4-15-2002

Direct Search for Charged Higgs Bosons in Decays of Top Quarks

V. M. Abazov
Joint Institute for Nuclear Research, Dubna, Russia

Gregory R. Snow
University of Nebraska-Lincoln, gsnow1@unl.edu

D0 Collaboration

Follow this and additional works at: http://digitalcommons.unl.edu/physicssnow

Part of the Physics Commons

Abazov, V. M.; Snow, Gregory R.; and Collaboration, D0, "Direct Search for Charged Higgs Bosons in Decays of Top Quarks" (2002). Gregory Snow Publications. 58.
http://digitalcommons.unl.edu/physicssnow/58

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Gregory Snow Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
Direct Search for Charged Higgs Bosons in Decays of Top Quarks

We present a search for charged Higgs bosons in decays of pair-produced top quarks in \( p \bar{p} \) collisions at \( \sqrt{s} = 1.8 \) TeV recorded by the D0 detector at the Fermilab Tevatron collider. With no evidence for signal, we exclude most regions of the \( (M_{H^\pm}, \tan\beta) \) parameter space where the decay \( t \rightarrow H^+ b \) has a branching fraction \( >0.36 \) and \( B(H^\pm \rightarrow \tau \nu_\tau) \) is large.

DOI: 10.1103/PhysRevLett.88.151803

The standard model (SM) relies on the Higgs mechanism for gauge-invariant generation of particle masses [1]. It contains a single complex scalar doublet, whose only observable particle is the neutral Higgs boson \( H^0 \). At present, no data limit the Higgs sector to a single doublet. In this Letter, we examine predictions of a two-Higgs-doublet model (THDM) that couples one doublet to up-type quarks and neutrinos, and the other to down-type quarks and charged leptons (type-II model), just as in the minimal supersymmetric extension of the SM [2]. For such coupling, flavor changing neutral currents are absent at tree level [2]. The additional degrees of freedom in this model provide a total of five observable Higgs fields: two neutral CP-even scalars \( h^0 \) and \( H^0 \), a neutral CP-odd scalar \( A^0 \), and two charged scalars \( H^\pm \). In what follows, we report on a search for evidence of an extension of the Higgs sector, in the form of a \( H^\pm \) boson, with the relevant parameters being its mass, \( M_{H^\pm} \), and the ratio of the vacuum expectation values of the doublets, \( \tan\beta \).

In the SM, the primary decay of the \( t \) quark is \( t \rightarrow W^+ b \). The addition of the second Higgs doublet provides the \( t \rightarrow H^+ b \) mode, with a branching fraction \( B(t \rightarrow H^+ b) \propto (m_t^2 \cot^2 \beta + m_W^2 \tan^2 \beta) + 4m_t^2 m_b^2 \). This function has a minimum when \( \tan\beta = \sqrt{m_t/m_W} \), and is symmetric in \( \tan\beta \) about this point. If \( \tan\beta \) differs by an order of magnitude from \( \sqrt{m_t/m_W} \), the branching fraction becomes large, and decreases as \( M_{H^\pm} \) increases. In this analysis, we assume \( B(t \rightarrow W^+ b) + B(t \rightarrow H^+ b) = 1 \). The masses of the three neutral scalars are assumed to be large enough to be suppressed in \( H^\pm \) decays. Also, at tree level, there are no direct \( H^\pm \) couplings to SM vector bosons. The only available decays of \( H^\pm \) are therefore fermionic, with coupling proportional to fermion mass. For \( M_{H^\pm} \) below \( \approx \)110 GeV, \( B(H^+ \rightarrow \tau^+ \nu) \approx 0.96 \) for \( \tan\beta > 2 \), and \( B(H^+ \rightarrow e^\pm \nu) \approx 1 \) for \( \tan\beta < 0.4 \). Because of large coupling to the top quark [3], \( B(H^+ \rightarrow t^+ b \rightarrow W^+ b \bar{b}) \) becomes important and eventually dominant at higher values of \( M_{H^\pm} \) for \( \tan\beta \approx \sqrt{m_t/m_b} \).

D0 has carried out two searches for \( t \rightarrow H^+ b \). An indirect search, which has been published [4], looked for a decrease in the \( t \bar{t} \rightarrow W^+ W^- b \bar{b} \) signal expected from the SM, and the direct search, reported here, that searches for the \( H^\pm \rightarrow \tau^\pm \nu \) decay mode. Direct searches have been carried out by CERN \( e^+ e^- \)-collider LEP experiments, and report a combined lower limit on \( M_{H^\pm} \) of 78.6 GeV [5]. CDF has also reported a direct search for \( H^{\pm} \), setting an upper limit on \( B(t \rightarrow H^+ b) \) in the range of 0.5 to 0.6 at 95% confidence level (C.L.) for masses in the range 60 to 160 GeV, assuming \( B(H^+ \rightarrow \tau \nu_\tau) = 1 \) [6].

In addition to the limits from the Tevatron and LEP, limits have also been published based on quantum corrections for type-II THDM in other processes. CLEO sets a limit of \( M_{H^\pm} > 124 \) GeV at 95% C.L., and for \( \tan\beta > 10 \), from their inclusive measurement of \( b \rightarrow s \gamma \) [7]. The L3 limit [8] on \( B(\rightarrow \tau + \nu_\tau) \), leads Ref. [9] to set a 90% C.L. limit of 0.27 GeV\(^{-1} \) \( > \) \( (\tan\beta)/M_{H^\pm} \). Finally, the branching ratios of \( \tau \rightarrow \nu_\tau K \) and \( \tau \rightarrow \nu_\tau (\gamma) \), yields a limit of 0.21 GeV\(^{-1} \) \( > \) \( (\tan\beta)/M_{H^\pm} \) at the 90% C.L. [10]. Although these limits exclude a larger part of available parameter space than our study, because of the difficulty of the measurements and ambiguities in theory, it is important to search for objects such as the \( H^\pm \) in all possible channels, and not to defer entirely to theory.

This analysis uses the same formulation and Monte Carlo (MC) tools as our indirect search. The theory is a leading-order perturbative calculation, requiring the \( t \rightarrow H^+ b \) coupling to be \( < 1 \), which limits the validity of our search to \( 0.3 < \tan\beta < 150 \). In addition, the calculation is unreliable for small \( |m_t - M_{H^\pm}| \) and for large decay widths for \( t \) and \( H^\pm \). This further limits our search to \( M_{H^\pm} < 160 \) GeV and \( B(t \rightarrow H^+ b) < 0.9 \).

A direct search for \( H^\pm \) divides naturally into two regions [11]: (1) small \( \tan\beta \), where final states are dominated by jets, with imbalance in transverse momentum (\( E_T \)), and (2) large \( \tan\beta \), where the final state contains up to two \( \tau \) leptons and large missing transverse energy (\( E_T \)). Because at small \( \tan\beta \) there is background from multijet production, we concentrate on large \( \tan\beta \) and \( t \bar{t} \rightarrow \tau^\pm \nu_\tau \bar{\nu}_\tau + \) jets final states. The experimental signature for \( t \rightarrow H^+ b \) is nearly identical to that for \( t \rightarrow W^+ b \). We therefore rely on the expected increase in absolute yield of \( \tau \) leptons at high \( \tan\beta \) to differentiate between the two modes.

The \( t \bar{t} \) data for this analysis were obtained from \( p \bar{p} \) collisions at \( \sqrt{s} = 1.8 \) TeV [12], and we consider both \( t \bar{t} \rightarrow H^+ H^- b \bar{b} \) and \( t \bar{t} \rightarrow H^\pm W^\mp b \bar{b} \) channels. Identification of the \( \tau \) relies on its hadronic decay modes, consisting primarily of one or three charged hadrons in a narrow jet, often accompanied by photons from \( \pi^0 \) decays, and a \( \nu_\tau \). There are two \( b \) jets per event, and, when one of the top quarks decays to \( Wb \), there are also two light quark jets (we consider only hadronic \( W \) modes). The event signature is therefore \( \nu + E_T \), with a roughly spherical
distribution in the detector, and at least one narrow jet. Consequently, we rely on a multijet + $E_T$ trigger, which comprises $62.2 \pm 3.1$ pb$^{-1}$ of integrated luminosity ($\mathcal{L}$).

To reduce background, we use a set of loose selections, and then a neural network (NN) for more restrictive cuts. The loose criteria require that the event have $\mathcal{E}_T > 25$ GeV, at least 4 jets, each with $E_T > 20$ GeV, but no more than 8 jets with $E_T > 8$ GeV.

We use a feed-forward NN [13] based on JETNET [14], with 3 input nodes, 7 hidden nodes, and 1 output node. The input variables are $\mathcal{E}_T$, and two of the three eigenvalues of the normalized momentum tensor. The NN is trained with 3 input nodes, 7 hidden nodes, and 1 output node. The NN is trained to determine the maximum sensitivity for our main background from multijet events. The chosen input variables are $E_T$, $\eta$, $\phi$, and two of the three eigenvalues of the covariance matrix, we use the fact that $\eta$ jets are narrower than normal hadronic jets in the energy range of our search. The variables used are the energy in each of the first five layers of our calorimeter, the log of the total energy, the ratio of the sum of the transverse energy of the two calorimeter towers with highest $E_T$ to the total jet energy, and ratios of jet energies in the central $3 \times 3$ and $5 \times 5$ calorimeter towers to the total jet energy.

Because the measured values of $\sigma_{t\bar{t}}$ and $m_t$ are based on the assumption that $B(t \rightarrow W^- b) = 1$, it may be regarded as specious to use either in calculating the expected number of events. For $t\bar{t}$ production, we therefore use a QCD calculation giving $\sigma_{t\bar{t}} = 5.5 \text{ pb}$ [19–21]. Any possible contamination from $t\bar{t} \rightarrow H^+ W^- b\bar{b}$, would affect the $m_t$ measurement by $<5\%$ for $M_{H^+} < 140$ GeV; we therefore use the value $m_t = 175$ GeV [22,23]. The selection efficiencies for signal and background are listed in Table I. Using this information, we expect $1.1 \pm 0.3$ events from $t\bar{t}$, $0.9 \pm 0.3$ from $W^+ +$ jets, and $3.2 \pm 1.5$ from multijet background, while we observe 3 events in the data. The jet energy, modeling of signal, and $\tau$ identification are the

---

**Table I.** Cumulative efficiencies ($\%$) after the three stages of event selection for $H^\pm$ signal and background, for $M_{H^\pm} = 95$ GeV. The errors are statistical and systematic uncertainties added in quadrature. Event types are (1) $t\bar{t} \rightarrow W^\pm H^\mp b\bar{b}$, $W \rightarrow q\bar{q}'$; (2) $t\bar{t} \rightarrow H^\mp W^\pm b\bar{b}$, $H \rightarrow \tau\nu_x$; (3) $t\bar{t} \rightarrow W^\mp W^\pm b\bar{b}$, $W \rightarrow \tau\nu_x$, $W \rightarrow q\bar{q}'$; and (4) $W \pm \pm 3$ jets, $W \rightarrow \tau\nu_x$, where we consider only $\tau \rightarrow j$ decays.

<table>
<thead>
<tr>
<th>Type</th>
<th>Loose selection</th>
<th>NN &gt; 0.91</th>
<th>$\tau$-id</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.0 ± 1.7</td>
<td>18.3 ± 0.9</td>
<td>50.0 ± 1.0</td>
</tr>
<tr>
<td>2</td>
<td>35.2 ± 1.6</td>
<td>12.9 ± 0.9</td>
<td>55.5 ± 1.0</td>
</tr>
<tr>
<td>3</td>
<td>45.1 ± 2.0</td>
<td>15.7 ± 1.0</td>
<td>3.8 ± 0.8</td>
</tr>
<tr>
<td>4</td>
<td>0.65 ± 0.04</td>
<td>0.17 ± 0.02</td>
<td>0.04 ± 0.01</td>
</tr>
</tbody>
</table>

---

**FIG. 1.** NN output for $t\bar{t} \rightarrow H^+ H^- b\bar{b}$ MC signal and multijet background, normalized to the same area.

**FIG. 2.** Data and the number of events expected from all SM backgrounds (light), and from extra $H^\pm$ sources (dark) for $\tan\beta = 150$ and $M_{H^\pm} = 95$ GeV, as a function of NN threshold.

---

151803-4
primary sources of systematic uncertainties. The first two are calculated as in Ref. [22], while uncertainty in \( \tau \) identification is calculated as in Ref. [17].

Had \( H^\pm \) bosons been produced in \( t\bar{t} \) decays, then the number of \( t\bar{t} \rightarrow \tau + \text{jets} \) events would have exceeded the expected number from SM processes, and the excess from \( H^\pm \) production would be particularly sensitive to contributions from \( H^\pm \). However, our data agree with the SM. Hence, to set a limit, we calculate the probability for data to fluctuate to the expectation from \( H^\pm \) sources. Figure 2 shows the number of events observed, the number expected from SM processes, and the excess from \( H^\pm \) for \( \tan \beta = 150 \) and \( M_{H^\pm} = 95 \text{ GeV} \), as a function of NN threshold. Above our NN cutoff of 0.91, there is clear inconsistency with the hypothesis of excess \( \tau \) production from \( H^\pm \) sources.

The probability that the number of expected events for a particular value of \( \tan \beta \) and \( M_{H^\pm} \) has fluctuated to the number of observed events \( (n_{\text{obs}}) \) is given by the joint posterior probability density for \( M_{H^\pm} \) and \( \tan \beta \):

\[
P(M_{H^\pm}, \tan \beta | n_{\text{obs}}) \approx \int G(L) \int G(n_B) \int G(A) \times P(n_{\text{obs}} | \mu) dA \, d\mu \, dL ,
\]

\( \mu \) is the Poisson probability of \( n_{\text{obs}} \) events, given expected background events, and \( P(n_{\text{obs}} | \mu) \) is the Poisson probability of \( n_{\text{obs}} \) events, given expectation: \( \mu(M_{H^\pm}, \tan \beta) = A(M_{H^\pm}, \tan \beta) \sigma(t\bar{t}) L + n_B \), where \( A(M_{H^\pm}, \tan \beta) \) is the sum of the products of the branching fractions and efficiencies from all sources of \( t\bar{t} \) decay. For a particular \( M_{H^\pm} \), and any \( \tan \beta \), the value of \( A \) is computed via MC (in leading order). The probabilities from Eq. (1) are then parametrized as a function of \( \tan \beta \) for fixed values of \( M_{H^\pm} \), and fitted as a function of \( M_{H^\pm} \) to obtain \( P(M_{H^\pm}, \tan \beta | n_{\text{obs}}) \), the Bayesian posterior probability density [24] shown in Fig. 3.

The prior probability distribution, as in the indirect search [4], is assumed to be uniform over the allowed regions of \( M_{H^\pm} \) and \( \log_{10}(\tan \beta) \) and zero elsewhere. This gives equal weight to all possible branching ratios in type II THDM. We further impose a lower limit on \( M_{H^\pm} \) of 75 GeV, to provide an overlap with the limit from LEP experiments. The C.L. exclusion boundary in the \((M_{H^\pm}, \tan \beta)\) plane is obtained by integrating the probability density \( P(M_{H^\pm}, \tan \beta | n_{\text{obs}}) \) around a contour of constant \( P \), such that the volume under the surface enclosed by that contour constitutes 95% of the volume under the full \( P(M_{H^\pm}, \tan \beta | n_{\text{obs}}) \) surface. A 10% change in the \( t\bar{t} \) cross section changes the excluded region by 10%, with the larger cross section yielding greater exclusion. The limits are shown in Fig. 4, along with results from our indirect D0 search, under the same assumptions. The exclusion region correspond to parameters that are <5% likely. Because the indirect search excludes simultaneously both large and small \( \tan \beta \), the exclusion contour at high \( \tan \beta \) represents approximately 2.5% of the volume under that posterior probability density surface. Also shown in Fig. 4 are the frequentist limits, wherein a point in the \((M_{H^\pm}, \tan \beta)\) plane is excluded when \( P(n_{\text{obs}} | M_{H^\pm}, \tan \beta) < 5\% \), which is related to the posterior probability through Bayes theorem [24]. Although the frequentist and Bayesian exclusion contours are shown on the same plot, they represent entirely different notions of probability [24].

In summary, our direct search for charged Higgs bosons in top quark decays shows no evidence of signal for \( M_{H^\pm} < 150 \text{ GeV} \). The region of small \( \tan \beta \) does not provide \( \tau \) leptons through couplings to \( H^\pm \), and therefore cannot be excluded. At large \( \tan \beta \), we extend the exclusion region beyond that of our indirect search. Assuming \( m_t = 175 \text{ GeV} \) and \( \sigma(t\bar{t}) = 5.5 \text{ pb} \), \( \tan \beta > 32.0 \) is excluded at the 95% C.L., for \( M_{H^\pm} = 75 \text{ GeV} \). The limits are less stringent at larger \( M_{H^\pm} \), until \( M_{H^\pm} = 150 \text{ GeV} \).
where no limit can be set. Using the results of this Letter and those of our indirect search, we exclude $B(t \to H^+ b) > 0.36$ at 95% C.L. in the region $0.3 < \tan \beta < 150$, and $M_{H^+} < 160$ GeV.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L’Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), and the A. P. Sloan Foundation.


