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Search for Neutral Higgs Bosons of the Minimal Supersymmetric Standard Model Decaying to τ Pairs in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1:96 TeV

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We present a search for neutral supersymmetric Higgs bosons decaying to τ pairs produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The data, corresponding to 310 pb^{-1} integrated luminosity, were collected with the Collider Detector at Fermilab in run II of the Tevatron. No significant excess above the standard model backgrounds is observed. We set exclusion limits on the production cross section times branching fraction to τ pairs for Higgs boson masses in the range from 90 to 250 GeV/c^2.

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One of the outstanding questions in particle physics is the dynamics of electroweak (EW) symmetry breaking and the origin of particle masses. In the standard model (SM), EW symmetry is spontaneously broken through the Higgs mechanism [1], which predicts the existence of a massive scalar Higgs boson h_{SM}. Theoretical difficulties related to divergent radiative corrections to the h_{SM} mass have natural solutions in supersymmetric (SUSY) models [2].

The minimal supersymmetric extension of the standard model (MSSM) [3] is the simplest realistic SUSY theory. The Higgs sector in the MSSM consists of two charged and three neutral scalar bosons. Assuming CP invariance, one of the neutral bosons (A) is CP-odd, and the other two (h, H) are CP-even. Throughout this Letter, we use h (H) for the lighter (heavier) CP-even neutral Higgs boson and ϕ to denote any of h, H, A. At tree level, the MSSM Higgs bosons are described by the mass of A (m_A), and $\tan\beta = v_u/v_d$, where v_u, v_d are the vacuum expectation values of the neutral Higgs fields that couple to up-type and down-type fermions, respectively. The Yukawa couplings of A to down-type fermions (such as the b quark and τ) are enhanced by a factor of $\tan\beta$ relative to the SM. For large $\tan\beta$, one of the CP-even bosons is nearly mass-degenerate with A and has similar couplings. The dominant production mechanisms of neutral MSSM Higgs bosons at hadron colliders are gluon fusion [4] and $b\bar{b}$ fusion [5,6]. The leading decay modes of A and the corresponding mass-degenerate CP-even Higgs boson are $\phi \to b\bar{b}$ ($\sim 90\%$) and $\phi \to \tau\tau$ ($\sim 10\%$).

In this Letter, we present the results of a search for neutral MSSM Higgs bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The data sample of 310 pb^{-1} integrated luminosity was collected with the upgraded Collider Detector at Fermilab (CDF II) between 2002 and 2004 in run II of the Tevatron. The search is performed in the $\phi \to \tau\tau$ decay channel for $90 < m_A < 250$ GeV$/c^2$. One τ is detected in the decay to an e or μ and neutrinos, and the other in the decay to hadrons and a neutrino. In the following, we use τ_e, τ_μ, and τ_{had} as shorthand notations for the decay modes $\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$, and $\tau \to$ hadronsν_τ, respectively. Previous and related searches in the di-τ channel are presented in Refs. [7,8].

CDF II [9] is a general purpose detector with tracking and calorimetry. The tracking system consists of silicon microstrip detectors and a cylindrical wire drift chamber. It is immersed in a 1.4 T magnetic field produced by a superconducting solenoid. Electromagnetic (EM) and hadronic (HAD) sampling calorimeters are located outside the solenoid and cover detector pseudorapidity $|\eta| < 3.6$, where $\eta = -\ln(\tan(\theta/2))$ and θ is the polar angle with respect to the proton beam. The calorimeters are divided into towers with projective geometry. A central electromagnetic shower maximum detector (CES) consisting of proportional chambers with anode wires parallel to the beam axis and orthogonal cathode strips is embedded in the EM calorimeter at a depth of six radiation lengths. The CES is used to determine the position of EM showers with spatial resolution of $\sim$0.5 cm. Muons are identified by a system of drift chambers located outside the calorimeter volume with combined coverage extending to $|\eta| < 1.5$. The luminosity is measured by gas Cherenkov counters located in the detector forward and backward regions ($3.7 < |\eta| < 4.7$) with 6% precision [10].

The search for $\phi \to \tau\tau$ requires detection of an e or μ (from τ_e, τ_μ) and the reconstruction of the τ_{had} decay products. Events are preselected with "lepton plus track" triggers [11]. The triggers require a lepton (e, μ) candidate and another track, both pointing to the central calorimeter ($|\eta| \lesssim 1.0$) and having azimuthal separation $\Delta\varphi > 10°$. The overall trigger efficiency for signal events passing the selection criteria described below is greater than 90%. The algorithms for e and μ identification are described in detail in Ref. [9]. The vector sum of the transverse momenta [12] of the neutrinos from τ decays appears as missing transverse energy ($\not{E}_T$), determined from the imbalance of energy deposition in the calorimeter [13]. The decay products in τ_{had} form narrow jets with low multiplicity of neutral and charged particles. The positions and energies of π^0's and photons are reconstructed with the CES detector and EM calorimeter, respectively. In this search, we do not distinguish reconstructed photons and π^0's, and all neutrals are assumed to be π^0's. A charged track with $p_T > 6$ GeV$/c$ pointing to a cluster of six or fewer contiguous calorimeter towers serves as a seed for a τ_{had} candidate. The direction of the track defines the axis of a signal cone of size α_{sig} and an isolation annulus extending from α_{sig} to $\alpha_{\text{iso}} = 0.52$ rad. The signal cone size depends on the calorimeter cluster energy E^{cl}: α_{sig} is the minimum of 0.17 and $(5\text{ GeV})/E^{\text{cl}}$ rad. To reduce position resolution effects, the minimum value of α_{sig} is set to 0.05 (0.1) rad for tracks (π^0's). The four-momentum of τ_{had} is calculated from tracks and π^0's in the signal cone. Particles in the isolation annulus are used to impose requirements that discriminate against quark and gluon jets: The scalar sum of the p_T of tracks (sum of E_T of π^0's) is required to be less than 1 GeV$/c$ (1 GeV). We select τ_{had} candidates with one or three tracks in the signal cone ($N_{\text{sig}}^{\text{trk}} = 1, 3$) with $p_T > 1$ GeV$/c$, consistent with the dominant τ decay modes. In the $N_{\text{sig}}^{\text{trk}} = 3$ case, the sum of the electric charges must be equal to ± 1. The invariant mass of the hadronic system is required to be less than 1.8 GeV$/c^2$. Electrons are rejected by imposing the condition $(E^{\text{cl}}/P_{\text{sig}}^{\text{trk}})(0.95 - f) > 0.1$, where f is the ratio of EM to HAD energy in the calorimeter cluster, and $P_{\text{sig}}^{\text{trk}}$ is the scalar sum of track momenta in the signal cone. Muons are suppressed by requiring $E_T^{\text{cl}} > 15$ GeV. The τ_{had} identification efficiency increases from 38% at transverse momentum of the hadronic system $p_T^{\text{had}} = 15$ GeV$/c$ to $\sim$46% for $p_T^{\text{had}} \gtrsim 25$ GeV$/c$. The probability for misidentifying a quark or gluon jet as τ_{had} is measured using jet data samples. It is $\sim$1.5% for jet transverse energy $E_T^{\text{jet}} = 20$ GeV, dropping to $\sim$0.1% for $E_T^{\text{jet}} = 100$ GeV.

The acceptances for signal and most of the backgrounds are determined from samples of Monte Carlo (MC) simulated events produced by the PYTHIA event generator [14] with CTEQ5L [15] parton distribution functions (PDF's). Tau decays are simulated by the TAUOLA package [16]. Detector response is simulated with a GEANT-based [17] model of the detector.

The dominant (and irreducible) background in the final sample of selected events is from inclusive Z/γ^* production with subsequent decays to τ pairs. It is estimated using MC simulated events with normalization corresponding to

$\sigma(p\bar{p} \to Z/\gamma^*) \times \mathrm{BR}(Z/\gamma^* \to ll) = 254.9$ pb in the dilepton mass region $66 < m_{ll} < 116$ GeV$/c^2$ [18]. The second largest background contribution comes from processes with quark or gluon jets misidentified as $\tau_{\rm had}$, such as dijet and multijet, W + jets, and γ + jets production. These backgrounds are estimated from the data by applying jet $\to$ $\tau_{\rm had}$ misidentification rates to jets in events that pass all selection criteria except for $\tau_{\rm had}$ identification. The validity of the predictions is verified using independent data samples representing the background processes. The third group of backgrounds includes $Z/\gamma^* \to ll$ ($l = e, \mu$), WW, WZ, ZZ, and $t\bar{t}$ production. Their contributions are determined from MC samples normalized to the theoretical cross sections.

The events in the $\tau_e\tau_{\rm had}$ ($\tau_\mu\tau_{\rm had}$) channel are selected by requiring one e (μ) candidate with $p_T^{e(\mu)} > 10$ GeV$/c$ and one $\tau_{\rm had}$ candidate with $p_T^{\rm had} > 15$ GeV$/c$ and opposite electric charge. Low-energy multijet backgrounds are suppressed by rejecting events with $|p_T^{e(\mu)}| + |p_T^{\rm had}| + |\not{E}_T| < 50$ GeV. Backgrounds from W + jet events are suppressed by imposing a requirement on the relative directions of the visible τ decay products and $\not{E}_T$. We define a unit vector $\hat{\zeta}$ along the bisector of the angle between the directions of e (μ) and $\tau_{\rm had}$ in the transverse plane. The projections $p_\zeta^{\rm vis} = (\vec{p}_{e(\mu)} + \vec{p}_{\rm had}) \cdot \hat{\zeta}$ and $p_\zeta^{\not{E}_T} = \vec{\not{E}}_T \cdot \hat{\zeta}$ are required to satisfy $p_\zeta^{\not{E}_T} > 0.6 p_\zeta^{\rm vis} - 10$ GeV$/c$. This condition removes $\sim$85% of the W + jet events passing the other selection criteria while retaining $\sim$95% of the signal. To suppress backgrounds from $Z \to ll$ decays with a misidentified lepton, we do not accept events with invariant mass of an e (μ) and a single-track $\tau_{\rm had}$ candidate within 10 GeV$/c^2$ of the Z mass. The combined signal acceptance for a Higgs boson of mass 90 GeV$/c^2$ (250 GeV$/c^2$) in the $\tau_e\tau_{\rm had}$ and $\tau_\mu\tau_{\rm had}$ channels is 0.8% (2.0%).

The systematic uncertainties for particle identification efficiency are 3.5% ($\tau_{\rm had}$), 1.3% (e), and 4.6% (μ). The uncertainties in trigger efficiency for the $\tau_e\tau_{\rm had}$ and $\tau_\mu\tau_{\rm had}$ channels are 2.1% and 1.4%, respectively. The uncertainty in the determination of backgrounds due to jet $\to \tau$ misidentification is 20%, resulting in 3% effect on the total background estimate. The systematic uncertainty in signal acceptance from event-level cuts is less than 2%. The imprecise knowledge of the PDF's introduces an additional 5.7% uncertainty on signal acceptance [19].

Figure 1 shows the track multiplicity distribution for $\tau_{\rm had}$ candidates in the data, along with the background predictions. The characteristic enhancement in the one- and three-track bins clearly shows the contribution from events with $\tau_{\rm had}$ in the final state. The total number of expected events from SM processes after applying all selection criteria is $N_{\rm SM} = 496 \pm 5(\rm stat) \pm 28(\rm syst) \pm 25(\rm lumi)$. The contributions from $Z/\gamma^* \to \tau\tau$, backgrounds with jet $\to \tau$ misidentification, and all remaining background sources are 405, 75, and 16, respectively.

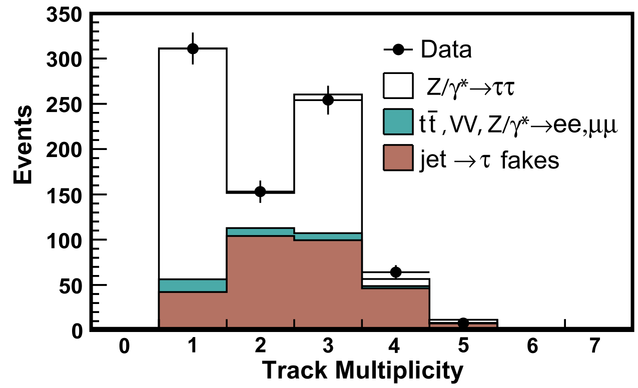

FIG. 1 (color online). Track multiplicity for hadronically decaying tau candidates before applying the opposite charge and $N_{\rm trk}^{\rm sig}$ requirements.

We observe 487 events, in agreement with $N_{\rm SM}$. To probe for a possible Higgs signal, we perform binned likelihood fits of the partially reconstructed mass of the di-τ system ($m_{\rm vis}$) defined as the invariant mass of the visible tau decay products and $\not{E}_T$. The backgrounds are allowed to float within limits set by Gaussian constraints corresponding to the systematic uncertainties in trigger efficiencies, particle identification, production cross sections, PDF's, event cuts, and luminosity measurement. Potential differences in $m_{\rm vis}$ shapes between data and the MC simulation in different channels are treated as systematic uncertainties. We create signal and background $m_{\rm vis}$ templates with the MC energy scales shifted from the nominal values according to the uncertainties and study the effect on hypothetical cross section measurements. The deviations from the results obtained with the nominal templates are parametrized in terms of the Higgs boson mass and input cross section. An example fit for $m_A = 140$ GeV$/c^2$ is shown in Fig. 2. We observe no signal evidence for $m_A = 90$–250 GeV$/c^2$ and set exclusion limits at 95% C.L. on $\sigma(p\bar{p} \to \phi + X) \times \mathrm{BR}(\phi \to \tau\tau)$ as

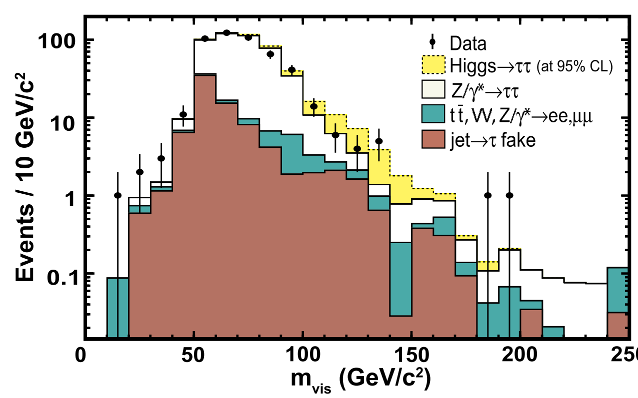

FIG. 2 (color online). Example fit of the $m_{\rm vis}$ distribution for signal with $m_A = 140$ GeV$/c^2$. Signal and background normalizations correspond to the fit results for signal exclusion at 95% C.L.

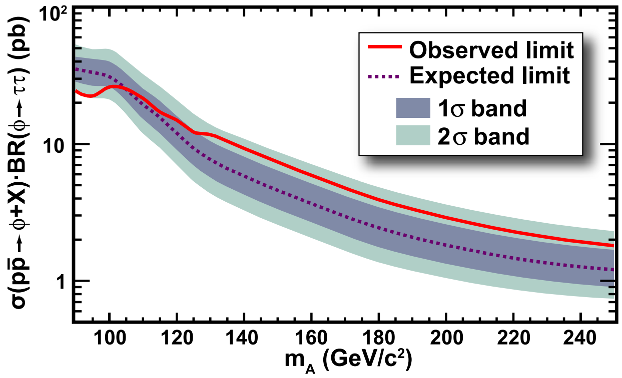

FIG. 3 (color online). Upper limits at 95% C.L. on Higgs production cross section times branching fraction to τ pairs. The expected limits from the pseudoexperiments are also shown.

shown in Fig. 3. The sensitivity of the limit-setting procedure is determined from MC simulations assuming no signal. The $m_{\rm vis}$ shape uncertainty leads to 15% (5%) deterioration of the limits for the low (high) end of the considered m_A region. The observed limits range from 24.4 pb for $m_A = 90~{\rm GeV}/c^2$, to 9.3 pb for $m_A = 140~{\rm GeV}/c^2$, to 1.8 pb for $m_A = 250~{\rm GeV}/c^2$.

Using the theoretical predictions for the MSSM Higgs boson production and decay to τ pairs, we interpret the limits on $\sigma(p\bar{p} \to \phi + X) \times {\rm BR}(\phi \to \tau\tau)$ as exclusions of parameter regions in the $\tan\beta$ vs m_A plane. The cross sections are obtained from SM calculations and scaling factors $\sigma_{\rm MSSM}/\sigma_{\rm SM}$ accounting for the modified Higgs couplings [20]. The cross sections for gluon fusion mediated by a b-quark loop are calculated with the HIGLU program [21]. The corresponding values for $b\bar{b} \to \phi + X$ are taken from Ref. [6]. The scaling factors and BR($\phi \to \tau\tau$) are calculated with the FEYNHIGGS program [22]. They depend on m_A, $\tan\beta$, the $SU(2)$ gaugino mass parameter M_2, the SUSY mass scale $M_{\rm SUSY}$, the squark mixing parameter X_t, the gluino mass $m_{\tilde{g}}$, and the Higgs mixing parameter μ. We consider four benchmarks [23]: the $m_h^{\rm max}$ and no-mixing scenarios, with $\mu > 0$ and $\mu < 0$. The excluded $\tan\beta$ vs m_A regions are shown in Fig. 4.

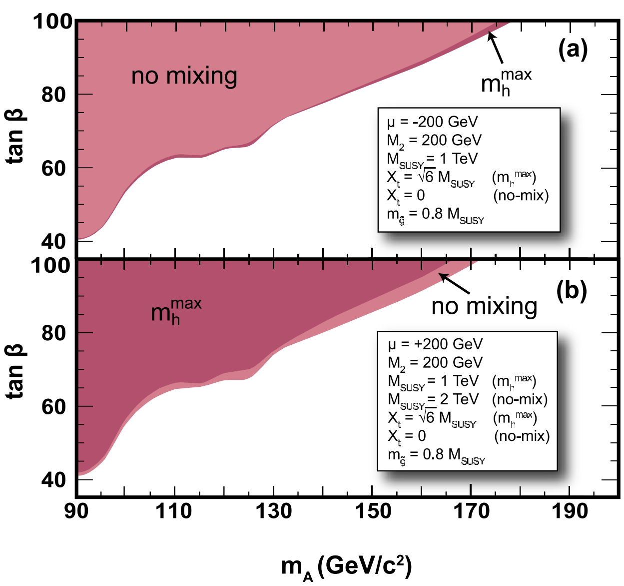

FIG. 4 (color online). Excluded regions in the $\tan\beta$ vs m_A plane for the $m_h^{\rm max}$ and no-mixing scenarios with (a) $\mu < 0$ and (b) $\mu > 0$.

The LEP experiments have excluded $m_A \lesssim 93~{\rm GeV}/c^2$ and higher-mass A for small $\tan\beta$ [24]. Our search is complementary, providing sensitivity in the large $\tan\beta$ region. The excluded parameter space in the $\tan\beta$ vs m_A plane for $\mu < 0$ is similar to the D0 results obtained in the $\phi \to b\bar{b}$ decay mode [25] and extends to higher m_A. Moreover, our results in the $\phi \to \tau\tau$ channel allow us to set comparable exclusions for scenarios with $\mu > 0$, as the lower production cross sections are compensated by an increase in BR($\phi \to \tau\tau$).

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