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EFFECT OF QCD CORRECTION ON THE CHARGED HIGGS SIGNATURE IN TOP QUARK DECAY

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ABSTRACT

We incorporate QCD corrections into the calculation of signals for charged Higgs bosons produced in t -quark decays at the tevatron energy, in the leading-log approximation. We find that the signal in the 2τ channel is enhanced by up to a factor of three in the region $\tan\beta \lesssim 1$, essentially closing this window where a light charged Higgs might escape discovery. The signal is reduced somewhat for large $\tan\beta$, but remains viable there.

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The results of the top search experiment at the tevatron $\bar{p}p$ collider [1] as well as the $B_d - \bar{B}_d$ mixing data [2] suggest a heavy top quark of mass $m_t > 80$ GeV. Further the radiative correction to the W, Z masses suggests a fairly definitive range of top quark mass, centered around $m_t \simeq 150$ GeV [3]. It is also reasonably certain that a top quark in this mass range would have an observable signal at the tevatron upgrade [4], with an expected luminosity of several hundred pb^{-1} per year. Besides providing the first direct evidence for top this will enable one to search for new particles in the top quark decay; the large mass of top offers the possibility of carrying on this search to a hitherto unexplored mass range. There has been a great deal of theoretical and phenomenological interest in one such new particle, i.e. the charged Higgs boson [5] appearing in the two-Higgs-doublet Versions of the Standard Model [6]. In particular, it has recently been shown in [7] that for $m_t \simeq 150$ GeV a systematic comparison of the top signal in different decay channels provides an effective signature for a charged Higgs boson up to a mass of ~ 100 GeV. And for the theoretically most attractive two-Higgs-doublet models, where the two doublets have Yukawa couplings to the $T_3 = +1/2$ and $-1/2$ fermions respectively [6], one expects an observable signal throughout the allowed range of the coupling parameter $\tan\beta$. Thus one can probe the charged Higgs mass range up to ~ 100 GeV unambiguously for these models.

The purpose of the present note is to estimate the effect of QCD correction on the above-mentioned charged Higgs search programme, which has not been taken into account so far. Indeed, it is only in the last few months that the prescription for QCD correction in the charged Higgs sector has been worked out [8,9], at the leading-log level. At this level, it turns out that the QCD correction can be essentially implemented by replacing the quark mass factor in the Yukawa coupling by its running mass, evaluated at the Higgs mass scale. Nonetheless, the effect appears to be quite significant over certain regions of the coupling parameter $\tan\beta$, as we shall see below. In particular for $\tan\beta \lesssim 1$, the charged Higgs signal in one of the most important channels gets enhanced by a factor of 2-3. Therefore, the effect seems to us worth emphasizing.

Before going on to the QCD correction, let us summarize the essential features of the two-Higgs-doublet model [6]. It contains two $SU(2)$ doublets of complex scalar fields

$$\begin{pmatrix} \phi_1^0 \\ \phi_1^- \end{pmatrix} \quad \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \quad (1)$$

with vacuum expectation values (vevs)

$$\langle \phi_1^0 \rangle = v_1/\sqrt{2}, \quad \langle \phi_2^0 \rangle = v_2/\sqrt{2},$$

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which satisfy the W mass constraint

$$v_1^2 + v_2^2 = v^2, \quad (v = 246 \text{ GeV}). \quad (2)$$

A key parameter of the model is the ratio of the two vevs

$$\tan\beta = v_2/v_1. \quad (3)$$

After removing the three Goldstone bosons one is left with five physical states – the neutral scalars h^0, H^0 and pseudoscalar A^0 along with the charged states $H^\pm$. We shall be concerned only with the charged states, i.e.

$$H^\pm = \phi_2^\pm \cos\beta - \phi_1^\pm \sin\beta. \quad (4)$$

The two-Higgs-doublet model is attractive for the following reasons. It is a minimal extension of the Standard Model which naturally satisfies the constraints of $\rho = 1$ and the absence of flavour-changing neutral currents at the tree level. While the first is guaranteed by the doublet structure of the Higgs, the second is ensured by choosing the Higgs-fermion couplings in accordance with the Glashow-Weinberg theorem [10]. It states that the tree level FCNC mediated by Higgs bosons will be absent if all fermions of a given electric charge have Yukawa couplings to only one Higgs doublet. A very important model automatically satisfying this theorem is the minimal supersymmetric extension of the Standard Model, where the up-type quarks have Yukawa couplings to one Higgs doublet (ϕ_2 say) while the down-type quarks and charged leptons couple to the other. This particular two-Higgs-doublet model has received wide attention [6] as it provides the most economical solution to the hierarchy problem of the Standard Model. Moreover, it offers the possibility of explaining the observed quark mass hierarchy $m_c \gg m_s$ and $m_t \gg m_b$ in terms of that of the vevs $v_2 \gg v_1$. In this model, the Yukawa couplings of the physical charged Higgs field of Eq. (4) to fermions are given by

$$\begin{aligned} \alpha = \frac{g}{\sqrt{2}m_W} H^+ & \left\{ \cot\beta V_{ij} m_u \bar{u}_i d_{jL} \right. \\ & + \tan\beta V_{ij} m_d \bar{u}_i d_{jR} \\ & \left. + \tan\beta m_\ell \bar{\nu}_j \ell_{jR} \right\} + h.c. \end{aligned} \quad (5)$$

where V_{ij} are the KM matrix elements. One has identical charged Higgs couplings to fermions in the E_6 superstring-inspired models [11] as well*. We shall concentrate

* The main phenomenological difference between the minimal SUSY and E_6 models is that while the former predicts a mass bound [6] $m_H > m_W$ the latter gives a less restrictive bound $m_H > 53$ GeV.

on the above coupling scheme in view of the considerable theoretical interest behind it. Besides, as shown in Ref. [7], it is only for this coupling scheme (Eq. (5)) that one expects an unambiguous charged Higgs signal throughout the allowed range of the coupling parameter $\tan\beta$.

The present constraints on the charged Higgs mass and coupling parameters are as follows.

(1) Charged Higgs search at LEP by the ALEPH Collaboration gives a lower mass bound of about 40 GeV [12].

(2) Validity of the perturbation theory implies upper bounds on the charged Higgs-fermion Yukawa couplings of Eq. (5). Requiring the tbH^+ coupling in the first term to be bounded by the size of the strong coupling $4\pi\alpha_s (\simeq 1.5)$ gives [13,14]:

$$\tan\beta > m_t/600 \text{ GeV} (\simeq 1/4). \quad (6)$$

The size of this coupling can also be constrained by the contribution of the charged Higgs exchange box diagram to $B_d - \bar{B}_d$ mixing and the corresponding loop diagrams to $b \rightarrow s\gamma$ decay and the ϵ'/ϵ ratio. A lower bound of $\tan\beta > 0.3\text{--}0.4$ has been obtained from these low energy processes, for $m_t = 150 \text{ GeV}$ and $m_H \leq 100 \text{ GeV}$ [13].

(3) The analogous perturbative limit on the tbH^+ coupling appearing in the second term of Eq. (5) gives

$$\tan\beta < 600 \text{ GeV}/m_b (\simeq 120). \quad (7)$$

Thus the region of phenomenological interest is $m_H > 40 \text{ GeV}$ and $\frac{1}{2} \lesssim \tan\beta \lesssim 100$. More conservatively one may stick to the lower bound of Eq. (6) ($\tan\beta > 1/4$), since the strongest bound from the low energy processes comes from the ϵ'/ϵ ratio which has experimental controversy. On the other hand, one obtains an even stronger bound from the LEP constraints on Higgs masses in the radiatively broken SUSY model, i.e. $\tan\beta \geq 1$ after including radiative correction effects due to a heavy top [15]. But this is, of course, a strongly model-dependent bound.

The size of the charged Higgs signal vs. the W boson background in top quark decay is controlled by the relative decay widths of $t \rightarrow bH^+$ and $t \rightarrow bW^+$. In the approximation of a diagonal KM matrix, one gets

$$\Gamma_{t \rightarrow bW^+} = \frac{g^2}{64\pi m_W^2 m_t} \lambda^{1/2} \left(1, \frac{m_b^2}{m_t^2}, \frac{m_W^2}{m_t^2} \right) \left[m_W^2 (m_t^2 + m_b^2) + (m_t^2 - m_b^2)^2 - 2m_W^4 \right] \quad (8)$$

The corresponding decay width into charged Higgs boson, in the coupling scheme of

Eq. (5), is

$$\Gamma_{t \rightarrow bH^+} = \frac{g^2}{64\pi m_H^2 m_t} \lambda^{1/2} \left(1, \frac{m_b^2}{m_t^2}, \frac{m_H^2}{m_t^2} \right) \left[(m_t^2 \cot^2 \beta + m_b^2 \tan^2 \beta) (m_t^2 + m_b^2 - m_H^2) + 4m_t^2 m_b^2 \right] \quad (9)$$

Thus one gets the branching fraction

$$B(t \rightarrow bH^+) = \Gamma_{t \rightarrow bH^+} / (\Gamma_{t \rightarrow bH^+} + \Gamma_{t \rightarrow bW^+}) \quad (10)$$

From Eq. (5) one can also calculate the two significant decay widths of a charged Higgs, i.e.

$$\Gamma_{H^+ \rightarrow \tau^+ \nu} = \frac{g^2 m_H}{32\pi m_W^2} m_\tau^2 \tan^2 \beta \quad (11)$$

$$\Gamma_{H^+ \rightarrow e^+ \nu} = \frac{3g^2 m_H}{32\pi m_W^2} (m_e^2 \cot^2 \beta + m_\tau^2 \tan^2 \beta) \quad (12)$$

and the branching fraction

$$B(H^+ \rightarrow \tau^+ \nu) = m_\tau^2 \tan^2 \beta / 3(m_e^2 \cot^2 \beta + m_\tau^2 \tan^2 \beta) + m_\tau^2 \tan^2 \beta. \quad (13)$$

The corresponding branching fractions for W decay are of course given by the universality of W coupling to leptons and quarks, i.e. $\simeq 1/9$ into each lepton pair and $\simeq 2/3$ into hadrons (apart from a small QCD enhancement effect for hadronic widths by $\sim 4\%$). The striking difference between the two sets of branching fractions makes it possible to separate the Higgs and W contributions by comparing the relative size of the $t\bar{t}$ signal in different final states [7]. Like W , the charged Higgs has also to be identified through its leptonic (i.e. τ) decay in view of the large QCD background for the hadronic channel. Thus, it is the product of the two branching fraction (10) and (13) that controls the size of the observable charged Higgs signal.

The largest effect of QCD correction occurs for the $H^+ \rightarrow c\bar{s}$ decay width of Eq. (12). A systematic derivation of the QCD correction to this process is given in a recent paper by Mendez and Pomarol [9] which closely follows the steps of the analogous QCD correction to the neutral Higgs decay $H^0 \rightarrow q\bar{q}$, given in Ref. [16]. Detailed evaluation of the first-order QCD diagrams can be found in these two papers. The virtual gluon exchange correction to the above decay vertex has both ultraviolet and infra-red singularities. The former is cancelled by the vertex counterterm and the latter by adding the real gluon emission from the decay quarks. Thus the net first order QCD

The $t\bar{t}$ signal in the hard dilepton channel,

$$t\bar{t} \rightarrow b\bar{b}W^+W^- \rightarrow \ell^+\ell^-\nu \quad (23)$$

can be used to predict the W^+W^- contribution to any of the above channels via universality. A sizeable excess over this prediction will constitute a charged Higgs signal, whose magnitude is also predicted via Eqs. (10) and (13). Thus the uncertainties associated with the $t\bar{t}$ production are effectively factored out.

We shall concentrate on the single and double τ -jet channels, corresponding to the decay of one or both of the charged bosons via Eqs. (19) and (21). In particular, the double τ -jet channel was shown in Ref. [7] to be the most promising one for charged Higgs search in terms of the signal to background ratio. Besides, it has the advantage of being free from the W +QCD jets background.

Figure 2 shows the effect of QCD corrections on the charged Higgs signal and the WW background in this channel*. The effect is seen to be significant in the region $\tan\beta \leq 1$, where it enhances the signal by about a factor of 3. In particular, the $\tan\beta \simeq 0.5$ region was problematic for the uncorrected signal both in terms of the signal size and the signal to background ratio [7]; but this is no longer so after the QCD correction. The QCD corrected signal is seen to be viable throughout the allowed range of $\tan\beta$ ($\simeq 0.5 - 100$) for a charged Higgs mass up to 100 GeV. However, if one takes the conservative lower bound of Eq. (6), then there is a region of small $\tan\beta$ ($\simeq 0.25 - 0.5$) where the signal becomes small due to the vanishing $H \rightarrow \tau\nu$ branching ratio. On the other hand, the single τ -jet channel of Fig. 3 is seen to give a viable charged Higgs signal for the small $\tan\beta$ region going down to $\tan\beta = 0.2$, but has a sizeable gap in the region $\tan\beta \sim 5$. The effect of the QCD correction in this case is more modest – it enhances the signal by $\sim 50\%$ in the range $\tan\beta = 0.5 - 1$. The enhancement goes away in the very small $\tan\beta$ region, where the dominant contribution to the signal comes from the HW intermediate state followed by $W \rightarrow \tau\nu$. Finally, one sees a small reduction of the signal size in the large $\tan\beta$ region in both channels. This comes from the QCD correction to the Yukawa coupling of the b quark (i.e. the middle term of Eq. (5)), but its effect is marginal.

In conclusion, the main effect of QCD correction is to enhance the charged Higgs signal in the region of small $\tan\beta$ (≤ 1). It is most significant in the double τ -jet channel

* Although the size of the WW background in any given channel depends on the charged Higgs mass and coupling parameter, this dependence goes away when it is normalized by the hard dilepton channel. The predicted value for this normalized quantity is identical to the Standard Model prediction.

where the enhancement factor is about three. That the QCD enhancement is restricted to a small range of the parameter space, i.e. $\tan\beta \leq 1$, is of course an artifact of the choice of parameter. If one had chosen, e.g. the parameter to be $\cot\beta$ instead, then the region of enhancement would cover over half the allowed parameter space. The effect is also important for another reason. It is one of the few physical processes where one sees a large QCD correction arising from the running mass. Indeed one has as yet no clear phenomenological confirmation of the effect of mass evolution. Thus the process discussed above provides not only an unambiguous charged Higgs probe up to $m_H = 100$ GeV, but it also provides an important test for the QCD evolution of quark mass over a significant part of the coupling parameter space. It should be admitted of course that this part of the coupling parameter ($\tan\beta$) space is disfavoured in specific models [15].

REFERENCES

- [1] CDF Collaboration: F. Abe et al., *Phys. Rev. Lett.* **64** (1990) 142; Fermilab-PUB-90/137-E;
L. Pondrom, Plenary talk at the 25th Int. Conf. On High Energy Physics, Singapore, 1990.
- [2] G. Altarelli and P. Franzini, *Z. Phys.* **C39** (1988) 271;
P. Franzini, *Phys. Rep.* **173** (1989) 1 and references therein.
- [3] J. Ellis and G. Fogli, *Phys. Lett.* **B232** (1989) 139;
P. Langacker, *Phys. Rev. Lett.* **63** (1989) 1920;
F. Halzen and D.A. Morris, *Phys. Lett.* **B37** (1990) 107;
E. Jenkins and A.V. Manohar, *Phys. Lett.* **B237** (1990) 259.
- [4] S. Gupta and D.P. Roy, *Z. Phys.* **C39** (1988) 417;
H. Baer, V. Barger and R.J.N. Phillips, *Phys. Rev.* **D39** (1989) 3310.
- [5] See, e.g., R.M. Barnett et al., Reports on the subgroup on top quark, Proc. of 1990 Summer Study in High Energy Physics, Snowmass, (to be published);
V. Barger and R.J.N. Phillips, *Phys. Rev.* **D41** (1990) 884;
A.C. Bawa, C.S. Kim and A.D. Martin, *Z. Phys.* **C47** (1990) 75.
- [6] For a review of the minimal Higgs sector and its extensions, see:
J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, *The Higgs Hunters' Guide*, Addison Wesley, Reading, MA (1990);
H.E. Haber, in *Phenomenology of the Standard Model and Beyond*, Eds. D.P. Roy and Probrat Roy, World Scientific (1989).

- [7] R.M. Godbole and D.P. Roy, *Phys. Rev. D*, to be published.
- [8] C.S. Li and R.J. Oakes, *Phys. Rev. D* **43** (1991) 855.
- [9] A. Mendez and A. Pomarol, *Phys. Lett. B* **252** (1990) 461.
- [10] S. Glashow and S. Weinberg, *Phys. Rev. D* **15** (1977) 1958; E.A. Paschos, *ibid.* **D15** (1977) 1966; K. Kang and J.E. Kim, *Phys. Lett. B* **64B** (1976) 93.
- [11] J.L. Hewett and T.L. Rizzo, *Phys. Rep.* **183** (1989) 193.
- [12] ALEPH Collaboration, *Phys. Lett. B* **241** (1990) 623; OPAL Collaboration, *Phys. Lett. B* **242** (1990) 299; DELPHI Collaboration, *Phys. Lett. B* **241** (1990) 449; L3 Collaboration, *Phys. Lett. B* **252** (1990) 511.
- [13] V. Barger, J.L. Hewett and R.J.N. Phillips, *Phys. Rev. D* **41** (1990) 3421.
- [14] A. Buras, P. Krawczyk, M.E. Lautenbacher and C. Salazar, *Nucl. Phys. B* **337** (1990) 284; J.F. Gunion and B. Grzadkowski, *Phys. Lett. B* **243** (1990) 301.
- [15] J. Ellis, G. Ridolfi and F. Zwirner, CERN preprint TH.5946/90 (1990); H. Haber and R. Hempfling, Santa Cruz preprint SCIPP-90-42 (1990).
- [16] M. Drees and K. Hikasa, *Phys. Lett. B* **240** (1990) 455.
- [17] E. Braaten and J.P. Leveille, *Phys. Rev. D* **22** (1980) 715.
- [18] This is computed using the QCD parameters of M. Glück, F. Hoffmann and E. Reya, *Z. Phys. C* **13**(1982) 119.

FIGURE CAPTIONS

Fig. 1. The branching fraction of a 150 GeV top quark into charged Higgs boson in the mass range of 60-100 GeV; and the branching fraction of the charged Higgs decay into a τ lepton. The effect of QCD correction in each case is shown by the line indicated in the parentheses.

Fig. 2. The charged Higgs signal and the WW background for $m_H = 60$ and 100 GeV in the double τ -jet channel of $t\bar{t}$ decay, with nominal cuts of $p_T > 10$ GeV for each τ -jet, > 20 GeV for the accompanying missing p_T and > 30 GeV for the two accompanying jets. The effect of QCD correction is shown by the lines indicated in the parentheses. The right-hand scale shows the expected number of events for an integrated luminosity of 100pb^{-1} [7].

Fig. 3. The charged Higgs signal and the WW background in the single τ -jet channel of $t\bar{t}$ decay, with nominal cuts of $p_T > 10$ GeV for the τ -jet, > 20 GeV for the accompanying missing p_T and > 30 GeV for the two hardest accompanying jets [7]. The effect of QCD correction are shown by the lines indicated in the parentheses. The right-hand scale shows the expected number of events for an integrated luminosity of 100pb^{-1} .

FIGURE 1

FIGURE 2

FIGURE 3