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Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

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Abstract

A search for neutral MSSM Higgs bosons in pp collisions at the LHC at a center-of-mass energy of 7 TeV is presented. The results are based on a data sample corresponding to an integrated luminosity of 36 pb^{-1} recorded by the CMS experiment. The search uses decays of the Higgs bosons to tau pairs. No excess is observed in the tau-pair invariant-mass spectrum. The resulting upper limits on the Higgs boson production cross section times branching fraction to tau pairs, as a function of the pseudoscalar Higgs boson mass, yield stringent new bounds in the MSSM parameter space.

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*See Appendix A for the list of collaboration members

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The standard model (SM) has been extremely successful in describing a wide range of phenomena in particle physics, and has survived some four decades of experimental testing. However, the only remaining undiscovered particle predicted by the SM, the Higgs boson [1–5], suffers from quadratically divergent self-energy corrections at high energies [6]. Numerous extensions to the SM have been proposed to address these divergences. One such model, supersymmetry [7], a symmetry between fundamental bosons and fermions, results in cancellation of the divergences at tree level. The minimal supersymmetric extension to the standard model (MSSM) requires the presence of two Higgs doublets. This leads to a more complicated Higgs boson sector, with five massive Higgs bosons: a light neutral scalar (h), two charged scalars ($H^{\pm}$), a heavy neutral CP-even state (H) and a neutral CP-odd state (A).

The masses of the MSSM Higgs boson states are specified up to radiative corrections mainly by two parameters, usually taken to be the mass of the pseudoscalar state, m_A, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. At large $\tan\beta$ (greater than about 20–30), the couplings of the Higgs bosons to down-type quarks are proportional to $\tan\beta$. As a result, the production cross section for two of the three neutral Higgs bosons can be nearly as large as that for the electroweak gauge bosons W and Z at a proton-proton collider such as the Large Hadron Collider (LHC). Two main production processes contribute to $\mathrm{pp} \to \phi + X$, where $\phi = h, H$, or A: gluon fusion through a b quark loop and direct $\mathrm{b\bar{b}}$ annihilation from the b parton density in the beam protons.

The mass relations among the neutral MSSM Higgs bosons are such that if $m_A \lesssim 130\,\mathrm{GeV}/c^2$, at large $\tan\beta$ the masses of the h and A are nearly degenerate, while that of the H is approximately 130 GeV/c^2. If $m_A \gtrsim 130\ \mathrm{GeV}/c^2$, then the masses of the A and H are nearly degenerate, while that of the h remains near 130 GeV/c^2. The precise value of the crossover point depends predominantly on the nature of the mass mixing in the top-squark states.

This Letter reports a search for MSSM neutral Higgs bosons in pp collisions at $\sqrt{s} = 7$ TeV at the LHC, using a data sample collected in 2010 corresponding to 36 pb^{-1} of integrated luminosity recorded by the Compact Muon Solenoid (CMS) experiment. This search is similar to those performed at the Tevatron [8] and complementary to the MSSM Higgs search at LEP [9].

The tau-pair decays of the neutral Higgs bosons, having a branching fraction of about 10%, serve as the best experimental signature for this search. The $\mathrm{b\bar{b}}$ mode, though it has a much larger branching fraction, suffers from an overwhelming background from QCD processes. Three final states where one or both taus decay leptonically are used: $\mathrm{e}\tau_h$, $\mu\tau_h$, and $\mathrm{e}\mu$, where we use the symbol τ_h to indicate a reconstructed hadronic decay of a τ.

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. Details of the CMS detector and its performance can be found elsewhere [10].

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the xy plane. We measure the pseudorapidity η of outgoing particles based on their polar angle according to $\eta \equiv -\ln(\tan\frac{\theta}{2})$.

The triggers used to select the events for this analysis are based on the presence of an electron and/or a muon trigger object [11, 12]. With increasing instantaneous luminosity, in order to

keep the online transverse momentum thresholds on electrons lower than those used in offline selections, special triggers requiring the presence of both a lepton and a charged track with an accompanying calorimeter pattern consistent with a τ decaying hadronically were adopted for the $e\tau_h$ and $\mu\tau_h$ channels.

The analysis presented here makes use of particle flow techniques which combine the information from all CMS subdetectors to identify and reconstruct individual particles in the event, namely muons, electrons, photons, and charged and neutral hadrons. The detailed description of the algorithm and its commissioning can be found elsewhere [13, 14]. The particle list is given as input to the jet, tau, and missing transverse energy reconstruction.

The main challenge in the identification of hadronic tau decays is overcoming the large background due to hadronic jets from QCD processes. Hadronic tau decays almost always yield one or three charged pions, plus zero to several neutral pions, depending on the decay mode. The algorithm used here starts with a high-transverse-momentum (p_{T}) reconstructed charged hadron, and combines it with other nearby reconstructed charged hadron and neutral pion candidates. The algorithm considers all possible combinations of these objects and determines which are consistent with the kinematics of tau decay. Among those, it chooses the most isolated in terms of the presence of nearby reconstructed particles. Requirements on the isolation variables determine an operating point in the space of tau identification efficiency versus the jet-to-tau misidentification rate. We optimize the full analysis for best sensitivity by choosing the "loose" operating point of the HPS algorithm [15].

For the $\mu\tau_h$ and $e\tau_h$ final states, we select events with an isolated muon or electron with $p_{\mathrm{T}} > 15$ GeV$/c$ and $|\eta| < 2.1$, and an oppositely charged τ_h with $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$ and $|\eta| < 2.3$. The transverse mass of the $\ell = \mathrm{e}, \mu$ with the missing transverse energy $\not{E}_{\mathrm{T}}$, obtained using all reconstructed particles in the event, is defined as $M_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}\not{E}_{\mathrm{T}}\,(1-\cos\Delta\phi)}$, where $\Delta\phi$ is the difference in azimuth between the e or μ and the $\not{E}_{\mathrm{T}}$ vector. We require $M_{\mathrm{T}} < 40$ GeV$/c^2$, in order to reduce the background from W+jets events. For the $e\mu$ final state, we select events with an isolated electron with $|\eta| < 2.5$ and an oppositely charged isolated muon, both with $p_{\mathrm{T}} > 15$ GeV$/c$ and $M_{\mathrm{T}} < 50$ GeV$/c^2$, calculated for each lepton separately. We reject events in which there are more than one e or μ.

The observed number of events in each channel appears in Table 1. The largest source of events selected with these requirements comes from $\mathrm{Z} \to \tau\tau$. We estimate the contribution from this process using a detailed GEANT4 simulation of the CMS detector, with the events modeled by the POWHEG Monte Carlo generator [16–19]. We determine the normalization for this process based on the number of observed $\mathrm{Z} \to \ell\ell$ events [20].

A significant source of background arises from QCD multijet events and W+jets events in which a jet is misidentified as τ_h, and there is a real or misidentified e or μ. The rates for these processes are estimated using the number of observed same-charge events, and cross-checked using the jet-to-tau misidentification rate measured in multijet events. Other background processes include $\mathrm{t\bar{t}}$ production and $\mathrm{Z} \to \mathrm{ee}/\mu\mu$ events, particularly in the $e\tau_h$ channel, due to the 2–3% probability for electrons to be misidentified as τ_h [15]. The small fake-lepton background from W+jets and QCD for the $e\mu$ channel is estimated using data. Table 1 shows the expected number of events for each of the background processes. The event generator PYTHIA6 [21] is used to model the Higgs boson signal and other backgrounds. The TAUOLA [22] package is used for tau decays in all cases.

To distinguish the Higgs boson signal from the background, we reconstruct the tau-pair mass using a likelihood technique. The algorithm estimates the original tau three-momenta by max-

Table 1: Number of estimated background events in the selected sample, observed number of events, and overall signal efficiency for $m_A = 200$ GeV$/c^2$ (including all branching fractions) for each search channel. Uncertainties do not include those on integrated luminosity or energy scales. The QCD multijet background for the eτ_h final state is the sum of the QCD multijet and γ+jet backgrounds.

Process	$\mu\tau_h$	eτ_h	eμ
$Z \to \tau\tau$	329 ± 77	190 ± 44	88 ± 5
$t\bar{t}$	6 ± 3	2.6 ± 1.3	7.1 ± 1.3
$Z \to \ell\ell$, jet $\to \tau_h$	6.4 ± 2.4	15 ± 6.2	-
$Z \to \ell\ell$	12.9 ± 3.5	109 ± 28	2.4 ± 0.3
$W \to \ell\nu$	54.9 ± 4.8	30.6 ± 3.1	
$W \to \tau\nu, \tau \to \ell\nu\bar{\nu}$	14.7 ± 1.3	7.0 ± 0.7	1.5 ± 0.5
QCD multijet and γ+jet	132 ± 14	181 ± 23	
WW/WZ/ZZ	1.6 ± 0.8	0.8 ± 0.4	3.0 ± 0.4
Total	557 ± 79	536 ± 57	102 ± 5
Observed	517	540	101
Signal Efficiency	0.0391	0.0245	0.00582

imizing a likelihood with respect to free parameters corresponding to the missing tau-neutrino momenta, and subject to all applicable 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 mass resolution is $\sim$21% at a Higgs boson mass of 130 GeV$/c^2$, to be compared with $\sim$24% for the (non-Gaussian) distribution of the invariant mass reconstructed from the visible tau-decay products. The observed reconstructed tau-pair mass distribution for all three channels is shown in Fig. 1.

Various imperfectly known or imperfectly simulated effects can alter the shape and normalization of the reconstructed tau-pair invariant-mass spectrum. The main sources of normalization uncertainties include the total integrated luminosity (11%) [23], background normalizations (Table 1), Z production cross section (4%), and lepton identification and isolation efficiency (0.2–2.0% depending on lepton type). The tau identification efficiency uncertainty is estimated to be 23% from an independent study [15]. Uncertainties that contribute to mass spectrum shape variations include the tau (3%), muon (1%), and electron (2%) energy scales, and uncertainties on the $\not{E}_T$ scale that is used for the tau-pair invariant-mass reconstruction [24]. The $\not{E}_T$ scale uncertainties contribute via the jet-energy scale (3%) and unclustered energy scale (10%), where the unclustered energy is defined as the energy remaining after vectorially subtracting leptons and objects clustered in jets with $p_T > 10\,\text{GeV}/c$.

To search for the presence of a Higgs boson signal in the selected events, we perform a maximum likelihood fit to the tau-pair invariant-mass spectrum. Systematic uncertainties are represented by nuisance parameters, which we remove by marginalization, assuming a log normal prior 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 modification of the spectrum shape [25].

The parameter representing the tau identification uncertainty affects taus from the Higgs boson

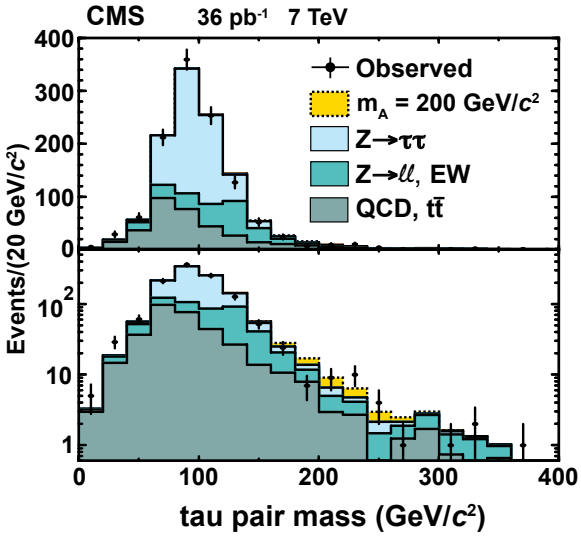

Figure 1: The reconstructed tau-pair invariant-mass distribution on linear (above) and logarithmic (below) scales, for the sum of the eτ_h, $\mu\tau_h$, and eμ final states, comparing the observed distributions (points with error bars) to the sum of the expected backgrounds (shaded histograms). The contribution from a Higgs boson signal ($m_A = 200$ GeV$/c^2$) is also shown, with normalization corresponding to the 95% upper bound on $\sigma_\phi \cdot B_{\tau\tau}$.

signal and the main background, $Z \to \tau\tau$, equally. This effectively allows the observed $Z \to \tau\tau$ events to provide an *in situ* calibration of this efficiency, except for Higgs boson masses near that of the Z. Near the Z mass, the tau identification efficiency uncertainty dominates in the eτ_h and $\mu\tau_h$ channels, and the eμ channel thus provides the greatest sensitivity.

The mass spectra show no evidence for the presence of a Higgs boson signal, and we set 95% CL (confidence level) upper bounds on the Higgs boson cross section times the tau-pair branching fraction (denoted by $\sigma_\phi \cdot B_{\tau\tau}$) using a Bayesian method assuming a uniform prior in $\sigma_\phi \cdot B_{\tau\tau}$. The invariant-mass spectrum in Fig. 1 shows the result of a fit with a Higgs boson signal corresponding to $m_A = 200$ GeV$/c^2$ present, for $\sigma_\phi \cdot B_{\tau\tau} = 8.71$ pb, the value above which we exclude at 95% CL.

Figure 2 shows the observed upper bound on $\sigma_\phi \cdot B_{\tau\tau}$ as a function of m_A, where we use as the signal acceptance model the combined mass spectra from the gg and b$\bar{\text{b}}$ production processes for h, A, and H, and assuming $\tan\beta = 30$ [26]. The plot also shows the one- and two-standard-deviation range of expected upper limits for various potential experimental outcomes. The observed limits are well within the expected range assuming no signal. The observed and expected upper limits are shown in Table 2.

We can interpret the upper limits on $\sigma_\phi \cdot B_{\tau\tau}$ in the MSSM parameter space of $\tan\beta$ versus m_A for an example scenario. We use here the $m_h^{\max}$ [27] benchmark scenario in which M_{SUSY} = 1 TeV$/c^2$; X_t = $2M_{\text{SUSY}}$; μ = 200 GeV$/c^2$; $M_{\tilde{g}}$ = 800 GeV$/c^2$; M_2 = 200 GeV$/c^2$; and $A_b = A_t$, where M_{SUSY} denotes the common soft-SUSY-breaking squark mass of the third generation; $X_t = A_t - \mu/\tan\beta$ the stop mixing parameter; A_t and A_b the stop and sbottom trilinear couplings, respectively; μ the Higgsino mass parameter; $M_{\tilde{g}}$ the gluino mass; and M_2 the SU(2)-gaugino mass parameter. The value of M_1 is fixed via the GUT relation $M_1 = (5/3)M_2 \sin\theta_{\text{W}}/\cos\theta_{\text{W}}$. In determining these bounds on $\tan\beta$, shown in Table 2 and in Fig. 3, we have used the central values of the Higgs boson cross sections as a function of $\tan\beta$ reported

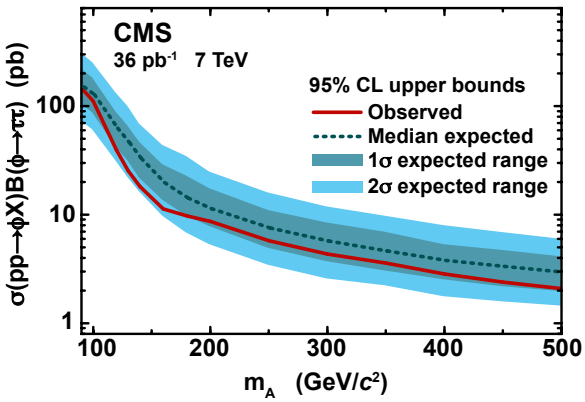

Figure 2: The expected one- and two-standard-deviation ranges and observed 95% CL upper limits on $\sigma_\phi \cdot B_{\tau\tau}$ as a function of m_A.

Table 2: Expected range and observed 95% CL upper limits for $\sigma_\phi \cdot B_{\tau\tau}$ as functions of m_A, and 95% CL upper bound on $\tan\beta$ in the $m_h^{\max}$ scenario described in the text. No bounds on $\tan\beta$ above 60 are quoted.

	95% CL Upper Limit				
m_A	Expected $\sigma_\phi \cdot B_{\tau\tau}$ (pb)			Observed	
(GeV/c^2)	-1σ	Median	$+1\sigma$	$\sigma_\phi \cdot B_{\tau\tau}$	$\tan\beta$
90	107.75	153.30	227.10	147.74	27.36
100	88.61	127.09	184.17	112.30	29.20
120	42.72	62.48	90.24	39.61	25.22
130	31.97	45.96	67.11	25.40	22.57
140	22.14	32.81	47.30	18.20	23.55
160	13.83	19.70	29.27	11.37	23.83
180	9.95	14.16	23.13	9.78	28.08
200	7.90	11.36	17.61	8.71	32.98
250	5.01	7.54	11.15	5.77	43.35
300	3.77	5.71	8.58	4.36	56.62
350	3.09	4.64	7.04	3.60	-
400	2.57	3.79	5.39	2.86	-
450	2.21	3.34	4.77	2.41	-
500	2.00	2.95	4.18	2.10	-

by the LHC Higgs Cross Section Working Group [26]. The cross sections have been obtained from the GGH@NNLO [28, 29] and HIGLU [30] programs for the gluon-fusion process and from the BBH@NNLO [31] program for the $b\bar{b} \to \phi$ process in the 5-flavor scheme, rescaling the corresponding Yukawa couplings by the MSSM factors calculated with FeynHiggs [32]. The $gg \to \phi$ cross-section calculations combine the full quark mass-dependent NLO QCD corrections [33] and NNLO corrections in the heavy-top-quark limit [28, 34, 35]. The effect of the theoretical uncertainties is illustrated in Fig. 3. We do not quote limits above $\tan\beta = 60$ as the theoretical relation between cross section and $\tan\beta$ becomes unreliable.

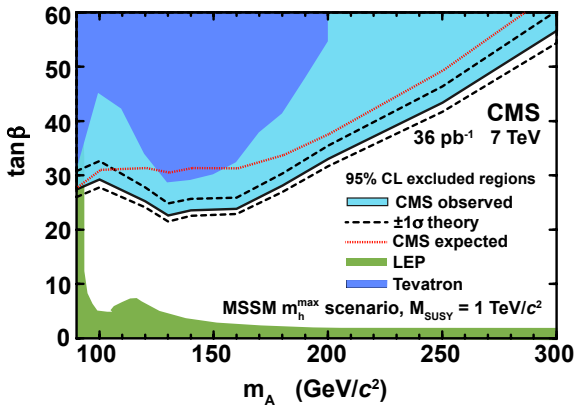

Figure 3: Region in the parameter space of $\tan\beta$ versus m_A excluded at 95% CL in the context of the MSSM $m_h^{\max}$ scenario, with the effect of $\pm 1\sigma$ theoretical uncertainties shown. The other shaded regions show the 95% CL excluded regions from the LEP and Tevatron experiments.

The present results exclude a region in $\tan\beta$ down to values smaller than those excluded by the Tevatron experiments [8] for $m_A \lesssim 140$ GeV/c^2, and significantly extend the excluded region of MSSM parameter space at larger values of m_A. Figure 3 also shows the region excluded by the LEP experiments [9].

In conclusion, we have performed a search for neutral MSSM Higgs bosons, using the first 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 36 pb^{-1}. The tau-pair decay mode in final states with one e or μ plus a hadronic decay of a tau, and the eμ final state were used. The observed tau-pair mass spectrum reveals no evidence for neutral Higgs boson production, and we determine an upper bound on the product of the Higgs boson cross section and tau-pair branching fraction as a function of m_A. These results, interpreted in the MSSM parameter space of $\tan\beta$ versus m_A, in the $m_h^{\max}$ scenario, exclude a previously unexplored region reaching as low as $\tan\beta = 23$ at $m_A = 130$ GeV/c^2.

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