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Keywords: BSM Higgs Boson, ATLAS

1. Introduction

After the discovery of a Higgs boson at the LHC in 2012 [1, 2], one of the most important remaining questions is whether the newly discovered particle is part of an extended scalar sector. A CP-odd Higgs boson, A, appears in many models with an extended scalar sector, e.g. in the case of the two-Higgs-doublet model (2HDM) [3].

The addition of a second Higgs doublet leads to five Higgs bosons after the electroweak symmetry breaking. The phenomenology of such a model is very rich and depends on the vacuum expectation values of the Higgs doublets, the CP properties of the Higgs potential and the values of its parameters and the Yukawa couplings of the Higgs doublets with the fermions. In general, it is possible to accommodate in the model a Higgs boson compatible to the one discovered at the LHC. In the case where the Higgs potential of the 2HDM is CP-conserving, the Higgs bosons after electroweak symmetry breaking are two CP-even (h and H), one CP-odd (A) and two charged ($H^{\pm}$) Higgs bosons. Many theories beyond the Standard Model (SM) include a second Higgs doublet, such as the minimal supersymmetric SM (MSSM) [4–8], axion models (e.g. Ref. [9]) and baryogenesis models (e.g. Ref. [10]). Searches for a CP-odd Higgs boson are reported in Refs. [11–14].

In this Letter, a search for a heavy, CP-odd Higgs boson decaying into a Z boson and the ∼125 GeV Higgs boson, h, is described. The $A \to Zh$ decay rate can be dominant for part of the 2HDM parameter space, especially for an A boson mass, m_A, below the $t\bar{t}$ threshold. In this case, the A boson is produced mainly via gluon fusion and its natural width is typically small: $\Gamma_A/m_A \lesssim \mathcal{O}(1\%)$.

The search is performed for m_A in the range 220 to 1000 GeV, reconstructing $Z \to \ell\ell$ decays (where $\ell = e, \mu$) with $h \to bb$ or $h \to \tau\tau$, as well as $Z \to \nu\nu$ with $h \to bb$. The reconstructed invariant mass (or transverse mass) of the Zh pair, employing the measured value of the h boson mass, m_h, to improve its resolution, is used to search for a signal.

2. Data and simulated samples

The data used in this search were recorded with the ATLAS detector in proton–proton collisions at a centre-of-mass energy of 8 TeV. The ATLAS detector is described in detail elsewhere [15]. The integrated luminosity of the data sample, selecting only periods where all relevant detector subsystems were operational, is 20.3 ± 0.6 fb^{-1} [16]. The data used in the $\ell\ell\tau\tau$ and $\ell\ell bb$ final states were collected using a combination of single-electron, single-muon, dielectron (ee) and dimuon ($\mu\mu$) triggers. Depending on the trigger choice, the p_{T}[1] thresholds vary from 24 to 60 GeV for the single-electron and single-muon triggers, and from 12 to 13 GeV for the ee and $\mu\mu$ triggers. The data used in the $\nu\nu bb$ final state were collected with a missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) trigger with a threshold of $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV.

Signal events from a narrow-width A boson produced via gluon fusion are generated with `MadGraph5` [17] for all final states considered in this search. The parton showering is performed with `PYTHIA8` [18, 19].

The production of W and Z bosons in association with jets is simulated with `SHERPA` [20]. Top-quark pair and single top-quark production is simulated with `POWHEG` [21–23] and `AcerMC` [24]. Production of WW, WZ, and ZZ dibosons are simulated using `POWHEG`. The WZ and ZZ processes include the production of off-shell Z bosons (Z^*) and photons ($\gamma*$). Finally, the production of the SM Higgs boson in association with a Z boson is considered as a background in this search. It is simulated using `PYTHIA8`.

The `CTEQ6L1` [25] set of parton distribution functions was used for samples generated with `MadGraph5` and PYTHIA8. The `CT10` [26] set was used for the other samples.

All generated samples are passed through the GEANT4-based [27] detector simulation of the ATLAS detector [28]. The simulated events are overlaid with minimum-bias events, to account for the effect of multiple interactions occurring in the same and neighbouring bunch crossings ("pile-up"). The events are reweighted so that the average number of interactions per bunch crossing agrees with the data.

3. Object reconstruction

Electrons are identified from energy clusters in the electromagnetic calorimeter that are matched to tracks in the inner detector [29]. Electrons are required to have $|\eta| < 2.47$ and $p_{\mathrm{T}} > 7$ GeV. Isolation requirements, defined in terms of the calorimetric energy or the p_{T} of tracks within cones around the object, as well as quality requirements are applied to distinguish electrons from jets.

Muons are reconstructed by matching tracks reconstructed in the inner detector to tracks or track segments in the muon spectrometer systems [30]. The muon acceptance is extended to the region $2.5 < |\eta| < 2.7$, which is outside the inner detector coverage, using only tracks reconstructed in the forward part of the muon detector. Muons used for this search must have $|\eta| < 2.7$, $p_{\mathrm{T}} > 6$ GeV and are also required to pass isolation requirements.

Jets are reconstructed using the anti-k_t algorithm [31] with radius parameter $R = 0.4$ and $p_{\mathrm{T}} >$ 20 GeV ($p_{\mathrm{T}} > 30$ GeV) for $|\eta| < 2.5$ ($2.5 < |\eta| < 4.5$). Low-p_{T} jets from pile-up are rejected with a requirement on the scalar sum of the p_{T} of the tracks associated with the jet: for jets with $|\eta| < 2.4$ and $p_{\mathrm{T}} < 50$ GeV, tracks associated with the primary vertex[2] must contribute over 50% to the sum. Jets from the decay of long-lived heavy-flavour hadrons are selected using a multivariate tagging algorithm (b-tagging) [32]. The b-tagging efficiency is 70% for jets from b-quarks in a sample of simulated $t\bar{t}$ events.

Hadronic decays of τ leptons (τ_{had}) [33] are reconstructed starting from clusters of energy in the calorimeter. A τ_{had} candidate must lie within $|\eta| < 2.47$, have a transverse momentum greater than 20 GeV, one or three associated tracks and a total charge of ± 1. Information on the collimation, isolation, and shower profile is combined into a multivariate discriminant to reduce backgrounds from quark- or gluon-initiated jets. Dedicated algorithms that reduce the number of electrons and muons misidentified as hadronic τ decays are applied. In this analysis, two τ_{had} identification selections are used —"loose" and "medium"— with efficiencies of about 65% and 55%, respectively.

The missing transverse momentum ($\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$) is computed using fully calibrated and reconstructed physics objects, as well as clusters of calorimeter-cell energy deposits that are not associated with any object [34]. In addition, a track-based missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\mathrm{\,miss}}$) is calculated as the negative vector sum of the transverse momenta of tracks with $|\eta| < 2.4$ and associated with the primary vertex.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Transverse momenta are computed from the three-momenta, $\vec{p}$, as $p_{\mathrm{T}} = |\vec{p}|\sin\theta$.

[2] The primary vertex is taken to be the reconstructed vertex with the highest Σp_{T}^2 of the associated tracks.

4. Search for $A \to Zh$ with $h \to \tau\tau$

In the search for $A \to Zh \to \ell\ell\tau\tau$, three channels are considered, distinguished by the way the $\tau\tau$ pair decays: two τ leptons decaying hadronically ($\tau_{\text{had}}\tau_{\text{had}}$), one leptonic and one hadronic decay ($\tau_{\text{lep}}\tau_{\text{had}}$) and, finally, two leptonic decays ($\tau_{\text{lep}}\tau_{\text{lep}}$). Electrons in the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels are rejected in the transition region between the barrel and end-cap of the detector ($1.37 < |\eta| < 1.52$). Muons in the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels are considered only for $|\eta| < 2.5$.

The resolution of the reconstructed A boson mass is improved using a mass-difference variable,

$$m_A^{\text{rec}} = m_{\ell\ell\tau\tau} - m_{\ell\ell} - m_{\tau\tau} + m_Z + m_h,$$

where m_Z is the mass of the Z boson, $m_h = 125$ GeV is the mass of the CP-even Higgs boson, $m_{\ell\ell}$ is the invariant mass of the two leptons associated with the Z boson decay, and $m_{\ell\ell\tau\tau}$ denotes the $\ell\ell\tau\tau$ invariant mass. The value of $m_{\tau\tau}$, the invariant mass of the τ's, is estimated with the Missing Mass Calculator (MMC) [35]. The mass resolution for all $\tau\tau$ channels ranges from 3% at $m_A = 220$ GeV to 5% at $m_A = 1$ TeV.

4.1. $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$

Events in the $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$ channel are required to contain exactly two opposite-sign charge leptons $\ell\ell$ (ee or $\mu\mu$) and exactly two opposite-sign charge τ_{had}. The p_{T} requirements for these objects are $p_{\text{T}} > 26$ GeV (15 GeV) for the leading (subleading) electron, $p_{\text{T}} >$ 25–36 GeV (10 GeV) for the leading (subleading) muon, depending on the trigger, and $p_{\text{T}} > 35$ GeV (20 GeV) for the leading (subleading) τ_{had} candidates. The τ_{had} candidates are required to satisfy the "loose" τ_{had} identification criterion. In addition, the $ee/\mu\mu$ invariant mass and the $\tau\tau$ invariant mass have to lie in the ranges $80 < m_{\ell\ell} < 100$ GeV and $75 < m_{\tau\tau} < 175$ GeV. Finally, the p_{T} of the $\ell\ell$ pair, p_{T}^Z, is required to be:

$$p_{\text{T}}^Z > \begin{cases} 125 \text{ GeV}, \text{ if } m_A^{\text{rec}} > 400 \text{ GeV} \\ 0.64 \times m_A^{\text{rec}} - 131 \text{ GeV}, \text{ otherwise.} \end{cases}$$

This requirement maximizes the sensitivity over the whole explored A mass range. In the region of $p_{\text{T}}^Z > 125$ GeV, there is little background present, so tightening the requirement results in no additional increase in sensitivity. The total acceptance times selection efficiency varies from 6.2%, for $m_A = 220$ GeV, to around 18% for the highest A boson masses considered.

The dominant background for this channel originates from events where one or both of the τ_{had}'s is a misidentified jet ("fake-τ_{had} background"). This background is dominated by Z+jets events, with small contributions from dibosons and events with top quarks, and it is estimated using a template method. The shape of the fake-τ_{had} background is taken from a control region (the "template region") that contains events satisfying all the $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$ selection criteria apart from the requirements for an opposite-sign charge $\tau_{\text{had}}\tau_{\text{had}}$ pair and the τ_{had} identification criteria. The fake-τ_{had} background is normalized by using two additional control regions. The first region, "A", contains events that satisfy the *signal* selection criteria, with the exception that the $m_{\tau\tau}$ constraint is inverted, i.e. $m_{\tau\tau} < 75$ GeV or $m_{\tau\tau} > 175$ GeV. The second region, "B", contains events that satisfy all the *template* selection criteria, with the exception that the $m_{\tau\tau}$ constraint is inverted, as in the region "A" definition. The ratio of the number of events in "A" to the number of events in "B" is used to scale the template region events in order to obtain the normalization of the fake-τ_{had} background.

In addition to the fake-τ_{had} background, there are also contributions from backgrounds with real $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$ objects in the event. These backgrounds come primarily from $ZZ^{(*)}$ production[3]. SM Higgs boson production in association with a Z boson is estimated using simulation, and contributes 17% of the total background.

4.2. $\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$

Events in the $\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$ channel are required to contain exactly three light leptons, $\mu\mu\mu$, $e\mu\mu$, $ee\mu$ or eee, and exactly one τ_{had}. The p_{T} requirements for these objects are $p_{\text{T}} > 26$ GeV (15 GeV) for the leading (remaining) electron(s), $p_{\text{T}} >$ 25–36 GeV (10 GeV) for the leading (remaining) muon(s), depending on the trigger, and $p_{\text{T}} > 20$ GeV for the τ_{had}. Subsequently, all the possible $\ell\ell$ pairs that are composed of opposite-sign charge, same-flavour leptons are selected. From these pairs, the pair that has the invariant mass closest to m_Z is considered to be the lepton pair from the Z boson decay. The third light lepton is considered to be the leptonic τ decay, and it is used along with the τ_{had} to define the $\tau_{\text{lep}}\tau_{\text{had}}$ pair. This light lepton is required

[3] The notation $ZZ^{(*)}$ is used here to include ZZ, $ZZ^\star$ and $Z\gamma^\star$

to have opposite-sign charge with respect to the τ_{had}. In addition, the τ_{had} is required to satisfy the "medium" τ_{had} identification requirement, and $m_{\ell\ell}$ and $m_{\tau\tau}$ have to lie in the ranges $80 < m_{\ell\ell} < 100$ GeV and $75 < m_{\tau\tau} < 175$ GeV. The total acceptance times selection efficiency varies from 6% for $m_A = 220$ GeV, to around 17% for the highest A boson masses considered.

About half of the total background for this channel comes from events where the τ_{had} and/or the light lepton is a misidentified jet ("fake-τ/ℓ background"). This background is dominated by diboson and Z+jets events and it is estimated using a template method. The shape of the fake-τ/ℓ background is taken from a control region (the "template region") that contains events satisfying all $\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$ selection criteria, apart from requiring "medium" τ_{had} identification criterion and opposite-sign charge for the $\tau_{\text{lep}}\tau_{\text{had}}$ pair. The fake-τ/ℓ background is normalized by using two additional control regions, defined similarly to those in the $\ell\ell\tau_{\text{had}}\tau_{\text{had}}$ channel.

The other half of the background comes from events with real $\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$ objects in the event. These backgrounds come primarily from $ZZ^{(*)}$ production. There is also a small (11%) contribution from the SM Higgs production in association with a Z boson, which is estimated using simulation.

4.3. $\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$

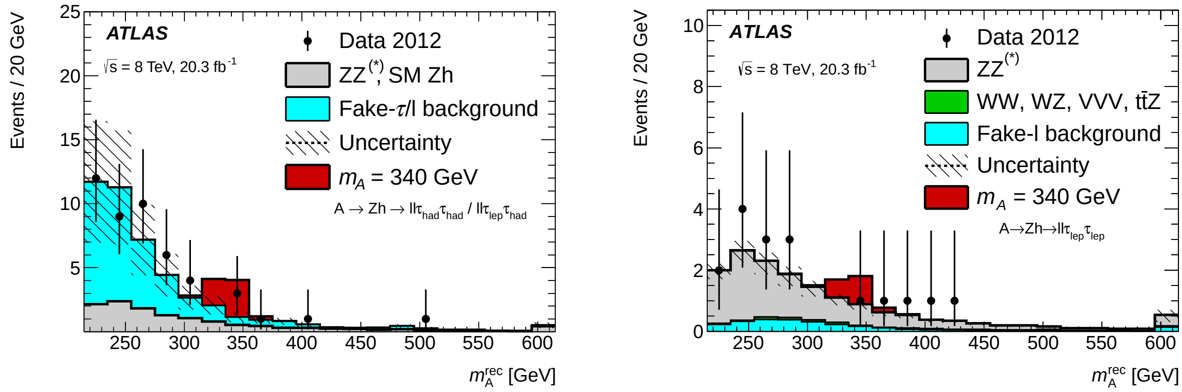
Events in the $\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$ channel are required to contain at least four leptons, which form one same-flavour and opposite-sign charge pair consistent with the Z mass ($80 < m_{\ell\ell} < 100$ GeV), and either a same-flavour or different-flavour pair with an invariant mass reconstructed with the MMC algorithm, consistent with a decay from the CP-even Higgs boson ($90 < m_{\tau\tau} < 190$ GeV). One muon is allowed to be reconstructed in the forward region ($2.5 < |\eta| < 2.7$) of the muon spectrometer, or to be identified in the calorimeter with $p_{\text{T}} > 15$ GeV and $|\eta| < 0.1$ [30]. The highest-p_{T} lepton must satisfy $p_{\text{T}} > 20$ GeV, and the second (third) lepton in p_{T} order must satisfy $p_{\text{T}} > 15$ GeV ($p_{\text{T}} > 10$ GeV). Among all the possible lepton quadruplets in an event the one minimizing the sum of the mass differences with respect to both the Z and h bosons is chosen.

Two different analysis categories are defined based on the lepton flavours in the Higgs boson decay: ee or $\mu\mu$ (SF), and $e\mu$ (DF). The expected background is very different in the two cases. For the SF channel, the background is dominated by $ZZ^{(*)}$ production with $Z \to ee/\mu\mu$ decays. For the DF channel, the main background is from the $ZZ^{(*)}$ process through the $Z \to \tau_{\text{lep}}\tau_{\text{lep}}$ decay chain, but other backgrounds are also important. The signal-to-noise ratio in the SF category is improved by using a set of requirements specifically targeted to suppress the main $ZZ^{(*)}$ background. First, a veto on the on-shell production of Z boson pairs is introduced, requiring the invariant mass of the h boson leptons to lie outside the Z peak: $m_h < 80$ GeV or $m_h > 100$ GeV. Background events are characterized by low missing transverse momentum and are further rejected by requiring $E_{\text{T}}^{\text{miss}} > 30$ GeV, and the azimuthal angle between the $E_{\text{T}}^{\text{miss}}$ direction and the Z boson transverse momentum to be greater than $\pi/2$. Furthermore, a requirement that the highest-p_{T} lepton of the $\ell\ell$ pair associated with the h boson has $p_{\text{T}} > 15$ GeV is applied, since it is found to be effective against backgrounds from Z+jets production. The total acceptance times selection efficiency varies from 6.5% (1.5%) for DF (SF) channel for $m_A = 220$ GeV, to around 20% for both channels for the highest A boson masses considered.

The subleading contributions to the background are from diboson and triboson production, $t\bar{t}$ production in association with a Z boson, and SM Higgs boson production. All these are determined from simulation and amount to about 95% (65%) of the total background in the SF (DF) category. The other background events have at least one lepton which is a misidentified jet or a lepton from a heavy-flavour quark decay and are dominated by Z+jets production, with a smaller contribution from top-quark production. These backgrounds are estimated using a control region where one or both of the leptons in the $\ell\ell$ pair associated with the $h \to \tau_{\text{lep}}\tau_{\text{lep}}$ decay fail to satisfy the isolation criteria. After subtraction of genuine sources of four-lepton events using simulation, the data are extrapolated to the *isolated* signal region using normalization factors derived from simulated samples.

4.4. Systematic uncertainties and results

The most important systematic uncertainty for the backgrounds with real $\ell\ell\tau\tau$ objects in the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{lep}}$ channels comes from the uncertainty on the theoretical cross sections used in the normalization. They are due to the parton distribution function choice, the renormalization and factorization scales, as well as the α_{S} value. This



(a) $\ell\ell\tau_{\rm lep}\tau_{\rm had} + \ell\ell\tau_{\rm had}\tau_{\rm had}$

(b) $\ell\ell\tau_{\rm lep}\tau_{\rm lep}$

Fig. 1. Distributions of the reconstructed A boson mass for the combined $\ell\ell\tau_{\rm had}\tau_{\rm had}$ and $\ell\ell\tau_{\rm lep}\tau_{\rm had}$ final states (a) and the $\ell\ell\tau_{\rm lep}\tau_{\rm lep}$ final states (b). The signal shown in both cases corresponds to $\sigma(gg \to A) \times {\rm BR}(A \to Zh) \times {\rm BR}(h \to \tau\tau) = 50$ fb with $m_A = 340$ GeV. The background contributions shown are the results of simulation and data-driven estimation methods. The background uncertainty is shown as a hatched area, and the overflow is included in the last bin.

amounts to an uncertainty on the normalization of this background of about 5.0% for the $\tau_{\rm lep}\tau_{\rm had}$ channel and 6.4% for $\tau_{\rm lep}\tau_{\rm lep}$. In the $\tau_{\rm had}\tau_{\rm had}$ channel, the largest contributions come from the $\tau_{\rm had}$ identification and energy scale and amounts to 8.9% [33]. The fake-$\tau_{\rm had}/\ell$ background systematic uncertainty for the $\tau\tau$ channels is dominated by the statistical uncertainty on data in control regions used for the background normalization. It amounts to a normalization uncertainty of 38% and 25% for the $\tau_{\rm lep}\tau_{\rm had}$ and $\tau_{\rm had}\tau_{\rm had}$ channels, respectively. For the $\tau_{\rm lep}\tau_{\rm lep}$ channel, the normalization uncertainty is 65% (25%) for the SF (DF) category.

The reconstructed A boson mass distributions for events passing the $\ell\ell\tau_{\rm had}\tau_{\rm had}$, $\ell\ell\tau_{\rm lep}\tau_{\rm had}$ and $\ell\ell\tau_{\rm lep}\tau_{\rm lep}$ selections are shown in Fig. 1. The number of events passing the $\ell\ell\tau\tau$ channel selections are shown in Table 1. The agreement of the expectation with data is very good.

Table 1
The number of predicted and observed events for the $\ell\ell\tau\tau$ channels.

	Expected Background	Data
$\ell\ell\tau_{\rm had}\tau_{\rm had}$	28 ± 6	29
$\ell\ell\tau_{\rm lep}\tau_{\rm had}$	17 ± 4	18
$\ell\ell\tau_{\rm lep}\tau_{\rm lep}$ (SF)	9.5 ± 0.6	10
$\ell\ell\tau_{\rm lep}\tau_{\rm lep}$ (DF)	7.2 ± 0.7	7

5. Search for $A \to Zh$ with $h \to bb$

This section describes the searches in the $A \to Zh \to \ell\ell bb$ and $A \to Zh \to \nu\nu bb$ channels.

5.1. $\ell\ell bb$ selection

Events in the $\ell\ell bb$ channel are selected by requiring either two electrons or two muons. In the case of muons they are required to be of opposite-sign charge. Leptons must have $p_{\rm T} > 7$ GeV, and electrons are restricted to $|\eta| < 2.47$, while muons must have $|\eta| < 2.7$. Tighter acceptance requirements are placed on one of the leptons in each event in order to increase the trigger efficiency and to reduce the multi-jet background, while keeping a high signal acceptance. These requirements are that the leptons have $p_{\rm T} > 25$ GeV, and, if they are muons, satisfy $|\eta| < 2.5$. A dilepton invariant mass window of $83 < m_{\ell\ell} < 99$ GeV is imposed to reduce top-quark and multi-jet backgrounds.

The $h \to bb$ decay is reconstructed by requiring two b-tagged jets with $p_{\rm T} > 45$ GeV (20 GeV) for the leading (subleading) jet. Events with more than two b-tagged jets are removed but all events with one or more additional jets failing b-tagging are retained. The $h \to bb$ decay is selected by requiring that the invariant mass of the two b-tagged jets lies within the range $105 < m_{bb} < 145$ GeV.

The top-quark background, which includes top-quark pair and single top-quark production, is reduced by requiring $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 3.5$ GeV$^{1/2}$, where H_{T} is defined as the scalar sum of the p_{T} of all jets and leptons in the event.

The reconstructed A boson mass, m_A^{rec}, is the invariant mass of the two leptons and two b-tagged jets. In this calculation, the four-momentum of each b-tagged jet is scaled by 125 GeV/m_{bb} in order to improve the resolution. The resulting m_A^{rec} resolution ranges from 2% at $m_A = 220$ GeV to 3% at $m_A = 1$ TeV.

In order to reduce the dominant Z+jets background, a requirement is imposed on the transverse momentum of the Z boson, p_{T}^Z, reconstructed from the two leptons: $p_{\mathrm{T}}^Z > 0.44 \times m_A^{\mathrm{rec}} - 106$ GeV, where m_A is in units of GeV. The requirement depends on m_A^{rec} since the background is generally produced at low p_{T}^Z, whereas the mean p_{T}^Z increases with m_A for the signal. The total acceptance times selection efficiency varies from 7%, for $m_A = 220$ GeV, to around 16% for the highest A boson masses considered.

5.2. $\nu\nu bb$ selection

The event selection in the $\nu\nu bb$ channel follows closely the SM $h \to bb$ analysis in Ref. [36]. Events are selected with $E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV, $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and no electrons or muons with $p_{\mathrm{T}} > 7$ GeV. In addition to the jet selection of the $\ell\ell bb$ analysis, additional restrictions are applied. In order to suppress top-quark background, which is larger than in the $\ell\ell bb$ channel, events are rejected if any of the following conditions is satisfied: there is a jet with $|\eta| > 2.5$; there are four or more jets; one of the b-tagged jets is the third-highest-p_{T} jet. In order to keep a high trigger efficiency, H_{T} is required to be above 120 GeV (150 GeV) for events with two (three) jets. There are also requirements on the separation between the two b-jets in the η–ϕ space, ΔR_{jj}, to suppress Z+jets and W+jets backgrounds as described in Ref. [36]. As in the $\ell\ell bb$ channel, the h boson is selected by requiring $105 < m_{bb} < 145$ GeV.

Additional requirements are imposed on angular quantities sensitive to the presence of neutrinos in order to suppress the multi-jet background: the azimuthal angle between $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$: $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$; the minimum azimuthal angle between $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and any jet $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] > 1.5$; and the azimuthal angle between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the b-jet pair $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, bb) > 2.8$. The total acceptance times selection efficiency varies from 4%, for $m_A = 400$ GeV, to around 7% for the highest A boson masses considered.

It is not possible to accurately reconstruct the invariant mass of the A boson due to the presence of neutrinos in the final state. Therefore, the transverse mass is used as the final discriminant: $m_A^{\mathrm{rec,T}} = \sqrt{(E_{\mathrm{T}}^{bb} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\mathrm{T}}^{\,bb} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$, where E_{T}^{bb} and $\vec{p}_{\mathrm{T}}^{\,bb}$ are the transverse energy and transverse momentum of the b-jet pair system. As in the $\ell\ell bb$ channel, the resolution is improved by scaling each b-tagged jet four-momentum by 125 GeV/m_{bb}.

5.3. Backgrounds

All backgrounds in $\ell\ell bb/\nu\nu bb$ final states are determined from simulation, apart from the multi-jet background, which is determined from data. The multi-jet background in the $\mu\mu bb$ final state is found to be negligible. In the $eebb$ final state, the background is determined by selecting a sample of events with the electron isolation requirement inverted. The sample is normalized by fitting the $m_{\ell\ell}$ distribution. In the $\nu\nu bb$ final state, the multi-jet background is determined by inverting the $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ requirement. The sample is normalized using the region with $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] < 0.4$.

The Z+jets simulated sample is split into different components according to the true flavour of the jets, i.e. $Z + ll$, $Z + cl$, $Z + cc$, $Z + bl$, $Z + bc$ and $Z + bb$, where l denotes a light quark (u, d, s) or a gluon. These components are constrained by defining control samples which have the same selection as the $\ell\ell bb$ final state, but with the requirements on the number of b-tagged jets changed to either zero or one. The samples are further divided into events with two or at least three jets. In order to improve the description of the data, corrections are applied to the simulation as a function of the azimuthal angle between the two leading jets, $\Delta\phi_{jj}$, for $Z + ll$ events and a function of p_{T}^Z for the other components, as described in detail in Ref. [36].

The W+jets background, which contributes significantly only in the $\nu\nu bb$ final state, is split into its components in the same way as the Z+jets sample. It is constrained by defining a sample of events that are selected using the $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers and contain exactly one lepton with $p_{\mathrm{T}} > 25$ GeV and a tightened isolation requirement. The transverse momentum of the lepton and $\vec{E}_T^{miss}$ system (p_T^W) is required to be above 120 GeV to approximately match the phase space of the signal region. The sample is split into events with zero, one or two b-tagged jets and into events with 2 and 3 jets. A correction depending on $\Delta\phi_{jj}$ is applied to $W+ll$ and $W+cl$ events, following studies similar to those performed for the Z+jets background [36].

A correction is made to the p_{T} distribution of $t\bar{t}$ production in the simulation to account for an observed discrepancy with the data [37]. The normalization of top-quark pair production in the $\ell\ell bb$ channel is measured by defining a sample of events with exactly one electron and one muon, one of which has $p_{\mathrm{T}} > 25$ GeV, and two b-tagged jets with $50 < m_{bb} < 180$ GeV.

5.4. Systematic uncertainties and results

The most important experimental systematic uncertainties in the $\ell\ell bb$ and $\nu\nu bb$ final states come from the jet energy scale uncertainty and the b-tagging efficiency.

The jet energy scale systematic uncertainty arises from several sources including uncertainties from the *in situ* calibration, pile-up dependent corrections and the jet flavour composition [38]. In addition, an uncertainty on the jet energy resolution is applied. The jet energy scale and resolution uncertainties are propagated to the $E_{\mathrm{T}}^{\mathrm{miss}}$. The uncertainty on $E_{\mathrm{T}}^{\mathrm{miss}}$ also has a contribution from hadronic energy that is not associated with jets [34].

The b-tagging efficiency uncertainty depends on jet p_{T} and comes mainly from the uncertainty on the measurement of the efficiency in $t\bar{t}$ events [32]. Similar uncertainties are derived for the c-tagging and light-flavour jet tagging [39].

Other experimental systematic uncertainties that are included but have a smaller impact are uncertainties from lepton energy scale and identification efficiency, the efficiency of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and the uncertainty on the multi-jet background estimate, which is taken to be 100% of the estimated number of events.

In addition to the experimental systematic uncertainties, modelling systematic uncertainties are applied, accounting for possible differences between the data and the simulation model used for each process. For the background samples, the procedure described in Ref. [36] is followed. The Z+jets and W+jets backgrounds include uncertainties on the relative fraction of the different flavour components, and on the m_{bb}, $\Delta\phi_{jj}$ and $p_{\mathrm{T}}^{Z}/p_{\mathrm{T}}^{W}$ distributions. For $t\bar{t}$ production, uncertainties on the top-quark transverse momentum, m_{bb}, $E_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{Z}/p_{\mathrm{T}}^{W}$ distributions are included. Uncertainties on the ratio of two-jet to three-jet events are also included for each background.

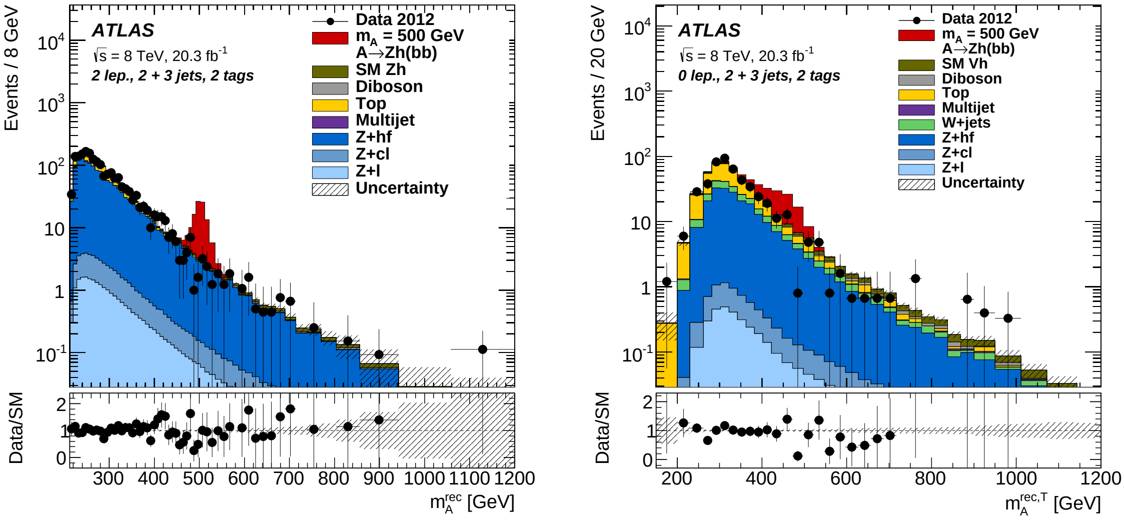
Table 2
Predicted and observed number of events for the $\ell\ell bb$ and $\nu\nu bb$ final states shown after the profile likelihood fit to the data.

	$\ell\ell bb$	$\nu\nu bb$
Z+jets	1443 ± 60	225 ± 11
W+jets	–	55 ± 8
Top	317 ± 28	203 ± 15
Diboson	30 ± 5	10.8 ± 1.6
SM Zh, Wh	31.7 ± 1.8	22.5 ± 1.2
Multi-jet	20 ± 16	3.2 ± 3.1
Total background	1843 ± 34	521 ± 12
Data	1857	511

The m_A^{rec} and $m_A^{\mathrm{rec,T}}$ distributions for events passing the $\ell\ell bb$ and $\nu\nu bb$ final-state selections, respectively, are shown in Fig. 2. The distributions are shown after a profile-likelihood fit, which constraints simultaneously the signal yield and the background normalization and shape, which is performed in the same manner as in Ref. [36]. The overall background is more constrained than the individual components, causing the errors of indvidual components to be anti-correlated. The number of events passing the $\ell\ell bb$ and $\nu\nu bb$ final state selections are shown in Table 2, where the values for the expectations and uncertainties are obtained from the profile-likelihood fit.

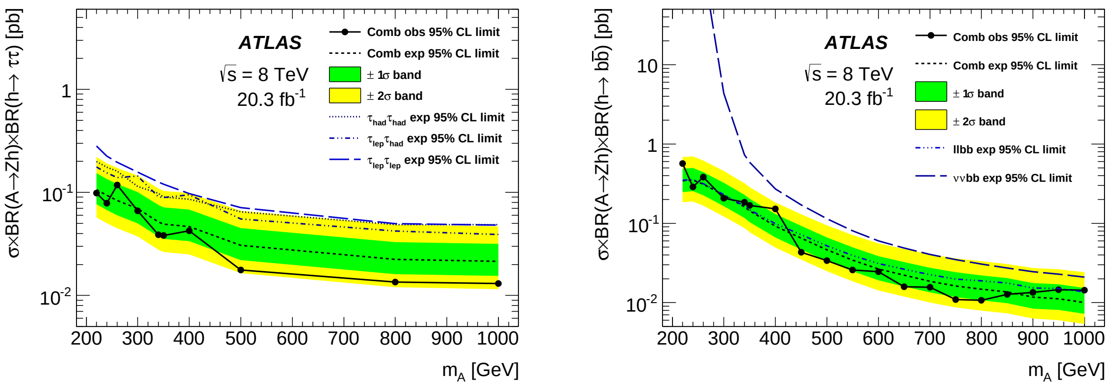
6. Results

In all channels, no significant excess of events is observed in the data compared to the prediction from SM background sources. The significance of local excesses is estimated using p-values calculated with a test statistic based on the profile likelihood [40]. The largest data excesses are at $m_A = 220$ GeV (p-value = 0.014) and $m_A = 260$ GeV (p-value = 0.14) in the combined final states with $h \to bb$ and $h \to \tau\tau$, respectively. Exclusion limits at the 95% confidence level (CL) are set on the production cross section times the branching ratio BR($A \to Zh$) as a function of the A boson mass. The exclusion limits are calculated with a modified frequentist method [41], also known as CLs, and the profile likelihood method, using the binned



(a) $\ell\ell bb$ (b) $\nu\nu bb$

Fig. 2. Distributions of the reconstructed A boson mass for the $\ell\ell bb$ final state (a) and the A boson transverse mass for the $\nu\nu bb$ final state (b). The signal shown in both cases corresponds to $\sigma(gg \to A) \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to bb) = 500$ fb with $m_A = 500$ GeV. The predicted distributions are shown after the profile likelihood fit to the data. The uncertainty is shown as a hatched area, and the overflow is included in the last bin.

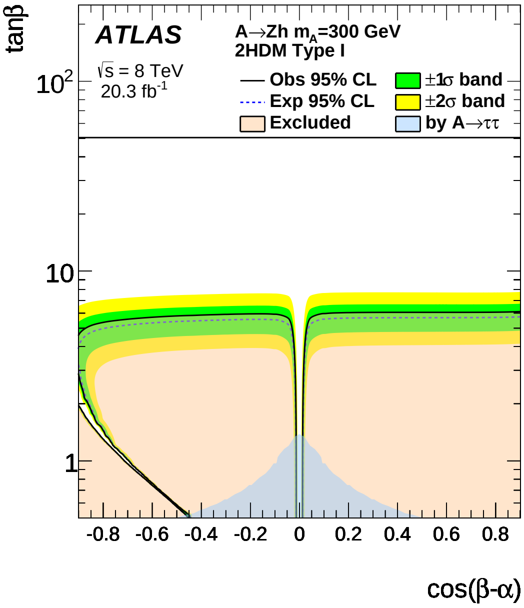


(a) $A \to Zh$, $h \to \tau\tau$ (b) $A \to Zh$, $h \to bb$

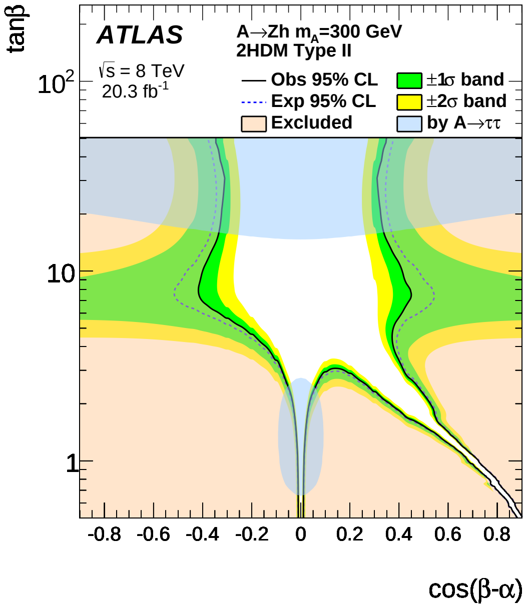
Fig. 3. Combined observed and expected upper limits at the 95% CL for the production cross section of a gluon-fusion-produced A boson times its branching ratio to Zh and branching ratio of h to (a) $\tau\tau$ and (b) bb. The expected upper limits for subchannels are also shown.

m_A^{rec} mass distributions for $\ell\ell\tau\tau$ and $\ell\ell bb$ final states and the binned $m_A^{\mathrm{rec,T}}$ distribution for the $\nu\nu bb$ final state.

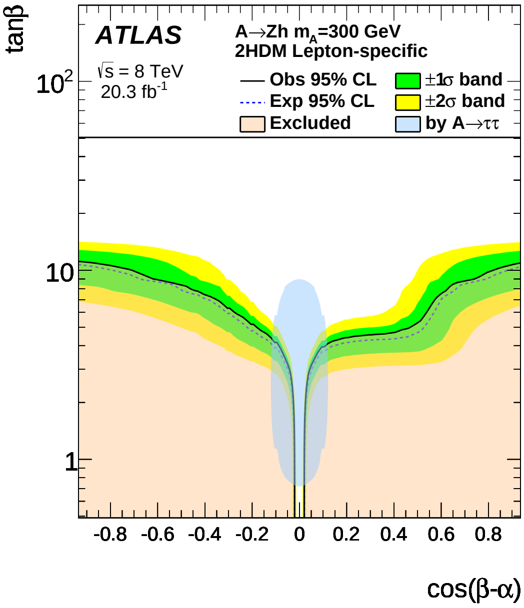
Fig. 3 shows the 95% CL limits on the production cross section times the branching ratio, $\sigma(gg \to A) \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to bb/\tau\tau)$, as well as the expected limits for each individual subchannel. The limit on the production times the branching ratio is in the range 0.098–0.013 pb and 0.57–0.014 pb for m_A in the range 220–1000 GeV for the $\tau\tau$ and bb channels, respectively. The $\tau\tau$ channels use few signal mass points beyond $m_A = 500$ GeV, since the



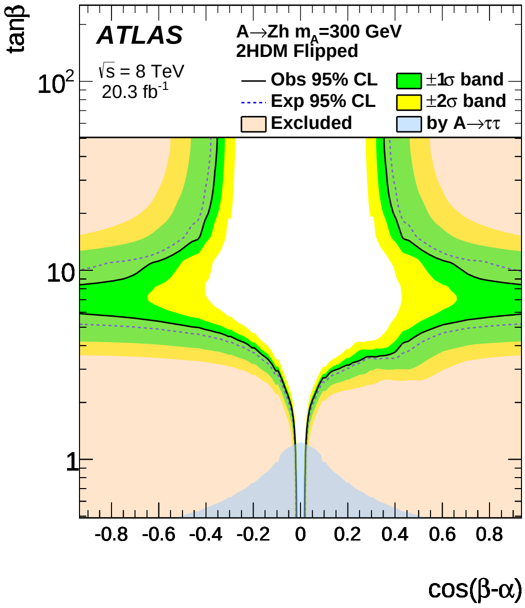
(a) Type-I 2HDM, $m_A = 300$ GeV



(b) Type-II 2HDM, $m_A = 300$ GeV

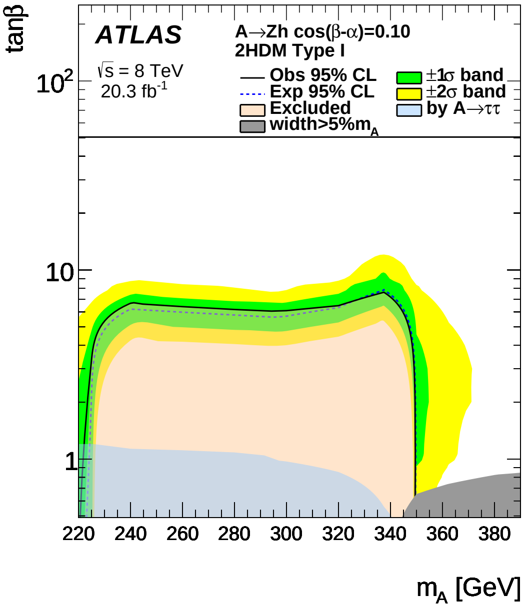


(c) Lepton-specific 2HDM, $m_A = 300$ GeV

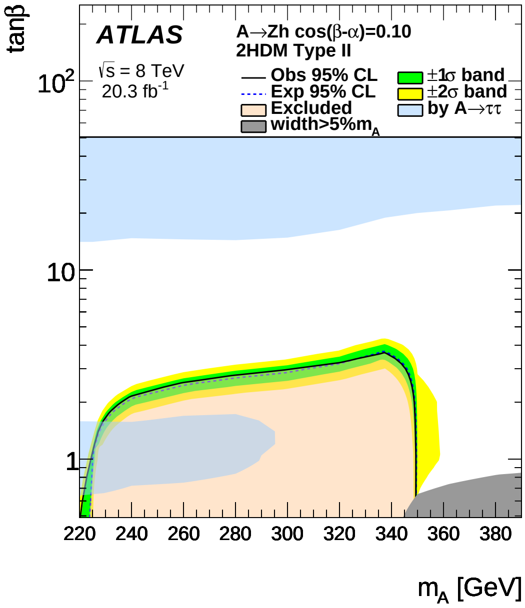


(d) Flipped 2HDM, $m_A = 300$ GeV

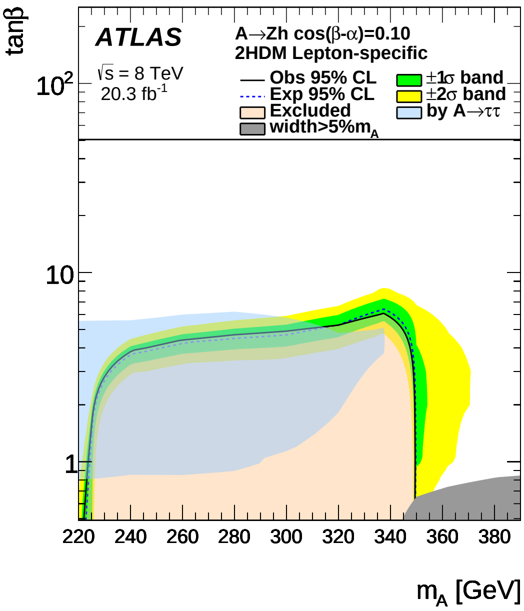
Fig. 4. The interpretation of the cross-section limits in the context of the various 2HDM types as a function of the parameters $\tan\beta$ and $\cos(\beta-\alpha)$ for $m_A = 300$ GeV: (a) Type-I, (b) Type-II, (c) Lepton-specific, and (d) Flipped. Variations of the natural width up to Γ_A/m_A=5% are taken into account. For Type-II and Flipped 2HDM, the b-associated production is included in addition to the gluon fusion. The narrow regions with no exclusion power in Type-I and Type-II at low $\tan\beta$ and far from $\cos(\beta-\alpha) = 0$ are caused by vanishing branching ratios of $h \to bb$ and/or $h \to \tau\tau$. The blue shaded area denotes the area excluded by taking into account the constraints on the CP-odd Higgs boson derived by considering the $A \to \tau\tau$ decay mode after reinterpreting the results in Ref. [13].



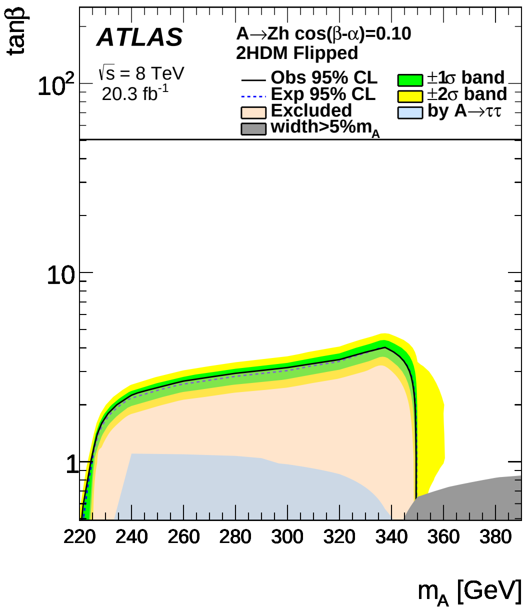
(a) Type-I 2HDM, $\cos(\beta - \alpha) = 0.1$



(b) Type-II 2HDM, $\cos(\beta - \alpha) = 0.1$



(c) Lepton-specific 2HDM, $\cos(\beta - \alpha) = 0.1$



(d) Flipped 2HDM, $\cos(\beta - \alpha) = 0.1$

Fig. 5. The interpretation of the cross-section limits in the context of the various 2HDM types as a function of the parameters $\tan\beta$ and m_A for $\cos(\beta - \alpha) = 0.1$: (a) Type-I (a), (b) Type-II, (c) Lepton-specific, and (d) Flipped. Variations of the natural width up to Γ_A/m_A=5% are taken into account. The grey solid area indicates that the width is larger than 5% of m_A. For Type-II and Flipped 2HDM, the b-associated production is included in addition to the gluon fusion. The blue shaded area denotes the area excluded by taking into account the constraints on the CP-odd Higgs boson derived by considering the $A \to \tau\tau$ decay mode after reinterpreting the results in Ref. [13].

predicted number of events in this region is very small.

The results of the search in the $\tau\tau$ and bb channels are combined in the context of the CP-conserving 2HDM [3], which has seven free parameters and four arrangements of the Yukawa couplings to fermions. In particular, the free parameters are the Higgs boson masses (m_h, m_H, m_A, $m_{H^\pm}$), the ratio of the vacuum expectation values of the two doublets ($\tan\beta$), the mixing angle between the CP-even Higgs bosons (α) and the potential parameter m_{12}^2 that mixes the two Higgs doublets. The Yukawa coupling arrangements distinguish four different 2HDM models, determining which of the two doublets, Φ_1 and Φ_2, couples to up- and down-type quarks and leptons. In the Type-I model, Φ_2 couples to all quarks and leptons, whereas in the Type-II, Φ_1 couples to down-type fermions and Φ_2 couples to up-type fermions. The Lepton-specific model is similar to Type-I apart from the fact that the leptons couple to Φ_1, instead of Φ_2. The Flipped model is similar to Type-II apart from the leptons coupling to Φ_2, instead of Φ_1. In all these models, the limit $\cos(\beta-\alpha) \to 0$ is such that the light CP-even Higgs boson, h, has indistinguishable properties from a SM Higgs boson with the same mass. The cross sections for production by gluon fusion are calculated using `SusHi` [42–47] and the branching ratios are calculated with `2HDMC` [48]. For the branching ratio calculations, it is assumed that $m_A = m_H = m_{H^\pm}$, $m_h = 125$ GeV and $m_{12}^2 = m_A^2 \tan\beta/(1+\tan^2\beta)$.

The constraints derived from the combined search in $\tau\tau$ and bb final states are presented as a function of 2HDM parameters. The exclusion region in the $\cos(\beta-\alpha)$ versus $\tan\beta$ plane for $m_A = 300$ GeV are shown in Fig. 4 for the four 2HDM models , while the constraints obtained in the m_A–$\tan\beta$ plane for $\cos(\beta-\alpha) = 0.10$ are shown in Fig. 5. The width of the A boson in the 2HDM may be larger than the experimental mass resolution, and it is taken into account in the 2HDM parameter exclusion regions for widths up to 5% of m_A. For Type-II and Flipped models, Higgs boson production in association with b-quarks dominates over gluon fusion for large $\tan\beta$ values ($\tan\beta \gtrsim 10$). The cross section for the b-associated production uses an empirical matching of the cross sections in the four- and five-flavour schemes [49]. Cross sections in the four-flavour scheme are calculated according to Refs. [50, 51] and cross sections in the five-flavour scheme are calculated using `SusHi`. The relative efficiencies for the b-associated and gluon fusion production as well as the predicted cross-section ratio are taken into account when deriving the constraints in the two-dimensional planes shown in Fig. 4. The b-associated production efficiencies are estimated using `PYTHIA8` and `SHERPA` samples. The regions of parameter space excluded at 95% CL by the $A \to \tau\tau$ decay mode are displayed in the same plots, using the results of a search for a heavy Higgs boson decaying into $\tau\tau$ (Ref. [13]), reinterpreted considering only the production of an A boson via gluon fusion and b-associated production. For m_A values below the $t\bar{t}$ kinematic threshold, the search presented here can exclude $\cos(\beta-\alpha)$ values down to a few percent for $\tan\beta$ values up to ≈ 3.

7. Conclusions

Data recorded in 2012 by the ATLAS experiment at the LHC, corresponding to an integrated luminosity of 20.3 fb^{-1} of proton–proton collisions at a centre-of-mass energy 8 TeV, are used to search for a CP-odd Higgs boson, A, decaying to Zh, where h denotes a light CP-even Higgs boson with a 125 GeV mass. No deviations from the SM background predictions are observed in the three final states considered: $Zh \to \ell\ell\tau\tau$, $Zh \to \ell\ell bb$, and $Zh \to \nu\nu bb$. Upper limits are set at the 95% confidence level for $\sigma(gg \to A) \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to f\bar{f})$ of 0.098–0.013 pb for $f = \tau$ and 0.57–0.014 pb for $f = b$ in the range of $m_A = 220$–1000 GeV. This Zh resonance search improves significantly the previously published constraints on CP-odd Higgs boson production in the low $\tan\beta$ region of the 2HDM.

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G. Aad[85], B. Abbott[113], J. Abdallah[152], S. Abdel Khalek[117], O. Abdinov[11], R. Aben[107], B. Abi[114], M. Abolins[90], O.S. AbouZeid[159], H. Abramowicz[154], H. Abreu[153], R. Abreu[30], Y. Abulaiti[147a,147b], B.S. Acharya[165a,165b,a], L. Adamczyk[38a], D.L. Adams[25], J. Adelman[108], S. Adomeit[100], T. Adye[131], T. Agatonovic-Jovin[13], J.A. Aguilar-Saavedra[126a,126f], M. Agustoni[17], S.P. Ahlen[22], F. Ahmadov[65,b], G. Aielli[134a,134b], H. Akerstedt[147a,147b], T.P.A. Åkesson[81], G. Akimoto[156], A.V. Akimov[96], G.L. Alberghi[20a,20b], J. Albert[170], S. Albrand[55], M.J. Alconada Verzini[71], M. Aleksa[30], I.N. Aleksandrov[65], C. Alexa[26a], G. Alexander[154], G. Alexandre[49], T. Alexopoulos[10], M. Alhroob[113], G. Alimonti[91a], L. Alio[85], J. Alison[31], B.M.M. Allbrooke[18], L.J. Allison[72], P.P. Allport[74], A. Aloisio[104a,104b], A. Alonso[36], F. Alonso[71], C. Alpigiani[76], A. Altheimer[35], B. Alvarez Gonzalez[90], M.G. Alviggi[104a,104b], K. 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Berta[129], C. Bertella[83], G. Bertoli[147a,147b], F. Bertolucci[124a,124b], C. Bertsche[113], D. Bertsche[113], M.I. Besana[91a], G.J. Besjes[106], O. Bessidskaia Bylund[147a,147b], M. Bessner[42], N. Besson[137], C. Betancourt[48], S. Bethke[101], A.J. Bevan[76], W. Bhimji[46], R.M. Bianchi[125], L. Bianchini[23], M. Bianco[30], O. Biebel[100], S.P. Bieniek[78], M. Biglietti[135a], J. Bilbao De Mendizabal[49], H. Bilokon[47], M. Bindi[54], S. Binet[117], A. Bingul[19c], C. Bini[133a,133b], C.W. Black[151], J.E. Black[144], K.M. Black[22], D. Blackburn[139], R.E. Blair[6], J.-B. Blanchard[137], J.E. Blanco[77], T. Blazek[145a], I. Bloch[42], C. Blocker[23], W. Blum[83,*], U. Blumenschein[54], G.J. Bobbink[107], V.S. Bobrovnikov[109,c], S.S. Bocchetta[81], A. Bocci[45], C. Bock[100], C.R. Boddy[120], M. Boehler[48], J.A. Bogaerts[30], A.G. Bogdanchikov[109], C. Bohm[147a], V. Boisvert[77], T. Bold[38a], V. Boldea[26a], A.S. Boldyrev[99], M. Bomben[80], M. Bona[76], M. 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Taylor[88], W. Taylor[160b], F.A. Teischinger[30], M. Teixeira Dias Castanheira[76], P. Teixeira-Dias[77], K.K. Temming[48], H. Ten Kate[30], P.K. Teng[152], J.J. Teoh[118], F. Tepel[176], S. Terada[66], K. Terashi[156], J. Terron[82], S. Terzo[101], M. Testa[47], R.J. Teuscher[159,k], J. Therhaag[21], T. Theveneaux-Pelzer[34], J.P. Thomas[18], J. Thomas-Wilsker[77], E.N. Thompson[35], P.D. Thompson[18], R.J. Thompson[84], A.S. Thompson[53], L.A. Thomsen[36], E. Thomson[122], M. Thomson[28], W.M. Thong[88], R.P. Thun[89,*], F. Tian[35], M.J. Tibbetts[15], R.E. Ticse Torres[85], V.O. Tikhomirov[96,ah], Yu.A. Tikhonov[109,c], S. Timoshenko[98], E. Tiouchichine[85], P. Tipton[177], S. Tisserant[85], T. Todorov[5,*], S. Todorova-Nova[129], J. Tojo[70], S. Tokár[145a], K. Tokushuku[66], K. Tollefson[90], E. Tolley[57], L. Tomlinson[84], M. Tomoto[103], L. Tompkins[144,ai], K. Toms[105], N.D. Topilin[65], E. Torrence[116], H. Torres[143], E. Torró Pastor[168], J. Toth[85,aj], F. 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Urrejola[83], G. Usai[8], A. Usanova[62], L. Vacavant[85], V. Vacek[128], B. Vachon[87], N. Valencic[107], S. Valentinetti[20a,20b], A. Valero[168], L. Valery[12], S. Valkar[129], E. Valladolid Gallego[168], S. Vallecorsa[49], J.A. Valls Ferrer[168], W. Van Den Wollenberg[107], P.C. Van Der Deijl[107], R. van der Geer[107], H. van der Graaf[107], R. Van Der Leeuw[107], N. van Eldik[30], P. van Gemmeren[6], J. Van Nieuwkoop[143], I. van Vulpen[107], M.C. van Woerden[30], M. Vanadia[133a,133b], W. Vandelli[30], R. Vanguri[122], A. Vaniachine[6], F. Vannucci[80], G. Vardanyan[178], R. Vari[133a], E.W. Varnes[7], T. Varol[40], D. Varouchas[80], A. Vartapetian[8], K.E. Varvell[151], F. Vazeille[34], T. Vazquez Schroeder[54], J. Veatch[7], F. Veloso[126a,126c], T. Velz[21], S. Veneziano[133a], A. Ventura[73a,73b], D. Ventura[86], M. Venturi[170], N. Venturi[159], A. Venturini[23], V. Vercesi[121a], M. Verducci[133a,133b], W. Verkerke[107], J.C. Vermeulen[107],

A. Vest[44], M.C. Vetterli[143,d], O. Viazlo[81], I. Vichou[166], T. Vickey[146c,ak], O.E. Vickey Boeriu[146c], G.H.A. Viehhauser[120], S. Viel[15], R. Vigne[30], M. Villa[20a,20b], M. Villaplana Perez[91a,91b], E. Vilucchi[47], M.G. Vincter[29], V.B. Vinogradov[65], J. Virzi[15], I. Vivarelli[150], F. Vives Vaque[3], S. Vlachos[10], D. Vladoiu[100], M. Vlasak[128], M. Vogel[32a], P. Vokac[128], G. Volpi[124a,124b], M. Volpi[88], H. von der Schmitt[101], H. von Radziewski[48], E. von Toerne[21], V. Vorobel[129], K. Vorobev[98], M. Vos[168], R. Voss[30], J.H. Vossebeld[74], N. Vranjes[13], M. Vranjes Milosavljevic[13], V. Vrba[127], M. Vreeswijk[107], R. Vuillermet[30], I. Vukotic[31], Z. Vykydal[128], P. Wagner[21], W. Wagner[176], H. Wahlberg[71], S. Wahrmund[44], J. Wakabayashi[103], J. Walder[72], R. Walker[100], W. Walkowiak[142], C. Wang[33c], F. Wang[174], H. Wang[15], H. Wang[40], J. Wang[42], J. Wang[33a], K. Wang[87], R. Wang[105], S.M. Wang[152], T. Wang[21], X. Wang[177], C. Wanotayaroj[116], A. Warburton[87], C.P. Ward[28], D.R. Wardrope[78], M. Warsinsky[48], A. Washbrook[46], C. Wasicki[42], P.M. Watkins[18], A.T. Watson[18], I.J. Watson[151], M.F. Watson[18], G. Watts[139], S. Watts[84], B.M. Waugh[78], S. Webb[84], M.S. Weber[17], S.W. Weber[175], J.S. Webster[31], A.R. Weidberg[120], B. Weinert[61], J. Weingarten[54], C. Weiser[48], H. Weits[107], P.S. Wells[30], T. Wenaus[25], D. Wendland[16], T. Wengler[30], S. Wenig[30], N. Wermes[21], M. Werner[48], P. Werner[30], M. Wessels[58a], J. Wetter[162], K. Whalen[29], A.M. Wharton[72], A. White[8], M.J. White[1], R. White[32b], S. White[124a,124b], D. Whiteson[164], D. Wicke[176], F.J. Wickens[131], W. Wiedenmann[174], M. Wielers[131], P. Wienemann[21], C. Wiglesworth[36], L.A.M. Wiik-Fuchs[21], A. Wildauer[101], H.G. Wilkens[30], H.H. Williams[122], S. Williams[107], C. Willis[90], S. Willocq[86], A. Wilson[89], J.A. Wilson[18], I. Wingerter-Seez[5], F. Winklmeier[116], B.T. Winter[21], M. Wittgen[144], J. Wittkowski[100], S.J. Wollstadt[83], M.W. Wolter[39], H. Wolters[126a,126c], B.K. Wosiek[39], J. Wotschack[30], M.J. Woudstra[84], K.W. Wozniak[39], M. Wu[55], S.L. Wu[174], X. Wu[49], Y. Wu[89], T.R. Wyatt[84], B.M. Wynne[46], S. Xella[36], D. Xu[33a], L. Xu[33b,al], B. Yabsley[151], S. Yacoob[146b,am], R. Yakabe[67], M. Yamada[66], Y. Yamaguchi[118], A. Yamamoto[66], S. Yamamoto[156], T. Yamanaka[156], K. Yamauchi[103], Y. Yamazaki[67], Z. Yan[22], H. Yang[33e], H. Yang[174], Y. Yang[152], S. Yanush[93], L. Yao[33a], W-M. Yao[15], Y. Yasu[66], E. Yatsenko[42], K.H. Yau Wong[21], J. Ye[40], S. Ye[25], I. Yeletskikh[65], A.L. Yen[57], E. Yildirim[42], K. Yorita[172], R. Yoshida[6], K. Yoshihara[122], C. Young[144], C.J.S. Young[30], S. Youssef[22], D.R. Yu[15], J. Yu[8], J.M. Yu[89], J. Yu[114], L. Yuan[67], A. Yurkewicz[108], I. Yusuff[28,an], B. Zabinski[39], R. Zaidan[63], A.M. Zaitsev[130,ab], A. Zaman[149], S. Zambito[23], L. Zanello[133a,133b], D. Zanzi[88], C. Zeitnitz[176], M. Zeman[128], A. Zemla[38a], K. Zengel[23], O. Zenin[130], T. Ženiš[145a], D. Zerwas[117], D. Zhang[89], F. Zhang[174], J. Zhang[6], L. Zhang[152], R. Zhang[33b], X. Zhang[33d], Z. Zhang[117], X. Zhao[40], Y. Zhao[33d,117], Z. Zhao[33b], A. Zhemchugov[65], J. Zhong[120], B. Zhou[89], C. Zhou[45], L. Zhou[35], L. Zhou[40], N. Zhou[164], C.G. Zhu[33d], H. Zhu[33a], J. Zhu[89], Y. Zhu[33b], X. Zhuang[33a], K. Zhukov[96], A. Zibell[175], D. Zieminska[61], N.I. Zimine[65], C. Zimmermann[83], R. Zimmermann[21], S. Zimmermann[48], Z. Zinonos[54], M. Zinser[83], M. Ziolkowski[142], L. Živković[13], G. Zobernig[174], A. Zoccoli[20a,20b], M. zur Nedden[16], G. Zurzolo[104a,104b], L. Zwalinski[30].

[1] Department of Physics, University of Adelaide, Adelaide, Australia
[2] Physics Department, 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; [(c)] Istanbul Aydin University, Istanbul; [(d)] Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
[5] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, 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, The University of Texas at Arlington, Arlington TX, United States of America
[9] Physics Department, University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[12] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
[13] Institute of Physics, University of Belgrade, Belgrade, Serbia
[14] Department for Physics and Technology, University of Bergen, Bergen, Norway
[15] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

[16] Department of Physics, Humboldt University, Berlin, Germany
[17] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[18] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[19] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Department of Physics, Dogus University, Istanbul; [(c)] Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
[20] [(a)] INFN Sezione di Bologna; [(b)] Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
[21] Physikalisches Institut, University of Bonn, Bonn, Germany
[22] Department of Physics, Boston University, Boston MA, United States of America
[23] Department of Physics, Brandeis University, Waltham MA, United States of America
[24] [(a)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)] Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)] Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)] Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[25] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[26] [(a)] National Institute of Physics and Nuclear Engineering, Bucharest; [(b)] National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; [(c)] University Politehnica Bucharest, Bucharest; [(d)] West University in Timisoara, Timisoara, Romania
[27] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[28] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[29] Department of Physics, Carleton University, Ottawa ON, Canada
[30] CERN, Geneva, Switzerland
[31] Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
[32] [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[33] [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)] Department of Physics, Nanjing University, Jiangsu; [(d)] School of Physics, Shandong University, Shandong; [(e)] Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; [(f)] Physics Department, Tsinghua University, Beijing 100084, China
[34] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
[35] Nevis Laboratory, Columbia University, Irvington NY, United States of America
[36] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[37] [(a)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; [(b)] Dipartimento di Fisica, Università della Calabria, Rende, Italy
[38] [(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
[39] Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[40] Physics Department, Southern Methodist University, Dallas TX, United States of America
[41] Physics Department, University of Texas at Dallas, Richardson TX, United States of America
[42] DESY, Hamburg and Zeuthen, Germany
[43] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[44] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[45] Department of Physics, Duke University, Durham NC, United States of America
[46] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] [(a)] E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
[56] Department of Physics, Hampton University, Hampton VA, United States of America
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
[58] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60] [(a)] Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; [(b)] Department of Physics, The University of Hong Kong, Hong Kong; [(c)] Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[61] Department of Physics, Indiana University, Bloomington IN, United States of America
[62] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[63] University of Iowa, Iowa City IA, United States of America
[64] Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
[65] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[66] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[67] Graduate School of Science, Kobe University, Kobe, Japan
[68] Faculty of Science, Kyoto University, Kyoto, Japan
[69] Kyoto University of Education, Kyoto, Japan
[70] Department of Physics, Kyushu University, Fukuoka, Japan
[71] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[72] Physics Department, Lancaster University, Lancaster, United Kingdom
[73] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[74] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[75] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[76] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[77] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[78] Department of Physics and Astronomy, University College London, London, United Kingdom
[79] Louisiana Tech University, Ruston LA, United States of America
[80] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[81] Fysiska institutionen, Lunds universitet, Lund, Sweden
[82] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[83] Institut für Physik, Universität Mainz, Mainz, Germany
[84] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[85] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[86] Department of Physics, University of Massachusetts, Amherst MA, United States of America
[87] Department of Physics, McGill University, Montreal QC, Canada
[88] School of Physics, University of Melbourne, Victoria, Australia
[89] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[90] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[91] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano, Italy
[92] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[93] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[94] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of

America
[95] Group of Particle Physics, University of Montreal, Montreal QC, Canada
[96] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[97] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[98] National Research Nuclear University MEPhI, Moscow, Russia
[99] D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[100] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[101] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[102] Nagasaki Institute of Applied Science, Nagasaki, Japan
[103] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[104] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[105] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
[106] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[107] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[108] Department of Physics, Northern Illinois University, DeKalb IL, United States of America
[109] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[110] Department of Physics, New York University, New York NY, United States of America
[111] Ohio State University, Columbus OH, United States of America
[112] Faculty of Science, Okayama University, Okayama, Japan
[113] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
[114] Department of Physics, Oklahoma State University, Stillwater OK, United States of America
[115] Palacký University, RCPTM, Olomouc, Czech Republic
[116] Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
[117] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[118] Graduate School of Science, Osaka University, Osaka, Japan
[119] Department of Physics, University of Oslo, Oslo, Norway
[120] Department of Physics, Oxford University, Oxford, United Kingdom
[121] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[122] Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
[123] Petersburg Nuclear Physics Institute, Gatchina, Russia
[124] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[125] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
[126] [(a)] Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; [(b)] Faculdade de Ciências, Universidade de Lisboa, Lisboa; [(c)] Department of Physics, University of Coimbra, Coimbra; [(d)] Centro de Física Nuclear da Universidade de Lisboa, Lisboa; [(e)] Departamento de Fisica, Universidade do Minho, Braga; [(f)] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); [(g)] Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[127] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[128] Czech Technical University in Prague, Praha, Czech Republic
[129] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[130] State Research Center Institute for High Energy Physics, Protvino, Russia
[131] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[132] Ritsumeikan University, Kusatsu, Shiga, Japan
[133] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[134] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata,

Roma, Italy
[135] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[136] [(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, 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-Agdal, Rabat, Morocco
[137] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[138] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
[139] Department of Physics, University of Washington, Seattle WA, United States of America
[140] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[141] Department of Physics, Shinshu University, Nagano, Japan
[142] Fachbereich Physik, Universität Siegen, Siegen, Germany
[143] Department of Physics, Simon Fraser University, Burnaby BC, Canada
[144] SLAC National Accelerator Laboratory, Stanford CA, United States of America
[145] [(a)] Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[146] [(a)] Department of Physics, University of Cape Town, Cape Town; [(b)] Department of Physics, University of Johannesburg, Johannesburg; [(c)] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[147] [(a)] Department of Physics, Stockholm University; [(b)] The Oskar Klein Centre, Stockholm, Sweden
[148] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[149] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
[150] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[151] School of Physics, University of Sydney, Sydney, Australia
[152] Institute of Physics, Academia Sinica, Taipei, Taiwan
[153] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[154] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[155] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[156] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[157] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[158] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[159] Department of Physics, University of Toronto, Toronto ON, Canada
[160] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON, Canada
[161] Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[162] Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
[163] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[164] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[165] [(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
[166] Department of Physics, University of Illinois, Urbana IL, United States of America
[167] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[168] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM),

University of Valencia and CSIC, Valencia, Spain
[169] Department of Physics, University of British Columbia, Vancouver BC, Canada
[170] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[171] Department of Physics, University of Warwick, Coventry, United Kingdom
[172] Waseda University, Tokyo, Japan
[173] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[174] Department of Physics, University of Wisconsin, Madison WI, United States of America
[175] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[176] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[177] Department of Physics, Yale University, New Haven CT, United States of America
[178] Yerevan Physics Institute, Yerevan, Armenia
[179] Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
[a] Also at Department of Physics, King's College London, London, United Kingdom
[b] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[c] Also at Novosibirsk State University, Novosibirsk, Russia
[d] Also at TRIUMF, Vancouver BC, Canada
[e] Also at Department of Physics, California State University, Fresno CA, United States of America
[f] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
[g] Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
[h] Also at Tomsk State University, Tomsk, Russia
[i] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[j] Also at Università di Napoli Parthenope, Napoli, Italy
[k] Also at Institute of Particle Physics (IPP), Canada
[l] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[m] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
[n] Also at Louisiana Tech University, Ruston LA, United States of America
[o] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
[p] Also at Department of Physics, National Tsing Hua University, Taiwan
[q] Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
[r] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
[s] Also at CERN, Geneva, Switzerland
[t] Also at Georgian Technical University (GTU),Tbilisi, Georgia
[u] Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
[v] Also at Manhattan College, New York NY, United States of America
[w] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
[x] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[y] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
[z] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[aa] Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[ab] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
[ac] Also at Section de Physique, Université de Genève, Geneva, Switzerland
[ad] Also at International School for Advanced Studies (SISSA), Trieste, Italy
[ae] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
[af] Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
[ag] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
[ah] Also at National Research Nuclear University MEPhI, Moscow, Russia
[ai] Also at Department of Physics, Stanford University, Stanford CA, United States of America
[aj] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

[ak] Also at Department of Physics, Oxford University, Oxford, United Kingdom
[al] Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[am] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
[an] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
* Deceased