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Search for a low-mass pseudoscalar Higgs boson produced in association with a $b\overline{b}$ pair in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

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Abstract

A search is reported for a light pseudoscalar Higgs boson decaying to a pair of τ leptons, produced in association with a $b\overline{b}$ pair, in the context of two-Higgs-doublet models. The results are based on pp collision data at a centre-of-mass energy of 8 TeV collected by the CMS experiment at the LHC and corresponding to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. Pseudoscalar boson masses between 25 and 80 GeV are probed. No evidence for a pseudoscalar boson is found and upper limits are set on the product of cross section and branching fraction to τ pairs between 7 and 39 pb at the 95% confidence level. This excludes pseudoscalar A bosons with masses between 25 and 80 GeV, with SM-like Higgs boson negative couplings to down-type fermions, produced in association with $b\overline{b}$ pairs, in Type II, two-Higgs-doublet models.

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1 Introduction

The discovery of a new boson with a mass close to 125 GeV [1–3], consistent with the standard model (SM) Higgs boson, has shed light on one of the most important questions of physics: the origin of the mass of elementary particles. Although all the measurements made up to now are in impressive agreement with the predictions of the SM [4, 5], the SM cannot address several crucial issues such as the hierarchy problem, the origin of the matter-antimatter asymmetry and the nature of dark matter [6–9]. Theories predicting new physics beyond the standard model have been proposed to address these open questions. Many of them predict the existence of more than one Higgs boson.

Two-Higgs-doublet models (2HDM) [10–14] are a particularly simple extension of the SM. Starting with the two doublet fields Φ_1 and Φ_2 and assuming an absence of CP violation in the Higgs sector, after $SU(2)_L$ symmetry breaking five physical states are left: two CP-even (h and H), one CP-odd (A), and two charged ($H^{\pm}$) bosons. To avoid tree-level flavour changing neutral currents, one imposes a Z_2 symmetry according to which the Lagrangian is required to be invariant under $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$. The result is four distinct classes of models, corresponding to different patterns of quark and lepton couplings. The most commonly considered are Type I and Type II. In Type I, all quarks and leptons obtain masses from $\langle\Phi_1\rangle$. In Type II, up-type quarks masses are derived from $\langle\Phi_1\rangle \equiv v_1$ and down-type quarks and charged leptons masses are derived from $\langle\Phi_2\rangle \equiv v_2$. In the limit of an exact Z_2 symmetry [15], the Higgs sector of a 2HDM can be described by six parameters: four Higgs boson masses (m_{h}, m_{H}, m_{A}, and $m_{\mathrm{H}^{\pm}}$), the ratio of the vacuum expectation values of the two doublets ($\tan\beta \equiv v_2/v_1$) and the mixing angle α of the two neutral CP-even Higgs states. Allowing a soft breaking of the Z_2 symmetry introduces a new Higgs mixing parameter m_{12}^2 [11]. In the "decoupling limit" of 2HDMs [16, 17], the masses m_{H}, m_{A}, and $m_{\mathrm{H}^{\pm}}$ are all large, $\cos(\beta-\alpha) \ll 1$, and h is the observed boson at 125 GeV and is SM-like. An SM-like h or H at 125 GeV can also be obtained in the "alignment limit" [16, 17] without the other bosons being heavy. This is an interesting case and can be compatible with the SM-like Higgs boson total width measurements and branching fractions even if one or more of the light Higgs bosons have a mass below half of 125 GeV provided one adjusts the model parameters so that the branching fraction of the SM Higgs boson to pairs of light Higgs bosons is very small. This scenario can be tested at the CERN LHC by searching for singly produced light bosons decaying to a pair of τ leptons with large cross sections. In Type II 2HDMs, if the Higgs coupling to the third generation of quarks is enhanced, as happens at large $\tan\beta$, a large production cross section is expected for the production of the low-mass A boson in association with $\mathrm{b\bar{b}}$. The cross section is of the order of 1 pb for regions of the 2HDM parameter space with $\sin(\beta-\alpha) \approx 1$, $\cos(\beta-\alpha) > 0$ and small m_{12}^2. The cross section can be much larger, between 10 and 100 pb, for some other regions of the parameter space, i.e. $\sin(\beta \pm \alpha) \approx 1$, $\cos(\beta-\alpha) < 0$ and $\tan\beta > 5$ [18, 19], where the coupling of the SM-like h boson to down-type fermions is negative ("wrong sign" Yukawa coupling). Consequently, given the large production cross section of the A boson in such scenarios, the LHC data are sensitive to its presence for some combinations of model parameters.

Previous searches for di-τ resonances [20, 21] have mainly focused on masses greater than the mass of the Z boson, for example in the context of the minimal supersymmetric standard model (MSSM) [22–24], which is a highly constrained 2HDM of Type II. In fact, a light pseudoscalar Higgs boson is excluded in the MSSM, but an A boson can still have quite a low mass in general 2HDMs, even given all the constraints from LEP, Tevatron and LHC data [18, 19].

This letter presents a search for a low-mass pseudoscalar Higgs boson produced in association with a $\mathrm{b\bar{b}}$ pair and decaying to a pair of τ leptons. Associated production of the A boson with a

$b\bar{b}$ pair has the advantage that there is a higher signal over background ratio relative to gluon-gluon fusion production. Such a signature is also relevant in the context of light pseudoscalar mediators and coy dark sectors [25]. The analysis is based on pp collision data at a centre-of-mass energy of 8 TeV recorded by the CMS experiment at the LHC in 2012. The integrated luminosity amounts to 19.7 fb^{-1}. The τ leptons are reconstructed via their muon, electron and hadronic decays. In the following, the terms leptons refer to electrons and muons, whereas τs that decay into hadrons+ν_τ are denoted by τ_h. The invariant mass distributions of the τ pairs in all three channels are used to search for pseudoscalar bosons with masses between 25 and 80 GeV.

2 The CMS detector and event samples

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. 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 a barrel and two endcap sections. Muons are detected in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [26].

The first level of the CMS triggering system (Level-1), composed of custom hardware processors, uses information from the calorimeters and the muons detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage.

A set of Monte Carlo (MC) simulated events is used to model the signal and backgrounds. Drell–Yan, W boson production associated to additional jets, production of top quark pairs ($t\bar{t}$), and diboson (WW, WZ and ZZ) backgrounds are generated using the leading order (LO) MADGRAPH 5.1 package [27]. Single top quark samples are produced using the next-to-leading-order (NLO) generator POWHEG (v1.0) [28]. Simulated samples of gluon-gluon fusion to $b\bar{b}A$ signal events are generated with PYTHIA 6.426 [29] for masses between 25 and 80 GeV in 5 GeV steps. As no loop is involved at leading order in the $b\bar{b}A$ production process, the product of acceptance and efficiency for signal only depends on the A boson mass, with no dependence on other model parameters. The simulated samples are produced using the CTEQ6L1 parton distribution function (PDF) set [30]. All the generated signal and background samples are processed with the simulation of the CMS detector based on GEANT 4 [31].

Additional events are added to the MC-simulated events, with weights corresponding to the luminosity profile in data, to simulate LHC conditions and the presence of other soft pp interactions (pileup) in the same or neighbouring bunch crossings of the main interaction. Finally, identical algorithms and procedures are used to reconstruct both simulated events and the collected data.

3 Event reconstruction

Event reconstruction is based on the particle-flow (PF) algorithm [32, 33], which aims to exploit the information from all subdetectors to identify individual particles (PF candidates): charged and neutral hadrons, muons, electrons, and photons. Complex objects, such as τ leptons that decay into hadrons and a neutrino, jets, and the imbalance in the transverse momentum in the event are reconstructed from PF candidates.

The deterministic annealing algorithm [34, 35] is used to reconstruct the collision vertices. The vertex with the maximum sum of squared transverse momenta (p_{T}^2) of all associated tracks is considered as the primary vertex. Muons, electrons, and τ_{h}s are required to originate from the primary collision vertex.

Muon reconstruction starts by matching tracks in the silicon tracker with tracks in the outer muon spectrometer [36]. A global muon track is fitted to the hits from both tracks. A preselection is applied to these muon tracks that includes requirements on their impact parameters, to distinguish genuine prompt muons from spurious muons or muons from cosmic rays. In addition, muons are required to pass isolation criteria to separate prompt muons from those associated with a jet, usually from the semi-leptonic decays of heavy quarks. The muon relative isolation is defined as the following [26]:

$$I_{\mathrm{rel}} = \left[\sum_{\text{charged}} p_{\mathrm{T}} + \max\left(0, \sum_{\text{neutral}} p_{\mathrm{T}} + \sum_{\gamma} p_{\mathrm{T}} - \frac{1}{2} \sum_{\text{charged,PU}} p_{\mathrm{T}} \right) \right] / p_{\mathrm{T}}^{\mu}, \tag{1}$$

where all sums are over the scalar p_{T} of particles inside a cone with size of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ relative to the muon direction, where η is the pseudorapidity and ϕ is the azimuthal angle (in radians) in the plane transverse to the beam axis, and "charged" corresponds to charged hadrons, muons, and electrons originating from the primary vertex, "neutral" refers to neutral hadrons and "charged,PU" refers to charged hadrons, muons, and electrons originating from other reconstructed vertices. The last of these sums is used to subtract the neutral pileup component in the computation, and the factor of $1/2$ reflects the approximate ratio of neutral to charged particles in jets [37].

Electron reconstruction starts from ECAL superclusters, which are groups of one or more associated clusters of energy deposited in the ECAL. Superclusters are matched to track seeds in the inner tracker (the closest layers of the tracker to the interaction point) and electron tracks are formed from those. Trajectories are reconstructed based on the modelling of electron energy loss due to bremsstrahlung, and are fitted using the Gaussian sum filter algorithm [38]. Electron identification is based on a multivariate (MVA) boosted decision tree technique [39] to discriminate genuine electrons from jets misidentified as electrons [40]. The most powerful variables for the discrimination of τ_{h} candidates are the ratio of energy depositions in the ECAL and HCAL, the angular difference between the track and supercluster, and the distribution of energy depositions in the electron shower. Relative isolation is defined in an analogous way to that of Eq. (1) and is used to distinguish prompt electrons from electrons within a jet.

Jets are reconstructed from PF candidates using the anti-k_{T} [41] algorithm with a distance parameter of 0.5, in the FASTJET package [42]. Several corrections are applied to the jet energies to reduce the effect of pileup and correct for the nonlinear response of the calorimeters [37]. To identify and reject jets from pileup, an MVA discriminator is defined based on information from the vertex and the jet distribution [43]. Jets identified as originating from a b quark, called b-tagged jets, are identified using the combined secondary vertex (CSV) algorithm [44], which is based on a likelihood technique, and exploits information such as the impact parameters of charged-particle tracks and the properties of reconstructed decay vertices.

The hadron-plus-strips (HPS) algorithm [45, 46] is used to reconstruct the τ_{h} candidates. It starts from a jet, and searches for candidates produced by the main hadronic decay modes of the τ lepton: either directly to one charged hadron, or via intermediate ρ and $a_1(1280)$ mesons to one charged hadron plus one or two neutral pions, or three charged hadrons with up to one neutral pion. The charged hadrons are usually long-lived pions, while the neutral pions decay rapidly into two photons. The HPS algorithm takes into account the possible conversion of photons into e^+e^- pairs in material in front of the ECAL, and their corresponding bremsstrahlung in the magnetic field with consequent broadening of the distribution of the shower. Strips are formed from energy depositions in the ECAL arising from electrons and photons. The strip sizes in ECAL are 0.05×0.20 in $\eta \times \phi$. The τ_h decay modes are reconstructed by combining the charged hadrons with ECAL strips. Neutrinos produced in τ_h decays are not reconstructed but contribute to E_T^{miss}. Isolation requirements based on an MVA technique take into account the p_T of PF candidates around the τ lepton direction and information related to its lifetime, such as the transverse impact parameter of the leading track of the τ_h candidate and its significance for decays to one charged hadron or the distance between the τ_h production and decay vertices and its significance for decays to three charged hadrons. Electrons can be misidentified as τ_h candidates with one track and ECAL strip. An MVA discriminator based on properties of the reconstructed electron, such as the distribution of the shower and the ratio of the ECAL and HCAL deposited energies, is used to improve pion/electron separation. Finally, another MVA discriminator is used to suppress muons reconstructed as τ_h candidates with one track. It exploits information about the energy deposited in the calorimeters with τ_h candidates, as well as hits and segments reconstructed in the muon spectrometers that can be matched to the components of the τ_h.

The missing transverse momentum vector $\vec{p}_T^{miss}$ is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as E_T^{miss}. To improve the resolution, and reduce the effect of pileup, a $\vec{p}_T^{miss}$ based on an MVA regression technique [47] is used, which takes into account several collections of particles from different vertices.

The invariant mass of the τ pair ($m_{\tau\tau}$) is used as the observable for the statistical interpretation of results in all channels and is reconstructed using the SVFIT algorithm [48]. The SVFIT algorithm uses a maximum likelihood technique where the likelihood takes as input the four-momenta of the visible decay products of the τ, the projection of $\vec{p}_T^{miss}$ along the x- and y-axes, as well as the covariance matrix of the components of $\vec{p}_T^{miss}$.

The relative $m_{\tau\tau}$ resolution obtained through the SVFIT algorithm is about 15% over the whole mass range. It is slightly higher for the $e\mu$ channel because of the presence of one additional neutrino.

4 Event selection

Three di-τ final states are considered: $\mu\tau_h$, $e\tau_h$, and $e\mu$. The $\mu\mu$ and ee final states are discarded because of their small branching fractions and large backgrounds, while $\tau_h\tau_h$ is not considered because of inefficiencies due to the trigger threshold.

The selection of events in the $\mu\tau_h$ or $e\tau_h$ final state starts from a trigger that requires a combination of a muon or electron with $p_T > 17$ or 22 GeV, respectively, and an isolated τ_h with $p_T > 20$ GeV. This combined trigger is seeded by a single muon or electron, with $p_T > 16$ or 20 GeV at Level-1. The offline selection requires a muon or electron with $p_T > 18$ or 24 GeV, respectively, and $|\eta| < 2.1$, and an oppositely charged τ_h candidate with $p_T > 22$ GeV and $|\eta| < 2.3$. Leptons are required to pass a tight identification [36, 40] and have a relative isolation, I_{rel}, <0.1. The τ_h candidates have to pass a tight working point of the MVA discriminant that combines isolation and lifetime information (resulting in a τ_h reconstruction and isolation efficiency of about 30% and a jet to τ_h misidentification rate between 0.5 and 1.0 per mille), as well as the requirements to suppress electron and muon candidates misidentified as τ_h, described in Section 3. Leptons and τ_h candidates are required to be separated by $\Delta R > 0.5$. Events with additional identified and isolated electrons or muons are discarded. To suppress W+jets and $t\bar{t}$ backgrounds, the transverse mass between the lepton transverse momentum $\vec{p}_T^{\ell}$ and $\vec{p}_T^{miss}$, defined in Eq. 2, is required to be smaller than 30 GeV,

$$M_T(\ell, \vec{p}_T^{miss}) = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - \cos \Delta\phi)}, \tag{2}$$

where $\Delta\phi$ is the azimuthal angle between the lepton transverse momentum and the $\vec{p}_T^{miss}$ vectors.

Events selected in the $e\mu$ channel must pass a trigger that requires a combination of an electron and a muon, with $p_T > 17(8)$ GeV for the leading (subleading) lepton. Depending on the flavour of the leading lepton that passes the trigger selection, events are required to have either a muon with $p_T > 18$ GeV and an electron with $p_T > 10$ GeV, or a muon with $p_T > 10$ GeV and an electron with $p_T > 20$ GeV. The fiducial regions for muons (electrons) are defined by $|\eta| < 2.1(2.3)$. Additionally, leptons with opposite charge are selected and required to be spatially separated by $\Delta R > 0.5$.

The muons and electrons are required to be isolated, with relative isolation less than 0.15 in the barrel ($|\eta| < 1.479$) and less than 0.1 in the endcaps ($|\eta| > 1.479$). In addition, both muons and electrons are required to pass the tight identification criteria as described in Section 3. Events having additional identified and isolated leptons are vetoed, similarly to the $\mu\tau_h$ and $e\tau_h$ channels. To reduce the large $t\bar{t}$ background in the $e\mu$ final state, a linear combination of the P_ζ and P_ζ^{vis} variables [49] is used. P_ζ and P_ζ^{vis} are defined as follows:

$$P_\zeta = \left(\vec{p}_T^{\mu} + \vec{p}_T^{e} + \vec{p}_T^{miss}\right) \cdot \hat{\zeta} \qquad \text{and} \qquad P_\zeta^{vis} = \left(\vec{p}_T^{\mu} + \vec{p}_T^{e}\right) \cdot \hat{\zeta}, \tag{3}$$

where $\hat{\zeta}$ is the unit vector of the axis bisecting the angle between $\vec{p}_T^{\mu}$ and $\vec{p}_T^{e}$ of the muon and electron candidates, respectively. These variables take into account the fact that the neutrinos produced in τ decays are mostly collinear with the visible τ decay products, but this is not true for neutrinos from the other sources, nor for misidentified τ_h candidates from background. The linear combination $P_\zeta - \alpha P_\zeta^{vis}$ is required to be greater than -40 GeV, with an optimal value of α of 1.85, determined in the CMS search for a MSSM Higgs boson in the $\tau\tau$ final state [21]. To further reduce $t\bar{t}$ and electroweak backgrounds in the $e\mu$ final state, the M_T between the dilepton transverse momentum and $\vec{p}_T^{miss}$, defined as in Eq. 2, is required to be less than 25 GeV.

In addition to the above selections, events in all channels are also required to have at least one b-tagged jet with $p_T > 20$ GeV and $|\eta| < 2.4$, which passes the working point of the CSV b-tagging discriminant (corresponding to b-tagging efficiency of about 65% and light-jet misidentification rate of about 1%) and the pileup MVA discriminant for jets, and is separated by at least $\Delta R = 0.5$ from the signal leptons.

5 Background estimation

One of the main backgrounds in all three channels is $Z/\gamma^* \to \tau\tau$. Drell–Yan events with invariant mass larger than 50 GeV are modelled using "embedded" event samples, as follows: $Z \to \mu\mu$ events are selected in data with an invariant mass larger than 50 GeV to remove the mass range biased by a trigger requirement. The reconstructed muons are replaced by simulated τ leptons that are subsequently decayed via TAUOLA [50]. To model the detector response to the τ decay products the GEANT based detector simulation is used. Jets, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, and τ_{h} are then reconstructed, while lepton isolations are recomputed [51]. This substantially reduces the uncertainties related to the modelling of the $E_{\mathrm{T}}^{\mathrm{miss}}$, the jet energy scale, and the b jet efficiency. Low-mass $Z/\gamma^* \to \tau\tau$ events, which cannot be covered by the embedded samples, are taken directly from a simulated sample.

Multijet events originated by QCD processes comprise another major background, especially at low di-τ mass. The contribution of the QCD multijet background arises from jet $\to$ τ_{h} misidentification and to a lesser extent from jet $\to \mu$ and jet $\to$ e misidentification, depending on the final state. Other contributions are due to the presence of muons or electrons from the semi-leptonic decays of heavy flavour quarks. This background is estimated from data.

Multijet background normalisation in the $\mu\tau_{\mathrm{h}}$ and $e\tau_{\mathrm{h}}$ final states is determined from a sample defined in the same way as the signal selection described in Section 4, except that the lepton and the τ_{h} candidate are required to have electric charge of same sign (SS). The events with the SS selection are dominated by multijets, and the limited contribution from the other processes is subtracted using predictions from simulated events. To take into account the difference in the multijet normalisation between the SS and opposite-sign (OS) regions, an OS/SS extrapolation factor is used to multiply the multijet yield in the SS region. This factor is measured in signal-free events selected with inverted lepton isolations ($0.2 < I_{\mathrm{rel}} < 0.5$) and a relaxed τ_{h} isolation. The OS/SS extrapolation factor is parameterised as a function of $m_{\tau\tau}$, and fitted with an exponentially decreasing function. This ratio is approximately equal to 1.2 for di-τ masses of 20 GeV, and decreases to about 1.1 for masses above 50 GeV.

The $m_{\tau\tau}$ distribution for the QCD multijet background is obtained from a control region in data by inverting the lepton isolation and relaxing the τ_{h} isolation. These two selections are required to attain a control region populated with QCD multijet events and obtain a sufficiently smooth $m_{\tau\tau}$ distribution. A correction has been applied to account for the differences between the nominal selection and the selection used to estimate the QCD multijet $m_{\tau\tau}$ distribution. The correction depends on the τ_{h} misidentification rate (the probability for a τ_{h}, that passes a looser isolation requirement, to pass the tight isolation selection). This rate is parameterised as a function of the p_{T} of the τ_{h} in three bins of pseudorapidity. It was checked that the $m_{\tau\tau}$ distributions obtained when the lepton isolation is inverted and the τ_{h} isolation is relaxed, are consistent within statistical uncertainties with the normal search procedure.

In the $e\mu$ final state, the QCD multijet background is measured simultaneously with other backgrounds using misidentified leptons in data, through a "misidentified-lepton" method [51], and requiring at least one jet misidentified as a lepton. The probability for loosely preselected leptons, mainly dominated by leptons within jets, to be identified as good leptons is measured in samples depleted of isolated leptons as a function of the p_{T} and η. Weights obtained from this measurement are applied to events in data with electrons and muons passing the loose preselection but not the nominal selection criteria, to extract the QCD multijet background contribution.

In the $\mu\tau_{\mathrm{h}}$ and $e\tau_{\mathrm{h}}$ final states, the W+jets background arises from events with a genuine isolated and identified lepton from the leptonic decay of a W boson and a jet misidentified as a τ_{h}. Its contribution is highly suppressed by requiring the M_{T} of the lepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ of Eq. (2) to be $<$30 GeV (low-M_{T} region). The W+jets normalisation is determined from collision data using the yield in the high-M_{T} ($>$70 GeV) sideband, multiplied by an extrapolation factor that is the ratio of the W+jets events in the high- and low-M_{T} regions in simulated events. The small contribution from other backgrounds in events selected with high-M_T selection is subtracted using the prediction from simulations. The distribution of $m_{\tau\tau}$ for the W+jets background is taken from simulation. A correction to the distribution, measured in a sample enriched in W+jets and as a function of the p_T of the lepton originating from the W boson, is applied to correct the differences between observed and simulated events. In the eμ final state, the W+jets background is estimated together with the backgrounds that contain at least one jet misidentified as a lepton, such as QCD multijets, as previously described.

The $Z/\gamma^* \to \mu\mu$ and $Z/\gamma^* \to$ ee processes contribute, respectively, to the $\mu\tau_h$ and eτ_h final states, because of the misidentification of a lepton as a τ_h. The normalisation and the distribution of $m_{\tau\tau}$ for these backgrounds are obtained from simulation.

The presence of genuine b jets from top quark decays makes the $t\bar{t}$ background contribution important. The $t\bar{t}$ background has true τ_h ≈70% of the times and misidentified τ_h in ≈30% of the times. The distribution of $m_{\tau\tau}$ for $t\bar{t}$ events is taken from simulation, but normalised to the measurement of the $t\bar{t}$ cross section [52]. A reweighting is applied to generated $t\bar{t}$ events to improve the modelling of the top quark p_T spectrum. This reweighting only depends on the simulated p_T of top and antitop quarks [52], and has a negligible impact on the final results. In addition, the $m_{\tau\tau}$ distributions observed in data and predicted by MC simulations are compared in a region with high purity of $t\bar{t}$ events, and depleted in signal, obtained by raising the p_T threshold of the leptons and τ_h, and requiring at least two b-tagged jets with a higher p_T threshold than that used in event selections described in Section 4. Good agreement is found between distributions in data and MC simulation.

Single top quark, diboson (WW, WZ, ZZ), and SM Higgs backgrounds represent a small fraction of the total background, and are taken from simulations and normalised to the NLO cross sections [51, 53, 54].

Scale factors to correct for residual discrepancies between data and MC simulation related to the lepton triggering, identification, and isolation are applied to the signal and the backgrounds estimated from MC simulations. These correction factors are determined using the "tag-and-probe" technique [45, 46, 55], which relies on the presence of two leptons from Z boson decays. No correction factor is applied to the τ_h candidate nor to the selected b jet, as the corrections are found to be consistent with unity. The uncertainties related to these scale factors are described in Section 6.

6 Systematic uncertainties

The results of the analysis are extracted from a fit based on the $m_{\tau\tau}$ distributions in each final state, as discussed in Section 7. Systematic uncertainties in the fit affect the normalisation or the shape of the $m_{\tau\tau}$ distribution for the signal and backgrounds. The normalisation uncertainties are summarised in Table 1.

The uncertainty in normalisation that affects the signal and most of the simulated backgrounds is related to the integrated luminosity at 8 TeV, which is measured with a precision of 2.6% [56]. Uncertainties in muon and electron identification and trigger efficiency, as well as in the τ_h identification efficiency, are determined using the "tag-and-probe" technique [45, 46, 55]. These uncertainties are about 2% for muon and electron and 8% for τ_h. Changes in acceptance due to the uncertainty in the b tagging efficiency and the b mistag rate range from 1 to 9% depending on the process. To estimate the uncertainty in the W+jets normalisation, the uncertainty in the extrapolation factor from the high-M_T sideband to the signal region is obtained by varying

$E_{\mathrm{T}}^{\mathrm{miss}}$ and its resolution by their uncertainties, leading to a 30% uncertainty. The uncertainty in the normalisation of QCD multijet background is obtained by adding the statistical uncertainty related to the sample size of the QCD multijet-dominated control region in quadrature with the uncertainty in the extrapolation factor from the control region to the signal region; this amounts to 20%. The normalisation uncertainty for the $\mathrm{t\bar{t}}$ background amounts to 10%; it is determined from a control region where both W bosons originating from the top and antitop quarks decay to τ leptons[51]. Uncertainties related to the diboson background cross section amount to 15% [57].

A 30% uncertainty in the signal strength (ratio of observed to expected cross sections) for the SM Higgs boson is applied [51]. Theoretical uncertainties arising from the underlying event and parton showering matching scale, PDF [58] and the dependence on factorisation and normalisation scales are considered for signal. The PDF uncertainty is taken as the difference in the signal acceptance for the signal simulation with CTEQ6L1, MSTW2008NLO [59], and NNPDF2.3NLO [60] PDF sets, leading to a 10% uncertainty. A 20% uncertainty in the signal normalisation is applied to take into account the possible difference in the product of acceptance and efficiency between the LO sample generated with PYTHIA6.4 and the NLO sample generated by the MADGRAPH5_aMC@NLO generator [61].

The τ_{h} and electron energy scales are among the systematic uncertainties affecting the $m_{\tau\tau}$ distributions. To estimate the effects of these uncertainties, the electron energy scale is changed by 1% or by 2.5% for electrons reconstructed in the barrel or in the endcap regions of the ECAL [40], respectively, while the τ_{h} energy scale is varied by 3% [46]. The top quark p_{T} reweighting correction, used for simulated $\mathrm{t\bar{t}}$ events to match the observed p_{T} spectrum in a dedicated control region, is changed between zero and twice the nominal value [52, 62]. The uncertainty in the τ_{h} misidentification rate correction of the QCD multijet and W+jets background distributions has been taken into account. To estimate this uncertainty, the τ_{h} misidentification rate correction has been changed between zero and twice its value. An additional trigger uncertainty is applied to the $\mu\tau_{\mathrm{h}}$ and $\mathrm{e}\tau_{\mathrm{h}}$ final states to cover possible differences between collision data and simulated events in the low-p_{T} lepton region, where the trigger efficiency has not yet reached its plateau. These low-p_{T} leptons are attributed an uncertainty that corresponds to half of the difference between the measured and the plateau efficiencies. Finally, uncertainties due to the limited number of simulated events, or the number of events in the control regions in data, are taken into account. These uncertainties are uncorrelated across the bins in each background distribution [63].

Among all systematic uncertainties, the ones that have the largest impact on the results are the τ_{h} energy scale, the uncertainties related to the jet to muon, electron or τ_{h} misidentification rates, and the uncertainties from the limited number of simulated events (or the observed events in data control regions). The impact of these individual uncertainties on the combined expected limit ranges between 5 and 10% depending on $m_{\tau\tau}$.

7 Results

The mass distributions for the $\mu\tau_{\mathrm{h}}$, $\mathrm{e}\tau_{\mathrm{h}}$ and $\mathrm{e}\mu$ channels are shown in Fig. 1. No significant excess of data is observed on top of the SM backgrounds. A binned maximum likelihood fit has been applied simultaneously to all three distributions, taking into account the systematic uncertainties as nuisance parameters. A log-normal probability distribution function is assumed for the nuisance parameters that affect the event yields of the various background contributions. Systematic uncertainties affecting the $m_{\tau\tau}$ distributions are assumed to have a Gaussian probability distribution function.

Table 1: Systematic uncertainties that affect the normalisation.

	Systematic source	Systematic uncertainty		
		$\mu\tau_h$	$e\tau_h$	$e\mu$
Normalisation	Integrated luminosity	2.6%	2.6%	2.6%
	Muon ID/trigger	2%	—	2%
	Electron ID/trigger	—	2%	2%
	τ_h ID/trigger	8%	8%	—
	Muon to τ_h misidentification rate	30%	—	—
	Electron to τ_h misidentification rate	—	30%	—
	b tagging efficiency	1–4%	1–4%	1–4%
	b mistag rate	1–9%	1–9%	1–9%
	E_T^{miss} scale	1–2%	1–2%	1–2%
	$Z/\gamma^* \to \tau\tau$ normalisation	3%	3%	3%
	$Z/\gamma^* \to \tau\tau$ low-mass normalisation	10%	10%	10%
	QCD multijet normalisation	20%	20%	—
	Reducible background normalisation	—	—	30%
	W+jets normalisation	30%	30%	—
	$t\bar{t}$ cross section	10%	10%	10%
	Diboson cross section	15%	15%	15%
	$H \to \tau\tau$ signal strength	30%	30%	30%
Theory	Underlying event and parton shower	1–5%	1–5%	1–5%
	Scales for A boson production	10%	10%	10%
	PDF for generating signal	10%	10%	10%
	NLO vs. LO	20%	20%	20%

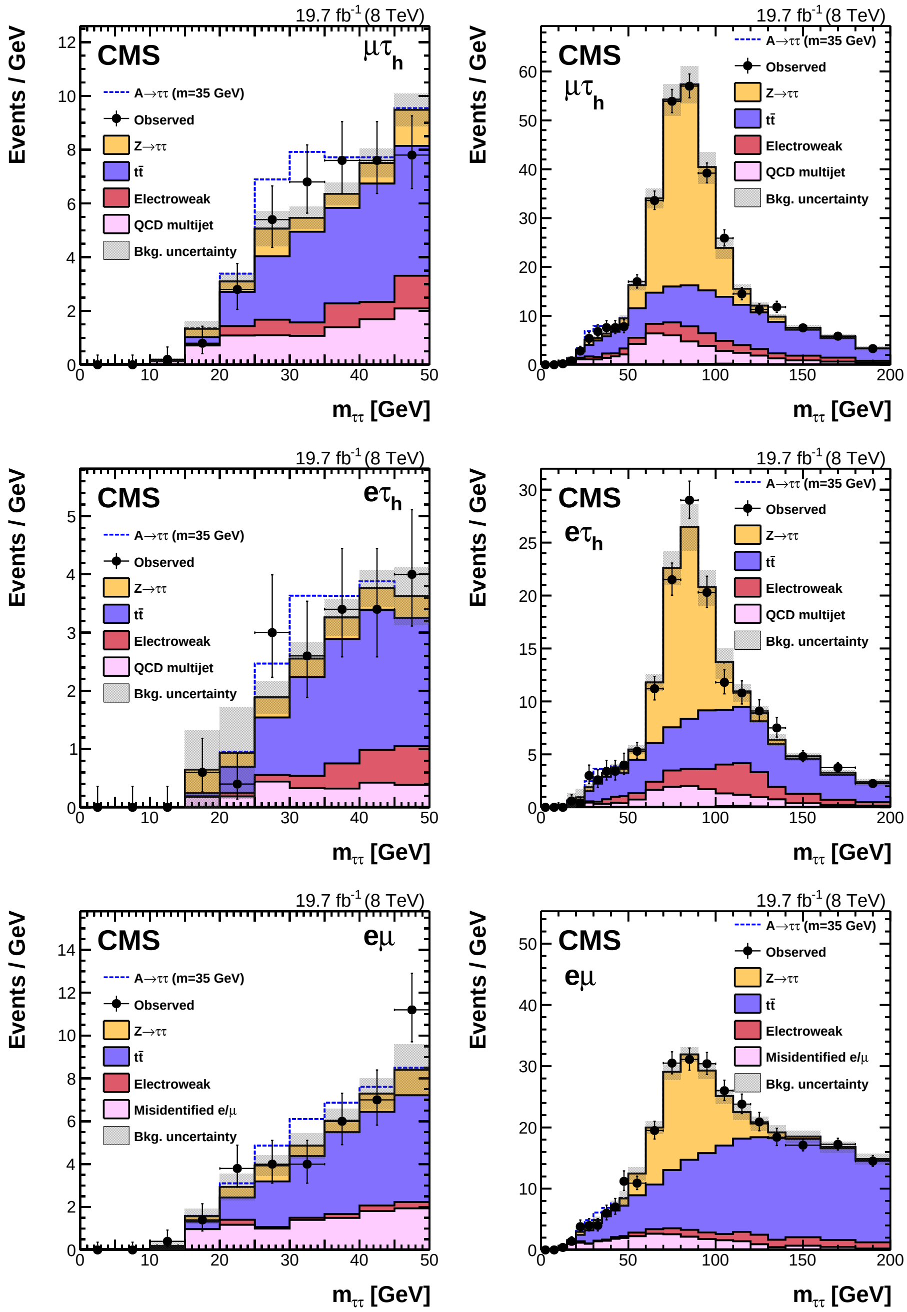

Figure 1: Observed and predicted $m_{\tau\tau}$ distributions in the $\mu\tau_h$ (top), $e\tau_h$ (middle), and $e\mu$ (bottom) channels. The plots on the left are the zoomed-in versions for $m_{\tau\tau}$ distributions below 50 GeV. A signal for a mass of $m_A = 35$ GeV is shown for a cross section of 40 pb. In $\mu\tau_h$ and $e\tau_h$ final states, the electroweak background is composed of $Z \to ee$, $Z \to \mu\mu$, W+jets, diboson, and single top quark contributions. In the $e\mu$ final state, the electroweak background is composed of diboson and single top backgrounds, while the misidentified e/μ background is due to QCD multijet and W+jets events. The contribution from the SM Higgs boson is negligible and therefore not shown. Expected background contributions are shown for the values of nuisance parameters (systematic uncertainties) obtained after fitting the signal + background hypothesis to the data.

Upper limits on the product of cross section and branching fraction of the pseudoscalar Higgs boson to $\tau\tau$ are set at 95% confidence level (CL) using the modified frequentist construction CL_s [64, 65] and the procedure is described in Refs. [66, 67]. The observed and expected limits on the $b\bar{b}A \rightarrow b\bar{b}\tau\tau$ process and the one and two standard deviation uncertainties on the expected limits are shown in Fig. 2. Among the three channels, $\mu\tau_h$ is the most sensitive one for the entire mass range because of the higher branching fraction relative to the $e\mu$ channel, lower trigger and offline thresholds on the lepton p_T relative to the $e\tau_h$ channel, and higher muon than electron identification efficiency. Although background yields increase sharply with the mass, the acceptance of the signal grows faster, providing thereby more stringent limits on the cross section at higher masses. The product of signal acceptance and efficiency in the $\mu\tau_h$ channel changes from 1.5×10^{-5} at an A boson mass of 25 GeV to 6×10^{-4} at $m_A = 80$ GeV. In the $e\tau_h$ channel it ranges from 3×10^{-6} at 25 GeV to 2×10^{-4} at 80 GeV, and finally in the $e\mu$ channel, it ranges from 1.3×10^{-5} at 25 GeV to 3.5×10^{-4} at 80 GeV. The trigger requirements and the p_T threshold of the leptons and τ_hs are the main factors in driving the signal acceptance and efficiency, especially at low masses.

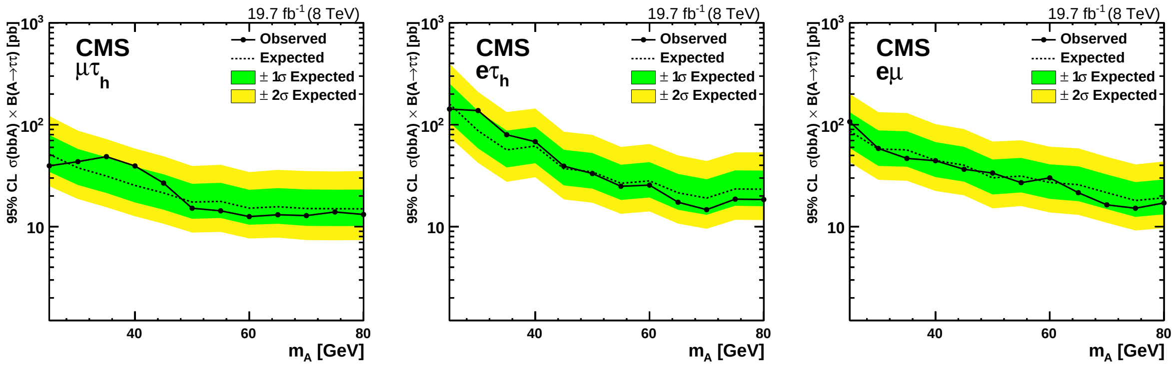

Figure 2: Observed and expected upper limits at 95% CL on the product of cross section and branching fraction for a light pseudoscalar Higgs boson produced in association with two b quarks, that decays to two τ leptons, in the $\mu\tau_h$ (left), $e\tau_h$ (middle), and $e\mu$ (right) channels. The 1σ and 2σ bands represent the 1 and 2 standard deviation uncertainties on the expected limits.

The upper limits from the combination of all final states are presented in Fig. 3, with exact values quoted in Table 2. They range from 7 to 39 pb for A boson masses between 25 and 80 GeV. In addition, superimposed in Fig. 3 are several typical production cross sections for the pseudoscalar Higgs boson produced in association with a pair of b quarks in Type II 2HDM, for m_A less than half of the 125 GeV Higgs boson (h), and for $\mathcal{B}(h \rightarrow AA) < 0.3$ [19]. The points are obtained from a series of scans in the 2HDM parameter space. Points with SM-like Yukawa coupling and small $\tan\beta$ have $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) > 0$, and low m_{12}^2, while points with "wrong sign" Yukawa coupling have $\sin(\beta \pm \alpha) \approx 1$, small $\cos(\beta - \alpha) < 0$, and $\tan\beta > 5$. While the combined results of the current analysis are not sensitive to the SM-like Yukawa coupling, they exclude the "wrong sign" Yukawa coupling for almost the entire mass range, and more generally for $\tan\beta > 5$. For masses greater than $m_h/2$, where the constraint on $\mathcal{B}(h \rightarrow AA) < 0.3$ is automatically satisfied, the production cross section of the pseudoscalar Higgs boson in association with a pair of b quarks is much larger [18]; consequently, the exclusion limit extends to masses up to 80 GeV.

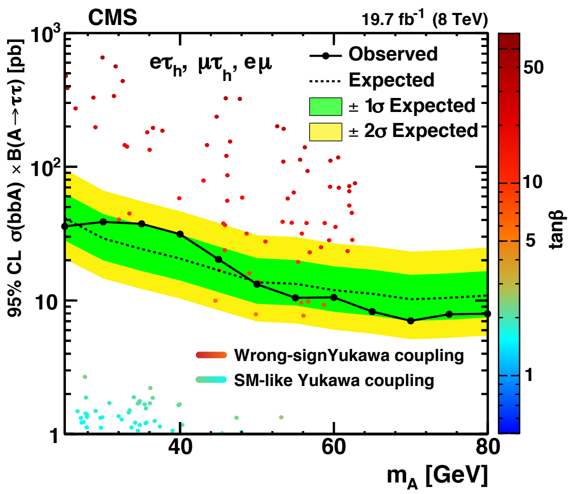

Figure 3: Expected cross sections for Type II 2HDM, superimposed on the expected and observed combined limits from this search. Cyan and green points, indicating small values of $\tan\beta$ as shown in the colour scale, have $\sin(\beta-\alpha) \approx 1$, $\cos(\beta-\alpha) > 0$, and low m_{12}^2, and correspond to models with SM-like Yukawa coupling, while red and orange points, with large $\tan\beta$, have $\sin(\beta+\alpha) \approx 1$, small $\cos(\beta-\alpha) < 0$, and $\tan\beta > 5$, and correspond to the models with a "wrong sign" Yukawa coupling. Theoretically viable points are shown only up to $m_A = m_h/2$ [19]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2: Expected and observed combined upper limits at 95% CL in pb, along with their 1 and 2 standard deviation uncertainties, in the product of cross section and branching fraction for pseudoscalar Higgs bosons produced in association with $b\bar{b}$ pairs.

m_A (GeV)	Expected limit (pb)					Observed limit (pb)
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
25	20.4	28.1	41.3	63.1	95.5	35.8
30	14.6	20.0	29.1	44.3	66.3	38.7
35	12.2	16.6	24.3	36.7	55.1	37.4
40	10.3	14.1	20.6	31.1	46.5	31.3
45	8.4	11.6	16.8	25.3	37.9	20.3
50	7.0	9.5	13.7	20.7	30.8	13.2
55	6.7	9.2	13.3	20.1	29.9	10.5
60	6.1	8.2	12.0	18.0	26.7	10.6
65	5.6	7.7	11.2	17.0	25.4	8.3
70	5.1	7.0	10.2	15.6	23.3	7.1
75	5.3	7.2	10.5	15.9	23.8	7.9
80	5.5	7.5	10.9	16.6	25.0	8.0

8 Summary

A search by the CMS experiment for a light pseudoscalar Higgs boson produced in association with a $b\overline{b}$ pair and decaying to a pair of τ leptons is reported. Three final states: $\mu\tau_h$, $e\tau_h$, and $e\mu$, are used where τ_h represents a hadronic τ decay. The results are based on proton-proton collision data accumulated at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of $19.7\,fb^{-1}$. Pseudoscalar boson masses between 25 and 80 GeV are probed. No evidence for a pseudoscalar boson is found and upper limits are set on the product of cross section and branching fraction to τ pairs between 7 and 39 pb at the 95% confidence level. This excludes pseudoscalar A bosons with masses between 25 and 80 GeV, with SM-like Higgs boson negative couplings to down-type fermion, produced in association with $b\overline{b}$ pairs, in Type II, two-Higgs-doublet models.

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