Enhanced Three-Body Decay of the Charged Higgs Boson

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If the charged Higgs boson H^+ exists with $m_{H^+} < m_t + m_b$, the conventional expectation is that it will decay dominantly into $c\bar{s}$ and $\tau^+\nu_\tau$. However, the three-body decay mode $H^+ \to W^+ b\bar{b}$ is also present and we show that it becomes very important in the low $\tan\beta$ region for $m_{H^+} \gtrsim 140$ GeV. We then explore its phenomenological implications for the charged-Higgs-boson search in top-quark decay. [S0031-9007(97)05252-6]

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The discovery of the top quark at the Tevatron collider [1,2] has generated a good deal of current interest in the search for new particles in the decay of the top quark. In particular, top-quark decay is known to be a promising reaction to look for the charged Higgs boson of a two-scalar doublet model and, in particular, the minimal supersymmetric standard model (MSSM) [3]. In the diagonal Cabbibo-Kobayshi-Maskawa (CKM) matrix approximation the MSSM charged Higgs boson couplings to the fermions are given by

$$\mathcal{L} = \frac{g}{\sqrt{2}\, m_W} H^+ [\cot\beta\, m_{ui} \bar{u}_i d_{iL} + \tan\beta\, m_{di} \bar{u}_i d_{iR} + \tan\beta\, m_{\ell i} \bar{\nu}_i \ell_{iR}] + \text{H.c.}, \qquad (1)$$

where $\tan\beta$ is the ratio of the vacuum expectation values of the two scalar doublets and the index i labels the quark and lepton generation. This interaction implies a large $H^+ tb$ Yukawa coupling when

$$\tan\beta \lesssim 1 \quad \text{and} \quad \tan\beta \gtrsim m_t/m_b, \qquad (2)$$

where one expects a large branching fraction for $t \to bH^+$ decay (given $m_t > m_{H^+}$). Interestingly, the regions $\tan\beta \sim 1$ and $\gtrsim m_t/m_b$ are favored by supersymmetric grand unified theory (SUSY-GUT) models for a related reason—i.e., the unification of the b and τ masses which requires a large negative contribution from the top Yukawa coupling to the renormalization group equation [4].

It should be noted that the perturbation theory limit on the $H^+ tb$ Yukawa coupling requires

$$0.2 < \tan\beta < 100, \qquad (3)$$

while the GUT scale unification constraint implies stricter limits

$$1 \le \tan\beta \le m_t/m_b, \qquad (4)$$

which are also required if one assumes the perturbation theory limit on the Yukawa coupling to remain valid up to the GUT scale [5]. Without any GUT scale ansatz, however, the allowed region of $\tan\beta$ extends down to 0.2. We shall assume only the particle content of the MSSM Higgs sector but no constraints from GUT scale physics. Our analysis will remain valid in any two-Higgs doublet model satisfying the coupling pattern of the MSSM as given by (1), i.e., the so-called class-II models [6].

For $m_t > m_{H^+}$ the dominant decay modes are usually assumed to be the two-body decays $H^+ \to c\bar{s}, \tau^+\nu$. The corresponding widths are

$$\Gamma_{cs} = \frac{3g^2 m_{H^+}}{32\pi m_W^2} (m_c^2 \cot^2\beta + m_s^2 \tan^2\beta), \qquad (5)$$

$$\Gamma_{\tau\nu} = \frac{g^2 m_{H^+}}{32\pi m_W^2} m_\tau^2 \tan^2\beta. \qquad (6)$$

The leading QCD correction is taken into account by substituting the quark mass parameters for Eqs. (1) and (5) by the running masses at the H^+ mass scale. Its most important effect is to reduce the charm quark mass m_c from 1.5 to 1 GeV [7]. Consequently, the two rates are approximately equal when $\tan\beta \sim 1$; the $\tau\nu$ (cs) rate dominates when $\tan\beta > 1$ $(\tan\beta < 1)$.

In this note we shall consider the phenomenological implications of a very important three-body decay channel of the Higgs boson, namely,

$$H^+ \to \bar{b} b W^+, \qquad (7)$$

where the bW^+ comes from a virtual t quark [8]. The dominant contribution comes from the top-quark exchange with a large Yukawa coupling of H^+ to the top quark given by the first term in Eq. (1). One can easily calculate the corresponding width as

$$\frac{d\Gamma_{\bar{b}bW}}{ds_{\bar{b}}\, ds_b} = \frac{1}{256\pi^3 m_{H^+}^3} \left(\frac{3g^4 m_t^4 \cot^2\beta}{4m_W^4 (m_t^2 - s_{\bar{b}})^2} \right) \times [m_W^2 (s_W - 2m_b^2) + (s_{\bar{b}} - m_b^2 - m_W^2) \times (s_b - m_b^2 - m_W^2)], \qquad (8)$$

where $s_{\bar{b}}$, s_b, and s_W are the 4-momentum squared transferred to the corresponding particles satisfying $s_{\bar{b}} + s_b + s_W = m_{H^+}^2 + m_W^2 + 2m_b^2$ [9].

Figure 1 compares the three-body decay width $\Gamma_{\bar{b}bW}$ with the two-body widths Γ_{cs} and $\Gamma_{\tau\nu}$ over the charged Higgs boson mass range 120–170 GeV at $\tan\beta = 1$. $\Gamma_{\bar{b}bW}$ is seen to be the dominant decay width for $m_{H^+} \gtrsim$

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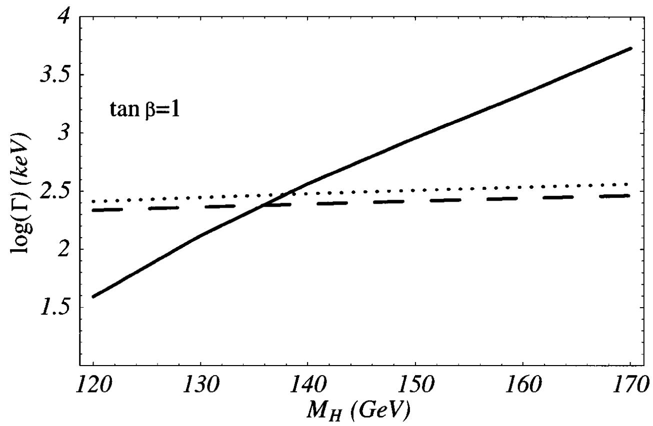

FIG. 1. Comparison of the three-body decay width $\Gamma_{H^+\to\bar{b}bW}$ (solid) with the two-body widths $\Gamma_{H^+\to c\bar{s}}$ (dashed) and $\Gamma_{H^+\to\tau^+\nu}$ (dots).

140 GeV, while the two-body decays dominate up to $m_{H^+} = 130$ GeV. The reason for this is the large H^+ Yukawa coupling to $t\bar{b}$, which is about 100 times larger than those to the $c\bar{s}$ and $\tau^+\nu$ channels. This can overcome the extra suppression factors due to the gauge coupling of the W as well as the three-body phase space, provided the off-shell propagator suppression factor is not too large. The latter is ensured for $m_{H^+} \gtrsim 140$ GeV. Thus the three-body decay (7) is the dominant mode for

$$m_{H^+} \gtrsim 140 \text{ GeV} \quad \text{and} \quad \tan\beta \lesssim 1\,, \tag{9}$$

while the $\tau\nu$ mode (6) dominates at larger $\tan\beta$. The $c\bar{s}$ mode is relatively small at all $\tan\beta$ for $m_{H^+} \gtrsim 140$ GeV. It may be noted here that the relative size of the H^+ decay widths at $\tan\beta = 1$ (Fig. 1) would hold for all values of $\tan\beta$ in the two-Higgs doublet model of type I [6].

This situation has a close parallel in the neutral scalar sector. For a neutral Higgs H^0 whose mass is slightly below the WW threshold a good detection channel is WW^* with $W^* \to \ell\nu$. In this case the decay $H^0 \to W\ell\nu$ is comparable to $H^0 \to \bar{b}b$ [6]. A related decay $H^+ \to W^+Z^*$ with $Z^* \to b\bar{b}$ is not considered because for multidoublet models there is no H^+W^-Z coupling [10].

The $H^\pm$ search strategies in top-quark decay have so far been based on the distinctive features of the channels

$$t \to bH^+ \to b\tau^+\nu\,, \tag{10}$$

$$t \to bH^+ \to bc\bar{s}\,, \tag{11}$$

vis-à-vis the standard model decay

$$t \to bW^+ \to b(\ell\nu, \tau\nu, q'\bar{q})\,. \tag{12}$$

As we have seen above, however, this strategy is valid only up to $m_{H^+} \simeq 130$ GeV. For $m_{H^+} \gtrsim 140$ GeV the $c\bar{s}$ mode (11) is overtaken by

$$t \to bH^+ \to b\bar{b}bW^+ \to b\bar{b}b(l\nu, \tau\nu, q'\bar{q}) \tag{13}$$

as the dominant decay mode for the low $\tan\beta(\lesssim 1)$ region. The distinctive feature of this new channel is evidently very different from those of the channels (10) and (11).

In order to assess the impact of the new channel (13) let us summarize the main features of the current H^+ search program in $t\bar{t}$ decay. It is based on two strategies: (i) Excess of $t\bar{t}$ events in the τ channel, and (ii) their deficit in the leptonic ($\ell = e, \mu$) channel with respect to the standard model prediction from (12). The first is appropriate for the large $\tan\beta$ region where the $\tau\nu$ channel (10) is the dominant channel of the charged Higgs decay. One can already get significant limits on m_{H^+} for very large $\tan\beta(\gtrsim m_t/m_b)$ from the CDF $t\bar{t}$ data in the $\ell\tau$ and inclusive τ channels [11,12]. This analysis can be extended down to lower values of $\tan\beta$ at the Tevatron upgrade and the LHC by exploiting the opposite states of τ polarization from $W^\pm$ and $H^\pm$ decays [13]. Evidently this type of analysis would not be affected by the new channel.

The second strategy is based on a suppression of the leptonic (e, μ) decay of the top due to the H^+ channels (10) and (11). [This is evident for the cs channel (11) but should also hold for the $\tau\nu$ channel (10) as well since the e, μ from τ decay are expected to be soft and hence suppressed by the p_T cut used in the analysis.] The experimental estimate of the $t\bar{t}$ cross section is based on the $\ell\ell$ and ℓ + multijet channels with a b tag, requiring leptonic decay of at least one of the top quarks. Thus the presence of the H^+ channels (10) and (11) would imply a decrease of this $t\bar{t}$ cross section, while the experimental estimate [14],

$$\sigma_{t\bar{t}}(\text{CDF} + \text{D0}) = 6.5^{+1.3}_{-1.2} \text{ pb}\,,$$

$$\sigma_{t\bar{t}}(\text{CDF}) = 7.6^{+1.8}_{-1.5} \text{ pb}\,, \tag{14}$$

is actually slightly higher than the QCD prediction of $\sigma_{t\bar{t}} \leq 5.6$ pb [15]. This has led to a significant lower limit on m_{H^+} at low $\tan\beta(\lesssim 1)$, assuming dominance of the cs decay channel (11) [16,17]. Evidently this method will be valid only up to $m_{H^+} = 130$ GeV. Beyond this value the dominant charged Higgs decay channel in the low $\tan\beta(\lesssim 1)$ region is (13), which does not imply any reduction in the leptonic decay of the top. Instead it implies an increase in the b-tagging efficiency due to the multi-b final state. Since the CDF cross section is largely based on the b-tagged events, the presence of the decay channel (13) would imply an increase of this cross section relative to the standard model prediction, instead of a decrease. Thus it will go in the same direction as the data.

Let us now look at the implications of the new $H^\pm$ decay channel (13) on Tevatron $t\bar{t}$ events more closely. In Fig. 2 we show the branching fractions for $t \to bH^+$ and $H^+ \to \bar{b}bW$ decays over the low $\tan\beta$ region for $m_{H^+} = 140$ and 150 GeV. Also shown in the product of these two branching fractions,

$$B = B(t \to b\bar{b}bW) = B(t \to bH^+)B(H^+ \to \bar{b}bW)\,, \tag{15}$$

which is about the same for both values of m_{H^+}. We see that this branching fraction lies in the range 5%–20%

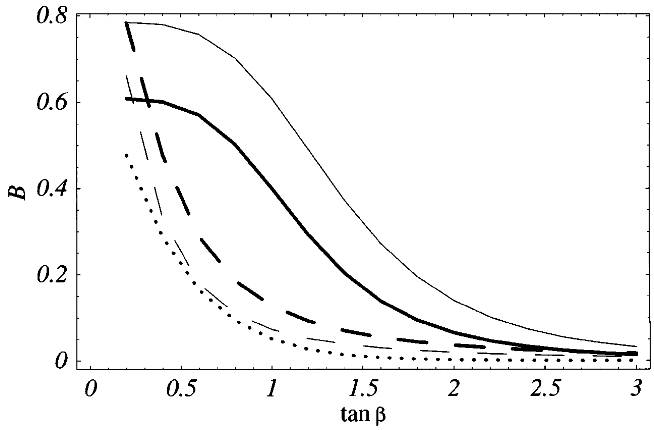

FIG. 2. Branching fractions for $t \to bH^+$ (dashed lines) and $H^+ \to \bar{b}bW$ (solid lines) decays for low $\tan\beta$. Heavy lines and thin lines correspond to $m_{H^+} = 140$ and $m_{H^+} = 150$ GeV, respectively. The dotted line corresponds to the product $B(t \to bH^+)B(H^+ \to \bar{b}bW)$ for $m_{H^+} = 140$ GeV (the plot for $m_{H^+} = 150$ GeV is practically identical).

for $\tan\beta = 1$–0.6. This corresponds to a probability of about 10%–40% ($\simeq 2B$) for the channel

$$\bar{t}t \to \bar{b}b\bar{b}bWW\,, \tag{16}$$

where one of the top quarks decays via an $H^\pm$ and we have made a first-order approximation in B. Thus the $2b$ and $4b$ final states occur with relative probabilities $1 - 2B$ and $2B$, respectively, where the former also includes a small contribution from the two-body decays of the $H^\pm$.

It should be mentioned here that the decay of the $H^\pm$ into a neutral Higgs and a real or virtual W boson is (whatever kinematically allowed) an additional source for a $4b$ final state such as (16). Within the MSSM this contribution can be significant over the low $\tan\beta$ region [8] depending on the SUSY breaking parameters. Thus the three-body decay considered above constitutes a minimal contribution to the $4b$ final state (16) generated by the decays of the charged Higgs boson.

We have studied the characteristic features of the above channel versus the standard model decay

$$\bar{t}t \to \bar{b}bWW \tag{17}$$

via a parton-level Monte Carlo program. While the ℓ and ν from W decay have very similar kinematic distributions in the two cases, there is a clear difference in the number of tagable b quarks. The CDF SVX detector has a tagging efficiency of $\epsilon_b = 0.24$ per b satisfying

$$E_T^b > 20 \text{ GeV}, \qquad |\eta_b| < 2\,, \tag{18}$$

which takes into account the loss of efficiency due to the limited rapidity coverage of the vertex detector ($|\eta_{\rm SVX}| \lesssim 1$) [18]. This is expected to go up to $\epsilon_b = 0.4$ per b for run II as the rapidity coverage of the vertex detector is extended to $|\eta_{\rm SVX}| = 2$. Table I shows the probability distribution of the numbers of b quarks per event satisfying the tagging criterion (18) for the signal (16) and the standard model background (17) channels. It shows that the majority of the signal events are expected to contain 3–4 tagable b quarks for $m_{H^+} = 140$ GeV (similar results hold for $m_{H^+} = 150$ GeV). It also shows the probability distribution for the expected numbers of b tags per event for the SVX tagging efficiency of $\epsilon_b = 0.24$, where we have assumed that the uncorrelated probability for tagging n out of N tagable b quarks is $P_n^N = \binom{N}{n}\epsilon_b^n(1 - \epsilon_b)^{N-n}$. The corresponding expectations for the run II efficiency $\epsilon_b = 0.4$ are shown in parentheses. The implications for the $t\bar{t}$ events in the b-tagged ℓ + multijet channel are discussed below.

As we see from this table the probability of inclusive single (≥ 1) b tag is 52.8% for the signal compared to 39.6% for the standard model decay, i.e., about $\frac{1}{3}$ higher. Consequently, the measured $\bar{t}t$ cross section will appear larger than the standard model prediction by $(1/3) \times (2B)$, i.e., about 13% for $B = 0.2$. This could account for at least part of the excess of the CDF $t\bar{t}$ cross section [14] over the standard model prediction. Even more significantly, the probability for inclusive double (≥ 2) b tag is 12.4% for the signal compared to only 5% for the standard model decay, i.e., an excess of 150%. This would imply an excess of double b tagged events over the standard model prediction by $3B$, i.e., 60% for $B = 0.2$. Again there seems to be an indication of such an excess in the CDF data [19]. It should be remarked, however, that the excess is expected to appear in the ≥ 3 jet events, but not in the 2 jet sample, except through fluctuations. It is therefore premature to link the reported excess to the above mechanism. It is important to note, however, that the size of the signal can have visible impact even at the level of the existing limited data.

It should be noted here that one expects a 20-fold rise in the number of $t\bar{t}$ events in the run II, and the efficiency of single and double tags to go up by a factor of 1.5 and

TABLE I. Probabilities for different numbers of tagable b quarks per event and numbers of b tags (per event) with $\epsilon_b = 0.24$ (0.4) for the $H^\pm$ signal ($m_{H^+} = 140$ GeV) and the standard model background.

	No. of tagable b's/event				No. of b tags/event		
Probability (%)	1	2	3	4	≥ 1	≥ 2	≥ 3
$\bar{t}t \to \bar{b}b\bar{b}bWW$ $(2B)$	4.7	25.6	50.6	18.9	52.8 (74.2)	12.4 (31.8)	(6.6)
$\bar{t}t \to \bar{b}bWW$ $(1 - 2B)$	13	87	$\cdots$	$\cdots$	39.6 (60.9)	5 (13.4)	$\cdots$

$\sim$3, respectively. Thus one expects about 1000 single ($\geq$1) and 200 double ($\geq$2) b-tagged events for CDF, and similar numbers for D0 (in run II). Even with a B of only 5%, this would correspond to an excess of $\sim$30 double b-tagged events, i.e., a $(2-3)\sigma$ effect. Moreover, the 6.6% efficiency for $\geq$3 b tags for the signal would imply at least 10–12 triple b tagged events for $B \geq 5\%$. Finally, one should be able to get additional constraints from the clustering of the reconstructed $H^{\pm}$ mass.

Thus the three-body decay channel provides a visible signature for a charged Higgs boson in top-quark decay over its region of dominance, i.e., $m_{H^+} \gtrsim 140$ GeV and $\tan\beta \lesssim 1$. This can be used to probe for an $H^{\pm}$ at the Tevatron run II over the mass range 140–150 GeV, and can be extended beyond 160 GeV at the LHC. We conclude with the hope that this channel will play an important role in the charged Higgs boson search program in the future.

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