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Search for neutral resonances decaying into a Z boson and a pair of b jets or τ leptons

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ABSTRACT

A search is performed for a new resonance decaying into a lighter resonance and a Z boson. Two channels are studied, targeting the decay of the lighter resonance into either a pair of oppositely charged τ leptons or a $b\bar{b}$ pair. The Z boson is identified via its decays to electrons or muons. The search exploits data collected by the CMS experiment at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.8 fb^{-1}. No significant deviations are observed from the standard model expectation and limits are set on production cross sections and parameters of two-Higgs-doublet models.

1. Introduction

The observation of a new particle with a mass of approximately 125 GeV was reported by the ATLAS and CMS experiments at the CERN LHC in the WW, ZZ and $\gamma\gamma$ final states [1–3]. Evidence of the decay of the particle to pairs of fermions ($\tau\tau$ and $b\bar{b}$) has also been reported in Refs. [4–6]. The measurements of branching fractions, production rates, spin and parity are all consistent with the predictions for the standard model (SM) Higgs boson [7,8], wherein a single doublet of Higgs fields is present. However, additional Higgs bosons are expected in simple extensions of the SM scalar sector, such as models with two Higgs-boson doublets (2HDMs) [9]. These models predict five physical Higgs particles that arise as a consequence of the electroweak symmetry-breaking mechanism: two neutral CP-even scalars (h, H), one neutral CP-odd pseudoscalar (A), and two charged scalars ($H^{\pm}$).

An important motivation for 2HDMs is that such models provide a way to accommodate the asymmetry between matter and antimatter observed in the universe [9,10]. An extension of the SM scalar sector with two Higgs boson doublets would also naturally arise in supersymmetry [11,12], which requires a scalar structure more complex than a single doublet. Axion models [13] provide a strong interaction that does not violate CP symmetry and give rise to an effective low-energy theory with two Higgs doublets. Finally, it has recently been noted [14] that certain realisations of 2HDMs can accommodate the muon g-2 anomaly [15] without violating present theoretical and experimental constraints.

In the most general case, 14 parameters describe the scalar sector of a 2HDM [9]. Only six free parameters remain once the experimental observations are included by imposing the so-called $\mathbb{Z}_2$ symmetry to suppress flavour changing neutral currents, and by fixing both the values of the mass of the recently discovered SM-like Higgs boson (125 GeV) [16] and the electroweak vacuum expectation value (246 GeV). The compatibility of a SM-like Higgs boson with 2HDMs is possible in the so-called alignment limit. The alignment limit is reached when $\cos(\beta-\alpha) \to 0$, where $\tan\beta$ is the ratio of the vacuum expectation values and α is the mixing angle of the two Higgs doublets. In such a regime, one of the CP-even scalars, h or H, is identified with the SM-like Higgs boson. A recent theoretical study [10] has shown that, in this limit, a large mass splitting (>100 GeV) between the A and H bosons would favour the electroweak phase transition that would be at the origin of baryogenesis in the early universe, satisfying thereby the currently observed matter–antimatter asymmetry. In this context, the most frequent decay mode of the pseudoscalar A boson would be $A \to ZH$. Since the analysis strategy presented in this paper is independent of the assumed model and parity of the res-

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onance, the results can also be interpreted in the reversed topology $H \to ZA$, where the expected 2HDM mass hierarchy is inverted and the mass of A is expected to be light [17]. For both topologies, the lighter scalar resonance (A or H) is not identified with the SM-like Higgs boson.

This paper describes the first CMS search for a new resonance decaying into a lighter resonance and a Z boson. Two searches are performed, targeting the decay of the lighter resonance into either a pair of oppositely charged τ leptons or a $b\bar{b}$ pair. In both cases, the Z boson is identified via its decay into a pair of oppositely charged electrons or muons (light leptons), labelled in the text by the symbol ℓ. The choice of $b\bar{b}$ and $\tau\tau$ final states is motivated by the large branching fractions predicted in most of the 2HDM phase space [18]. For the $\ell\ell\tau\tau$ channel, the following $\tau\tau$ final states are considered: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$, where τ_h indicates the decays $\tau \to \text{hadrons} + \nu_\tau$. Given its sensitivity to the 2HDM parameter space region where $\cos(\beta - \alpha) \approx 0$, the search presented in this paper is complementary to other related searches performed in the same final state by the ATLAS and CMS collaborations [19,20].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Located in concentric layers within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of one barrel and two endcap sections. These layers provide coverage up to a pseudorapidity $|\eta| = 2.5$. Extensive forward calorimetry complements are provided by the endcap detectors for $|\eta| < 5.2$. Combining the energy measurement in the ECAL with the measurement in the tracker, the momentum resolution for electrons with $p_T \approx 45$ GeV from $Z \to ee$ decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps [21]. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. They cover the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps [22]. The first level of the CMS trigger system uses information from the calorimeters and muon detectors to select the most interesting events. A high-level trigger processor farm decreases the event rate from approximately 100 kHz to 600 Hz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in Ref. [23].

3. Data and simulated samples

The data used for this search were collected by the CMS experiment at $\sqrt{s} = 8$ TeV, and correspond to a total integrated luminosity of 19.8 fb^{-1}. The average number of interactions per bunch crossing (pileup) in the data was 21 [24]. Events were selected using dielectron and dimuon triggers [21,22]. These triggers have p_T thresholds of 17 and 8 GeV for the leading and subleading lepton respectively, and require relatively loose reconstruction and identification criteria.

The main SM background processes giving rise to prompt leptons are W/Z + jets, $t\bar{t}$ + jets, tW, and diboson production (WW, ZZ, and WZ). The SM background contribution from ZZ is generated at next-to-leading order (NLO) with POWHEG 1.0 [25] for the $\ell\ell\tau\tau$ channel and using the leading-order (LO) MadGraph 5.1 Monte Carlo (MC) program [26], matched to PYTHIA 6.4 [27] for the parton showering and hadronization, for the $\ell\ell$bb channel. Single top quark events are generated at NLO using POWHEG 1.0. Simulated events for other samples are obtained using the MadGraph 5.1 MC matched to PYTHIA 6.4. The PYTHIA parameters affecting the description of the underlying event are set to those of the Z2* tune [28]. All generators used for processes including τ leptons in the final state are interfaced with TAUOLA 2.4 [29] for the simulation of the τ decays. The detector response is simulated using a detailed description of CMS, based on the Geant4 toolkit [30]. The simulated samples account for contributions from pileup collisions that reflect the distributions observed in data. The trigger and reconstruction efficiency in the simulation is rescaled by as much as 2% in order to match that measured in the data [24].

Two benchmark 2HDM processes are considered as signal: $H \to ZA$ and $A \to ZH$, where the lightest boson (pseudoscalar or scalar, according to the process) can decay to $\tau\tau$ or $b\bar{b}$, and the Z decays to $\ell\ell$. The MadGraph 5.1 program, interfaced to PYTHIA 6.4 and TAUOLA 2.4, was used to generate signal samples corresponding to different values of A and H masses (m_A and m_H, respectively). The same properties of the SM Higgs boson are assigned to the lightest scalar boson, h, and its mass m_h is fixed at 125 GeV. The identification of the observed Higgs boson, together with all its measured properties, with the scalar h constrains the phenomenologically reliable parameter space regions to not depart from the SM-like condition $\cos(\beta - \alpha) \approx 0$. This corresponds to the so-called alignment limit [31]. Considering the parameter space still allowed by direct searches [12], the chosen values for $\cos(\beta - \alpha)$ and $\tan\beta$ are 0.01 and 1.5, respectively, and type-II Yukawa couplings are assumed for the benchmark processes.

The masses of the charged Higgs bosons ($m_{H^\pm}$) are kept equal to the highest mass involved in the signal process (m_H or m_A) to preserve the degeneracy $m^2_{H^\pm} \approx m^2_{H/A}$ [17], denoting with $m_{H/A}$ the mass of the scalar H or the mass of the pseudoscalar A. The value of the m_{12} parameter, the soft $\mathbb{Z}_2$ symmetry breaking mass, was set to $m^2_{12} = m^2_{H^\pm} \tan\beta/(1 + \tan^2\beta)$, according to the minimal supersymmetric standard model (MSSM) parametrisation [11]. The value of the complex couplings λ_6 and λ_7 in this parametrisation are set to zero, in order to avoid tree-level CP violation. The production cross sections, used for the normalisation of the signal samples, are computed using the SusHi 1.4 program [32], which provides next-to-next-to-leading-order (NNLO) predictions. The branching fraction for the heavy and light Higgs bosons are obtained using the 2HDMC 1.6 program [33], following the guidelines in Refs. [34,35].

The signal benchmark where the light boson decays into $\tau\tau$ is simulated for values of $m_{H/A}$ and $m_{A/H}$ varying in the ranges 200–1000 and 15–900 GeV, respectively, with the constraint $m_{H/A} > m_{A/H} + m_Z$. For the $\ell\ell$bb analysis the lower bound for the invariant mass $m_{A/H}$ goes down to 10 GeV. The region where m_H is smaller than m_h is not pertinent in this model.

4. Event reconstruction and selection

Event reconstruction is based on the particle-flow algorithm [36,37], which exploits information from all the CMS subdetectors to identify and reconstruct individual particles in the event: muons, electrons, photons, charged and neutral hadrons. Such particles are algorithmically combined to form the jets, the τ_h candidates, the missing transverse momentum $\vec{p}_T^{\text{miss}}$, defined as the projection on the plane perpendicular to the beams of the negative vector sum of the particles momenta and its magnitude, denoted as E_T^{miss}. To minimise the contributions from pileup interactions, charged tracks are required to originate from the primary vertex (reconstructed using the deterministic annealing algorithm [38]), which is the one characterised by the largest p_T^2 sum of its associated tracks.

Electrons are identified by combining information from tracks and ECAL clusters, including energy depositions from final-state radiation [21]. Muons are identified through a combined fit to position measurements from both the inner tracker and the muon detectors [22]. The τ_h objects are identified and reconstructed using the "hadron-plus-strips" algorithm [39], which uses charged hadrons and photons to reconstruct the main hadronic decay modes of the τ lepton: one charged hadron, one charged hadron and photons, and three charged hadrons. Electrons and muons can be misidentified as hadronic taus if produced in jets or if close-by activity from pile-up or bremsstrahlung is present. These misidentifications are suppressed using dedicated criteria based on the consistency between the measurements in the tracker, the calorimeters, and the muon detector [39]. To reject nonprompt or misidentified leptons, requirements are imposed on the isolation criteria, based on the sum of deposited energies. The absolute lepton isolation I_{abs} is defined by the scalar sum of the p_T of the charged particles from the primary vertex, neutral hadrons, and photons in an isolation cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ ($\Delta R = 0.3$ for electrons), centred around the lepton direction. To reduce the effect from pileup, the energy deposit released in the isolation cone by charged particles not associated with the primary vertex is subtracted from the neutral particles p_T scalar sum. For electrons and muons the relative isolation, defined as $I_{rel} = I_{abs}/p_T$, is used.

Jets are clustered using the anti-k_T algorithm [40], with a distance parameter of 0.5, as implemented in the FastJet software package [41]. Charged particles not associated with the primary vertex are excluded by means of the charged-hadron subtraction technique [42]. The remaining energy originating from pileup interactions, including the neutral components, is subtracted based on the median energy density in the detector computed through the effective jet area technique [43]. The identification of b quark initiated jets is achieved through the combined secondary vertex (CSV) algorithm [44], which exploits observables related to the long lifetime of B hadrons.

4.1. Selection for $Z \to \ell\ell$

In selecting $\ell\ell$bb and $\ell\ell\tau\tau$ events, the leptons from Z boson decay are required to be well within the CMS trigger and detector acceptance of $p_T > 20$ GeV and $|\eta| < 2.5$ for electrons, and $p_T > 20$ GeV, $|\eta| < 2.4$ for muons. Muon momentum-scale [22] and electron energy corrections [21] are applied to recover the global shift of the scale observed between data and simulation. The requirement on the relative isolation for the leptons is set to $I_{rel} < 0.15$ for electrons and $I_{rel} < 0.2$ for muons in selecting $\ell\ell$bb events. For the leptons from the Z boson, in the case of $\ell\ell\tau\tau$ events, the required relative isolation is $I_{rel} < 0.3$. The presence of two reconstructed same-flavour, oppositely charged lepton candidates forming a pair with invariant mass in the range of 76–106 GeV is required to suppress contamination of non-resonant Drell–Yan + jets and $t\bar{t}$ processes. In events where multiple Z candidates are present, the lepton pair with the invariant mass closest to the nominal Z boson mass [45] is chosen.

4.2. Event selection for $\ell\ell$bb

For the $\ell\ell$bb search, the jets are selected to be in the kinematic region $p_T > 30$ GeV and $|\eta| < 2.4$. At least two CSV b-tagged jets are required to be present in the event, to reduce the contribution of Z + light-parton jets (originating from gluons or u, d, or s quarks) events. The threshold on the b tagging discriminator corresponds to a b tagging efficiency greater than 65% and to a misidentification probability for light-parton jets of 1% [44]. The two b-tagged jets with highest values of the CSV discriminant are considered as candidate decay products of the new light resonance.

The E_T^{miss} significance [46,47], representing a χ^2 difference between the observed result for E_T^{miss} and the $E_T^{miss} = 0$ hypothesis, is used to suppress background events originating from $t\bar{t}$ processes. This variable provides an event-by-event assessment of the likelihood that the observed missing transverse energy is consistent with zero given the reconstructed content of the event and known measurement resolutions. This variable is a stronger discriminant against $t\bar{t}$ background than E_T^{miss} alone and also provides smaller systematic uncertainties. The distribution of the $t\bar{t}$ component motivates the requirement on the E_T^{miss} significance to be smaller than 10.

4.3. Event selection for $\ell\ell\tau\tau$

To increase the signal sensitivity in the high $\tau\tau$ mass region, the $\ell\ell\tau\tau$ event selection includes the requirement of a transversely boosted Z boson ($p_T > 20$ GeV), together with a large (>1.5 rad) azimuthal angle between the Z boson flight direction and $\vec{p}_T^{miss}$, particularly effective in suppressing the Z + jets background. In addition to the two light leptons required to reconstruct the Z boson, two additional oppositely charged and different-flavor leptons (e, μ, and τ_h) are used to reconstruct the A or H boson candidate. The requirements on the pseudorapidity for light leptons are the same as for the Z decay leptons, with the p_T threshold lowered to 10 GeV. The τ_h candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.3$. The relative isolation for electrons and muons, and the absolute isolation for τ leptons are required to be smaller than 0.3 and 2 GeV, respectively. Since the Z + jets background is characterised by a softer lepton transverse momentum spectrum than the signal one, this background is reduced by selecting events with high L_T, where L_T indicates the scalar sum of the visible p_T of the decay products from a $\tau\tau$ pair. Both the isolation requirements and the value of the L_T threshold are determined as a result of an optimisation procedure that maximises the expected significance of the searched signal. The optimal requirement on the L_T quantity is found by scanning the threshold between 20 and 200 GeV, at intervals of 20 GeV.

Jets are required to have $p_T > 30$ GeV and $|\eta| < 4.7$. To reduce the large $t\bar{t}$ background, all events with at least one jet with $p_T > 20$ GeV and $|\eta| < 2.4$, reconstructed as a jet originating from a b quark according to the output of the CSV discriminator used for tagging, are vetoed.

To calculate the $\tau\tau$ invariant mass, the secondary-vertex fit algorithm (svfit) [48] is used, a likelihood-based method that combines the reconstructed $\vec{p}_T^{miss}$ and its resolution with the momentum of the visible τ decay products to obtain an estimator of the mass of the parent particle.

5. Modelling of the background

5.1. The $\ell\ell$bb channel

The relevant sources of background for the $\ell\ell$bb final state originate from Z + jets processes, $t\bar{t}$ and tW production, diboson production, and vector boson production in association with a SM Higgs boson. The contributions of Z + jets and $t\bar{t}$ backgrounds are measured by means of a data-based method, the diboson and tW backgrounds are normalised to the CMS measurements. For these backgrounds, the shapes are taken from MC, while the normalisations are extracted from data. The vector boson production in association with a SM Higgs boson is normalised to the theoretical prediction.

The comparison of data and predictions after the selection of events for the $\ell\ell$bb final state shows the importance of an accurate theoretical calculation of the Z + jets production rate. In particular, in the 400–700 GeV range of the $m_{\ell\ell\mathrm{bb}}$ distribution, the data is found to exceed the LO prediction by up to two standard deviations, depending on the considered mass. This excess is no longer significant when NLO QCD corrections, as implemented in aMC@NLO [49], are included in the modelling of the Z + jets process. For this reason, the LO predictions are corrected using a reweighting technique, in order to account for NLO QCD effects. To this end, it becomes necessary to apply the reweighting according to the parton (or hadron) flavour of the jets in the generated event. The ratio NLO/LO of the light- and heavy-flavour components of the $m_{\ell\ell\mathrm{jj}}$ distribution is each fitted with a third-order polynomial and a separate reweighting of the shape of the light and heavy flavour components of $m_{\ell\ell\mathrm{jj}}$ is applied, resulting in better agreement with the data.

To determine the Z + jets and $\mathrm{t\bar{t}}$ normalisation, a data-based method is exploited. Data-derived correction factors for simulation are obtained after an additional categorisation of the Z + jet background events, based on the flavour (b jet or not) and multiplicity (exactly two jets or three or more jets) of the reconstructed jets. These categories are sensitive to NLO effects related to the modelling of extra jets [50]. Scale factors (SFs) are introduced for the $\mathrm{t\bar{t}}$ background and the light and heavy flavour components of Z + jets background. These are left free to float in a two-dimensional fit of the distributions predicted by the simulation to the data. The distributions used as input are the product of the CSV discriminants of the two selected jets, and the invariant mass of the lepton pair from the Z boson decay in the range $60 < m_{\ell\ell} < 120$ GeV. The first observable is sensitive to the contribution from non-b jets, whereas the second one is sensitive to the contribution of the $\mathrm{t\bar{t}}$ production process. The fit is performed simultaneously in four different categories: electrons, muons, exactly two jets, and more than two jets. The SF for the $\mathrm{t\bar{t}}$ is found to be very close to the unity, while for the Z + jets process the SFs depart from unity by as much as 1.3 for the light flavour component.

The overall yields from diboson and tW processes are normalised to the CMS measurements [51–54]. The associated production of a Z boson together with the Higgs-like scalar boson (Zh) is also accounted for as background, and normalised to the expected theoretical cross section [55].

5.2. The $\ell\ell\tau\tau$ channel

Methods based on both data and simulation are used to estimate the residual background after event selection. Normalisations and mass distributions in the ZZ, Zh, as well as for the minor fully leptonic WWZ, WZZ, ZZZ and $\mathrm{t\bar{t}Z}$ backgrounds are estimated from simulation. The Z + jets and WZ + jets contributions are measured by means of a data-based method.

Production of Z + jets and WZ + jets constitutes the main source of background when at least one lepton is misidentified. Misidentified light leptons arise from semileptonic decays of heavy-flavour quarks, decays in flight of hadrons, and photon conversions, while jets originating from quarks or gluons can be misidentified as τ_h. Backgrounds with at least one misidentified lepton are estimated from control samples in data starting from the estimation of the lepton misidentification probabilities. The lepton misidentification probability is defined as the probability that a genuine jet, satisfying loose lepton identification criteria (which refer to the so-called "loose" lepton), also passes the identification criteria required for a lepton candidate in the signal region (so-called "tight" lepton). This probability is measured for each lepton flavour using a data sample where a Z candidate is selected, and an additional single lepton (electron, muon, or τ_h) passes the loose identification requirements. Counting the fraction of such loose leptons that also pass the tight lepton identification criteria in the p_T bins of the reconstructed jet closest, in ΔR, to the loose lepton, yields the misidentification probability f as a function of p_T. The contribution from genuine leptons arising from the WZ and ZZ production are subtracted. Once the misidentification probabilities are computed, three control regions (CR) are defined with a Z candidate and two opposite-sign leptons, as follows: the CR_{00} wherein both leptons pass loose identification criteria but not the tight ones; CR_{10} region, wherein one lepton passes tight identification requirements, the other only loose criteria, and the loose lepton is the τ_h with lower p_T in the $\tau_\mathrm{h}\tau_\mathrm{h}$ channel, the light lepton in the $\ell\tau_\mathrm{h}$ channels, and the electron in the eμ channel; the CR_{01} region, which is similar to CR_{10} but the loose lepton is the τ_h with higher p_T in the $\tau_\mathrm{h}\tau_\mathrm{h}$ channel, the τ_h in the $\ell\tau_\mathrm{h}$ channels, and the muon in the eμ channel. The estimated N_misID of the background with at least one misidentified lepton from a pair of closest-jet p_T bins is given by:

$$N_\mathrm{misID} = N_{10}\frac{f_1}{1-f_1} + N_{01}\frac{f_2}{1-f_2} - N_{00}\frac{f_1 f_2}{(1-f_1)(1-f_2)}, \qquad (1)$$

where N_{00}, N_{01}, and N_{10} denote the number of events from the CR_{00}, CR_{01}, and CR_{10} control regions, respectively, with closest jets in the considered p_T bins, and f_1 and f_2 indicate the misidentification probabilities associated with the two different flavor (except for the $\tau_\mathrm{h}\tau_\mathrm{h}$ final state) loose leptons in the p_T bins. The expression in Eq. (1) takes into account both the background with two misidentified leptons (mostly from Z+jets) and that from only one misidentified lepton (primarily from WZ + jets).

The contamination from genuine leptons in the control regions from the SM Zh, WWZ, WZZ, ZZZ, $\mathrm{t\bar{t}Z}$, and ZZ processes is estimated from simulation, and subtracted from N_{00}, N_{01}, and N_{10}. The total background in the signal region is obtained by summing the contributions from all pairs of p_T bins.

6. Systematic uncertainties

The systematic uncertainties are reported in the following paragraphs and summarised in Table 1.

The uncertainty on the integrated luminosity recorded by CMS is estimated to be 2.6% [56].

The systematic uncertainties associated with the lepton efficiency SFs, used to correct the simulation and derived from studies at the Z peak using the tag-and-probe (T&P) method [22,21], are approximately 1% for muons and 2% for electrons, and affect both signal and background processes in the same way. Also, the uncertainties on the double muon and double electron trigger efficiencies are evaluated to be 1% from similar studies at the Z peak [24].

The uncertainty on the jet energy scale is derived from the method of Ref. [57] and the parameters describing the shape of the energy distribution are varied by one standard deviation (SD). The effect is estimated separately on the background and on the signal, resulting in a 3–5% variation, depending on the p_T and η of the jets. The uncertainty on signal and background yields induced by the imperfect knowledge of the jet energy resolution is estimated to be 3% [57].

The uncertainties affecting b tagging efficiencies are p_T-dependent, and vary from 3% to 12% (for $p_\mathrm{T} > 30$ GeV) [44]. The impact of these uncertainties on the normalisation of signal is 5% for background and 4–6% for signal in the $\ell\ell$bb analysis, and about 1% in the $\ell\ell\tau\tau$ analysis. The uncertainty in the mistagging rate is found to have a negligible impact.

Table 1
Summary of systematic uncertainties for both $\ell\ell\tau\tau$ and $\ell\ell$bb final states.

Source	Uncertainty [%]	
	$H \to ZA \to \ell\ell bb$	$H \to ZA \to \ell\ell\tau\tau$
Luminosity	2.6	2.6
Lepton identification/isolation/scale	1–2	1–2
Lepton trigger efficiency	1	1
Jet energy scale	3–5	3–5
Jet energy resolution	3	3
b-tagging and mistag efficiency	4–6	1
Signal modelling (PDF, scale)	5–6	5–6
Background norm. (ZZ)	11	11
Background norm. (Z + jets and $t\bar{t}$)	<8	–
Background norm. (tW, WW, WZ and Zh)	8–23	–
Z + jet background modelling	5–30	–
Signal efficiency extrapolation	3–50	–
Tau identification/isolation	–	6
Tau energy scale	–	3
Reducible background estimate	–	40

The systematic uncertainty on the signal is evaluated by varying the set of parton distribution functions (PDFs) according to the PDF4LHC prescriptions [58–60] and the factorisation and renormalisation scales by varying their values by a factor one half and two. An effect of 5–6% is estimated for the entire mass range for both $\ell\ell\tau\tau$ and $\ell\ell$bb final states. This uncertainty is estimated by propagating these variations through the signal simulation and reconstruction sequence and thus accounts for uncertainties related to both signal cross section and acceptance.

Finally, an 11% uncertainty is assigned to the ZZ normalisation from the cross section measured by CMS [51].

For the $\ell\ell$bb final state, the uncertainty on the SFs used for normalisation of Z + jets and $t\bar{t}$ backgrounds is derived from the statistical uncertainty resulting from the fit used to derive these SFs and it is estimated to be <8%. An additional systematic uncertainty associated with the $m_{\ell\ell bb}$ spectrum correction, described in Sec. 5, ranges from 5% for $m_{\ell\ell bb}$ below 700 GeV to 30% for masses at the TeV scale. An uncertainty of 8% is assigned to the normalisation of the WW process, corresponding to the uncertainties in the cross section measured by CMS [52]. A similar uncertainty is assigned also to the WZ process, which shares the same sources of uncertainties in the cross section measurement. For the minor tW background, the uncertainty is estimated as 23%, also based on the measured cross section [54]. A 7% uncertainty is assigned to the Zh process, reflecting the uncertainty on the theoretical cross section [55]. Given the small cross section for this SM process compared to other background processes, its contribution to the background normalisation uncertainty has been calculated to be less than 1% and is thus considered negligible. In order to interpolate smoothly the signal efficiency across the parameter space, additional mass points for the $\ell\ell$bb final state are processed using a parametric simulation [61], tuned for delivering a realistic approximation of the CMS response in the reconstruction of physics objects used in this search. For this reason, an additional source of uncertainty is introduced for the SF applied to these samples to reproduce the efficiency measured with the full simulation. This is measured for the different signal points in the m_H–m_A plane and it is close to 3% in most of the phase space, but rises to 50% at the boundaries of the sensitivity region.

In the $\ell\ell\tau\tau$ final state, the uncertainty of 6% [39] in the τ_h identification efficiency, which has been determined using a T&P method, has been taken into account. The τ_h energy scale uncertainty is within 3% [39] and only affects the shapes of the $\tau\tau$ mass distributions. The systematic uncertainties estimated for e, μ, τ_h and jet energy scales are propagated to $\vec{p}_T^{miss}$ and to the mass distributions. The propagation to $\vec{p}_T^{miss}$ involves a sum of the energies of each object first and a consequent subtraction of such contributions once the nominal energy scales (or resolutions) are varied up and down by one SD (for e, μ, τ_h, and jets). One of the main systematic uncertainties is related to the nonprompt background estimation. This uncertainty has been evaluated using simulation by comparing the direct estimate of the backgrounds with that obtained using the procedure adopted in the analysis, but applied to simulated events. The discrepancy between the two estimates never exceeds 40%. This value is thus considered as the uncertainty on the estimates of the reducible background yield for all channels and all L_T thresholds.

7. Results

The analysis searches for new resonance decays by comparing data to simulation in the two-dimensional plane defined by the four-body ($m_{\ell\ell bb}$ or $m_{\ell\ell\tau\tau}$) and two-body (m_{bb} or $m_{\tau\tau}$) invariant masses. The numerical values for the upper limits or the significance of a local excess are obtained using the asymptotic method described in Ref. [62]. The CL$_S$ method [63,64] is used to determine the 95% confidence level (CL) upper limits on the excluded signal cross section. For both final states, the limits in the lower-right triangle of the mass plane, which corresponds to the process A → ZH, are obtained by mirroring the results obtained in the upper-left triangle, since the signal efficiencies for H → ZA and A → ZH are equal for the same masses of the heavy and light Higgs bosons in the two processes.

7.1. *The $\ell\ell$bb channel*

For the $\ell\ell$bb final state, results are obtained using a counting approach, which can be reinterpreted in other theoretical models with the same final state. Results are reported in bins of m_{bb} and $m_{\ell\ell bb}$ masses, in the range from 10 GeV to 1 TeV for m_{bb}, and from 140 GeV to 1 TeV for $m_{\ell\ell bb}$. To define the proper granularity of the binning, a study is performed using signal benchmark points and evaluating the width of the m_{bb} and $m_{\ell\ell bb}$ peaks in the considered mass range. The average reconstructed width, defined as one SD, for m_{bb} and $m_{\ell\ell bb}$ is found to be approximately 15% of the considered mass. The bin widths have been chosen to be ±1.5 SD around each considered mass point.

The efficiency, defined as the fraction of generated signal events reconstructed after the final selection, is calculated with the full CMS simulation and reconstruction software at 13 representative signal points in the m_H–m_A mass plane. The signal efficiencies for the rest of the plane are obtained by interpolating the ratio between the full simulation and the parametric simulation (typically

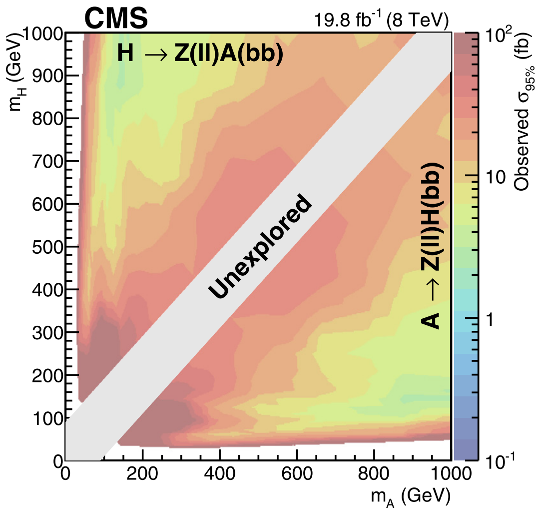

Fig. 1. Observed 95% CL upper limits on $\sigma_{H/A \to ZA/H \to \ell\ell bb}$ as a function of m_A and m_H.

0.9), calculated in each of the 13 signal mass points, and scaling the efficiencies calculated using the parametric simulation by this interpolated ratio. The resulting signal efficiency ranges from 8% at $(m_A, m_H) = (100, 300)$ GeV to 13% at $(300, 600)$ GeV.

Fig. 1 shows the observed upper limits on the product of the cross section (σ) and branching fraction ($\mathcal{B}$) for the $\ell\ell$bb final state in the m_H–m_A plane. The achieved sensitivity provides an exclusion limit at 95% CL of approximately 10 fb for a large fraction of the two-dimensional mass plane. In particular, the observed limit ranges from just above 1 fb for m_H close to 1 TeV to 100 fb for $m_H < 300$ GeV. The validity of these results is applicable to models allowing the existence of both A and H bosons with a natural width smaller than 15% of their masses.

Two moderate excesses are observed for the $\ell\ell$bb channel in the regions around $(m_{bb}, m_{\ell\ell bb}) = (95, 285)$ GeV and $(575, 660)$ GeV. According to the procedure described at Ref. [65], they have local significances of 2.6 and 2.85 SD respectively, which become globally 1.6 and 1.9 SD, once accounting for the look-elsewhere effect [66]. The low-mass excess is more compatible with the signal hypothesis, both in terms of yield and width. The reconstructed invariant mass distributions for the bb and $\ell\ell$bb systems, in the regions around this excess, are reported in Fig. 2 and compared with the expectations from background processes. A 2HDM type-II benchmark signal at $m_H = 270$ GeV and $m_A = 104$ GeV, normalised to the NNLO SusHi prediction, is also superimposed.

7.2. The $\ell\ell\tau\tau$ channel

In the context of the $\ell\ell\tau\tau$ analysis, a search based on the $m_{\tau\tau}$ distribution is performed. For every considered pair of H and A mass values, the search is performed in eight $\tau\tau$ SVFIT binned mass distributions, each corresponding to one of the eight considered final states. Variable bin widths are adopted in order to account for the mass resolution. A simultaneous likelihood fit to the observed distributions is performed with the expected distributions from the background-only and signal plus background hypotheses. The normalisation of the signal distribution is a free parameter in the fit. No significant deviations are observed in data from the SM expectation. The SVFIT mass distributions of the $\tau\tau$ pair in the eight different final states are shown in Fig. 3. The chosen signal corresponds to $m_H = 350$ GeV and $m_A = 90$ GeV, which is the one closest to the centre of the bin in which the highest

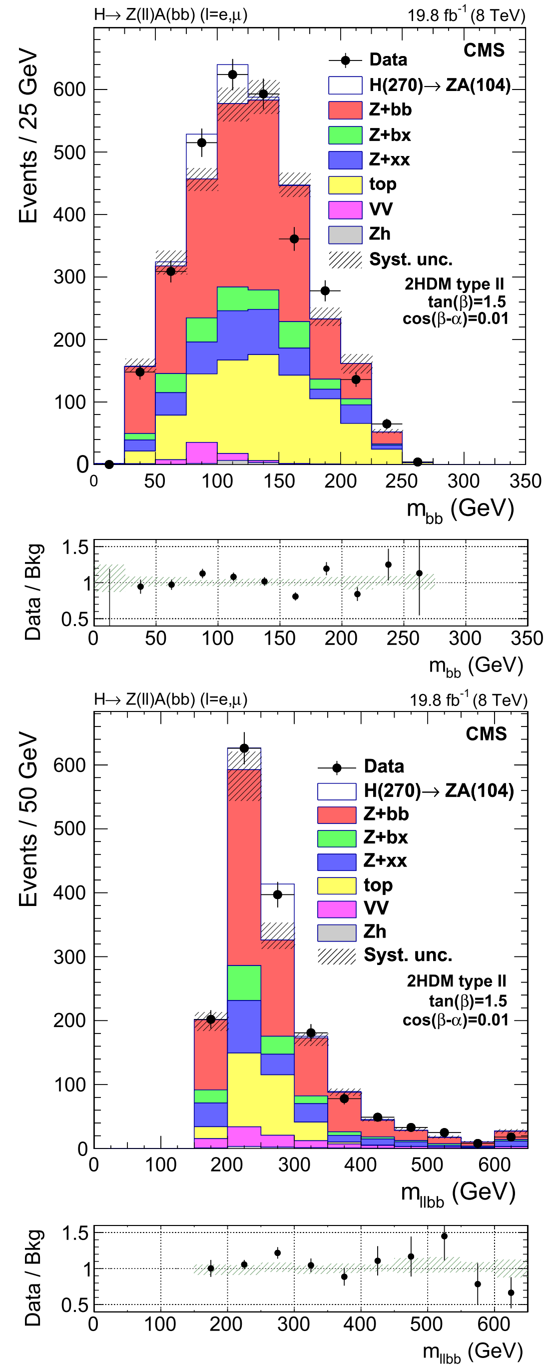

Fig. 2. (Top) The m_{bb} spectrum for events selected in the $222 < m_{\ell\ell bb} < 350$ GeV region for data and simulation and the relative ratio. (Bottom) The $m_{\ell\ell bb}$ spectrum for events selected inside the $72 < m_{bb} < 114$ GeV region for data and simulation and the relative ratio. The signal corresponding to $m_H = 270$ GeV and $m_A = 104$ GeV, normalised to the NNLO SusHi cross section, is superimposed for $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$ in the 2HDM type-II scenario. The overall systematic uncertainties in the simulation are reported as a hatched band.

excess is observed in the $\ell\ell$bb channel. The shown shapes correspond to $L_T > 40$ GeV for eμ, $L_T > 60$ GeV for eτ_h and $\mu\tau_h$, and $L_T > 80$ GeV for $\tau_h\tau_h$.

Fig. 4 shows the limit on $\sigma\,\mathcal{B}$ for the $\ell\ell\tau\tau$ final state in the m_H–m_A plane. Signal cross sections of about 5–10 fb are excluded in most of the m_H–m_A plane ($500 < m_{H/A} < 1000$ GeV and $90 < m_{A/H} < 400$ GeV).

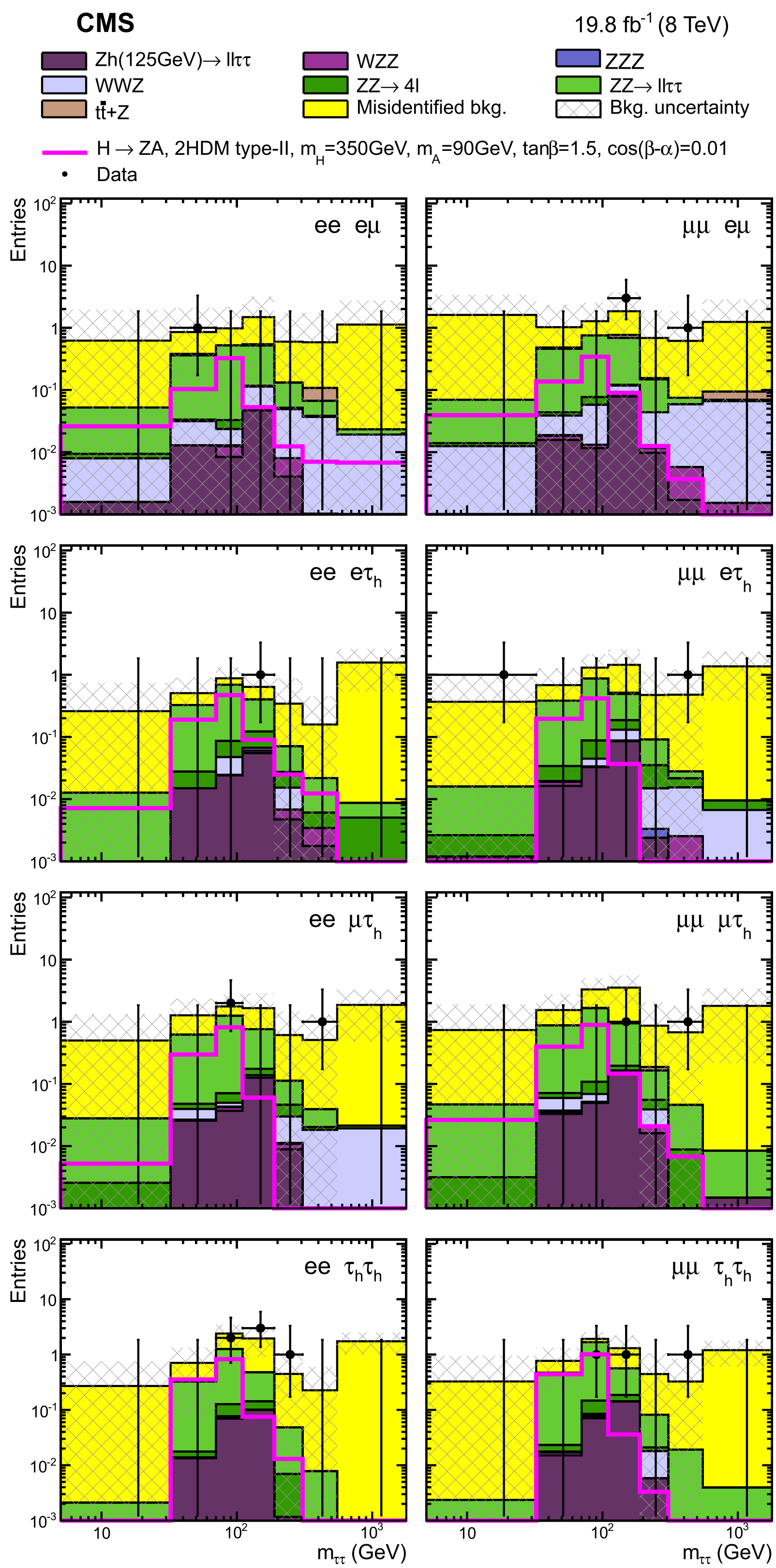

Fig. 3. SVFIT mass distributions for different final states of the $H \to ZA \to \ell\ell\tau\tau$ process, where the Z boson decays to ee (right column) and $\mu\mu$ (left column). The expected signal corresponding to $m_H = 350$ GeV and $m_A = 90$ GeV, whose cross section times branching fraction is normalised to the NNLO SusHi prediction, is superimposed for $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$ in the 2HDM type-II scenario. Only statistical uncertainties are reported as a hatched band.

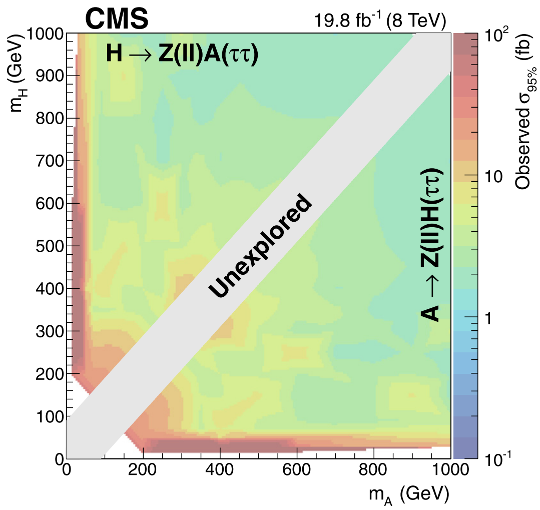

Fig. 4. Observed 95% CL upper limits on $\sigma_{H/A \to ZA/H \to \ell\ell\tau\tau}$ as a function of m_A and m_H.

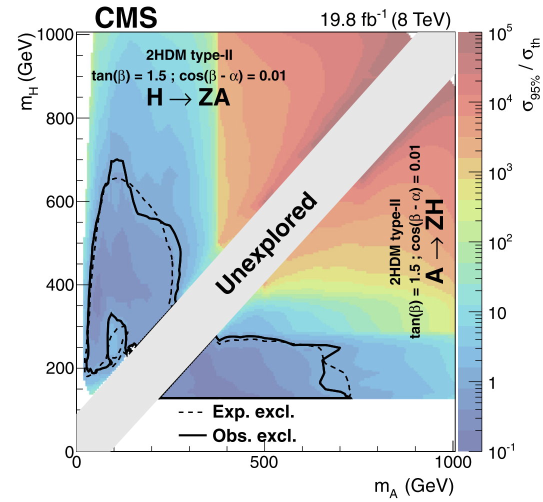

Fig. 5. Observed limits on the signal strength $\mu = \sigma_{95\%}/\sigma_{th}$ for the 2HDM benchmark, after combining results from $\ell\ell$bb and $\ell\ell\tau\tau$ final states. The cross sections are normalised to the NNLO SusHi prediction, for a 2HDM type-II scenario with $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$. The dashed contour shows the region expected to be excluded. The solid contour shows the region excluded by the data.

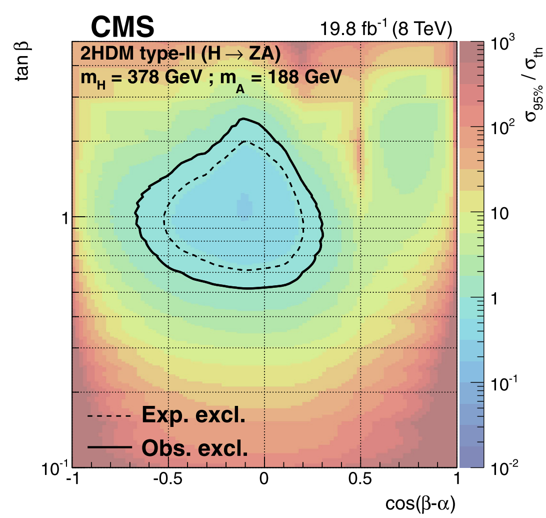

Fig. 6. Observed limits on the signal strength $\mu = \sigma_{95\%}/\sigma_{th}$ for the 2HDM benchmark after combining results from $\ell\ell$bb and $\ell\ell\tau\tau$ final states. The cross sections are normalised to the NNLO SusHi prediction. Limits are shown in the 2HDM parameters $\cos(\beta-\alpha)$ and $\tan\beta$ for the signal masses of $m_H = 378$ GeV and $m_A = 188$ GeV. The dashed contour shows the region expected to be excluded. The solid contour shows the region excluded by the data.

7.3. Combination in the context of 2HDM

Observed and expected upper limits on the signal cross section modifier $\mu = \sigma_{95\%}/\sigma_{th}$ are also derived and reported in Fig. 5, where σ_{th} is the theory cross section of the 2HDM signal benchmark used in this analysis. The results are obtained from the combination of the $\ell\ell$bb and $\ell\ell\tau\tau$ final states. This search is not able to exclude the high-mass regions where $m_A > 300$ GeV and $m_H > 300$ GeV, due to the drop in the signal cross section, where the $A/H \to t\bar{t}$ channel opens up for $m_{A/H} > 2m_t$, where m_t is the top quark mass [18]. Furthermore, in the region where highly-boosted topologies start contributing ($m_H \approx 10 m_A$), the sensitivity is lower relative to the rest of the plane, primarily caused by the inefficiency in reconstructing signal decay products in such a regime. Still, a significant portion of the benchmark masses is excluded for a 2HDM type-II scenario with $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$, delimited by the solid contour in Fig. 5. The observed 95% CL exclusion region is localised in the range $m_H = 200$–700 GeV and $m_A = 20$–270 GeV for the decay $H \to ZA$, and similarly in the range $m_A = 200$–700 GeV and $m_H = 120$–270 GeV for the $A \to ZH$ decay. The feature observed in the exclusion limit for the region around $(m_A, m_H) = (75$–$100, 200$–$300)$ GeV is the result of an interplay between the larger Z + jets background yields expected in this region and the quickly evolving signal cross section. The effect is visible in the expected limits and becomes slightly broader in the observed ones given the concurrent presence in the same region of a moderate data excess. The region where $|m_H - m_A| < m_Z$ is kinematically inaccessible.

The limits on μ can be also visualised as a function of the 2HDM parameters $\tan\beta$ and $\cos(\beta - \alpha)$ for a given pair of m_A and m_H, from the combination of $\ell\ell$bb and $\ell\ell\tau\tau$ final states. Results are given in Fig. 6, where the exclusion limits on the parameters are shown for $m_H = 378$ GeV and $m_A = 188$ GeV, a mass pair chosen to be within the exclusion region of Fig. 5. The area contained within the solid line shows the parameter space excluded for the chosen mass pair, where $\tan\beta$ lies between 0.5 and 2.3 and $\cos(\beta - \alpha)$ between -0.7 and 0.3.

8. Summary

The paper describes the first CMS search for a new resonance decaying into a lighter resonance and a Z boson. Two searches have been performed, targeting the decay of the lighter resonance into either a pair of oppositely charged τ leptons or a $b\bar{b}$ pair. The Z boson is identified via its decays to electrons or muons. The search is based on data corresponding to an integrated luminosity of 19.8 fb^{-1} in proton–proton collisions at $\sqrt{s} = 8$ TeV. Deviations from the SM expectations are observed with a global significance of less than 2 SD and upper limits on the product of cross section and branching fraction are set. The search excludes $\sigma\mathcal{B}$ as low as 5 fb and 1 fb for the $\ell\ell$bb and $\ell\ell\tau\tau$ final states, respectively, depending on the light and heavy resonance mass values.

Limits are also set on the mass parameters of the type-II 2HDM model that predicts the processes $H \to ZA$ and $A \to ZH$, where H and A are CP-even and CP-odd scalar bosons, respectively. Combining the $\ell\ell$bb and $\ell\ell\tau\tau$ final states, the specific model corresponding to the parameter choice $\cos(\beta - \alpha) = 0.01$ and $\tan\beta = 1.5$ is excluded for m_H in the range 200–700 GeV and m_A in the range

20–270 GeV with $m_H > m_A$, or alternatively for m_A in the range 200–700 GeV and m_H in the range 120–270 GeV with $m_A > m_H$.

Limits on the signal cross section modifier are also derived as a function of $\tan\beta$ and $\cos(\beta-\alpha)$ parameters. As a result, for specific m_H–m_A mass values, a fairly large region in the parameter space $\tan\beta$ *vs.* $\cos(\beta-\alpha)$ is excluded. This covers a region unexplored so far, that cannot be probed by studying production and decay modes of the SM-like Higgs boson. In particular, for $m_H = 378$ GeV and $m_A = 188$ GeV, a range where $\tan\beta$ lies between 0.5 and 2.3 and $\cos(\beta-\alpha)$ between −0.7 and 0.3 is excluded, after the combination of the $\ell\ell$bb and $\ell\ell\tau\tau$ final states.

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