Search for Charged Higgs Bosons in Decays of Top Quark Pairs

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We present a search for charged Higgs bosons in decays of pair-produced top quarks using 109.2 ± 5.8 pb^{-1} of data recorded from $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV by the D0 detector during 1992–1996 at the Fermilab Tevatron. No evidence is found for charged Higgs production, and most parts of the $[M_{H^+}, \tan\beta]$ parameter space where the decay $t \to H^+ b$ has a branching fraction close to or larger than that for $t \to W^+ b$ are excluded at 95% confidence level. Assuming $m_t =$ 175 GeV and $\sigma(p\overline{p} \to t\overline{t}) = 5.5$ pb, for $M_{H^+} = 60$ GeV, we exclude $\tan\beta < 0.97$ and $\tan\beta > 40.9$. [S0031-9007(99)09417-X]

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The Higgs sector of the standard model (SM) consists of a single complex doublet scalar field responsible for breaking electroweak symmetry and generating gauge boson masses. The simplest extension of the Higgs sector to two complex doublets appears in many theories beyond the SM, including supersymmetry (SUSY). Our study is based on the two-Higgs-doublet model, where one doublet couples to up-type quarks and neutrinos, and the other couples to down-type quarks and charged leptons, as required by SUSY [1]. Under these circumstances, electroweak symmetry breaking leads to five physical Higgs bosons: two neutral scalars h^0 and H^0, a neutral pseudoscalar A^0, and a pair of charged scalars $H^{\pm}$. The extended Higgs sector has two new parameters: M_{H^+} and $\tan\beta$, where $\tan\beta$ is defined as the ratio of the vacuum expectation values of the two Higgs fields.

Direct searches for $e^+e^- \to H^+H^-X$ at LEP have set lower limits of 57.5–59.5 GeV on M_{H^+} at the 95% confidence level (C.L.) irrespective of $\tan\beta$ [2]. A measurement of the inclusive $b \to s\gamma$ decay rate gives CLEO an indirect limit of $M_{H^+} > 244 + 63/(\tan\beta)^{1.3}$ GeV, assuming only a two-Higgs-doublet extension to the SM [3]. From a measurement of the $b \to \tau\nu X$ branching fraction, ALEPH constrains $\tan\beta/M_{H^+} < 0.52\ \mathrm{GeV}^{-1}$ at 90% C.L. [4]. Based on a search for charged Higgs in decays of pair-produced top quarks using hadronic decays of the τ lepton, CDF has published limits in the $[M_{H^+}, \tan\beta]$ parameter space for $\tan\beta > 5$ [5]. Our search, also for $H^{\pm}$ in decays of $t\bar{t}$, covers the entire range of $\tan\beta$ in which leading order perturbative calculations are valid.

At leading order, the H^+ coupling to a down-type (up-type) quark or neutral (charged) lepton is proportional to the fermion mass multiplied by $\tan\beta$ ($\cot\beta$). The SM requires a t quark to decay almost exclusively to a W boson and a b quark, i.e., $B(t \to W^+b) \approx 1$. However, if $H^{\pm}$ exist with $M_{H^+} < m_t - m_b$, and $\tan\beta$ is either very large or very small, then $B(t \to H^+b)$ can be significant. We assume $B(t \to H^+b) + B(t \to W^+b) = 1$. For any given $\tan\beta$, $B(t \to H^+b)$ decreases as M_{H^+} increases. It is further assumed that M_{S^0} ($S^0 = h^0$, H^0, or A^0) are large enough for the decays $H^+ \to S^0W^+$ to be highly suppressed for real or virtual S^0 and W^+ bosons. Decays $H^+ \to V^0W^+$, where $V^0 = \gamma$ or Z, are absent at the tree level [6]. Hence, H^+ can decay only to fermion-antifermion pairs. Consequently, if $M_{H^+} < m_t - m_b$, one might expect $H^+ \to \tau^+\nu$ (favored if $\tan\beta$ is large) and $H^+ \to c\bar{s}$ (favored if $\tan\beta$ is small) to be the only significant possibilities. Indeed, $B(H^+ \to \tau^+\nu) \approx 1$ if $\tan\beta > 10$. But if $\tan\beta < 2$ and $M_{H^+} > 130$ GeV, then the large mass of the t quark causes $B(H^+ \to t^*\bar{b} \to W^+b\bar{b})$ to exceed $B(H^+ \to c\bar{s})$ [7].

Figure 1 shows the region of the $[M_{H^+}, \tan\beta]$ plane examined in this analysis. The lower and upper boundaries on $\tan\beta$ (0.3, 150) are required for the applicability of perturbative calculations in H^+ Yukawa coupling to t and b quarks. The minimum for M_{H^+} is chosen at 50 GeV, somewhat below the most recent lower limits from LEP. This search is restricted to $M_{H^+} <$ 160 GeV, somewhat less than $m_t - m_b$ (assuming $m_t =$ 175 GeV); otherwise, the width of the charged Higgs $\Gamma(H^+)$ becomes too large (>7.5 GeV) near the upper boundary on $\tan\beta$, and leading-order calculations become unreliable. For the same reason, $\Gamma(t)$ is required to be <15 GeV. Since $\Gamma(t \to W^+b) \approx 1.5$ GeV, irrespective of $[M_{H^+}, \tan\beta]$, this amounts to requiring $B(t \to H^+b) \leq$ 0.9, and thereby excludes from our analysis the dark-shaded regions at the two bottom corners of Fig. 1. The cross-hatched regions correspond to $B(t \to H^+b) > 0.5$. Also shown in Fig. 1 are the decay modes of H^+ that dominate in different parts of the parameter space. Analogous charge-conjugate expressions hold for H^-.

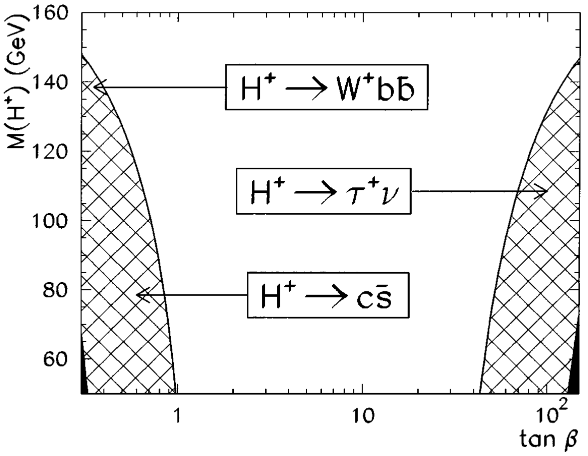

FIG. 1. The parameter space explored in this analysis. Regions where $B(t \to H^+b) > 0.5$ are shown cross hatched, with the labels for various decay modes of the charged Higgs indicating their regions of dominance. Regions where $B(t \to H^+b) > 0.9$ (dark-shaded areas) are not considered.

For each top quark, there are four possible decay modes whose branching fractions depend on M_{H^+} and $\tan\beta$: (1) $t \to W^+b$; (2) $t \to H^+b$, $H^+ \to c\bar{s}$; (3) $t \to H^+b$, $H^+ \to W^+b\bar{b}$; and (4) $t \to H^+b$, $H^+ \to \tau^+\nu$. If the decay mode of t ($\bar{t}$) is denoted by i (j), then the total acceptance for any set of selection criteria is given by

$$A(M_{H^+}, \tan\beta) = \sum_{i,j=1}^{4} \epsilon_{i,j}(M_{H^+}) B_i(M_{H^+}, \tan\beta) \times B_j(M_{H^+}, \tan\beta), \qquad (1)$$

where $\epsilon_{i,j}$ is the efficiency for channel $\{i, j\}$, and B_iB_j is the branching fraction. All B_i depend strongly on both M_{H^+} and $\tan\beta$; $\epsilon_{1,1}$ depends on neither, and all other $\epsilon_{i,j}$ depend on M_{H^+}, but not on $\tan\beta$.

A strong dependence of signal characteristics on the parameters of the model makes an appearance search for signal a difficult task. We therefore perform a disappearance search using selection criteria optimized for the SM channel $\{1, 1\}$. One expects the efficiencies of these criteria for channels involving $t \to H^+b$ decays to be substantially different from that for channel $\{1, 1\}$. Consequently, if the assumption of $B_1 = 1$ leads to a measurement of the top quark pair production cross section $\sigma(t\bar{t})$ in good agreement with theoretical predictions, then those regions of the $[M_{H^+}, \tan\beta]$ parameter space, where B_i is sufficiently large for any $i \neq 1$ can be excluded. This strategy serves us well for $i = 2$ and 4, but not for $i = 3$.

The D0 detector is described in Ref. [8]. We use the same reconstruction algorithms for jets, muons, and electrons as used in our previous top quark analyses, and the same event selection criteria as for the measurement of $\sigma(t\bar{t})$ in lepton + jets final states [9]. These criteria are optimized for $t\bar{t}$ events, where both top quarks decay to Wb, with one W decaying into $e\bar{\nu}$ or $\mu\bar{\nu}$, and the other into a $q\bar{q}'$ pair. The final state in such events is characterized by a high-p_T isolated lepton, large missing transverse energy ($\not\!\!E_T$), and four jets. The main sources of the background are W + jets events and QCD multijet events with a misidentified lepton and large $\not\!\!E_T$. Two of the jets in signal events are initiated by b quarks. A b jet can be tagged by a muon contained within the jet ($\epsilon B \approx 0.2$ per $t\bar{t}$ event). Since such tagging is unlikely in background events, other requirements can be less restrictive for an event containing a μ-tagged jet. This class of μ-tagged events is denoted by ℓ + jets/μ. Events without a μ-tagged jet, denoted by ℓ + jets, are subject to stricter requirements on kinematics. Details of the selection criteria, summarized in Table I, can be found in Ref. [9]. For $m_t = 175$ GeV, the selection efficiency for $t\bar{t} \to W^+bW^-\bar{b}$ events is $[3.42 \pm 0.11(\text{stat}) \pm 0.55(\text{syst})]\%$. The jet energy scale, particle identification, and modeling of the signal are the primary sources of systematic uncertainty. The integrated luminosity, the number of observed events, and the expected $t\bar{t}$ signal [assuming $B(t \to W^+b) = 1$] and background are given in Table II.

The measured values of $\sigma(t\bar{t})$ [9,10] and m_t [11,12] are based on the assumption of $B(t \to W^+b) = 1$, and cannot be used in this analysis. Hence, in our search, $\sigma(t\bar{t})$ and m_t serve as input parameters. However, for $M_{H^+} < 140$ GeV, the method used by D0 to extract m_t from $t\bar{t} \to$ lepton + jets events [11] yields the correct value of m_t within ~5% even when $t \to H^+b$ decays are allowed. Hence, we choose $m_t = 175$ GeV. Production of $t\bar{t}$ takes place primarily via strong interactions, and the cross section is not affected by the existence of $H^\pm$ (assuming no contribution from SUSY processes). Calculations of $\sigma(t\bar{t})$ based on QCD should therefore be reasonable [13–15]. A special version of ISAJET [16] that includes the process $H^+ \to W^+b\bar{b}$ is used for Monte Carlo simulation of $t\bar{t}$ events, and a similarly modified version of PYTHIA [17] is used for verification of the efficiencies.

TABLE I. The ℓ + jets and ℓ + jets/μ event selection criteria.

	ℓ + jets	ℓ + jets/μ
$p_T(l)$	>20 GeV	>20 GeV
$\lvert\eta_{e(\mu)}\rvert$	<2.0 (1.7)	<2.0 (1.7)
$\not\!\!E_T$	>25 GeV	>20 GeV
$E_T(j)$	>15 GeV	>20 GeV
$\lvert\eta_j\rvert$	<2.0	<2.0
No. of jets (n_j)	≥4	≥3
No. of μ tags	0	≥1
Aplanarity	>0.065	>0.040
$H_T \equiv \sum_{i=1}^{n_j} E_T(j_i)$	>180 GeV	>110 GeV
$p_T(l) + \not\!\!E_T$	>60 GeV	⋯
$\lvert\eta(W)\rvert$	<2.0	⋯

Table II shows that the hypothesis of $B_1 \approx 1$ agrees well with our experimental result. Using Monte Carlo samples, the efficiencies and corresponding uncertainties are calculated at several values of M_{H^+}, and parametrized for each channel. The efficiencies for all channels, for $M_{H^+} = 125$ GeV, are listed in Table III. The dependence of efficiency on M_{H^+} varies from channel to channel, but efficiencies for a given channel rarely differ by more than a factor of 2 over the range of M_{H^+} considered. While $\epsilon_{2,2}$ is practically zero (since $H^+ \to c\bar{s}$ gives neither a high-p_T isolated lepton nor large $\not\!\!E_T$), $\epsilon_{1,3}$ and $\epsilon_{3,3}$ are close to $\epsilon_{1,1}$. Consequently, we can exclude at a high level of confidence those regions of parameter space where $B_2 \approx 1$ (small $\tan\beta$, small M_{H^+}), because, with almost no observable signal, it is extremely unlikely that an expected background of 11.2 ± 2.0 events fluctuated to the observed 30. However, in regions where B_3 is comparable to or larger than B_1 (small $\tan\beta$, large M_{H^+}), the expected number of events is about the same as that observed, and therefore such regions cannot be excluded. Low efficiencies for $t\bar{t}$ decays involving $H^+ \to \tau^+\nu$ help exclude regions where B_4 is large (large $\tan\beta$).

For n_{obs} observed events, the joint posterior probability density for M_{H^+} and $\tan\beta$ is given by

$$P(M_{H^+}, \tan\beta \,|\, n_{\text{obs}}) \propto \int G(\mathcal{L}) \int G(n_B) \int G(A) \times P(n_{\text{obs}} \,|\, \mu)\, dA\, dn_B\, d\mathcal{L}\,, \tag{2}$$

where $P(n_{\text{obs}} \,|\, \mu)$, is the Poisson probability of observing n_{obs} events, given a total (signal + background) expectation of

$$\mu(M_{H^+}, \tan\beta) = A(M_{H^+}, \tan\beta)\sigma(t\bar{t})\mathcal{L} + n_B\,, \tag{3}$$

and G represents a Gaussian distribution. The means and widths of the Gaussians for the integrated luminosity $\mathcal{L}$ and the number of background events n_B are given in Table II, while those for the acceptance $A(M_{H^+}, \tan\beta)$ are calculated using Eq. (1), with parametrized functions for $\epsilon_{i,j}$, and leading order calculations of B_i, B_j.

Equation (2), which we parametrize as a function of M_{H^+} and $\tan\beta$, gives a Bayesian posterior probability density for those parameters [18]. The prior distribution is assumed to be uniform in M_{H^+} and in $\log_{10}(\tan\beta)$.

TABLE II. The integrated luminosity, the number of observed events, and the expectations from background and SM $t\bar{t}$ signal (assuming $m_t = 175$ GeV; $\sigma(t\bar{t}) = 5.5$ pb), for ℓ + jets and ℓ + jets/μ selections combined.

Integrated luminosity, $\mathcal{L}$	109.2 ± 5.8 pb
Estimated background, n_B	11.2 ± 2.0
Expected signal (SM), n_S	19.7 ± 3.5
Total events expected (SM)	30.9 ± 4.0
Events observed, n_{obs}	30

TABLE III. The efficiencies $\epsilon_{i,j}$ of our selection criteria (in %), for $m_t = 175$ GeV and $M_{H^+} = 125$ GeV, for various decay modes of $t\bar{t}$. The row indices (i) denote: (1) $t \to W^+b$; (2) $t \to H^+b$, $H^+ \to c\bar{s}$; (3) $t \to H^+b$, $H^+ \to W^+b\bar{b}$; and (4) $t \to H^+b$, $H^+ \to \tau^+\nu$. The respective charge conjugate decays are denoted by the column indices (j).

	1	2	3	4
1	3.42 ± 0.56	2.23 ± 0.37	3.35 ± 0.61	1.36 ± 0.25
2	2.23 ± 0.37	0.04 ± 0.01	2.21 ± 0.37	1.07 ± 0.20
3	3.35 ± 0.61	2.21 ± 0.37	3.71 ± 0.67	1.74 ± 0.36
4	1.36 ± 0.25	1.07 ± 0.20	1.74 ± 0.36	0.41 ± 0.09

Assuming instead that the prior is uniform in M_{H^+} and in $B(H^+ \to \tau^+\nu)$ does not significantly alter the posterior distribution. To calculate probabilities, a Monte Carlo integration is carried out by spanning the parameter space in steps of 5 GeV in M_{H^+} from 50 to 160 GeV, with 25 uniform steps in $\log_{10}(\tan\beta)$ covering the range $0.3 < \tan\beta < 150$ at each value of M_{H^+}, and performing 200 000 trials of Eq. (2) at each step. The predicted probability for observing $n_{\rm obs}$ events, evaluated at $M_{H^+} = 80$ GeV, for different values of $\tan\beta$, is shown in Fig. 2(a), while Fig. 2(b) shows the posterior probability density for $\tan\beta$ corresponding to $n_{\rm obs} = 30$, and for $M_{H^+} = 80$ GeV. The 95% C.L. exclusion boundary in the $[M_{H^+}, \tan\beta]$ plane is obtained by integrating the probability density $P(M_{H^+}, \tan\beta \mid n_{\rm obs})$, given by Eq. (2), between contours of constant P. The results, corresponding to $m_t = 175$ GeV, are shown in Fig. 3 for three values of $\sigma(t\bar{t})$. The largest value of $\sigma(t\bar{t})$ (5.5 pb, with QCD resummation scale set to m_t [13]) yields the most conservative limits. Tighter limits are set for smaller values of $\sigma(t\bar{t})$, such as those given in Refs. [14,15]. Figure 3 also shows the result of a frequentist analysis of our data wherein a point in the $[M_{H^+}, \tan\beta]$ parameter space is excluded if more than 95% of the trials of Eq. (2) at that point yield $n_{\rm obs} < 30$. Due caution must be exercised in comparing Bayesian and frequentist results since the interpretation of "confidence level" is different between the two. If m_t is varied in the range $170 < m_t < 180$ GeV, then, for $\sigma(t\bar{t}) = 5.0$ pb, the excluded region increases with increasing m_t by an amount comparable to that from a similar fractional decrease in $\sigma(t\bar{t})$ with m_t fixed at 175 GeV.

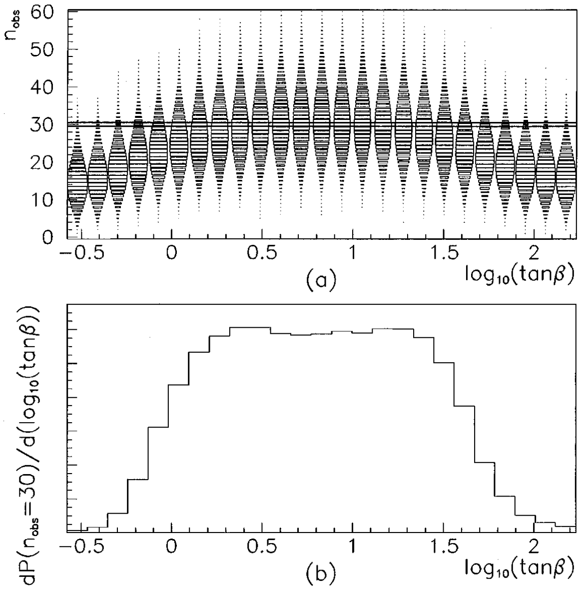

FIG. 2. (a) Distribution of the number of Monte Carlo experiments in the $n_{\rm obs}$ vs $\log_{10}(\tan\beta)$ plane for $m_t = 175$ GeV, $\sigma(t\bar{t}) = 5.0$ pb, and $M_{H^+} = 80$ GeV. (b) Posterior probability density for $\tan\beta$, given the experimentally observed value of $n_{\rm obs} = 30$ [the slice shown in (a)], for the above parameters.

To summarize, in a search for a charged Higgs boson that considers all of its fermionic decay modes, we find no evidence of a signal in the region of $M_{H^+} < 160$ GeV, we improve previous limits in the region of large $\tan\beta$, and we exclude a significant part of the previously unexplored region of small $\tan\beta$. Assuming $m_t = 175$ GeV and $\sigma(t\bar{t}) = 5.5$ pb, $\tan\beta < 0.97$ and $\tan\beta > 40.9$ are excluded at 95% C.L. for $M_{H^+} = 60$ GeV. The limits become less stringent with increasing M_{H^+}. Within the range $0.3 < \tan\beta < 150$, no lower limit can be set on $\tan\beta$ for $M_{H^+} > 124$ GeV, and no upper limit for $M_{H^+} > 153$ GeV. A comparison between Figs. 1 and 3 shows that all regions of the $[M_{H^+}, \tan\beta]$ parameter space where $B(t \to H^+b) > 0.45$, except where $B(H^+ \to W^+b\bar{b})$ is large, are excluded at 95% C.L.

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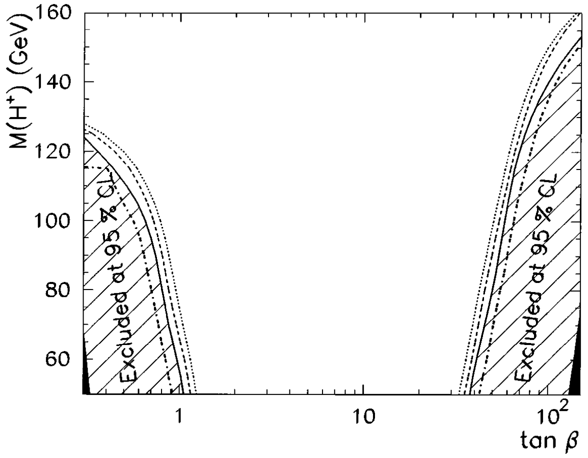

FIG. 3. The 95% C.L. exclusion boundaries in the $[M_{H^+}, \tan\beta]$ plane for $m_t = 175$ GeV, and value of $\sigma(t\bar{t})$ set to 5.5 pb (hatched areas, solid lines), 5.0 pb (dashed lines), and 4.5 pb (dotted lines). The thicker dot-dashed lines inside the hatched area represent the exclusion boundaries obtained from a frequentist analysis with $\sigma(t\bar{t}) = 5.5$ pb.

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