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Abstract

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 using 62.2 pb^{-1} of data recorded by the DØ detector at the Fermilab Tevatron collider. No evidence is found for signal, and we exclude at 95% confidence most regions of the $(M_{H^\pm}, \tan\beta)$ parameter space where the decay $t \rightarrow H^+ b$ has a branching fraction greater than 0.36 and $B(H^\pm \rightarrow \tau\nu_\tau)$ is large.

The standard model (SM) relies on the Higgs mechanism for gauge-invariant generation of particle masses. It contains a single complex scalar doublet field, whose only observable particle is the neutral Higgs boson, H^0. At present, no experimental results limit the Higgs sector to a single doublet. In this Letter, we examine predictions of a two-Higgs-doublet model that couples one doublet to up-type quarks and neutrinos, and the other to down-type quarks and charged leptons, as is the case in the minimal supersymmetric extension of the SM. For this choice of Higgs couplings, flavor changing neutral currents are absent at tree-level [1]. 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 a minimal extension of the Higgs sector, in the form of a charged Higgs boson. The relevant parameters for this study are the mass of the charged Higgs, $M_{H^{\pm}}$, and the ratio of the vacuum expectation values of the doublets, $\tan\beta$.

In the SM, the primary decay of the t quark is $t \to W^+b$. The addition of the second Higgs doublet provides the $t \to H^+b$ mode, if it is kinematically allowed. If $\tan\beta$ were larger or smaller by about an order of magnitude than $\sqrt{m_t/m_b}$, the branching fraction $B(t \to H^+b)$ could then be large, but would decrease as $M_{H^{\pm}}$ increased. In this analysis, we assume $B(t \to W^+b) + B(t \to H^+b) = 1$. The masses of the three neutral scalars are assumed to be large enough to be suppressed in $H^{\pm}$ decays. At tree level, there are no direct $H^{\pm}$ couplings to SM vector bosons or to flavor changing neutral currents. Therefore, the only available decays of $H^{\pm}$ are fermionic, with the coupling proportional to the fermion mass. For $M_{H^{\pm}}$ below ≈ 110 GeV, $B(H^+ \to \tau^+\nu) \approx 0.96$ for $\tan\beta > 2$, and $B(H^+ \to c\bar{s}) \approx 1$ for $\tan\beta < 0.4$. Because of the large coupling to the top quark[2], $B(H^+ \to t^*\bar{b} \to W^+b\bar{b})$ becomes important and eventually dominant for $\tan\beta < \sqrt{m_t/m_b}$ at higher values of $M_{H^{\pm}}$.

DØ has carried out two independent searches for evidence of $t \to H^+b$ and $\bar{t} \to H^-\bar{b}$. An indirect search, which has been published [3], looked for a decrease in the $t\bar{t} \to W^+W^-b\bar{b}$ signal expected on the basis of the SM. The direct search, reported here, looks for evidence of the $H^{\pm}$ through its characteristic decay modes. Direct searches have been carried out by LEP experiments, and report a combined lower limit on $M_{H^{\pm}}$ of 77.4 GeV [4]. CDF has also reported a direct search for $H^{\pm}$, setting an upper limit on $B(t \to H^+b)$ in the range of 0.5 to 0.6 at the 95% confidence level (CL) for masses in the range 60 to 160 GeV, assuming $B(H^+ \to \tau\nu_\tau) = 1$ [5].

This analysis uses the same formulation and Monte Carlo (MC) tools as used in the indirect search by DØ. The theory is a leading-order perturbative calculation, thereby requiring the $t \to H^+b$ 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 regions where $M_{H^{\pm}} < 160$ GeV and $B(t \to H^+b) < 0.9$.

A direct search for $H^{\pm}$ is divided naturally into two regions of $\tan\beta$ [6]: (1) small $\tan\beta$, where final states are dominated by jets, and there is no apparent imbalance in transverse momentum (E_T), and (2) large $\tan\beta$, where the main final state contains up to two τ leptons and large missing transverse energy ($\not\!\!E_T$). Because at small $\tan\beta$ there is much background from multijet production, we concentrate on large $\tan\beta$ and $t\bar{t} \to \tau\bar{\tau}\nu_\tau\bar{\nu}_\tau$+jets final states. The experimental signature for $t \to H^+b$ is nearly identical to that for $t \to W^+b$.

We therefore rely on the expected increase in absolute yield of τ leptons at high $\tan\beta$ for differentiating between the two decay modes.

The data for this analysis were collected using the D0 detector [7] during the 1994-1995 run of the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.8$ TeV. For this study, we consider $t\bar{t} \to H^+H^-b\bar{b}$ and $t\bar{t} \to H^{\pm}W^{\mp}b\bar{b}$ decays. Identification of the τ relies on its hadronic decay modes, consisting primarily of one or three charged hadrons in a very narrow jet, often accompanied by photons from π^0 decays, and a ν_τ. There are two b jets per event, and, when one of the top quarks decays to Wb, there are also two light quark jets, because we only consider hadronic W modes. The event signature used in our search is therefore jets + $\not\!\!E_T$, with a roughly spherical distribution in the detector, and at least one very narrow jet. Consequently, we rely on a multijet + $\not\!\!E_T$ trigger to collect the search sample, which comprises 62.2 ± 3.1 pb^{-1} of integrated luminosity ($\mathcal{L}$). To reduce the background, we start with a set of loose selection criteria and then use a neural network (NN) to make more restrictive cuts. The loose criteria require that the event have $\not\!\!E_T > 25$ 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 [8] based on JETNET [9], with 3 input nodes, 7 hidden nodes, and 1 output node. The 3 input variables are the $\not\!\!E_T$, and two of the three eigenvalues of the normalized momentum tensor. The NN is trained on both signal ($t \to H^+b$), and background. The sample used for training the NN on signal, $t\bar{t} \to H^+H^-b\bar{b}$, is generated using ISAJET [10], with both Higgs bosons decaying to $\tau\nu_\tau$, and the τ leptons decaying to hadrons and ν_τ. The response of the NN is relatively insensitive to the Higgs mass, we therefore use only a single value, $M_{H^\pm} = 95$ GeV. The same NN is also used for classifying $t\bar{t} \to H^{\pm}W^{\mp}b\bar{b}$ channels, since the efficiency for this channel is comparable to that of the training sample.

The primary sources of background are from mismeasured multijet events, and $W+\geq 3$ jet events. We therefore train the NN on multijet background events from data; even if a $H^\pm$ signal is present in the data, it is expected to be very small, so this sample corresponds effectively to pure background. The $W+$ jets background is modeled using VECBOS [11] for parton production, and ISAJET for hadronization. Figure 1 shows the separation achieved for the Higgs signal relative to our primary source of background from multijet events. The

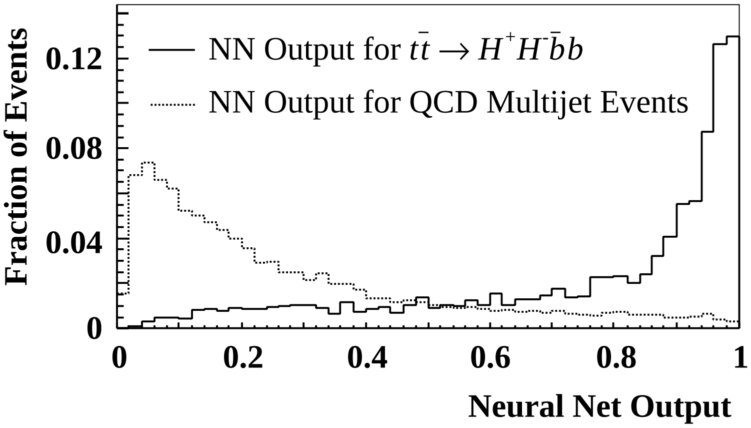

FIG. 1. The NN output for $t\bar{t} \to H^+H^-b\bar{b}$ MC signal and multijet data background. The two distributions are normalized to the same area.

chosen NN cutoff of 0.91, is based on a series of MC experiments used to determine the maximum charged Higgs search sensitivity. In the event that no signal is found, this also provides the maximum area in $(M_{H^\pm},\ \tan\beta)$ space that could be excluded in our analysis.

After applying the NN selection, we require that events have at least one hadronically decaying τ lepton. The selection used in this analysis follows that of our $W \to \tau\nu_\tau$ study [12]. The principal requirement involves the identification of a single narrow jet in each event ($\sqrt{\sigma_\eta^2 + \sigma_\phi^2} \leq 0.25$, where the σ correspond to the jet widths in η and ϕ), with 1 to 7 charged tracks, and jet E_T of $10 < E_T < 60$ GeV in a cone of $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$. In addition to the criteria in Ref. [12], we require that the discriminant $\chi_b^2 - \chi_s^2 > 0$, where χ_s^2 is the χ^2 determined from a covariance matrix calculated from $W \to \tau\nu_\tau$ MC events, and χ_b^2 is the χ^2 determined from a covariance matrix based on a background sample of multijet events. The χ^2 for the background sample uses the leading jet in each event ($E_T > 20$ GeV).

Because the measured values of $\sigma_{t\bar{t}}$ and m_t are based on the assumption that $B(t \to Wb) = 1$, it may be regarded improper to use either in calculating the expected number of events. For $t\bar{t}$ production, we use a QCD calculation giving $\sigma_{t\bar{t}} = 5.5$ pb [13–15]. Any possible contamination from $t\bar{t} \to H^\pm W^\mp b\bar{b}$, would not affect the DØ mass measurement by more than 5% for $M_{H^\pm} < 140$ GeV, therefore we use the value $m_t = 175$ GeV [16,17]. The selection efficiencies for signal and background are listed in Table I. Combining the theoretical cross section, m_t, and the efficiencies, the expected numbers of events from SM sources and the number of events observed in our data are listed in Table II.

Our measurement agrees with the SM, therefore we conclude that there is no evidence for charged Higgs boson production, and proceed to set a limit on $M_{H^\pm}$ and $\tan\beta$. If $H^\pm$ bosons were in fact produced in $t\bar{t}$ decays, then the number of $t\bar{t} \to \tau +$ jets events in our data would have increased at high $\tan\beta$, because $B(H^+ \to \tau\nu_\tau) = 0.96$ in that region, while $B(W^+ \to \tau\nu_\tau) = 0.11$. Consequently, in the absence of $t \to H^+ b$ events, regions of parameter space where the number of events from $H^\pm$ decay is expected to be large, can be excluded at high confidence. To set a limit, we calculate the probability for our data to fluctuate to the expectation from $H^\pm$ sources. Figure 2 shows the number of events observed in the data, the number expected from SM processes, and the extra number expected from $H^\pm$ contributions for $\tan\beta = 150$ and $M_{H^\pm} = 95$ GeV, as a function of NN threshold. Our data show agreement with the SM, but above our NN cutoff of 0.91, there is a clear inconsistency with the hypothesis of excess τ production from $H^\pm$ sources.

To calculate the probability that the number of expected events for a particular value

TABLE I. Cumulative efficiencies (in %) after the three stages of event selection for $H^\pm$ signal and background. Event types are: (1) $t\bar{t} \to W^\pm H^\mp b\bar{b}$, $W \to q\bar{q}'$, $H \to \tau\nu_\tau$; (2) $t\bar{t} \to H^\pm H^\mp b\bar{b}$, $H \to \tau\nu_\tau$; (3) $t\bar{t} \to W^\pm W^\mp b\bar{b}$, $W \to \tau\nu_\tau$, $W \to q\bar{q}'$; and (4) $W+ \geq 3$ jets, $W \to \tau\nu_\tau$, where for all event types $\tau \to$ jet.

Event type	Loose selection	NN > 0.91	τ-id
(1)	50.0 ± 1.7	18.3 ± 0.9	5.0 ± 1.0
(2)	35.2 ± 1.6	12.9 ± 0.9	5.5 ± 1.0
(3)	45.1 ± 2.0	15.7 ± 1.0	3.8 ± 0.8
(4)	0.65 ± 0.04	0.17 ± 0.02	0.04 ± 0.01

TABLE II. Number of SM events expected after all selections.

$t\bar{t}$	1.1 ± 0.3
W+jets	0.9 ± 0.3
QCD multijets	3.2 ± 1.5
Total SM	5.2 ± 1.6
Observed events	3

of $\tan\beta$ and $M_{H^\pm}$ has fluctuated to the number of observed events (n_{obs}), we use the joint posterior probability density for $M_{H^\pm}$ and $\tan\beta$, given by

$$P(M_{H^\pm}, \tan\beta | n_{obs}) \propto \int G(\mathcal{L}) \int G(n_B) \int G(A) \times P(n_{obs}|\mu)\, dA\, dn_B\, d\mathcal{L}, \tag{1}$$

where G represent Gaussian distributions, n_B is the number of expected background events, and $P(n_{obs}|\mu)$ is the Poisson probability of observing n_{obs} events given a total expectation of

$$\mu(M_{H^\pm}, \tan\beta) = A(M_{H^\pm}, \tan\beta)\, \sigma(t\bar{t})\, \mathcal{L} + n_B, \tag{2}$$

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 $M_{H^\pm}$, the value of A for any $\tan\beta$ is computed using leading-order calculations for the branching fractions, and Monte Carlo for determining efficiencies. The probabilities from Eq. 1 are then parameterized as a function of $\tan\beta$ for fixed values of $M_{H^\pm}$. These parameterized dependences on $\tan\beta$ are fitted as a function of $M_{H^\pm}$ to obtain $P(M_{H^\pm}, \tan\beta|n_{obs})$. This Bayesian posterior probability density [18] for $M_{H^\pm}$ and $\tan\beta$ is shown in Fig. 3.

The prior probability distribution is assumed to be uniform over the previously discussed allowed regions of $M_{H^\pm}$ and $\log(\tan\beta)$ and zero elsewhere. We further impose a lower limit on $M_{H^\pm}$ of 75 GeV, to provide an overlap with the limit from the LEP experiments.

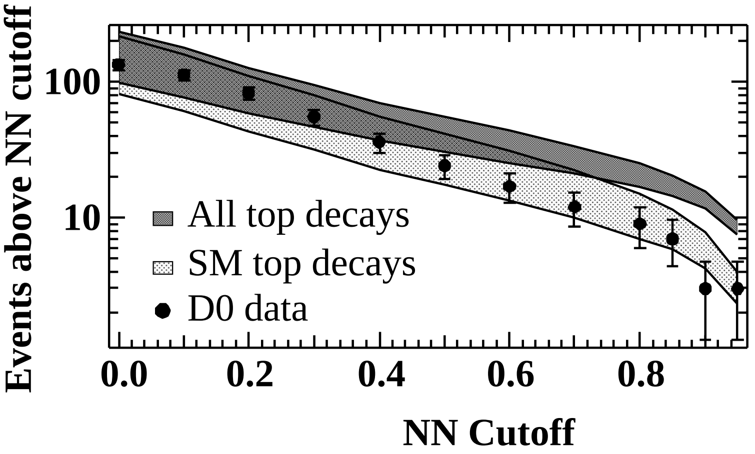

FIG. 2. Data superimposed on the number of events expected from standard $t\bar{t} \rightarrow \tau + X$ decays and other SM backgrounds (light), and from the addition of $H^\pm$ sources (dark) for $\tan\beta = 150$ and $M_{H^\pm} = 95$ GeV, as a function of NN threshold.

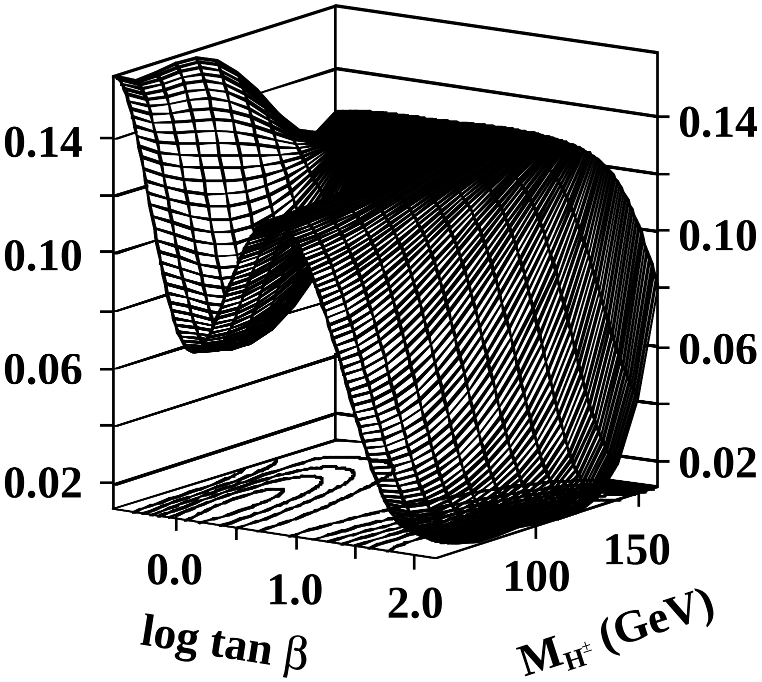

FIG. 3. Surface formed by $P(M_{H^\pm}, \tan\beta|n_{obs})$. The ordinate has arbitrary normalization.

The 95% CL exclusion boundary in the ($M_{H^\pm}$, $\tan\beta$) plane is obtained by integrating the probability density $P(M_{H^\pm}, \tan\beta|n_{obs})$ 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 $P(M_{H^\pm}, \tan\beta|n_{obs})$ surface. The limits are shown in Fig. 4, along with the results from the indirect DØ search, using the same assumptions. The exclusion boundaries correspond to regions of parameter space 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 results, wherein a point in the ($M_{H^\pm}$, $\tan\beta$) plane is excluded when $P(n_{obs}|M_{H^\pm}, \tan\beta) < 5\%$, which is related to the posterior probability through Bayes theorem:

$$P(M_{H^\pm}, \tan\beta|n_{obs}) = \frac{P(n_{obs}|M_{H^\pm}, \tan\beta)P(M_{H^\pm}, \tan\beta)}{P(n_{obs})} \tag{3}$$

Although the frequentist and Bayesian exclusion contours are shown on the same plot, they cannot be compared directly, because they represent entirely different probabilities.

In summary, our direct search for charged Higgs bosons in top quark decays shows no evidence of signal for $M_{H^\pm} < 150$ GeV. The region of small $\tan\beta$ does not provide τ 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 $m_t = 175$ GeV and $\sigma(t\bar{t}) = 5.5$ pb, $\tan\beta > 32.0$ is excluded at the 95% CL, for $M_{H^\pm} = 75$ GeV. The limits are less stringent at larger $M_{H^\pm}$, until $M_{H^\pm} = 150$ 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% CL in the region $0.3 < \tan\beta < 150$, and $M_{H^\pm} < 160$ GeV.

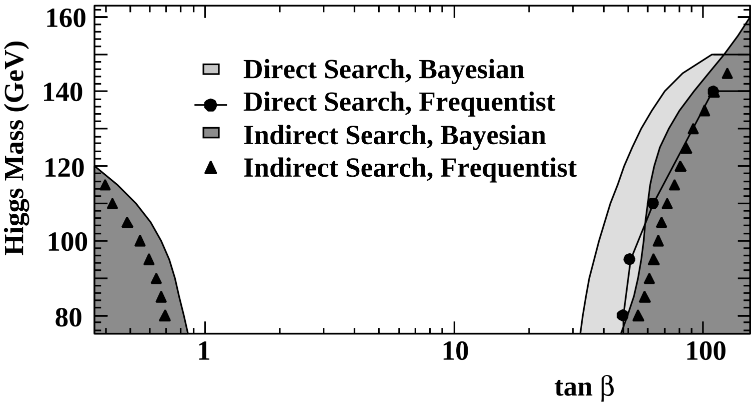

FIG. 4. The 95% CL exclusion boundary in the ($M_{H^{\pm}}$, $\tan\beta$) plane for $m_t = 175$ GeV, and $\sigma(t\bar{t}) = 5.5$ pb.

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