SLAC-PUB-6354
SCIPP 93/29
September 1993
T/E

ENERGY DISTRIBUTION OF THE LEPTONS IN TOP DECAY TO CHARGED HIGGS*

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ABSTRACT

We analyze the energy distribution of the leptons coming from the top decay $t \to bH^+,\ bW^+ \to bl^+\nu$. The correlation between the lepton energy distribution and the top spin may be useful for distinguishing the H^+ signature from the W background. Such a correlation can also be useful for disentangling the two different $H^+\bar{t}b$ couplings and determining the experimental value of $\tan\beta$.

To appear in the Proceedings of the Workshop on
Physics at Current Accelerators and the Supercollider
Argonne National Laboratory, Argonne, Illinois
June 2-5, 1993

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Charged Higgs bosons (H^+) are present in models with two scalar doublets or a more extended Higgs sector [1]. One notorious example is the minimal supersymmetric model (MSSM). In a general two Higgs doublet model (THDM) the charged Higgs mass is a free parameter. In the MSSM, however, it is bounded from below, $m_{H^+} \gtrsim m_W$. Experimentally, the LEP Higgs search [2] provides a model-independent lower bound, $m_{H^+} \gtrsim m_Z/2$. The recent experimental [3] upper bound on the decay $b \to s\gamma$ also constrains m_{H^+} but in a model-dependent way [4]. For example, in a THDM where one Higgs doublet is responsible for generating the masses of the down-type fermions and the other Higgs doublet generates those of the up-type (model II of ref. [1]) we have $m_{H^+} \gtrsim 300$ GeV. Although the MSSM belongs to this type of model, this bound does not apply to it because one also has to consider the contribution of the superpartners [4].

If $m_{H^+} < m_t - m_b$, the top quark can decay to H^+b providing a source of charged Higgs bosons. The $t \to H^+b$ branching ratio depends on the $H^+\bar{t}b$ coupling which is given by (model II)

$$\frac{ig}{2\sqrt{2}m_W} H^+\bar{t}\left[m_t \cot\beta(1-\gamma_5) + m_b \tan\beta(1+\gamma_5)\right] b \; + \; h.c., \tag{1}$$

where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. From eq. (1), we have

$$\Gamma(t \to H^+b) = \frac{G_F m_t}{8\sqrt{2}\pi}\left(1 - \frac{m_{H^+}^2}{m_t^2}\right)^2 \left[m_t^2 \cot^2\beta + m_b^2 \tan^2\beta\right] , \tag{2}$$

where we have neglected all purely kinematic factors of m_b that are not enhanced by $\tan\beta$. Hence, the width of $t \to H^+b$ is large and comparable to the standard decay mode, $t \to W^+b$, for large or small values of $\tan\beta$, *i.e.*, $\tan\beta < 1$ or $\tan\beta > 20$. In fig. 1, we show $\mathrm{BR}(t \to H^+b)/\mathrm{BR}(t \to W^+b)$ as a function of $\tan\beta$ for different values of the charged Higgs mass. We can see that the BR has a minimum at $\tan\beta \sim 5$. For $\tan\beta$ around this value (this region, $1 < \tan\beta < 20$, is favored by low-energy supersymmetric models), the detection of H^+ may be difficult [5]–[7]. Even if the $t \to H^+b$ branching ratio and m_{H^+} can be measured, there will still be an ambiguity in the value of $\tan\beta$, *i.e.*, $\tan\beta$ is a double-valued function of $\mathrm{BR}(t \to H^+b)$.

In this paper we will compute the energy distribution of the leptons coming from the decay $t \to bH^+ \to bl^+\nu$ and compare to that of leptons from the decay $t \to bW^+ \to bl^+\nu$ for polarized top quarks. Expected differences in these distributions can be useful for distinguishing between charged Higgs signals and W signals. Furthermore, the lepton energy distribution from $t \to bH^+ \to bl^+\nu$ is sensitive to the two terms of the coupling (1) and will help resolve the ambiguity in $\tan\beta$.

The idea is based on the correlation between the lepton energy and the top helicity [8]: The decay $t \to W^+b$ is dominated by a V–A interactions, *i.e.*, the b is always left-handed. If the top mass is large, the W is longitudinal and a t_L will

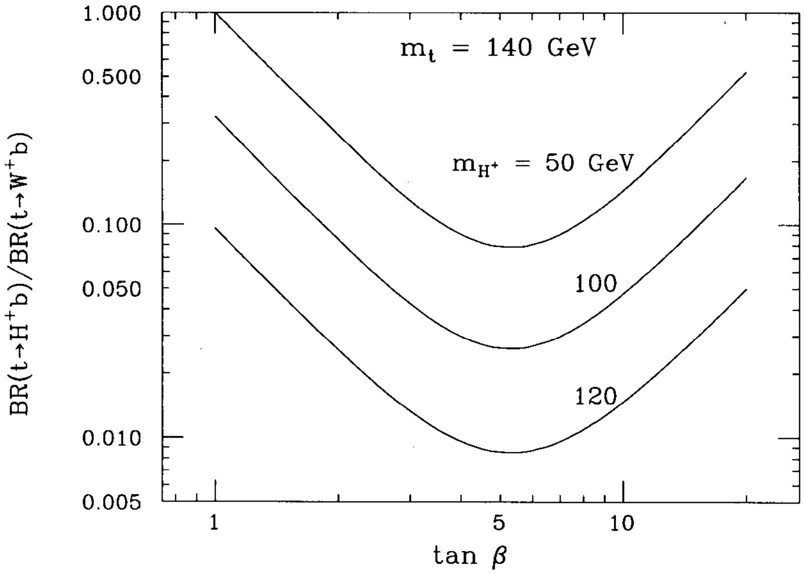

Figure 1: Ratio between the decay $t \longrightarrow H^+b$ and $t \longrightarrow W^+b$.

decay to an energetic b_L (since it has to go forward to carry the top spin) and to a less-energetic W that will decay into a less-energetic lepton. Similarly, a t_R will tend to decay to a more-energetic lepton. This correlation has been shown to be useful in probing CP violation in top production [9]. Let us consider now the H^+b top decay mode. If this decay is dominated by the term proportional to $(1-\gamma_5)$ in (1), the b will also be left-handed and we will have a similar energy dependence as the Wb decay mode. Nevertheless, for $\tan\beta > 1$ the term proportional to $(1+\gamma_5)$ cannot be neglected. This term involves a b_R and therefore the relative energies of b and H^+ (or their decay leptons) are reversed: t_L will produce an energetic lepton and t_R a less-energetic one.

In figs. 2 and 3 we show the lepton energy spectra for a t_L and t_R respectively decaying through an on-shell H^+ or W. We have taken $m_t = 140$ GeV, $E_t = 250$ GeV, $m_{H+} = 100$ GeV and $\tan\beta = 10$. In the t_L decay, one can appreciate a significant difference between the H^+ and W curve. Such a difference is smaller for t_R. For small values of $\tan\beta$, the second term of (1) is small and the H^+ curve is shifted to the left (right) for t_L (t_R).

In future hadron or e^+e^- colliders the numbers of t_L will be similar to that of t_R –unless we polarize the initial beams. Therefore, the differences in the energy spectra of the decay leptons from H^+ and W cannot be appreciated. Nevertheless, if the center of mass energy of the $t\bar{t}$ pair is much larger that $2m_t$, we will have

$$N(t_L\bar{t}_R) \approx N(t_R\bar{t}_L) \gg N(t_L\bar{t}_L),\, N(t_R\bar{t}_R)\,. \qquad (3)$$

This is the case of the e^+e^- Next Linear Collider (NLC) where $\sqrt{s} = 500$ GeV or 1 TeV. Considering (3), the strategy seems clear for enhancing the sample of Higgs-

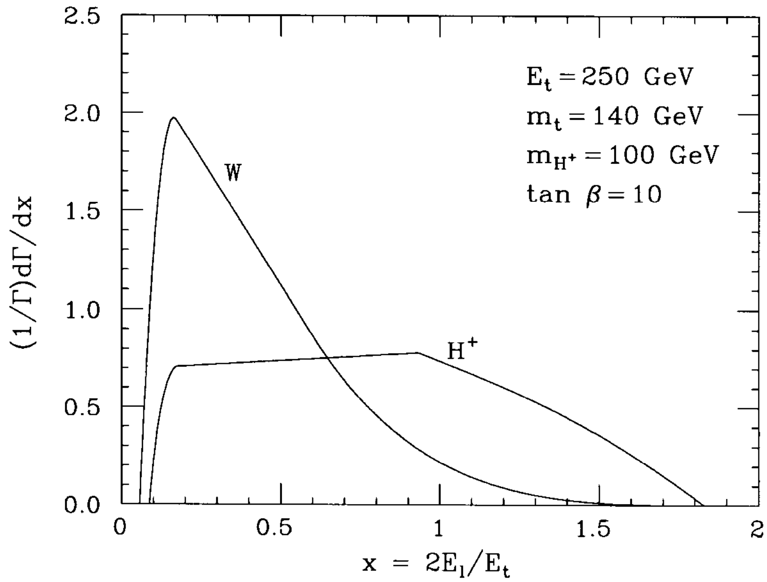

Figure 2: Lepton energy distribution for t_L decaying through an on-shell H^+ or W.

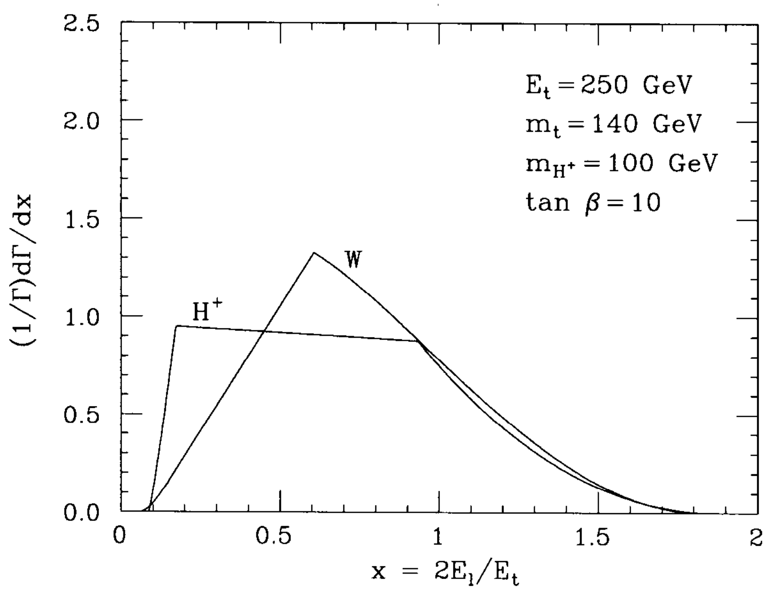

Figure 3: Lepton energy distribution for t_R decaying through an on-shell H^+ or W.

mediated decays. First, select $t\bar{t}$ events where one top decays to a τ and the other decays to a lepton ($\ell = e, \mu$). For $t\bar{t} \to W^+W^-$ events the energies of the lepton and the τ will be comparable; both energetic for $t_R\bar{t}_L$ or both non-energetic for $t_L\bar{t}_R$. However, for $t\bar{t} \to H^\pm W^\mp$ the lepton and the τ will typically have different energies. Thus, we can enhance the $H^\pm W^\mp$ sample relative to the W^+W^- by selecting for events with $E(\tau) \gg E(\ell)$ or $E(\ell) \gg E(\tau)$.

To get an idea of how the kinematic cuts can enhance the $H^\pm W^\mp$ signal, we show in table 1 the number of $\ell - \tau$ pairs expected from $t\bar{t} \to W^+W^-, H^\pm W^\mp \to \ell\tau$ for an e^+e^- collider with $\sqrt{s} = 500$ GeV and luminosity of 50 fb^{-1}. As before we take $m_t = 140$ GeV and $m_{H^+} = 100$ GeV. Since for $\tan\beta > 1$, H^+ decays into $\tau\nu$ with a branching ratio close to one[1], a clear signal of a charged Higgs from a top decay will be the breaking of lepton universality [7], *i.e.*, an excess of $N_{\ell\tau}$ over $N_{\ell\ell}$. We have computed $N_{\ell\tau}^{WW} \equiv N_{\ell\ell}^{WW}$ and $N_{\ell\tau}^{HW}$ without cuts, and with $x_{\ell,\tau} \equiv 2E_{\ell,\tau}/E_t$ restricted to simultaneously lie between $1.2 < x_\ell < 2$ and $0 < x_\tau < 0.5$ or with x_ℓ and x_τ interchanged. These rather strict cuts definitely increase the percentage of $H^\pm W^\mp$ events, although at a considerable loss of statistics. In addition, for values of $\tan\beta$ that give equal $\mathrm{BR}(t \to H^+b)$ the cuts increase the small differences in $N_{\ell\tau}^{HW}$ that arise from the dependence of $\mathrm{BR}(H^+ \to \tau\nu)$ on $\tan\beta$.

In this paper we have shown that the differences in the lepton energy spectra from top decay to H^+ and W^+ may be useful in enhancing the charged Higgs signal and for studying its couplings. Using correlations in the $t\bar{t}$ pairs (3), we exhibited this difference by making simple cuts on the lepton energies at the NLC to enhance the Higgs signal. It remains to be seen whether this effect can be used at hadron colliders, where the $t\bar{t}$ correlations are presumably weaker. Further analysis is required in order to optimize the use of the lepton energy information, especially in conjunction with other techniques for enhancing the H^+ signal, such as τ polarization [11] or b tagging [7]. The lepton energy spectra should be particularly useful at an NLC with polarized beams, which can produce a large sample of longitudinally polarized top quarks.

[1]QCD corrections [10] reduce considerably the $H^+ \to c\bar{s}$ branching ratio and therefore enhance $\mathrm{BR}(H^+ \to \tau\nu)$.

Table 1

$\tan\beta$	1.4	20	2.8	10	3.5	8
$\mathrm{BR}(t \to H^+ b)$	$1.4 \cdot 10^{-1}$		$4.5 \cdot 10^{-2}$		$3.3 \cdot 10^{-2}$	
$N_{\ell\tau}^{WW}$ (no cuts)	1157		1439		1475	
$N_{\ell\tau}^{HW}$ (no cuts)	1459	1736	603	610	453	455
$N_{\ell\tau}^{WW}$ (cuts)	40		50		51	
$N_{\ell\tau}^{HW}$ (cuts)	106	185	46	63	36	46

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