Search for Neutral Minimal Supersymmetric Standard Model Higgs Bosons Decaying to Tau Pairs in pp Collisions at \([\sqrt{s}] = 7\text{TeV}\)

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

S. Chatrchyan et al.*
(CMS Collaboration)
(Received 9 April 2011; published 8 June 2011)

A search for neutral minimal supersymmetric standard model (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 $\text{pb}^{-1}$ 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.

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 scalar sector, with five massive Higgs bosons: a light neutral state ($h$), two charged states ($H^{\pm}$), 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 approximately 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 $pp \rightarrow \phi + X$, where $\phi = h, H, A$: gluon fusion through a $a b$ quark loop and direct $b\bar{b}$ annihilation from the $b$ parton density in the beam protons.

The mass relations among the neutral MSSM Higgs bosons are such that if $m_A < 130 \text{ GeV}/c^2$, at large $\tan \beta$ the masses of the $h$ and $A$ are nearly degenerate, while that of the $H$ is approximately 130 $\text{ GeV}/c^2$. If $m_A > 130 \text{ GeV}/c^2$, then the masses of the $A$ and $H$ are nearly degenerate, while that of the $h$ remains near 130 $\text{ GeV}/c^2$. 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 $\text{pb}^{-1}$ 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 roughly 10%, serve as the best experimental signature for this search. The $b\bar{b}$ 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: $e\tau_\nu, \mu\tau_\nu, \text{ and } e\mu$, where we use the symbol $\tau_\nu$ to indicate a reconstructed hadronic decay of a $\tau$.

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 or 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 $\theta$ is measured from the positive $z$ axis and the azimuthal angle $\phi$ is measured in the $xy$ plane. We measure the pseudorapidity $\eta$ of outgoing particles based on their polar angle according to $\eta = -\ln(\tan\frac{\theta}{2})$.

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 $\tau$ 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 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, specific to each final state, 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 $p_T > 15$ GeV/$c$ and $|\eta| < 2.1$, and an oppositely charged $\tau_h$ with $p_T > 20$ GeV/$c$ and $|\eta| < 2.3$. The transverse mass of the $e$, $\mu$ with the missing transverse energy $E_T$, obtained using all reconstructed particles in the event, is defined as

$$M_T = \sqrt{2p_T^2 - E_T(1 - \cos \Delta \phi)}$$

where $\Delta \phi$ is the difference in azimuth between the $e$ or $\mu$ and the $E_T$ vector. We require $M_T < 40$ 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 with $|\eta| < 2.1$, both with $M_T > 15$ GeV/$c$ and $M_T < 50$ GeV/$c^2$ (to reject $WW$ and $t\bar{t}$ events), calculated for each lepton separately. We reject events in which there are more than one $e$ or $\mu$.

After the above requirements, the trigger requirements have an efficiency of roughly 90% in the three search channels for $Z \rightarrow \tau\tau$ events.

The observed number of events in each channel appears in Table I. The largest source of events selected with these requirements comes from $Z \rightarrow \tau\tau$. 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 $Z \rightarrow \tau\tau$ and $Z \rightarrow \mu\mu$ events [20].

A significant source of background arises from QCD multijet events and $W +$ jets events in which a jet is misidentified as $\tau_h$, and there is a real or misidentified $e$ or $\mu$. 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 $t\bar{t}$ production and $Z \rightarrow ee/\mu\mu$ events, particularly in the $e\tau_h$ channel, due to the 2–3% probability for electrons to be misidentified as $\tau_h$ [15]. The small fake-lepton background from $W +$ jets and QCD for the $e\mu$ channel is estimated using data. Table I 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 maximizing 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

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu\tau_h$</th>
<th>$e\tau_h$</th>
<th>$e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>329 ± 77</td>
<td>190 ± 44</td>
<td>88 ± 5</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>6 ± 3</td>
<td>2.6 ± 1.3</td>
<td>7.1 ± 1.3</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$, jet $\rightarrow \tau_h$</td>
<td>6.4 ± 2.4</td>
<td>15 ± 6.2</td>
<td>⋯</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>12.9 ± 3.5</td>
<td>109 ± 28</td>
<td>2.4 ± 0.3</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>54.9 ± 4.8</td>
<td>30.6 ± 3.1</td>
<td></td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$, $\tau \rightarrow \ell\nu\bar{\nu}$</td>
<td>14.7 ± 1.3</td>
<td>7.0 ± 0.7</td>
<td>1.5 ± 0.5</td>
</tr>
<tr>
<td>QCD multijet and $\gamma +$ jet</td>
<td>132 ± 14</td>
<td>181 ± 23</td>
<td></td>
</tr>
<tr>
<td>$WW/WW/WZ/ZZ$</td>
<td>1.6 ± 0.8</td>
<td>0.8 ± 0.4</td>
<td>3.0 ± 0.4</td>
</tr>
<tr>
<td>Total</td>
<td>557 ± 79</td>
<td>536 ± 57</td>
<td>102 ± 5</td>
</tr>
<tr>
<td>Observed</td>
<td>517</td>
<td>540</td>
<td>101</td>
</tr>
<tr>
<td>Signal Efficiency</td>
<td>0.0391</td>
<td>0.0245</td>
<td>0.00582</td>
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</table>
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
summed over all three channels is shown in Fig. 1.

Various imperfectly known or imperfectly simulated
effects can alter the shape and normalization of the recon-
structed tau-pair invariant-mass spectrum. The main
sources of normalization uncertainties include the total
integrated luminosity (11%) [23], background normaliza-
tions (Table I), $Z$ production cross section (4%), and lepton
identification and isolation efficiency (0.2–2.0% depending
on lepton type). The tau identification efficiency uncer-
tainty is estimated to be 23% from an independent study
[15]. The uncertainty due to trigger efficiencies is 0.2% for
the $\mu\tau_h$ and $e\mu$ channels, and 2.0% for the $e\tau_h$ channel.

Uncertainties that contribute to mass-spectrum shape varia-
tions include the tau (3%), muon (1%), and electron (2%)
energy scales, and uncertainties on the $E_T$ scale that is used
for the tau-pair invariant-mass reconstruction [24]. The $E_T$
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
$p_T > 10$ 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 uncer-
tainties 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 continu-
ous modification of the spectrum shape [25].

The parameter representing the tau identification uncer-
tainty affects taus from the Higgs boson signal and the
main background, $Z \rightarrow \tau\tau$, equally. This effectively allows
the observed $Z \rightarrow \tau\tau$ events to provide an in situ calibra-
tion 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 $e\tau_h$ and $\mu\tau_h$ chan-
nels, and the $e\mu$ 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 $\sigma_{\phi}B_{\tau\tau}$) using a
Bayesian method assuming a uniform prior in $\sigma_{\phi}B_{\tau\tau}$.
The invariant-mass spectrum in Fig. 1 shows the result
of a fit with a Higgs boson signal corresponding to
$m_{\phi} = 200$ GeV/$c^2$ present, for $\sigma_{\phi}B_{\tau\tau} = 8.71$ pb,
the value above which we exclude at 95% CL.

Figure 2 shows the observed upper bound on $\sigma_{\phi}B_{\tau\tau}$ as a
function of $m_{\phi}$, where we use as the signal acceptance
the combined mass spectra from the $gg$ and $b\bar{b}$
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 vari-
ous potential experimental outcomes. The observed limits

![FIG. 1 (color online). The reconstructed tau-pair invariant-
mass distribution on linear (above) and logarithmic (below)
scales, for the sum of the $e\tau_h$, $\mu\tau_h$, and $e\mu$ 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 ($m_{\phi} =
200$ GeV/$c^2$) is also shown, with normalization corresponding
to the 95% upper bound on $\sigma_{\phi}B_{\tau\tau}$.](231801-3)

![FIG. 2 (color online). The expected one- and two-standard-
development ranges and observed 95% CL upper limits on $\sigma_{\phi}B_{\tau\tau}$
as a function of $m_{\phi}$. The signal acceptance is based on the MSSM
model described in the text, assuming $\tan \beta = 30$.](231801-3)
We can interpret the upper limits on $\sigma_{B_{\tau}}$ versus $m_A$ for an example scenario. We use here the $m_{h}^{\text{max}}$ [27,28] benchmark scenario in which $M_{SUSY} = 1\text{ TeV}/c^2$, $X_t = 2M_{SUSY}$, $\mu = 200\text{ GeV}/c^2$, $M_{2} = 800\text{ GeV}/c^2$, $M_{2} = 200\text{ GeV}/c^2$, and $A_{b} = A_{t}$, where $M_{SUSY}$ denotes the common soft-SUSY-breaking squark mass of the third generation; $X_t = A_t - / tan\beta$ the stop mixing parameter; $A_t$ and $A_b$ the stop and sbottom trilinear couplings, respectively; $\mu$ the Higgsino mass parameter; $M_{\tilde{g}}$ the gluino mass; and $M_{\tilde{Z}}$ the SU(2)-gaugino mass parameter. The value of $M_{1}$ is fixed via the GUT relation $M_{1} = (5/3)M_{2}\sin^2\theta_{W}/\cos\theta_{W}$. In determining these bounds on $\sigma_{B_{\tau}}$, shown in Table II and in Fig. 3, we have used the central values of the Higgs boson cross sections as a function of $m_A$ reported by the LHC Higgs Cross Section Working Group [26]. The cross sections have been obtained from the GGH@NNLO [29,30] and HIGLU [31] programs for the gluon-fusion process and from the BBH@NNLO [32] program for the $b\bar{b} \rightarrow \phi$ process in the five-flavor scheme, rescaling the corresponding Yukawa couplings by the MSSM factors calculated with FeynHiggs [33]. The $gg \rightarrow \phi$ cross-section calculations combine the full quark mass-dependent NLO QCD corrections [34] and NNLO corrections in the heavy-top-quark limit [29,35,36]. 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.

The present results exclude a region in $\tan\beta$ down to values smaller than those excluded by the Tevatron experiments [8] for $m_A \approx 140\text{ GeV}/c^2$, 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 $\mu$ plus a hadronic decay of a tau, and the $e\mu$ 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 $m_{h}^{\text{max}}$ scenario, exclude a previously unexplored region reaching as low as $\tan\beta = 23$ at $m_A = 130\text{ GeV}/c^2$.

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia,
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