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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 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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anticycloshile-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 $\eta = -\ln(\tan(\theta/2))$.

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 $	au$ decaying hadronically were adopted for the $\ell\tau_h$ 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, 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 $\ell\tau_h$ 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 with $p_T > 20$ GeV/c and $|\eta| < 2.3$. The transverse mass of the $\ell = e, \mu$ with the missing transverse energy $E_T$, obtained using all reconstructed particles in the event, is defined as

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

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 $Z \rightarrow \ell\ell/\mu\mu$ 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>
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<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>70.0 ± 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>
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</tr>
<tr>
<td>$WW/WZ/ZZ$</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>
to the 95% upper bound on energy scales, and uncertainties on the variations include the tau (3%), muon (1%), and electron (2%). Uncertainties that contribute to mass-spectrum shape var-
is the energy remaining after vectorially subtracting leptons and objects clustered in jets with $p_T > 10 \text{ GeV}/c$.

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 I), $Z$ 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]. 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 variations 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 $p_T > 10 \text{ GeV}/c$.

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 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 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 $e\tau_h$ and $\mu \tau_h$ channels, 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 $m_A = 200 \text{ GeV}/c^2$ present, for $\sigma_{\phi} B_{\tau\tau} = 8.71 \text{ pb}$, 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 $m_A$, where we use as the signal acceptance model the combined mass spectra from the $gg$ and $bb$ 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

![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 ($m_A = 200 \text{ GeV}/c^2$) is also shown, with normalization corresponding to the 95% upper bound on $\sigma_{\phi} B_{\tau\tau}$.](231801-3.png)

![FIG. 2 (color online). The expected one- and two-standard-deviation ranges and observed 95% CL upper limits on $\sigma_{\phi} B_{\tau\tau}$ as a function of $m_A$. The signal acceptance is based on the MSSM model described in the text, assuming $\tan \beta = 30$.](231801-4.png)
are within the expected range assuming no signal. The observed and expected upper limits are shown in Table II.

We can interpret the upper limits on \( \sigma_{\phi}B_{\tau\tau} \) in the MSSM parameter space of \( \tan\beta \) versus \( m_A \) for an example scenario. We use here the \( m_h^{\text{max}} \) benchmark scenario in which \( M_{\text{SUSY}} = 1 \text{ TeV}/c^2 \), \( X_t = 2M_{\text{SUSY}} \), \( \mu = 200 \text{ GeV}/c^2 \), \( M_{\tilde{g}} = 800 \text{ GeV}/c^2 \), \( M_{\tilde{Z}} = 200 \text{ GeV}/c^2 \), and \( A_b = A_t \), where \( M_{\text{SUSY}} \) 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 \( M_{\tilde{t}} \) is fixed via the GUT relation \( M_{\tilde{t}} = (5/3)M_{\tilde{g}} \sin\omega_W/\cos\omega_W \). In determining these bounds on \( \tan\beta \), 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 \( \text{GGH@NNLO} \) [29,30] and \( \text{HIGLU} \) [31] programs for the gluon-fusion process and from the \( \text{BBH@NNLO} \) [32] program for the \( \bar{b}b \rightarrow \phi \) process in the five-flavor scheme, rescaling the corresponding Yukawa couplings by the MSSM factors calculated with \( \text{FeynHiggs} \) [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 \( m_A \leq 140 \text{ GeV}/c^2 \), 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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aDeceased.
bAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
cAlso at Universidade Federal do ABC, Santo Andre, Brazil.
dAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France, USA.
eAlso at Suez Canal University, Suez, Egypt.
fAlso at British University, Cairo, Egypt.
gAlso at Fayoum University, El-Fayoum, Egypt.
hAlso at Soltan Institute for Nuclear Studies, Warsaw, Poland.
iAlso at Massachusetts Institute of Technology, Cambridge, USA.
jAlso at Université de Haute-Alsace, Mulhouse, France.
kAlso at Brandenburg University of Technology, Cottbus, Germany.
lAlso at Moscow State University, Moscow, Russia.
mAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
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pAlso at University of Visva-Bharati, Santiniketan, India.
qAlso at Sharif University of Technology, Tehran, Iran.
rAlso at Shiraz University, Shiraz, Iran.
sAlso at Isfahan University of Technology, Isfahan, Iran.
t Also at Facoltà Ingegneria Università di Roma “La Sapienza”, Roma, Italy.
uAlso at Università della Basilicata, Potenza, Italy.
v Also at Università degli studi di Siena, Siena, Italy.
wAlso at California Institute of Technology, Pasadena, USA.
xAlso at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
yAlso at University of California, Los Angeles, Los Angeles, USA.
z Also at University of Florida, Gainesville, USA.
aaAlso at Université de Genève, Geneva, Switzerland.
Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy.
ccAlso at INFN Sezione di Roma, Università di Roma “La Sapienza”, Roma, Italy.
ddAlso at University of Athens, Athens, Greece.
eeAlso at The University of Kansas, Lawrence, USA.
ffAlso at Institute for Theoretical and Experimental Physics, Moscow, Russia.
ffAlso at Paul Scherrer Institut, Villigen, Switzerland.

Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
iAlso at Gaziosmanpasa University, Tokat, Turkey.
jAlso at Adiyaman University, Adiyaman, Turkey.
kAlso at Mersin University, Mersin, Turkey.
ilAlso at Izmir Institute of Technology, Izmir, Turkey.
mmAlso at Kafkas University, Kars, Turkey.
nAlso at Suleyman Demirel University, Isparta, Turkey.
oAlso at Ege University, Izmir, Turkey.
pAlso at Rutherford Appleton Laboratory, Didcot, United Kingdom.
qqAlso at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
rrAlso at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
sAlso at Utah Valley University, Orem, USA.
sAlso at Institute for Nuclear Research, Moscow, Russia.
uAlso at Erzincan University, Erzincan, Turkey.