Signatures for the Charged Higgs Decay of the Top Quark at the Tevatron

Duane A. Dicus

Center for Particle Physics,
Department of Physics,
University of Texas at Austin,
Austin, TX 78712

David J. Muller and Satyanarayan Nandi

Department of Physics,
Oklahoma State University,
Stillwater, OK 74078

ABSTRACT

We investigate the effect that a charged Higgs decay channel for the top quark has on the signature for top quark pair production at the Tevatron. The branching ratios for the various multijet and multilepton final states arising from $t\bar{t}$ production are obtained for a wide range of values for $\tan \beta$ and the charged Higgs boson mass. In addition, the effect of the charged Higgs decay of the top quark on the 2 b-tagged jets and 1 lepton channel is considered.

1e-mail address: phbd057@utxvms.cc.utexas.edu
2e-mail address: qgd@okstate.edu
3e-mail address: shaown@vms.ucc.okstate.edu
1 Introduction

The discovery of the top quark by the CDF and D0 collaborations potentially opens a window for the discovery of new physics beyond the standard model. With the top quark’s discovery, all the particles of the standard model have been found with the exception of the Higgs boson. Since the top quark’s mass is so much larger than that of the other known fermions, the physics of the top should provide a useful window into the electroweak symmetry breaking mechanism. It can also provide information on new TeV scale physics such as low energy supersymmetry, especially if some of the new particles are less massive than the top quark and can thereby be directly produced.

One popular scenario for new physics involves extended Higgs sectors. This is particularly true in supersymmetric theories where more than one Higgs doublet is required for anomaly cancellation and to give masses to both up-type and down-type quarks. The minimal supersymmetric standard model (MSSM) takes the minimal Higgs structure of two doublets. Of the eight degrees of freedom in this model, three are absorbed to give mass to the W and Z bosons which leaves three neutral Higgs bosons and a charged Higgs boson pair. If the charged Higgs boson is light enough, then it is possible that the top quark has a nonstandard decay mode into these bosons. If this is the case, then top quark events observed at colliders such as the Tevatron would differ from the standard model (SM) expectation. Thus, the charged Higgs boson will either be detected through top quark decay or some bound will be placed on the mass of the charged Higgs boson through its nondetection.

Numerous limits have already been placed on the values that the mass of the charged Higgs boson and \( \tan \beta \) can take. One such limit can be obtained from the following relation which holds at tree level

\[
M_{H^\pm}^2 = M_{A^0}^2 + M_W^2
\]

where \( M_{H^\pm} \) is the mass of the charged Higgs boson and \( M_{A^0} \) is the mass of the pseudoscalar Higgs. The current ALEPH 95% C.L. limit of \( M_{A^0} > 62.5 \) GeV for \( \tan \beta > 1 \) \cite{1} then implies that \( M_{H^\pm} > 100 \) GeV. For such values of \( \tan \beta \), the one-loop corrections tend to shift the charged Higgs mass down from its tree-level value by less than 10 GeV. The size of the correction decreases with increasing \( \tan \beta \) \cite{2}. Moreover, limits from the nonobservation of direct pair production of charged Higgs bosons at LEP (including LEP2) set lower bounds on the charged Higgs mass. At the 95% confidence level, the DELPHI collaboration sets a lower bound of 54.4 GeV, ALEPH sets a lower bound of 52 GeV, and OPAL sets a lower bound of 52.0 GeV \cite{3}.
Bounds on the values for $M_{H^\pm}$ and $\tan \beta$ have also been obtained by considering the charged Higgs contribution to inclusive semi-tauonic $B$-decays \cite{4}. Recently, the supersymmetric short-distance QCD corrections have been incorporated into the analysis. Using the current bounds on the sparticle masses, the bound

$$\tan \beta \lesssim 0.43(M_{H^\pm}/\text{GeV})$$  \hspace{1cm} (2)

at the $2\sigma$ level for $\mu < 0$ is obtained (the $\mu$ term in the superpotential is taken to be $-\mu H_1 H_2$). For $\mu > 0$ these decays could yield no bound at all \cite{5}.

The CDF collaboration at the Tevatron has searched for charged Higgs decays of the top quark \cite{6}. Recently they have searched for evidence of such decays by considering hadronic decays of the tau lepton since the charged Higgs decays primarily to the tau for $\tan \beta > 4$. Seven events meet their cuts with an expected background of $7.4 \pm 2.0$ events. A region in the $\tan \beta - M_{H^\pm}$ plane is thereby excluded. In particular, charged Higgs bosons with $M_{H^\pm} < 147(158)$ GeV are excluded in the large $\tan \beta$ limit ($\tan \beta > 100$) for a top quark mass of 175 GeV and top production cross section $\sigma_{tt} = 5.0(7.5)\text{ pb}$. Moreover, to maintain consistency with the then observed top quark cross section of $\sigma_{\text{obs}} = 6.8^{+3.6}_{-2.4}\text{ pb}$, $\sigma_{\text{tt}}$ must increase at higher $\tan \beta$ to compensate for the lower branching ratio into the SM mode $\text{Br}(tt \rightarrow Wb\bar{W}b)$. This excludes more of the parameter space \cite{6}.

Similarly, Guchait and Roy have used Tevatron top quark data in the lepton plus $\tau$ channel to obtain a significant limit on the $H^\pm$ mass in the large $\tan \beta$ region \cite{7}. They consider the lepton plus multijet channel looking for departures from the SM prediction due to the charged Higgs’ preferential coupling to the tau lepton. They thereby obtain an exclusion area in the $\tan \beta - M_{H^\pm}$ plane. Quantitatively, they obtain a mass limit of 100 GeV for $\tan \beta \geq 40$ increasing to 120 GeV at $\tan \beta \geq 50$. Essentially the same analysis was performed by Guasch and Solà but with the MSSM quantum corrections included \cite{8}. They demonstrated that these corrections have a substantial impact on the allowed parameter space. In particular, for $\mu > 0$, these corrections decrease the cross section for the $\tau$ signal and a light charged Higgs mass ($\sim 100$ GeV) could hold for essentially any (perturbative) value of $\tan \beta$.

In this paper, we investigate the signature for top quark production at hadronic colliders for the case where the charged Higgs boson is light enough for the top quark to decay into it. We determine the branching ratios for the decays into various numbers of jets and leptons as a function of $\tan \beta$ and the charged Higgs mass.
2 Theory

The MSSM contains two Higgs doublets. One Higgs doublet couples to the up-type quarks and the neutrinos, while the other couples to the down-type quarks and the charged leptons. Three of the eight degrees of freedom are absorbed to give mass to the $W$ and $Z$ bosons. This leaves five physical Higgs bosons: three neutral ($h^0$, $H^0$, and $A^0$) and a charged pair ($H^\pm$). If the charged Higgs is lighter than the top quark, then it is possible that the top quark decays in part through the charged Higgs. The allowed decays for the top quark in the MSSM are then $t \to bW^+$ and $t \to bH^+$; there are no other decay modes ignoring intergenerational mixing. The interactions of the charged Higgs bosons with quarks are represented by the Lagrangian:

$$ L = \frac{g}{2\sqrt{2}M_W} H^+ \left[ \cot \beta U_M U_L + \tan \beta U_D D_R \right] + h.c. \quad (3) $$

where $U$ represents the three generations of up-type quarks and $D$ represents the three generations of down-type quarks. $M_U$ and $M_D$ are diagonal up and down quark mass matrices. We have set the CKM matrix to the identity matrix since we are neglecting the small intergenerational mixings for our analysis. $\tan \beta \equiv v_2/v_1$ where $v_1$ is the vacuum expectation value (vev) for the Higgs doublet that couples to the down-type quarks and $v_2$ is the vev for the Higgs doublet that couples to up-type quarks. The widths for the top quark’s decays are then

$$ \Gamma(t \to bW) = \frac{g^2}{64\pi M_W^2 M_t} \lambda^1/2(1, M_W^2, M_t^2, M_t^2) \times $$

$$ \left[ M_W^2(M_t^2 + M_b^2) + (M_t^2 - M_b^2)^2 - 2M_W^4 \right] \quad (4) $$

$$ \Gamma(t \to bH) = \frac{g^2}{64\pi M_W^2 M_t} \lambda^1/2(1, M_W^2, M_H^2, M_t^2) \times $$

$$ \left[ (M_t^2 \cot^2 \beta + M_b^2 \tan^2 \beta)(M_t^2 + M_b^2 - M_H^2) + 4M_t^4 M_b^4 \right] \quad (5) $$

where $\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$. The branching fraction for $t \to bH^+$ is large ( $> 10\%$ ) for $\tan \beta \leq 1$ and $\tan \beta > \frac{M_t}{M_b}$.

The charged Higgs in turn decays into the standard fermions. Its coupling to the fermions increases with their mass, so the primary decay modes to consider for the charged Higgs are $H^+ \to c\bar{s}$ and $H^+ \to \nu_\tau \bar{\tau}$. The widths for these decays are

$$ \Gamma(H^+ \to c\bar{s}) = \frac{3g^2}{32\pi M_H M_W^2} \lambda^{1/2}(1, M_H^2, M_W^2) \times $$

3
\[\Gamma(H^+ \to \nu \tau) = \frac{g^2}{32\pi M_H^3 M_W^2} (M_H^2 - M^2_{H^+})^2 M^2_{H^+} \tan^2 \beta. \]  
(7)

For small $\tan \beta$, the decay $H^+ \to c \bar{s}$ dominates, while for large $\tan \beta$, the decay $H^+ \to \nu \tau \bar{\tau}$ dominates. The branching ratio for $H^+ \to \nu \tau \bar{\tau}$ is essentially unity for $\tan \beta > 4$.

3 Analysis and Results

In this analysis we study the possible Tevatron signatures for charged Higgs production through top quark decay in the context of the MSSM. The cuts employed are that final state charged leptons (electrons and muons) must have a $p_T$ greater than 20 GeV and a pseudorapidity, $\eta \equiv -\ln(\tan \frac{\theta}{2})$ (where $\theta$ is the polar angle with respect to the proton beam direction), of magnitude less than 1. Jets must have an $E_T > 15$ GeV and $|\eta| < 2$. In addition, hadronic final states within a cone size of $\Delta R \equiv \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4$ are merged to a single jet. The signature here for the hadronic decay of the $\tau$ lepton is to a single thin jet and we assume this is always true. Leptons within this cone radius of a jet are discounted. Throughout this analysis, the mass of the top quark is taken to be 175 GeV in accordance with current CDF and D0 collaboration measurements.

There are several possible final states available from top pair production. With the two decay possibilities of $t \to W^+ b$ and $t \to H^+ b$, there can be up to two $b$-jets from the decays of the top quarks. For the $W$ decay channel, which is the only channel available to the SM, the $W$ bosons can decay to as many as two jets each or they can each decay leptonically. Thus in the SM case, one can expect after implementing the cuts any number of jets up to six and any number of charged leptons up to 2. Introducing the possibility of the top quark decaying via the charged Higgs boson changes the branching ratios for decay into these various channels. For $\tan \beta > 4$, the charged Higgs decays primarily into the $\tau$ lepton. With the hadronic decay of the $\tau$ being to a single thin jet, there should be a depletion in the number of events with large numbers of jets when the branching ratio for $t \to H^+ b$ becomes appreciable. As $\tan \beta$ falls below $\sim 4$, the branching ratio for $H^+ \to \tau \nu_\tau$ decreases and the branching ratio for $H^+ \to c \bar{s}$ increases correspondingly. The values for the branching ratios change particularly sharply for $\tan \beta \sim 1$: for a charged Higgs mass of 110 GeV, the branching ratio for $H^+ \to \tau \nu_\tau$ is $\sim 0.94$ for $\tan \beta = 3$ and is $\sim 0.31$ for $\tan \beta = 1$. Thus for small $\tan \beta$, $H^+ \to c \bar{s}$ becomes the dominant decay mode of the charged
Higgs and we expect a depletion in events with leptons. Events that contain leptons are distinctive. This is particularly true for final states containing two leptons. While production rates for these dilepton modes is rather small, their distinctive signature allows for a good separation from background. Thus the two-jets and two-leptons mode, which has the largest branching ratio of the dilepton modes, could be useful for charged Higgs detection after a long collider run. Fig. 1 shows a plot of the branching ratio versus charged Higgs mass for the two-jets dilepton mode. Each curve represents a different value for \( \tan \beta \). As the figure shows, the curves for the various values of \( \tan \beta \) all lie below the SM expectation. Thus if the decay \( t \to H^+ b \) is allowed, there will be a depletion of events for this mode which already had a small branching ratio in the SM case. For \( M_{H^\pm} \) around 110 GeV, the branching ratio can be as low as half the SM expectation.

The 2-jets dilepton mode occurs when the decays of the \( W \) or \( H^\pm \) from each top quark leads to an \( e \) or a \( \mu \) either directly or indirectly. For \( \tan \beta > 4 \), the predominant decay mode of the charged Higgs is to the \( \tau \) lepton. Since the electrons and muons from the subsequent tau decays occur farther along the decay chain than \( e \)'s and \( \mu \)'s from direct \( W \) decay, there is less energy available for the electrons and muons from the \( \tau \) decays than in \( W \) decays. Thus the electrons and muons from the tau decays tend to be softer and less likely to meet the \( p_T \) cuts. Thus as \( \tan \beta \) increases (and so as \( \text{BR}(t \to H^+ b) \) increases), the branching ratio for the two jet and two lepton decay mode gets smaller. The branching ratios for this mode increase to the SM value as \( M_{H^\pm} \) increases towards 170 GeV and the phase space available for the charged Higgs decay of the top quark goes to zero.

The depletion in two-jets dilepton events is considerable for low values of \( \tan \beta \) as well. For \( \tan \beta = 1 \), Fig. 1 shows that the branching ratio for the two-jets dilepton mode decreases rapidly as the charged Higgs mass decreases. This is due to the fact that as \( \tan \beta \) falls below approximately 6, the branching ratio for \( t \to H^+ b \) increases. Moreover, as \( \tan \beta \) falls below 3, the branching ratio for \( H^+ \to c \bar{\sigma} \) increases rapidly. Thus as \( \tan \beta \) decreases, events with large numbers of leptons become less plentiful. For \( \tan \beta = 1 \) and \( M_{H^\pm} = 110 \) GeV, for example, the branching ratio for \( H^+ \to c \bar{\sigma} \) is 69%. Hence the depletion in dilepton events with two jets relative to the SM case is due here to a general lack of leptonic decays of the charged Higgs boson. Those \( e \)'s and \( \mu \)'s coming indirectly from the charged Higgs also tend to be soft as discussed above and tend to be eliminated by the \( p_T \) cuts.

The single lepton decay modes have the advantage that they are produced at a more substantial rate than the dilepton modes while retaining some of the distinctiveness that lepton modes offer. The plots of the branching ratios versus the charged Higgs mass for these modes are shown in Fig. 2. Fig. 2a shows the plot for the four
jets and one lepton case. We can see that the branching ratios for this mode are all below the SM case. Moreover, the solid curves show that as the value for tan $\beta$ increases above 5, the branching ratio decreases. As tan $\beta$ falls below 5, there is likewise a decrease in the branching ratio for the 4 jets-1 lepton mode.

We begin our analysis of Fig. 2a by considering the case where tan $\beta > 5$. Two of the jets in the 4 jets-1 lepton mode are typically b-jets coming from the decay of the top quarks. This leaves two ways in which we can obtain a total of four jets and one charged lepton. The first way is for both of the top quarks to decay via the $W$ with one $W$ decaying hadronically and the other leptonically. The other way is for one of the top quarks to decay via the $W^{\pm}$ which subsequently decays hadronically and the other top decaying via the $H^{\pm}$ which decays indirectly to an $e$ or $\mu$ through the $\tau$. Other possibilities would involve the subsequent hadronic decays of the $\tau$ leptons from charged Higgs decays, but these can not contribute to this mode as they lead to only one jet instead of the required two. Since only a subset of the possible top decays can give rise to the 4 jets-1 lepton mode, there will be a decrease in the number of events in this mode. This decrease is made more pronounced by the relative softness of the electrons and muons coming from the $H^{\pm}$ decay chain which tends to eliminate them when the $p_T$ cuts are applied. As tan $\beta$ increases beyond 5, the branching ratio for this mode decreases because of the increase in charged Higgs production. The minimum deviation from the SM occurs for tan $\beta$ $\sim$ 6 – 7 as this is where the minimum in the branching ratio for $t \rightarrow H^{+}b$ occurs.

We now consider the case for tan $\beta < 5$. For tan $\beta = 3$, $H^{\pm}$ production increases somewhat from tan $\beta = 5$, but the branching ratio for $H^{+} \rightarrow \tau \nu_\tau$ remains close to one. As a result, we get slightly fewer events for this mode compared to the tan $\beta = 5$ case. For tan $\beta = 1$, on the other hand, there is not only more $H^{\pm}$ production than in the tan $\beta = 3$ case (the increase is by a factor of $\sim 5$), but the branching ratio for $H^{+} \rightarrow e$ has increased from 0.06 to 0.69. Thus there is a decrease in 4jets-1 lepton events due to a general decrease in leptonic events.

The three jets and single lepton mode, whose branching ratio as a function of $M_{H^{\pm}}$ is given in Fig. 2b, shows rather different behavior. In the large tan $\beta$ region, the branching ratios for this mode are all above the SM expectation. These tend to increase with increasing tan $\beta$. These features can be qualitatively understood as follows. Two of the jets are almost always b-jets coming from the decays of $t$ and $\bar{t}$. The remaining one jet and one lepton must come from the decays of the $W$ and charged Higgs bosons. For the tan $\beta > 5$ case, the branching ratios before cuts for obtaining one jet (indirectly from $\tau$ decay) and one $e$ or $\mu$ (directly or indirectly from $\tau$ decay) from $WW$, $WH$, and $HH$ are 0.18, 0.19, and 0.22, respectively. Thus, charged Higgs production naturally gives rise to branching ratios for the 3 jets-1 lepton mode.
that are larger than the SM case. There are also other contributing factors for this increase. We have seen that the branching ratios for the 4 jets-1 lepton case tend to be below the SM value. The events that would have had four jets but failed to meet the isolation cuts for two of the jets could be taken as a three jets and one lepton event. Finally, the branching ratios for the 3 jets and 1 lepton mode increase as tan \( \beta \) increases due to the corresponding increase in \( \text{BR}(t \rightarrow H^+b) \).

The branching ratio curves in Fig. 2b also show another interesting feature. For large values of tan \( \beta \), as the charged Higgs mass decreases from 170 GeV, the branching ratios increase. However, this increase flattens out and the the branching ratios start to decrease around 140 GeV. This decrease becomes sharper around 120 GeV through 100 GeV. This decrease is due to the increase in the branching ratio for \( t \rightarrow H^+b \) as the charged Higgs mass decreases so that more of the leptons are soft leptons from charged Higgs decay which tend to be more easily eliminated by the \( p_T \) cut. In any case, the various factors that try to either increase or decrease the branching ratio for the 3 jets-1 lepton mode tend to keep the branching ratios roughly constant. The tan \( \beta = 80 \) branching ratio varies by less than 15% over the mass range.

For the low tan \( \beta \) region, the branching ratios for the 3 jets and 1 lepton mode tend to fall below the SM expectation as shown by the tan \( \beta = 1 \) and 1.25 curves in Fig. 2b. This is due to the general decrease in events containing leptons as tan \( \beta \) falls below 4 and the branching ratio for \( H^+ \rightarrow c\bar{s} \) increases. Indeed, for tan \( \beta \approx 1 \) and a charged Higgs mass of 110 GeV, \( H^+ \rightarrow c\bar{s} \) is the dominant decay mode with a branching ratio of 69%. The graph shows a corresponding drop of 15% in the branching ratio below the SM value.

Fig. 2c shows the branching ratios for the two jets and one lepton mode. The values of the branching ratios are larger than the SM case except for tan \( \beta = 1 \) and increase with tan \( \beta \) for tan \( \beta > 5 \). In this mode, two of the jets are almost always the b-jets coming from the decays of \( t \) and \( \bar{t} \). The main process generating the 2 jets-1 lepton events is then for both the \( W \) and charged Higgs bosons to decay via the leptonic mode and then have one of the charged leptons (typically from the charged Higgs) fail to meet the cuts. For tan \( \beta > 5 \), the leptonic branching ratios for the \( WW \), \( WH \), and \( HH \) decays are 0.07, 0.18, and 0.12, respectively. Thus, Higgs production gives rise to branching ratios for this mode that are larger than the SM expectation. As tan \( \beta \) increases, the branching ratios increase due to the increasing branching ratio for \( t \rightarrow H^+b \). For tan \( \beta = 3 \), \( H^\pm \) production increases somewhat from tan \( \beta = 5 \), but the branching ratio for \( H^+ \rightarrow \tau \nu \) is still close to one. As a result, the branching ratio for the 2 jets and 1 lepton mode is somewhat larger than for the tan \( \beta = 5 \) case. The tan \( \beta = 1 \) curve is below the SM case due to a decrease in leptonic events as \( H^+ \rightarrow c\bar{s} \) is the dominant decay mode for the charged Higgs.
Events with purely hadronic final states are less interesting due to the fact that they are harder to separate from the background at hadronic colliders. Nevertheless, these events can still be a source of interesting information on charged Higgs decays of the top. Fig. 3 shows the branching ratios for the purely hadronic modes. Figs. 3a and 3b show the 6 jets and 5 jets modes, respectively. As they show, the branching ratios tend to fall below the SM case. This is again due to the general depletion in events with large numbers of jets as the rate for top quark decay to the charged Higgs is increased. Fig. 3c shows the 4 jets case. Like the 3 jets-1 lepton case, this case has the branching ratios being roughly constant. Here this is due to a decrease in large jet activity being balanced by events failing to meet the cuts in the 5 jets-0 lepton mode and the 4 jets-1 lepton modes (an increase in events with charged Higgs bosons means an increase in softer leptons that will be less likely to meet the $p_T$ cuts). Figs. 3d and 3e show the branching ratios for the 3 jets and 2 jets modes. Here the branching ratios are all above the SM case and increase with increasing $\tan\beta$ and decreasing $M_{H^\pm}$. Thus, a significant enhancement in the dijet production where both jets are high $p_T$ b-tagged jets could be an interesting signal for charged Higgs production. For $\tan\beta > 4$, this is yet again due to the fact that increasing the probability for $t \to H^+b$ increases the number of events with smaller numbers of jets. For $\tan\beta < 4$, the increase is due to a general depletion of events with charged leptons.

In order to gain a sense of the size of the branching ratios of the various decay modes relative to each other, histograms of the branching ratios for a few representative cases are shown in Fig. 4. The SM expectation is given in Fig. 4a. Figs. 4b and 4c show the case where $M_{H^\pm} = 110$ GeV and $\tan\beta = 3$ and 50, respectively. The $\tan\beta = 3$ histogram is quite similar to the SM case owing to the fact that the top quark decays primarily via the $W$ boson for this value of $\tan\beta$. We can see some depletion in the 6 jets-0 lepton bin as a result of the depletion in large jet activity associated with charged Higgs production where the charged Higgs decays primarily via the tau lepton. This effect is much more pronounced in the $\tan\beta = 50$ case as shown in Fig. 4c. Here the branching ratio for top decay to the charged Higgs is appreciable (35%). We can see that the branching ratios for events with large numbers of jets, such as the 6 jets-0 lepton, 5 jets-0 lepton, and the 4 jets-1 lepton cases, have significant drops in their branching ratios. On the other hand, events with fewer numbers of jets have an increase in their branching ratios as demonstrated by the 3 jets-0 lepton and 2 jets-0 lepton cases.

The CDF Collaboration has recently performed a search for new particles (“$X$”) decaying into $b\bar{b}$ produced in association with $W$ bosons decaying into electrons or muons [4]. Specifically, they selected events that contain an electron or muon and two jets, at least one of which is $b$-tagged. Their main motivation was to look for
W + SM Higgs events, but presumably the acceptances are roughly the same for
the W + charged Higgs production. We can obtain events with this signature when
one top quark decay to a W which then decays leptonically and the other top quark
decays to a charged Higgs which then decays to a tau whose decay products fail to
satisfy the cuts. This would leave us with two b-jets and a charged lepton. The
branching ratios for such events are depicted in Fig. 5. As the graph demonstrates,
the branching ratio for this decay mode increases dramatically as $M_{H^\pm}$ decreases
and the rate of top quark decay via the charged Higgs increases. For example, with
$M_{H^\pm} = 110$ GeV and $\tan \beta = 65$, the branching ratio for this mode is 6.6%. The
standard model expectation is about 3.8%, so we expect an excess cross section for
this mode of about 0.2 pb assuming $\sigma_{\bar{t}t} = 7.5$ pb. Using the mean value of the top
quark pair production cross section reported by CDF, $\sigma_{\bar{t}t} = 7.5$ pb, this means that
the production cross section for this mode is about 0.5 pb. The CDF results set a
95% C.L. upper limit on $\sigma_{WX} \cdot B(X \rightarrow b\bar{b})$ of 20 pb for $M_X = 110$ GeV. Factoring in
the W decay rate to $e$'s and $\mu$'s gives a 2 b-jets and 1 lepton cross section of about
5 pb. Thus the CDF results do not impose any real restriction on the charged Higgs
decays of the top quark. As the total integrated luminosity increases for runs at the
upgraded Tevatron, the charged Higgs signal may be observable in this mode. The
absence of this signal will exclude some region of the $M_{H^\pm}$-$\tan \beta$ parameter space.

4 Conclusion

If the charged Higgs boson is light enough, it can provide an additional decay channel
for the top quark. It can thereby potentially be detected at the Tevatron through top
quark pair production. The presence of this charged Higgs production at the Tevatron
would manifest itself through a change in the branching ratios for the various final
states available to top pair production. Indeed, we have seen that the inclusion of
the decay $t \rightarrow H^+ b$ leads to a decrease in events with large numbers of jets for a
given number of leptons. In particular, this is true for the 2-jets dilepton mode and
the 4-jets and lepton mode; both of which are important low background channels
for investigating top quark production at the Tevatron. There is likewise a general
increase in events with smaller numbers of jets as the rate for $t \rightarrow H^+ b$ increases.

Current CDF data on the 2 b-jets and 1 lepton channel do not pose any real
restriction on the charged Higgs decays of the top quark. On the other hand, data
from an upgraded Tevatron could potentially detect the charged Higgs boson in this
mode or rule out some significant portion of the $M_{H^\pm}$-$\tan \beta$ parameter space.
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Figure 1: Branching fractions as a function of the charged Higgs mass for the 2 jets and 2 leptons case. From top to bottom, the solid curves are for $\tan \beta = 5, 20, 35, 50, 65, 80,$ and $95,$ respectively. From top to bottom, the dashed curves are for $\tan \beta = 3, 1.5,$ and $1.$ The horizontal line indicates the SM expectation.
(a) The 4 jets and 1 lepton case. From top to bottom, the solid curves are for tan $\beta = 5, 20, 35, 50, 65, 80, \text{ and } 95$. The upper dashed curve is for tan $\beta = 3$, while the lower one is for tan $\beta = 1$.

(b) The 3 jets and 1 lepton case. From top to bottom, the solid curves are for tan $\beta = 95, 80, 65, 50, 35, 20, \text{ and } 5$. The upper dashed curve is for tan $\beta = 1.25$, while the lower one is for tan $\beta = 1$.

(c) The 2 jets and 1 lepton case. From top to bottom, the solid curves are for tan $\beta = 95, 80, 65, 50, 35, 20, \text{ and } 5$. The upper dashed curve is for tan $\beta = 3$ and the lower dashed curve is for tan $\beta = 1$.

Figure 2: Branching fractions as a function of the charged Higgs mass for the single lepton modes. The horizontal line in each plot shows the SM expectation.
(a) The 6 jets and 0 lepton case. From top to bottom, the solid curves are for \( \tan \beta = 5, 20, 35, 50, 65, 80, \) and 95. The upper dashed curve is for \( \tan \beta = 3 \) and the lower dashed curve is for \( \tan \beta = 1 \).

(b) The 5 jets and 0 lepton case. From top to bottom, the solid curves are for \( \tan \beta = 5, 20, 35, 50, 65, 80, \) and 95.

(c) The 4 jets and 0 lepton case. From top to bottom, the solid curves are for \( \tan \beta = 95, 80, 65, 50, 35, 20, \) and 5. The dashed curves are for \( \tan \beta = 1 \) and \( \tan \beta = 3 \).

Figure 3: Branching fractions as a function of the charged Higgs mass for the purely hadronic modes. The horizontal line in each plot shows the SM expectation.
(d) The 3 jets and 0 lepton case. From top to bottom, the solid curves are for $\tan \beta = 95, 80, 65, 50, 35, 20,$ and $5$. The upper dashed curve is for $\tan \beta = 1$ and the lower one is for $\tan \beta = 3$.

(e) The 2 jets and 0 lepton case. From top to bottom, the solid curves are for $\tan \beta = 95, 80, 65, 50, 35, 20,$ and $5$. The upper dashed curve is for $\tan \beta = 1$ and the lower one is for $\tan \beta = 3$.

Figure 3: continued.
(a) The standard model expectation. 

(b) The MSSM case where $\tan \beta = 3$ and $M_{H^\pm} = 110 \text{ GeV}$. 

(c) The MSSM case where $\tan \beta = 50$ and $M_{H^\pm} = 110 \text{ GeV}$. 

Figure 4: Histograms of the branching ratios for the possible decay modes in top quark pair production.
Figure 5: Branching fractions as a function of the charged Higgs mass for the two b-tagged jets and single lepton mode. From top to bottom, the curves are for $\tan \beta = 95$, 80, 65, 50, 35, 20, and 5. The dashed lines are for $\tan \beta = 3$ and 1. The solid horizontal line depicts the SM expectation.