Search for Higgs bosons predicted in two-Higgs-doublet models via decays to tau lepton pairs in 1.96 TeV $p\bar{p}$ collisions

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We present the results of a search for Higgs bosons predicted in two-Higgs-doublet models, in the case where the Higgs bosons decay to tau lepton pairs, using 1.8 fb^{-1} of integrated luminosity of $p\bar{p}$ collisions recorded by the CDF II experiment at the Fermilab Tevatron. Studying the invariant mass distribution in events where one or both tau leptons decay leptonically, no evidence for a Higgs boson signal is observed. The result is used to infer exclusion limits in the two-dimensional parameter space of $\tan\beta$ versus m_A.

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Understanding the origin of electroweak symmetry breaking is one of the central goals of particle physics. The Higgs mechanism [1] in the standard model (SM) provides a possible explanation, but the calculated mass of the Higgs boson suffers from large radiative corrections. Remedies for this problem such as supersymmetry [2] require at least two Higgs doublets [3] and result in a more complicated Higgs boson sector than that of the SM. The minimal supersymmetric standard model (MSSM) [4] predicts the existence of three neutral Higgs bosons. The MSSM is an example of a Type II two-Higgs-doublet model (Type II 2HDM) in which there is a light scalar h, a heavy scalar H, and a pseudoscalar A. The masses of these states are governed mainly by two parameters in the theory, usually taken to be $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets, and m_A, the mass of the pseudoscalar.

In $p\bar{p}$ collisions at 1.96 TeV center of mass energy at the Fermilab Tevatron, Type II 2HDM Higgs bosons would be predominantly produced by gluon-gluon fusion through a b quark loop [5] or by $b\bar{b}$ fusion [6]. The couplings and masses of the Higgs bosons are such that if $\tan\beta$ is greater than about 20 and m_A is smaller (greater) than about 125 GeV/c^2, one finds that the h (H) and A are nearly degenerate in mass, and are produced with a cross section proportional to $\tan^2\beta$, while the production of H (h) is suppressed.

These $\tan^2\beta$-enhanced production cross sections can be much greater than the corresponding ones for a SM Higgs, lying in the range 0.1 – 10 pb depending on the masses of the Higgs bosons. The Higgs bosons decay to fermion pairs with a partial width proportional to the fermion mass squared; thus the decays $\phi \to b\bar{b}$ and $\phi \to \tau^+\tau^-$ (with $\phi = h, A, H$) predominate, with the branching ratio to $b\bar{b}$ approximately 90% and the branching ratio to $\tau^+\tau^-$ about 9% for $m_A > 100$ GeV/c^2.

This Letter presents the results of a search for the production of Higgs bosons in Type II 2HDM such as the MSSM, using data collected with the CDF II detector at the Fermilab Tevatron $p\bar{p}$ collider corresponding to 1.8 fb^{-1} of integrated luminosity. Full details of the analysis are available elsewhere [7]; this result supersedes our previously published result [8], and is similar to the search performed by the D0 Collaboration [9].

The analysis presented here uses the tau pair decay modes, since it is possible to efficiently trigger on and reconstruct the leptons in decays of the tau lepton to $e\nu\bar{\nu}$ or $\mu\nu\bar{\nu}$. Indeed, despite the 10× larger branching ratio to $b\bar{b}$, the search in the tau mode is more sensitive because the SM background is much smaller.

CDF II [10] is a general-purpose detector with an overall cylindrical geometry surrounding the $p\bar{p}$ interaction region. The three-dimensional trajectories of charged particles produced in $p\bar{p}$ collisions are measured at small radii (< 30 cm) using multiple layers of silicon microstrip detectors, and at outer radii (> 30 cm) with a multi-wire drift chamber. The tracking system is inside a solenoidal magnet with uniform 1.4 T magnetic field oriented along the beam direction. Outside the solenoid are the electromagnetic and hadronic calorimeters, which are segmented in pseudorapidity (η) and azimuth in a projective "tower" geometry [11]. A set of strip and wire chambers located at a depth of six radiation lengths aids in identifying photons and electrons from the electromagnetic shower shape. Muons are identified by a system of drift chambers and scintillators placed outside the calorimeter steel, which acts as an absorber for hadrons. The integrated luminosity of the $p\bar{p}$ collisions is measured using Čerenkov luminosity counters [12].

Events with a high-p_T (8 GeV/c or more) e or μ candidate plus a high-p_T charged track (5 GeV/c or more) or a second e or μ (4 GeV/c or more) are identified using high-speed trigger electronics and are recorded for later analysis. The performance of the trigger and lepton identification algorithms is described in detail elsewhere [13, 14].

We seek events with tau pairs where one or both taus decay leptonically (excluding e^+e^- and $\mu^+\mu^-$ which suffer from excessive background from Z/γ^* production). These final states are denoted $e{+}\tau$, $\mu{+}\tau$, and $e{+}\mu$ (where "τ" here means the reconstructed hadronic part of a tau decay). The reconstruction of hadronic decays of tau leptons [15] relies on defining tau signal and isolation region cones centered around seed tracks having $p_T > 6$ GeV/c; we demand one or three charged tracks in the tau cone, and include in addition any π^0 candidates. The main way to discriminate between hadronic tau lepton decays and hadronic jets from quantum chromodynamic processes is to demand no additional charged tracks or π^0 candidates in an isolation annulus outside the tau signal cone but within 30° of the tau seed track. The optimal half-angle of the tau signal cone decreases with increasing visible tau energy due to the Lorentz boost of the tau lepton,

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TABLE I: Mean expected SM backgrounds and observed numbers of selected events in the final sample. The uncertainties include all systematic effects, some of which are correlated.

Background	$e+\mu$	$e+\tau$	$\mu+\tau$
$Z/\gamma^* \to \tau^+\tau^-$	605 ± 51	1378 ± 117	1353 ± 116
$Z/\gamma^* \to e^+e^-$	1.5 ± 1.2	70 ± 10	negl.
$Z/\gamma^* \to \mu^+\mu^-$	17.9 ± 4.5	negl.	107 ± 13
dibosons	11.4 ± 3.7	4.2 ± 2.1	3.3 ± 1.8
$t\bar{t}$	9.1 ± 3.3	4.0 ± 2.1	3.3 ± 1.9
W+jet, multijet	57.1 ± 13.5	467 ± 73	285 ± 46
Total	702 ± 55	1922 ± 141	1752 ± 129
Observed	726	1979	1666

further aiding the discrimination of taus from jets. Additional suppression of hadronic jets comes from imposing a mass requirement on the tau candidate decay products. Electrons and muons are removed using information from the calorimeters and muon detectors.

To select the $e+\tau$ and $\mu+\tau$ events we require an isolated e or μ with $p_T > 10$ GeV/c, and a τ with visible hadronic decay products with total $p_T > 15$ GeV/c (20 GeV/c for three-charged-pion decays). For the $e+\mu$ channel we require one lepton to have $p_T > 10$ GeV/c and the other to have $p_T > 6$ GeV/c.

The main SM contributions to the selected event sample include $Z/\gamma^* \to \tau^+\tau^-$, and W+jet events where $W \to \ell\nu$ (with $\ell = e, \mu$) and the hadronic jet is misidentified as a hadronically decaying τ. The W+jet events are largely removed by requiring that the missing transverse energy $\vec{\not\!\!E}_T$ not point along the direction opposite the momentum of the ℓ+τ system. The remaining W+jet background, and all other background stemming from jets misreconstructed as taus ("fakes") is estimated from events recorded with a jet trigger. There are small contributions from $Z \to e^+e^-$, $Z \to \mu^+\mu^-$, diboson, and $t\bar{t}$ production.

The acceptances for signal and the non-fake backgrounds are estimated from samples of simulated events produced by the PYTHIA event generator [16] with CTEQ5L [17] parton distribution functions. The Higgs boson widths are those for an MSSM model with $\tan\beta = 50$. Tau decays are simulated by the TAUOLA package [18]. A GEANT-based [19] model simulates the interactions of all final state particles in the detector.

Table I shows the mean expected contributions of SM sources, and the number of observed events in the three channels. The uncertainties listed include all systematic effects discussed below, including correlations.

To discriminate a Higgs boson signal from the backgrounds, we perform a binned likelihood fit of background and signal to the observed distribution of the "visible mass" m_{vis}, derived from the sum of the observed lepton four-momenta and the missing transverse energy. Figure 1 shows the observed and fit distributions for the search channels, including the contribution from a Higgs boson signal as described below.

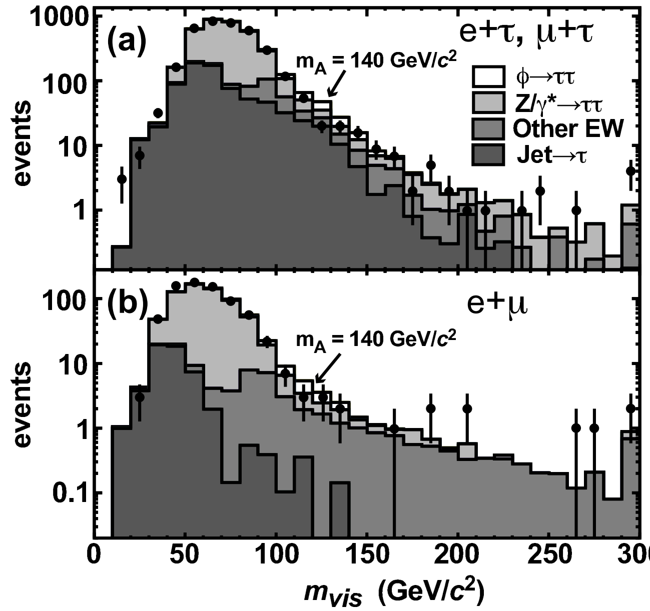

FIG. 1: Observed and predicted distributions of m_{vis} for the $e+\tau$ and $\mu+\tau$ channels (a) and $e+\mu$ channel (b). The predicted signal distribution (for $\phi = h/A/H$) corresponds to that for $m_A = 140$ GeV/c^2 signal assuming a value of the cross section excluded at 95% C.L. Note that in each plot the last bin is an overflow bin. Here "Other EW" refers to all SM backgrounds other than $Z/\gamma^* \to \tau\tau$ and background arising from jet$\to \tau$ misidentification.

Various uncertainties limit the sensitivity of our search. The one with the largest effect is due to the imprecisely known tau energy. The distribution of the observed transverse momentum of the τ in $W \to \tau\nu$ events constrains the ratio of the reconstructed tau energy in the observed events to that in the simulation to less than 1%, but the residual uncertainty allows for shifts in the background m_{vis} spectra mimicking a Higgs boson signal, particularly for the lower masses considered ($m_A < 140$ GeV/c^2). At larger Higgs boson masses the search sensitivity is limited more by other systematic effects considered, including the lepton trigger and identification uncertainties (2.4% for electrons, 2.7% for muons, and 4.2% for hadronically decaying taus), the uncertainty in the integrated luminosity (6%), $Z \to \tau^+\tau^-$ cross section (2.2%), and Higgs boson production cross section (5.7%) [20].

We represent all the systematic uncertainties by Gaussian-constrained nuisance parameters in the likelihood, and eliminate these parameters by maximizing the likelihood with respect to them. This procedure is numerically nearly identical to eliminating them by Bayesian marginalization with a Gaussian prior density, which takes much longer to compute.

The resulting likelihood is calculated as a function of the Higgs boson signal cross section times branching ratio to tau pairs $\sigma \cdot B$, and then converted to a posterior density in $\sigma \cdot B$ assuming a uniform prior density. We exclude with 95% C.L. any $\sigma \cdot B$ above which 5% of the posterior probability lies.

The likelihood as a function of $\sigma \cdot B$ reveals no evidence for the presence of a Higgs boson signal, and all nuisance parameters remain consistent with their nominal values. Figure 1 and other kinematic distributions not shown in this Letter all reveal excellent agreement of the observed distributions with the predictions. We therefore proceed to use the null result to infer upper limits on the Higgs boson production cross section.

Table II lists the observed 95% C.L. upper limits on $\sigma \cdot B$, and the median upper limits expected under the null hypothesis. Figure 2 depicts the results, including $\pm 1\sigma$ and $\pm 2\sigma$ ranges for the expected limits. We note that these bounds would apply to any scalar with similar production kinematics decaying to tau pairs. The Higgs boson signal distribution shown in Fig. 1 corresponds to that excluded at 95% C.L. for $m_A = 140$ GeV/c^2.

We can interpret the upper limits on $\sigma \cdot B$ in the context of the MSSM parameters $\tan\beta$ and m_A. The resulting excluded regions are shown in Fig. 3 for various assumptions about the sign of the higgsino mass parameter μ and two extremes for the nature of scalar top mixing [21], denoted m_h^{max} and "no mixing." The excluded regions are the most stringent published to date, and are remarkably insensitive to changes in theoretical assumptions due to cancellation of effects in the Higgs boson production and decay [22].

In summary, we have used a sample of data from the Tevatron collider recorded by the CDF II detector corresponding to 1.8 fb^{-1} of integrated luminosity to search for Higgs bosons predicted in two-Higgs-doublet models, via the Higgs boson decays to tau lepton pairs. No evidence for a Higgs boson signal is observed, and we use the null result to infer cross sections excluded at the 95% C.L. as a function of the Higgs mass, and 95% C.L. excluded regions of the MSSM parameter space $\tan\beta$ versus m_A.

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TABLE II: Observed 95% C.L. upper limits, and median expected limits under the null hypothesis on the Higgs boson production cross section times branching ratio $\sigma \cdot B$ versus m_A.

m_A GeV/c^2	median expected limit (pb)	observed limit (pb)
90	28.115	28.978
100	19.884	23.465
110	9.382	11.063
120	5.447	5.288
130	3.374	2.770
140	2.340	1.812
150	1.751	1.392
160	1.400	1.198
170	1.124	1.051
180	0.933	0.880
190	0.782	0.808
200	0.707	0.709
230	0.470	0.505
250	0.379	0.451

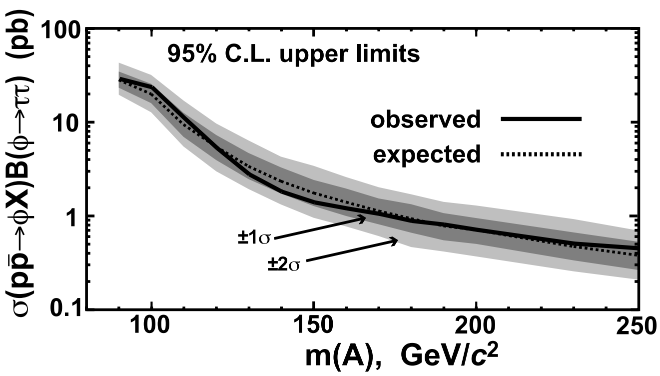

FIG. 2: Observed 95% C.L. upper limits on the cross section for $\phi = h/A/H$ production as a function of m_A. The grey bands show the median expected limit under the null hypothesis, and indicate the ± 1- and ± 2-standard-deviation ranges.

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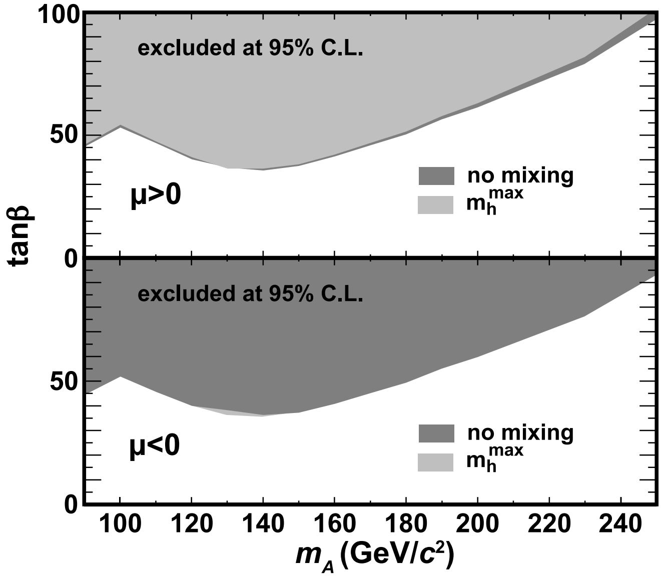

FIG. 3: Regions in the MSSM plane of $\tan\beta$ versus m_A excluded at 95% C.L. assuming heavy ($\sim$1 TeV/c^2) sfermions. The top panel shows excluded regions for higgsino mass parameter $\mu > 0$, and the bottom panel shows excluded regions for $\mu < 0$. Each panel shows the slightly different excluded regions for two scalar top mixing scenarios.

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