



# Search for Higgs boson decays into a pair of light bosons in the $bb\mu\mu$ final state in $pp$ collision at $\sqrt{s} = 13$ TeV with the ATLAS detector



The ATLAS Collaboration <sup>\*</sup>

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## ABSTRACT

A search for decays of the Higgs boson into a pair of new spin-zero particles,  $H \rightarrow aa$ , where the  $a$ -bosons decay into a  $b$ -quark pair and a muon pair, is presented. The search uses  $36.1 \text{ fb}^{-1}$  of proton–proton collision data at  $\sqrt{s} = 13$  TeV recorded by the ATLAS experiment at the LHC in 2015 and 2016. No significant deviation from the Standard Model prediction is observed. Upper limits at 95% confidence level are placed on the branching ratio  $(\sigma_H/\sigma_{SM}) \times \mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu)$ , ranging from  $1.2 \times 10^{-4}$  to  $8.4 \times 10^{-4}$  in the  $a$ -boson mass range of 20–60 GeV. Model-independent limits are set on the visible production cross-section times the branching ratio to the  $bb\mu\mu$  final state for new physics,  $\sigma_{\text{vis}}(X) \times \mathcal{B}(X \rightarrow bb\mu\mu)$ , ranging from 0.1 fb to 0.73 fb for  $m_{\mu\mu}$  between 18 and 62 GeV.

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## 1. Introduction

The discovery of the Standard Model (SM) Higgs boson [1,2] has opened up new avenues to search for physics beyond the SM (BSM) with perspectives to search for non-SM or “exotic” decays of the Higgs boson. Such searches could provide unique access to hidden-sector particles that are singlets under the SM gauge transformations [3]. Exotic decays of the Higgs boson are predicted by many new-physics models [3,4], including those with an extended Higgs sector [5–9], dark matter (DM) models [10–14], models with a first-order electroweak phase transition [15,16] and theories with neutral naturalness [17,18]. These models have also been used to explain the observations of a  $\gamma$ -ray excess from the galactic centre (GC) by the Fermi Large Area Telescope [19,20]. For example, a model for the GC  $\gamma$ -ray excess was proposed in which 30 GeV DM particles pair-annihilate dominantly through a CP-odd scalar mediator that subsequently decays into SM fermions [13]. If the mediator is sufficiently lighter than the SM Higgs boson ( $H$ ) then  $H$  decay into the mediator pair can be observed at the LHC.

Existing measurements constrain the BSM or “exotic” branching ratio ( $\mathcal{B}$ ) of the 125 GeV Higgs boson decays to less than approximately 34% at 95% confidence level [21]. Due to the narrow width ( $\sim 4$  MeV) of the Higgs boson, even a small non-SM coupling of  $\mathcal{O}(10^{-2})$  can lead to  $\mathcal{O}(10\%)$  branching ratio into BSM states. This potentially large  $\mathcal{B}(H \rightarrow \text{BSM states})$  motivates direct searches for exotic  $H$  decays.

The analysis presented in this Letter performs the search in the  $bb\mu\mu$  final state. The  $a$ -boson can be either a scalar or a pseudoscalar under parity transformations, since the decay mode considered in this search is not sensitive to the difference in coupling. Assuming that the  $a$ -boson mixes with the SM Higgs boson and inherits its Yukawa couplings to fermions, the largest branching ratio is expected to be to the heaviest fermions accessible by kinematics ( $2m_a < m_H$ ), where  $m_a$  and  $m_H$  are the  $a$ -boson and Higgs boson masses. For  $m_a \gtrsim 10$  GeV this means the  $a$ -boson would decay preferentially into  $bb$ . However, in models with enhanced lepton couplings such as the Type-III 2HDM [22], the  $a \rightarrow \mu\mu$  branching ratio can also be relatively large. Additionally, the sensitivity of a given channel does not depend only on the expected signal rate in a particular model, but also on the efficiency for triggering and reconstructing events of interest. The presence of a clean dimuon resonance provides a distinctive signature that can be used for triggering and precision mass reconstruction, which helps to suppress background.

Searches for the Higgs boson with a mass of 125 GeV decaying into two spin-zero particles,  $H \rightarrow aa$ , have been performed in various final states in ATLAS and CMS [23–29]. The CMS search with  $\sqrt{s} = 8$  TeV data in the  $bb\mu\mu$  final state set 95% CL limits on  $(\sigma_H/\sigma_{SM}) \times \mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu)$  between  $2 \times 10^{-4}$  and  $8 \times 10^{-4}$  in the  $a$ -boson mass range of 25–62.5 GeV [25]. In Type-III 2HDM+S scenario with  $\tan \beta = 2$  [4], where  $\tan \beta$  denotes the ratio of the vacuum expectation values of the two Higgs fields, these limits translate into upper limits on  $(\sigma_H/\sigma_{SM}) \times \mathcal{B}(H \rightarrow aa)$  ranging between 13% and 50%. Some of the most stringent limits up to date for Type-III 2HDM+S with  $\tan \beta = 2$  come from the CMS search with  $\sqrt{s} = 13$  TeV data in the  $bb\tau\tau$  final state, setting the up-

<sup>\*</sup> E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

per limits on  $(\sigma_H/\sigma_{SM}) \times \mathcal{B}(H \rightarrow aa)$  between 4% and 26% in the  $a$ -boson mass range of 15–60 GeV [28].

## 2. Data and simulation

The search presented in this Letter is based on the  $36.1 \text{ fb}^{-1}$  dataset of proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 13 \text{ TeV}$  recorded by the ATLAS experiment at the LHC during 2015 and 2016. The ATLAS experiment [30] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle.<sup>1</sup> It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. Events are collected with single-muon triggers requiring the muon  $p_T$  to be above 24 or 26 GeV, depending on the data-taking period. The trigger efficiency for the signal events with the muon  $p_T$  on the trigger plateau is about 80%.

Simulated events are used to model the signal and SM backgrounds processes. Higgs boson production through the gluon–gluon fusion (ggF) and vector-boson fusion (VBF) processes was modelled at next-to-leading order (NLO) using POWHEG-Box v2 [31–33] interfaced with PYTHIA 8.186 [34] using the AZNLO set of tuned parameters [35] for the simulation of the  $bb\mu\mu$  decay of the Higgs boson, as well as for parton showering and hadronisation. The ggF Higgs boson production rate is normalised to the total cross-section predicted by a next-to-next-to-next-to-leading-order QCD calculation with NLO electroweak corrections applied [36–40]. The VBF production rate is normalised to an approximate next-to-next-to-leading-order (NNLO) QCD cross-section with NLO electroweak corrections applied [41–44]. Five mass points were simulated in the range  $m_a = 20$ –60 GeV in steps of 10 GeV for both ggF and VBF production.

SHERPA 2.2.1 [45] with the NNPDF3.0 [46] set of parton distribution functions (PDF) was used for the generation of Drell–Yan,  $W$  + jets and diboson ( $WW$ ,  $WZ$ ,  $ZZ$ ) backgrounds. Cross-sections were calculated at NNLO QCD accuracy for  $Z^{(*)}/\gamma^* + \text{jets}$  and  $W + \text{jets}$  production [47] and at NLO including LO contributions with two additional partons for the diboson processes [45,48,49]. The  $t\bar{t}$  and single-top-quark samples were generated with POWHEG-Box v2 [32] using the CT10 PDF set [50] interfaced with PYTHIA v6.428 [51] and the Perugia 2012 set of tuned parameters [52] for the parton shower. The mass of the top quark ( $m_t$ ) was set to 172.5 GeV. The parameter  $h_{\text{damp}}$  in POWHEG, used to regulate the high- $p_T$  radiation, was set to  $m_t$  for improved agreement between data and simulation in the high  $p_T$  region [53]. The cross-section of  $t\bar{t}$  was calculated at NNLO in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms [54,55]. The cross-section for single-top-quark production was calculated with the prescriptions in Refs. [56,57]. The production of  $t\bar{t}$  pairs in association with  $W/Z$  bosons (denoted by  $t\bar{t}V$ ) was modelled with samples generated at LO using MADGRAPH5\_AMC@NLO v2.2.2 [58] and showered with PYTHIA v8.186. The samples are normalised to NLO cross-sections [59,60].

Additional  $pp$  collisions generated with PYTHIA v8.186 were overlaid to model the effects of additional interactions in the same and neighbouring bunch crossings (pile-up) for all simulated

events. The pile-up simulation used the A2 set of tuned parameters [61] and the MSTW2008LO PDF set [62]. All the samples were processed through the full ATLAS detector simulation [63] based on GEANT4 [64] and processed with the same reconstruction algorithm as used for data.

## 3. Selection criteria

Interaction vertices from proton–proton collisions are reconstructed from at least two tracks with transverse momentum ( $p_T$ ) larger than 0.4 GeV, and are required to be consistent with the beamspot envelope. The primary vertex (PV) is identified as the one with the largest  $\sum p_T^2$  of associated tracks [65].

Muon candidates are reconstructed using the information from the inner detector and the muon spectrometer [66]. They are required to satisfy “medium” identification criteria [66], be matched to the PV and have  $p_T > 7 \text{ GeV}$  and  $|\eta| < 2.7$ . Additionally, the muons must satisfy the following criteria: the projected longitudinal impact parameter  $|z_0 \sin\theta|$  must be less than 0.5 mm and the ratio of the transverse impact parameter  $d_0$  to its estimated uncertainty  $\sigma_{d_0}$ ,  $|d_0/\sigma_{d_0}|$ , must be less than 3. Finally, the selected muons must fulfil requirements on the scalar sum of  $p_T$  of additional inner detector tracks and on the sum of the  $E_T$  of calorimeter topological clusters [67] in a cone of size  $\Delta R = 0.2$  around the muon to ensure they satisfy “tight” isolation criteria [66]. These requirements select signal muons with an identification efficiency of  $\sim 94\%$  and isolation efficiency ranging between  $\sim 91\%$  for  $m_a = 20 \text{ GeV}$  and  $\sim 95\%$  for  $m_a = 60 \text{ GeV}$ .

Jets are reconstructed using the anti- $k_r$  algorithm [68] implemented in the FASTJET package [69] with a radius parameter  $R = 0.4$  applied to topological clusters of energy deposits in calorimeter cells. Jets from pile-up are suppressed with the use of tracking information as detailed in Ref. [70]. All selected jets are required to have  $p_T > 20 \text{ GeV}$ ,  $|\eta| < 2.5$  and must pass quality requirements defined to minimise the impact of detector effects, beam backgrounds and cosmic rays.

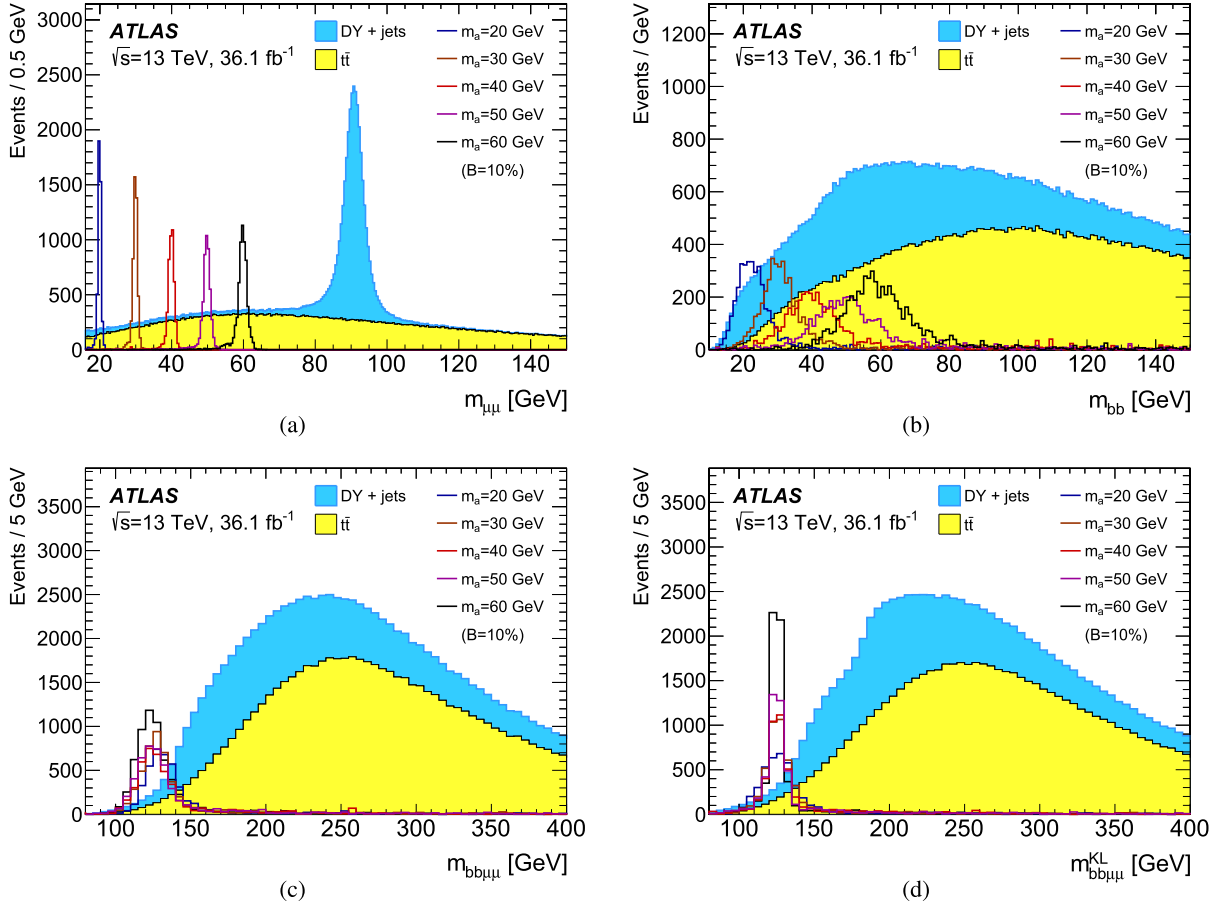
Jets consistent with the hadronisation of a  $b$ -quark ( $b$ -jets) are identified using a multivariate discriminant [71,72]. This analysis uses the 77%  $b$ -jet identification efficiency working point for which the purity of the  $b$ -tagged sample is approximately 95%, while the probability of misidentifying a jet initiated by a charm quark as a  $b$ -jet is approximately 16%, as determined from a sample of simulated  $t\bar{t}$  events.

In order to reject non-prompt muons from the decay of hadrons within a jet, an overlap removal algorithm is applied. If a jet is found within  $\Delta R = 0.4$  of the muon candidate, the overlap is resolved in the following way: if there are more than two tracks with  $p_T > 500 \text{ MeV}$  associated with the jet then the muon is removed from the event, otherwise the muon is retained and the jet is removed.

The missing transverse momentum ( $E_T^{\text{miss}}$ ) used in the analysis is calculated as the magnitude of the negative vector sum ( $\vec{p}_T^{\text{miss}}$ ) of the transverse momenta of all selected and calibrated objects in the event and the additional “soft” term that takes into account tracks not associated with any of these objects [73]. The “soft” term is calculated from inner detector tracks matched to the PV and included to achieve a better  $E_T^{\text{miss}}$  resolution.

Events are required to have exactly two  $b$ -tagged jets with  $p_T > 20 \text{ GeV}$  and exactly two reconstructed muons of opposite charge, with the leading muon having  $p_T > 27 \text{ GeV}$  to be in the maximum-efficiency regime of the trigger and the subleading muon having  $p_T > 7 \text{ GeV}$ . The dimuon invariant mass ( $m_{\mu\mu}$ ) is required to be between 16 GeV and 64 GeV. The upper bound on  $m_{\mu\mu}$  is defined by the assumption that the 125 GeV Higgs boson decays into two

<sup>1</sup> The ATLAS Collaboration 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  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in units of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .



**Fig. 1.** The (a)  $m_{\mu\mu}$ , (b)  $m_{bb}$  before the KL fit, (c)  $m_{bb\mu\mu}$  before and (d)  $m_{bb\mu\mu}^{\text{KL}}$  after the KL fit for events after the preselection stage, but removing the upper bound on  $m_{\mu\mu}$ . The  $t\bar{t}$  contribution is modelled with the simulated sample normalised to the theoretical cross-section. The Drell-Yan contribution is taken from data templates (described in the text) and normalised to the total yield predicted by the Drell-Yan simulation. The signal distributions for all five simulated  $m_a$  are also shown assuming the SM Higgs boson cross-section (including ggF, VBF and  $VH$  production) and  $B(H \rightarrow aa \rightarrow bb\mu\mu) = 10\%$ . The branching ratio in this and all subsequent figures is chosen so as to give good visibility on the plot.

on-shell particles of equal masses, while the lower bound is motivated by the kinematics of the  $a$ -boson decays. For lower values of  $m_a$ , most of the signal jets fall below the reconstruction threshold and the jets tend to overlap geometrically in the detector so that the sensitivity of the analysis to the  $H \rightarrow aa$  signal decreases. This set of selection criteria is referred to as the “preselection”.

Signal events are characterised by the invariant mass of the two  $b$ -jets ( $m_{bb}$ ) being equal, within the detector resolution, to the dimuon invariant mass and the four-object mass ( $m_{bb\mu\mu}$ ) being approximately 125 GeV. One side of the  $H \rightarrow aa$  decay ( $a \rightarrow \mu\mu$ ) is measured with approximately ten times better resolution than the other side of the decay ( $a \rightarrow bb$ ), as shown in Figs. 1(a) and 1(b).

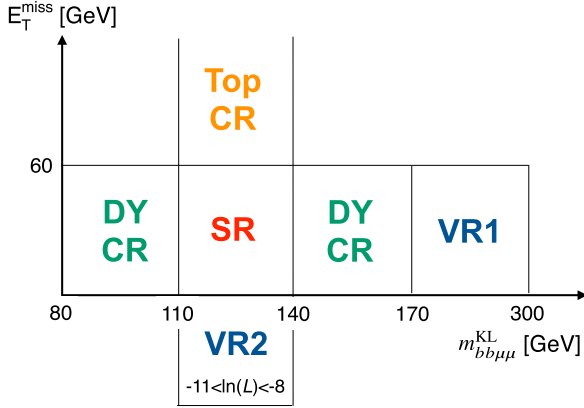
A kinematic-likelihood (KL) fit [74] exploiting the symmetry of  $H \rightarrow aa$  decays is performed to test the compatibility of an event with the  $m_{bb} \simeq m_{\mu\mu}$  hypothesis and improve the  $m_{bb\mu\mu}$  resolution in signal events. The KL fit finds the energies of the leading ( $\hat{E}_{b_1}$ ) and subleading ( $\hat{E}_{b_2}$ )  $b$ -jets that maximise the likelihood for an event with measured leading and subleading  $b$ -jet energies  $E_{b_1}$  and  $E_{b_2}$  and with dimuon invariant mass  $m_{\mu\mu}$ . The likelihood is defined as follows,

$$L = W(\hat{E}_{b_1}, E_{b_1}) \cdot W(\hat{E}_{b_2}, E_{b_2}) \cdot F_{\text{BW}}(m_{bb}^{\text{KL}}, m_{\mu\mu}),$$

where  $m_{bb}^{\text{KL}}$  is the dijet invariant mass computed from the  $b$ -jet four-momenta corresponding to  $\hat{E}_{b_1}$  and  $\hat{E}_{b_2}$ ,  $W$  is the transfer function of the  $b$ -jets, and  $F_{\text{BW}}$  is a Breit–Wigner function centred

on  $m_{\mu\mu}$  with a width that is small compared to the  $m_{bb}$  resolution. The transfer function  $W(\hat{E}_{b_1}, E_{b_1})$  is a double Gaussian probability density function derived from simulated events as a function of jet  $p_T$  and  $\eta$  using the difference between true and reconstructed energies. The fit determines a maximum-likelihood value of  $L$  (denoted by  $\ln(L^{\text{max}})$ ), which quantifies how well an event fits to the constraints. The  $b$ -jet momenta determined by the fit are used to recompute the four-body mass denoted  $m_{bb\mu\mu}^{\text{KL}}$ . As seen in Fig. 1(d), the resolution of the  $m_{bb\mu\mu}^{\text{KL}}$  distribution for the signal is improved by up to a factor of two compared to the pre-fit  $m_{bb\mu\mu}$  shown in Fig. 1(c), while the background shape within the  $m_{bb\mu\mu}$  signal peak remains almost unchanged with the yields rising by  $\sim 20\%$ . This allows the analysis to place tighter constraints on the difference between the reconstructed invariant mass of the  $bb\mu\mu$  system and  $m_H$ , rejecting more background events and obtaining higher signal significance.

Two criteria based on the kinematic likelihood fit are applied to select signal-like events and reject background events that do not fit the  $m_{bb} = m_{\mu\mu}$  constraint well:  $|m_{bb\mu\mu}^{\text{KL}} - m_H| < 15$  GeV and  $\ln(L^{\text{max}}) > -8$ . Finally, the  $E_T^{\text{miss}} < 60$  GeV requirement rejects a large portion of  $t\bar{t}$  pairs where both top quarks decay semileptonically, while retaining most of the signal events. Adding these three requirements after the preselection stage defines the signal-enhanced region (SR). A search for a localised excess above the expected background is performed in multiple  $m_{\mu\mu}$  bins of the SR



**Fig. 2.** Illustration of the signal, control and validation regions used in the analysis. The  $E_T^{\text{miss}}$  requirement in the VR2 region is the same as in the SR. The corresponding DY-template regions are defined in the same way except that the two- $b$ -tag requirement is changed to a zero- $b$ -tag requirement.

centred around the hypothesised  $m_a$ . A bin width of 2 GeV is chosen for  $16 < m_{\mu\mu} \leq 40$  GeV, 3 GeV for  $40 < m_{\mu\mu} < 50$  GeV and 4 GeV for  $50 \leq m_{\mu\mu} < 64$  GeV respectively, in order to maximise the sensitivity.

#### 4. Backgrounds

The dominant backgrounds in the signal region are Drell–Yan (DY) dimuon events in association with  $b$ -quarks and pair production of top quarks where both  $W$  bosons from top quarks decay into muons. Each of the dominant backgrounds amounts to approximately 50% of the total background in the SR. Two control regions (CR) are defined to constrain the contributions of the dominant backgrounds in the signal region. They are chosen such that they have negligible signal contamination, but are kinematically close to the SR to reduce model dependence. The top control region (TCR) is defined by applying the same selection criteria as for the signal region, but inverting the requirement on the missing transverse momentum to  $E_T^{\text{miss}} > 60$  GeV. According to the simulation, approximately 95% of the events in TCR originate from  $t\bar{t}$  production. The Higgs boson mass sidebands of the signal region are used as the Drell–Yan control region (DYCR): the constraint on the  $bb\mu\mu$  invariant mass after the KL fit is inverted to  $80 < m_{bb\mu\mu}^{\text{KL}} < 110$  GeV or  $140 < m_{bb\mu\mu}^{\text{KL}} < 170$  GeV. The DYCR consists of about 50% DY events and about 50%  $t\bar{t}$  events.

The shapes of the  $t\bar{t}$  kinematic variables are modelled using simulated events, while the distributions for the Drell–Yan process are taken from data templates as described below. The  $t\bar{t}$  simulated sample and the DY templates are normalised in profile likelihood fits to the data. In one fit variant, the two background normalisations are simultaneously determined from the event yields in the TCR and DYCR assuming no presence of signal. In a second variant, the two background normalisations and the signal strength are determined using the event yields measured in the TCR, DYCR, and a given signal window. Two validation regions are defined to compare the number of observed events with the number of SM events predicted by the fit. One validation region (VR1) is defined in the high tail of the  $bb\mu\mu$  invariant mass distribution,  $170 < m_{bb\mu\mu}^{\text{KL}} < 300$  GeV, while for the second validation region (VR2) only the requirement on the  $\ln(L^{\text{max}})$  is changed relative to the SR,  $-11 < \ln(L) < -8$ . All the analysis regions are illustrated in Fig. 2.

The DY templates for each of the kinematic variables considered in a particular region of the analysis (SR, CR or VR) are taken from the data in a corresponding template region (DYTR).

For each analysis region the associated DYTR is defined by changing the two- $b$ -tag requirement (present in every SR, CR and VR) to a zero- $b$ -tag requirement, while keeping all other selection requirements the same. All the DYTR are  $> 90\%$  pure in DY events. The small contribution from non-DY backgrounds, namely  $t\bar{t}$ , dibosons,  $W$  + jets, single-top and  $t\bar{t}V$ , is subtracted from the data in a DYTR using the simulated samples, and the remaining data events are assigned to the DY template. To construct  $b$ -jet-based variables, such as  $m_{bb}$  and  $m_{bb\mu\mu}$ , in a DYTR the two leading non-tagged jets are taken and used in the computation instead of the  $b$ -jets.

It is verified in both the simulation and the data that the shapes of all the muon-based variables (most importantly  $m_{\mu\mu}$ ) are consistent between the sample with no  $b$ -tagged jets and the sample with two  $b$ -tagged jets. To account for differences in jet kinematics between the DYTR dominated by light-flavour jets and the corresponding analysis region dominated by heavy-flavour jets, an event-reweighting based on the leading jet  $p_T$  is applied to the events in the DYTR. The event weights are derived in the data after the preselection as the ratio of the leading  $b$ -tagged jet  $p_T$  in the two- $b$ -tag sample to the leading jet  $p_T$  in the sample with zero  $b$ -tags. An improvement in the modelling of jet-based kinematic variables after the reweighting is verified both in simulation and in data in the DYCR, while the shape of the  $m_{\mu\mu}$  distribution remains unchanged.

Minor backgrounds include diboson production,  $W$  boson production in association with  $b$ -jets (with one non-prompt muon satisfying the isolation criteria) and production of a single top quark or  $t\bar{t}$  pair in association with a vector boson. The contribution of the minor backgrounds in the signal region is at the percent level. They are estimated using simulation normalised to the best available theory prediction.

#### 5. Systematic uncertainties

Dominant sources of experimental systematic uncertainty are the calibration and resolution of jet energies and muon momenta, the measurement of the  $b$ -tagging efficiency and the measurement of the scale and resolution of the soft term of the missing transverse momentum. Each of these uncertainties affects the  $t\bar{t}$  yields by up to 14% in any of the  $m_{\mu\mu}$  bins of the signal region. Other experimental uncertainties have a sub-percent effect on the expected yields. These include the uncertainties in the measurement of muon identification and isolation efficiencies and the uncertainties associated with the integrated luminosity and the simulation of pile-up interactions. The uncertainty in the combined 2015 + 2016 integrated luminosity is 2.1%. It is derived, following a methodology similar to that detailed in Ref. [75], from a calibration of the luminosity scale using  $x$ - $y$  beam-separation scans performed in August 2015 and May 2016.

Four sources of theoretical uncertainty in the modelling of the  $t\bar{t}$  process are considered in the analysis. As the  $t\bar{t}$  simulation is normalised to the data in TCR, all of these uncertainties are applied to the acceptance ratio between TCR and SR. Hadronisation and parton-showering model uncertainties are estimated using a sample generated with POWHEG and showered by HERWIG++ v2.7.1 and comparing it with the nominal POWHEG sample showered with PYTHIA v6.428. The uncertainty due to the choice of the event generator is estimated by comparing the expected yields obtained using a  $t\bar{t}$  sample generated with AMC@NLO and one that is generated with POWHEG. Both samples are showered with HERWIG++ v2.7.1. The event generator and hadronisation/parton-showering uncertainties are found to have the largest effect among all the uncertainties affecting the total  $t\bar{t}$  expectation in the signal region:  $\sim 18\%$  and  $\sim 16\%$ , respectively. Systematic uncertainties in the mod-

elling of initial- and final-state radiation (ISR and FSR) are assessed with POWHEG samples showered with two alternative settings of PYTHIA v6.428. The first of these uses the PERUGIA2012radHi tune and has the renormalisation and factorisation scales set to twice the nominal value, resulting in more radiation in the final state. In addition, it has  $h_{\text{damp}}$  set to  $2 \times m_t$ . The second sample, using the PERUGIA2012radLo tune, has  $h_{\text{damp}} = m_t$  and the renormalisation and factorisation scales are set to half of their nominal values, resulting in less radiation in the event. This uncertainty has about a 5% effect on the final  $t\bar{t}$  yields. Finally, the uncertainties due to the choice of PDF are evaluated by taking the maximum difference in the acceptance ratio between TCR and SR obtained with the nominal CT10 set and the alternative PDF4LHC15 set [76]. The PDF uncertainty has up to a 2% effect on the final  $t\bar{t}$  yields.

The uncertainties in the theoretical cross-sections (described earlier in this Letter) are assigned to the minor backgrounds whose yields are taken directly from the simulation: dibosons (10%), single top (5%) and  $t\bar{t}V$  (13%). A 100% uncertainty is applied to the  $W$  + jets process to account for the limited precision of the simulation when modelling the non-prompt muons satisfying the isolation criteria. Due to the minor contribution of the  $W$  + jets background to the analysis, this uncertainty has negligible effect. As these backgrounds have very small contributions to the SR, no theoretical uncertainties affecting the acceptance have been applied.

The systematic uncertainties applied to the data-driven DY template include the uncertainties in the shape of the template due to the background subtraction and different jet-flavour composition between the DYTR and SR. The uncertainty in the background subtraction is estimated from a comparison of the nominal template after the non-DY backgrounds are subtracted and the template where no subtraction is performed. The effect of this systematic uncertainty on the DY yields in the signal region is up to 4%. The uncertainty in the template shape due to the jet-flavour composition is assessed by comparing the nominal template extracted from the DYTR with zero  $b$ -tagged jets to the template extracted from the corresponding region, but with exactly one  $b$ -tagged jet. The average per-bin difference between the two templates in the  $m_{\mu\mu}$  distribution is taken as an overall uncertainty in the shape, amounting to 14%.

The systematic uncertainties affecting the acceptance of the  $H \rightarrow aa$  signal that correspond to the QCD scale uncertainties, the process of parton showering and hadronization and the choice of PDF set are evaluated. The renormalisation and factorisation scales are independently varied up and down from their nominal value by a factor of two and the largest resulting change is taken as the overall uncertainty due to the QCD scale. The parton-shower uncertainties are derived by independently shifting up and down the PYTHIA internal parameters that control the amount of ISR and FSR. Uncertainties due to the PDF are evaluated by taking the maximum difference between the yields obtained with the nominal PDF set and the alternative PDF4LHC15 and NNPDF3.0 PDF sets. The uncertainties due to the missing higher-order QCD corrections are applied to the ggF and VBF Higgs boson production cross-sections, amounting to 3.9% and 2.1%, respectively [36,77]. The uncertainties due to the choice of PDF and  $\alpha_s$  are also applied to the Higgs boson cross-section, amounting to 3.2% for ggF and 0.4% for VBF production [36,77].

Additionally, the ggF signal sample is compared with the alternative sample generated using the NNLOPS approach [78]. The Higgs boson rapidity distribution in the original POWHEG signal sample is found to be consistent with the one predicted by the NNLOPS calculations, while the Higgs boson transverse momentum ( $p_T(H)$ ) distribution is found to be harder than the one obtained using the NNLOPS approach. A reweighting is derived as a function of  $p_T(H)$  by fitting the ratio of the two generated  $p_T$

**Table 1**

Summary of the dominant post-fit systematic uncertainties on the background and signal yields. The uncertainties are expressed as a percentage of the total background (middle column) and signal (rightmost column) yields per  $m_{\mu\mu}$  bin of the signal region. Shown are the uncertainties that exceed 2% in at least one  $m_{\mu\mu}$  bin.

Source	Total background [%]	Signal [%]
DY: normalisation	9.3–15	–
DY: flavour composition	6.9–11	–
DY: background subtraction	0.4–2.4	–
$t\bar{t}$ : hard-scatter generation	3.6–8.6	–
$t\bar{t}$ : hadronisation/parton-shower	3.2–7.7	–
$t\bar{t}$ : normalisation	2.1–5.0	–
$t\bar{t}$ : ISR/FSR	1.0–2.4	–
MC statistics	2.4–4.9	2.3–4.6
$b$ -tagging	0.6–1.5	17–19
Jet-energy resolution	0.3–2.9	5.2–8.4
Jet-energy scale	0.3–2.9	3.9–6.5
Muon- $p_T$ resolution	0.1–2.2	0.3–1.2
Luminosity	< 0.01	2.1
Signal: QCD scale	–	6
Signal: ISR/FSR	–	4
Signal: ggF cross-section	–	–
- missing higher-order QCD	–	3.6–3.8
- PDF & $\alpha_s$	–	2.8–3.0
Signal: $VH$ contribution	–	3.5
Signal: $p_T(H)$ reweighting	–	2.3–2.5

distributions with a continuous function. The ggF signal sample is then reweighted with this function to obtain the nominal signal prediction. A 2.5% difference in the SR event yields observed between the weighted and unweighted sample is applied as a systematic uncertainty in the modelling of  $p_T(H)$ .

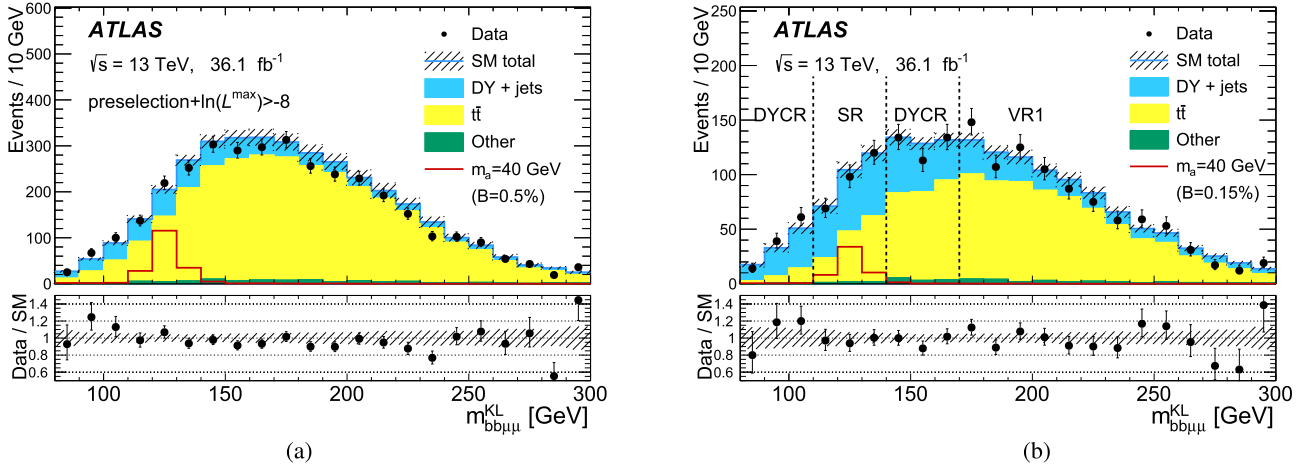
The signal contribution of the Higgs boson produced in the association with a vector boson ( $VH$ ) is taken into account by increasing the total cross-section of the ggF and VBF processes by an estimated 3.5%  $VH$  contribution. A 100% uncertainty is applied to this procedure to account for kinematic differences between the estimated  $VH$  contribution and the generated ggF and VBF processes. The contribution from other Higgs boson production processes is minor and therefore not included.

Table 1 shows a summary of the dominant post-fit systematic uncertainties in the total background and signal yields across multiple  $m_{\mu\mu}$  bins of the signal region. All of the uncertainties shown in Table 1, except the normalisation and cross-section uncertainties, affect the shapes of the signal and background distributions and therefore the extrapolation of the predicted yields from the CRs to the SR.

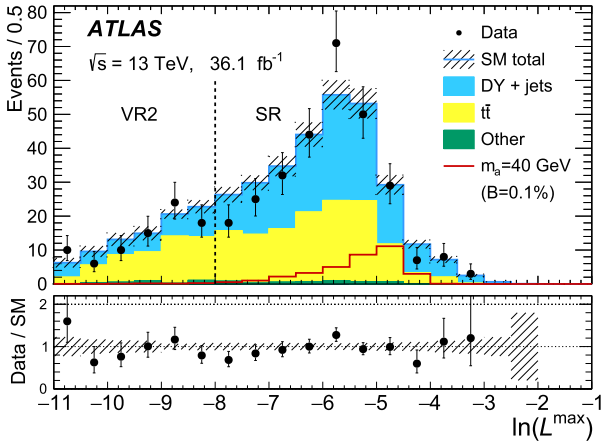
## 6. Results

The expected SM background in each of the analysis regions is determined by a profile likelihood fit to the data. The numbers of observed and predicted events in each of the bins included in the likelihood are described by Poisson probability density functions. The systematic uncertainties are implemented as nuisance parameters constrained by Gaussian distributions with widths corresponding to the sizes of the uncertainties.

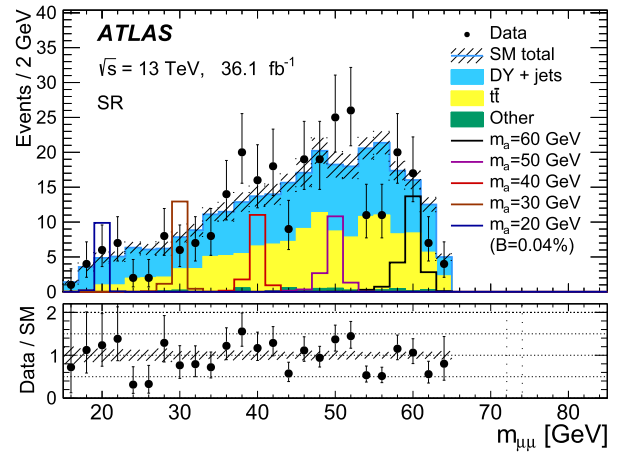
The background-only version of the fit is performed to verify that the post-fit background yields agree with the data in the VRs and SR. In this version of the fit, only the data in TCR and DYCR are used to constrain the  $t\bar{t}$  and DY backgrounds and determine their normalisation factors. Both TCR and DYCR are considered as one bin each. The free fit parameters are the overall normalisation factors for the  $t\bar{t}$  and Drell–Yan backgrounds. The derived  $t\bar{t}$  (DY) normalisation factors are then applied to the number of  $t\bar{t}$  (DY) events as predicted by the simulation (template) in any of the VR



**Fig. 3.** The predicted and observed  $m_{bb\mu\mu}^{KL}$  distributions (a) after the preselection and the KL-fit  $\ln(L^{\max}) > -8$  constraint and (b) across DYCR, SR and VR1 (shown separated by vertical dashed lines). Both are shown after the background-only fit and differ only in the  $E_T^{\text{miss}} < 60$  GeV criterion being applied in (b). The signal distribution for  $m_a = 40$  GeV is also shown assuming the SM Higgs boson cross-section (including ggF, VBF and VH production) and (a)  $\mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu) = 0.5\%$  and (b)  $\mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu) = 0.15\%$ . The hashed bands show the total statistical and systematic uncertainties of the backgrounds.



**Fig. 4.** The predicted and observed KL-fit  $\ln(L^{\max})$  distribution across VR2 and SR (shown separated by a vertical dashed line) after the background-only fit. The signal distribution for  $m_a = 40$  GeV is also shown assuming the SM Higgs boson cross-section (including ggF, VBF and VH production) and  $\mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu) = 0.1\%$ . The hashed bands show the total statistical and systematic uncertainties of the backgrounds.



**Fig. 5.** The predicted and observed  $m_{\mu\mu}$  distributions in the SR after the background-only fit. The signal distributions are also shown assuming the SM Higgs boson cross-section (including ggF, VBF and VH production) and  $\mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu) = 0.04\%$ . The hashed bands show the total statistical and systematic uncertainties of the backgrounds.

or SR bins. The post-fit distributions are shown in Figs. 3–5. Both the normalisation and the shapes of the predicted background distributions describe the data well in all of the analysis control and validation regions, as well as in the SR. The post-fit yields in five  $m_{\mu\mu}$  bins of the SR, for which the signal sample was simulated, are shown in Table 2.

Since no significant deviation from the predicted background is observed in the signal region, upper limits on signal yields at 95% confidence level (CL) are set as a function of  $m_{\mu\mu}$  using the CL<sub>s</sub> prescription [79,80]. A series of profile likelihood fits is applied to the data in order to test 36 hypotheses for the  $m_a$  value in steps half the size of the mass-bin width optimised in each  $m_{\mu\mu}$  region. In each fit the likelihood function is based on the observed and predicted yields in a SR  $m_{\mu\mu}$  bin corresponding to the  $m_a$  hypothesis under test and on the expected and measured yields in the TCR and DYCR. The profile likelihood is maximised to extract the best-fit values for the signal strength and the  $t\bar{t}$  and DY normalisation factors.

Model-dependent limits are set on  $(\sigma_H/\sigma_{SM}) \times \mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu)$  assuming the signal acceptance  $\times$  efficiency as given by

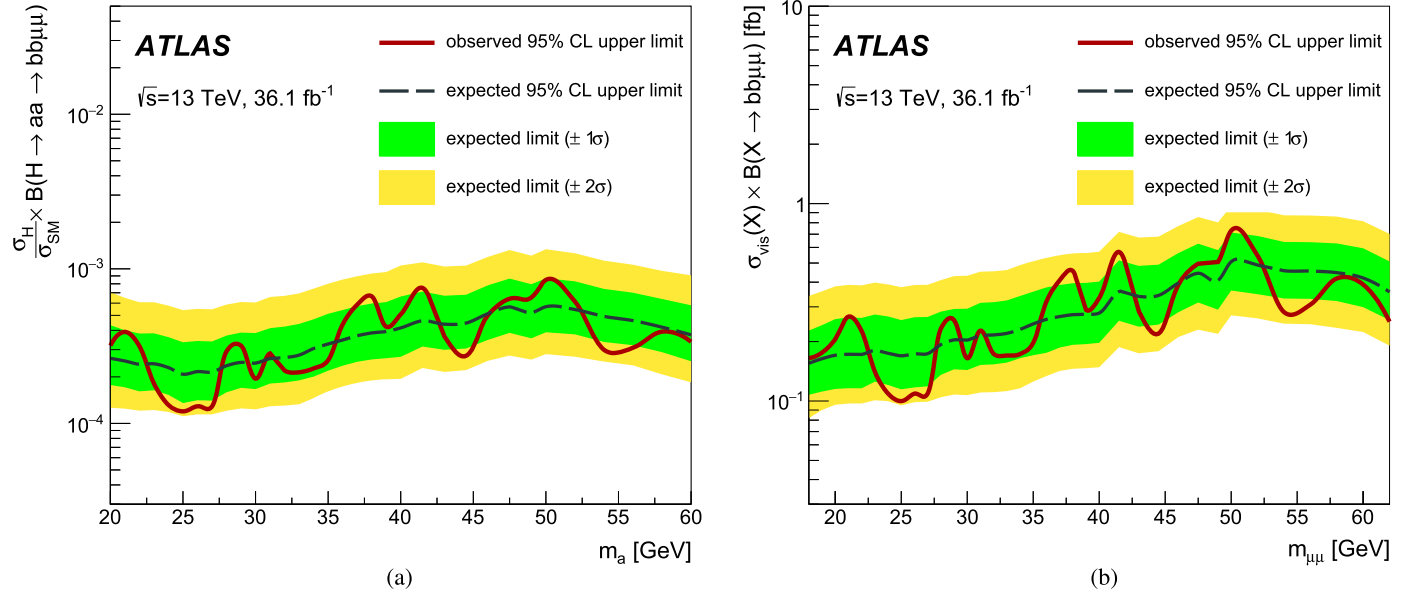
the simulation. The signal acceptance  $\times$  efficiency varies between 1.3% and 2.5% for ggF production and between 0.94% and 3.2% for VBF Higgs boson production. To obtain the signal yield for masses for which no events were simulated, the acceptance  $\times$  efficiency is interpolated with spline functions between the five simulated points. All signal-related uncertainties are taken into account in the likelihood, with an additional 3% interpolation uncertainty applied to the intermediate masses. The limits are set in the  $20 \leq m_a \leq 60$  GeV range for which the signal samples were simulated and range between  $2 \times 10^{-4}$  and  $10^{-3}$  (see Fig. 6(a)).

A model-independent fit that does not include any prediction for the signal yields in SRs and CRs is also performed. The upper limit on the number of BSM events for each mass bin of the SR is translated to a 95% CL upper bound on the visible cross-section for new physics times branching ratio into  $bb\mu\mu$  final state (including the KL fit constraint on  $m_{bb} \sim m_{\mu\mu}$  and the four-object invariant mass constraint  $m_{bb\mu\mu}^{KL} \sim m_H$ ),  $\sigma_{\text{vis}}(X) \times \mathcal{B}(X \rightarrow bb\mu\mu)$ . The visible cross-section is defined as the product of the production cross-section and acceptance  $\times$  efficiency ( $\sigma_{\text{vis}}(X) = \sigma_{\text{prod}}(X) \times \epsilon_X$ ) of a potential signal after all the analysis selection criteria have been

**Table 2**

Total and individual background yields in five representative  $m_{\mu\mu}$  bins of the signal region. The yields are the post-fit values as determined by the background-only fit. The uncertainties shown include all systematic uncertainties and the statistical MC uncertainty.  $W + \text{jets}$  contribution in the SR is found to be negligible and is therefore not shown in the table.

$m_{\mu\mu}$ bin [GeV]	[19–21]	[29–31]	[39–41]	[48–52]	[58–62]
Observed events	6	6	16	48	29
Total background	$4.84 \pm 0.97$	$7.8 \pm 1.2$	$13.7 \pm 2.2$	$37.9 \pm 5.1$	$30.8 \pm 4.2$
$t\bar{t}$	$0.96 \pm 0.29$	$3.08 \pm 0.74$	$6.6 \pm 1.5$	$18.1 \pm 4.3$	$14.8 \pm 3.3$
DY	$3.88 \pm 0.92$	$4.5 \pm 1.1$	$7.1 \pm 1.7$	$19.0 \pm 4.5$	$15.5 \pm 3.6$
Dibosons	$< 0.01$	$< 0.01$	$0.02^{+0.04}_{-0.02}$	$0.26 \pm 0.16$	$0.3 \pm 0.1$
Single top	$< 0.01$	$0.2 \pm 0.2$	$< 0.01$	$0.65^{+0.97}_{-0.65}$	$0.09^{+0.19}_{-0.09}$
$t\bar{t}V$	$< 0.01$	$< 0.01$	$< 0.01$	$0.01^{+0.02}_{-0.01}$	$0.05 \pm 0.03$



**Fig. 6.** The (a) observed and expected upper limits at the 95% confidence level on  $\mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu)$  given the SM Higgs boson production cross-section in the ggF, VBF and  $VH$  modes and (b) model-independent upper limits on the visible cross-section for new physics times branching ratio to the  $bb\mu\mu$  final state  $\sigma_{\text{vis}}(X) \times \mathcal{B}(X \rightarrow bb\mu\mu)$ .

applied. The limits range from 0.1 fb to 0.73 fb, depending on the dimuon mass, and are shown in Fig. 6(b). The most significant excess of data over the SM prediction is found at  $m_{\mu\mu} = 38$  GeV, with a local significance of 1.6 standard deviations.

## 7. Conclusions

In summary, a search for exotic decays of the Higgs boson into two spin-zero particles in the  $bb\mu\mu$  final state is presented. The analysis uses  $36.1 \text{ fb}^{-1}$  of  $pp$  collision data collected by ATLAS during the 2015 and 2016 runs of the LHC at  $\sqrt{s} = 13$  TeV. The search for a narrow dimuon resonance is performed over the range  $18 \text{ GeV} \leq m_{\mu\mu} \leq 62 \text{ GeV}$  using mass bins that are 2, 3 or 4 GeV wide depending on  $m_{\mu\mu}$ . No significant excess of the data above the SM prediction is observed. Upper limits are set on  $(\sigma_H/\sigma_{\text{SM}}) \times \mathcal{B}(H \rightarrow aa \rightarrow bb\mu\mu)$  and range between  $1.2 \times 10^{-4}$  and  $8.4 \times 10^{-4}$ , depending on  $m_a$ . In Type-III 2HDM+S scenario with  $\tan \beta = 2$  these limits translate into upper limits on  $(\sigma_H/\sigma_{\text{SM}}) \times \mathcal{B}(H \rightarrow aa)$  ranging between 7% and 47%. The same analysis, implementing all selection criteria including  $m_{bb} \sim m_{\mu\mu}$  and  $m_{bb\mu\mu}^{\text{KL}} \sim m_H$  constraints, is used to set the model-independent limits on the visible cross-section for new physics times branching ratio to the  $bb\mu\mu$  final state ( $\sigma_{\text{vis}}(X) \times \mathcal{B}(X \rightarrow bb\mu\mu)$ ), ranging from 0.1 fb to 0.73 fb, depending on the dimuon mass.

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M. Aaboud<sup>34d</sup>, G. Aad<sup>99</sup>, B. Abbott<sup>125</sup>, O. Abdinov<sup>13,\*</sup>, B. Abeloos<sup>129</sup>, D.K. Abhayasinghe<sup>91</sup>, S.H. Abidi<sup>164</sup>, O.S. AbouZeid<sup>39</sup>, N.L. Abraham<sup>153</sup>, H. Abramowicz<sup>158</sup>, H. Abreu<sup>157</sup>, Y. Abulaiti<sup>6</sup>, B.S. Acharya<sup>64a,64b,p</sup>, S. Adachi<sup>160</sup>, L. Adamczyk<sup>81a</sup>, J. Adelman<sup>119</sup>, M. Adersberger<sup>112</sup>, A. Adiguzel<sup>12c,aj</sup>, T. Adye<sup>141</sup>, A.A. Affolder<sup>143</sup>, Y. Afik<sup>157</sup>, C. Agheorghiesei<sup>27c</sup>, J.A. Aguilar-Saavedra<sup>137f,137a,ai</sup>, F. Ahmadov<sup>77,ag</sup>, G. Aielli<sup>71a,71b</sup>, S. Akatsuka<sup>83</sup>, T.P.A. Åkesson<sup>94</sup>, E. Akilli<sup>52</sup>, A.V. Akimov<sup>108</sup>, G.L. Alberghi<sup>23b,23a</sup>, J. Albert<sup>173</sup>, P. Albicocco<sup>49</sup>, M.J. Alconada Verzini<sup>86</sup>, S. Alderweireldt<sup>117</sup>, M. Aleksa<sup>35</sup>, I.N. Aleksandrov<sup>77</sup>, C. Alexa<sup>27b</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>125</sup>, B. Ali<sup>139</sup>, G. Alimonti<sup>66a</sup>, J. Alison<sup>36</sup>, S.P. Alkire<sup>145</sup>, C. Allaire<sup>129</sup>, B.M.M. Allbrooke<sup>153</sup>, B.W. Allen<sup>128</sup>, P.P. Allport<sup>21</sup>, A. Aloisio<sup>67a,67b</sup>, A. Alonso<sup>39</sup>, F. Alonso<sup>86</sup>, C. Alpigiani<sup>145</sup>, A.A. Alshehri<sup>55</sup>, M.I. Alstady<sup>99</sup>, B. Alvarez Gonzalez<sup>35</sup>, D. Álvarez Piqueras<sup>171</sup>, M.G. Alviggi<sup>67a,67b</sup>, B.T. Amadio<sup>18</sup>, Y. Amaral Coutinho<sup>78b</sup>, L. Ambroz<sup>132</sup>, C. Amelung<sup>26</sup>, D. Amidei<sup>103</sup>, S.P. Amor Dos Santos<sup>137a,137c</sup>, S. Amoroso<sup>44</sup>, C.S. Amrouche<sup>52</sup>, C. Anastopoulos<sup>146</sup>, L.S. Ancu<sup>52</sup>, N. Andari<sup>142</sup>, T. Andeen<sup>11</sup>, C.F. Anders<sup>59b</sup>, J.K. Anders<sup>20</sup>, K.J. Anderson<sup>36</sup>, A. Andreazza<sup>66a,66b</sup>, V. Andrei<sup>59a</sup>, C.R. Anelli<sup>173</sup>, S. Angelidakis<sup>37</sup>, I. Angelozzi<sup>118</sup>, A. Angerami<sup>38</sup>, A.V. Anisenkov<sup>120b,120a</sup>, A. Annovi<sup>69a</sup>, C. Antel<sup>59a</sup>, M.T. Anthony<sup>146</sup>, M. Antonelli<sup>49</sup>, D.J.A. Antrim<sup>168</sup>, F. Anulli<sup>70a</sup>, M. Aoki<sup>79</sup>, J.A. Aparisi Pozo<sup>171</sup>, L. Aperio Bella<sup>35</sup>, G. Arabidze<sup>104</sup>, J.P. Araque<sup>137a</sup>, V. Araujo Ferraz<sup>78b</sup>, R. Araujo Pereira<sup>78b</sup>, A.T.H. Arce<sup>47</sup>, R.E. Ardell<sup>91</sup>, F.A. Arduh<sup>86</sup>, J-F. Arguin<sup>107</sup>, S. Argyropoulos<sup>75</sup>, A.J. Armbruster<sup>35</sup>, L.J. Armitage<sup>90</sup>, A. Armstrong<sup>168</sup>, O. Arnaez<sup>164</sup>, H. Arnold<sup>118</sup>, M. Arratia<sup>31</sup>, O. Arslan<sup>24</sup>, A. Artamonov<sup>109,\*</sup>, G. Artoni<sup>132</sup>, S. Artz<sup>97</sup>, S. Asai<sup>160</sup>, N. Asbah<sup>57</sup>, A. Ashkenazi<sup>158</sup>, E.M. Asimakopoulou<sup>169</sup>, L. Asquith<sup>153</sup>, K. Assamagan<sup>29</sup>, R. Astalos<sup>28a</sup>, R.J. Atkin<sup>32a</sup>, M. Atkinson<sup>170</sup>, N.B. Atlay<sup>148</sup>, K. Augsten<sup>139</sup>, G. Avolio<sup>35</sup>, R. Avramidou<sup>58a</sup>, M.K. Ayoub<sup>15a</sup>, G. Azuelos<sup>107,aw</sup>, A.E. Baas<sup>59a</sup>, M.J. Baca<sup>21</sup>, H. Bachacou<sup>142</sup>, K. Bachas<sup>65a,65b</sup>, M. Backes<sup>132</sup>, P. Bagnaia<sup>70a,70b</sup>, M. Bahmani<sup>82</sup>, H. Bahrasemani<sup>149</sup>, A.J. Bailey<sup>171</sup>, J.T. Baines<sup>141</sup>, M. Bajic<sup>39</sup>, C. Bakalis<sup>10</sup>, O.K. Baker<sup>180</sup>, P.J. Bakker<sup>118</sup>, D. Bakshi Gupta<sup>93</sup>, E.M. Baldin<sup>120b,120a</sup>,

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 R. Cardarelli<sup>71a</sup>, F.C. Cardillo<sup>146</sup>, I. Carli<sup>140</sup>, T. Carli<sup>35</sup>, G. Carlino<sup>67a</sup>, B.T. Carlson<sup>136</sup>, L. Carminati<sup>66a,66b</sup>,  
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 M. Sessa <sup>72a,72b</sup>, H. Severini <sup>125</sup>, F. Sforza <sup>167</sup>, A. Sfyrila <sup>52</sup>, E. Shabalina <sup>51</sup>, J.D. Shahinian <sup>143</sup>,  
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 P.E. Sidebo <sup>151</sup>, E. Sideras Haddad <sup>32c</sup>, O. Sidiropoulou <sup>35</sup>, A. Sidoti <sup>23b,23a</sup>, F. Siegert <sup>46</sup>, Dj. Sijacki <sup>16</sup>,  
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 K. Smolek <sup>139</sup>, A. Smykiewicz <sup>82</sup>, A.A. Snesarev <sup>108</sup>, I.M. Snyder <sup>128</sup>, S. Snyder <sup>29</sup>, R. Sobie <sup>173,ae</sup>,  
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 D. Sosa <sup>59b</sup>, C.L. Sotiropoulou <sup>69a,69b</sup>, S. Sottocornola <sup>68a,68b</sup>, R. Soualah <sup>64a,64c,j</sup>, A.M. Soukharev <sup>120b,120a</sup>,  
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 J. Weingarten <sup>45</sup>, M. Weirich <sup>97</sup>, C. Weiser <sup>50</sup>, P.S. Wells <sup>35</sup>, T. Wenaus <sup>29</sup>, T. Wengler <sup>35</sup>, S. Wenig <sup>35</sup>,  
 N. Wermes <sup>24</sup>, M.D. Werner <sup>76</sup>, P. Werner <sup>35</sup>, M. Wessels <sup>59a</sup>, T.D. Weston <sup>20</sup>, K. Whalen <sup>128</sup>,

N.L. Whallon<sup>145</sup>, A.M. Wharton<sup>87</sup>, A.S. White<sup>103</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, R. White<sup>144b</sup>, D. Whiteson<sup>168</sup>, B.W. Whitmore<sup>87</sup>, F.J. Wickens<sup>141</sup>, W. Wiedenmann<sup>178</sup>, M. Wielers<sup>141</sup>, C. Wiglesworth<sup>39</sup>, L.A.M. Wiik-Fuchs<sup>50</sup>, A. Wildauer<sup>113</sup>, F. Wilk<sup>98</sup>, H.G. Wilkens<sup>35</sup>, L.J. Wilkins<sup>91</sup>, H.H. Williams<sup>134</sup>, S. Williams<sup>31</sup>, C. Willis<sup>104</sup>, S. Willocq<sup>100</sup>, J.A. Wilson<sup>21</sup>, I. Wingerter-Seez<sup>5</sup>, E. Winkels<sup>153</sup>, F. Winklmeier<sup>128</sup>, O.J. Winston<sup>153</sup>, B.T. Winter<sup>24</sup>, M. Wittgen<sup>150</sup>, M. Wobisch<sup>93</sup>, A. Wolf<sup>97</sup>, T.M.H. Wolf<sup>118</sup>, R. Wolff<sup>99</sup>, M.W. Wolter<sup>82</sup>, H. Wolters<sup>137a,137c</sup>, V.W.S. Wong<sup>172</sup>, N.L. Woods<sup>143</sup>, S.D. Worm<sup>21</sup>, B.K. Wosiek<sup>82</sup>, K.W. Woźniak<sup>82</sup>, K. Wraight<sup>55</sup>, M. Wu<sup>36</sup>, S.L. Wu<sup>178</sup>, X. Wu<sup>52</sup>, Y. Wu<sup>58a</sup>, T.R. Wyatt<sup>98</sup>, B.M. Wynne<sup>48</sup>, S. Xella<sup>39</sup>, Z. Xi<sup>103</sup>, L. Xia<sup>175</sup>, D. Xu<sup>15a</sup>, H. Xu<sup>58a,e</sup>, L. Xu<sup>29</sup>, T. Xu<sup>142</sup>, W. Xu<sup>103</sup>, B. Yabsley<sup>154</sup>, S. Yacoob<sup>32a</sup>, K. Yajima<sup>130</sup>, D.P. Yallup<sup>92</sup>, D. Yamaguchi<sup>162</sup>, Y. Yamaguchi<sup>162</sup>, A. Yamamoto<sup>79</sup>, T. Yamanaka<sup>160</sup>, F. Yamane<sup>80</sup>, M. Yamatani<sup>160</sup>, T. Yamazaki<sup>160</sup>, Y. Yamazaki<sup>80</sup>, Z. Yan<sup>25</sup>, H.J. Yang<sup>58c,58d</sup>, H.T. Yang<sup>18</sup>, S. Yang<sup>75</sup>, Y. Yang<sup>160</sup>, Z. Yang<sup>17</sup>, W.-M. Yao<sup>18</sup>, Y.C. Yap<sup>44</sup>, Y. Yasu<sup>79</sup>, E. Yatsenko<sup>58c,58d</sup>, J. Ye<sup>41</sup>, S. Ye<sup>29</sup>, I. Yeletsikh<sup>77</sup>, E. Yigitbasi<sup>25</sup>, E. Yildirim<sup>97</sup>, K. Yorita<sup>176</sup>, K. Yoshihara<sup>134</sup>, C.J.S. Young<sup>35</sup>, C. Young<sup>150</sup>, J. Yu<sup>8</sup>, J. Yu<sup>76</sup>, X. Yue<sup>59a</sup>, S.P.Y. Yuen<sup>24</sup>, B. Zabinski<sup>82</sup>, G. Zacharis<sup>10</sup>, E. Zaffaroni<sup>52</sup>, R. Zaidan<sup>14</sup>, A.M. Zaitsev<sup>121,ao</sup>, T. Zakareishvili<sup>156b</sup>, N. Zakharchuk<sup>44</sup>, J. Zalieckas<sup>17</sup>, S. Zambito<sup>57</sup>, D. Zanzi<sup>35</sup>, D.R. Zaripovas<sup>55</sup>, S.V. Zeiβner<sup>45</sup>, C. Zeitnitz<sup>179</sup>, G. Zemaityte<sup>132</sup>, J.C. Zeng<sup>170</sup>, Q. Zeng<sup>150</sup>, O. Zenin<sup>121</sup>, D. Zerwas<sup>129</sup>, M. Zgubič<sup>132</sup>, D.F. Zhang<sup>58b</sup>, D. Zhang<sup>103</sup>, F. Zhang<sup>178</sup>, G. Zhang<sup>58a</sup>, H. Zhang<sup>15c</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>15c</sup>, L. Zhang<sup>58a</sup>, M. Zhang<sup>170</sup>, P. Zhang<sup>15c</sup>, R. Zhang<sup>58a</sup>, R. Zhang<sup>24</sup>, X. Zhang<sup>58b</sup>, Y. Zhang<sup>15d</sup>, Z. Zhang<sup>129</sup>, P. Zhao<sup>47</sup>, X. Zhao<sup>41</sup>, Y. Zhao<sup>58b,129,ak</sup>, Z. Zhao<sup>58a</sup>, A. Zhemchugov<sup>77</sup>, B. Zhou<sup>103</sup>, C. Zhou<sup>178</sup>, L. Zhou<sup>41</sup>, M.S. Zhou<sup>15d</sup>, M. Zhou<sup>152</sup>, N. Zhou<sup>58c</sup>, Y. Zhou<sup>7</sup>, C.G. Zhu<sup>58b</sup>, H.L. Zhu<sup>58a</sup>, H. Zhu<sup>15a</sup>, J. Zhu<sup>103</sup>, Y. Zhu<sup>58a</sup>, X. Zhuang<sup>15a</sup>, K. Zhukov<sup>108</sup>, V. Zhulanov<sup>120b,120a</sup>, A. Zibell<sup>174</sup>, D. Zieminska<sup>63</sup>, N.I. Zimine<sup>77</sup>, S. Zimmermann<sup>50</sup>, Z. Zinonos<sup>113</sup>, M. Zinser<sup>97</sup>, M. Ziolkowski<sup>148</sup>, G. Zobernig<sup>178</sup>, A. Zoccoli<sup>23b,23a</sup>, K. Zoch<sup>51</sup>, T.G. Zorbas<sup>146</sup>, R. Zou<sup>36</sup>, M. Zur Nedden<sup>19</sup>, L. Zwalinski<sup>35</sup>

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany, NY, United States of America

<sup>3</sup> Department of Physics, University of Alberta, Edmonton, AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America

<sup>7</sup> Department of Physics, University of Arizona, Tucson, AZ, United States of America

<sup>8</sup> Department of Physics, University of Texas at Arlington, Arlington, TX, United States of America

<sup>9</sup> Physics Department, National and Kapodistrian University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup> Department of Physics, University of Texas at Austin, Austin, TX, United States of America

<sup>12</sup> (a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (c) Department of Physics, Bogazici University, Istanbul; (d) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

<sup>13</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>14</sup> Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain

<sup>15</sup> (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing;

(d) University of Chinese Academy of Science (UCAS), Beijing, China

<sup>16</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia

<sup>17</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>18</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America

<sup>19</sup> Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany

<sup>20</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>21</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>22</sup> Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia

<sup>23</sup> (a) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; (b) INFN Sezione di Bologna, Italy

<sup>24</sup> Physikalisches Institut, Universität Bonn, Bonn, Germany

<sup>25</sup> Department of Physics, Boston University, Boston, MA, United States of America

<sup>26</sup> Department of Physics, Brandeis University, Waltham, MA, United States of America

<sup>27</sup> (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara, Romania

<sup>28</sup> (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

<sup>29</sup> Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America

<sup>30</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

<sup>31</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

<sup>32</sup> (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

<sup>33</sup> Department of Physics, Carleton University, Ottawa, ON, Canada

<sup>34</sup> (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;

(e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco

<sup>35</sup> CERN, Geneva, Switzerland

- <sup>36</sup> Enrico Fermi Institute, University of Chicago, Chicago, IL, United States of America
- <sup>37</sup> LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- <sup>38</sup> Nevis Laboratory, Columbia University, Irvington, NY, United States of America
- <sup>39</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>40</sup> (a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- <sup>41</sup> Physics Department, Southern Methodist University, Dallas, TX, United States of America
- <sup>42</sup> Physics Department, University of Texas at Dallas, Richardson, TX, United States of America
- <sup>43</sup> (a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm, Sweden
- <sup>44</sup> Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- <sup>45</sup> Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>46</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>47</sup> Department of Physics, Duke University, Durham, NC, United States of America
- <sup>48</sup> SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>49</sup> INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>50</sup> Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- <sup>51</sup> II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- <sup>52</sup> Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- <sup>53</sup> (a) Dipartimento di Fisica, Università di Genova, Genova; (b) INFN Sezione di Genova, Italy
- <sup>54</sup> II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>55</sup> SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>56</sup> LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- <sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States of America
- <sup>58</sup> (a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; (b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; (c) School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; (d) Tsung-Dao Lee Institute, Shanghai, China
- <sup>59</sup> (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>60</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>61</sup> (a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, University of Hong Kong, Hong Kong; (c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>62</sup> Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- <sup>63</sup> Department of Physics, Indiana University, Bloomington, IN, United States of America
- <sup>64</sup> (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>65</sup> (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>66</sup> (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>67</sup> (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>68</sup> (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>69</sup> (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>70</sup> (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>71</sup> (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>72</sup> (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>73</sup> (a) INFN-TIFPA; (b) Università degli Studi di Trento, Trento, Italy
- <sup>74</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- <sup>75</sup> University of Iowa, Iowa City, IA, United States of America
- <sup>76</sup> Department of Physics and Astronomy, Iowa State University, Ames, IA, United States of America
- <sup>77</sup> Joint Institute for Nuclear Research, Dubna, Russia
- <sup>78</sup> (a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; (b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (c) Universidade Federal de São João del Rei (UFSJ), São João del Rei; (d) Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
- <sup>79</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- <sup>80</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>81</sup> (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>82</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- <sup>83</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>84</sup> Kyoto University of Education, Kyoto, Japan
- <sup>85</sup> Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>86</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>87</sup> Physics Department, Lancaster University, Lancaster, United Kingdom
- <sup>88</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>89</sup> Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- <sup>90</sup> School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- <sup>91</sup> Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- <sup>92</sup> Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>93</sup> Louisiana Tech University, Ruston, LA, United States of America
- <sup>94</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden
- <sup>95</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- <sup>96</sup> Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
- <sup>97</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>98</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- <sup>99</sup> CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- <sup>100</sup> Department of Physics, University of Massachusetts, Amherst, MA, United States of America
- <sup>101</sup> Department of Physics, McGill University, Montreal, QC, Canada
- <sup>102</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>103</sup> Department of Physics, University of Michigan, Ann Arbor, MI, United States of America
- <sup>104</sup> Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States of America
- <sup>105</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- <sup>106</sup> Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
- <sup>107</sup> Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- <sup>108</sup> P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- <sup>109</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

- <sup>110</sup> National Research Nuclear University MEPhI, Moscow, Russia  
<sup>111</sup> D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia  
<sup>112</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany  
<sup>113</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany  
<sup>114</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan  
<sup>115</sup> Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan  
<sup>116</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America  
<sup>117</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands  
<sup>118</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands  
<sup>119</sup> Department of Physics, Northern Illinois University, DeKalb, IL, United States of America  
<sup>120</sup> <sup>(a)</sup> Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; <sup>(b)</sup> Novosibirsk State University, Novosibirsk, Russia  
<sup>121</sup> Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia  
<sup>122</sup> Department of Physics, New York University, New York, NY, United States of America  
<sup>123</sup> Ohio State University, Columbus, OH, United States of America  
<sup>124</sup> Faculty of Science, Okayama University, Okayama, Japan  
<sup>125</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America  
<sup>126</sup> Department of Physics, Oklahoma State University, Stillwater, OK, United States of America  
<sup>127</sup> Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic  
<sup>128</sup> Center for High Energy Physics, University of Oregon, Eugene, OR, United States of America  
<sup>129</sup> LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France  
<sup>130</sup> Graduate School of Science, Osaka University, Osaka, Japan  
<sup>131</sup> Department of Physics, University of Oslo, Oslo, Norway  
<sup>132</sup> Department of Physics, Oxford University, Oxford, United Kingdom  
<sup>133</sup> LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France  
<sup>134</sup> Department of Physics, University of Pennsylvania, Philadelphia, PA, United States of America  
<sup>135</sup> Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia  
<sup>136</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America  
<sup>137</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP; <sup>(b)</sup> Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Departamento de Física, Universidade de Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain; <sup>(g)</sup> Dep Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal  
<sup>138</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic  
<sup>139</sup> Czech Technical University in Prague, Prague, Czech Republic  
<sup>140</sup> Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic  
<sup>141</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom  
<sup>142</sup> IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France  
<sup>143</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States of America  
<sup>144</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile  
<sup>145</sup> Department of Physics, University of Washington, Seattle, WA, United States of America  
<sup>146</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom  
<sup>147</sup> Department of Physics, Shinshu University, Nagano, Japan  
<sup>148</sup> Department Physik, Universität Siegen, Siegen, Germany  
<sup>149</sup> Department of Physics, Simon Fraser University, Burnaby, BC, Canada  
<sup>150</sup> SLAC National Accelerator Laboratory, Stanford, CA, United States of America  
<sup>151</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden  
<sup>152</sup> Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States of America  
<sup>153</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom  
<sup>154</sup> School of Physics, University of Sydney, Sydney, Australia  
<sup>155</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan  
<sup>156</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia  
<sup>157</sup> Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel  
<sup>158</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel  
<sup>159</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece  
<sup>160</sup> International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan  
<sup>161</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan  
<sup>162</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan  
<sup>163</sup> Tomsk State University, Tomsk, Russia  
<sup>164</sup> Department of Physics, University of Toronto, Toronto, ON, Canada  
<sup>165</sup> <sup>(a)</sup> TRIUMF, Vancouver, BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto, ON, Canada  
<sup>166</sup> Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan  
<sup>167</sup> Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America  
<sup>168</sup> Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America  
<sup>169</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden  
<sup>170</sup> Department of Physics, University of Illinois, Urbana, IL, United States of America  
<sup>171</sup> Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain  
<sup>172</sup> Department of Physics, University of British Columbia, Vancouver, BC, Canada  
<sup>173</sup> Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada  
<sup>174</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany  
<sup>175</sup> Department of Physics, University of Warwick, Coventry, United Kingdom  
<sup>176</sup> Waseda University, Tokyo, Japan  
<sup>177</sup> Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel  
<sup>178</sup> Department of Physics, University of Wisconsin, Madison, WI, United States of America  
<sup>179</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany  
<sup>180</sup> Department of Physics, Yale University, New Haven, CT, United States of America  
<sup>181</sup> Yerevan Physics Institute, Yerevan, Armenia

<sup>a</sup> Also at Borough of Manhattan Community College, City University of New York, NY, United States of America.

<sup>b</sup> Also at California State University, East Bay, United States of America.

<sup>c</sup> Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

- <sup>d</sup> Also at CERN, Geneva, Switzerland.
- <sup>e</sup> Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
- <sup>f</sup> Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
- <sup>g</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
- <sup>h</sup> Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.
- <sup>i</sup> Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.
- <sup>j</sup> Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
- <sup>k</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
- <sup>l</sup> Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, United States of America.
- <sup>m</sup> Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
- <sup>n</sup> Also at Department of Physics, California State University, Fresno CA, United States of America.
- <sup>o</sup> Also at Department of Physics, California State University, Sacramento CA, United States of America.
- <sup>p</sup> Also at Department of Physics, King's College London, London, United Kingdom.
- <sup>q</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- <sup>r</sup> Also at Department of Physics, Stanford University, United States of America.
- <sup>s</sup> Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
- <sup>t</sup> Also at Department of Physics, University of Michigan, Ann Arbor MI, United States of America.
- <sup>u</sup> Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
- <sup>v</sup> Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
- <sup>w</sup> Also at Graduate School of Science, Osaka University, Osaka, Japan.
- <sup>x</sup> Also at Hellenic Open University, Patras, Greece.
- <sup>y</sup> Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
- <sup>z</sup> Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
- <sup>aa</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
- <sup>ab</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- <sup>ac</sup> Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
- <sup>ad</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- <sup>ae</sup> Also at Institute of Particle Physics (IPP), Canada.
- <sup>af</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- <sup>ag</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- <sup>ah</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
- <sup>ai</sup> Also at Instituto de Física Teórica de la Universidad Autónoma de Madrid, Spain.
- <sup>aj</sup> Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
- <sup>ak</sup> Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
- <sup>al</sup> Also at Louisiana Tech University, Ruston LA, United States of America.
- <sup>am</sup> Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.
- <sup>an</sup> Also at Manhattan College, New York NY, United States of America.
- <sup>ao</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- <sup>ap</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia.
- <sup>aq</sup> Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey.
- <sup>ar</sup> Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
- <sup>as</sup> Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
- <sup>at</sup> Also at The City College of New York, New York NY, United States of America.
- <sup>au</sup> Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
- <sup>av</sup> Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- <sup>aw</sup> Also at TRIUMF, Vancouver BC, Canada.
- <sup>ax</sup> Also at Università di Napoli Parthenope, Napoli, Italy.
- \* Deceased.