RARE SUPERSYMMETRIC TOP QUARK DECAYS

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ABSTRACT

Two supersymmetric decays of the top quark, $t \to H^+ b$ and $t \to \tilde{u}_1 \tilde{\chi}^0$, are discussed within the framework of the Minimal Supersymmetric Standard Model with radiatively induced breaking of $SU(2) \times U(1)$. The present possibility of detecting these decays, given the available bounds on supersymmetric parameters, is compared with the situation a Next $e^+e^-$ Linear Collider would face if supersymmetric particles were still undiscovered after LEP II. The indirect implications for $t \to H^+ b$ and $t \to \tilde{u}_1 \tilde{\chi}^0$ of a possible detection of the bottom quark decay $b \to s\gamma$ at the Standard Model level are taken into account.

1. Introduction

Among the rare supersymmetric decays of the top quark, subject of this talk, I have chosen to discuss only two decays which can be far from rare \cite{1}: the two decays into charged Higgs plus bottom, $t \to H^+ b$, and into the supersymmetric partner of the top or stop, $\tilde{u}_1$, plus neutralino, $t \to \tilde{u}_1 \tilde{\chi}^0$. I have left out Flavour Changing Neutral Current (FCNC) decays such as $t \to c\gamma$, $t \to cZ$ and $t \to c\chi^0$, which negligible in the Standard Model (SM) \cite{1}, cannot be brought up to detectable levels in supersymmetry. Non-trivial enhancements for the decay $t \to c\chi$ (and more modest ones for $t \to c\gamma$, $t \to cZ$ \cite{2}) can be obtained in a non-supersymmetric context, with the SM Higgs sector extended in a non-conventional way to contain two doublets. This topic is subject of an independent contribution to this conference \cite{3}.

Although much had been said about $t \to H^+ b$ and $t \to \tilde{u}_1 \tilde{\chi}^0$ in the past (see references in \cite{7}), no investigation had been performed to find out whether the ranges of masses needed for these decays to be kinematically allowed, are actually present in realistic supersymmetric models. Worrisome indications about rather heavy charged Higgs $H^\pm$ to be expected within the Minimal Supersymmetric Standard Model (MSSM) have been recently brought up \cite{4}. Moreover, discussions have been triggered by refs. \cite{5} about the possibility of having the channel $t \to H^+ b$ closed by the observation of the bottom quark decay $b \to s\gamma$ with a Branching Ratio compatible with the SM prediction.

Some work has been done to investigate the prospects for these two top quark decays at the moment, given the present limits on supersymmetric parameters coming from LEP I and the TEVATRON, and in the situation that supersymmetric

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particles are still undiscovered after LEP II [6, 7]. The framework considered is the MSSM with spontaneous breaking of the gauge group $SU(2) \times U(1)$ induced by renormalization effects of the mass parameters appearing in the tree-level potential of the neutral Higgs sector of this model. The embedding in a generic grand-unified scheme is also considered. Details regarding the procedure followed in this search and the approximations made are given in [6], while a more thorough discussion of the results presented here can be found in [7].

The experimental situation which the Next Linear $e^+e^-$ Collider would have to face after LEP I and LEP II is mimicked by imposing different lower bounds to the supersymmetric particles: gluinos $\tilde{g}$, charginos $\tilde{\chi}^-$ (the lightest is conventionally denoted as $\tilde{\chi}^-_2$), neutralinos $\tilde{\chi}^0$, charged and neutral sleptons $\tilde{l}, \tilde{\nu}$, up- and down-squarks $\tilde{u}, \tilde{d}$, and neutral Higgses (with $h^0_2$ the lightest of the two CP-even states). I shall refer to these two choices of bounds as SET I and SET II. They are specifically given by:

\begin{align*}
\text{SET I:} & \quad m_{\tilde{g}}^- > 120 \text{ GeV}, \quad m_{\tilde{d}, \tilde{u}}^- > 100 \text{ GeV}, \quad m_{\tilde{u}_1}^- > 45 \text{ GeV}, \\
m_{\tilde{\chi}_2^-}^- & > 45 \text{ GeV}, \quad m_{\tilde{\nu}_1}^- > 45 \text{ GeV}, \quad m_{\tilde{t}_1}^- > 45 \text{ GeV}, \\
m_{h^0_2} & > 30 \text{ GeV}, \quad m_{\tilde{\chi}_1^0}^- > 20 \text{ GeV}, \quad (1)
\end{align*}

\begin{align*}
\text{SET II:} & \quad m_{\tilde{g}}^- > 140 \text{ GeV}, \quad m_{\tilde{d}, \tilde{u}}^- > 120 \text{ GeV}, \quad m_{\tilde{u}_1}^- > 80 \text{ GeV}, \\
m_{\tilde{\chi}_2^-}^- & > 80 \text{ GeV}, \quad m_{\tilde{\nu}_1}^- > 80 \text{ GeV}, \quad m_{\tilde{t}_1}^- > 80 \text{ GeV}, \\
m_{h^0_2} & > 70 \text{ GeV}, \quad m_{\tilde{\chi}_1^0}^- > 40 \text{ GeV}, \quad (2)
\end{align*}

where the limit on $m_{\tilde{\chi}_1^0}$ in SET II is induced by the limit on $m_{\tilde{\chi}_2^-}$. The present limits from the TEVATRON are kept into account in SET I (in the way considered more appropriate for the MSSM) and a mild improvement is assumed for SET II; see [7].

The results shown in this talk are limited to $m_t = 150 \text{ GeV}$, but similar features are obtained for different values of $m_t$. 

Figure 1: Allowed values of $m_{\tilde{H}^-}$ for the decay $t \rightarrow H^+b$
2. Decay $t \rightarrow H^+b$

A systematic study of the $(m, M)$ supersymmetric parameter space in the range $0 \leq m \leq 500\text{ GeV}$, $-250 \leq M \leq 250\text{ GeV}$ for several values of $\tan \beta$, between 3 and 35\textsuperscript{†}, leads to the values of masses for the charged Higgs $H^-$ shown in fig. 1. When SET I of lower bounds is imposed, masses as small as $90\text{ GeV}$ are obtained for the highest values of $\tan \beta$ considered (from 28 to 35). The available phase space (the running mass $m_b(M_Z)$ is here $\sim 3.6\text{ GeV}$) shrinks rapidly when $\tan \beta$ decreases, reaching a minimum around $\tan \beta = 9$, for which the smallest $m_{H^-}$ obtained is $\sim 120\text{ GeV}$. The minimum allowed value of $m_{H^-}$ tends to increase again up to $m_{H^-} \sim 100\text{ GeV}$ when $\tan \beta$ is reduced from 9 to 3.

Figure 2: $\tan \beta$ dependence of the ratio $R_H$

Not visible in this figure is the fact that the low values of masses obtained for $\tan \beta = 3$ are less “probable” than for high $\tan \beta$, since obtained in much smaller regions of the same $(m, M)$ parameter space considered; see [6].

The results described here differ from the ones presented in [4]. The disagreement may be due to differences in the assumptions underlying the two calculations, although the precise reason is not yet clear.

A strong dependence on $\tan \beta$ is present also in the expression for the width $\Gamma(t \rightarrow H^+b)$. The ratio $R_H \equiv \Gamma(t \rightarrow H^+b)/\Gamma(t \rightarrow W^+b)$ plotted in fig. 2 versus $\tan \beta$ for three different values of $m_{H^-}$, points to the intermediate values of $\tan \beta$ as to the disfavored ones.

The overall $(m_{H^-}, \tan \beta)$ dependence of this ratio for the phase space of fig. I, SET I, is shown in fig. 3.

The value $\tan \beta = 3$ yields a maximum ratio $R_H$ of about 5%; intermediate values, $3 < \tan \beta < 15$, are doubly penalized by the intrinsic drop in the rate shown in

\textsuperscript{†}For the rationale behind this choice of values for $\tan \beta$, see [4].
Figure 3: Ratio $R_H$ for the points in fig. 1, SET I

fig. 2 and the fact that the masses $m_{H^-}$ obtained in these cases are heavier; values of $\tan \beta$ greater than 25 can give ratios $R_H$ as big as $20-30\%$. The subsequent decay of $H^-$ into the pair $\tau, \nu_\tau$, with a rate practically equal to one (for the values of $\tan \beta$ considered here) contributes to making the prospects for the detection of this decay mode rather optimistic; for a discussion on this issue see [8].

However, one has to be aware of the fact that an increase of the lower bounds of supersymmetric particles up to the values of SET II drastically reduces the phase space available for this decay, as shown in fig. 1. The expected rates, which can be read with some effort from fig. 3, are still far from small.

A last check has been performed [6, 7] to verify whether the indirect constraints on the supersymmetric parameter space due to the expected, imminent detection of the decay $b \to s\gamma$ at the SM level can be strong enough to kinematically forbid this decay mode. The ranges of masses $m_{H^-}$ one is left with, after imposing that the values of $BR(b \to s\gamma)$ in the MSSM be limited to the interval $2.9-4.8 \times 10^{-4}$ (the range of allowed values of $BR(b \to s\gamma)$ within the SM for the same value of $m_t$ [6]), are shown in fig. 4 for the two sets of lower bounds, SET I, SET II.

3. Decay $t \to \tilde{u}_1 \tilde{\chi}_0$

The presence of large left-right entries in the up-squark mass matrix is such to allow one light mass eigenstate $\tilde{u}_1$, or stop, in principle, much lighter than the remaining squarks. Moreover, also the mass of the lightest neutralino, $\tilde{\chi}_0^1$ can be rather light within the MSSM. An investigation of the 2-dimensional parameter space $(m, M)$ for six values of $\tan \beta$, i.e. 3, 9, 15, 20, 25, 30, leads to the results shown

$^\dagger$The results in fig. 4 for SET I, are slightly more optimistic than those shown at the conference. The lower values of $\tan \beta$ were then found to be forbidden, due to the neglect of some subleading contributions to $BR(b \to s\gamma)$. However, even now, the density of points obtained in these cases is still rather small.
in fig. 3 for the allowed phase space of the decay $t \to \tilde{u}_1 \tilde{\chi}^0$, when the set of lower bounds SET I is considered. As in the case of $t \to H^+ b$, the region of parameter space studied is limited to the range $0 \leq m \leq 500 \text{ GeV}$, $-250 \leq M \leq 250 \text{ GeV}$, except for $\tan \beta = 30$. In this case, in fact, viable masses $m_{\tilde{u}_1}$, $m_{\tilde{\chi}_0^1}$ are obtained for $m$ and $|M|$ as big as 700 GeV and 350 GeV, respectively.

Also for this decay, the size of the allowed phase space decreases for increasing values of $\tan \beta$, reaches a minimum, and starts increasing again after $\tan \beta = 15$. The dependence on $\tan \beta$ of the width $\Gamma(t \to \tilde{u}_1 \tilde{\chi}^0)$ is less pronounced than for the decay $t \to H^+ b$. The rates obtained for all values of $\tan \beta$ considered in this case, are plotted in fig. 3; they can be $\sim 10\%$ for the lowest allowed values of $m_{\tilde{u}_1}$.

The produced $\tilde{u}_1$ can then decay as $\tilde{u}_1 \to \tilde{\chi}_1^\pm b$, if $m_{\tilde{\chi}_1^\pm} < m_{\tilde{u}_1}$. This is the case for all the points in fig. 3 located below the solid lines, which practically coincide, except for $\tan \beta = 3, 30$, with the contours of the regions obtained.

The alternatives, when $m_{\tilde{\chi}_1^\pm} > m_{\tilde{u}_1}$, for $\tan \beta = 3, 30$ and 25 (in a tiny corner at the lower values of $m_{\tilde{u}_1}$), are, in principle, the three-body decays mediated by virtual charginos, $\tilde{u}_1 \to b\tilde{\nu}_1$, $b\tilde{\nu}_1\tilde{\nu}$, and $\tilde{u}_1 \to bW^+ \tilde{\chi}^0$, mediated by a virtual chargino and/or a down-squark.

However, given the values of $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_0}$ in the points above the solid lines, it is clear that this last possibility can only occur with off-shell $W$-bosons. Moreover, an explicit check of the values of masses which sleptons have in the regions of phase space where $m_{\tilde{\chi}_1^\pm} > m_{\tilde{u}_1}$, leads to the conclusion that also $\tilde{u}_1 \to b\tilde{\nu}_1$, $b\tilde{\nu}_1\tilde{\nu}$ occur as four-body decay, with virtual sleptons producing leptons plus neutralinos. The prospects of sizeable decay rates for stop lighter than charginos look, therefore, rather grim.

However, the MSSM provides another interesting possibility: the two-body decay mode $\tilde{u}_1 \to c\tilde{\chi}_1^0$, a FCNC decay due to the coupling $\tilde{\chi}^0 - u_i - \tilde{u}_j$ ($i \neq j$) induced through renormalization effects by the soft supersymmetry-breaking terms. In spite of the
small coupling, this decay mode is clearly winning when compared to the four-body decay channels, which suffer from severe phase space suppressions [9].

It is interesting to observe that the two decays $t \rightarrow H^+b$, $t \rightarrow \tilde{u}_1\tilde{\chi}^0$, are sensitive to different regions of the supersymmetric parameter space. The highest rates for $t \rightarrow \tilde{u}_1\tilde{\chi}^0$ can be obtained in regions were $m_{H^-}$ is already far too big for $t \rightarrow H^+b$ to be kinematically allowed, see [7]. Therefore, in the case of a heavy charged Higgs, the decay $t \rightarrow \tilde{u}_1\tilde{\chi}^0$ would, in principle, play the role of the “golden” top-decay-candidate, if all the other supersymmetric masses could be frozen at the values obtained in this search. However, an increase in $m_{H^-}$ brings up with itself also other masses. The reduction of the available phase space when the lower bounds SET II are applied, is as severe as the one suffered by $t \rightarrow H^+b$, with only two tiny regions of points remaining for $\tan\beta = 3$ and 30. The ratio $\Gamma(t \rightarrow \tilde{u}_1\tilde{\chi}^0)/\Gamma(t \rightarrow W^+b)$, though, can still reach $5-6\%$, even in points where $m_{H^-} \gg 150\text{ GeV}$.

Bad news for this decay mode come from the indirect constraints which may be imposed by the detection of $b \rightarrow s\gamma$ at the SM level. Few points of the phase space shown in fig. [4] for SET I, remain. They all are at values of $m_{\tilde{u}_1} \gtrsim 80\text{ GeV}$. However, the possibility of detecting $t \rightarrow \tilde{u}_1\tilde{\chi}^0$ seems to be completely closed if the
Figure 6: Rates for the decay $t \to \tilde{u}_1 \tilde{X}^0$

$b \to s\gamma$ constraints are implemented on the phase space available when the lower limits SET II are imposed.

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6. References

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