Top-quark decay in models with Higgs triplets

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It is well known that if the charged Higgs scalar ($H^{\pm}$) is lighter than the top quark (t) then the decay $t \to bH^+$ will dominate over the usual charged-current decays via the W in the two-Higgs-doublet extension of the standard model. We show that in models with Higgs fields in triplet representations, the fine-tuning of the ratio of triplet to doublet vacuum expectation values required by constraints on the ρ parameter naturally leads to competitive charged-Higgs-boson and W decay modes for the t quark if its mass is below $M_W + m_b \simeq 85$ GeV. In these models we show that the branching fraction for $t \to b\tau\nu$ is always enhanced whereas the corresponding branching fraction for $t \to bl\nu$ is suppressed. Universality violation is one of the best probes of this scenario.

The Higgs sector of the standard model (SM), which is responsible for generating gauge-boson and fermion masses, remains mysterious. Whereas the SM predicts only one physical neutral Higgs scalar after spontaneous symmetry breaking (SSB), extensions of the Higgs sector can also lead to charged Higgs fields as well.[1] Most of the studies of the phenomenology of charged Higgs boson have concentrated on the two-Higgs-doublet model[2] (THDM) since it naturally leads to the successful relation[3] $\rho = M_W^2/M_Z^2 c_W^2 = 1$ at the tree level and can easily avoid problems associated with flavor-changing neutral currents.[4] Even in this class of models, the couplings of the charged Higgs field ($H^{\pm}$) to the usual fermions is not uniquely determined in terms of the ratio of the vacuum expectation values (VEV's) of the two Higgs doublets $v_{1,2}$ (there being four possible coupling assignments). All of the THDM's do share a common feature. For values of $\tan\beta \equiv v_2/v_1$ of order unity, the decay modes of the top quark (t) will be very substantially modified, if not completely dominated, by the charged-Higgs-boson decay mode, $t \to bH^+$ (if kinematically allowed), especially when $m_t < M_W + m_b$ (Ref. 5). In fact, if $t \to bH^+$ dominates the usual charged-current decay via virtual W exchange, e.g., $t \to bl\nu$, the conventional searches for the top at hadron colliders are invalidated since they assume that the top quark has a reasonable leptonic branching fraction[5,6] B_l. Since B_l is necessarily drastically reduced, the lower limits on m_t arising from hadron-collider searches[7–9] are substantially weakened.

In this paper we wish to explore another class of models in which the usual Higgs doublet is augmented by an additional scalar triplet. In order to obtain values of ρ near unity in agreement with current experiments, the ratio of triplet to doublet VEV's, v_T/v_D, must be quite small[3] $\lesssim 0.08$. Since the charged-Higgs-boson coupling to fermions is suppressed by v_T/v_D in these models, it may be possible for the conventional charged-current decays of the top quark to remain dominant even when the $t \to bH^+$ decay is kinematically allowed. This would be in sharp contrast to the THDM discussed above and would demonstrate that the existence of a light H^+ does *not necessarily* imply the dominance of the $t \to bH^+$ decay mode.

As is well known, there are two possible hypercharge assignments for the Higgs triplet consistent with the requirement that one multiplet member obtains a nonzero VEV: $Y=0$ or -2. We will concentrate on the $Y=-2$ case in our discussion below but essentially identical results are obtained in the case of $Y=0$. Note, however, that the constraints on the ratio v_T/v_D are somewhat stricter in the case of $Y=0$ (Ref. 3). Let us write the doublet and triplet Higgs fields in this model as

$$\begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} = \begin{pmatrix} 1/\sqrt{s}\,(v_D + \rho_D + i\eta_D) \\ \phi^- \end{pmatrix}, \quad \begin{pmatrix} \chi^0 \\ \chi^- \\ \chi^= \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2}(v_T + \rho_T + i\eta_T) \\ \chi^- \\ \chi^= \end{pmatrix}. \tag{1}$$

We then obtain $M_W^2 = \frac{1}{4}g^2(v_D^2 + 2v_T^2)$, $M_Z^2 = (g^2/4c_W^2)(v_D^2 + 4v_T^2)$ or

$$\rho = \frac{1 + 2v_T^2/v_D^2}{1 + 4v_T^2/v_D^2} \le 1 . \tag{2}$$

The couplings of the ordinary fermions to the field $\phi^{\pm}$ are dictated by the fact that it is the doublet VEV v_D, which generates their masses while the fermions do not couple to the triplet. Thus we find that the origin of the charged-Higgs-boson couplings to fermions to arise from the interaction term

$$\mathcal{L}_{\text{int}} = \frac{1}{\sqrt{2}v_D}\{\, \bar{U}[M_U V(1-\gamma_5) - VM_D(1+\gamma_5)]\bar{D} - m_l \bar{\nu}(1+\gamma_5)l\,\}\phi^+ + \text{H.c.} , \tag{3}$$

where $M_{U,D}$ are the diagonal $Q = \frac{2}{3}$ and $-\frac{1}{3}$ quark mass matrices, V is the usual Kobayashi-Maskawa (KM) mixing matrix, etc. Unfortunately, $\phi^{\pm}$ and $\chi^{\pm}$ mix to form the mass eigenstates $G^\pm$ and $H^\pm$, where the massless $G^\pm$ Goldstone boson is absorbed by $W^\pm$ to generate its mass and $H^\pm$ is the physical charged Higgs boson. Clearly the rotation

$$\begin{bmatrix}\phi^\pm\\ \chi^\pm\end{bmatrix}=\begin{bmatrix}\cos\gamma & \sin\gamma\\ -\sin\gamma & \cos\gamma\end{bmatrix}\begin{bmatrix}G^\pm\\ H^\pm\end{bmatrix} \tag{4}$$

will diagonalize the charged-scalar mass matrix so that the $H^\pm$ interaction is essentially given by Eqs. (3) with $\phi^+\to\sin\gamma H^+$. Thus to determine the fermionic couplings of $H^\pm$ completely one must find $\sin\gamma$ in terms of the VEV's v_D and v_T by an explicit calculation of the $\phi^\pm$-$\chi^\pm$ mass matrix. Following Ref. 10, where the most general Higgs potential involving one doublet and one triplet representation are considered, one finds that

$$\sin\gamma=\sqrt{2}v_T/v_D(1+2v_T^2/v_D^2)^{-1/2} . \tag{5}$$

(A specific model of the kind considered here is the triplet-Majoron model[11] which is now ruled out by recent data from the CERN e^+e^- collider LEP; we consider a more general form of the Higgs potential in our analysis and thus avoid any conflict with existing data.) Using the relation between M_W and v_T/v_D above we obtain the final form of the $H^\pm$ interaction with fermions in this model:

$$\mathcal{L}_{H^\pm}=\frac{g}{2\sqrt{2}M_W}\tan\gamma\{\,\bar{U}[M_U V(1-\gamma_5)-VM_D(1+\gamma_5)]D - m_l\bar{\nu}(1+\gamma_5)l\}H^\pm+\text{H.c.} , \tag{6}$$

where $\tan\gamma=\sqrt{2}v_T/v_D$. As advertised, the coupling strength of $H^\pm$ to fermions is naturally reduced in this model since $v_T^2/v_D^2\ll 1$ due to ρ parameter constraint. In fact, one finds directly

$$\tan\gamma=\left[\frac{1-\rho}{2\rho-1}\right]^{1/2} \tag{7}$$

which explicitly shows that as ρ is pushed towards unity, $\tan\gamma\to 0$. Note that since $\tan^2\gamma\ll 1$, unless $t\to bH^+$ (with H^+ on shell), is kinematically allowed, the existence of H^+ will not appreciably modify the usual charged-current (CC) t decay. Also if $t\to bW^+$ (with W^+ on shell), is kinematically allowed, CC modes will necessarily dominate the decay. We thus restrict ourselves to the kinematic region where the top decays to real $H^\pm$ and virtual $W^\pm$.

Our analysis now follows the procedure of Refs. 5 and 6. We take the following input parameters in our calculations: $M_W=80.0$, $m_\tau=1.7841$, $m_s=0.2$, $m_b=5.2$, and $m_c=1.5$ (all in GeV) with all other fermions except top massless and $|V_{ud}|=0.9744$, $|V_{us}|=0.220$, $|V_{ub}|=0.0043$, $|V_{cs}|=0.95$, $|V_{cd}|=0.207$, and $|V_{cb}|=0.043$; all of which are consistent with all CC data including the recent observations of $b\to u$ transitions by ARGUS and CLEO (Ref. 12). The decay rate for $t\to bH^+$ in this model is found to be

$$\Gamma(t\to bH^+)=\frac{G_F m_t^2}{8\sqrt{2}\pi}|V_{tb}|^2\tan^2\gamma\lambda^{1/2}(1,r_b,r_t)\times[(1-r_b)^2-r_H(1+r_b)] , \tag{8}$$

where λ is the usual triangle function and $r_{b,H}\equiv m_{b,H}^2/m_t^2$. The partial decay widths of H^+ are now given by (where u,d represents arbitrary $Q=\frac{2}{3}$ and $-\frac{1}{3}$ quarks, respectively)

$$\Gamma(H^+\to l^+\nu)=\frac{G_F m_l^2}{4\sqrt{2}\pi}m_H\tan^2\gamma ,$$
$$\Gamma(H^+\to u\bar{d})=\frac{3G_F m_H}{4\sqrt{2}\pi}|V_{ud}|^2(m_u^2+m_d^2)\tan^2\gamma , \tag{9}$$

where terms of order m_l^2/m_H^2 and $m_{u,d}^2/m_H^2$ have been neglected. Equation (9) allows us to calculate the various branching fractions for $H^\pm$. The standard virtual W decay rate of the top is given as usual by (Γ_W being the W width)

$$\Gamma(t\to bW^*\to b\alpha\bar{\beta}) = \frac{G_F^2M_W^4}{96\pi^3}m_t^3N_C|V_{tb}|^2|V_{\alpha\beta}|^2 \times\int_{(m_\alpha+m_\beta)^2}^{(m_t-m_b)^2}\frac{dm_X^2\tilde{\Gamma}(t\to bX)}{(m_X^2-M_W^2)^2+(\Gamma_W M_W)^2} \tag{10}$$

with $N_C(V_{\alpha\beta})$ being the appropriate color [Kobayashi-Maskawa (KM)] factor for the $\alpha\bar{\beta}$ final state, respectively, and, with $r_X\equiv m_X^2/m_t^2$,

$$\tilde{\Gamma}=\lambda^{1/2}(1,r_X,r_b)[(1+r_b)^2+r_X(1+r_b)-2r_X^2] . \tag{11}$$

We can now examine the decays of the top for the kinematic range where t decays by $t\to bH^+$ (on shell H^+) and $t\to bW^+$ (virtual $W^\pm$ only). It is just in this mass range in which the usual collider limits on m_t can be weakened by the presence of a light H^+. We will assume $m_H\gtrsim 20$ GeV in the analysis which follows due to the bound arising from recent charged-Higgs-boson searches at the KEK e^+e^- collider TRISTAN (Ref. 13).

In order to probe the relative sizes of the W^* and H^+ contributions to top decay, we follow Refs. 5 and 6 and examine the following quantities:

$$B_l\equiv\frac{\Gamma(t\xrightarrow{\text{cc}} bl\nu)}{\Gamma(t\to\text{all})} ,$$
$$B_\tau\equiv\frac{\Gamma(t\xrightarrow{\text{cc}} b\tau\nu)+\Gamma(t\to bH^+)B(H^+\to\tau\nu)}{\Gamma(t\to\text{all})} , \tag{12}$$
$$B_W\equiv\frac{\Gamma(t\to bW^*)}{\Gamma(t\to\text{all})} .$$

B_l is simply the e- or μ-leptonic branching fraction of the top where the $t\to bl\nu$ decay proceeds via charged currents (W^*) only. B_τ is the corresponding branching fraction for the decay $t\to b\tau\nu$ which gets contributions from both charged currents (W^*) and the decay of $H^+\to\tau\nu$ subsequent to the $t\to bH^+$ decay. $B(H^+\to\tau\nu)$ is just the branching fraction for the $H^+\to\tau\nu$ mode. B_W simply compares the rate of all W^+ decays to the total width.

Figure 1 shows the value of B_l as a function of the H^+ mass for different values of v_T/v_D consistent with the ρ

parameter constraint ($v_T/v_D \lesssim 0.08$) with different values of m_t assumed. Several features are immediately apparent from this figure: (i) for fixed values of m_t and m_H, as v_T/v_D increases the H^+ contribution to the width increases and lowers the value of B_l; (ii) for fixed values of m_H and v_T/v_D, as m_t increases the effect of H^+ decreases due to the proximity of the W pole so that B_l more closely approaches its SM value; (iii) for m_t and v_T/v_D fixed, increasing m_H reduces the H^+ contribution to the top width and B_l again tends to its SM value. It is interesting to note that for m_t in the 50–80 GeV range, the ρ parameter constraint does not allow B_l to fall by more than a factor of $\simeq 5-6$ from its SM value. Thus, while the top search limits which depend on the branching fraction for $t \to bl\nu$ decay are weakened in this model, they are not entirely negated. For example, the current limit on m_t from the Collider Detector of the Fermilab (CDF) Collaboration of 77 GeV is not substantially decreased due to the sharp rise in both the pair production ($t\bar{t}$) and single production (via $W^\pm \to t\bar{b}, \bar{t}b$) cross sections as m_t decreases below 77 GeV. A crude estimate indicates that this limit is at most reduced by only $\simeq 7-10$ GeV. Thus, although the charged Higgs boson may participate quite strongly in top decay, the enforcement of the ρ parameter constraint hinders H^+ from completely dominating top decays as the charged Higgs boson does in the TDHM. As constraints on ρ improve, B_l will be forced even closer to its SM value and the modification in B_l due to H^+ decreases substantially.

Once the top is discovered, one can compare the branching fractions for the two process $t \to bl\nu$ and $t \to b\tau\nu$ to test for any universality violation since this provides a sensitive probe for the $t \to bH^+$ decay. Figure 2 shows the values of B_τ as a function of m_H in this model for different choices of m_t and different values of v_T/v_D. As an example, consider the case $m_t = 80$ GeV, $m_H = 50$ GeV, and $v_T/v_D = 0.075$; here we find $B_l \simeq 8.5\%$ while B_τ is twice as large: $B_\tau \simeq 17\%$. For smaller values of m_t or m_H this violation of universality is even larger while for fixed m_t, m_H a decrease in the value of v_T/v_D leads to a subsequent decrease in universality violation. Even for $v_T/v_D = 0.03$. with $m_t = 80$ GeV and $m_H = 50$

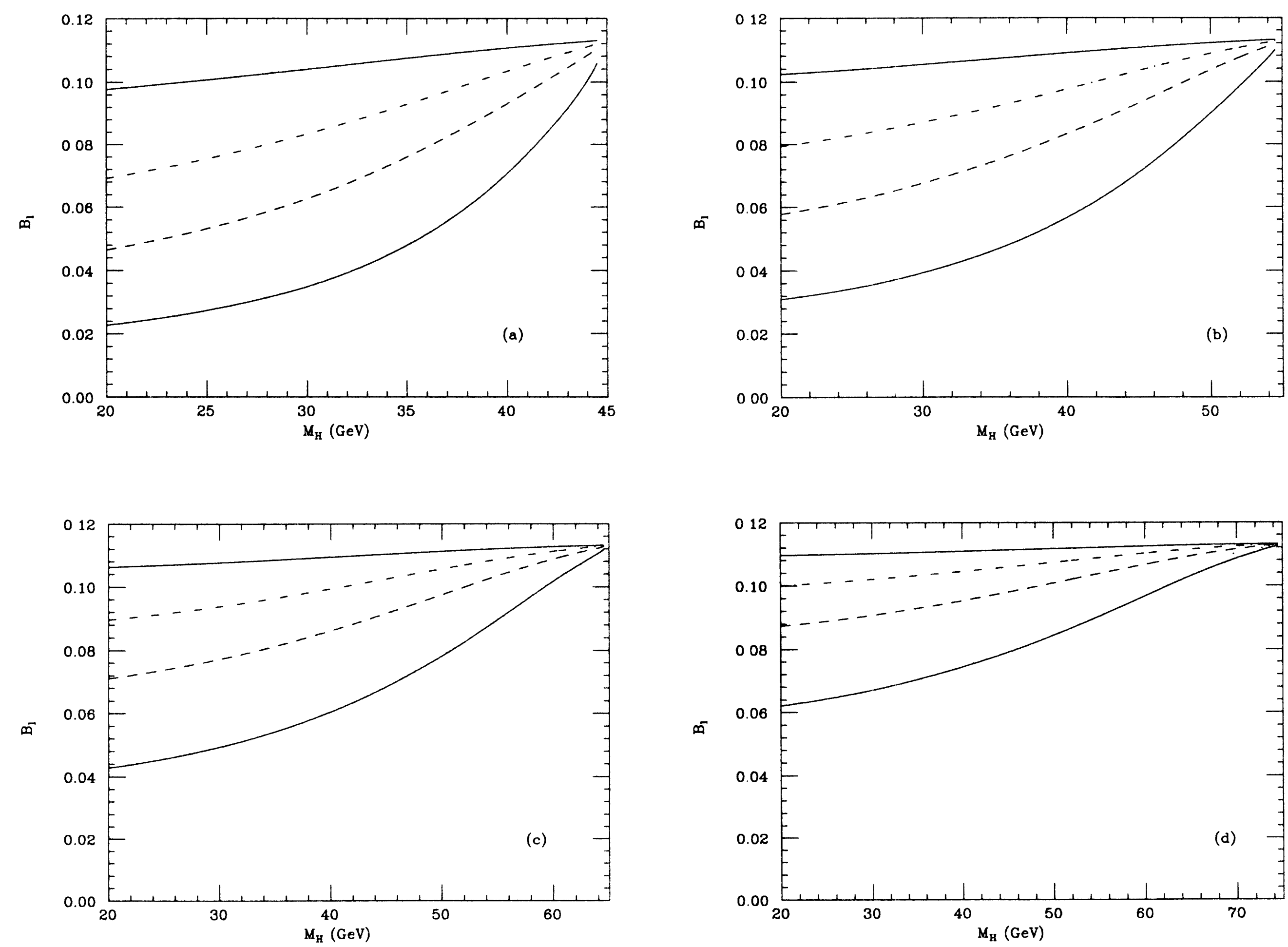

FIG. 1. Leptonic branching fraction B_l for the decay $t \to bl\nu$ as a function of the charged-Higgs-boson model (m_H) for top-quark masses of (a) 50, (b) 60, (c) 70, and (d) 80 GeV. The upper (lower) solid, dashed-dotted, dashed, and dotted curves correspond to $v_T/v_D = 0.015$, (0.075), 0.030, 0.045, and 0.060, respectively.

GeV, B_τ/B_l still differs from unity by $\approx 50\%$. As discussed in Ref. 5, it may be possible to observe the $t \to bH^+ \to b\tau\nu$ decay chain at hadron colliders but we may have to wait until LEP II before one can thoroughly probe this top-quark-mass range and determine the ratio B_τ/B_l.

In order to get a better feel for the relative size of the W^* and H^+ contributions to the total width of the top in this model, we consider the ratio B_W which is the branching fraction for top decay into W^*. Figure 3 shows B_W as a function of m_H for different values of v_T/v_D and choices of m_t; for example, with $m_t=70$ GeV, $m_H=40$ GeV, and $v_T/v_D=0.075$ we find that $B_W \simeq 0.5$. This means that for this choice of parameters, only half of the decays of the top quark proceed via virtual W exchange. Figure 3 clearly shows that if either m_t or m_H increases or if v_T/v_D decreases then B_W tends to unity with reasonable rapidity and the predictions of the SM are quickly recovered.

The main points resulting from this analysis are as follows.

(i) The couplings of the charged Higgs boson to fermions in the present model are suppressed by a factor of v_T/v_D in comparison to what is found in the THDM. This can significantly alter the possible influence of a light charged Higgs boson in the decay of the top quark when compared with what one might expect in the THDM. The ratio v_T/v_D is bounded from above by existing constraints on the ρ parameter and must be reasonably small: $\rho \lesssim 0.08$. These constraints will be greatly improved in the reasonably near future.

(ii) For top quarks in the kinematic range $m_H+m_b \leq m_t m_W+m_b$, the rate for the charged-Higgs-boson decay modes of the top are generally found to be competitive with or smaller than those which proceed via virtual W exchange, but they are never totally dominant unlike what one finds in the THDM. Thus, even if $t \to bH^+$ is kinematically allowed, it need not dominate the decay of the top quark.

(iii) The leptonic branching fraction of top in this model is decreased by at most a factor of 5–6 in comparison to its SM value and this results in a weakening of the

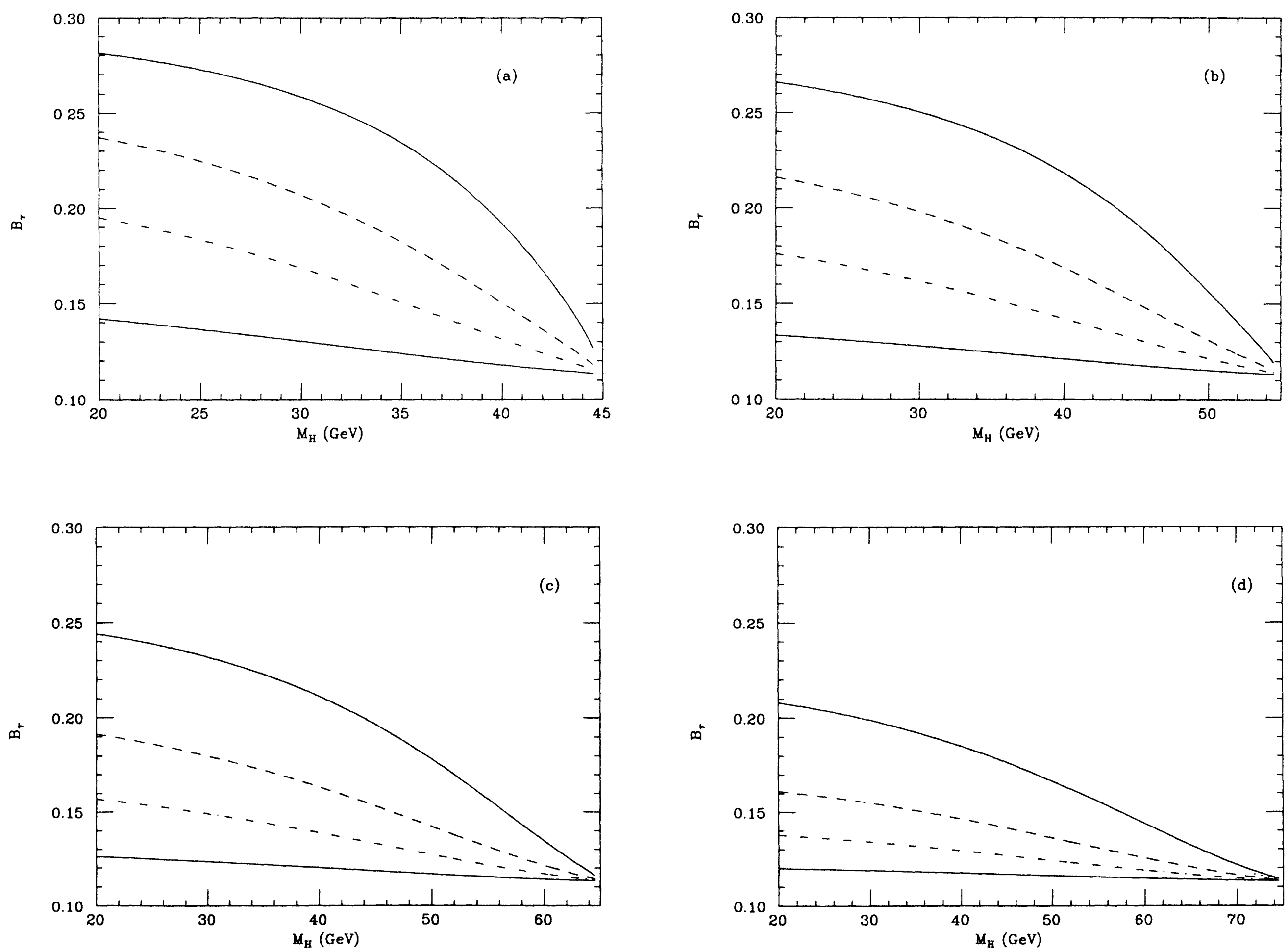

FIG. 2. Same as Fig. 1 but for the τ-leptonic branching fraction B_τ for the decay $t \to b\tau\nu$.

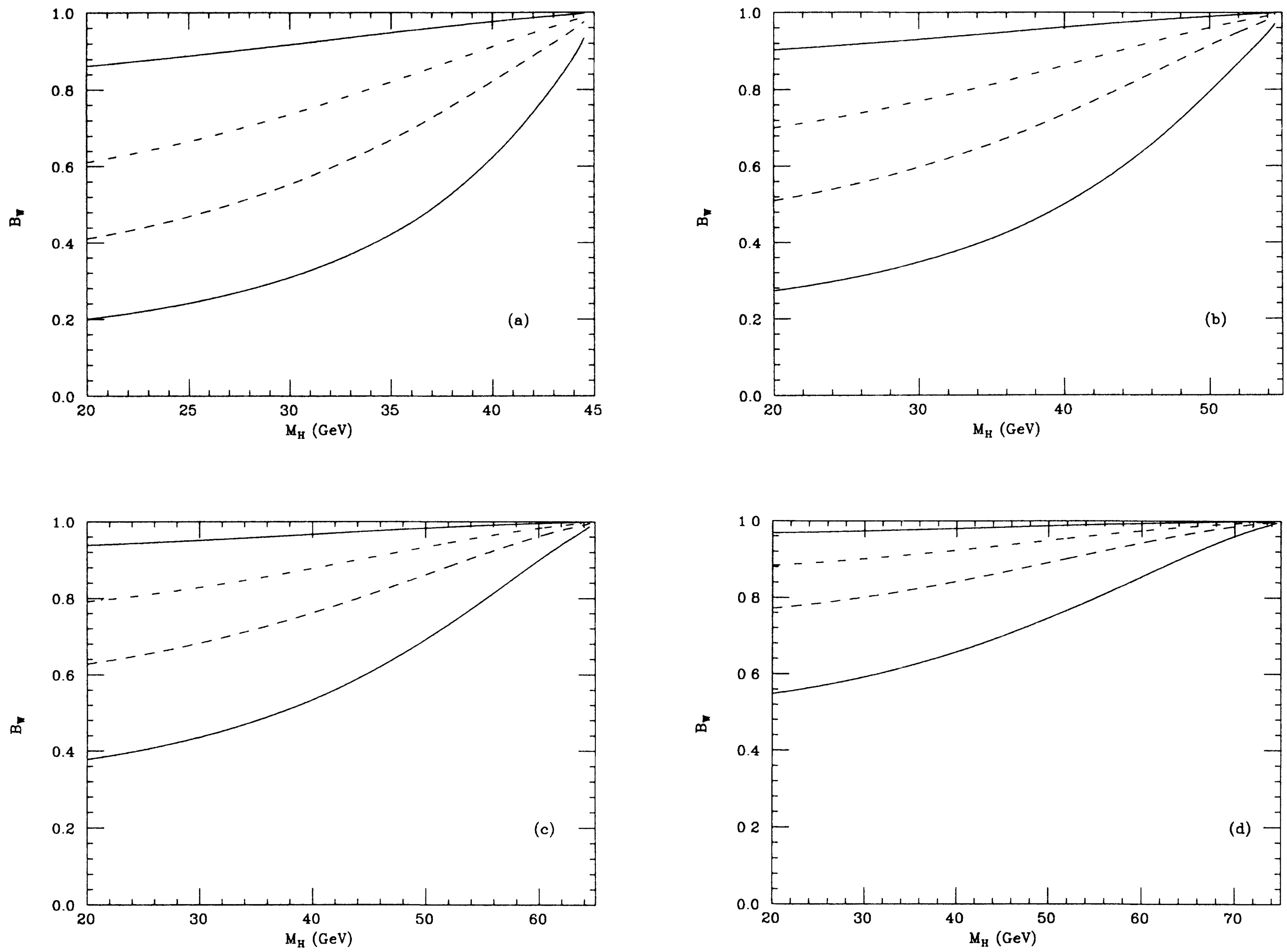

FIG. 3. Same as Fig. 2 but for the sum of the virtual-W decay-mode branching fractions, B_W.

CDF limits on m_t by only 7–10 GeV. This differs substantially from what happens in the THDM where the CDF limits can be entirely evaded.

(iv) Since the influence of H^+ exchange is substantially smaller in this model than in the THDM, the best test for the effects of H^+ in top decay is the observation of universality violation in the semileptonic decay. This must await a probe of the above mass range by LEP II.

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