0)$.

A modified frequentist method known as CL_S [99] is used to compute the one-sided 95% confidence level (C.L.) exclusion regions.

3. Combined fit

The combined results for the 7 and 8 TeV data samples account for the correlations between the analyses due to common systematic uncertainties.

The correlation of all respective nuisance parameters is assumed to be 100% except for those that are statistical in origin or have a different source for the two data sets. Uncorrelated systematics include the statistical component of the jet energy scale calibration and the luminosity uncertainty. All theoretical uncertainties are treated as correlated.

C. Systematic uncertainties

Uncertainties enter the fit as nuisance parameters in the likelihood function [Eq. (11)]. Uncertainties (both theoretical and experimental) specific to individual processes are described in Secs. V and VI; experimental uncertainties common to signal and background processes are described in this subsection. The impact on the yields and distributions from both sources of uncertainty is also discussed.

1. Sources of uncertainty

The dominant sources of experimental uncertainty on the signal and background yields are the jet energy scale and resolution, and the b -tagging efficiency. Other sources of uncertainty are the lepton resolutions and identification and trigger efficiencies, missing transverse momentum measurement, and the luminosity calculation. The uncertainty on the integrated luminosity in the 8 TeV data analysis is 2.8%. It is derived following the same methodology as in Ref. [100], from a preliminary calibration of the luminosity scale derived from beam-separation scans. The corresponding uncertainty in the 7 TeV data analysis is 1.8%.

The jet energy scale is determined from a combination of test beam, simulation, and *in situ* measurements [27]. Its uncertainty is split into several independent categories: modeling and statistical uncertainties on the extrapolation of the jet calibration from the central region (η intercalibration), high- p_T jet behavior, MC nonclosure uncertainties, uncertainties on the calorimeter response and calibration of the jets originating from light quarks or gluons, the b -jet energy scale uncertainties, uncertainties due to modeling of in-time and out-of-time pile-up, and uncertainties on *in situ* jet energy corrections. All of these categories are further subdivided by the physical source of the uncertainty. For jets used in this analysis ($p_T > 25$ GeV and $|\eta| \leq 4.5$), the jet energy scale uncertainty ranges from 1% to 7%, depending on p_T and η . The jet energy resolution varies from 5% to 20% as a function of the jet p_T and η . The relative uncertainty on the resolution, as determined from *in situ* measurements, ranges from 2% to 40%, with the largest value of the resolution and relative uncertainty occurring at the p_T threshold of the jet selection.

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The method used to evaluate the b -jet tagging efficiency uses a sample dominated by dileptonic decays of top-quark pairs. This method is based on a likelihood fit to the data, which combines the per-event jet-flavor information and the expected momentum correlation between the jets to allow the b -jet tagging efficiency to be measured to high precision [30]. To further improve the precision, this method is combined with a second calibration method, which is based on samples containing muons reconstructed in the vicinity of the jet. The uncertainties related to b -jet identification are decomposed into six uncorrelated components using an eigenvector method [32]. The number of components is equal to the numbers of p_T bins used in the calibration, and the uncertainties range from $< 1\%$ to 7.8% . The uncertainties on the misidentification rate for light-quark jets depend on p_T and η , and have a range of 9% – 19% . The uncertainties on c -jets reconstructed as b -jets range between 6% and 14% depending on p_T only.

The reconstruction, identification, isolation, and trigger efficiencies for electrons and muons, as well as their momentum scales and resolutions, are estimated using $Z \rightarrow ee/\mu\mu$, $J/\psi \rightarrow ee/\mu\mu$, and $W \rightarrow e\nu/\mu\nu$ decays [20,23]. The uncertainties on the lepton and trigger efficiencies are smaller than 1% except for the uncertainty on the electron identification efficiency, which varies between 0.2% and 2.7% depending on p_T and η , and the uncertainties on the isolation efficiencies, which are the largest for $p_T < 15$ GeV and yield 1.6% and 2.7% for electrons and muons, respectively.

The changes in jet energy and lepton momenta due to varying them by their systematic uncertainties are propagated to E_T^{miss} ; the changes in the high- p_T object momenta and in E_T^{miss} are, therefore, fully correlated [33]. Additional contributions to the E_T^{miss} uncertainty arise from the modeling of low-energy particle measurements (soft terms). In the calorimeter, these particles are measured as calibrated clusters of cells that are above a noise threshold but not associated with reconstructed physics objects. The longitudinal and perpendicular (with respect to the hard component of the missing transverse momentum) components of the soft terms are fit with Gaussian functions in data and MC DY samples in order to assess the associated uncertainties. The uncertainties are parametrized as a function of the magnitude of the summed p_T of the high- p_T objects, and are evaluated in bins of the average number of interactions per bunch crossing. Differences of the mean and width of the soft term components between data and MC result in variations on the mean of the longitudinal component of about 0.2 GeV, while the uncertainty on the resolution of the longitudinal and perpendicular components is 2% on average.

Jet energy and lepton momentum scale uncertainties are also propagated to the p_T^{miss} calculation. The systematic uncertainties related to the track-based soft term are based on the balance between tracks not associated with charged

leptons and jets and the total transverse momentum of the hard objects in the event. These uncertainties are calculated by comparing the properties of p_T^{miss} in $Z \rightarrow ee, \mu\mu$ events in real and simulated data, as a function of the magnitude of the summed p_T of the hard p_T objects in the event. The variations on the mean of the longitudinal component are in the range 0.3 – 1.4 GeV and the uncertainties on the resolution on the longitudinal and perpendicular components are in the range 1.5 – 3.3 GeV, where the lower and upper bounds correspond to the range of the sum of the hard p_T objects below 5 GeV and above 50 GeV, respectively.

2. Impact on yields and distributions

In the likelihood fit, the experimental uncertainties are varied in a correlated way across all backgrounds and all signal and control regions, so that uncertainties on the extrapolation factors α described in Sec. VI are correctly propagated. If the normalization uncertainties are less than 0.1% they are excluded from the fit. If the shape uncertainties (discussed below) are less than 1% in all bins, they are excluded as well. Removing such small uncertainties increases the performance and stability of the fit.

In the fit to the m_T distribution to extract the signal yield, the predicted m_T shape from simulation is used for all of the backgrounds except W + jets and multijets. The impact of experimental uncertainties on the m_T shapes for the individual backgrounds and signal are evaluated, and no significant impact is observed for the majority of the experimental uncertainties. Those experimental uncertainties that do produce statistically significant variations of the shape have no appreciable effect on the final results, because the uncertainty on the m_T shape of the total background is dominated by the uncertainties on the normalizations of the individual backgrounds. The theoretical uncertainties on the WW and $W\gamma^* m_T$ shape are considered in the $n_j \leq 1$ categories, as discussed in Secs. VIA 1 and VID. In the $n_j \geq 2$ ggF-enriched category, only the theoretical uncertainties on the top-quark m_T shape are included (see Sec. VIB 4).

The O_{BDT} output distribution is fit in the $n_j \geq 2$ VBF-enriched category, and as with the m_T distribution its shape is taken from the MC simulation, except for the W + jets and multijet background processes. The theoretical uncertainties on the top-quark O_{BDT} shape are included in the analysis, as described in Sec. VIB 4.

Table XXII(a) shows the relative uncertainties on the combined predicted signal yield, summed over all the lepton-flavor channels, for each n_j category for the 8 TeV analysis. They represent the final postfit uncertainties on the estimated yields. The first two entries show the perturbative uncertainties on the ggF jet-bin acceptances in the exclusive $n_j = 0$ and $n_j = 1$ categories. The following entries are specific to the QCD scale uncertainties on the inclusive $n_j \geq 2$ and $n_j \geq 3$ cross sections, and on the total

TABLE XXII. Sources of systematic uncertainty (in %) on the predicted signal yield (N_{sig}) and the cumulative background yields (N_{bkg}). Entries marked with a dash (-) indicate that the corresponding uncertainties either do not apply or are less than 0.1%. The values are postfit and given for the 8 TeV analysis.

	$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
(a) Uncertainties on N_{sig} (in %)				
ggF H , jet veto for $n_j = 0$, ϵ_0	8.1	14	12	-
ggF H , jet veto for $n_j = 1$, ϵ_1	-	12	15	-
ggF H , $n_j \geq 2$ cross section	-	-	-	6.9
ggF H , $n_j \geq 3$ cross section	-	-	-	3.1
ggF H , total cross section	10	9.1	7.9	2.0
ggF H acceptance model	4.8	4.5	4.2	4.0
VBF H , total cross section	-	0.4	0.8	2.9
VBF H acceptance model	-	0.3	0.6	5.5
$H \rightarrow WW^*$ branching fraction	4.3	4.3	4.3	4.3
Integrated luminosity	2.8	2.8	2.8	2.8
Jet energy scale & resolution	5.1	2.3	7.1	5.4
$p_{\text{T}}^{\text{miss}}$ scale & resolution	0.6	1.4	0.1	1.2
f_{recoil} efficiency	2.5	2.1	-	-
Trigger efficiency	0.8	0.7	-	0.4
Electron id., isolation, reconstruction eff.	1.4	1.6	1.2	1.0
Muon id., isolation, reconstruction eff.	1.1	1.6	0.8	0.9
Pile-up model	1.2	0.8	0.8	1.7
(b) Uncertainties on N_{bkg} (in %)				
WW theoretical model	1.4	1.6	0.7	3.0
Top theoretical model	-	1.2	1.7	3.0
VV theoretical model	-	0.4	1.1	0.5
$Z/\gamma^* \rightarrow \tau\tau$ estimate	0.6	0.3	1.6	1.6
$Z/\gamma^* \rightarrow ee, \mu\mu$ estimate in VBF	-	-	-	4.8
Wj estimate	1.0	0.8	1.6	1.3
jj estimate	0.1	0.1	1.8	0.9
Integrated luminosity	-	-	0.1	0.4
Jet energy scale & resolution	0.4	0.7	0.9	2.7
$p_{\text{T}}^{\text{miss}}$ scale & resolution	0.1	0.3	0.5	1.6
b -tagging efficiency	-	0.2	0.4	2.0
Light- and c -jet mistag	-	0.2	0.4	2.0
f_{recoil} efficiency	0.5	0.5	-	-
Trigger efficiency	0.3	0.3	0.1	-
Electron id., isolation, reconstruction eff.	0.3	0.3	0.2	0.3
Muon id., isolation, reconstruction eff.	0.2	0.2	0.3	0.2
Pile-up model	0.4	0.5	0.2	0.8

cross section and the acceptance. The latter includes the uncertainties due to the PDF variations, UE/PS and generator modeling, as described in Table X. The uncertainties on the VBF production process are also shown but are of less importance. The dominant uncertainties on the signal yields are theoretical. The uncertainties on the f_{recoil} selection efficiency (relevant to the $Z/\gamma^* \rightarrow ee, \mu\mu$ estimate in the $n_j \leq 1$ categories) are applied only in the $ee/\mu\mu$ channels.

Table XXII(b) shows the leading uncertainties on the cumulative background yields for each n_j category. The first three entries are theoretical and apply to the WW , top-quark, and VV processes (see Sec. VI). The remaining uncertainties arise from the modeling of specific backgrounds and from experimental uncertainties.

Table XXIII summarizes the above postfit uncertainties on the total signal and backgrounds yields. The uncertainties shown are divided into three categories: statistical, experimental, and theoretical. The statistical uncertainties are only relevant in the cases where the background estimates rely on the data. For example, the entry under N_{WW} in $n_j = 0$ represents the uncertainty on the sample statistics in the WW control region. The uncertainties on N_{top} in the $n_j \leq 1$ categories also include the uncertainties on the corrections applied to the normalization factors. The uncertainties from the number of events in the control samples used to derive the $W + \text{jets}$ and multijet extrapolation factors are listed under the experimental category, as discussed in Sec. VIC. Uncertainties on the total $W + \text{jets}$ estimate are reduced compared to the values quoted in

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TABLE XXIII. Composition of the postfit uncertainties (in %) on the total signal (N_{sig}), total background (N_{bkg}), and individual background yields in the signal regions. The total uncertainty (Total) is decomposed into three components: statistical (Stat), experimental (Expt), and theoretical (Theo). Entries marked with a dash (-) indicate that the corresponding uncertainties either do not apply or are less than 1%. The values are given for the 8 TeV analysis.

Sample	Total error	Stat. error	Expt. syst. error	Theo. syst. error
$n_j = 0$				
N_{sig}	16	-	6.7	15
N_{bkg}	2.5	1.5	1.2	1.7
N_{WW}	4.2	2.4	2.3	2.6
N_{top}	7.4	2.3	4.2	5.6
N_{misid}	17	-	9.9	14
N_{VV}	9.9	4.8	4.6	7.4
$N_{\tau\tau}$ (DY)	34	1.7	33	7.2
$N_{ee/\mu\mu}$ (DY)	30	14	26	5.5
$n_j = 1$				
N_{sig}	22	-	5.3	22
N_{bkg}	3	1.7	1.4	2.1
N_{WW}	7.7	5.5	2.7	4.6
N_{top}	5	3.4	2.9	2.3
N_{misid}	18	-	11	14
N_{VV}	14	8.9	6.1	8.5
$N_{\tau\tau}$ (DY)	27	3.3	26	6.3
$N_{ee/\mu\mu}$ (DY)	39	27	26	7.4
$n_j \geq 2$ ggF				
N_{sig}	23	-	8.6	22
N_{bkg}	4.2	1.5	2.2	3.2
N_{WW}	20	-	8.7	18
N_{top}	7.9	2.6	3.4	6.7
N_{misid}	29	-	16	24
N_{VV}	32	-	9.6	31
$N_{\tau\tau}$ (DY)	18	8	13	10
$N_{ee/\mu\mu}$ (DY)	15	-	14	4
$n_j \geq 2$ VBF				
N_{sig}	13	-	6.8	12
N_{bkg}	9.2	4.7	6.4	4.5
N_{WW}	32	-	14	28
N_{top}	15	9.6	7.6	8.5
N_{misid}	22	-	12	19
N_{VV}	20	-	12	15
$N_{\tau\tau}$ (DY)	40	25	31	2.9
$N_{ee/\mu\mu}$ (DY)	19	11	15	-

Table XV, because they are largely uncorrelated between lepton p_T bins (statistical uncertainties on the $Z + \text{jets}$ data sample) and between the lepton flavors (systematic uncertainties on the OC correction factor). The uncertainty due to the limited sample of background MC events for all the considered processes is included in the experimental component.

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Background contamination in the control regions causes anti-correlations between different background processes, resulting in an uncertainty on the total background smaller than the sum in quadrature of the individual process uncertainties. This effect is called “cross talk” and is most prominent between the WW and top-quark backgrounds in the $n_j = 1$ category. The uncertainties on the background estimates, as described in Sec. VI, cannot be directly compared to the ones presented in Table XXIII. The latter uncertainties are postfit and are subject to subtle effects, such as the cross talk mentioned above, and also pulls and data constraints (defined below) on the various nuisance parameters.

D. Checks of fit results

The fit simultaneously extracts the signal strength μ and the set of auxiliary parameters θ . This process adjusts the initial prefit estimation of every parameter θ as well as its uncertainty, Δ_θ . The fit model is designed to avoid any significant constraints on the input uncertainties to minimize the assumptions on the correlations between the phase spaces in which they are measured and applied. This is achieved by having mostly single-bin control regions. Of central importance is the prefit and postfit comparison of how the variation of a given systematic source translates to an uncertainty on μ .

The impact of a single nuisance parameter θ is assessed by considering its effect on the signal strength, i.e.,

$$\Delta_{\hat{\mu},\pm} = \hat{\mu}(\hat{\theta} \pm \Delta_\theta) - \hat{\mu}(\hat{\theta}), \quad (13)$$

where $\hat{\mu}$ is the postfit value of the signal strength. In the following, quantities with a hat represent postfit parameter values or their uncertainties.

The values $\hat{\mu}(\hat{\theta} \pm \Delta_\theta)$ are the result of a fit with one θ varied by $\pm \Delta_\theta$ around the postfit value for θ , namely $\hat{\theta}$. All other θ are floating in these fits. In the prefit scenario, the Δ_θ are taken as their prefit values of ± 1 , as θ is constrained by a unit Gaussian. The postfit scenario is similar, but with $\hat{\theta}$ varied by its postfit uncertainty of $\Delta_{\hat{\theta}}$. This uncertainty is found by a scan about the maximum so that the likelihood ratio takes the values $-2 \ln(\mathcal{L}(\hat{\theta} \pm \Delta_{\hat{\theta}})/\mathcal{L}(\hat{\theta})) = 1$. The corresponding impact on $\hat{\mu}$ is $\Delta_{\hat{\mu}}$.

When Δ_θ is less than the prefit value, θ is said to be data constrained. In this case the systematic uncertainty is reduced below its input value given the information from the data. This can result from the additional information that the data part of the likelihood injects. As can be seen from Table XXIV, only a few of the uncertainties are data constrained, and only one of them is data constrained by more than 20%. That is the WW generator modeling that includes the m_T shape uncertainties correlated with the uncertainties on the extrapolation factor α_{WW} . The data constraint in this case comes from the high- m_T tail of the

TABLE XXIV. Impact on the signal strength $\hat{\mu}$ from the prefit and postfit variations of the nuisance parameter uncertainties, Δ_θ . The + (−) column header indicates the positive (negative) variation of Δ_θ and the resulting change in $\hat{\mu}$ is noted in the entry (the sign represents the direction of the change). The right-hand side shows the pull of θ and the data constraint of Δ_θ . The pulls are given in units of standard deviations (σ) and Δ_θ of ± 1 means no data constraint. The rows are ordered by the size of a change in $\hat{\mu}$ due to varying θ by the postfit uncertainty Δ_θ .

Systematic source	Impact on $\hat{\mu}$					Impact on $\hat{\theta}$	
	Prefit $\Delta_{\hat{\mu}}$		Postfit $\Delta_{\hat{\mu}}$		Plot of postfit $\pm\Delta_{\hat{\mu}}$	Pull, $\hat{\theta}$ (σ)	Constraint, Δ_{θ}
	+	−	+	−			
ggF H , PDF variations on cross section	−0.06	+0.06	−0.06	+0.06		−0.06	± 1
ggF H , QCD scale on total cross section	−0.05	+0.06	−0.05	+0.06		−0.05	± 1
WW , generator modeling	−0.07	+0.06	−0.05	+0.05		0	± 0.7
Top quarks, generator modeling on α_{top} in ggF cat.	+0.03	−0.03	+0.03	−0.03		−0.40	± 0.9
Misid of μ , OC uncorrelated corr factor α_{misid} , 2012	−0.03	+0.03	−0.03	+0.03		0.48	± 0.8
Integrated luminosity, 2012	−0.03	+0.03	−0.03	+0.03		0.08	± 1
Misid of e , OC uncorrelated corr factor α_{misid} , 2012	−0.03	+0.03	−0.02	+0.03		−0.06	± 0.9
ggF H , PDF variations on acceptance	−0.02	+0.02	−0.02	+0.02		−0.03	± 1
Jet energy scale, η intercalibration	−0.02	+0.02	−0.02	+0.02		0.45	± 0.95
VBF H , UE/PS	−0.02	+0.02	−0.02	+0.02		0.26	± 1
ggF H , QCD scale on ϵ_1	−0.01	+0.03	−0.01	+0.03		−0.10	± 0.95
Muon isolation efficiency	−0.02	+0.02	−0.02	+0.02		0.13	± 1
VV , QCD scale on acceptance	−0.02	+0.02	−0.02	+0.02		0.09	± 1
ggF H , UE/PS	−	−0.02	−	−0.02		0	± 0.9
ggF H , QCD scale on acceptance	−0.02	+0.02	−0.02	+0.02		0	± 1
Light jets, tagging efficiency	+0.02	−0.02	+0.02	−0.02		0.21	± 1
ggF H , generator modeling on acceptance	+0.01	−0.02	+0.01	−0.02		0.10	± 1
ggF H , QCD scale on $n_j \geq 2$ cross section	−0.01	+0.02	−0.01	+0.02		−0.04	± 1
Top quarks, generator modeling on α_{top} in VBF cat.	−0.01	+0.02	−0.01	+0.02		−0.16	± 1
Electron isolation efficiency	−0.02	+0.02	−0.02	+0.02		−0.14	± 1

−0.1

−0.05

0

0.05

0.1

signal region, which contains a large fraction of WW events.

The postfit values for θ modify the rates of signal and background processes, and the data constraints affect the corresponding uncertainties. The results of these shifts are summarized in Table XXIV for a set of 20 nuisance parameters ordered by the magnitude of Δ_μ (Higgs signal hypothesis is taken at $m_H = 125$ GeV). The highest-ranked nuisance parameter is the uncertainty on the total ggF cross section due to the PDF variations. It changes $\hat{\mu}$ by $-0.06/+0.06$ when varied up and down by Δ_θ , respectively. It is followed by the uncertainty on the total ggF cross section due to QCD scale variations and WW generator modeling uncertainty. Other uncertainties that have a significant impact on $\hat{\mu}$ include the effects of generator modeling on α_{top} , the systematic uncertainties on α_{misid} originating from a correction for oppositely charged electrons and muons, the luminosity determination for 8 TeV data, and various theoretical uncertainties on the ggF and VBF signal production processes. In total there are 253 nuisance parameters which are divided into three main categories: experimental uncertainties (137 parameters), theoretical uncertainties (72 parameters), and normalization uncertainties (44 parameters). They are further divided into more categories as shown in Table XXVI.

VIII. YIELDS AND DISTRIBUTIONS

The previous section described the different parameters of the simultaneous fit to the various signal categories defined in the preceding sections. In particular, the signal and background rates and shapes are allowed to vary in order to fit the data in both the signal and control regions, within their associated uncertainties.

In the figures and tables presented in this section, background processes are individually normalized to their postfit rates, which account for changes in the normalization factors (β) and for pulls of the nuisance parameters (θ). The varying background composition as a function of m_T (or O_{BDT} in the $n_j \geq 2$ VBF-enriched category) induces a shape uncertainty on the total estimated background. As described in Sec. VII C, additional specific shape uncertainties are included in the fit procedure and are accounted for in the results presented in Sec. IX. No specific m_T shape uncertainties are applied to the figures since their contribution to the total systematic uncertainty band was found to be negligible. The Higgs boson signal rate is normalized to the observed signal strength reported in Sec. IX.

This section is organized as follows. The event yields are presented in Sec. VIII A for each signal category including the statistical and systematic uncertainties. The relevant distributions in the various signal regions are shown in

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TABLE XXV. Signal region yields with uncertainties. The tables give the ggF- and VBF-enriched postfit yields for each n_j category, separated for the 8 and 7 TeV data analyses. The N_{signal} columns show the expected signal yields from the ggF and VBF production modes, with values scaled to the observed combined signal strength (see Sec. IX C). For each group separated of rows separated by a vertical gap, the first line gives the combined values for the different subchannels or BDT bins. The yields and the uncertainties take into account the pulls and data constraints of the nuisance parameters, and the correlations between the channels and the background categories. The quoted uncertainties include the theoretical and experimental systematic sources and those due to sample statistics. Values less than 0.1 (0.01) events are written as 0.0 (-).

Channel	Summary				Composition of N_{bkg}						
	N_{obs}	N_{bkg}	N_{ggF}	N_{VBF}	N_{WW}	N_t	$N_{\text{t}\bar{\text{t}}}$	N_{Wj}	N_{jj}	N_{VV}	N_{DY}
(a) 8 TeV data sample											
$n_j = 0$	3750	3430 ± 90	300 ± 500	8 ± 4	2250 ± 95	112 ± 9	195 ± 15	360 ± 60	16 ± 5	420 ± 40	78 ± 21
$e\mu, \ell_2 = \mu$	1430	1280 ± 40	129 ± 20	3.0 ± 2.1	830 ± 34	41 ± 3	73 ± 6	149 ± 29	10.1 ± 3.6	167 ± 21	14 ± 2.4
$e\mu, \ell_2 = e$	1212	1106 ± 35	97 ± 15	2.5 ± 0.6	686 ± 29	33 ± 3	57 ± 5	128 ± 31	3.8 ± 1.5	184 ± 23	14 ± 2.4
$ee/\mu\mu$	1108	1040 ± 40	77 ± 15	2.4 ± 1.7	740 ± 40	39 ± 3	65 ± 5	82 ± 16	2 ± 0.5	68 ± 7	50 ± 21
$n_j = 1$	1596	1470 ± 40	102 ± 26	17 ± 5	630 ± 50	150 ± 10	385 ± 20	108 ± 20	8.2 ± 3.0	143 ± 20	51 ± 13
$e\mu, \ell_2 = \mu$	621	569 ± 19	45 ± 11	7.4 ± 2	241 ± 20	58 ± 4	147 ± 7	51 ± 11	5.7 ± 2.0	53 ± 10	13.8 ± 3.3
$e\mu, \ell_2 = e$	508	475 ± 18	35 ± 9	6.1 ± 1.4	202 ± 17	45 ± 3	119 ± 6	37 ± 9	2.3 ± 0.9	60 ± 10	9.3 ± 2.5
$ee/\mu\mu$	467	427 ± 21	22 ± 6	3.6 ± 1.8	184 ± 15	46 ± 4	119 ± 10	19 ± 4	0.2 ± 0.1	31 ± 4	28 ± 12
$n_j \geq 2, \text{ggF } e\mu$	1017	960 ± 40	37 ± 11	13 ± 1.4	138 ± 28	56 ± 5	480 ± 40	54 ± 25	62 ± 22	56 ± 18	117 ± 21
$n_j \geq 2, \text{VBF}$	130	99 ± 9	7.7 ± 2.6	21 ± 3	11 ± 3.5	5.5 ± 0.7	29 ± 5	4.7 ± 1.4	2.8 ± 1.0	4.4 ± 0.9	38 ± 7
$e\mu$ bin 1	37	36 ± 4	3.3 ± 1.2	4.9 ± 0.5	5.0 ± 1.5	3.0 ± 0.6	15.6 ± 2.6	3.2 ± 1.0	2.3 ± 0.8	2.3 ± 0.7	3.6 ± 1.5
$e\mu$ bin 2	14	6.5 ± 1.3	1.4 ± 0.5	4.9 ± 0.5	1.7 ± 0.7	0.3 ± 0.4	2.0 ± 1.0	0.4 ± 0.1	0.3 ± 0.1	0.7 ± 0.2	0.6 ± 0.2
$e\mu$ bin 3	6	1.2 ± 0.3	0.4 ± 0.3	3.8 ± 0.7	0.3 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	-	-	0.1 ± 0.0	0.2 ± 0.1
$ee/\mu\mu$ bin 1	53	46 ± 6	1.7 ± 0.6	2.6 ± 0.3	3.1 ± 1.0	1.7 ± 0.3	10.1 ± 1.6	0.9 ± 0.2	0.2 ± 0.1	1.0 ± 0.3	28 ± 5
$ee/\mu\mu$ bin 2	14	8.4 ± 1.8	0.7 ± 0.3	3.0 ± 0.4	0.9 ± 0.3	0.3 ± 0.2	1.2 ± 0.5	0.2 ± 0.1	-	0.3 ± 0.1	5.2 ± 1.7
$ee/\mu\mu$ bin 3	6	1.1 ± 0.4	0.2 ± 0.2	2.1 ± 0.4	0.1 ± 0.1	0.1 ± 0.0	0.2 ± 0.1	-	-	-	0.5 ± 0.3
(b) 7 TeV data sample											
$n_j = 0$	594	575 ± 24	49 ± 8	1.4 ± 0.2	339 ± 24	20.5 ± 2.1	38 ± 4	74 ± 15	1.3 ± 0.6	79 ± 10	23 ± 6
$e\mu, \ell_2 = \mu$	185	186 ± 8	19 ± 3	0.5 ± 0.0	116 ± 8	7 ± 1	14 ± 2	19 ± 5	-	24 ± 3	4.8 ± 1
$e\mu, \ell_2 = e$	195	193 ± 12	15 ± 2.4	0.5 ± 0.0	95 ± 7	5.3 ± 0.5	10 ± 1	37 ± 9	1.1 ± 0.5	41 ± 6	4.1 ± 0.9
$ee/\mu\mu$	214	196 ± 11	16 ± 3.1	0.5 ± 0.1	128 ± 10	8 ± 1	14 ± 2	18 ± 4	0.2 ± 0.1	14 ± 2	14 ± 5
$n_j = 1$	304	276 ± 15	16 ± 4	3.2 ± 0.3	103 ± 15	22 ± 2	58 ± 6	20 ± 4	3.2 ± 1.6	32 ± 8	38 ± 6
$e\mu, \ell_2 = \mu$	93	75 ± 4	5.7 ± 1.6	1.2 ± 0.1	33 ± 5	7 ± 1	18 ± 2	5 ± 1	-	9 ± 2	2.7 ± 0.4
$e\mu, \ell_2 = e$	91	76 ± 5	4.5 ± 1.2	0.9 ± 0.1	28 ± 4	6 ± 1	16 ± 2	10 ± 2	0.7 ± 0.3	14 ± 4	2.3 ± 0.7
$ee/\mu\mu$	120	125 ± 9	5.3 ± 1.6	1.2 ± 0.2	43 ± 6	9 ± 1	24 ± 3	5 ± 1	2.5 ± 1.4	9 ± 2	33 ± 6
$n_j \geq 2, \text{VBF}$	9	7.8 ± 1.8	0.9 ± 0.3	2.7 ± 0.3	1.2 ± 0.4	0.3 ± 0.1	1.6 ± 0.8	0.4 ± 0.1	0.1 ± 0.0	0.5 ± 0.2	3.4 ± 1.5
$e\mu$ bin 1	6	3.0 ± 0.9	0.4 ± 0.2	0.6 ± 0.1	0.5 ± 0.2	0.2 ± 0.1	0.9 ± 0.5	0.1 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.8 ± 0.6
$e\mu$ bins 2-3	0	0.7 ± 0.2	0.2 ± 0.1	1.1 ± 0.1	0.2 ± 0.1	-	0.3 ± 0.2	-	-	-	-
$ee/\mu\mu$ bins 1-3	3	4.1 ± 1.3	0.3 ± 0.1	1.0 ± 0.1	0.5 ± 0.2	0.1 ± 0.0	0.4 ± 0.3	0.3 ± 0.1	-	0.2 ± 0.1	2.5 ± 1.1

Sec. VIII B. Section VIII C summarizes the differences in the event and object selection, the signal treatment and the background estimates with respect to the previously published analysis [5].

A. Event yields

Table XXV shows the postfit yields for all of the fitted categories in the 8 TeV [Table XXV(a)] and 7 TeV [Table XXV(b)] data analyses. The signal yields are scaled

with the observed signal strength derived from the simultaneous combined fit to all of the categories. All of the background processes are normalized to the postfit β values (where applicable) and additionally their rates take into account the pulls of the nuisance parameters. The observed and expected yields are shown, for each n_j category, separately for the $e\mu$ and $ee/\mu\mu$ channels. The sum of the expected and observed yields is also reported. The uncertainties include both the statistical and systematic components.

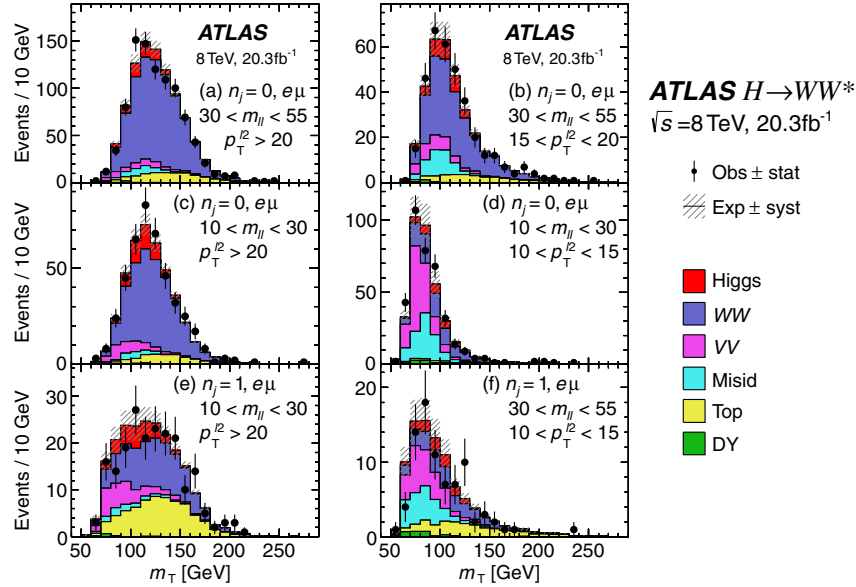


FIG. 29 (color online). Postfit transverse mass distributions in the $e\mu$ $n_j \leq 1$ categories in the 8 TeV data analysis, for specific $m_{\ell\ell}$ and $p_T^{\ell\ell}$ ranges. The plots are made after applying all the selection requirements (see Tables V and VI). The signal processes are scaled with the observed signal strength μ from the fit to all the regions and the background normalizations include the postfit β values and effects from the pulls of the nuisance parameters. See Fig. 5 for plotting details.

As described in the previous section, the changes in the normalization factors and the pulls of the nuisance parameters can affect the expected rates of the signal and background processes. The differences between the prefit (tables in Sec. IV) and postfit (Table XXV) expected rates for each background process are compared to the total uncertainty on that expected background, yielding a significance of the change. In the analysis of the $n_j \leq 1$ category of the 8 TeV data, most of the changes are well below one standard deviation. In the $e\mu$ $n_j = 0$ sample, the expected multijet background is increased by 1.3 standard deviations (equivalent to a 30% increase in the expected multijet background prediction which corresponds to 2% of the signal prediction) due to the positive pulls of the three nuisance parameters assigned to the uncertainties on the extrapolation factor. A negative pull of the nuisance parameter associated with the uncertainties on the DY f_{recoil} selection efficiency changes the $Z/\gamma^* \rightarrow ee, \mu\mu$ yield in the $ee/\mu\mu$ $n_j = 0$ sample by 1.6 standard deviations (equivalent to a 40% decrease in DY in this category which corresponds to 25% of the signal prediction).

B. Distributions

The transverse mass formed from the dilepton and missing transverse momenta (m_T) is used as the final discriminant in the extraction of the signal strength in the $n_j \leq 1$ and $n_j \geq 2$ ggF-enriched categories. The

likelihood fit exploits the differences in m_T shapes between the signal and background processes.

Several of the m_T distributions for the $e\mu$ sample (corresponding to different choices of the $m_{\ell\ell}$ and $p_T^{\ell\ell}$ bins) in the $n_j \leq 1$ categories are shown in Fig. 29. The background composition, signal contribution, and the separation in the m_T distributions between signal and background are different for each region. In general, as shown in Figs. 29(a)–(c), the WW process dominates the background contributions in regions with $n_j = 0$; the difference between these distributions is due to the varying signal contribution and background m_T shape. In contrast, Fig. 29(d) shows that VV and W + jets processes are dominant backgrounds in the $10 < m_{\ell\ell} < 30$ GeV and $10 < p_T^{\ell\ell} < 15$ GeV region. For most of the distributions shown in Fig. 29, agreement between data and MC is improved qualitatively when including the expected signal from a Standard Model Higgs boson with $m_H = 125$ GeV.

The m_T distributions for the $ee/\mu\mu$ samples in the $n_j \leq 1$ categories are shown in Fig. 30. In contrast to the $e\mu$ distributions, the residual DY background is present in these samples at low values of m_T .

For the ggF-enriched $n_j \geq 2$ category, Fig. 31 shows the m_T distribution. In contrast to the $n_j \leq 1$ distributions, the dominant backgrounds arise from top-quark and $Z/\gamma^* \rightarrow \tau\tau$ production (shown together with the negligible contribution from $Z/\gamma^* \rightarrow ee, \mu\mu$).

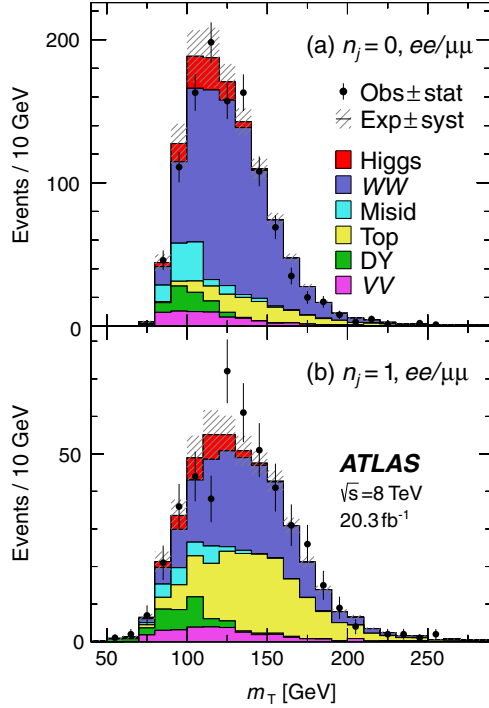
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FIG. 30 (color online). Postfit transverse mass distributions in the $n_j \leq 1$, $ee/\mu\mu$ categories in the 8 TeV analysis. See Figs. 5 and 29 for plotting details.

For the VBF-enriched $n_j \geq 2$ category, a selection-based analysis, which uses the m_T distribution as the discriminant, is used as a cross-check of the BDT result. In this case, m_T is divided into three bins (with boundaries at 80 and 130 GeV) and an additional division in m_{jj} at 1 TeV is used in the $e\mu$ channel to profit from the difference in shapes between signal and background processes. Figure 32(a) shows the m_T distribution before the division into the high- and low- m_{jj} regions. Figure 32(b) shows the scatter plot of m_{jj} versus m_T . The areas with the highest signal-to-background ratio are characterized by low m_T and high m_{jj} .

Figures 33(a) and 33(c) show the O_{BDT} outputs in the $e\mu$ and $ee/\mu\mu$ samples, respectively. In terms of VBF signal production, the third BDT bin provides the highest purity, with a signal-to-background ratio of approximately 2. The m_T variable is an input to the BDT and its distributions after the BDT classification are shown in Figs. 33(b) and 33(d), combining all three BDT bins, for the $e\mu$ and $ee/\mu\mu$ samples, respectively.

Figure 34 shows the m_T distributions in the 7 TeV analysis in the various signal regions in the $n_j \leq 1$ categories. Characteristics similar to those in the 8 TeV analysis are observed, but with fewer events.

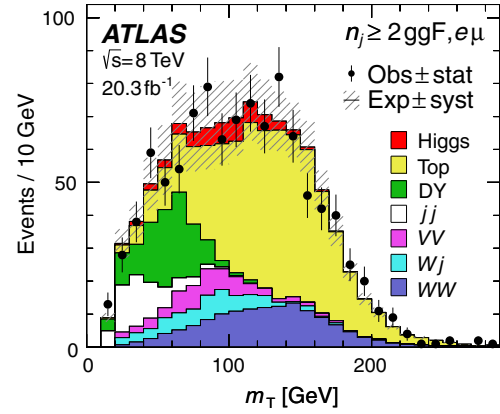
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FIG. 31 (color online). Postfit transverse mass distribution in the $n_j \geq 2$ ggF-enriched category in the 8 TeV analysis. See Figs. 5 and 29 for plotting details.

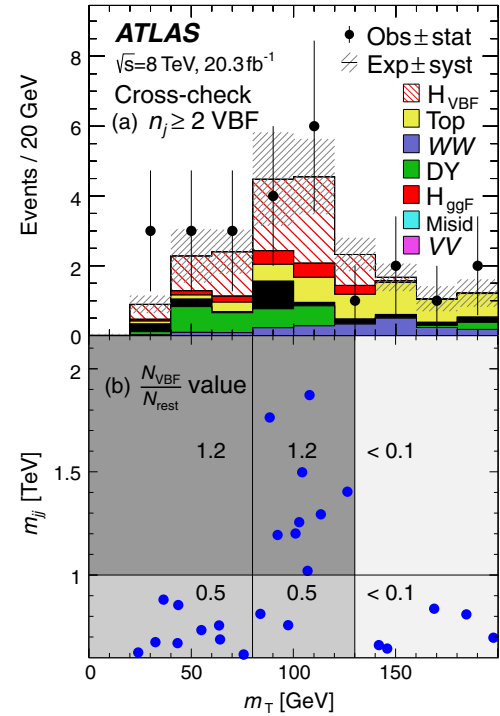


FIG. 32 (color online). Postfit distributions in the cross-check analysis in the $e\mu + ee/\mu\mu$ $n_j \geq 2$ VBF-enriched category in the 8 TeV data analysis: (a) m_T and (b) m_{jj} versus m_T scatter plot for data. For each bin in (b), the ratio $N_{\text{VBF}}/N_{\text{rest}}$ is stated in the plot, where N_{rest} includes all processes other than the VBF signal. See Figs. 5 and 29 for plotting details.

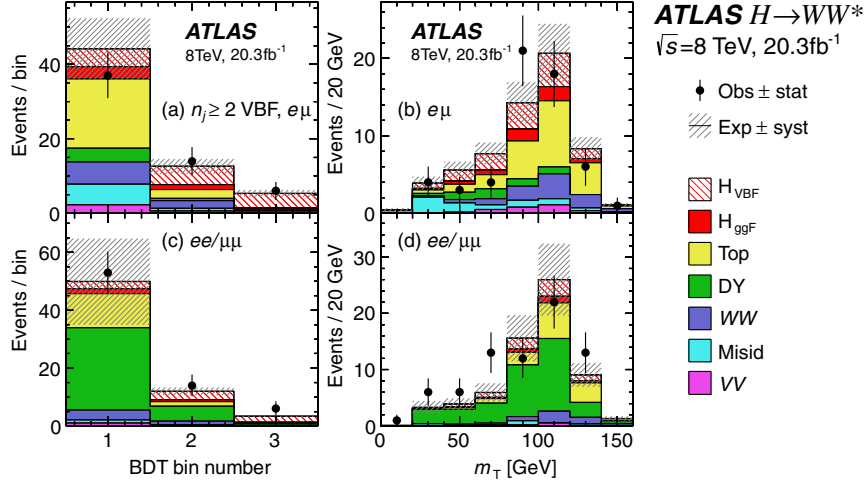


FIG. 33 (color online). Postfit BDT and transverse mass distributions in the $n_j \geq 2$ VBF-enriched category in the 8 TeV data analysis: (a) BDT output in $e\mu$, (b) m_T in $e\mu$, (c) BDT output in $ee/\mu\mu$, and (d) m_T in $ee/\mu\mu$. For (b) and (d), the three BDT bins are combined. See Figs. 5 and 29 for plotting details.

Finally, Fig. 35(a) shows the combined m_T distribution, summed over the lepton-flavor samples and the $n_j \leq 1$ categories for the 7 and 8 TeV data analyses. To illustrate the significance of the excess of events observed in data with respect to the total background, the systematic uncertainty on the signal is omitted. The uncertainty band accounts for the correlations between the signal regions, including between the 7 and 8 TeV data, and for the varying size of the uncertainties as a function of m_T . Figure 35(b) shows the residuals of the data with respect to the total estimated background compared to the expected m_T distribution of a SM Higgs boson with $m_H = 125$ GeV scaled

by the observed combined signal strength (see Sec. IX). The level of agreement observed in Fig. 35(b) between the background-subtracted data and the expected Higgs boson signal strengthens the interpretation of the observed excess as a signal from Higgs boson decay.

C. Differences with respect to previous results

The analysis presented in this paper has better sensitivity than the previous ATLAS analysis [5]. The most important changes—described in detail below—include improvements in the object identification, the signal acceptance, the background estimation and modeling, and the fit procedure.

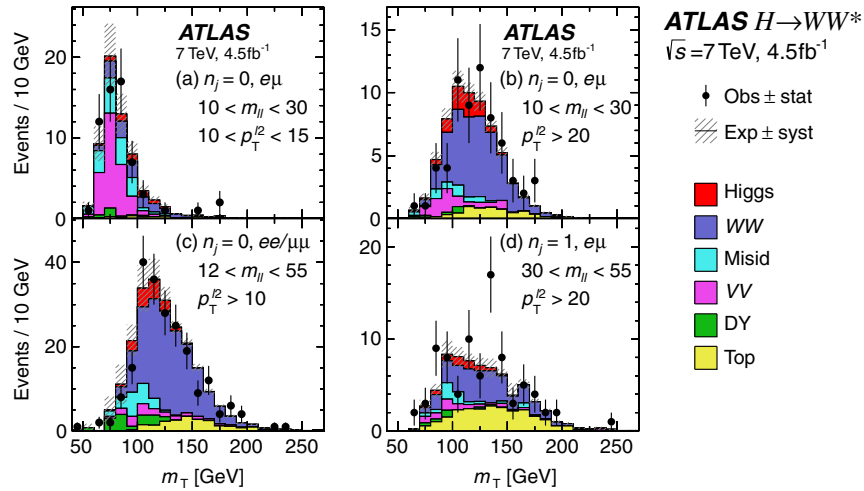


FIG. 34 (color online). Postfit transverse mass distributions in the $n_j \leq 1$ categories in the 7 TeV data analysis, for specific $m_{\ell\ell}$ and $p_T^{\ell\ell}$ ranges. The plots are made after applying all the selection requirements (see Sec. IV E). See Figs. 5 and 29 for plotting details.

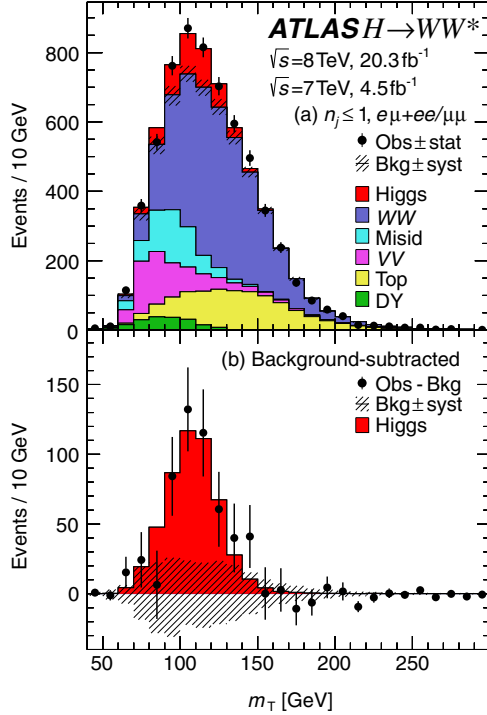
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FIG. 35 (color online). Postfit combined transverse mass distributions for $n_j \leq 1$ and for all lepton-flavor samples in the 7 and 8 TeV data analyses. The plot in (b) shows the residuals of the data with respect to the estimated background compared to the expected distribution for an SM Higgs boson with $m_H = 125\text{ GeV}$; the error bars on the data are statistical ($\sqrt{N_{\text{obs}}}$). The uncertainty on the background (shown as the shaded band around 0) is at most about 25 events per m_T bin and partially correlated between bins. Background processes are scaled by postfit normalization factors and the signal processes by the observed signal strength μ from the likelihood fit to all regions. Their normalizations also include effects from the pulls of the nuisance parameters.

Electron identification is based on a likelihood technique [23] that improves background rejection. An improved definition of missing transverse momentum, p_T^{miss} based on tracks, is introduced in the analysis since it is robust against pile-up and provides improved resolution with respect to the true value of missing transverse momentum.

Signal acceptance is increased by 75% (50%) in the $n_j = 0$ (1) category. This is achieved by lowering the $p_T^{\ell 2}$ threshold to 10 GeV. Dilepton triggers are included in addition to single lepton triggers, which allows reduction of the $p_T^{\ell 1}$ threshold to 22 GeV. The signal kinematic region in the $n_j \leq 1$ categories is extended from 50 to 55 GeV. The total signal efficiency, including all signal categories and production modes, at 8 TeV and for a Higgs boson mass of 125.36 GeV increased from 5.3% to 10.2%.

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The methods used to estimate nearly all of the background contributions in the signal region are improved. These improvements lead to a better understanding of the normalizations and thus the systematic uncertainties. The rejection of the top-quark background is improved by applying a veto on b -jets with $p_T > 20\text{ GeV}$, which is below the nominal 25 GeV threshold in the analysis. A new method of estimating the jet b -tagging efficiency is used. It results in the cancellation of the b -tagging uncertainties between the top-quark control region and signal regions in the $n_j = 1$ categories. The $Z/\gamma^* \rightarrow \tau\tau$ background process is normalized to the data in a dedicated high-statistics control region in the $n_j \leq 1$ and $n_j \geq 2$ ggF-enriched categories. The VV backgrounds are normalized to the data using a new control region, based on a sample with two same-charge leptons. Introducing this new control region results in the cancellation of most of the theoretical uncertainties on the VV backgrounds. The multijet background is now explicitly estimated with an extrapolation factor method using a sample with two anti-identified leptons. Its contribution is negligible in the $n_j \leq 1$ category, but it is at the same level as $W + \text{jets}$ background in the $n_j \geq 2$ ggF-enriched category. A large number of improvements are applied to the estimation of the $W + \text{jets}$ background, one of them being an estimation of the extrapolation factor using $Z + \text{jets}$ instead of dijet data events.

Signal yield uncertainties are smaller than in the previous analysis. The uncertainties on the jet multiplicity distribution in the ggF signal sample, previously estimated with the Stewart-Tackmann technique [80], are now estimated with the jet-veto-efficiency method [79]. This method yields more precise estimates of the signal rates in the exclusive jet bins in which the analysis is performed.

The $n_j \geq 2$ sample is divided into VBF- and ggF-enriched categories. The BDT technique, rather than a selection-based approach, is used for the VBF category. This improves the sensitivity of the expected VBF results by 60% relative to the previously published analysis. The ggF-enriched category is a new subcategory that targets ggF signal production in this sample.

In summary, the analysis presented in this paper brings a gain of 50% in the expected significance relative to the previous published analysis [5].

IX. RESULTS AND INTERPRETATIONS

Combining the 2011 and 2012 data in all categories, a clear excess of signal over the background is seen in Fig. 35. The profile likelihood fit described in Sec. VII B is used to search for a signal and characterize the production rate in the ggF and VBF modes. Observation of the inclusive Higgs boson signal, and evidence for the VBF production mode, are established first. Following that, the excess in data is characterized using the SM Higgs boson as the signal hypothesis, up to linear rescalings of the production cross sections and decay modes. Results include

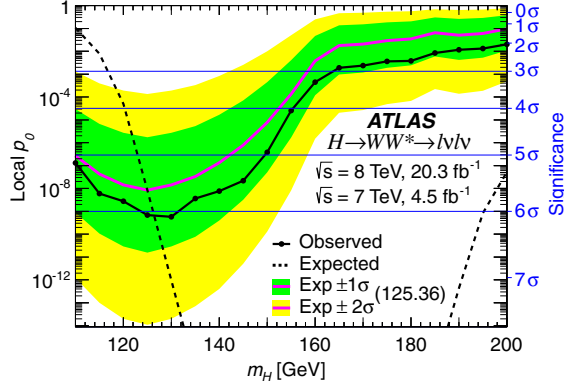


FIG. 36 (color online). Local p_0 as a function of m_H . The observed values are shown as a solid line with points where p_0 is evaluated. The dashed line shows the expected values given the presence of a signal at each x -axis value. The expected values for $m_H = 125.36$ GeV are given as a solid line without points; the inner (outer) band shaded darker (lighter) represents the one (two) standard deviation uncertainty.

the inclusive signal strength as well as those for the individual ggF and VBF modes. This information is also interpreted as a measurement of the vector-boson and fermion couplings of the Higgs boson, under the assumptions outlined in Ref. [67]. Because this is the first observation in the $WW^* \rightarrow \ell\nu\ell\nu$ channel using ATLAS data, the exclusion sensitivity and observed exclusion limits as a function of m_H are also presented to illustrate the improvements with respect to the version of this analysis used in the 2012 discovery [4]. Finally, cross-section measurements, both inclusive and in specific fiducial regions, are presented. All results in this section are quoted for a Higgs boson mass corresponding to the central value of the ATLAS measurement in the $ZZ \rightarrow 4\ell$ and $\gamma\gamma$ decay modes, $m_H = 125.36 \pm 0.41$ GeV [9].

A. Observation of the $H \rightarrow WW^*$ decay mode

The test statistic q_μ , defined in Sec. VII B, is used to quantify the significance of the excess observed in Sec. VIII. The probability that the background can fluctuate to produce an excess at least as large as the one observed in data is called p_0 and is computed using q_μ with $\mu = 0$. It depends on the mass hypothesis m_H through the distribution used to extract the signal (m_T or O_{BDT}). The observed and expected p_0 are shown as a function of m_H in Fig. 36. The observed curve presents a broad minimum centered around $m_H \approx 130$ GeV, in contrast with the higher p_0 values observed for lower and higher values of m_H . The shapes of the observed and expected curves are in good agreement.

The probability p_0 can equivalently be expressed in terms of the number of standard deviations, referred to as the local significance (Z_0 defined in Sec. VII B 2). The value of p_0 as

a function of m_H is found by scanning m_H in 5 GeV intervals. The minimum p_0 value is found at $m_H = 130$ GeV and corresponds to a local significance of 6.1 standard deviations. The same observed significance within the quoted precision is found for $m_H = 125.36$ GeV. This result establishes a discovery-level signal in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel alone. The expected significance for a SM Higgs boson at the same mass is 5.8 standard deviations.

In order to assess the compatibility with the SM expectation for a Higgs boson of mass m_H , the observed best-fit $\hat{\mu}$ value as a function of m_H is shown in Fig. 37. The observed $\hat{\mu}$ is close to zero for $m_H > 160$ GeV and crosses unity at $m_H \approx 125$ GeV. The increase of $\hat{\mu}$ for small values of m_H is expected in the presence of a signal with mass $m_H = 125.36$ GeV, as is also shown in Fig. 37. The dependence of $\hat{\mu}$ on the value of m_H ($d\hat{\mu}/dm_H = -0.078$ GeV at $m_H = 125.36$ GeV) arises mostly from the dependence of the WW^* branching fraction on m_H .

The assumption that the total yield is predicted by the SM is relaxed to evaluate the two-dimensional likelihood contours of (m_H, μ) , shown in Fig. 38. The value ($\mu = 1$, $m_H = 125.36$ GeV) lies well within the 68% C.L. contour, showing that the signal observed is compatible with those in the high-resolution channels.

B. Evidence for VBF production

The $n_j \geq 2$ VBF-enriched signal region was optimized for its specific sensitivity to the VBF production process, as described in particular in Sec. IV. Nevertheless, as can be seen in Table XXV, the ggF contribution to this signal region is large, approximately 30%, so it has to be profiled by the global fit together with the extraction of the significance of the signal strength of the VBF production process.

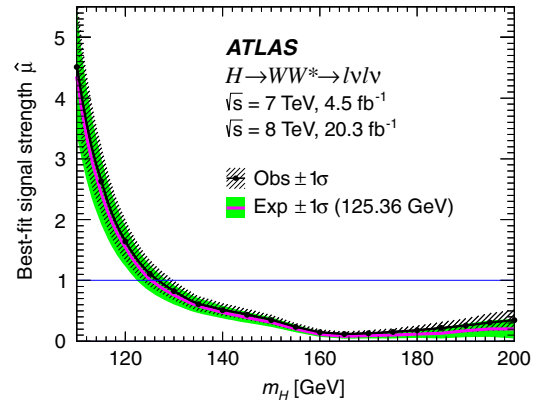


FIG. 37 (color online). Best-fit signal strength $\hat{\mu}$ as a function of m_H . The observed values are shown as a solid line with points where $\hat{\mu}$ is evaluated. The expected values for $m_H = 125.36$ GeV are shown as a solid line without points. The dashed and shaded (solid) bands represent the one standard deviation uncertainties for the observed (expected) values.

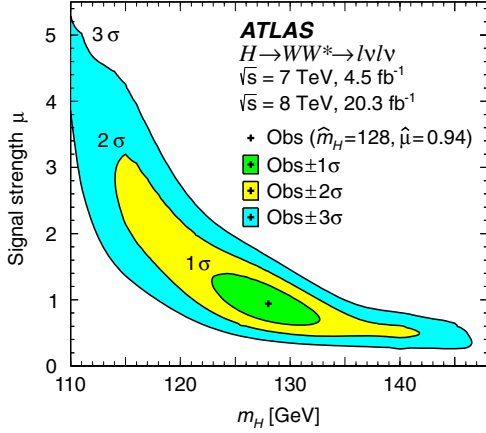
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FIG. 38 (color online). Observed signal strength μ as a function of m_H as evaluated by the likelihood fit. The shaded areas represent the one, two, and three standard deviation contours with respect to the best-fit values $\hat{m}_H$ and $\hat{\mu}$.

The global likelihood can be evaluated as a function of the ratio $\mu_{\text{VBF}}/\mu_{\text{ggF}}$, with both signal strengths varied independently. The result is illustrated in Fig. 39, which has a best-fit value for the ratio of

$$\frac{\mu_{\text{VBF}}}{\mu_{\text{ggF}}} = 1.26^{+0.61}_{-0.45}(\text{stat})^{+0.50}_{-0.26}(\text{syst}) = 1.26^{+0.79}_{-0.53}. \quad (14)$$

The value of the likelihood at $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ can be interpreted as the observed significance of the VBF production process for $m_H = 125.36$ GeV, and corresponds to 3.2 standard deviations; the expected significance is 2.7 standard deviations. This establishes the evidence for the VBF production mode in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final state. The significance derived from testing the ratio $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ is equivalent to the significance of testing $\mu_{\text{VBF}} = 0$, though testing the ratio is conceptually advantageous since the branching fraction cancels in this parameter, while it is implicit in μ_{VBF} .

This result was verified with the cross-check analysis described in Sec. IV C, in which the multivariate discriminant is replaced with a series of event selection requirements motivated by the VBF topology. The expected and observed significances at $m_H = 125.36$ GeV are 2.1 and 3.0 standard deviations, respectively. The compatibility of the 8 TeV results from the cross-check and O_{BDT} analyses

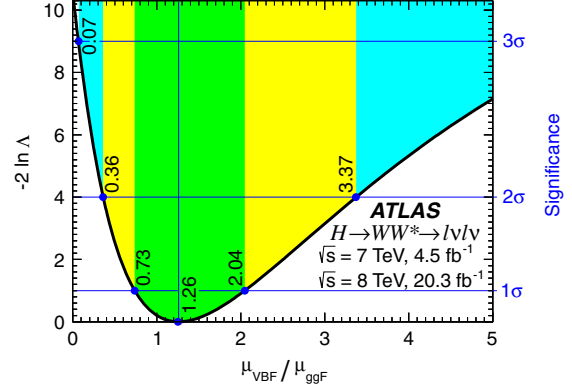
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FIG. 39 (color online). Likelihood scan as a function of $\mu_{\text{VBF}}/\mu_{\text{ggF}}$ for $m_H = 125.36$ GeV. The value of the likelihood at $\mu_{\text{VBF}}/\mu_{\text{ggF}} = 0$ gives the significance of the VBF signal at 3.2 standard deviations. The inner (middle) [outer] band shaded darker (lighter) [darker] represents the one (two) [three] standard deviation uncertainty around the central value represented by the vertical line.

was checked with pseudoexperiments, considering the statistical uncertainties only and fixing μ_{ggF} to 1.0. With those caveats, the probability that the difference in Z_0 values is larger than the one observed is 79%, reflecting good agreement.

C. Signal strength μ

The parameter μ is used to characterize the inclusive Higgs boson signal strength as well as subsets of the signal regions or individual production modes. First, the ggF and VBF processes can be distinguished by using the normalization parameter μ_{ggF} for the signal predicted for the ggF signal process, and μ_{VBF} for the signal predicted for the VBF signal process. This can be done for a fit to any set of the signal regions in the various categories. In addition, to check that the measured value is consistent among categories, different subsets of the signal regions can be fit. For example, the $n_j = 0$ and $n_j = 1$ categories can be compared, or the $e\mu$ and $ee/\mu\mu$ categories. To derive these results, only the signal regions are separated; the control region definitions do not change. In particular, the control regions defined using only $e\mu$ events are used, even when only $ee/\mu\mu$ signal regions are considered.

The combined Higgs signal strength μ , including 7 and 8 TeV data and all signal region categories, is

$$\begin{aligned} \mu &= 1.09^{+0.16}_{-0.15}(\text{stat})^{+0.08}_{-0.07}(\text{expt})^{+0.15}_{-0.12}(\text{theo}) \pm 0.03^{(\text{lumi})}_{(\text{syst})} \\ &= 1.09^{+0.16}_{-0.15}(\text{stat})^{+0.17}_{-0.14}(\text{syst}) \\ &= 1.09^{+0.23}_{-0.21}. \end{aligned} \quad (15)$$

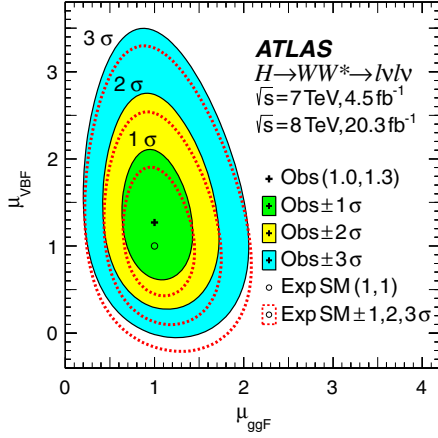


FIG. 40 (color online). Likelihood scan as a function of μ_{ggF} and μ_{VBF} . The best-fit observed (expected SM) value is represented by the cross symbol (open circle) and its one, two, and three standard deviation contours are shown by solid lines surrounding the filled areas (dotted lines). The x - and y -axis scales are the same to visually highlight the relative sensitivity.

The uncertainties are divided according to their source. The statistical uncertainty accounts for the number of observed events in the signal regions and profiled control regions. The statistical uncertainties from Monte Carlo simulated samples, from nonprofiled control regions, and from the extrapolation factors used in the W + jets background estimate are all included in the experimental uncertainties here and for all results in this section. The theoretical uncertainty includes uncertainties on the signal acceptance and cross section as well as theoretical uncertainties on the background extrapolation factors and normalizations. The expected value of μ is $1^{+0.16}_{-0.15}(\text{stat})^{+0.17}_{-0.13}(\text{syst})$.

In order to check the compatibility with the SM predictions of the ggF and VBF production processes, μ_{ggF} and μ_{VBF} can be simultaneously determined through a fit to all categories because of the different sensitivity to these processes in the various categories. In this fit, the VH contribution is included although there is no dedicated category for it, and the SM value for the ratio $\sigma_{\text{VBF}}/\sigma_{\text{VH}}$ is assumed. Technically, the signal strength $\mu_{\text{VBF}+\text{VH}}$ is measured, but because the contribution from VH is negligible, the notation μ_{VBF} is used. The corresponding two-dimensional likelihood contours as a function of μ_{ggF} and μ_{VBF} are shown in Fig. 40. Using the same treatment, the separate signal strengths can be measured. The results are

$$\begin{aligned} \mu_{\text{ggF}} &= 1.02 \pm 0.19 \quad {}^{+0.22}_{-0.18} = 1.02 \quad {}^{+0.29}_{-0.26} \\ \mu_{\text{VBF}} &= 1.27 \quad {}^{+0.44}_{-0.40} \quad {}^{+0.30}_{-0.21} = 1.27 \quad {}^{+0.53}_{-0.45} \quad (\text{stat}) \quad (\text{syst}) \end{aligned} \quad (16)$$

The details of the uncertainties on μ , μ_{ggF} , and μ_{VBF} are shown in Table XXVI. The statistical uncertainty is the largest single source of uncertainty on the signal strength results, although theoretical uncertainties also play a substantial role, especially for μ_{ggF} .

The signal strength results are shown in Table XXVII for $m_H = 125.36$ GeV. The table includes inclusive results as well as results for individual categories and production modes. The expected and observed significance for each category and production mode is also shown. The μ values are consistent with each other and with unity within the assigned uncertainties. In addition to serving as a consistency check, these results illustrate the sensitivity of the different categories. For the overall signal strength, the contribution from the $n_j \geq 2$ VBF category is second only to the $n_j = 0$ ggF category, and the $n_j \geq 2$ ggF category contribution is comparable to those in the $n_j = 0$ and $n_j = 1$ $ee/\mu\mu$ categories.

For all of these results, the signal acceptance for all production modes is evaluated assuming a SM Higgs boson. The VH production process contributes a small number of events, amounting to about 1% of the expected signal from the VBF process. It is included in the predicted signal yield, and where relevant, is grouped with the VBF signal assuming the SM value of the ratio $\sigma_{\text{VBF}}/\sigma_{\text{VH}}$. The small ($<1\%$) contribution of $H \rightarrow \tau\tau$ to the signal regions is treated as signal, assuming the branching fractions as predicted by the SM.

D. Higgs couplings to fermions and vector bosons

The values of μ_{ggF} and μ_{VBF} can be used to test the compatibility of the fermionic and bosonic couplings of the Higgs boson with the SM prediction using a framework motivated by the leading-order interactions [67]. The parametrization uses the scale factors κ_F , applied to all fermionic couplings, and κ_V , applied to all bosonic couplings; these parameters are unity for the SM.

In particular, the ggF production cross section is proportional to κ_F^2 through the top-quark or bottom-quark loops at the production vertex, and the VBF production cross section is proportional to κ_V^2 . The branching fraction $\mathcal{B}_{H \rightarrow WW^*}$ is proportional to κ_V^2 and inversely proportional to a linear combination of κ_F^2 and κ_V^2 . This model assumes that there are no non-SM decay modes, so the denominator corresponds to the total decay width in terms of the fermionic and bosonic decay amplitudes. The formulas, following Ref. [67], are

$$\begin{aligned} \mu_{\text{ggF}} &\propto \frac{\kappa_F^2 \cdot \kappa_V^2}{(\mathcal{B}_{H \rightarrow f\bar{f}} + \mathcal{B}_{H \rightarrow gg})\kappa_F^2 + (\mathcal{B}_{H \rightarrow VV})\kappa_V^2}, \\ \mu_{\text{VBF}} &\propto \frac{\kappa_V^4}{(\mathcal{B}_{H \rightarrow f\bar{f}} + \mathcal{B}_{H \rightarrow gg})\kappa_F^2 + (\mathcal{B}_{H \rightarrow VV})\kappa_V^2}. \end{aligned} \quad (17)$$

The small contribution from $\mathcal{B}_{H \rightarrow \gamma\gamma}$ depends on both κ_F and κ_V and is not explicitly shown. Because $(\mathcal{B}_{H \rightarrow f\bar{f}} + \mathcal{B}_{H \rightarrow gg}) \approx 0.75$, κ_F^2 is the dominant component of the denominator

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TABLE XXVI. Summary of uncertainties on the signal strength μ . The table gives the relative uncertainties for inclusive Higgs production (left), ggF production (middle), and VBF production (right). For each group separated by a horizontal line, the first line gives the combined result. The “profiled signal region” indicates the contribution of the uncertainty on the ggF signal yield to the μ_{VBF} measurement and vice versa. The “misid factor” is the systematic uncertainty related to the $W + \text{jets}$ background estimation. The “ $Z/\gamma^* \rightarrow ee, \mu\mu$ ” entry corresponds to uncertainties on the f_{recoil} selection efficiency for the $n_j \leq 1$ $ee/\mu\mu$ category. The “muons and electrons” entry includes uncertainties on the lepton energy scale, lepton momentum corrections, lepton trigger efficiencies, and lepton isolation efficiencies. The “jets” uncertainties include the jet energy scale, jet energy resolution, and the b -tagging efficiency. Values are quoted assuming $m_H = 125.36$ GeV. The plot for VBF (third column) has a different scale than the other columns to show the relative uncertainties per column. The entries marked with a dash are smaller than 0.01 or do not apply.

Source	Observed $\mu = 1.09$			Observed $\mu_{\text{ggF}} = 1.02$			Observed $\mu_{\text{VBF}} = 1.27$		
	Error + -	Plot of error (scaled by 100)		Error + -	Plot of error (scaled by 100)		Error + -	Plot of error (scaled by 100)	
Data statistics	0.16 0.15			0.19 0.19			0.44 0.40		
Signal regions	0.12 0.12			0.14 0.14			0.38 0.35		
Profiled control regions	0.10 0.10			0.12 0.12			0.21 0.18		
Profiled signal regions	- -			0.03 0.03			0.09 0.08		
MC statistics	0.04 0.04			0.06 0.06			0.05 0.05		
Theoretical systematics	0.15 0.12			0.19 0.16			0.22 0.15		
Signal $H \rightarrow WW^* \mathcal{B}$	0.05 0.04			0.05 0.03			0.07 0.04		
Signal ggF cross section	0.09 0.07			0.13 0.09			0.03 0.03		
Signal ggF acceptance	0.05 0.04			0.06 0.05			0.07 0.07		
Signal VBF cross section	0.01 0.01			- -			0.07 0.04		
Signal VBF acceptance	0.02 0.01			- -			0.15 0.08		
Background WW	0.06 0.06			0.08 0.08			0.07 0.07		
Background top quark	0.03 0.03			0.04 0.04			0.06 0.06		
Background misid. factor	0.05 0.05			0.06 0.06			0.02 0.02		
Others	0.02 0.02			0.02 0.02			0.03 0.03		
Experimental systematics	0.07 0.06			0.08 0.08			0.18 0.14		
Background misid. factor	0.03 0.03			0.04 0.04			0.02 0.01		
Bkg. $Z/\gamma^* \rightarrow ee, \mu\mu$	0.02 0.02			0.03 0.03			0.01 0.01		
Muons and electrons	0.04 0.04			0.05 0.04			0.03 0.02		
Missing transv. momentum	0.02 0.02			0.02 0.01			0.05 0.05		
Jets	0.03 0.02			0.03 0.03			0.15 0.11		
Others	0.03 0.02			0.03 0.03			0.06 0.06		
Integrated luminosity	0.03 0.03			0.03 0.02			0.05 0.03		
Total	0.23 0.21			0.29 0.26			0.53 0.45		

for $\kappa_F^2 \gtrsim \frac{1}{3}\kappa_V^2$. As a result, the κ_F^2 dependence for the ggF process approximately cancels, but the rate remains sensitive to κ_V . Similarly, the VBF rate scales approximately with κ_V^4/κ_F^2 and the VBF channel provides more sensitivity to κ_F than the ggF channel does in this model. Because Eq. (17) contains only κ_F^2 and κ_V^2 , this channel is not sensitive to the sign of κ_F or κ_V .

The likelihood scan as a function of κ_V and κ_F is shown in Fig. 41. Both the observed and expected contours are shown, and are in good agreement. The relatively low discrimination among high values of κ_F in the plot is due to the functional behavior of the total ggF yield. The product $\sigma_{\text{ggF}} \cdot \mathcal{B}$ does not depend on κ_F in the limit where $\kappa_F \gg \kappa_V$, so the sensitivity at high κ_F values is driven by the value of μ_{VBF} . The VBF process rapidly vanishes in the limit where

$\kappa_F \gg \kappa_V$ due to the increase of the Higgs boson total width and the consequent reduction of the branching fraction to WW bosons. Therefore, within this framework, excluding $\mu_{\text{VBF}} = 0$ excludes $\kappa_F \gg \kappa_V$.

The best fit values are

$$\begin{aligned}
 \kappa_F &= 0.93^{+0.24}_{-0.18} \\
 \kappa_V &= 1.04^{+0.07}_{-0.08}
 \end{aligned}
 \begin{aligned}
 &+0.21 \\
 &-0.14 \\
 &+0.07 \\
 &-0.08
 \end{aligned}
 = 0.93 \pm 0.11 \quad (18)$$

(stat) (syst)

and their correlation is $\rho = 0.47$. The correlation is derived from the covariance matrix constructed from the second-order mixed partial derivatives of the likelihood, evaluated at the best-fit values of κ_F and κ_V .

TABLE XXVII. Signal significance Z_0 and signal strength μ . The expected (Exp) and observed (Obs) values are given; μ_{exp} is unity by assumption. For each group separated by a horizontal line, the highlighted first line gives the combined result. The plots correspond to the values in the table as indicated. For the μ plot, the thick line represents the statistical uncertainty (Stat) in the signal region, the thin line represents the total uncertainty (Tot), which includes the uncertainty from systematic sources (Syst). The uncertainty due to background sample statistics is included in the latter. The last two rows report the results when considering ggF and VBF production modes separately. The values are given assuming $m_H = 125.36$ GeV.

Sample	Signal significance			Expected		Observed uncertainty						Observed central value	
	Exp. Z_0	Obs. Z_0	Bar graph of observed Z_0	Tot. err. +	Tot. err. -	Tot. err. +	Tot. err. -	Stat. err. +	Stat. err. -	Syst. err. +	Syst. err. -	μ_{obs}	$\mu_{\text{obs}} \pm \text{stat. (thick)} \pm \text{total (thin)}$
$n_j = 0$	3.70	4.08		0.35	0.30	0.37	0.32	0.22	0.22	0.30	0.23	1.15	
$e\mu, \ell_2 = \mu$	2.89	3.07		0.41	0.36	0.43	0.38	0.30	0.29	0.32	0.24	1.08	
$e\mu, \ell_2 = e$	2.36	3.12		0.49	0.44	0.54	0.48	0.38	0.37	0.39	0.30	1.40	
$ee/\mu\mu$ category	1.43	0.71		0.74	0.70	0.68	0.66	0.45	0.44	0.51	0.50	0.47	
$n_j = 1$	2.60	2.49		0.51	0.41	0.50	0.41	0.33	0.32	0.38	0.26	0.96	
$e\mu$ category	2.56	2.83		0.51	0.42	0.56	0.45	0.35	0.35	0.43	0.29	1.16	
$ee/\mu\mu$ category	1.02	0.21		1.12	0.98	1.02	0.97	0.80	0.76	0.63	0.61	0.19	
$n_j \geq 2$, ggF, $e\mu$	1.21	1.44		0.96	0.83	0.91	0.84	0.70	0.68	0.70	0.49	1.20	
$n_j \geq 2$, VBF-enr.	3.38	3.84		0.42	0.36	0.45	0.38	0.36	0.33	0.27	0.19	1.20	
$e\mu$ category	3.01	3.02		0.48	0.40	0.47	0.39	0.40	0.35	0.24	0.16	0.98	
$ee/\mu\mu$ category	1.58	2.96		0.84	0.67	0.97	0.78	0.83	0.71	0.51	0.33	1.98	
All n_j , all signal	5.76	6.06		0.23	0.20	0.23	0.21	0.16	0.15	0.17	0.14	1.09	
ggF as signal	4.34	4.28		0.30	0.24	0.29	0.26	0.19	0.19	0.22	0.18	1.02	
VBF as signal	2.67	3.24		0.50	0.43	0.53	0.45	0.44	0.40	0.30	0.21	1.27	

E. Exclusion limits

The analysis presented in this paper has been optimized for a Higgs boson of mass $m_H = 125$ GeV, but, due to the low mass resolution of the $\ell\nu\ell\nu$ channel, it is sensitive to SM-like Higgs bosons of mass up to 200 GeV and above.

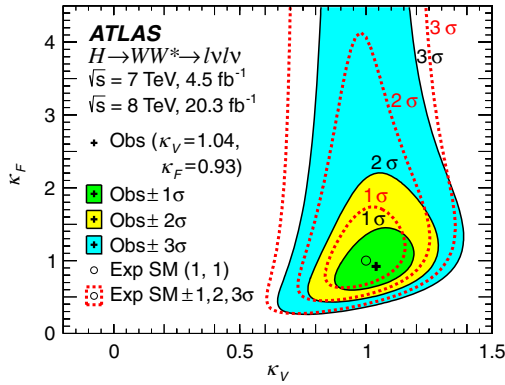


FIG. 41 (color online). Likelihood scan as a function of κ_V and κ_F . The best-fit observed (expected SM) value is represented by the cross symbol (open circle) and its one, two, and three standard deviation contours are shown by solid lines surrounding the filled areas (dotted lines). Note that the y axis spans a wider range than the x axis.

The exclusion ranges are computed using the modified frequentist method CL_s [99]. A SM Higgs boson of mass m_H is considered excluded at 95% C.L. if the value $\mu = 1$ is excluded at that mass. The analysis is expected to exclude a SM Higgs boson with mass down to 114 GeV at 95% C.L. The clear excess of signal over background, shown in the previous sections, results in an observed exclusion range of $132 < m_H < 200$ GeV, extending to the upper limit of the search range, as shown in Fig. 42.

F. Higgs boson production cross sections

The measured signal strength can be used to evaluate the product $\sigma \cdot \mathcal{B}_{H \rightarrow WW^*}$ for Higgs boson production at $m_H = 125.36$ GeV, as well as for the individual ggF and VBF production modes. The central value is simply the product of μ and the predicted cross section used to define it. The uncertainties are similarly scaled, except for the theoretical uncertainties related to the total production yield, which do not apply to this measurement. These are the QCD scale and PDF uncertainties on the total cross sections, and the uncertainty on the branching fraction for $H \rightarrow WW^*$, as described in Sec. V. In practice, the corresponding nuisance parameters are fixed to their nominal values in the fit, effectively removing these uncertainties from consideration. Inclusive cross-section measurements are performed for ggF and VBF production. The cross section is also measured for ggF production in

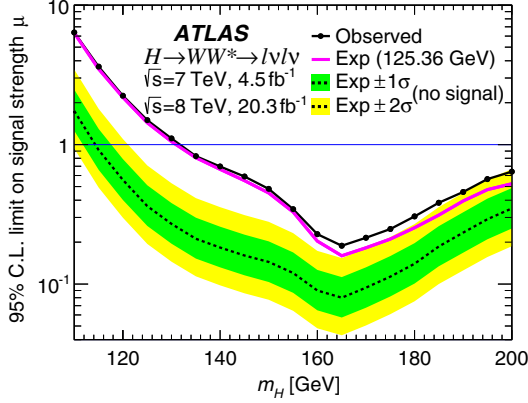
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FIG. 42 (color online). CL_s exclusion plot for $110 \leq m_H \leq 200$ GeV. The observed values are shown as a solid line with points where the limit is evaluated. The expected values for a signal at 125.36 GeV are given as a solid line without points. The expected values for scenarios without signal are given by the dotted line. The inner (outer) band shaded darker (lighter) represents the one (two) standard deviation uncertainty on the value for expected without signal. The limit of 132 GeV (114 GeV) on m_H for the observed (expected no signal) scenario can be seen at low values of m_H .

defined fiducial volumes; this approach minimizes the impact of theoretical uncertainties.

1. Inclusive cross sections

Inclusive cross sections are evaluated at both 7 and 8 TeV for the ggF production process and at 8 TeV for the VBF production process. The 7 TeV VBF cross section is not measured because of the large statistical uncertainty. The signal strengths used for ggF and VBF are determined through a simultaneous fit to all categories as described in Sec. IX C. The small VH contribution, corresponding to 0.9%, is neglected, and its expected fractional yield is added linearly to the total uncertainty. The 7 TeV signal strength $\mu_{\text{ggF}}^{7 \text{ TeV}}$ and 8 TeV signal strengths $\mu_{\text{ggF}}^{8 \text{ TeV}}$ and $\mu_{\text{VBF}}^{8 \text{ TeV}}$ are

$$\begin{aligned}
 \mu_{\text{ggF}}^{7 \text{ TeV}} &= 0.57 & +0.52 & +0.36 & +0.14 \\
 & & -0.51 & -0.34 & -0.004 \\
 \mu_{\text{ggF}}^{8 \text{ TeV}} &= 1.09 & \pm 0.20 & +0.19 & +0.14 \\
 & & & -0.17 & -0.09 \\
 \mu_{\text{VBF}}^{8 \text{ TeV}} &= 1.45 & +0.48 & +0.38 & +0.11 \\
 & & -0.44 & -0.24 & -0.06 \\
 & & (\text{stat}) & (\text{syst}) & (\text{sig})
 \end{aligned} \quad (19)$$

where (sig) indicates the systematic uncertainties on the total signal yield for the measured process, which do not affect the cross-section measurement. The effect of uncertainties on the signal yield for other production modes is included in the systematic uncertainties. In terms of the measured signal strength, the inclusive cross section is defined as

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$$\begin{aligned}
 (\sigma \cdot \mathcal{B}_{H \rightarrow WW^*})_{\text{obs}} &= \frac{(N_{\text{sig}})_{\text{obs}}}{\mathcal{A} \cdot \mathcal{C} \cdot \mathcal{B}_{WW \rightarrow \ell \nu \ell \nu}} \cdot \frac{1}{\int L dt} \\
 &= \hat{\mu} \cdot (\sigma \cdot \mathcal{B}_{H \rightarrow WW^*})_{\text{exp}}. \quad (20)
 \end{aligned}$$

In this equation, $\mathcal{A}$ is the kinematic and geometric acceptance, and $\mathcal{C}$ is the ratio of the number of measured events to the number of events produced in the fiducial phase space of the detector. The product $\mathcal{A} \cdot \mathcal{C}$ is the total acceptance for reconstructed events. The cross sections are measured using the last line of the equation, and the results are

$$\begin{aligned}
 \sigma_{\text{ggF}}^{7 \text{ TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 2.0 \pm 1.7 & +1.2 & -1.1 & = 2.0 & +2.1 & -2.0 & \text{pb} \\
 \sigma_{\text{ggF}}^{8 \text{ TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 4.6 \pm 0.9 & +0.8 & -0.7 & = 4.6 & +1.2 & -1.1 & \text{pb} \\
 \sigma_{\text{VBF}}^{8 \text{ TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 0.51 & +0.17 & -0.15 & +0.13 & -0.08 & = 0.51 & +0.22 & -0.17 & \text{pb}. \\
 & & (\text{stat}) & (\text{syst}) & & & & & & (21)
 \end{aligned}$$

The predicted cross-section values are 3.3 ± 0.4 pb, 4.2 ± 0.5 pb, and 0.35 ± 0.02 pb, respectively.

These are derived as described in Sec. V, and the acceptance is evaluated using the standard signal MC samples.

2. Fiducial cross sections

Fiducial cross-section measurements enable comparisons to theoretical predictions with minimal assumptions about the kinematics of the signal and possible associated jets in the event. The cross sections described here are for events produced within a fiducial volume closely corresponding to a ggF signal region. The fiducial volume is defined using generator-level kinematic information, as specified in Table XXVIII. In particular, the total p_T of the

TABLE XXVIII. Fiducial volume definitions for fiducial cross sections. The selection is made using only $e\mu$ events. Events in which one or both W bosons decay to $\tau\nu$ are excluded from the fiducial volume, but are present in the reconstructed volume. Energy-related quantities are in GeV.

Type	$n_j = 0$	$n_j = 1$
Preselection	$p_T^{\ell^1} > 22$ $p_T^{\ell^2} > 10$ opposite-charge $\ell\ell$ $m_{\ell\ell} > 10$ $p_T^{\nu\nu} > 20$	
n_j dependent	$\Delta\phi_{\ell\ell,\nu\nu} > \pi/2$ $p_T^{\ell\ell} > 30$ - - $m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$	- - $m_T^\ell > 50$ $m_{\tau\tau} < 66$ $m_{\ell\ell} < 55$ $\Delta\phi_{\ell\ell} < 1.8$

neutrino system ($p_T^{\nu\nu}$) replaces the p_T^{miss} , and each lepton's p_T is replaced by the generated lepton p_T , where the lepton four-momentum is corrected by adding the four-momenta of all photons within a cone of size $\Delta R = 0.1$ to account for energy loss through QED final-state radiation. These quantities are used to compute m_T^ℓ . Jets are defined at hadron level, i.e., after parton showering and hadronization but before detector simulation. To minimize dependence on the signal model, and therefore the theoretical uncertainties, only $e\mu$ events in the $n_j \leq 1$ categories are used. Also, only the 8 TeV data sample is used for these measurements.

The measured fiducial cross section is defined as

$$\sigma_{\text{fid}} = \frac{(N_{\text{sig}})_{\text{obs}}}{\mathcal{C}} \cdot \frac{1}{\int L dt} = \hat{\mu} \cdot (\sigma \cdot \mathcal{B}_{H \rightarrow WW^* \rightarrow e\nu\mu\nu})_{\text{exp}} \cdot \mathcal{A}, \quad (22)$$

with the multiplicative factor $\mathcal{A}$ being the sole difference with respect to the inclusive cross-section calculation. The measured fiducial cross section is not affected by the theoretical uncertainties on the total signal yield nor by the theoretical uncertainties on the signal acceptance. The total uncertainty is reduced compared to the value for the inclusive cross section because the measured signal yield is not extrapolated to the total phase space.

The correction factors for $n_j = 0$ and $n_j = 1$ events, $\mathcal{C}_{0j}^{\text{ggF}}$ and $\mathcal{C}_{1j}^{\text{ggF}}$, are evaluated using the standard signal MC sample. The reconstructed events include leptons from τ decays, but for simplicity, the fiducial volume is defined without these contributions. According to the simulation, the fraction of measured signal events within the fiducial volume is 85% for $n_j = 0$ and 63% for $n_j = 1$.

The values of the correction factors are

$$\begin{aligned} \mathcal{C}_{0j}^{\text{ggF}} &= 0.507 \pm 0.027, \\ \mathcal{C}_{1j}^{\text{ggF}} &= 0.506 \pm 0.022. \end{aligned} \quad (23)$$

The experimental systematic uncertainty is approximately 5%. Remaining theoretical uncertainties on the $\mathcal{C}_{0j}^{\text{ggF}}$ values were computed by comparing the ggF predictions of POWHEG + HERWIG, POWHEG + PYTHIA8, and POWHEG + PYTHIA6, and are found to be approximately 2% and are neglected. The acceptance of the fiducial volume is

$$\begin{aligned} \mathcal{A}_{0j}^{\text{ggF}} &= 0.206 \pm 0.030, \\ \mathcal{A}_{1j}^{\text{ggF}} &= 0.075 \pm 0.017. \end{aligned} \quad (24)$$

The uncertainties on the acceptance are purely theoretical in origin and the largest contributions are from the effect of the QCD scale on the jet multiplicity requirements.

The cross-section values are computed by fitting the μ values in the $n_j = 0$ and $n_j = 1$ categories. The VBF

contribution is subtracted assuming the expected yield from the SM instead of using the simultaneous fit to the VBF signal regions as is done for the inclusive cross sections. The non-negligible ggF yield in the VBF categories would require an assumption on the ggF acceptance for different jet multiplicities, whereas the fiducial cross-section measurement is intended to avoid this type of assumption. The effect of the theoretical uncertainties on the VBF signal yield is included in the systematic uncertainties on the cross sections. The obtained signal strengths are

$$\begin{aligned} \mu_{0j,e\mu}^{\text{ggF}} &= 1.39 \quad \pm 0.27 \quad \begin{matrix} +0.21 \\ -0.19 \end{matrix} \quad \begin{matrix} +0.27 \\ -0.17 \end{matrix} \\ \mu_{1j,e\mu}^{\text{ggF}} &= 1.14 \quad \begin{matrix} +0.42 \\ -0.41 \end{matrix} \quad \begin{matrix} +0.27 \\ -0.26 \end{matrix} \quad \begin{matrix} +0.42 \\ -0.17 \end{matrix} \end{aligned} \quad (25)$$

(stat) (syst) (sig)

where (sig) indicates the systematic uncertainties on the signal yield and acceptance, which do not apply to the fiducial cross-section measurements. The corresponding cross sections, evaluated at $m_H = 125.36$ GeV and using the 8 TeV data, are

$$\begin{aligned} \sigma_{\text{fid},0j}^{\text{ggF}} &= 27.6 \quad \begin{matrix} +5.4 \\ -5.3 \end{matrix} \quad \begin{matrix} +4.1 \\ -3.9 \end{matrix} = 27.6 \quad \begin{matrix} +6.8 \\ -6.6 \end{matrix} \text{ fb} \\ \sigma_{\text{fid},1j}^{\text{ggF}} &= 8.3 \quad \begin{matrix} +3.1 \\ -3.0 \end{matrix} \quad \begin{matrix} +2.0 \\ -1.9 \end{matrix} = 8.3 \quad \begin{matrix} +3.7 \\ -3.5 \end{matrix} \text{ fb}. \end{aligned} \quad (26)$$

(stat) (syst)

The predicted values are 19.9 ± 3.3 fb and 7.3 ± 1.8 fb, respectively.

X. CONCLUSIONS

An observation of the decay $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ with a significance of 6.1 standard deviations is achieved by an analysis of ATLAS data corresponding to 25 fb^{-1} of integrated luminosity from $\sqrt{s} = 7$ and 8 TeV pp collisions produced by the Large Hadron Collider at CERN. This observation confirms the predicted decay of the Higgs boson to W bosons, at a rate consistent with that given by the Standard Model. The SM predictions are additionally supported by evidence for VBF production in this channel, with an observed significance of 3.2 standard deviations.

For a Higgs boson with a mass of 125.36 GeV, the ratios of the measured cross sections to those predicted by the Standard Model are consistent with unity for both gluon-fusion and vector-boson-fusion production:

$$\begin{aligned} \mu &= 1.09 \quad \begin{matrix} +0.23 \\ -0.21 \end{matrix}, \\ \mu_{\text{ggF}} &= 1.02 \quad \begin{matrix} +0.29 \\ -0.26 \end{matrix}, \\ \mu_{\text{VBF}} &= 1.27 \quad \begin{matrix} +0.53 \\ -0.45 \end{matrix}. \end{aligned} \quad (27)$$

The measurement uncertainties are reduced by 30% relative to the prior ATLAS $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ measurements due to improved analysis techniques. The corresponding cross section times branching fraction values are

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$$\begin{aligned}
\sigma_{\text{ggF}}^{7 \text{ TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 2.0^{+2.1}_{-2.0} \text{ pb}, \\
\sigma_{\text{ggF}}^{8 \text{ TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 4.6^{+1.2}_{-1.1} \text{ pb}, \\
\sigma_{\text{VBF}}^{8 \text{ TeV}} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 0.51^{+0.22}_{-0.17} \text{ pb}.
\end{aligned} \tag{28}$$

These total cross sections, as well as the fiducial cross sections measured in the exclusive $n_j = 0$ and $n_j = 1$ categories, allow future comparisons to the more precise cross section calculations currently under development.

The analysis strategies described in this paper set the stage for more precise measurements using future collisions at the LHC. The larger data sets will significantly reduce statistical uncertainties; further modeling and analysis improvements will be required to reduce the leading systematic uncertainties. Future precise measurements of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay will provide more stringent tests of the detailed SM predictions of the Higgs boson properties.

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APPENDIX A: STATISTICAL TREATMENT DETAILS

1. Binning of fit variables

The m_T distribution is used in the likelihood fit for the ggF-enriched n_j samples (see Sec. VII). Figure 43 shows an example of the binned m_T distribution in the most sensitive kinematic region of $n_j = 0$ and $e\mu$ lepton-flavor category. The optimization procedure for the widths was discussed in Sec. VII A. Table XXIX gives the details of the binning for every kinematic region. The m_T range between the bin 1 (around 80 GeV) and the last bin (around 120 GeV) is binned in variable widths. For kinematic regions in the $n_j = 0$ category, the variable widths are approximately 6 GeV; for $n_j = 1$, the widths are approximately 10 GeV. For both samples, the rms of the bin widths from the mean bin width is approximately 1 GeV. Lastly, the ggF-enriched $n_j \geq 2$ and the cross-check VBF-enriched $n_j \geq 2$ categories use the same set of fixed m_T bin boundaries with bins of variable width.

2. Drell-Yan estimate in $ee/\mu\mu$ for $n_j \leq 1$

The details of the treatment for the Drell-Yan estimate for the $ee/\mu\mu$ category in the $n_j \leq 1$ sample are described.

The method uses additional control regions to constrain the parameters corresponding to the selection efficiencies of contributing processes categorized into “DY” and “non-DY”; the latter includes the signal events. The variable f_{recoil} is used to separate the two categories, and to divide the sample into “pass” and “fail” subsamples. In the $ee/\mu\mu$ categories, the pass samples are enriched in non-DY events and, conversely, the fail samples are enriched in DY events. The residual cross-contamination is estimated using additional control regions.

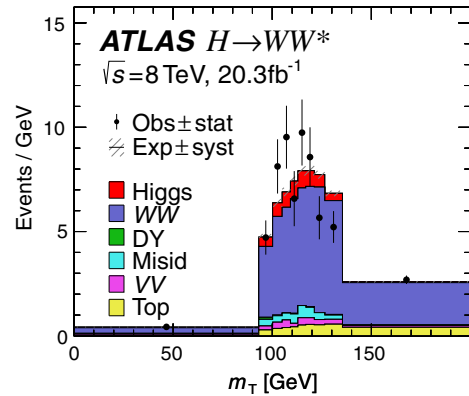


FIG. 43 (color online). Transverse mass distribution shown with variable bin widths as used in the likelihood fit. The most sensitive signal region is shown ($n_j = 0$, $e\mu$, and $\ell_2 = \mu$ in $m_{\ell\ell} > 30$ GeV and $p_T^{\ell_2} > 20$ GeV).

TABLE XXIX. m_T bins for the likelihood fit in the 8 TeV analysis. The first bin spans 0 to “bin 2 left edge”; the last bin spans “last bin left edge” to ∞ . The bin widths w_b of those between the first and last bins are given. The mean of the variable width bins, $\bar{w} = \sum_b w_b / (n_{\text{bins}} - 2)$, is given as well as the rms of the deviation with respect to the mean, $\sqrt{\sum_b (\bar{w} - w_b)^2 / (n_{\text{bins}} - 2)}$. All energy-related quantities are in GeV.

Category					Bin left edge		Bin widths w_b for bin b									Mean width, rms of deviation		
Sample	ℓ_2	$m_{\ell\ell}$	$p_{\text{T}}^{\ell_2^2}$	n_{bins}	bin 2	last bin	2	3	4	5	6	7	8	9	$\bar{w}$	rms	Plot of $\bar{w} \pm \text{rms}$	
$n_j = 0$																		
$e\mu$	μ	10–30	10–15	10	74.5	118.2	5.9	5.0	4.5	4.5	4.5	5.0	5.8	8.5	5.5	1.3		
$e\mu$	μ		15–20	10	81.6	122.1	6.3	4.6	4.1	4.0	4.1	4.5	5.3	7.6	5.1	1.2		
$e\mu$	μ		20–∞	10	93.7	133.7	6.3	4.6	3.8	3.9	3.8	4.3	5.2	8.1	5.0	1.4		
$e\mu$	μ	30–55	10–15	10	84.1	124.7	6.4	4.6	4.4	4.0	4.4	4.4	5.2	7.2	5.1	1.1		
$e\mu$	μ		15–20	10	86.3	125.8	6.0	4.7	4.4	4.0	4.0	4.2	5.1	7.1	4.9	1.0		
$e\mu$	μ		20–∞	10	93.2	135.4	7.0	4.8	4.2	3.8	3.9	4.2	5.3	9.0	5.3	1.7		
$e\mu$	e	10–30	10–15	10	76.7	118.0	5.8	4.5	4.2	4.0	4.5	4.7	5.7	7.9	5.2	1.2		
$e\mu$	e		15–20	10	80.8	121.4	5.9	4.8	4.4	3.9	4.1	4.6	5.3	7.6	5.1	1.1		
$e\mu$	e		20–∞	10	93.1	133.6	6.7	4.9	4.0	3.8	3.8	4.2	5.0	8.1	5.1	1.5		
$e\mu$	e	30–55	10–15	10	84.9	125.7	6.0	4.7	4.3	3.9	4.1	4.4	5.4	8.0	5.1	1.3		
$e\mu$	e		15–20	10	85.0	125.2	6.6	4.8	4.1	3.9	3.9	4.2	5.2	7.5	5.0	1.3		
$e\mu$	e		20–∞	10	93.5	135.8	6.8	4.9	4.2	3.8	3.8	4.3	5.5	9.0	5.3	1.7		
$ee/\mu\mu$	-	12–55	10–∞	10	95.1	128.8	4.9	4.0	3.5	3.3	3.4	3.6	4.3	6.7	4.2	1.1		
$n_j = 1$																		
$e\mu$	μ	10–30	10–15	6	79.0	118.7	10.5	8.5	8.8	11.9	-	-	-	-	9.9	1.4		
$e\mu$	μ		15–20	6	81.6	119.7	10.6	9.6	8.4	9.5	-	-	-	-	9.5	0.8		
$e\mu$	μ		20–∞	6	86.7	127.4	11.2	9.1	9.3	11.1	-	-	-	-	10.2	1.0		
$e\mu$	μ	30–55	10–15	6	79.6	116.0	9.1	9.2	8.3	9.8	-	-	-	-	9.1	0.5		
$e\mu$	μ		15–20	6	81.9	120.2	10.3	9.2	8.6	10.2	-	-	-	-	9.6	0.7		
$e\mu$	μ		20–∞	6	87.4	127.9	11.1	8.7	9.3	11.4	-	-	-	-	10.1	1.1		
$e\mu$	e	10–30	10–15	6	88.1	123.3	9.9	7.9	7.3	10.1	-	-	-	-	8.8	1.2		
$e\mu$	e		15–20	6	88.2	123.9	9.7	7.9	7.8	10.3	-	-	-	-	8.9	1.1		
$e\mu$	e		20–∞	6	92.0	130.2	9.5	8.2	8.9	11.6	-	-	-	-	9.6	1.3		
$e\mu$	e	30–55	10–15	6	87.0	121.7	8.9	9.1	7.0	9.7	-	-	-	-	8.7	1.0		
$e\mu$	e		15–20	6	87.4	123.2	9.6	8.1	8.6	9.5	-	-	-	-	9.0	0.6		
$e\mu$	e		20–∞	6	91.2	129.0	10.1	8.3	8.1	11.3	-	-	-	-	9.5	1.3		
$ee/\mu\mu$	-	12–55	10–∞	6	96.9	126.7	8.3	6.5	6.3	8.7	-	-	-	-	7.5	1.1		
$n_j \geq 2$ ggF																		
$e\mu$	-	10–55	10–∞	4	50.0	130.0	30	50	-	-	-	-	-	-	40	10	Not displayed	
$n_j \geq 2$ VBF cross-check																		
$e\mu$	-	10–55	10–∞	4	50.0	130.0	30	50	-	-	-	-	-	-	40	10	Not displayed	
$ee/\mu\mu$	-	12–55	10–∞	4	50.0	130.0	30	50	-	-	-	-	-	-	40	10	Not displayed	

Of particular interest is the data-derived efficiency of the f_{recoil} selection for the DY and non-DY events. The efficiency of the applied f_{recoil} selection on DY events (on ε_{DY}) is obtained from the $ee/\mu\mu$ sample in the Z peak (in the Z CR), defined by the dilepton mass range $|m_{\ell\ell} - m_Z| < 15$ GeV. Events in the Z CR are relatively pure in DY. The ε_{DY} estimates the efficiency of the selection due to neutrinoless events with missing transverse momentum due to misreconstruction, or “fake missing transverse momentum.” The same parameter appears in two terms, one for the Z CR and the other for the signal region, each composed of two Poisson functions.

The non-DY events with neutrino final states, or “real missing transverse momentum,” contaminate both the Z CR and the SR, and the two corresponding f_{recoil} selection efficiencies, $\varepsilon'_{\text{non-DY}}$ and $\varepsilon_{\text{non-DY}}$, are evaluated separately. The non-DY efficiency in the Z CR, $\varepsilon'_{\text{non-DY}}$, is evaluated using the Z CR selection except with the $e\mu$ sample, which is pure in non-DY events. The SR efficiency $\varepsilon_{\text{non-DY}}$ is evaluated using the $ee/\mu\mu$ SR selection (described in Sec. VI E 2) applied to an $e\mu$ sample.

The fit CR part of the likelihood function [Eq. (11)] contains two Poisson functions that represent events—in the Z mass window in the $ee/\mu\mu$ category—that pass or fail the f_{recoil} selection:

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$$\begin{aligned} & f(N_{\text{pass}}^{\text{ZCR}} | \beta'_{\text{DY}} \cdot \epsilon_{\text{DY}} \cdot B_{\text{DY}}^{\text{ZCR}} + \epsilon'_{\text{non-DY}} \cdot B_{\text{non-DY}}^{\text{ZCR}}) \cdot \\ & f(N_{\text{fail}}^{\text{ZCR}} | \beta'_{\text{DY}} \cdot (1 - \epsilon_{\text{DY}}) \cdot B_{\text{DY}}^{\text{ZCR}} + (1 - \epsilon'_{\text{non-DY}}) \cdot B_{\text{non-DY}}^{\text{ZCR}}), \end{aligned} \quad (\text{A1})$$

where N is the observed number of events and B the background estimate without applying an f_{recoil} selection. The superscript denotes the Z CR mass window; the subscript pass (fail) denotes the sample of events that pass (fail) the f_{recoil} selection; and the subscripts DY (non-DY) denotes background estimates for the Drell-Yan (all except Drell-Yan) processes. The non-DY estimate, $B_{\text{non-DY}}^{\text{ZCR}}$, is a sum of all contributing processes listed in Table I; normalization factors, such as β_{WW} , that are described in Sec. VI are implicitly applied to the corresponding contributions. The Drell-Yan estimate is normalized explicitly by a common normalization factor β'_{DY} applied to both the passing and failing subsamples of the Z peak.

The $\epsilon'_{\text{non-DY}}$ parameter above is determined using events in the $e\mu$ category. The corresponding Poisson functions are included in the likelihood:

$$\begin{aligned} & f(N_{\text{pass}}^{\text{ZCR}, e\mu} | \epsilon'_{\text{non-DY}} \cdot B_{\text{non-DY}}^{\text{ZCR}, e\mu}) \cdot \\ & f(N_{\text{fail}}^{\text{ZCR}, e\mu} | (1 - \epsilon'_{\text{non-DY}}) \cdot B_{\text{non-DY}}^{\text{ZCR}, e\mu}), \end{aligned} \quad (\text{A2})$$

where the $e\mu$ in the superscript denotes the Z CR mass window for events in the $e\mu$ category; all other notation follows the convention for Eq. (A1). The DY contamination in this region is implicitly subtracted.

The SR part of the likelihood also contains two Poisson functions—using the same ϵ_{DY} above, but a different β_{DY} and $\epsilon_{\text{non-DY}}$ corresponding to the SR—is

$$\begin{aligned} & f(N_{\text{pass}}^{\text{SR}} | \beta_{\text{DY}} \cdot \epsilon_{\text{DY}} \cdot B_{\text{DY}}^{\text{SR}} + \epsilon_{\text{non-DY}} \cdot B_{\text{non-DY}}^{\text{SR}}) \cdot \\ & f(N_{\text{fail}}^{\text{SR}} | \beta_{\text{DY}} \cdot (1 - \epsilon_{\text{DY}}) \cdot B_{\text{DY}}^{\text{SR}} + (1 - \epsilon_{\text{non-DY}}) \cdot B_{\text{non-DY}}^{\text{SR}}), \end{aligned} \quad (\text{A3})$$

where SR denotes the signal region selection and β_{DY} is the common normalization factor for the Drell-Yan estimate for the pass and fail subsamples.

The parameter $\epsilon_{\text{non-DY}}$ is constrained following the same strategy as Eq. (A2) with

$$\begin{aligned} & f(N_{\text{pass}}^{\text{SR}, e\mu} | \epsilon_{\text{non-DY}} \cdot B_{\text{non-DY}}^{\text{SR}, e\mu}) \cdot \\ & f(N_{\text{fail}}^{\text{SR}, e\mu} | (1 - \epsilon_{\text{non-DY}}) \cdot B_{\text{non-DY}}^{\text{SR}, e\mu}), \end{aligned} \quad (\text{A4})$$

where the $e\mu$ in the superscript denotes the $ee/\mu\mu$ SR selection (including the one on f_{recoil}) applied to events in the $e\mu$ category. As noted before, the DY contamination in this region is implicitly subtracted.

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3. Top-quark estimate for $n_j = 1$

The details of the *in situ* treatment for the b -tagging efficiency for the top-quark estimate for $n_j = 1$ category are described.

The method uses two control regions within the $n_j = 2$ sample: those with one and two b -jets. These CRs constrain the normalization parameter for the b -tagging efficiency of top-quark events ($\beta_{b\text{-tag}}$) and for the top-quark cross section in these regions (β_{top}).

The Poisson terms for the control regions are

$$\begin{aligned} & f(N_{2j}^{2b} | \beta_{\text{top}} \cdot \beta_{b\text{-tag}} \cdot B_{\text{top}}^{2b} + B_{\text{other}}) \cdot \\ & f(N_{2j}^{1b} | \beta_{\text{top}} \cdot B_{\text{top}}^{1b} + \beta_{\text{top}} \cdot (1 - \beta_{b\text{-tag}}) \cdot B_{\text{top}}^{2b} + B_{\text{other}}), \end{aligned} \quad (\text{A5})$$

where N_{2j}^{1b} (N_{2j}^{2b}) corresponds to the number of observed events with one (two) b -jets; B_{top}^{1b} (B_{top}^{2b}) is the corresponding top-quark estimates from MC samples; and B_{other} are the rest of the processes contributing to the sample.

The parameter β_{top} enters only in the above terms, while $\beta_{b\text{-tag}}$ is applied to other regions. In the top-quark CR, one factor of β_{top} is applied to the expected top-quark yield. In the SR and the WW CR, the treatment is of the same form as the second line of Eq. (A5) applied to the $n_j = 1$ sample, i.e., the estimated top-quark background is $B_{\text{top}}^{0b} + (1 - \beta_{b\text{-tag}}) \cdot B_{\text{top}}^{1b}$.

In summary, the difference between the observed and the expected b -tagging efficiency corrects the number of estimated untagged events in the SR.

APPENDIX B: BDT PERFORMANCE

Section IV C motivated the choice of variables used in the $n_j \geq 2$ VBF-enriched category based on their effectiveness in the cross-check analysis. Many of the variables exploit the VBF topology with two forward jets and no activity in the central region. The main analysis in this category is based on the multivariate technique that uses those variables as inputs to the training of the BDT. The training is optimized on the simulated VBF signal production and it treats simulated ggF production as a background. Figures 44 and 45 show the distributions of the input variables in the $e\mu$ and $ee/\mu\mu$ samples, respectively. The comparison is based only on MC simulation and it shows the separation between the VBF signal and the background processes, motivating the use of the chosen variables.

The O_{BDT} distributions are shown in Fig. 46. The lowest O_{BDT} score is assigned to the events that are classified as background, and the highest score selects the VBF signal events. This separation can be seen in these distributions. The final binning configuration is four bins with boundaries

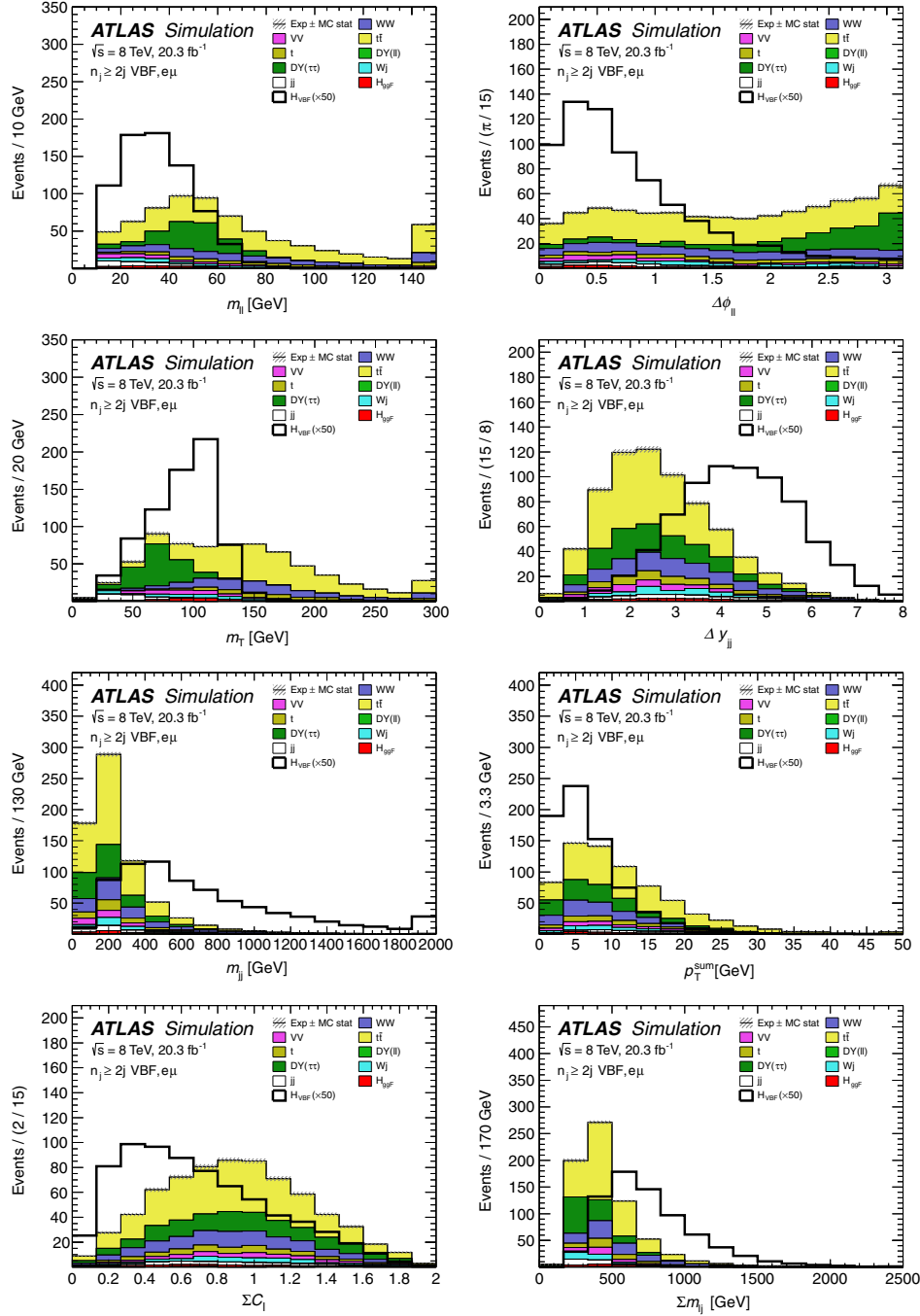


FIG. 44 (color online). Distributions of the variables used as inputs to the training of the BDT in the $e\mu$ sample in the 8 TeV data analysis. The variables are shown after the common preselection and the additional selection requirements in the $n_j \geq 2$ VBF-enriched category, and they include: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T , and Δy_{jj} (top two rows); m_{jj} , p_T^{sum} , ΣC_ℓ , and $\Sigma m_{\ell\ell}$ (bottom two rows). The distributions show the separation between the VBF signal and background processes (ggF signal production is treated as such). The VBF signal is scaled by 50 to enhance the differences in the shapes of the input variable distributions. The SM Higgs boson is shown at $m_H = 125$ GeV. The uncertainties on the background prediction are only due to MC sample size.

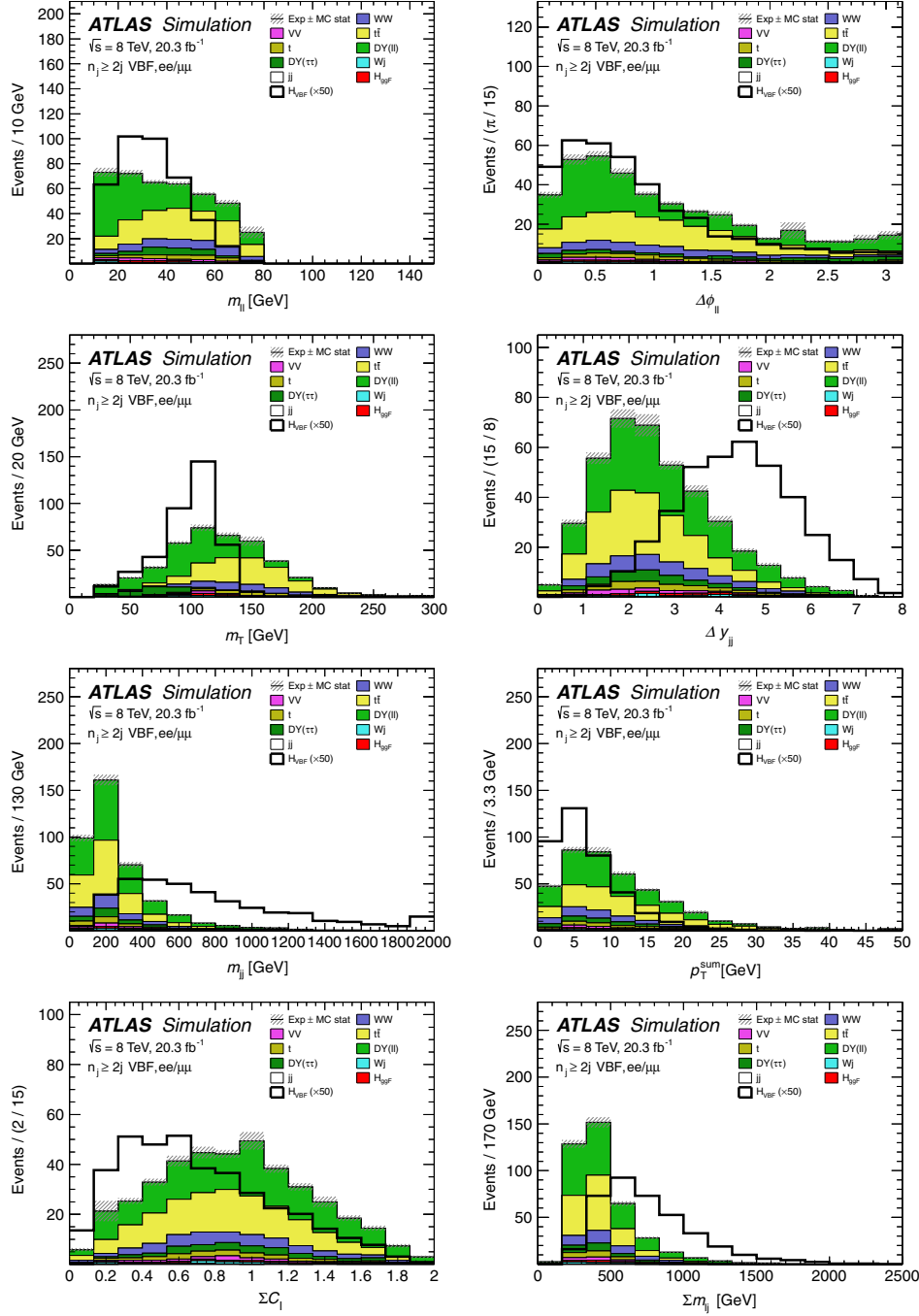
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FIG. 45 (color online). Distributions of the variables used as inputs to the training of the BDT in the $ee/\mu\mu$ sample in the 8 TeV data analysis. The variables are shown after the common preselection and the additional selection requirements in the $n_j \geq 2$ VBF-enriched category, and they include $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T , and Δy_{jj} (top two rows); m_{jj} , p_T^{sum} , ΣC_ℓ , and $\Sigma m_{\ell j}$ (bottom two rows). The distributions show the separation between the VBF signal and background processes (ggF signal production is treated as such). The VBF signal is scaled by 50 to enhance the differences in the shapes of the input variable distributions. The SM Higgs boson is shown at $m_H = 125$ GeV. The uncertainties on the background prediction are only due to MC sample size.

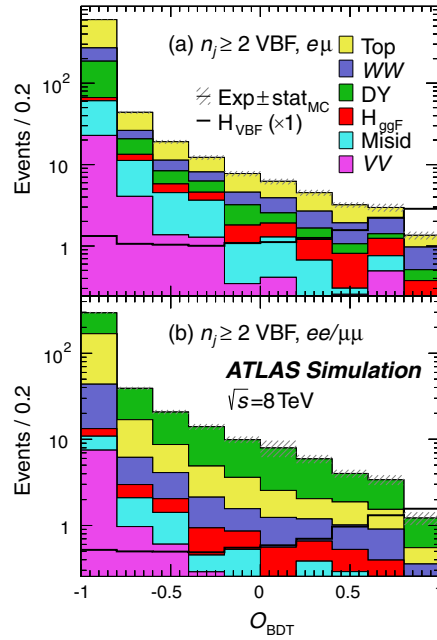


FIG. 46 (color online). Distributions of BDT output in the $n_j \geq 2$ VBF-enriched category in the (a) $e\mu$ and (b) $ee/\mu\mu$ samples in the 8 TeV data analysis. The distributions show the separation between the VBF signal and background processes (ggF signal production is treated as such). The VBF signal is overlaid to show the differences in the shapes with respect to the background prediction. The DY contribution in (b) is stacked on top, unlike in the legend, to show the dominant contribution; the other processes follow the legend order. The SM Higgs boson is shown at $m_H = 125$ GeV. The uncertainties on the background prediction are only due to MC sample size.

at $[-1, -0.48, 0.3, 0.78, 1]$, and with bin numbering from 0 to 3. The background estimation and the signal extraction is then performed in bins of O_{BDT} . Figure 47 shows the data-to-MC comparison of the input variables in the three highest O_{BDT} bins. Good agreement is observed in all the distributions. The event properties of the observed events in the highest BDT bin in the $n_j \geq 2$ VBF-enriched category are shown in Table XXX.

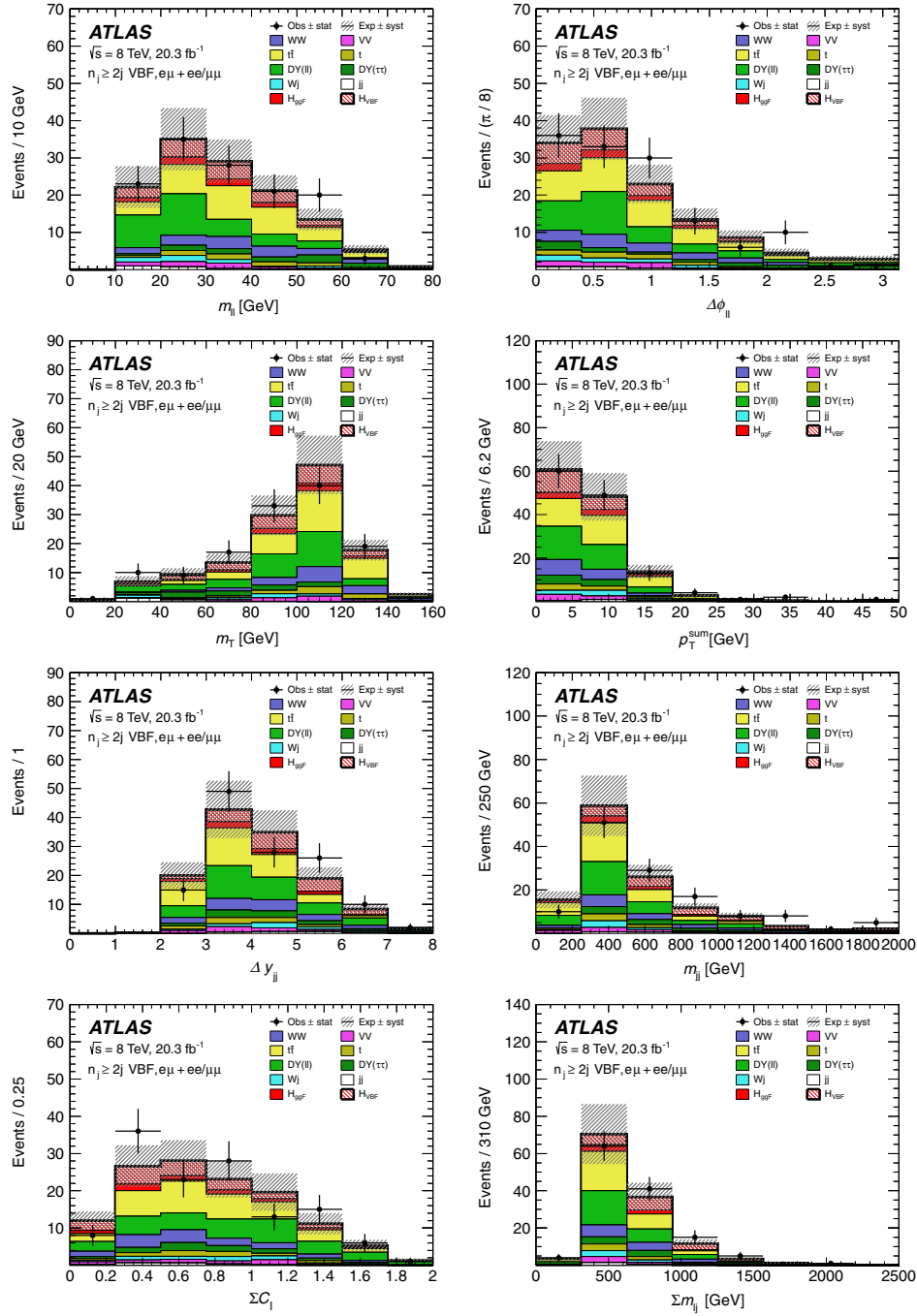
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FIG. 47 (color online). Comparisons of the observed and expected distributions of the variables used as inputs to the training of the BDT in the $e\mu + ee/\mu\mu$ samples in the 8 TeV data analysis. The variables are shown after the common preselection and the additional selection requirements in the $n_j \geq 2$ VBF-enriched category, and after the BDT classification selecting the final signal region (BDT bins 1–3, $O_{\text{BDT}} > -0.48$). The variables shown are $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T , and p_T^{sum} (top two rows); Δy_{jj} , m_{jj} , ΣC_ℓ , and Σm_ℓ (bottom two rows). The SM Higgs boson is shown at $m_H = 125$ GeV. Both the statistical and systematic uncertainties are included.

TABLE XXX. Event properties of the Higgs candidates in BDT bin 3 ($O_{\text{BDT}} > 0.78$) of the $n_j \geq 2$ VBF-enriched category in the 8 TeV data analysis. The energy-related quantities are in GeV.

Sample	O_{BDT}	BDT input variables								p_T and η of leptons and jets							
		m_T	$m_{\ell\ell}$	$\Delta\phi_{\ell\ell}$	ΣC_ℓ	m_{jj}	Δy_{jj}	$\Sigma m_{\ell j}$	p_T^{sum}	$p_T^{\ell 1}$	$p_T^{\ell 2}$	$\eta_{\ell 1}$	$\eta_{\ell 2}$	p_T^{j1}	p_T^{j2}	η_{j1}	η_{j2}
$e\mu$ sample	0.92	113	19.8	0.26	0.25	1290	5.30	810	3.2	50	15	0.6	-0.1	110	74	2.9	-2.4
	0.88	102	27.2	0.62	0.83	530	3.75	540	2.5	39	16	-0.5	0.4	80	79	-2.7	1.1
	0.85	87	19.9	0.02	1.01	1770	7.55	1510	4.8	73	20	1.6	2.2	50	32	3.8	-3.8
	0.84	105	26.5	0.64	0.86	1500	5.58	1250	7.4	84	21	0.8	0.7	115	73	2.4	-3.2
	0.81	43	31.7	1.08	0.05	850	5.44	710	2.2	48	20	0.5	0.4	84	37	-2.2	3.2
	0.78	84	37.2	0.18	0.76	810	5.26	660	4.8	29	18	-1.5	0.1	82	41	-2.4	2.9
$ee/\mu\mu$ sample	0.92	66	38.9	0.18	0.33	1370	5.15	1060	2.2	61	31	0.4	1.2	118	90	-3.2	2.0
	0.91	102	27.4	0.65	0.24	1260	5.97	780	2.5	34	23	-0.5	0.2	101	40	-3.1	2.9
	0.89	81	26.3	0.08	0.57	670	3.97	1210	8.1	147	44	1.4	1.1	168	49	-1.3	2.7
	0.81	118	57.6	2.31	0.28	700	3.90	610	6.6	32	29	1.3	0.8	113	83	-1.2	2.7
	0.81	116	18.5	0.33	0.19	670	3.97	650	2.9	54	25	-1.7	-1.3	119	68	0.4	-3.6
	0.80	108	50.1	0.80	0.87	740	4.68	660	2.1	46	15	-0.4	-2.0	123	41	-2.5	2.2

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A morphing technique for signal modelling in a multidimensional space of coupling parameters

The ATLAS Collaboration

Abstract

This note describes a morphing method that produces signal models for fits to data in which both the affected event yields and kinematic distributions are simultaneously taken into account. The signal model is morphed in a continuous manner through the available multi-dimensional parameter space.

Searches for deviations from Standard Model predictions for Higgs boson properties have so far used information either from event yields or kinematic distributions. The combined approach described here is expected to substantially enhance the sensitivity to beyond the Standard Model contributions.

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1. Introduction

The properties of the newly discovered Higgs boson have been extensively probed by the ATLAS and CMS experiments using LHC Run 1 proton-proton collision data at $\sqrt{s} = 7$ and 8 TeV [1–4]. The studies of the tensor structure of the Higgs boson couplings to gauge bosons were based on signal models including at most one or two beyond-the-standard-model coupling parameters at a time, with all remaining Beyond the Standard Model (BSM) parameters set to zero. For Run 2, it is envisioned to have signal models which depend on a larger number of coupling parameters, in order to account for possible correlations among them. Additional coupling parameters in the Higgs coupling to Standard Model (SM) particles change the predicted cross section, as well as the shape of differential distributions. In this context, it is necessary to revise the existing signal modelling methods and provide alternatives which are better suited for such a multidimensional parameter space.

For this purpose, a morphing method has been developed and implemented. It provides a continuous description of arbitrary physical signal observables such as cross sections or differential distributions in a multidimensional space of coupling parameters. The morphing-based signal model is a linear combination of a minimal set of orthogonal base samples (templates) spanning the full coupling parameter space. The weight of each template is derived from the coupling parameters appearing in the signal matrix element.

Morphing is more than a simple interpolation technique, in that it is not limited to the points in the range spanned by the input samples. In fact, the choice of the input samples is arbitrary, and any set of input samples satisfying the required conditions to build the morphing function will span the entire space, independent of their precise coordinates.

This note is structured as follows. In Section 2, the morphing method will be introduced in detail and compared to the established approach of reweighing events according to re-computed matrix elements. The coupling parametrisation model used in Run 1 ATLAS analysis is presented in Section 3 to serve later as an example for validating the procedure.

The extraction of Higgs boson coupling parameters with a maximum likelihood fit using a model constructed by the morphing method is described in Section 4. The validation results are presented in Section 5. In Section 6 an example study which uses the morphing method to construct a signal model and extract parameters of interest is conducted. In this study the impact of various BSM parameters in the vector-boson-fusion (VBF) production vertex of the Higgs boson on various VBF-specific physical observables is studied. Finally, the conclusions are given in Section 7.

All studies in Sections 5 and 6 are on generator level only, with the exception of the morphing validation described in Section 5.2. This section uses the final discriminating distributions of the ATLAS Run 1 $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis [1] as input for the validation of the morphing technique. Backgrounds are explicitly not taken into account in the example studies.

Higher order QCD and EW corrections are not considered. In the presented work a single resonance with a mass of 125 GeV is assumed. The total width of the Higgs boson is fixed to the SM expectation of 4 MeV and a modification caused by the coupling parameters is not taken into account. For a correct modelling of the total width all coupling parameters of a model need to be considered, not only the parameters that enter in the Higgs boson production or decay. If all parameters that influence the total width are known, the morphing technique can be used to describe the dependence of the total width on the coupling parameters of a model.

2. Signal morphing and comparison to matrix element reweighting

2.1. Morphing principles

The morphing procedure is based on the concepts of the morphing of (possibly multi-dimensional) histograms described in Reference [5]. It is introduced to describe the dependence of a given physical observable T on an arbitrary configuration of a set of non-SM Higgs boson couplings $\vec{g}_{\text{target}} \equiv \{g_{\text{SM}}, g_{\text{BSM},1}, \dots, g_{\text{BSM},n}\}$ to known particles. This dependence is described by a morphing function

$$T_{\text{out}}(\vec{g}_{\text{target}}) = \sum_i w_i(\vec{g}_{\text{target}}; \vec{g}_i) T_{\text{in}}(\vec{g}_i), \quad (1)$$

which linearly combines the values or differential distributions T_{in} at a number of selected discrete coupling configurations $\vec{g}_i = \{g_{\text{SM},i}, \vec{g}_{\text{BSM},i}\}$. The input distributions T_{in} are normalised to their expected cross sections such that T_{out} includes not only the correct shape, but also the correct cross section prediction. Here, g_{SM} denotes the Higgs boson coupling predicted by the Standard Model. Morphing only requires that any differential cross section can be expressed as a polynomial in coupling parameters. For calculation at lowest order and using the narrow-width approximation for a resonance, this yields a second order polynomial each in production and decay.

In practice, the template distributions T_{in} are obtained from the Monte Carlo (MC) simulation of the signal process for a given coupling configuration $\vec{g}_i$. The minimal number N of Monte Carlo samples needed to describe the signal at all possible coupling configurations, depends on the number n of studied non-SM coupling parameters. The contribution of each sample T_{in} is weighted by a weight w_i based on the assumption that the value of a physical observable is proportional to the squared matrix element for the studied process

$$T \propto \mathcal{M}^2. \quad (2)$$

The weights w_i can therefore be expressed as functions of the coupling parameters in the matrix element $\mathcal{M}$. In this case T can be anything derived from the Matrix element, for example a whole MC sample.

The described procedure allows for a continuous description in an n -dimensional parameter space. A feature-complete implementation has been developed within the RooFit package [6], making use of HistFactory [7]. The provided signal model can therefore be used in commonly used RooFit workspaces in a straightforward, blackbox-like way.

In the remainder of this section, several examples for the construction of the model with the morphing method will be shown for the case of Higgs boson production and decay with only one or two non-SM coupling parameters. Subsequently, a generalisation to an n -dimensional coupling parameter space will be presented. Finally, the method is compared and contrasted with the well-established matrix element reweighting approach [8].

2.2. Morphing with one non-SM coupling parameter in the production or decay vertex

As the most simple case, a morphing function is determined with only one non-SM Higgs coupling g_{BSM} contributing to the decay or production in addition to the SM Higgs boson coupling g_{SM} . A typical example is a mixture of the SM and CP-odd Higgs boson couplings to two vector bosons, studied in detail in LHC Run 1 [1, 2].

The matrix element of such a scenario for given values of $\{g_{\text{SM}}, g_{\text{BSM}}\}$ can be written as a sum of the pure SM and the pure BSM contribution¹

$$\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}}) = g_{\text{SM}} \cdot \mathcal{O}_{\text{SM}} + g_{\text{BSM}} \cdot \mathcal{O}_{\text{BSM}}. \quad (3)$$

This translates into the description of a physical observable T from the above signal process,

$$T(g_{\text{SM}}, g_{\text{BSM}}) \propto |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2 = g_{\text{SM}}^2 \cdot \mathcal{O}_{\text{SM}}^2 + g_{\text{BSM}}^2 \cdot \mathcal{O}_{\text{BSM}}^2 + g_{\text{SM}} \cdot g_{\text{BSM}} \cdot 2\Re(\mathcal{O}_{\text{SM}}^* \mathcal{O}_{\text{BSM}}). \quad (4)$$

This can be used to morph to an arbitrary parameter point.

The number of input distributions required to morph to an arbitrary parameter point $\vec{g}_{\text{target}} = \{g_{\text{SM}}, g_{\text{BSM}}\}$ is equal to the unique terms in the matrix element squared, which is three in this case. It is sufficient to generate a pure SM distribution $T_{\text{in}}(1, 0)$, a pure BSM distribution $T_{\text{in}}(0, 1)$ and a mixed distribution $T_{\text{in}}(1, 1)$. Using the proportionalities to the matrix element squared one obtains

$$\begin{aligned} T_{\text{in}}(1, 0) &\propto |\mathcal{O}_{\text{SM}}|^2, \\ T_{\text{in}}(0, 1) &\propto |\mathcal{O}_{\text{BSM}}|^2, \\ T_{\text{in}}(1, 1) &\propto |\mathcal{O}_{\text{SM}}|^2 + |\mathcal{O}_{\text{BSM}}|^2 + 2\Re(\mathcal{O}_{\text{SM}}^* \mathcal{O}_{\text{BSM}}). \end{aligned} \quad (5)$$

Applying these three equations to Equation 4 results in the morphing function for a distribution at an arbitrary parameter point

$$T_{\text{out}}(g_{\text{SM}}, g_{\text{BSM}}) = \underbrace{(g_{\text{SM}}^2 - g_{\text{SM}}g_{\text{BSM}})}_{=w_1} T_{\text{in}}(1, 0) + \underbrace{(g_{\text{BSM}}^2 - g_{\text{SM}}g_{\text{BSM}})}_{=w_2} T_{\text{in}}(0, 1) + \underbrace{g_{\text{SM}}g_{\text{BSM}}}_{=w_3} T_{\text{in}}(1, 1). \quad (6)$$

¹ In this and the following section, the notation $\mathcal{O}$ will be used for the amplitude, whereas the notation $\mathcal{M}$ will be used for fully computed matrix elements. However, since the difference is only conceptual, the symbols are used interchangeably.

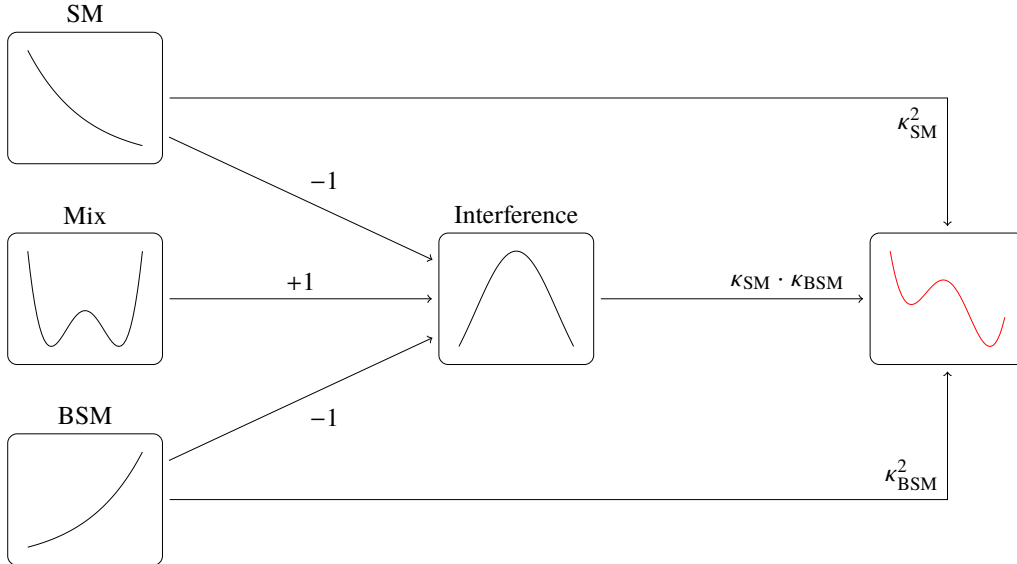


Figure 1: Illustration of the morphing procedure in a simple showcase.

The derivation of this is graphically depicted in Figure 1.

The output distribution can be created by only using the three input distributions multiplied by the appropriate weight factor w_i . Since fixed parameters for the input distributions were used, the weights only depend on the desired parameters for the output distribution.

To minimise later statistical uncertainty in the considered parameter space, it is favourable to be flexible in choosing the parameters for the input distributions. In order to develop a generalisation for a morphing function with arbitrary input parameters $\vec{g}_i$, the proportionality to the matrix element squared of the three input distributions can be written in the following way:

$$T_{\text{in}}(g_{\text{SM},i}, g_{\text{BSM},i}) \propto g_{\text{SM},i}^2 |O_{\text{SM}}|^2 + g_{\text{BSM},i}^2 |O_{\text{BSM}}|^2 + 2g_{\text{SM},i}g_{\text{BSM},i}\mathcal{R}(O_{\text{SM}}^* O_{\text{BSM}}), \quad i = 1, \dots, 3. \quad (7)$$

Now, the following ansatz can be made for the morphing function:

$$\begin{aligned} T_{\text{out}}(g_{\text{SM}}, g_{\text{BSM}}) = & \underbrace{(a_{11}g_{\text{SM}}^2 + a_{12}g_{\text{BSM}}^2 + a_{13}g_{\text{SM}}g_{\text{BSM}})}_{w_1} T_{\text{in}}(g_{\text{SM},1}, g_{\text{BSM},1}) \\ & + \underbrace{(a_{21}g_{\text{SM}}^2 + a_{22}g_{\text{BSM}}^2 + a_{23}g_{\text{SM}}g_{\text{BSM}})}_{w_2} T_{\text{in}}(g_{\text{SM},2}, g_{\text{BSM},2}) \\ & + \underbrace{(a_{31}g_{\text{SM}}^2 + a_{32}g_{\text{BSM}}^2 + a_{33}g_{\text{SM}}g_{\text{BSM}})}_{w_3} T_{\text{in}}(g_{\text{SM},3}, g_{\text{BSM},3}). \end{aligned} \quad (8)$$

Until this point this contains unknown variables a_{ij} . For any of the input parameters, the morphing function should regain the input distribution

$$T_{\text{out}} = T_{\text{in}} \quad \text{for} \quad \vec{g}_{\text{target}} = \vec{g}_i. \quad (9)$$

This results in exactly the right number of constraints needed to recover the unknown variables a_{ij}

$$\begin{aligned} 1 &= a_{11}g_{\text{SM},1}^2 + a_{12}g_{\text{BSM},1}^2 + a_{13}g_{\text{SM},1}g_{\text{BSM},1} \\ 0 &= a_{21}g_{\text{SM},1}^2 + a_{22}g_{\text{BSM},1}^2 + a_{23}g_{\text{SM},1}g_{\text{BSM},1} \\ &\dots \end{aligned} \quad (10)$$

All constraints can be written in a compact matrix form

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} g_{\text{SM},1}^2 & g_{\text{SM},2}^2 & g_{\text{SM},3}^2 \\ g_{\text{BSM},1}^2 & g_{\text{BSM},2}^2 & g_{\text{BSM},3}^2 \\ g_{\text{SM},1}g_{\text{BSM},1} & g_{\text{SM},2}g_{\text{BSM},2} & g_{\text{SM},3}g_{\text{BSM},3} \end{pmatrix} = \mathbb{I} \quad (11)$$

$$\Leftrightarrow A \cdot G = \mathbb{I}.$$

The unique solution $A = G^{-1}$ requires the input parameters to fulfil the condition $\det(G) \neq 0$.

2.3. Morphing with one non-SM coupling parameter in both production and decay

Having a BSM parameter applied in production and decay requires certain adjustments in calculating the morphing function. For simplicity a scenario is discussed for two parameters g_{SM} and g_{BSM} , which are now (in contrast to the previous section) applied in the production and decay vertex. An example for such a

scenario would be Higgs boson production via VBF with decays into two vector bosons V using the SM and one BSM HVV operator.

Again the matrix element squared can be factorised in the following way, assuming the narrow width approximation:

$$\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}}) = (g_{\text{SM}} \cdot \mathcal{O}_{\text{SM},p} + g_{\text{BSM}} \cdot \mathcal{O}_{\text{BSM},p}) \cdot (g_{\text{SM}} \cdot \mathcal{O}_{\text{SM},d} + g_{\text{BSM}} \cdot \mathcal{O}_{\text{BSM},d}). \quad (12)$$

By squaring the matrix element additional interference terms emerge

$$\begin{aligned} |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2 &= (g_{\text{SM}} \mathcal{O}_{\text{SM},p} + g_{\text{BSM}} \mathcal{O}_{\text{BSM},p})^2 \cdot (g_{\text{SM}} \mathcal{O}_{\text{SM},d} + g_{\text{BSM}} \mathcal{O}_{\text{BSM},d})^2 \\ &= g_{\text{SM}}^4 \cdot \mathcal{O}_{\text{SM},p}^2 \mathcal{O}_{\text{SM},d}^2 + g_{\text{BSM}}^4 \cdot \mathcal{O}_{\text{BSM},p}^2 \mathcal{O}_{\text{BSM},d}^2 \\ &\quad + g_{\text{SM}}^3 g_{\text{BSM}} \cdot (\mathcal{O}_{\text{SM},p}^2 \Re(\mathcal{O}_{\text{SM},d}^* \mathcal{O}_{\text{BSM},d}) + \Re(\mathcal{O}_{\text{SM},p}^* \mathcal{O}_{\text{BSM},p}) \mathcal{O}_{\text{SM},d}^2) \\ &\quad + g_{\text{SM}}^2 g_{\text{BSM}}^2 \cdot (\mathcal{O}_{\text{SM},p}^2 \mathcal{O}_{\text{BSM},d}^2 + \mathcal{O}_{\text{BSM},p}^2 \mathcal{O}_{\text{SM},d}^2) \\ &\quad + g_{\text{SM}} g_{\text{BSM}}^3 \cdot (\mathcal{O}_{\text{BSM},p}^2 \Re(\mathcal{O}_{\text{SM},d}^* \mathcal{O}_{\text{BSM},d}) + \Re(\mathcal{O}_{\text{SM},p}^* \mathcal{O}_{\text{BSM},p}) \mathcal{O}_{\text{BSM},d}^2). \end{aligned} \quad (13)$$

Equation 13 is a 4th order polynomial in the coupling parameters g . Each unique term in coupling parameters requires an input distribution for the morphing, which results in 5 different samples for this scenario. The morphing function for arbitrary values of g_{SM} and g_{BSM} for the input distributions is obtained in a similar way as for the previous case. First the input distributions are proportional to the matrix element squared

$$T_{\text{in}}(g_{\text{SM},i}, g_{\text{BSM},i}) \propto |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2, \quad i = 1, \dots, 5. \quad (14)$$

Again, an ansatz is used for the morphing function

$$\begin{aligned} T_{\text{out}}(g_{\text{SM}}, g_{\text{BSM}}) &= \underbrace{(a_{11}g_{\text{SM}}^4 + a_{12}g_{\text{SM}}^3g_{\text{BSM}} + a_{13}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{14}g_{\text{SM}}g_{\text{BSM}}^3 + a_{15}g_{\text{BSM}}^4)}_{w_1} T_{\text{in}}(g_{\text{SM},1}, g_{\text{BSM},1}) \\ &= \underbrace{(a_{21}g_{\text{SM}}^4 + a_{22}g_{\text{SM}}^3g_{\text{BSM}} + a_{23}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{24}g_{\text{SM}}g_{\text{BSM}}^3 + a_{25}g_{\text{BSM}}^4)}_{w_2} T_{\text{in}}(g_{\text{SM},2}, g_{\text{BSM},2}) \\ &= \underbrace{(a_{31}g_{\text{SM}}^4 + a_{32}g_{\text{SM}}^3g_{\text{BSM}} + a_{33}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{34}g_{\text{SM}}g_{\text{BSM}}^3 + a_{35}g_{\text{BSM}}^4)}_{w_3} T_{\text{in}}(g_{\text{SM},3}, g_{\text{BSM},3}) \\ &= \underbrace{(a_{41}g_{\text{SM}}^4 + a_{42}g_{\text{SM}}^3g_{\text{BSM}} + a_{43}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{44}g_{\text{SM}}g_{\text{BSM}}^3 + a_{45}g_{\text{BSM}}^4)}_{w_4} T_{\text{in}}(g_{\text{SM},4}, g_{\text{BSM},4}) \\ &= \underbrace{(a_{51}g_{\text{SM}}^4 + a_{52}g_{\text{SM}}^3g_{\text{BSM}} + a_{53}g_{\text{SM}}^2g_{\text{BSM}}^2 + a_{54}g_{\text{SM}}g_{\text{BSM}}^3 + a_{55}g_{\text{BSM}}^4)}_{w_5} T_{\text{in}}(g_{\text{SM},5}, g_{\text{BSM},5}). \end{aligned} \quad (15)$$

Requiring that the output distribution reproduces the input distributions at their respective parameters, constraints are set to calculate the unknown variables a_{ij} in the morphing function.

In matrix form, all constraints are written as

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{pmatrix} \cdot \begin{pmatrix} g_{\text{SM},1}^4 & g_{\text{SM},2}^4 & g_{\text{SM},3}^4 & g_{\text{SM},4}^4 & g_{\text{SM},5}^4 \\ g_{\text{SM},1}^3 g_{\text{BSM},1} & g_{\text{SM},2}^3 g_{\text{BSM},2} & g_{\text{SM},3}^3 g_{\text{BSM},3} & g_{\text{SM},4}^3 g_{\text{BSM},4} & g_{\text{SM},5}^3 g_{\text{BSM},5} \\ g_{\text{SM},1}^2 g_{\text{BSM},1}^2 & g_{\text{SM},2}^2 g_{\text{BSM},2}^2 & g_{\text{SM},3}^2 g_{\text{BSM},3}^2 & g_{\text{SM},4}^2 g_{\text{BSM},4}^2 & g_{\text{SM},5}^2 g_{\text{BSM},5}^2 \\ g_{\text{SM},1} g_{\text{BSM},1}^3 & g_{\text{SM},2} g_{\text{BSM},2}^3 & g_{\text{SM},3} g_{\text{BSM},3}^3 & g_{\text{SM},4} g_{\text{BSM},4}^3 & g_{\text{SM},5} g_{\text{BSM},5}^3 \\ g_{\text{BSM},1}^4 & g_{\text{BSM},2}^4 & g_{\text{BSM},3}^4 & g_{\text{BSM},4}^4 & g_{\text{BSM},5}^4 \end{pmatrix} = \mathbb{I} \quad \Leftrightarrow \quad A \cdot G = \mathbb{I}. \quad (16)$$

Again, the input parameters must be chosen such that the requirement $\det(G) \neq 0$ is satisfied.

2.4. Generalisation to higher-dimensional parameter space

After the instructional examples provided above in sections 2.2 and 2.3, it is now straightforward to spell out a step-by-step explanation on how to construct the morphing function for processes with an arbitrary number of free coupling parameters in two vertices.

1. Construct a general matrix element squared

$$|\mathcal{M}(\vec{g})|^2 = \underbrace{\left(\sum_{x \in p,b} g_x \mathcal{O}(g_x) \right)^2}_{\text{production}} \cdot \underbrace{\left(\sum_{x \in d,b} g_x \mathcal{O}(g_x) \right)^2}_{\text{decay}}. \quad (17)$$

2. Expand the matrix element squared to a 4th degree polynomial in the coupling parameters

$$|\mathcal{M}(\vec{g})|^2 = \sum_{i=1}^N X_i \cdot P_i(\vec{g}), \quad (18)$$

X_i is a prefactor, which will be represented by an input distribution. In the 4th degree polynomial $P_i(\vec{g}) = g_a g_b g_c g_d$ of the coupling parameters $\vec{g}$, the same coupling can occur multiple times (e.g. g_{SM}^4 or $g_{\text{BSM},1} g_{\text{BSM},2} g_{\text{BSM},3}^2$). The number of different expressions in the polynomial N is equal to the number of samples needed for the morphing.

3. Next generate input distributions at arbitrary but fixed parameter points $\vec{g}_i$

$$T_{\text{in},i} \propto |\mathcal{M}(\vec{g}_i)|^2. \quad (19)$$

4. Construct the morphing function with an ansatz

$$T_{\text{out}}(\vec{g}) = \sum_{i=1}^N \underbrace{\left(\sum_{j=1}^N A_{ij} P_j(\vec{g}) \right)}_{w_i(\vec{g})} T_{\text{in},i}. \quad (20)$$

$$= \vec{P}(\vec{g}) \cdot A \vec{T}, \quad (21)$$

where the second line is the first one recast in matrix notation. The matrix A has to be calculated to obtain the full morphing function.

5. Thus, exploit that the output distribution should be equal to the input distribution at the respective input parameters

$$T_{\text{out}}(\vec{g}_i) = T_{\text{in},i} \quad \text{for} \quad i = 1, \dots, N. \quad (22)$$

which can also be cast in matrix notation as

$$\begin{aligned} A \cdot (P_j(\vec{g}_i))_{ij} &= \mathbb{1} \\ \Leftrightarrow A \cdot G &= \mathbb{1}. \end{aligned} \quad (23)$$

6. The unique solution $A = G^{-1}$ requires the input parameters to fulfil the condition $\det(G) \neq 0$.

When the aim is to perform a likelihood fit on some (pseudo-)data T_d , the minimisation condition is

$$\hat{\vec{g}}(T_d) = \arg \min_{\vec{g}} -2 \ln P \left(T_d \mid \mu = \sum_{i=1}^N \left(\sum_{j=1}^N A_{ij} P_j(\vec{g}) \right) T_{\text{in},i} \right). \quad (24)$$

From this it becomes apparent that only the polynomials $P_j(\vec{g})$ need to be recalculated during the minimisation process, while the non-trivial quantities A_{ij} and $T_{\text{in},i}$ stay fixed.

The error propagation of statistical uncertainties to the output T_{out} is conceptually straightforward. Since the $\vec{g}_i$ are free parameters, the matrix A carries no uncertainty besides numerical fluctuations. Thus, uncertainties only propagate via linear combinations. The question of how the input parameters $\vec{g}_i$ need to be chosen such that the expected uncertainty of the output is minimal, within some parameter region of interest, is non-trivial and will be addressed in future studies.

The number of base samples increases if there are additional coupling parameters to be considered in the production or decay vertex, for example in the case of a combination of measurements in several production and decay modes. However, the general morphing principle remains the same and the method can be generalised to a higher-dimensional coupling parameter space. The number N of input base samples depends on how many of the n studied coupling parameters enter the production and/or the decay vertex.

In case of the gluon fusion process with subsequent decays to vector bosons, the production and decay will have a completely disjoint set of couplings, and the number of input samples will be

$$N_{\text{ggF}} = n_p \cdot \frac{n_p + 1}{2} \cdot n_d \cdot \frac{n_d + 1}{2}, \quad (25)$$

where n_p are the number of parameters included for the production and n_d the number of parameters included for the decay.

For the VBF Higgs boson production with subsequent decay into vector bosons, when considering the exact same set of couplings in the production and the decay vertex, the number of samples is given by

$$N_{\text{VBF}} = \binom{4 + n_s - 1}{4}, \quad (26)$$

where n_s is the number samples that are shared in production and decay. Both expressions are just the number of terms in the polynomial obtained upon calculation of the matrix element. A general expression

for n_p couplings appearing only in production, n_d couplings appearing only in decay and n_s couplings shared in production and decay can be obtained by careful counting as

$$N = \frac{n_p (n_p + 1)}{2} \cdot \frac{n_d (n_d + 1)}{2} + \binom{4 + n_s - 1}{4} \quad (27)$$

$$+ \left(n_p \cdot n_s + \frac{n_s (n_s + 1)}{2} \right) \cdot \frac{n_d (n_d + 1)}{2} \quad (28)$$

$$+ \left(n_d \cdot n_s + \frac{n_s (n_s + 1)}{2} \right) \cdot \frac{n_p (n_p + 1)}{2} \quad (29)$$

$$+ \frac{n_s (n_s + 1)}{2} \cdot n_p \cdot n_d + (n_p + n_d) \binom{3 + n_s - 1}{3}. \quad (30)$$

In this expression the counting is split for (27) terms pure in production and decay, or pure in shared, (28) terms pure in decay and mixed in production and shared or purely shared, (29) terms pure in production and mixed in decay and shared or purely shared, and (30) terms mixed in both, and terms mixed in one and purely shared in the other.

This is a general definition of the number of samples N in terms of number of coupling parameters n . For example Equation 25 can be reproduced by setting $n_s = 0$ and Equation 26 by $n_p = 0$ and $n_d = 0$.

The full generality of this method is not exploited in the remainder of this note. The cases discussed here are outlined in Table 1.

2.5. Comparison to the matrix element reweighting method

The morphing method presented here is complimentary to the well-known matrix element method. Hence, the latter method is briefly summarised with the intent of highlighting the differences between the methods as well as how the two methods complement each other.

The calculation of theory predictions for e. g. differential cross sections is most conveniently performed via Monte Carlo integration techniques. In these techniques the distribution in question is probed with a finite set of phase space points, which are then treated analogously to observed collision events in data analysis. These probing points, or Monte Carlo events, may carry a certain weight – an arbitrary number assigned by the generator to encode the magnitude of the contribution of this phase space point to the distribution of interest. Some generators choose to use adaptive Monte Carlo techniques to adjust their sampling distribution according to the probed distribution. This ensures that the event weights generated are within a certain (narrow) acceptance band, thus reducing uncertainty of the result. Having events with different weights contributing to the same distribution does not pose any conceptual problems.

Section,	Process	n_p	n_d	n_s	N
5.1.1	ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ truth	1	2	0	3
5.1.2	VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ truth	0	0	3	15
5.2	ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ reconstructed	1	3	0	6
6	VBF $H \rightarrow \mu\mu$ truth	13	1	0	91

Table 1: Overview of the showcases presented in this note in terms of the n -dimensional generalisation.

Since the weight of an event is a measure of the probability assigned to this phase space point (taking into account the sampling distribution of the generator), it is related to the matrix element of the process in question. For some theoretical framework α , the event weight depends on the parton distribution functions f_1 and f_2 as well as on the transfer or (detector) resolution function $W(x, y)$:

$$\omega_\alpha(x) \propto P_\alpha(x) = \frac{1}{\sigma} \int d\phi(y) |\mathcal{M}_\alpha(y)|^2 dw_1 dw_2 f_1(w_1) f_2(w_2) W(x, y). \quad (31)$$

This translates the true quantities of the simulated particles y to the observable quantities x of the same particles after detector simulation and reconstruction and, most notably, on the modulus square of the matrix element $\mathcal{M}_\alpha$ of this transition within the given theoretical framework [8].

As the detector resolution simulation is highly non-trivial and commonly the most expensive part of the event generation process, it has become common practice to generate and simulate events for some theoretical setup α and then, afterwards, translate them to a different theoretical setup α' by considering the ratio between the matrix elements, i. e.

$$\omega_{\alpha'}(y) = \omega_\alpha(y) \frac{|\mathcal{M}_{\alpha'}(y)|^2}{|\mathcal{M}_\alpha(y)|^2}, \quad (32)$$

where the knowledge of the generator information y for the simulated events is exploited to be able to reweight them according to the matrix element values.

This method is related to the morphing technique presented here in that it allows to exploit precomputed results to perform an exact translation into a different theoretical framework. However the matrix element reweighting is a technique that only requires a single input sample and performs the translation on an event-by-event basis, whereas the morphing technique requires several input samples, but is capable of morphing entire distributions of observables. Given the expense of iterating over large input datasets and performing the matrix element calculation on every event, the new morphing method is several orders of magnitude faster in a typical scenario and thus provides the ability to (precisely) approximate the matrix-element weighting in iterative procedures like fits. In order to achieve the same interpolation power with matrix element reweighting, one would need to produce a vast number of reweighted samples, hugely exceeding the number of input samples for the morphing.

However, as the morphing technique requires a (possibly large) number of input samples, it still requires a large amount of resources to be provided upfront for generating and especially simulating the input samples. Therefore a hybrid approach using both methods in a complementary fashion by using matrix element reweighting to save time on detector simulation when creating input samples for applications of morphing is very promising.

3. Parametrisation in the frame of the Higgs characterisation model

The morphing method is completely independent from the parametrisation that is chosen to model non-SM couplings in the interaction of the Higgs boson to SM particles.

For the validation of the morphing method in Section 5.1 the parametrisation of the Higgs characterisation model [9] is chosen. This model has been used in the recently published ATLAS Run 1 analysis [1].

The Higgs characterisation model describes the non-SM couplings of the Higgs boson based on an effective field theory approach. Within this model, the effective Lagrangian for the interaction of a spin-0 particle with gauge bosons is given by

$$\begin{aligned} \mathcal{L}_0^V = & \left\{ c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right. \\ & - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\ & - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\ & - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right] \\ & - \frac{1}{4\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\ & - \frac{1}{2\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \\ & \left. - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W} (W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.) \right] \right\} \mathcal{X}_0, \end{aligned} \quad (33)$$

where the notation

$$c_\alpha \equiv \cos(\alpha), \quad s_\alpha \equiv \sin(\alpha) \quad (34)$$

is used.

All couplings $\kappa_{Hxx'}$ describe CP-even interactions, and coupling strengths $\kappa_{Axx'}$ CP-odd interactions. Here, c_α is the mixing angle between CP-even and CP-odd couplings. Couplings $g_{Xyy'}$ are defined to reproduce the Standard Model couplings in case of CP-even interactions and a CP-odd 2HDM with $\tan(\beta) = 1$ for CP-odd ones. In the Standard Model CP-even couplings Hgg , $HZ\gamma$ and $H\gamma\gamma$ appear at loop level. In the Higgs characterisation model those interactions are described as effective couplings. The respective coupling strengths $g_{Hyy'}$ are defined in [9] to retrieve the SM coupling value when setting κ_{Hgg} , $\kappa_{HZ\gamma}$, $\kappa_{H\gamma\gamma}$ to one. For the SM VBF production the contributions of $HZ\gamma$ and $H\gamma\gamma$ are very small in comparison to the tree level coupling to a pair of Z or W bosons. Therefore those contributions can be neglected, and the Standard Model is retrieved from the above equation by setting $c_\alpha = 1$ and $\kappa_{SM} = 1$, with all other couplings $\kappa_{Xyy'}$ set to zero. For gluon fusion Higgs production the SM is recovered by setting $c_\alpha = 1$ and $\kappa_{Hgg} = 1$.

Λ is the cut-off scale of the effective theory and BSM couplings are suppressed by a factor $\frac{1}{\Lambda}$. For a more detailed description of the model see Reference [9]. In this note, the cut-off scale Λ is fixed to 1 TeV and c_α to $\frac{1}{\sqrt{2}}$.

4. Extracting parameters

The morphing method presented here is related to interpolation techniques already implemented HistFactory [7], like Moment Morphing [5], and is intended for use on physical observables such as cross sections or distributions retrieved after the full processing of event generation, simulation, digitisation, reconstruction and selection. The described procedure has been implemented in RooFit [6]. Some detail on the implementation is provided in this section.

The implementation has been performed as a single class by the name of `RooEFTMorphFunc`, analogous to other interpolation techniques already implemented in the RooStats statistics framework. The input is retrieved from an external file, which should contain the physical quantities subject to the morphing (total or differential cross sections) as well as the sets of input parameters. The user is expected to provide details on the model in which the morphing should be performed, either by providing a list of available couplings and vertices in which they appear manually, or by using one of the pre-made constructors for different Higgs boson production and decay mechanisms that are currently implemented that include VBF and ggF Higgs boson production with weak bosonic decay modes.

The implementation uses the procedure outlined in Section 2.4 to construct a morphing function on the setup provided, where the physical inputs T are typically incorporated by histograms. The couplings g , which might have been provided by the user or created by the class internally, can either be free parameters or be incorporated as derived quantities depending on some other parameter set, most notably the set of coupling strength parameters κ . The matrix inversion required for the construction of the morphing function is usually performed via the standard matrix implementation of the ROOT software framework [10], but this can be replaced by the more sophisticated boost linear algebra library uBLAS [11] at compile-time, which allows higher numeric accuracy of the result if required.

The `RooEFTMorphFunc` adheres to the standard RooStats interface of interpolation functions, thus standard minimisation techniques to perform likelihood fits of the morphing function to some target distribution can be applied. With these techniques the couplings act as free parameters to be constrained by the fit, independent of whether they were user-provided or automatically generated.

For the purpose of the studies presented in the following sections, backgrounds, treatment of the total width, and systematic uncertainties have been neglected. As a test statistic for the fits, $\tilde{t}_\mu$ [12], which is minus twice a log-likelihood ratio with the signal parameter(s) constrained to be in the physical region, has been used.

5. Validation results

The validation of the morphing method is divided into two parts. In the first part the validation is performed on distributions from MC truth information. The second part of the validation is based on simulated distributions at reconstruction level after full Run 1 analysis selections of the ATLAS $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis group described in Reference [1].

New samples have been produced for the validation described in Section 5.1, which is performed on the generator level after the parton showering and hadronisation, but without accounting for the detector effects. Samples of events from gluon fusion and VBF Higgs production processes with subsequent decays into two W or Z bosons have been produced for the SM and several non-SM coupling configurations with the `MADGRAPH5_AMC@NLO` [13] event generator. Parton showers and their hadronisations are generated with `Pythia8` [14].

The Higgs characterisation (HC) model [9] has been used as a framework for the BSM configurations within the generator. Two different versions of the model are available. The default HC model is used for the VBF processes, whereas for the gluon fusion only the SM production via a heavy quark loop is assumed. The later is modelled by an effective operator, which is implemented in the HC-heft model. All processes are generated at the leading order and with $\sqrt{s} = 13$ TeV, using the leading-order PDF set NNPDF23.

Distributions of several variables sensitive to non-SM couplings are used for validation. Definitions for the angular observables shown here can be found in Reference [15]. In addition, for VBF production the azimuthal angle between the tagging jets $\Delta\phi_{jj}$ is used, which has good discriminant power between CP-odd and CP-even BSM parameters as shown in Reference [16]. Jet candidates are reconstructed using the anti- k_t algorithm [17, 18] with a distance parameter of $R = 0.4$. All input and validation distributions are generator level only, except the ones in the morphing validation described in Section 5.2. This section is using the final discriminating distributions of the ATLAS Run 1 $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis [1] for the validation of the morphing technique.

5.1. Validation on MC truth information

The validation is based on a reduced parameter set that consists of the SM coupling, one additional non-SM CP-even ($c_\alpha \cdot \kappa_{HVV}$) and one CP-odd coupling ($s_\alpha \cdot \kappa_{AVV}$) (equation 33). The parameters for the input samples are chosen to reduce the statistical uncertainty from the morphing function in the desired parameter space. All SM couplings are set to 1 and the non-SM parameter limits are taken such that a pure non-SM sample would have the SM cross section.

5.1.1. Validation in ggF $H \rightarrow ZZ^* \rightarrow 4\ell$

As a simple example a ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ study for only one parameter of interest, the non-SM coupling parameter κ_{Azz} , has been performed. The parameters of the samples used for this study are listed in Table 2.

All samples are produced with the SM couplings set to their nominal values, e.g. $\cos(\alpha) \cdot \kappa_{Hgg} = 1$. The error bars shown reflect the Monte Carlo statistical uncertainty from a total of 50.000 Monte Carlo generated events. In Figure 2 the comparison between morphing function output (dashed) and distributions of two reference points as listed in Table 2 can be seen. Distributions $\cos(\theta_1)$ and Φ , which are sensitive to the presence of non-SM couplings, are shown for validation. θ_1 is the angle between the on-shell Z boson and its negatively charged lepton, ϕ is the angle between the decay planes of the two Z bosons calculated in the rest frame of the Higgs boson [1].

For both validation samples, which incorporate SM and CP-odd admixtures with positive and with negative non-SM coupling strength, the morphing output agrees very well within the statistical uncertainty with the generated distributions.

	κ_{SM}	κ_{Azz}	κ_{Hgg}	$\cos \alpha$
Input Sample 0	1.000	0.000	1.000	1.000
Input Sample 1	0.000	13.938	1.414	0.707
Input Sample 2	1.414	13.938	1.414	0.707
Validation Sample 1	1.000	0.250	1.414	0.707
Validation Sample 2	1.414	-2.000	1.414	0.707

Table 2: Overview of the samples used in Section 5.1.1.

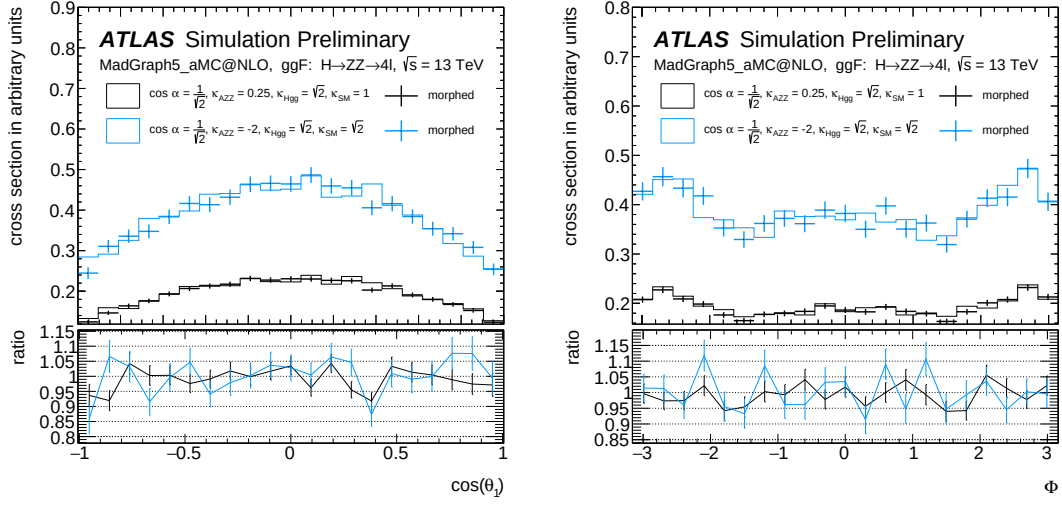


Figure 2: Distributions of $\cos(\theta_1)$, where θ_1 is the angle between the on-shell Z boson and its negatively charged lepton (left) and the angle ϕ (right) between the decay planes of the two Z bosons for events generated in the ggF $H \rightarrow ZZ^* \rightarrow 4\ell$ process at 13 TeV, calculated in the rest frame of the Higgs boson [1]. Generated validation samples (solid) as well as predictions calculated via morphing (dashed) are shown. The ratios between the morphing output and the validation distributions are shown in the lower panels.

5.1.2. Validation in VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

In addition to the SM coupling κ_{SM} two non-SM couplings κ_{HWW} and κ_{AWW} are used for validation. All three operators act on the production and decay vertex which results in 15 input samples needed for the morphing. Besides these 15 input samples additional validation samples are produced to have statistically independent distributions.

An overview of all generated samples in the parameter space can be found in Figure 3, where the two additional validation samples have been highlighted and dubbed **v0** and **v1**. Their parameters have been chosen randomly. For each sample, 50.000 Monte Carlo events have been generated. The cross sections calculated in arbitrary units using the morphing technique can be seen in Figure 4 (left). Using larger absolute non-SM coupling values results in larger rates for both non-SM coupling parameters.

The relative uncertainty arising from the morphing function on the number of events is shown in Figure 4 (right). In the considered parameter space the relative Monte Carlo statistical uncertainty remains very small, in the range of ca. 2-3%, whereas outside the region the uncertainty grows the further away the parameters lie from the input samples. This explains both the local maxima in the central parameter region and the rapid increase in the outer region.

For this channel, the kinematic observable used is the azimuthal angle between the two tagging jets $\Delta\phi_{jj}$. All input distributions for morphing and validation are scaled to their respective cross section in arbitrary units and shown in Figure 5. When morphing to one of the input samples a perfect match is obtained. The morphing is also tested against statistically independent validation samples, as shown in Figure 6, exhibiting agreement within $\sim 5\%$ of the input samples and the morphing.

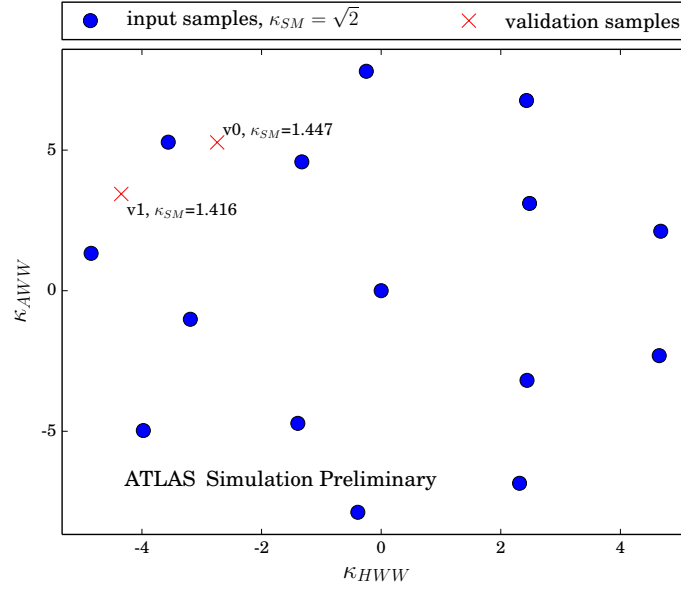


Figure 3: Overview of produced samples for morphing validation in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ channel. The SM coupling g_{SM} is set to 1 for all input samples and the limits for the BSM parameters are taken such that a pure BSM sample would have the SM cross section. The parameters for the validation samples are taken randomly in the desired parameter space.

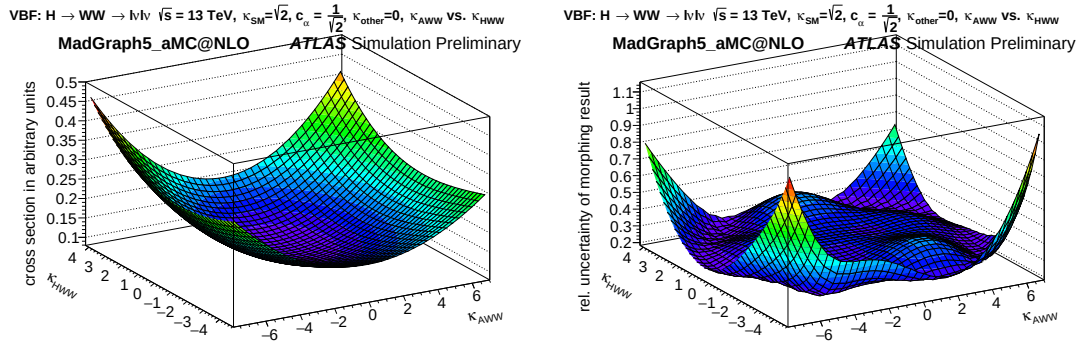


Figure 4: The number of expected events in the considered parameter space for $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ calculated with the morphing method is shown on the left. The relative uncertainty on the number of expected events propagated from the morphing function can be seen on the right.

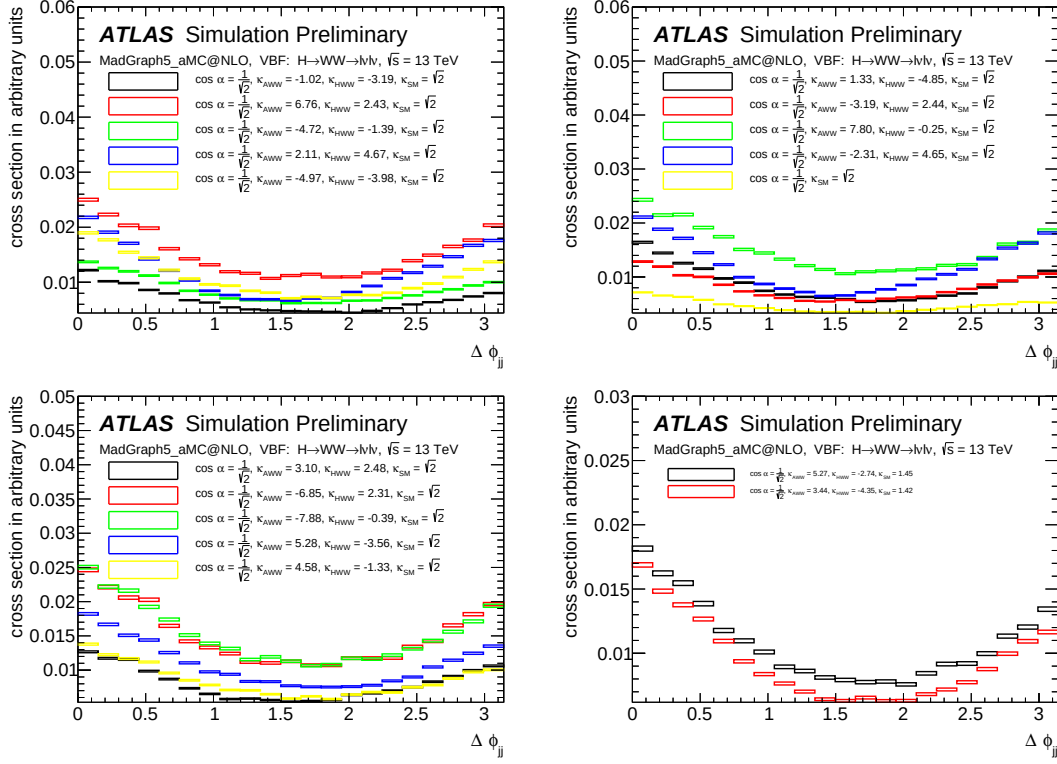


Figure 5: Input and validation distributions used for the morphing validation, using 50.000 Monte Carlo events each. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

In addition, the fitting procedure is tested. When fitting to the SM or one of the other BSM input samples used as pseudo-data, again a perfect agreement is obtained and the nominal parameter values are recovered. The correlation between the parameters are shown in Table 3.

The same fitting procedure is applied to the statistically independent validation distributions and is shown in Figure 7. The correlation results of these fits are listed in Table 4. There is a strong correlation between the SM and BSM CP-odd κ_{AWW} coupling parameter, as they both have a large impact on the event rate.

	κ_{SM}	κ_{HWW}	κ_{AWW}		κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	0.15	-0.23	κ_{SM}	1.00	0.20	0.77
κ_{HWW}	0.15	1.00	0.36	κ_{HWW}	0.20	1.00	0.75
κ_{AWW}	-0.23	0.36	1.00	κ_{AWW}	0.77	0.75	1.00

Table 3: Correlation matrix for the SM input sample (left) and one BSM sample (right)

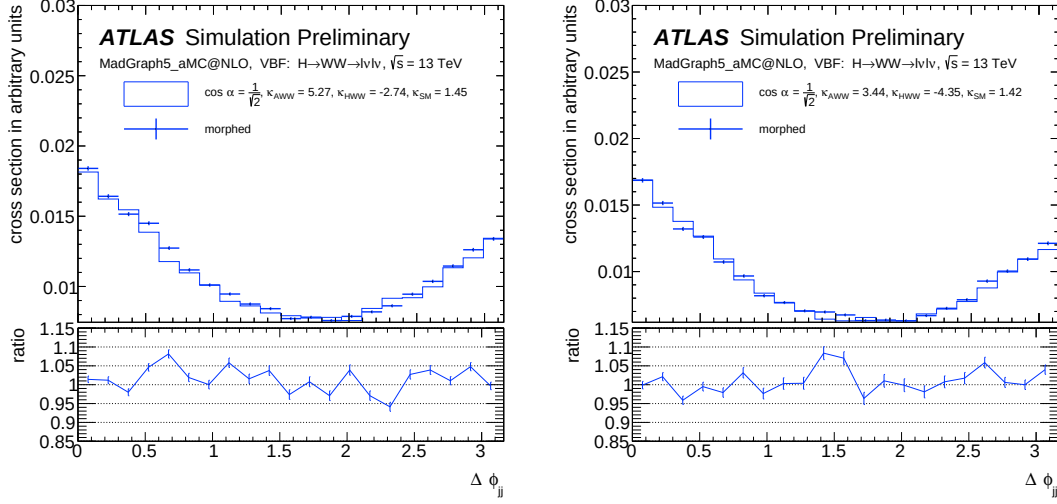


Figure 6: Validation of the morphing using statistically independent distributions. Both morphing results agree within the statistical uncertainty of the morphing.

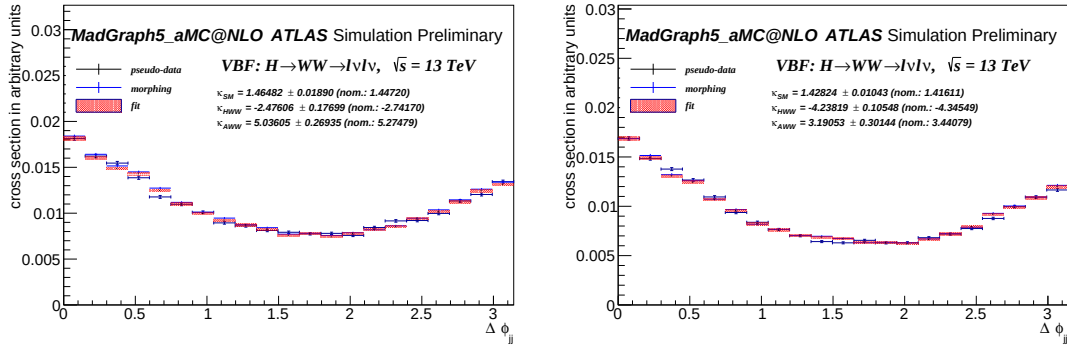


Figure 7: Results obtained by morphing with the known input parameters as well as morphing obtained with the parameters extracted from the fit.

	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	0.20	-0.95
κ_{HWW}	0.20	1.00	0.09
κ_{AWW}	-0.95	0.09	1.00

	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	0.49	-0.93
κ_{HWW}	0.49	1.00	-0.16
κ_{AWW}	-0.93	-0.16	1.00

Table 4: Correlation matrix from the fit to the v_0 (left) and v_1 (right) samples as defined in Figure 3, corresponding to the fits shown in Figure 7.

5.2. Validation on MC reconstruction level with full analysis selection

In order to validate the morphing procedure after taking detector effects into account, the fully reconstructed Monte Carlo samples of the Run 1 $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis [1] have been used as a showcase example.

Mixing of the SM with one additional non-SM parameter, κ_{HZZ} or κ_{AZZ} , has been studied in this publication using the parametrisation of the Higgs characterisation model described in Section 3 with the following notation

$$\tilde{\kappa}_{HZZ} = \frac{1}{4} \cdot \frac{v}{\Lambda} \cdot \kappa_{HZZ}, \quad \tilde{\kappa}_{AZZ} = \frac{1}{4} \cdot \frac{v}{\Lambda} \cdot \kappa_{AZZ}. \quad (35)$$

This check of the morphing is based on the analysis described in [1], where only the dominant production process, gluon fusion Higgs production, has been taken into account. The inputs to the morphing validation in this section are the final distributions of the $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure analysis. Detector effects are taken into account and the full analysis selection described in the before mentioned publication has been applied. For the Run 1 tensor structure measurement a range of $[-10, 10]$ in a step size of 0.25 for the non-SM coupling parameters has been probed.

One of the observables considered for the morphing validation is the angle Φ between the decay planes of the two intermediate Z bosons, which has also been used for the validation described in Section 5.1.1. The other used observable is $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$, which is one of the final discriminating variables of the $H \rightarrow ZZ^* \rightarrow 4\ell$ tensor structure measurement. This observable is sensitive to the amplitude of CP-odd admixtures in the HZZ coupling structure. A more detailed description of both variables can be found on pages 17 and 24 in the original publication.

Arbitrary distributions from the ggF $H \rightarrow 4\mu$ channel at 8 TeV have been chosen for the validation. The configuration of the morphing input samples, as well of the validation samples, is shown in Table 5.

	$\tilde{\kappa}_{\text{SM}}$	$\tilde{\kappa}_{HZZ}$	$\tilde{\kappa}_{AZZ}$
Input sample 1	1	0	0
Input sample 2	0	1	0
Input sample 3	0	0	1
Input sample 4	1	1	0
Input sample 5	0	1	1
Input sample 6	1	0	1
Validation sample Φ	1	-2	0
Validation sample Φ	1	-1.25	0
Validation sample $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$	1	0	5
Validation sample $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$	1	0	3.25

Table 5: Values of the coupling parameters for the morphing input and validation samples

The configuration of the input samples can be chosen arbitrarily, the only condition being that the corresponding morphing matrix is invertible, as derived in Section 2.4.

The validation sample used for Φ uses a SM-like CP-even scenario, whereas the validation sample used for $\text{TO}(\tilde{\kappa}_{AZZ}, \alpha)$ employs a CP-odd scenario to show that morphing works in both cases. A comparison of the distribution of the validation samples and the output of the morphing function is shown in Figure 8.

The perfect agreement of the morphed distributions with the validation samples is expected, since they are not statistically independent. The input samples as well as the validation samples were obtained by ME-reweighting of a single, large sample, as discussed in Section 2.5. Figure 8 shows that more complicated observables can be morphed with this method as well. The correlations between the spin-CP variable distributions used as inputs to the observables are fully reproduced by the morphing.

Overall the morphing validation in this section demonstrates that the described morphing technique is not restricted to generator level. As long as analysis acceptance and detector effects are correctly described in the input distributions, the morphing function is able to describe arbitrary coupling parameter configurations.

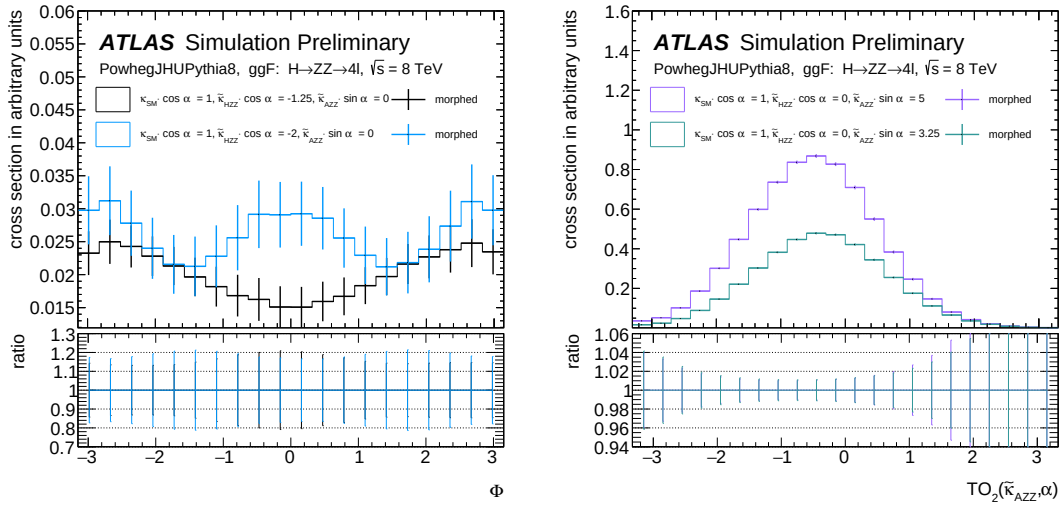


Figure 8: $ggF H \rightarrow ZZ \rightarrow 4\mu$ distributions at 8 TeV published in Reference [1] comparing the shapes of physical observables Φ and $TO_2(\tilde{\kappa}_{AZZ}, \alpha)$ for two validation points obtained via Matrix Element reweighting with the output of the morphing function. The perfect agreement is due to the fact both distributions stem from the same original sample.

6. Impact of non-SM coupling parameters in the VBF production vertex

Production of the Higgs boson via vector boson fusion (VBF) is highly sensitive to SM higher order or non-SM contributions in the HVV production vertex.

So far there are no, or very loose experimental constraints on the contribution of the BSM coupling parameters to the VBF production. Therefore the purpose of this work is to study the VBF vertex and identify with the help of the morphing method described in the previous chapters, a set of relevant non-SM contributions. As a point of reference of the relevance of the parameters a fit to pseudo-data generated for an SM scenario at 13 TeV has been performed, assuming an uncertainty of 8% on the measured cross section (compared to roughly 20% for the ATLAS and CMS combined result from Run 1 [19]). All studied distributions are generator level only and no backgrounds are taken into account.

For the purpose of this study, the Lagrangian of the Higgs characterisation model (presented in Equation 33) describing the interaction of a scalar (Higgs) particle coupling to a pair of gauge bosons is used, including operators up to dimension 6 and their cross terms. The cut-off scale $\Lambda = 1$ TeV is chosen arbitrarily.

6.1. Sample Production

In order to study the BSM contributions in the VBF production, a Higgs boson decay that does not interfere with the production is chosen. For this publication $H \rightarrow \mu\mu$ has been used for purely technical reasons.

The VBF Higgs production process with subsequent decays into two W or two Z bosons has been produced for the SM and several BSM coupling configurations with MADGRAPH5_AMC@NLO [13] event generator. To retain gauge invariance the VBF production also includes the diagrams of the Higgs boson production in association with a hadronically decaying vector boson. Parton showers and their hadronisations are generated with Pythia8 [14] using the A14 tune [20]. The Higgs characterisation (HC) model [9] has been used as a framework for the BSM configurations within the generator.

6.2. Choice of Samples

In total there are 15 non-SM coupling parameters in the HVV vertex described as in the Higgs characterisation model in Equation 33. A subset of 13 parameters contributes to the VBF production vertex, listed in Table 6.

κ_{SM}	1
$\kappa_{H\gamma\gamma}$	203.22
$\kappa_{A\gamma\gamma}$	408.62
$\kappa_{HZ\gamma}$	109.13
$\kappa_{AZ\gamma}$	986.88
κ_{HZZ}	5.75
κ_{AZZ}	6.96
κ_{HWW}	3.36
κ_{AWW}	3.92
$\kappa_{H\partial W R} = \Re(\kappa_{H\partial W})$	0.76
$\kappa_{H\partial W I} = \Im(\kappa_{H\partial W})$	0.84
$\kappa_{H\partial A}$	1.77
$\kappa_{H\partial Z}$	1.37

Table 6: The listed values of the coupling parameters reproduce the Standard Model cross section at $\sqrt{s} = 13$ TeV. A combination of these parameters, where either the positive or the negative of the listed value is taken, is used to construct the 91 input samples for the presented VBF production vertex study.

In order to describe all BSM parameters in production with the morphing method, 91 input samples are necessary. Each sample was generated with 30.000 Monte Carlo events. The configurations of those samples were chosen with the following requirements:

1. Experimental sensitivity: Chose values of BSM parameters within experimental sensitivity. The Run 1 limit on VBF cross section is $\sigma_{\text{VBF}} \lesssim (1 + \frac{1}{4}) \cdot \sigma_{\text{VBF,SM}}$. Values of the coupling parameters

have been calculated to reproduce the SM cross section for pure BSM samples [19]. The values are listed in Table 6.

2. Run 1 results: No large deviations from the SM were found in Run 1 [19], therefore the input samples, with the exception of the pure SM sample itself, are all mixtures of SM with one or two additional BSM parameters.
3. Well defined coverage of BSM parameter phase space: Mixtures of SM plus one additional BSM parameter have been used as input with both positive and negative values for the BSM coupling strength.
4. Input samples can also represent smaller morphing input sets: Parameter configurations were chosen in such a way that also input sample sets which allow morphing to distributions with $n = 2, \dots, 13$ BSM parameters are well represented.

6.3. Results

Events with a $H \rightarrow \mu\mu$ candidate and at least two jets are selected. Muons are required to be oppositely charged and to be within the ATLAS detector acceptance defined by $p_{T,\mu} > 6$ GeV and $|\eta_\mu| < 2.7$. Jets on generator truth level are reconstructed using the anti- k_t algorithm [17, 18] with a distance parameter of $R = 0.4$. A minimum transverse momentum of 20 GeV is required for jets, as well as a pseudo-rapidity of $|\eta_j| < 5.0$. Additionally the jets have to have a minimum distance of $\Delta R_{jj} > 5$. This results in the selection of an VH suppressed phase space, for future studies this requirement will be removed in order to ensure an inclusive selection.

The study has been conducted taking the following distributions in the di-jet system into account: $\Delta\eta_{jj}$, $\Delta\Phi_{jj}$, m_{jj} and $p_{T,j1}$. Distributions for the comparison of SM with mixing of SM plus BSM CP-even coupling κ_{HWW} are shown in Figure 9. The distributions in m_{jj} and $\Delta\eta_{jj}$ are correlated. The observable $\Delta\Phi_{jj}$ includes sign information of the BSM coupling parameter for κ_{HZZ} , κ_{HZA} and κ_{HWW} . The distributions $p_{T,j1}$ and $\Delta\eta_{jj}$ are sign-sensitive for $\kappa_{H\partial Z}$ and $\kappa_{H\partial W_R}$.

For the study of the VBF production the above observables are combined into one final distribution var_{4d} shown in Figure 13, which takes into account all correlations between the input variables. The combined variable var_{4d} is constructed in the following manner;

$$\text{var}_{4d} = 3^3 \cdot i_{\Delta\eta_{jj}} + 3^2 \cdot i_{m_{jj}} + 3 \cdot i_{p_{T,j1}} + i_{\Delta\Phi_{jj}},$$

where the values of each of the four variables are divided into three bins

$$i_{\text{var}} = \begin{cases} 0 & \text{var} < \left(\min_{\text{var}} + \frac{1}{3} \cdot (\max_{\text{var}} - \min_{\text{var}}) \right) \\ 1 & \left(\min_{\text{var}} + \frac{1}{3} \cdot (\max_{\text{var}} - \min_{\text{var}}) \right) \leq \text{var} < \left(\min_{\text{var}} + \frac{2}{3} \cdot (\max_{\text{var}} - \min_{\text{var}}) \right) \\ 2 & \text{var} \geq \left(\min_{\text{var}} + \frac{2}{3} \cdot (\max_{\text{var}} - \min_{\text{var}}) \right) \end{cases}.$$

The minimum and maximum values of each variable are listed in Table 7.

A multidimensional model of this combined distribution has been constructed for the VBF signal, based on the morphing function, which is implemented as described in Section 4.

The sensitivity to the coupling parameters and their correlations are retrieved by fitting a SM pseudo-dataset produced at 13 TeV with an assumed statistical uncertainty of 8%.

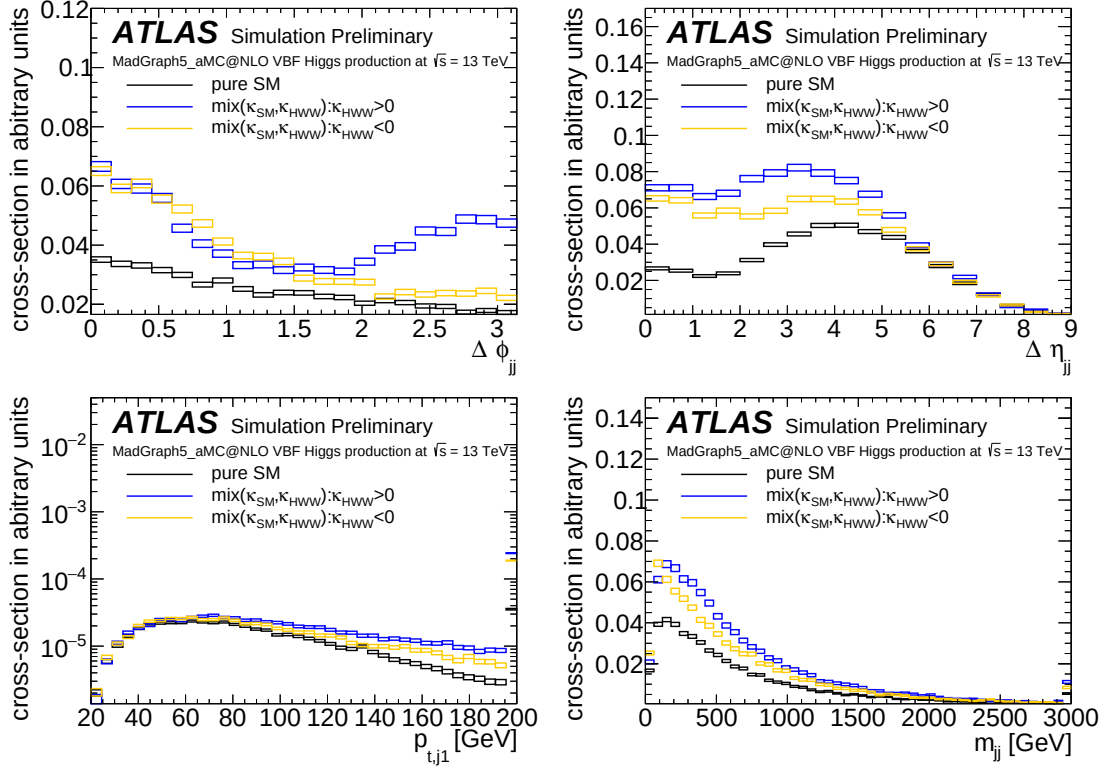


Figure 9: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even HWW couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

	$\Delta\eta_{jj}$	m_{jj} [GeV]	$p_{T,j1}$ [GeV]	$\Delta\Phi_{jj}$
min	0	0	20	0
max	6	1000	200	π

Table 7: Minimum and maximum values of the VBF production jet variables $\Delta\eta_{jj}$, m_{jj} , $p_{T,j1}$ and $\Delta\Phi_{jj}$.

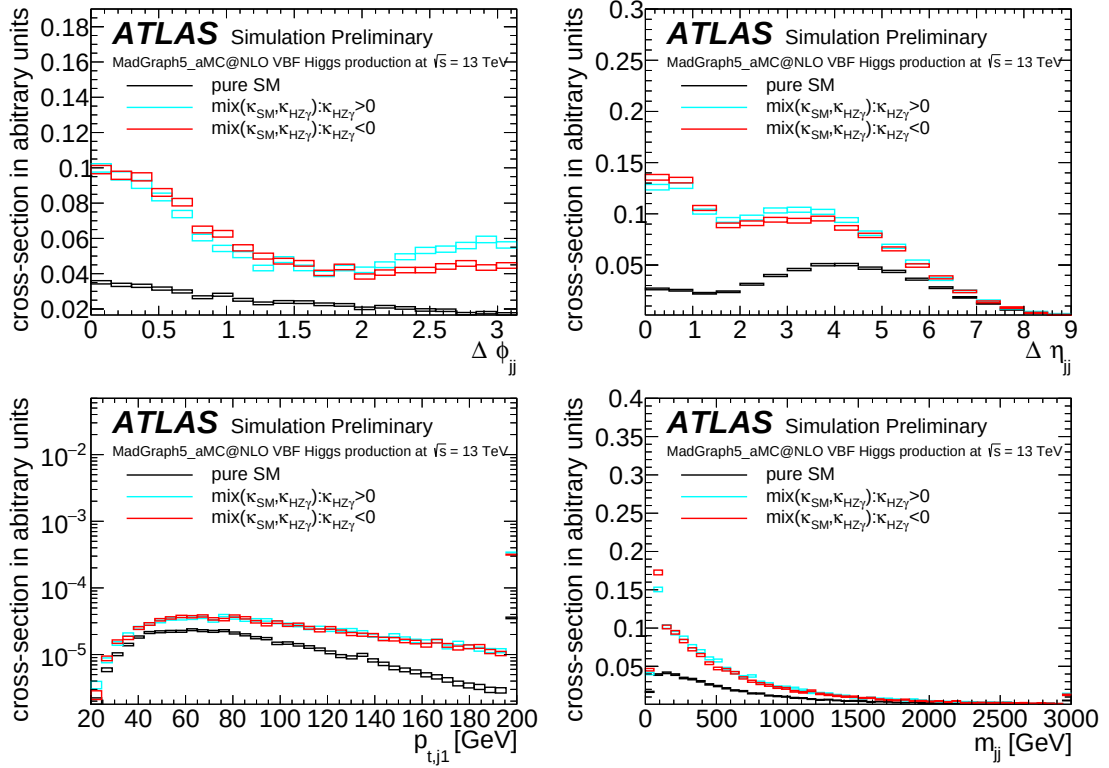


Figure 10: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even $HZ\gamma$ couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

In Table 8 the post-fit values of all coupling parameters and their respective fit errors are listed. The value of the fit error provides insight about the sensitivity of the Monte Carlo signal distribution to this parameter for the given scenario, where large uncertainties correspond to small sensitivity.

The post-fit covariance matrix is shown in Table 9. Depicted values can be compared, for example, to theoretical predictions of BSM coupling parameter correlations. Of course, these correlation values are only valid for the SM and might be dramatically different for other scenarios.

Based on these findings it is foreseen to be able to reduce the dimensionality of the required parameter space by means of a principal component analysis and subsequent reparametrisation and neglecting of parameters to which there is little to no sensitivity. Also, careful study might allow to choose a set of input samples that provide a smaller statistical uncertainty on the fit results.

parameter	post-fit value	+	-
Λ	1000.		
$\cos \alpha$	0.71		
$\kappa_{H\ell\ell}$	1.41		
$\kappa_{A\gamma\gamma}$	0	+219	-441
κ_{Aww}	0	+3	-2.6
$\kappa_{Az\gamma}$	0	+441	-398
κ_{Azz}	0	+2.7	-1.3
$\kappa_{H\gamma\gamma}$	0	+236	-91
$\kappa_{H\partial\gamma}$	0	+0.3	-0.6
$\kappa_{H\partial wI}$	0	+1.6	-0
$\kappa_{H\partial wR}$	0	+0.5	-0.3
$\kappa_{H\partial z}$	0	+1.2	-0.5
κ_{Hww}	0	+1.5	-3
$\kappa_{Hz\gamma}$	0	+38	-49
κ_{Hzz}	0	+8	-2.5
κ_{SM}	1.41	+0.22	-0.11

Table 8: Values of the coupling parameters and their respective errors after fitting to SM pseudo-data with 8% cross section uncertainty. The top rows list the input parameters that were fixed to their nominal values during the fit.

	$\kappa_{A\gamma\gamma}$	κ_{Aww}	$\kappa_{Az\gamma}$	κ_{Azz}	$\kappa_{H\gamma\gamma}$	$\kappa_{H\partial\gamma}$	$\kappa_{H\partial wI}$	$\kappa_{H\partial wR}$	$\kappa_{H\partial z}$	κ_{Hww}	$\kappa_{Hz\gamma}$	κ_{Hzz}	κ_{SM}
$\kappa_{A\gamma\gamma}$	1	0.101	-0.093	0.045	0.113	-0.348	-0.046	0.132	-0.118	-0.167	0.058	0.062	-0.171
κ_{Aww}	0.101	1	0.306	-0.377	-0.355	0.220	-0.151	-0.573	0.747	0.282	0.143	-0.245	-0.130
$\kappa_{Az\gamma}$	-0.093	0.306	1	-0.089	0.170	-0.044	-0.056	0.106	0.008	-0.026	0.208	-0.092	-0.056
κ_{Azz}	0.045	-0.377	-0.089	1	-0.222	0.165	0.415	0.240	-0.326	0.316	0.147	-0.449	0.093
$\kappa_{H\gamma\gamma}$	0.113	-0.355	0.170	-0.222	1	-0.122	-0.201	0.174	-0.262	-0.457	-0.018	0.249	0.004
$\kappa_{H\partial\gamma}$	-0.348	0.220	-0.044	0.165	-0.122	1	-0.151	-0.380	0.369	0.231	0.299	-0.314	0.199
$\kappa_{H\partial wI}$	-0.046	-0.151	-0.056	0.415	-0.201	-0.151	1	0.090	-0.101	0.247	-0.156	-0.180	-0.002
$\kappa_{H\partial wR}$	0.132	-0.573	0.106	0.240	0.174	-0.380	0.090	1	-0.944	-0.116	-0.331	0.208	0.019
$\kappa_{H\partial z}$	-0.118	0.747	0.008	-0.326	-0.262	0.369	-0.101	-0.944	1	0.193	0.294	-0.191	0.081
κ_{Hww}	-0.167	0.282	-0.026	0.316	-0.457	0.231	0.247	-0.116	0.193	1	-0.136	-0.747	-0.065
$\kappa_{Hz\gamma}$	0.058	0.143	0.208	0.147	-0.018	0.299	-0.156	-0.331	0.294	-0.136	1	-0.399	0.230
κ_{Hzz}	0.062	-0.245	-0.092	-0.449	0.249	-0.314	-0.180	0.208	-0.191	-0.747	-0.399	1	0.029
κ_{SM}	-0.171	-0.130	-0.056	0.093	0.004	0.199	-0.002	0.019	0.081	-0.065	0.230	0.029	1

Table 9: Covariance matrix of the coupling parameters after fitting to SM pseudo-data with 8% cross section uncertainty.

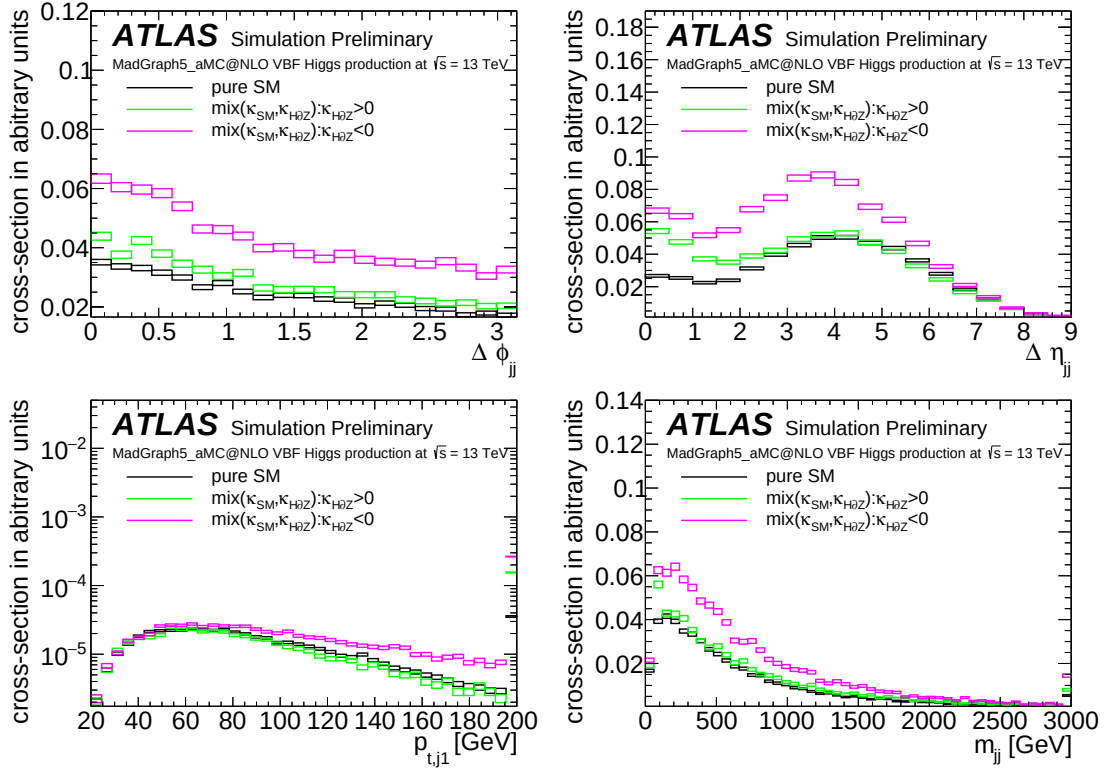


Figure 11: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even $H\partial Z$ couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

7. Conclusions

This note describes a method for modelling signal parameters and distributions in a multidimensional space of coupling parameters. This method is capable of continuously morphing signal distributions and rates based on a minimal orthogonal set of independent base samples. Therefore it allows to directly fit for the coupling parameters that describe the SM and possibly non-SM interaction of the Higgs boson with fermions and bosons of the SM.

The morphing method has been shown to perform as expected using generator-level and reconstruction-level distributions. In addition, a preliminary study on the impact of BSM coupling parameters in the context of VBF Higgs boson production has been performed, acting both as a proof-of-concept for elaborate studies using this method and as a showcase for the performance of the morphing method.

This method can be utilised to test the properties of the Higgs boson during the LHC Run 2 data-taking period and beyond.

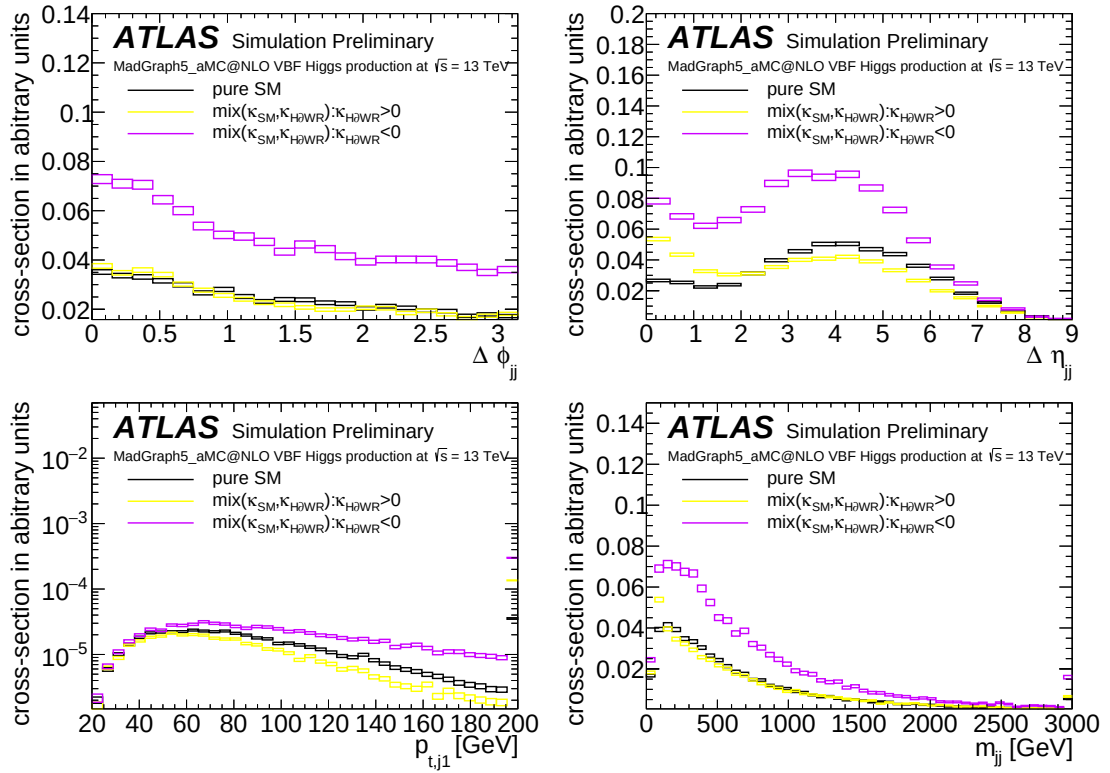


Figure 12: VBF $H \rightarrow \mu\mu$ distributions for $\Delta\Phi_{jj}$ (top left), $p_{T,j1}$ (bottom left), m_{jj} (top right) and $\Delta\eta_{jj}$ (bottom right) with mixing of SM and BSM CP-even $H\partial W_R$ couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

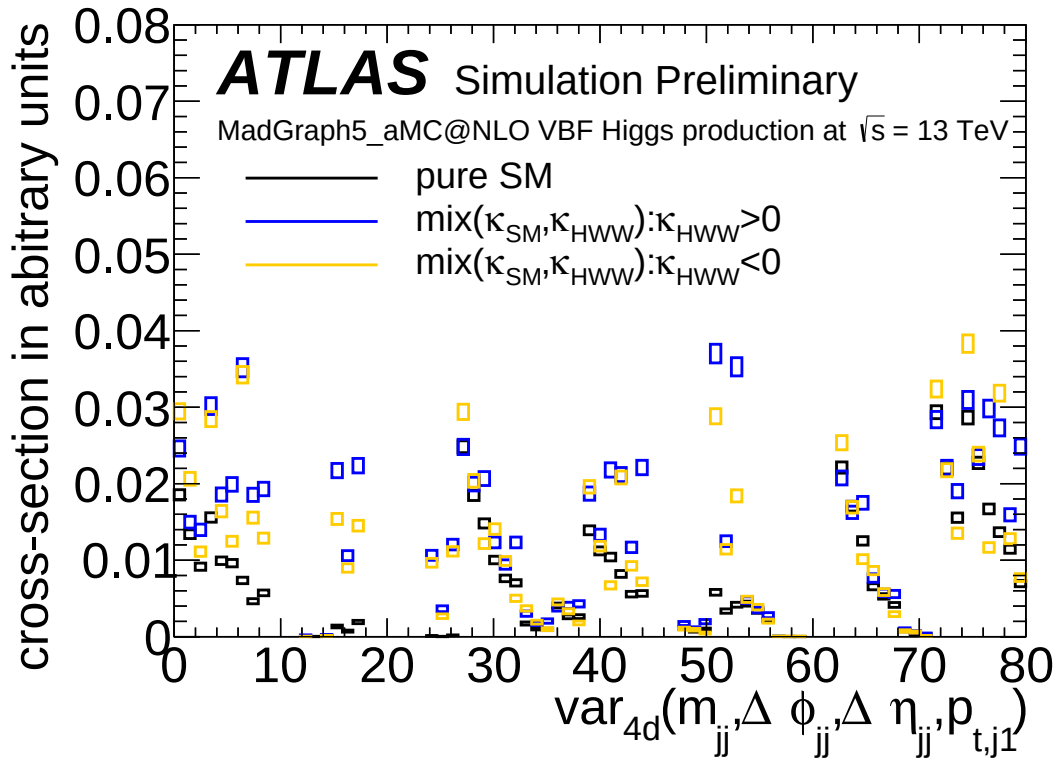


Figure 13: VBF $H \rightarrow \mu\mu$ distribution of var_{4d} , which is a combination of $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, m_{jj} and $p_{T,j1}$ into one discriminating variable, shown for SM and mixing of SM with BSM CP-even HWW couplings. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

A. Additional validation

A.1. Validation in VBF $H \rightarrow ZZ^* \rightarrow 4\ell$

VBF $H \rightarrow ZZ^* \rightarrow 4\ell$ is studied with two non-SM coupling parameters, κ_{HZZ} and κ_{AZZ} , in production and decay.

As listed in Table 1, 15 morphing input samples are needed in order to model such a mixture. The parameters of the the input samples, as well as a set of of 5 validation samples are listed in Table 10. Each sample was produced with 50.000 Monte Carlo events.

As a validation variable $\Delta\Phi_{jj}$ as defined at the beginning of this section has been chosen, but the distribution of any other non-SM coupling sensitive distribution in the jet or $H \rightarrow 4\ell$ decay system can be predicted. The morphing to two validation points (2 and 4 in Table 10) in comparison to the generated distribution, is shown in Figure 14. All distributions are shown normalised to their respective cross sections.

The morphing function describes shape and cross section, depending on the non-SM coupling parameters, in reasonable agreement with the validation distributions.

A.2. Validation in ggF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

In gluon fusion production for the decay to WW , the azimuthal angle between two leptons $\Delta\phi_{ll}$, which has already been used in the spin and parity measurement by ATLAS [21], is taken as validation distribution.

	$\cos \alpha$	κ_{AZZ}	κ_{HZZ}	κ_{SM}
Input Sample 0	0.707	-9.366	0.952	1.414
Input Sample 1	0.707	3.655	5.189	1.414
Input Sample 2	0.707	-5.510	-7.817	1.414
Input Sample 3	0.707	-4.574	4.922	1.414
Input Sample 4	0.707	7.739	-3.261	1.414
Input Sample 5	0.707	0.513	-5.612	1.414
Input Sample 6	0.707	-11.654	4.921	1.414
Input Sample 7	0.707	-0.781	8.461	1.414
Input Sample 8	0.707	9.135	1.544	1.414
Input Sample 9	0.707	-13.764	-2.333	1.414
Input Sample 10	0.707	-7.100	-3.737	1.414
Input Sample 11	0.707	10.696	5.635	1.414
Input Sample 12	0.707	14.112	-1.435	1.414
Input Sample 13	0.707	0.000	0.000	1.414
Input Sample 14	0.707	6.898	-7.420	1.414
Validation Sample 0	0.707	8.494	0.862	1.385
Validation Sample 1	0.707	-0.039	7.104	1.400
Validation Sample 2	0.707	1.814	-2.976	1.424
Validation Sample 3	0.707	-10.565	1.343	1.449
Validation Sample 4	0.707	10.735	5.051	1.391

Table 10: Overview of the samples used in Section A.1

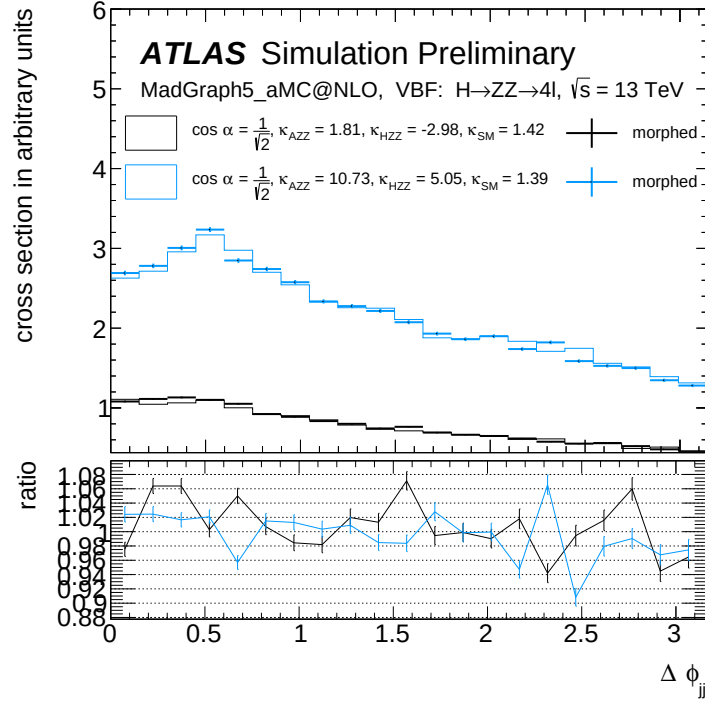


Figure 14: Distributions of the $\Delta \phi_{jj}$, the angle between leading and sub leading jet for events generated in the VBF $H \rightarrow ZZ^* \rightarrow 4\ell$ process at 13 TeV. Generated validation samples (solid) as well as predictions calculated via morphing (dashed) are shown. The ratio between morphing output and validation distribution is depicted in the lower panel.

In addition to the SM coupling κ_{SM} two non-SM couplings, κ_{HWW} and κ_{AWW} , are used for validation. All three operators act on the decay vertex which results in 6 input samples needed for the morphing. Besides these 6 input samples additional validation samples are produced to have statistically independent distributions.

An overview of all generated samples in the parameter space can be found in Figure 15. The samples were generated with 50.000 Monte Carlo events each. The cross sections calculated in arbitrary units using the morphing technique can be seen in Figure 16 (left). Using larger absolute non-SM coupling values results in larger rates for both non-SM coupling parameters. The relative Monte Carlo statistical uncertainty arising from the morphing function on the number of events is shown in Figure 16 (right). In the considered parameter space the relative Monte Carlo statistical uncertainty remains very small, in the range of ca. 2-3%, whereas outside the region the uncertainty grows the further away the parameters lie from the input samples. This explains both the local maxima in the central parameter region and the rapid increase in the outer region.

For this channel the kinematic observable used is the azimuthal angle between the two leptons $\Delta \phi_{ll}$. All input distributions for morphing and validation are scaled their respective cross section in arbitrary units and shown in Figure 17. Two tests of the morphing method are covered. First the morphing to the input distributions is tested (cf. Figure 18). Since the validation samples are among the inputs a perfect agreement

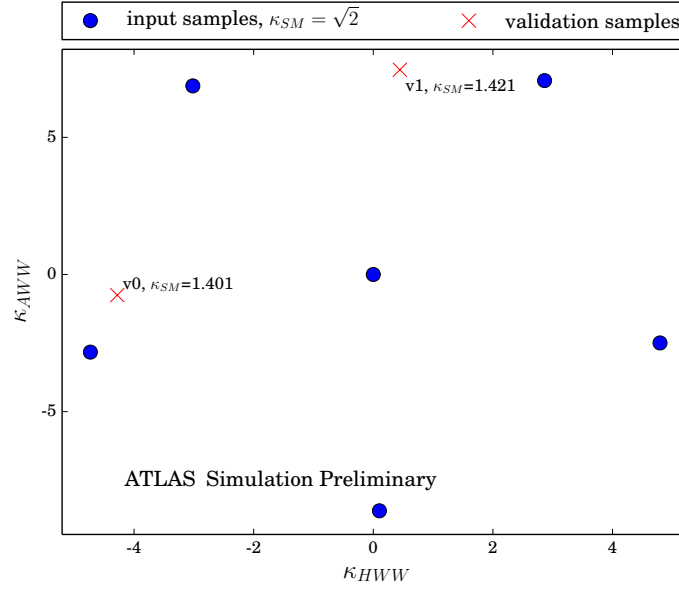


Figure 15: Overview of produced samples for morphing validation in the $ggF H \rightarrow WW^* \rightarrow e\nu\mu\nu$ channel. The SM couplings g_{Hgg} and g_{SM} are set to 1 for all input samples and the limits for the BSM parameters are taken such that a pure BSM sample would have the SM cross section. The parameters for the validation samples are taken randomly in the desired parameter space.

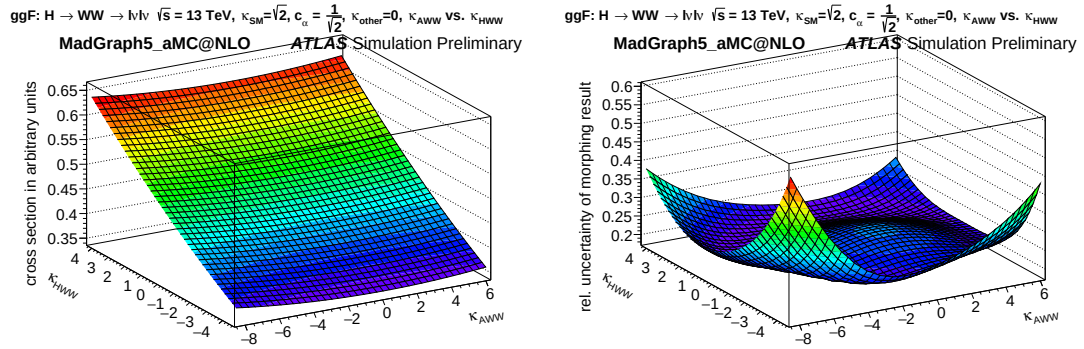


Figure 16: The number of expected events in the considered parameter space for $ggF H \rightarrow WW^* \rightarrow e\nu\mu\nu$ calculated with the morphing method is shown on the left. The relative Monte Carlo statistical uncertainty on the number of expected events propagated from the morphing function can be seen on the right.

is seen, as expected. Similar results are obtained for the other input samples and are not shown. Second the morphing is tested on statistically independent validation samples (cf. Figure 19), which shows reasonable agreement of the input samples and the morphing.

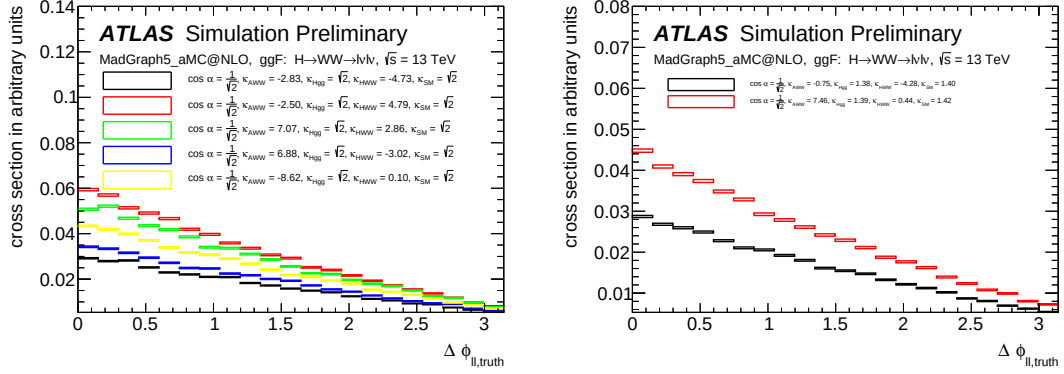


Figure 17: Input and validation distributions used for the morphing validation, generated from 50.000 Monte Carlo events each. The size of the boxes correspond to the Monte Carlo statistical uncertainties.

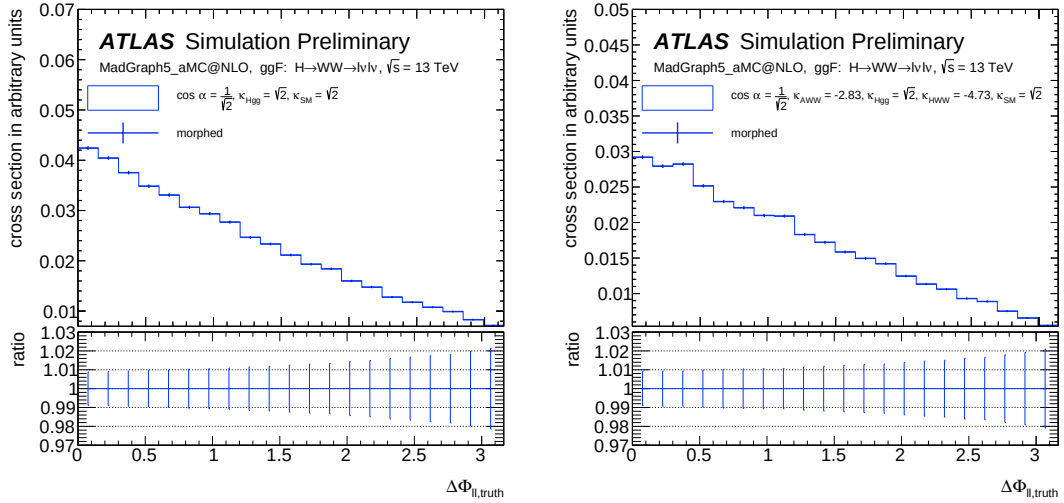


Figure 18: Validation of the morphing using input distributions. The SM distribution (left) and one input distribution (right) show perfect agreement as expected for statistically dependent samples.

In addition, the fitting procedure is tested. When fitting to the SM or one of the other BSM input samples used as pseudo-data as shown in Figure 20, again a perfect agreement is obtained and the nominal parameter values are recovered. For comparison, the morphing result is also shown. The Monte Carlo statistical uncertainty is used both for display of the error bars and in the fit. The uncertainties on the fit parameters give an idea of the sensitivity on the parameter. The correlation between the parameters are shown in Table 11.

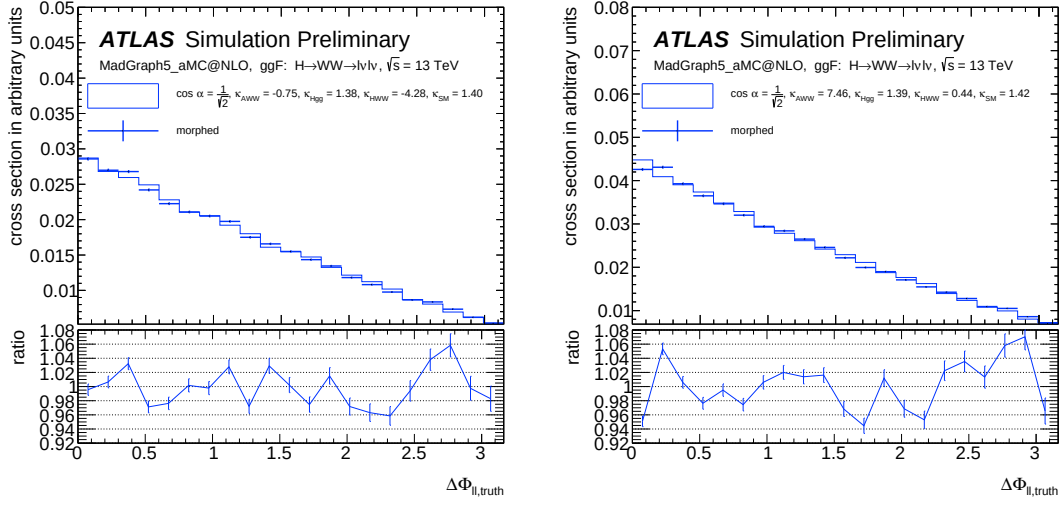


Figure 19: Validation of the morphing using statistically independent distributions. Both morphing results agree within the statistical uncertainty of the morphing.

The same fitting procedure is applied to the statistically independent validation distributions and is shown in Figure 21. the correlation for these fits are listed in Table 12.

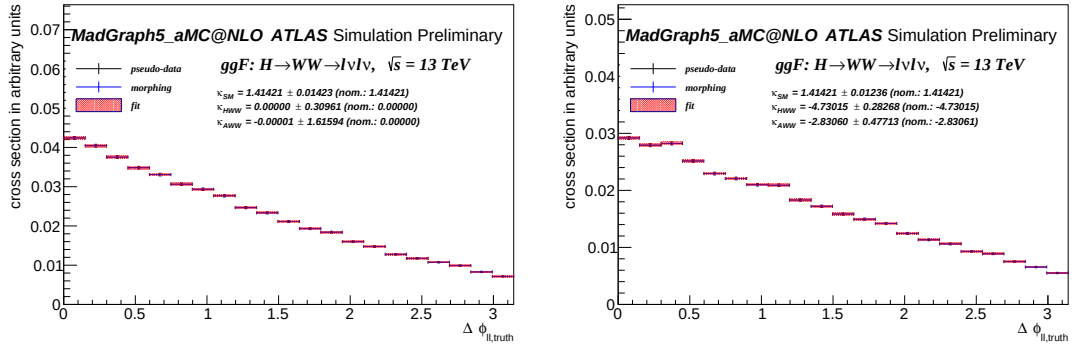


Figure 20: Fit validation to the SM input sample (left) and one of the BSM input samples (right).

B. Additional material for approval

B.1. Additional material for VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

left	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	-0.16	0.16
κ_{HWW}	-0.16	1.00	-0.99
κ_{AWW}	0.16	-0.99	1.00

right	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	-0.53	0.60
κ_{HWW}	-0.53	1.00	-0.99
κ_{AWW}	0.60	-0.99	1.00

Table 11: Correlation matrix for the SM input sample and one BSM sample corresponding to the fits in Figure 20.

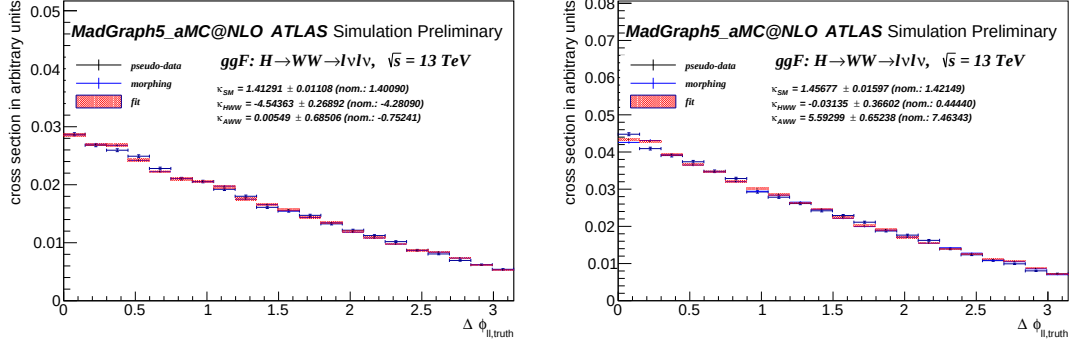


Figure 21: Fit validation to validation samples v0 (left) and v1 (right).

v0	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	-0.12	0.11
κ_{HWW}	-0.12	1.00	-0.99
κ_{AWW}	0.11	-0.99	1.00

v1	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	-0.37	0.18
κ_{HWW}	-0.37	1.00	-0.97
κ_{AWW}	0.18	-0.97	1.00

Table 12: Correlation matrix for the validation distributions v0 and v1 corresponding to the fits in Figure 21.

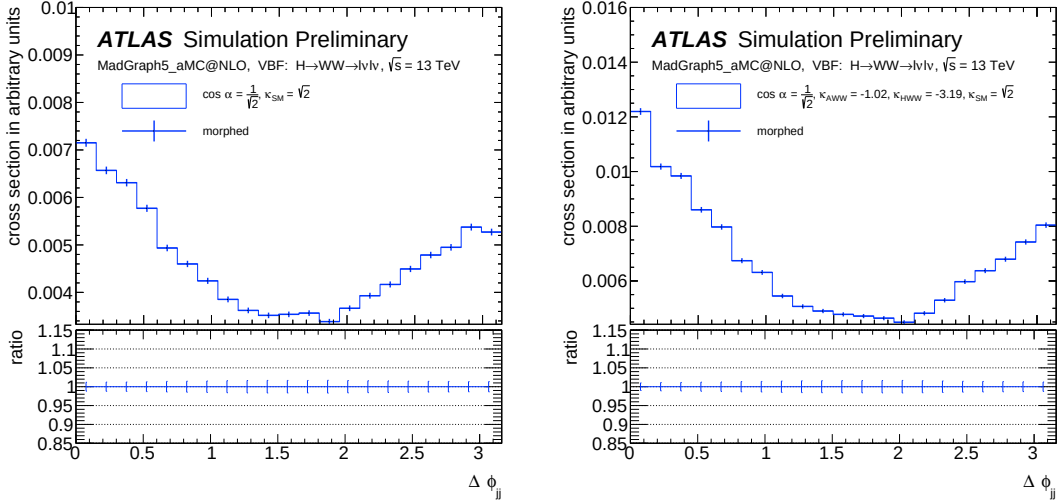


Figure 22: Validation of the morphing using input distributions. The SM distribution (left) and one input distribution (right) show perfect agreement. This is expected, since the target distributions are among the input distributions.

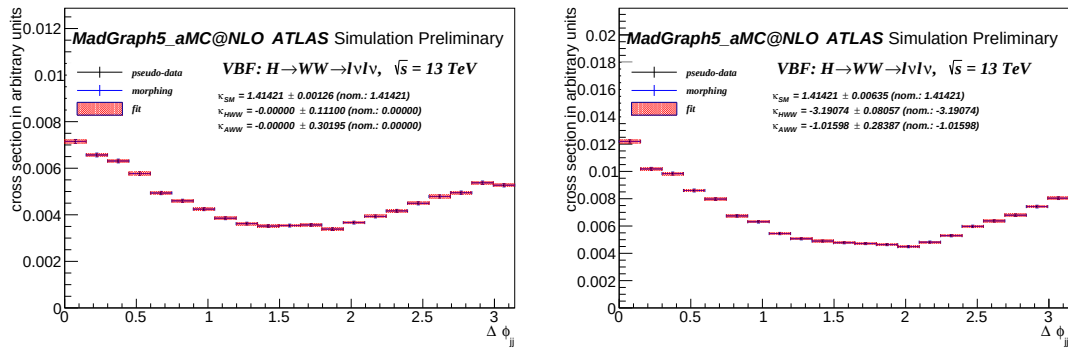


Figure 23: Validation of the morphing fit to input samples, recovering the nominal parameter values.

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Searches for heavy diboson resonances in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



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ABSTRACT: Searches for new heavy resonances decaying to WW , WZ , and ZZ bosons are presented, using a data sample corresponding to 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the CERN Large Hadron Collider. Analyses selecting $\nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$ and $qqqq$ final states are combined, searching for a narrow-width resonance with mass between 500 and 3000 GeV. The discriminating variable is either an invariant mass or a transverse mass. No significant deviations from the Standard Model predictions are observed. Three benchmark models are tested: a model predicting the existence of a new heavy scalar singlet, a simplified model predicting a heavy vector-boson triplet, and a bulk Randall-Sundrum model with a heavy spin-2 graviton. Cross-section limits are set at the 95% confidence level and are compared to theoretical cross-section predictions for a variety of models. The data exclude a scalar singlet with mass below 2650 GeV, a heavy vector-boson triplet with mass below 2600 GeV, and a graviton with mass below 1100 GeV. These results significantly extend the previous limits set using pp collisions at $\sqrt{s} = 8$ TeV.

KEYWORDS: Hadron-Hadron scattering (experiments)

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1 Introduction

Diboson resonances are predicted in several extensions to the Standard Model (SM), such as composite Higgs models [1, 2], technicolour [3–5], warped extra dimensions [6–8], Two-Higgs-doublet models (2HDM) [9], and Grand Unified Theories [10–13]. The search for high-mass resonances decaying into vector bosons benefits greatly from the increase in centre-of-mass energy of proton-proton collisions at the Large Hadron Collider (LHC) from $\sqrt{s} = 8$ TeV (Run 1) to 13 TeV (Run 2). This would result in more abundant production of new particles with masses significantly in excess of a TeV, in processes initiated by gg , gq or qq .¹

This paper reports a search for a charged or neutral resonant state, with a mass between 500 GeV and 3 TeV, decaying to WW , ZZ or WZ bosons, with subsequent decays of the W and Z bosons to quarks or leptons. Four different decay modes are considered: the fully hadronic mode ($qqqq$), and the semileptonic modes ($\ell\ell qq$, $\ell\nu qq$ and $\nu\nu qq$). Decays of the W or Z bosons to quarks are reconstructed as single jets with a large radius parameter. These jets are required to have features characteristic of a two-body decay, and are identified as W or Z bosons using the jet mass and jet substructure [14, 15].

¹To simplify notation, antiparticles are denoted by the same symbol as the corresponding particles.

Three specific signal models are used to assess the sensitivity of the search, to optimise the event selection, and to search for local excesses in the observed data. The first is an extension of the SM with an additional heavy, CP-even, scalar singlet decaying to longitudinally polarised bosons [16]. The second is the Heavy Vector Triplet (HVT) parameterisation [17], predicting $W' \rightarrow WZ$ and $Z' \rightarrow WW$ processes. The third model, known as a bulk Randall-Sundrum (RS) graviton model, features a spin-2 graviton (G^*) decaying to WW or ZZ . The G^* is the first Kaluza-Klein mode in a RS model [6, 18] with a warped extra dimension with curvature κ , where the SM fields are allowed to propagate in the bulk of the extra dimension [19–21].

Both ATLAS and CMS have searched for heavy diboson resonances in various final states in the $\sqrt{s} = 7$ TeV and 8 TeV datasets [22–31]. As an example, CMS set a lower limit of 1.7 TeV at the 95% confidence level (CL) on the mass of a W' boson predicted by an Extended Gauge Model (EGM) [32] using the fully hadronic channel [26]. The $qqqq$, $\ell\ell qq$, $\ell\nu qq$ channels were combined by ATLAS using the bulk RS G^* model and the EGM W' boson as benchmarks [31]. Observed lower limits at 95% CL of 1.81 TeV on the EGM W' mass and of 810 GeV on the bulk G^* mass were obtained, assuming $\kappa/\bar{M}_{\text{Pl}} = 1$ (where $\bar{M}_{\text{Pl}}$ is the reduced Planck mass) for the bulk G^* signal hypothesis. The largest deviation from the predicted background in that analysis was a 2.5σ local excess close to a mass of 2 TeV.

2 ATLAS detector and data sample

The ATLAS detector [33] is a general-purpose particle detector used to investigate a broad range of physics processes. It includes inner tracking devices surrounded by a superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer inside a system of toroid magnets. The inner detector (ID) consists of a silicon pixel detector including the newly installed Insertable B-Layer [34], a silicon microstrip detector and a straw tube tracker. It is situated inside a 2 T axial magnetic field from the solenoid and provides precision tracking of charged particles with pseudorapidity² $|\eta| < 2.5$. The straw tube tracker also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It is composed of sampling calorimeters with either liquid argon or scintillator tiles as the active medium. The muon spectrometer (MS) provides muon identification and measurement for $|\eta| < 2.7$ and detectors for triggering in the region $|\eta| < 2.4$. The ATLAS detector has a two-level trigger system to select events for offline analysis [35].

²ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Rapidity is also defined relative to the beam axis as $y = 0.5 \ln[(E + p_z)/(E - p_z)]$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

The data used in this analysis were recorded with the ATLAS detector during the 2015 run and correspond to an integrated luminosity of $3.2 \pm 0.2 \text{ fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$. The measurement of the integrated luminosity is derived, following a methodology similar to that detailed in ref. [36], from a preliminary calibration of the luminosity scale using x - y beam-separation scans performed in August 2015. The data are required to satisfy a number of conditions ensuring that the detector was operating well while the data were recorded.

3 Signal and background simulation

The Monte Carlo (MC) simulation of three benchmark signal models is used to optimise the sensitivity of the search and to interpret the results.

The first model extends the SM by adding a new, heavy, neutral Higgs boson, using the narrow-width approximation (NWA) benchmark [37, 38]. Results are then interpreted within a model of a CP-even scalar singlet S [16]. The model is parameterised by: an energy scale $\Lambda = 1 \text{ TeV}$; a coefficient c_H scaling the coupling of S to the Higgs boson; and a coefficient c_3 scaling the coupling of S to gluons. Two benchmark scenarios are considered, one in which c_3 is set via *naive dimensional analysis* (NDA) to be $c_3 = (1/4\pi)^2$, with $c_H = 0.9$; and another in which the coupling to gluons is *Unsuppressed* and $c_3 = 1/8\pi$, with $c_H = 0.5$. The value of c_3 determines the production cross-section and the decay width to gluons, while decays to W or Z bosons account for the remaining decay width. In the Unsuppressed scenario considered in this paper, the total branching ratio to WW , ZZ or HH increases from 59% at 500 GeV, to 70% at 2 TeV and to 73% at 5 TeV. For the NDA scenario, this branching ratio is always above 99%. The ratio of $WW:ZZ:HH$ partial widths is approximately 2:1:1 in both scenarios, and couplings to fermions and transversely polarised bosons are set to zero.

The second model is based on the HVT phenomenological Lagrangian which introduces a new triplet of heavy vector bosons that contains three states with identical masses: the two electrically charged W' bosons and the electrically neutral Z' boson. The Lagrangian parameterises the couplings of the new HVT with the SM fields in a generic manner. This parameterisation allows a large class of models to be described, in which the new triplet field mixes with the SM vector bosons. The coupling between the new triplet and the SM fermions is given by the combination of parameters $g^2 c_F / g_V$, where g is the SM $\text{SU}(2)_L$ gauge coupling, c_F is a multiplicative factor that modifies the coupling to fermions, and g_V represents the coupling strength of the known W and Z bosons to the new vector bosons. Similarly, the coupling between the Higgs boson and the new triplet is given by the combination $g_V c_H$, where c_H is a multiplicative factor that modifies the coupling to the Higgs boson. Other coupling parameters involving more than one heavy vector boson give negligible contributions to the overall cross-sections for the processes of interest here. Two benchmarks are used [17]. In the first one, referred to as *model-A* with $g_V = 1$, the branching ratios of the new HVT to fermions and gauge bosons are similar to those predicted by some extensions of the SM gauge group [39]. This model, although severely constrained by searches for new resonances decaying to leptons [40–43], is included because

of its similarity to the EGM W' model used as a benchmark in previous searches [31]. In the second model, referred to as *model-B* with $g_V = 3$, the fermionic couplings of the new HVT are suppressed, and branching ratios are similar to the ones predicted by composite Higgs boson models [44–46]. In both benchmarks the width of the HVT is narrower than the detector resolution, and the kinematic distributions relevant to this search are very similar. Off-shell and interference effects are not considered.

The third model considered is the so-called bulk RS model [19]. This model extends the original RS model with one warped extra dimension [6, 7] by allowing the SM fields to propagate in the bulk of the extra dimension. This avoids constraints on the original RS model from limits on flavour-changing neutral currents and electroweak precision measurements [47]. This model is characterised by the dimensionless coupling constant $\kappa/\bar{M}_{\text{Pl}} \sim \mathcal{O}(1)$. In this model the branching ratio of the Kaluza-Klein graviton (G^*) to pairs of vector bosons, WW or ZZ , is larger than 30%.

For the NWA Higgs boson model, samples are generated for gluon fusion production with QCD corrections up to next-to-leading order (NLO), assuming a Higgs boson decay width of 4 MeV. Events are generated using POWHEG BOX [48] v1 r2856 with the CT10 parton distribution function (PDF) set [49] interfaced to PYTHIA 8.186 [50] using the AZNLO [51] tune of the underlying event.

Benchmark samples of the HVT and bulk RS graviton are generated using MADGRAPH5_AMC@NLO 2.2.2 [52] interfaced to PYTHIA 8.186 with the NNPDF23LO PDF set [53] for resonance masses ranging from 0.5 TeV to 5 TeV. For the HVT interpretation, samples are generated according to model A, for resonance masses ranging from 0.5 TeV to 3 TeV for the semileptonic channels and from 1.2 TeV to 3 TeV for the fully hadronic search. Interpretation in the HVT model-B, $g_V = 3$ scenario uses the model A signal samples rescaled to the predicted cross-sections from model-B. For the bulk RS graviton model, the curvature scale parameter $\kappa/\bar{M}_{\text{Pl}}$ is assumed to be 1. Table 1 shows the resonance width and the product of cross-sections and branching ratios for the various models.

MC samples are used to model the shape and normalisation of the relevant kinematic distributions for most SM background processes in the $\nu\nu q\bar{q}$, $\ell\nu q\bar{q}$ and $\ell\ell q\bar{q}$ searches. Events containing W or Z bosons with associated jets are simulated using the SHERPA 2.1.1 [54] generator. Matrix elements (ME) are calculated for up to two partons at NLO and four partons at leading order (LO) using the Comix [55] and OpenLoops [56] ME generators. They are merged with the SHERPA parton shower (PS) [57] using the ME+PS@NLO prescription [58]. The CT10 PDF set is used in conjunction with a dedicated set of tuned parton-shower parameters developed by the SHERPA authors. For the generation of top-antitop pairs ($t\bar{t}$) and single top-quarks in the Wt - and s -channels the POWHEG BOX v2 [48, 59, 60] generator with the CT10 PDF set is used. Electroweak (t -channel) single-top-quark events are generated using the POWHEG BOX v1 generator. This generator uses the four-flavour scheme for the NLO ME calculations together with the four-flavour PDF set CT10f4 [49]. For all top-quark processes, top-quark spin correlations are preserved; for t -channel production, top-quarks are decayed using MADSPIN [61]. The parton shower, fragmentation, and the underlying event are simulated using PYTHIA 6.428 [62] with the CTEQ6L1 [63] PDF sets and the set of tuned parameters known as the “Perugia

m [TeV]	Scalar			HVT W' and Z'			G^*		
	WW		ZZ	WW		WZ	WW		ZZ
	Γ	$\sigma \times \text{BR}$	$\sigma \times \text{BR}$	Γ	$\sigma \times \text{BR}$	$\sigma \times \text{BR}$	Γ	$\sigma \times \text{BR}$	$\sigma \times \text{BR}$
	[GeV]	[fb]	[fb]	[GeV]	[fb]	[fb]	[GeV]	[fb]	[fb]
0.8	3.9	37	18	32	354	682	46	301	155
1.6	33	2.5	1.3	51	38.5	79.3	96	4.4	2.2
2.4	111	0.32	0.16	74	4.87	10.6	148	0.28	0.14

Table 1. The resonance width (Γ) and the product of cross-section times branching ratio ($\sigma \times \text{BR}$) for diboson final states, for different values of the pole mass m of the resonances for a representative benchmark for the spin-0, spin-1 and spin-2 cases. The table shows the predictions by the CP-even scalar model ($\Lambda = 1$ TeV, $c_H = 0.9$, $c_3 = 1/16\pi^2$), by model-B of the HVT parameterisation ($g_V = 3$), and by the graviton model ($\kappa/\bar{M}_{\text{Pl}} = 1$). In the case of the scalar and HVT models, the alternate benchmarks (Unsuppressed scenario, model-A) correspond to a different cross-section but similar resonance width and ratios between the branching ratios into $WW/WZ/ZZ$.

2012 tune” [64]. The top-quark mass is assumed to be 172.5 GeV. The EVTGEN v1.2.0 program [65] is used for the bottom- and charm-hadron decays.

The cross-sections calculated at next-to-next-to-leading order (NNLO) accuracy for W/Z +jets [66] and at NNLO+NNLL (next-to-next-to-leading-logarithm) accuracy for $t\bar{t}$ production [67] are used to normalise the samples for the optimisation studies, but the final normalisations of these dominant backgrounds are determined by fitting kinematic distributions to the data. For single-top-quark production, cross-sections are taken from ref. [68].

Diboson processes with one boson decaying hadronically and the other decaying leptonically are simulated using the SHERPA 2.1.1 generator. They are calculated for up to one (ZZ) or no (WW , WZ) additional partons at NLO, and up to three additional partons at LO using the Comix and OpenLoops ME generators. They are merged with the SHERPA PS using the ME+PS@NLO prescription. The CT10 PDF set is used in conjunction with a dedicated parton-shower tuning developed by the SHERPA authors. Cross-section values from the generator, which are at NLO accuracy, are used.

The dominant background in the fully hadronic final state is from multi-jet events. While the background in this search is estimated directly from data, samples of simulated dijet events are produced, using PYTHIA 8.186 with the NNPDF23LO PDFs and the parton-shower parameter set known as the “A14 tune” [69], to characterise the invariant mass distribution of the dijet final state and optimise the sensitivity of the search. The EVTGEN v1.2.0 program is used for the bottom- and charm-hadron decays.

All simulated MC samples include the effect of multiple proton-proton interactions in the same and neighbouring bunch crossings (pile-up) by overlaying simulated minimum-bias events, generated with PYTHIA 8.186, on each generated signal or background event. The generated samples are processed through the GEANT4-based ATLAS detector simulation [70, 71]. Simulated events are reconstructed with the standard ATLAS reconstruction software used for collision data. Table 2 summarises the background MC samples used.

Process	PDF	Generator
$W/Z + \text{jets}$	CT10	SHERPA 2.1.1
$t\bar{t}$	CT10	POWHEG BOX v2+PYTHIA 6.428
Single top-quark (Wt , s -channel)	CT10	POWHEG BOX v2+PYTHIA 6.428
Single top-quark (t -channel)	CT104f	POWHEG BOX v1+PYTHIA 6.428 + MADSPIN 2.1.2
Diboson (WW , WZ , ZZ)	CT10	SHERPA 2.1.1
Dijet	NNPDF23LO	PYTHIA 8.186

Table 2. Generators and PDFs used in the simulation of the various background processes.

4 Object reconstruction and selection

Electrons are reconstructed from clusters of energy deposits in the EM calorimeter that match a track reconstructed in the ID. The electrons used are required to have transverse momentum $p_T > 7 \text{ GeV}$ and $|\eta| < 2.47$. They are identified using a likelihood identification criterion described in ref. [72]. The levels of identification are categorised as “loose”, “medium” and “tight”, which correspond to approximately 96%, 94% and 88% identification efficiency for an electron with transverse energy (E_T) of 100 GeV, where E_T is defined in terms of the energy E and of the polar angle θ as $E_T = E \sin \theta$.

Muons are reconstructed by combining ID and MS tracks. They are classified as “medium” if they satisfy identification requirements based on the number of hits in the different ID and MS subsystems and on the compatibility of track curvature measurements in the two subsystems [73]. An additional sample of “loose” muons is constructed including all medium muons, muons identified by combining an ID track with at least one track segment reconstructed in the MS, and muons reconstructed in the $|\eta| < 0.1$ region, where the MS is lacking coverage, by associating an ID track to an energy deposit in the calorimeters compatible with a minimum-ionising particle. Muons are required to have $p_T > 7 \text{ GeV}$ and $|\eta| < 2.7$. The loose and medium muons have average efficiencies of about 98% and 96% for $|\eta| < 2.5$, respectively.

In order to ensure that leptons originate from the interaction point, requirements of $|d_0^{\text{BL}}|/\sigma_{d_0^{\text{BL}}} < 5$ (3) and $|z_0^{\text{BL}} \sin \theta| < 0.5 \text{ mm}$ are imposed on the tracks associated with the electrons (muons), where d_0^{BL} is the transverse impact parameter of the track with respect to the measured beam line (BL) position determined at the point of closest approach of the track to the beam line, $\sigma_{d_0^{\text{BL}}}$ is the uncertainty in the measured d_0^{BL} , z_0^{BL} is the difference between the longitudinal position of the track along the beam line at the point where d_0^{BL} is measured and the longitudinal position of the primary interaction vertex,³ and θ is the polar angle of the track. Lepton isolation criteria are defined based on low values for the scalar sum of transverse momenta of tracks with $p_T > 1 \text{ GeV}$ within a ΔR cone around

³If more than one vertex is reconstructed, the one with the highest sum of p_T^2 of the associated tracks is regarded as the primary vertex.

the lepton, whose size depends upon its p_T , and excluding the track associated with the lepton (*track isolation*). These criteria are optimised for a uniform efficiency of 99% in the (p_T, η) plane for leptons from $Z \rightarrow \ell\ell$ decays in $Z + \text{jets}$ events. Calorimeter isolation is also used for the $\ell\nu qq$ channel, using an isolation variable constructed from calorimeter activity within a cone of radius $\Delta R = 0.2$ around the lepton candidate. The isolation criteria depend on both p_T and η , and accept 95% of $Z \rightarrow \ell\ell$ events while maximising the rejection of leptons originating in jets.

Jets are reconstructed from three-dimensional topological clusters of energy deposits in the calorimeter calibrated at the EM scale [74], using the anti- k_t algorithm [75] with two different radius parameters of $R = 1.0$ and $R = 0.4$, hereafter referred to as large- R jets (denoted by “ J ”) and small- R jets (denoted by “ j ”), respectively. The four-momenta of the jets are calculated as the sum of the four-momenta of the clusters, which are assumed to be massless.

The p_T of small- R jets are corrected for losses in passive material, the non-compensating response of the calorimeter, and contributions from pile-up [76]. They are required to have $p_T > 20$ GeV and $|\eta| < 2.4$. For small- R jets with $p_T < 50$ GeV, a jet vertex tagger (JVT) [77] discriminant, based on tracking and vertexing information, is required to be larger than 0.64, where the JVT is a multivariate tagger used to identify and remove jets with a large contribution from pile-up. In addition, small- R jets are discarded if they are within a cone of size $\Delta R < 0.2$ around an electron candidate, or if they have less than three associated tracks and are within a cone of size $\Delta R < 0.2$ around a muon candidate. However, if a small- R jet with three or more associated tracks is within a cone of size $\Delta R < 0.4$ around a muon candidate, or any small- R jet is within a region $0.2 < \Delta R < 0.4$ around an electron candidate, the corresponding electron or muon candidate is discarded. Small- R track-jets are defined by applying the same jet reconstruction algorithms to inner-detector tracks treated as having the pion mass, and used to avoid overlap between $qqqq$ sideband regions and searches for Higgs boson pair production, as discussed in section 6.

For the large- R jets, the original constituents are calibrated using the local cluster weighting algorithm [78] and reclustered using the $k_\perp$ algorithm [79] with a radius parameter of $R_{\text{sub-jet}} = 0.2$, to form a collection of sub-jets. A sub-jet is discarded if it carries less than 5% of the p_T of the original jet. The constituents in the remaining sub-jets are then used to recalculate the large- R jet four-momentum, and the jet energy and mass are further calibrated to particle level using correction factors derived from simulation [80]. The resulting “trimmed” [81] large- R jets are required to have $p_T > 200$ GeV and $|\eta| < 2.0$. Large- R jets are required to have an angular separation of $\Delta R > 1.0$ from electron candidates.

The large- R jets are used to reconstruct the hadronically decaying W/Z (“ V ”) boson. A boson tagger [14, 15, 82, 83] is subsequently used to distinguish the boosted hadronically decaying V boson from jets originating from quarks (other than the top-quark) or gluons. The tagger is based on the mass of the jet m_J and a variable $D_2^{(\beta=1)}$, defined in ref. [82], that is sensitive to the compatibility of the large- R jet with a two-prong decay topology. The large- R jet is identified by the boson tagger as a W (Z) candidate with its mass within 15 GeV of the expected W (Z) mass peak, which is estimated from simulated events to be 83.2 GeV (93.4 GeV). Large- R jets with mass within 15 GeV from both the

W and Z peaks are assigned both hypotheses. For context, the resolution ranges from 8 GeV to 15 GeV in the jet p_T range used in the analysis. Additionally, a p_T -dependent selection on the $D_2^{(\beta=1)}$ variable is configured so that the average identification efficiency for longitudinally polarised, hadronically decaying W or Z bosons is 50%. This selection rejects more than 90% of the background. Large- R track-jets are defined by applying the same jet reconstruction and filtering algorithms to inner-detector tracks treated as having the pion mass. These jets are ghost-associated to large- R jets and used for the evaluation of systematic uncertainties, as discussed in section 7.

Small- R jets and small- R track-jets containing b -hadrons are identified using the MV2 b -tagging algorithm [84], which has an efficiency of 85% in simulated tt events. The jets thus selected are referred to as b -jets in the following. The corresponding misidentification rate for selecting b -jet candidates originating from a light quark or gluon is less than 1%. The misidentification rate for selecting c -jets as b -jet candidates is approximately 17%.

The missing transverse momentum, $\mathbf{E}_T^{\text{miss}}$, with magnitude E_T^{miss} , is calculated as the negative vectorial sum of the transverse momenta of calibrated objects, such as electrons, muons, and small- R jets. Charged-particle tracks compatible with the primary vertex and not matched to any of those objects are also included in the $\mathbf{E}_T^{\text{miss}}$ reconstruction [85, 86]. For multi-jet background rejection, a similar quantity, $\mathbf{p}_T^{\text{miss}}$, is computed using only charged-particle tracks originating from the reconstructed primary vertex to substitute for the calorimeter-based measurements of jet four-momenta. Its magnitude is denoted by p_T^{miss} . Both tiers of the ATLAS trigger system also reconstruct E_T^{miss} . The triggers used in this paper reconstruct E_T^{miss} based on calorimeter information, and do not include corrections for muons.

The identification efficiency, energy scale, and resolution of jets, leptons and b -jets are measured in data and correction factors are derived, which are applied to the simulation to improve the modelling of the data.

5 Event selection

This analysis focuses on identifying diboson events in which at least one vector boson V decays hadronically, and is performed in four different channels identified by the decay of the other vector boson: $qqqq$, $\nu\nu qq$, $\ell\nu qq$ and $\ell\ell qq$. Event selection criteria are chosen to guarantee the statistical independence of the channels. The criteria are summarised in table 3, and described in more detail below.

Events are selected at trigger level by requiring at least one large- R jet with $p_T > 360$ GeV in the $qqqq$ channel, large E_T^{miss} in the $\nu\nu qq$ channel, large E_T^{miss} or at least one electron in the $\ell\nu qq$ channel, and at least one electron or muon in the $\ell\ell qq$ channel. All trigger requirements guarantee full efficiency in the kinematic region considered in the analysis. A primary vertex is required to be reconstructed from at least three charged-particle tracks with $p_T > 400$ MeV.

At least one large- R jet is required, with $p_T > 200$ GeV, $|\eta| < 2.0$ and $m_J > 50$ GeV. Events are then divided by different pre-selection criteria into different channels according to the number of “baseline” and “good” leptons that are reconstructed. A baseline lepton is

a loose muon or electron candidate with $p_T > 7$ GeV and $|\eta| < 2.7$ or $|\eta| < 2.47$, respectively, which passes a relaxed set of track-isolation and impact parameter requirements. A good lepton has $p_T > 25$ GeV and is either a muon with $|\eta| < 2.5$, or an electron with $|\eta| < 2.47$ excluding the transition region between barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$), which passes identification and isolation requirements as discussed in section 4.

Events with no reconstructed baseline lepton and with $E_T^{\text{miss}} > 250$ GeV are assigned to the $\nu\nu qq$ channel. Events are assigned to the $qqqq$ channel if they have no good leptons, $E_T^{\text{miss}} < 250$ GeV, an additional large- R jet meeting the same selection criteria as the other large- R jet, and if the large- R jet with leading p_T satisfies a requirement of $p_T > 450$ GeV to ensure full trigger efficiency. Events with exactly one good lepton which satisfies tight track and calorimeter isolation requirements, and which is either a medium muon or tight electron, or a medium electron with $p_T > 300$ GeV, are assigned to the $\ell\nu qq$ channel. Events with exactly two same-flavour good leptons where one meets medium selection criteria, the invariant mass of the dilepton system passes a Z boson mass window selection of $83 < m_{ee}/\text{GeV} < 99$ or $66 < m_{\mu\mu}/\text{GeV} < 116$, and, in the case of muons, the two leptons are oppositely charged, are assigned to the $\ell\ell qq$ channel.

Additional event topology requirements are applied to pre-selected events in order to suppress backgrounds. In the $\nu\nu qq$ channel, contributions from non-collision backgrounds and multi-jet production are suppressed by requiring $p_T^{\text{miss}} > 30$ GeV, $|\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^{\text{miss}})| < \pi/2$ and by requiring that the minimum azimuthal separation between $\mathbf{E}_T^{\text{miss}}$ and any small- R jet is greater than 0.6.

In the $qqqq$ channel, the separation in rapidity between the two large- R jets, $|y_{J_1} - y_{J_2}|$, is required to be below 1.2, and their transverse momentum asymmetry, $(p_{T,J_1} - p_{T,J_2})/(p_{T,J_1} + p_{T,J_2})$, is required to be below 0.15. To further reduce the multi-jet background, large- R jets are required to have $N_{\text{trk}} < 30$ charged-particle tracks with $p_T > 500$ MeV, where the tracks must be consistent with the primary vertex and be matched to the calorimeter jet [87]. The matching is made prior to trimming, and is determined by representing each track by a collinear “ghost” constituent with negligible energy during jet reconstruction (“ghost association”).

In the $\ell\nu qq$ channel, events are required to have no small- R jet identified as a b -jet outside a cone of radius $\Delta R = 1.0$ around the selected large- R jet to reject backgrounds from $t\bar{t}$ production, and to have $E_T^{\text{miss}} > 100$ GeV in order to reject multi-jet background. The leptonically decaying W candidate is required to have $p_{T,\ell\nu} > 200$ GeV, where the neutrino is assigned transverse momentum $\mathbf{E}_T^{\text{miss}}$ and its momentum along the z -axis, p_z , is obtained by imposing a W boson mass constraint to the ℓ - $\mathbf{E}_T^{\text{miss}}$ system.⁴ A new resonance with mass $m_{\ell\nu J}$ decaying into two bosons, both at fairly central rapidity, would often impart significant transverse momentum to the bosons relative to the resonance mass. The p_T of the two vector-boson candidates is therefore required to have $p_{T,J}/m_{\ell\nu J} > 0.4$ and $p_{T,\ell\nu}/m_{\ell\nu J} > 0.4$. In the $\ell\ell qq$ channel, similar requirements on the p_T of the two vector-boson candidates are applied, namely $p_{T,J}/m_{\ell\ell J} > 0.4$ and $p_{T,\ell\ell}/m_{\ell\ell J} > 0.4$.

⁴The longitudinal momentum p_z is taken to be the smaller in absolute value of the two solutions of the resulting quadratic equation. If a complex value is obtained, the real component is chosen.

Selection level	Channel			
	$qqqq$	$\nu\nu qq$	$\ell\nu qq$	$\ell\ell qq$
Trigger	Large-R jet, $p_T > 360$ GeV	E_T^{miss}	$E_T^{\text{miss}}(\mu\nu qq)$ or single electron ($e\nu qq$)	single electron or muon
Large-R jet	$\geq 2, N_{\text{trk}} < 30,$ $p_{T,J_1} > 450$ GeV, $p_{T,J_2} > 200$ GeV	$\geq 1,$ $p_{T,J} > 200$ GeV		
Baseline leptons	0	0	≥ 1	≥ 2
Good leptons	0	0	1 medium μ or tight [†] e	2 e or 2 μ , loose + medium
Topology	$E_T^{\text{miss}} < 250$ GeV, $ y_{J_1} - y_{J_2} < 1.2,$ $\frac{p_{T,J_1} - p_{T,J_2}}{p_{T,J_1} + p_{T,J_2}} < 0.15$	$E_T^{\text{miss}} > 250$ GeV, $p_T^{\text{miss}} > 30$ GeV, $ \Delta\phi(\mathbf{E}_T^{\text{miss}}, p_T^{\text{miss}}) < \frac{\pi}{2},$ $ \Delta\phi(\mathbf{E}_T^{\text{miss}}, j) > 0.6$	no b -jet with $\Delta R(j, J) < 1.0,$ $E_T^{\text{miss}} > 100$ GeV, $p_{T,\ell\nu} > 200$ GeV, $p_{T,J}/m_{\ell\nu J} > 0.4,$ $p_{T,\ell\nu}/m_{\ell\nu J} > 0.4$	$p_{T,J}/m_{\ell\ell J} > 0.4,$ $p_{T,\ell\ell}/m_{\ell\ell J} > 0.4,$ $83 < m_{ee}/\text{GeV} < 99,$ $66 < m_{\mu\mu}/\text{GeV} < 116$
Discriminant	m_{JJ}	m_T	$m_{\ell\nu J}$	$m_{\ell\ell J}$

[†] The electron, if over 300 GeV in p_T , need only be medium.

Table 3. Event selection criteria in the four analysis channels. Baseline and good leptons are defined in the text.

Events are classified as WW , WZ , or ZZ by applying the corresponding selection criteria to the two boson candidates. If the number of boson-tagged jets exceeds the number of hadronically decaying bosons required by the decay channel, the leading- p_T jets are used. The final discrimination between resonant signal and backgrounds is done in a one-dimensional distribution either of mass or of transverse mass. In the $qqqq$ channel, the invariant mass of the jet pair, m_{JJ} , is used in the fiducial region $1\text{ TeV} < m_{JJ} < 3.5\text{ TeV}$ whose lower bound is chosen to guarantee full trigger efficiency. In the $\nu\nu qq$ channel, the transverse mass of the $J - \mathbf{E}_T^{\text{miss}}$ system, $m_T = \sqrt{(E_{T,J} + E_T^{\text{miss}})^2 - (\mathbf{p}_{T,J} + \mathbf{E}_T^{\text{miss}})^2}$ is used. In the $\ell\nu qq$ channel, $m_{\ell\nu J}$ is used. In the $\ell\ell qq$ channel, the p_T of the dilepton system is scaled event-by-event by a single multiplicative factor to set the dilepton invariant mass $m_{\ell\ell}$ to the mass of the Z boson (m_Z) in order to improve the diboson mass resolution. The invariant mass $m_{\ell\ell J}$ is used as the discriminant.

Table 3 shows a summary of the event selection criteria in the four channels. The combined acceptance times efficiency for a heavy resonance decaying to dibosons is as large as 18% for $W' \rightarrow WZ$ and also for $Z' \rightarrow WW$ in the HVT model-A benchmark assuming $g_V = 1$. In the bulk RS benchmark with $\kappa/\bar{M}_{\text{Pl}} = 1$, it reaches up to 17% for $G^* \rightarrow WW$, and 14% for $G^* \rightarrow ZZ$. The acceptance times efficiency is estimated with respect to the branching ratio of the signal benchmarks to the specific diboson final state and takes into account the W and Z boson branching ratios. Figure 1 summarises the acceptance times efficiency for the different channels as a function of the scalar, HVT, and G^* masses, considering only decays of the resonance into VV . The mass ranges used in the different channels are reflected in the figure. After all selection criteria are applied, reconstructed diboson mass resolutions for a W' with a mass of 2 TeV, decaying to WZ , are 3% for $\ell\ell qq$, 5.5% for $\ell\nu qq$, and 6% for $qqqq$.

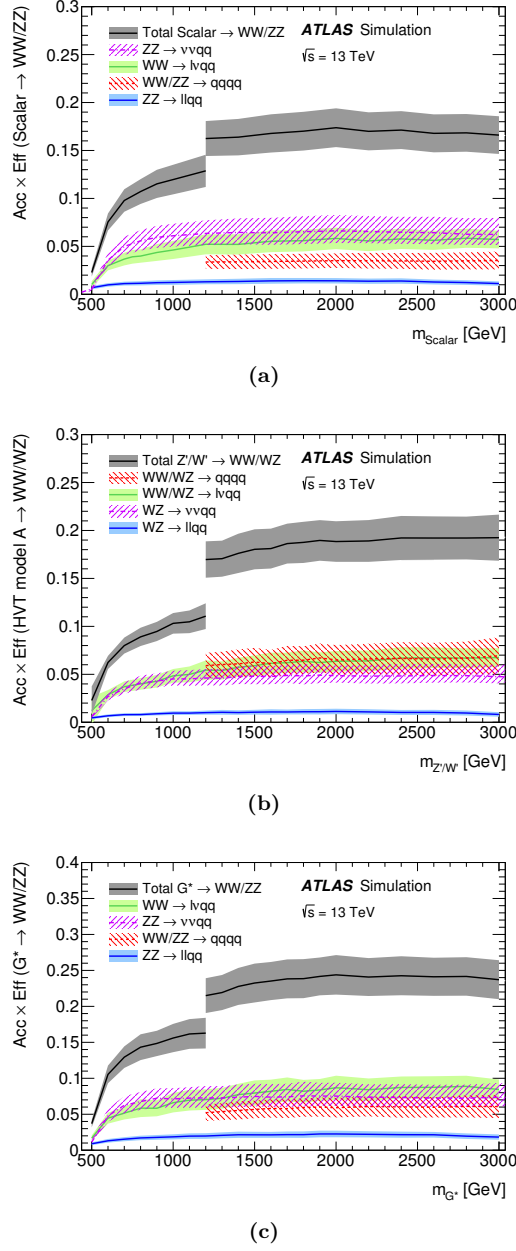


Figure 1. Signal acceptance times efficiency as a function of the resonance mass, for the different channels contributing to the searches for (a) a scalar resonance decaying to WW and ZZ , (b) HVT decaying to WW and WZ and (c) bulk RS gravitons decaying to WW and ZZ . The branching ratio of the new resonance decaying to dibosons is included in the denominator of the efficiency calculation. The coloured bands represent the total statistical and systematic uncertainties. In the case of the $qqqq$ channel, only signals with resonance masses beyond 1.2 TeV, for which the mass peak is fully reconstructed in the fiducial m_{JJ} region, are considered.

6 Background estimation

The background contamination in the signal regions is different for each of the channels studied. Different background estimation strategies are used for the fully hadronic and semileptonic channels.

In the $qqqq$ channel, the dominant background originates from multi-jet events, with significantly smaller contributions due to SM W/Z + jet, diboson, tt and single-top-quark production. As all of these processes are expected to produce a smoothly falling m_{JJ} spectrum, the overall background is modelled in terms of a probability density function

$$f(x) = N(1 - x)^{p_2 + \xi p_3} x^{p_3}, \quad (6.1)$$

where $x = m_{JJ}/\sqrt{s}$, p_2 and p_3 are dimensionless shape parameters, ξ is a constant whose value is chosen to minimise the correlation between p_2 and p_3 , and N is an overall normalisation factor. The functional form in eq. (6.1) is validated using background simulation and validation regions in data, defined to be similar to the signal region but with a few differences. Instead of selecting events where the mass of the large- R jet is consistent with the mass of the W or Z boson, events are selected to have a large- R jet with a mass in the sideband regions, 110–140 GeV or 50–65 GeV, and without applying the requirement on the track multiplicity. Specifically, it is required that either both jets have a mass in the range 110–140 GeV and there are less than two b -tagged track-jets matched by ghost-association to either jet, or that one jet has a mass in the range 110–140 GeV and the other in the range 50–65 GeV. These regions are defined such that the kinematic properties of the selected events are similar to the signal region, and overlap with searches for Higgs boson pair production is avoided.

In the $\nu\nu qq$ channel, the dominant background is Z + jets production with significant contributions from W + jets, tt , and SM diboson production. In the $\ell\nu qq$ channel, the dominant backgrounds are W + jets and tt production. In the $\ell\ell qq$ channel, where two same-flavour leptons with an invariant mass close to the Z mass are selected, Z + jets production is by far the dominant background. All three channels also have contributions at the level of a few percent from single-top-quark and diboson production. The single-top-quark process contributes 15% of the total top-quark background in the $\ell\nu qq$ channel, 10% in the $\nu\nu qq$, and a negligible amount for the $\ell\ell qq$ channel. The multi-jet background enters the signal regions of the semileptonic channels through semileptonic hadron decays and through jets misidentified as leptons, and this background is found to be negligibly small in all three channels.

In the $\nu\nu qq$, $\ell\nu qq$, and $\ell\ell qq$ channels, the modelling of W/Z +jets backgrounds is constrained using dedicated control regions. A region enriched in W + jets events is used to control the W + jets background normalisation in the $\nu\nu qq$ and $\ell\nu qq$ channels; events in this region are required to fall in the sidebands of the m_J distribution and to have one reconstructed good muon. A region enriched in Z +jets events is used to control the Z +jets backgrounds in the $\nu\nu qq$ and $\ell\ell qq$ channels; events in this region are also required to fall in the sidebands of the m_J distribution, but to have two reconstructed good leptons.

The tt background is estimated in the $\nu\nu qq$ and $\ell\nu qq$ channels using a control region enriched in top-quark pairs. This control region is defined as the W + jets control region, without the m_J sideband criterion and with the added requirement of at least one additional b -jet with a separation $\Delta R > 1$ from the large- R jet. The tt background for the $\ell\ell qq$ channel is estimated from MC simulation.

The W , Z and tt control regions are included in the combined profile likelihood fit described in section 8 to help constrain the W +jets, Z +jets and tt normalisation in the signal regions.

The diboson contributions to the $\nu\nu qq$, $\ell\nu qq$ and $\ell\ell qq$ channels are estimated using MC simulation. Single-top-quark production is constrained by the tt control region using the same normalisation factor as for tt .

7 Systematic uncertainties

The most important sources of systematic uncertainty are those related to the energy scale and resolution of the large- R jet p_T , mass, and $D_2^{(\beta=1)}$. The systematic uncertainties related to the scales of the large- R jet p_T , mass and $D_2^{(\beta=1)}$ are extracted following the technique described in ref. [80]. Track-jets are geometrically matched to calorimeter jets, and for each observable of interest, e.g. p_T , mass, or $D_2^{(\beta=1)}$, a systematic uncertainty is estimated from the comparison of the ratio of the matched track-jet observable to the calorimeter-jet observable between simulation and data. For the jet p_T and mass, $\sqrt{s} = 13$ TeV data and simulation are used. For $D_2^{(\beta=1)}$, $\sqrt{s} = 8$ TeV simulation and data are used, and an additional uncertainty is added to account for the differences between 8 TeV and 13 TeV [14]. The uncertainties in the large- R jet p_T , mass, and $D_2^{(\beta=1)}$ scale are 5%, 6% and 10%, respectively.

The resolution of each of these large- R jet observables is determined as the standard deviation of a Gaussian fit to the distribution of the observable response defined as the ratio of the calorimeter-jet observable to a simulated-particle-level jet observable. The relative uncertainties in these resolutions are estimated based on previous studies with $\sqrt{s} = 7$ TeV data and $\sqrt{s} = 13$ TeV simulation. For the large- R jet p_T [80] and mass resolution a 20% uncertainty is assigned, while for the $D_2^{(\beta=1)}$ resolution a 10% uncertainty is assigned. The large- R jet mass resolution uncertainty is estimated from variations in data and simulation in the widths of the W -jet mass peaks in tt events [80]. The $D_2^{(\beta=1)}$ resolution uncertainty is estimated by comparing 13 TeV simulation samples from different generators and shower simulations [14].

Other subdominant experimental systematic uncertainties include those in the lepton energy and momentum scales, in lepton identification efficiency, in the efficiency of the trigger requirements, and in the small- R jet energy scale and resolution. All experimental systematic uncertainties are treated as fully correlated among all channels.

Uncertainties are also taken into account for possible differences between data and the simulation model that is used for each process.

In the $\nu\nu qq$ channel, an uncertainty on the shape of the m_T spectrum for the W + jets and Z + jets backgrounds is extracted by comparing the nominal shape ob-

tained with SHERPA to the one obtained with an alternative sample generated with MADGRAPH5_AMC@NLO.

In the $\ell\nu qq$ channel, an uncertainty on the shape of the $m_{\ell\nu J}$ distribution of the dominant W + jets background is obtained by comparing the $m_{\ell\nu J}$ shape in simulation and in data in the W + jets control region after the expected tt and diboson contributions are subtracted. The ratio of the data distribution to that predicted by MC is fitted with a first-order polynomial and its deviation from unity is used as a modelling uncertainty.

In the $\ell\ell qq$ channel, an uncertainty on the shape of the $m_{\ell\ell J}$ spectrum for the Z + jets background is assessed by comparing the shape difference between the SHERPA predictions and the data-driven estimate using events in the Z control region.

The data and simulation agree very well for events in the top-quark control region. The uncertainty in the shape of the mass distributions for the $\nu\nu qq$, $\ell\nu qq$ and $\ell\ell qq$ channels from the tt background is estimated by comparing a sample generated using aMC@NLO [52] interfaced with PYTHIA 8.186 to the nominal tt sample. Additional systematic uncertainties in parton showering and hadronisation are evaluated by comparing the nominal sample showered with PYTHIA to one showered with HERWIG [88]. Samples of tt events generated with the factorisation and renormalisation scales doubled or halved are compared to the nominal sample, and the largest difference observed in the mass discriminants is taken as an additional uncertainty arising from the QCD scale uncertainty.

Theoretical uncertainties in the SM diboson production cross-section, including the effect of PDF and scale uncertainties, are taken into account and amount to about 10% [89]. An uncertainty in the shape of the predicted diboson $m_{\ell\ell J}$ spectrum in the $\ell\ell qq$ channel is derived by comparing MC samples generated by SHERPA and POWHEG BOX. Shape uncertainties are found to have negligible impact in the $\nu\nu qq$ and $\ell\nu qq$ channels.

The uncertainties in the modelling of the Z + jets and W + jets backgrounds are treated as uncorrelated since they are evaluated differently in each channel. For the tt background, the modelling uncertainty is treated as correlated between the $\ell\nu qq$ and $\ell\ell qq$ channels, and uncorrelated with the modelling uncertainty in the $\nu\nu qq$ channel. The diboson normalisation uncertainty is taken as correlated among the $\nu\nu qq$, $\ell\nu qq$ and $\ell\ell qq$ channels.

Uncertainties in the signal acceptance arise from the choice of PDF and from the amount of initial- and final-state radiation present in simulated signal events. The PDF-induced uncertainties in the signal acceptance for semileptonic decay channels are derived using the PDF4LHC recommendations [90]; in all channels the resulting uncertainty is at most 4%. PDF-induced uncertainties are not evaluated for the $qqqq$ channel, where they are subdominant to other acceptance effects. The uncertainty in the integrated luminosity has an impact of 5% on the signal normalisation. All signal acceptance uncertainties are treated as fully correlated across all search channels.

The uncertainty in modelling background distribution shapes in the $qqqq$ channel is found to be negligible compared to statistical uncertainties in the background fit parameters. An additional uncertainty in the signal normalisation is introduced in the $qqqq$ channel to take into account potentially different efficiencies of the $N_{\text{trk}} < 30$ requirement in data and simulation. This uncertainty is estimated in a data control sample enriched in W/Z + jets events, where the W/Z bosons decay to quarks. This control sample is obtained

Channel	Signal region (selection)	Scalar mass range [TeV]	HVT W' and Z' mass range [TeV]	G^* mass range [TeV]
$qqqq$	$WW + ZZ$	1.2–3.0	–	1.2–3.0
	$WW + WZ$	–	1.2–3.0	–
$\nu\nu qq$	WZ	–	0.5–3.0	–
	ZZ	0.5–3.0	–	0.5–3.0
$\ell\nu qq$	$WW + WZ$	–	0.5–3.0	–
	WW	0.5–3.0	–	0.5–3.0
$\ell\ell qq$	WZ	–	0.5–3.0	–
	ZZ	0.5–3.0	–	0.5–3.0

Table 4. Channels, signal regions and mass ranges where the channels contribute to the search.

by applying the $D_2^{(\beta=1)}$ selection only to the highest- p_T large- R jet in dijet events. The m_J distribution is fitted in subsamples with different track multiplicity selections to obtain the rates of W/Z decays in each sample. From these the uncertainty from the track multiplicity cut is estimated to be 6%.

For all the considered signal hypotheses, the impact of each source of uncertainty on the search is evaluated in terms of the corresponding contribution to the total uncertainty in the fitted number of signal events, as obtained after the statistical procedure described in the next section. The dominant contribution is due to large- R jet scale uncertainties and amounts to about 35% of the total uncertainty. Additional contributions are due to uncertainties in the modelling and normalisation of backgrounds in the $\nu\nu qq$, $\ell\nu qq$ and $\ell\ell qq$ channels (about 20%), and small- R jet energy scale uncertainties (about 10%). Sub-leading contributions have an overall impact of less than about 15%.

8 Statistical analysis

In the combined analysis to search for a scalar resonance decaying to WW or ZZ , HVT decaying to WW or WZ , and bulk G^* decaying to WW or ZZ , all four individual channels are used. Table 4 summarises the signal region and mass range in which the individual channels contribute to the search.

The statistical interpretation of these results uses the data modelling and handling toolkits RooFit [91], RooStats [92] and HistFactory [93]. It proceeds by defining the likelihood function $L(\mu, \vec{\theta})$ for a particular model, with an implicit signal description, in terms of the signal strength μ , and the additional set of nuisance parameters $\vec{\theta}$ which can be related to both background and signal. The likelihood function is computed considering in each channel bins of the discriminating variable; the binning is chosen based on the expected mass resolution and statistical uncertainty, as estimated from simulation. The nuisance parameters are either free to float, as in the case of the p_2 and p_3 parameters used in the $qqqq$ channel to estimate the background, or constrained from external studies represented by Gaussian terms. The likelihood for the combination of the four search channels is the

product of the Poisson likelihoods for the individual channels, except in the case of common nuisance parameters,

$$L(\mu, \vec{\theta}) = \prod_c \prod_i \text{Pois} \left(n_{c_i}^{\text{obs}} | n_{c_i}^{\text{sig}}(\mu, \vec{\theta}) + n_{c_i}^{\text{bkg}}(\vec{\theta}) \right) \prod_k f_k(\theta'_k | \theta_k). \quad (8.1)$$

The terms $n_{c_i}^{\text{obs}}$ represent the number of events observed, and the terms $n_{c_i}^{\text{sig}}, n_{c_i}^{\text{bkg}}$, the number of events expected from signal or background in bin i of the discriminant from channel c . The term $f_k(\theta'_k | \theta_k)$ represents the set of constraints on $\vec{\theta}$ from auxiliary measurements θ'_k : these constraints include normalisation and shape uncertainties in the signal and background models, and, except for the $qqqq$ channel, include the statistical uncertainties of the simulated bin content. The W +jets normalisation is a free parameter in the combined likelihood fit in all the channels. The normalisation of the Z +jets background in the $\ell\ell qq$ and $\nu\nu qq$ channels is a free parameter in the combined likelihood fit. In the $\ell\nu qq$ channel, where the contribution from Z +jets is small, the normalisation obtained from MC simulation is used instead, with an 11% systematic uncertainty assigned. The $t\bar{t}$ normalisation in the $\ell\nu qq$ and $\nu\nu qq$ channels is a free parameter in the combined likelihood fit. In the $\ell\ell qq$ channel, where the $t\bar{t}$ background contribution is small, its normalisation is based on the theoretical cross-section with a 10% systematic uncertainty assigned.

The likelihood function $L(\mu, \vec{\theta})$ is used to construct the profile-likelihood-ratio test statistic [94], defined as:

$$t = -2 \ln \lambda(\mu) = -2 \ln \left(\frac{L(\mu, \hat{\vec{\theta}}(\mu))}{L(\hat{\mu}, \hat{\vec{\theta}})} \right), \quad (8.2)$$

where $\hat{\mu}$ and $\hat{\vec{\theta}}$ are the values of the parameters that maximise the likelihood function $L(\mu, \vec{\theta})$ globally, and $\hat{\vec{\theta}}(\mu)$ are the values of $\vec{\theta}$ which maximise the likelihood function given a certain value of μ . The parameter $\hat{\mu}$ is required to be non-negative. This test statistic is used to derive the statistical results of the analysis.

For calculating p -values, which test the compatibility of the data with the background-only model, the numerator of eq. (8.2) is evaluated for the background-only hypothesis, i.e. signal strength $\mu = 0$. In extracting upper limits, the calculation is modified such that if $\hat{\mu} > \mu$, $\lambda(\mu)$ is taken to be 1; this ensures that a signal larger than expected is not taken as evidence against a model. The asymptotic distributions of the above test statistic are known and described in ref. [95], and this methodology is used to obtain the results in this paper.

Upper limits on the production cross-section times branching ratio to diboson final states for the benchmark signals are set using the modified-frequentist CL_s prescription [96], where the probability of observing λ to be larger than a particular value, is calculated using a one-sided profile likelihood. The calculations are done using the lowest-order asymptotic approximation, which was validated to better than 10% accuracy using pseudo-experiments. All limits are set at the 95% confidence level (CL).

	Control Regions			Signal Regions			
	W +jets	Z +jets	$t\bar{t}$	$\nu\nu q\bar{q}$	$\ell\ell q\bar{q}$	$\ell\nu q\bar{q}$	$q\bar{q}q\bar{q}$
SM Diboson	53 ± 8	15 ± 4	12 ± 3	70 ± 8	12 ± 2	64 ± 9	
$t\bar{t}$, single- t	325 ± 49	1.4 ± 0.8	780 ± 34	170 ± 15	1.2 ± 0.9	230 ± 31	
Z +jets	17 ± 3	387 ± 19	2.5 ± 0.7	385 ± 24	102 ± 7	11 ± 2	
W +jets	797 ± 66		54 ± 13	208 ± 23		397 ± 31	
Total Background	1193 ± 31	403 ± 19	849 ± 29	832 ± 26	115 ± 7	702 ± 20	128 ± 11
Observed	1200	406	848	838	109	691	128

Table 5. Expected and observed yields in signal and control regions for the $W' \rightarrow WZ$ signal hypothesis. Yields and uncertainties are evaluated after a background-only fit to the data. The background for the $q\bar{q}q\bar{q}$ channel is evaluated *in situ* and only the total background yield is indicated. The W +jets background for the Z +jets control region and the $\ell\ell q\bar{q}$ signal region is negligible. The uncertainty in the total background estimate can be smaller than the sum in quadrature of the individual background contributions due to anti-correlations between the estimates of different background sources.

9 Results

The background estimation techniques described in section 6 are applied to the selected data, and the results in the four different analysis channels are shown in figure 2 for the channels relevant to the HVT (WZ, WW) search and in figure 3 for those relevant to the scalar resonance and bulk RS $G^* \rightarrow WW, ZZ$ searches, respectively. Both figures represent background-only fits to the data. The total yields in the different signal and control regions for the HVT WZ channel are also shown in table 5. Good agreement is found between the data and the background-only hypothesis. The most significant excess over the expected background is observed in the scalar selection for a mass of 1.6 TeV, with a p -value equivalent to a local significance of 2.5 standard deviations. Upper limits at the 95% CL are set on the production cross-section times the branching ratio of new resonances decaying to diboson final states.

Figure 4 shows the observed and expected 95% CL model-independent limits on the production cross-section times branching ratio of a narrow-width scalar resonance, as a function of its mass, in the WW and ZZ channels combined. The constraints are compared with the CP-even scalar singlet model described in section 3, for the NDA and Unsuppressed scenarios. Masses below 2650 GeV are excluded for the Unsuppressed scenario. Figure 5 shows the exclusion contours in the $(c_H/\Lambda, c_3/\Lambda)$ parameter space, derived from the cross-section limits for three sample masses.

Figure 6 shows the observed and expected limits obtained in the search for an HVT decaying to WW or WZ states as a function of the mass of the HVT, compared to the theoretical predictions for the HVT model A assuming $g_V = 1$ and the HVT model-B assuming $g_V = 3$. For HVT model-B, new gauge bosons with masses below 2600 GeV are excluded at the 95% CL. Results are also shown in figure 7 in terms of exclusion contours in the HVT parameter space $(g^2 c_F/g_V, g_V c_H)$ for different resonance masses [97].

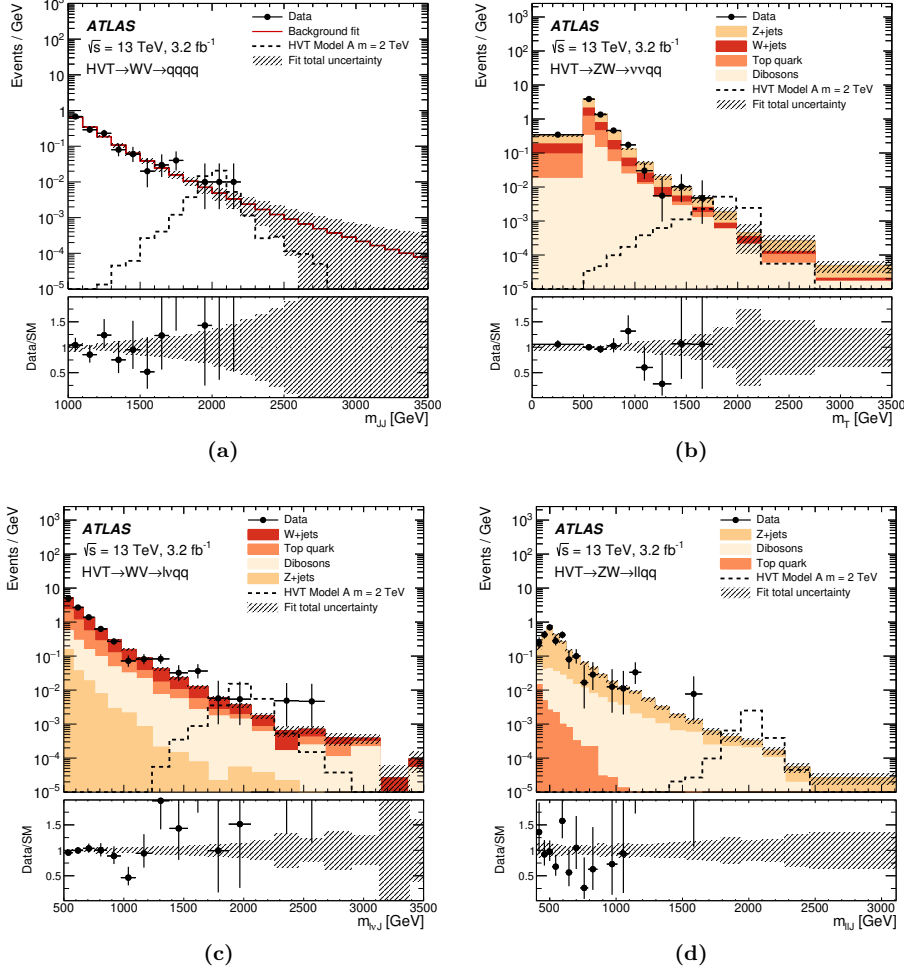


Figure 2. Distribution of the data compared to the background estimate for the analysis discriminant in the signal regions for the HVT search; (a) the m_{JJ} distribution in the $qqqq$ channel, (b) the m_T distribution in the $\nu\nu qq$ channel, (c) $m_{\ell\nu J}$ in the $\ell\nu qq$ channel, and (d) $m_{\ell\ell J}$ in the $\ell\ell qq$ channel. The “Top quark” distribution includes both the $t\bar{t}$ and single-top-quark backgrounds. The upper panels show the distribution of the observed data and estimated backgrounds as a function of the analysis discriminants. The observed data are shown as points, solid colours represent the different background contributions and the shaded bands reflect the systematic uncertainties in the estimated background. The lower panels show the ratio of the observed data to the estimated background as a function of the analysis discriminant. The decay modes “WV” or “ZW” indicate the mass requirements placed on the hadronically decaying boson, where a “W” or “Z” indicates a narrow mass window around the corresponding boson mass, and a “V” indicates the wider mass window including both the W and Z boson masses. More details are given in the text.

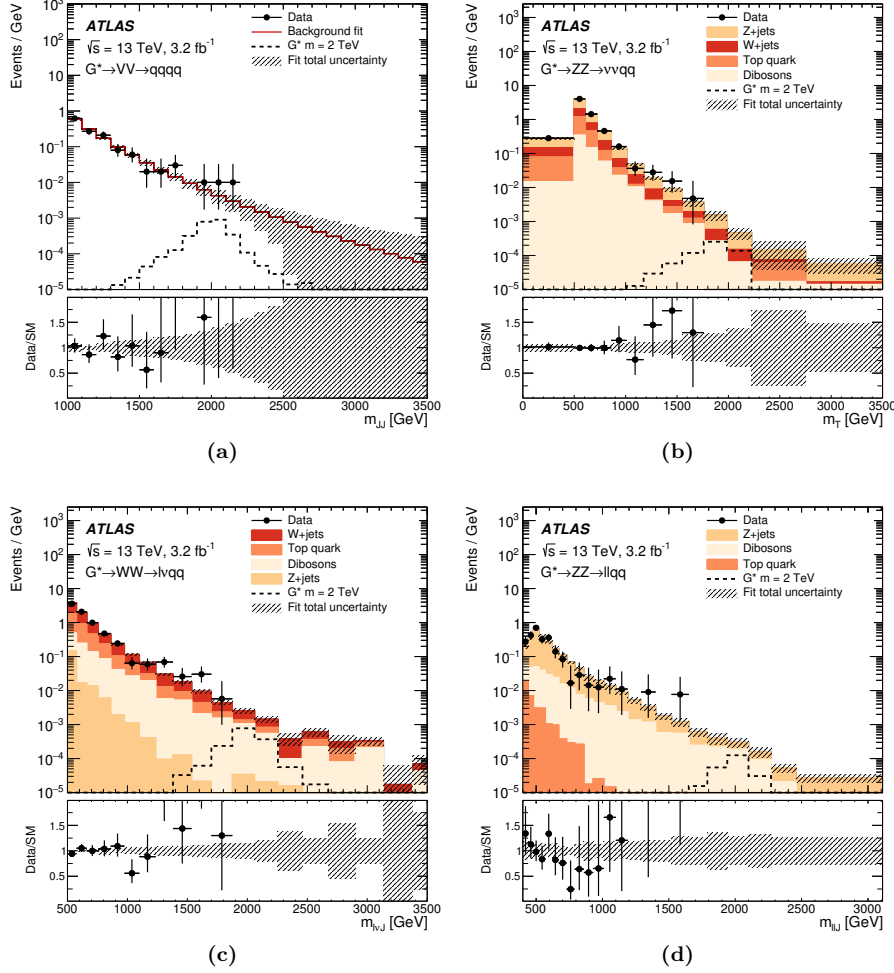


Figure 3. Distribution of the data compared to the background estimate for the analysis discriminant in the signal regions for the scalar and bulk RS G^* searches; (a) the m_{JJ} distribution in the $qqqq$ channel, (b) the m_T distribution in the $\nu\nu qq$ channel, (c) $m_{l\nu J}$ in the $\ell\nu qq$ channel, and (d) $m_{l\ell J}$ in the $\ell\ell qq$ channel. The “Top quark” distribution includes both the $t\bar{t}$ and single-top-quark backgrounds. The upper panels show the distribution of the observed data and estimated backgrounds as a function of the analysis discriminants. The observed data are shown as points, solid colours represent the different background contributions and the shaded bands reflect the systematic uncertainties in the estimated background. The lower panels show the ratio of the observed data to the estimated background as a function of the analysis discriminant. The decay modes “ WW ”, “ ZZ ”, or “ VV ” indicate the mass requirements placed on the hadronically decaying boson, where a “ W ” or “ Z ” indicates a narrow mass window around the corresponding boson mass, and a “ V ” indicates the wider mass window including both the W and Z boson masses. More details are given in the text.

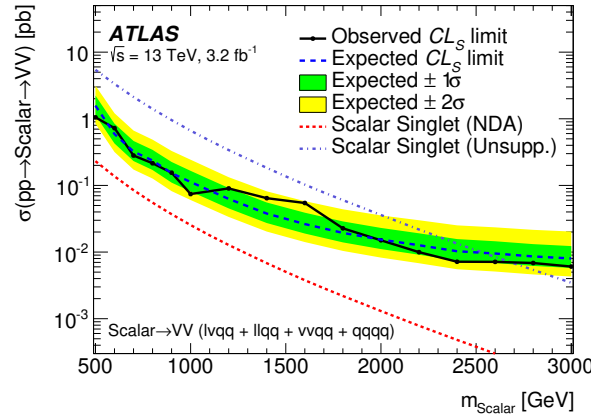


Figure 4. Observed and expected 95% CL limits on the cross-section times branching ratio to diboson final states for a narrow-width scalar resonance, as a function of its mass, combining the WW and ZZ decay modes.

Similarly, in figure 8 the observed and expected limits obtained in the search for a bulk G^* decaying to WW or ZZ final states are shown and compared to the theoretical prediction for the bulk RS G^* model assuming $\kappa/\bar{M}_{\text{Pl}} = 1$. Bulk RS G^* decaying to WW or ZZ in this model are excluded if their mass is below 1100 GeV.

No combination of these results with those at 8 TeV [31] has been performed. However, the results of the 8 TeV data analysis in the EGM W' model have been used to estimate its sensitivity to the HVT model A, including corrections for the difference in beam energy and the line-shape of the resonance. This study shows that the current analysis is more sensitive to the HVT model A for triplet masses above 1.6 TeV, and that the ratio of the expected cross-section limit to the theoretical cross-section improves by a factor two for triplet masses of 2 TeV.

10 Conclusion

A search is performed for resonant WW , WZ or ZZ production in final states with at least one hadronically decaying vector boson, using 3.2 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ recorded in 2015 by the ATLAS detector at the LHC. No significant excesses are found in data compared to the SM predictions. Limits on the production cross-section times branching ratio into vector-boson pairs are obtained as a function of the resonance mass for resonances arising from a model predicting the existence of a new heavy scalar singlet, from a simplified model predicting a heavy vector-boson triplet, or from a bulk Randall-Sundrum model with a heavy spin-2 graviton. A scalar resonance with mass below 2650 GeV predicted by the Unsuppressed model, a heavy vector-boson triplet predicted by model-B with $g_v = 3$ of the HVT parameterisation with mass below 2600 GeV, and a graviton in the bulk Randall-Sundrum model ($\kappa/\bar{M}_{\text{Pl}} = 1$) with mass below 1100 GeV are excluded at the 95% confidence level. Limits are also expressed in terms of the parameters characterising the simplified models considered.

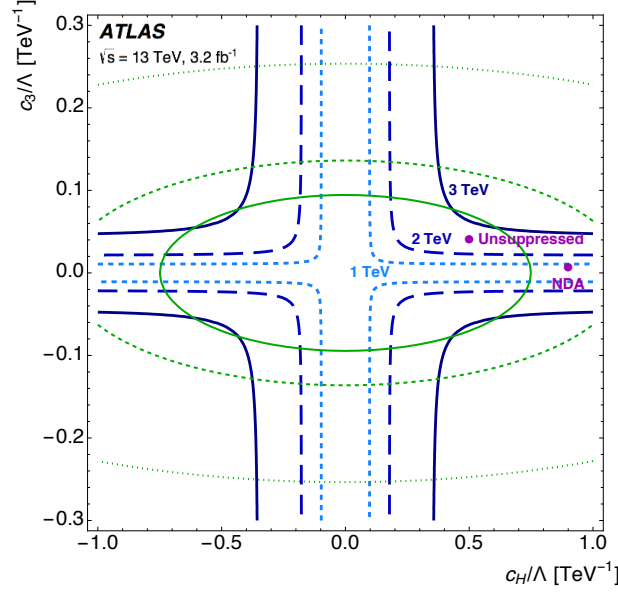


Figure 5. Observed 95% CL exclusion contours in the parameter space ($c_H/\Lambda, c_3/\Lambda$) for scalar resonances of mass 1 TeV, 2 TeV and 3 TeV. The region inside each green ellipse indicates, for the corresponding assumed mass, the part of the parameter space in which the ratio of the resonance's total width Γ to its mass m is below 5%, which is comparable to the experimental mass resolution. Points inside the ellipse, but where the absolute values of the c_H/Λ and c_3/Λ parameters are larger than at the exclusion contour, are considered to be excluded at a CL greater than 95%. The solid lines correspond to results for a resonance mass of 3 TeV; the long-dashed lines correspond to a resonance mass of 2 TeV; the short-dashed lines correspond to a resonance mass of 1 TeV. Parameters for the Unsuppressed and NDA benchmark models are also shown.

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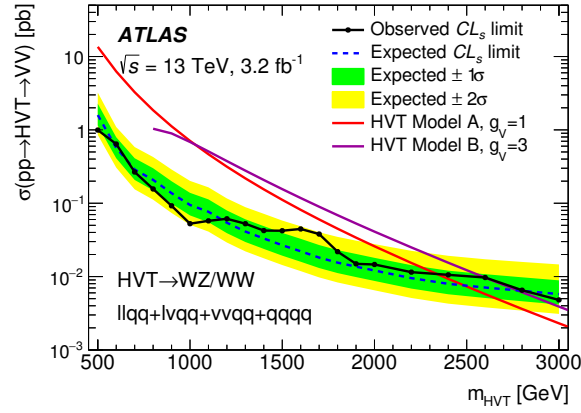


Figure 6. The observed and expected 95% CL limits on the cross-section times branching ratio to diboson final states for the HVT scenario, compared to the theoretical predictions for the HVT model-A with $g_V = 1$ (red line) and model-B with $g_V = 3$ (purple line).

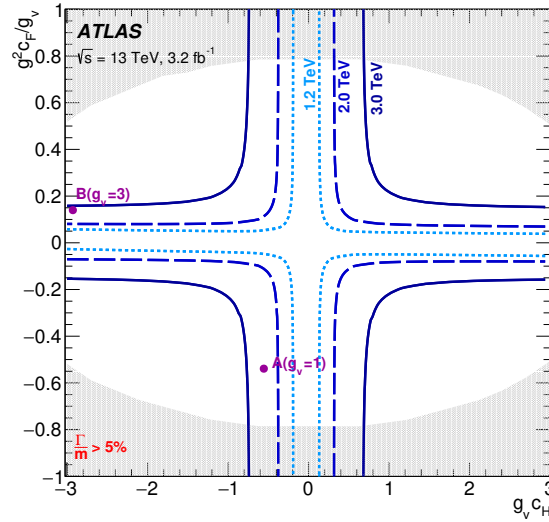


Figure 7. Observed 95% CL exclusion contours in the HVT parameter space ($g^2c_F/g_V, g_Vc_H$) for resonances of mass 1 TeV, 2 TeV and 3 TeV. Parameters for the benchmark models-A and -B are also shown. The grey area indicates the part of the parameter space in which the ratio of the resonance's total width Γ to its mass m is higher than 5%, which is comparable to the experimental mass resolution.

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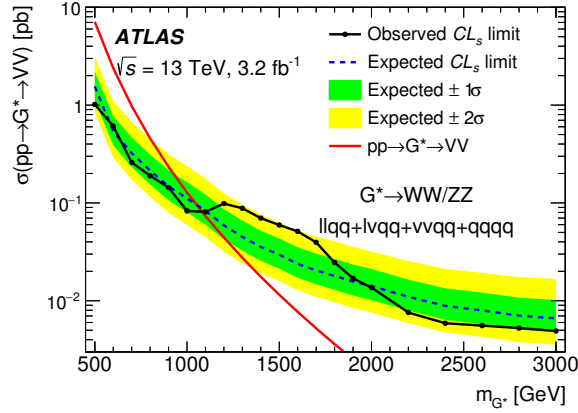


Figure 8. The observed and expected 95% CL limits on the cross-section times branching ratio to diboson final states for bulk RS G^* , compared to the theoretical prediction for $\kappa/\bar{M}_{\text{Pl}} = 1$ (red line).

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Search for Minimal Supersymmetric Standard Model Higgs bosons H/A and for a Z' boson in the $\tau\tau$ final state produced in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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Abstract A search for neutral Higgs bosons of the minimal supersymmetric standard model (MSSM) and for a heavy neutral Z' boson is performed using a data sample corresponding to an integrated luminosity of 3.2 fb^{-1} from proton–proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC. The heavy resonance is assumed to decay to a $\tau^+\tau^-$ pair with at least one τ lepton decaying to final states with hadrons and a neutrino. The search is performed in the mass range of 0.2–1.2 TeV for the MSSM neutral Higgs bosons and 0.5–2.5 TeV for the heavy neutral Z' boson. The data are in good agreement with the background predicted by the Standard Model. The results are interpreted in MSSM and Z' benchmark scenarios. The most stringent constraints on the MSSM m_A – $\tan\beta$ space exclude at 95 % confidence level (CL) $\tan\beta > 7.6$ for $m_A = 200$ GeV in the $m_h^{\text{mod+}}$ MSSM scenario. For the Sequential Standard Model, a Z'_{SSM} mass up to 1.90 TeV is excluded at 95 % CL and masses up to 1.82–2.17 TeV are excluded for a Z'_{SFM} of the strong flavour model.

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1 Introduction

The discovery of a scalar particle at the LHC [1,2] has provided important insight into the mechanism of electroweak symmetry breaking. Experimental studies of the new particle [3–7] demonstrate consistency with the standard model (SM) Higgs boson [8–13]. However, it remains possible that the discovered particle is part of an extended scalar sector, a scenario that is favoured by a number of theoretical arguments [14,15].

The minimal supersymmetric standard model (MSSM) [16–20] is the simplest extension of the SM that includes supersymmetry. The MSSM requires two Higgs doublets of opposite hypercharge. Assuming that CP symmetry is conserved, this results in one CP-odd (A) and two CP-even (h, H) neutral Higgs bosons and two charged Higgs bosons ($H^\pm$). At tree level, the properties of the Higgs sector in the MSSM depend on only two non-SM parameters, which can be chosen to be the mass of the CP-odd Higgs boson, m_A , and the ratio of the vacuum expectation values of the two doublets, $\tan\beta$. Beyond tree level, additional parameters affect the Higgs sector, the choice of which defines various MSSM benchmark scenarios. In some scenarios, such as $m_h^{\text{mod+}}$ [21], the top-squark mixing parameter is chosen such that the mass of the lightest CP-even Higgs boson, m_h , is close to the measured mass of the Higgs boson that was discovered at the LHC. A different approach is employed in the hMSSM scenario [22,23] in which the value of m_h can be used, with certain assumptions, to predict the remaining masses and couplings of the MSSM Higgs bosons without explicit reference to the soft supersymmetry-breaking parameters. The couplings of the MSSM heavy Higgs bosons to down-type fermions are enhanced with respect to the SM for large $\tan\beta$

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values, resulting in increased branching fractions to τ leptons and b -quarks,¹ as well as a higher cross section for Higgs boson production in association with b -quarks. This has motivated a variety of searches for a scalar boson in $\tau\tau$ and $b\bar{b}$ final states at LEP [24], the Tevatron [25–27] and the LHC [28–32].

Heavy Z' gauge bosons appear in several models [33–37] and are a common extension of the SM [38]. Such Z' bosons can appear in theories extending the electroweak gauge group, where lepton universality is typically conserved. A frequently used benchmark is the sequential standard model (SSM) [39], which contains a single additional Z' boson with the same couplings as the SM Z boson. Some models offering an explanation for the high mass of the top-quark, predict instead that such bosons couple preferentially to third-generation fermions [40–43]. A model predicting additional weak gauge bosons Z' and W' coupling preferentially to third-generation fermions is the strong flavour model (SFM) [41, 43].

Direct searches for high-mass resonances decaying to $\tau\tau$ have been performed by the ATLAS [44] and CMS [45] collaborations using 5 fb^{-1} of integrated luminosity at $\sqrt{s} = 7\text{ TeV}$. ATLAS [46] updated the search with 20 fb^{-1} of integrated luminosity at $\sqrt{s} = 8\text{ TeV}$. Indirect limits on Z' bosons with non-universal flavour couplings have been set based on measurements from LEP [47].

This paper presents the results of a search for neutral MSSM Higgs bosons as well as high-mass Z' resonances in the $\tau\tau$ decay mode using 3.2 fb^{-1} of proton–proton collision data collected with the ATLAS detector [48] in 2015 at a centre-of-mass energy of 13 TeV . The search is performed for the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ decay modes, where τ_{lep} represents the decay of a τ lepton to an electron or a muon and neutrinos and τ_{had} represents the decay to one or more hadrons and a neutrino. The search considers narrow resonances in the mass range of $0.2\text{--}1.2\text{ TeV}$ and $\tan\beta$ range of $1\text{--}60$ for the MSSM Higgs bosons. For the Z' boson search, the mass range of $0.5\text{--}2.5\text{ TeV}$ is considered. Higgs boson production through gluon–gluon fusion and in association with b -quarks is considered (Fig. 1a–c), with the latter mode dominating for high $\tan\beta$ values. Hence both the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are split into b -tag and b -veto categories, based on the presence or absence of jets originating from b -quarks in the final state. Since a Z' boson is expected to be predominantly produced via a Drell–Yan process (Fig. 1d), there is little gain in splitting the data into b -tag and b -veto categories. Hence, the Z' analysis uses an inclusive selection instead.

¹ Throughout this paper the inclusion of charge-conjugate decay modes is implied.

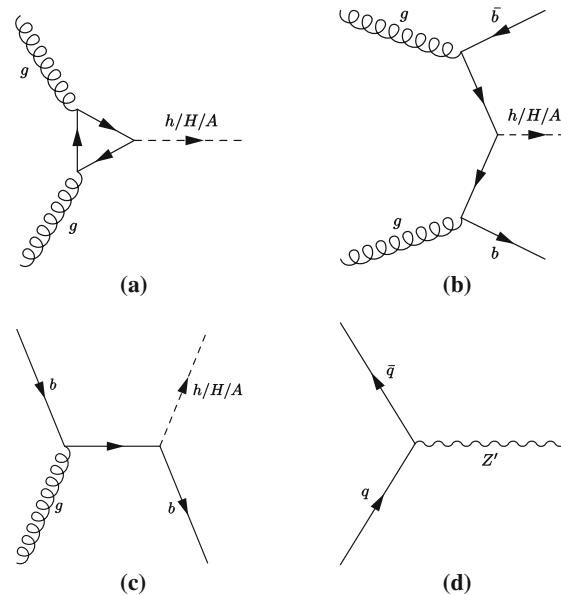


Fig. 1 Lowest-order Feynman diagrams for **a** gluon–gluon fusion and b -associated production in the **b** four-flavour and **c** five-flavour schemes of a neutral MSSM Higgs boson. Feynman diagram for Drell–Yan production of a Z' boson at lowest order (**d**)

2 Data sample and Monte Carlo simulation

The ATLAS detector [48] at the LHC consists of an inner tracking detector with a coverage in pseudorapidity² up to $|\eta| = 2.5$ surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters extending up to $|\eta| = 4.9$ and a muon spectrometer covering $|\eta| < 2.7$. A new innermost layer was added to the pixel tracking detector after the end Run-1 at a radial distance of 3.3 cm from the beam line [49, 50]. The ATLAS trigger system consists of a hardware-based first level trigger, followed by a software-based high-level trigger (HLT). The integrated luminosity used in this search, considering the data-taking periods of 2015 in which all relevant detector subsystems were operational, is 3.2 fb^{-1} . The luminosity measurement and its uncertainty are derived following a methodology similar to that detailed in Ref. [51], from a calibration of the luminosity scale using x – y beam-separation scans performed in August 2015.

² ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Simulated events with a heavy neutral MSSM Higgs boson produced via gluon–gluon fusion and in association with b -quarks are generated with the POWHEG-BOX v2 [52–54] and MADGRAPH5_aMC@NLO 2.1.2 [55,56] programs, respectively. The CT10 [57] and CT10nlo_nf4 [58] sets of parton distribution functions (PDFs) are used, respectively. PYTHIA 8.210 [59] with the AZNLO [60] (A14 [61]) set of tuned parameters, or “tune”, is used for the parton shower, underlying event and hadronization in the gluon–gluon fusion (b -associated) production. The production cross sections for the various MSSM scenarios are calculated using SusHi [62] for gluon fusion production [63–75] and b -associated production in the five-flavour scheme [76]; b -associated production in the four-flavour scheme is calculated according to Refs. [77,78]. The final b -associated production cross section is obtained by using the method in Ref. [79] to match the four-flavour and five-flavour scheme cross sections. The masses and the couplings of the Higgs bosons are computed with FeynHiggs [80–84], whereas the branching fraction calculation follows the procedure described in Ref. [85]. In the case of the hMSSM scenario, the procedure described in Ref. [23] is followed for the production cross sections and HDECAY [86] is used for the branching fraction calculation.

The Z' signals are simulated by reweighting a leading-order (LO) $Z/\gamma^* \rightarrow \tau\tau$ sample using the TauSpinner algorithm [87–89] to account for spin effects in the τ decays. The $Z/\gamma^* \rightarrow \tau\tau$ sample, enriched with high invariant mass events, is generated with PYTHIA 8.165 [90] using the NNPDF2.3LO PDF set [91] and the A14 tune for the underlying event. Interference between the Z' signals and the SM Z/γ^* production is not included.

The simulated backgrounds consist of the production of Z +jets, W +jets, $t\bar{t}$ pairs, single top quarks and electroweak dibosons ($WW/WZ/ZZ$). These are modelled with several event generators as described below, while contributions from multi-jet production are estimated with data as described in Sect. 5.

Simulated samples of Z +jets events for the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels and W +jets events for the $\tau_{\text{lep}}\tau_{\text{had}}$ channel are produced using POWHEG-BOX v2 interfaced to PYTHIA 8.186 with the AZNLO tune. In this sample, PHOTOS++ v3.52 [92,93] is used for final-state QED radiation. A dedicated W +jets sample binned in p_T^W , produced using the SHERPA 2.1.1 generator [94], is used in the $\tau_{\text{had}}\tau_{\text{had}}$ channel in order to enhance the number of events with high invariant mass. For this sample, matrix elements are calculated for up to two partons at next-to-leading order (NLO) and four partons at LO, merged with the SHERPA parton shower model using the ME+PS@NLO prescription [95]. Spin correlation effects between the W boson and its decay products are simulated with the TauSpinner program. All W/Z +jets samples use the CT10 PDF set and are normalized

to the next-to-next-to-leading-order (NNLO) cross sections calculated using FEWZ [96–98].

The POWHEG-BOX v2 program with the CT10 PDF set is used for the generation of $t\bar{t}$ pairs and single top quarks in the Wt - and s -channels. Samples of t -channel single-top-quark events are produced with the POWHEG-BOX v1 generator employing the four-flavour scheme for the NLO matrix element calculations together with the fixed four-flavour scheme PDF set CT10f4; the top-quark decay is simulated with MadSpin [99]. For all samples of top-quark production, the spin correlations are preserved and the parton shower, fragmentation and underlying event are simulated using PYTHIA 6.428 [100] with the CTQ6L1 PDF set and the corresponding Perugia 2012 tune [101]. Final-state QED radiation is simulated using PHOTOS++ v3.52. The top-quark mass is set to 172.5 GeV. The $t\bar{t}$ production sample is normalized to the NNLO cross section, including soft-gluon resummation to next-to-next-to-leading-logarithm accuracy (Ref. [102] and references therein). The normalization of the single-top-quark event samples uses an approximate NNLO calculation from Refs. [103–105].

Finally, diboson processes are simulated using the SHERPA 2.1.1 program with the CT10 PDF. They are calculated for up to one additional parton at NLO, depending on the process, and up to three additional partons at LO. The diboson samples use the NLO cross sections SHERPA calculates.

The simulation of b - and c -hadron decays for all samples, excluding those generated with SHERPA, uses EvtGen v1.2.0 [106]. All simulated samples include the effect of multiple proton-proton interactions in the same and neighbouring bunch crossings (“pile-up”) by overlaying simulated minimum-bias events on each generated signal or background event. These minimum-bias events are generated with PYTHIA 8.186 [90,100], using the A2 tune [107] and the MSTW2008LO PDF [108]. Each sample is simulated using the full GEANT4 [109,110] simulation of the ATLAS detector, with the exception of the b -associated MSSM Higgs boson signal, for which the ATLFast-II [110,111] fast simulation framework is used. Finally, the Monte Carlo (MC) samples are processed through the same reconstruction software as for the data.

3 Object reconstruction and identification

The primary vertex of each event is chosen as the proton–proton vertex candidate with the highest sum of the squared transverse momenta of all associated tracks. Electron candidates are reconstructed from energy deposits in the electromagnetic calorimeter associated with a charged-particle track measured in the inner detector. The final electron candidates are required to pass the “loose” likelihood-based iden-

tification selection [112, 113], to have a transverse energy $E_T > 15$ GeV and to be in the fiducial volume of the inner detector, $|\eta| < 2.47$. The transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$) is excluded.

Muon candidates are reconstructed from track segments in the muon spectrometer, matched with tracks found in the inner detector within $|\eta| < 2.5$. The tracks of the final muon candidates are refit using the complete track information from both detector systems and are required to have a transverse momentum $p_T > 15$ GeV and to pass the “loose” muon identification requirements [114].

Both the electrons and muons are required to pass a p_T -dependent isolation selection, which utilizes both calorimetric and tracking information, with an efficiency of 90 % (99 %) for transverse momentum of $p_T = 25$ (60) GeV. The isolation provides an efficiency that grows as a function of lepton p_T , since the background from jets faking leptons becomes less important as the lepton p_T increases. The contributions from pile-up and the underlying event activity are corrected on an event-by-event basis using the ambient energy density technique [115].

Jets are reconstructed from topological clusters [116] in the calorimeter using the anti- k_t algorithm [117], with a radius parameter value $R = 0.4$. To reduce the effect of pile-up, a jet vertex tagger algorithm is used for jets with $p_T < 50$ GeV and $|\eta| < 2.4$. It employs a multivariate technique based on jet energy, vertexing and tracking variables to determine the likelihood that the jet originates from pile-up [118]. In order to identify jets containing b -hadrons (b -jets), a multivariate algorithm is used [119, 120]. A working point that corresponds to an average efficiency of 70 % for b -jets in $t\bar{t}$ simulated events is chosen. The misidentification rates for c -jets, τ -jets and jets initiated by light quarks or gluons for the same working point and in the same sample of simulated $t\bar{t}$ events are approximately 10, 4 and 0.2 % respectively.

Hadronic decays of τ leptons are predominantly characterized by the presence of one or three charged particles, accompanied by a neutrino and possibly neutral pions. The reconstruction of the visible decay products, hereafter referred to as $\tau_{\text{had-vis}}$, starts with jets with $p_T > 10$ GeV. The $\tau_{\text{had-vis}}$ candidate must have energy deposits in the calorimeters in the range $|\eta| < 2.5$, with the transition region between the barrel and end-cap calorimeters excluded. Additionally, they must have $p_T > 20$ GeV, one or three associated tracks and an electric charge of ± 1 . A multivariate boosted decision tree (BDT) identification, based on calorimetric shower shape and track multiplicity of the $\tau_{\text{had-vis}}$ candidates, is used to reject backgrounds from jets. In this analysis, two $\tau_{\text{had-vis}}$ identification criteria are used: “loose” and “medium” with efficiencies measured in $Z \rightarrow \tau\tau$ decays of about 60 % (50 %) and 55 % (40 %) for one-track (three-track) $\tau_{\text{had-vis}}$ candidates, respectively [121]. An additional dedicated likelihood-based

veto is used to reduce the number of electrons misidentified as $\tau_{\text{had-vis}}$.

Signals in the detector can be used in more than one reconstructed object. Objects that have a geometric overlap are removed according to the following priorities:

- Jets within a $\Delta R = 0.2$ cone around a selected $\tau_{\text{had-vis}}$ are excluded.
- Jets within a $\Delta R = 0.4$ cone around an electron or muon are excluded.
- Any $\tau_{\text{had-vis}}$ within a $\Delta R = 0.2$ cone around an electron or muon is excluded.
- Electrons within a $\Delta R = 0.2$ cone around a muon are excluded.

The missing transverse momentum (E_T^{miss}) is calculated as the modulus of the negative vectorial sum of the $\mathbf{p}_T$ of all fully reconstructed and calibrated jets and leptons [122]. This procedure includes a “soft term”, which is calculated based on the inner-detector tracks originating from the primary vertex that are not associated to reconstructed objects.

4 Search channels

4.1 $\tau_{\text{lep}}\tau_{\text{had}}$ channel

Events in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel are recorded using single-muon triggers and a logical-OR combination of single-electron triggers. Single-electron triggers with p_T thresholds of 24 GeV, 60 GeV and 120 GeV are used for the $\tau_e\tau_{\text{had}}$ channel. For the $\tau_\mu\tau_{\text{had}}$ channel, a single-muon trigger with a p_T threshold of 50 GeV is used if the muon p_T is larger than 55 GeV and a single-muon trigger with a p_T threshold of 20 GeV is used otherwise. The triggers impose electron and muon quality requirements which are tighter for the triggers with lower p_T thresholds.

Events must have at least one identified $\tau_{\text{had-vis}}$ candidate and either one electron or one muon candidate which is geometrically matched to the HLT object that triggered the event. Events with more than one electron or muon fulfilling the criteria described in Sect. 3 are rejected in order to reduce the backgrounds from $Z/\gamma^* \rightarrow \ell\ell$ production, where $\ell = e, \mu$. The selected lepton must have a transverse momentum $p_T > 30$ GeV and pass the “medium” identification requirement.

The $\tau_{\text{had-vis}}$ candidate is required to have $p_T > 25$ GeV, pass the “medium” BDT-based identification requirement and lie in the range $|\eta| < 2.3$. The latter requirement is motivated by a larger rate of electrons misidentified as $\tau_{\text{had-vis}}$ candidates at higher $|\eta|$ values: the rate is above 10 % for $|\eta| > 2.3$, while it ranges from 0.5 to 3 % for lower $|\eta|$ values. If there is more than one $\tau_{\text{had-vis}}$ candidate, the candidate with the highest p_T is selected and the others are treated as

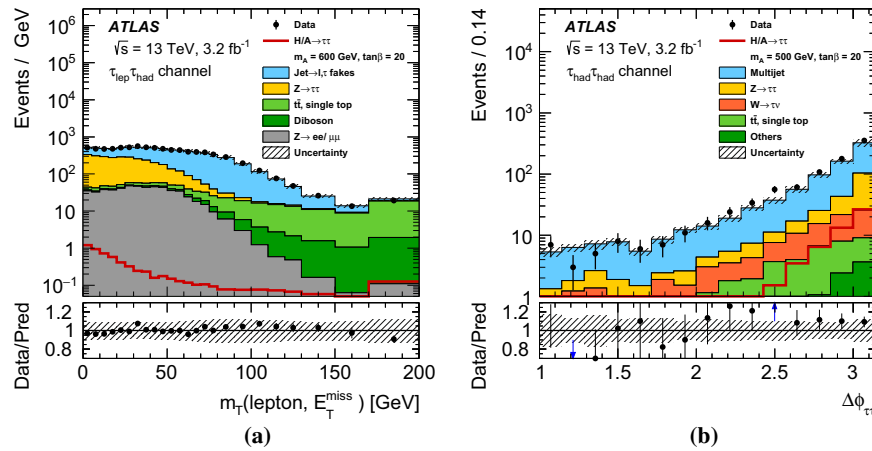


Fig. 2 The distributions of **a** $m_T(\ell, E_T^{\text{miss}})$ in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel and **b** $\Delta\phi(\tau_{\text{had-vis},1}, \tau_{\text{had-vis},2})$ for the $\tau_{\text{had}}\tau_{\text{had}}$ channel for the inclusive selection with the criterion for the variable displayed removed. The label

“Others” in **b** refers to contributions due to diboson, $Z(\rightarrow \ell\ell)$ +jets and $W(\rightarrow \ell\nu)$ +jets production. Bins have a varying size and overflows are included in the last bin of the distribution on the left

jets. Finally, the identified lepton and the $\tau_{\text{had-vis}}$ are required to have opposite electric charge.

Subsequently, the following selection requirements are applied:

- $\Delta\phi(\tau_{\text{had-vis}}, \ell) > 2.4$.
- $m_T(\ell, E_T^{\text{miss}}) \equiv \sqrt{2p_T(\ell)E_T^{\text{miss}}[1 - \cos \Delta\phi(\ell, E_T^{\text{miss}})]} < 40 \text{ GeV}$.
- For the $\tau_e\tau_{\text{had}}$ channel, events are vetoed if the invariant mass of the electron and the visible τ lepton decay products is in the range $80 < m_{\text{vis}}(e, \tau_{\text{had-vis}}) < 110 \text{ GeV}$.

The requirement on $\Delta\phi(\tau_{\text{had-vis}}, \ell)$ gives an overall reduction of SM backgrounds with little signal loss. The requirement on $m_T(\ell, E_T^{\text{miss}})$, the distribution of which is shown in Fig. 2a, serves to remove events that originate from processes containing a W boson: in signal events, the missing transverse momentum is usually in the same direction as the τ_{lep} , resulting in a low value of $m_T(\ell, E_T^{\text{miss}})$. The requirement on $m_{\text{vis}}(e, \tau_{\text{had-vis}})$ reduces the contribution of $Z \rightarrow ee$ decays, where an electron is misidentified as a $\tau_{\text{had-vis}}$ candidate. These selection criteria define the inclusive $\tau_{\text{lep}}\tau_{\text{had}}$ selection.

4.2 $\tau_{\text{had}}\tau_{\text{had}}$ channel

Events in the $\tau_{\text{had}}\tau_{\text{had}}$ channel are selected by a trigger that requires a single $\tau_{\text{had-vis}}$ satisfying the “medium” $\tau_{\text{had-vis}}$ identification criterion with $p_T > 80 \text{ GeV}$. The leading $\tau_{\text{had-vis}}$ candidate in p_T must geometrically match the HLT object. A p_T requirement is applied to the leading $\tau_{\text{had-vis}}$ candidate, $p_T > 110 \text{ GeV}$, and to the sub-leading $\tau_{\text{had-vis}}$

candidate, $p_T > 55 \text{ GeV}$. Furthermore, the leading (sub-leading) $\tau_{\text{had-vis}}$ candidate has to satisfy the “medium” (“loose”) $\tau_{\text{had-vis}}$ identification criterion. Events with electrons or muons fulfilling the loose selection criteria described in Sect. 3 (with the exception of the isolation requirement) are vetoed to reduce electroweak background processes and guarantee orthogonality with the $\tau_{\text{lep}}\tau_{\text{had}}$ channel.

The leading and sub-leading $\tau_{\text{had-vis}}$ candidates must have opposite electric charge and have a back-to-back topology in the transverse plane, $\Delta\phi(\tau_{\text{had-vis},1}, \tau_{\text{had-vis},2}) > 2.7$. The distribution of $\Delta\phi(\tau_{\text{had-vis},1}, \tau_{\text{had-vis},2})$ before this requirement is shown in Fig. 2b. This selection defines the inclusive $\tau_{\text{had}}\tau_{\text{had}}$ selection.

4.3 Event categories

In the search for Z' bosons, the event selections described in Sects. 4.1 and 4.2 result in a signal selection efficiency³ varying between 0.8% (2.0%) at $m_{Z'} = 500 \text{ GeV}$ and 3.4% (3.8%) at $m_{Z'} = 2.5 \text{ TeV}$ for the $\tau_{\text{lep}}\tau_{\text{had}}$ ($\tau_{\text{had}}\tau_{\text{had}}$) channel. In the search for the H/A bosons, events satisfying the inclusive selection are categorized to exploit the two different signal production modes as follows:

- b -veto: no b -tag jets in the event,
- b -tag: at least one b -tag jet in the event.

³ The term “signal selection efficiency” refers to the fraction of signal events decaying to $\tau_{\text{lep}}\tau_{\text{had}}$ or $\tau_{\text{had}}\tau_{\text{had}}$ that are subsequently reconstructed within the detector acceptance and pass the selection requirements.

In the b -veto category, the H/A signal selection efficiency varies between 2% at $m_A = 200$ GeV and 7% at $m_A = 1.2$ TeV for the gluon–gluon fusion production mode in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, and from 0.1 to 15% in the $\tau_{\text{had}}\tau_{\text{had}}$ channel for the same mass range. In the b -tagging category, the signal selection efficiency varies from 0.5% at $m_A = 200$ GeV to 2% at $m_A = 1.2$ TeV for the b -associated production mode in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, and from 0.1 to 6% in the $\tau_{\text{had}}\tau_{\text{had}}$ channel.

4.4 Di-tau mass reconstruction

The di-tau mass reconstruction is critical in achieving good separation between signal and background. However, its reconstruction is challenging due to the presence of neutrinos from the τ lepton decays. The mass reconstruction used for both the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels is the total transverse mass, defined as

$$m_T^{\text{tot}} = \sqrt{m_T^2(E_T^{\text{miss}}, \tau_1) + m_T^2(E_T^{\text{miss}}, \tau_2) + m_T^2(\tau_1, \tau_2)}, \quad (1)$$

where $m_T(a, b)$ is defined as

$$m_T(a, b) = \sqrt{2p_T(a)p_T(b)[1 - \cos \Delta\phi(a, b)]} \quad (2)$$

and τ refers to the visible decay of the τ lepton (ℓ or $\tau_{\text{had-vis}}$). More complex mass reconstruction techniques were investigated, but they did not improve the expected sensitivity.

5 Background estimation

The background processes can be categorized according to whether the electron/muon and/or the $\tau_{\text{had-vis}}$ are correctly identified. Backgrounds from processes with correctly identified $\tau_{\text{had-vis}}$, electrons and muons, or where the $\tau_{\text{had-vis}}$ is due to a misidentified electron/muon in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, are estimated from simulation. Data-driven techniques are used for processes where the $\tau_{\text{had-vis}}$, or both the lepton and $\tau_{\text{had-vis}}$ are misidentified. The background contributions originating from processes where only the lepton is misidentified are found to be negligible.

5.1 $\tau_{\text{lep}}\tau_{\text{had}}$ background estimate

The main backgrounds in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel arise from $Z \rightarrow \tau\tau$ production, followed by processes with a misidentified $\tau_{\text{had-vis}}$ in the b -veto category and $t\bar{t}$ production, with either a true τ lepton or a jet misidentified as a $\tau_{\text{had-vis}}$, in the b -tag category.

Background processes where the τ_{had} candidate, or both the lepton and τ_{had} candidates, arise from misidentified jets

are dominated by W +jets ($t\bar{t}$) and multi-jet processes, for the b -veto (b -tag) category. A data-driven “fake factor” (FF) technique is used to estimate the contribution of these processes to the signal region. The fake factors are derived separately for the b -veto and b -tag categories using fake factor control regions (see Table 1) dominated by a particular background process (Pr), and are defined as:

$$\text{FF}(\text{Pr}) = \frac{N(\text{nominal}\tau_{\text{had-vis}}\text{ID}, \text{Pr})}{N(\text{anti-}\tau_{\text{had-vis}}\text{ID}, \text{Pr})}, \quad (3)$$

where $N(\text{nominal}\tau_{\text{had-vis}}\text{ID}, \text{Pr})$ is the number of $\tau_{\text{had-vis}}$ candidates in data satisfying the “medium” $\tau_{\text{had-vis}}$ identification criterion and $N(\text{anti-}\tau_{\text{had-vis}}\text{ID}, \text{Pr})$ is the number of $\tau_{\text{had-vis}}$ candidates failing this criterion but meeting a loose requirement on the BDT score. The latter requirement defines the “anti- τ_{had} ” sub-region, which selects the same kind of objects mimicking $\tau_{\text{had-vis}}$ candidates as those fulfilling the identification criteria. The true τ_{had} contamination in the fake factor control regions is subtracted using simulation. In all the control regions, the fake factors are parameterized as a function of the transverse momentum and number of tracks of the reconstructed $\tau_{\text{had-vis}}$ object.

The fake factor for W +jets and $t\bar{t}$ backgrounds, $\text{FF}(W+\text{jets}/t\bar{t})$, is measured in a fake factor control region that is identical to the signal region, except that the $m_T(\ell, E_T^{\text{miss}})$ selection criterion is reversed to $m_T(\ell, E_T^{\text{miss}}) > 60$ (70) GeV for the $\tau_{\mu}\tau_{\text{had}}$ ($\tau_e\tau_{\text{had}}$) channel. The purity of the W +jets background in the b -veto category of the control region is about 95%, while in the b -tag category both the W +jets and $t\bar{t}$ processes contribute. The fake factor value for the b -tag category was found to be compatible with the value corresponding to the b -veto category. To improve the statistical precision, the fake factor measured in a control region without requirements on the number of b -tags is used for the b -tag category. The same fake factor is used in the search for the Z' boson. For multi-jet events (MJ), the fake factor $\text{FF}(\text{MJ})$ is measured in a fake factor control region defined by inverting the isolation requirement on the electron or muon. The purity of multi-jet events in this control region exceeds 99%. The fake factors are derived separately for the b -veto and b -tag categories by requiring no b -tag and at least one b -tag, respectively. For the Z' analysis, no b -tag requirement is considered.

The shapes and normalization of background contributions in the signal region are then estimated by applying these fake factors to events that pass the anti- τ_{had} region selection but otherwise satisfy all signal region requirements. In this analysis, the fake factors are combined and weighted by the predicted contribution of each background process to the anti- τ_{had} region:

$$\text{FF}(\text{comb}) = \text{FF}(W+\text{jets}/t\bar{t}) \times r_{W/t\bar{t}} + \text{FF}(\text{MJ}) \times r_{\text{MJ}}, \quad (4)$$

Table 1 Description of the control regions used in the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels

$\tau_{\text{lep}}\tau_{\text{had}}$ signal region	$\Delta\phi(\tau, \ell) > 2.4, m_T(\ell, E_T^{\text{miss}}) < 40 \text{ GeV},$ Veto $80 < m_{e,\tau} < 110 \text{ GeV}$ for $\tau_e\tau_{\text{had}},$ $N_{b\text{-tag}} \geq 1$ (b -tag category), $N_{b\text{-tag}} = 0$ (b -veto category) or no requirement (Z' category)
W +jets/ $t\bar{t}$ fake factor control region	$m_T(\ell, E_T^{\text{miss}}) > 70$ (60) GeV for $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}),$ different $\tau_{\text{had-vis}}$ identification for anti- τ_{had} sub-region
$t\bar{t}$ validation region	$N_{b\text{-tag}} \geq 1, m_T(\ell, E_T^{\text{miss}}) > 100 \text{ GeV}$
Multi-jet fake factor control region	Invert e, μ isolation requirement, different $\tau_{\text{had-vis}}$ identification for anti- τ_{had} sub-region
Multi-jet control region for r_{MJ} estimation	$m_T(\ell, E_T^{\text{miss}}) < 30 \text{ GeV},$ no e, μ isolation requirement, no $\tau_{\text{had-vis}}$ passing loose identification, $N_{\text{jet}} \geq 1$ (b -veto category), $N_{\text{jet}} \geq 2$ (b -tag category)
Control region for correction of electrons misidentified as $\tau_{\text{had-vis}}$	$80 < m_{e,\tau} < 110 \text{ GeV}$ for 1-track $\tau_{\text{had-vis}}$ $90 < m_{e,\tau} < 100 \text{ GeV}$ for 3-track $\tau_{\text{had-vis}}$
$\tau_{\text{had}}\tau_{\text{had}}$ selection	$\Delta\phi(\tau_{\text{had-vis},1}, \tau_{\text{had-vis},2}) > 2.7,$ $N_{b\text{-tag}} \geq 1$ (b -tag category), $N_{b\text{-tag}} = 0$ (b -veto category) or no requirement (Z' category)
Multi-jet fake factor control region	Pass single-jet trigger, leading $\tau_{\text{had-vis}}$ fails medium identification, no tracks, nor charge requirements for leading $\tau_{\text{had-vis}},$ $\frac{p_T^{\tau_{\text{had-vis},2}}}{p_T^{\tau_{\text{had-vis},1}}} > 0.3,$ no $\Delta\phi(\tau_{\text{had-vis},1}, \tau_{\text{had-vis},2})$ requirement
Fake-rate control region	Pass single-muon trigger, isolated muon with $p_T > 55 \text{ GeV},$ $\tau_{\text{had-vis}}$ with $p_T > 50 \text{ GeV}, \Delta\phi(\mu, \tau_{\text{had-vis}}) > 2.4,$ $\sum_{L=\mu,\tau} \cos \Delta\phi(L, E_T^{\text{miss}}) < 0$ (for b -veto category only)
$W \rightarrow \mu\nu$ control region for W +jets m_T^{tot} correction	Pass single-muon trigger, isolated muon with $p_T > 110 \text{ GeV},$ $\tau_{\text{had-vis}}$ with $p_T > 55 \text{ GeV}$

where r_{MJ} denotes the fraction of multi-jet events in the anti- τ_{had} region and $r_{W/t\bar{t}} = 1 - r_{\text{MJ}}$. This neglects the differences between the fake factors for W +jets/ $t\bar{t}$ and other processes, such as Z production. The parameter r_{MJ} is estimated, separately for the b -veto and b -tag categories, in two steps using a data-driven method. First, the rates at which jets are misidentified as electrons or muons are measured from the ratio of leptons passing and failing the lepton isolation requirement in a region enriched in multi-jet events. This multi-jet control region is defined in Table 1. The predicted multi-jet rate is then applied to events in the anti- τ_{had} sub-region that also fail the lepton isolation, in order to calculate r_{MJ} as a function of $\tau_{\text{had-vis}}$ p_T separately for the $\tau_e\tau_{\text{had}}$ and $\tau_\mu\tau_{\text{had}}$ channels. When the fake factor is applied to the anti- τ_{had} sub-region events, the contributions from correctly identified $\tau_{\text{had-vis}}$ and from electrons and muons misidentified as $\tau_{\text{had-vis}}$ candidates are subtracted using the default MC simulation described in Sect. 2.

Background processes where the electron or the muon is identified as a $\tau_{\text{had-vis}}$ object are modelled using simulation. The main source of such backgrounds is $Z(\rightarrow$

ee)+jets events in the $\tau_e\tau_{\text{had}}$ channel, which are reduced using the $m_{\text{vis}}(e, \tau_{\text{had}})$ mass-window veto described in Sect. 4.1. To account for mismodelling of electrons misidentified as $\tau_{\text{had-vis}}$ objects in $Z \rightarrow ee$ +jets events, the simulation is corrected as a function of the lepton η using data control regions defined by reversing the mass-window criterion, as listed in Table 1. The correction amounts to 15 % for three-track $\tau_{\text{had-vis}}$, while for the one-track $\tau_{\text{had-vis}}$ objects the correction varies from 20 % in the barrel region to up to 200 % in the end-cap region.

The m_T^{tot} distributions in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel are shown in Fig. 3a, b for the W +jets control region and the $t\bar{t}$ validation region, respectively. The latter is identical to the b -tag category definition, except for the $m_T(\ell, E_T^{\text{miss}})$ requirement, which is reversed to $m_T(\ell, E_T^{\text{miss}}) > 100 \text{ GeV}$.

5.2 $\tau_{\text{had}}\tau_{\text{had}}$ background estimate

The dominant background process for the $\tau_{\text{had}}\tau_{\text{had}}$ channel is multi-jet production, the cross section of which is several orders of magnitude higher than that of the signal processes.

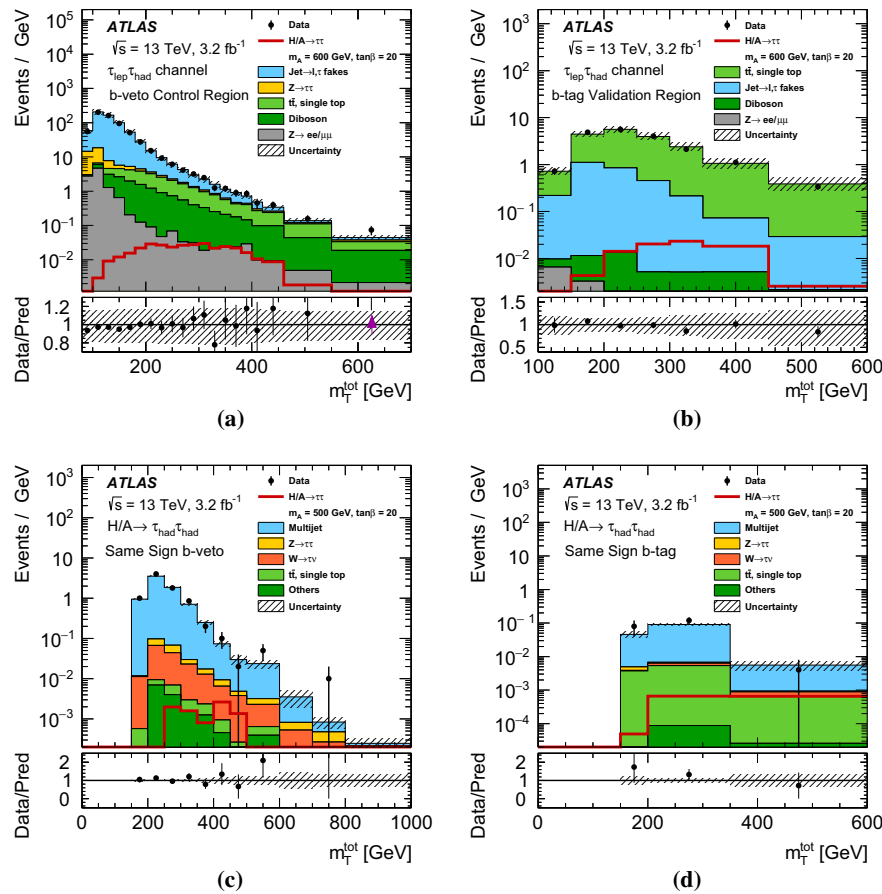


Fig. 3 The distributions of m_T^{tot} in **a** the $\tau_{\text{lep}}\tau_{\text{had}}$ channel W +jets control region, **b** the $t\bar{t}$ validation region of the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, **c** the $\tau_{\text{had}}\tau_{\text{had}}$ channel b -veto same-sign validation region and **d** the $\tau_{\text{had}}\tau_{\text{had}}$ channel b -tag same-sign validation region. The various control and validation regions are defined in Table 1. The data are compared to the background prediction and a hypothetical MSSM $H/A \rightarrow \tau\tau$ signal

($m_A = 500$ GeV and $\tan\beta = 20$). The Monte Carlo statistics of the signal is limited in the background-dominated regions. The label “Others” in **c** and **d** refers to contributions due to diboson, $Z(\rightarrow \ell\ell)$ +jets and $W(\rightarrow \ell\nu)$ +jets production. The background uncertainty includes statistical and systematic uncertainties. The bins have a varying size and overflows are included in the last bin of the distributions

Despite the large suppression of this background thanks to the event selection, a sizeable contribution of events with two jets misidentified as $\tau_{\text{had-vis}}$ candidates remains. A fake factor technique is used to normalize and model this background. Fake factors parameterized as a function of $p_T(\tau_{\text{had-vis}})$ and the number of tracks are derived from a control region enriched with multi-jet events, described in Table 1. The factors are derived independently for the b -tag and b -veto categories in the search for H/A bosons, and inclusively in the search for Z' bosons. They are then applied to data events where the leading $\tau_{\text{had-vis}}$ has passed the $\tau_{\text{had-vis}}$ identification requirement in the signal region, while the sub-leading $\tau_{\text{had-vis}}$ candidate has passed only a loose requirement on the

BDT score. The contributions from non-multi-jet production processes are subtracted using simulation.

For $t\bar{t}$ and W +jets events, along with other simulated background processes, the probability of a jet being misidentified as a $\tau_{\text{had-vis}}$ is modelled with a “fake-rate” technique. The rates of jets being misidentified as a $\tau_{\text{had-vis}}$ are measured from data as a function of the transverse momentum and number of tracks of the reconstructed $\tau_{\text{had-vis}}$. The fake-rate control regions are described in Table 1 and are enriched in $W(\rightarrow \mu\nu)$ +jets for the b -veto category and $t\bar{t}$ events for the b -tag category,

The fake rate is then applied to the simulated events as a weight for each of the reconstructed $\tau_{\text{had-vis}}$ that does not

match geometrically a true τ lepton. Fake rates derived in the fake-rate control region of the b -tag category are used for simulated $t\bar{t}$ and single top quark events, while fake rates obtained in the b -veto control region are applied to the remaining processes. An additional weight is applied to $W \rightarrow \tau\nu$ +jets events as a function of m_T^{tot} , to improve the modelling of the kinematics of the W +jets simulated events. The reweighting function is derived by fitting the ratio of the data to the simulation for the $W(\rightarrow \mu\nu)$ +jets process in an additional $W \rightarrow \mu\nu$ control region, defined in analogy with the inclusive signal selection and described in Table 1.

A same-sign validation region, enriched with events where at least one jet is misidentified as a $\tau_{\text{had-vis}}$, is obtained by inverting the opposite-sign requirement of the two $\tau_{\text{had-vis}}$ candidates. Distributions of m_T^{tot} in the $\tau_{\text{had}}\tau_{\text{had}}$ channel same-sign validation region are shown in Fig. 3c, d. The good performance multi-jet background estimation method is demonstrated by the agreement of the data with the background prediction.

6 Systematic uncertainties

The signal efficiency and the background estimates are affected by uncertainties associated with the detector simulation, the signal modelling and the data-driven background determination.

The integrated luminosity measurement has an uncertainty of 5% and is used for all MC samples. Uncertainties related to the detector are included for all signal and backgrounds that are estimated using simulated samples. These uncertainties are also taken into account for simulated samples that are used in the derivation of data-driven background estimates. All instrumental systematic uncertainties arising from the reconstruction, identification and energy scale of $\tau_{\text{had-vis}}$ candidates, electrons, muons, (b -)jets and the soft term of the E_T^{miss} measurement are considered. The effect of the energy scale uncertainties on the objects is propagated to the E_T^{miss} determination. The electron, muon, jet and E_T^{miss} systematic uncertainties described above are found to have a very small effect.

Systematic uncertainties resulting from the data-driven background estimates are derived as follows. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, the combined fake-factor method includes uncertainties in the W +jets/ $t\bar{t}$ fake factors, the multi-jet fake factors, and the r_{MJ} estimation. For the W +jets fake factors the main uncertainties arise from the dependence on $\Delta\phi(\tau_{\text{had-vis}}, E_T^{\text{miss}})$, from the difference between the relative contributions of quark- and gluon-initiated jets faking $\tau_{\text{had-vis}}$ in the control region and the signal region, and from the contamination by backgrounds other than W +jets in the control region, which are estimated using simulation. The uncertainty is parameterized as a function of the

anti- $\tau_{\text{had-vis}}$ p_T and amounts approximately to 17% for jets misidentified as one-track τ candidates and varies between 16 and 34% for jets misidentified as three-track τ candidates. Uncertainties related to non- W +jets events were studied and have no significant impact on the fake-factor determination. For the multi-jet fake factors and r_{MJ} , the uncertainty is dominated by the number of data events in the control region and the subtraction of the remaining non-multi-jet backgrounds using simulation. Typical values of the total uncertainties for r_{MJ} are between 7 and 20% and for the multi-jet fake factors between 10 and 20%, depending on the channel and the $\tau_{\text{had-vis}}$ candidate p_T . In addition, the effect on the background estimate due to the anti- τ_{had} region definition is examined. The loose $\tau_{\text{had-vis}}$ identification requirement used in the definition of this region is varied to estimate the corresponding uncertainty, which is 5 and 1% in the $\tau_e\tau_{\text{had}}$ and the $\tau_\mu\tau_{\text{had}}$ channel, respectively.

In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, the uncertainty in the fake-factor measurement used for the multi-jet background estimation is obtained as the sum in quadrature of the statistical uncertainty of the measurement and the difference between the fake factors determined from same-sign and from opposite-sign events. The fake rates for jets misidentified as $\tau_{\text{had-vis}}$ are determined from data. The main systematic uncertainty arises from the statistical uncertainty of the fake-rate measurement and it ranges from 7 to 30% as a function of the $\tau_{\text{had-vis}}$ p_T . In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, the uncertainty in the parameters of the function used to reweight the $W \rightarrow \tau\nu$ +jets background is propagated to the m_T^{tot} distribution, where its effect ranges from 5 to 20%.

Theoretical cross-section uncertainties are considered for all backgrounds estimated using simulation. For Z +jets and diboson production, uncertainties of 5% and 6% are used, respectively, combining PDF+ α_S and scale variation uncertainties in quadrature. For $t\bar{t}$ [102] and single top-quark [123, 124] production, a 6% uncertainty is assigned based on scale, PDF and top-quark mass uncertainties. Additional uncertainties related to initial- and final-state radiation modelling, tune and (for $t\bar{t}$ only) the choice of the hdamp parameter value in POWHEG-BOX v2, which controls the amount of radiation produced by the parton shower, were also taken into account [125]. The uncertainty in the fragmentation model is evaluated by comparing $t\bar{t}$ events generated with POWHEG-BOX v2 interfaced to either HERWIG++ [126] or PYTHIA6. The POWHEG+HERWIG++ and aMC@NLO+HERWIG++ generators are used to estimate the uncertainty in generating the hard scatter. The variation of the b -tag category acceptance for these uncertainties is from -10 to $+30\%$ (-33 to $+38\%$) in the $\tau_{\text{lep}}\tau_{\text{had}}$ ($\tau_{\text{had}}\tau_{\text{had}}$) channel.

Uncertainties related to signal modelling are discussed in the following. Uncertainties due to the factorization

and renormalization scale choices are estimated from the effect on the signal acceptance of doubling or halving these factors either coherently or oppositely. Uncertainties due to the initial- and final-state radiation, as well as multiple parton interaction for the signal are also taken into account. These uncertainties are estimated from the PYTHIA8 A14 tune [61] for the b -associated production and the AZNLO PYTHIA8 tune [60] for the gluon–gluon fusion production. The envelope of the variations resulting from the use of the alternative PDFs in the PDF4LHC15_nlo_100 [127] set is used in order to estimate the PDF uncertainty for gluon–gluon fusion production. For the b -associated production uncertainty, a comparison among NNPDF30_nlo_as_0118_nf_4 [127], CT14nlo_NF4 [58], MSTW2008nlo68cl_nf4 [128] and CT10_nlo_nf4 [57] PDF sets is employed. Since no statistically significant effect on the shape of the reconstructed mass distribution is observed, each contribution is taken solely as a normalization uncertainty. The total uncertainty ranges between 15 and 25 %.

7 Results

The parameter of interest is the signal strength, μ . It is defined as the ratio of the observed to the predicted value of the cross section times branching fraction, where the prediction is evaluated for a particular MSSM or Z' assumption. Hence, the value $\mu = 0$ corresponds to the absence of a signal, whereas the value $\mu = 1$ indicates the presence of a signal as predicted by the theoretical model under study. To estimate μ , a likelihood function constructed as the product of Poisson probability terms is used. Signal and background predictions depend on systematic uncertainties, which are parameterized as nuisance parameters and are constrained using Gaussian probability distributions. For the MSSM Higgs boson search a binned likelihood function is constructed in bins of the m_T^{tot} distributions, chosen to ensure sufficient background statistics in each bin. The search for a Z' boson is a counting experiment, summing the number of events above a certain m_T^{tot} threshold. The threshold is chosen for each Z' mass hypothesis to maximize the expected significance and ranges from 400 GeV at low Z' mass to 750 GeV at high Z' mass. The asymptotic approximation is used with the test statistic $\tilde{q}_\mu$ [129] to test the compatibility of the data with the assumed signal.

The number of observed $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ data events, along with the predicted event yields from background and signal processes, in the signal regions are shown in Table 2. The observed event yields are compatible with the expected event yield from SM processes, within uncertainties. The m_T^{tot} mass distributions are shown in Fig. 4. The results from the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are com-

Table 2 Observed number of events and background predictions in the b -tag and b -veto categories for the $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. The background predictions and uncertainties are obtained from the statistical procedure discussed in Sect. 7. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, the processes other than “Jet $\rightarrow \ell$, $\tau_{\text{had-vis}}$ fakes” require a true hadronically decaying τ lepton or an electron or muon misidentified as a $\tau_{\text{had-vis}}$. The expected signal yields for the $m_h^{\text{mod+}}$ scenario are shown for comparison

	b -tag category	b -veto category
$\tau_e\tau_{\text{had}}$ channel		
$Z \rightarrow \tau\tau$ +jets	42 ± 7	4500 ± 250
Jet $\rightarrow \ell$, $\tau_{\text{had-vis}}$ fakes	128 ± 18	5400 ± 350
$Z \rightarrow \ell\ell$ +jets	3.6 ± 1.5	590 ± 120
$t\bar{t}$ and single top quark	115 ± 16	35 ± 5
Diboson	0.33 ± 0.07	44 ± 4
Total prediction	289 ± 24	10600 ± 360
Data	275	10619
ggH $m_A = 500$ GeV, $\tan\beta = 20$	0.020 ± 0.010	1.2 ± 0.2
bbH $m_A = 500$ GeV, $\tan\beta = 20$	6.4 ± 1.7	7.4 ± 1.9
$\tau_\mu\tau_{\text{had}}$ channel		
$Z \rightarrow \tau\tau$ +jets	42 ± 6	5500 ± 300
Jet $\rightarrow \ell$, $\tau_{\text{had-vis}}$ fakes	109 ± 14	2760 ± 170
$Z \rightarrow \ell\ell$ +jets	5.2 ± 0.6	830 ± 50
$t\bar{t}$ and single top quark	136 ± 15	40 ± 5
Diboson	0.34 ± 0.07	55 ± 5
Total prediction	293 ± 19	9200 ± 300
Data	312	9163
ggH $m_A = 500$ GeV, $\tan\beta = 20$	0.016 ± 0.005	1.1 ± 0.2
bbH $m_A = 500$ GeV, $\tan\beta = 20$	3.3 ± 1.3	6.4 ± 1.7
$\tau_{\text{had}}\tau_{\text{had}}$ channel		
$Z \rightarrow \tau\tau$ +jets	1.9 ± 0.3	146 ± 20
Multi-jet	17 ± 3	396 ± 16
$W \rightarrow \tau\nu$ + jets	1.1 ± 0.2	45 ± 7
$t\bar{t}$ and single top quark	11 ± 3	4.5 ± 0.9
Others	0.13 ± 0.03	6.3 ± 0.8
Total prediction	31 ± 4	598 ± 21
Data	23	628
ggH $m_A = 500$ GeV, $\tan\beta = 20$	0.034 ± 0.014	2.2 ± 0.7
bbH $m_A = 500$ GeV, $\tan\beta = 20$	8 ± 3	15 ± 5

bined to improve the sensitivity to H/A and Z' boson production.

The fractional contributions of the most important sources of systematic uncertainty to the total uncertainty in the signal cross-section measurement are shown for two signal assumptions: Table 3 (top) represents an MSSM Higgs boson hypothesis ($m_A = 500$ GeV, $\tan\beta = 20$) and Table 3 (bottom) corresponds to an SSM Z' boson hypothesis ($m_{Z'} = 1.75$ TeV). As shown in this table, the sensitivity of the search is limited by statistical uncertainties.

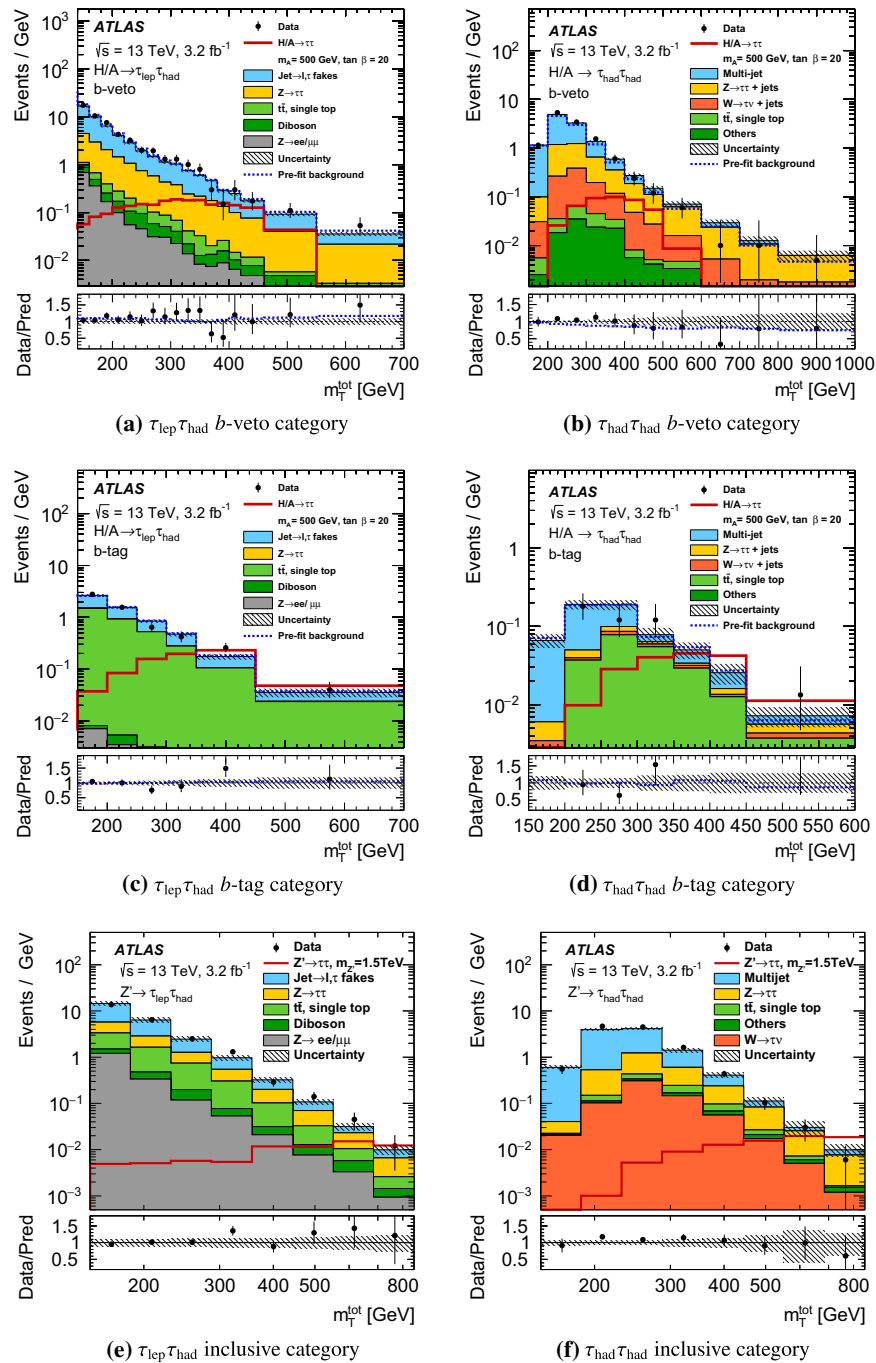


Fig. 4 The distribution of m_T^{tot} for the b -veto category of the **a** $\tau_{\text{lep}}\tau_{\text{had}}$ and **b** $\tau_{\text{had}}\tau_{\text{had}}$ channels, the b -tag category of the **c** $\tau_{\text{lep}}\tau_{\text{had}}$ and **d** $\tau_{\text{had}}\tau_{\text{had}}$ channels, and the inclusive category of the **e** $\tau_{\text{lep}}\tau_{\text{had}}$ and **f** $\tau_{\text{had}}\tau_{\text{had}}$ channels. The label “Others” in **b**, **d** and **f** refers to contributions due to diboson, $Z(\rightarrow \ell\ell)$ +jets and $W(\rightarrow \ell\nu)$ +jets production. For the b -veto and b -tag categories, the binning displayed is that enter-

ing into the statistical fit discussed in Sect. 7, while the predictions and uncertainties for the background and signal processes are obtained from the fit under the hypothesis of no signal. The inclusive category distributions are shown before any statistical fit. Overflows are included in the last bin of the distributions

Table 3 Fractional impact of the most important sources of systematic uncertainty on the total uncertainty of the signal strength, for (top) the MSSM signal hypothesis of $m_A = 500$ GeV, $\tan \beta = 20$, (bottom) the Z'_{SSM} signal hypothesis of $m_{Z'} = 1.75$ TeV. For each source of uncertainty, $F_{\pm} = \pm \frac{\sigma_{\text{source}}^2}{\sigma_{\text{total}}^2}$ is defined as the positive (negative) fractional contribution to the signal strength uncertainty

Source of uncertainty	F_- (%)	F_+ (%)
MSSM analysis		
$t\bar{t}$ and single-top-quark backgrounds normalization	−13	+11
$\tau_{\text{had-vis}}$ energy scale	−3	+8
τ_{had} trigger	−0.5	+10
Signal acceptance	−6	+1.9
Jet-to- $\tau_{\text{had-vis}}$ fake rate ($\tau_{\text{lep}}\tau_{\text{had}}$)	−1.5	+2.4
Multi-jet background ($\tau_{\text{had}}\tau_{\text{had}}$)	−0.4	+0.3
$t\bar{t}$ background modelling	−0.1	+1.0
Jet-to- $\tau_{\text{had-vis}}$ fake rate ($\tau_{\text{had}}\tau_{\text{had}}$)	−0.2	+0.2
Jet-to-vertex association	−0.1	+0.1
Statistics (data and simulation)	−75	+65
Z'_{SSM} analysis		
$\tau_{\text{had-vis}}$ energy scale	−13	+5
Pile-up	−0.015	+1.3
Z+jets backgrounds cross section and acceptance	−0.3	+0.4
Signal PDF	−0.3	+0.5
Jet-to- $\tau_{\text{had-vis}}$ fake rate ($\tau_{\text{had}}\tau_{\text{had}}$)	−0.3	+0.3
$\tau_{\text{had-vis}}$ identification	−0.19	+0.18
Luminosity	−0.16	+0.15
$W \rightarrow \tau\nu$ +jets background reweighting ($\tau_{\text{had}}\tau_{\text{had}}$)	−0.17	+0.10
Statistics (data and simulation)	−85	+92

The data are found to be in good agreement with the predicted background yields and hence the results are given as exclusion limits. These are set using the modified frequentist method known as CL_s [130]. Observed and expected 95 % confidence level (CL) upper limits on the cross section times branching fraction for the production of a single scalar boson H/A decaying to $\tau\tau$, as a function of the mass of the boson $m_{H/A}$, are shown in Fig. 5a, b. The limits are calculated for both the gluon–gluon fusion and b -associated production modes, using a combination of the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels and assuming the natural width of the boson to be negligible compared to the experimental resolution (as expected over the probed MSSM parameter space). The lowest excluded cross section times branching fraction values

range from $\sigma \times BR = 1.4$ pb at $m_{H/A} = 200$ GeV to $\sigma \times BR = 0.025$ pb at $m_{H/A} = 1.2$ TeV for a scalar boson produced via gluon–gluon fusion. Similarly, for the b -associated production mechanism the lowest excluded values range is from $\sigma \times BR = 1.6$ pb at $m_{H/A} = 200$ GeV to $\sigma \times BR = 0.028$ pb at $m_{H/A} = 1.2$ TeV.

The observed and expected 95 % CL limits on $\tan \beta$ as a function of m_A , for the combination of $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels in the MSSM $m_h^{\text{mod+}}$ and hMSSM scenarios are shown in Fig. 5c, d. The expected limit in the $m_h^{\text{mod+}}$ scenario is compared to the expected limits from the individual $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. For the $m_h^{\text{mod+}}$ figure, lines of constant m_h and m_H are shown. For the hMSSM scenario, the exclusion arising from the SM Higgs boson coupling measurements of Ref. [131] is also shown, in addition to the ATLAS Run-1 $H/A \rightarrow \tau\tau$ search result of Ref. [28]. The $\tan \beta$ constraints in the hMSSM scenario are stronger than those in the $m_h^{\text{mod+}}$ scenario. This is due to the presence of low-mass neutralinos in the $m_h^{\text{mod+}}$ scenario that reduce the $H/A \rightarrow \tau\tau$ branching fraction and which are absent in the hMSSM scenario. In the hMSSM scenario, the most stringent constraints on $\tan \beta$ for the combined search exclude $\tan \beta > 7.1$ for $m_A = 200$ GeV and $\tan \beta > 39$ for $m_A = 1$ TeV at the 95 % CL. In the MSSM $m_h^{\text{mod+}}$ scenario, the 95 % CL upper limits exclude $\tan \beta > 7.6$ for $m_A = 200$ GeV and $\tan \beta > 47$ for $m_A = 1$ TeV. The feature of the expected limits in the hMSSM scenario exclusion plot at around $m_A = 350$ GeV is due to the behaviour of the branching ratio $A \rightarrow \tau\tau$ close to the $A \rightarrow t\bar{t}$ kinematic threshold. Some sensitivity of the search is also expected around $\tan \beta \sim 1$, $m_A \sim 200$ GeV due to the increase of the gluon–gluon fusion cross section induced by the increased coupling to the top quark.

In the search for the Z' boson, the observed number of events in the signal regions of the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are consistent with the SM predictions. The resulting 95% CL upper limits are set on the cross section times branching fraction as a function of the mass and shown in Fig. 6a. These results are interpreted in the context of the SSM and SFM in Fig. 6a, b, respectively. The resulting observed (expected) lower limit on the mass of the Z'_{SSM} boson is 1.90 (1.84) TeV. In the search for the Z'_{SFM} boson, results are presented as a function of $\sin^2 \phi$, where ϕ is the mixing angle between the two SU(2) gauge eigenstates of the model. Masses below 1.82–2.17 TeV are excluded in the range $0.1 < \sin^2 \phi < 0.5$, assuming no $\mu - \tau$ mixing. For the value of $\sin^2 \phi = 0.03$, the lower limit on the mass of a Z'_{SFM} boson is 2.12 TeV, extending the limits from previous direct and indirect searches by more than 200 GeV.

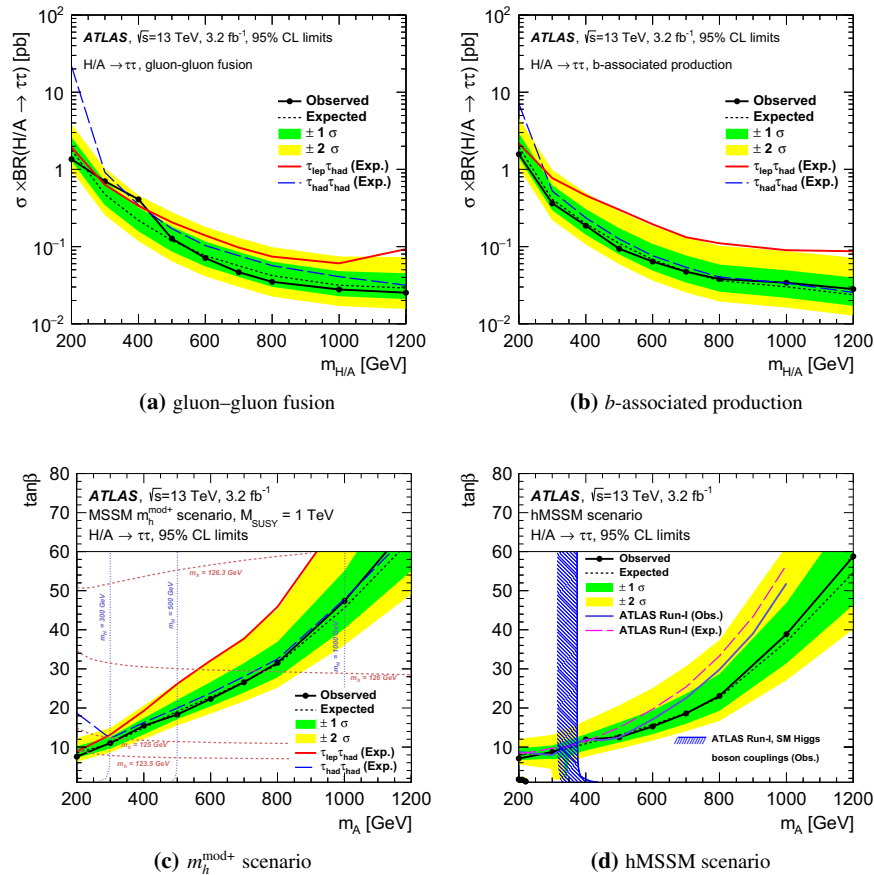


Fig. 5 The observed and expected 95% CL upper limits on the production cross section times branching fraction of a scalar particle are shown for the combination of the $\tau_{\text{lep}}\tau_{\text{had}}$ and the $\tau_{\text{had}}\tau_{\text{had}}$ channels. The production mechanism of $H/A \rightarrow \tau\tau$ is assumed to be **a** gluon-gluon fusion or **b** b -associated production. For comparison, the expected limits for the individual channels, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$, are shown as well. The observed and expected 95% CL limits on $\tan\beta$ as a func-

tion of m_A are shown in **c** for the MSSM $m_h^{\text{mod}+}$ scenario and **d** for the hMSSM scenario. For comparison, the expected limits from the individual channels, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$, are given in **c**, while the observed and expected limits from the ATLAS Run-1 analysis in Ref. [28] are shown in **d**. Dashed lines of constant m_h and m_H are shown in red and blue, respectively

8 Conclusions

A search for neutral Higgs bosons of the minimal supersymmetric standard model (MSSM) and for a Z' gauge boson decaying to a pair of τ leptons is performed using a data sample corresponding to an integrated luminosity of 3.2 fb^{-1} from proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector at the LHC. The search finds no indication of an excess over the expected background in the channels considered. Limits are set at the 95% CL, which provide constraints in the MSSM parameter space. Model-independent upper limits on the production cross section times the $\tau\tau$ branching fraction of a scalar boson versus its mass, in both the gluon-gluon fusion and b -associated production modes, are presented. The upper limits on the cross

section times branching fraction range from 1.4 (1.6) pb at $m_{H/A} = 200 \text{ GeV}$ to 0.025 (0.028) pb at $m_{H/A} = 1.2 \text{ TeV}$ for a scalar boson produced via gluon-gluon fusion (b -associated production). In the context of the MSSM $m_h^{\text{mod}+}$ scenario, the most stringent 95% CL upper limit on $\tan\beta$ for the combined search is $\tan\beta < 7.6$ for $m_A = 200 \text{ GeV}$. This analysis extends the limits of the previous searches for the mass range $m_A > 500 \text{ GeV}$. The search for a Z' boson is interpreted in the context of the sequential standard model (SSM) and the strong flavour model (SFM). Upper limits at the 95% CL are set on the cross section times branching fraction as a function of the Z' mass. The observed lower limit on the Z' mass is 1.90 TeV for a Z'_{SSM} and ranges from 1.82 to 2.17 TeV as a function of the $\sin^2\phi$ parameter for a Z'_{SFM} .

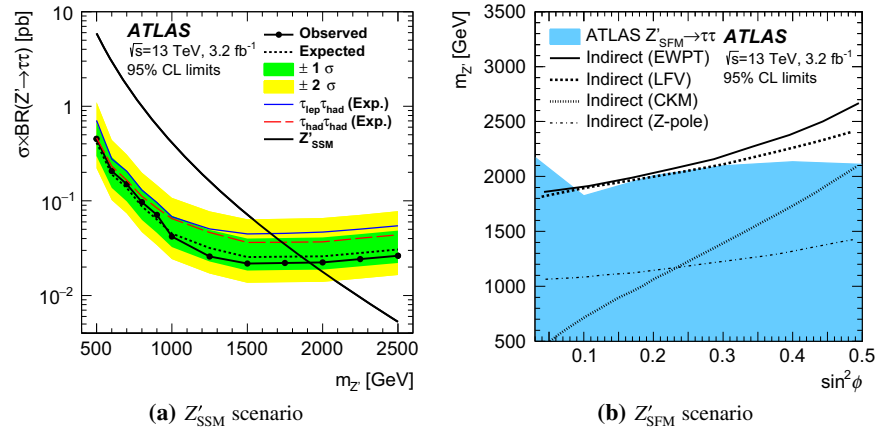


Fig. 6 The 95 % CL upper limit on the cross section times branching fraction for a $Z' \rightarrow \tau\tau$ in **a** the Sequential Standard Model and 95% CL exclusion on **b** the SFM parameter space, overlaid with indirect lim-

its at 95 % CL from fits to electroweak precision measurements [132], lepton flavour violation [133], CKM unitarity [134] and Z-pole measurements [41]

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ATLAS NOTE

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Combined measurements of the Higgs boson production and decay rates in $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ final states using pp collision data at $\sqrt{s} = 13$ TeV in the ATLAS experiment

The ATLAS Collaboration

Abstract

This note presents combined measurements based on Higgs boson production cross sections and branching ratios using more than 13.3 fb^{-1} of proton-proton collision data recorded by the ATLAS experiment at the LHC at $\sqrt{s} = 13$ TeV. The combination is based on the analyses of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels. Results are derived for these two decay modes and five sets of production processes for a Higgs boson rapidity $|y_H| < 2.5$ and for a Higgs boson mass of $125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV. The global signal strength, defined as the ratio in the full phase space (including $|y_H| \geq 2.5$) between the observed total signal yield and the Standard Model expectation, is measured to be $\mu = 1.13^{+0.18}_{-0.17}$. The cross section of $pp \rightarrow H + X$ in the full phase space is determined from fiducial cross section measurements to be $59.0^{+9.7}_{-9.2}(\text{stat.})^{+4.4}_{-3.5}(\text{syst.})$ pb, to be compared with the Standard Model prediction of $55.5^{+2.4}_{-3.4}$ pb. No significant deviation from the Standard Model expectations is observed.

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1 Introduction

This note presents combined measurements based on Higgs boson production cross sections and branching ratios using proton-proton collision data produced by the LHC at a centre-of-mass energy of $\sqrt{s} = 13$ TeV and recorded by the ATLAS detector. The analysis is based on the measurements performed in the individual $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels [1, 2].

Higgs boson production and decays were studied at $\sqrt{s}$ of 7 and 8 TeV and were found to be consistent with expectations from the Standard Model (SM) [3]. The data sample already collected so far at $\sqrt{s} = 13$ TeV allows initial measurements with comparable precision. With the increased data sample that will be taken during the next years, these measurements will reach much higher precision and probe the Higgs sector in depth.

SM production of the Higgs boson at the LHC is dominated by the gluon fusion process $gg \rightarrow H$, followed by the vector-boson fusion process $qq' \rightarrow qq'H$. Associated production with a W boson $q\bar{q}' \rightarrow WH$, a Z boson $q\bar{q}/gg \rightarrow ZH$ or with a pair of top quarks $q\bar{q}/gg \rightarrow t\bar{t}H$ also have sizeable contributions. The WH and ZH production processes are collectively referred to as the VH process. Smaller contributions are expected from production in association with b quarks $b\bar{b}H$ and production in association with a single top quark (tH) with the latter proceeding through either the $qb \rightarrow tHq'$ or $gb \rightarrow WtH$ process. The theoretical calculations of the Higgs boson production cross sections and decay branching ratios have been compiled in Refs. [4–7]. The combined analysis considers five sets of production processes: ggF ($gg \rightarrow H$ and $b\bar{b}H$), VBF ($qq' \rightarrow qq'H$), VH_{had} ($q\bar{q}/gg \rightarrow ZH$ and $q\bar{q}' \rightarrow WH$ with hadronic decays of W/Z), VH_{lep} ($q\bar{q}/gg \rightarrow ZH$ and $q\bar{q}' \rightarrow WH$ with decays of W/Z to charged leptons and/or neutrinos) and top ($q\bar{q}/gg \rightarrow t\bar{t}H$ and tH).

Products of Higgs boson production cross sections of process i (σ_i) and branching ratios to the final state f (B^f), $\sigma_i \cdot B^f = (\sigma \cdot B)_i^f$ (following the notation in Ref. [3]), are reported for $|y_H| < 2.5$, where y_H is the Higgs boson rapidity. This corresponds to the "stage-0" simplified template cross sections from Ref. [8]. For Higgs boson rapidity $|y_H| > 2.5$, the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ analyses have a negligible acceptance. The separation of the production processes is achieved by exploiting the differences in event topologies and kinematics of the different production processes through categorisation of events. The results for $(\sigma \cdot B)_{ggF}^f$ and $(\sigma \cdot B)_{VBF}^f$ for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ are presented in the two-dimensional plane to show their correlation. In addition, production cross sections σ_i for a Higgs boson rapidity $|y_H| < 2.5$ are measured by assuming the SM Higgs branching ratios to $\gamma\gamma$ and ZZ^* , and by concurrently determining the ratio of the branching ratios to $\gamma\gamma$ and ZZ^* .

A measurement of the global signal strength μ , which is defined as the ratio of the observed total signal yield to the total signal yield expected from the SM, used as a single scaling factor for all production processes and decay modes, is presented after extrapolation to the full phase space. The measurement is based on the same categorisation of events as the measurements introduced above to benefit from the sensitivity improvement of this technique.

Table 1 summarises the four different fit models based on event categorisation and the number of measured parameters in each fit model.

The measurement of the total cross section, extrapolated to the full phase space, based on the fiducial cross section measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ follows a different strategy: instead of attempting to separate the different Higgs boson production processes or using the categorisation to enhance the sensitivity, the inclusive event samples are used to minimise the model dependence. Differences in the

Table 1: Summary of the fit strategies based on event categorisation used in this note.

Fit model	Number of parameters of interest	Section
Independent $\sigma_i \cdot B^f$	7	4.1
Independent σ_i assuming SM B^f	5	4.2
$(\sigma \cdot B)_{ggF}^{ZZ}$, $\sigma_{VBF}/\sigma_{ggF}$ and $B^{\gamma\gamma}/B^{ZZ}$	3	4.3
Global signal strength μ	1	5

acceptances and in the experimental effects between the different production modes are considered as systematic uncertainties in the measurement of the total cross section. All measurements are performed under the assumption that the Higgs boson mass is $125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV [9].

Section 2 introduces the data sample that the measurements presented are based on, gives an overview of the simulation samples for Higgs boson production, as well as a brief review of the analyses in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels. Section 3 provides a short introduction into the underlying statistical technique that is used. Sections 4–6 present the measurements as discussed above, and Section 7 gives a summary.

2 Analysis

2.1 Data sample

The proton-proton collision data were collected by the ATLAS experiment in 2015 and 2016, with the LHC operating at a centre-of-mass energy of 13 TeV. The ATLAS detector is described in detail elsewhere [10, 11].

The analysis only considers events taken during stable beam conditions and when the full detector was operational and delivered data of good quality. The dataset amounts to 13.3 fb^{-1} for the $H \rightarrow \gamma\gamma$ analysis and to 14.8 fb^{-1} for the $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis, of which 3.2 fb^{-1} were collected in 2015 and the rest in 2016. The mean number of proton-proton interactions per bunch crossing (also referred to as event pileup) was approximately equal to 14 in the 2015 dataset and to 22 in the 2016 dataset.

2.2 Samples of simulated Higgs boson events

Higgs boson production via gluon-gluon fusion ($gg \rightarrow H$) is simulated at next-to-leading-order (NLO) accuracy in QCD using the POWHEG Box [12–15], with the CT10 parton distribution function (PDF) [16]. The mass and natural width of the Higgs boson are chosen to be $m_H = 125$ GeV and $\Gamma_H = 4.07$ MeV [6], respectively. The parton-level events produced by the POWHEG Box are passed to PYTHIA8 [17] to provide parton showering, hadronisation and multiple parton interactions (MPI). The sample is normalised such that it reproduces the total cross section predicted by a next-to-next-to-next-to-leading-order (N³LO) QCD calculation with NLO electroweak corrections applied [7, 18–21]. Additional corrections are applied to the shape of the Higgs boson transverse momentum distribution to reproduce the distribution

predicted by HRES2.1 [22] at NNLO+NNLL, which includes the effects of top- and bottom-quark masses and uses dynamical renormalisation and factorisation scales. To avoid a sizeable effect on the fraction of events with two or more jets and to preserve their consistency with the most precise available calculations, the corrections are computed after subtracting the transverse momentum spectrum of events with two or more jets from the simulation from the HRES2.1 prediction and the simulation. The reweighting is only applied to events with fewer than two jets.

Higgs boson production via vector-boson fusion (VBF: $qq' \rightarrow qq'H$) is generated to NLO accuracy in QCD using the PowHEG Box [23] with the CT10 PDF. The parton-level events are passed to PYTHIA8 to provide parton showering, hadronisation and MPI. The VBF sample is normalised to an approximate-NNLO QCD cross section with NLO electroweak corrections applied [7, 24–26]. Higgs boson production in association with a vector boson (VH: $q\bar{q} \rightarrow ZH$, $q\bar{q}' \rightarrow WH$) is produced at leading-order (LO) accuracy in QCD using PYTHIA8 with the NNPDF2.3LO PDF set [27]. The samples are normalised to cross sections calculated at NNLO in QCD with NLO electroweak corrections [28, 29] including the NLO QCD corrections [30] for $gg \rightarrow ZH$ [7].

Higgs boson production in association with a top–antitop pair ($q\bar{q}/gg \rightarrow t\bar{t}H$) is produced at NLO accuracy in QCD using MG5_aMC [31] with the NNPDF2.3 PDF and interfaced to PYTHIA8 to provide parton showering, hadronisation and MPI. The $t\bar{t}H$ sample is normalised to a cross section calculation accurate to NLO in QCD with NLO electroweak corrections applied [7, 32–35].

Higgs boson production via bottom-quark fusion ($b\bar{b}H$) is produced using MG5_aMC [36] interfaced to PYTHIA8, and is normalised to a cross section calculation accurate to NNLO in QCD [7, 37–39]. The sample includes the effect of interference with the gluon fusion production mechanism. Higgs boson production in association with a single top-quark and a W-boson (tHW) is produced at LO accuracy using MG5_aMC interfaced to HERWIG++ [40]. Higgs boson production in association with a single top-quark, a b-quark and a light quark ($tHjb$) is produced at LO accuracy using MG5_aMC interfaced to PYTHIA8. The tHW and $tHjb$ samples are normalised to calculations accurate to NLO in QCD [7, 41].

The particle-level Higgs boson events are passed through a GEANT 4 [42, 43] simulation of the ATLAS detector [44] and reconstructed using the same analysis software as used for the data. Event pileup is included in the simulation by adding inelastic proton–proton collisions, such that the average number of interactions per bunch crossing reproduces that observed in the data. The inelastic proton–proton collisions were produced using PYTHIA8.

2.3 Analyses in the individual decay channels

The event categorisation used for the results presented in Sections 4 and 5 is optimised for the best separation of the Higgs boson production processes. For each decay channel, the events are divided into a number of mutually exclusive categories based on reconstructed event kinematics and topology. These are defined such that each category is sensitive primarily to a given production mode. A further subdivision of the categories is made, based e.g. on the number of jets in the final state; details are given in Ref. [1, 2] and a brief reminder is given in Sections 2.3.1 and 2.3.2 below. The Standard Model predictions for the relative contribution of the different production modes to each category are taken as a "template". These serve as the basis of the fit of the yields of different production modes times corresponding branching ratios.

Table 2 gives an overview of the event categories for both decay modes used for the measurement of the simplified template cross sections and the inclusive signal strength, which is described in more detail in the following Sections.

Table 2: Categories entering in the combined measurements for the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ decay modes as described in [2] and [1] respectively. Each category is designed to separate a specific set of production processes, as summarised in the columns named target.

$H \rightarrow ZZ^* \rightarrow 4\ell$		$H \rightarrow \gamma\gamma$	
Category	Target	Category	Target
VH -leptonic	VHlep	$t\bar{t}H$ leptonic	top
0-jet	ggF	$t\bar{t}H$ hadronic	top
1-jet	ggF	VH dilepton	VHlep
2-jet VBF-like	VBF	VH one-lepton	VHlep
2-jet VH -like	VHhad	VH Emiss	VHlep
		VH hadronic loose	VHhad
		VH hadronic tight	VHhad
		VBF loose	VBF
		VBF tight	VBF
		ggH central low- p_{Tl}	ggF
		ggH central high- p_{Tl}	ggF
		ggH fwd low- p_{Tl}	ggF
		ggH fwd high- p_{Tl}	ggF

2.3.1 $H \rightarrow ZZ^* \rightarrow 4\ell$

The $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis [1] reconstructs the Z and the Z^* bosons in their decays to electrons and muons. It uses five event categories to separate the different Higgs boson production modes. The VH leptonic category requires the presence of at least one additional lepton. The remaining events are categorised according to their jet multiplicity into categories with zero, exactly one and at least two jets, and the two-jet category is split into a VBF- and a VH -enriched region using the dijet invariant mass. In the jet-multiplicity based categories boosted decision trees (BDTs) based on the kinematic variables of jets and Z bosons are used to separate the different Higgs production processes from the SM ZZ^* background. In the two-jet VH category, the BDT discriminant is designed to separate VH production from VBF and gluon fusion production, in the two-jet VBF category, the BDT is trained to separate VBF production from gluon fusion production, in the one-jet category the BDT discriminant is built to separate VBF production from gluon fusion production and SM ZZ^* background, and in the zero-jet category the BDT is trained to separate the Higgs signal, dominated by gluon fusion production, from SM ZZ^* background.

Only events with an invariant four-lepton mass between 118 and 129 GeV are considered in the analysis. In the jet categories, the signal is extracted through a binned fit to the BDT discriminant, while the signal estimation in the VH leptonic category is based on event counting. The remaining $ZZ^* \rightarrow 4\ell$ background is estimated from the Monte Carlo simulation, while the Z +jets and $t\bar{t}$ backgrounds are estimated from control regions in the data.

2.3.2 $H \rightarrow \gamma\gamma$

The $H \rightarrow \gamma\gamma$ analysis [2] is based on 13 exclusive event categories targetting the five Higgs boson production modes introduced in Section 1. For categories enriched in $t\bar{t}H$ production, the leptonic as well as fully hadronic decay signatures of the $t\bar{t}$ system are considered. The leptonic selection requires at least one lepton, at least two jets and one of them should be identified as originating from a b -quark (b -tagged), as well as missing transverse momentum E_T^{miss} or at least two b -tagged jets. In the hadronic selection, events with at least five jets with at least one b -tag are required. Five categories are enriched in VH production: the dilepton category requires two same-flavor, opposite-sign leptons consistent with a Z -boson decay; the one-lepton category requires exactly one lepton and a minimum E_T^{miss} significance (defined as $E_T^{\text{miss}}/\sqrt{\sum E_T}$, where $\sum E_T$ is the scalar sum of the transverse energies of all objects used in the estimation of the missing transverse momentum); the E_T^{miss} category requires zero leptons, high E_T^{miss} significance and a minimum diphoton transverse momentum; and the two hadronic VH categories require two jets consistent with a V decay and employ a BDT based on diphoton and dijet variables. The selection of the two categories enriched in VBF events requires two jets loosely consistent with VBF topology and is based on a BDT combining six kinematic variables, among which the azimuthal difference between the diphoton and the dijet system, $\Delta\phi_{\gamma\gamma-jj}$ serves as an implicit third-jet veto. The remaining events are separated according to the pseudo-rapidity of the two photons and the p_{T_i} of the diphoton system (defined as the orthogonal component of the diphoton momentum when projected on the axis given by the difference of the momenta of the two photons, in analogy to Refs. [45, 46]), which separates events with different diphoton invariant mass resolution and further discriminates VBF and gluon fusion production.

The signal is extracted by a fit to the diphoton invariant mass distribution applied simultaneously to all event categories. The background shape is parameterised in each event category and determined from data.

3 Statistical model

The statistical treatment is described in Refs. [3, 47–51]. The parameters of interest each represent a product of a Higgs production cross section and a branching ratio in the fit described in Section 4.1, and reparameterisations thereof in the fits described in Sections 4.2, 4.3, and 5. In the present analysis we consider the five sets of production modes introduced in Section 1 (ggF, VBF, VHhad, VHlep, and top), and detailed further in Section 4, and two Higgs decay channels (ZZ^* and $\gamma\gamma$), giving initially 10 parameters to be estimated. For the fit described in Section 6, the parameter of interest is the inclusive Higgs production cross section (no split by production processes) times branching ratio.

These parameters can be used to predict the mean numbers of events in bins corresponding to different kinematic regions for several event topologies. These regions are designed to be sensitive primarily to a given Higgs boson production mode and decay channel, as described in Section 2.3. An exception is the fit described in Section 6, which does not rely on event categorisation, and uses only one bin. A likelihood function is constructed that treats the number of events found in each bin as an independent Poisson-distributed value, or is based on the unbinned diphoton invariant mass distribution in the case of low-statistics event categories in $H \rightarrow \gamma\gamma$.

The predicted mean number of events in each bin depends as well on additional nuisance parameters, related to the uncertainty on the electromagnetic and jet energy scale systematic uncertainties, luminosity,

background shape, etc. In total there are about 200 nuisance parameters, which are determined by the fit, although their values themselves are not of particular interest. Some of these are constrained by the same data. Other nuisance parameters are constrained by auxiliary information such as independent control measurements. In this case, the estimated value of the nuisance parameter is constrained by either a Gaussian or a log-normal distribution, and a corresponding multiplicative term is included in the likelihood function (further details can be found in Refs. [47, 48]). Uncertainties are treated as either uncorrelated or fully (anti-)correlated. Uncertainties that are fully (anti-)correlated between different event categories or between different decay channels share the same nuisance parameter.

The sources of theoretical uncertainties related to the Higgs boson signal considered in the measurements of the cross sections are uncertainties in the acceptance of the different categories due to missing higher-order QCD corrections, uncertainties in the PDFs [52, 53], and uncertainties in the modelling of the underlying event and parton shower (UE/PS). The nuisance parameter related to the uncertainties due to missing higher-order QCD correction for the inclusive 2-jet acceptance in the VBF categories is shared between $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$, and so is the nuisance parameter associated to the effect of the uncertainties due to missing higher-order QCD correction in the splitting of the signal in the $p_{T\ell}$ categories [22, 54] in $H \rightarrow \gamma\gamma$ and the 0- and 1-jet categories [55–57] in $H \rightarrow ZZ^* \rightarrow 4\ell$. The nuisance parameters associated with UE/PS uncertainties are also correlated between the two decay channels.

For the measurement of the signal strength, uncertainties on the predicted cross section are taken into account, including uncertainties from missing higher-order QCD corrections, as well as uncertainties on the PDFs and α_s . These uncertainties are fully correlated between the different decay channels. In addition, theoretical and parametric uncertainties on the decay branching ratios are included [7, 58–61]. The correlation scheme for these systematic uncertainties follows the strategy reported in Ref. [3]. All the experimental sources of uncertainties shared by the two analyses are correlated in the combined fit, notably the uncertainties on the electromagnetic energy scale and resolution, the muon energy scale, the jet energy scale and resolution, as well as uncertainties related to the reconstruction and isolation efficiencies of electrons, and the uncertainties related to the identification and isolation efficiencies of muons.

The statistical procedure results in a likelihood function $L(\alpha, \theta)$, where α represents the 10 parameters of interest and θ is the set of nuisance parameters. A statistical test of hypothetical α values is carried out using the profile likelihood ratio [62]

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \hat{\theta})} . \quad (1)$$

In the numerator, the nuisance parameters are varied to maximise the likelihood function for given fixed values of the parameters of interest α (conditional maximum-likelihood). In the denominator, both the parameters of interest and the nuisance parameters are varied to maximise the likelihood function (unconditional maximum-likelihood). The choice of the parameters of interest depends on the test under consideration, with the remaining parameters being “profiled”, i.e., similarly to nuisance parameters they are set to the values that maximise the likelihood function for the given fixed values of the parameters of interest. Asymptotically, a test statistic $-2 \ln \Lambda(\alpha)$ of several parameters of interest α is distributed as a χ^2 distribution with n degrees of freedom, where n is the dimensionality of the vector α . An example for the distribution of $-2 \ln \Lambda(\alpha)$ for the measurement of $(\sigma \cdot \text{B})_{\text{ggF}}^{ZZ}$ described in Section 4 is shown in Figure 1. All results presented in the following Sections are based on likelihood evaluations and give confidence level (CL) intervals assuming the asymptotic approximation.

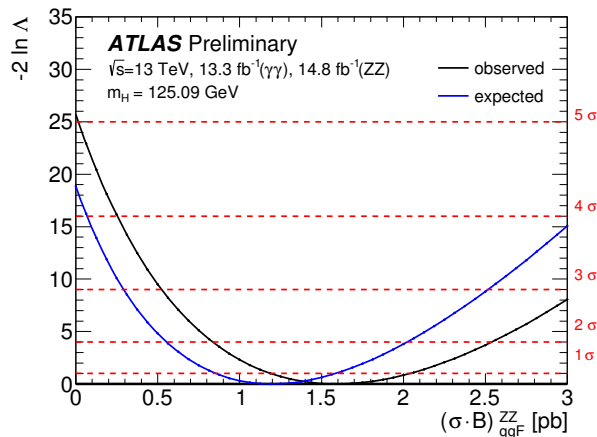


Figure 1: $-2 \ln \Lambda(\alpha)$ scan for the measurement of $(\sigma \cdot B)_{ggF}^{ZZ}$ described in Section 4. The number of degrees of freedom in this example is $\text{ndf} = 1$, and the intervals defined by the intersections with the dashed lines are the confidence level intervals for about 68.3% (1σ), 95.4% (2σ), 99.7% (3σ) and higher than 99.99% (4 and 5σ) respectively.

The compatibility with the Standard Model, p_{SM} , is quantified using the p -value [62]¹ obtained from the value of $-2 \ln \Lambda(\alpha = \alpha_{SM})$, where α is the set of parameters of interest and α_{SM} are their Standard Model values, and assuming asymptotic χ^2 distribution with a number of degrees of freedom equal to the number of parameters of interest of the test statistic.

4 Combined results for cross sections and branching ratios

The combined analysis of the different decay channels is performed in the statistical framework introduced in Section 3, with $(\sigma \cdot B)_i^f = \sigma_i \cdot B^f$ as parameters of interest, where σ_i is the cross section for production process i (for $|y_H| < 2.5$, referred to as “central” below), B^f is the branching fraction for the final state f .

The sets of production modes considered were introduced in Section 1: ggF , VBF , VH_{had} , VH_{lep} and top .

With the present data sample and the decay channels taken into account, the combined analysis is only sensitive to a subset of all possible production processes, which motivates the grouping of production processes as follows:

- $b\bar{b}H$ is coupled with $gg \rightarrow H$ by assuming SM predictions for the ratio of the two processes, and the combined cross section of the two processes will be reported, labelled “ ggF ”.
- tH is coupled with $t\bar{t}H$, by assuming SM predictions for the ratio of the $pp \rightarrow tH$ and the $pp \rightarrow t\bar{t}H$ cross sections, together reported as “ top ”.

¹ The p -value is defined as the probability to obtain a value of the test statistic that is at least as high as the observed value, under the hypothesis that is being tested.

- WH and ZH are merged, separately for the hadronic V and the leptonic (including charged leptons and neutrinos) decays, into $V(\rightarrow q\bar{q})H$ and $V(\rightarrow \text{leptons})H$, reported as “VHhad” and “VHlep”, respectively. The merging assumes the SM prediction for the ratio of the production cross sections and includes the contributions from both $q\bar{q} \rightarrow VH$ and $gg \rightarrow ZH$.

Table 3 shows the value of the fraction between the central and the total cross section per production process, calculated using the simulated samples described in Section 2.2. These fractions, and the theoretical calculations in Ref. [7], are used to calculate the values of the SM prediction for the measured cross sections shown in the following Sections.

In the models considered below, the original parameters of interest, $(\sigma \cdot B)_i^f$, are determined in the analysis described in Section 4.1. For the analyses described in Sections 4.2 and 4.3 the respective parameters of interest are expressed in terms of the $(\sigma \cdot B)_i^f$. Theoretical uncertainties are included for those quantities that are fixed to the SM predictions.

Table 3: Ratio between the central and the total cross section per production process. The uncertainties related to the finite size of the simulated samples used to calculate the fractions are of the order of 5%, and not reported in the table. The values of the fraction between the central and the total cross section for $b\bar{b}H$ and tH are assumed to have a negligible impact on the calculation of the SM predictions shown in the following Sections, and they are set to one.

Process	Contributing to	$\sigma_i(y_H < 2.5)/\sigma_i$
$gg \rightarrow H$	ggF	0.907
$qq' \rightarrow qq'H$	VBF	0.932
$q\bar{q}' \rightarrow WH(W \rightarrow \text{had.})$	VHhad	0.870
$q\bar{q}/gg \rightarrow ZH(Z \rightarrow \text{had.})$	VHhad	0.900
$q\bar{q}' \rightarrow WH(W \rightarrow \text{lep.})$	VHlep	0.869
$q\bar{q} \rightarrow ZH(Z \rightarrow \text{lep.})$	VHlep	0.900
$gg \rightarrow ZH(Z \rightarrow \text{lep.})$	VHlep	0.965
$q\bar{q}/gg \rightarrow t\bar{t}H$	top	0.985

4.1 Parameterisation using independent products of cross sections and branching fractions

The first model provides measurements for a total of seven of the $(\sigma \cdot B)_i^f$: the product of the cross sections for ggF (σ_{ggF}), VBF (σ_{VBF}), VHhad (σ_{VHhad}), VHlep (σ_{VHlep}) and top (σ_{top}) are measured in the central region, with the branching fractions into $\gamma\gamma$ and ZZ^* . While the measured $(\sigma \cdot B)_i^f$ are for the specific final state f , the combined analysis allows for a correlation of the systematic uncertainties as described in Section 3. Among the ten $(\sigma \cdot B)_i^f$, the three that are not well enough constrained from data are fixed to the respective SM predictions: $(\sigma \cdot B)_{\text{VHhad}}^{ZZ}$, $(\sigma \cdot B)_{\text{VHlep}}^{ZZ}$ and $(\sigma \cdot B)_{\text{top}}^{ZZ}$. The $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis does not have any event category sensitive to Higgs boson production in association with top quarks, and very few events in the categories sensitive to VH production. Measurements are obtained for the parameters of interest given in Table 4. Theoretical uncertainties on the predicted SM cross section ratios that are fixed in the analysis as described above are taken into account. The combination of the nuisance parameters

due to the assumptions on the correlation scheme between the $H \rightarrow ZZ^* \rightarrow 4\ell$ and the $H \rightarrow \gamma\gamma$ analyses, and the specific definition of **ggF**, **VBF**, **VHhad**, **VHlep** and **top** generate the small differences between the results in Table 5 and the ones presented in Ref. [1] and Ref. [2].

Table 4: Parameters of interest for the measurement of $(\sigma \cdot B)_i^f$.

Decay mode	ggF	VBF	VHhad	VHlep	top
$H \rightarrow \gamma\gamma$	$(\sigma \cdot B)_{\text{ggF}}^{\gamma\gamma}$	$(\sigma \cdot B)_{\text{VBF}}^{\gamma\gamma}$	$(\sigma \cdot B)_{\text{VHhad}}^{\gamma\gamma}$	$(\sigma \cdot B)_{\text{VHlep}}^{\gamma\gamma}$	$(\sigma \cdot B)_{\text{top}}^{\gamma\gamma}$
$H \rightarrow ZZ^*$	$(\sigma \cdot B)_{\text{ggF}}^{ZZ}$	$(\sigma \cdot B)_{\text{VBF}}^{ZZ}$	fixed to SM	fixed to SM	fixed to SM

Table 5: Best fit values of $(\sigma \cdot B)_i^f$ for each specific channel $i \rightarrow H \rightarrow f$, as obtained from the generic parameterisation with 7 parameters as given in Table 4. The SM predictions [7] are shown for each $(\sigma \cdot B)_i^f$.

		$H \rightarrow ZZ^*$	$H \rightarrow \gamma\gamma$
ggF	Best fit value (pb)	$1.58^{+0.46}_{-0.39}$	$0.063^{+0.030}_{-0.029}$
	SM prediction (pb)	1.18 ± 0.07	0.101 ± 0.006
VBF	Best fit value (fb)	350^{+260}_{-200}	18^{+6}_{-6}
	SM prediction (fb)	93.0 ± 2.8	8.00 ± 0.29
VHhad	Best fit value (fb)	fixed to SM	$-2.5^{+6.8}_{-5.8}$
	SM prediction (fb)	36.0 ± 1.2	3.09 ± 0.12
VHlep	Best fit value (fb)	fixed to SM	$1.0^{+2.5}_{-1.9}$
	SM prediction (fb)	17.0 ± 0.5	1.46 ± 0.05
top	Best fit value (fb)	fixed to SM	$-0.3^{+1.6}_{-1.2}$
	SM prediction (fb)	15.9 ± 1.5	1.36 ± 0.13

Figure 2 shows the cross sections $(\sigma \cdot B)_i^f$ as given in Table 4 for **ggF**, **VBF**, **VHhad**, **VHlep** and **top** measured in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$. The fit results displayed are normalised to the SM predictions for the various parameters and the grey bands indicate the theoretical uncertainties in these predictions. A summary of the measured cross sections $(\sigma \cdot B)_i^f$ is shown in Table 5.

The **ggF** and **VBF** cross sections are measured with the best precision. As the event categories from which they are mainly constrained typically have substantial contributions from both $gg \rightarrow H$ and **VBF**, the measured cross sections of the two sets of production modes are correlated. To compare the contours in the $(\sigma \cdot B)_{\text{ggF}}^f - (\sigma \cdot B)_{\text{VBF}}^f$ plane, as measured in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ when the remaining parameters of interest are profiled, the values of $(\sigma \cdot B)_i^f$ are divided by the branching fraction for the decay mode f predicted by the SM, B_{SM}^f , as shown in Figure 3.

The uncertainties on the electromagnetic energy resolution and the photon identification efficiency play the most important role among the experimental errors. The uncertainties on the acceptance of gluon fusion production in the categories with a specific number of jets in the event are the most prominent theoretical uncertainties.

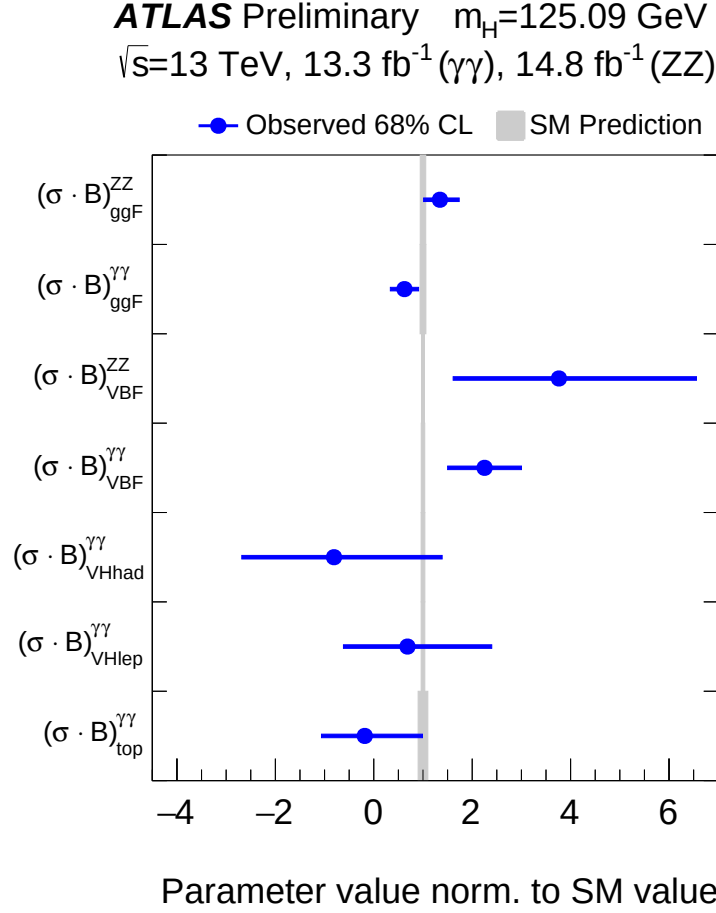


Figure 2: Cross sections $(\sigma \cdot B)_i^f$ as given in Table 4 for ggF, VBF, VHhad, VHlep and top measured in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$. The fit results are normalised to the SM predictions for the various parameters and the grey bands indicate the theoretical uncertainties in these predictions. The blue error bars show the full uncertainty, including experimental uncertainties and theoretical uncertainties that impact the measurements.

The compatibility between the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}} = 11\%$.

4.2 Parameterisation using independent production cross sections and assuming SM Higgs decay branching fractions

The second model focuses on the measurement of the production cross sections assuming SM Higgs decay branching fractions. In this model, the cross sections for ggF (σ_{ggF}), VBF (σ_{VBF}), VHhad (σ_{VHhad}), VHlep (σ_{VHlep}) and top (σ_{top}) are measured in the central region. Theoretical uncertainties on the predicted SM

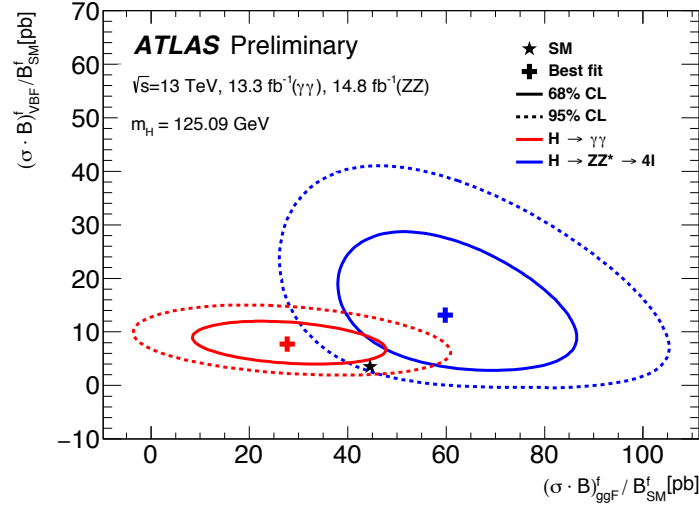


Figure 3: Contours in the $(\sigma \cdot B)_{ggF}^f / B_{SM}^f - (\sigma \cdot B)_{VBF}^f / B_{SM}^f$ plane as measured in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$, together with the SM prediction.

branching fractions and assumed SM cross section ratios as described above are taken into account.

Figure 4 and Table 6 show the cross sections for ggF, VBF, VHhad, VHlep and top. The fit results displayed in Figure 4 are normalised to the SM predictions for the various parameters and the grey bands indicate the theoretical uncertainties in these predictions.

The compatibility between the measurement and the SM prediction corresponds to a p -value of $p_{SM} = 21\%$.

Table 6: Best fit values of the production cross sections σ_i assuming SM Higgs decay branching fractions. The SM predictions [7] are shown for each σ_i .

	Best fit value (pb)	SM prediction (pb)
σ_{ggF}	$47.8^{+9.8}_{-9.4}$	44.5 ± 2.3
σ_{VBF}	$7.9^{+2.8}_{-2.4}$	3.52 ± 0.07
σ_{VHhad}	$-2.5^{+2.9}_{-2.6}$	1.36 ± 0.03
σ_{VHlep}	$0.32^{+1.07}_{-0.79}$	0.64 ± 0.02
σ_{top}	$-0.11^{+0.67}_{-0.54}$	0.60 ± 0.06

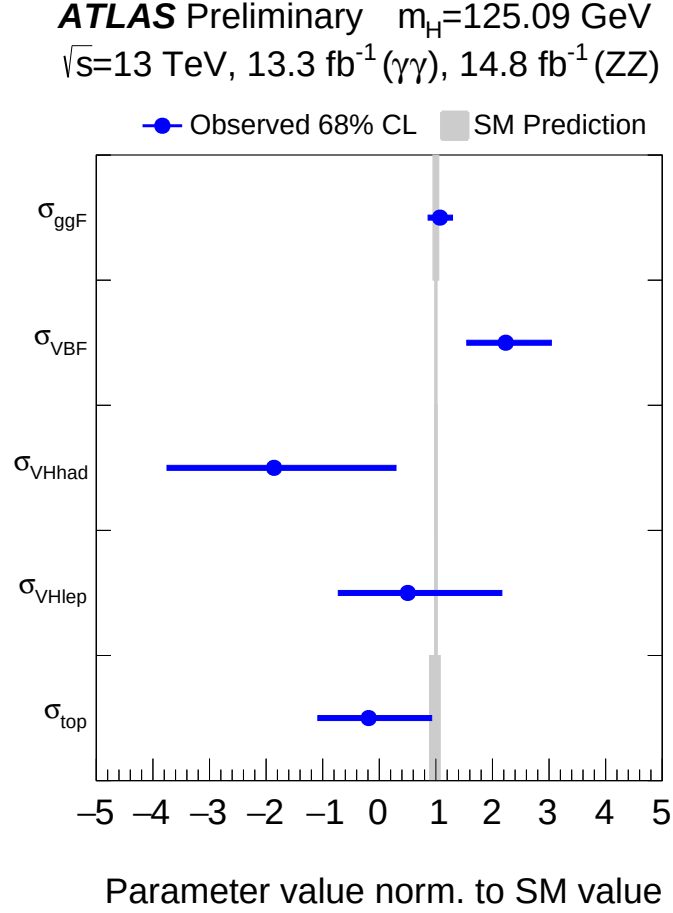


Figure 4: Cross sections for ggF , VBF , $VHhad$, $VHlep$ and top measured with the assumption of SM branching fractions. The fit results are normalised to the SM predictions for the various parameters and the grey bands indicate the theoretical uncertainties in these predictions. The blue error bars show the full uncertainty, including experimental uncertainties and theoretical uncertainties that impact the measurements.

4.3 Parameterisation using ratios of cross sections and of branching fractions

The third model provides measurements of ratios of cross sections and of branching fractions extracted from a combined fit to the data by normalising the production cross section for process i to ggF and the branching ratio for final state f to B^{ZZ} . The product of the cross section and the branching fraction $(\sigma \cdot B)_i^f$ can then be expressed using the ratios as:

$$(\sigma \cdot B)_i^f = (\sigma \cdot B)_{ggF}^{ZZ} \cdot \left(\frac{\sigma_i}{\sigma_{ggF}} \right) \cdot \left(\frac{B^f}{B^{ZZ}} \right), \quad (2)$$

where the σ_i are the cross sections considered in Section 4.2. With the present data sample and the decay channels taken into account, the combined analysis is only sensitive to $(\sigma \cdot B)_{\text{ggF}}^{\text{ZZ}}$, $\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$ and $B^{\gamma\gamma}/B^{\text{ZZ}}$. In the combined fit, the remaining ratios between cross sections and ggF are profiled.

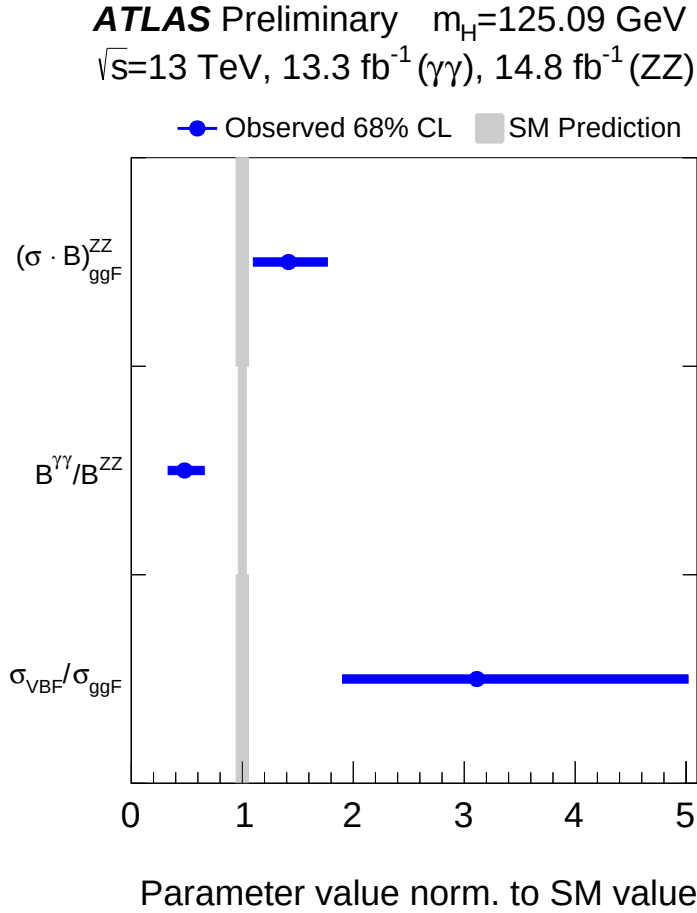


Figure 5: Measurement of $(\sigma \cdot B)_{\text{ggF}}^{\text{ZZ}}$, $\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$ and $B^{\gamma\gamma}/B^{\text{ZZ}}$. The fit results are normalised to the SM predictions for the various parameters and the grey bands indicate the theoretical uncertainties in these predictions. The remaining ratios between production cross sections and ggF are profiled in the combined fit. The blue error bars show the full uncertainty, including experimental uncertainties and theoretical uncertainties that impact the measurements.

Figure 5 shows the measurement of $(\sigma \cdot B)_{\text{ggF}}^{\text{ZZ}}$, $\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$ and $B^{\gamma\gamma}/B^{\text{ZZ}}$ compared to their SM expectation. The fit results displayed in Figure 5 are normalised to the SM predictions for the various parameters and the grey bands indicate the theoretical uncertainties in these predictions.

The compatibility between the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}} = 5\%$.

Evidence for the the vector-boson fusion production process is established at $\sqrt{s} = 13 \text{ TeV}$, with a local

significance of 4.0σ (1.9σ expected), based on the value of $-2\ln\Lambda(\sigma_{\text{VBF}}/\sigma_{\text{ggF}} = 0)$ and assuming asymptotic distribution of the test statistic.

Table 7: Best-fit values of the cross section $(\sigma \cdot \text{B})_{\text{ggF}}^{\text{ZZ}}$ and of the ratios $\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$ and $\text{B}^{\gamma\gamma}/\text{B}^{\text{ZZ}}$. The remaining ratios between production cross sections and ggF are profiled in the combined fit. The SM predictions [7] are shown in the last column.

Parameter	Best-fit value	SM prediction
$(\sigma \cdot \text{B})_{\text{ggF}}^{\text{ZZ}}$ (pb)	$1.67^{+0.41}_{-0.37}$	1.18 ± 0.07
$\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$	$0.25^{+0.15}_{-0.10}$	0.079 ± 0.004
$\text{B}^{\gamma\gamma}/\text{B}^{\text{ZZ}}$	$0.041^{+0.015}_{-0.013}$	0.086 ± 0.003

5 Signal strength measurements

The global signal strength μ is determined, following the measurements performed at $\sqrt{s} = 7$ and 8 TeV [3]. It is a single parameter, defined as the ratio of the observed yield and its SM expectation

$$\mu = \frac{\sigma \times \text{B}}{(\sigma \times \text{B})^{\text{SM}}}, \quad (3)$$

and is a single scaling factor for all production processes and decay modes, after extrapolation to the full phase space (including $|y_H| \geq 2.5$). It depends on the SM predictions for each production mode cross section and decay branching ratio, and the uncertainties on these predictions are folded into the measurement as described in Section 3.

Higgs boson production is observed in the analysed dataset with a local significance of about 10σ (8.6σ expected), based on the value of $-2\ln\Lambda(\mu = 0)$ and assuming asymptotic distribution of the test statistic. The global signal strength is measured to be $\mu = 1.13^{+0.18}_{-0.17}$. The compatibility between the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}} = 43\%$.

6 Combination of total cross sections

The measurements of the total cross section are based on the measured inclusive signal yields, and no attempt is made to disentangle the different Higgs boson production modes. The event yields measured in $H \rightarrow \gamma\gamma$ [2] and $H \rightarrow \text{ZZ}^* \rightarrow 4\ell$ [1] decays are corrected for detector effects, fiducial acceptances, and branching ratios. The corrections are derived assuming that the cross-section ratios between the different production modes follow the SM prediction. Uncertainties are assigned on this assumption by allowing for variations consistent with Ref. [3]. The combination of the two decay channels is performed using the statistical framework presented in Section 3.

Results are presented for centre-of-mass energies of 7, 8, and 13 TeV, corresponding to integrated luminosities of 4.5 fb^{-1} , 20.3 fb^{-1} and 13.3 fb^{-1} ($H \rightarrow \gamma\gamma$) – 14.8 fb^{-1} ($H \rightarrow \text{ZZ}^* \rightarrow 4\ell$), respectively. The

measurements at 7 and 8 TeV are taken from Ref. [63]. The measured cross sections probe the properties of the Higgs boson and can be compared to state-of-the-art theoretical calculations at the three different centre-of-mass energies.

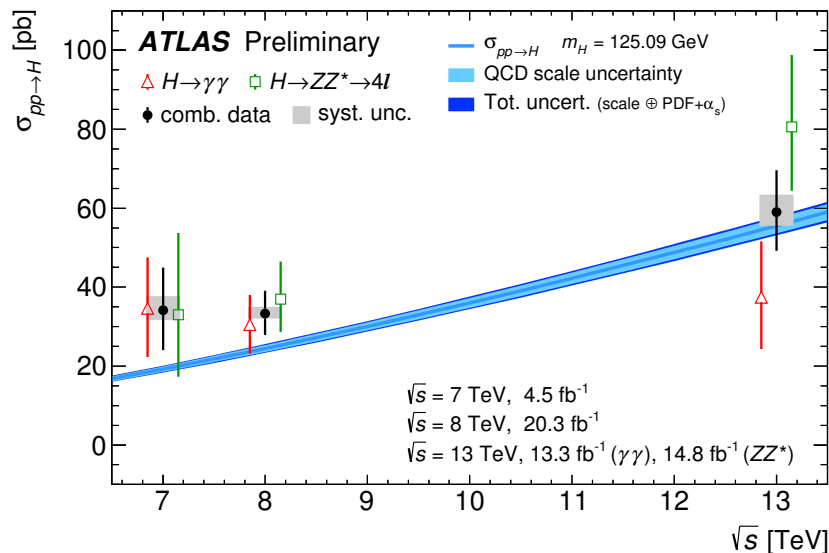


Figure 6: Total $pp \rightarrow H + X$ cross sections measured at different centre-of-mass energies compared to Standard Model predictions up to N^3LO in QCD. The red triangles show the measurements from the $H \rightarrow \gamma\gamma$ channel, the green rectangles show the measurements from the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel, and the black dots show the combinations of these two channels. The grey bands on the combined measurements represent the systematic uncertainty, while the black lines are the total uncertainty. The SM predictions (for a Higgs boson mass of 125.09 GeV [9]) are shown as a smooth curve, which is obtained by applying a third-order polynomial fit to the values available in Ref. [7]. The light (dark) blue band shows the uncertainty from missing higher-order QCD corrections (total uncertainty). The theoretical uncertainties are partially correlated between different values of the centre-of-mass energy.

The total $pp \rightarrow H + X$ cross sections at centre-of-mass energies of 7, 8 and 13 TeV measured in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ are shown in Table 8 and Figure 6, along with their combination. For comparison, the SM predictions for the total cross section at the three centre-of-mass energies are given. To derive the breakdown of the uncertainties, the statistical uncertainties are obtained by fixing all nuisance parameters for the systematic uncertainties to their best-fit values and taking the quadratic difference with respect to the result of the fit where all parameters are allowed to vary. The systematic uncertainties are smaller than the statistical uncertainties for the measurements at all three center-of-mass energies. The results of the two decay channels are compatible within the quoted uncertainties, and no deviation from the SM predictions is observed.

7 Conclusions

Combined measurements based on Higgs boson production cross sections and branching ratios using proton-proton collision data produced by the LHC at $\sqrt{s} = 13 \text{ TeV}$ and recorded by the ATLAS detector

Table 8: Total $pp \rightarrow H + X$ cross sections measured using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decays, and their combination, for centre-of-mass energies of 7, 8 and 13 TeV. The SM predictions [7] are computed for a Higgs boson mass of 125.09 GeV [9].

Decay channel	Total cross section ($pp \rightarrow H + X$)		
	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	$\sqrt{s}=13$ TeV
$H \rightarrow \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \rightarrow ZZ^* \rightarrow 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

are presented. The analysis is based on the measurements performed in the individual $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ decay channels.

Higgs boson production is observed in the 13 TeV dataset with a local significance of about 10σ (8.6σ expected), and evidence for production via vector boson fusion is seen with a local significance of about 4σ (1.9σ expected).

Products of Higgs boson production cross sections and branching ratios are measured for a Higgs boson rapidity $|y_H| < 2.5$ for five sets of production processes, **ggF**, **VBF**, **VHhad**, **VHlep**, and **top**. In addition, production cross sections are measured by assuming the SM Higgs branching ratios to $\gamma\gamma$ and ZZ^* , and by concurrently determining the ratio of the branching ratios to $\gamma\gamma$ and ZZ^* .

The global signal strength, defined as the ratio of the observed total signal yield to the SM expectation, is measured to be $\mu = 1.13^{+0.18}_{-0.17}$.

The cross section of $pp \rightarrow H + X$ in the full phase space is determined from fiducial cross section measurements to be $59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb. Using also previous measurements at 7 and 8 TeV, the centre-of-mass dependence of the total Higgs production cross section is compared to theoretical predictions.

No significant deviation from the Standard Model predictions is observed.

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ATLAS CONF Note

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Measurements of the Higgs boson production cross section via Vector Boson Fusion and associated WH production in the $WW^* \rightarrow \ell\nu\ell\nu$ decay mode with the ATLAS detector at $\sqrt{s} = 13$ TeV

The ATLAS Collaboration

10th November 2016

Measurements of the Higgs boson production cross section via Vector Boson Fusion (VBF) and associated WH production using $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decays are presented. The analyses use events produced in proton-proton collisions collected with the ATLAS detector at the LHC in 2015 and 2016. The data correspond to an integrated luminosity of 5.8 fb^{-1} recorded at $\sqrt{s} = 13$ TeV. The total production cross sections are measured to be $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*} = 1.4^{+0.9}_{-0.7} \text{ pb}$ and $\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*} = 0.9^{+1.3}_{-1.2} \text{ pb}$. The ratios of the measured value to the expected value of the total production cross section times branching fraction for VBF and WH production, μ_{VBF} and μ_{WH} , correspond to $\mu_{\text{VBF}} = 1.7^{+1.1}_{-0.9}$ and $\mu_{WH} = 3.2^{+4.4}_{-4.2}$, assuming a Higgs boson mass of $m_H = 125 \text{ GeV}$. Since the measurements are statistically limited, 95% confidence-level upper limits on the cross section times branching fraction of 3.0 pb and 3.3 pb are set for VBF and WH production, respectively.

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1 Introduction

Since the observation of a new particle by the ATLAS [1] and CMS [2, 3] collaborations in the search for the Standard Model (SM) Higgs boson in 2012, the mass, spin, and CP of this new particle have been measured by both collaborations [4–6], establishing this new particle to be compatible with the SM Higgs boson. Measurements of the Higgs boson mass yield a value of $125.09 \pm 0.24 \text{ GeV}$ [4]. The strengths of its couplings to gauge bosons and fermions have also been explored [7]. In all cases the results are consistent with SM predictions within their precision.

Direct observations of the Higgs boson in individual decay channels as well as measurements of its cross sections in different production modes provide essential insight in the true nature of the Higgs boson and its comparison with the SM. One of the most sensitive decay channels is the final state in which this particle decays into a pair of W bosons and the W bosons decay leptonically, $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$, where ℓ denotes an electron or muon; τ leptons are not considered in this analysis, except through their leptonic decays.

This note focusses on the study of the VBF production of the SM Higgs boson and the associated WH production. In case of VBF, the Higgs boson is produced by the fusion of vector bosons radiated by the interacting quarks. In the associated production of WH , the Higgs boson is produced in the Higgs-strahlung process where a Higgs boson is radiated off a W boson. Other SM Higgs boson production modes are the gluon-gluon fusion production process (ggF) where two interacting gluons produce a Higgs boson predominantly through a top-quark loop, the associated production of a Higgs boson and a Z boson (ZH), and the associated production of a Higgs boson and a top-quark pair ($t\bar{t}H$). Studies of $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$ at $\sqrt{s} = 7 \text{ TeV}$ and 8 TeV with the ATLAS detector probed the couplings of the Higgs boson in ggF, VBF, and VH production modes [8, 9].

In this note, analyses of the VBF and WH production modes are performed at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$, using 5.8 fb^{-1} of proton-proton collision data collected with the ATLAS detector in 2015 and 2016. The VBF analysis selects events with two leptons and at least two jets. Due to the large Drell-Yan (DY) background $Z \rightarrow ee/\mu\mu$, only final states with opposite charge and different lepton flavours $e\mu/\mu e$ ¹ are taken into account in the VBF analysis. The WH analysis selects events with three leptons of a total electric charge of $\pm e$. The total cross section times branching fraction, $\sigma \cdot \mathcal{B}(H \rightarrow WW^*)$, and the signal strength μ , defined as the ratio of the measured signal cross section to the SM prediction, are extracted for the VBF and WH production modes. In both analyses the signal includes events with $W \rightarrow \tau \nu$ decays if the τ lepton decays subsequently to either $e \nu_e \nu_\tau$ or $\mu \nu_\mu \nu_\tau$.

In each production channel analysis (either VBF or WH), events from all other Higgs production mechanisms are treated as background. For these backgrounds, Standard Model cross sections, branching fractions, and acceptances for $m_H = 125 \text{ GeV}$ are assumed.

The document is organised as follows: Section 2 gives a brief description of the ATLAS detector, Section 3 summarises the simulated event samples used in these analyses, and Section 4 describes the selection criteria for final state objects. The event selection and background estimation for the VBF and WH analyses are summarised in Section 5, followed by a discussion of the evaluation of systematic uncertainties in Section 6. Finally, the results of each analysis are presented in Section 7, and the conclusion is given in Section 8.

¹ The lepton flavour ordering reflects the lepton p_T ordering. The first lepton has the higher p_T and is referred to as the leading lepton, whereas the second lepton correspondingly is referred to as the subleading lepton.

2 ATLAS detector

ATLAS [10] is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry² and close to 4π coverage in solid angle. ATLAS consists of an inner tracking detector (ID) surrounded by a thin 2 T superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroid magnets, each with eight coils.

The ID covers the pseudorapidity range $|\eta| < 2.5$ and consists of multiple layers of silicon pixel and microstrip detectors, and a straw-tube transition radiation tracker. Since the beginning of 2015, the pixel detector has an additional innermost layer positioned at a radial distance of 3.3 cm [11]. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) sampling calorimeters. The hadronic calorimeter consists of steel and scintillator tiles in the central region and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic measurements, respectively. The MS consists of separate trigger and high-precision tracking chambers that measure the deflection of muons in the magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region $|\eta| < 2.7$ with three stations of drift-tube layers, except for the forward region, $|\eta| > 2.4$, where the innermost station is equipped with cathode strip chambers. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel and thin gap chambers in the endcap regions. A two-level trigger system is used. The first-level trigger is hardware-based, using a subset of the detector information, and reduces the event rate to about 80 kHz. This is followed by a software-based trigger level, which reduces the rate further to about 1 kHz.

3 Signal and background modelling

The Monte Carlo (MC) generators used to model signal and background processes are listed in Table 1. For most processes, separate programs are used to generate the hard scattering process and to model the parton showering (PS), hadronisation, and the underlying event (UE). The CT10 parton distribution function (PDF) set [12] is used for the generation of the hard scattering process in PowHEG-Box v2 [13–15] and SHERPA v2.1.1 [16], while for MADGRAPH 5 (version 2.2.1 and 2.2.2) [17] the NNPDF23LO PDF set [18] is used. In case the PS is performed with PYTHIA 8 [19], the CTEQ6L1 PDF set [20] is used with the AZNLO [21] tune when interfaced to PowHEG-Box v2 and with the A14 [22] tune when interfaced to MADGRAPH 5. In connection with PYTHIA, EVTGEN 1.2.0 [23] is used for the modelling of the bottom and charm hadron decays. In the SHERPA generation the PS uses parameters described in Ref. [24].

In these analyses, the signal contributions considered include the VBF and WH production processes, while the ggF and the ZH production processes are considered as backgrounds. Contributions from $t\bar{t}H$ and $b\bar{b}H$ production are negligible due to their smaller cross sections and are therefore not considered. The VBF, VH and ggF production processes are modelled using PowHEG-Box v2+PYTHIA 8.186. For the VH samples, the MiNLO approach [25] is used. The Higgs boson mass set in the generation is 125 GeV, which is compatible with the measured value.

² ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y axis points upward. The pseudorapidity η is defined as $\eta = -\ln \tan(\theta/2)$, where the polar angle θ is measured with respect to the z -axis. The azimuthal angle ϕ is measured with respect to the x -axis.

Table 1: Monte Carlo generators used to model the signal and background processes with the corresponding product of the cross section (σ) and branching fraction ($\mathcal{B}$) for the Higgs production modes at $\sqrt{s} = 13\text{TeV}$. The uncertainties quoted include the uncertainties from QCD scale, PDF, α_S and branching fraction. The mass of the Higgs boson is set to $m_H = 125\text{GeV}$, and the $H \rightarrow WW^*$ decay is assumed. Precise MC generator versions are provided in the text.

Mode	MC generator	$\sigma \cdot \mathcal{B}$ (pb)	Background	MC generator
ggF	POWHEG [13–15]+PYTHIA 8 [19]	$10.38^{+0.58}_{-0.77}$	$q\bar{q}/g \rightarrow \ell\ell\ell\ell, \ell\nu\ell\ell, \ell\nu\ell\nu$	SHERPA [16]
VBF	POWHEG +PYTHIA 8	0.808 ± 0.021	$gg \rightarrow \ell\ell\ell\ell, \ell\nu\ell\nu$	SHERPA
WH	POWHEG +PYTHIA 8 (MiNLO [25])	0.293 ± 0.007	EW $\ell\ell\ell\ell, \ell\nu\ell\ell, \ell\nu\ell\nu$	SHERPA
ZH	POWHEG +PYTHIA 8 (MiNLO)	$0.189^{+0.008}_{-0.007}$	$q\bar{q}/g \rightarrow WW, Z^{(*)}Z^{(*)} \rightarrow \ell\nu\ell\nu$	POWHEG +PYTHIA 8
			$t\bar{t}, tW$	POWHEG +PYTHIA 6 [38]
			$t\bar{t}W/Z, tZ$	MADGRAPH 5 [17]
			$W\gamma, Z\gamma$	SHERPA
			Z+jets	MADGRAPH 5
			VBF $q\bar{q} \rightarrow (Z \rightarrow \tau\tau)q\bar{q}$	SHERPA
			WWW, WWZ, ZZW, ZZZ	SHERPA

The VBF signal cross section is computed with approximate next-to-next-to-leading order (NNLO) QCD corrections [26, 27] and full next-to-leading order (NLO) electroweak (EW) corrections [28–30], resulting in a cross section of $\sigma_{\text{VBF}}^{\text{tot}} = 3.782 \text{ pb}_{-0.3\%}^{+0.4\%}$ (QCD scale) $\pm 2.1\%$ (PDF + α_S). The cross sections of the associated VH production processes are calculated at NNLO QCD accuracy [31, 32] and NLO EW accuracy [33], yielding a cross section for WH production of $\sigma_{WH}^{\text{tot}} = 1.373 \text{ pb}_{-0.7\%}^{+0.5\%}$ (QCD scale) $\pm 1.9\%$ (PDF + α_S). The ggF signal cross section is computed at next-to-next-to-next-to-leading order accuracy in QCD [34]. NLO EW corrections are also applied [35, 36]. The branching fraction for the $H \rightarrow WW^*$ decay is calculated using HDECAY [37].

The diboson processes are major backgrounds in this analysis. SHERPA v2.1.1 is used to model the $q\bar{q}/g$ -initiated diboson processes and the loop-induced gg -initiated diboson processes. They are calculated for up to zero or one additional partons at NLO and up to three additional partons at LO accuracy in the matrix element and are merged with the parton shower using the ME+PS@NLO prescription [39]. EW diboson processes for the $\ell\ell\ell\ell, \ell\nu\ell\ell$ and $\ell\nu\ell\nu$ final states are generated with up to two partons in the matrix element at LO accuracy using SHERPA v2.1.1. In the VBF analysis POWHEG-Box v2+PYTHIA 8.210 is used to model the $q\bar{q}/g$ -initiated WW and $Z^{(*)}Z^{(*)} \rightarrow \ell\nu\ell\nu$ production. Here, the cross section of the $q\bar{q}/g \rightarrow WW$ process is corrected to NNLO accuracy [40] and the cross section of the $gg \rightarrow WW$ process to NLO accuracy [41].

The $t\bar{t}$ and the Wt production are generated with POWHEG-Box v2 interfaced to PYTHIA 6.428 [38] for parton showering, using the PERUGIA2012 [42] tune and the CTEQ6L1 PDF set in the showering. The predicted $t\bar{t}$ production cross section is calculated with the TOP++2.0 program to NNLO in perturbative QCD, including soft-gluon resummation to NNLL [43–50], and assuming a top-quark mass of 172.5 GeV. The $t\bar{t}W/Z$ and tZ processes are generated at LO using MADGRAPH 5 version 2.2.2 ($t\bar{t}W/Z$) and 2.2.1 (tZ) interfaced with PYTHIA 8.186 ($t\bar{t}W/Z$) and PYTHIA 6.428 (tZ). In the present analysis the “top-quark” background collectively refers to the $t\bar{t}$ and the Wt production in the VBF analysis, while in the WH analysis this category also includes the $t\bar{t}W/Z$ and tZ processes.

The $Z\gamma$ and $W\gamma$ backgrounds are modelled with SHERPA v2.1.1 using multi-leg LO accuracy for up to three extra partons [51]. The production of a Z boson in association with jets is modelled by MADGRAPH 5 version 2.2.2 at LO interfaced with PYTHIA 8.186. Here, the matrix element calculation is done using multi-leg LO accuracy for up to four additional partons. The overlap in events between the $Z\gamma$ and Z+jets

samples is removed by rejecting $Z\gamma$ events in the Z +jets samples. The Z boson production via the vector boson fusion process with $Z \rightarrow \tau\tau$ decay is modelled by SHERPA at LO. The W +jets process modelling in the VBF analysis is based on a data driven method described in Section 5.1, while it is assumed to be negligible in the WH analysis. The WH analysis includes the triboson background processes WWW , WWZ , ZZW , and ZZZ with up to six genuine leptons, which are modelled with SHERPA v2.1.1 at NLO accuracy. Double parton scattering processes are not included due to their assumed negligible effect.

The effect of multiple pp interactions in the same and neighbouring bunch crossings (pile-up) is included by overlaying minimum-bias interactions simulated with PYTHIA 8.186 using the MSTW2008LO PDF [52] and the A2 [53] set of tuned parameters on each generated signal and background interaction. The number of overlaid interactions is reweighted such that the distribution of the average number of interactions per pp bunch crossing in the simulation matches that observed in data (on average 14 (21) interactions per bunch crossing in 2015 (2016)). The generated samples are processed with a detector simulation based on GEANT 4 [54, 55], and the same ATLAS reconstruction software is used as for collision data. Additional corrections obtained from measurements in the data are applied to the simulation to account for differences between data and simulation in *e.g.* the reconstruction of leptons, photons and jets.

4 Object selection

Selected events are required to have at least one primary vertex consisting of at least two associated tracks, each with transverse momentum of $p_T > 400\text{MeV}$, as defined in Ref. [56]. If an event has more than one reconstructed primary vertex, the one with the largest track $\sum p_T^2$ is selected for subsequent analysis.

Electrons are reconstructed from clusters of energy deposits in the electromagnetic calorimeter that match to ID tracks, and are identified using criteria based on the calorimeter shower shape, the quality of the match between the track and the cluster, and the amount of transition radiation emitted in the ID, as described in Ref. [57]. For electrons with transverse energy $15\text{GeV} < E_T < 25\text{GeV}$, a likelihood-based selection [57] at the “tight” operating point is used for its improved background rejection. For $E_T > 25\text{GeV}$, the “medium” selection criteria are used for higher efficiency. Electrons are further required to have a pseudorapidity of $|\eta| < 2.47$, excluding $1.37 < |\eta| < 1.52$, which corresponds to the transition region between the barrel and the endcap electromagnetic calorimeters.

Muons are reconstructed by combining ID and MS tracks with consistent trajectories and curvatures. An overall fit of hits from the ID track, energy loss in the calorimeter and the hits of the track in the muon system is used to form muon candidates, as described in Ref. [58]. They are required to pass the “medium” [58] identification criteria, have $p_T > 15\text{GeV}$, and $|\eta| < 2.5$. Muons with $p_T < 25\text{GeV}$ are further required to pass “tight” identification criteria in the VBF analysis.

To ensure that the leptons originate from the primary vertex, extra requirements are imposed on the longitudinal and transverse impact parameters. Furthermore, the leptons must also be isolated from other objects in the event according to the “gradient” isolation criterion, which is p_T and η dependent and is based on the calorimeter and track information as described in Ref. [57, 58].

Jets are reconstructed from clusters of energy deposits in the calorimeter [59–61] using the anti- k_t algorithm with distance parameter $R = 0.4$ [62]. The four-momenta of jets are corrected for the effects of calorimeter non-compensation, signal losses due to noise threshold effects, energy lost in non-instrumental regions, and contributions from pile-up [63]. A residual correction from *in-situ* measure-

ments, exploiting the p_T balance in Z +jet, γ +jet, and dijet events, is applied to refine the jet calibration. To further suppress jets from pile-up, a multivariable tagger called “jet vertex tagger” (JVT) [63] is used for jets with $20\text{GeV} < p_T < 60\text{GeV}$ and $|\eta| < 2.4$. Jets are required to pass a JVT threshold which has 92% efficiency for signal jets. In addition, jets are discarded if they are within a cone of size $\Delta R < 0.2$ of an electron candidate, or if they have fewer than three associated tracks and are within a cone of size $\Delta R < 0.2$ of a muon candidate. For the remaining jet-lepton pairings within $\Delta R < 0.4$, the lepton is rejected if the jet passes the JVT requirement.

To categorise events with respect to the jet multiplicity, N_{jet} , the jets are required to have $p_T > 25\text{GeV}$ if $|\eta| < 2.4$ and $p_T > 30\text{GeV}$ for $2.4 < |\eta| < 4.5$. The increased threshold in the forward region reduces the contribution from jets produced in pile-up collisions. Jets containing b -hadrons are identified using the MV2C10 b -tagging algorithm [64] with an efficiency of 85%, a jet p_T -threshold of 20GeV , and a jet pseudorapidity of $|\eta| < 2.5$. The expected rejection factors³ against jets originating from a light quark or gluon and jets containing c -hadrons are 33 and 3, respectively. The jets recognised as b -quark-induced are called b -jets in this note.

The two neutrinos from the W decays in signal events produce a momentum imbalance in the transverse plane. The missing transverse momentum, $\mathbf{E}_T^{\text{miss}}$, in each event is calculated from the negative vectorial sum of the transverse momenta of all calibrated selected objects, such as electrons, muons, and jets. Tracks compatible with the primary vertex and not matched to any of those objects are also included in the $\mathbf{E}_T^{\text{miss}}$ reconstruction [65, 66].

5 Event categorisation and background estimation

This section describes the categorisation of selected events and background estimation for the VBF and WH analyses. Generally, events are collected by a set of single-lepton triggers [67], with minimal p_T thresholds of 24GeV for electrons, and 20 (24) GeV for muons in 2015 (2016) data. At least one of the lepton candidates described in Section 4 is required to match a trigger object for the event to be selected.

The VBF analysis selects events with one electron and one muon, and at least two jets which satisfy the characteristic VBF event topology described below. The lepton with the higher p_T is identified as leading lepton and the other lepton as sub-leading lepton. The WH analysis focuses on signatures with the W boson decaying leptonically, and thus requires three identified leptons (electrons or muons) with total charge $\pm e$, in the presence of missing transverse momentum. In order to ensure that the two analyses are mutually orthogonal, events with a third lepton are vetoed in the VBF analysis.

The contributions of major background processes in the signal regions (SRs) are estimated either by measurements using dedicated data samples or by MC simulated samples where the predicted yields are normalised to data with a normalisation factor (NF). The NF is determined using a data sample, denoted as control region (CR), enriched in the corresponding type of background and is defined as the ratio of the measured background yield to the one predicted by the MC.

Both the VBF and WH analyses are based on the experience that was gained with the analyses at 7TeV and 8TeV [8, 9].

³ The rejection factor is defined as the inverse of the probability that a tagged b -jet originates from a c quark or a light-flavour quark.

5.1 The VBF analysis

The characteristic signature of a VBF event is the presence of two high-rapidity energetic jets with large separation in rapidity, and a reduced emission of coloured particles between the two jets. In order to fully exploit the correlations among various discriminating variables, a multivariate analysis with a boosted decision tree (BDT) [68–70] is developed.

The VBF analysis adopts a basic pre-selection. Events are required to contain exactly one electron and one muon with opposite electric charge. The leading lepton is required to have $p_T > 25\text{GeV}$ for electrons, and $p_T > 22$ (25)GeV for muons in the 2015 (2016) data. The sub-leading lepton is required to have $p_T > 15\text{GeV}$. Low-mass meson resonances and Drell-Yan events are removed by requiring a dilepton invariant mass, $m_{\ell\ell} > 10\text{GeV}$. A requirement of $N_{\text{jet}} \geq 2$ is applied to enhance the contribution from VBF signal events, and a b -jet veto is applied to reject top-quark background.

Eight discriminating variables are used to train the BDT, following closely the BDT used in Ref. [8]. These variables exploit either properties of the $H \rightarrow WW^*$ decay, which is the case for $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, and m_T , or properties of the VBF signature, which is the case for Δy_{jj} , m_{jj} , p_T^{tot} , $\sum_{\ell,j} m_{\ell j}$, and $\eta_\ell^{\text{centrality}}$. The spin-zero nature of the Higgs boson, together with the structure of the weak interaction in the W boson decays, preferentially produces leptons with a small azimuthal separation angle $\Delta\phi_{\ell\ell}$ and a small dilepton invariant mass $m_{\ell\ell}$. In addition, Higgs boson candidates peak in the distribution of the transverse mass m_T , which is defined as $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$ where $E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$. The rapidity gap of the two leading jets Δy_{jj} , and their invariant mass m_{jj} , tend to be larger for VBF signal events than for background events. The total transverse momentum p_T^{tot} , defined as the magnitude of the vectorial sum $\mathbf{p}_T^{\ell_1} + \mathbf{p}_T^{\ell_2} + \mathbf{E}_T^{\text{miss}} + \sum \mathbf{p}_T^{\text{jets}}$, is larger for backgrounds with significant soft gluon radiation. The sum of the invariant masses of all four possible lepton-jet pairs $\sum_{\ell,j} m_{\ell j}$ is larger for the VBF signal due to its event topology. The lepton η -centrality $\eta_\ell^{\text{centrality}}$ quantifies the positions of the leptons with respect to the leading jets in the η -plane and is defined as $\eta_\ell^{\text{centrality}} = |\eta_\ell - \frac{\sum \eta_{jj}}{2}| / \frac{\Delta\eta_{jj}}{2}$ where $\sum \eta_{jj} = \eta_{j1} + \eta_{j2}$ and $\Delta\eta_{jj} = |\eta_{j1} - \eta_{j2}|$. Small values of $\eta_\ell^{\text{centrality}}$ correspond to configurations where leptons are close to the centre of the di-jet system. Hence $\eta_\ell^{\text{centrality}}$ tends to have a smaller value for VBF signal events. The BDT is trained after the pre-selection cuts to improve the statistics of simulated samples used in the training. Events from ggF $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ production are included in the background processes when training the BDT. The variables with the highest ranking in the training, $m_{\ell\ell}$ and Δy_{jj} , are shown in Fig. 1 after all selection cuts have been applied.

After the BDT is trained, three additional cuts are applied to further reject events from background processes. The “outside-lepton-veto” (OLV) requires the leptons to reside within the rapidity gap spanned by the two leading jets, as preferred by VBF event topology. The “central-jet-veto” (CJV) rejects events with additional jets with $p_T > 20\text{GeV}$ in the rapidity gap of the two leading jets, suppressing backgrounds in which events tend to have more colour flow and jet activity, such as $t\bar{t}$. The $Z \rightarrow \tau\tau$ veto eliminates most of the $Z \rightarrow \tau\tau$ background by requiring the invariant mass of the $\tau\tau$ system ($m_{\tau\tau}$), calculated using the collinear approximation [71], to be away from the Z -boson resonance, specifically $m_{\tau\tau} < 66.2\text{GeV}$. Table 2 summarises the entire VBF selection.

The BDT score is defined in the range of -1 to 1, with signal-like events having a score close to one and background-like events a score close to -1. The bin widths for the statistical analysis are optimised for the expected significance while keeping each bin sufficiently populated. The chosen configuration is three bins with boundaries at $[-1, -0.8, 0.7, 1]$. The lowest bin contains the majority of data events

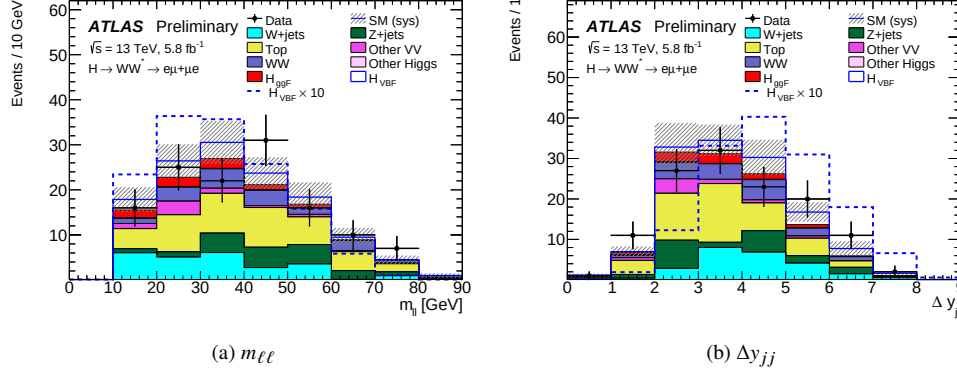


Figure 1: Distributions of $m_{\ell\ell}$ and Δy_{jj} in the VBF SR. The backgrounds are normalised as is described in Section 5.1.1. The dashed histogram represents the VBF signal scaled with a factor of 10. The hatched band (denoted as “SM (sys)”) includes MC statistical, experimental, and theory systematic uncertainties associated with the prediction of the signal and background processes.

	Signal region	$Z \rightarrow \tau\tau$ CR	Top-quark CR
Two isolated leptons ($\ell = e, \mu$) with opposite charge			
Preselection	$p_T^{\text{lead}} > 25\text{GeV}$ ($p_T^{\text{lead}} > 22\text{GeV}$ for muons in 2015), $p_T^{\text{sublead}} > 15\text{GeV}$	$m_{\ell\ell} > 10\text{GeV}$, $N_{\text{jet}} \geq 2$	
	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$
A BDT is trained at this level.			
Eight discriminant variables are used: $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_T , Δy_{jj} , m_{jj} , p_T^{tot} , $\sum_{\ell,j} m_{\ell j}$, and $\eta_{\ell}^{\text{centrality}}$			
Selection	$m_{\tau\tau} < 66.2\text{GeV}$	$ m_{\tau\tau} - m_Z < 25\text{GeV}$	–
	–	$m_{\ell\ell} < 80\text{GeV}$	–
	OLV applied, CJV applied, $\text{BDT} > -0.8$		
	SR1: $-0.8 < \text{BDT} \leq 0.7$	–	–
	SR2: $0.7 < \text{BDT} \leq 1$	–	–

Table 2: Event selection criteria used to define the signal and control regions in the VBF analysis. Definitions including the p_T thresholds for jet counting are given in the text.

(1490 events), is dominated by top-quark background, and has a very small signal-to-background ratio. It is therefore not used in the statistical analysis. The remaining BDT distribution in the signal region is shown in Figure 2. In the following the bin $[-0.8, 0.7]$ is denoted SR1 and the bin $[0.7, 1]$ is denoted SR2.

5.1.1 Background estimation

Several processes contribute to the background in the VBF analysis: $t\bar{t}$ and single top-quark production (denoted as “top-quark”), non-resonant WW , $Z \rightarrow \tau\tau$ production, W +jets production, ggF Higgs boson

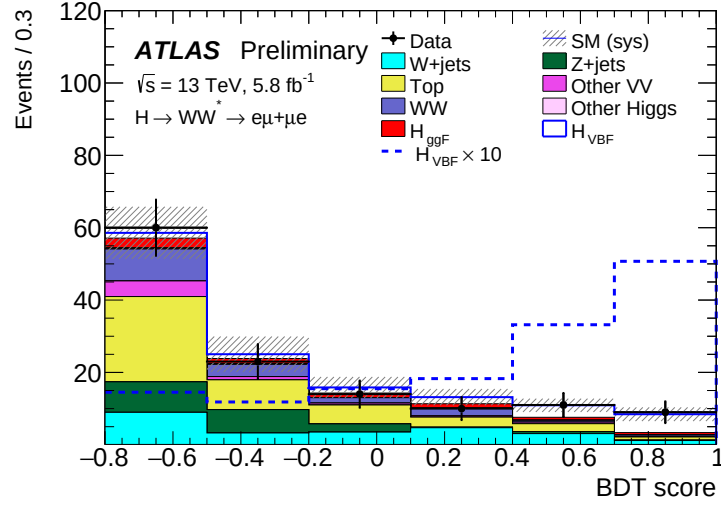


Figure 2: Distribution of the BDT output score in the VBF SR. The backgrounds are normalised as is described in Section 5.1.1. The dashed histogram represents the VBF signal scaled with a factor of 10. The hatched band (denoted as “SM (sys)”) includes MC statistical, experimental, and theory systematic uncertainties associated with the prediction of the signal and background processes.

production, and diboson production other than WW (denoted as “Other VV ”) including $W\gamma^*$, $W\gamma$, WZ , and ZZ events. The top-quark and the $Z \rightarrow \tau\tau$ background normalisations are estimated from data using control regions, that are fitted simultaneously together with the SR to extract the NFs. The definitions of these control regions are given below and summarised in Table 2.

The top-quark CR is defined to be the same as the SR, except that exactly one b -tagged jet is required to enrich the region in top-quarks, while keeping the flavour composition similar with respect to the SR. The purity of top-quark events in the CR is 92% and the resulting top-quark NF is $0.91 \pm 0.06(\text{stat})^{+0.44}_{-0.30}(\text{sys})$. The largest contributions to the systematic uncertainties on the NF arise from uncertainties on the MC modelling of $t\bar{t}$, on the energy scale and resolution of the jets, and on the b -tagging. The BDT score distribution in the top-quark CR is shown in Figure 3 (a).

The $Z \rightarrow \tau\tau$ CR is defined using the invariant mass of the $\tau\tau$ system ($m_{\tau\tau}$). The $Z \rightarrow \tau\tau$ CR requires events with $m_{\tau\tau}$ within 25GeV of m_Z , otherwise passing the full VBF selection as described in Section 5.1, and in addition requiring $m_{\ell\ell}$ less than 80GeV to suppress top contamination, resulting into a purity of $Z \rightarrow \tau\tau$ events of 61%. The resulting $Z \rightarrow \tau\tau$ NF is $0.87 \pm 0.20(\text{stat})^{+0.21}_{-0.18}(\text{sys})$ where the systematic uncertainties are dominated by the limited MC statistics and the uncertainties on the energy scale and resolution of the jets. The BDT score distribution of the $Z \rightarrow \tau\tau$ CR can be found in Figure 3 (b).

The background contribution due to mis-identified leptons, consisting mainly of W +jets events, is estimated using a control sample of events in which one of the two lepton candidates satisfies the identification and isolation criteria used to define the signal sample, and the other lepton, called anti-identified, fails to meet the nominal identification and isolation criteria but satisfies less restrictive ones. Events in this sample are otherwise required to satisfy all of the SR selection criteria. The contamination of

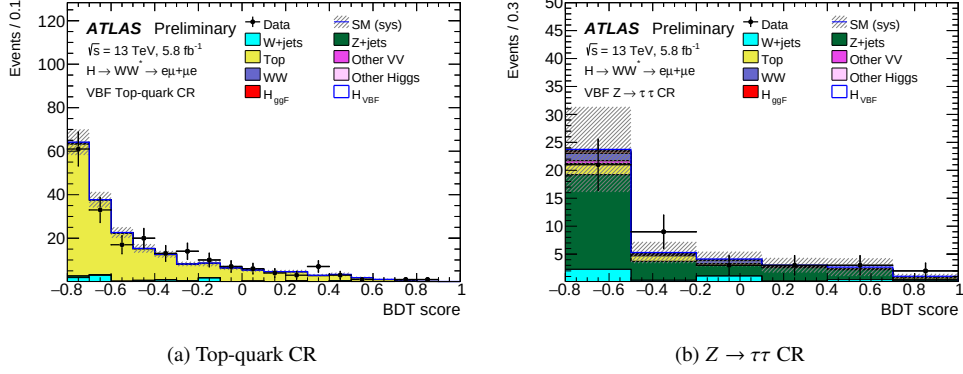


Figure 3: Observed distributions of BDT score in (a) the VBF top-quark CR and (b) the VBF $Z \rightarrow \tau\tau$ CR after the NF have been applied. The hatched band (denoted as “SM (sys)”) includes MC statistical, experimental, and theory systematic uncertainties associated with the prediction of the signal and background processes.

mis-identified leptons in the SR is determined by scaling the number of events in the control region, after subtracting contributions from prompt leptons, by an extrapolation factor, called the fake factor. The fake factors are measured in two di-jet data samples that are collected either using low- p_T single-lepton prescaled triggers or using the single-lepton triggers that define the signal region. In each of the data samples the fake factor is the ratio of the number of fully identified leptons to the number of anti-identified leptons, measured in bins of anti-identified lepton p_T and η . If the anti-identified lepton in the W +jets control sample matches the triggered lepton, the fake factors measured in the di-jet sample using signal triggers are applied. Otherwise, the fake factors measured in the prescaled data are used. This estimation method has been validated in MC-based closure tests. Uncertainties are applied on the difference in sample composition between the di-jet and the W +jets dataset, as described in Section 6.1.

The small background contributions from non-resonant diboson processes (WW , $W\gamma^*$, $W\gamma$, and WZ) are estimated from the predicted inclusive cross sections and MC acceptance. Due to the signal-like final state of non-resonant WW a CR with sufficient statistics and purity is not defined. The modelling of the MC prediction for all non-resonant diboson processes has been checked in a validation region and corresponding theoretical uncertainties are assigned as described in Section 6.

5.2 The WH analysis

The pre-selection of the WH analysis requires exactly three isolated leptons (electrons or muons) with $p_T > 15\text{GeV}$ of total charge $\pm e$. After these requirements, contributions from background processes that include more than one misidentified lepton, such as the W +jets production and the production of $b\bar{b}$ pairs, are negligible. The three leptons in an event are classified by identifying ℓ_0 as the lepton with unique charge, ℓ_1 as the lepton closer in $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ to ℓ_0 , and ℓ_2 as the remaining one.

The selection criteria described in this section have been optimised in order to reduce the most relevant background processes, such as $WZ/W\gamma^*$, $Z\gamma$, Z +jets, and top-quark processes.

To separate the sample populated by backgrounds with Z bosons, such as $WZ/W\gamma^*$, $ZZ^{(*)}$ with a misidentified lepton, and $Z\gamma$ with γ conversion, the analysis distinguishes events with at least one pair of same

Category	Z-dominated SR ≥ 1 SFOS pair	Z-depleted SR no SFOS pair
Preselection	Three isolated leptons ($p_T > 15$ GeV) total charge = ± 1 ≥ 1 lepton matches to the trigger	
Background Rejection	$N_{\text{jet}} \leq 1, N_{b\text{-jet}} = 0$ $E_T^{\text{miss}} > 50$ GeV $ m_{\ell^+\ell^-} - m_Z > 25$ GeV $m_{\ell^+\ell^-}^{\text{max}} < 200$ GeV $m_{\ell^+\ell^-}^{\text{min}} > 12$ GeV	$-$ $Z/\gamma^* \rightarrow ee$ veto $m_{\ell^+\ell^-}^{\text{min}} > 6$ GeV
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ topology	$\Delta R_{\ell_0\ell_1} < 2.0$	

Table 3: Event selection criteria used to define the signal categories in the WH analysis. The preselection and the cuts on $N_{\text{jet}}, N_{b\text{-jet}}, m_{\ell^+\ell^-}^{\text{max}}$ and $\Delta R_{\ell_0\ell_1}$ are common to both Z-dominated and Z-depleted categories.

flavour opposite sign (SFOS) leptons from events without any such pair. The sample with SFOS pairs contains 3/4 of the signal but suffers from the irreducible backgrounds containing Z bosons, while the sample without such pairs contains only 1/4 of the signal and is mainly affected by backgrounds that are reducible through stringent lepton identification criteria. Events with at least one pair of SFOS leptons are classified in the “Z-dominated” category, while events without any SFOS pairs are classified in the “Z-depleted” category.

The selection criteria for both categories are summarised in Table 3. Top-quark background is rejected by requiring fewer than two jets in each event and by applying a b -jet veto on jets with $p_T > 20$ GeV and $|\eta| < 2.4$. A selection criterion of $E_T^{\text{miss}} > 50$ GeV is applied in the Z-dominated category to reject background events without neutrinos in the final state. A “Z-mass veto” is applied in the Z-dominated category by requiring the invariant masses of all SFOS pairs to be 25 GeV away from the Z boson mass. To reduce the $WZ/W\gamma^*$ background, the largest opposite-sign di-lepton invariant mass is required to be less than 200 GeV. In the Z-depleted category, $WZ/W\gamma^*$ events also enter via a charge-flip of an electron when the Z/γ^* decays to an electron pair. Such events are suppressed by rejecting any same-sign electron pairs with a mass within 10 GeV from the Z boson mass if one or both electrons have $|\eta| > 0.8$, denoted as $Z/\gamma^* \rightarrow ee$ veto. Background events containing non-prompt leptons from heavy flavoured meson decays are rejected by requiring the smallest invariant opposite-sign di-lepton mass in the event to be larger than 12 GeV (6 GeV) in the Z-dominated (Z-depleted) category.

Finally the angular separation between ℓ_0 and ℓ_1 , $\Delta R_{\ell_0,\ell_1}$, is required to be smaller than 2 radians. This cut favours the Higgs boson decay topology with respect to that of $WZ/W\gamma^*$ events.

Figure 4 shows the $m_{\ell_0\ell_2}$ distribution, namely the invariant mass of opposite charge leptons, after the $N_{\text{jet}} \leq 1$ and $N_{b\text{-jet}} = 0$ requirements in the Z-dominated and the Z-depleted categories, respectively. The variable $m_{\ell_0\ell_2}$ is used in the event selection to reduce the background from Z bosons. The Z-dominated category is dominated by the diboson processes with Z bosons and Z+jets events with a jet faking a lepton. The Z-depleted category is dominated by the top background, with marginal contamination from the $WZ/W\gamma^*$ and Z+jets events.

In this analysis, $Z\gamma$ events are separated from Z+jets events according to their event kinematics, utilising

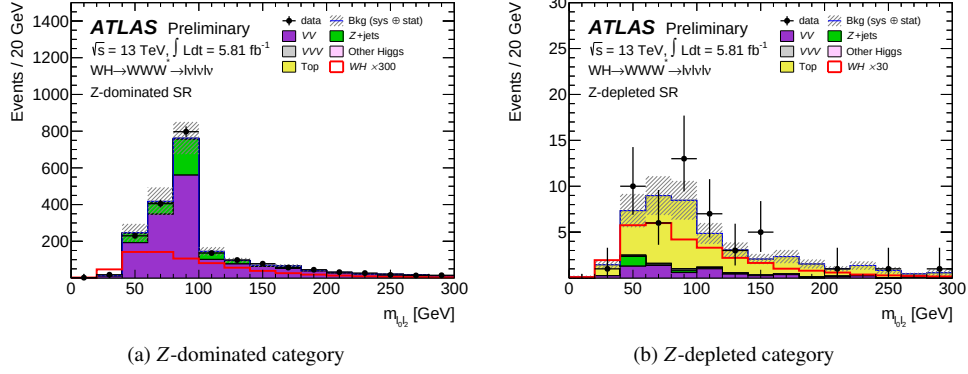


Figure 4: The $m_{\ell_0\ell_2}$ distribution in (a) the Z-dominated category and (b) the Z-depleted category after the $N_{\text{jet}} \leq 1$, $N_{b\text{-jet}} = 0$ requirements in the WH analysis. The VV category includes $WZ/W\gamma^*$, $ZZ^{(*)}$, WW , $Z\gamma$, $W\gamma$; the VVV category includes WWW , WWZ , WZZ ; the Other Higgs category includes ggF , VBF , ZH , $VH(\tau^+\tau^-)$. The NFs extracted by the likelihood fit are applied. The error band includes MC statistical, experimental, and theory systematic uncertainties associated with the prediction of the signal and background processes.

$m_{\ell\ell\ell}$, the invariant mass of the three-lepton system: events that satisfy the condition of $|m_{\ell\ell\ell} - m_Z| < 15\text{GeV}$ are categorised as $Z\gamma$ while events that fail the condition are categorised as $Z\text{+jets}$. In the WH analysis this definition of $Z\text{+jets}$ and $Z\gamma$ background is used consistently everywhere.

5.2.1 Background estimation

Important background processes for this analysis are $WZ/W\gamma^*$, $Z\gamma$, $Z\text{+jets}$, and top-quark processes. The normalisations of all these processes are estimated using control regions. The definitions of these CRs are briefly described below and summarised in Table 4. Except for the top-quark background where different CRs are defined for the Z-dominated and Z-depleted categories, all measured NFs are applied to both categories.

The $WZ/W\gamma^*$ and $Z\gamma$ CRs are defined by modifying one or a few selection criteria from the Z-dominated SR. In case of the $WZ/W\gamma^*$ CR the Z-mass veto is inverted, resulting into a $WZ/W\gamma^*$ purity of 92%. The resulting NF for the $WZ/W\gamma^*$ process is 1.24 ± 0.09 (stat) ± 0.07 (sys). The largest contributions to the systematic uncertainties on the $WZ/W\gamma^*$ NF arise from uncertainties on the energy scale of the jets and on the pile-up. The $Z\gamma$ CR is defined by removing the Z-mass veto and reversing the cut on E_T^{miss} , and by requiring $|m_{\ell\ell\ell} - m_Z| < 15\text{ GeV}$. Additionally, this CR is required to contain only $\mu\mu e$ and eee events. The purity of the $Z\gamma$ CR is 83% and the extracted $Z\gamma$ NF is 0.83 ± 0.08 (stat) ± 0.20 (sys).

Events entering the CRs that target backgrounds with one fake lepton, i.e. $Z\text{+jets}$ and top-quark, are required to have one lepton without any isolation requirement. This requirement significantly increases the statistics and purity in these CRs, without significantly changing the fake lepton composition in the relevant SRs.

The $Z\text{+jets}$ CRs are defined by reversing the E_T^{miss} cut and the Z-mass veto from the definition of the Z-dominated SR, as well as requiring $|m_{\ell\ell\ell} - m_Z| \geq 15\text{GeV}$. Since the normalisation of the $Z\text{+jets}$ background is expected to be different when the additional fake lepton is identified as an electron or a

Table 4: Event selection criteria used to define the control regions in the WH analysis given with respect to the cuts of the corresponding reference SR.

CR	Process	Reference SR	Changes w.r.t. reference SR
CRa	$WZ/W\gamma^*$	Z-dominated	≥ 1 SFOS pair with $ m_{\ell\ell} - m_Z < 25$ GeV
CRb	$Z\gamma$	Z-dominated	no Z-mass veto $ m_{\ell\ell\ell} - m_Z < 15$ GeV $E_T^{\text{miss}} < 50$ GeV only $eee, \mu\mu e$
CRc	Z+jets	Z-dominated	≥ 1 SFOS pair with $ m_{\ell\ell} - m_Z < 25$ GeV $E_T^{\text{miss}} < 50$ GeV $ m_{\ell\ell\ell} - m_Z > 15$ GeV one lepton without an isolation requirement (NFs are derived for e -fake sample and μ -fake sample separately)
CRd	Top quark	Z-dominated	no $m_{\ell^+\ell^-}^{\text{max}}$ and $\Delta R_{\ell_0\ell_1}$ cuts at least 1 jet one b -jet one lepton without an isolation requirement
CRe	Top quark	Z-depleted	no $m_{\ell^+\ell^-}^{\text{max}}$ and $\Delta R_{\ell_0\ell_1}$ cuts at least 1 jet one b -jet one lepton without an isolation requirement

muon, two distinct NFs are derived from the CR: one for events with the flavour combinations $\mu\mu e + eee$ (e -fake) and the other for $\mu\mu\mu + ee\mu$ (μ -fake). The purity in the e -fake (μ -fake) sample is 58% (55%). The obtained Z+jets NFs are $0.69 \pm 0.07(\text{stat}) \pm 0.14$ (sys) for the e -fake sample, and $0.70 \pm 0.07(\text{stat}) \pm 0.13$ (sys) for the μ -fake sample.

Two top-quark CRs are defined with respect to the Z-dominated and Z-depleted SRs. This is done to take into account the differences in the top-quark contributions entering each category, which could possibly be introduced by the different threshold of the E_T^{miss} selection. The top-quark background is the dominant background in the Z-depleted SRs. Events in the top-quark CRs are required to have at least one jet and exactly one b -jet. In addition, the selection criteria on the largest and smallest invariant mass of opposite sign leptons, and $\Delta R_{\ell_0\ell_1}$ are removed. The purity of the top-quark CR is 98% (99%) in the Z-dominated (Z-depleted) category. The top NF is $0.97 \pm 0.06(\text{stat}) \pm 0.04$ (sys) in the Z-dominated category, and $0.89 \pm 0.06(\text{stat}) \pm 0.04$ (sys) in the Z-depleted category. The largest contribution to the systematic uncertainties on the top NF arises from the b -tagging uncertainty. In addition to the background processes mentioned above, triboson production, in particular $WWW^{(*)}$, represents an irreducible background. The contribution of this process in the SRs is compatible with the WH signal. Due to the low cross-section for this process it is difficult to define a control region which would be statistically meaningful, therefore the MC prediction is taken for this process.

Figure 5 shows the $m_{\ell_0\ell_2}$ distribution in the most important CRs in the Z-dominated and Z-depleted categories, i.e. the $WZ/W\gamma^*$ CR and the Z-depleted Top CR, with the normalisation factors applied. Good agreement of the modeling prediction with the measured data is observed.

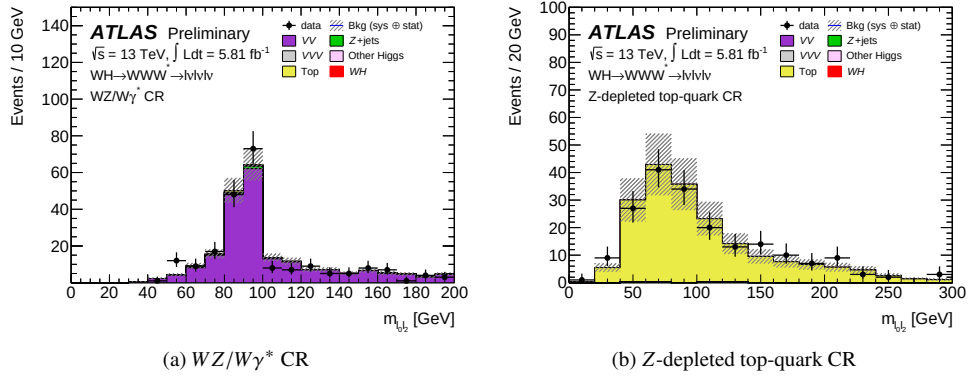


Figure 5: The $m_{\ell_0\ell_2}$ distribution in (a) the $WZ/W\gamma^*$ CR and (b) the Z-depleted top-quark CR. The VV category includes $WZ/W\gamma^*$, $ZZ^{(*)}$, WW , $Z\gamma$, $W\gamma$; the VVV category includes WWW , WWZ , WZZ ; the Other Higgs category includes ggF , VBF , ZH , $VH(\tau^+\tau^-)$. The NFs extracted by the likelihood fit are applied. The error band includes MC statistical, experimental, and theory systematic uncertainties associated with the prediction of the signal and background processes.

6 Systematic uncertainties

The systematic uncertainties on the measured signal strength can be grouped into two categories: experimental and theoretical uncertainties. Experimental uncertainties include uncertainties on the selection and reconstruction efficiencies and on the calibration of physics objects, such as the jet energy scale and resolution, as well as uncertainties on the procedure used to derive the data-driven background estimations. Theoretical uncertainties include uncertainties on the modelling of signal and background processes, such as the choice of the QCD renormalisation and factorisation scales, the PDF model used, the estimation of the underlying event properties, and the way hadronization and showering are modelled.

In this section the sources of systematic uncertainties are discussed. The determination of the impact of each uncertainty on the results is described in Section 7. The leading systematic uncertainties in the measurements of the coupling strength and cross section are summarised in Table 5 for the VBF and in Table 6 for the WH analysis.

6.1 Experimental uncertainties

To estimate the uncertainties on lepton reconstruction, identification, momentum/energy scale and resolution, and isolation criteria, $J/\psi \rightarrow \ell^+\ell^-$ and $Z \rightarrow \ell^+\ell^-$ decays in data and simulation are exploited [57, 58]. In particular, muon momentum resolution and scale calibrations are derived from a template fit that compares the invariant di-muon mass evaluated in $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ candidate events in data and

MC. The corresponding uncertainties are computed from variations of several fit parameters, following the procedure described in Ref. [72].

The jet energy scale, resolution, and their uncertainties are derived by combining information from simulation, test-beam data, and *in-situ* measurements [59, 73, 74]. The jet energy scale uncertainty is 1% - 5.5% depending on the jet p_T and η . Additional contributions from the jet flavour composition, η -intercalibration, single particle response, punch-through, calorimeter response to different jet flavours, and pileup are taken into account. Since the analysis makes use of b -tagging, uncertainties on the b - and c -tagging efficiencies and mistag rate [64] are also taken into account.

All uncertainties on energy scales and resolution are propagated to the missing transverse momentum. In addition, the uncertainties on E_T^{miss} relative to the soft term have been estimated using different MC generators [73], based on the analysis of $Z \rightarrow \mu\mu$ events.

In the VBF analysis, a method is developed for the estimation of the background from mis-identified leptons, as described in Section 5.1.1, where a di-jet data sample is used to measure the fake factor of mis-identified leptons. The fake factor is then applied to a W +jets control sample. To account for the difference in jet flavour composition between the W +jets sample and the di-jet sample, a data sample enriched with Z +jets is selected, which has a sample composition close to W +jets but has limited statistical precision. The envelope of differences between the fake factors measured from the di-jet and the Z +jets samples is assigned as an uncertainty. In addition, a systematic uncertainty estimated from MC is assigned to cover the sample composition difference between W +jets and Z +jets. Other uncertainties associated with the method, including those from subtraction of electroweak processes and statistical uncertainties of the fake factors, are also taken into account.

In the WH analysis a systematic uncertainty is assigned on the the Z +jets e -fake NF to account for the difference in the composition of the flavour of the faking leptons between the SRs and the Z +jets e -fake CR, which is caused by the different definitions of the lepton isolation between the two regions. An uncertainty of 18% is taken as the envelope of the fluctuations of the NF observed when the lepton isolation definition is varied.

The preliminary uncertainty on the combined 2015+2016 integrated luminosity is 2.0%. It is derived following a methodology similar to that detailed in Ref. [75] from a preliminary calibration of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016. The uncertainties on the individual luminosity values for 2015 and 2016 are combined as uncorrelated. An additional uncertainty is assigned on the modelling of the pile-up events. The simulated samples are reweighted so that the distribution of the number of pile-up collisions matches the one observed in data. The uncertainties on this reweighting factor originate from a measurement of the average number of pile-up events as a function of the average number of vertices yielding uncertainties of +6%/-14%.

6.2 Theoretical uncertainties

For each process, the theoretical uncertainties considered are QCD scale variations, parton shower / underlying event modelling (“PS/UE”) differences, PDF model uncertainties. PDF uncertainties are evaluated from the envelope of the CT10 68% confidence level eigenvectors added in quadrature with the maximal difference between the results obtained with CT10 and those obtained with either MSTW [52] or

NNPDF [18]. The uncertainties on the absolute expected yields of signal events in each SR are correlated to account for migrations between the signal regions. Other uncertainties specific to the process are considered for ggF production.

The nominal VBF, WH , and ggF MC samples are generated using PowHEG+PyTHIA 8. QCD scale uncertainties are evaluated by independently varying the values of the renormalisation μ_R and the factorisation scales μ_F , in PowHEG calculations. Both scales are independently multiplied by a factor of 2.0 or 0.5 relative to the nominal value $\mu_0 = m_H$. The PS/UE uncertainties are evaluated for VBF and ggF by comparing the nominal PowHEG prediction interfaced with PyTHIA 8 and HERWIG 7 [76, 77] using the UEEE5 tune [78]. Additionally, in case of VBF, an uncertainty is assigned to the choice of generator where PowHEG + PyTHIA 8 is compared to MG5_AMC+PyTHIA 8.

The evaluation of the ggF background in the VBF SR includes an uncertainty on the acceptance of the central-jet veto. The uncertainty is evaluated using the Stewart-Tackmann (ST) method [79], which treats the inclusive $H+2$ -jet and $H+3$ -jet cross sections as uncorrelated. The inclusive $H+2$ -jet and $H+3$ -jet cross sections and their uncertainties are determined at NLO and LO respectively, using MG5_AMC [17] resulting in an uncertainty of 28% for $H+2$ -jet and 32% for the $H+3$ -jet cross sections. QCD scale uncertainties are also evaluated in each measurement range of the BDT output, and are 3% in BDT SR1, and 32% in BDT SR2. In addition to the jet-veto uncertainty, also an uncertainty is assigned to the choice of generator where PowHEG + PyTHIA 8 is compared to MG5_AMC+PyTHIA 8 which has NLO accuracy for up to two additional jets.

Most of the background processes are normalised using data control regions, as described in the previous sections. The theoretical uncertainties in this case are on the extrapolation from the control to the signal regions, N_{SR}/N_{CR} , where N_{SR} and N_{CR} are the MC estimates in the SR and CR, respectively.

For the non-resonant WW background in the VBF channel, the QCD scale uncertainties are evaluated with SHERPA where non-resonant $WW+2$ jets production is included in the matrix element. The PS/UE uncertainty is evaluated by comparing the extrapolation factors for the nominal PowHEG+PyTHIA 8 sample to the predictions from PowHEG interfaced to HERWIG++ [76]. To evaluate an uncertainty due to the choice of the MC generator, a comparison of PowHEG + PyTHIA8 and SHERPA is performed and results in a 50% uncertainty, which is the largest source of theory uncertainties on non-resonant WW prediction in the VBF analysis. Part of this uncertainty is driven by a slight disagreement in the modelling of forward jets in SHERPA v2.1 with experimental data, while another part is due to the higher precision in the prediction of non-resonant $WW+2$ jets events compared to PowHEG.

In case of the top-quark background, variations are evaluated with PowHEG + PyTHIA 6 where simultaneously the renormalisation and factorisation scales, the PowHEG h_{damp} parameter regulating high- p_T radiation, and the corresponding UE tune are varied [80]. For the PS/UE uncertainty the prediction of PowHEG+PyTHIA 6 is compared with PowHEG+HERWIG++. An uncertainty on the choice of the generator is assigned by comparing PowHEG+HERWIG++ with MG5_AMC+HERWIG++. Additionally, the uncertainty on the treatment of interference between $t\bar{t}$ and Wt is assessed by comparing samples with two different schemes for removing common diagrams from the MC samples. The dominant source of uncertainty in both the VBF and WH analyses is the generator uncertainty of 35% in case of VBF and 21% in case of WH .

The theoretical uncertainties on the $WZ/W\gamma^*$ production constitute another major theoretical uncertainty in the WH analysis. The uncertainties due to the choice of QCD scales as well as the resummation scale are evaluated using SHERPA. Additional uncertainties from comparing the prediction from SHERPA

Table 5: List of the leading sources of uncertainties on the measured signal strength, μ_{VBF} , in the VBF analysis. All uncertainties are given in percent. Only the ten leading systematic uncertainties as well as the MC statistical uncertainty are shown. The total uncertainty stated in the last row is the total uncertainty estimated by the likelihood fit, thus including correlations among the nuisance parameters. The total systematic uncertainty stated in the next to last row is obtained subtracting in quadrature the statistical uncertainties from the total uncertainty.

Source	$\Delta\mu_{\text{VBF}}/\mu_{\text{VBF}} [\%]$
Statistical	+60 / -50
Fake factor, sample composition	+18 / -15
MC statistical	± 15
VBF generator	+14 / -5
WW generator	+11 / -7
QCD scale for ggF signal for $N_{\text{jet}} \geq 3$	+8 / -7
Jet energy resolution	+8 / -7
b -tagging	+8 / -6
Pile-up	+8 / -6
QCD scale for ggF signal for $N_{\text{jet}} \geq 2$	± 6
JES flavour composition	+6 / -4
WW renormalisation scale	± 5
Total systematic	+33 / -26
Total uncertainty	+70 / -50

with the prediction from POWHEG+PYTHIA 8 are assigned, resulting in an uncertainty of 4% and 8% in the Z-dominated and Z-depleted regions, respectively.

Uncertainties on WWW^* production are obtained by comparing the predictions by SHERPA and VBFNLO [30, 81, 82]. The difference in the normalisation, after applying the NLO k -factor to the VBFNLO prediction, is 20%, while the differences in the acceptance are 13% and 4% in the Z-dominated and Z-depleted regions, respectively. Since no CR is defined for this process, these uncertainties are directly applied to the estimated event yield.

Table 6: List of the leading sources of uncertainties on the measured signal strength, μ_{WH} , in the WH analysis. All uncertainties are given in percent. Only the ten leading systematic uncertainties as well as the MC statistical uncertainty are shown. The total uncertainty stated in the last row is the total uncertainty estimated by the likelihood fit, thus including correlations among the nuisance parameters. The total systematic uncertainty stated in the next to last row is obtained subtracting in quadrature the statistical uncertainties from the total uncertainty.

Source	$\Delta\mu_{WH}/\mu_{WH}$ [%]
Statistical	+120 / -100
MC statistical	+60 / -70
Pile-up	+22 / -26
Jet energy resolution	+22 / -23
Top-quark generator	+17 / -20
b -tagging	+10 / -11
Top-quark PS/UE	+7 / -8
JES flavour comp.	+8 / -5
JES η intercalibration	+7 / -6
$WZ/W\gamma^*$ generator	+7 / -6
Top-quark QCD scales	+6 / -7
$WZ/W\gamma^*$ resum. scale	± 5
Total systematic	+70 / -80
Total uncertainty	+140 / -130

7 Results

The extraction of the signal yields and the determination of the signal strength parameter μ individually in the VBF and in the WH analysis, are the result of a statistical analysis of the data samples described in Section 5.

The signal yields are extracted using the profile likelihood ratio method that consists in maximising a binned likelihood function $\mathcal{L}(\mathbf{n}|\mu;\theta)$. The signal extraction and the likelihood are described in full detail in Ref. [8] and briefly summarised in the following. The likelihood is the product of Poisson distributions for each signal and control region, where the mean values are chosen as the sum of the expected yields of signal and background contributions in each bin. The symbol $\mathbf{n}$ represents the observed events in each bin of all signal and control regions. The signal and background expectations are functions of μ and a set of nuisance parameters, θ . The signal strength μ multiplies the SM predicted signal event yield of each category, while background NFs, included as nuisance parameters, represent corrections for background sources normalised to data. Signal and background predictions depend on systematic uncertainties that are described by nuisance parameters. The normalisation factors are left free when maximising the likelihood function, while the constraints are chosen to be log-normal distributions.

The profile likelihood-ratio test statistic is used to test the background-only or background-and-signal hypotheses. It is defined as $q_\mu = -2 \ln(\mathcal{L}(\mu;\hat{\theta}_\mu)/\mathcal{L}(\hat{\mu};\hat{\theta}))$. The denominator does not depend on μ . The quantities $\hat{\mu}$ and $\hat{\theta}$ are the values of μ and θ , respectively, that maximise $\mathcal{L}$. The numerator depends on the values $\hat{\theta}_\mu$ that maximise $\mathcal{L}$ for a given value of μ . One can extract the statistical significance Z from p_0 by translating from the Gaussian tail probability. The p_0 value is computed from the test statistic q_μ , evaluated at $\mu = 0$, and is defined to be the probability to obtain a value of q_μ larger than the observed value under the background-only hypothesis. More details on the statistical methods used can be found in Ref. [83].

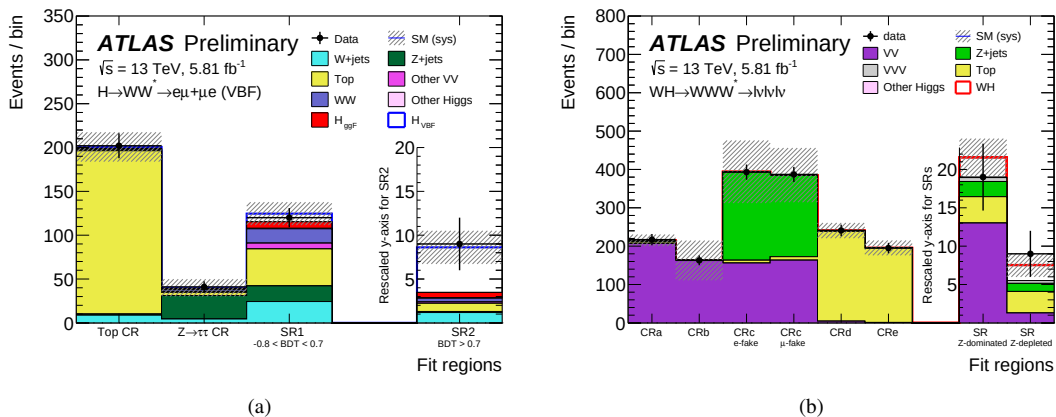


Figure 6: Fit regions of (a) the VBF analysis and (b) the WH analysis. The signal and background predictions are normalised to the results of the corresponding likelihood fit. The most sensitive SR categories, SR2 in case of VBF and Z-dominated, Z-depleted SRs in case of WH , are displayed with a different y axis to make the signal contribution more visible. The hatched band (denoted as “SM (sys)”) includes MC statistical, experimental, and theory systematic uncertainties associated with the prediction of the signal and background processes.

Table 7: MC and Data yields for the VBF analysis in the SRs and CRs. SR1 corresponds to $-0.8 < \text{BDT} < 0.7$ and SR2 to $0.7 < \text{BDT} < 1$. Normalisation factors derived from maximising the likelihood function are applied. The errors include MC statistical uncertainties on the yield, NF statistical uncertainties, detector systematic uncertainties and theory systematic uncertainties. The sum of all the contributions may differ from the total value due to rounding. In the determination of the uncertainties on the total background correlations have been taken into account.

Category	SR1	SR2	Top CR	Z+jets CR
VBF	9.3 ± 3.6	5.1 ± 1.8	1.7 ± 0.6	1.1 ± 0.4
Other Higgs	8.0 ± 4.0	0.7 ± 0.4	1.1 ± 0.2	1.2 ± 0.0
WW	13.0 ± 8.0	0.4 ± 0.2	1.4 ± 0.5	2.0 ± 0.9
Other VV	6.6 ± 2.6	0.2 ± 0.1	0.2 ± 0.0	0.8 ± 0.2
Top quark	42.2 ± 7.6	0.9 ± 0.7	186 ± 17	3.6 ± 1.6
W+jets	24.3 ± 9.2	1.2 ± 0.7	8.8 ± 4.0	4.4 ± 2.2
Z+jets	18.0 ± 9.9	0.1 ± 0.1	1.3 ± 1.0	27 ± 10
Total background	115 ± 13	3.5 ± 1.9	199 ± 17	38.8 ± 9.8
Observed	120	9	202	41

In the VBF analysis a simultaneous fit is performed to two ranges of the BDT output distribution in the signal region as well as to the yields of the top-quark CR and the $Z \rightarrow \tau\tau$ CR. An overview of the fit regions is given in Fig. 6(a) comparing the observed yields to the post-fit yields. Details on the yields in SR and CRs are given in Table 7. Anti-correlations between the uncertainty on the $Z \rightarrow \tau\tau$ normalisation, the top-quark normalisation, the W+jets background estimation, and the jet energy scale yield a reduction in uncertainty on the total estimated background. The observed (expected) significance in the presented measurement of VBF production is 1.9σ (1.2σ) assuming a Higgs boson mass of 125GeV.

In case of the WH analysis the simultaneous fit is performed to the yields of the Z-dominated and Z-depleted SRs as well as to the top-quark CRs, the $WZ/W\gamma^*$ CR, the $Z\gamma$ CR, and the Z+jets CRs. The measurement of WH production has an observed (expected) significance of 0.77σ (0.24σ). The post-fit yields are given in Tables 8 and 9, respectively for SRs and CRs, and the fit regions are illustrated in Fig. 6(b).

The VBF-specific result is extracted by considering the ggF and VH production modes as background, using the SM predicted cross-sections and treating their uncertainties as nuisance parameters. In the case of the WH analysis, the ggF, VBF, and ZH production modes are considered as background.

The fit results for the signal strength for the VBF and WH production modes are respectively:

$$\begin{aligned}\mu_{\text{VBF}} &= 1.7^{+1.0}_{-0.8}(\text{stat})^{+0.6}_{-0.4}(\text{sys}) \\ \mu_{WH} &= 3.2^{+3.7}_{-3.2}(\text{stat})^{+2.3}_{-2.7}(\text{sys})\end{aligned}$$

Since the contribution of the ggF production process to the background in the VBF analysis is not negligible, the impact of a beyond-SM contribution to ggF production on the μ_{VBF} result has been assessed. A scan of μ_{VBF} as a function of μ_{ggF} was performed changing μ_{ggF} up and down by one hundred percent, i.e. from the SM $\mu_{\text{ggF}} = 1$ to $\mu_{\text{ggF}} = 0$ or to $\mu_{\text{ggF}} = 2$. This results in a variation of μ_{VBF} of 25% which is well below the precision of the given measurement.

Table 8: MC and Data yields for the SRs of the WH analysis. Normalisation factors derived from maximising the likelihood function are applied. The errors include MC statistical uncertainties on the yield, NF statistical uncertainties, detector systematic uncertainties and theory systematic uncertainties. The sum of all the contributions may differ from the total value due to rounding. In the determination of the uncertainties on the total background correlations have been taken into account.

Category	Z-dominated	Z-depleted
WH	2.6 ± 1.0	2.0 ± 0.8
Other Higgs	0.1 ± 0.0	0.1 ± 0.0
VV	13.0 ± 1.6	1.3 ± 0.4
VVV	0.5 ± 0.1	0.4 ± 0.1
Top quark	3.4 ± 0.9	2.8 ± 0.8
Z+jets	2.0 ± 1.6	1.1 ± 1.1
Total background	19.1 ± 2.4	5.6 ± 1.5
Observed	19	9

Table 9: MC and Data yields for the CRs of the WH analysis. Normalisation factors derived from maximising the likelihood function are applied. The errors include MC statistical uncertainties on the yield, NF statistical uncertainties, detector systematic uncertainties and theory systematic uncertainties. The sum of all the contributions may differ from the total value due to rounding. In the determination of the uncertainties on the total background correlations have been taken into account.

Category	CRa	CRb	CRc e -fake	CRc μ -fake	CRd	CRe
WH	1.0 ± 0.4	0.3 ± 0.0	0.4 ± 0.1	0.5 ± 0.0	0.2 ± 0.1	0.1 ± 0.1
Other Higgs	0.8 ± 0.0	0.0 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
VV	207 ± 15	163 ± 53	156 ± 13	163 ± 14	4.4 ± 0.8	1.0 ± 0.5
VVV	0.9 ± 0.2	0.0 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.1	0.2 ± 0.0
Top quark	3.7 ± 0.6	0.4 ± 0.2	7.3 ± 0.9	9.1 ± 1.2	234 ± 19	194 ± 19
Z+jets	2.5 ± 1.2	0.0 ± 0.0	230 ± 83	212 ± 73	2 ± 0.7	0.1 ± 0.1
Total background	215 ± 15	163 ± 52	394 ± 82	385 ± 71	240 ± 20	195 ± 19
Observed	217	163	393	387	241	195

The measured signal strength, $\mu_{\text{VBF}}(\mu_{WH})$, can be used to evaluate the product $\sigma_{\text{VBF}(WH)} \cdot \mathcal{B}_{H \rightarrow WW^*}$ for the VBF (associated WH) production mode, respectively. The central value is the product of μ and the predicted cross section used to define it. The uncertainties are similarly scaled, except for the theoretical uncertainties related to the total predicted signal yield, which do not apply to this measurement. Since these uncertainties are small compared to leading uncertainties in both signal strength measurements, the cross sections are calculated to be:

$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*} = 1.4^{+0.8}_{-0.6}(\text{stat})^{+0.5}_{-0.4}(\text{sys}) \text{ pb}$$

$$\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*} = 0.9^{+1.1}_{-0.9}(\text{stat})^{+0.7}_{-0.8}(\text{sys}) \text{ pb}$$

The predicted cross section times branching fraction values are 0.808 ± 0.021 pb and 0.293 ± 0.007 pb for VBF and WH , respectively. Since the observed significances of the cross section results are below 3σ , upper limits at 95% confidence level are obtained for the cross section times branching fraction results. The limits are computed using the modified frequentist method CL_S [84]. They are 3.0 pb for VBF and 3.3 pb for associated WH production.

8 Conclusion

Data from $\sqrt{s} = 13$ TeV proton-proton collisions, corresponding to a total integrated luminosity of 5.8 fb^{-1} , have been used to measure the Higgs boson signal strength in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel and in the VBF and associated WH production modes. The observed (expected) signal significance at $m_H = 125.0$ GeV is 1.9σ (1.2σ) standard deviations for VBF and 0.77σ (0.24σ) for WH . The signal strength is determined as $\mu_{\text{VBF}} = 1.7^{+1.1}_{-0.9}$ and $\mu_{WH} = 3.2^{+4.4}_{-4.2}$ and the corresponding cross section times branching ratios are $\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*} = 1.4^{+0.9}_{-0.7}$ pb and $\sigma_{WH} \cdot \mathcal{B}_{H \rightarrow WW^*} = 0.9^{+1.3}_{-1.2}$ pb. Upper limits at 95% confidence level are 3.0 pb and 3.3 pb for VBF and WH production, respectively. All results are in agreement with the SM predictions.

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Appendix

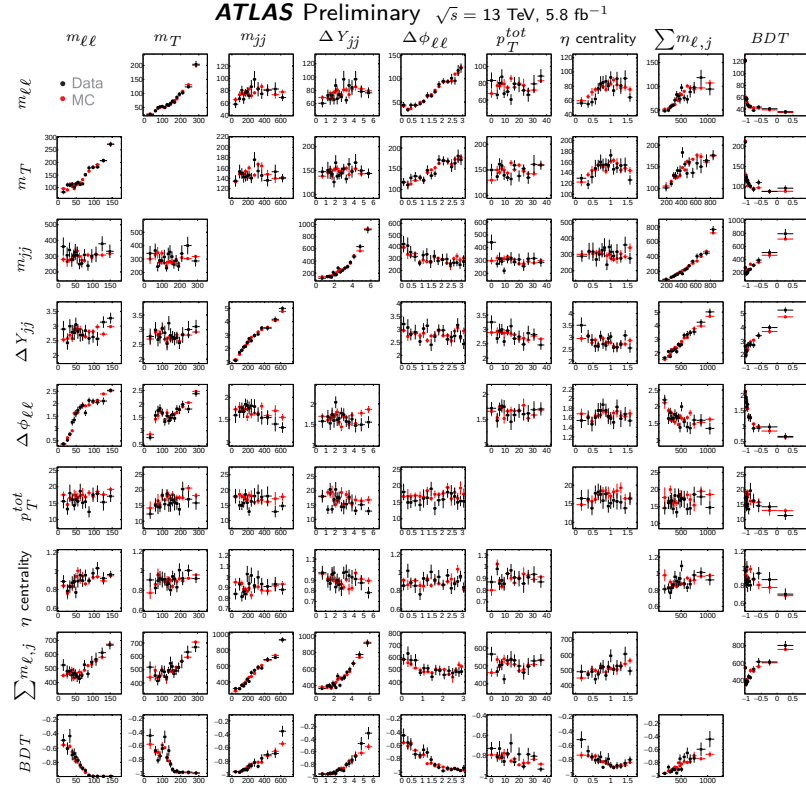


Figure 7: Correlation plots of BDT classification variables in the signal region of BDT ($-1 < BDT < 1$). For variable v_x and v_y in row x and column y , the distributions of $\langle v_x \rangle$ versus $\langle v_y \rangle$, and vice versa, are shown for each pair of training variable in the BDT as well as the correlation of each training variable with BDT. The black points show the data profiles, the red points show the profiles of the MC model, that includes all signal and background predictions. The uncertainties are statistical only.

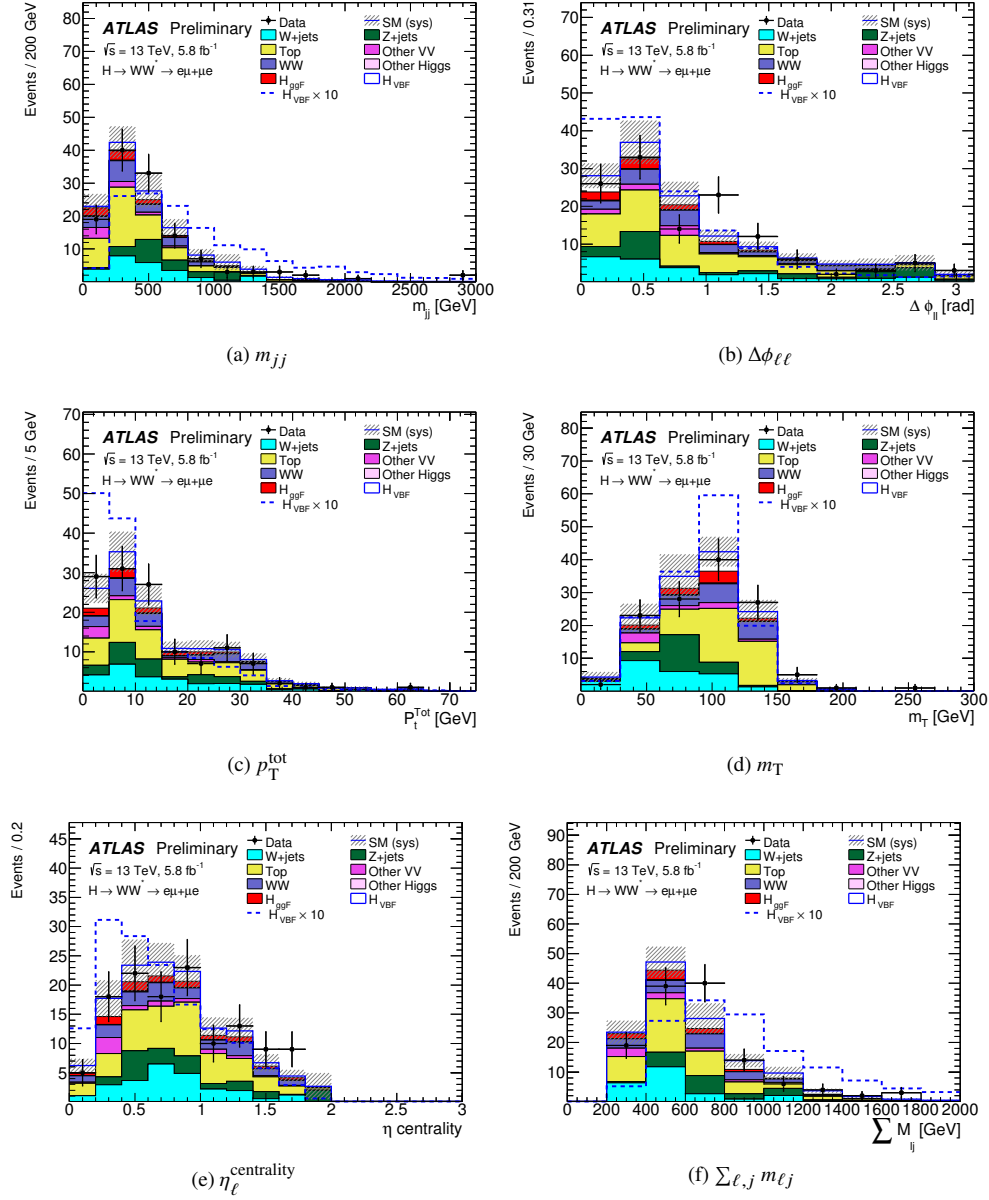


Figure 8: Distributions of the topological variables in the VBF SR in the 13 TeV data analysis. The m_{jj} and $\Delta\phi_{\ell\ell}$ (top row), p_T^{tot} and m_T (middle row); and $\eta_{\ell}^{\text{centrality}}$ and $\sum_{\ell,j} m_{\ell j}$ (bottom row) distributions are shown after the $\text{BDT} > -0.8$ requirement. The backgrounds are normalised as is described in Section 5.1.1. The dashed histogram represents the VBF signal scaled with a factor of 10 and the hatched band includes MC statistical and systematic uncertainties associated with the prediction.

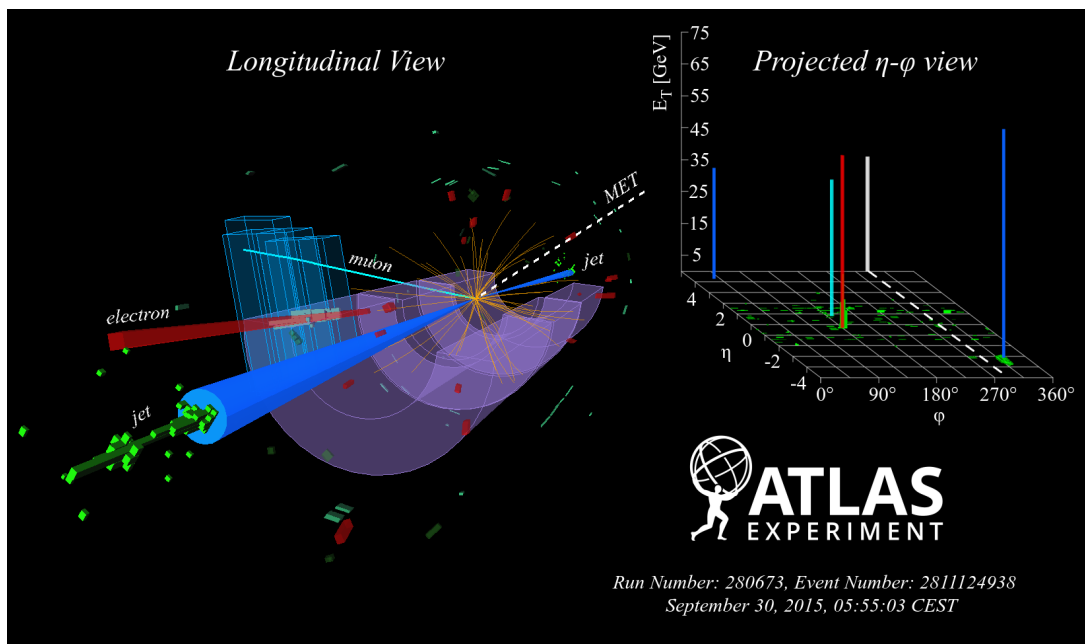


Figure 9: Event displays of a $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$ candidates in the VBF signal region with a BDT score of 0.9. The neutrinos are represented by missing transverse momentum (MET, dotted line) that point away from the $e\mu$ system. The event shows well-separated jets that are characteristic of VBF production and a small value of $\Delta\phi_{\ell\ell}$, which is characteristic of the signal.



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Measurement of the W^+W^- production cross section in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with the ATLAS experiment

The ATLAS Collaboration^{*}

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ABSTRACT

The production of opposite-charge W -boson pairs in proton–proton collisions at $\sqrt{s} = 13$ TeV is measured using data corresponding to 3.16 fb^{-1} of integrated luminosity collected by the ATLAS detector at the CERN Large Hadron Collider in 2015. Candidate W -boson pairs are selected by identifying their leptonic decays into an electron, a muon and neutrinos. Events with reconstructed jets are not included in the candidate event sample. The cross-section measurement is performed in a fiducial phase space close to the experimental acceptance and is compared to theoretical predictions. Agreement is found between the measurement and the most accurate calculations available.

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1. Introduction

The measurement of the production properties of opposite-charge W -boson pairs (denoted by WW in this Letter) is an important test of the Standard Model (SM) of particle physics. This process is sensitive to the strong interaction between quarks and gluons and probes the electroweak gauge structure of the SM.

Measurements of WW production were first conducted at LEP [1] using electron–positron collisions. Measurements in hadron collisions were first carried out at the Tevatron by the CDF [2,3] and DØ [4] Collaborations. At the Large Hadron Collider (LHC), the WW production cross sections have been measured in proton–proton collisions for centre-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV by the ATLAS [5,6] and CMS [7,8] Collaborations. In order to match the experimental precision and address discrepancies between data and theory reported in some of the 8 TeV results, significant progress has been made in theoretical calculations to include higher-order corrections in perturbative Quantum Chromodynamics (pQCD) [9–14]. The WW signal is composed of three leading sub-processes: $q\bar{q} \rightarrow WW$ production¹ (in the t - and s -channels), non-resonant $gg \rightarrow WW$ production, and resonant $gg \rightarrow H \rightarrow WW$ production (with both gg -initiated processes occurring through a quark loop). These sub-processes are known theoretically at different orders in the strong coupling constant α_s .

This Letter describes a measurement of WW production in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector using the data collected during the 2015 run. The cross sec-

tion is measured within a phase space close to the geometric and kinematic acceptance of the experimental analysis, i.e. a fiducial phase space, in the $WW \rightarrow e^\pm \nu \mu^\mp \nu$ (denoted in the following by $WW \rightarrow e\mu$) decay channel. In addition, the ratio of cross sections at 13 TeV and 8 TeV centre-of-mass energies in the respective fiducial phase spaces is presented. Both measurements are compared to the latest theoretical predictions.

2. The ATLAS detector

The ATLAS detector [15,16] is a multi-purpose particle detector with a cylindrical geometry.² It consists of layers of inner tracking detectors surrounded by a superconducting solenoid, calorimeters, and a muon spectrometer. The inner detector (ID) is situated inside a 2 T magnetic field generated by the solenoid and provides precision tracking for charged particles with pseudorapidity $|\eta| < 2.5$. The calorimeter covers the pseudorapidity range $|\eta| < 4.9$. Within $|\eta| < 2.47$ the finely segmented electromagnetic calorimeter identifies electromagnetic showers and measures their energy and position, providing electron identification together with the ID. The muon spectrometer (MS) surrounds the calorimeters and includes three large air-core toroidal superconducting magnets with eight

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¹ In this Letter, the notation $q\bar{q} \rightarrow WW$ is used to include both the $q\bar{q}$ and qg initial states for WW production.

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² The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal pp interaction point at the centre of the detector. The positive x -axis is defined by the direction from the interaction point towards the centre of the LHC ring, with the positive y -axis pointing upwards, while the beam direction is along the z -axis. Cylindrical coordinates (r, ϕ) are used in the transverse (x, y) plane, ϕ being the azimuthal angle around the beam direction. The pseudorapidity is defined in terms of the polar angle θ from the z -axis as $\eta = -\ln[\tan(\theta/2)]$. The distance in η - ϕ space between two objects is defined as $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Transverse energy is computed as $E_T = E \cdot \sin\theta$.

coils each, providing muon identification and measurement in the region $|\eta| < 2.7$ and triggering in the region $|\eta| < 2.4$. A two-level trigger system is used to select events in real time. It consists of a hardware-based first-level trigger and a software-based high-level trigger. The latter uses reconstruction software with algorithms similar to the offline versions.

3. Data and Monte Carlo samples

The analysis is based on data collected with the ATLAS detector during the 2015 data-taking period. Events with pp collisions at $\sqrt{s} = 13$ TeV and all relevant detector components functional have been used. This data sample corresponds to an integrated luminosity of $\mathcal{L} = 3.16 \text{ fb}^{-1}$.

Monte Carlo (MC) event generators are used to model signal and background processes. The WW , WZ , and ZZ diboson processes (where Z stands for Z/γ^*) with $q\bar{q}$ initial states are simulated at next-to-leading order (NLO) in pQCD with the POWHEG-BOX v2 event generator [17–21] using the CT10 NLO [22] parton distribution functions (PDFs). For the modelling of the parton shower and non-perturbative effects such as fragmentation and the underlying event, POWHEG-BOX v2 is interfaced to PYTHIA v8.210 [23] with the AZNLO [24] set of tuned parameters and the CTEQ6L1 [25] PDF. The invariant mass of the leptons originating from the Z boson or photon in the ZZ and WZ samples is required to satisfy $m_{\ell\ell} > 7$ GeV. A sample of WZ events generated with SHERPA v2.1.1 [26] with $m_{\ell\ell} > 0.45$ GeV is used to study systematic uncertainties. The cross sections given by the event generator are at NLO in QCD while the WW , WZ and ZZ samples are normalised using their respective inclusive next-to-next-to-leading order (NNLO) predicted cross sections [9,27–29]. The configuration of the POWHEG-BOX v2 event generator, as described above, reproduces the distribution predicted by NNLO calculations matched to resummation calculations up to next-to-next-to-leading logarithm (NNLL) [9,10] for the transverse momentum of the WW system (p_T^{WW}) in the range relevant to this analysis, so no further steps are taken to explicitly include resummation effects in the WW signal samples. The resonant $gg \rightarrow H \rightarrow WW$ signal contribution is simulated with the POWHEG-BOX v2 event generator [30] and normalised using the inclusive next-to-next-to-next-to-leading order (N³LO) predicted cross section [31]. The non-resonant $gg \rightarrow WW$ signal contribution is modelled with SHERPA v2.1.1 at leading order (LO) using OpenLoops with up to one additional parton in the final state [32] and normalised using the inclusive NLO predicted cross section [33].

The $Z(\rightarrow e\bar{e}/\mu\bar{\mu}/\tau\bar{\tau}) + \text{jets}$ production processes are simulated with the Madgraph5_aMC@NLO v2.2.2 [34] event generator interfaced to Pythia v8.186. The matrix elements for Z production with up to four associated partons are calculated at LO and the NNPDF2.3 LO PDF set [35] is used. The PHOTOS++ program version 3.52 [36] is used for QED emissions from electroweak vertices and charged leptons. Alternative samples of $Z(\rightarrow \tau\bar{\tau}) + \text{jets}$ are produced with different MC event generators for the estimation of systematic uncertainties in the modelling: POWHEG-BOX v2 with NLO matrix elements interfaced to PYTHIA v8.210, and SHERPA v2.2.0 with NLO matrix-element accuracy up to two associated partons and with LO accuracy for three and four associated partons. The $Z + \text{jets}$ events are normalised using the NNLO Z production cross section [37].

The SHERPA v2.1.1 event generator is used to model the $W\gamma$ and $Z\gamma$ processes with LO matrix element calculations for events with up to 3 partons in the final state matched to parton shower, using the CT10 NLO PDF set and with the γ transverse momentum greater than 10 GeV.

The POWHEG-BOX v2 event generator [38,39] with the CT10 NLO PDF is used for the generation of $t\bar{t}$ and single top quarks in the Wt channel. Parton shower, fragmentation, and the underlying event are simulated using PYTHIA v6.428 [40] with the CTEQ6L1 PDF and the Perugia 2012 [41] set of parameters. The top-quark mass is set to 172.5 GeV. Alternative samples are generated with different settings to assess the uncertainty in modelling top-quark events. For estimating the effect of parton shower and hadronisation modelling an alternative sample is generated with the POWHEG-BOX v2 event generator interfaced to HERWIG++ [42]. A comparison between this sample and a different one produced with Madgraph5_aMC@NLO interfaced to HERWIG++ is used to estimate the uncertainty associated to the matrix-element implementation and the matching to the parton showers. Separate alternative samples are also generated with POWHEG-BOX v2 interfaced to PYTHIA v6.428 with extra jet radiation emitted in the matrix element and in the parton shower. In addition, the modelling of the overlap at NLO between Wt and $t\bar{t}$ diagrams [43] is studied. The effect is assessed by generating Wt events with different schemes for overlap removal using the POWHEG-BOX v2 event generator interfaced to PYTHIA v6.428 for the simulation of parton showering and non-perturbative effects. These samples are simulated following the recommendations documented in Ref. [44]. The $t\bar{t}$ samples are normalised using the NNLO+NNLL soft-gluon resummation prediction [45], while the Wt samples are normalised using the NLO+NNLL prediction [46].

The EvtGen v1.2.0 [47] program is used for the properties of the bottom and charm hadron decays in all samples generated using the POWHEG-BOX v2 and Madgraph5_aMC@NLO v2.2.2 programs. The generated samples are passed through a simulation of the ATLAS detector based on GEANT4 [48,49]. They are overlaid with additional proton–proton interactions (pile-up) generated with PYTHIA v8.210 and the distribution of the average number of interactions per bunch crossing is reweighted to agree with the corresponding data distribution. The simulated events are reconstructed and analysed with the same algorithms as the data and are corrected with data-driven correction factors to account for differences between data and simulation in lepton and jet reconstruction and identification.

4. Event reconstruction and selection

The WW event candidates are selected by requiring exactly one electron and one muon of opposite charge in the event, and significant missing transverse momentum, as described below. Events with a same-flavour lepton pair are not used because they have larger background from the Drell–Yan process.

Candidate events are preselected by either a single-muon or single-electron trigger requiring transverse momentum $p_T > 20$ or 24 GeV respectively. The efficiency of the trigger for selecting WW events is approximately 99% for events that pass the offline selection.

Leptons are required to originate from the primary vertex, defined as the reconstructed vertex with the largest sum of the p_T^2 of the associated tracks. The longitudinal impact parameter of each lepton track, defined as the distance along the beam line between the track and the point of closest approach of the track to the primary vertex, multiplied by the sine of the track θ angle, is required to be less than 0.5 mm. Furthermore, the significance of the transverse impact parameter calculated with respect to the beam line, $|d_0/\sigma_{d_0}|$, is required to be less than 3.0 (5.0) for muons (electrons).

Electron candidates are reconstructed from the combination of a cluster of energy deposits in the electromagnetic calorimeter and a track in the ID [50]. Candidate electrons must satisfy the *Tight* quality definition described in Ref. [50]. Muon candidates are re-

Table 1

Lepton, jet, and event selection criteria for WW candidate events. In the table ℓ stands for e or μ . The definitions of identification and isolation are given in Refs. [50] and [51].

Selection requirement	Selection value
p_T^ℓ	> 25 GeV
η^ℓ	$ \eta^\ell < 2.47$ (excluding $1.37 < \eta^\ell < 1.52$), $ \eta^\mu < 2.4$
Lepton identification	Tight (electron), Medium (muon)
Lepton isolation	Gradient working point
Number of additional leptons ($p_T > 10$ GeV)	0
$m_{e\mu}$	> 10 GeV
Number of jets with $p_T > 25(30)$ GeV, $ \eta < 2.5(4.5)$	0
Number of b -tagged jets ($p_T > 20$ GeV, 85% op. point)	0
$E_{T, \text{Rel}}^{\text{miss}}$	> 15 GeV
p_T^{miss}	> 20 GeV

constructed by combining a track in the ID with a track in the MS [51]. The *Medium* criterion, as defined in Ref. [51], is applied to the combined tracks. The leptons are required to be isolated using information from ID tracks and calorimeter energy clusters in a cone around the lepton. The expected isolation efficiency for prompt leptons is at least 90% (99%) at a p_T of 25 (60) GeV using a so-called *gradient* working point [50,51].

Jet candidates are reconstructed within the calorimeter acceptance using the anti- k_t jet clustering algorithm [52] with a radius parameter of $R = 0.4$ which combines clusters of topologically-connected calorimeter cells [53]. The jet energy is calibrated by applying a p_T - and η -dependent correction derived from MC simulation with additional corrections based on data [54]. As part of the jet energy calibration a pile-up correction based on the concept of jet area is applied to the jet candidates [55]. The jet-vertex-tagger (JVT) technique [56] is used to separate hard-scatter jets from pile-up jets within the acceptance of the tracking detector by requiring a significant fraction of the jet's summed track p_T to come from tracks associated with the primary vertex. A jet-vertex-tagger requirement of $\text{JVT} > 0.64$ for jets with $p_T < 50$ GeV and $|\eta| < 2.4$ is applied. This requirement has an efficiency that increases with the jet p_T and is between 87% and 98% for selecting hard-scatter jets with p_T in the range 20–50 GeV. Candidate jets are discarded if they lie within a cone of size $\Delta R = 0.2$ around an electron or, for jets with less than three associated tracks, around a muon candidate. If a jet with three or more associated tracks lies within $\Delta R < 0.4$ of a muon, or $0.2 < \Delta R < 0.4$ of an electron, the corresponding lepton candidate is discarded. Within the ID acceptance, jets originating from the fragmentation of b -hadrons (b -jets) are identified using a multivariate algorithm [57,58]. The chosen operating point has an efficiency of 85% for selecting jets containing b -hadrons and a rejection factor of 28 for light-quark jets, as estimated in a sample of simulated $t\bar{t}$ events and validated with data.

The missing transverse momentum is computed as the negative of the vectorial sum of the transverse momenta of the reconstructed objects selected in the analysis (i.e. electrons, muons, and jets), and a soft term based on the tracks associated with the primary vertex but not with the hard objects explicitly used in the missing transverse momentum computation [59]. The magnitude of the missing transverse momentum is denoted by E_T^{miss} in the following. The jet selection in the E_T^{miss} computation is chosen to provide a compromise between good resolution and scale, with the requirement of $p_T > 20$ GeV for all jets, and an additional $\text{JVT} > 0.64$ requirement for jets in the region of $|\eta| < 2.4$. In Drell–Yan production of τ -lepton pairs with subsequent decay to an $e\mu$ pair, the direction of the missing transverse momentum tends to align with a final-state lepton. To suppress this contamination a requirement is imposed on the missing transverse momentum component perpendicular to the direction in the $r\text{--}\phi$ plane of the lepton closest to the missing transverse momentum

direction, as defined in Ref. [6]. This variable is denoted in the following by $E_{T, \text{Rel}}^{\text{miss}}$. In addition, a more pile-up-robust track-based missing transverse momentum variable of magnitude p_T^{miss} is computed within the ID acceptance [59], using only ID tracks associated with the primary vertex.

The signal region (SR) in which the measurement is performed is defined as follows. Candidate WW events are required to have one electron and one muon, each with $p_T > 25$ GeV, of opposite charge. The electron is required to be in the region $|\eta| < 2.47$, excluding the transition region between the barrel and endcap calorimeters. For the muon, $|\eta| < 2.4$ is required. To reduce the background from other diboson processes, the events are required to have no additional electron or muon with $p_T > 10$ GeV. To suppress the background contribution from top quarks, events are required to have no jets with $p_T > 25$ (30) GeV in $|\eta| < 2.5$ (4.5), and no b -jets with $p_T > 20$ GeV. In addition, the requirements $E_{T, \text{Rel}}^{\text{miss}} > 15$ GeV, $p_T^{\text{miss}} > 20$ GeV, and the invariant mass of the lepton pair $m_{e\mu} > 10$ GeV suppress Drell–Yan background contributions. The lepton, jet, and event selection criteria are summarised in Table 1.

5. Background estimation

After applying the event selection requirements described in Section 4, the dominant background in the WW candidate sample is top-quark ($t\bar{t}$ and single top) production with neither jet nor b -jet above the veto thresholds within the acceptance. Drell–Yan production of a τ -lepton pair that decays leptonically can also give rise to the $e\mu$ final state. Multi-jet production with two jets misidentified as leptons, or W + jets production with leptonic W decay and a jet misidentified as a lepton (collectively referred to as W + jets background below) can be mistakenly accepted as candidate events. This background category includes events where an electron or a muon is produced from a semileptonic decay of a bottom or charm hadron and WW events where one W decays leptonically and the other hadronically. Other diboson (WZ , ZZ , $W\gamma$ and $Z\gamma$) production contributes a smaller background. Minor background processes are modelled with MC simulations, while data-driven methods are used to determine the dominant backgrounds and backgrounds with a misidentified lepton. The normalisations of top-quark and Drell–Yan backgrounds are determined from dedicated control regions after a simultaneous fit, described in detail in Section 8. The phase spaces of top-quark and Drell–Yan control regions are chosen to be close to the one of the signal region. Modelling uncertainties for each of the backgrounds, discussed here, as well as the systematic and statistical uncertainties given in Section 8, are included as nuisance parameters in the fit.

The top-quark background control region is defined by requiring one jet with $p_T > 25$ GeV and at least one b -jet with

$p_T > 20$ GeV in the ID acceptance region of $|\eta| < 2.5$, in an event sample selected with the same lepton criteria as the signal region and no requirement on $E_{T, \text{Rel}}^{\text{miss}}$. This control region has an estimated top purity of 93%. The top-quark background, comprising $t\bar{t}$ and Wt contributions, is normalised to data in this control region and both the detector and modelling uncertainties affect the extrapolation of $t\bar{t}$ and Wt from the control region to the signal region. These include $t\bar{t}$ (Wt) cross section uncertainties of 6% (10%) as well as the modelling of the parton shower and initial-state jet radiation. For the $t\bar{t}$ process the uncertainties also include the choice of MC matrix-element generator, while for the Wt process they include the modelling of the overlap and interference at NLO between Wt and $t\bar{t}$ diagrams estimated by comparing the nominal Wt MC sample with an alternative sample generated with a different scheme for overlap removal. The uncertainties in modelling the $t\bar{t}$ and Wt processes are estimated by comparing the results from the different MC samples presented in Section 3.

The event characteristics of $e\mu$ final states from Drell–Yan production of τ -lepton pairs include an $e\mu$ invariant mass below the Z mass, and lower $E_{T, \text{Rel}}^{\text{miss}}$. In the Drell–Yan background control region, the $e\mu$ invariant mass is required to be $45 < m_{e\mu} < 80$ GeV, and either or both of the $E_{T, \text{Rel}}^{\text{miss}}$ and p_T^{miss} requirements are reversed to make the sample orthogonal to that in the signal region while all other selection requirements remain the same. The Drell–Yan control region has a purity of about 95%, and the Drell–Yan modelling uncertainties are taken into account by comparing different MC event generators, as discussed in Section 3.

Determining the background from W + jets production requires good knowledge of the lepton misidentification rate, which is best derived from data. The yield from W + jets production is estimated using data event samples that are selected with different lepton selection criteria: a loose lepton identification criterion is defined, leptons are selected using either the loose or the default (as used in the signal region) lepton identification criteria, and events are classified according to whether the leptons, that all satisfy the loose criteria, satisfy or not the default identification criteria. With the introduction of the efficiencies of the default lepton identification relative to the loose lepton identification for both real and misidentified leptons, a system of four equations can be solved to estimate the number of events meeting the default lepton identification criteria. This follows the same procedure as that described in Ref. [6]. For electrons, the loose identification corresponds to the *medium* criterion defined in Ref. [50] without isolation requirements. For muons, the loose identification is the same as the default one, except that the isolation requirement is omitted. The efficiencies for jet misidentification are determined for electrons and muons separately as a function of the lepton p_T and are cross-checked with a two-dimensional parameterisation in the lepton p_T and η . These efficiencies are measured using data in a control region with one lepton, at least one jet and requirements on the lepton- $E_{T, \text{Rel}}^{\text{miss}}$ transverse mass and $E_{T, \text{Rel}}^{\text{miss}}$ to suppress the prompt-lepton contribution from W + jet production. The remaining W + jets contribution in the selected control sample is subtracted using the MC prediction. The efficiencies for real leptons are determined from W MC simulations with correction factors obtained by comparing $Z \rightarrow \ell\ell$ events in data and MC simulation. The systematic uncertainties for lepton misidentification include variations of the control region definition, the cross section uncertainties used for the subtraction of the contributions from real leptons, and the method bias (non-closure), which is estimated by comparing the prediction for the W + jet background contribution from MC simulation with the result of the experimental method applied to the same MC sample.

The estimate of the diboson background from WZ , ZZ , $W\gamma$ and $Z\gamma$ processes is based on MC simulation. The diboson back-

Table 2

Definition of the $WW \rightarrow e\mu$ fiducial phase space, where $\ell = e$ or μ .

Fiducial selection requirement	Cut value
p_T^ℓ	> 25 GeV
$ \eta_\ell $	< 2.5
$m_{e\mu}$	> 10 GeV
Number of jets with $p_T > 25(30)$ GeV, $ \eta < 2.5(4.5)$	0
$E_{T, \text{Rel}}^{\text{miss}}$	> 15 GeV
E_T^{miss}	> 20 GeV

ground uncertainty is estimated by comparing the yields of the dominant process, WZ , predicted by two different event generators, SHERPA and POWHEG-BOX, for which a difference of 30% is observed. Such uncertainty is then applied to the whole diboson contribution.

The observed numbers of events in the signal region, and the top-quark and Drell–Yan control regions, are shown later in Table 3.

6. Fiducial cross-section definition

The WW cross section is evaluated in the fiducial phase space of the $e\mu$ decay channel. The fiducial phase space is defined in Table 2 as selection criteria for MC events with no detector simulation. Electrons and muons are required at particle level to stem from one of the W bosons produced in the hard scatter and their respective momenta after QED final-state radiation are vectorially added to the momenta of photons emitted in a cone of size $\Delta R = 0.1$ around the lepton direction. Final-state particles with lifetime greater than 30 ps are clustered into jets (referred to as particle-level jets) using the same algorithm as for detector-level jets, i.e. with the anti- k_t algorithm with radius parameter $R = 0.4$. The selected charged leptons and neutrinos from W -boson decays are not included in the jet clustering. The fiducial phase space at particle level does not make any requirement on b -quark jets. The missing transverse momentum is defined at particle level as the transverse component of the vectorial sum of the neutrino momenta. In Table 2, the missing transverse momentum magnitude is denoted as E_T^{miss} , while its component perpendicular to the closest lepton in the r - ϕ plane is denoted as $E_{T, \text{Rel}}^{\text{miss}}$.

The fiducial cross section is defined as

$$\sigma_{WW \rightarrow e\mu}^{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}, \quad (1)$$

where $\mathcal{L}$ is the integrated luminosity, N_{obs} is the observed number of events, N_{bkg} is the estimated number of background events and C is a factor that accounts for detector inefficiencies and contributions from τ -lepton decays. The factor C is estimated in simulation as the ratio of the number of signal events with one electron and one muon (including those from τ decays) passing the selection requirements at detector level listed in Section 4 to those passing the fiducial selection (excluding $W \rightarrow \tau\nu$ decays) at particle level. Therefore C implicitly corrects for the contribution of $W \rightarrow \tau\nu$ decays, which is estimated in MC simulations to be 8%, based on their acceptance relative to the signal $WW \rightarrow e\mu$ channel and the relative branching fractions from the MC simulation.

7. Systematic uncertainties

Systematic uncertainties in the WW cross-section measurement in the fiducial phase space arise from the reconstruction of leptons and jets, the background determination, pile-up and luminosity uncertainties, and the procedures used to correct for detector effects.

The uncertainty in the C factor in Eq. (1) is dominated by experimental sources. Uncertainties in the lepton and jet reconstruction affect the signal acceptance in the fiducial phase space. The effects are estimated by varying the energy or momentum scale and the resolution of leptons and jets, and the correction factors for the trigger, reconstruction, identification and isolation efficiencies, within their uncertainties estimated in dedicated data analyses [50, 51, 54]. Uncertainties in the E_T^{miss} reconstruction and b -tagging are also taken into account based on the studies in Ref. [59] and Ref. [57] respectively. The impact of the hard-object uncertainties in the E_T^{miss} is estimated by individually varying each of their associated uncertainties and recalculating E_T^{miss} for each variation. In addition, uncertainties in the scale and resolution of the E_T^{miss} soft term are estimated using data as discussed in Refs. [59] and [60].

The full set of detector-related uncertainties is taken into account in the background estimation. The statistical uncertainties stemming from the size of the MC samples used for the background estimates and from the size of the data samples used for data-driven estimations in the control regions are also considered as systematic uncertainties. The uncertainties due to the modelling of background processes in the signal and control regions are estimated by comparing different event generators, as discussed in Sections 3 and 5.

The MC samples are reweighted to reproduce the distributions in data of the average number of interactions per bunch crossing, and additionally the number of reconstructed primary vertices per event. The uncertainty due to pile-up is estimated as the difference between the two. An uncertainty of 2.1% in the integrated luminosity affects the cross-section measurement and the MC-based estimate of backgrounds. It is determined following the same methodology as that detailed in Ref. [61] based on a calibration of the luminosity scale using x - y beam-separation scans performed in August 2015. The beam energy uncertainty of 0.66% (from Ref. [62]) gives a 1.7% uncertainty in the theoretical cross section, which is not accounted for in the predictions quoted in this Letter.

Uncertainties in the C factor due to theoretical sources are also included. The uncertainties associated with PDFs are taken as the largest of either the CT10 NLO eigenvector uncertainty band at 68% confidence level, or the difference among the central values of CT10 NLO, MSTW2008nlo [63] and NNPDF3.0 [64] PDFs. The uncertainty associated with higher-order QCD corrections is estimated by varying renormalisation (μ_R) and factorisation (μ_F) scales independently by factors of 2 and 0.5 with the constraint $0.5 \leq \mu_F/\mu_R \leq 2$. The effects of parton shower, hadronisation and underlying event models (referred to here as *parton shower* for simplicity) are accounted for by comparing the default MC prediction for WW production, which uses PYTHIA v8.210 for modelling of these effects, with the prediction obtained with the models implemented in HERWIG++.

A full list of systematic uncertainties and their impact on the cross-section measurement is given in Table 4.

8. The fiducial cross-section measurement

The fiducial cross section $\sigma_{WW \rightarrow e\mu}^{\text{fid}}$ is extracted by minimising a negative log-likelihood function, based on observed and expected numbers of events in the signal region, as defined by the signal event selection, and in the top-quark and Drell-Yan control regions, as defined in Section 5. The likelihood consists of a product of Poisson probability density functions for the orthogonal regions. This procedure allows a simultaneous measurement of the signal process cross section and of the contributions from the top-quark and Drell-Yan processes. Systematic uncertainties are taken into account as constrained nuisance parameters in the log-likelihood

Table 3

Observed number of events in data and estimated numbers of events from signal and background processes in the signal and control regions. The numbers of events from signal and background processes are the result of the simultaneous fit, i.e. are constrained to match the data in the signal and control regions. The quoted uncertainties account for statistical and systematic components on the number of events for each process and do not include the uncertainties in the C factor. The correlations among processes for common systematic uncertainties are accounted for in the total uncertainties.

Process	Signal region	Top-quark control region	Drell-Yan control region
WW signal	997 ± 69	49 ± 12	75.3 ± 5.4
Drell-Yan	62 ± 23	49 ± 29	1568 ± 45
$t\bar{t}$ + single top	177 ± 33	2057 ± 81	3.5 ± 1.6
W + jets/multi-jet	78 ± 41	70 ± 55	0 ± 17
Other dibosons	38 ± 12	6.3 ± 3.5	19.2 ± 6.1
Total	1351 ± 37	2232 ± 47	1666 ± 41
Data	1351	2232	1666

Table 4

Breakdown of the relative uncertainties in the fiducial cross-section measurement as a result of the simultaneous fit to signal and control regions. “Electron” and “Muon” uncertainties include contributions from trigger, energy/momentum reconstruction, identification and isolation.

Sources of uncertainty	Relative uncertainty for $\sigma_{WW \rightarrow e\mu}^{\text{fid}}$
Jet selection and energy scale & resolution	7.3%
b -tagging	1.3%
E_T^{miss} and p_T^{miss}	1.7%
Electron	1.0%
Muon	0.4%
Pile-up	0.9%
Luminosity	2.1%
Top-quark background theory	2.4%
Drell-Yan background theory	1.5%
W + jet and multi-jet background	3.8%
Other diboson backgrounds	1.1%
Parton shower	3.1%
PDF	0.2%
QCD scale	0.2%
MC statistics	1.2%
Data statistics	3.7%
Total uncertainty	11%

function. The methodology accounts for uncertainties and their correlations across signal and background processes. It is found that the Drell-Yan and top-quark processes need to be scaled relative to their MC predictions by 1.03 ± 0.03 and 0.875 ± 0.035 respectively to match the observed data yields in the corresponding control regions. The uncertainties of the quoted scale factors are driven by the data statistics in the respective control regions and do not include modelling uncertainties on the respective processes. The number of events observed in data and the estimated numbers of signal and background events together with their total uncertainties are reported in Table 3. The correction factor C is calculated to be 0.60 ± 0.04 , where the uncertainty accounts for the systematic effects discussed in Section 7. The measured signal cross section is

$$\sigma_{WW \rightarrow e\mu}^{\text{fid}} = 529 \pm 20 \text{ (stat.)} \pm 50 \text{ (syst.)} \pm 11 \text{ (lumi.) fb.}$$

The total uncertainty is dominated by systematic sources, as described in Section 7, of which the largest contribution originates from the experimental jet selection and calibration. The correlations of the fit parameters in the signal and control regions are taken into account in the computation of the total uncertainties.

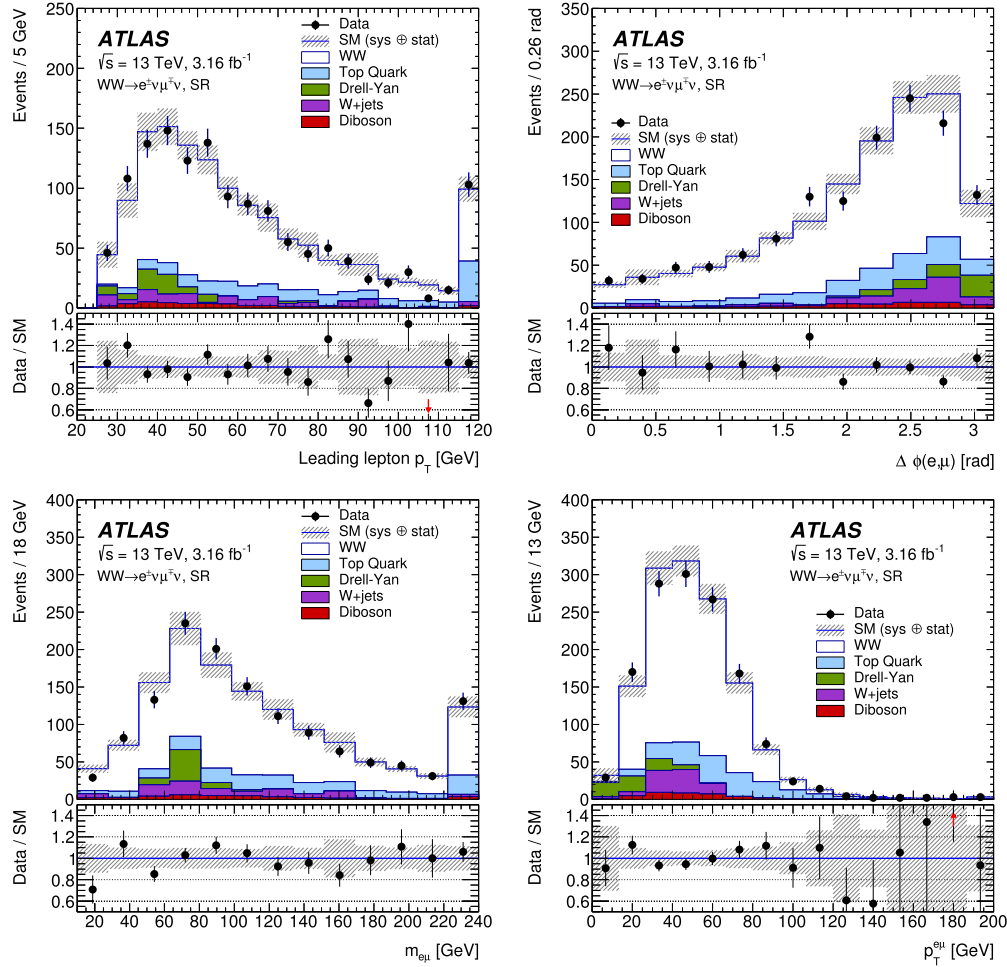


Fig. 1. Lepton and dilepton kinematic variables in the signal region. In the figure $m_{e\mu}$ and $p_T^{e\mu}$ are the invariant mass and the transverse momentum of the $e\mu$ system respectively, and $\Delta\phi(e,\mu)$ is the azimuthal angle between the two leptons. Data are shown together with the MC and data-driven predictions for the signal and background production processes after the fit to the data in the signal and control regions. The last bin in each distribution is the overflow. In the legend, SM stands for the total contribution of the estimated SM processes and the uncertainty band includes the MC statistical and systematic uncertainties as a result of the fit.

The contributions to the relative uncertainty in the fiducial cross-section measurement are summarised in Table 4. Fig. 1 shows distributions of kinematic variables from data events in the signal region in comparison with the signal and background contributions estimated from the simultaneous fit to signal and control regions.

9. Theoretical predictions and ratio to the 8 TeV measurement

Theoretical predictions are calculated in the total phase space (σ_{WW}^{tot}) and include the $q\bar{q} \rightarrow WW$, the non-resonant $gg \rightarrow WW$, and the resonant $gg \rightarrow H \rightarrow WW$ sub-processes. The $q\bar{q} \rightarrow WW$ production cross section is known to $\mathcal{O}(\alpha_s^2)$ (NNLO) [9, 13], the non-resonant gg sub-process is known to $\mathcal{O}(\alpha_s^3)$ [33], and the resonant $gg \rightarrow H \rightarrow WW$ cross section is calculated to $\mathcal{O}(\alpha_s^3)$ [65] taking into account the $H \rightarrow WW$ branching fraction [66]. The sum of these sub-processes is denoted by nNNLO+H in the following. In its calculation, the interference between the three sub-processes is neglected. At the given orders of α_s listed above, the $q\bar{q} \rightarrow WW$ process does not interfere with either of the gg -induced processes and the interference between the

gg -induced processes has little contribution to the cross section in the measured phase space. As in the 8 TeV cross-section measurement, possible contributions from double parton interactions are not considered as their contribution is expected to be negligible [6].

The renormalisation and factorisation scales are set to the W boson mass for the $q\bar{q}$ and non-resonant gg processes, and to $m_H/2$ for $gg \rightarrow H \rightarrow WW$. The uncertainties in the $q\bar{q} \rightarrow WW$ cross section are estimated by varying the two scales independently by factors of 0.5 and 2 with the constraint $0.5 \leq \mu_F/\mu_R \leq 2$, while the uncertainties in the non-resonant and resonant gg cross sections are estimated by simultaneously varying μ_R and μ_F by factors of 0.5 and 2. The uncertainties in $gg \rightarrow WW$ and $gg \rightarrow H \rightarrow WW$ processes include a 3.2% contribution from PDF uncertainties computed in Ref. [67]. For the $q\bar{q} \rightarrow WW$ process, PDF uncertainties are estimated as the largest of either the CT10 NLO eigenvector uncertainty band (at 68% confidence level) or the difference among the central values of CT10 NLO, MSTW2008nlo and NNPDF3.0 PDFs, amounting to 1.8%. The uncertainties associated with the individual sub-processes are propa-

Table 5

Theoretical predictions for the WW cross-section sub-processes and their associated uncertainties in the full phase space (σ_{WW}^{tot}) calculated up to the given order in α_s together with the respective acceptance corrections (A) for the fiducial phase space and the fiducial cross sections ($\sigma_{WW \rightarrow e\mu}^{\text{fid}}$). The resonant $gg \rightarrow H \rightarrow WW$ is calculated up to $\mathcal{O}(\alpha_s^2)$ for σ_{WW}^{tot} and to $\mathcal{O}(\alpha_s^3)$ for $\sigma_{WW \rightarrow e\mu}^{\text{fid}}$ and A . A correction is applied to $\sigma_{WW \rightarrow e\mu}^{\text{fid}}$ and A to account for non-perturbative effects. The quoted uncertainties include scale variations and PDF uncertainties, with the latter being evaluated at NLO. The scale uncertainties are treated as correlated, whereas PDF uncertainties are treated as uncorrelated between the $q\bar{q}$ and the gg -induced processes. The values of the branching ratio of leptonic W -boson decay used for each sub-process are those reported in their respective References, while for the resonant gg sub-process $\mathcal{B} = 0.1083$ [69] is used.

$pp \rightarrow WW$ sub-process	Order of α_s	σ_{WW}^{tot} [pb]	A [%]	$\sigma_{WW \rightarrow e\mu}^{\text{fid}}$ [fb]
$q\bar{q}$ [9,13]	$\mathcal{O}(\alpha_s^2)$	111.1 ± 2.8	16.20 ± 0.13	422_{-11}^{+12}
gg (non-resonant) [33]	$\mathcal{O}(\alpha_s^3)$	$6.82_{-0.55}^{+0.42}$	$28.1_{-2.3}^{+2.7}$	44.9 ± 7.2
$gg \rightarrow H \rightarrow WW$ [68][30]	$\mathcal{O}(\alpha_s^2)$ tot. / $\mathcal{O}(\alpha_s^3)$ fid.	$10.45_{-0.79}^{+0.61}$	4.5 ± 0.6	11.0 ± 2.1
$q\bar{q} + gg$ (non-resonant) + $gg \rightarrow H \rightarrow WW$	nNNLO+H	$128.4_{-3.8}^{+3.5}$	$15.87_{-0.14}^{+0.17}$	478 ± 17

gated to the σ_{WW}^{tot} prediction for the nNNLO+H combination: scale uncertainties of different processes are added linearly, while PDF uncertainties are considered uncorrelated across processes. The $q\bar{q}$ production makes up 87% of the total cross section while the non-resonant and resonant gg production sub-processes account for 5% and 8% respectively.

For direct comparison to the experimental result, theoretical predictions are also calculated in the same phase space as the measurement ($\sigma_{WW \rightarrow e\mu}^{\text{fid}}$) for the $q\bar{q}$ and non-resonant gg processes. A correction of 0.972 ± 0.001 is applied to parton-level calculations for $\sigma_{WW \rightarrow e\mu}^{\text{fid}}$ to account for the contribution of non-perturbative effects due to multi-parton interactions and hadronisation. This correction was calculated by comparing the particle-level cross section as predicted by the MC simulation with one obtained with a dedicated event generation where these effects are disabled in PYTHIA v8.210. The uncertainty includes the MC statistical uncertainty and the systematic component estimated by comparing the above correction with the one estimated with the non-perturbative model implemented in the HERWIG++ MC event generator. The calculations reported here do not include high-order electroweak corrections. In Ref. [70] it is estimated that electroweak corrections up to NLO reduce the WW cross section by 3–4% in a phase space close to the one used in this analysis. The $q\bar{q}$ and non-resonant gg fiducial cross sections are calculated with the programs presented in Refs. [9,13] and [33] respectively. For the resonant $gg \rightarrow H \rightarrow WW$ process, no fiducial calculation is available at $\mathcal{O}(\alpha_s^3)$. Therefore, this fiducial cross section is calculated by correcting the cross section in the full phase space (σ_{WW}^{tot}) by the geometrical and kinematic acceptance A as determined using the MC event generator POWHEG-BOX v2 interfaced to PYTHIA v8.210 for parton showering and non-perturbative effects and the branching ratio ($\mathcal{B}$) for fully leptonic final states, $\mathcal{B} = 0.1083$ [69]:

$$\sigma_{WW \rightarrow e\mu}^{\text{fid}} = 2 \times \sigma_{WW}^{\text{tot}} \times A \times \mathcal{B}^2. \quad (2)$$

In this determination of the $gg \rightarrow H \rightarrow WW$ fiducial cross section, uncertainties from PDFs and scale uncertainties are considered for both A and σ_{WW}^{tot} , while parton shower uncertainties are also estimated for A . The $q\bar{q}$ and non-resonant gg acceptances are calculated using the ratios of the respective fiducial cross section to the total cross section. The uncertainties in the A factors for $q\bar{q}$ and non-resonant gg processes are estimated following the same methodology as for σ_{WW}^{tot} and considering both the scale and PDF uncertainties as correlated between $\sigma_{WW \rightarrow e\mu}^{\text{fid}}$ and σ_{WW}^{tot} . The total uncertainty in A in the nNNLO+H calculation is then determined from the propagation of the A factor uncertainties for the individual sub-processes. The PDF uncertainties are found to be dominant and to lead to an uncertainty of 2.5% and 3.2% on A for the $q\bar{q}$ and gg sub-processes respectively.

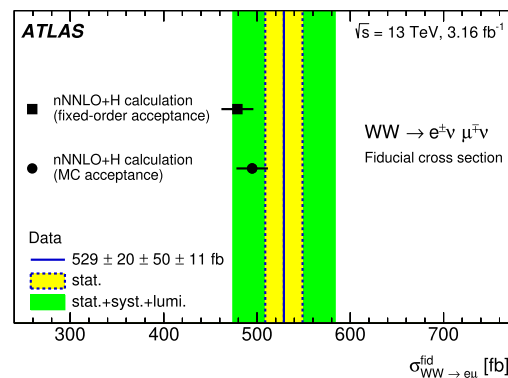


Fig. 2. The measured fiducial cross section at $\sqrt{s} = 13$ TeV in comparison with the nNNLO+H prediction in the fiducial phase space with two different acceptance calculations. The vertical bands around the measurement indicate the statistical uncertainty (yellow) and the sum in quadrature of statistical, systematic and luminosity uncertainties (green). The beam energy uncertainty is not taken into account.

The theoretical cross-section predictions for each production sub-process and the nNNLO+H combination in the total and fiducial phase spaces as well as the A factors (corrected for non-perturbative effects) are given together with their estimated uncertainties in Table 5. Fig. 2 shows the comparison of the nNNLO+H prediction with the measurement presented in the previous section. Fig. 2 also reports, as an alternative prediction, the σ_{WW}^{tot} calculation for the nNNLO+H combination corrected by the acceptance A calculated using the MC event generator POWHEG-BOX v2 + PYTHIA v8.210 for the $q\bar{q}$ and resonant $gg \rightarrow H \rightarrow WW$ processes, and SHERPA v2.1.1 for the non-resonant gg process. In this calculation the acceptance factor is estimated to be $A = (16.4 \pm 0.9)\%$ where the uncertainty includes the parton shower modelling (taken as the difference between PYTHIA v8.210 and HERWIG++ showers), PDF uncertainty (estimated as the largest difference between the CT10 NLO eigenvector uncertainty band and the MSTW2008nlo and NNPDF3.0 PDF central values), scale uncertainty associated with the jet veto requirement estimated as in Ref. [71] and the residual renormalisation and factorisation scale uncertainty (estimated by varying the two scales independently by factors of 2 and 0.5).

The nNNLO+H prediction agrees within uncertainties with the experimental cross-section measurement in the fiducial phase space.

The cross section in the full phase space (σ_{WW}^{tot}) is determined by extrapolating the measurement in the fiducial phase space by inverting Eq. (2) and using the acceptance value from the nNNLO+H calculation as in Table 5: $\sigma_{WW}^{\text{tot}} = 142 \pm 5$ (stat.) $\pm$

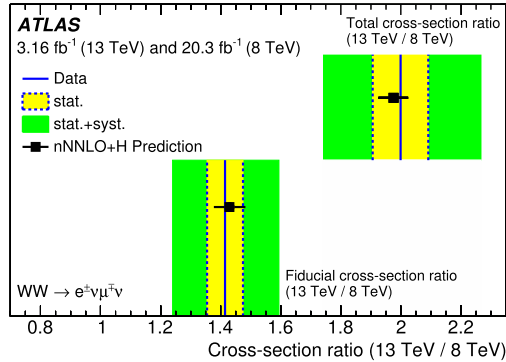


Fig. 3. Measurements of the ratios of cross sections at the two centre-of-mass energies of 13 and 8 TeV in the fiducial and total phase spaces. For the 8 TeV cross sections the results from Ref. [6] are used. The measurements are compared to the nNNLO+H predictions for the ratios of cross sections in the fiducial phase spaces of the two analyses at 13 and 8 TeV and in the total phase space, with their respective uncertainties. The beam energy uncertainty is not taken into account.

$13 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$. This is in agreement with the nNNLO+H prediction of $128.4^{+3.5}_{-3.8} \text{ pb}$.

Using the fiducial cross section measured for $WW \rightarrow e\mu$ production at 8 TeV centre-of-mass energy [6] in the fiducial phase space detailed in Ref. [6], the ratio of cross sections at the two centre-of-mass energies of 13 and 8 TeV is:

$$\frac{\sigma_{13 \text{ TeV}, WW \rightarrow e\mu}^{\text{fid}}}{\sigma_{8 \text{ TeV}, WW \rightarrow e\mu}^{\text{fid}}} = 1.41 \pm 0.06 \text{ (stat.)} \pm 0.16 \text{ (syst.)} \pm 0.04 \text{ (lumi.)}.$$

All uncertainties are treated as uncorrelated between the measurements at the two beam energies: no attempt is made to exploit the jet energy scale correlations between the two data-taking periods at different beam energies. The same ratio is calculated for the total cross sections at 13 and 8 TeV and is found to be $2.00 \pm 0.08 \text{ (stat.)}^{+0.25}_{-0.24} \text{ (syst.)} \pm 0.06 \text{ (lumi.)}$. Fig. 3 shows the measured ratios of cross sections in the fiducial and total phase spaces and the comparison with their respective nNNLO+H predictions with scale uncertainties treated as correlated between the two centre-of-mass energies, while the PDF uncertainties are considered uncorrelated. The predictions for the ratio in the fiducial and total phase spaces are 1.43 ± 0.05 and 1.98 ± 0.05 respectively, and are in agreement with the experimental results.

10. Conclusions

The cross section for production of W^+W^- pairs in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ is measured in a fiducial phase space of the $e\mu$ final state in which events with reconstructed jets are excluded. The data used in the analysis correspond to an integrated luminosity of 3.16 fb^{-1} collected by the ATLAS detector at the LHC in 2015. The measurement is made in a relatively pure signal region with the contamination from the dominant background processes estimated using data in dedicated control regions. The measured cross section is $529 \pm 20 \text{ (stat.)} \pm 50 \text{ (syst.)} \pm 11 \text{ (lumi.) fb}$ and is found to be consistent with the most up-to-date SM predictions that include high-order QCD effects. Furthermore, the ratio of the measured fiducial cross sections at 13 and 8 TeV centre-of-mass energies is compared to the theory predictions with reduced uncertainties, thanks to their cancellation in the ratio.

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Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36 fb^{-1} of pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector

The ATLAS Collaboration

A search for heavy neutral Higgs bosons and Z' bosons is performed using a data sample corresponding to an integrated luminosity of 36.1 fb^{-1} from proton–proton collisions at $\sqrt{s} = 13\text{ TeV}$ recorded by the ATLAS detector at the LHC during 2015 and 2016. The heavy resonance is assumed to decay to $\tau^+\tau^-$ with at least one tau lepton decaying to final states with hadrons and a neutrino. The search is performed in the mass range of 0.2–2.25 TeV for Higgs bosons and 0.2–4.0 TeV for Z' bosons. The data are in good agreement with the background predicted by the Standard Model. The results are interpreted in benchmark scenarios. In the context of the hMSSM scenario, the data exclude $\tan\beta > 1.0$ for $m_A = 0.25\text{ TeV}$ and $\tan\beta > 42$ for $m_A = 1.5\text{ TeV}$ at the 95% confidence level. For the Sequential Standard Model, Z'_{SSM} with $m_{Z'} < 2.42\text{ TeV}$ is excluded at 95% confidence level, while Z'_{NU} with $m_{Z'} < 2.25\text{ TeV}$ is excluded for the non-universal $G(221)$ model that exhibits enhanced couplings to third-generation fermions.

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1 Introduction

The discovery of a scalar particle [1, 2] at the Large Hadron Collider (LHC) [3] has provided important insight into the mechanism of electroweak symmetry breaking. Experimental studies of the new particle [4–8] demonstrate consistency with the Standard Model (SM) Higgs boson [9–14]. However, it remains possible that the discovered particle is part of an extended scalar sector, a scenario that is favoured by a number of theoretical arguments [15, 16].

The Minimal Supersymmetric Standard Model (MSSM) [15, 17, 18] is the simplest extension of the SM that includes supersymmetry. The MSSM requires two Higgs doublets of opposite hypercharge. Assuming that CP symmetry is conserved, this results in one CP-odd (A) and two CP-even (h, H) neutral Higgs bosons and two charged Higgs bosons ($H^\pm$). At tree level, the properties of the Higgs sector in the MSSM depend on only two non-SM parameters, which can be chosen to be the mass of the CP-odd

Higgs boson, m_A , and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. Beyond tree level, a number of additional parameters affect the Higgs sector, the choice of which defines various MSSM benchmark scenarios. In some scenarios, such as $m_h^{\text{mod+}}$ [19], the top-squark mixing parameter is chosen such that the mass of the lightest CP-even Higgs boson, m_h , is close to the measured mass of the Higgs boson that was discovered at the LHC. A different approach is employed in the hMSSM scenario [20, 21] in which the measured value of m_h can be used, with certain assumptions, to predict the remaining masses and couplings of the MSSM Higgs bosons without explicit reference to the soft supersymmetry-breaking parameters. The couplings of the MSSM heavy Higgs bosons to down-type fermions are enhanced with respect to the SM Higgs boson for large $\tan\beta$ values, resulting in increased branching fractions to τ -leptons and b -quarks, as well as a higher cross section for Higgs boson production in association with b -quarks. This has motivated a variety of searches for a scalar boson (generically called ϕ) in $\tau\tau$ and bb final states¹ at LEP [22], the Tevatron [23–25] and the LHC [26–31].

Heavy Z' gauge bosons appear in many extensions of the SM [32–36] and while they are typically considered to obey lepton universality, this is not necessarily a requirement. In particular, models in which the Z' boson couples preferentially to third-generation fermions may be linked to the high mass of the top quark [37–40] or to recent indications of lepton flavour universality violation in semi-tauonic B meson decays [41]. One such model is the non-universal $G(221)$ model [38–40], which contains a Z'_{NU} boson that can exhibit enhanced couplings to tau leptons. In this model the SM $SU(2)$ gauge group is split into two parts: one coupling to fermions of the first two generations and one coupling to third generation fermions. The mixing between these groups is described by the parameter $\sin^2\phi$, with $\sin^2\phi < 0.5$ corresponding to enhanced third generation couplings. A frequently used benchmark model is the Sequential Standard Model (SSM), which contains a Z'_{SSM} boson with couplings identical to the SM Z boson. By evaluating the impact on the signal sensitivity from changing the Z'_{SSM} couplings, limits on Z'_{SSM} can be reinterpreted for a broad range of models. Indirect limits on Z' bosons with non-universal flavour couplings have been derived from measurements at LEP [42]. The most sensitive direct searches for high-mass resonances decaying to ditau final states have been performed by the ATLAS and CMS collaborations using data collected at $\sqrt{s} = 8$ and 13 TeV [31, 43, 44].

This paper presents the results of a search for neutral MSSM Higgs bosons as well as high-mass Z' resonances in the ditau decay mode using 36.1 fb^{-1} of proton–proton collision data at a centre-of-mass energy of 13 TeV collected with the ATLAS detector [45] in 2015 and 2016. The search is performed in the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ decay modes, where τ_{lep} represents the decay of a τ -lepton to an electron or a muon and neutrinos, whereas τ_{had} represents the decay to one or more hadrons and a neutrino. The search considers narrow resonances² with masses of 0.2–2.25 TeV and $\tan\beta$ of 1–58 for the MSSM Higgs bosons. For the Z' boson search, a mass range of 0.2–4 TeV is considered. Higgs boson production through gluon–gluon fusion and in association with b -quarks is considered (Figures 1(a)–1(c)), with the latter mode dominating for high $\tan\beta$ values. Hence, both the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are split into b -tag and b -veto categories, based on the presence or absence of jets tagged as originating from b -quarks in the final state. Since a Z' boson is expected to be predominantly produced via a Drell–Yan process (Figure 1(d)), there is little gain in splitting the data into b -tag and b -veto categories. Hence, the Z' analysis uses an inclusive selection instead.

The paper is structured as follows. Section 2 provides an overview of the ATLAS detector. The event samples used in the analysis, recorded by the ATLAS detector or simulated using the ATLAS simulation framework, are reported in Section 3. The event reconstruction is presented in Section 4. A description

¹ The notation $\tau\tau$ and bb is used as shorthand for $\tau^+\tau^-$ and $b\bar{b}$ throughout this paper.

² A resonance is considered “narrow” if the lineshape has no impact on experimental observables.

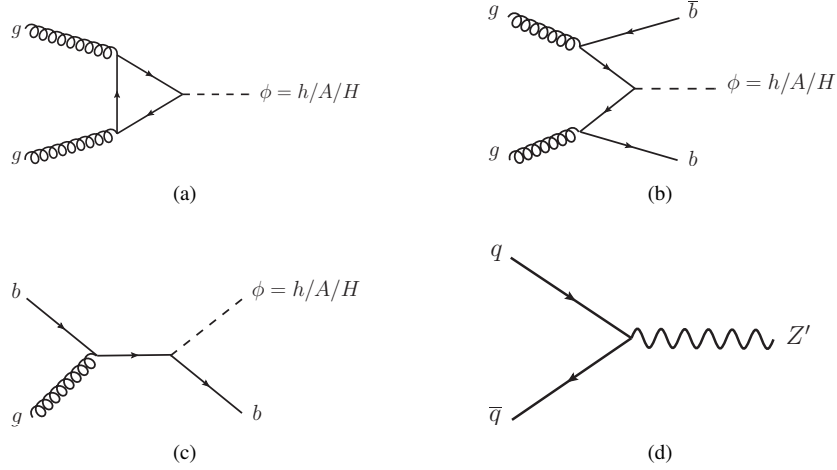


Figure 1: Lowest-order Feynman diagrams for (a) gluon–gluon fusion and b -associated production of a neutral MSSM Higgs boson in the (b) four-flavour and (c) five-flavour schemes and (d) Drell–Yan production of a Z' boson.

of the event selection criteria is given in Section 5. Section 6 explains the estimation of background contributions, followed by a description of systematic uncertainties in Section 7. Results are presented in Section 8, followed by concluding remarks in Section 9.

2 ATLAS detector

The ATLAS detector [45] at the LHC covers nearly the entire solid angle around the collision point.³ It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroid magnets. The inner-detector system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$.

The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track. The innermost layer, known as the insertable B-Layer [46], was added in 2014 and provides high-resolution hits at small radius to improve the tracking performance. The pixel detector is surrounded by the silicon microstrip tracker, which usually provides four two-dimensional measurement points per track. These silicon detectors are complemented by the transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$. The transition radiation tracker also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

³ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the interaction point to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) electromagnetic calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$, to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters that cover $1.5 < |\eta| < 3.2$. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules, optimised for electromagnetic and hadronic measurements respectively, in the region $3.1 < |\eta| < 4.9$.

The muon spectrometer comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions.

A two-level trigger system is used to select interesting events [47, 48]. The level-one trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 100 kHz. This is followed by the software-based high-level trigger, which reduces the event rate to 1 kHz.

3 Data and simulated event samples

The results in this paper use proton–proton collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the LHC during 2015 and 2016. The data correspond to a total integrated luminosity of 36.1 fb^{-1} after requiring that all relevant components of the ATLAS detector are in good working condition. Selected events must satisfy criteria designed to reduce backgrounds from cosmic rays, beam-induced events and calorimeter noise [49]. They must also contain at least one primary vertex with at least two associated tracks. The primary vertex is chosen as the proton–proton vertex candidate with the highest sum of the squared transverse momenta of the associated tracks.

Simulated events are used to estimate the signal efficiencies and some of the background contributions. The simulated event samples are normalised using their theoretical cross sections and the integrated luminosity. Simulated events with a heavy neutral MSSM Higgs boson produced via gluon–gluon fusion and in association with b -quarks were generated at next-to-leading order (NLO) with POWHEG-Box v2 [50–52] and MG5_aMC@NLO 2.1.2 [53, 54] (using the four-flavour scheme), respectively. The CT10 [55] set of parton distribution functions (PDFs) was used in the generation of gluon–gluon fusion events while CT10nlo_nf4 [56] was used to produce the b -associated signal samples. PYTHIA 8.210 [57] with the AZNLO [58] (A14 [59]) set of tuned parameters (tune) was used together with the CTEQ6L1 [60] (NNPDF2.3LO [61]) PDF set for the parton shower calculation at leading order (LO), underlying event and hadronisation in the gluon–gluon fusion (b -associated) production. The gluon–gluon fusion sample was generated assuming SM couplings and underestimates the loop contribution from b -quarks at high $\tan\beta$, which can impact the Higgs boson p_T spectrum. Generator-level studies indicate this has a negligible impact on the final mass distribution and only a few percent impact on the signal acceptance, except for mass hypotheses below 400 GeV where the impact can be up to 10%, so the effect is neglected.

The production cross sections and branching fractions for the various MSSM scenarios are taken from Ref. [62]. The cross sections for gluon–gluon fusion production are calculated using SusHi [63], including NLO supersymmetric-QCD corrections [64–69], next-to-next-to-leading-order (NNLO) QCD corrections for the top quark [70–74], as well as light-quark electroweak effects [75, 76]. The b -associated production cross sections in the five-flavour scheme are also calculated using SusHi based on bbh@nnlo [77], and those for b -associated production in the four-flavour scheme (where b -quarks are not considered as partons) are calculated according to Refs. [78, 79]. The final b -associated production cross section is obtained by using the method described in Ref. [80] to match the four-flavour and five-flavour scheme cross sections. The masses and mixing (and effective Yukawa couplings) of the Higgs bosons are computed with FEYNHIGGS [81–86] for all scenarios, with the exception of the hMSSM. In the case of the hMSSM scenario, Higgs masses and branching fractions are computed using HDECAY [87, 88]. Branching fractions for all other scenarios use a combination of results calculated by HDECAY, FEYNHIGGS and PROPHECY4f [89, 90].

The Z' signal events are modelled with a LO Z/γ^* sample that is reweighted with the TAU SPINNER algorithm [91–93], which correctly accounts for spin effects in the τ -lepton decays. The Z/γ^* sample, enriched in events with high invariant mass, was generated with PYTHIA 8.165 [94, 95] using the NNPDF2.3LO PDF set and the A14 tune for the parton-shower and underlying-event parameters. Interference between the Z' and the SM Z/γ^* production is not included, as it is highly model dependent. Higher-order QCD corrections are applied to the simulated event samples. These corrections to the event yields are made with a mass-dependent rescaling to NNLO in the QCD coupling constant, as calculated with VRAP 0.9 [96] and the CT14NNLO PDF set. Electroweak corrections are not applied to the Z' signal samples due to the large model dependence.

The multijet background in both channels is estimated using data, while non-multijet backgrounds in which a quark- or gluon-initiated jet is misidentified as a hadronic tau decay (predominantly W +jets and $t\bar{t}$) are modelled using data in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel and simulation with data-driven corrections in the $\tau_{\text{had}}\tau_{\text{had}}$ channel, as described in Section 6. The remaining background contributions arise from Z/γ^* +jets, W +jets, $t\bar{t}$, single top-quark and diboson (WW , WZ and ZZ) production. These contributions are estimated using the simulated event samples described below.

Events containing Z/γ^* +jets were generated with POWHEG-Box v2 [97] interfaced to the PYTHIA 8.186 parton shower model. The CT10 PDF set was used in the matrix element. The AZNLO tune was used, with PDF set CTEQ6L1, for the modelling of non-perturbative effects. Photon emission from electroweak vertices and charged leptons was performed with PHOTOS++ 3.52 [98]. The same setup was used to simulate W +jets events for background subtraction in the control regions of the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. The Z/γ^* +jets samples were simulated in slices with different masses of the off-shell boson. The event yields are corrected with a mass-dependent rescaling at NNLO in the QCD coupling constant, computed with VRAP 0.9 and the CT14NNLO PDF set. Mass-dependent electroweak corrections are computed at NLO with MCSANC 1.20 [99], and these include photon-induced contributions ($\gamma\gamma \rightarrow \ell\ell$ via t - and u -channel processes) computed with the MRST2004QED PDF set [100].

The modelling of the W +jets process in the case of the $\tau_{\text{had}}\tau_{\text{had}}$ channel was done with the SHERPA 2.2.0 [101] event generator. Matrix elements were calculated for up to two partons at NLO and four partons at LO using COMIX [102] and OPENLOOPS [103] merged with the SHERPA parton shower [104] using the ME+PS@NLO prescription [105]. The CT10nlo PDF set was used in conjunction with dedicated parton shower tuning developed by the SHERPA authors. The W +jets production is normalised to the NNLO cross sections with FEWZ [96, 106, 107].

For the generation of $t\bar{t}$ or a single top quark in the Wt -channel and s -channel, the PowHEG-Box v2 event generator was used with the CT10 PDF set in the matrix element calculation. Electroweak t -channel single-top-quark events were generated with the PowHEG-Box v1 event generator. This event generator uses the four-flavour scheme for the NLO matrix elements calculations together with the fixed four-flavour PDF set CT10f4. For all top processes, top-quark spin correlations were preserved (for t -channel, top quarks were decayed with MADSPIN [108]). The parton shower, hadronisation, and the underlying event were simulated using PYTHIA 6.428 with the CTEQ6L1 PDF sets and the corresponding Perugia 2012 tune [109]. The top mass was set to 172.5 GeV. The $t\bar{t}$ production sample is normalised to the predicted production cross section as calculated with the TOP++2.0 program to NNLO in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-log (NNLL) order (Ref. [110] and references therein). For the single-top-quark event samples, an approximate calculation at NLO in QCD for the s -channel and t -channel [111, 112] and an NLO+NNLL calculation for the Wt -channel [113] are used for the normalisation.

Diboson processes were modelled using the SHERPA 2.1.1 event generator and they were calculated for up to one (ZZ) or no (WW, WZ) additional partons at NLO and up to three additional partons at LO using COMIX and OPENLOOPS merged with the SHERPA parton shower using the ME+PS@NLO prescription. The CT10 PDF set was used in conjunction with dedicated parton shower tuning developed by the SHERPA authors. The event generator cross sections are used in this case (already at NLO). In addition, the SHERPA diboson sample cross section was scaled down to account for its use of $\alpha_{\text{QED}} = 1/129$ rather than $1/132$ corresponding to the use of current PDG parameters as input to the G_μ scheme.

Properties of the bottom and charm hadron decays were set with the EVTGEN v1.2.0 program [114] in samples that were not produced with SHERPA. Simulated minimum-bias events were overlaid on all simulated samples to include the effect of multiple proton–proton interactions in the same and neighbouring bunch crossings (“pile-up”). These minimum-bias events were generated with PYTHIA 8.186, using the A2 tune [115] and the MSTW2008LO PDF [116]. Each sample was simulated using the full GEANT 4 [117, 118] simulation of the ATLAS detector, with the exception of the b -associated MSSM Higgs boson signal, for which the ATLFastII [119] fast simulation framework was used. Finally, the simulated events are processed through the same reconstruction software as the data.

4 Event reconstruction

Electron candidates are reconstructed from energy deposits in the electromagnetic calorimeter associated with a charged-particle track measured in the inner detector [120–122]. The electron candidates are required to pass a “loose” likelihood-based identification selection, to have a transverse momentum $p_T > 15$ GeV and to be in the fiducial volume of the inner detector, $|\eta| < 2.47$. The transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$) is excluded.

Muon candidates are reconstructed in the range $|\eta| < 2.5$ by matching tracks found in the muon spectrometer to tracks found in the inner detector [123]. The tracks of the muon candidates are re-fitted using the complete track information from both detector systems. They are required to have a transverse momentum $p_T > 7$ GeV and to pass a “loose” muon identification requirement.

The selected lepton (electron or muon) in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel must then have $p_T > 30$ GeV and pass a “medium” identification requirement. This lepton is considered isolated if it meets p_T - and η -dependent isolation criteria utilising calorimetric and tracking information. The criteria correspond to an efficiency

of 90% (99%) for a transverse momentum of $p_T = 25$ (60) GeV. The efficiency increases with lepton p_T as the requirements are relaxed to account for the decreased background from misidentified jets.

Jets are reconstructed from topological clusters of energy depositions [124] in the calorimeter using the anti- k_t algorithm [125, 126], with a radius parameter value $R = 0.4$. The average energy contribution from pile-up is subtracted according to the jet area and the jets are calibrated as described in Ref [127]. They are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. To reduce the effect of pile-up, a jet vertex tagger algorithm is used for jets with $p_T < 60$ GeV and $|\eta| < 2.4$. It employs a multivariate technique based on jet energy, vertexing and tracking variables to determine the likelihood that the jet originates from or is heavily contaminated by pile-up [128]. In order to identify jets containing b -hadrons (b -jets), a multivariate algorithm is used, which is based on the presence of tracks with a large impact parameter with respect to the primary vertex, the presence of displaced secondary vertices and the reconstructed flight paths of b - and c -hadrons associated with the jet [129, 130]. The algorithm has an average efficiency of 70% for b -jets and rejections of approximately 13, 56 and 380 for c -jets, hadronic tau decays and jets initiated by light quarks or gluons, respectively, as determined in simulated $t\bar{t}$ events.

Hadronic tau decays are composed of a neutrino and a set of visible decay products ($\tau_{\text{had-vis}}$), typically one or three charged pions and up to two neutral pions. The reconstruction of the visible decay products is seeded by jets [131]. The $\tau_{\text{had-vis}}$ candidates must have $p_T > 25$ (45) GeV in the $\tau_{\text{lep}}\tau_{\text{had}}$ ($\tau_{\text{had}}\tau_{\text{had}}$) channel, $|\eta| < 2.5$ excluding $1.37 < |\eta| < 1.52$, one or three associated tracks and an electric charge of ± 1 . The leading- p_T $\tau_{\text{had-vis}}$ candidate in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel and the two leading- p_T $\tau_{\text{had-vis}}$ candidates in the $\tau_{\text{had}}\tau_{\text{had}}$ channel are then selected and all remaining candidates are considered as jets. A Boosted Decision Tree (BDT) identification procedure, based on calorimetric shower shapes and tracking information is used to reject backgrounds from jets [132, 133]. Two $\tau_{\text{had-vis}}$ identification criteria are used: “loose” and “medium”, specified in Section 5. The criteria correspond to efficiencies of about 60% (50%) and 55% (40%) in $Z/\gamma^* \rightarrow \tau\tau$ events and rejections of about 30 (30) and 50 (100) in multijet events, for one-track (three-track) $\tau_{\text{had-vis}}$ candidates, respectively. An additional dedicated likelihood-based veto is used to reduce the number of electrons misidentified as $\tau_{\text{had-vis}}$ in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, providing 95% efficiency and a background rejection between 20 and 200, depending on the pseudorapidity of the $\tau_{\text{had-vis}}$ candidate.

Geometrically overlapping objects are removed in the following order: (a) jets within $\Delta R = 0.2$ of selected $\tau_{\text{had-vis}}$ candidates are excluded, (b) jets within $\Delta R = 0.4$ of an electron or muon are excluded, (c) any $\tau_{\text{had-vis}}$ candidate within $\Delta R = 0.2$ of an electron or muon is excluded, (d) electrons within $\Delta R = 0.2$ of a muon are excluded.

The missing transverse momentum, $\mathbf{E}_T^{\text{miss}}$, is calculated as the negative vectorial sum of the $\mathbf{p}_T$ of all fully reconstructed and calibrated physics objects [134, 135]. This procedure includes a “soft term”, which is calculated using the inner-detector tracks that originate from the hard-scattering vertex but are not associated with reconstructed objects.

5 Event selection

5.1 $\tau_{\text{lep}}\tau_{\text{had}}$ channel

Events in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel are recorded using single-electron and single-muon triggers with p_T thresholds ranging from 20 to 140 GeV and various isolation criteria. The events must contain at least

one $\tau_{\text{had-vis}}$ candidate passing the medium identification, exactly one isolated lepton (from here on referred to as ℓ) that is geometrically matched to the trigger signature (implying $|\eta| < 2.4$ in the $\tau_\mu\tau_{\text{had}}$ channel), and no additional reconstructed leptons. The identified $\tau_{\text{had-vis}}$ candidate must have $|\eta| < 2.3$ to reduce background from misidentified electrons. The isolated lepton and identified $\tau_{\text{had-vis}}$ candidate must have opposite electric charge and be back to back in the transverse plane: $|\Delta\phi(\mathbf{p}_T^\ell, \mathbf{p}_T^{\tau_{\text{had-vis}}})| > 2.4$ rad, as tau leptons from the decay of heavy neutral resonances are typically produced back to back in the transverse plane. To reduce background from W + jets production, the transverse mass of the isolated lepton and the missing transverse momentum,

$$m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) \equiv \sqrt{2p_T^\ell E_T^{\text{miss}} [1 - \cos \Delta\phi(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}})]},$$

must be less than 40 GeV. To reduce background from $Z \rightarrow ee$ production in the $\tau_e\tau_{\text{had}}$ channel, events where the isolated lepton and identified $\tau_{\text{had-vis}}$ candidate have an invariant mass between 80 and 110 GeV are rejected. The signal acceptance times efficiency for this selection (calculated with respect to all possible ditau final states) varies between 1% and 7% depending on the mass. The maximum occurs for signals with masses of around 0.8 TeV, while degradations occur at lower masses due to the lepton and $\tau_{\text{had-vis}}$ p_T thresholds and at higher masses due to the $\tau_{\text{had-vis}}$ reconstruction and identification efficiencies. A summary of the selection is given in Table 1 of Section 6.

5.2 $\tau_{\text{had}}\tau_{\text{had}}$ channel

Events in the $\tau_{\text{had}}\tau_{\text{had}}$ channel are recorded using single-tau triggers with p_T thresholds of 80, 125 or 160 GeV, depending on the data-taking period. Events must contain at least two $\tau_{\text{had-vis}}$ candidates with $p_T > 65$ GeV and no electrons or muons. The leading- p_T $\tau_{\text{had-vis}}$ candidate must be geometrically matched to the trigger signature and must exceed the trigger p_T threshold by 5 GeV. The leading and sub-leading $\tau_{\text{had-vis}}$ candidates must satisfy the “medium” and “loose” identification criteria, respectively. They must also have opposite electric charge and be back to back in the transverse plane: $|\Delta\phi(\mathbf{p}_T^{\tau_1}, \mathbf{p}_T^{\tau_2})| > 2.7$ rad. The signal acceptance times efficiency for this selection also varies between 1% and 7% for signals with masses of 0.35 TeV or higher, but decreases rapidly for lower masses due to the higher $\tau_{\text{had-vis}}$ p_T thresholds. A summary of the selection is given in Table 1 of Section 6.

5.3 Event categories

Events satisfying the selection criteria in the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are categorised to exploit the different production modes in the MSSM. Events containing at least one b -tagged jet enter the b -tag category, while events containing no b -tagged jets enter the b -veto category. The categorisation is not used for the Z' search.

5.4 Ditau mass reconstruction

The ditau mass reconstruction is important for achieving good separation between signal and background. However, ditau mass reconstruction is challenging due to the presence of neutrinos from the τ -lepton

decays. Therefore, the mass reconstruction used for both the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels is the total transverse mass, defined as:

$$m_{\text{T}}^{\text{tot}} \equiv \sqrt{(p_{\text{T}}^{\tau_1} + p_{\text{T}}^{\tau_2} + E_{\text{T}}^{\text{miss}})^2 - (\mathbf{p}_{\text{T}}^{\tau_1} + \mathbf{p}_{\text{T}}^{\tau_2} + \mathbf{E}_{\text{T}}^{\text{miss}})^2},$$

where $\mathbf{p}_{\text{T}}^{\tau_1}$ and $\mathbf{p}_{\text{T}}^{\tau_2}$ are the momenta of the visible tau decay products (including τ_{had} and τ_{lep}) projected into the transverse plane. More complex mass reconstruction techniques were investigated, but they did not improve the expected sensitivity.

6 Background estimation

The dominant background contribution in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel arises from processes where the $\tau_{\text{had-vis}}$ candidate originates from a quark- or gluon-initiated jet (henceforth called jet). This contribution is estimated using a data-driven fake-factor technique, described in Section 6.1. The events are divided into those where the selected lepton is correctly identified, predominantly from W +jets ($t\bar{t}$) production in the b -veto (b -tag) channel, and those where the selected lepton arises from a jet, predominantly from multijet production. Backgrounds where both the $\tau_{\text{had-vis}}$ and lepton candidates originate from electrons, muons or taus (real-lepton) arise from $Z/\gamma^* \rightarrow \tau\tau$ production in the b -veto category and $t\bar{t}$ production in the b -tag category, with minor contributions from $Z/\gamma^* \rightarrow \ell\ell$, diboson and single top-quark production. These contributions are estimated using simulation. Corrections are applied to the simulation to account for mismodelling of the trigger, reconstruction, identification and isolation efficiencies, the electron to $\tau_{\text{had-vis}}$ misidentification rate and the momentum scales and resolutions. To help constrain the normalisation of the $t\bar{t}$ contribution, a control region rich in $t\bar{t}$ events (CR-T) is defined and included in the statistical fitting procedure. The other major background contributions can be adequately constrained in the signal regions. Events in this control region must pass the signal selection for the b -tag category, but the $m_{\text{T}}(\mathbf{p}_{\text{T}}^{\ell}, \mathbf{E}_{\text{T}}^{\text{miss}})$ selection is replaced by $m_{\text{T}}(\mathbf{p}_{\text{T}}^{\ell}, \mathbf{E}_{\text{T}}^{\text{miss}}) > 110$ (100) GeV in the $\tau_e\tau_{\text{had}}$ ($\tau_{\mu}\tau_{\text{had}}$) channel. The tighter selection in the $\tau_e\tau_{\text{had}}$ channel is used to help suppress the larger multijet contamination. The region has $\sim 90\%$ $t\bar{t}$ purity.

The dominant background in the $\tau_{\text{had}}\tau_{\text{had}}$ channel is multijet production, which is estimated using a fake-factor technique similar to the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, described in Section 6.2. Other important background contributions come from $Z/\gamma^* \rightarrow \tau\tau$ production at high $m_{\text{T}}^{\text{tot}}$ in the b -veto category, $t\bar{t}$ production in the b -tag category, and to a lesser extent $W(\rightarrow \ell\nu)$ +jets, single top-quark, diboson and $Z/\gamma^*(\rightarrow \ell\ell)$ +jets production. These contributions are estimated using simulation. To improve the modelling, events in the simulation that contain jets misidentified as $\tau_{\text{had-vis}}$ candidates are weighted by fake-rates measured in W +jets and $t\bar{t}$ control regions in data.

Fake-factor techniques are employed in both channels and use events in control regions (CRs) where a selected $\tau_{\text{had-vis}}$ fails identification or a selected lepton fails isolation. The events are weighted by transfer-factors (fake-factors) measured in orthogonal fakes regions (FRs) to predict a given background contribution. The fake-factors are defined as the number of events in data that pass ($N_{\text{data}}^{\text{pass}}$) divided by the number that fail ($N_{\text{data}}^{\text{fail}}$) a specified selection requirement. The corresponding number of background events (N_{bkg}) is subtracted and they are parameterised with a set of auxiliary variables ($\mathbf{x}$):

$$f(\mathbf{x}) \equiv \frac{N_{\text{data}}^{\text{pass}}(\mathbf{x}) - N_{\text{bkg}}^{\text{pass}}(\mathbf{x})}{N_{\text{data}}^{\text{fail}}(\mathbf{x}) - N_{\text{bkg}}^{\text{fail}}(\mathbf{x})}.$$

Table 1: Definition of signal, control and fakes regions used in the analysis. The symbol ℓ represents the selected electron or muon candidate and τ_1 (τ_2) represents the leading (sub-leading) $\tau_{\text{had-vis}}$ candidate.

Channel	Region	Selection
$\tau_{\text{lep}}\tau_{\text{had}}$	SR	ℓ (trigger, isolated), τ_1 (medium), $q(\ell) \times q(\tau_1) < 0$, $ \Delta\phi(\mathbf{p}_T^\ell, \mathbf{p}_T^{\tau_1}) > 2.4$, $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) < 40$ GeV, veto $80 < m(\mathbf{p}^\ell, \mathbf{p}^{\tau_1}) < 110$ GeV ($\tau_e\tau_{\text{had}}$ channel only)
	CR-1	Pass SR except: τ_1 (very-loose, fail medium)
	CR-2	Pass SR except: τ_1 (very-loose, fail medium), ℓ (fail isolation)
	MJ-FR	Pass SR except: τ_1 (very-loose), ℓ (fail isolation)
	W-FR	Pass SR except: $70(60) < m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) < 150$ GeV in $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) channel
	CR-T	Pass SR except: $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) > 110(100)$ GeV in the $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) channel, b -tag category only
	L-FR	ℓ (trigger, selected), jet (selected), no loose $\tau_{\text{had-vis}}$, $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) < 30$ GeV
$\tau_{\text{had}}\tau_{\text{had}}$	SR	τ_1 (trigger, medium), τ_2 (loose), $q(\tau_1) \times q(\tau_2) < 0$, $ \Delta\phi(\mathbf{p}_T^{\tau_1}, \mathbf{p}_T^{\tau_2}) > 2.7$
	CR-1	Pass SR except: τ_2 (fail loose)
	DJ-FR	jet trigger, $\tau_1 + \tau_2$ (no identification), $q(\tau_1) \times q(\tau_2) < 0$, $ \Delta\phi(\mathbf{p}_T^{\tau_1}, \mathbf{p}_T^{\tau_2}) > 2.7$, $p_T^{\tau_2}/p_T^{\tau_1} > 0.3$
	W-FR	μ (trigger, isolated), τ_1 (no identification), $ \Delta\phi(\mathbf{p}_T^\mu, \mathbf{p}_T^{\tau_1}) > 2.4$, $m_T(\mathbf{p}_T^\mu, \mathbf{E}_T^{\text{miss}}) > 40$ GeV, b -veto category only
	T-FR	Pass W-FR except: b -tag category only

For reference, a summary of the signal, control and fakes regions used for the background estimation techniques described in this section is provided in Table 1.

6.1 Jet background estimate in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel

The background contribution in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel where the $\tau_{\text{had-vis}}$ candidate originates from a jet is estimated using a fake-factor method to weight events in a control region which has the same selection as the signal region (SR), but where the $\tau_{\text{had-vis}}$ candidate fails identification (CR-1). The method, however, must be extended to account for the fact that multijet and W +jets (or $t\bar{t}$) events have significantly different fake-factors, which is mainly due to a different fraction of quark-initiated jets, which are typically more narrow and produce fewer hadrons than gluon-initiated jets, and are thus more likely to pass the $\tau_{\text{had-vis}}$ identification. The procedure, depicted in Figure 2, is described in the following.

The contribution from W +jets (and $t\bar{t}$) events where the $\tau_{\text{had-vis}}$ candidate originates from a jet is estimated from events in CR-1 that remain after subtracting the multijet contribution (estimated using the technique described below) and the real-lepton contribution (estimated using simulation). The events are weighted by the W +jets tau fake-factor (f_W):

$$N_{W+\text{jets}}^{\text{SR}}(v; \mathbf{x}) = f_W(\mathbf{x}) \times \left[N_{\text{data}}^{\text{CR-1}}(v; \mathbf{x}) - N_{\text{multijet}}^{\text{CR-1}}(v; \mathbf{x}) - N_{\text{real-lepton}}^{\text{CR-1}}(v; \mathbf{x}) \right],$$

where v is the variable being modelled (e.g. m_T^{tot}) and $\mathbf{x}$ is the set of auxiliary variables from the f_W parameterisation: $\tau_{\text{had-vis}}$ p_T , $\tau_{\text{had-vis}}$ track multiplicity and the azimuthal $\tau_{\text{had-vis}}-\mathbf{E}_T^{\text{miss}}$ separation, $|\Delta\phi(\mathbf{p}_T^{\tau_{\text{had-vis}}}, \mathbf{E}_T^{\text{miss}})|$. The fake-factor f_W is measured in the W +jets fakes-region (W-FR) defined in Section 6.1.1.

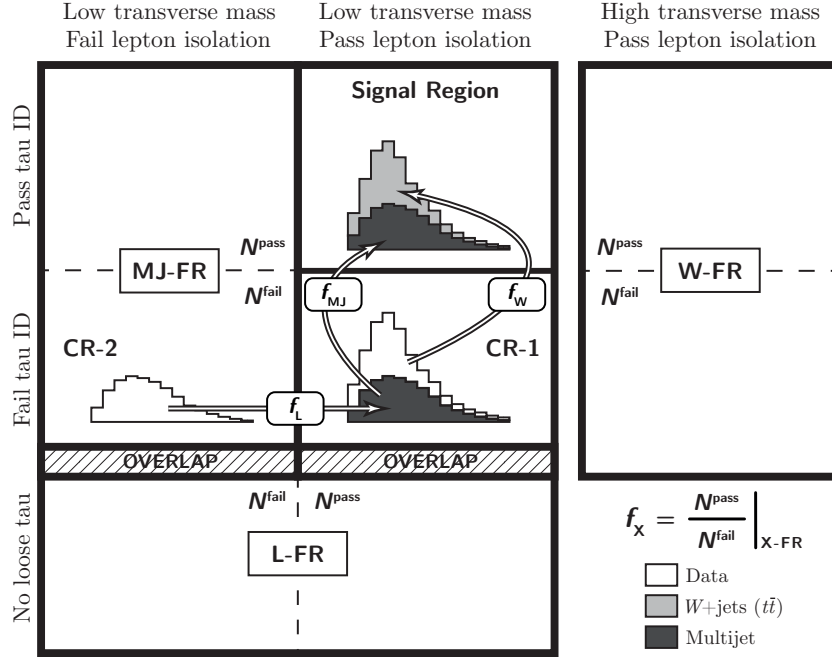


Figure 2: Schematic of the fake-factor background estimation in the $\tau_{lep}\tau_{had}$ channel. The fake-factors, f_X ($X = MJ, W, L$), are defined as the ratio of events in data that pass/fail the specified selection requirements, measured in the fakes-regions: MJ-FR, W-FR and L-FR, respectively. The multijet contribution is estimated by weighting events in CR-2 by the product of f_L and f_{MJ} . The contribution from W +jets and $t\bar{t}$ events where the $\tau_{had-vis}$ candidate originates from a jet is estimated by subtracting the multijet contribution from CR-1 and then weighting by f_W . There is a small overlap of events between L-FR and the CR-1 and CR-2 regions. The contribution where both the selected $\tau_{had-vis}$ and lepton originate from leptons is estimated using simulation (not shown here).

The multijet contributions in both CR-1 ($N_{multijet}^{CR-1}$) and SR ($N_{multijet}^{SR}$) are estimated from events where the $\tau_{had-vis}$ fails identification and the selected lepton fails isolation (CR-2). The non-multijet background is subtracted using simulation and the events are weighted first by the lepton-isolation fake-factor (f_L), yielding $N_{multijet}^{CR-1}$, and then by the multijet tau fake-factor (f_{MJ}):

$$N_{multijet}^{SR}(v; \mathbf{x}, \eta^\ell) = f_{MJ}(\mathbf{x}) \times N_{multijet}^{CR-1}(v; \mathbf{x}, \eta^\ell),$$

$$N_{multijet}^{CR-1}(v; \mathbf{x}, \eta^\ell) = f_L(\eta^\ell) \times \left[N_{data}^{CR-2}(v; \mathbf{x}, \eta^\ell) - N_{non-MJ}^{CR-2}(v; \mathbf{x}, \eta^\ell) \right],$$

where η^ℓ is the pseudorapidity of the isolated lepton, which is used to parameterise f_L . The fake-factor f_{MJ} is measured in the multijet fakes-region (MJ-FR) defined in Section 6.1.1 and the fake-factor f_L is measured in the lepton fakes-region (L-FR) defined in Section 6.1.2.

6.1.1 Tau identification fake-factors

Both f_W and f_{MJ} are parameterised as functions of $\tau_{had-vis}$ p_T , $\tau_{had-vis}$ track multiplicity and $|\Delta\phi(\mathbf{p}_T^{\tau_{had-vis}}, \mathbf{E}_T^{miss})|$. The $|\Delta\phi(\mathbf{p}_T^{\tau_{had-vis}}, \mathbf{E}_T^{miss})|$ dependence is included to encapsulate correlations between

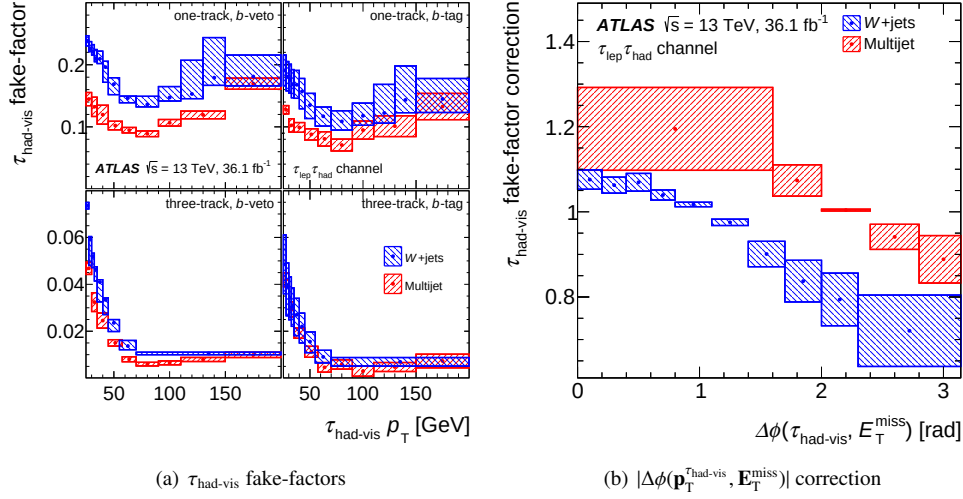


Figure 3: The $\tau_{\text{had-vis}}$ identification fake-factors and the sequential $|\Delta\phi(\mathbf{p}_T^{\tau_{\text{had-vis}}}, \mathbf{E}_T^{\text{miss}})|$ correction in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. The multijet fake-factors are for the 2016 dataset only. The bands include all uncertainties.

the $\tau_{\text{had-vis}}$ identification and energy response, which impact the $\mathbf{E}_T^{\text{miss}}$ calculation. Due to the limited size of the control regions, the $|\Delta\phi(\mathbf{p}_T^{\tau_{\text{had-vis}}}, \mathbf{E}_T^{\text{miss}})|$ dependence is extracted as a sequential correction and is only applied in the b -veto channel. The selection for W-FR and MJ-FR are the same as for SR with modifications described in the following. The medium $\tau_{\text{had-vis}}$ identification criterion is replaced by a very loose criterion with an efficiency of about 99% for $\tau_{\text{had-vis}}$ and a rejection of about 2 (3) for one-track (three-track) jets. Events passing the medium identification criterion enter the fake-factor numerators, while those failing enter the denominators. The very loose identification reduces differences between f_W and f_{MJ} , as it tends to reject gluon-initiated jets, enhancing the fraction of quark-initiated jets in W-FR and MJ-FR. This selection is also applied consistently to CR-1. A comparison of the two fake-factors and their respective $|\Delta\phi(\mathbf{p}_T^{\tau_{\text{had-vis}}}, \mathbf{E}_T^{\text{miss}})|$ corrections are shown in Figures 3(a) and 3(b).

In the W-FR, the $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}})$ criterion is replaced by $70(60) < m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) < 150$ GeV in the $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) channel. The purity of W+jets events that pass the $\tau_{\text{had-vis}}$ identification is $\sim 85\%$ in the b -veto category. The b -tag category is dominated by $t\bar{t}$ events, but the purity of events where the $\tau_{\text{had-vis}}$ candidate originates from a jet is only $\sim 40\%$ due to the significant fraction of $\tau_{\text{had-vis}}$ from W boson decays. The multijet and real-lepton backgrounds are subtracted from W-FR analogously to CR-1 in the W+jets estimate. Due to the large $\tau_{\text{had-vis}}$ contamination in the b -tag region, f_W is not split by category, but the b -veto parameterisation is used in the b -tag region, with a p_T -independent correction factor of 0.8 (0.66) for one-track (three-track) $\tau_{\text{had-vis}}$. The correction factor is obtained from a direct measurement of the fake-factors in b -tag events. The subtraction of the simulated samples is affected by experimental uncertainties and uncertainties in production cross sections, which amount to 10%. The total uncertainty in the multijet estimate is also propagated to the subtraction. Due to the large contamination for b -tag events in the W-FR, a 50% uncertainty is assigned to the correction factor applied to the b -veto parameterisation. The applicability of f_W measured in the W-FR to CR-1 is investigated by studying f_W as a function of $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}})$ and the observed differences (up to $\sim 10\%$) are assigned as a systematic uncertainty. A 30% uncertainty is assigned to the sequential $|\Delta\phi(\mathbf{p}_T^{\tau_{\text{had-vis}}}, \mathbf{E}_T^{\text{miss}})|$ correction, based on

variations observed as a function of $\tau_{\text{had-vis}} p_T$.

In MJ-FR, the selected lepton must fail isolation. The multijet purity for events that pass the $\tau_{\text{had-vis}}$ identification in this region is $\sim 88\%$ for the b -veto category and $\sim 93\%$ for the b -tag category. All non-multijet contamination is subtracted from MJ-FR using simulation. The fake-factor f_{MJ} is further split by category (b -veto, b -tag) and by data-taking period (2015, 2016) to account for changing isolation criteria in the trigger that affect MJ-FR differently to SR. The applicability of f_{MJ} measured in MJ-FR to CR-1 is investigated by studying f_{MJ} as a function of the lepton isolation and the observed differences are assigned as a systematic uncertainty. The statistical uncertainty from the limited size of MJ-FR is significant, particularly for the smaller 2015 dataset. The impact of a potential mismodelling in the subtraction of simulated non-multijet events containing non-isolated leptons is investigated by varying the subtraction by 50%, but is found to be small compared to the other sources of systematic uncertainty. A constant uncertainty of 20% in f_{MJ} is used to envelop these variations. A 50% uncertainty is assigned to the sequential $|\Delta\phi(\mathbf{p}_T^{\tau_{\text{had-vis}}}, \mathbf{E}_T^{\text{miss}})|$ correction.

6.1.2 Lepton isolation fake-factor

The fake-factor f_L is measured in L-FR, which must have exactly one selected lepton, $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) < 30 \text{ GeV}$ and no $\tau_{\text{had-vis}}$ candidates passing the loose identification but rather at least one selected jet (not counting the b -tagged jet in the b -tag region). The selection is designed to purify multijet events while suppressing W +jets and $t\bar{t}$ events. Events where the selected lepton passes (fails) isolation enter the f_L numerator (denominator). All non-multijet contributions are subtracted using simulation. The fake-factors are parameterised as a function of lepton $|\eta|$, and are further split by lepton type (electron, muon), category (b -veto, b -tag) and into two regions of muon p_T , due to differences in the isolation criteria of the low- and high- p_T triggers in the $\tau_\mu\tau_{\text{had}}$ channel. A 20% uncertainty in the background subtraction is considered, motivated by observations of the tau identification performance in W +jets events. The applicability of f_L measured in L-FR to events in MJ-FR is investigated by altering the $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}})$ selection and the observed differences are assigned as a systematic uncertainty. The statistical uncertainty from the limited size of L-FR is also considered, but is relatively small. The total uncertainty in f_L is 5–50%.

6.2 Jet background estimate in the $\tau_{\text{had}}\tau_{\text{had}}$ channel

The fake-factor technique used to estimate the dominant multijet background in the $\tau_{\text{had}}\tau_{\text{had}}$ channel is described in Section 6.2.1. The method used to weight simulated events to estimate the remaining background containing events with $\tau_{\text{had-vis}}$ candidates that originate from jets is described in Section 6.2.2.

6.2.1 Multijet events

The contribution of multijet events in SR is estimated by weighting events in a control region that has the same selection as SR, but where the sub-leading $\tau_{\text{had-vis}}$ candidate fails identification (CR-1), by the dijet tau fake-factor (f_{DJ}), which is measured in the dijet fakes-region (DJ-FR):

$$N_{\text{multijet}}^{\text{SR}}(v; \mathbf{y}) = f_{\text{DJ}}(\mathbf{y}) \times [N_{\text{data}}^{\text{CR-1}}(v; \mathbf{y}) - N_{\text{non-MJ}}^{\text{CR-1}}(v; \mathbf{y})],$$

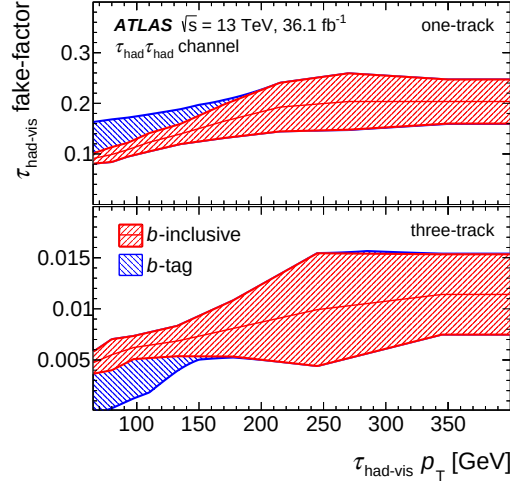


Figure 4: The $\tau_{\text{had-vis}}$ identification fake-factors in the $\tau_{\text{had}}\tau_{\text{had}}$ channel. The red band indicates the total uncertainty when used with a b -inclusive or b -veto selection. The blue band indicates the additional uncertainty when used with a b -tag selection.

where $\mathbf{y}$ is the set of auxiliary variables from the f_{DJ} parameterisation: sub-leading $\tau_{\text{had-vis}}$ p_{T} and sub-leading $\tau_{\text{had-vis}}$ track multiplicity. Unlike in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, CR-1 is completely dominated by multijet events, so a single fake-factor is sufficient. The non-multijet contamination in CR-1, $N_{\text{non-MJ}}^{\text{CR-1}}$, amounts to $\sim 1.6\%$ ($\sim 7.0\%$) in the b -veto (b -tag) channel, and is subtracted using simulation.

The selection for the DJ-FR is designed to be as similar to the signal selection as possible, while avoiding contamination from $\tau_{\text{had-vis}}$. Events are selected by single-jet triggers with p_{T} thresholds ranging from 60 to 380 GeV, with all but the highest-threshold trigger being prescaled. They must contain at least two $\tau_{\text{had-vis}}$ candidates, where the leading candidate has $p_{\text{T}} > 85$ GeV and also exceeds the trigger threshold by 10%, and the sub-leading candidate has $p_{\text{T}} > 65$ GeV. The $\tau_{\text{had-vis}}$ candidates must have opposite charge sign, be back to back in the transverse plane, $|\Delta\phi(\mathbf{p}_{\text{T}}^{\tau_1}, \mathbf{p}_{\text{T}}^{\tau_2})| > 2.7$ rad and the p_{T} of the sub-leading $\tau_{\text{had-vis}}$ must be at least 30% of the leading $\tau_{\text{had-vis}}$ p_{T} . Unlike in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, the very loose $\tau_{\text{had-vis}}$ identification is not required as the background is dominated by a single process (multijet production), so there is no need to restrict the contribution from gluon-initiated jets. The fake-factors are measured using the sub-leading $\tau_{\text{had-vis}}$ candidate to avoid trigger bias and to be consistent with their application in CR-1. The purity of multijet events that pass the $\tau_{\text{had-vis}}$ identification is 98–99% (93–98%) for the b -veto (b -tag) categories. The non-multijet contamination is subtracted using simulation. The dominant uncertainty in the fake-factors is typically due to the limited size of the DJ-FR, and is 10–50%; however, the subtraction of the non-multijet contamination can also result in uncertainties up to 50%. An additional uncertainty is considered when applying the fake-factors in the b -tag category, which accounts for changes in the jet composition with respect to the inclusive selection of the DJ-FR. As the differences are extracted from comparisons in control regions, they are one-sided. The fake-factors are shown in Figure 4.

6.2.2 Non-multijet events

In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, backgrounds originating from jets that are misidentified as $\tau_{\text{had-vis}}$ in processes other than multijet production (predominantly W +jets in the b -veto and $t\bar{t}$ in the b -tag categories) are estimated using simulation. Rather than applying the $\tau_{\text{had-vis}}$ identification to the simulated jets, they are weighted by fake-rates as in Ref. [43]. This not only ensures the correct fake-rate, but also enhances the statistical precision of the estimate, as events failing the $\tau_{\text{had-vis}}$ identification are not discarded. The fake-rate for the sub-leading $\tau_{\text{had-vis}}$ candidate is defined as the ratio of the number of candidates that pass the identification to the total number of candidates. The fake-rate for the leading $\tau_{\text{had-vis}}$ candidate is defined as the ratio of the number of candidates that pass the identification and the single-tau trigger requirement to the total number of candidates.

The fake-rates applied to $t\bar{t}$ and single-top-quark events are calculated from a fakes region enriched in $t\bar{t}$ events (T-FR), while the fake-rates for all other processes are calculated in a fakes region enriched in W +jets events (W-FR). Both T-FR and W-FR use events selected by a single-muon trigger with a p_T threshold of 50 GeV. They must contain exactly one isolated muon with $p_T > 55$ GeV that fired the trigger, no electrons and at least one $\tau_{\text{had-vis}}$ candidate with $p_T > 50$ GeV. The events must also satisfy $|\Delta\phi(\mathbf{p}_T^\mu, \mathbf{p}_T^{\tau_{\text{had-vis}}})| > 2.4$ rad and $m_T(\mathbf{p}_T^\mu, \mathbf{E}_T^{\text{miss}}) > 40$ GeV. The events are then categorised into b -tag and b -veto categories, defining T-FR and W-FR, respectively. Backgrounds from non- $t\bar{t}$ (non- W +jets) processes are subtracted from T-FR (W-FR) using simulation. The fake-rates are measured using the leading- p_T $\tau_{\text{had-vis}}$ candidate and are parameterised as functions of the $\tau_{\text{had-vis}}$ p_T and track multiplicity. The uncertainty in the fake-rates is dominated by the limited size of the fakes regions and can reach 40%.

7 Systematic uncertainties

In this section, uncertainties affecting the simulated signal and background contributions are discussed. These include uncertainties associated with the determination of the integrated luminosity, the detector simulation, the theoretical cross sections and the modelling from the event generators. The uncertainties associated with the data-driven background estimates are discussed in Section 6.

The uncertainty in the combined 2015+2016 integrated luminosity is 3.2%, which affects all simulated samples. It is derived, following a methodology similar to that detailed in Ref. [136], from a preliminary calibration of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016. The uncertainty related to the overlay of pile-up events is estimated by varying the average number of interactions per bunch crossing by 9%. The uncertainties related to the detector simulation manifest themselves through the efficiency of the reconstruction, identification and triggering algorithms, and the energy scale and resolution for electrons, muons, $\tau_{\text{had-vis}}$, (b -)jets and the $\mathbf{E}_T^{\text{miss}}$ soft term. These uncertainties are considered for all simulated samples; their impact is taken into account when estimating signal and background contributions and when subtracting contamination from regions in the data-driven estimates. The effects of the particle energy-scale uncertainties are propagated to $\mathbf{E}_T^{\text{miss}}$. The uncertainty in the $\tau_{\text{had-vis}}$ identification efficiency as determined from measurements of $Z \rightarrow \tau\tau$ events is 5–6%. At high p_T , there are no abundant sources of real hadronic tau decays from which an efficiency measurement could be made. Rather, the tau identification is studied in high- p_T dijet events as a function of the jet p_T , which indicates that there is no degradation in the modelling of the detector response as a function of the p_T of tau candidates. Based on the limited precision of these studies, an additional uncertainty of

20%/TeV (25%/TeV) for one-track (three-track) $\tau_{\text{had-vis}}$ candidates with $p_T > 150$ GeV is assigned. The $\tau_{\text{had-vis}}$ trigger efficiency uncertainty is 3–14%. The uncertainty in the $\tau_{\text{had-vis}}$ energy scale is 2–3%. The probability for electrons to be misidentified as $\tau_{\text{had-vis}}$ is measured with a precision of 3–14% [133]. The electron, muon, jet and $\mathbf{E}_T^{\text{miss}}$ systematic uncertainties described above are found to have a very small impact.

Theoretical cross-section uncertainties are taken into account for all backgrounds estimated using simulation. For Z/γ^* +jets production, uncertainties are taken from Ref. [137] and include variations of the PDF sets, scale, α_S , beam energy, electroweak corrections and photon-induced corrections. A single 90% CL eigenvector variation uncertainty is used, based on the CT14nnlo PDF set. The variations amount to a $\sim 5\%$ uncertainty in the total number of Z/γ^* +jets events within the acceptance. For diboson production, an uncertainty of 10% is used [101, 138]. For $t\bar{t}$ [110] and single top-quark [111, 112] production, the assigned 6% uncertainty is based on PDF, scale and top-quark mass variations. Additional uncertainties related to initial- and final-state radiation modelling, tune and (for $t\bar{t}$ only) the choice of `hdamp` parameter value in PowHEG-Box v2, which controls the amount of radiation produced by the parton shower, are also taken into account [139]. The uncertainty due to the hadronisation model is evaluated by comparing $t\bar{t}$ events generated with PowHEG-Box v2 interfaced to either Herwig++ [140] or PyTHIA 6. To estimate the uncertainty in generating the hard scatter, the PowHEG and MG5_aMC@NLO event generators are compared, both interfaced to the Herwig++ parton shower model. The uncertainties in the W + jets cross section have a negligible impact in the $\tau_{\text{had}}\tau_{\text{had}}$ channel and the W + jets simulation is not used in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel.

For MSSM Higgs boson samples, various sources of uncertainty which impact the signal acceptance are considered. The impact from varying the factorisation and renormalisation scales up and down by a factor of two, either coherently or oppositely, is taken into account. Uncertainties due to the modelling of initial- and final-state radiation, as well as multiple parton interaction are also taken into account. These uncertainties are estimated from variations of the PyTHIA 8 A14 tune [59] for the b -associated production and the AZNLO PyTHIA 8 tune [58] for the gluon–gluon fusion production. The envelope of the variations resulting from the use of the alternative PDFs in the PDF4LHC15_nlo_nf4_30 (PDF4LHC15_nlo_100) [141] set is used to estimate the PDF uncertainty for the b -associated (gluon–gluon fusion) production. The total uncertainty for the MSSM Higgs boson samples is typically 1–4%, which is dominated by variations of the radiation and multiple parton interactions, with minor impact from scale variations. The Z' signal acceptance uncertainties are expected to be negligible.

For both the MSSM Higgs boson and Z' samples, uncertainties in the integrated cross section are not included in the fitting procedure used to extract experimental cross-section limits. The uncertainty for Z' is included when overlaying model cross sections, in which case it is calculated using the same procedure as for the Z/γ^* +jets background.

8 Results

The number of observed events in the signal regions of the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels together with the predicted event yields from signal and background processes are shown in Table 2. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, all events estimated using the data-driven fake-factor technique are grouped as $\text{Jet} \rightarrow \tau$ fake, while events where the $\tau_{\text{had-vis}}$ originates from a jet are removed from the other processes. In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, the multijet process is estimated using the fake-factor technique while contributions from all other processes are estimated using simulation with data-driven corrections for the $\tau_{\text{had-vis}}$ candidates that

Table 2: Observed number of events and predictions of signal and background contributions in the b -veto and b -tag categories of the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. The background predictions and uncertainties (including both the statistical and systematic components) are obtained before (pre-fit) and after (post-fit) applying the statistical fitting procedure discussed in Section 8. The individual uncertainties are correlated, and do not necessarily add in quadrature to the total background uncertainty. The label “Others” refers to contributions from diboson, $Z/\gamma^*(\rightarrow \ell\ell)+\text{jets}$ and $W(\rightarrow \ell\nu)+\text{jets}$ production. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, events containing a $\tau_{\text{had-vis}}$ candidate that originate from jets are removed from all processes other than $\text{Jet} \rightarrow \tau$ fake. The expected pre-fit contributions from A and H bosons with masses of 300, 500 and 800 GeV and $\tan\beta = 10$ in the hMSSM scenario are also shown.

Channel	Process	b -veto		b -tag	
		pre-fit	post-fit	pre-fit	post-fit
$\tau_{\text{lep}}\tau_{\text{had}}$	$Z/\gamma^* \rightarrow \tau\tau$	92 000 $\pm$ 11 000	96 400 $\pm$ 1600	670 $\pm$ 140	690 $\pm$ 70
	Diboson	880 $\pm$ 100	920 $\pm$ 70	6.3 $\pm$ 1.7	6.5 $\pm$ 1.4
	$t\bar{t}$ and single top-quark	1050 $\pm$ 170	1090 $\pm$ 130	2800 $\pm$ 400	2680 $\pm$ 80
	$\text{Jet} \rightarrow \tau$ fake	83 000 $\pm$ 5000	88 800 $\pm$ 1700	3000 $\pm$ 400	3390 $\pm$ 170
	$Z/\gamma^* \rightarrow \ell\ell$	15 800 $\pm$ 1200	16 200 $\pm$ 700	86 $\pm$ 21	89 $\pm$ 16
	SM Total	193 000 $\pm$ 13 000	203 400 $\pm$ 1200	6500 $\pm$ 600	6850 $\pm$ 120
	Data	203 365		6843	
	A/H (300)	720 $\pm$ 80	–	236 $\pm$ 32	–
	A/H (500)	112 $\pm$ 11	–	39 $\pm$ 5	–
	A/H (800)	10.7 $\pm$ 1.1	–	4.8 $\pm$ 0.6	–
$\tau_{\text{had}}\tau_{\text{had}}$	Multijet	3040 $\pm$ 240	3040 $\pm$ 90	106 $\pm$ 32	85 $\pm$ 10
	$Z/\gamma^* \rightarrow \tau\tau$	610 $\pm$ 230	770 $\pm$ 80	7.5 $\pm$ 2.9	8.6 $\pm$ 1.3
	$W(\rightarrow \tau\nu)+\text{jets}$	178 $\pm$ 31	182 $\pm$ 15	4.0 $\pm$ 1.0	4.1 $\pm$ 0.5
	$t\bar{t}$ and single top-quark	26 $\pm$ 9	29 $\pm$ 4	60 $\pm$ 50	74 $\pm$ 15
	Others	25 $\pm$ 6	27.4 $\pm$ 2.1	1.0 $\pm$ 0.5	1.1 $\pm$ 0.4
	SM Total	3900 $\pm$ 400	4050 $\pm$ 70	180 $\pm$ 60	173 $\pm$ 16
	Data	4059		154	
	A/H (300)	130 $\pm$ 50	–	44 $\pm$ 19	–
	A/H (500)	80 $\pm$ 33	–	28 $\pm$ 12	–
	A/H (800)	11 $\pm$ 4	–	5.1 $\pm$ 2.2	–

originate from jets. The numbers are given before (pre-fit) and after (post-fit) applying the statistical fitting procedure described in Section 8.1. The observed event yields are compatible with the expected event yields from SM processes, within uncertainties. The $m_{\text{T}}^{\text{tot}}$ distributions in the signal regions are shown in Figures 5(a)–5(d) and in the CR-T in Figure 6.

8.1 Fit model

The parameter of interest is the signal strength, μ . It is defined as the ratio of the observed to the predicted value of the cross section times branching fraction, where the prediction is evaluated at a particular point in the parameter space of the theoretical model in question (MSSM or Z' benchmark scenarios). Hence, the value $\mu = 0$ corresponds to the absence of a signal, whereas the value $\mu = 1$ indicates the presence of a signal as predicted by the model. To estimate μ , a likelihood function constructed as the product of Poisson probability terms is used. A term is included for each bin in the $m_{\text{T}}^{\text{tot}}$ distributions from the $\tau_e\tau_{\text{had}}$, $\tau_{\mu}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. When fitting MSSM models to the data, the distributions are separated into b -tag and b -veto events to enhance sensitivity to the gluon–gluon fusion and b -associated

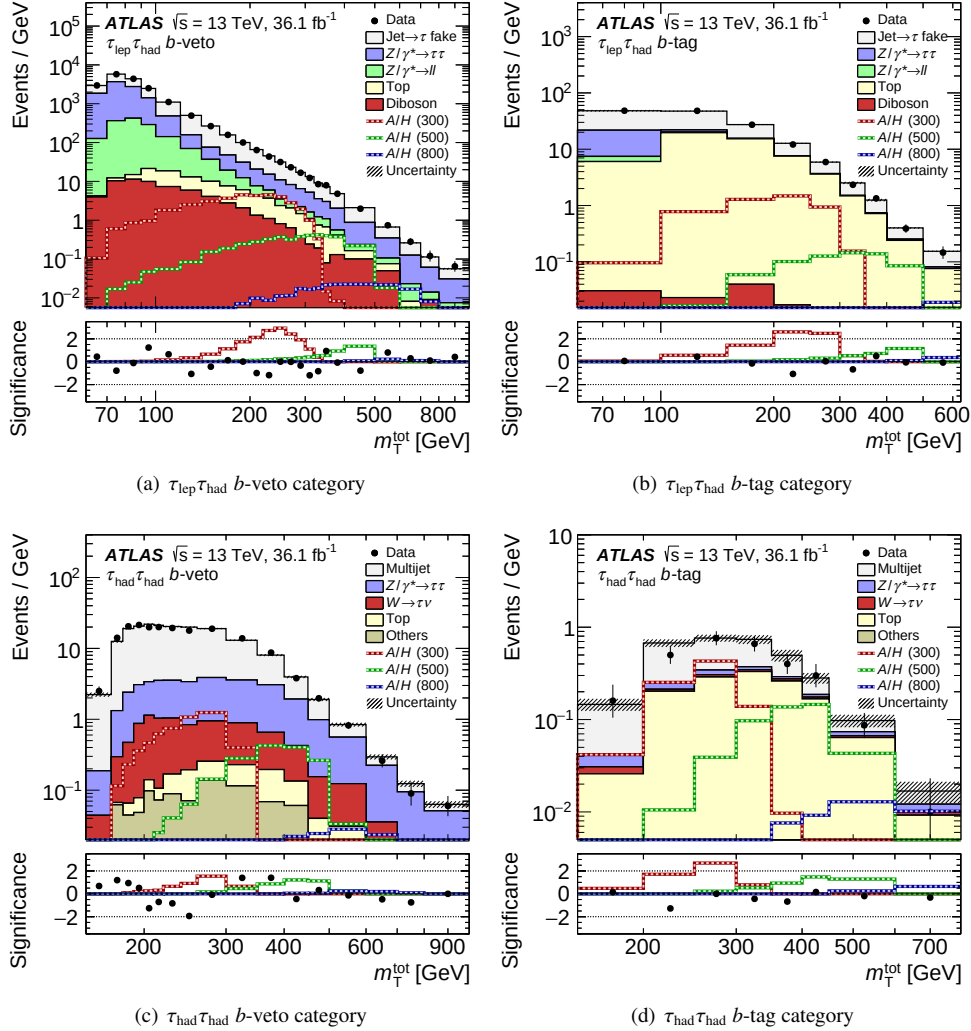


Figure 5: Distributions of m_T^{tot} for the (a) b -veto and (b) b -tag categories of the $\tau_{\text{lep}}\tau_{\text{had}}$ channel and the (c) b -veto and (d) b -tag categories of the $\tau_{\text{had}}\tau_{\text{had}}$ channel. The label “Others” refers to contributions from diboson, $Z/\gamma^*(\rightarrow \ell\ell)+\text{jets}$ and $W(\rightarrow \ell\nu)+\text{jets}$ production. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, events containing $\tau_{\text{had-vis}}$ candidates that originate from jets are removed from all processes other than Jet $\rightarrow \tau$ fake. The binning displayed is that entering into the statistical fit discussed in Section 8, with minor modifications needed to combine the $\tau_{\text{lep}}\tau_{\text{had}}$ channels and with underflows and overflows included in the first and last bins, respectively. The predictions and uncertainties for the background processes are obtained from the fit under the hypothesis of no signal. The combined prediction for A and H bosons with masses of 300, 500 and 800 GeV and $\tan\beta = 10$ in the hMSSM scenario are superimposed. The significance of the data given the fitted model and its uncertainty is computed in each bin following Ref. [142] and is shown in the lower panels. The expected significance of the hypothetical Higgs boson signals are also overlaid.

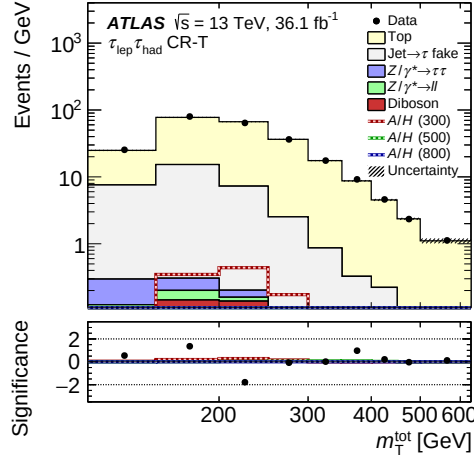


Figure 6: Distribution of m_T^{tot} in the $t\bar{t}$ enriched control region (CR-T) of the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. Events containing $\tau_{\text{had-vis}}$ candidates that originate from jets are removed from all processes other than $\text{Jet} \rightarrow \tau$ fake. The binning displayed is that entering into the statistical fit discussed in Section 8, with minor modifications needed to combine the $\tau_{\text{lep}}\tau_{\text{had}}$ channels and with underflows and overflows included in the first and last bins, respectively. The predictions and uncertainties for the background processes are obtained from the fit under the hypothesis of no signal. The combined prediction for A and H bosons with masses of 300, 500 and 800 GeV and $\tan\beta = 10$ in the hMSSM scenario are superimposed. The significance of the data given the fitted model and its uncertainty is computed in each bin following Ref. [142] and is shown in the lower panel. The expected significance of the hypothetical Higgs boson signals are also overlaid.

production modes, while the inclusive distributions are used for Z' models. In all cases, the distributions in the CR-T regions of the $\tau_e\tau_{\text{had}}$ and $\tau_\mu\tau_{\text{had}}$ channels are added, which help constrain uncertainties in the $t\bar{t}$ background. Signal and background predictions depend on systematic uncertainties, which are parameterised as nuisance parameters that are constrained using Gaussian probability density functions. The asymptotic approximation is used with the test statistic $\tilde{q}_\mu$ [143] to compare the likelihoods of the null hypothesis (SM only) and the assumed signal hypothesis (SM plus signal) given the data. The bin widths are chosen to ensure a sufficient number of background events in each bin. The results from the $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are combined to improve the sensitivity to signal. For ditau resonance masses below about 0.6 TeV, the sensitivity is dominated by the $\tau_{\text{lep}}\tau_{\text{had}}$ channels, while the $\tau_{\text{had}}\tau_{\text{had}}$ channel is most sensitive in the higher mass range.

8.2 Cross-section limits

The data are found to be in good agreement with the predicted background yields, and the results are given in terms of exclusion limits. These are set using the modified frequentist CL_s method [144]. Upper limits on the cross section times branching fraction for ϕ and Z' bosons are set at the 95% confidence level (CL) as a function of the boson mass. They are obtained by multiplying the extracted limits on μ by the respective predicted cross sections. The ϕ boson limits assume the natural width of the boson to be negligible compared to the experimental resolution (as expected over the probed MSSM parameter space). They cover the mass range 0.2–2.25 TeV and are shown separately for gluon–gluon fusion and b -quark associ-

ated production. The limits on Z' bosons are calculated assuming an SSM Z' and extend up to 4 TeV. The limits are shown in Figures 7(a)–7(c). They are in the range 0.78–0.0058 pb (0.70–0.0037 pb) for gluon–gluon fusion (b -associated) production of scalar bosons with masses of 0.2–2.25 TeV and 1.56–0.0072 pb for Drell–Yan production of Z' bosons with masses of 0.2–4 TeV. A small downward fluctuation at a mass of ~ 0.3 TeV is observed in all limits, while a small upward fluctuation for gluon–gluon fusion and Z' bosons is seen around 0.5 TeV and a broad deficit is seen for the b -quark associated production over the entire mass range. These features arise primarily because of a deficit of events in the range 200–250 GeV followed by a mild excess in the range 300–400 GeV in Figure 5(c), and by a consistent deficit of events across the whole range in Figure 5(d). Modifications of the Z' chiral coupling structure can result in changes of up to 40% in the Z' cross-section limits. Reducing the Z' width can improve the limits by up to $\sim 30\%$, while increasing the width to 36% can degrade the limits by up to $\sim 70\%$. Figures 8(a) and 8(b) show the observed and expected 95% CL upper limits on the production cross section times branching fraction for $\phi \rightarrow \tau\tau$ as a function of the fractional contribution from b -associated production ($\sigma_{bb}/[\sigma_{bb} + \sigma_{gg}]$) and the scalar boson mass.

The impact of systematic uncertainties on the $\phi \rightarrow \tau\tau$ 95% CL cross section upper limits are calculated by comparing the expected upper limit in the case of no systematic uncertainties, μ_{stat}^{95} , with a limit calculated by introducing a group of systematic uncertainties, μ_i^{95} . The systematic uncertainty impacts are shown in Figure 9(a) for gluon–gluon fusion production and Figure 9(b) for b -associated production as functions of the scalar boson mass. The major uncertainties are grouped according to their origin, while minor uncertainties are collected as “Others”.

In the low mass range, the sensitivity is dominated by the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, and the major uncertainties arise from the estimate of the dominant W + jets background. Due to the large contribution the fit is able to significantly constrain the uncertainties in this background. In the intermediate mass range the tau energy scale uncertainty becomes dominant. The fit is able to effectively constrain this conservative uncertainty due to the large contribution from $Z/\gamma^* \rightarrow \tau\tau$ and $t\bar{t}$ in each of the categories. At very high masses, the uncertainty in the identification efficiency for high- p_T $\tau_{\text{had-vis}}$ candidates becomes dominant, and due to the lack of significant $Z/\gamma^* \rightarrow \tau\tau$ and $t\bar{t}$ at high mass, this uncertainty remains relatively unconstrained. The addition of the CR-T region distributions to the fit allows the uncertainties in the $t\bar{t}$ modelling to be well constrained and as such, they have little impact on the sensitivity.

8.3 MSSM interpretation

The data are interpreted in terms of the MSSM. Figure 10 shows regions in the m_A – $\tan\beta$ plane excluded at 95% CL in the $m_h^{\text{mod}+}$ and hMSSM scenarios. Constraints in the hMSSM scenario are stronger than those in the $m_h^{\text{mod}+}$ scenario due to the presence of low-mass neutralinos in the $m_h^{\text{mod}+}$ scenario that reduce the $H/A \rightarrow \tau\tau$ branching fraction and which are absent in the hMSSM scenario. In the hMSSM scenario, the most stringent observed (expected) constraints on $\tan\beta$ for the combined search exclude $\tan\beta > 1.0$ (5.5) for $m_A = 0.25$ TeV and $\tan\beta > 42$ (48) for $m_A = 1.5$ TeV at 95% CL. The expected exclusion limit and bands around $m_A = 350$ GeV reflect the behaviour of the $A \rightarrow \tau\tau$ branching fraction close to the $A \rightarrow t\bar{t}$ kinematic threshold for low $\tan\beta$, allowing for some exclusion in this region. However, when m_A is above the $A \rightarrow t\bar{t}$ production threshold, this additional decay mode reduces the sensitivity of the $A \rightarrow \tau\tau$ search for low $\tan\beta$. In the MSSM $m_h^{\text{mod}+}$ scenario, the observed (expected) 95% CL upper limits exclude $\tan\beta > 5.1$ (7.0) for $m_A = 0.25$ TeV and $\tan\beta > 51$ (57) for $m_A = 1.5$ TeV.

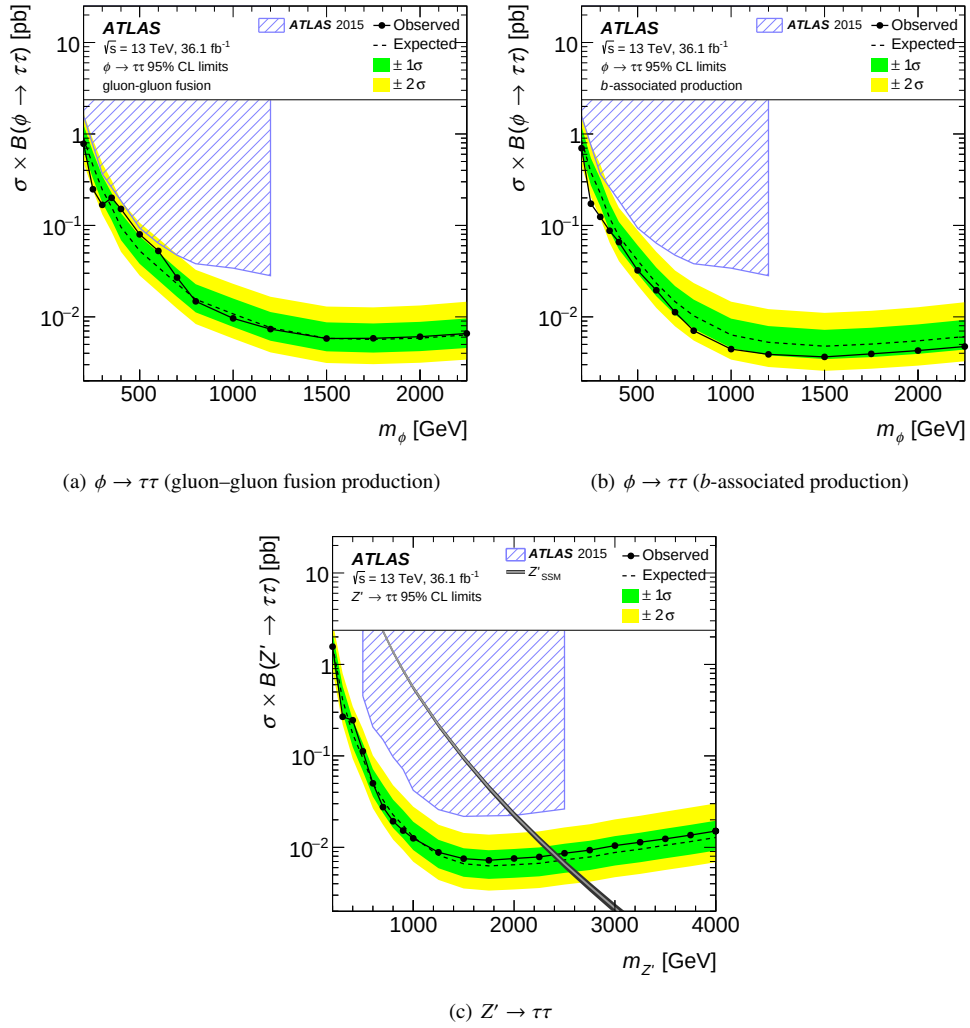


Figure 7: The observed and expected 95% CL upper limits on the production cross section times branching fraction for a scalar boson produced via (a) gluon–gluon fusion and (b) b -associated production, and for (c) gauge bosons. The limits are calculated from a statistical combination of the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. The excluded regions from the 2015 data ATLAS search [31] are depicted by the hatched blue fill. The predicted cross section for a Z'_{SSM} boson is overlaid in (c), where the band depicts the total uncertainty.

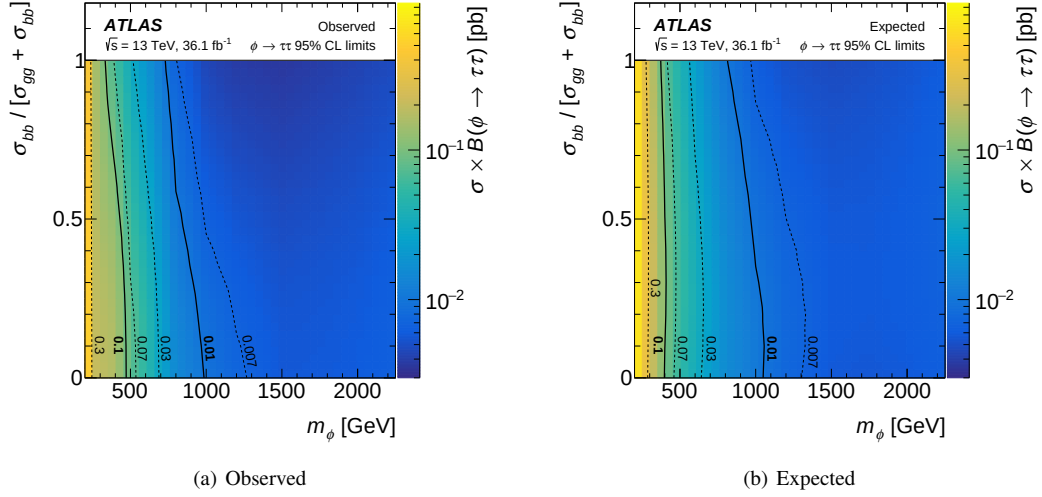


Figure 8: The (a) observed and (b) expected 95% CL upper limit on the production cross section times branching fraction for $\phi \rightarrow \tau\tau$ as a function of the fractional contribution from b -associated production and the scalar boson mass. The solid and dashed lines represent contours of fixed $\sigma \times B$.

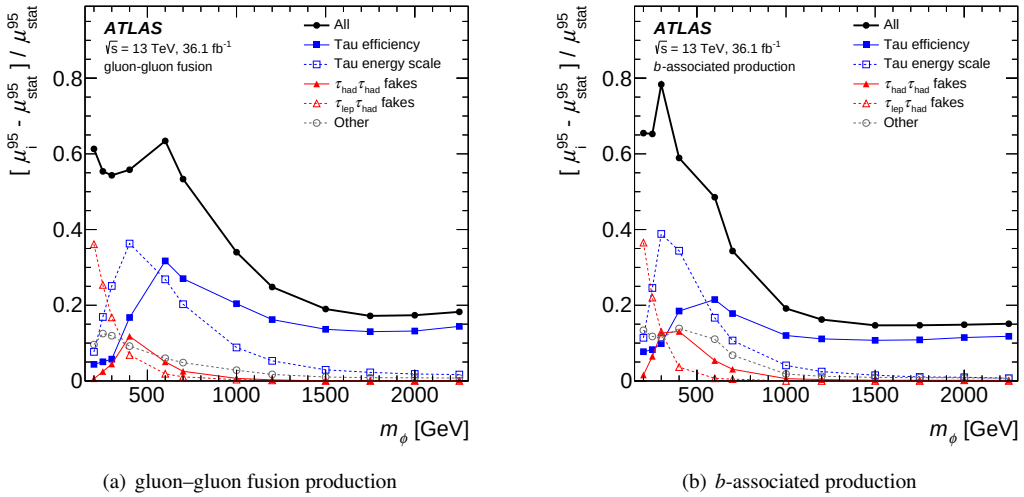


Figure 9: Impact of major groups of systematic uncertainties on the $\phi \rightarrow \tau\tau$ 95% CL cross section upper limits as a function of the scalar boson mass, separately for the (a) gluon-gluon fusion and (b) b -associated production mechanisms.

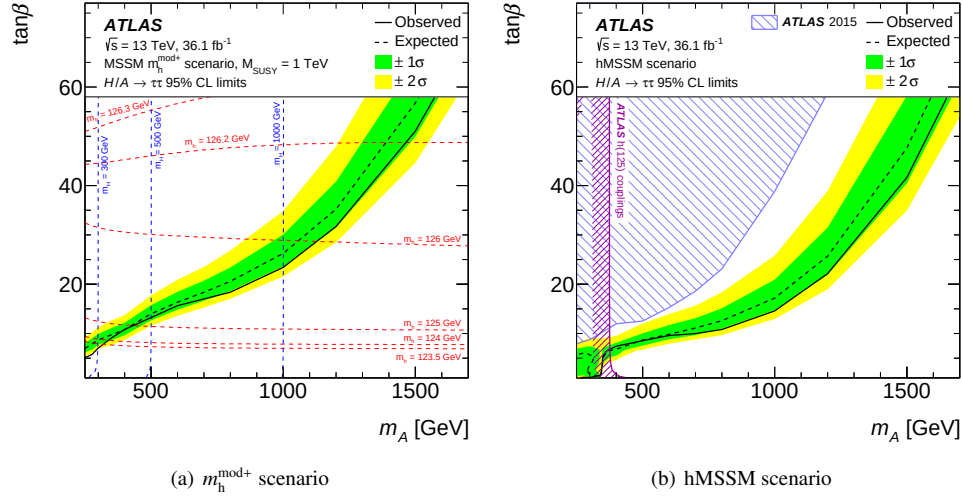


Figure 10: The observed and expected 95% CL upper limits on $\tan\beta$ as a function of m_A in the MSSM (a) $m_h^{\text{mod}+}$ and (b) hMSSM scenarios. For the $m_h^{\text{mod}+}$ scenario, dashed lines of constant m_h and m_H are shown in red and blue, respectively. For the hMSSM scenario, the exclusion arising from the SM Higgs boson coupling measurements of Ref. [145] and the exclusion limit from the ATLAS 2015 $H/A \rightarrow \tau\tau$ search result of Ref. [31] are shown.

8.4 Z' interpretations

The data are also interpreted in terms of Z' models. As shown in Figure 7(c), the observed (expected) lower limit on the mass of a Z'_{SSM} boson is 2.42 (2.47) TeV at 95% CL. Limits at 95% CL are also placed on Z'_{NU} bosons as a function of $m_{Z'}$ and the mixing angle between the heavy and light SU(2) gauge groups, ϕ , as shown in Figure 11. Masses below 2.25–2.60 TeV are excluded in the range $0.03 < \sin^2\phi < 0.5$ assuming no μ – τ mixing.

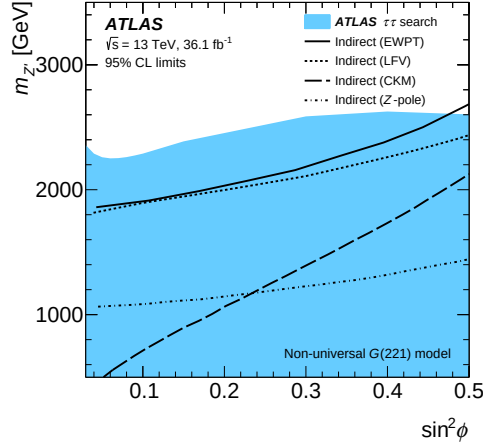


Figure 11: The 95% CL exclusion in the non-universal $G(221)$ parameter space overlaid with indirect upper limits at 95% CL from fits to electroweak precision measurements [146], lepton flavour violation [147], CKM unitarity [148] and Z-pole measurements [38].

9 Conclusion

A search for neutral Higgs bosons as predicted in the Minimal Supersymmetric Standard Model and Z' bosons decaying to a pair of τ -leptons is performed using a data sample from proton–proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC, corresponding to an integrated luminosity of 36.1 fb^{-1} . The $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels are analysed and no indication of an excess over the expected SM background is found. Upper limits on the cross section for the production of scalar and Z' bosons times the branching fraction to ditau final states are set at 95% CL, significantly increasing the sensitivity and the explored mass range compared to previous searches. They are in the range $0.78\text{--}0.0058 \text{ pb}$ ($0.70\text{--}0.0037 \text{ pb}$) for gluon–gluon fusion (b -associated) production of scalar bosons with masses of $0.2\text{--}2.25 \text{ TeV}$ and $1.56\text{--}0.0072 \text{ pb}$ for Drell–Yan production of Z' bosons with masses of $0.2\text{--}4 \text{ TeV}$. In the context of the hMSSM scenario, the most stringent limits for the combined search exclude $\tan\beta > 1.0$ for $m_A = 0.25 \text{ TeV}$ and $\tan\beta > 42$ for $m_A = 1.5 \text{ TeV}$ at 95% CL. In the context of the Sequential Standard Model, Z'_{SSM} bosons with masses less than 2.42 TeV are excluded at 95% CL, while $m_{Z'_{\text{NU}}} < 2.25\text{--}2.60 \text{ TeV}$ is excluded in the range $0.03 < \sin^2\phi < 0.5$ in the non-universal $G(221)$ model.

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Search for heavy resonances decaying into WW in the $e\nu\mu\nu$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

A search for neutral heavy resonances is performed in the $WW \rightarrow e\nu\mu\nu$ decay channel using pp collision data corresponding to an integrated luminosity of 36.1 fb^{-1} , collected at a centre-of-mass energy of 13 TeV by the ATLAS detector at the Large Hadron Collider. No evidence of such heavy resonances is found. In the search for production via the quark–antiquark annihilation or gluon–gluon fusion process, upper limits on $\sigma_X \times B(X \rightarrow WW)$ as a function of the resonance mass are obtained in the mass range between 200 GeV and up to 5 TeV for various benchmark models: a Higgs-like scalar in different width scenarios, a two-Higgs-doublet model, a heavy vector triplet model, and a warped extra dimensions model. In the vector-boson fusion process, constraints are also obtained on these resonances, as well as on a Higgs boson in the Georgi–Machacek model and a heavy tensor particle coupling only to gauge bosons.

1 Introduction

The measured properties [1–4] of the Higgs boson discovered in 2012 by the ATLAS [5] and CMS [6] collaborations at the Large Hadron Collider (LHC) are, within experimental uncertainties, consistent with those predicted for the Standard Model (SM) Higgs boson, h . Nevertheless, the SM is thought to be an incomplete theory and many scenarios beyond the SM (BSM) predict an extended Higgs sector [7, 8]. Diboson vector and tensor resonances are also predicted in several other extensions to the SM, such as in composite Higgs models [9, 10] and models with warped extra dimensions [11–14].

This article reports on the results of a search for heavy neutral resonances decaying into two W bosons, which then decay into the $e\nu\mu\nu$ final state, either directly or via leptonic tau decays with additional neutrinos. The analysis is based on the full pp collision dataset collected by the ATLAS detector in 2015 and 2016 at the centre-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb^{-1} .

The results are interpreted in terms of different benchmark models. For the case of a scalar resonance produced by gluon–gluon fusion (ggF) or vector-boson fusion (VBF), two scenarios with different intrinsic widths are considered. Constraints on the heavy neutral scalar in two-Higgs-doublet models (2HDM) are also obtained. The neutral member of the fiveplet in the Georgi–Machacek (GM) model [15, 16] also serves as a reference model in the VBF production mode. The parameterisation of heavy vector triplet (HVT) Lagrangians [17, 18] permits the interpretation of searches for spin-1 resonances in a generic way. The bulk Randall–Sundrum (RS) model [11, 19] features a spin-2 Kaluza–Klein (KK) graviton excitation (G_{KK}) decaying into WW , while a tensor resonance signal in the VBF production mode is based on an effective Lagrangian model (ELM) [20].

A previous search for a heavy Higgs boson in the $e\nu\mu\nu$ final state was performed by ATLAS [21] based on a data sample with an integrated luminosity of 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV. The CMS Collaboration also published a search for a high-mass scalar decaying into two W bosons in the fully leptonic final state [22], using datasets at $\sqrt{s} = 7$ and 8 TeV with integrated luminosities of 4.9 fb^{-1} and 19.4 fb^{-1} , respectively. A search for heavy resonances in the RS models in the leptonic decays of the WW channel, using a dataset of 4.7 fb^{-1} at 7 TeV [23], was reported by the ATLAS Collaboration. The ATLAS and CMS collaborations have obtained constraints on the HVT and bulk RS models, based on other decay modes of the VV channels, with V being either a W or a Z boson [24–36]. The search in the $e\nu\mu\nu$ decay mode is complementary to searches performed in other decay modes. In particular, the sensitivity to low mass resonances is higher in the fully leptonic final state than in final states that include jets due to background from jet production.

The article is organised as follows. Section 2 presents the various models used in this analysis. Section 3 describes the ATLAS detector. The data and simulated event samples are discussed in Section 4. The event reconstruction and selection are described in Sections 5 and 6, respectively, followed by the background estimation techniques in Section 7. Systematic uncertainties are discussed in Section 8 and the results are presented in Section 9. Finally, the conclusions are given in Section 10.

2 Theoretical models

The different signal models studied are presented in Table 1. One scenario for the heavy scalar assumes that the scalar has a width much smaller than the detector resolution. This is referred to as the narrow-

Table 1: Summary of the different signal models and resonances considered in the analysis. The resonance spin and production mode are also specified with ggF for gluon–gluon fusion, qqA for quark–antiquark annihilation and VBF for vector-boson fusion.

Model	Resonance spin	Production mode		
		ggF	qqA	VBF
NWA	Spin-0	x		x
2HDM		x		x
LWA		x		x
GM				x
HVT	Spin-1		x	x
Bulk RS	Spin-2	x		
ELM				x

width approximation (NWA). Larger widths (large-width assumption, LWA) of 5%, 10% and 15% of the heavy Higgs boson mass, are also considered. The choice of the width range for the heavy Higgs boson is motivated by the fact that, for several of the most relevant BSM models, widths above 15% are already excluded by indirect limits [37].

The 2HDM comes in different types [38], defined by assumptions about the couplings of each of the Higgs doublets and the discrete symmetries imposed. This analysis considers Type I, where one Higgs doublet couples to vector bosons while the other couples to fermions, and Type II of the minimal supersymmetric (SUSY)-like model in which one Higgs doublet couples to up-type quarks and the other one to down-type quarks and charged leptons. This analysis uses a generic charge-conjugation- and parity-conserving (CP-conserving) 2HDM with a softly broken Z_2 symmetry [38] which has several free parameters: (i) four masses m_h , m_H , m_A and $m_{H^\pm}$ for the two CP-even neutral states, the pseudo-scalar and the charged Higgs boson pair, respectively, (ii) a mixing angle α between the CP-even neutral Higgs fields, and (iii) the ratio of the vacuum expectation values of the two Higgs doublets $\tan \beta = v_2/v_1$. The benchmark is defined by setting $m_h = 125$ GeV and the masses of the supersymmetric particles heavy enough so that Higgs boson decays into SUSY particles are kinematically forbidden. The cross sections and branching fractions are calculated with SusHi and 2HDMC [39, 40].

The GM model extends the Higgs sector with the addition of a real and a complex triplet of $SU(2)_L$ in a way which preserves the SM value of $\rho = M_W^2/(M_Z^2 \cos^2 \theta_W) = 1$ at tree level, with m_W , m_Z and θ_W being the W and Z boson mass and the weak mixing angle, respectively. The physical states include a fermiophobic fiveplet, H_5 , of custodial $SU(2)$ symmetry which couples preferentially to vector bosons [41]. For that reason, the GM model is less constrained [42], when produced by the VBF process, than other standard benchmark models of a triplet Higgs field, such as the little Higgs model [43] or the left–right symmetric model [44]. The model has many parameters [45, 46], but, if the other new Higgs bosons are heavier than those of the H_5 multiplet, the only production mode is via the VBF process. The cross section and decay width into VV are then proportional to a single parameter, $\sin^2 \theta_H$, which characterises the fraction of the gauge boson masses generated by the triplet Higgs fields.

The HVT Lagrangian [18] parameterises the couplings of the new spin-1 heavy bosons to SM particles in a generic manner and allows their mixing with SM gauge bosons. The s -channel production mechanism of the heavy gauge bosons is primarily via $q\bar{q}$ annihilation (qqA). The HVT bosons couple to the Higgs boson and SM gauge bosons with coupling strength $c_h g_V$ and to the fermions with coupling strength $g^2 c_F / g_V$, where g is the SM $SU(2)_L$ gauge coupling, c_h and c_F are multiplicative factors that modify the

couplings to the Higgs boson and to the fermions, and g_V represents its coupling strength to the W and Z bosons. For the case of vector-boson fusion, it is assumed that there is no coupling to fermions so that non-VBF production processes are suppressed.

The spin-2 G_{KK} is the first Kaluza–Klein excitation of the graviton in the RS model with a warped extra dimension [11, 19], where the SM fields are localised in the bulk [12–14]. This model is characterised by the dimensionless coupling constant $k/\bar{M}_{Pl} \sim \mathcal{O}(1)$ where k determines the curvature of the space, and where $\bar{M}_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck scale.

For the VBF production mode, the spin-2 signal is based on an effective Lagrangian approach with Λ as a characteristic energy scale of the underlying new physics [20],

$$\mathcal{L} = \frac{1}{\Lambda} T_{\mu\nu} \left(f_1 B^{\alpha\nu} B_\alpha^\mu + f_2 W_i^{\alpha\nu} W_\alpha^{i\mu} + 2f_5 (D^\mu \Phi)^\dagger (D^\nu \Phi) \right).$$

Here, f_i are variable coupling parameters, $T_{\mu\nu}$ is the spin-2 singlet field, $B^{\alpha\nu}$ and $W_i^{\alpha\nu}$ are the electroweak field strength tensors, and Φ is the scalar Higgs field. The covariant derivative D^μ is $D^\mu = \partial^\mu - igW_i^\mu \sigma^i/2 - ig'YB^\mu$, where σ^i are the Pauli matrices, Y the weak hypercharge, and g and g' the corresponding gauge coupling constants. The model differs from the RS model in that the couplings to fermions or gluons are not included in the Lagrangian. Also, the BSM amplitude is multiplied by a form factor which is a function of a cut-off scale Λ_{ff} and a suppression power n_{ff} in order to preserve unitarity at high energies:

$$f(p_1^2, p_2^2, k_{sp2}^2) = \left(\frac{\Lambda_{ff}^2}{|p_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|k_{sp2}^2| + \Lambda_{ff}^2} \right)^{n_{ff}},$$

where p_1^2 and p_2^2 are the squared invariant masses of the incoming electroweak bosons and k_{sp2}^2 is the squared invariant mass of the sum of the initial boson momenta, equivalent to that of an s -channel spin-2 particle. The specific parameter settings for the signal models used are given in Section 4.

3 ATLAS detector

The ATLAS detector [47, 48] is a general-purpose particle detector used to investigate a broad range of physics processes. It includes an inner tracking detector (ID) surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer (MS) incorporating three large superconducting toroidal magnets with eight coils each. The ID consists of fine-granularity silicon pixel and microstrip detectors, and a straw-tube tracker. It is immersed in a 2 tesla axial magnetic field produced by the solenoid and provides precision tracking for charged particles in the range $|\eta| < 2.5$, where η is the pseudorapidity of the particle.¹ The straw-tube detector also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It is composed of sampling calorimeters with either liquid argon (LAr) or scintillator tiles as the active medium, and lead, steel, copper, or tungsten as the absorber material. The MS provides muon identification and momentum measurements for $|\eta| < 2.7$. The ATLAS detector has a two-level trigger system [49] to select events for further analysis.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

4 Data and simulation samples

The data used in this analysis were collected with a single-electron or single-muon trigger. These triggers have a transverse energy or momentum threshold, E_T or p_T , that depends on the data-taking period, with the lowest threshold varying between 20 GeV and 26 GeV. The trigger efficiency for WW events passing the offline event selection (Section 6) is greater than 99%. Data quality criteria are applied to ensure that events are recorded with stable beam conditions and with all relevant subdetector systems operational.

Samples of simulated signal and background events are used to optimise the event selection and to estimate the signal acceptance and the background yields from various SM processes.

The sample for the NWA heavy Higgs boson signal was produced with PowHEG-Box 2.0 [50–52] which calculates separately the ggF [53] and VBF [54] production mechanisms with matrix elements up to next-to-leading order (NLO) in quantum chromodynamics (QCD). It uses the CT10 NLO parton distribution function (PDF) set [55] and is interfaced with PYTHIA 8.186 [56] for the $H \rightarrow WW$ decays, for parton showering and hadronisation. A set of tuned parameters called the AZNLO tune [57] is used to describe the underlying event. The NWA Higgs boson is generated with a width of 4 MeV. This event sample is also used to constrain the 2HDM. The LWA heavy Higgs boson signal was simulated at NLO using the MADGRAPH5_AMC@NLO 2.3.2 event generator [58] with the NNPDF23LO PDF set [59]. The generated particles at matrix element level are showered by PYTHIA 8.186 with the A14 tune [60] for the underlying event. The mass of the heavy Higgs boson signals considered in this analysis spans the range between 200 GeV and 4 (3) TeV for the ggF-induced (VBF-induced) signals. Both NWA and LWA samples were generated in steps of 100 GeV up to 1 TeV, and in steps of 200 GeV thereafter.

The PowHEG-Box samples describe the production of a ggF-induced heavy Higgs boson in association with one jet at leading-order (LO) precision, while further jets are emulated by the parton shower generator, PYTHIA. A more precise calculation of higher jet multiplicities is provided by using MADGRAPH5_AMC@NLO 2.3.2 to simulate $gg \rightarrow H$ events in association with up to two jets at NLO precision. Here, the overlap between identical final states generated at the matrix element (ME) and the parton shower (PS) stage is removed using FxFx merging [61]. The fraction of ggF events passing the event selection requirements of the $N_{\text{jet}} = 1$ and $N_{\text{jet}} \geq 2$ VBF categories (defined later in Section 6) predicted by the PowHEG-Box event generator is reweighted to match that of the MADGRAPH5_AMC@NLO FxFx samples. The corresponding scale factors are calculated for several hypothetical heavy Higgs boson masses. It is the largest, 1.14, for the 200 GeV mass point, and decreases with increasing resonance mass to a value of 0.85 for the 4 TeV mass point, for the $N_{\text{jet}} = 1$ VBF category. The corresponding numbers are 0.91 and 0.73 for the $N_{\text{jet}} \geq 2$ VBF category.

Benchmark samples for the GM, HVT and bulk RS models were generated at LO using MADGRAPH5_AMC@NLO interfaced to PYTHIA 8.186 with the NNPDF23LO PDF set. A value of $\sin \theta_H = 0.4$ is chosen for the GM benchmark model. For the HVT interpretation in the $q\bar{q}$ annihilation mode, samples were generated according to the extended gauge symmetry model A [18] with $g_V = 1$. In the VBF mode, samples were generated using the same g_V value but setting the couplings to the fermions to zero so that the new vector boson couples only to the SM vector and Higgs bosons. For the bulk RS model, a curvature scale parameter $k/\bar{M}_{\text{Pl}}$ of either 0.5 or 1 is considered. The ELM VBF spin-2 signals were generated at LO with VBFNLO 3.0.0 beta 2 [62] with the NNPDF30LO PDF set [63] and using the following parameter setting [20]: $\Lambda_{ff} = 3$ TeV, $n_{ff} = 4$, $\Lambda = 1.5$ TeV and $f_1 = f_2 = f_3 = 1$. The mass range considered is between 200 GeV and 5 TeV for the KK graviton signal, between 250 GeV and 5 TeV for the HVT qqA

signal, between 200 GeV and 1 TeV for the GM and ELM VBF signals, and between 300 GeV and 1 TeV for the HVT VBF signal.

The main sources of SM background include events from the production of single top quarks, $t\bar{t}$, dibosons (WW , WZ and ZZ), Z/γ^* +jets and W +jets. Single-top-quark simulated events were generated with POWHEG-Box 2.0 [64, 65] using the CT10 NLO PDF set interfaced to PYTHIA 6.428 [66] for parton showering and hadronisation, with the PERUGIA2012 tune [67] and CTEQ6L1 PDF [68] to describe the underlying event. The $t\bar{t}$ events were generated with POWHEG-Box 2.0 [69] using the NNPDF30NLO PDF set [63] interfaced to PYTHIA 8.186 for parton showering and hadronisation, with the A14 tune and CTEQ6L1 PDF to describe the underlying event. The sample was generated by setting the resummation damping parameter h_{damp} to 1.5 times the top-quark mass, m_{top} , which was set to 172.5 GeV. The h_{damp} parameter controls the ME/PS matching and effectively regulates the high- p_T radiation. The EVTGEN 1.2.0 [70] package was used to model the properties of the bottom and charm hadron decays. Diboson samples were generated with SHERPA 2.1.1 [71–75] for the gg production processes and SHERPA 2.2.1 for the $q\bar{q}$ production processes, using the CT10 NLO and NNPDF30NNLO PDF sets, respectively. The SHERPA event generator for the latter processes produces up to one additional parton at NLO and up to three additional partons at LO. Production of W and Z bosons in association with jets was also simulated using SHERPA 2.1.1 with the CT10 NLO PDF set, where b - and c -quarks are treated as massive particles. The $gg \rightarrow WW$ production also includes the contribution of the SM Higgs boson at 125 GeV and the interference effects between the continuum and Higgs resonance processes. The VBF part of SM Higgs boson production was generated with POWHEG-Box [54] interfaced to PYTHIA 8.186 for parton showering and hadronisation.

The effect of multiple pp interactions in the same and neighbouring bunch crossings (pile-up) was included by overlaying minimum-bias collisions, simulated with PYTHIA 8.186, on each generated signal and background event. The number of overlaid collisions is such that the distribution of the average number of interactions per pp bunch crossing in the simulation matches the pile-up conditions observed in the data, which is about 25 interactions per bunch crossing on average. The generated samples were processed through a GEANT4-based detector simulation [76, 77], followed by the standard ATLAS reconstruction software used for collision data.

5 Event reconstruction

Events used in this analysis are required to have at least one primary vertex with a minimum of two associated tracks, each with transverse momentum $p_T > 400$ MeV. If there is more than one vertex reconstructed in an event that meets these conditions, the one with the highest sum of track p_T^2 is chosen as the primary vertex.

Electrons are reconstructed from clusters of energy deposits in the electromagnetic calorimeter that match a track reconstructed in the ID. They are identified using the likelihood identification criteria described in Ref. [78]. The electrons used in this analysis are required to pass the “MediumLH” selection for $p_T > 25$ GeV ² or the “TightLH” selection for $p_T < 25$ GeV and be within $|\eta| < 2.47$, excluding the transition region between the barrel and endcaps in the LAr calorimeter ($1.37 < |\eta| < 1.52$). These “MediumLH” and “TightLH” selection categories have identification efficiencies of 94% and 88%,

² For electrons, p_T is defined as the magnitude of the transverse component of the electron momentum as measured using the electromagnetic calorimeter.

respectively, for electrons with p_T of 100 GeV. The corresponding probabilities to misidentify hadrons as electrons are approximately 0.5% and 0.3%, respectively.

Muons are reconstructed by combining ID and MS tracks that have consistent trajectories and curvatures [79]. The muon candidates used in this analysis are required to have $|\eta| < 2.5$ and pass the “Medium” selection for $p_T > 25$ GeV or the “Tight” selection for $p_T < 25$ GeV, defined on the basis of the quality of the reconstruction and identification. These selections have a reconstruction efficiency of approximately 96% and 92%, respectively, for muons originating from the decay of W bosons [80]. The corresponding probabilities to misidentify hadrons as muons are approximately 0.2% and 0.1%, respectively.

To ensure that leptons originate from the interaction point, a requirement of $|d_0|/\sigma_{d_0} < 5$ (3) is imposed on the electrons (muons) and $|z_0 \sin \theta| < 0.5$ mm is applied to both lepton types. Here d_0 and z_0 are the transverse and longitudinal impact parameters of the lepton with respect to the primary vertex, respectively, and σ_{d_0} is the uncertainty in the measured value of d_0 . In addition, electrons and muons are required to be isolated from other tracks and calorimetric activities by applying p_T - and η -dependent isolation criteria. For muons, the calorimeter isolation is based on energy deposits in the calorimeter within a cone ΔR of 0.2 around the muons. The muon track isolation uses a variable cone size starting at $\Delta R = 0.3$ and shrinking with increasing p_T of the muon [81]. The same calorimeter isolation is used for electrons, and the electron track isolation uses a variable cone size starting at $\Delta R = 0.2$. The efficiency of these isolation requirements is 90% for both lepton types with p_T of 25 GeV, increasing to 99% at 60 GeV.

Jets are reconstructed from three-dimensional clusters of energy deposits in the calorimeters using the anti- k_t algorithm [82] with a radius parameter of $R = 0.4$ implemented in the FastJet package [83]. The four-momenta of the jets are calculated as the sum of the four-momenta of their constituents, which are assumed to be massless. Jets are corrected for energy from pile-up using the pile-up subtraction based on jet areas [84]. The jet energy scale is estimated in Ref. [85]. Jets are required to have $p_T > 30$ GeV and $|\eta| < 4.5$.

For jets with $p_T < 60$ GeV and $|\eta| < 2.5$, the multivariate “jet vertex tagger” algorithm [86] is used to suppress jets from pile-up interactions. To avoid double counting, jets of any transverse momentum are discarded if they are within a cone of size $\Delta R = 0.2$ around an electron candidate or if they have fewer than three associated tracks and are within a cone of size $\Delta R = 0.2$ around a muon candidate. If the separation between a lepton and a jet is within $0.2 < \Delta R < 0.4$, the lepton is rejected.

To estimate the number of b -tags in the event, jets with $p_T > 20$ GeV and within $|\eta| < 2.5$ are considered to contain a b -hadron if they yield a b -tagging algorithm discriminant value exceeding a reference value. The MV2c10 algorithm [87, 88] is chosen at the 85% b -tagging efficiency benchmark point, estimated from b -jets in simulated $t\bar{t}$ events. The misidentification rate for jets which originate from a light quark or gluon is less than 1%, while it is approximately 17% for c -jets.

The missing transverse momentum, with magnitude E_T^{miss} , is calculated as the negative vectorial sum of the transverse momenta of calibrated electrons, muons, and jets, as well as tracks with $p_T > 500$ MeV compatible with the primary vertex and not associated with any of these [89].

Table 2: Selection conditions and phase space definitions used in the ggF and VBF signal regions.

SR _{ggF}	SR _{VBF1J}	SR _{VBF2J}
Common selections		
$N_{b\text{-tag}} = 0$ $ \Delta\eta_{\ell\ell} < 1.8$ $m_{\ell\ell} > 55 \text{ GeV}$ $p_{\text{T}}^{\ell,\text{lead}} > 45 \text{ GeV}$ $p_{\text{T}}^{\ell,\text{sublead}} > 30 \text{ GeV}$ veto if $p_{\text{T}}^{\ell,\text{other}} > 15 \text{ GeV}$ $\max(m_{\text{T}}^W) > 50 \text{ GeV}$		
ggF phase space	VBF1J phase space	VBF2J phase space
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{\text{jet}} = 1$ and $ \eta_j > 2.4, \min(\Delta\eta_{j\ell}) > 1.75$	$N_{\text{jet}} \geq 2$ and $m_{jj} > 500 \text{ GeV}, \Delta y_{jj} > 4$

6 Event selection

As a first step, WW candidate events are selected by requiring two oppositely charged, different-flavour leptons (e or μ). Both leptons must satisfy the minimal quality criteria discussed in Section 5. When ordered in p_{T} , these leptons are called the leading and subleading ones, $p_{\text{T}}^{\ell,(\text{sub})\text{lead}}$. In order to suppress the background from diboson processes, a veto is imposed on events with an additional lepton with $p_{\text{T}}^{\ell,\text{other}} > 15 \text{ GeV}$.

Three event categories are defined: two disjoint categories optimised for the VBF production, VBF $N_{\text{jet}} = 1$ and VBF $N_{\text{jet}} \geq 2$, and one quasi-inclusive category (excluding the VBF phase space) dedicated to the ggF or qqA signal. The selections that define the signal regions (SRs) are summarised in Table 2 for the three event categories, SR_{VBF1J}, SR_{VBF2J} and SR_{ggF}, respectively.

The variables used in the selections are the most discriminating ones chosen by a boosted decision tree (BDT) [90], based on the NWA signal samples. These are $p_{\text{T}}^{\ell,\text{lead}}$, the invariant mass of the leading and subleading leptons, $m_{\ell\ell}$, and the pseudorapidity difference between the two leptons, $\Delta\eta_{\ell\ell}$. The first two variables provide good separation between a heavy resonance signal and the WW and top-quark background. The separation of signal from background based on the $\Delta\eta_{\ell\ell}$ distribution is found to have a reasonable efficiency and allows, at the same time, a control region to be defined for the WW background (Section 7.2). For each selected variable, the selection criterion is set by maximising the signal significance in the presence of background.

In order to further suppress the top-quark background, events with at least one b -tagged jet ($N_{b\text{-tag}} \geq 1$) are rejected from the signal regions. To reduce the Z +jets and W +jets contributions, two other variables are used: $p_{\text{T}}^{\ell,\text{sublead}}$ and the maximum value of the transverse mass calculated with either of the two leptons and the missing transverse momentum, m_{T}^W . The latter variable is defined as:

$$m_{\text{T}}^W = \sqrt{2p_{\text{T}}^{\ell}E_{\text{T}}^{\text{miss}} \left(1 - \cos(\phi^{\ell} - \phi^{E_{\text{T}}^{\text{miss}}})\right)},$$

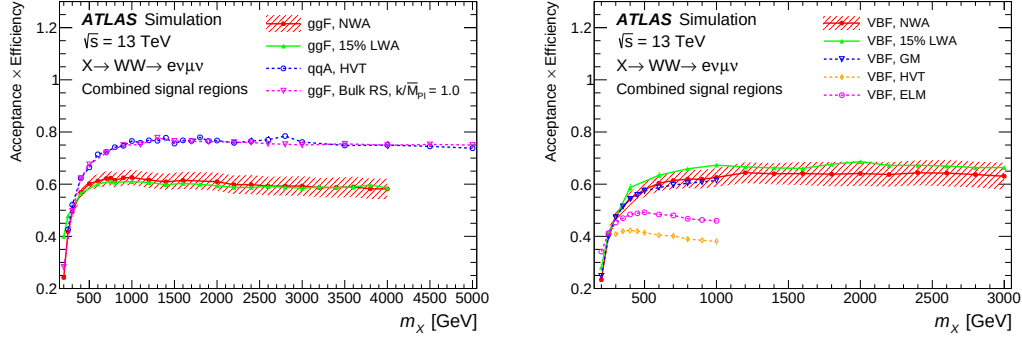


Figure 1: Acceptance times efficiency as a function of signal mass for the ggF or qqA (left) and VBF (right) productions. All three signal event categories are combined. The hatched band around the NWA signal curve shows the typical size of the total statistical and systematic uncertainties.

where p_T^ℓ and ϕ^ℓ are the transverse momentum and azimuthal angle of a given lepton and $\phi_{E_T^{\text{miss}}}$ is the azimuthal angle of the missing transverse momentum vector. For the VBF $N_{\text{jet}} = 1$ category, two discriminating variables are used to minimise the contribution of the ggF signal: the pseudorapidity of the jet, η_j , and the minimum value of the pseudorapidity difference between the jet and either of the leptons, $\min(|\Delta\eta_{j\ell}|)$. For the VBF $N_{\text{jet}} \geq 2$ category, the invariant mass, m_{jj} , and the rapidity difference, Δy_{jj} , of the two leading jets are used to select the VBF signal.

The NWA and LWA signal acceptance times the efficiency, after all selection requirements for a 700 GeV ggF signal, is approximately 50% in the quasi-inclusive ggF category and 5% or less in the VBF $N_{\text{jet}} = 1$ and $N_{\text{jet}} \geq 2$ categories. For a 700 GeV VBF signal, it is between 15% and 25% for the three event categories. The acceptance times efficiency for the three event categories combined, as a function of resonance mass, is shown in Figure 1 for the different signals. For the spin-1 and spin-2 signals, the range up to 1 TeV is considered in the case of VBF model processes. For samples with lower resonance masses, the acceptance times efficiency is lower because the leptons are softer. This is also the reason why the search is limited to signal mass values greater than about 200 GeV. The same selection is applied to all models and the different selection efficiencies between the models are mainly due to different $\Delta\eta_{\ell\ell}$ distributions for the different spin states.

The discriminating variable used for the statistical analysis (Section 9) in this search is the transverse mass defined as

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2},$$

where

$$E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2},$$

and $\mathbf{p}_T^{\ell\ell}$ is the transverse momentum vector of the leading and subleading leptons.

7 Background estimation

The dominant background for the $e\nu\mu\nu$ final state is due to events with top quarks and due to SM WW events. Additional contributions to the background arise from V +jets and the diboson processes VZ ,

$V\gamma$ and $V\gamma^*$. Since the discriminating variable used for this search is the transverse mass, m_T , both the normalisation and the shape of the background m_T distribution must be estimated. The shape of the background is modelled using simulated events while the top-quark and WW background normalisations are determined by a simultaneous fit (Section 9) to the data in m_T -binned distributions in the signal regions and the total event yields in control regions. The normalisation factors of the fit, named “post-fit” normalisation factors hereafter, provide the best overall matching between the number of observed data events and the corresponding SM background expectations in all the signal and control regions. The control regions are defined by criteria similar to those used for the signal regions, but with some requirements loosened or reversed to obtain signal-depleted samples, enriched in the relevant background. These criteria are summarised in Table 3.

The following subsections describe the methods used to estimate the most important background processes, namely top quark, WW , and W +jets. The Z/γ^* +jets and non- WW diboson background contributions are small. The Z/γ^* +jets Monte Carlo (MC) samples are normalised using NNLO cross sections [91] and the non- WW ones with NLO cross sections from the SHERPA event generator. The small background from the $m_h \simeq 125$ GeV Higgs boson resonance and its off-shell component is included and its interference with the continuum WW background is taken into account.

7.1 Top-quark background

Events containing top quarks can be produced as a $t\bar{t}$ pair or as a single top quark in association with either a W boson or a quark of another flavour. In this analysis, contributions from $t\bar{t}$ and single-top-quark events are estimated together, with their relative contributions determined by their predicted cross sections and by their relative acceptances obtained from MC simulation. The single-top-quark contribution varies from about 10% to 30% depending on the signal event category.

The normalisation of the top-quark background for the quasi-inclusive ggF category is determined in a control region (Top CR_{ggF}) where one jet is required to be b -tagged in addition to the signal region selection. The purity of the top-quark background in this CR is high (97%) and thus allows the modelling of the MC simulation to be validated. The distribution of the simulated leading lepton p_T in the Top CR_{ggF} is found to disagree with the data and the ratio between the data and the simulation decreases with increasing $p_T^{\ell, \text{lead}}$. The simulated distribution is corrected in the SR_{ggF} and corresponding CRs with factors obtained by fitting the ratio with a linear function. The correction varies between +4% and -10% as $p_T^{\ell, \text{lead}}$ increases from 50 GeV to 200 GeV.

The top-quark background control regions for the VBF categories (Top CR_{VBF}) have a small number of data events and are therefore merged. At least one jet is required to be b -tagged. In addition, the selection thresholds imposed on $m_{\ell\ell}$ and $p_T^{\ell, (\text{sub})\text{lead}}$ are relaxed to 10 GeV and 25 GeV, respectively, and the selection on $|\Delta\eta_{\ell\ell}|$ and $\max(m_T^W)$ is removed. The threshold value on $m_{\ell\ell}$ of 10 GeV is used to suppress background contributions from low-mass resonances decaying into different-flavour final states via $\tau^+\tau^-$. In this control region, the purity of the top-quark background is 96%, and no mis-modelling of the $p_T^{\ell, \text{lead}}$ distribution is observed.

The post-fit normalisation factors from the simultaneous fit are 0.96 ± 0.05 and $1.12^{+0.13}_{-0.12}$ in the ggF and the VBF control regions, respectively, where the uncertainty quoted corresponds to the combined statistical and systematic uncertainties.

Table 3: Summary of all the selections used in the ggF and VBF WW and top-quark control regions. The common selection “veto if $p_T^{\ell, \text{other}} > 15 \text{ GeV}$ ” applied to all the regions is not explicitly shown.

WW CR _{ggF}	Top CR _{ggF}	WW CR _{VBF1J}	Top CR _{VBF}
$N_{b\text{-tag}} = 0$ $ \Delta\eta_{\ell\ell} > 1.8$ $m_{\ell\ell} > 55 \text{ GeV}$ $p_T^{\ell, \text{lead}} > 45 \text{ GeV}$ $p_T^{\ell, \text{sublead}} > 30 \text{ GeV}$ $\max(m_T^W) > 50 \text{ GeV}$	$N_{b\text{-tag}} = 1$ $ \Delta\eta_{\ell\ell} < 1.8$	$N_{b\text{-tag}} = 0$ $(\Delta\eta_{\ell\ell} > 1.8 \text{ or } 10 \text{ GeV} < m_{\ell\ell} < 55 \text{ GeV})$ $p_T^{\ell, \text{lead}} > 25 \text{ GeV}$ $p_T^{\ell, \text{sublead}} > 25 \text{ GeV}$ –	$N_{b\text{-tag}} \geq 1$ – $m_{\ell\ell} > 10 \text{ GeV}$
Excluding VBF1J and VBF2J phase space		VBF1J phase space	VBF1J and VBF2J phase space

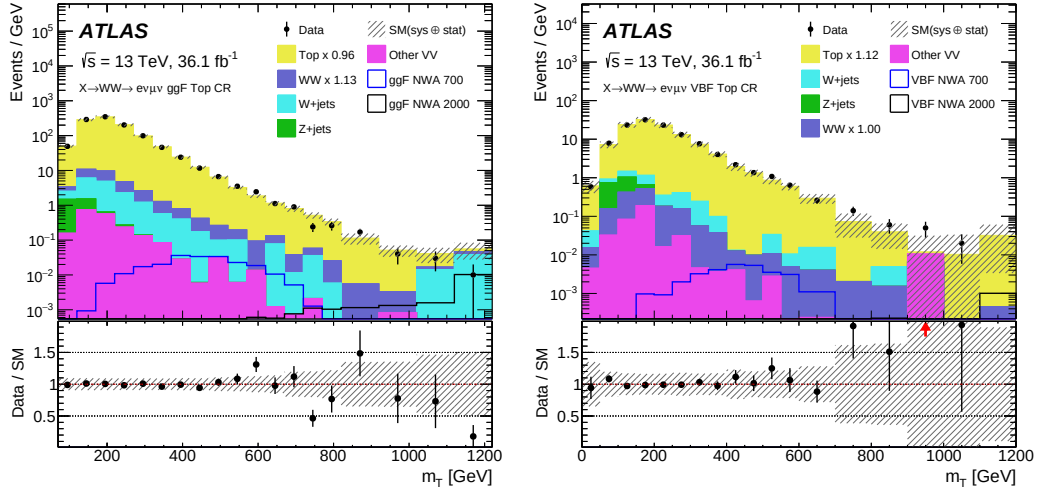


Figure 2: Transverse mass distribution in the ggF (left) and VBF (right) top-quark control regions. In each plot, the last bin contains the overflow. The hatched band in the upper and lower panels shows the combined statistical, experimental and theoretical uncertainties in the predictions. The arrow in the lower right panel indicates that an entry is outside of the vertical scale. The top-quark and WW background event yields are scaled using the indicated normalisation factors obtained from the simultaneous fit to all signal and control regions. The heavy Higgs boson signal event yield, normalised to the expected limits on $\sigma_H \times B(H \rightarrow WW)$, is shown for masses of 700 GeV and 2 TeV in the NWA scenario.

Figure 2 shows the m_T distributions in the ggF and VBF top-quark CRs. The different background components are scaled according to the event yields obtained from the simultaneous fit. The fit uses only the integrated event yields in the control regions. The shape of the distributions is compared between data and MC predictions and found to be in good agreement after the application of the $p_T^{\ell, \text{lead}}$ correction described above for the ggF top-quark CR. The shapes of the m_T distribution for 700 GeV and 2 TeV NWA Higgs boson signals are also shown, normalised to the expected limits on $\sigma_H \times B(H \rightarrow WW)$ from this analysis. The ggF contribution from the SM Higgs boson is included in the WW component. The SM Higgs boson VBF contribution is negligibly small and is not shown in this and following figures.

7.2 WW background

The WW CR for the quasi-inclusive ggF category (WW CR_{ggF}) uses the same selection as for the SR except for $|\Delta\eta_{\ell\ell}|$ which is reversed so that the CR and SR are orthogonal. The selection conditions are shown in Table 3. The m_T distributions of the $q\bar{q}$ SHERPA MC sample in the SR_{ggF} and WW CR_{ggF} are compared at MC generator level with corresponding predictions combining NNLO QCD calculations [92] with NLO electroweak (EW) corrections [93]. While the integrated yields of the distributions agree within 3% in both the SR_{ggF} and the WW CR_{ggF}, a small m_T shape difference is observed, particularly in the SR. The m_T distributions of the SHERPA samples are thus reweighted to the combined NNLO QCD and NLO EW predictions. The post-fit normalisation factor obtained from the simultaneous fit for the WW contributions in the quasi-inclusive ggF categories is 1.13 ± 0.09 , where the uncertainty quoted corresponds to the combined statistical and systematic uncertainties. The post-fit purity of the WW background in the control region is 51%.

In order to select more data events, the WW CR for the $N_{\text{jet}} = 1$ VBF category (WW CR_{VBF1J}) uses a slightly different selection (shown in Table 3) from the one in the SR, but still disjoint from the SR. The normalisation factor obtained from the same simultaneous fit for the WW contribution in the WW CR_{VBF1J} is 1.0 ± 0.2 , where the uncertainty quoted corresponds to the combined statistical and systematic uncertainties. The post-fit purity of the WW background in the control region is 44%.

The WW contribution in the $N_{\text{jet}} \geq 2$ VBF category is about 20%, and its prediction is taken from simulation because it is difficult to isolate a kinematic region with a sufficient number of WW events and with a small contamination from the top-quark background.

Figure 3 shows the m_T distributions in the WW CR_{ggF} and CR_{VBF1J}. The different background contributions are scaled according to the event yields obtained from the simultaneous fit. For the WW control regions only integrated event yields are used in the fit, like in the fits of the top control regions.

7.3 W +jets background

Events with W bosons produced in association with jets may enter the SR when a jet is misidentified as a lepton. Due to the difficulties in accurately modelling the misidentification process in the simulation, the W +jets background contribution is estimated using the data-driven method developed for the SM $h \rightarrow WW$ analysis [94]. A sample of events is used which satisfies all event selection criteria, except that one of the two lepton candidates fails to meet the quality criteria for being an identified lepton but satisfies a less restrictive selection, referred to as “anti-identified”. Anti-identified muons (electrons) have loosened isolation and impact parameter (likelihood identification) selection criteria as compared to the identified selection. From this data sample the non- W +jets contribution, dominated by top-quark and WW background processes, is subtracted on the basis of MC predictions. The W +jets purity of the samples is 46%, 59% and 22% for the quasi-inclusive ggF, $N_{\text{jet}} = 1$ and $N_{\text{jet}} \geq 2$ VBF categories, respectively.

The W +jets contamination in the signal region is then determined by scaling the number of events in the background-subtracted data sample by an extrapolation factor, which is the ratio of the number of identified leptons to the number of anti-identified leptons in a data sample of dijet events in bins of lepton p_T and η . The dijet sample is collected using prescaled low- p_T single-lepton triggers with thresholds of 12 GeV for electrons and 14 GeV for muons. Events are selected with exactly one candidate lepton, back-to-back with the leading jet. Electroweak processes in the dijet event sample, dominated by W +jets and Z/γ^* background contributions, are subtracted. The dominant systematic uncertainty in the estimation

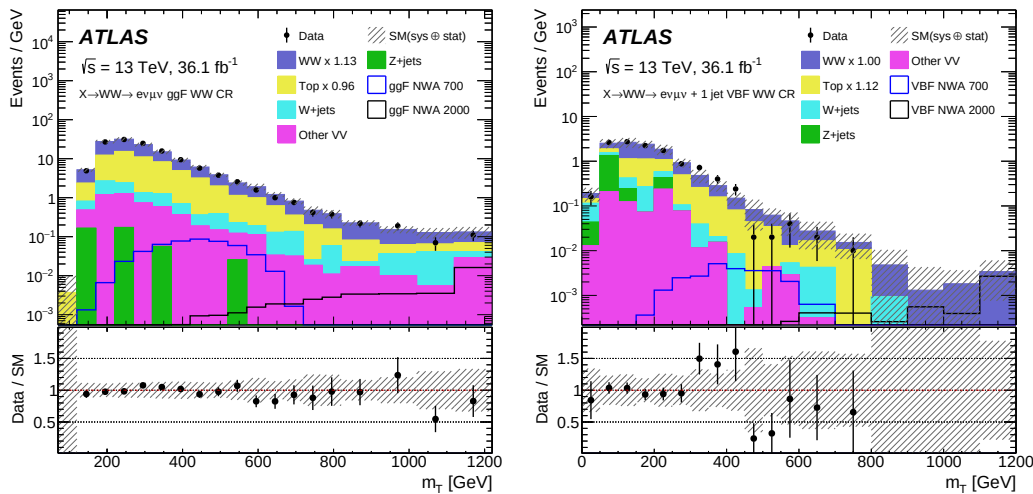


Figure 3: Transverse mass distribution in the quasi-inclusive ggF (left) and $N_{\text{jet}} = 1$ VBF WW (right) control regions. In each plot, the last bin contains the overflow. The hatched band in the upper and lower panels shows the combined statistical, experimental and theoretical uncertainties in the predictions. The top-quark and WW background events are scaled using the indicated normalisation factors obtained from the simultaneous fit to all signal and control regions. The heavy Higgs boson signal event yield, normalised to the expected limits on $\sigma_H \times B(H \rightarrow WW)$, is shown for masses of 700 GeV and 2 TeV in the NWA scenario.

of the W +jets background is due to the differences between dijet and W +jets sample characteristics. All systematic uncertainties associated with this background estimate are listed in Section 8.1.

8 Systematic uncertainties

In this section, experimental and theoretical uncertainties in the normalisation and shape of the m_T distributions of the background and the signal are described. Except for those explicitly mentioned here, the shape uncertainties are small and thus neglected. Overall, the systematic uncertainty dominates, except in the tails of the m_T distributions where the statistical uncertainty is larger.

8.1 Experimental uncertainties

The dominant sources of experimental uncertainty in the signal and background yields are the jet energy scale and resolution (Jet) [85], the b -tagging efficiency (b -tag) [87], and the pile-up modelling [86]. Other systematic uncertainties such as those associated with trigger efficiencies, lepton reconstruction and identification efficiencies, lepton momentum scales and resolutions [78, 80], missing transverse momentum reconstruction [89] and the jet vertex tagger [86] are also considered when evaluating systematic effects on the shape and normalisation of the background, or the shape and efficiency of the signal yield. The uncertainty associated with the pile-up modelling is assessed by performing a variation of $\pm 9\%$ in the number of simulated pile-up interactions to cover the uncertainty in the ratio of the predicted and measured cross sections of non-diffractive inelastic events producing a hadronic system of mass $m_{X,\text{had}} > 13$ GeV [95].

For the main background from top-quark and WW processes, the impact of the most important experimental systematic uncertainties is summarised in Tables 4 and 5 together with dominant theoretical uncertainties. The maximum changes in yield for the up and down variations are shown in the various signal and control regions. The correlation between the SRs and CRs is taken into account in the simultaneous fit.

Systematic effects due to lepton identification efficiencies, momentum and scale resolutions, are found to be approximately 1%. They are not shown in the tables. The last column in the tables shows the total uncertainty, including these small uncertainty sources.

The data-driven W +jets background estimate is subject to several sources of systematic uncertainty. The subtraction of the subdominant electroweak processes (Section 7.3) has a significant impact on the extrapolation factor calculation at high lepton p_T . The subtraction is varied, as described in Ref. [94], and the variation of the event yield in the signal region is taken as the uncertainty. The method assumes that the extrapolation factors of the dijet and W +jets samples are equal. Differences in the jet flavour composition between dijet and W +jets events introduce an additional systematic uncertainty. This is evaluated as the sum in quadrature of two contributions: differences between the extrapolation factors calculated with dijet samples and Z +jets samples in data, and differences between the extrapolation factors evaluated with W +jets and Z +jets MC samples. Finally, the statistical uncertainties of the different data and MC samples used to evaluate the extrapolation factors are taken as an additional source of systematic uncertainty. The overall relative systematic uncertainty of the W +jets background is found to be approximately 35% for each of the three signal event categories, with the dominant uncertainty being associated with the jet flavour composition.

The uncertainty in the total 2015 and 2016 integrated luminosity is 2.1%. It is derived, following a methodology similar to that detailed in Ref. [96], from van der Meer scans performed in August 2015 and May 2016, calibrated at high luminosity by various luminosity detectors.

8.2 Theoretical uncertainties of the background

For background sources which are normalised using control regions, theoretical uncertainties are evaluated for the extrapolation from the control region to the signal region.

For the top-quark and WW background, theoretical uncertainties in the extrapolation are evaluated according to the prescription from the LHC Higgs Cross Section Working Group [97]. The uncertainties include the impact of missing higher-order corrections, PDF variations and other MC modelling. The dominant theoretical uncertainties are shown in Tables 4 and 5.

For the top-quark background, the uncertainty from the event generator and parton shower modelling (ME+PS) is estimated by comparing the nominal POWHEG-Box+PYHTIA8 generated samples with those from an alternative event generator, SHERPA 2.2.1. The uncertainty named “Scale” corresponds to variations of the renormalisation μ_R and factorisation μ_F scales as well as h_{damp} . The variations for μ_R and μ_F are between 0.5 and 2 from their nominal scale of $\sqrt{m_{\text{top}}^2 + p_T^2}$, with p_T being the top-quark transverse momentum. The parameter h_{damp} is varied between m_{top} and $2 \cdot m_{\text{top}}$ from its nominal scale $h_{\text{damp}} = 1.5 \cdot m_{\text{top}}$. In the analysis the single-top-quark and $t\bar{t}$ processes are studied together. An uncertainty of 20% [98, 99] is assigned to the relative contribution of the single-top-quark processes, corresponding to the source “Single top” in Table 4. The PDF uncertainty is obtained by taking the envelope of the uncertainty of the NNPDF30NLO PDF set and its differences in central value with the CT14 [100] and MMHT 2014 [101] PDF sets, following the recommendations of Ref. [55]. The PDF uncertainties are m_T dependent and

Table 4: Relative impact (in %) of dominant experimental and theoretical uncertainties in the event yields for the top-quark background processes in the three signal regions (SR_{ggF} , SR_{VBF1J} and SR_{VBF2J}) and the top-quark and WW control regions (Top $CR_{ggF/VBF}$ and the WW $CR_{ggF/VBF1J}$). Jet and b -tag sources dominate the experimental uncertainty while ME+PS, Scale, Single top and PDF are the dominant theoretical uncertainties. The last column shows the total uncertainty including those not listed here.

Source	Jet	b -tag	ME+PS	Scale	Single top	PDF	Total
SR_{ggF}	5.2	17	1.3	3.0	4.2	2.9	19
SR_{VBF1J}	9.6	7.8	1.0	1.6	5.9	3.5	15
SR_{VBF2J}	9.7	14	9.5	5.0	2.1	3.6	21
Top CR_{ggF}	2.2	4.8	0.34	0.21	2.6	4.3	7.3
WW CR_{ggF}	5.3	18	1.1	6.3	4.0	3.8	20
Top CR_{VBF}	8.2	3.5	10	1.5	1.3	3.6	14
WW CR_{VBF1J}	9.9	8.3	9.4	3.9	5.3	3.4	18

Table 5: Relative impact (in %) of dominant experimental and theoretical uncertainties in the event yields for the WW background processes in the three signal regions (SR_{ggF} , SR_{VBF1J} and SR_{VBF2J}) and the WW control regions (WW $CR_{ggF/VBF1J}$). Jet and Pile-up sources dominate the experimental uncertainty while ME+PS, μ_R , Resummation and PDF are the dominant theoretical uncertainties. The last column shows the total uncertainty including those not listed here.

Source	Jet	Pile-up	ME+PS	μ_R	Resummation	PDF	Total
SR_{ggF}	1.2	1.8	2.4	1.7	3.1	1.3	5.0
SR_{VBF1J}	17	2.8	11	7.3	5.0	1.0	23
SR_{VBF2J}	18	3.1	38	18	1.4	1.3	47
WW CR_{ggF}	1.1	1.8	2.6	0.95	2.9	2.3	5.2
WW CR_{VBF1J}	16	4.5	12	11	2.3	1.6	23

increase from 2% to 10% with m_T . This m_T dependence is taken into account in the signal regions. In the ggF quasi-inclusive category, two additional shape systematic uncertainties associated with the scale variations and the p_T reweighting for the leading lepton in the top-quark background are applied, the latter corresponding to $\pm 50\%$ of the reweighting correction. These two uncertainties are comparable and vary from a few percent at low m_T to about 10% at $m_T \simeq 1$ TeV, without affecting the integrated event yield of the top-quark background in the category.

For the WW background, the ME+PS modelling uncertainty is obtained by comparing the nominal SHERPA 2.2.1 sample with an alternative sample generated with POWHEG-Box+PYTHIA8. The renormalisation, factorisation, and resummation scales are varied separately by factors of 0.5 and 2.0. The uncertainty corresponding to the factorisation scale variation is smaller than the other uncertainties and is not shown. The PDF uncertainty for the WW background is obtained and treated in the same way as for the top-quark background. In the ggF quasi-inclusive category, an additional shape uncertainty from ME+PS is applied. It varies from a few percent at low m_T to about 20% at $m_T \simeq 1$ TeV. There are no significant shape uncertainties in the m_T distributions in the VBF categories.

In addition to the scale uncertainties described above, a relative uncertainty of $\pm 50\%$ is assigned to the reweighting corrections of the $q\bar{q} \rightarrow WW$ SHERPA sample to the combined NNLO QCD and NLO EW predictions in the ggF SR and WW CR.

The $gg \rightarrow (h^*) \rightarrow WW$ process, where the SM 125 GeV Higgs boson is off-shell, is modelled at leading order with the SHERPA event generator with a K -factor of 1.7 that is used to account for higher-order cross-section corrections with an uncertainty of 60%, following the studies in Refs. [102–105].

Other small background processes, such as WZ , ZZ , $Z/\gamma^* + \text{jets}$ and WW in the $N_{\text{jet}} \geq 2$ VBF category, do not have their own control regions. They are normalised to the theoretical predictions. The uncertainties in their yields due to the uncertainties in the predictions are evaluated with the same prescription as described above. The impact of these uncertainties is small (see Tables 6 and 7 in Section 9).

8.3 Theoretical uncertainties in the signal predictions

Theoretical uncertainties in the signal acceptance include effects due to the choice of QCD renormalisation and factorisation scales, the PDF set as well as the underlying-event modelling, the parton shower model and the parton shower tune. These uncertainties are evaluated separately in each of the three event categories as a function of the resonance mass and independently for ggF- and VBF-induced resonances.

The effect of missing higher-order corrections in QCD on the signal acceptance is estimated by varying the renormalisation and factorisation scales independently by factors of 0.5 and 2.0 from the nominal scale of $\sqrt{m_H^2 + p_{T,H}^2}$, with m_H and $p_{T,H}$ being the mass and the transverse momentum of the heavy Higgs boson, respectively. The acceptance values obtained with these modified MC samples are compared to the signal acceptance of the nominal sample. For resonances produced via ggF, these uncertainties are found to be negligible in the quasi-inclusive ggF and $N_{\text{jet}} = 1$ VBF categories, while in the $N_{\text{jet}} \geq 2$ VBF category they range between 2.5% and 0.2% for a resonance mass varying from 200 GeV to 4 TeV (unless stated otherwise, the following uncertainties are quoted for the same mass range). For resonances produced via vector-boson fusion, these uncertainties range from 0.9% to 2.8% in the quasi-inclusive ggF category, from 1.9% to 3.6% in the $N_{\text{jet}} = 1$ VBF category and from 1.0% to 7.3% in the $N_{\text{jet}} \geq 2$ VBF category.

The PDF-induced uncertainties in the signal acceptance are determined in the same way as for the top-quark and WW background processes. For the ggF-induced (VBF-induced) signal, these uncertainties reach 0.4% (1.7%), 1.5% (1.2%) and 1.6% (1.5%) for the quasi-inclusive ggF, $N_{\text{jet}} = 1$ and $N_{\text{jet}} \geq 2$ VBF event categories, respectively.

The uncertainties corresponding to the parton shower tune and the underlying event are derived by moving independently, up or down, the PYTHIA internal parameters that are associated with final-state radiation or the multiple parton interactions to study separately their influence on the signal acceptance of the various signal mass points. These uncertainties are compared for each event category and mass point to the uncertainties from the choice of parton shower model, which are estimated by comparing the results obtained for the nominal parton shower generator to those obtained using HERWIG++ [106, 107]. The tune uncertainties are found to be smaller than the shower uncertainties for all mass points. Thus only the latter uncertainties are considered in the final results. The corresponding uncertainties for ggF-induced signals increase from 1.3% to 3.1%, from 13% to 28%, and from 2.3% to 15% for increasing resonance masses in the quasi-inclusive ggF, $N_{\text{jet}} = 1$ and $N_{\text{jet}} \geq 2$ VBF categories, respectively. The uncertainties for VBF-induced signals increase from 4.3% to 19%, from 5.1% to 9.0%, and from 3.3% to 8.0% in the three categories.

In addition, uncertainties due to missing higher-order corrections in QCD are evaluated for ggF-induced processes for each event category, considering also event migration effects between different event categories. This follows the method proposed by Stewart and Tackmann [108]. The corresponding uncertainties

Table 6: Event yields in the signal and control regions for the quasi-inclusive ggF category. The predicted background yields and uncertainties are calculated after the simultaneous fit to the data in all the SRs and the CRs including those from Table 7. The statistical and systematic uncertainties are combined. The notation “VV” represents non- WW diboson background.

	SR _{ggF}	Top CR _{ggF}	WW CR _{ggF}
WW	$11\,500 \pm 800$	810 ± 110	$3\,350 \pm 220$
Top quark	$11\,800 \pm 600$	$52\,550 \pm 330$	$2\,610 \pm 180$
Z/γ^*	$1\,420 \pm 110$	111 ± 20	21.0 ± 2.0
W +jets	$1\,180 \pm 320$	710 ± 190	280 ± 70
VV	866 ± 34	101 ± 12	250 ± 11
Background	$26\,740 \pm 170$	$54\,290 \pm 250$	$6\,510 \pm 80$
Data	26 739	54 295	6 515

range from 3% to 10% for the quasi-inclusive ggF category and from 4% to 30% (30% – 60%) for the $N_{\text{jet}} = 1$ ($N_{\text{jet}} \geq 2$) VBF event categories.

9 Results

The statistical method used to interpret the results of the search is described in Ref. [109]. A likelihood function $\mathcal{L}$ is defined as the product of Poisson probabilities associated with the number of events in bins of the m_T distributions in the signal regions and of the total yields in the control regions. Each source of systematic uncertainty is parameterised by a corresponding nuisance parameter θ constrained by a Gaussian function.

The m_T distributions in the signal regions are divided into 18 (8) bins for the ggF quasi-inclusive ($N_{\text{jet}} = 1$ and ≥ 2 VBF) categories. The bins are of variable size to reflect the increasing width of the m_T distribution of the expected signal with increasing mass, while keeping the statistical precision of the background contributions in each bin sufficiently high.

The numbers of events predicted and observed in the signal and control regions are shown for the quasi-inclusive ggF categories in Table 6 and for the VBF $N_{\text{jet}} = 1$ and ≥ 2 categories in Table 7. These yields are obtained from a simultaneous fit to the data in all the SRs and the CRs. The fitted signal event yield is consistent with zero. The background compositions depend strongly on the event categories: the top-quark and WW processes are comparable in SR_{ggF} and SR_{VBF1J} while the top-quark events dominate in SR_{VBF2J}. The large reduction of the total background uncertainty is due to strong anti-correlations between some of the uncertainty sources of the top-quark and WW background. The m_T distributions in SR_{ggF}, SR_{VBF1J} and SR_{VBF2J} are shown in Figure 4. As no excess over the background prediction is observed, upper limits at 95% confidence level (CL) are set on the production cross section times the branching fraction, $\sigma_X \times B(X \rightarrow WW)$, for signals in each benchmark model.

The 95% CL upper limits are computed using the modified frequentist method known as CL_s [110], using the asymptotic approximation of the distribution of a test statistic [111], q_μ , a function of the signal

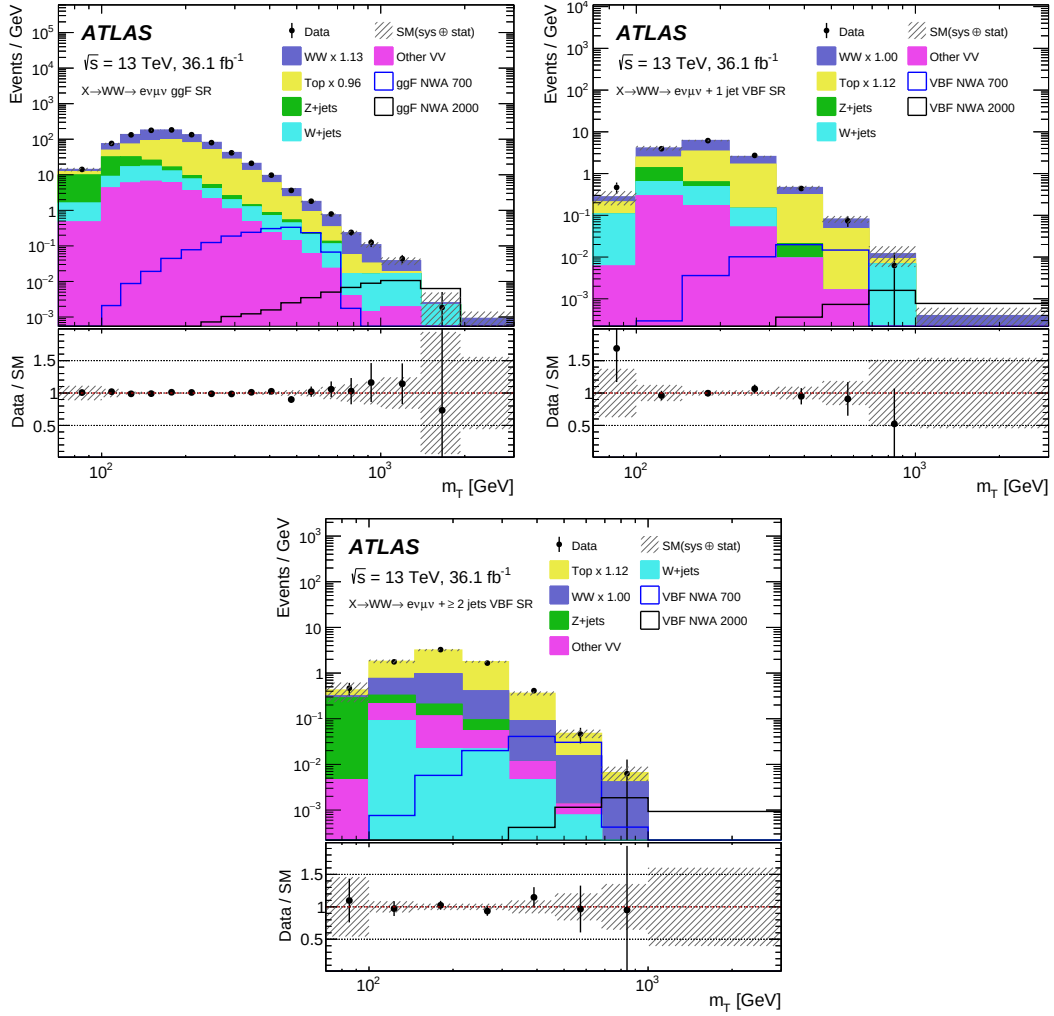


Figure 4: Post-fit distributions of the transverse mass m_T in the SR_{ggF} (top left), SR_{VBF1J} (top right) and SR_{VBF2J} (bottom) categories. In each plot, the last bin contains the overflow. The hatched band in the upper and lower panels shows the total uncertainty of the fit. The top-quark and WW background event yields are scaled using the indicated normalisation factors obtained from the simultaneous fit to all signal and control regions. The heavy Higgs boson signal event yield is normalised to the expected limits on $\sigma_H \times B(H \rightarrow WW)$ and is shown for masses of 700 GeV and 2 TeV in the NWA scenario.

Table 7: Event yields in the signal and control regions for the $N_{\text{jet}} = 1$ and ≥ 2 VBF categories. The predicted background yields and uncertainties are calculated after the same simultaneous fit to the data in all the event categories as in Table 6. The statistical and systematic uncertainties are combined. The notation “VV” represents non- WW diboson background.

	SR _{VBF1J}	SR _{VBF2J}	Top CR _{VBF}	WW CR _{VBF1J}
WW	390 ± 50	120 ± 26	61 ± 11	265 ± 32
Top quark	450 ± 50	391 ± 24	5 650 ± 90	167 ± 18
Z/ γ^*	45 ± 11	24 ± 6	68 ± 19	74 ± 12
W+jets	52 ± 13	8.9 ± 2.5	91 ± 24	43 ± 11
VV	32 ± 7	16.6 ± 1.9	20 ± 9	38 ± 4
Background	972 ± 29	563 ± 22	5 890 ± 80	596 ± 22
Data	978	560	5 889	594

strength μ , defined as the ratio of the measured $\sigma_X \times B(X \rightarrow WW)$ to that of the prediction:

$$q_\mu = -2 \ln \left(\frac{\mathcal{L}(\mu; \hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu}; \hat{\theta})} \right).$$

The quantities $\hat{\mu}$ and $\hat{\theta}$ are those values of μ and θ , respectively, that unconditionally maximise $\mathcal{L}$. The numerator depends on the values $\hat{\theta}_\mu$ that maximise $\mathcal{L}$ for a given value of μ .

Limits are obtained separately for ggF and VBF production for the NWA and LWA signal hypotheses. To derive the expected limits on the ggF (VBF) production modes, the VBF (ggF) production cross section is set to zero so that the expected limits correspond to the background-only hypothesis. To derive the observed limits on the ggF (VBF) production mode, the VBF (ggF) production cross section is treated as a nuisance parameter in the fit and profiled, in the same way as dealing with the normalisation factors of the different background processes. This approach avoids making any assumption about the presence or absence of the signal in any of these production modes.

Figure 5 shows the 95% CL upper limits on $\sigma_H \times B(H \rightarrow WW)$ as a function of m_H for a Higgs boson in the NWA scenario in the mass range $200 \text{ GeV} \leq m_H \leq 4(3) \text{ TeV}$ for the ggF (VBF) production. Values above 6.4 pb (1.3 pb) at $m_H = 200 \text{ GeV}$ and above 0.008 pb (0.006 pb) at 4 (3) TeV are excluded at 95% CL by the quasi-inclusive ggF (VBF) NWA analysis. The main systematic uncertainties affecting the limits are the p_T correction for the leading lepton in the top-quark background, scale variations for the top-quark background, the parton shower modelling of the WW MC generator, and the jet energy scale and resolution uncertainties. Limits are consistent with those expected in the absence of a signal over the investigated mass range. The fact that the observed limits are more stringent than the expected ones for mass values beyond 2 TeV is explained by the deficit in data at the high m_T tail in Figure 4. These limits are extracted using the asymptotic approximation and their accuracy is verified to be consistent within about 5% at 800 GeV and better than 20% at 2 TeV and beyond using pseudo-experiments.

The analysis can be extended to a more general case where the relative fraction of the ggF production cross section varies over the total ggF and VBF production cross section. The corresponding 95% CL upper exclusion limits for a signal at 800 GeV are shown in Figure 6. The dependence of the limits on the ggF fraction for other masses is similar but becomes slightly stronger (weaker) for lower (higher) mass values. The limit values for a ggF fraction of 0 and 1 are comparable with the VBF and ggF limits shown

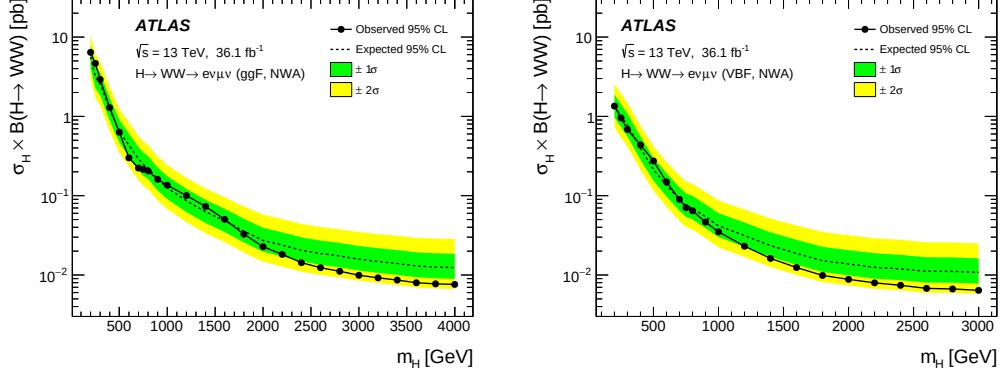


Figure 5: Upper limits at 95% CL on the Higgs boson production cross section times branching fraction $\sigma_H \times B(H \rightarrow WW)$ in the $e\nu\mu\nu$ channel, for ggF (left) and VBF (right) signals with narrow-width lineshape as a function of the signal mass. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit.

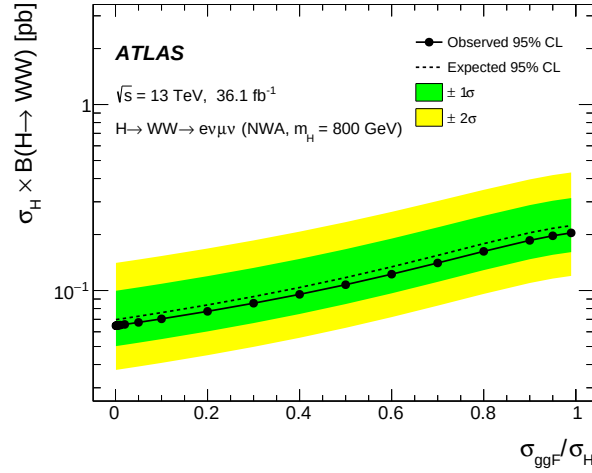


Figure 6: Upper limits at 95% CL on the total ggF and VBF Higgs boson production cross section times branching fraction $\sigma_H \times B(H \rightarrow WW)$ in the $e\nu\mu\nu$ channel, for a signal at 800 GeV as a function of the ggF cross section divided by the combined ggF and VBF production cross section. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit.

in Figure 5 at the same mass value. The VBF limits are tighter than the ggF limits since the VBF $N_{\text{jet}} \geq 2$ signal region has the smallest background contribution and thus is the most sensitive.

The NWA exclusion limit shown above can be further translated to exclusion contours in the 2HDM for the phase space where the narrow-width approximation is valid. The 95% CL exclusion contours for Type I and Type II in the plane of $\tan\beta$ and $\cos(\beta - \alpha)$ for three mass values of 200 GeV, 300 GeV and 500 GeV are shown in Figure 7. For a fixed value of $\cos(\beta - \alpha) = -0.1$, 95% CL exclusion limits on $\tan\beta$ as a function of the heavy Higgs boson mass are shown in Figure 8. The coupling of the heaviest CP-even

Higgs boson to vector bosons is proportional to $\cos(\beta - \alpha)$ and in the decoupling limit $\cos(\beta - \alpha) \rightarrow 0$, the light CP-even Higgs boson is indistinguishable from a SM Higgs boson with the same mass. The range of $\cos(\beta - \alpha)$ and $\tan \beta$ explored is limited to the region where the assumption of a heavy narrow-width Higgs boson with negligible interference is valid. When calculating the limits at a given choice of $\cos(\beta - \alpha)$ and $\tan \beta$, the relative rate of ggF and VBF production in the fit is set to the prediction of the 2HDM for that parameter choice. The white regions in the exclusion plots indicate regions of parameter space which are not excluded by the present analysis.

For the LWA scenario, the interference effects among the heavy boson, the light Higgs boson at 125 GeV and the SM WW continuum background were studied and found to have negligible impact on the exclusion limits. The 95% CL upper limits are shown in Figure 9. The limits for signal widths of 5%, 10% and 15% are comparable with those from the NWA scenario for the VBF signals while for the ggF signals, the limits weaken slightly at high masses as the width increases. For the LWA 15% case, the upper exclusion limit ranges between 5.2 pb (1.3 pb) at $m_H = 200$ GeV and 0.02 pb (0.006 pb) at 4 (3) TeV for the ggF (VBF) signals.

Figure 10 shows the limits on the resonance production cross section times branching fraction $\sigma_X \times B(X \rightarrow WW)$ and $\sin \theta_H$ for a scalar GM signal with masses between 200 GeV and 1 TeV. At the observed limit, the width is narrower than the experimental resolution [46]. The current sensitivity is not sufficient to exclude the benchmark model with $\sin \theta_H = 0.4$.

Limits are derived in the mass range from 250 GeV to 5 TeV and from 300 GeV to 1 TeV for a qqA and VBF HVT signal, respectively, as shown in Figure 11. For the qqA production, signals below about 1.3 TeV are excluded at 95% CL. No limit can be set for the VBF production in the benchmark model that assumes a coupling strength to gauge bosons $g_V = 1$ and a coupling to fermions $c_F = 0$. The model has an intrinsic width much narrower than the detector resolution.

Figure 12 shows the limits on a $G_{KK} \rightarrow WW$ signal for two different couplings: $k/\bar{M}_{Pl} = 1$ and $k/\bar{M}_{Pl} = 0.5$, for masses between 200 GeV and 5 TeV, and for an ELM spin-2 VBF signal for masses between 200 GeV and 1 TeV. The observed limits exclude a KK graviton signal lighter than 1.1 TeV (750 GeV) with the higher (lower) coupling, while the current sensitivity is not sufficient to exclude the ELM spin-2 VBF signal.

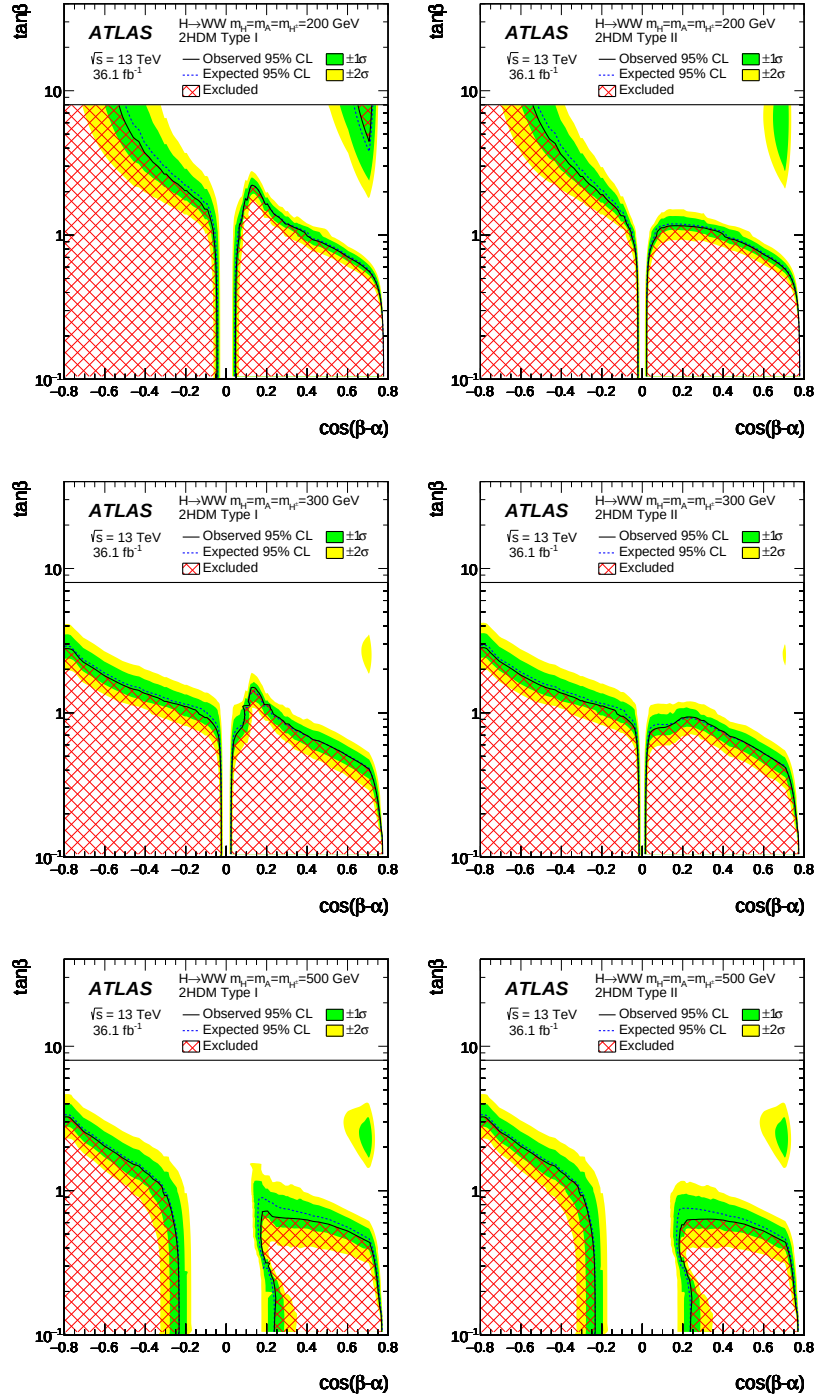


Figure 7: Exclusion contours at 95% CL in the plane of $\tan\beta$ and $\cos(\beta - \alpha)$ for Type I (left) and Type II (right) 2HDM signals with three mass values of 200 GeV (top), 300 GeV (middle) and 500 GeV (bottom). The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit and the hatched regions are excluded.

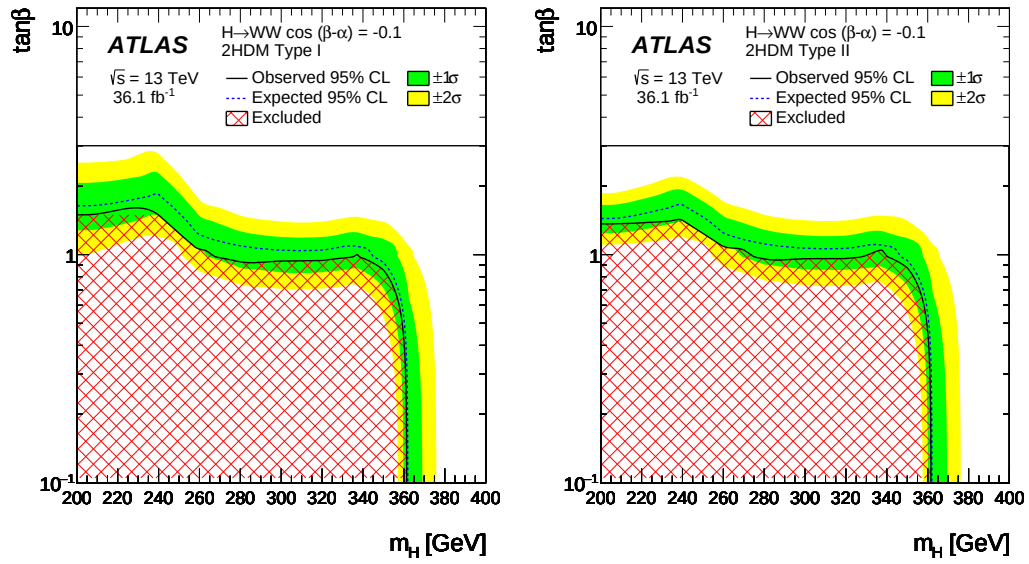


Figure 8: Exclusion contours at 95% CL in the plane of $\tan\beta$ and m_H for Type I (left) and Type II (right) 2HDM signals with $\cos(\beta - \alpha) = -0.1$. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit and the hatched regions are excluded. The other heavy Higgs boson states A and $H^\pm$ are assumed to have the same mass as H .

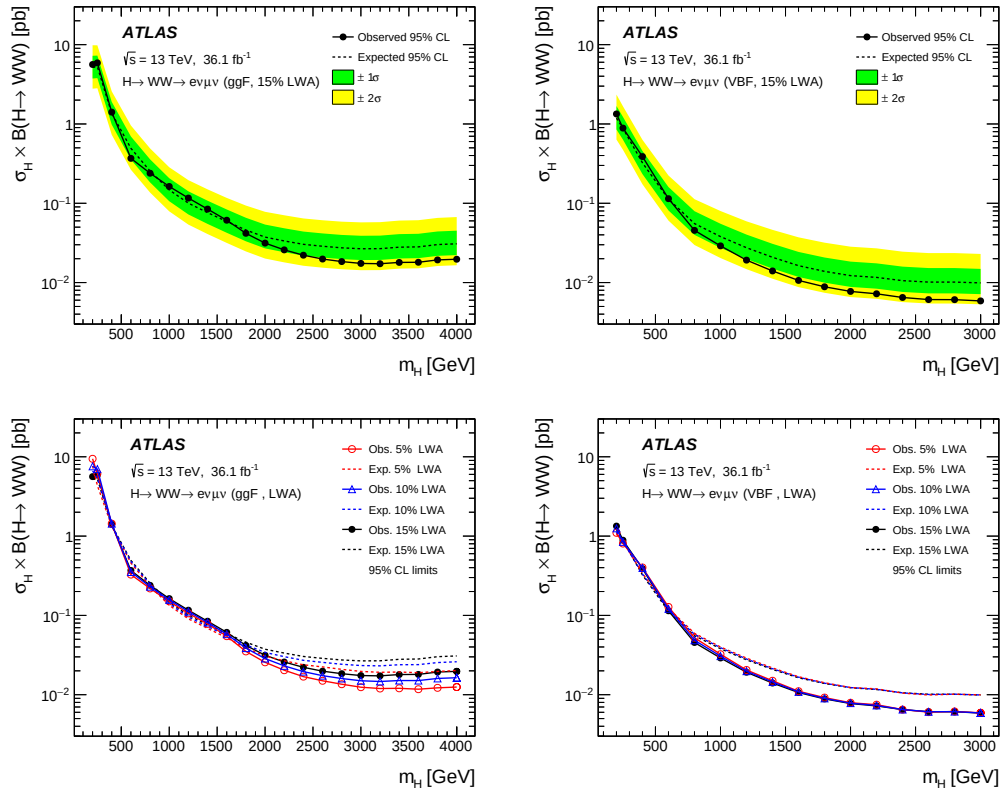


Figure 9: Upper limits at 95% CL on the Higgs boson production cross section times branching fraction $\sigma_H \times B(H \rightarrow WW)$ in the $e\nu\mu\nu$ channel, for a signal with a width of 15% of the mass (top) and the comparison of three different widths (bottom) for the ggF (left) and VBF (right) production. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit.

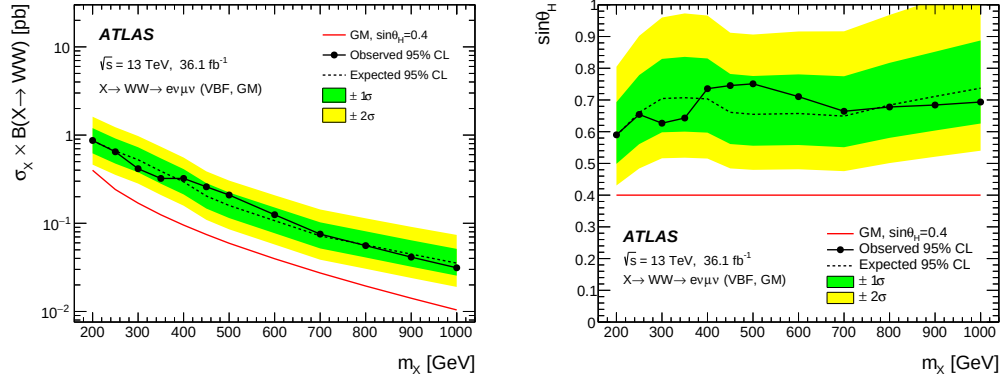


Figure 10: Upper limits at 95% CL on the resonance production cross section times branching fraction $\sigma_X \times B(X \rightarrow WW)$ (left) and on $\sin\theta_H$ (right) in the $e\nu\mu\nu$ channel, for a GM signal. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit. The full curves without dots correspond to the predicted theoretical cross section and the model parameter used in the benchmark model, respectively.

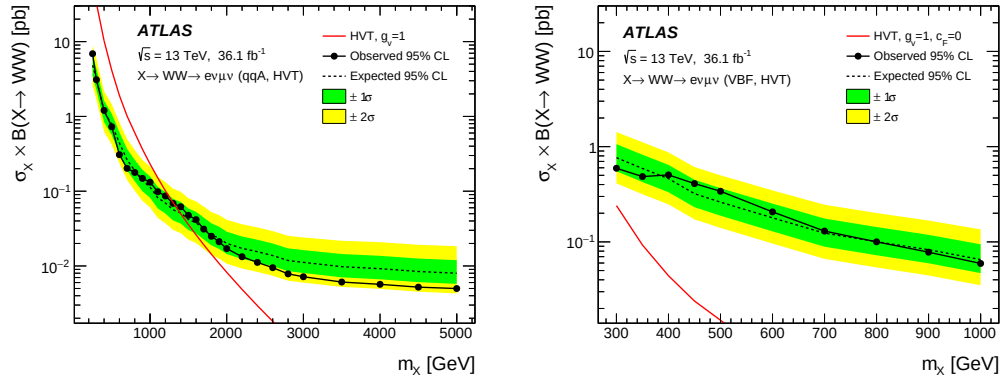


Figure 11: Upper limits at 95% CL on the resonance production cross section times branching fraction $\sigma_X \times B(X \rightarrow WW)$ in the $e\nu\mu\nu$ channel, for HVT qqA (left) and VBF (right) signals. The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit. The full curves without dots correspond to the predicted theoretical cross sections.

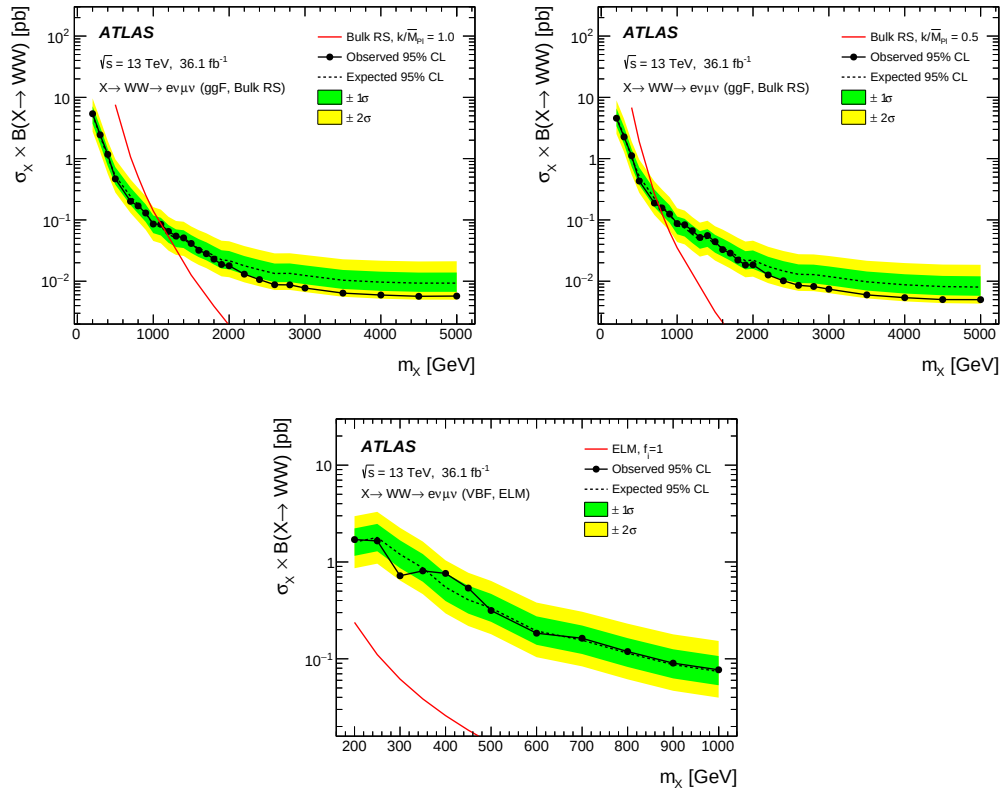


Figure 12: Upper limits at 95% CL on the resonance production cross section times branching fraction $\sigma_X \times B(X \rightarrow WW)$ in the $\nu_e \nu_\mu \nu$ channel, for a graviton signal with two different couplings of $k/\bar{M}_{Pl} = 1$ (left) and $k/\bar{M}_{Pl} = 0.5$ (right), and for an ELM spin-2 VBF signal (bottom). The inner and outer bands show the $\pm 1\sigma$ and $\pm 2\sigma$ ranges around the expected limit. The full curves without dots correspond to the predicted theoretical cross sections.

10 Conclusion

A search for heavy neutral resonances decaying into a WW boson pair in the $e\nu\mu\nu$ channel performed by the ATLAS Collaboration at the LHC is presented. The search uses proton–proton collision data collected at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 36.1 fb^{-1} . No significant excess of events beyond the Standard Model background prediction is found in the mass range between 200 GeV and up to 5 TeV. Upper limits are set on the product of the production cross section and the $X \rightarrow WW$ branching fraction in several scenarios: a high-mass Higgs boson with a narrow width or with intermediate widths (of 5%, 10% and 15% of the heavy Higgs boson mass), as well as other spin-0, spin-1, and spin-2 signals. For the narrow-width heavy Higgs boson signals, values above 6.4 pb at $m_H = 200 \text{ GeV}$ and above 0.008 pb at 4 TeV are excluded at 95% confidence level for the gluon–gluon fusion production mode. The corresponding values for the vector-boson fusion production modes are 1.3 pb and 0.006 pb at 200 GeV and 3 TeV, respectively. For the signals of the heavy vector triplet model A produced by quark–antiquark annihilation and of the Randall–Sundrum graviton model with $k/\bar{M}_{\text{Pl}} = 1$ and 0.5, mass values below 1.3 TeV, 1.1 TeV and 750 GeV are excluded, respectively.

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