QUANTUM EFFECTS ON TOP QUARK DECAY PHYSICS IN THE MSSM*

JOAN SOLÀ

Grup de Física Teòrica
and
Institut de Física d'Altes Energies
Universitat Autònoma de Barcelona
08193 Bellaterra (Barcelona), Catalonia, Spain

(Received January 14, 1997)

We analyze the one-loop effects (strong and electroweak) on $t \to W^+ b$ and on the unconventional mode $t \to H^+ b$ within the MSSM. The latter decay turns out to be an excellent laboratory to unveil "virtual" Supersymmetry.

PACS numbers: 14.65. Ha

In the near and middle future, with the upgrade of the Tevatron, the advent of the LHC, and the possible construction of an $e^+ e^-$ supercollider, new results on top quark physics, and perhaps also on Higgs physics, will be obtained in interplay with Supersymmetry that may be extremely helpful to complement the precious information already collected at LEP from Z-boson physics. Here we wish to dwell on the phenomenology of supersymmetric top quark decays with an eye on these future developments. While a simple tree-level study of $t \to W^+ b$ is blind to potentially underlying new physics, quantum effects have the power to shed some light on physics beyond the SM. Similarly, whereas a tree-level study of $t \to H^+ b$ is insensitive to the nature of the Higgs sector to which H^+ belongs, a careful study of the leading quantum effects on that decay could be the clue to unravel the potential supersymmetric nature of the charged Higgs. In particular, it should be useful to distinguish it from a charged Higgs belonging to a general two-Higgs doublet model. Now, part of these quantum effects, viz. the conventional QCD corrections, cannot distinguish the structure of the underlying Higgs model. Nevertheless, their knowledge is indispensable to probe the existence

* Presented at the Cracow International Symposium on Radiative Corrections to the Standard Model, Cracow, Poland, August 1–5, 1996.

of additional sources of strong virtual corrections beyond the SM. Here we will present the full one-loop quantum effects on the top decays $t \to W^+ b$ and $t \to H^+ b$ mediated by the plethora of supersymmetric partners, such as squarks, sleptons, gluinos, chargino-neutralinos and the various Higgs bosons of the Minimal Supersymmetric Standard Model (MSSM) [1], and shall compare them with the standard QCD corrections.

Why do we expect potentially large virtual SUSY signatures in top quark physics? In the MSSM the spectrum of Higgs-like particles and of Yukawa couplings is far and away richer than in the SM. In this respect, a crucial fact affecting the results of our work is that in such a framework the bottom-quark Yukawa coupling may counterbalance the smallness of the bottom mass, $m_b \simeq 5\,\mathrm{GeV}$, at the expense of a large value of $\tan\beta$ – the ratio of the vacuum expectation values (VEV's) of the two Higgs doublets – the upshot being that the top-quark and bottom-quark Yukawa couplings (normalized with respect to the SU(2) gauge coupling) as they stand in the superpotential, read

$$\lambda_t \equiv \frac{h_t}{g} = \frac{m_t}{\sqrt{2}\,M_W\,\sin\beta} \quad , \quad \lambda_b \equiv \frac{h_b}{g} = \frac{m_b}{\sqrt{2}\,M_W\,\cos\beta}\,, \tag{1}$$

and can be of the same order of magnitude, perhaps even showing up in "inverse hierarchy": $h_t < h_b$ for $\tan\beta > m_t/m_b$. Clearly, both at large and small values of $\tan\beta$ the Yukawa couplings (1) can be greatly enhanced as compared to the SM. We shall use the range $0.7 \lesssim \tan\beta \lesssim$60–70 in our numerical analysis.

To evaluate the relevant quantum corrections, we shall adopt the on-shell renormalization scheme [2] where the fine structure constant, α, and the masses of the gauge bosons, fermions and scalars are the renormalized parameters (α-scheme). Apart from the well-known $t\,b\,W^+$ interaction, the Lagrangian describing the vertex $t\,b\,H^+$ in the MSSM reads as follows:

$$\mathcal{L}_{Htb} = \frac{g\,V_{tb}}{\sqrt{2}M_W}\,H^+\,\bar{t}\,[m_t\cot\beta\,P_L + m_b\tan\beta\,P_R]\,b + \mathrm{h.c.}\,, \tag{2}$$

where $P_{L,R} = 1/2(1 \mp \gamma_5)$ are the chiral projector operators, $\tan\beta$ is the ratio between the vacuum expectation values of the two Higgs doublets of the MSSM and V_{tb} is the corresponding CKM matrix element–henceforth we set $V_{tb} = 1$.

The basic free parameters of our analysis concerning the electroweak sector are contained in the stop and sbottom mass matrices ($q = t, b$):

$$\mathcal{M}_{\tilde{q}}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 . \end{pmatrix}\,, \tag{3}$$

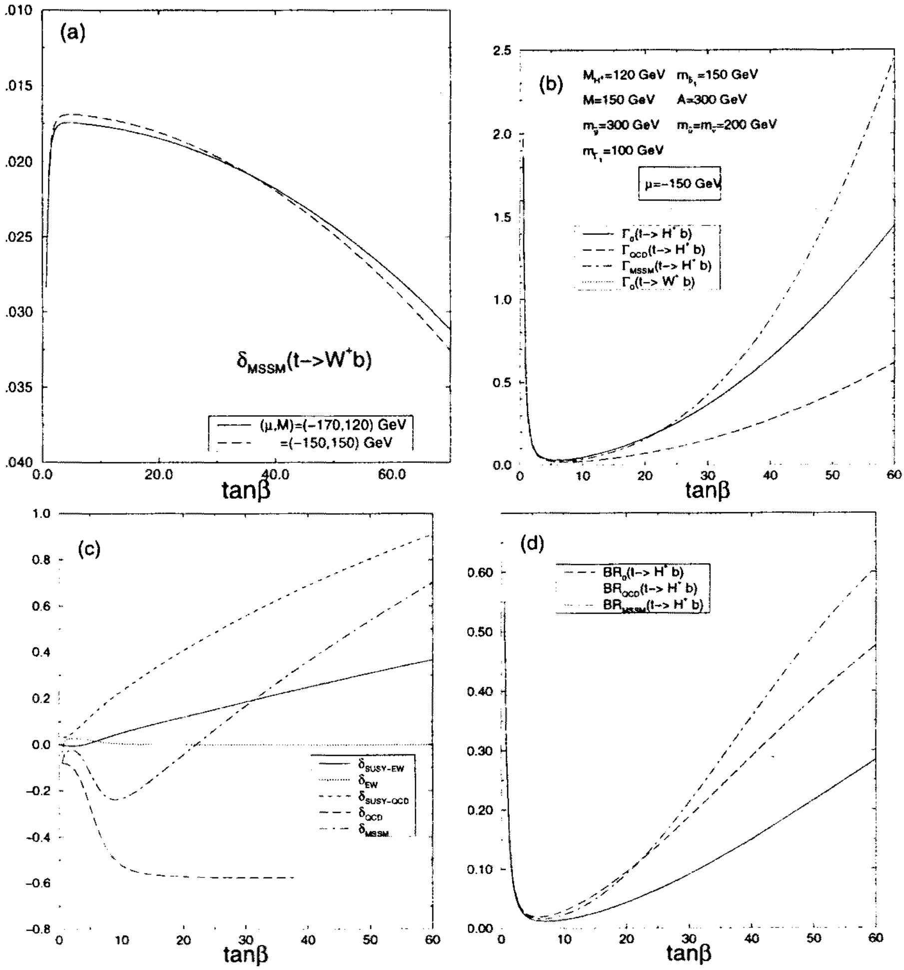

Fig. 1. (a) Typical SUSY corrections to Γ_W as a function of $\tan\beta$ and given values of the other parameters (rest of parameters as in Fig. 1b); (b) Γ_H as a function of $\tan\beta$, for the tree-level, QCD-corrected and full MSSM-corrected partial width; (c) The various types of SUSY corrections to Γ_H, including the full MSSM correction, as compared to the standard QCD ($\delta_{\rm QCD}$) and non-SUSY electroweak ($\delta_{\rm EW}$) corrections, as a function of $\tan\beta$; (d) As in (b), but for the branching ratio.

$$
\begin{aligned}
\mathcal{M}_{11}^2 &= M_{\tilde{q}_L}^2 + m_q^2 + \cos 2\beta (T_q^3 - Q_q \sin^2\theta_W)\, M_Z^2\,, \\
\mathcal{M}_{22}^2 &= M_{\tilde{q}_R}^2 + m_q^2 + Q_q \cos 2\beta \sin^2\theta_W\, M_Z^2\,, \\
\mathcal{M}_{12}^2 &= m_q\, M_{LR}^q \\
M_{LR}^{\{t,b\}} &= A_{\{t,b\}} - \mu\{\cot\beta, \tan\beta\}\,.
\end{aligned} \tag{4}
$$

We denote by $m_{\tilde{q}_1}$, $(q = t, b)$ the lightest stop/sbottom mass-eigenvalue. For the sake of simplicity, we treat the sbottom mass matrix assuming that $\theta_b = \pi/4$, so that the two diagonal entries are equal. The stop mixing angle, instead, is determined by the input parameters quoted in Fig. 1(b). As for the SUSY strongly interacting sector, the only new parameter is the gluino mass, $m_{\tilde{g}}$.

Another fundamental ingredient of our renormalization framework is our definition of $\tan\beta = v_2/v_1$ beyond the tree-level, which is essential to compute the electroweak corrections to $t \to H^+ b$. Any definition will generate a counterterm, $\tan\beta \to \tan\beta + \delta\tan\beta$, which depends on the specific renormalization condition. There are many possible strategies. The ambiguity is related to the fact that this parameter is just a Lagrangian parameter and as such it is not a physical observable. Its value beyond the tree-level is renormalization scheme dependent. For example, we may wish to define $\tan\beta$ in a process-independent ("universal") way as the ratio v_2/v_1 between the true VEV's after renormalization of the Higgs potential. In this case a consistent choice to cancel the tadpole terms in the renormalization of the Higgs potential is to require $\delta v_1/v_1 = \delta v_2/v_2$, and this entails

$$\frac{\delta\tan\beta}{\tan\beta} = \frac{1}{2}\left(\delta Z_{H_2} - \delta Z_{H_1}\right), \tag{5}$$

where δZ_{H_i} $(i = 1, 2)$ are the Higgs doublet field renormalization constants. Nevertheless, one may eventually like to fix the on-shell renormalization condition on $\tan\beta$ in a more physical way, *i.e.* by relating it to some concrete physical observable, so that it is the measured value of this observable that is taken as an input rather than the VEV's of the Higgs potential. Following this practical attitude, we choose as a physical observable the decay width of the charged Higgs boson into τ-lepton and associated neutrino:

$$\Gamma(H^+ \to \tau^+ \nu_\tau) = \frac{\alpha m_{\tau^+}^2 M_{H^+}}{8 M_W^2 s_W^2} \tan^2\beta\,. \tag{6}$$

This should be a very good choice, since this decay is the leading decay mode of H^+ at high $\tan\beta$, which is the regime where $t \to H^+ b$ is competitive with $t \to W^+ b$. This definition produces the following counterterm:

$$\frac{\delta\tan\beta}{\tan\beta} = \frac{\delta v}{v} - \frac{1}{2}\delta Z_{H^+} + \cot\beta\,\delta Z_{HW} + \Delta_\tau\,, \tag{7}$$

where $v^2 = v_1^2 + v_2^2$; δZ_{H^+} and δZ_{HW} are the field renormalization constants assoiated to H^+ and the $H^+ - W^+$ mixing, and Δ_τ is the full set of MSSM corrections to the decay $H^+ \to \tau^+ \nu_\tau$.

After explicit calculation of all the counterterms in our renormalization scheme, as well as of the full plethora of MSSM corrections to the three-processes: $t \to W^+\,b$, $t \to H^+\,b$ and $H^+ \to \tau^+\,\nu_\tau$, we are ready to present the outcome of our analysis. We do it in terms of the quantum corrections

$$\delta = \frac{\Gamma_{W,H} - \Gamma^{(0)}_{W,H}}{\Gamma^{(0)}_{W,H}} \equiv \frac{\Gamma(t \to \{W^+, H^+\}\,b) - \Gamma^{(0)}(t \to \{W^+, H^+\}\,b)}{\Gamma^{(0)}(t \to \{W^+, H^+\}\,b)}\,, \quad (8)$$

with respect to the corresponding tree-level width $\Gamma^{(0)}$. We plot in Figs. 1(a)–1(d) a clear-cut résumé of our main numerical results [3–5]. A quick inspection reveals that the SUSY corrections to Γ_H are much larger than those affecting to Γ_W. In the latter case, the situation is as follows (see Ref. [3] and references therein): the ordinary QCD effects are of order -8%, the Higgs effects are negligible and the SUSY corrections (mainly electroweak-like) can reach $\delta \simeq -3\%$ only for very large values of $\tan\beta$ near the perturbative limit $\tan\beta = 60$. In contrast, the corrections to Γ_H are already sizeable for $\tan\beta \gtrsim m_t/m_b \simeq 35$. The dominant MSSM effects on Γ_H are, by far, the QCD and SUSY-QCD ones, but for $\mu < 0$ (which in practice is the only tenable possibility [5]) they have opposite signs. Therefore, there is a crossover point of the two strongly interacting dynamics, where the conventional QCD loops are fully cancelled by the SUSY-QCD loops. This leads to a funny situation, namely, that the total MSSM correction is given by just the subleading, albeit non-negligible, electroweak supersymmetric contribution: $\delta_{\rm MSSM} \simeq \delta_{\rm SUSY-EW}$. The crossover point occurs at $\tan\beta \gtrsim m_t/m_b$, where $\delta_{\rm SUSY-EW} \gtrsim 20$. For larger and larger $\tan\beta$ beyond m_t/m_b, the total (positive) MSSM correction grows very fast, since the SUSY-QCD loops largely overcompensate the standard QCD corrections. As a result, the net effect on the partial width appears to be opposite in sign to what might naively be "expected" (*i.e.* the QCD sign). This should leave an indelible imprint on the quantum dynamics of the decay mode $t \to H^+\,b$ which could be crucial to identify the SUSY nature of H^+. While a first significant test of these effects could possibly be performed at the upgraded Tevatron, a more precise verification would most likely be carried out in future experiments at the LHC.

The author is very grateful to J. Guasch and R.A. Jiménez for their help in the preparation of this manuscript. This work has been partially supported by CICYT under project No. AEN95-0882.

REFERENCES

[1] H. Nilles, *Phys. Rep.* **110**, 1 (1984); H. Haber, G. Kane, *Phys. Rep.* **117**, 75 (1985).

[2] M. Böhm, H. Spiesberger, W. Hollik, *Fortschr. Phys.* **34**, 687 (1986); W. Hollik, *Fortschr. Phys.* **38**, 165 (1990).

[3] D. Garcia, W. Hollik, R.A. Jiménez, J. Solà, *Nucl. Phys.* **B 427**, 53 (1994); A. Dabelstein, W. Hollik, R.A. Jiménez, C. Jünger, J. Solà, *Nucl. Phys.* **B456**, 75 (1995).

[4] J. Guasch, R.A. Jiménez, J. Solà, *Phys. Lett.* **B360**, 47 (1995).

[5] J. A. Coarasa, D. Garcia, J. Guasch, R.A. Jiménez, J. Solà, preprint UAB-FT-397 [hep-ph/9607485].