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PHYSICAL REVIEW D **80,** 051107(R) (2009)

Search for charged Higgs bosons in decays of top quarks

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(Received 30 June 2009; published 30 September 2009)

We present a search for charged Higgs bosons in decays of top quarks, in the mass range $80 < m_{H^\pm} < 155$ GeV, assuming the subsequent decay $H^+ \to \tau^+ \nu_\tau$ (and its charge conjugate). Using 0.9 fb^{-1} of lepton + jets data collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider, operating at a center of mass energy $\sqrt{s} = 1.96$ TeV, we find no evidence for a $H^\pm$ signal. Hence we exclude branching ratios $B(t \to H^+ b) > 0.24$ for $m_{H^\pm} = 80$ GeV and $B(t \to H^+ b) > 0.19$ for $m_{H^\pm} = 155$ GeV at the 95% C.L.

DOI: 10.1103/PhysRevD.80.051107 PACS numbers: 14.65.Ha, 12.60.Fr, 14.80.Cp

The electroweak symmetry breaking sector of the standard model (SM) contains a single SU(2) complex scalar doublet field that provides gauge-invariant generation of particle masses, with the only observable particle being the electrically neutral Higgs boson H^0 [1]. Here, we search for evidence of a richer structure. The simplest extension to the SM Higgs sector involves the addition of a second

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SU(2) complex scalar doublet, which introduces five spin-0 particles, three that are neutral and two that are charged ($H^{\pm}$) [2]. The fermion couplings to the Higgs doublets are not specified *a priori*, and the only requirement is that flavor changing neutral currents are not allowed at lowest level in perturbation theory. One possibility, the type II model, couples the up-type fermions to one Higgs doublet and the down-type fermions to the other, as required in the minimal supersymmetric extension to the SM (MSSM) [2]. In addition, the MSSM constrains the five Higgs masses through two free parameters: $\tan\beta$, the ratio of the vacuum expectation values of the two doublets, and the mass of any one of the physical Higgs bosons. We choose $m_{H^{\pm}}$ for the latter.

Since the Yukawa coupling to the $H^{\pm}$ boson increases with fermion mass for all values of $\tan\beta$, top and bottom quarks in this model are expected to have large Yukawa couplings. Therefore, if $m_{H^{\pm}} < m_t - m_b$, the decay $t \to H^+ b$ (and its charge conjugate) is expected to have a large branching fraction for all $\tan\beta$. Further, for large values of $\tan\beta$ ($\tan\beta \geq 10$), the charged Higgs decays predominantly to a τ lepton and its associated neutrino with $B(H^+ \to \tau^+ \nu_\tau) \approx 1$. Hence if the $H^{\pm}$ boson exists and $B(t \to H^+ b)$ is substantial, a search optimized for the study of SM decays of $t\bar{t}$ to lepton + jets final states should show a deficit of events relative to the SM prediction because of differences in decay branching fractions and in kinematic distributions. Any such deficit could therefore be indicative of the presence of charged Higgs bosons in decays of the top quark.

Direct searches for $H^{\pm}$ bosons have been performed at the LEP e^+e^- collider at CERN [3] and at the Tevatron $p\bar{p}$ collider at Fermilab [4]. With no evidence of a signal, the LEP experiments set a combined limit of $m_{H^{\pm}} > 78.6$ GeV independent of $B(H^+ \to \tau^+ \nu_\tau)$, while the Tevatron experiments have set limits in the context of a type II two Higgs doublet model that exclude regions of the $[\tan\beta, m_{H^{\pm}}]$ parameter space [5]. Searches for indirect evidence of $H^{\pm}$ bosons through radiative decays of B mesons at B factories provide a combined limit of $m_{H^{\pm}} > 295$ GeV [6–8]. Although B factories exclude a larger part of parameter space than our current study, it is important to search for objects such as the $H^{\pm}$ bosons through all possible channels and not defer entirely to theory.

In this article, we describe the search for charged Higgs bosons from top quark decays in $t\bar{t}$ events with one lepton (electron e or muon μ) and at least three jets. A representative Feynman diagram for such events is shown in Fig. 1, where one of the top quarks decays to a W boson and a b quark, as in the SM, and the other decays to a $H^{\pm}$ boson and a b quark. For our signal, we consider events in which the W boson decays leptonically (e, μ, or τ, with the τ decaying to an e or μ and two neutrinos), while the charged Higgs boson decays to a τ and a neutrino and the τ decays to a neutrino and hadrons. The final state

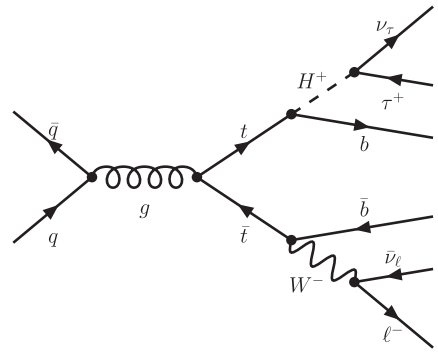

FIG. 1. Representative Feynman diagram for charged Higgs boson production in top quark decays at the Tevatron ($\ell = e$ or μ).

therefore consists of an isolated lepton (e or μ) with large transverse momentum (p_T), significant missing transverse energy ($\not{E}_T$) from the escaping neutrinos, and at least three jets: two from the b quarks and one from the decay of the τ. No attempt is made to identify τ leptons in such decays. Some of the signal can also come from events where the τ from the $H^{\pm}$ boson decays leptonically, while the W boson decays into a quark-antiquark pair, thereby giving two jets. In that case, there will be four jets in the final state. Finally, if both top quarks decay into charged Higgs bosons, which then decay into τ leptons, and one τ decays leptonically while the other decays into a jet, this can also contribute to the signal. The largest backgrounds to these processes are from SM decays of $t\bar{t}$ pairs and W + jets production, along with smaller contributions from the production of single top quarks, dibosons (WW, WZ, and ZZ), and Z + jets. An additional source of background is from multijet events, in which a jet mimics an electron or a muon from b (or c) quark decay appears to be isolated.

We analyze 0.90 ± 0.05 fb^{-1} of data recorded with the D0 detector [9,10]. The trigger required a reconstructed jet and an electromagnetic energy cluster in the electron channel or a jet and a muon candidate in the muon channel. We base this analysis on a previous one that extracted the $t\bar{t}$ production cross section within the framework of the SM, i.e., assuming $B(t \to W^+ b) = 1$ [11]. The principal difference is that here we consider an additional decay mode ($t \to H^+ b$) and attempt to measure $B \equiv B(t \to H^+ b)$ under the constraint $B(t \to W^+ b) + B(t \to H^+ b) = 1$. For any measurement of B, $m_{H^{\pm}}$ is treated as a fixed parameter. Measurements are made for several values of $m_{H^{\pm}}$.

We apply the same event selection criteria as in Ref. [11] to separate $t\bar{t}$ production from background. These are summarized in Table I. We impose an additional requirement of $\sum p_T(\text{jet}) > 120$ GeV for events with only three jets and separate the events into two jet-multiplicity bins (3 jets and >3 jets) to improve signal discrimination.

To model the background distributions, W + jets and Z + jets events are generated using ALPGEN [13], while

TABLE I. Summary of event selections.

	e + jets channel	μ + jets channel
Lepton (ℓ)	$p_T > 20$ GeV $\lvert\eta\rvert < 1.1$ [12]	$p_T > 20$ GeV $\lvert\eta\rvert < 2.0$
$\not{E}_T$	$\not{E}_T > 20$ GeV	$\not{E}_T > 25$ GeV
$\Delta\phi(\ell, \not{E}_T)$ [12] ($\not{E}_T$ in GeV)	$>0.7\pi - 0.045\not{E}_T$	$>2.1\pi - 0.033\not{E}_T$
Jets	>2, $p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$ $p_T(\text{jet 1}) > 40$ GeV	

SINGLETOP [14] is used for single top quark events. The events are passed through PYTHIA [15] for parton showering and hadronization. Diboson and SM $t\bar{t}$ events are generated using PYTHIA. The non-SM decay modes of $t\bar{t}$ events where one or both top quarks decay to a charged Higgs boson, are also generated using PYTHIA. The Monte Carlo (MC) events for the $H^{\pm}$ signal are produced at the following values of $m_{H^{\pm}}$: 80, 100, 120, 140, 150, and 155 GeV. All MC generated events are processed through the D0 detector simulation based on GEANT [16], followed by application of the same reconstruction algorithms as used on D0 data. Subsequent corrections are also applied to MC events to account for trigger efficiencies and differences between MC events and data in object reconstruction efficiencies and resolutions.

To determine the number of background multijet events, we use a data sample with looser electron identification or weaker muon isolation criteria, as described in Ref. [11]. The normalization of the W + jets contribution is determined differently in the current analysis, as discussed below. For the prediction of yields for the single top quark, diboson, and Z + jets events, we use next-to-leading order cross sections [17]. The number of $t\bar{t}$ events is obtained by summing the different top quark decay modes according to their accepted branching fractions and respective selection efficiencies (ϵ) as follows:

$$N_{t\bar{t}} = [(1-B)^2 \cdot \epsilon_{WW} + 2(1-B)B \cdot \epsilon_{WH} + B^2 \cdot \epsilon_{HH}] \cdot \sigma(t\bar{t}) \cdot \int \mathcal{L}dt, \tag{1}$$

where WW represents SM decays of the top quark, WH and HH represent non-SM decays of one or both top quarks, respectively, and $\int \mathcal{L}dt$ is the integrated luminosity. We use $\sigma(t\bar{t}) = 7.48^{+0.55}_{-0.72}$ pb for a top quark mass of $m_t = 172.4 \pm 1.2$ GeV [18], and consider B as the parameter of interest for any fixed value of $m_{H^{\pm}}$. The selection efficiencies for the WW decay modes in the different channels are $\approx 2\%$, which includes all corrections and trigger effects. The corresponding efficiencies for the WH (HH) modes vary between 1.5%–0.5% (1.2%–0.3%) for different values of $m_{H^{\pm}}$.

To differentiate between $t\bar{t}$ and background, we define a multivariate discriminant

$$\mathcal{D}(\mathbf{x}) = \frac{p(\mathbf{x}|\mathcal{S})}{p(\mathbf{x}|\mathcal{S}) + p(\mathbf{x}|\mathcal{B})}, \tag{2}$$

where p is the probability density for a set of observed variables $\mathbf{x}$, given the signal ($\mathcal{S}$) or background ($\mathcal{B}$) class of events. The signal comprises $t\bar{t}$ events which include $H^{\pm}$ decays of the top quark and hence depends on the values of B and $m_{H^{\pm}}$. For the construction of the discriminant, we define the signal for only one value of B that corresponds to the SM scenario ($B = 0$). The background is defined by all non-$t\bar{t}$ events. The variables for the different final states are listed in Table II. The normalization for the W + jets template is obtained from the low-$\mathcal{D}$ region ($\mathcal{D} < 0.45$), which is background dominated, by setting the sum of all backgrounds and signal in this region to the corresponding observed number of events. We recompute the normalization for each value of B and $m_{H^{\pm}}$. The number of predicted (and observed) events for the full range of $\mathcal{D}$ appears in Table III for $B = 0$. The corresponding distributions are shown for $m_{H^{\pm}} = 120$ GeV in Fig. 2 for $e + >3$ jets, for $B = 0$ and $B = 0.5$, in (a) and (b), respectively. We see that the data agree well with the SM predictions. Similar agreement is seen in all other channels. Hence we proceed to set upper limits on the non-SM branching fraction $B(t \to H^+ b)$.

We use a modified frequentist approach [20] to set limits at the 95% C.L. in the high-$\mathcal{D}$ region since it is $t\bar{t}$ dominated. Sources of uncertainty on the predicted yields are included with correlations across samples and channels. Their estimated values are provided in Table IV. Note that all these uncertainties are applied to the W + jets normalization assuming full anticorrelation because of the manner in which the W + jets normalization is derived as explained above. The dominant sources of uncertainties are from the integrated luminosity, the jet energy calibration, and the $t\bar{t}$ cross section. The uncertainties from the normalization of multijet, single top quark, diboson, and Z + jets events have a less pronounced effect on the B limits because of the smaller contribution of these samples in the high discriminant region. We consider the distribution in

TABLE II. Variables used to define the discriminant $\mathcal{D}$. $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and i indexes the list of N_j jets ordered in decreasing p_T.

Variable	Channel
$\sum_{i=3}^{N_j} p_T(i)$	all
$\sum_{i=1}^{N_j} p_T(i) / \sum_{i=1}^{N_j} p_z(i)$	e + 3 jets, $e + >3$ jets
$\sum_{i=1}^{N_j} p_T(i) + p_T(e) + \not{E}_T$	e + 3 jets, $e + >3$ jets
$\Delta R(\ell, \text{jet1})$	all
$\Delta R(\text{jet1}, \text{jet2})$	$e + >3$ jets, $\mu + >3$ jets
$\Delta\phi(\ell, \not{E}_T)$	μ + 3 jets, $\mu + >3$ jets
$\Delta\phi(\text{jet1}, \not{E}_T)$	e + 3 jets, μ + 3 jets
Sphericity $\mathcal{S}$ [19]	all but μ + 3 jets
Aplanarity $\mathcal{A}$ [19]	all but μ + 3 jets

TABLE III. Event yields after all selections for channels separated by lepton flavor and jet multiplicity. We assume $B(t \to H^+ b) = 0$ so that $t\bar{t}$ includes only SM decays of the top quarks. The "other MC" comprises single top quark, diboson, and Z + jets events. (The uncertainty on the total SM prediction includes correlations across samples.)

Source	e + 3 jets	μ + 3 jets	e + >3 jets	μ + >3 jets
Signal ($t\bar{t}$)	148.8 ± 20.0	108.2 ± 14.7	130.4 ± 19.4	105.6 ± 15.4
W + jets	535.4 ± 47.9	572.4 ± 34.7	79.2 ± 17.3	152.0 ± 16.5
Other MC	102.5 ± 14.6	106.7 ± 15.3	33.1 ± 4.8	35.0 ± 5.3
Multijets	194.2 ± 30.5	33.5 ± 13.9	60.2 ± 10.1	10.4 ± 5.7
Total SM prediction	980.9 ± 25.8	820.8 ± 27.6	302.9 ± 13.1	303.0 ± 15.6
Observed	948	812	320	306

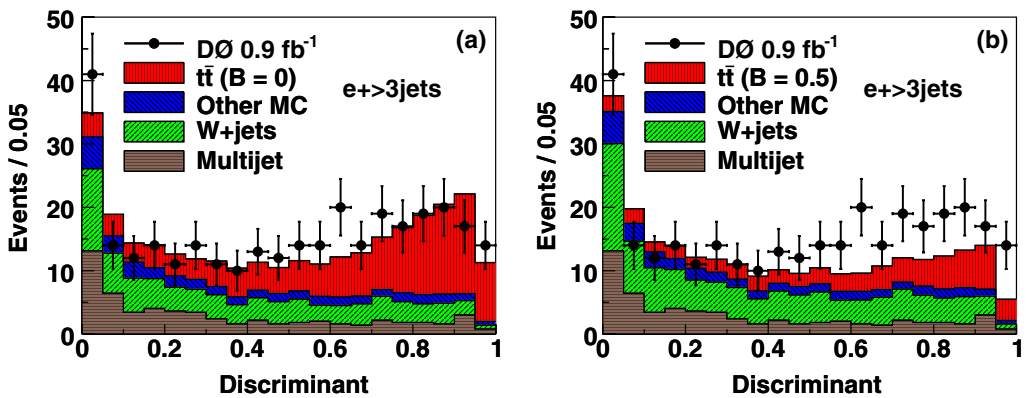

FIG. 2 (color online). Distributions in the discriminant $\mathcal{D}$ for $m_{H^\pm} = 120$ GeV in e + >3 jets, for (a) $B = 0$ (SM), and (b) $B = 0.5$.

$\mathcal{D}$ above 0.55 in the >3 jets channels and 0.6 in the 3 jets channels, a choice determined by maximizing the sensitivity of the analysis in MC simulation. The sensitivity is defined as the median of limits obtained from an ensemble of background plus SM $t\bar{t}$ ($B = 0$) pseudoexperiments in each channel. We call these the expected limits and show them by the dashed curve in Fig. 3 along with their ±1 standard-deviation (SD) intervals by the crosshatched region. The observed limits, using D0 data, are shown by the solid curve in Fig. 3.

TABLE IV. Uncertainties (equivalent to ±1 SD) from different components affecting the predicted yields. "Other MC" comprises single top quark, diboson, and Z + jets events.

Component	Uncertainty [%]
Integrated luminosity	6.1
Primary vertex modeling	2.2
Trigger efficiency	0.5–2.8
Lepton identification	2.2–2.6
Jet energy calibration	5.0
Jet identification	2.0–2.4
Jet energy resolution	0.1–1.8
Multijets normalization	15.7–54.8
Other MC normalization	11.0–12.0
$\sigma(t\bar{t})$	7.4–9.6
m_t	2.1
MC statistics	0.9–25.0

The upper limit on $B(t \to H^+ b)$ can be used to exclude regions of the $[\tan\beta, m_{H^\pm}]$ parameter space in the context of the MSSM. Since the MSSM has several free parameters, we select them according to the $m_h^{\max}$ scenario described in Ref. [21]. This provides the maximum range in the mass of the lightest neutral Higgs boson as a function of $\tan\beta$. The exclusion bounds are calculated using FEYNHIGGS [22], which includes the two-loop QCD and MSSM corrections. Figure 4 shows the expected and observed excluded regions, and the theoretically inaccessible region defined as the boundary where certain Higgs parameters acquire unphysical values.

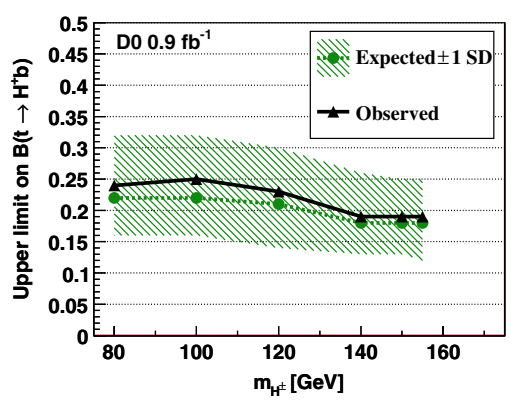

FIG. 3 (color online). The 95% C.L. limits on $B(t \to H^+ b)$ for different values of $m_{H^\pm}$.

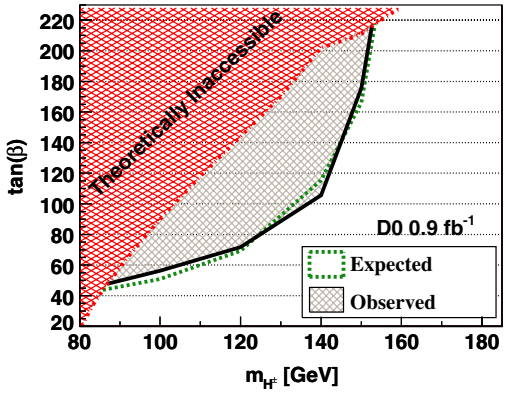

FIG. 4 (color online). The MSSM exclusion regions for the $m_h^{\max}$ scenario.

In summary, we have analyzed 0.90 ± 0.05 fb^{-1} of lepton + jets data at D0, and found no evidence for top quark decays to charged Higgs bosons. Hence we set upper limits at the 95% C.L. on $B(t \to H^+ b)$ ranging from 0.24 for $m_{H^\pm} = 80$ GeV to 0.19 for $m_{H^\pm} = 155$ GeV.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom, and RFBR (Russia); CNPq, FAPERJ, FAPESP, and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC, and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); and the Alexander von Humboldt Foundation (Germany).

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