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

**A B S T R A C T**

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 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 $(\sigma_H/\sigma_{SM}) \times B(\mu\mu)$, ranging from $2.0 \times 10^{-4}$ to $8.4 \times 10^{-4}$ in the $b$-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, $\sigma(\mu\mu) \times B(X \rightarrow bb\mu\mu)$, ranging from 0.1 fb to 0.73 fb for $m_{\mu\mu}$ between 18 and 62 GeV.

© 2018 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP3.

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 $(B)$ 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 $O(10^{-2})$ can lead to $O(10\%)$ branching ratio into BSM states. This potentially large $B(H \rightarrow$ 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 $m_a \geq 10$ 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 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 $(\sigma_H/\sigma_{SM}) \times B(\mu\mu)$ between $2 \times 10^{-4}$ and $8 \times 10^{-4}$ in the $b$-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 $(\sigma_H/\sigma_{SM}) \times B(\mu\mu)$ 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 $bb\mu\mu$ final state, setting the up-
per limits on \((\sigma_{\tilde{t}}/\sigma_{\tilde{t}\tilde{t}}) \times B(H \to \tilde{t}a)\) 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 fb\(^{-1}\) dataset of proton–proton collisions at a centre-of-mass energy of \(\sqrt{s} = 13\) 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.\(^1\) 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 \(bb\tilde{\mu}\tilde{\nu}\) 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-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 \(m_h = 20–60\) 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 \(Z^{\pm}/\gamma^* +\) jets and W + 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 \(h_{\text{hemp}}\) in POWHEG, used to regulate the high-\(p_T\) radiation, was set to \(h_{\text{hemp}}\) 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 \(t\bar{t}W\)) 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 NNLO 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 \(p_T > 7\) 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 \(\sigma_d\), \(|d_0/\sigma_d|\), must be less than 3. Finally, the selected muons must fulfill 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 [68]. These requirements select signal muons with an identification efficiency of \(\sim 94\%\) and isolation efficiency ranging between \(\sim 91\%\) for \(m_h = 20\) GeV and \(\sim 95\%\) for \(m_h = 60\) GeV.

Jets are reconstructed using the anti-\(k_T\) 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 \(p_T > 20\) 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 \(p_T > 500\) 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 the 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 \(p_T > 20\) GeV and exactly two reconstructed muons of opposite charge, with the leading muon having \(p_T > 27\) GeV to be in the maximum-efficiency regime of the trigger and the subleading muon having \(p_T > 7\) 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

\(^1\) 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 \(\eta\) as \(\eta = -\ln \tan(\theta/2)\). Angular distance is measured in units of \(\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}\).
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 $H \to aa$ 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 ($m_{b\mu\mu}$) being approximately 125 GeV. One side of the $H \to aa$ decay ($a \to \mu\mu$) is measured with approximately ten times better resolution than the other side of the decay ($a \to bb$), as shown in Figs. 1(a) and 1(b).

A kinematic-likelihood (KL) fit [74] exploiting the symmetry of $H \to aa$ decays is performed to test the compatibility of an event with the $m_{bb} \approx m_{\mu\mu}$ hypothesis and improve the $m_{b\mu\mu}$ 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,

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

where $m_{bb}^{2}$ 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 $F_{BW}$ 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 $m_{b\mu\mu}^{KL}$. As seen in Fig. 1(d), the resolution of the $m_{b\mu\mu}^{KL}$ distribution for the signal is improved by up to a factor of two compared to the pre-fit $m_{b\mu\mu}$ shown in Fig. 1(c), while the background shape within the $m_{b\mu\mu}$ 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: $|m_{b\mu\mu}^{KL} - m_{\mu\mu}| < 15$ GeV and $\ln(L_{\text{max}}) > -8$. Finally, the kinematic $p_T^{\text{miss}} < 60$ 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.
centred around the hypothesised \( m_b \). 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 \( E_T^{\text{miss}} \geq 60 \) 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 \( b\bar{b}q\bar{q} \) invariant mass after the KL fit is inverted to \( 80 < m_{b\mu\mu}^{\text{KL}} < 110 \) GeV or \( 140 < m_{b\mu\mu}^{\text{KL}} < 170 \) 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 \( b\bar{b}q\bar{q} \) invariant mass distribution, \( 170 < m_{b\mu\mu}^{\text{KL}} < 300 \) 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 \( m_{b\mu} \) and \( m_{b\mu\mu} \), 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 using 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 AM@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: ~18% and ~16%, respectively. Systematic uncertainties in the mod-
gh× 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 PERUGIA2012dradH 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 $\hat{h}_{\text{amp}}$ set to $2 \times m_{t}$. The second sample, using the PERUGIA2012radLo tune, has $\hat{h}_{\text{amp}} = m_{t}$ 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 $\bar{t}t$ 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 $\bar{t}t$ 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 $p_{T}$ 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.

### 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 25% in at least one $m_{\mu\mu}$ bin.

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

### 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–Yang 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 settings.
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 CLs prescription \([79,80]\). A series of profile likelihood fits is applied to the data in order to test 36 hypotheses for the \( m_0 \) 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 \( m_0 \) hypothesis under test and on the expected and measured yields in the TCR and DYC. 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 \((\sigma_{\text{obs}}/\sigma_{\text{MC}}) \times B(H \rightarrow aa \rightarrow bb\mu\mu)\) 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 \( 20 \leq m_0 \leq 60 \text{ GeV} \) range for which the signal samples were simulated and range between \( 2 \times 10^{-4} \) and \( 10^{-7} \) (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 \( m_{\mu\mu} \sim m_{\mu\mu} \)) and the four-object invariant mass constraint \( m_{\text{HH}} \sim m_{\mu\mu} \), \( \sigma_{\text{obs}}(X) \times B(X \rightarrow bb\mu\mu) \). The visible cross-section is defined as the product of the production cross-section and acceptance \( \times \) efficiency \( (\sigma_{\text{obs}}(X) = \sigma_{\text{prod}}(X) \times \epsilon_X) \) 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.

<table>
<thead>
<tr>
<th>( m_{\mu\mu} ) bin [GeV]</th>
<th>[19–21]</th>
<th>[29–31]</th>
<th>[39–41]</th>
<th>[48–52]</th>
<th>[58–62]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>6</td>
<td>6</td>
<td>16</td>
<td>48</td>
<td>29</td>
</tr>
<tr>
<td>Total background</td>
<td>4.84 ± 0.97</td>
<td>7.8 ± 1.2</td>
<td>13.7 ± 2.2</td>
<td>37.9 ± 5.1</td>
<td>30.8 ± 4.2</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>0.96 ± 0.29</td>
<td>3.08 ± 0.74</td>
<td>6.6 ± 1.5</td>
<td>18.1 ± 4.3</td>
<td>14.8 ± 3.3</td>
</tr>
<tr>
<td>DY</td>
<td>3.88 ± 0.92</td>
<td>4.5 ± 1.1</td>
<td>7.1 ± 1.7</td>
<td>19.0 ± 4.5</td>
<td>15.5 ± 3.6</td>
</tr>
<tr>
<td>Dibosons</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>0.02 ± 0.04</td>
<td>0.26 ± 0.16</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Single top</td>
<td>&lt; 0.01</td>
<td>0.2 ± 0.2</td>
<td>&lt; 0.01</td>
<td>0.65 ± 0.97</td>
<td>0.09 ± 0.19</td>
</tr>
<tr>
<td>( t\bar{t} \nu )</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>0.01 ± 0.04</td>
<td>0.05 ± 0.03</td>
</tr>
</tbody>
</table>

Fig. 6. The (a) observed and expected upper limits at the 95% confidence level on \( \mathcal{B}(H \to aa \to bb_{\mu\mu}) \) 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 \( \sigma_{\nu\nu}(X) \times \mathcal{B}(X \to bb_{\mu\mu}) \).

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 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 \( 18 \) GeV \( \leq m_{\mu\mu} \leq 62 \) 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 \( \sigma_{\nu\nu}(X) \times \mathcal{B}(H \to aa \to bb_{\mu\mu}) \) and range between \( 1.2 \times 10^{-4} \) and \( 8.4 \times 10^{-4} \), depending on \( m_{\nu} \). In Type-III 2HDM+S scenario with \( \tan \beta = 2 \) these limits translate into upper limits on \( \sigma_{\nu\nu}(X) \times \mathcal{B}(H \to aa) \) ranging between 7% and 47%.

The same analysis, implementing all selection criteria including \( m_{bb} \sim m_{\mu\mu} \) and \( m_{bb_{\mu\mu}} \sim m_{H} \) 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 \( \sigma_{\nu\nu}(X) \times \mathcal{B}(X \to bb_{\mu\mu}) \), ranging from 0.1 fb to 0.73 fb, depending on the dimuon mass.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MINE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR, MESTD, Serbia; MSSR, Slovakia; ARRS and MIZS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST; TI, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, Canarie, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne.
and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristea programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [81].

References


1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Department of Physics, SUNY Albany, Albany, NY, United States of America
3 Department of Physics, University of Alberta, Edmonton, AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydın University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America
7 Department of Physics, University of Arizona, Tucson, AZ, United States of America
8 Department of Physics, University of Texas at Arlington, Arlington, TX, United States of America
9 Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Department of Physics, University of Texas at Austin, Austin, TX, United States of America
12 (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, Boğaziçi University, Istanbul; (d) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14 Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15 (a) Department 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 Sciences (UCAS), Beijing, China
16 Institute of Physics, University of Belgrade, Belgrade, Serbia
17 Department for Physics and Technology, University of Bergen, Bergen, Norway
18 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America
19 Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
20 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
21 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
22 Centro de Investigaciones, Universidad Antonio Narbigh, Bogota, Colombia
23 (a) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; (b) INFN Sezione di Bologna, Italy
24 Physikalisches Institut, Universität Bonn, Bonn, Germany
25 Department of Physics, Boston University, Boston, MA, United States of America
26 Department of Physics, Brandeis University, Waltham, MA, United States of America
27 Transliamnia University of Brasov, Brasov; (a) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (b) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timișoara, Timișoara, Romania
28 (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
29 Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America
30 Department of Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
32 (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
33 Department of Physics, Carleton University, Ottawa, ON, Canada
34 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies – Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires (CENSTEN), Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakesh; (d) Faculté des Sciences, Université Mohamed Premier et LPTPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
35 CERN, Geneva, Switzerland