
CMS Physics Analysis Summary

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Search for heavy scalar resonances decaying to a pair of Z bosons in the 4-lepton final state at 13 TeV

The CMS Collaboration

Abstract

A search for a heavy scalar resonance decaying to two Z bosons and subsequently to four leptons is presented, where the leptons can be electrons or muons. The results are based on the proton-proton collision data collected by the CMS experiment at the LHC at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1} . The searches are performed in a model independent way over a range of resonance mass from 130 GeV to 3 TeV, considering both narrow and wide width scenarios, and assuming that the resonance is produced via gluon fusion or vector boson fusion. For the wide width scenarios, the interference between the signal, the standard model Higgs production, and the continuum background are taken into account. No significant excess with respect to the standard model predictions is observed in the examined phase space, and upper limits at 95% confidence level on the production cross section of the resonance multiplied by the branching ratio of decaying to two Z bosons are computed.

1 Introduction

In 2012, the ATLAS and CMS Collaborations discovered a boson [1, 2] with mass close to 125 GeV, and with properties consistent with those expected for the Higgs boson (H) predicted by the standard model (SM) of particle physics. This discovery represents a major breakthrough for the field of particle physics, and a significant validation for the SM that postulated the existence of this particle as excitation of the Higgs field.

The SM, however, presents some limitations as it does not include a description of gravity and dark matter, nor it explains the hierarchy problem of the Higgs boson mass, the origin of the matter-antimatter asymmetry, etc. These questions drive the searches for physics phenomena beyond the SM (BSM), and models extending the SM attempting to address them. In many such BSM models, additional scalar resonances are predicted, e.g. the additional Higgs boson in the two-Higgs doublet model (2HDM) [3], and the radion in Warped Extra Dimension models [4–6].

In this note, the search for a heavy scalar resonance X is presented in the decay channels $X \rightarrow ZZ \rightarrow 4\ell$, where the leptons ℓ are electrons (e) or muons (μ). This analysis relies on the full Run 2 proton-proton collisions dataset collected by the CMS experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1} . The ZZ final state is one of the dominant decay channels for an SM-like Higgs boson with masses above the $2 M_Z$ threshold. Since the mass of the new resonance is not known, the search is performed in a wide range of masses from 130 GeV up to 3 TeV, similar to what was done with the Higgs boson search prior to its discovery in 2012. Previous searches for a new boson decaying to Z bosons have been performed by the CMS [7, 8] and ATLAS [9, 10] Collaborations using data collected in Run 1 and Run 2 of the Large Hadron Collider (LHC), but no significant excess has been observed. The presence of a signal hint at 680 GeV [10] has been advocated [11], calling for a search for heavy resonances in the ZZ final state in the CMS experiment.

The lineshape of the new scalar particle X is parametrized in a model-independent way, i.e. the resonance mass (M_X) and width (Γ_X) are assumed to be unknown. Furthermore, the two dominant production mechanisms of a Higgs-like scalar boson at the LHC are considered: gluon fusion (ggF) and vector boson fusion (VBF). A parameter f_{VBF} is defined as the fraction of VBF production with respect to the total cross section, and it is considered as a parameter regulating the production mechanism of the new resonance. The new particle X can present a large width which leads to a sizable interference between the $X \rightarrow ZZ \rightarrow 4\ell$ process and SM background production of $ZZ \rightarrow 4\ell$. This interference modifies both the kinematic distributions and the overall yield of the BSM contribution. The interference effect is present for both ggF and VBF production, and it is considered in this study. All the described effects are included in the analysis in a parametric way, in a likelihood fit to the data. The matrix element (ME) formalism is used both for the parameterization of the likelihood and for the construction of optimal observables for event categorization.

This note is organized as follows: Section 2 briefly describes the CMS detector; Section 3 lists the datasets and MC simulation samples used in the analysis; Section 4 reports the reconstruction of the involved objects and the event selection criterion; Section 5 introduces the discriminating variables and how they are computed; Section 6 denotes the event categorization; Section 7, 8 and 9 introduce the approaches to signal, background and interference modeling which are used to construct the probability distribution functions in the statistical model; Section 10 illustrates the systematic uncertainties to be considered; Section 11 shows the expected results of the cross section upper limits; and finally the main highlights of this note are summarized in Section 12.

2 The CMS detector

The central core of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a 3.8 T magnetic field to bend charged particles. The subdetectors are arranged in layers, from the closest to the beam pipe outwards: a silicon inner tracker covering the pseudorapidity region of $|\eta| < 2.5$, a tungstate crystal electromagnetic calorimeter (ECAL) covering $|\eta| < 3.0$, a brass/scintillator hadronic calorimeter (HCAL) covering $|\eta| < 3.0$ and muon gas chambers embedded in the steel flux-return yoke outside the solenoid covering $|\eta| < 2.4$. An iron/quartz-fiber hadronic forward calorimeter (HF) is also configured in the region of $3.0 < |\eta| < 5.0$. A more detailed description can be found in [12].

To reduce event rates and collect events of interest, a two-level trigger system is used. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of approximately 100 kHz within a fixed latency of about 4 μ s [13]. The second level, known as the high-level trigger (HLT), consists of a set of processors running the full event reconstruction software optimized for fast processing, and reduces the event rate to approximately 1 kHz [14].

3 Data and simulation samples

This analysis relies on the proton-proton collision data collected by the CMS experiment at the Large Hadron Collider (LHC) in 2016, 2017 and 2018, corresponding to an integrated luminosity of 36.3, 41.5 and 59.7 fb^{-1} , respectively [15–17].

Candidate events firstly pass through the online selection, before undergoing the offline reconstruction of different particle candidates and event selection [18, 19], which are described in Section 4. The online selection is based on di-electron, di-muon, and electron-muon HLT algorithms. Additional triggers, requiring three leptons with loose p_T thresholds and no isolation criteria, as well as single-lepton triggers are used to increase the efficiency. The different p_T thresholds used in the triggers are listed in Table 1 for the different data-taking periods.

Table 1: Thresholds applied on the p_T of the leading/subleading leptons for the single lepton (e, μ), dilepton ($e/e, e/\mu, \mu/\mu$), and trilepton ($e/e/e, e/e/\mu, e/\mu/\mu, \mu/\mu/\mu$) HLT algorithms used in each data-taking period. All values are in GeV.

	e	μ	e/e	e/ μ	μ/μ	e/e/e	e/e/ μ	e/ μ/μ	$\mu/\mu/\mu$
2016	25	20	17/12	17/8, 8/23	17/8	16/12/8	12/12/8	9/9/9	12/10/5
2017	35	27	17/8	23/8, 12/23	17/8	16/12/8	12/12/8	9/9/9	10/5/5
2018	32	24	23/12	23/8, 12/23	17/8	-	12/12/8	9/9/9	10/5/5

The measurement of trigger efficiency follows the strategy adopted in [20], using the tag-and-probe method [21]. The efficiency is found to be greater than 99% in most of the phase space, and is compatible between the observed data and simulation within statistical uncertainties.

Monte Carlo (MC) simulated samples are used to study the modeling of signal, background, and interference processes, and to estimate their contributions. Signal samples are generated at next-to-leading order (NLO) in perturbative quantum chromodynamics (pQCD) with the POWHEG v2 [22–24] generator, for the ggF and VBF production mechanisms. The decay of the resonances to four leptons is modeled with JHUGEN 7.0.2 [25–28], including corrections for the ZZ branching fraction, and correct modeling of the angular correlation among the fermions. Signal samples are generated in a wide range of masses M_χ from 125 GeV to 3 TeV with the width Γ_χ set according to the SM Higgs boson expectation for M_χ up to 1 TeV, predicted by the

Complex Pole Scheme (CPS) [29, 30]. For samples with $M_X > 1$ TeV, the width is set to $0.5M_X$, because CPS only predicts the width up to $M_X = 1$ TeV. The searches will be performed on different width assumptions, not restricted to the widths predicted by CPS.

For a more accurate estimation, an event-by-event weighting procedure is applied to the signal simulation with ggF production, to take advantage of the NNLOPS accuracy [31] available. The weight is applied as a function of the generator level number of jets and p_T of the resonance, obtained as the ratio between NNLOPS and POWHEG generators, the latter being used for the MC generation.

The dominant background process originates from the production of two Z bosons from quark antiquark annihilation, $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$, which is simulated at NLO in pQCD with POWHEG 2.0 [32]. The full differential cross section has been computed at next-to-next-to-leading order (NNLO) [33], but it is not yet available in a parton-level event generator, therefore NNLO/NLO K factors for the $q\bar{q} \rightarrow ZZ$ background are applied to the POWHEG sample as a function of M_{ZZ} . Additional NLO electroweak corrections depending on the initial state quark flavor and kinematics are applied to the $q\bar{q} \rightarrow ZZ$ background process in the region $M_{ZZ} > 2M_Z$, where the corrections have been computed.

Another important background is the loop induced production of two Z bosons through gluon fusion, $gg \rightarrow ZZ \rightarrow 4\ell$, which is generated at leading order (LO) in pQCD with MCFM 7.0 [34–36]. It has been shown [37] that the soft collinear approximation is able to describe the background cross section and the interference term at NNLO, and further computations show that the K factors at NLO are very similar for the signal and for the background [38] and at NNLO for the signal and interference terms [39]. Therefore, the LO to NNLO K factor computed for $gg \rightarrow H \rightarrow ZZ$ as a function of M_{ZZ} , using the HNNLO v2 programs [40–42], is used to weight the $gg \rightarrow ZZ$ simulation [43].

The background from vector boson fusion, $qqZZ \rightarrow qq4\ell$, is also generated at LO with MCFM 7.0. The backgrounds of triple vector boson production (WWZ, WZZ) are simulated at NLO using MADGRAPH5_AMCATNLO [44], and the backgrounds from the production of top quarks associated with vector bosons ($t\bar{t}Z$, $t\bar{t}ZZ$, $t\bar{t}WW$) are generated using MADGRAPH at LO.

Additional samples of WZ, Drell-Yan+jets, and top quark antiquark pair production ($t\bar{t}$) are used in the studies for the estimation of reducible backgrounds (described in Section 8.2). The first two processes are simulated using MADGRAPH5_AMCATNLO [44], while the last is estimated with POWHEG at NLO in pQCD [45].

Additionally, samples for off-shell production of the Higgs boson are generated at LO with MCFM 7.0, with both ggF and VBF production mechanisms. These samples are used to study the interferences. The Matrix Element Likelihood Approach (MELA) [2, 46] is used to compute likelihoods based on the topologies of events and matrix elements of different processes. Based on that, certain weights are computed to reweight the samples to model the interference between the SM Higgs boson and SM backgrounds.

All MC samples are interfaced with PYTHIA to simulate parton showering and hadronization effects. Version 8.230 [47] is used for all data-taking periods, with the CUETP8M1 tune [48] for 2016 and the CP5 tune [49] for 2017 and 2018. Parton distribution functions are taken from NNPDF 3.1 [50]. The response of the CMS detector is modeled with GEANT4 [51]. The simulated events are reconstructed with the same algorithms used for data, and the number of pileup events distribution per bunch crossing is reweighted to match that observed in data.

4 Event reconstruction and selection

The particle-flow (PF) algorithm [52] reconstructs and identifies individual particles in the event, with an optimized combination of the various raw information from each subdetector. The energy of photons is measured from the ECAL. The electrons are reconstructed by matching the reconstructed tracks in the inner tracker and the ECAL cluster, the latter considering also the bremsstrahlung photon showers geometrically close enough to the electron track. The energy of electrons is obtained from the combination of the track momentum at the primary interaction vertex and the cluster energy. The energy of muons is measured from the track momenta in both the inner tracker and the muon detector. The energy of charged hadrons is determined by combining the track in the inner tracker and the matched energy deposits in both ECAL and HCAL, with corrections to take into account the imperfect linear energy response of calorimeters. Finally, the energy of neutral hadrons is determined from the energy deposits from ECAL and HCAL, corrected correspondingly.

Muons with $p_T^\mu > 5$ GeV are reconstructed within the acceptance region of the detector, corresponding to $|\eta^\mu| < 2.4$, combining the information from the silicon tracker and the muon system [19]. The matching between the inner tracker and the muon chambers can be performed both starting from the inner detector outwards, or from the outer detector inwards. Cases where inner tracks are matched to segments in only one or two muon stations are also used to recover situations of very low p_T muons that do not traverse the entire detector. The muons considered in this analysis are selected from the muon track candidates by applying loose requirements on the track in the muon system and the inner tracker, taking into account their compatibility with small energy deposits in the ECAL and HCAL. For each muon, the impact parameter significance (SIP), defined as the ratio of the 3-dimensional impact parameter with respect to the primary vertex (PV) to its uncertainty, is required to be lower than 4. This ensures the suppression of non-prompt leptons from in-flight decays of hadrons or photons conversions.

To discriminate the muon candidates from the Z boson decay from those from the hadrons decays within jets, a requirement in the isolation $\mathcal{I}^\mu < 0.35$ is imposed. The isolation is defined as:

$$\mathcal{I}^\mu = \frac{1}{p_T^\mu} \left(\sum_{\text{charged hadrons}} p_T + \max \left[\sum_{\text{neutral hadrons}} p_T + \sum_{\text{photons}} p_T - \frac{1}{2} \sum_{\text{charged hadrons}} p_T^{\text{PU}}, 0 \right] \right). \quad (1)$$

All the summations are performed with only PF particles i within an angular cone of $\Delta R(\mu, i) = \sqrt{(\eta^\mu - \eta^i)^2 + (\phi^\mu - \phi^i)^2} < 0.3$. The first summation considers charged hadrons originating from the primary vertex. The second term ($\max[..., 0]$) considers the neutral particles, including neutral hadrons and photons. The contribution of neutral particles from pileup is subtracted, which is estimated as half of the contribution of charged hadrons from pileup ($\frac{1}{2} \sum_{\text{charged hadrons}} p_T^{\text{PU}}$).

Electrons with $p_T^e > 7$ GeV are reconstructed by combining information from the ECAL and the tracker [18], within the detector acceptance region, $|\eta^e| < 2.5$. The same requirements on the impact parameter as the muon candidates is applied to electrons. Electrons are identified with a dedicated Boosted Decision Tree (BDT) algorithm based on the eXtreme Gradient Boosting (XGBoost) framework [53], containing also isolation information. The algorithm was developed for [20] and trained for [54].

The photons arising from the final state radiation (FSR) of the selected leptons are recovered to improve the mass resolution of the Z boson candidates. PF photons satisfying $p_T^\gamma > 2$ GeV,

$|\eta^\gamma| < 2.4$ and isolation $\mathcal{I}^\gamma < 1.8$ are considered as FSR candidates. Each candidate is associated to the closest lepton in the event and is required to have $\Delta R(\gamma, \ell)/E_{T,\gamma}^2 < 0.012$ and $\Delta R(\gamma, \ell) < 0.5$. For each lepton, only the photon with the lowest $\Delta R(\gamma, \ell)/E_{T,\gamma}^2$ is retained. The FSR candidates are excluded from the computation of the muon isolation.

The reconstruction and selection efficiency of leptons are measured with the tag-and-probe method, individually for electrons and muons, in bins of p_T and η , selecting the events of Z boson production in both data and simulation. The difference between the efficiency computed in data and simulation is used to correct all simulation samples. The lepton energy scale and resolution is calibrated with events of known resonances decaying to two leptons, in bins of p_T and η . Details are described in [18, 19].

Hadronic jets are clustered from PF particles using the infrared- and collinear-safe anti- k_T algorithm [55] with a radius of 0.4. The jet energy is computed from the vectorial sum of all PF particles belonging to it. To account for the fact that the reconstructed jet energy is on average 5 to 10% larger than that in data, particles from pileup vertices are discarded from the jet composition, and residual corrections are applied. The corrections are derived exploiting events with dijet topology, as well as $\gamma + \text{jet}$, $Z + \text{jet}$ and multijet events [56]. In this analysis, hadronic jets are required to have $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 4.7$. They are identified implementing requirements on their energy fraction of different types of particles, and are required to have $\Delta R > 0.4$ with respect to all selected leptons and associated photons. For jets with $p_T^{\text{jet}} < 50$ GeV, a dedicated identification algorithm is used to reject jets from pileup [57].

The jet flavor is identified by the DeepCSV algorithm [58–60], a deep-neural-network based algorithm to tag heavy flavor jets. Jets passing the medium working points are regarded as b jets. The b tagging information is used to divide the reconstructed events in categories, to enhance the sensitivity to VBF production. VBF jets are very likely to be in the forward region with $|\eta| > 2.5$, which is not covered by the inner tracker. Since the b tagging algorithm highly relies on the secondary vertex detection from the inner tracker, it mainly helps when the VBF jets are less forward.

The described PF objects are used as input to the event selection, which targets events with at least four well-defined and isolated leptons originating from the PV. The FSR photons are included in the invariant mass computation. The event selection follows that employed in [20] and is described in the following.

The Z boson candidates are built from pairs of leptons with opposite charge and same flavor, with $12 \text{ GeV} < M_Z < 120 \text{ GeV}$. The ZZ candidates are then formed by selecting two of the Z boson candidates. The Z boson candidate with invariant mass closer to the nominal Z boson mass [61] is defined as Z_1 , while the other is identified as Z_2 . Three mutually exclusive final states are defined on the basis of the flavors of the four leptons in the event: 4μ , $4e$, and $2e2\mu$. The ZZ candidates are required to satisfy the following requirements:

- Any two of the four leptons must have $\Delta R(\ell_1, \ell_2) > 0.02$.
- The Z_1 is required to have $M_{Z_1} > 40$ GeV.
- Among the four leptons, the one with the highest p_T should have $p_T > 20$ GeV, and the second highest has $p_T > 10$ GeV.
- Any two of the four leptons with opposite charge should have $M_{\ell^+\ell^-} > 4$ GeV, to suppress QCD multijet events.
- In the 4μ and $4e$ final states, the selected ZZ candidate could come from processes containing one Z boson and a low mass resonance. To suppress this, two alternative

Z boson candidates are built by swapping the two positive leptons in the two Z boson candidates. The alternative Z boson candidate with the invariant mass closer to M_Z is noted as Z_a , the other as Z_b . The ZZ candidate is discarded if $|M_{Z_a} - M_Z| < |M_{Z_b} - M_Z|$ and $M_{Z_b} < 12$ GeV.

- The invariant mass of the ZZ candidate should be greater than 70 GeV.

The signal region is defined as events with at least one ZZ candidate satisfying all the above requirements. If more than one ZZ candidate passes the selection, the one with the highest $D_{\text{bkg}}^{\text{kin}}$ is chosen. The $D_{\text{bkg}}^{\text{kin}}$ is a variable calculated based on the ZZ kinematics and matrix elements, which will be defined in Section 5. This selection almost never happens for signal events or background processes like $g\bar{g} \rightarrow ZZ$ or $q\bar{q} \rightarrow ZZ$. It can be more frequent for minor background processes with additional leptons, like $t\bar{t}ZZ$.

Compared to the measurements of the SM Higgs boson [20], the trigger requirements and event selections are the same, while the alignment and calibrations of the CMS detector has been updated.

5 Observables

The resonant signal would appear as a peak in the distribution of the reconstructed 4-lepton mass $M_{4\ell}^{\text{reco}}$, which provides significant discrimination against backgrounds, thanks to the good energy resolution of the electrons and muons. The mass resolution at 125 GeV is around 1 GeV, and increases to around 30 GeV in the $4e$ final state, 60 GeV in the $2e2\mu$ final state, and 90 GeV in the 4μ final state at 3 TeV. The left plot of Figure 1 shows the $M_{4\ell}^{\text{reco}}$ distributions of different signal hypotheses, together with background processes and observed data, considering the full Run 2 dataset. All the signal and background distributions are estimated from MC simulation, except the $Z + X$ background introduced in Section 8.2, estimated with a data-driven method. The *other* background includes triboson productions, as well as $t\bar{t}$ plus vector bosons.

The backgrounds are almost flat in the region from around 130 GeV to around 180 GeV, then grow significantly until around 200 GeV and then decrease. Signal processes with different masses and production modes are shown, normalized to have the same cross section as the SM Higgs boson production. They have the widths predicted by the CPS used in the MC simulation, describing the shape of an SM-like Higgs boson with different masses. The signals present very concentrated distributions at low resonance masses, and can be prominent above backgrounds if such resonances are produced with high enough cross sections. The distributions grow wider at high resonance masses because the relative Higgs width for an SM-like Higgs becomes much larger at higher masses.

Besides $M_{4\ell}^{\text{reco}}$, another observable, the kinematic discriminant $D_{\text{bkg}}^{\text{kin}}$, is considered in the analysis, computed using MELA. It is defined as the likelihood ratio:

$$D_{\text{bkg}}^{\text{kin}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}^{\text{q}\bar{\text{q}}}(\vec{\Omega}^{\text{H} \rightarrow 4\ell} | M_{4\ell}^{\text{reco}})}{\mathcal{P}_{\text{sig}}^{\text{g}\bar{\text{g}}}(\vec{\Omega}^{\text{H} \rightarrow 4\ell} | M_{4\ell}^{\text{reco}})} \right]^{-1}. \quad (2)$$

In the equation, $\mathcal{P}_{\text{bkg}}^{\text{q}\bar{\text{q}}}$ corresponds to the probability of the event being $q\bar{q} \rightarrow 4\ell$ process-like, calculated with the matrix element from MCFM; $\mathcal{P}_{\text{sig}}^{\text{g}\bar{\text{g}}}$ defines the probability of the event having similar kinematics as the SM Higgs boson production via gluon fusion, calculated with the matrix element from JHUGEN. $\vec{\Omega}^{\text{H} \rightarrow 4\ell}$ refers to the angular phase space of the 4ℓ system.

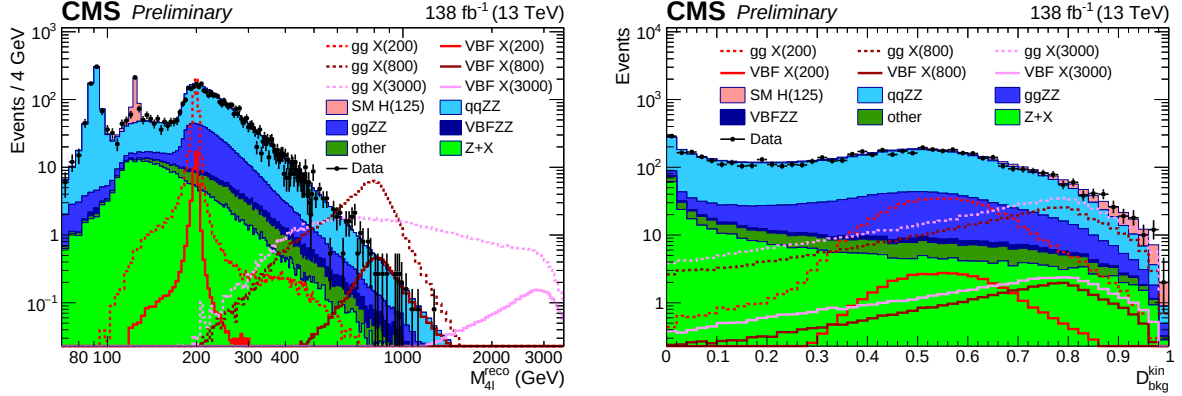


Figure 1: Left: the $M_{4\ell}^{\text{reco}}$ distributions of signal and background processes estimated from the MC simulation. Observed data are superimposed as well. The signal lineshapes shown in the plot show the width predicted by the CPS, describing the shape of an SM-like Higgs boson with different masses. Right: The $D_{\text{bkg}}^{\text{kin}}$ distributions of signal and background processes estimated from the MC simulation, together with the observed data.

The $D_{\text{bkg}}^{\text{kin}}$ distributions are illustrated in the right plot of Figure 1 with different signal hypotheses together with background processes and observed data. The backgrounds are mainly distributed around 0 and around 0.5, while the signals are concentrated around 0.8, except for $M_X = 200$ GeV which is concentrated around 0.5. The reason for this is that the 200 GeV signal has kinematics very similar to the main ZZ backgrounds, which have two on-shell Z bosons with $M_{4\ell}^{\text{reco}}$ distributed around 200 GeV. Except that, $D_{\text{bkg}}^{\text{kin}}$ is a powerful tool to discriminate signals at different masses against backgrounds, even if it is computed assuming the SM Higgs boson topology.

The observables $M_{4\ell}^{\text{reco}}$ and $D_{\text{bkg}}^{\text{kin}}$ are used to build the two-dimensional templates to discriminate signals from backgrounds in the likelihood fit.

6 Event categorization

Events are categorized based on the topologies of the hadronic jets and MELA discriminants, to improve the sensitivity of the VBF signals. The categorization criteria are the same as those used in the high mass analysis performed previously by CMS [8]. Two mutually exclusive categories are defined: the VBF-tagged category, containing events satisfying dedicated requirements, and the untagged category, containing the remaining events (mainly produced via gluon fusion).

The VBF-tagging criteria firstly include the following requirements, based on the fact that a VBF signal event contains two energetic jets, with a negligible probability to be b jets:

- no extra electron or muon passing the lepton selection reported in Section 4 should be present in the event;
- there should be at least two jets passing the jet selection described in Section 4;
- if the number of jets passing the jet selection is equal to 2 or 3, then the number of b tagged jets should be no more than 1; otherwise, the number of b tagged jets is required to be 0. This condition is a compromise between rejecting backgrounds with b jets and retaining VBF signals which contains light jets mistagged as b jets. Only jets within the acceptance region of the inner tracker are considered by the b

tagging algorithm.

In addition, the discriminant $D_{2\text{jet}}^{\text{VBF}}$, computed with MELA, is defined as:

$$D_{2\text{jet}}^{\text{VBF}} = \left[1 + \frac{\mathcal{P}_{\text{HJJ}}(\vec{\Omega}^{\text{H+JJ}} | M_{4\ell}^{\text{reco}})}{\mathcal{P}_{\text{VBF}}(\vec{\Omega}^{\text{H+JJ}} | M_{4\ell}^{\text{reco}})} \right]^{-1}, \quad (3)$$

where $\mathcal{P}_{\text{HJJ}}$ is the probability for an event to have similar topology as an SM Higgs boson produced via ggF, associated with two additional jets, while $\mathcal{P}_{\text{VBF}}$ is the probability for an event to behave similarly as a SM Higgs boson produced via VBF. The $\vec{\Omega}^{\text{H+JJ}}$ refers to the angular phase space of the 4ℓ system and the 2 most energetic jets. The probabilities are also calculated with JHUGEN matrix elements.

Figure 2 shows the $D_{2\text{jet}}^{\text{VBF}}$ distributions of signal and background processes. Both the ggF signal and background processes are distributed at around 0, while the VBF signal processes are distributed around 1, proving the great discriminating power of the discriminant. For the VBF signals, there is a small fraction of events distributed around 0, because there is a slight possibility that the two jets involved in $\vec{\Omega}^{\text{H+JJ}}$ are not the two VBF jets.

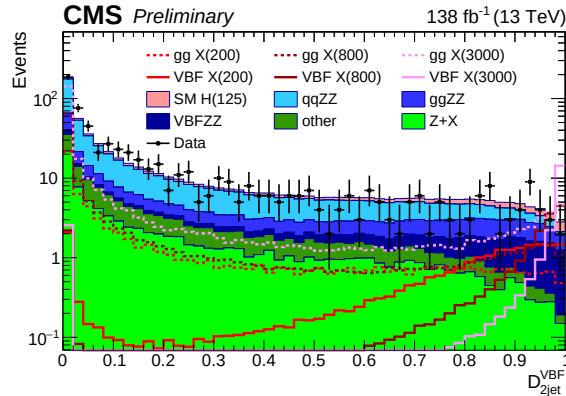


Figure 2: The $D_{2\text{jet}}^{\text{VBF}}$ distribution of signal and background processes together with observed data, combining the full Run 2 dataset. Only events passing the lepton and jet number selections for the VBF-tagging category contribute to this distribution. To be selected in the VBF-tagged category, events are required to have $D_{2\text{jet}}^{\text{VBF}} > 0.46$.

Similar to $D_{\text{bkg}}^{\text{kin}}$, $D_{2\text{jet}}^{\text{VBF}}$ is defined with respect to SM Higgs boson production, but it can also be used to discriminate the VBF signals at any mass. The performance is found to be better at higher masses. To be selected in the VBF-tagged category, events are required to have $D_{2\text{jet}}^{\text{VBF}} > 0.46$. This requirement, already used in previous analyses [20, 54] to categorize VBF signals, is found to be optimal also for this analysis, after performing a dedicated study.

7 Signal modeling

In order to ensure the model-independence of the analysis and allow a large number of signal hypotheses to be tested, a parametric approach is used to model different processes. This method was already introduced in the previous analysis [8].

The signal model is obtained by performing a parametrization of the signal templates simulated using MC. Given the mass M_χ and decay width Γ_χ of the resonance, the probability

distribution function (PDF) of the signal process is defined as

$$\mathcal{P}_{\text{sig}}(M_{4\ell}^{\text{reco}}, D_{\text{bkg}}^{\text{kin}} | M_X, \Gamma_X) = \{[\mathcal{P}(M_{4\ell}^{\text{gen}} | M_X, \Gamma_X) \times \mathcal{E}(M_{4\ell}^{\text{gen}})] \otimes \mathcal{R}(M_{4\ell}^{\text{reco}} | M_{4\ell}^{\text{gen}})\} \times \mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}}). \quad (4)$$

Where:

- $\mathcal{P}(M_{4\ell}^{\text{gen}} | M_X, \Gamma_X)$ describes the signal analytical lineshape, where $M_{4\ell}^{\text{gen}}$ is the 4ℓ mass at generator level;
- $\mathcal{E}(M_{4\ell}^{\text{gen}})$ is the signal efficiency, that takes into account the probability of the signal to fall in the acceptance region of the detector, as well as the reconstruction, selection and categorization efficiencies;
- $\mathcal{R}(M_{4\ell}^{\text{reco}} | M_{4\ell}^{\text{gen}})$ is the signal resolution function, that converts the distribution from generator level to detector level, to take into account the finite energy resolution of the detector;
- $\mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}})$ is a two-dimensional conditional PDF that extends the formula to two dimensions.

The analytical lineshape of the signal can be described as the differential production cross section $\frac{d\sigma(\text{pp} \rightarrow X \rightarrow ZZ)}{dM_{4\ell}^{\text{gen}}}$, and is based on [29, 62]. It is defined as:

$$\mathcal{P}(M_{4\ell}^{\text{gen}} | M_X, \Gamma_X) = \frac{\sigma(M_{4\ell}^{\text{gen}})}{\pi} \cdot \frac{2M_X M_{4\ell}^{\text{gen}} \Gamma_X}{[(M_{4\ell}^{\text{gen}})^2 - M_X^2]^2 + M_X^2 \Gamma_X^2}. \quad (5)$$

The spin-0 propagator is described by the Breit-Wigner function; the other factors contributing to the production cross section, including the proton parton distribution functions, the matrix element, and the kinematic phase space, are all included in $\sigma(M_{4\ell}^{\text{gen}})$, which is extracted with the MCFM generator [34–36].

The signal efficiency $\mathcal{E}(M_{4\ell}^{\text{gen}})$ is defined as the number of events passing the trigger and event selection, and falling in a certain category, divided by the number of total generated events. It is computed in each final state and data taking period, for each production mechanism. It is estimated from the signal simulation as a function of $M_{4\ell}^{\text{gen}}$ and then parameterized with analytical functions. Figure 3 shows the signal efficiency computed for the 2018 dataset as examples. In general, the efficiency is higher in the final states with muons. More than 90% of ggF signal events are selected in the untagged category, reaching an efficiency from 14% to 80%. For VBF signal events, at low mass, the efficiencies are similar in both categories while at high mass the fraction of VBF-tagged events decreases because the two VBF jets tend to be less energetic, since the most part of the parton energies contributes to the heavy resonance.

The signal resolution is described as the Double Crystal Ball (DCB) function [63] of $\Delta M_{4\ell} = M_{4\ell}^{\text{reco}} - M_{4\ell}^{\text{gen}}$, with all its parameters dependent on $M_{4\ell}^{\text{gen}}$:

$$\mathcal{R}(M_{4\ell}^{\text{reco}} | M_{4\ell}^{\text{gen}}) = \text{DCB}(\Delta M_{4\ell}, \mu(M_{4\ell}^{\text{gen}}), \sigma(M_{4\ell}^{\text{gen}}), \alpha_1(M_{4\ell}^{\text{gen}}), n_1(M_{4\ell}^{\text{gen}}), \alpha_2(M_{4\ell}^{\text{gen}}), n_2(M_{4\ell}^{\text{gen}})). \quad (6)$$

To compute the dependence on $M_{4\ell}^{\text{gen}}$, all signal samples are combined and divided into different bins of $M_{4\ell}^{\text{gen}}$. The distribution of $\Delta M_{4\ell}$ is then extracted and fitted with the DCB function to obtain the values of the six parameters. Each parameter's dependence on $M_{4\ell}^{\text{gen}}$ is fitted using the following function:

$$f_p = a_{p,0} + a_{p,0.5}x^{0.5} + a_{p,1}x + a_{p,1.5}x^{1.5} + a_{p,2}x^2 + a_{p,2.5}x^{2.5}, x = M_{4\ell}^{\text{gen}}, \quad (7)$$

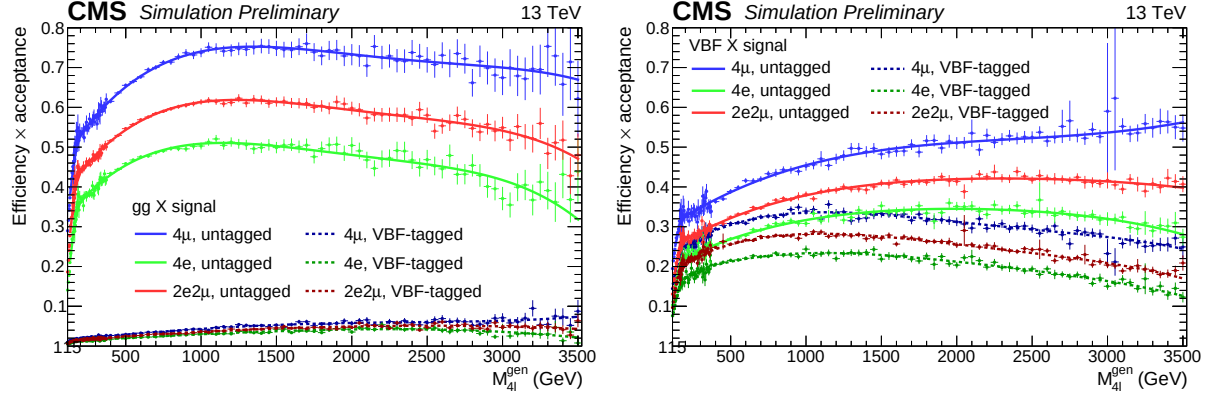


Figure 3: The signal efficiency times acceptance as a function of $M_{4\ell}^{\text{gen}}$ computed for the 2018 dataset. The left plot shows the results of ggF signals, and the right plot shows those of VBF signals. In each plot, the efficiency times acceptance in each final state and category is shown: blue dots and curves represents the 4μ final state, green ones represents the $4e$ final state, and red ones represents the $2e2\mu$ final state; the solid lines with lighter colors represent the untagged category, and the dashed lines with darker colors represent the VBF-tagged category. Both the data points and fitted curves are shown. In other data taking periods, the results are similar.

where $p = \mu, \sigma, \alpha_1, n_1, \alpha_2, n_2$. A simultaneous fit is then performed, combining all $M_{4\ell}^{\text{gen}}$ bins, taking all $a_{p,i}$ as the parameters to be fitted. The method is applied individually for each production mechanism, in each final state and data taking period.

From the above steps, the parametric statistical model is built as a function of $M_{4\ell}^{\text{reco}}$. Examples are shown in Figure 4, with different mass and width assumptions, in the two production mechanisms. With $\Gamma_X = 4$ MeV, $M_{4\ell}^{\text{reco}}$ is mostly distributed around M_X ; when the width is large, a large fraction of off-shell productions can be observed, especially for the signals with $M_X = 130$ GeV and 3000 GeV.

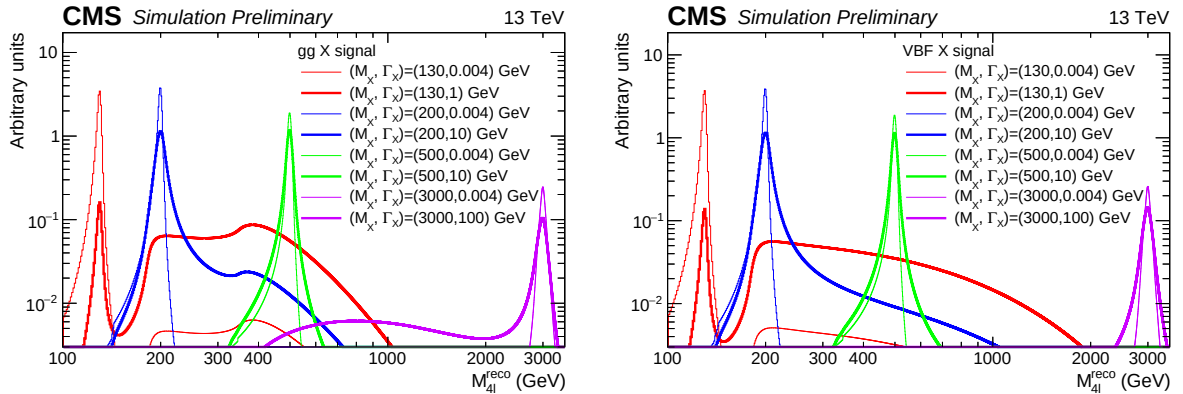


Figure 4: The signal $M_{4\ell}^{\text{reco}}$ shapes with different M_X, Γ_X , produced via ggF (left) or VBF (right).

To build the 2-dimensional PDF, the conditional PDF $\mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}})$ is obtained from the $M_{4\ell}^{\text{reco}}$ versus $D_{\text{bkg}}^{\text{kin}}$ distribution extracted from the signal MC simulation. In each $M_{4\ell}^{\text{reco}}$ bin, the distribution is normalized to unity. Figure 5 shows examples of the distributions, for the two production mechanisms, in the 4μ final state.

The signal model is validated by comparing to the $M_{4\ell}^{\text{reco}}$ distribution extracted from the MC simulation. The MC is reweighted based on MELA to adjust the lineshape defined by CPS

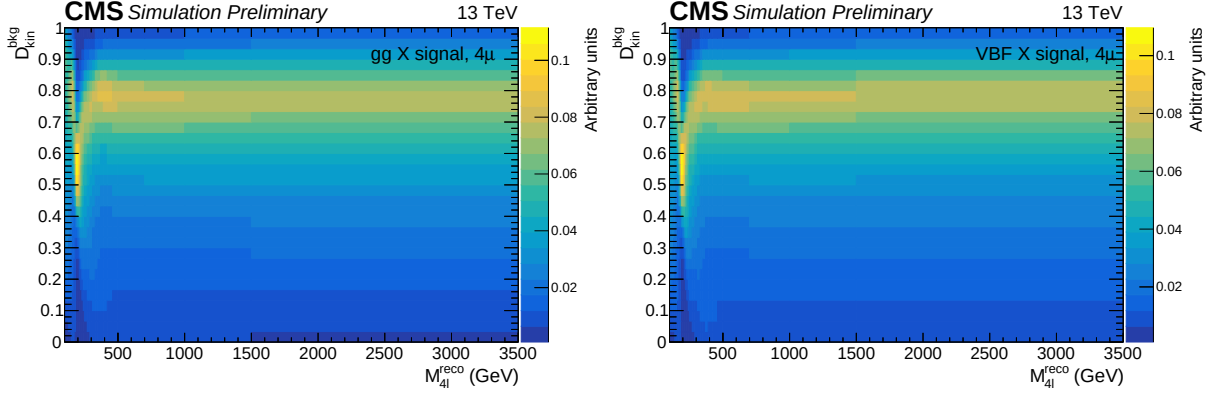


Figure 5: The distributions of $M_{4\ell}^{\text{gen}}$ v.s. $D_{\text{bkg}}^{\text{kin}}$ for the ggF (left) and VBF (right) production mechanism, in the 4μ final state, estimated from the signal simulation. No categorization is applied.

to the usual Breit-Wigner one. The statistical model shows good compatibility with the MC simulation after setting M_χ and Γ_χ in the lineshape (Equation 5) accordingly.

8 Background modeling

8.1 Irreducible backgrounds

The dominant background contribution comes from $q\bar{q} \rightarrow ZZ$, and the subdominant background arises from $gg \rightarrow ZZ$. Another irreducible background is $qqZZ \rightarrow qq4\ell$, referred to as VBFZZ. Triboson production (WZZ, WWZ) and $t\bar{t}$ plus vector boson production ($t\bar{t}Z, t\bar{t}ZZ, t\bar{t}WW$) are also taken into account, referred to as “other” background. All of them are estimated from simulation.

The PDFs of different backgrounds are built with different methods. For $q\bar{q} \rightarrow ZZ$, and other backgrounds, the PDF is defined as:

$$\mathcal{P}_{\text{bkg}}(M_{4\ell}^{\text{reco}}, D_{\text{bkg}}^{\text{kin}}) = \mathcal{P}(M_{4\ell}^{\text{reco}}) \times \mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}}), \quad (8)$$

where the one-dimensional PDFs $\mathcal{P}(M_{4\ell}^{\text{reco}})$ are empirical functions obtained from the simulated $M_{4\ell}^{\text{reco}}$ distributions, and the conditional PDF $\mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}})$ is obtained from the $M_{4\ell}^{\text{reco}}$ versus $D_{\text{bkg}}^{\text{kin}}$ distributions from the simulation. The Z + X background shares the same equation, with PDFs extracted from the control regions based on the data-driven method introduced in Section 8.2.

For $gg \rightarrow ZZ$ and VBFZZ, the one-dimensional PDF is built using $M_{4\ell}^{\text{gen}}$ (instead of $M_{4\ell}^{\text{reco}}$) by fitting empirical functions to the $M_{4\ell}^{\text{gen}}$ distributions from the simulation. This is because their generator-level lineshapes are needed to build the interference lineshape. Then the PDF is convoluted with the energy resolution function introduced in Section 7 to build the $M_{4\ell}^{\text{reco}}$ PDF, and then it is multiplied by the conditional PDF $\mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}})$ extracted from MC simulation.

The SM Higgs boson is also an irreducible background of this analysis, and is modeled using the same approach as signals, by setting $M_\chi = 125$ GeV and $\Gamma_\chi = 4.1$ MeV in Equation 5.

8.2 Reducible backgrounds

The reducible backgrounds involve at least one selected lepton originating from the misidentification of a light jet, or from in-flight decays of mesons or heavy flavor jets. They are dominated by the DY process (Z/γ +jets), and are also composed of other processes including $t\bar{t}$, WZ, WW, QCD multijet events. These background processes are named as $Z + X$ in this analysis. The $Z + X$ contribution is estimated from the dedicated control regions in data, with the Fake Rate method, used in [20, 54]. The yield of $Z + X$ in the signal region is evaluated by multiplying the yields estimated in the control regions with the misidentification rate of the lepton, denoted as f_e and f_μ . These rates are defined as the fraction of leptons which pass all the lepton selection criteria in Section 4 except the identification and isolation requirement, to pass also the identification and isolation requirement. The f_e and f_μ are measured in another control region containing events with one Z candidate composed of two leptons passing the full selection criteria, plus exactly one additional lepton (e or μ) without the identification and isolation requirement. This region is denoted as $Z + \ell$. The misidentification rates are measured for this additional lepton, as a function of its p_T , and separately for the barrel or endcap region.

Two methods are used to estimate $Z + X$: opposite sign (OS) and same sign (SS) methods. In the OS method, the Z candidate in the $Z + \ell$ region is required to have $|M_Z - 91.1876 \text{ GeV}| < 7 \text{ GeV}$ to reduce contamination from photon conversion, which is estimated separately; the control region used to estimate the yields of events with one Z candidate passing all the selection, together with two additional opposite-sign leptons, at least one of which fails the identification and isolation requirement. In the SS method, the mass window of the $Z + \ell$ region is not constrained, but a dedicated approach is used to estimate the contribution of photon conversion; the control region used to estimate the yields of events with one Z candidate passing all the selection, together with two additional same-sign leptons, both without the identification and isolation requirement. The estimated yields from the two methods are compatible within uncertainties, therefore the final yield estimation obtained as the weighted average between the estimation from the two methods, in each final state and data taking period. The shapes of the variables considered in the analysis, however, are taken from the SS method, because the OS method introduces much larger statistical fluctuations.

The PDF of $Z + X$ is built similarly as Equation 8, where $\mathcal{P}(M_{4\ell}^{\text{reco}})$ is the empirical function built from the Landau distribution, fitted on the $M_{4\ell}^{\text{reco}}$ shape from the SS method; and $\mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}})$ is obtained from the $M_{4\ell}^{\text{reco}}$ versus $D_{\text{bkg}}^{\text{kin}}$ distribution from the SS method.

Due to the different composition between the control regions where misidentification rates are computed and where they are applied, an additional systematic uncertainty is considered. It is estimated from MC simulation, and the value is around 30%, depending on the final state. This uncertainty is combined with the statistical uncertainties from all control regions to form the final systematic uncertainty of $Z + X$ background.

9 Interference modeling

In this analysis the finite width hypothesis is considered, in addition to the narrow width assumption. Therefore, the interference of the signal with other processes needs to be considered, as it can be significant when the signal width is large. The modeling of the interference follows the same approach used in [8]. For the ggF production, three interferences are considered: among the ggF signal, ggF SM Higgs boson, and $gg \rightarrow ZZ$. Similar for the VBF production, three interferences sources are included: among the VBF signal, VBF SM Higgs boson, and

VBFZZ. The PDF of each source of interference is built as:

$$\mathcal{P}_{\text{int}} = [\mathcal{P}_{\text{int}}(M_{4\ell}^{\text{gen}} | \mathcal{P}_{\text{sig}}(M_{4\ell}^{\text{gen}}), \mathcal{P}_{\text{bkg}}(M_{4\ell}^{\text{gen}}), \text{phases}) \otimes \mathcal{R}(M_{4\ell}^{\text{reco}} | M_{4\ell}^{\text{gen}})] \cdot \mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}}). \quad (9)$$

Firstly, the interference lineshape $\mathcal{P}_{\text{int}}(M_{4\ell}^{\text{gen}} | \mathcal{P}_{\text{sig}}(M_{4\ell}^{\text{gen}}), \mathcal{P}_{\text{bkg}}(M_{4\ell}^{\text{gen}}), \text{phases})$ contains contributions from both the amplitudes and phases of the two interfering processes. The amplitudes are extracted from the lineshapes of the signals, SM Higgs boson, and interfering backgrounds. The phases of the scalar propagators (signals and SM Higgs boson) are computed from the kinematics, while the phases in other parts of the matrix elements are derived directly from the corresponding generators.

Secondly, the resolution functions are the same as the signals introduced in Section 7, which are universal for any processes with four genuine leptons.

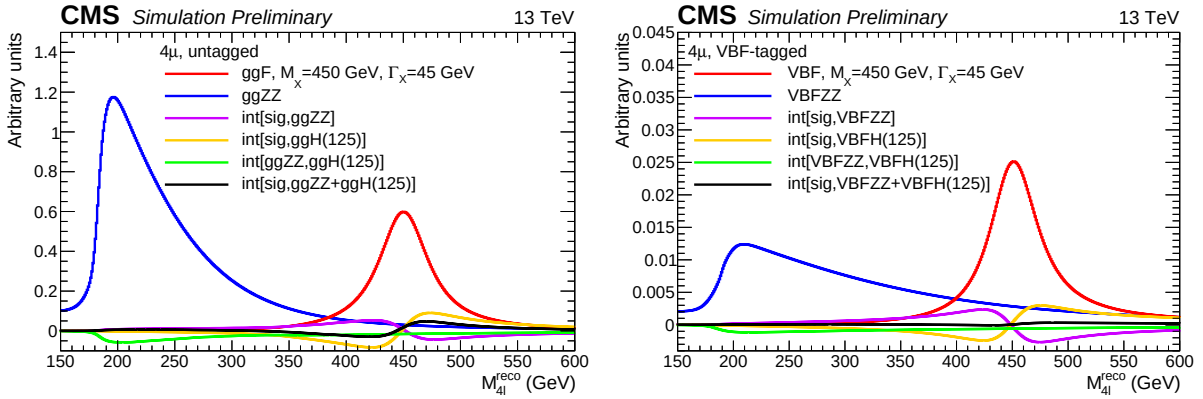


Figure 6: Examples of interference lineshapes. The left (right) plot depicts the lineshape of the ggF (VBF) signal with $M_\chi = 450$ GeV, $\Gamma_\chi = 45$ GeV in the red curve, the lineshape of the $gg \rightarrow ZZ$ (VBFZZ) background in the blue curve, and the lineshapes of the three interferences in the violet, orange and green curves. The left plot is in the 4μ final state and untagged category; the right plot is in the 4μ final state and VBF-tagged category.

Figure 6 shows examples of the interference lineshapes. Not only the interference but also the signal and interfering backgrounds are shown. The interferences between the SM Higgs boson and non-resonant backgrounds ($gg \rightarrow ZZ$ or VBFZZ) are mostly negative. The interference between the signal and the SM Higgs boson and the interference between the signal and non-resonant backgrounds have opposite signs in the region close to the signal, and almost cancel each other out in the VBF scenario. The negative component of the interference model is not a problem in the likelihood fit because it is included in the process combining the signal, backgrounds and interferences, which is always positive.

At last, the conditional PDF $\mathcal{P}(D_{\text{bkg}}^{\text{kin}} | M_{4\ell}^{\text{reco}})$ for the interferences are converted from the $M_{4\ell}^{\text{reco}}$ versus $D_{\text{bkg}}^{\text{kin}}$ distribution extracted from dedicated simulation. By weighting the MC simulation of off-shell Higgs boson production and the signal samples with the variables computed by MELA, one can obtain the simulation of the interferences among the signal process, the SM Higgs boson and non-resonant backgrounds ($gg \rightarrow ZZ$ or VBFZZ).

The interference model is validated by comparing the $M_{4\ell}^{\text{reco}}$ shape from the interference model to the $M_{4\ell}^{\text{reco}}$ distribution obtained from the MC simulation. Some discrepancies are observed, stemming from possible imperfections of the phase estimation. Dedicated correction factors are computed and applied to the interference between SM Higgs boson and non-resonant back-

grounds and the interference between signals and backgrounds. Additional systematic uncertainties are assigned to the interferences, ranging from 9.5% to 11% for the ggF production and 13% to 18% for the VBF production.

10 Systematic uncertainties

The systematic uncertainties are divided into experimental uncertainties and theoretical uncertainties. The experimental ones come from the imperfect knowledge of the detector and experimental measurements; the theoretical ones come from the fact that the theoretical computation has finite precision.

10.1 Experimental uncertainties

The integrated luminosities are measured with uncertainties individually in the 2016, 2017 and 2018 data-taking periods [15–17]. The uncertainties range from 1% to 3%, and are partially correlated among different periods. They affect the normalization of all processes weighted by luminosities, including signal, interference and background processes, except $Z + X$.

The lepton efficiency uncertainties involve all the selection steps from trigger, reconstruction to event selection efficiency. They are dominated by the uncertainties of lepton identification and isolation. They affect the yields of all the processes estimated from MC simulation. The lepton efficiency is measured with the tag-and-probe method, in both observed data and simulation. The same method as [54] is used to extract the uncertainties. Muons and electrons are treated as uncorrelated since the selection of these objects is different. For muons, the uncertainty ranges from 0.2% to 2% in the 4μ final state, and 0.2% to 1.4% in the $2e2\mu$ final state. For electrons, the uncertainty ranges from 3% to 11% in the $4e$ final state, and 2% to 6% in the $2e2\mu$ final state. The uncertainty for muons is significantly lower than electrons, mainly because the muon efficiency measurement takes advantage of both the Z and J/ψ resonances, the latter improving the measurement at low p_T , while the electron efficiency measurement only relies on the Z resonance. The uncertainty values are computed individually for each background; for the ggF and VBF signals, the values have a dependence on their masses, therefore a parameterization as a function of $M_{4\ell}^{\text{gen}}$ is built and used to compute the uncertainty values for any given signal.

The lepton energy scale and resolution impacts the shapes of processes convolved with the energy resolution function, including signals, interferences, and interfering backgrounds. Uncertainties for muons and electrons are considered as uncorrelated. The uncertainties are estimated by comparing the $Z \rightarrow \ell\ell$ invariant mass distributions in the simulation with those from the observed data. The energy scale uncertainty is 0.03% (0.15%) for muons (electrons), and it affects the final states containing muons (electrons) by shifting the μ in Equation 6 for the energy resolution. The energy resolution uncertainty is 3% (10%) for muons (electrons), and it affects the final states containing muons (electrons) by changing the σ in Equation 6. The values are quoted from [64].

Jet energy scale and resolution do not have impacts on the total signal or background efficiency, but affect the categorization, since the VBF-tagging criteria include the selection on jets. These uncertainties affect all processes except $Z + X$. Jet energy scale uncertainties originate from various sources, and they are partially correlated among data-taking periods, while the uncertainties of jet energy resolution is considered as uncorrelated among all final states and data-taking periods. In general, the uncertainties amount to around 0.1% for the untagged categories and 1% to 4% for the VBF-tagged categories.

The jet b tagging efficiency uncertainties also affect the VBF categorization efficiency, similarly

to jet energy scale and resolution. To estimate them, the b-tagging efficiencies are varied to ± 1 standard deviation, the number of jets that pass the b-tagger are re-counted, and the shifted categorization is performed. The uncertainties are estimated to be less than 0.1%.

For the signal processes, values of jet-related uncertainties are averaged over all mass points, since no mass dependence is observed.

The $Z + X$ estimation uncertainties involve the statistical fluctuations in the control regions and the additional 30% uncertainty to take into account different composition in the control regions where misidentification rates are computed and applied. The uncertainties are around 31% overall, treated as uncorrelated among final states and data-taking periods.

The uncertainties to account for the interference mismodeling are introduced in Section 9. They range from 9.5% to 11% for the ggF interference and from 13% to 18% for the VBF interference.

10.2 Theoretical uncertainties

Theoretical uncertainties do not depend on the configurations of data-taking periods or the performance of the detector, therefore they are correlated among all data-taking periods.

The uncertainty in the branching ratio of $X \rightarrow ZZ \rightarrow 4\ell$ affects the normalization of all signal and SM Higgs boson processes. According to the theoretical computations [65], the uncertainties are around 2% for the SM Higgs boson and decrease at higher masses. A value of 2% for all mass points is considered in order to be conservative.

The uncertainty from the renormalization and factorization scales is determined by varying these scales between 0.5 and 2 times their nominal value, while keeping their ratio between 0.5 and 2. This uncertainty affects all processes except the $Z + X$ background, and it ranges from 1% to 15% depending on the processes, final state, and category. For the qqZZ background, it also affects the $M_{4\ell}^{\text{reco}}$ shape.

The uncertainty in parton distribution functions (PDFs) and α_s is estimated by varying the PDF set or α_s to ± 1 standard deviation compared with the default NNPDF set [66, 67]. The uncertainties range from 0.1% to 7%. For the qqZZ background, the PDF uncertainty affects the $M_{4\ell}^{\text{reco}}$ shape, like the renormalization and factorization scales.

For signal processes, the uncertainties in renormalization and factorization scales, PDFs and α_s are parameterized as a function of $M_{4\ell}^{\text{gen}}$. For a given signal process, its lineshape is weighted by the parameterization function, and the uncertainty is computed as the yield difference between the weighted and nominal lineshapes.

The initial and final state radiation scales are used by PYTHIA to model the underlying events, as well as the fragmentation and hadronization of partons. It affects all processes. The uncertainties in this source are estimated by varying the scales to 4 or 0.25 times the nominal values. The uncertainty ranges from 0.4% to 10%. For signal processes, the values are averaged over all mass points, similarly to the jet-related uncertainties.

A 10% uncertainty in the determination of the K factor used for the $gg \rightarrow ZZ$ prediction is applied. For the $q\bar{q} \rightarrow ZZ$ background, the uncertainties affect the $M_{4\ell}^{\text{reco}}$ shape, ranging from 0.1% at low mass to 30% at high mass.

10.3 Summary on systematic uncertainties

Systematic uncertainties are treated as nuisance parameters in the fit. They are summarized in Table 2.

Table 2: Summary of the experimental and theoretical uncertainties used in this analysis. Some experimental uncertainties are calculated for each data-taking periods. Uncertainties affecting only normalization are treated as nuisance parameters with a log-normal distribution, specified as “norm”. Those affecting variable shapes are specified as “shape”.

Experimental uncertainties					
Year	2016	2017	2018	Effects	Affected processes
Luminosity	1.2%	2.3%	2.5%	norm	all except Z +X
e efficiency	3-10%	3-9%	3-9%	norm	all except Z +X
μ efficiency	1-2%	1-2%	1-2%	norm	all except Z +X
$e(\mu)$ energy scale	0.15(0.03)%			shape	all with energy convolution
$e(\mu)$ energy resolution	10(3)%			shape	all with energy convolution
jet energy scale	$\approx 1\%$			norm	all except Z +X
jet energy resolution	$\approx 1\%$			norm	all except Z +X
jet b-tagging efficiency	0.1%			norm	all except Z +X
ggF interference	9-11%			norm	interferences
VBF interference	13-18%			norm	interferences
Z + X (4μ)	30%	30%	30%	norm	Z +X
Z + X ($4e$)	31%	31%	30%	norm	Z +X
Z + X ($2e2\mu$)	31%	30%	30%	norm	Z +X
Theoretical uncertainties					
BR($X \rightarrow ZZ$)	2%			norm	signals
QCD scale	1-15%			shape: qqZZ norm: others	all except Z +X
PDF	0.1-7%			shape: qqZZ norm: others	all except Z +X
α_s	0.1-7%			norm	all except Z +X
pythia scale	0.4-10%			norm	all except Z +X
qqZZ K factor	0.1-30%			shape	qqZZ
ggZZ K factor	10%			norm	ggZZ

11 Results

The aim of this analysis is to search for an additional scalar resonance in a wide mass range. The overall signal strength is defined as:

$$\mu = \frac{\sigma(\text{pp} \rightarrow X \rightarrow ZZ)}{\sigma_{\text{model}}(\text{pp} \rightarrow X \rightarrow ZZ)} \quad (10)$$

where $\sigma(\text{pp} \rightarrow X \rightarrow ZZ)$ refers to the production cross section of the resonance multiplied by the branching ratio of $X \rightarrow ZZ$; $\sigma_{\text{model}}(\text{pp} \rightarrow X \rightarrow ZZ)$ is the value set in the statistical model. Then the fraction of VBF signal is defined as the VBF production cross section divided by the total cross section:

$$f_{\text{VBF}} = \frac{\sigma(\text{qq} \rightarrow X \rightarrow ZZ)}{\sigma(\text{pp} \rightarrow X \rightarrow ZZ)} = \frac{\sigma(\text{qq} \rightarrow X \rightarrow ZZ)}{\sigma(\text{gg} \rightarrow X \rightarrow ZZ) + \sigma(\text{qq} \rightarrow X \rightarrow ZZ)}, \quad (11)$$

such that the signal strengths for ggF production and VBF production are

$$\mu_{\text{ggF}} = \mu \cdot (1 - f_{\text{VBF}}), \quad \mu_{\text{VBF}} = \mu \cdot f_{\text{VBF}}. \quad (12)$$

By setting $f_{\text{VBF}} = 0$ (1), one can test the pure ggF (VBF) production mechanisms.

Then, the total PDF multiplied by the total predicted yield is defined as:

$$\mathcal{P}(\vec{x}|\mu, \vec{\theta}) = \sum_{s=\text{ggF}, \text{VBF}} [\mu_s \cdot S_s(\vec{\theta}) \cdot \mathcal{P}_s(\vec{x}|\vec{\theta}) + \sqrt{\mu_s} \cdot I_s(\vec{\theta}) \cdot \mathcal{P}_{s,\text{int}}(\vec{x}|\vec{\theta})] + \sum_b B_b(\vec{\theta}) \cdot \mathcal{P}_b(\vec{x}|\vec{\theta}). \quad (13)$$

The first summation considers the signal and interference processes, and the second one considers the backgrounds, looping over the background processes $q\bar{q} \rightarrow ZZ$, $gg \rightarrow ZZ$, $\text{VBF}ZZ$, $Z + X$, other, and interferences between the SM Higgs boson and non-resonant backgrounds. The $\vec{x} = (M_{4\ell}^{\text{reco}}, D_{\text{bkg}}^{\text{kin}})$ are the discriminating variables. S_s , I_s and B_b are the expected yields: for signals and interferences, they are computed from signal and interference models introduced in Section 7 and 9; for backgrounds, they are computed from the MC simulation, except $Z + X$, which is computed with the Fake Rate method in Section 8.2. The nuisance parameters $\vec{\theta}$ are used to take into account systematic uncertainties. Both the yields and shapes of each process can depend on the nuisance parameters.

Extended unbinned likelihood fits are performed by fitting the background-only model to the observed data, using the COMBINE tool [68]. Figure 7 shows the comparison between the observed data and the background model with all parameters at their best-fit values. The total $M_{4\ell}^{\text{reco}}$ and $D_{\text{bkg}}^{\text{kin}}$ distribution, as well as the $M_{4\ell}^{\text{reco}}$ distributions in different ranges of $D_{\text{bkg}}^{\text{kin}}$ are illustrated. The distributions from the background model and the observed data are compatible within uncertainties in general. Studies on the nuisance parameters also show that they are not significantly shifted from the nominal values by the fit.

Upper limits at 95% confidence level on $\sigma(\text{pp} \rightarrow X \rightarrow ZZ)$ are computed using the CL_s method [69, 70], based on the asymptotic formulae [71]. Figure 8 shows the results for the narrow width assumption, with Γ_X set to 4.1 MeV, and signal-background interference excluded. The M_X ranges from 130 GeV to 3 TeV. Different hypothesis for the production mechanisms are considered: pure ggF production, pure VBF production, and no prior knowledge on the production, i.e. with f_{VBF} left floating. Both the observed results from observed data and the expected results with background-only hypothesis are computed.

The exclusion limits range from 0.05-0.1 pb in the low mass region to 0.005 pb in the high mass region. In general, the limits are higher at 130 GeV due to the presence of the SM Higgs boson

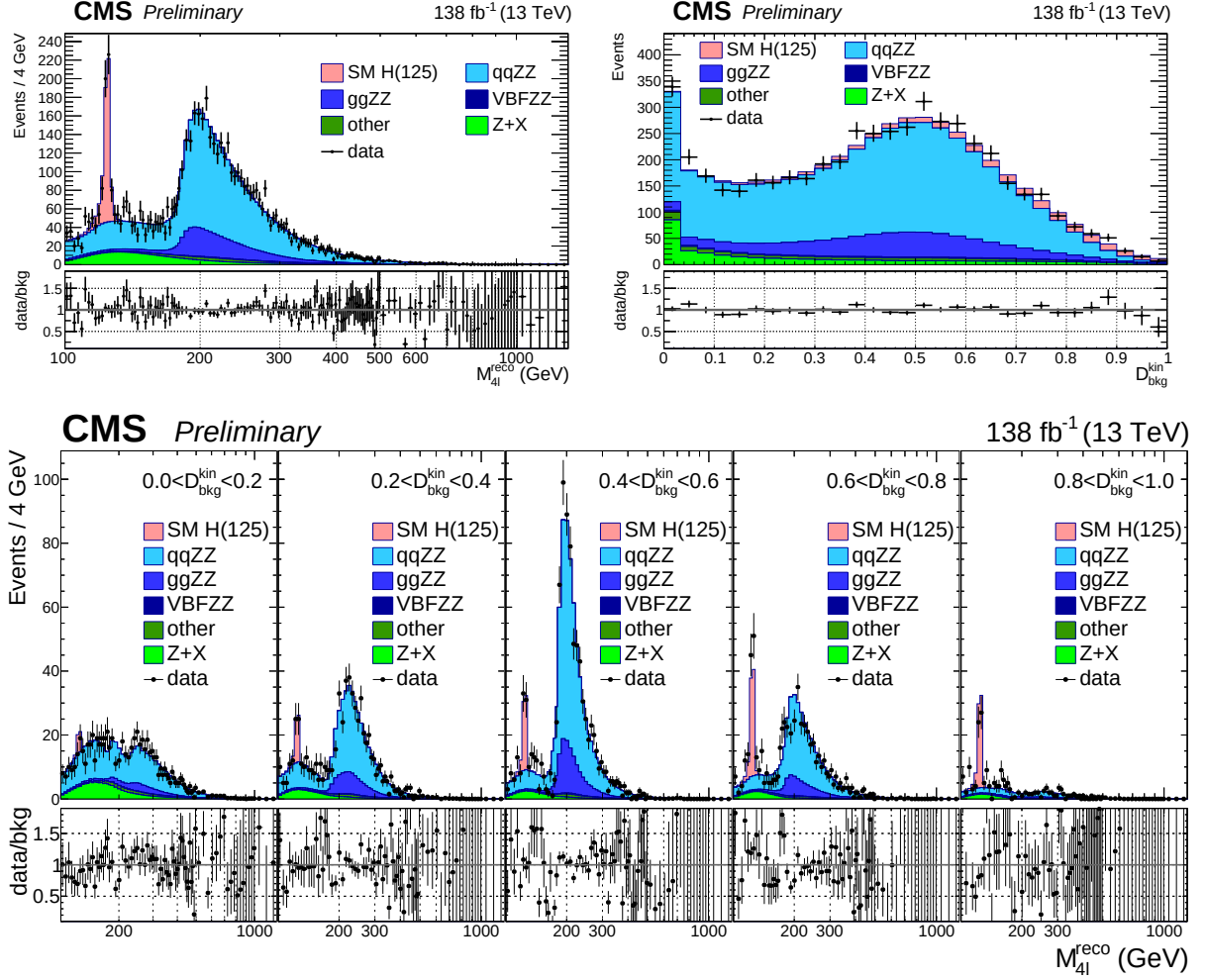


Figure 7: The $M_{4\ell}^{\text{reco}}$ and $D_{\text{bkg}}^{\text{kin}}$ distributions with the full Run 2 dataset, for backgrounds and observed data. The distributions for backgrounds are extracted from the statistical model, with all nuisance parameters at their best-fit values (post-fit). The top left plot shows the distribution of $M_{4\ell}^{\text{reco}}$; the top right plot shows the distribution of $D_{\text{bkg}}^{\text{kin}}$; the bottom plot shows the distribution of $M_{4\ell}^{\text{reco}}$ in bins of $D_{\text{bkg}}^{\text{kin}}$.

as a background, and at 200 GeV due to the fact that most of the backgrounds are concentrated there. The limits for the VBF production mechanism is lower than the ones for ggF because in the VBF-tagged category the backgrounds are much lower and the signal-to-background ratio is higher. The results with f_{VBF} floating are mostly similar to the results of pure ggF production, with the fitted value of f_{VBF} close to 0.

In the majority of the mass points, the observed results are within the ± 2 standard deviation band. The local p-value [72] is computed as a function of M_X , shown in Figure 9. The local significance goes above 2σ at around 138, 176, 240, 280 and 360 GeV, and reaches the maximum of 3.02σ at 137.8 GeV. The global significance, considering the look-elsewhere effect [73], is estimated to be 1.85σ .

Finite width assumptions are also tested, with Γ_X fixed at 1 GeV, 10 GeV or 100 GeV. The results are shown in Figure 10. From NWA to 1 GeV width assumption, the limits get lower at low masses mainly because of the off-shell production present above 200 GeV where the signal efficiency is much higher (especially for signals below 200 GeV), as well as thanks to the

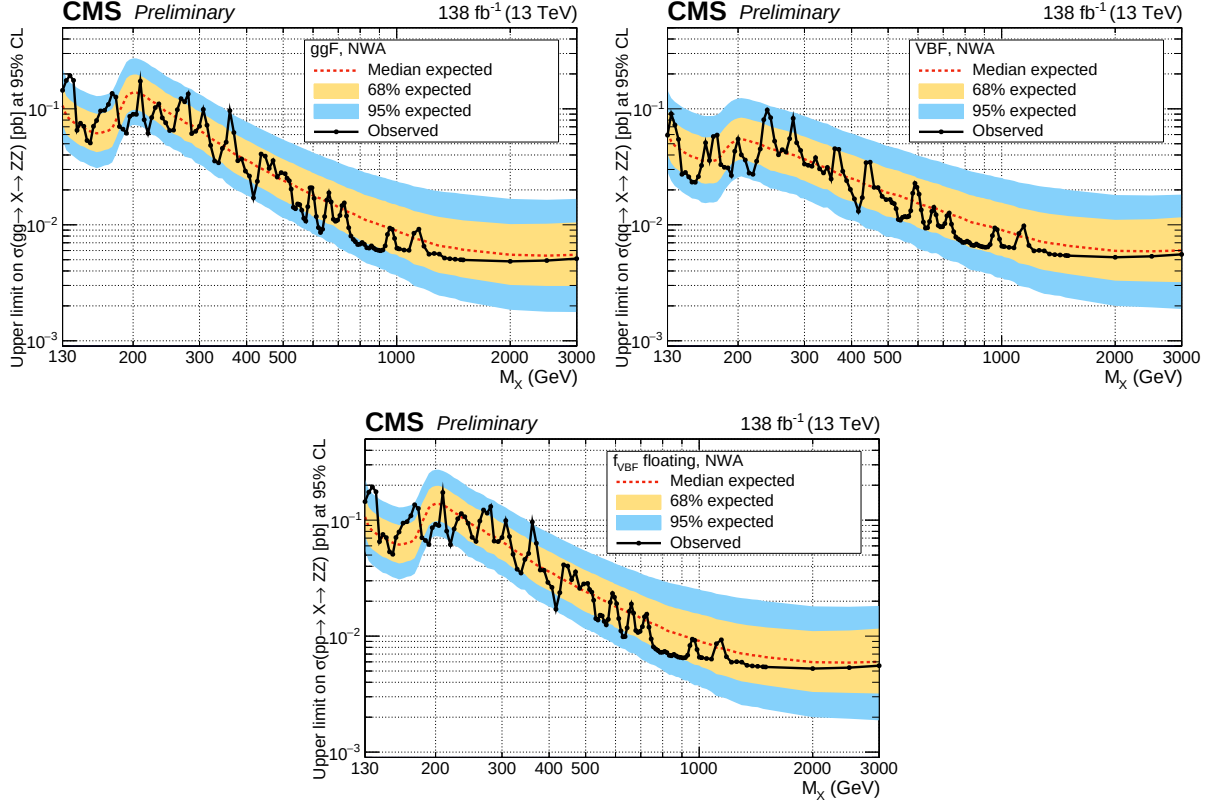


Figure 8: The upper limits on $\sigma(pp \rightarrow X \rightarrow ZZ)$ with M_X from 130 GeV to 3 TeV and narrow width assumption. The top left plot shows the results of pure ggF production; the top right plot shows the pure VBF production; and the bottom plot shows the results with f_{VBF} floating.

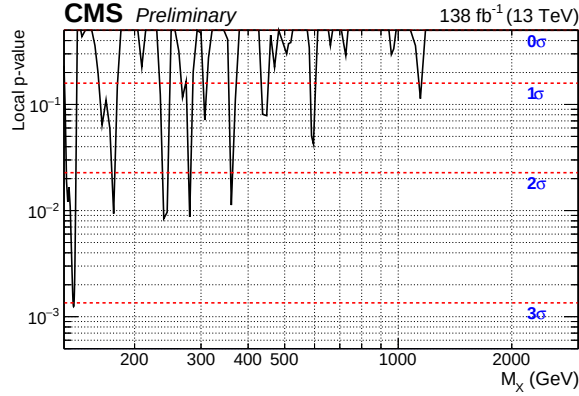


Figure 9: The local p-value as a function of M_X , with f_{VBF} floating.

contribution from the interferences (for ggF signals at around 200 GeV). From 1 GeV to 10 GeV width assumption, the results get slightly less stringent mainly because of the more smeared $M_{4\ell}^{\text{reco}}$ distributions. From 10 GeV to 100 GeV width assumption, the results get more flattened because the $M_{4\ell}^{\text{reco}}$ distributions are widely spread; at around 200 GeV the limits get even more stringent, because $M_{4\ell}^{\text{reco}}$ is spread to the region where the backgrounds are lower.

Comparing the observed results with the expected ones, no excess is observed, and the fluctuations are mostly within the ± 2 standard deviation band. It is evident that at $M_X < 200$ GeV with $\Gamma_X = 1, 10$ GeV, as well as the whole mass range for $\Gamma_X = 100$ GeV, the observed results

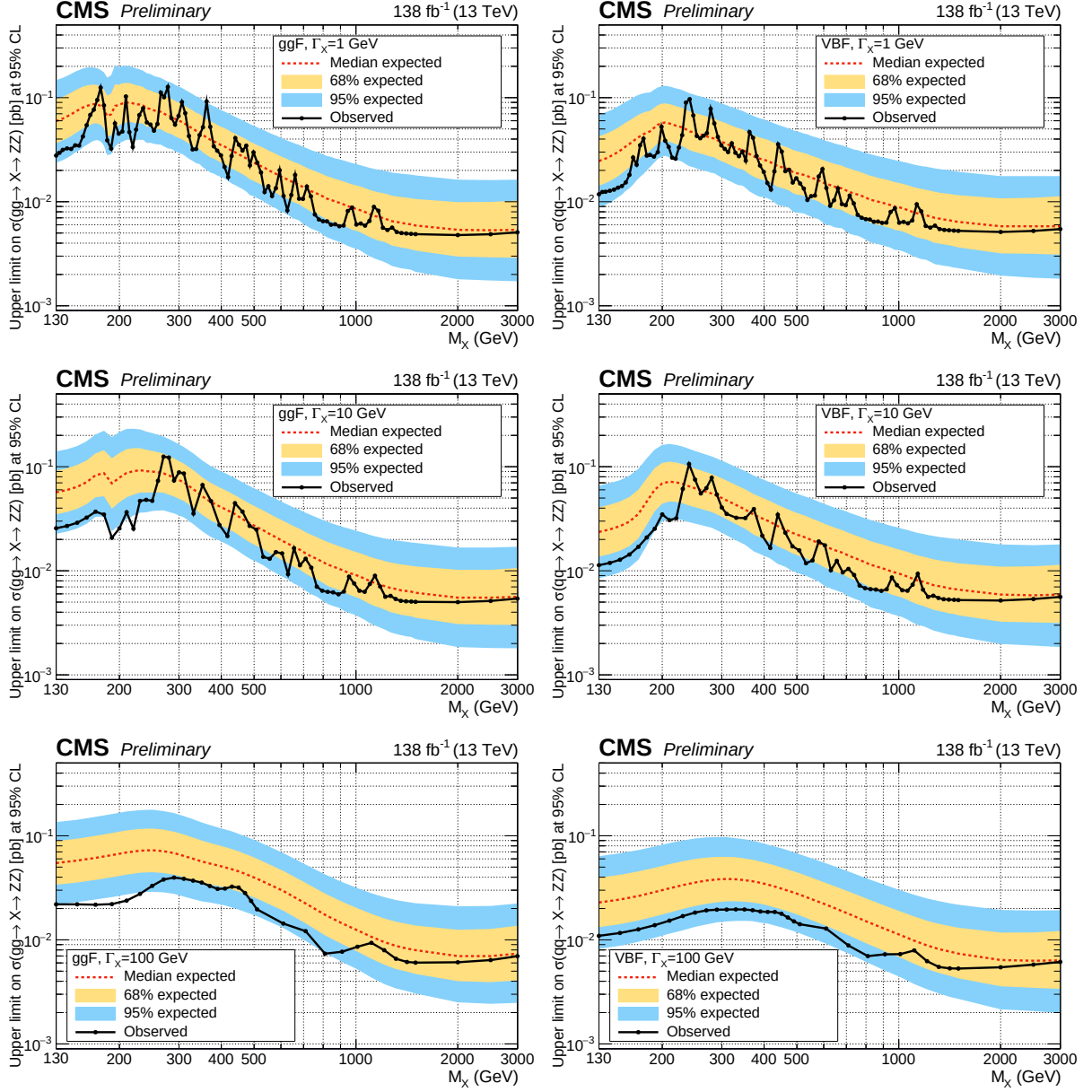


Figure 10: The expected upper limits on $\sigma(pp \rightarrow X \rightarrow ZZ)$ with M_X from 130 GeV to 3 TeV and $\Gamma_X = 1$ (top), 10 (middle) and 100 (bottom) GeV. The left column shows the results of pure ggF production and the right column shows the pure VBF production.

are systematically lower than the median expected results. The background model has slightly larger yields than the observed data, therefore the observed results is biased to be more stringent. Such an impact is more evidently seen by signals which are widely spread, because the deficit of data with respect the background expectations is correlated across the large ranges through the signal lineshape. Signals at low masses ($M_X < 200$ GeV) are widely spread mainly due to the off-shell production, and some examples have been shown in Figure 4. The off-shell production of those low mass signals takes around 50% to 96% for $\Gamma_X = 1$ GeV, 92% to 98% for $\Gamma_X = 10$ GeV, and greater than 99% for $\Gamma_X = 100$ GeV. On the other hand, all signals with $\Gamma_X = 100$ GeV are widely spread due to the large width.

In addition, results scanning not only M_X but also Γ_X are computed, to cover more parameter

space. The results are shown in Figure 11. Each curve corresponds to a value of Γ_X/M_X , ranging from 0 (which means NWA) to 0.3. At smaller widths, the observed results fluctuate around the median expected ones; with the width growing, the observed results get smeared out, and the excesses gradually disappear or go below the median expected results.

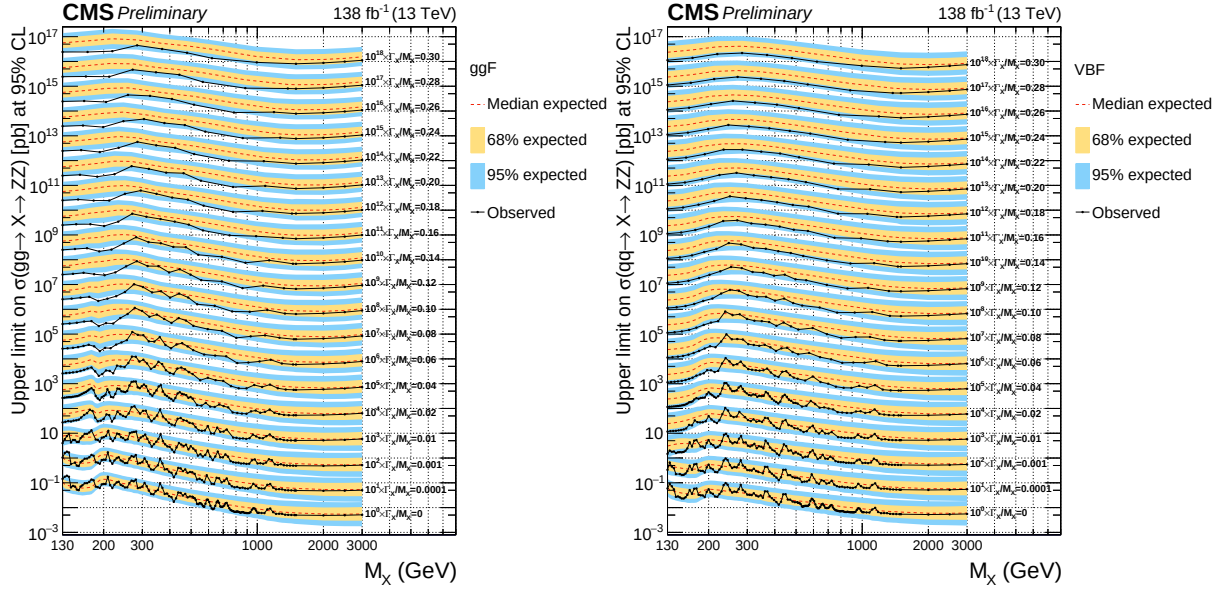


Figure 11: The observed upper limits on $\sigma(pp \rightarrow X \rightarrow ZZ)$ with M_X from 130 GeV to 3 TeV and Γ_X/M_X from NWA to 0.3. The top plot shows the results of pure ggF production and the bottom plot shows the pure VBF production.

12 Summary

Searches for a spin-0 resonance decaying to a pair of Z bosons in the 4-lepton final state are performed using the full Run 2 dataset collected with the CMS detector, corresponding to an integrated luminosity of 138 fb^{-1} . The mass of the resonance is scanned over a range from 130 GeV to 3 TeV, and different decay width assumptions are tested. A model-independent approach for the signal, background, and interference model is used. No significant excess is observed. Only a fluctuation is seen at 137.8 GeV with the narrow width assumption, reaching a global significance of around 1.85σ . The upper limits at 95% confidence level on the production cross section multiplied by the decay branching ratio of $X \rightarrow ZZ$ are calculated for different masses, decay widths and production mechanisms.

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