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Search for the Top Quark Decaying to a Charged Higgs Boson in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present the results of a search in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV for the top quark decaying to a charged Higgs boson ($H^\pm$). We search for dilepton final states from the decay chain $t\bar{t} \rightarrow HH$ (or HW, or WW) + $b\bar{b} \rightarrow ll + X$. In a sample of 19.3 pb^{-1} collected during 1992–93 with the Collider Detector at Fermilab, we observe 2 events with a background estimation of 3.0 ± 1.0 events. Limits at 95% C.L. in the $(M_{\rm top}, M_{H^\pm})$ plane are presented. For the case $M_{\rm top} < M_W + M_b$, we exclude at 95% C.L. the entire $(M_{\rm top}, M_{H^\pm})$ plane for the branching ratio $B(H \rightarrow \tau\nu)$ larger than 75%. We also interpret the results in terms of the parameter $\tan\beta$ of two-Higgs-doublet models.

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Within the context of the standard model, the top quark decay can only be mediated by the charged vector boson W. We have recently presented evidence for an excess of events for which the most natural interpretation is production of top quark pairs with a top mass of 174 ± 16 GeV/c^2 [1]. Other searches have placed a 95% C.L. lower limit on the top mass $M_{\rm top}$ of 131 GeV/c^2 [2], also assuming standard model decays. Without this assumption, the experimental lower limit on the top mass $M_{\rm top}$ is 62 GeV/c^2 [3]. The existence of charged Higgs bosons, predicted by supersymmetry [4] and other models, provides one way of generating nonstandard top decays. Direct searches at the CERN e^+e^- collider LEP have resulted in the lower limit on the charged Higgs boson mass $M_{H^\pm}$ about 45 GeV/c^2 [5].

In this Letter we present a search for the decay $t \rightarrow Hb$, assuming that this is an allowed decay as well as $t \rightarrow Wb$. We thus search for the dilepton final states from the decay chain $t\bar{t} \rightarrow HH$ (or HW, or WW) + $b\bar{b} \rightarrow ll + X$. We assume the charged Higgs boson is lighter than $M_{\rm top} - M_b$. Most of the top acceptance for top decays in this channel comes from electrons and muons from $H \rightarrow \tau\nu \rightarrow l\nu\nu\nu$ and $W \rightarrow l\nu$, but leptons from b decay also contribute. This analysis extends the results of our previous search for the hadronic chain $H \rightarrow \tau\nu$, $\tau \rightarrow$ hadrons + ν [6].

The branching ratios for $t \rightarrow Hb$ and $t \rightarrow Wb$ depend on the top quark mass, Higgs boson mass, and $\tan\beta$, which is the ratio of the Higgs boson vacuum expectation values in two-Higgs-doublet models [7], as in the minimal extension of the standard model. If the top quark mass is heavier than $M_W + M_b$, both the standard model decay channel ($t \rightarrow Wb$) and the charged Higgs boson decay channel ($t \rightarrow Hb$) of the top quark are allowed. If the top quark mass is lighter than $M_W + M_b$, the charged Higgs boson decay channel is dominant.

The charged Higgs boson decays predominantly via $H \rightarrow \tau\nu$ or $H \rightarrow c\bar{s}$ when it is lighter than the top quark, assuming no neutral Higgs boson decay modes are allowed. The branching ratio $B(H \rightarrow \tau\nu)$ is model dependent and is a function of $\tan\beta$ [7]; for $\tan\beta > 1$ the τ decay mode dominates.

The major sources of background in the dilepton modes are WW production; $Z \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$; $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$, $\Upsilon \rightarrow e^+e^-, \mu^+\mu^-$; continuum Drell-Yan; QCD production of $b\bar{b}$ and $c\bar{c}$; and $W +$ hadron where the hadron is misidentified as a lepton.

The Collider Detector at Fermilab (CDF) [8] and the identification of electrons and muons are described in detail elsewhere [9]. Electron candidates are identified by the presence of a track in the central tracking chamber (CTC) that extrapolates to an electromagnetic energy cluster in the pseudorapidity region $|\eta| < 1.2$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the beam axis. Muon candidates are identified by a track segment in drift chambers outside the calorimeters matched to a CTC track. Neutrinos give rise to missing energy transverse to the beam direction ($\not\!E_T$), which is measured as the negative vector sum of the transverse energy in all calorimeter towers in the pseudorapidity range $|\eta| < 3.6$ and corrected for high P_T muons.

In this analysis [10], we require at least one lepton with transverse momentum (P_T) greater than 6 GeV/c and a second lepton with $P_T > 9$ GeV/c; these thresholds accept more than 25% of the top to charged Higgs boson decays. After the P_T and lepton identification cuts, we have 3826 events which passed the inclusive electron trigger and 5987 events which passed the inclusive muon trigger. Several topology cuts are applied to reduce the backgrounds (see Table I). We require at least one lepton to pass a calorimeter isolation (E_{iso}) cut, in which the measured transverse energy deposited in a cone of radius 0.4 in η-ϕ space around the lepton (excluding the lepton energy) must be less than 2 GeV. The second lepton must pass a loose isolation cut of $E_{\text{iso}} < 8$ GeV. For ee and $\mu\mu$ events we remove the J/ψ, Υ, low mass Drell-Yan, and b sequential decays ($b \rightarrow cl\nu \rightarrow sll\nu\nu$) by requiring the dilepton invariant mass $M_{ee,\mu\mu} > 12$ GeV/c^2. We remove Z events in the range $70 < M_{ee,\mu\mu} < 110$ GeV/c^2. For $e\mu$ events, we use a cut of $M_{e\mu} > 10$ GeV/c^2 to remove b sequential decays and reduce the $b\bar{b}$ and fake $e\mu$ backgrounds. We require $\not\!E_T > 20$ GeV with $\not\!E_T$ significance greater than 2.4. The $\not\!E_T$ significance, denoted as S, is defined as $\not\!E_T$ divided by the square root of the total sum E_T of the event. For events which have a high P_T (>25 GeV/c) lepton with $E_{\text{iso}} < 2$ GeV, we require the azimuthal angle between the $\not\!E_T$ and this lepton to be less than 165°. This cut reduces background from $W +$ jet events in which the W decays leptonically and the jet is misidentified as a lepton, since the high P_T lepton and the $\not\!E_T$ from a real W tend to be back-to-back in the transverse plane. We call this cut the W removal cut. We also require the azimuthal angle between the $\not\!E_T$ direction and the direction of the closest lepton or jet to exceed 30°. This requirement suppresses both the $Z \rightarrow \tau\tau$ background in which $\not\!E_T$ along the lepton direction can arise from neutrinos originating from the decay of the τ lepton and the Drell-Yan background in which $\not\!E_T$ can be due to jet energy mismeasurement and thus lies along the jet direction. After the isolation, invariant mass, $\not\!E_T$ significance, and W removal cuts, we plot the azimuthal angle between the direction of $\not\!E_T$ and the direction of the closest lepton or jet versus the $\not\!E_T$ in Fig. 1. We list the numbers of events which pass the cuts in sequence in Table I. Two candidate events are found after all the topology cuts. One is an $e\mu$ event found also in the top dilepton search [1] and the other is an ee event.

We use the ISAJET Monte Carlo program [1] and a CDF detector simulation to determine the acceptance and the combined efficiency of the topology cuts. We list the efficiencies of the cuts for $t\bar{t} \rightarrow HbHb$ as measured with the Monte Carlo simulation for three M_{top}, $M_{H^\pm}$ combinations in Table I. We measure the efficiency of the lepton identification cuts from the Z and J/ψ data. The dominant uncertainties in the detection efficiency come from a limited understanding of initial state gluon radiation (8%), lepton identification (10%), detector simulation (5%), and Monte Carlo statistics (5%).

The dilepton background from WW production is determined from an ISAJET Monte Carlo calculation with a

TABLE I. Number of data events which pass the cuts and number of events expected for $tt \rightarrow HbHb$ as measured with the Monte Carlo simulation for three $M_{\text{top}}, M_{H^\pm}$ combinations.

Cuts	Events surviving (data)	Events expected (signal) M_{top}, $M_{H^\pm}$ (GeV/c^2) 100, 95	100, 45	70, 45
P_T, fiducial, ID	9204	26.8	47.5	197
Isolation	3868	23.7	19.4	127
Invariant Mass	2009	21.2	17.6	113
$\not\!E_T > 20$ GeV	39	16.5	12.0	55
$S > 2.4$	27	15.7	9.8	46
W removal	12	11.8	8.7	41
$\Delta\phi(\not\!E_T, \text{l or jet}) > 30°$	2	9.9	5.2	29
All cuts	2	9.9	5.2	29

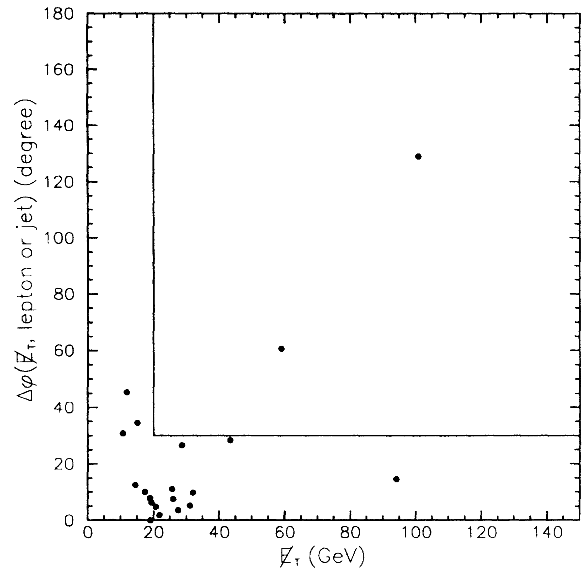

FIG. 1. $\Delta\phi(\not\!\!E_T$-lepton or jet) vs $\not\!\!E_T$ after isolation, invariant mass, $\not\!\!E_T$ significance, and W removal cuts for the data events.

cross section calculated with the HMRS(B) structure function [12]. We expect 0.9 ± 0.3 events from WW background. Background from $Z \rightarrow \tau\tau \rightarrow e\mu, ee, \mu\mu$ is studied using a data sample of $Z \rightarrow ee$ events and replacing each electron by a simulated τ which then decays into e or μ. We expect 0.43 ± 0.10 events from this background. Similarly, Drell-Yan ee and $\mu\mu$ backgrounds are studied by using Z data to obtain rejection factors for P_T and event topology cuts. These factors are then applied to the observed continuum ee and $\mu\mu$ mass spectrum for isolated dilepton events. We expect 0.38 ± 0.27 events from Drell-Yan backgrounds.

Heavy flavor backgrounds, mostly $b\bar{b}$, have been studied using the ISAJET Monte Carlo program. Normalizing the number of events in the Monte Carlo sample by counting $e\mu$ events in the b sequential peak ($M_{e\mu} < 5$ GeV/c^2) in the data, we expect 0.5 ± 0.5 events from these backgrounds.

Events from QCD multijet or $W +$ jet process, with at least one jet misidentified as a lepton, conversion electron, or muon from hadron decay in flight, can mimic the $t\bar{t}$ signature. These backgrounds are estimated by measuring the probabilities for tracks or calorimeter clusters from a jet background sample to satisfy electron or muon identification cuts. Applying these probabilities to the number of events in the data with a lepton together with an additional cluster or track results in a background estimate of 0.8 ± 0.8 events.

Other backgrounds, such as WZ and $Z \rightarrow b\bar{b}$, have been studied and are negligible. The total background in the ee, $\mu\mu$, and $e\mu$ categories is 3.0 ± 1.0 events.

Given 2 events observed and 3.0 ± 1.0 events expected from the backgrounds, we have found no evidence for $t\bar{t}$ production in which the top decays to a charged Higgs boson. We expect 5 to 10 events for $t\bar{t} \rightarrow HbHb$ production with top mass 100 GeV and Higgs boson mass from 45 to 95 GeV. A 95% C.L. upper limit on the number of expected signal events is calculated using the distribution obtained by convoluting a Poisson distribution with a Gaussian distribution [13] describing the total systematic uncertainty. This number is used along with the total detection efficiency as a function of $M_{\rm top}$, $M_{H^\pm}$, and $B(H \rightarrow \tau\nu)$ to provide an upper limit on the $t\bar{t}$ production cross section. To remain independent of the background calculation, we do not subtract the backgrounds. Comparing our upper limit with the lower limit (at one sigma) of the theoretical $\sigma_{t\bar{t}}$ [14], we can exclude regions of the $(M_{\rm top}, M_{H^\pm})$ plane at 95% C.L. for

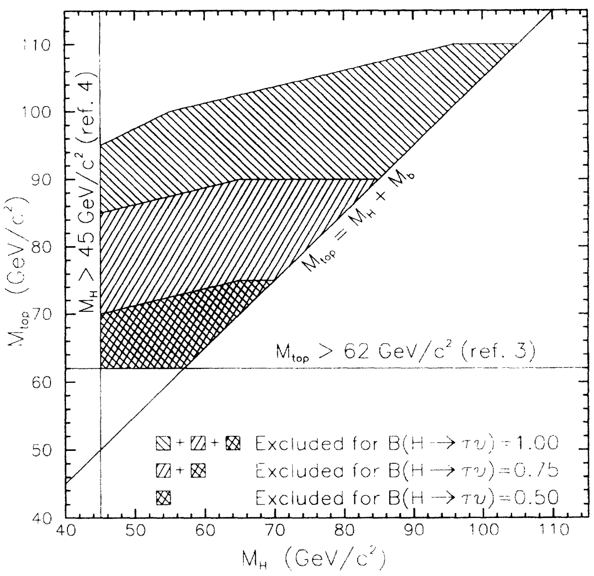

FIG. 2. Regions of $(M_{\rm top}, M_{H^\pm})$ plane excluded at 95% C.L. for $B(t \rightarrow Hb) = 1.0$.

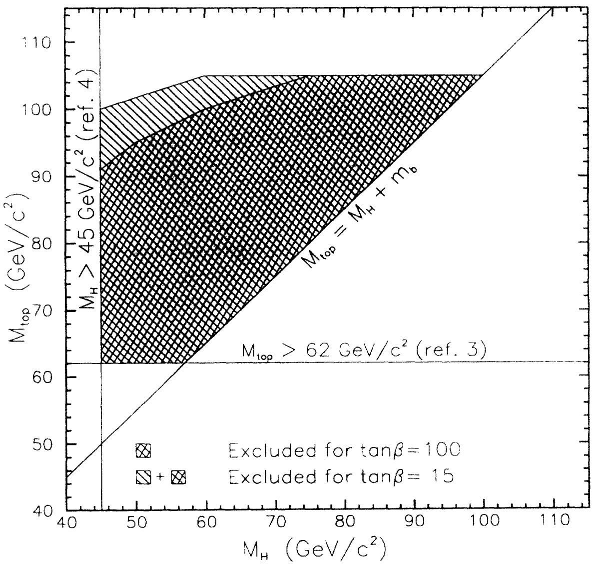

FIG. 3. Regions of $(M_{\rm top}, M_{H^\pm})$ plane excluded at 95% C.L. for two-Higgs-doublet models.

TABLE II. Measured upper limits on the cross section $\sigma_{t\bar{t}}$ in pb at 95% C.L. for a given top mass and Higgs boson mass combination for several tanβ values. The last column lists the lower limits (at one sigma) of the theoretical $\sigma_{t\bar{t}}$ for different top masses [14].

		Cross section limit $\sigma_{t\bar{t}}$ in pb (95% C.L.)						
	M_{top}			$M_{H^\pm}$ (GeV/c^2)				$\sigma_{t\bar{t}}$ (theory)
tanβ	(GeV/c^2)	45	55	65	80	95	105	in pb
	110	122	95.5	81.7	69.8	62.0	61.3	52.7
	105	108	94.5	76.1	65.0	63.4		67.3
100	100	122	91.3	80.9	70.0	65.9		86.3
	95	124	106	97.4	71.3			112
	90	145	109	93.5	83.0			148
	110	76.2	69.6	66.4	65.4	64.3	64.4	52.7
15	105	67.8	67.5	62.2	60.8	59.9		67.3
	100	75.8	70.0	68.3	66.2	65.2		86.3
	110	67.8	65.9	65.0	64.8	64.4	64.5	52.7
5	105	61.2	62.3	59.8	59.4	59.2		67.3
	100	68.0	66.5	66.1	65.5	65.2		86.3
	110	76.0	70.8	68.1	66.8	65.3	64.8	52.7
2	105	67.6	67.3	63.3	61.7	60.3		67.3
	100	75.0	71.0	69.5	67.4	65.8		86.3
	110	163	140	124	106	87.6	73.6	52.7
	105	146	136	116	97.4	77.0		67.3
1	100	166	144	128	104	77.1		86.3
	95	186	158	141	106			112
	90	232	191	160	115			148

a given $B(t \to Hb)$ and $B(H \to \tau\nu)$. Figure 2 shows the excluded region for $B(t \to Hb) = 1.0$ and $B(H \to \tau\nu) = 0.5, 0.75$, and 1.0. For the case $M_{\text{top}} < M_W + M_b$, we exclude the entire $(M_{\text{top}}, M_{H^\pm})$ plane when the $B(t \to Hb) = 1.0$ and $B(H \to \tau\nu) > 75\%$.

We also interpret our result in two-Higgs-doublet models. We use the branching ratios $B(t \to Hb)$, $B(t \to Wb)$, and $B(H \to \tau\nu)$ from Ref. [7]. In Table II, we list the measured upper limits on $\sigma_{t\bar{t}}$ at 95% C.L. for different tanβ values. We also list the theoretical lower limits on $\sigma_{t\bar{t}}$ [14] for different top masses. In Fig. 3 we present the limits in the $(M_{\text{top}}, M_{H^\pm})$ plane for two tanβ values.

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