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Hidden Top Quark Decay to Charged Higgs Scalars at the Tevatron

A.G. Akeroyd[1]

Department of Mathematical Sciences, Centre for Particle Theory,
University of Durham,
Durham DH1 3LE, England.

Abstract

Charged Higgs scalars light enough to contribute to top quark decays are possible in various non–minimal Higgs models. We show that such a decay would be consistent with the current Tevatron data, and will remain hidden until a larger luminosity can be achieved.

[1] A.G.Akeroyd@durham.ac.uk

1 Introduction

The CDF [1] and D0 [2] Collaborations have recently announced strong evidence for the existence of the top quark, the isospin partner to the b quark required in the Standard Model (SM), using 67 pb^{-1} and 50 pb^{-1} data samples respectively of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. A signal consistent with $t\overline{t} \to W^+W^-b\overline{b}$ has been observed, exceeding the background prediction by 4.8σ [1] and 4.6σ [2]. In Refs. [1], [2] the branching ratio BR ($t \to Wb$) is taken to be 100%, and this is a valid assumption in the minimal SM (i.e. one Higgs doublet); the decays $t \to cZ$, $t \to uZ$ are absent at tree level due to the GIM mechanism, and the charged current processes $t \to Ws$, $t \to Wd$ are negligible due to heavy CKM matrix suppression ($|V_{ts}| \approx |V_{td}| \approx 0$).

However, if one enlarges the Higgs sector (i.e. non–minimal SM[2]) by adding more doublets and/or triplets, then charged Higgs bosons are predicted. Such structures are required in many extensions of the SM (e.g. SUSY, left–right symmetric models), but can also be considered purely in the context of the non–minimal SM. The vertex Htb is usually predicted in such models and could be quite large due to Higgs bosons coupling in proportion to mass. In some extended models (although not all), $M_H \leq m_t - m_b$ is still allowed by current electroweak precision tests, and if such a light $H^\pm$ exists then on–shell $t \to Hb$ decays will occur. This would provide an alternative decay channel for the top quark and is an option not considered in Refs. [1],[2]. It is the aim of this work to examine whether the presence of a light $H^\pm$ is compatible or not with the CDF data. We shall consider in particular the case of $M_H \leq 80$ GeV i.e. $H^\pm$ within the discovery range of LEP2.

The paper is organised as follows. In Section 2 we briefly review the various extended Higgs models that may contain a light $H^\pm$. Section 3 examines how significant the channel $t \to Hb$ can be, while Section 4 studies how one would search for $H^\pm$. In Section 5 we apply the analyses of Sections 3 and 4 to the current data sample from the Tevatron, while Section 6 considers prospects at an upgraded Tevatron and at the Large Hadron Collider (LHC). Finally Section 7 contains our conclusions.

2 Extended Higgs Sectors

The minimal SM consists of one Higgs doublet ($T = 1/2$, $Y = 1$), although extended sectors can be considered and have received substantial attention in the literature. For a general review see Ref. [3]. There are two main constraints on such models:

(i) There must be an absence of flavour changing neutral currents (FCNC).

(ii) The rho parameter, $\rho = M_W^2/(M_Z^2 \cos^2\theta_W)$, must be very close to one.

[2]Defined by assuming no new particles apart from Higgs bosons.

Condition (i) is satisfied by constraining the Yukawa couplings to the fermions [4]. Condition (ii) requires models with only doublets, to which any number of singlets ($T = 0$, $Y = 0$) can be added. Models with triplets ($T = 1$) can also be considered, although obtaining $\rho \approx 1$ is achieved in a less natural way than for cases with only doublets.

The theoretical structure of the two–Higgs–doublet model (2HDM) is well known [3], while the general multi–Higgs–doublet model (MHDM) [5] has received substantially less attention. In the MHDM it is conventional to assume that one of the charged scalars is much lighter than the others and thus dominates the low–energy phenomenology[3]. The relevant part of the Lagrangian for the 2HDM and MHDM can be written as [5]:

$$\mathcal{L} = (2\sqrt{2}G_F)(X\overline{U}_L V M_D D_R + Y\overline{U}_R V M_U D_L + Z\overline{N}_L M_E E_R)H^+ + h.c. \quad (1)$$

Here U_L, U_R (D_L, D_R) denote left– and right–handed up (down) type quark fields, N_L is the left–handed neutrino field, and E_R the right–handed charged lepton field. M_D, M_U, M_E are the diagonal mass matrices of the down type quarks, up type quarks and charged leptons respectively. V is the CKM matrix, and X, Y and Z are coupling constants (see below).

The CP conserving 2HDM which is usually considered in the literature [3] contains an important parameter

$$\tan\beta = v_2/v_1 \quad (2)$$

with v_1 and v_2 being real vacuum expectation values (VEVs) of the two Higgs doublets and $0 \leq \beta \leq \pi/2$. There are 4 variants of the 2HDM depending on how the doublets are coupled to the fermions. Their coupling constants are given in Table 1 [6]. In the

	Model I	Model I′	Model II	Model II′
X	$-\cot\beta$	$-\cot\beta$	$\tan\beta$	$\tan\beta$
Y	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
Z	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Table 1: The values of X, Y and Z in the 2HDM.

MHDM X, Y and Z are *arbitrary* complex numbers. It follows that combinations of parameters like XY^* have different values depending on the model under consideration, thus leading to phenomenological differences. This has important consequences, particularly when one calculates loop diagrams involving $H^\pm$. One such decay, $b \to s\gamma$, is sensitive to charged scalars and has recently been observed for the first time by the CLEO Collaboration. The value for the branching ratio was measured to be [7]

$$\mathrm{BR}(b \to s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4} \quad (3)$$

[3]In a model with N doublets there exists $(N-1)$ $H^\pm$s.

which corresponds to

$$1 \times 10^{-4} \leq \mathrm{BR}(b \to s\gamma) \leq 4.2 \times 10^{-4} \ \ (95\% \ cl) \ . \tag{4}$$

The theoretical calculation of the branching ratio appears in Refs. [8], [9], [10], [11]. From this it can be shown [5], [12], [13] that the above bound constrains M_H from the 2HDM (Model II and II$'$) to be ≥ 260 GeV, while no bound can be obtained on M_H from the 2HDM (Model I and I$'$) and the MHDM. Hence it is possible that an on–shell $H^{\pm}$ from these latter models contributes to top decay, and may even be light enough to be detectable at LEP2 [13], [14]. Also, we note that the most popular model with Higgs isospin triplets (HTM) [15], [16], predicts a charged scalar $H_3^{\pm}$ which has exactly the same couplings as $H^{\pm}$ (2HDM, Model I), and thus may also contribute to top decay and/or be detectable at LEP2 [17]. For all these $H^{\pm}$s there exists a lower bound from LEP [18] of $M_H \geq 41.7$ GeV.

An important constraint on $\cot\beta$ is obtained from precision measurements of the $Z \to b\overline{b}$ vertex. Charged scalars with a tree level Htb coupling contribute to this decay, and Ref. [5] shows that

$$|\cot\beta| \leq 0.8. \tag{5}$$

This bound is for $m_t = 180$ GeV and $M_H \leq 200$ GeV, and provides a stronger constraint on $|\cot\beta|$ than can be obtained from the decay $b \to s\gamma$.

In order to search for $H^{\pm}$ one needs to consider its decays. The various branching ratios (BRs) are shown in Table 2, with l referring to either an electron or a muon. For

	Jets	$\tau\nu_\tau$	$l\nu_l$
$H^{\pm}$ (2HDM, Model I)	67%	33%	0%
$H^{\pm}$ (2HDM, Model I$'$)	$\leq 46\%$	$\geq 54\%$	0%
$H^{\pm}$ (MHDM)	$0 \to 100\%$	$0 \to 100\%$	0%
$W^{\pm}$	67%	11%	22%

Table 2: The branching ratios for $H^{\pm}$ and $W^{\pm}$.

the 2HDM (Model I) the BRs are independent of $\tan\beta$, while in the 2HDM (Model I$'$) the constraint of Eq. (5) creates the inequalities in Table 2. In the MHDM the BRs are dependent on the arbitrary parameters X, Y and Z, and thus span the full range $0 \to 100\%$.

3 Top Quark Decay to Charged Higgs

In this section we evaluate how competitive the decay channel $t \to Hb$ can be compared to the conventional $t \to Wb$. The Feynman rule for the Htb vertex is given by [3]

$$\frac{igV_{tb}}{2\sqrt{2}M_W}[m_b X(1+\gamma_5) + m_t Y(1-\gamma_5)] \ . \tag{6}$$

Here V_{tb} is a CKM matrix element and g is the usual SU(2) gauge coupling. The 2HDM (Models I and I′) requires the replacements $X = -\cot\beta$ and $Y = \cot\beta$. From Eq. (6) one can evaluate the partial width and thus BR $(t \to H^+ b)$ [3]:

$$\frac{\mathrm{BR}(t \to H^+ b)}{\mathrm{BR}(t \to W^+ b)} = \frac{p_{H^+}}{p_{W^+}} \times \frac{[(m_b^2 + m_t^2 - M_H^2)(m_b^2 + m_t^2) - 4m_b^2 m_t^2]\cot^2\beta}{M_W^2(m_t^2 + m_b^2 - 2M_W^2) + (m_t^2 - m_b^2)^2} \ . \qquad (7)$$

Here p_{H^+} and p_{W^+} refer to the magnitude of the three momentum of the H^+ and W^+ measured in the rest frame of the top quark. We take $m_t = 174$ GeV, $m_b = 5$ GeV and $M_W = 80.3$ GeV.

In Figure 1 we plot BR $(t \to H^+ b)$ as a function of $\tan\beta$ for $M_H = 50$ GeV (comfortably in the LEP2 range), for $M_H = M_W$ (at the edge of the LEP2 range), and for $M_H = 130$ GeV (out of LEP2 range). We recall that Eq. (5) states $|\cot\beta| \leq 0.8$ or equivalently $|\tan\beta| \geq 1.25$. Using this bound we see from Figure 1 that large values of BR $(t \to H^+ b)$ are still possible e.g. for $M_H = 50$ GeV and $\tan\beta = 1.25$, BR $(t \to H^+ b) = 38\%$. As $\tan\beta$ increases BR $(t \to H^+ b)$ falls, dropping to $\approx 1\%$ at $\tan\beta = 10$. Hence for large enough $\tan\beta$ and/or M_H the top decay to charged Higgs will be difficult to detect experimentally. We shall be particularly interested in the case of $M_H \leq M_W$ i.e. for $H^\pm$ in the discovery range of LEP2.

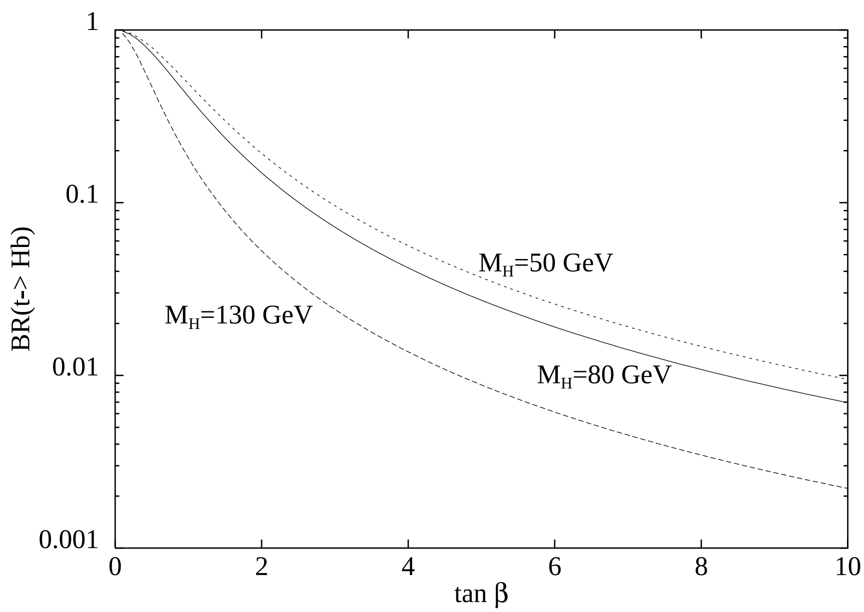

Figure 1: BR $(t \to Hb)$ as a function of $\tan\beta$ for $M_H = 50$, 80 and 130 GeV.

In the MHDM, BR $(t \to H^+ b)$ depends not on $\tan\beta$ but instead on $|X|$ and $|Y|$.

However, it is easily verified from Eq. (7) (unless $|X|$ is unnaturally large – see below) that the strongly dominant part is proportional to $|Y|^2$ which has the same constraint as $\cot\beta$ (Eq. 5). Therefore Figure 1 can be used for the MHDM, with the replacement $\tan\beta \to |Y|^{-1}$ on the ordinate axis. We note that there exists an unnatural region of parameter space, $|X| \geq 30$ and $|Y| \leq 0.1$,[4] which would allow larger BRs in the MHDM for a given M_H than is ever possible in the 2HDM. We shall not consider this possibility.

4 Signature of the Charged Higgs

We shall consider two ways with which to detect $H^\pm$ from top decays. The first method is to search in the lepton channel. We see from Table 2 that the decays of $H^\pm$ violate lepton universality due to a preference to couple to the heaviest lepton (τ). This is in contrast to the lepton decays of $W^\pm$. The second method is to search for the quark decays of $H^\pm$ by reconstructing the invariant masses of the jets. A significant peak separate from that of $W^\pm$ would be distinctive. A search using the di–lepton channel $t\bar{t} \to H^+H^-b\bar{b} \to llX$ (via $H^\pm \to \tau\nu_\tau \to l\nu_l\overline{\nu}_\tau\nu_\tau$) has been performed [19] although we shall not consider this method here. We shall focus first on the $\tau\nu_\tau$ decays of $H^\pm$. A previous search in this channel has been performed at the Tevatron using a 4 pb^{-1} data sample [20]. Here BR $(t \to Hb)$=100% was assumed which we know now to be untrue since $m_t > M_W + m_b$, and so on–shell $t \to Wb$ decays are definitely present. In Ref. [20] the process $t\bar{t} \to H^+H^-b\bar{b} \to \tau^+\tau^-\nu_\tau\overline{\nu}_\tau b\bar{b}$ was searched for with the trigger being missing $E_T \geq 25$ GeV. From Figure 1 we see that BR $(t \to H^+b)$ can be as low as 1%, and in such cases the above detection method is certainly not relevant for future searches. One must rely on the process $t\bar{t} \to H^\pm W^\mp b\bar{b} \to l\nu_l\tau\nu_\tau b\bar{b}$, with a hard isolated lepton ($l = e$ or μ) to act as a trigger [1], [2]. We also require a τ jet to which various cuts will be made [20]. Non $t\bar{t}$ backgrounds, although sizeable, are substantially reduced when the above requirements are applied. The main background is from $t\bar{t} \to W^+W^-b\bar{b} \to l\nu_l\tau\nu_\tau b\bar{b}$ which fakes the signal from $H^\pm W^\mp$ and is usually the more common top decay process. Fortunately this background can be reduced by making use of the polarisation of the $\tau^\pm$. To be specific we shall focus on W^- and H^-, thus following the notation of Ref. [21].

Weak vector bosons couple to left–handed fermions and right–handed antifermions, and thus $W^- \to \tau_L^-\overline{\nu}_\tau$. However this is not so for the charged Higgs (H^-) which couples to right handed fermions via $H^- \to \tau_R^-\overline{\nu}_\tau$. This is a consequence of the Yukawa couplings. It has been known for some time that the momentum distribution of the decay products from $\tau^\pm$ depend on its polarisation [22]. Ref. [21] analyses

[4]There is an experimental constraint on the product $|X||Y|$ coming from the measurement of $b \to s\gamma$. Ref. [5] uses $|X||Y| \leq 4$ for $M_H \leq 80$ GeV, although with the new measurement in Eq. (3), $|X||Y| \leq 3.3$ is more accurate.

these differences for the hadronic decays $\tau^- \to \pi^-\nu_\tau$, $\rho^-\nu_\tau$, $a_1^-\nu_\tau$. It concludes that the energetic particles coming from W^- are primarily a_{1T}^- and ρ_T^-, with the subscript T referring to a transversely polarised meson. In comparison, the energetic particles coming from H^- are ρ_L^-, a_{1L}^-, and π^- with L referring to a longitudinally polarised meson. The case of the energetic π^- from H^- can easily be understood in the following way. Due to polarisation of the parent τ^-, spin conservation favours emission of the π^- in the direction of motion of the τ^-. This results in the p_T spectrum in the context of $t\bar{t}$ production of the π^- being boosted compared to those pions coming from W^- decay (in the latter case the π^- prefers to be emitted *opposite* to the direction of the parent τ^-). Therefore the fragmentation function of π^- from τ_R^- is harder than that from τ_L^-, and so a hard pion is a signal of H^- decay.

The subsequent decays of $\rho^- \to \pi^0\pi^-$ and $a_1^- \to \pi^-\pi^-\pi^+$, $\pi^0\pi^0\pi^-$ have different energy distributions depending on the polarisation of the parent meson. Ref. [21] shows that for the ρ_L^- the final state pions will be much more asymmetric in energy than those originating from ρ_T^-. For the case of the a_{1T}^- the three pions tend to share the energy equally, while for the a_{1L}^- one or two of them are soft with the rest hard. Hence the signature of the H^- is a final state of one or more energetic pions.

It is straightforward to evaluate the theoretical prediction for the number of energetic pions from top decay. We take first the case of $t\bar{t} \to W^+W^-b\bar{b}$. One of the Ws is decayed to $l\nu_l$ to act as a trigger for the event, while the other is decayed to $\tau\nu_\tau$. The theoretical prediction is:

$$N_{l\tau}^{WW} = 2(1 - B_H)^2 N_{t\bar{t}} \times \mathrm{BR}\ (W \to l\nu_l) \times \mathrm{BR}\ (W \to \tau\nu_\tau) e_{l\tau}\ . \tag{8}$$

Here B_H is a shorthand for BR $(t \to Hb)$ and $N_{t\bar{t}}$ is the number of $t\bar{t}$ pairs produced. The parameter $e_{l\tau}$ is an overall efficiency for detecting an energetic pion from the above event, incorporating any kinematical cuts. It can be written as

$$e_{l\tau} = e_l \times \sum_{i=1}^{3} e_{i,\pi} \times \mathrm{BR}\ (\tau^- \to \pi^-\nu_\tau + X_i)\ . \tag{9}$$

The summation is over the three possible decays of τ^- to pions: X_2, X_3 are extra pions originating from $\tau^- \to \rho^-\nu_\tau$, and $a_1^-\nu_\tau$ respectively, while $X_1 \equiv 0$. For the case of $t\bar{t} \to W^\pm H^\mp b\bar{b}$ theory predicts

$$N_{l\tau}^{WH} = 2(1 - B_H) B_H N_{t\bar{t}} \times \mathrm{BR}\ (W \to l\nu_l) \times \mathrm{BR}\ (H \to \tau\nu_\tau) e'_{l\tau}\ , \tag{10}$$

with $e'_{l\tau}$ being different to $e_{l\tau}$. This latter difference arises due to the polarisation of the parent τ and thus $e_{i,\pi} \neq e'_{i,\pi}$. There are two ways of searching for violation of lepton universality. The first method (applied in Ref. [23] to the SSC) requires an isolation cut on the energetic pion. This eliminates virtually all of the QCD background, although also has the disadvantage of removing most of the hard pions originating from ρ^- and

a_1^-. A second method (suggested in Ref. [24]) aims to include these latter decays by rejecting the isolation cut, and instead making a cut on $\Delta E_T \equiv |E_T^{\pm} - E_T^0|$ i.e. the total E_T carried by the charged pions minus the total E_T carried by the neutral pions. The signal favours large ΔE_T. This method keeps more of the signal than would be kept by making the isolation cut, although the QCD background is larger. The lepton trigger efficiency, e_l and e_l', depends only on m_t and is therefore the same for both events. We will ignore the case of both top quarks decaying to a charged Higgs ($N_{l\tau}^{HH}$) for the following reasons:

(i) BR ($t \to Hb$) could well be very small (see Figure 1).

(ii) The trigger here would be $H \to \tau\nu_\tau \to l\nu_l\nu_\tau\overline{\nu}_\tau$. This process would be suppressed in models with lower BR ($H \to \tau\nu_\tau$) i.e. 2HDM (Model I), HTM and various MHDM, coupled with the fact that BR ($\tau \to l\nu_l\nu_\tau$) $\approx 36\%$.

(iii) The trigger decay in (ii) predicts l with less p_T than for the l originating from $W \to l\nu_l$. Hence it is less likely to pass the lepton trigger cut.

Reasons (ii) and (iii) also allow us to ignore events $N_{\tau\tau}^{WW}$ which fake $N_{l\tau}^{WW}$. We can quantify the amount of deviation from universality that would be caused by a non–zero $N_{l\tau}^{WH}$:

$$N_\sigma = \frac{N_{l\tau}^{WH}}{\sqrt{N_{l\tau}^{WH} + N_{l\tau}^{WW}}} \; , \tag{11}$$

with N_σ being the number of standard deviations by which the observed number of hard, isolated pions exceeds that predicted from universality. This concludes our account of the search for $H \to \tau\nu_\tau$.

The second method is to consider the $H \to cs$ decay and reconstruct the invariant masses of the jets. This method would be needed for the case of a 'leptophobic' Higgs i.e. BR ($H \to \tau\nu_\tau$) $\to 0\%$ and BR ($H \to cs$) $\to 100\%$, which is possible in the MHDM for large $|Y|$ and small $|X|$, $|Z|$. The trigger will again be a hard isolated lepton originating from $W \to l\nu_l$. Three jets need to be reconstructed in the opposite hemisphere to the lepton (i.e. the jets originating from $t \to Hb \to csb$), with one of them a tagged b jet (efficiency e_b'). Ref. [23] deals with this method applied to the SSC, and the analysis is also relevant for the Tevatron with a few minor modifications e.g. the p_T cuts given in Ref. [23] are larger than those required at the Tevatron due to $\sqrt{s}$ at the SSC being much greater. Adding the invariant masses of the non b jets will result in a peak centered on M_H. However, one must be careful here because in the MHDM it is possible to have a large BR ($H \to cb$) [13]; in this scenario there is a chance of the wrong b jet being tagged and therefore the wrong jets would be used to reconstruct the invariant mass of $H^\pm$. However, BR ($H \to cb$) $\geq 30\%$ would be needed to cause significant problems here, and Ref. [13] shows that the parameter space for this large branching ratio is quite small.

Requiring that the three–jet invariant mass is centered on m_t reduces the background further. A clear peak would be strong evidence for $H^\pm$. Ref. [23] suggests the following simple rule for this method to provide a significant peak at M_H:

$$\mathrm{BR}\ (t \to Hb) \times \mathrm{BR}\ (H \to cs) \geq 0.05\,. \tag{12}$$

This result was obtained by using the ISAJET Monte Carlo, comparing the size of the $H^\pm$ peak to the $W^\pm$ background for different values of $\tan\beta$ and M_H. It is only valid for a large event sample (at the SSC $N_{t\bar{t}} = 10^7 \to 10^8$), and so will be more relevant at an upgraded Tevatron and/or LHC. If Eq. (12) is satisfied, the statistical significance of the peak at M_H is greater with a larger event sample, i.e. at the LHC. We note that Eq. (12) was derived using SSC detection efficiencies; however it will still be valid at the Tevatron to a good approximation.[5]

In this section we have studied two direct ways with which one may search for $H^\pm$. In the next section we shall apply these techniques to the current data sample from the Tevatron to see if a light ($\leq$ 80 GeV) charged Higgs boson could have been observed.

5 Analysis at the Tevatron

The current CDF data sample at the Tevatron [1] contains 67 pb^{-1}. For $\sigma_{t\bar{t}}$ we shall use the MRS(A) partons [25] which suggests a value of 4.5 pb if $m_t = 174$ GeV[6] [27]. Ref. [28] estimates that the theoretical error in $\sigma_{t\bar{t}}$ is ±30%. We can now evaluate the expected number of $t\bar{t}$ pairs, and then use Eqs. (8 → 10) to predict the number of hard pions for various values of BR ($t \to Hb$).

We shall take $N_{t\bar{t}} = 300$; from Table 2 one has BR ($W \to l\nu_l$) = 22% and BR ($W \to \tau\nu_\tau$) = 11%. If there is no charged Higgs boson i.e. BR ($t \to Wb$) = 100% then one has from Eq. (8):

$$N^{WW}_{l\tau} = 14.5 \times e_{l\tau}\ . \tag{13}$$

The efficiency $e_{l\tau}$ is given by Eq. (9), and we shall discuss its value below. The prediction for $N^{WH}_{l\tau}$ is given by Eq. (10). We shall take BR ($t \to Hb$) = 38% for illustrative purposes i.e. the maximum BR for $M_H = 50$ GeV (see Figure 1). Thus we obtain:

$$N^{WH}_{l\tau} = 31.1 \times \mathrm{BR}\ (H \to \tau\nu_\tau) \times e'_{l\tau}\ . \tag{14}$$

We shall consider the search strategy using an isolation cut on the charged pion. As mentioned before this eliminates most of the QCD background. The charged pion is required to contain at least 80% of the energy in a cone of size $\Delta R = 0.2$, as well as

[5] The ratio e_b/e'_b contributes to the relative size of the peaks at M_W and M_H. This is the only factor which may invalidate Eq. (12) for use at the Tevatron.

[6] We note that a recent calculation [26] suggests $\sigma_{t\bar{t}} = 5.52^{+0.07}_{-0.45}$ pb.

possessing $E_T \geq 20$ GeV. This removes most of the W background contribution from ρ and a_1 and most of the signal contribution from a_1 [24]. Therefore we may use the following approximations in Eq. (9):

$$e_{2,\pi} = e_{3,\pi} = e'_{3,\pi} = 0. \tag{15}$$

The efficiency $e'_{l\tau}$ will be larger than $e_{l\tau}$ for the following reasons. Most importantly, $e'_{1,\pi} > e_{1,\pi}$ i.e. pions originating from $H^{\pm}$ are more energetic (see Section 4) and are more likely to pass an energy cut than those from $W^{\pm}$. Using the figures in Ref. [24] we can approximate $e_{1,\pi} = 0.26$. Also we want to maximise the signal for illustrative purposes and so take

$$e'_{1,\pi} = 1.0 \ , \ e'_{2,\pi} = 1.0. \tag{16}$$

The $E_T > 20$ GeV cut has little effect on $e'_{1,\pi}$ and $e'_{2,\pi}$; the isolation cut hardly affects the π contribution but removes part of the ρ contribution. Hence in reality $e'_{2,\pi} < 1$. For heavier $H^{\pm}$ the pion is on average more energetic and so $e'_{i,\pi}$ will increase. The trigger efficiencies for an isolated, $p_T \geq 20$ GeV lepton (e_l, e'_l) are close to 100% [29]. Combining the above efficiencies, it is clear that $e'_{l\tau} > e_{l\tau}$. From Table 2 we can obtain the value of BR ($H \to \tau\nu_\tau$) for the various Higgs models. The maximum signal is obtained when BR ($H \to \tau\nu_\tau$) $\to$ 100%[7] and we will use this in our calculation. The remaining parameter values needed are BR ($\tau \to \pi\nu_\tau$) = 12.5% and BR ($\tau \to \rho\nu_\tau$) = 24.0%.

Using the above values for efficiencies and BRs in Eqs. (13) and (14) we find

$$N_{l\tau}^{WW} = 0.48 \ \text{ and } \ N_{l\tau}^{WH} = 11.35. \tag{17}$$

Using Eq. (11) we see that to obtain a 5σ signal $N_{l\tau}^{WH} = 25$ is required and this is far from the prediction of 11.35. Also, we used the most favourable values for BR ($H \to \tau\nu_\tau$), BR ($t \to Hb$) and $e'_{l\tau}$. Lower values for these parameters would decrease $N_{l\tau}^{WH}$ further e.g. for $M_H = 50$ GeV, $\tan\beta = 3$ and BR ($H \to \tau\nu_\tau$) = 33% (Model I) we find $N_{l\tau}^{WH} = 1.45$. Therefore we conclude that, over the vast majority of parameter (M_H, $\tan\beta$) space, $H^{\pm}$ would not provide a statistically significant signal given the current data at the Tevatron. The other method available to us exploits the quark decays of $H^{\pm}$. From Eq. (10), with BR ($H \to cs$) replacing BR ($H \to \tau\nu_\tau$), we again see that too few events are produced.

The conclusion of the above analyses is that a direct signature of $H^{\pm}$ cannot be obtained using the current data sample from the Tevatron. However an indirect signature might be possible. The top quark search [1] relied on an excess of $W + 4$ jet events over the QCD background. The events searched for consisted of one W

[7] This situation is only possible in the 2HDM (Model I′) for $\tan\beta \geq 3$ and in the MHDM. However, in the calculation we also use BR ($t \to Hb$) = 38%, and both these BRs can only be satisfied simultaneously in the MHDM for $|X|^{-1} = -|Y|^{-1} = \tan\beta = 1.25$ and $|Z|$ large.

providing the hard lepton trigger, while the other decays to two quarks. A light $H^{\pm}$ can mimic this signal although it would suppress the expected number of events in this channel ($N_{\rm W4j}$), and so increase the experimentally measured cross section for $t\bar{t}$ production. We shall now quantify this for various values of BR ($t \to Wb$). The experimentally measured cross–section ($\sigma_{\rm exp}$) can be written as

$$\sigma_{\rm exp} = \frac{N_{W4j}}{ke} \tag{18}$$

with e ($= e_l e_b$) being a detection efficiency for the W plus 4 jets channel, and k is a parameter depending on branching ratios and machine luminosity. To a good approximation the efficiency e remains the same whether we input a charged Higgs or not.[8] However, the presence of $H^{\pm}$ will change k while N_{W4j} is a fixed experimental measurement irrespective of which theory we are considering. In the following analysis we shall consider Model I which has a larger BR ($H^{\pm} \to$ jets) than Model I′ (see Table 2). Therefore the latter model would suppress N_{W4j} more. In the MHDM BR ($H^{\pm} \to$ jets) may take any value between 0% and 100%. Table 3 shows how k (for 67 pb^{-1}) varies with different values of BR ($t \to Wb$). Ref. [1] assumes BR

BR ($t \to Wb$)	k (pb^{-1})
100%	19.75
99%	19.55
95%	18.76
90%	17.76
62%	12.24

Table 3: The variation of k with BR ($t \to Wb$).

($t \to Wb$) = 100% and $\sigma_{\rm exp}$ is measured to be $6.8^{+3.6}_{-2.4}$ pb. From Eq. (18) one can see that if BR ($t \to Wb$) = x% with $x < 100$ the CDF measurement would be scaled by the ratio $k(100\%)/k(x\%)$. The lower error bar on $\sigma_{\rm exp}$ currently lies within the region of $\sigma_{\rm theo}$ ($= 4.5 \pm 1.35$ pb with $m_t = 174$ GeV), and the inclusion of $t \to Hb$ decays will shift the $\sigma_{\rm exp}$ data point to higher values. If BR ($t \to Hb$) = 24.8% then the lower error bar on $\sigma_{\rm exp}$ lies just outside the maximum value of $\sigma_{\rm theo}$ (5.85 pb). Therefore lower branching ratios than this are more desirable. From Figure 1 we see that a considerable parameter space exists for BR ($t \to Hb$) $\leq 5\%$; in such cases $\sigma_{\rm exp}$ would only be increased by $\approx 5\%$ and so a sizeable portion of the lower error bar would still lie within the region of $\sigma_{\rm theo}$. Therefore we conclude that top quark decays to charged Higgs scalars are consistent with the current CDF data over a very large parameter space of $\tan\beta$ and M_H. Therefore $H^{\pm}$ may lie in the energy range of LEP2.

[8]Ref. [23] shows that e_l is independent of M_H while e_b depends relatively weakly on M_H, especially in the mass range 50 GeV $\leq M_H \leq$ 80 GeV which gives larger BR ($t \to Hb$).

The Tevatron will continue to operate until the end of 1995, eventually collecting 140 pb^{-1} of data. From Eqs. (13) and (14) one sees that this twofold increase would only provide a statistically significant signal for a minute part of parameter space. The most favourable choice of parameters (used previously) gives $N_\sigma = 4.8$. Higher luminosity colliders are required and these are studied in the next section.

6 Prospects at an Upgraded Tevatron/LHC

There is a proposal to increase the luminosity of the Tevatron by an order of magnitude and it is thought that 2 fb^{-1} might be possible by the year 2000. Further proposals are for future luminosities of 20 fb^{-1} and/or $\sqrt{s} = 4$ TeV. Finally, by the year 2010 the Large Hadron Collider (LHC) should be operating. Table 4 [30] summarises the properties of these colliders. We shall now consider the detection prospects of $H^\pm$

	$\sqrt{s}$ (TeV)	$\sigma_{t\bar{t}}$ (pb)	L $(\mathrm{fb})^{-1}$	Operation
Tevatron	1.8	4.5	2	2000
Tevatron*	1.8	4.5	20	> 2000
Di–Tevatron	4	26	$2 \to 20$	> 2000
LHC	14	430	100	2010

Table 4: Important parameters at future colliders.

via top quark decay at each of these colliders. In this section we shall concentrate on studying the mass range 80 GeV $\leq M_H \leq m_t - m_b$; this is because LEP2 will search for $M_H \leq 80$ GeV [13], [14] before any of the above colliders will operate. An analysis of the detection prospects of the minimal SUSY $H^\pm$ at the upgraded Tevatron appears in Ref. [24]. The Higgs models we are studying differ noticeably from the SUSY $H^\pm$ with respect to BR $(t \to Hb)$. The difference arises because SUSY requires Model II couplings [3] and thus BR $(t \to Hb)$ has a sinusoidal dependence on $\tan\beta$ with a minimum at $\tan\beta \approx 6$. In contrast we are studying Model I and I′ type couplings which cause BR $(t \to Hb)$ to fall with increasing $\tan\beta$ (Figure 1). Therefore $H^\pm$ in these latter models will always be hidden for large enough $\tan\beta$.

Starting with an upgraded Tevatron providing 2 fb^{-1}, we again make use of Eqns. (8) and (10) using the same values for the efficiencies as in Section 5. The number of $t\bar{t}$ pairs ($N_{t\bar{t}}$) will now be taken to be 9000 although there is still a theoretical error here of ±30%. In Figures 2 and 3 we plot Eq. (11) which shows the excess (quantified as a number of standard deviations above that predicted from universality) of high–energy pions caused by $H^\pm$ decay.

Figure 2 (for Model I′) shows that for $M_H = 80$ GeV, $N_\sigma \geq 5\sigma$ is maintained until $\tan\beta \approx 5.5$ while $N_\sigma \geq 3\sigma$ is managed until $\tan\beta \approx 8$. For heavier M_H the signal is obviously weaker; for $M_H = 130$ GeV, $N_\sigma \geq 5\sigma$ $(\geq 3\sigma)$ is maintained only until

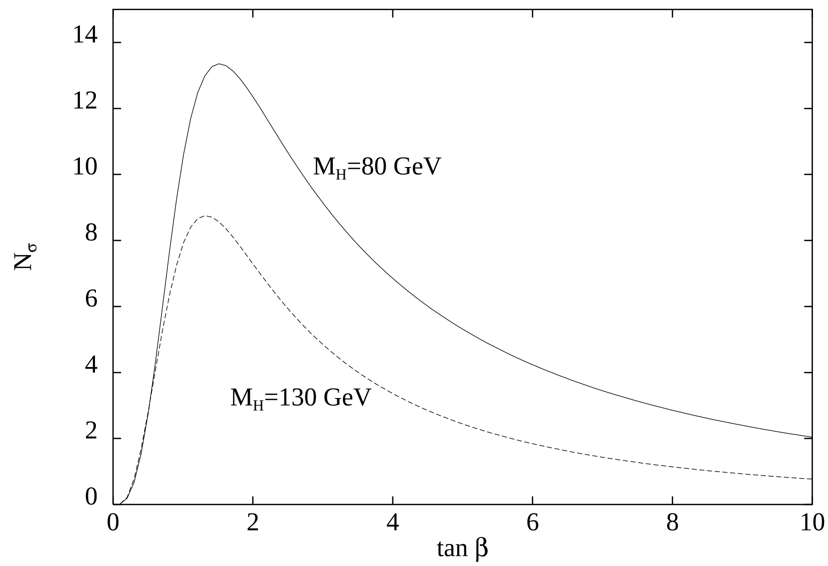

Figure 2: N_σ as a function of of $\tan\beta$ for Model I$'$ with $M_H = 80$ and 130 GeV. The Tevatron with $L = 2$ fb^{-1} is considered.

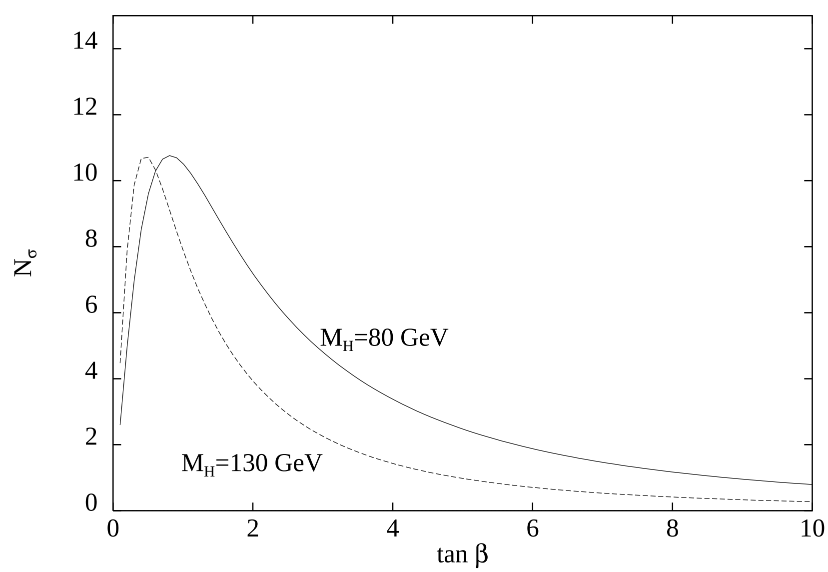

Figure 3: Same as Figure 2 but for Model I.

$\tan\beta \approx 3(5)$. For Model I (Figure 3) the situation is worse due to the inferior BR $(H \to \tau\nu_\tau)$. In the MHDM, BR $(H \to \tau\nu_\tau)$ can take any value from $0\% \to 100\%$. However the case of BR $(H \to \tau\nu_\tau) = 100\%$ approximates to Figure 2 as $\tan\beta$ increases.[9]

Prospects are improved at the Tevatron* (20 fb^{-1}), Di–Tevatron (2 fb^{-1}) and Di–Tevatron (20 fb^{-1}); these would scale N_σ by 3.2, 2.4 and 7.6 respectively. The latter collider would maintain a 5σ signal in Model I$'$ (Model I) for $M_H = 130$ GeV if $\tan\beta \leq 11$ (8).

The other detection method available is to reconstruct the invariant masses of the quark decays of $H^\pm$. Certainly this method will be needed in the case of a leptophobic Higgs (see Section 4) which is possible in the MHDM. Figure 4 shows that for such a Higgs a noticeable peak at M_H can be obtained if $M_H = 80$ GeV (130 GeV) for $\tan\beta \leq 3.5$ (2). Figure 5 is the analogous plot for Model I and I$'$; it is clear that in Model I reconstructing the $H \to$ jets channel is competitive with the previously considered $H \to \tau\nu_\tau$ decay (if $L = 2$ fb^{-1}). A noticeable peak would be present for $M_H = 80$ GeV (130 GeV) if $\tan\beta \leq 3$ (1.7). In comparison from Figure 3 we see that the cases of $M_H = 80$ GeV, $\tan\beta = 3$ and $M_H = 130$ GeV, $\tan\beta = 1.7$ both give $N_\sigma = 5$. Hence the detection methods are competitive. At the Tevatron* and Di–Tevatron the increased L and/or $\sqrt{s}$ enhances N_σ and so the $H \to \tau\nu_\tau$ channel offers the best prospects for Model I. In Model I$'$ this is the case even when $L = 2$ fb^{-1}.

Finally we shall consider the LHC. Using the same values for the various efficiencies as was used at the Tevatron, Figure 6 shows that for $M_H = 130$ GeV in Model I$'$ (Model I) $N_\sigma \geq 5$ is maintained until $\tan\beta = 25$ (15). However, using similar efficiencies to those used in Ref. [23] (which are for the SSC) we find that the above values of $\tan\beta = 25$ and 15 must be replaced by 8 and 5. A b–tag is included here and $e_l = 0.46$ is taken, while at the Tevatron $e_l \approx 1.0$ and no b–tag is required. Also, Ref. [23] does not make use of $\tau^- \to \rho^-\nu_\tau \to \pi^0\pi^-\nu_\tau$. Despite this reduced coverage, it is clear that the LHC will probe a significant region of $\tan\beta$ and M_H parameter space, especially if the efficiencies used in Ref. [23] are improved.

7 Conclusions

We have studied the prospects for detecting charged Higgs scalars ($H^\pm$) contributing to top quark decay ($t \to Hb$) in the context of the non–minimal Standard Model. Considered were $H^\pm$s from the 2HDM (Models I and I$'$), HTM and MHDM, all of which escape the mass bounds from $b \to s\gamma$ and thus may be light enough to contribute to top quark decay. Two detection methods were presented:

[9] In Model I$'$ BR $(H \to \tau\nu_\tau) \approx 100\%$ for $\tan\beta \geq 3$.

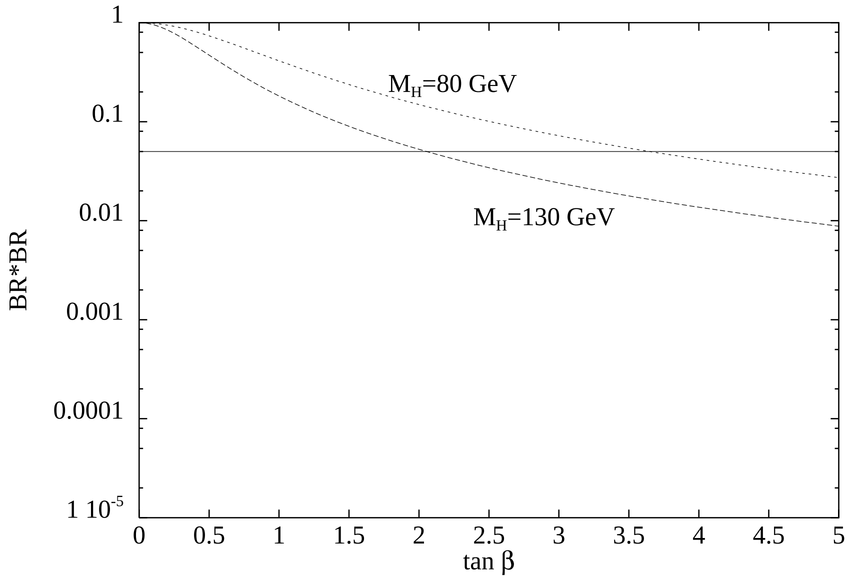

Figure 4: BR $(t \to Hb)\times$BR $(H \to cs)$ as a function of $\tan\beta$ for a leptophobic $H^{\pm}$ with $M_H = 80$ and 130 GeV. The detectable region lies above the line BR×BR=0.05.

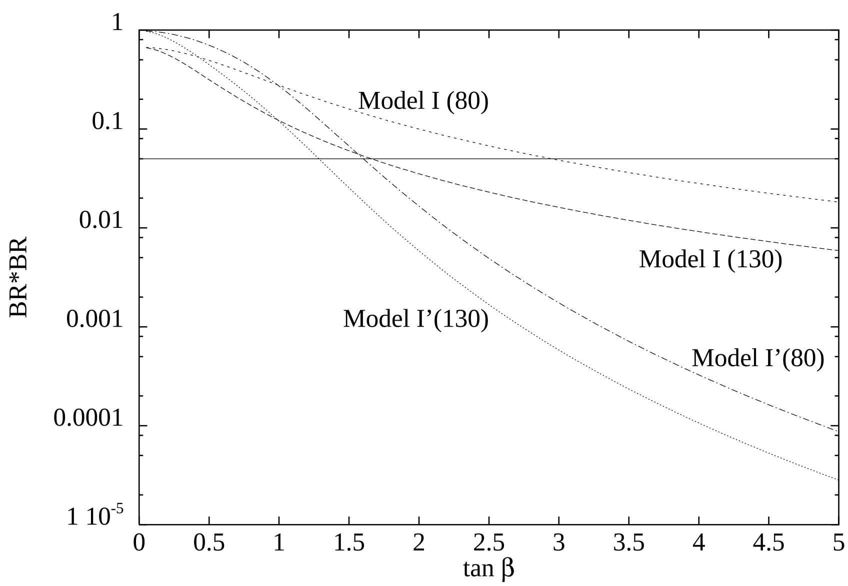

Figure 5: Same as Figure 4 but for Model I and I′.

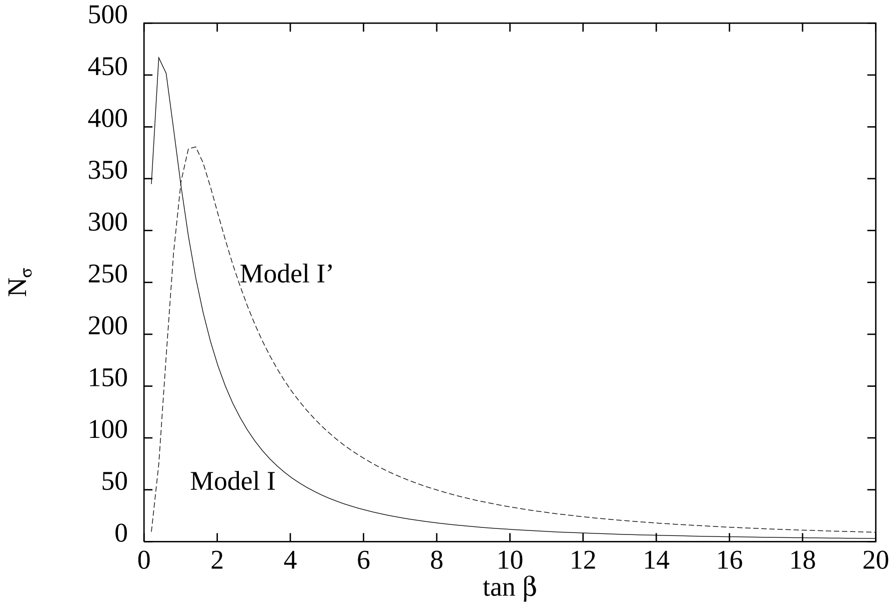

Figure 6: N_σ as a function of $\tan\beta$ for both Model I′ and Model I′ at the LHC. $M_H = 130$ GeV is taken.

(i) Searching for an excess of energetic pions ($\pi^\pm$) over that predicted from lepton universality.

(ii) Reconstructing the quark decays of $H^\pm$.

Neither method is able to extract a statistically significant signature of $H^\pm$ with the current CDF data sample (67 pb^{-1}) at the Tevatron, and even the expected 140 pb^{-1} (available by the end of 1995) will prove insufficient over most of the parameter (M_H, $\tan\beta$) space. Thus the existence of a light $H^\pm$ (50 GeV $\leq M_H \leq m_t - m_b$) is fully consistent with current data, and may be searched for at LEP2. Prospects are much better at proposed higher energy/luminosity colliders. At an upgraded Tevatron of $L = 2$ fb^{-1} method (i) will provide (in Model I′ for $M_H = 80$ GeV) an energetic pion excess of 5σ (3σ) if $\tan\beta \leq 5.5$ (8). For $M_H = 130$ GeV an excess of 5σ (3σ) is maintained until $\tan\beta = 3$ (5). For Model I the situation is worse due to the inferior BR ($H \to \tau\nu_\tau$). A Di–Tevatron with $\sqrt{s} = 4$ TeV and $L = 20$ fb^{-1} would provide a 5σ signal for $\tan\beta \leq 11$ (8) in Model I′ (Model I) for $M_H = 130$ GeV. The LHC would improve the coverage to 25 and 15 respectively.

Method (ii) is necessary for the case of a leptophobic Higgs with BR ($H \to$ jets) $\approx$ 100% which is possible in the MHDM. A noticeable peak at M_H can be obtained for

$M_H = 80$ GeV (130 GeV) if $\tan\beta \leq 3.5$ (2). For larger $\tan\beta$ the detection of a leptophobic $H^{\pm}$ appears unlikely in top quark decay and other production methods must be considered. For Model I method (ii) is competitive with method (i) at the Tevatron ($L = 2$ fb^{-1}), but in all other cases method (i) offers the best detection prospects.

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