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Search for neutral Higgs bosons decaying to tau pairs in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

A search for neutral Higgs bosons decaying to tau pairs at a center-of-mass energy of 7 TeV is performed using a dataset corresponding to an integrated luminosity of 4.6 fb^{-1} recorded by the CMS experiment at the LHC. The search is sensitive to both the standard model Higgs boson and to the neutral Higgs bosons predicted by the minimal supersymmetric extension of the standard model (MSSM). No excess of events is observed in the tau-pair invariant-mass spectrum. For a standard model Higgs boson in the mass range of 110–145 GeV upper limits at 95% confidence level (CL) on the production cross section are determined. We exclude a Higgs boson with $m_{\mathrm{H}} = 115$ GeV with a production cross section 3.2 times of that predicted by the standard model. In the MSSM, upper limits on the neutral Higgs boson production cross section times branching fraction to tau pairs, as a function of the pseudoscalar Higgs boson mass, m_{A}, sets stringent new bounds in the parameter space, excluding at 95% CL values of $\tan\beta$ as low as 7.1 at $m_{\mathrm{A}} = 160$ GeV in the $m_{\mathrm{h}}^{\mathrm{max}}$ benchmark scenario.

1. Introduction

An important goal of the LHC physics program is to ascertain the mechanism of electroweak symmetry breaking, through which the W and Z bosons attain mass, while the photon remains massless. In the standard model (SM) [1–3], this is achieved via the Higgs mechanism [4–9], which also predicts the existence of a scalar Higgs boson. However, this particle has not yet been observed by experiments. Moreover, the mass of the Higgs boson is quadratically divergent at high energies [10]. Supersymmetry [11] is a well known extension to the SM which allows the cancellation of this divergence.

The minimal supersymmetric standard model (MSSM) contains two Higgs doublets, giving rise to five physical states: a light neutral CP-even state (h), a heavy neutral CP-even state (H), a neutral CP-odd state (A), and a pair of charged states ($\mathrm{H}^{\pm}$) [12–15]. The mass relations between these particles depend on the MSSM parameter $\tan\beta$, the ratio of the Higgs fields vacuum expectation values. We focus on the $m_{\mathrm{h}}^{\mathrm{max}}$ [16,17] benchmark scenario in which $M_{\mathrm{SUSY}} = 1$ TeV; $X_t = 2M_{\mathrm{SUSY}}$; $\mu = 200$ GeV; $M_{\tilde{g}} = 800$ GeV; $M_2 = 200$ GeV; and $A_b = A_t$. Here, M_{SUSY} denotes the common soft-SUSY-breaking squark mass of the third generation; $X_t = A_t - \mu/\tan\beta$ is the stop mixing parameter; A_t and A_b are the stop and sbottom trilinear couplings, respectively; μ the Higgsino mass parameter; $M_{\tilde{g}}$ the gluino mass; and M_2 is the SU(2)-gaugino mass parameter. The value of M_1 is fixed via the unification relation $M_1 = (5/3)M_2 \sin\theta_{\mathrm{W}}/\cos\theta_{\mathrm{W}}$. In this scenario for values of $\tan\beta \gtrsim 15$, if $m_{\mathrm{A}} \lesssim 130$ GeV the masses of the h and A are almost degenerate, while the mass of the H is around 130 GeV. Conversely, if $m_{\mathrm{A}} \gtrsim 130$ GeV, the masses of the A and H are almost degenerate, while the mass of the h remains near 130 GeV. This will thus always lead to one neutral Higgs boson at 130 GeV and two neutral Higgs bosons with almost degenerate mass of m_{A}.

Direct searches for the SM Higgs boson at the Large Electron–Positron Collider (LEP) set a limit on the mass $m_{\mathrm{H}} > 114.4$ GeV at 95% confidence level (CL) [18]. The Tevatron collider experiments exclude the SM Higgs boson in the mass range 162–166 GeV [19], and the ATLAS experiment in the mass ranges 112.9–115.5, 131–238, and 251–466 GeV [20]. Precision electroweak data constrain the mass of the SM Higgs boson to be less than 158 GeV [21]. Direct searches for neutral MSSM Higgs bosons have been reported by LEP, the Tevatron, and both LHC experiments, and set limits on the MSSM parameter space in the $\tan\beta$–m_{A} plane [22–26].

This Letter reports a search for the SM and the neutral MSSM Higgs bosons using final states with tau pairs in proton–proton collisions at $\sqrt{s} = 7$ TeV at the LHC. We use a data sample collected in 2011 corresponding to an integrated luminosity of 4.6 fb^{-1} recorded by the Compact Muon Solenoid (CMS) [27] experiment. Three independent tau-pair final states where one or both taus decay leptonically are studied: $\mathrm{e}\tau_h + \mathrm{X}$, $\mu\tau_h + \mathrm{X}$, and $\mathrm{e}\mu + \mathrm{X}$, where we use the symbol τ_h to indicate a reconstructed hadronic decay of a tau.

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In the case of the SM Higgs boson, the gluon-fusion production mechanism has the largest cross section. However, in the mass region of interest, background from Drell–Yan production of tau pairs overwhelms the expected Higgs boson signal. This search therefore relies upon the signature of Higgs bosons produced via vector boson fusion (VBF) or in association with a high-p_T jet. In the former case, the distinct topology of two jets with a large rapidity separation greatly reduces the background. In the latter, requiring a high-p_T jet both suppresses background, and improves the measurement of the tau-pair invariant mass.

In the MSSM case, two main production processes contribute to $pp \to \phi + X$, where $\phi = h$, H, or A: gluon fusion through a b-quark loop and direct $b\bar{b}$ annihilation from the b-quark content of the beam protons. In the latter case, there is a significant probability that a b-quark jet is produced centrally in association with the Higgs boson due to the enhanced $b\bar{b}\phi$ coupling. Requiring a b-quark jet increases the sensitivity of the search by reducing the Z + jets background.

2. CMS detector

The CMS detector is described in detail elsewhere [27]. 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 are the silicon pixel and strip tracker, which cover a pseudorapidity region of $|\eta| < 2.5$. Here, the pseudorapidity is defined as $\eta = -\ln(\tan\theta/2)$, where θ is the polar angle of the trajectory of the particle with respect to the direction of the counterclockwise beam. The lead tungstate crystal electromagnetic calorimeter and the brass-scintillator hadron calorimeter surround the tracking volume and cover $|\eta| < 3$. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry which extends the coverage to $|\eta| < 5$. Muons are measured in gas-ionization detectors embedded in the steel return yoke, with a coverage of $|\eta| < 2.4$.

3. Trigger and event selection

The analysis makes use of the three independent tau-pair final states, $e\tau_h + X$, $\mu\tau_h + X$, and $e\mu + X$. In all three channels, there is substantial background, both from processes with similar experimental signatures, and from unrelated hadronic activity in the detector.

The trigger selection required a combination of electron, muon and tau trigger objects [28–30]. The identification criteria and p_T thresholds of these objects were progressively tightened as the LHC instantaneous luminosity increased over the data-taking period.

A particle-flow algorithm [31–33] is used to combine information from all CMS subdetectors to identify and reconstruct individual particles in the event, namely muons, electrons, photons, and charged and neutral hadrons. From the resulting particle list jets, hadronically-decaying taus, and missing transverse energy (E_T^{miss}), defined as the negative of the vector sum of the transverse momenta, are reconstructed. The jets are identified using the anti-k_T jet algorithm [34,35] with a distance parameter of $R = 0.5$. Hadronically-decaying taus are reconstructed using the hadron plus strips (HPS) algorithm, which considers candidates with one or three charged pions and up to two neutral pions [36].

For the $e\tau_h + X$ and $\mu\tau_h + X$ final states, in the region $|\eta| < 2.1$, we select events with an electron of $p_T > 20$ GeV or a muon of $p_T > 17$ GeV, together with an oppositely charged τ_h of $p_T >$ 20 GeV within the range $|\eta| < 2.3$. For the $e\mu + X$ final state, we select events with an electron of $|\eta| < 2.3$ and an oppositely charged muon of $|\eta| < 2.1$, requiring $p_T > 20$ GeV for the highest-p_T lepton and $p_T > 10$ GeV for the next-to-highest-p_T lepton. For the $e\tau_h + X$ and $\mu\tau_h + X$ final states, we reject events with more than one electron or more than one muon of $p_T > 15$ GeV.

Taus from Higgs boson decays are typically isolated from the rest of the event activity, in contrast to background from jets, which are typically immersed in considerable hadronic activity. For each lepton candidate (e, μ, or τ_h), a cone is constructed around the lepton direction at the event vertex. An isolation variable is constructed from the scalar sum of the transverse energy of all reconstructed particles contained within the cone, excluding the contribution from the lepton candidate itself.

In 2011, an average of ten proton–proton interactions occurred per LHC bunch crossing, making the assignment of the vertex of the hard-scattering process non-trivial. For each reconstructed collision vertex, the sum of the p_T^2 of all tracks associated to the vertex is computed. The vertex for which this quantity is the largest is assumed to correspond to the hard-scattering process, and is referred to as the primary vertex. A correction is applied to the isolation variable to account for effects of additional interactions. For charged particles, only those associated with the primary vertex are considered in the isolation variable. For neutral particles, a correction is applied by subtracting the energy deposited in the isolation cone by charged particles not associated with the primary vertex, multiplied by a factor of 0.5. This factor corresponds approximately to the ratio of neutral to charged hadron production in the hadronization process of pile-up interactions. An η, p_T, and lepton-flavor dependent threshold on the isolation variable of less than roughly 10% of the candidate p_T is applied.

To correct for the contribution to the jet energy due to pile-up, a median energy density (ρ) is determined event by event. The pile-up contribution to the jet energy is estimated as the product of ρ and the area of the jet and subsequently subtracted from the jet transverse energy [37]. In the fiducial region for jets of $|\eta| <$ 4.7, jet energy corrections are also applied as a function of the jet E_T and η [38].

In this analysis, due to the small mass of the tau and the large transverse momentum, the neutrinos produced in the decay tend to be produced nearly collinear with the visible products. Conversely, in W + jets events, one of the main backgrounds, the high mass of the W results in a neutrino approximately opposite to the lepton in the transverse plane, while a jet is misidentified as a tau. In the $e\tau_h + X$ and $\mu\tau_h + X$ channels of the SM Higgs boson search, which focuses on lower masses (less than 145 GeV), we therefore require the transverse mass

$$m_T = \sqrt{2 p_T E_T^{miss} \left(1 - \cos(\Delta\phi)\right)} \tag{1}$$

to be less than 40 GeV, where p_T is the lepton transverse momentum, and $\Delta\phi$ is the difference in ϕ of the lepton and E_T^{miss} vector.

In the MSSM search channels and in the $e\mu + X$ SM search channel, we use a discriminator formed by considering the bisector of the directions of the visible tau decay products transverse to the beam direction, denoted as the ζ axis [39]. From the projections of the visible decay product momenta and the E_T^{miss} vector onto the ζ axis, two values are calculated:

$$P_\zeta = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta + E_T^{miss} \cdot \zeta, \tag{2}$$

$$P_\zeta^{vis} = p_{T,1} \cdot \zeta + p_{T,2} \cdot \zeta, \tag{3}$$

where the indices $p_{T,1}$ and $p_{T,2}$ indicate the transverse momentum of two reconstructed leptons. For the $e\tau_h + X$ and $\mu\tau_h + X$ channels in the MSSM search we require $P_\zeta - 0.5 \cdot P_\zeta^{vis} > -20$ GeV and for the $e\mu + X$ channel we require $P_\zeta - 0.85 \cdot P_\zeta^{vis} > -25$ GeV.

To further enhance the sensitivity of the search for Higgs bosons both in the MSSM and in the SM, we split the sample of

Table 1
Numbers of expected and observed events in the event categories as described in the text for the $e\tau_h + X$ channel. Also given are the expected signal yields and efficiencies for an MSSM Higgs boson with $m_A = 120$ GeV and $\tan\beta = 10$, and for an SM Higgs boson with $m_A = 120$ GeV. Combined statistical and systematic uncertainties on each estimate are reported. For the yield estimates for the Higgs signal the production cross sections for h and A, which have almost degenerate masses, are taken into account. The quoted efficiencies do not include the branching fraction into $\tau\tau$.

Process	SM			MSSM	
	0/1-Jet	Boosted	VBF	Non-b-Tag	b-Tag
$Z \to \tau\tau$	$13\,438 \pm 977$	190 ± 14	19 ± 1	$14\,259 \pm 1037$	135 ± 9
Multijets	6365 ± 299	27 ± 3	15 ± 2	6404 ± 301	100 ± 7
W + jets	2983 ± 216	62 ± 4	4.2 ± 0.4	5432 ± 377	39 ± 3
$Z \to ll$	5170 ± 464	28 ± 4	5 ± 1	6146 ± 502	28 ± 4
$t\bar{t}$	63 ± 7	42 ± 6	2 ± 1	47 ± 7	75 ± 11
Dibosons	68 ± 21	5 ± 2	0.1 ± 0.1	105 ± 22	1 ± 1
Total background	$28\,087 \pm 1142$	354 ± 17	45 ± 2.9	$32\,392 \pm 1249$	378 ± 17
$H \to \tau\tau$	53 ± 9	2.7 ± 0.6	2.0 ± 0.2	279 ± 29	26 ± 4
Data	27 727	318	43	32 051	391
Signal efficiency					
$gg \to \phi$	–	–	–	$1.0 \cdot 10^{-2}$	$9.0 \cdot 10^{-5}$
$gg \to bb\phi$	–	–	–	$1.1 \cdot 10^{-2}$	$1.5 \cdot 10^{-3}$
$gg \to H$	$9.1 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	$2.9 \cdot 10^{-5}$	–	–
$qq \to qqH$	$5.2 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	$3.3 \cdot 10^{-3}$	–	–
$qq \to Ht\bar{t}$ or VH	$7.8 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$2.8 \cdot 10^{-5}$	–	–

Table 2
Numbers of expected and observed events in the event categories as described in the text for the $\mu\tau_h + X$ channel. Also given are the expected signal yields and efficiencies for an MSSM Higgs boson with $m_A = 120$ GeV and $\tan\beta = 10$, and for an SM Higgs boson with $m_A = 120$ GeV. Combined statistical and systematic uncertainties on each estimate are reported. For the yield estimates for the Higgs signal the production cross sections for h and A, which have almost degenerate masses, are taken into account. The quoted efficiencies do not include the branching fraction into $\tau\tau$.

Process	SM			MSSM	
	0/1-Jet	Boosted	VBF	Non-b-Tag	b-Tag
$Z \to \tau\tau$	$28\,955 \pm 2054$	295 ± 22	36 ± 2	$29\,795 \pm 2114$	259 ± 18
Multijets	7841 ± 141	36 ± 2	23 ± 2	6387 ± 115	160 ± 9
W + jets	5827 ± 392	65 ± 4	9 ± 1	9563 ± 628	110 ± 9
$Z \to ll$	777 ± 70	5 ± 1	1.0 ± 0.2	924 ± 115	3 ± 1
$t\bar{t}$	147 ± 15	94 ± 12	4 ± 1	101 ± 15	145 ± 20
Dibosons	178 ± 55	9 ± 4	0.4 ± 0.4	217 ± 46	5 ± 2
Total background	$43\,725 \pm 2097$	504 ± 26	73 ± 3.9	$46\,987 \pm 2211$	681 ± 30
$H \to \tau\tau$	96 ± 17	3.9 ± 0.8	3.0 ± 0.5	502 ± 52	45 ± 6
Data	43 612	500	76	47 178	680
Signal efficiency					
$gg \to \phi$	–	–	–	$1.8 \cdot 10^{-2}$	$1.8 \cdot 10^{-4}$
$gg \to bb\phi$	–	–	–	$2.0 \cdot 10^{-2}$	$2.6 \cdot 10^{-3}$
$gg \to H$	$1.7 \cdot 10^{-2}$	$3.9 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	–	–
$qq \to qqH$	$8.6 \cdot 10^{-3}$	$2.6 \cdot 10^{-3}$	$5.2 \cdot 10^{-3}$	–	–
$qq \to Ht\bar{t}$ or VH	$1.5 \cdot 10^{-2}$	$3.3 \cdot 10^{-3}$	$4.2 \cdot 10^{-5}$	–	–

selected events into several mutually exclusive categories based on the jet multiplicity and b-jet content.

In the MSSM case, there is a large probability for having a b-tagged jet in the central region. We use an algorithm based on the impact parameter of the tracks associated to the event vertex to identify b-tagged jets [40]. The MSSM search has two categories:

b-Tag category: We require at most one jet with $p_T > 30$ GeV and at least one b-tagged jet with $p_T > 20$ GeV.
Non-b-Tag category: We require at most one jet with $p_T > 30$ GeV and no b-tagged jet with $p_T > 20$ GeV.

The SM search has three categories:

VBF category: We require at least two jets with $p_T > 30$ GeV, $|\Delta\eta_{jj}| > 4.0$, $\eta_1 \cdot \eta_2 < 0$, and a dijet invariant mass $m_{jj} > 400$ GeV, with no other jet with $p_T > 30$ GeV in the rapidity region between the two jets.
Boosted category: We require one jet with $p_T > 150$ GeV, and, in the $e\mu$ channel, no b-tagged jet with $p_T > 20$ GeV.
0/1-Jet category: We require no more than one jet with $p_T > 30$ GeV, and if such a jet is present, it must have $p_T < 150$ GeV.

The observed number of events for each category, as well as the expected number of events from various background processes are shown in Tables 1–3 together with expected signal yields and efficiencies. The largest source of events selected with these requirements is $Z \to \tau\tau$ decays. We estimate the contribution from this process using an observed sample of $Z \to \mu\mu$ events, where the reconstructed muons are replaced by the reconstructed particles from simulated tau decays, a procedure called ‘embedding’.

Table 3
Numbers of expected and observed events in the event categories as described in the text for the $e\mu + X$ channel. Also given are the expected signal yields and efficiencies for an MSSM Higgs boson with $m_A = 120$ GeV and $\tan\beta = 10$, and for an SM Higgs boson with $m_A = 120$ GeV. Combined statistical and systematic uncertainties on each estimate are reported. For the yield estimates for the Higgs signal the production cross sections for h and A, which have almost degenerate masses, are taken into account. The quoted efficiencies do not include the branching fraction into $\tau\tau$.

Process	SM			MSSM	
	0/1-Jet	Boosted	VBF	Non-b-Tag	b-Tag
$Z \to \tau\tau$	$11\,787 \pm 790$	98 ± 11	16 ± 4	$11\,718 \pm 797$	112 ± 11
Multijet and W + jets	483 ± 145	9 ± 3	2 ± 1	474 ± 147	15 ± 5
$t\bar{t}$	427 ± 41	70 ± 8	14 ± 3	161 ± 15	289 ± 35
Dibosons	570 ± 91	21 ± 4	2.0 ± 0.6	527 ± 84	55 ± 10
Total background	$13\,267 \pm 809$	197 ± 14	34 ± 5	$12\,881 \pm 815$	471 ± 38
$H \to \tau\tau$	36 ± 6	1.0 ± 0.3	1.0 ± 0.2	161 ± 10	17 ± 1.6
Data	13 152	189	26	12 761	468
Signal efficiency					
$gg \to \phi$	–	–	–	$6.4 \cdot 10^{-3}$	$9.4 \cdot 10^{-5}$
$bb \to bb\phi$	–	–	–	$5.8 \cdot 10^{-3}$	$9.8 \cdot 10^{-4}$
$gg \to H$	$6.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-4}$	$3.0 \cdot 10^{-5}$	–	–
$qq \to qqH$	$3.0 \cdot 10^{-3}$	$8.1 \cdot 10^{-4}$	$2.0 \cdot 10^{-3}$	–	–
$qq \to Ht\bar{t}$ or VH	$3.8 \cdot 10^{-3}$	$6.8 \cdot 10^{-4}$	$1.5 \cdot 10^{-6}$	–	–

The normalization for this process is determined from the measurement of the $Z \to ee$ and $Z \to \mu\mu$ cross section [41].

Another significant source of background is multijet events in which there is one jet misidentified as an isolated electron or muon, and a second jet misidentified as τ_h. W + jets events in which there is a jet misidentified as a τ_h are also a source of background. The rates for these processes are estimated using the number of observed same-charge tau pair events, and from events with large transverse mass, respectively. Other background processes include $t\bar{t}$ production and $Z \to ee/\mu\mu$ events, particularly in the $e\tau_h + X$ channel due to the 2–3% probability for electrons to be misidentified as τ_h [36]. The small background from W + jets and multijet events for the $e\mu$ channel where jets are misidentified as isolated leptons is derived by measuring the number of events with one good lepton and a second which passes relaxed selection criteria, but fails the nominal lepton selection. This sample is extrapolated to the signal region using the efficiencies for such loose lepton candidates to pass the nominal lepton selection. These efficiencies are measured in data using multijet events. Backgrounds from $t\bar{t}$ and di-boson production are estimated from simulation using the MadGraph [42] event generator to simulate the shapes for $t\bar{t}$ events and pythia 6.424 [43] to simulate the shapes for di-boson events. The event yields are normalized to the inclusive cross sections: $\sigma_{t\bar{t}} = 164.4 \pm 14.3$ pb and $\sigma_{WW} = 55.3 \pm 8.3$ pb as measured with an analysis similar to that described in [44,45] using a larger data sample.

To model the MSSM and SM Higgs boson signals the event generators pythia and powheg [46] are used, respectively. The tauola [47] package is used for tau decays in all cases. Additional next-to-next-to-leading order (NNLO) K-factors from FeHiPro [48,49] are applied to the Higgs boson p_T spectrum from Higgs boson events produced via gluon fusion.

The presence of pile-up is incorporated by simulating additional interactions and then reweighting the simulated events to match the distribution of additional interactions observed in data. The events in the embedded $Z \to \tau\tau$ sample and in other background samples obtained from data contain the correct distribution of pile-up interactions. The missing transverse energy response from simulation is corrected using a prescription, based on data, developed for inclusive W and Z cross section measurements [41], where Z bosons are reconstructed in the dimuon channel, and the missing transverse energy scale and resolution calibrated as a function of the Z boson transverse momentum.

4. Tau-pair invariant mass reconstruction

To distinguish the Higgs boson signal from the background, we reconstruct the tau-pair mass using a maximum likelihood technique [26]. The algorithm estimates the original momentum components of the two taus by maximizing a likelihood with respect to free parameters corresponding to the missing neutrino momenta, subject to kinematic constraints. Other terms in the likelihood take into account the tau-decay phase space and the probability density in the tau transverse momentum, parametrized as a function of the tau-pair mass. This algorithm yields a tau-pair mass with a mean consistent with the true value, and a distribution with a nearly Gaussian shape. The standard deviation of the mass resolution is estimated to be 21% at a Higgs boson mass of 130 GeV, compared with 24% for the (non-Gaussian) distribution of the invariant mass spectrum reconstructed from the visible tau-decay products in the inclusive selection. The resolution improves to 15% in the b-Tag category in the MSSM analysis and in the Boosted and VBF categories in the SM analysis where the Higgs boson is produced with significant transverse momentum.

5. Systematic uncertainties

Various imperfectly known or simulated effects can alter the shape and normalization of the invariant mass spectrum. The main contributions to the normalization uncertainty include the uncertainty in the total integrated luminosity (4.5%) [50], jet energy scale (2–5% depending on η and p_T), background normalization (Tables 1–3), Z boson production cross section (2.5%) [41], lepton identification and isolation efficiency (1.0%), and trigger efficiency (1.0%). The tau-identification efficiency uncertainty is estimated to be 6% from an independent study using a tag-and-probe technique [41]. The lepton identification and isolation efficiencies are stable as a function of the number of additional interactions in the bunch crossing in data and in Monte Carlo simulation. The b-tagging efficiency carries an uncertainty of 10%, and the b-mistag rate is accurate to 30% [51]. Uncertainties that contribute to mass spectrum shape variations include the tau (3%), muon (1%), and electron (1% in the barrel region, 2.5% in the endcap region) energy scales. The effect of the uncertainty on the E_T^{miss} scale, mainly due to pile-up effects, is incorporated by varying the mass spectrum shape as described in the next section.

The various production cross sections and branching fractions for SM and MSSM Higgs bosons and corresponding uncertainties are taken from [52–77]. Theoretical uncertainties on the Higgs production cross section are included in the SM and the MSSM search. For the SM signal, these uncertainties range from 12 to 30% for gluon fusion, depending on the event category, and 10% for VBF production. The uncertainty for the MSSM signal depends on $\tan\beta$ and m_A and ranges from 20 to 25%.

6. Maximum likelihood fit

To search for the presence of a Higgs boson signal in the selected events, we perform a binned maximum likelihood fit to the tau-pair invariant-mass spectrum, $m_{\tau\tau}$. The fit is performed jointly across the three SM and two MSSM event categories, but independently in the two cases.

Systematic uncertainties are represented by nuisance parameters in the fitting process. We assume log-normal priors for normalization parameters, and Gaussian priors for mass-spectrum shape uncertainties. The uncertainties that affect the shape of the mass spectrum, mainly those corresponding to the energy scales, are represented by nuisance parameters whose variation results in a continuous perturbation of the spectrum shape [78].

7. Results

Figs. 1 and 2 show for the SM and MSSM, respectively, the distributions of the tau-pair mass $m_{\tau\tau}$ summed over the three search channels, for each category, compared with the background prediction. The background mass distributions show the results of the fit using the background-only hypothesis.

The invariant mass spectra for both the MSSM and SM categories show no evidence for the presence of a Higgs boson signal, and we therefore set 95% CL upper bounds on the Higgs boson cross section times the branching fraction into a tau pair. For calculations of exclusion limits, we use the modified frequentist construction CL_s [79–81]. Theoretical uncertainties on the Higgs boson production cross sections are taken into account as systematic uncertainties in the limit calculations.

7.1. Limits on MSSM Higgs boson production

For the $m_h^{\max}$ benchmark scenario as described above we set a 95% CL upper limit on $\tan\beta$ as a function of the pseudoscalar Higgs boson mass m_A from the observed di-tau mass distributions in the b-Tag and non-b-Tag event categories (see Table 4). Signal contributions from h, H and A production are considered. The mass values of h and H, as well as the ratio between the gluon fusion process and the associated production with b quarks, depend on the value of $\tan\beta$. To account for this, we perform a scan of $\tan\beta$ for each mass hypothesis, using the Higgs boson cross sections as a function of $\tan\beta$ as reported by the LHC Cross Section Working Group [52]. For the gluon-fusion process these cross sections have been obtained from the GGH@NNLO [56,82,83] and HIGLU [84] programs. For the $b\bar{b} \to \phi$ process, the four-flavor calculation [85,86] and the five-flavor calculation as implemented in the BBH@NNLO [87] program have been combined using the Santander scheme [88]. Rescaling of the corresponding Yukawa couplings by the MSSM factors calculated with FeynHiggs [89–91] has been applied.

Fig. 3 also shows the region excluded by the LEP experiments [22]. The results reported in this Letter considerably extend the exclusion region of the MSSM parameter space and supersede limits reported by CMS using a smaller data sample collected in 2010 [26].

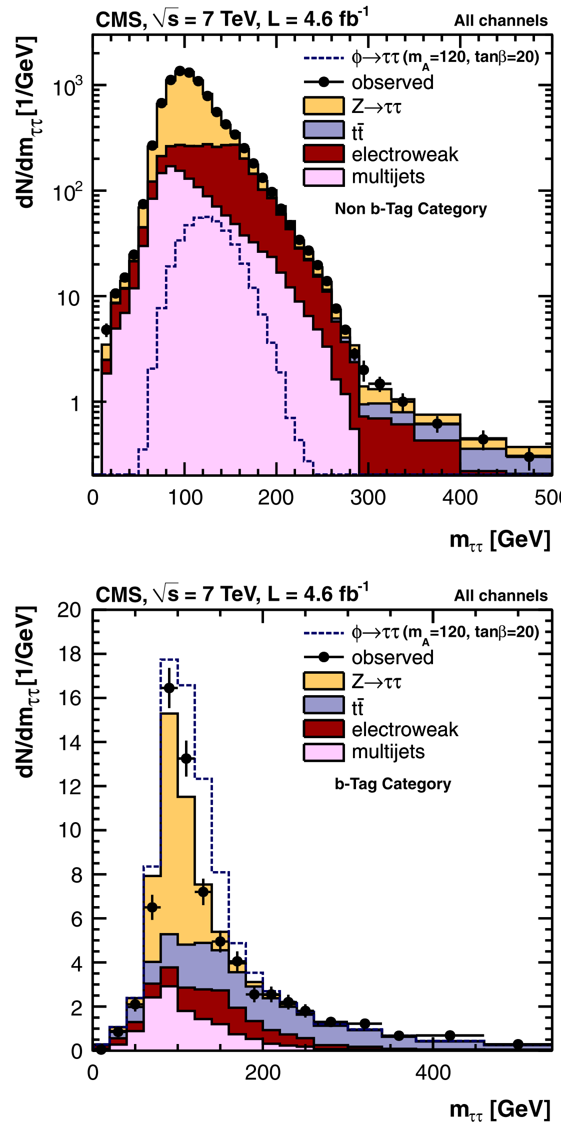

Fig. 1. Distribution of the tau-pair invariant mass, $m_{\tau\tau}$, in the MSSM Higgs boson search categories: Non-b-Tag category (top), b-Tag category (bottom). The background labeled 'electroweak' combines the contribution from W + jets, $Z \to ll$, and diboson processes.

7.2. Limits on SM Higgs boson production

The 0/1-Jet, VBF and Boosted categories are used to set a 95% CL upper limit on the product of the Higgs boson production cross section and the $H \to \tau\tau$ branching fraction, $\sigma_H \times \mathrm{BR}(H \to \tau\tau)$, with respect to the SM Higgs expectation, σ/σ_{SM}. Fig. 4 shows the observed and the mean expected 95% CL upper limits for Higgs boson mass hypotheses ranging from 110 to 145 GeV. The bands represent the one- and two-standard-deviation probability intervals around the expected limit. Table 5 shows the results for selected mass values. We set a 95% upper limit on σ/σ_{SM} in the range of 3–7.

8. Summary

We have reported a search for SM and neutral MSSM Higgs bosons, using a sample of CMS data from proton–proton collisions at a center-of-mass energy of 7 TeV at the LHC, corresponding to an integrated luminosity of 4.6 fb^{-1}. The tau-pair decay mode in final states with one e or μ plus a hadronic decay of a tau, and

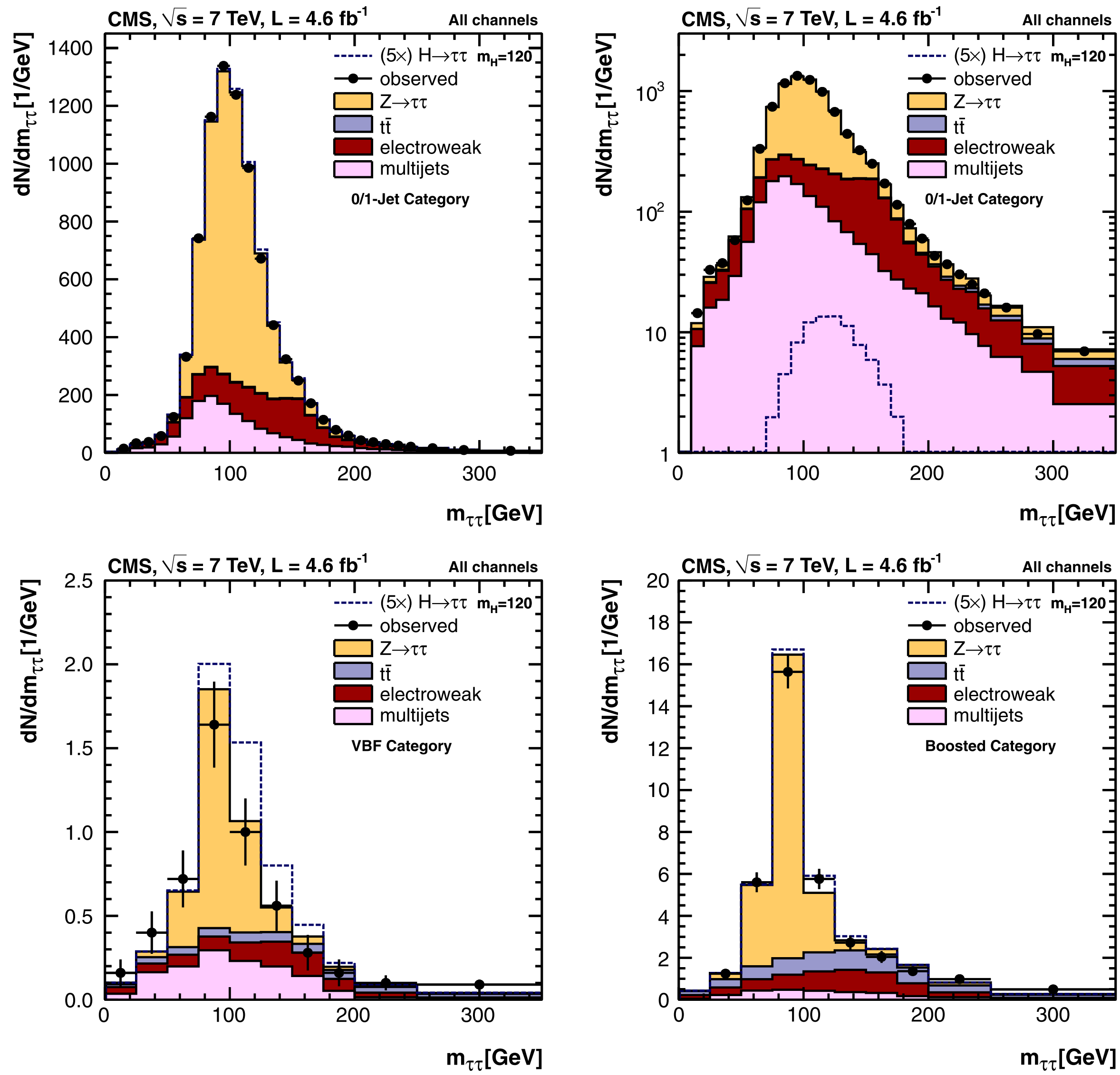

Fig. 2. Distribution of the tau-pair invariant mass, $m_{\tau\tau}$, in the SM Higgs boson search categories: 0/1-Jet (top row, linear and log vertical scale), VBF (lower left), and Boosted (lower right). The background labeled 'electroweak' combines the contribution from W + jets, $Z \to ll$, and diboson processes.

Table 4
Expected range and observed 95% CL upper limits for $\tan\beta$ as a function of m_A, for the MSSM search.

MSSM Higgs	Expected $\tan\beta$ limit					Obs. $\tan\beta$ limit
m_A [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
90	5.19	7.01	8.37	10.6	12.8	12.2
100	6.49	7.45	8.78	10.8	13.4	11.8
120	4.50	6.47	8.09	9.89	12.0	9.84
130	5.37	6.71	7.85	9.69	11.5	9.03
140	5.62	6.63	7.90	9.69	11.6	8.03
160	5.57	6.99	8.51	10.4	12.5	7.11
180	6.75	8.14	9.53	11.3	13.8	7.50
200	7.84	9.12	10.5	12.8	15.0	8.46
250	10.3	12.3	13.9	16.8	19.4	13.8
300	13.5	15.7	18.4	21.4	24.5	20.9
350	17.7	20.1	23.0	26.9	31.1	29.1
400	21.9	24.3	27.9	32.4	37.3	37.3
450	25.0	29.2	33.3	38.8	44.7	45.2
500	30.3	35.7	40.5	47.1	55.0	51.9

the $e\mu$ final state are used. The observed tau-pair mass spectra reveal no evidence for neutral Higgs boson production. In the SM case we determine a 95% CL upper limit in the mass range of 110–145 GeV on the Higgs boson production cross section. We exclude a Higgs boson with $m_A = 115$ GeV with a production cross section 3.2 times of that predicted by the standard model. In the MSSM

Table 5
Expected range and observed 95% CL upper limits on the cross section, divided by the expected SM Higgs cross section as a function of m_A, for the SM search.

SM Higgs	Expected limit					Obs. limit
m_A [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
110	1.83	2.36	3.30	4.76	6.63	3.20
115	1.61	2.13	2.97	4.23	5.86	3.19
120	1.65	2.17	3.03	4.33	6.07	3.62
125	1.75	2.19	3.05	4.38	6.01	4.27
130	1.82	2.37	3.31	4.72	6.43	5.08
135	2.25	2.96	4.06	5.77	7.87	5.39
140	2.39	2.99	4.17	5.85	7.99	5.46
145	3.06	3.97	5.45	7.65	10.7	7.00

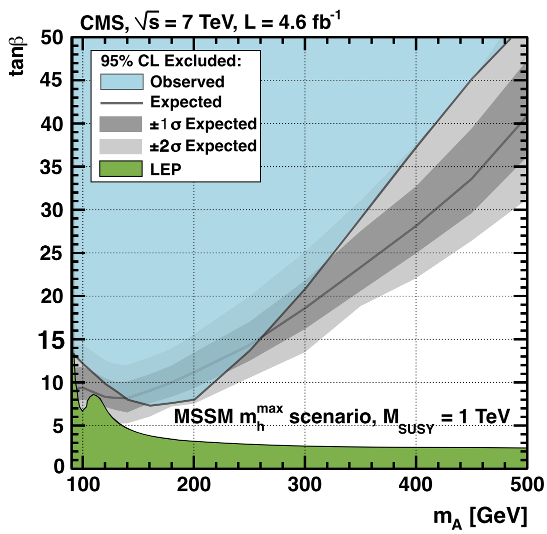

Fig. 3. Region in the parameter space of $\tan\beta$ versus m_A excluded at 95% CL in the context of the MSSM m_h^{max} scenario. The expected one- and two-standard-deviation ranges and the observed 95% CL upper limits are shown together with the observed excluded region.

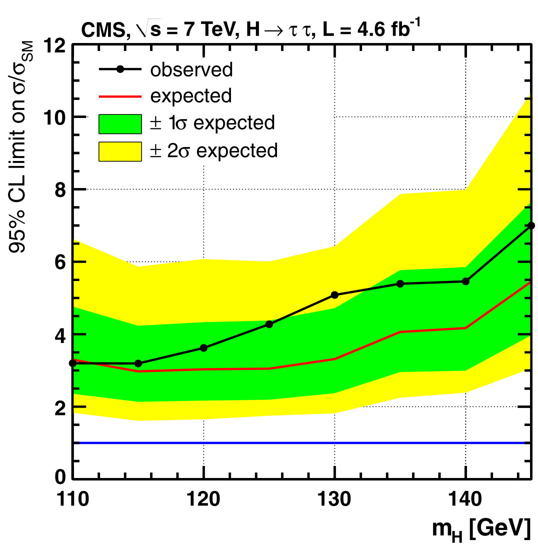

Fig. 4. The expected one- and two-standard-deviation ranges are shown together with the observed 95% CL upper limits on the cross section, normalized to the SM expectation for Higgs boson production, as a function of m_A.

case, we determine a 95% CL upper bound on the value of $\tan\beta$ as a function of m_A, for the m_h^{max} scenario. This search excludes a previously unexplored region reaching as low as $\tan\beta = 7.1$ at $m_A = 160$ GeV.

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