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We reanalyze the decays of the lightest top squark $\tilde{t}_1$ in the Minimal Supersymmetric extension of the Standard Model. For relatively small $\tilde{t}_1$ masses, the four–body decay mode into the LSP, a bottom quark and two massless fermions, $\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$, can dominate in a wide range of the parameter space over the loop–induced decay into a charm quark and the LSP, $\tilde{t}_1 \to c\chi_1^0$. For larger $\tilde{t}_1$ masses, the three–body decays $\tilde{t}_1 \to Wb\chi_1^0$, $H^+b\chi_0^1$ and $bl^+\tilde{\nu}$, $b\tilde{l}^+\nu$ could open up; some of them will still dominate over the loop induced $\tilde{t}_1 \to c\chi_1^0$ decay.

1. Introduction

In the Minimal Supersymmetric extension of the Standard Model (MSSM) [1], the phenomenology of the top squarks is rather special. Indeed, due to the large value of m_t, the two current eigenstates $\tilde{t}_L$ and $\tilde{t}_R$ could strongly mix, and this leads to a mass eigenstate $\tilde{t}_1$ possibly much lighter than the other squarks, and even lighter than the top quark itself. If $\tilde{t}_1$ is lighter than the t–quark and the chargino [and also lighter than the scalar leptons], the two–body decay modes [2] into a top quark and the lightest neutralino [which, in the MSSM with conserved R–parity, is expected to be the lightest SUSY particle (LSP)] and into a bottom quark and the lightest chargino, $\tilde{t}_1 \to t\chi_1^0$ and $b\chi_1^+$, are kinematically forbidden at the tree–level. The main $\tilde{t}_1$ decay channel is then expected to be the loop–induced and flavor–changing decay into a charm quark and the LSP [3]: $\tilde{t}_1 \to c\chi_1^0$. For instance, the search for $\tilde{t}_1$ at LEP and at the Tevatron, rely in general on the fact that the branching ratio $\mathrm{BR}(\tilde{t}_1 \to c\chi_1^0)$ is close to one [4].

However, there is another decay mode which is possible in the MSSM, even if $\tilde{t}_1$ is the next–to–lightest SUSY particle [provided that $m_{\tilde{t}_1} > m_{\chi_1^0} + m_b$]: the four–body decay into a b–quark, the LSP and two massless fermions: $\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$ [5, 6]. This mode is mediated by virtual top quark, chargino, sbottom, slepton and first/second generation squark exchange, and is of the same order of perturbation theory as the decay $\tilde{t}_1 \to c\chi_1^0$, i.e. $\mathcal{O}(\alpha^3)$; in principle, it can therefore compete with the latter channel.

In this note, we reanalyze this decay mode and show that if the exchanged particles do not have a too large virtuality, it can in fact dominate over the loop induced decay channel in some areas of the MSSM parameter space. We also reanalyze the three–body decays of the $\tilde{t}_1$ state into $Wb\chi_1^0$, $H^+b\chi_0^1$ [7] and $bl^+\tilde{\nu}$, $b\tilde{l}^+\nu$ [3] final states, which are kinematically accessible for heavier stops. When the channels, $\tilde{t}_1 \to b\chi_1^+$ and $t\chi_1^0$ are closed, some of these decays also dominate over the loop induced mode.

2.2 The Loop Induced Decay Mode

If the top squarks are heavy enough, their main decay modes will be into top quarks and neutralinos, $\tilde{t}_i \to t\chi_j^0$ [j=1–4], and bottom quarks and charginos, $\tilde{t}_i \to b\chi_j^+$ [j=1–2]. If these modes are kinematically not accessible, the lightest top squark can decay into a charm quark and the lightest neutralino, $\tilde{t}_1 \to c\chi_1^0$. This mode is mediated by one–loop diagrams: vertex diagrams as well as squark and quark self–energy diagrams [where bottom squarks, charginos, charged W and Higgs bosons are running in the loops]. The flavor transition $b \to c$ occurs through the charged currents. Adding the various contributions, a divergence is left out which must be subtracted by adding a counterterm to the scalar self–mass diagrams. When working in the minimal Supergravity framework where the squark masses are unified at the GUT scale, the divergence is subtracted using a soft–counterterm at $\Lambda_{\rm GUT}$, generating a large residual logarithm $\log(\Lambda^2_{\rm GUT}/M_W^2) \sim 65$ in the amplitude. This logarithm gives the leading contribution to the $\tilde{t}_1 \to c\chi_1^0$ amplitude and makes the decay width rather large. [The decay width is though suppressed by the CKM matrix element $V_{cb} \sim 0.05$ and the (running) b quark mass squared $m_b^2 \sim (3~{\rm GeV})^2$].

However, there are scenarii in which the decay rate $\Gamma(\tilde{t}_1 \to c\chi_1^0)$ can be rather small: (i) First, the large logarithm $\log(\Lambda^2_{\rm GUT}/M_W^2) \sim 65$ appears only because the choice of the renormalization condition is made at $\Lambda_{\rm GUT}$, but in a general MSSM where the squark masses are not unified at some very high scale, one could chose a low energy counterterm; in this case no large logarithm would appear. (ii) If the lightest top squark is a pure right–handed state [as favored by the constrains [8] from high–precision electroweak data], the amplitude involves only one component which can be made small by choosing small values of the trilinear coupling A_b and/or large values of the (common) SUSY-breaking scalar mass $\tilde{m}_q$. (iii) Even in the presence of stop mixing, for a given choice of MSSM parameters, large cancellations can occur between the various terms in the loop amplitude; in addition, the t–$\tilde{t}_1$–χ_0^1 coupling, which enters as a global factor, can be very tiny.

Thus, the decay rate $\Gamma(\tilde{t}_1 \to c\chi_1^0)$ might be very small, opening the possibility for the three– or four–body decay modes to dominate. We will analyze the interplay between the three modes and concentrate in our numerical analysis on the case of the "unconstrained MSSM": we will assume a common soft scalar mass for the three generations of squarks and sleptons and for isospin $\pm 1/2$ states: $m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_R} \equiv m_{\tilde{q}}$ and $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R} \equiv m_{\tilde{l}}$ [$m_{\tilde{b}_L}$=$m_{\tilde{t}_L}$ and $m_{\tilde{\nu}_L}$=$m_{\tilde{\tau}_L}$ by virtue of SU(2) invariance]. The splitting between different particles, and in particular between the two top squarks [we will take into account the mixing not only in the stop sector, but also in the sbottom and stau sectors, where it might be significant for large values of the parameters μ and $\tan\beta$] will be then only due to the D–terms, the fermion masses and to the off–diagonal entries in the sfermion mass matrices. [Note that in this case, in most of the parameter space, the stop mixing angle is either close to $\pi/2$ (no mixing) or to $\pm\pi/4$ (maximal mixing) for respectively, small and large values of the off–diagonal entry $m_t\tilde{A}_t$ of the matrix $M^2_{\tilde{t}}$.] Furthermore, we will assume that the mixing between different generations is absent at the tree level [otherwise the mode $\tilde{t}_1 \to t\chi_1^0$ occurs already at this level].

3. The Three– and Four–Body Decay Modes

The four–body decay mode $\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$, proceeds through several diagrams, as shown in Fig. 1. There are first the W–boson exchange diagrams with virtual $\tilde{t}, \tilde{b}$ and $\chi_{1,2}^{\pm}$ states, a similar set of diagrams is obtained by replacing the W–boson by the H^+ boson and a third type of diagrams consist of up and down type slepton and first/second generation squark exchanges. The decay rate has been calculated in Ref. [6] taking into account all diagrams and interferences. The various contributions are summarized below:

i) Because in the MSSM, $H^{\pm}$ has a mass larger than M_W and has tiny Yukawa couplings to light fermions, it does not give rise to large contributions. The squark exchange diagrams give also small contributions since squarks are expected to be much heavier than the $\tilde{t}_1$ state [2]. The contribution of the diagram with an exchanged t–quark is only important if the stop mass is of the order of $m_t + m_{\chi_1^0} \gtrsim \mathcal{O}(250 \text{ GeV})$.

ii) In contrast to squarks, slepton [and especially $\tilde{\nu}$] exchange diagrams might give substantial contributions, since $\tilde{l}$ masses of $\mathcal{O}(100 \text{ GeV})$ are still experimentally allowed [2]. In fact, when the difference between $m_{\tilde{t}_1}$ and $m_{\chi_1^+}$ and $m_{\tilde{l}}$ is not large, the third diagram in Fig. 1 will give the dominant contribution to the four–body decay mode.

iii) The most significant contributions to the four–body decay mode will come in general from the first diagram in Fig. 1, when the virtuality of the chargino is not too large. In particular, for an exchanged χ_1^+ with a mass not much larger than 100 GeV, the decay width can be substantial even for top squark masses of the order of 100 GeV.

Thus, a good approximation [especially for a light top squark $m_{\tilde{t}_1} \sim \mathcal{O}(100 \text{ GeV})$] is to take into account only the lightest chargino and slepton exchange diagrams. All the other contributions can be neglected.

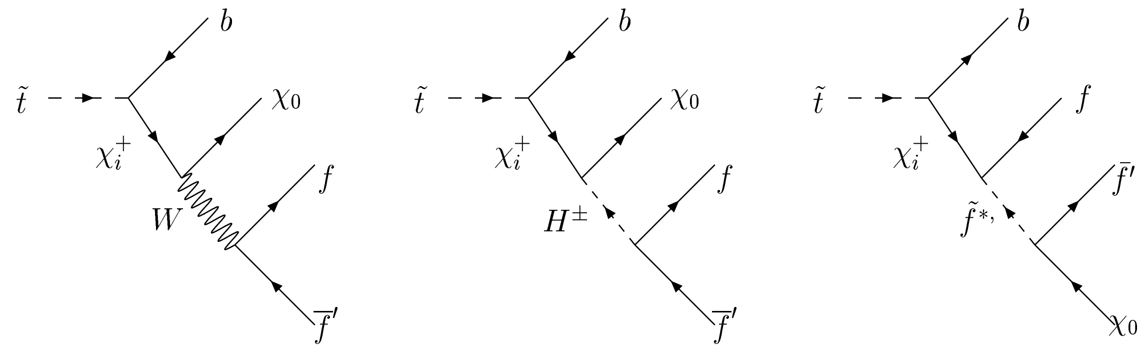

Figure 1: Generic Feynman diagrams contributing to the decay $\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$.

For larger stop masses, when the W, the $H^{\pm}$ boson and/or the sfermion $\tilde{f}^*$ are kinematically allowed to be on mass–shell, one will then have a three–body decay mode of the $\tilde{t}_1$. These modes have been discussed earlier in Refs. [3, 7]. We have recalculated [9] the partial decay widths of all these three–body decay modes: $\tilde{t}_1 \to Wb\chi_1^0,\ H^+b\chi_0^1$ and $bl^+\tilde{\nu},\ b\tilde{l}^+\nu$. When kinematically possible, some if these channels will also continue to dominate over the loop induced mode in some areas of the MSSM parameter space.

4. Numerical examples

In the subsequent numerical results for the four–body decays, we include the contributions of all diagrams and show the branching ratio $\mathrm{BR}(\tilde{t}_1 \to b\chi_1^0 f\bar{f}')$ in the unconstrained MSSM scenario discussed above, for stop masses in the range $m_{\tilde{t}_1} = 100$–200 GeV, accessible at a future e^+e^- linear collider with c.m. energies around $\sqrt{s} \sim 500$ GeV. For the gaugino sector, we have chosen the value $\tan\beta = 2.5$ [to suppress the rate for the loop induced decay mode which dominates for high values of $\tan\beta$], a gaugino mass parameter $M_2 = 200$ GeV [to allow for light charginos and neutralinos] and three values of the higgsino mass parameter $\mu = 300, 450$ and 700 GeV. This leads to the $(m_{\chi_1^0}, m_{\chi_1^\pm})$ couples [in GeV]: $(87.8, 163), (91.8, 181)$ and $(93.8, 190)$. The trilinear coupling A_t is varied to fix $m_{\tilde{t}_1}$ while the coupling A_b is fixed to $A_b = -100$ GeV; M_A is taken to be 500 GeV.

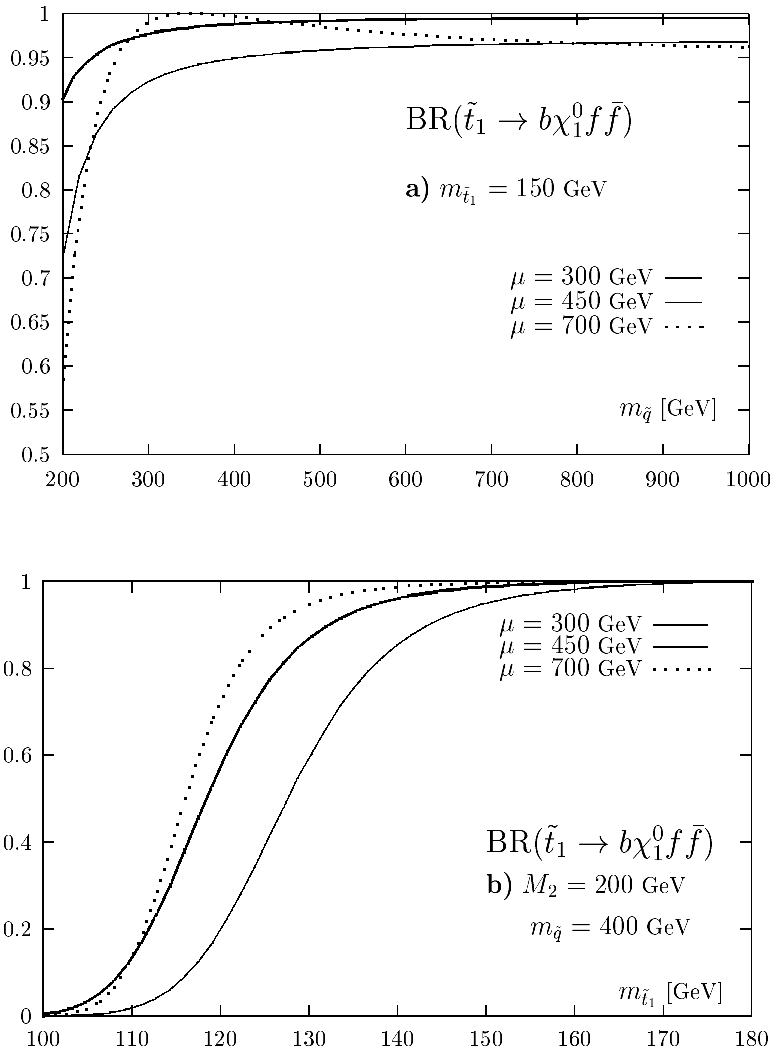

Figure 2: The branching ratio $\mathrm{BR}(\tilde{t}_1 \to b\chi_1^0 f\bar{f}')$ as a function of $m_{\tilde{q}}$ for $m_{\tilde{t}_1} = 150$ GeV (a) and as a function of $m_{\tilde{t}_1}$ for $m_{\tilde{q}} = 400$ GeV (b); $\tan\beta = 2.5$.

In Fig. 2a, BR($\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$) is shown as a function of the soft SUSY breaking scalar mass $m_{\tilde{q}}$ for $m_{\tilde{t}_1} = 150$ GeV. One sees that it is larger than 95% for almost all values of the parameter $m_{\tilde{q}}$. This is first due to the fact that the phase space is favorable in this case [i.e. the virtuality of the chargino is relatively small], and also because for this particular choice of parameters, there are large cancellations in the amplitude for the decay width $\Gamma(\tilde{t}_1 \to c\chi_1^0)$. Fig. 2b shows BR($\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$) as a function of $m_{\tilde{t}_1}$ for a fixed value of the common squark and slepton mass $m_{\tilde{q}} = m_{\tilde{l}} = 400$ GeV, and for the same parameters $\tan\beta$, μ and M_2 as before. As can be seen, the branching ratio is very small in the lower stop mass range where the virtuality of the exchanged chargino is rather large, and increases with increasing $m_{\tilde{t}_1}$ to reach values close to unity near the $m_{\tilde{t}_1} \sim m_b + m_{\chi_1^+}$ threshold where the two–body decay mode $\tilde{t}_1 \to b\chi_1^+$ opens up.

In the previous figure, sleptons were taken too heavy to contribute substantially to the decay rate $\Gamma(\tilde{t}_1 \to b\chi_1^0 f\bar{f}')$ since we assumed the common slepton mass to be $m_{\tilde{l}} = m_{\tilde{q}} > 200$ GeV. In Fig. 3, we relax the assumption $m_{\tilde{l}} = m_{\tilde{q}}$ and show BR($\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$) as a function of the sneutrino mass $m_{\tilde{\nu}}$ [the masses of the other sleptons are then fixed and are of the same order of magnitude] for $m_{\tilde{t}_1} = 80$ GeV, $M_2 = 120$ GeV, $\mu = 300$ GeV and three values of $m_{\tilde{q}} = 300, 500$ and 800 GeV. As can be noticed, the contribution of sleptons can substantially enhance the four–body decay branching ratio for relatively small values of $m_{\tilde{l}}$. For larger values, the sleptons become too virtual and we are left only with the contribution of the chargino $\chi_1^\pm$ discussed above.

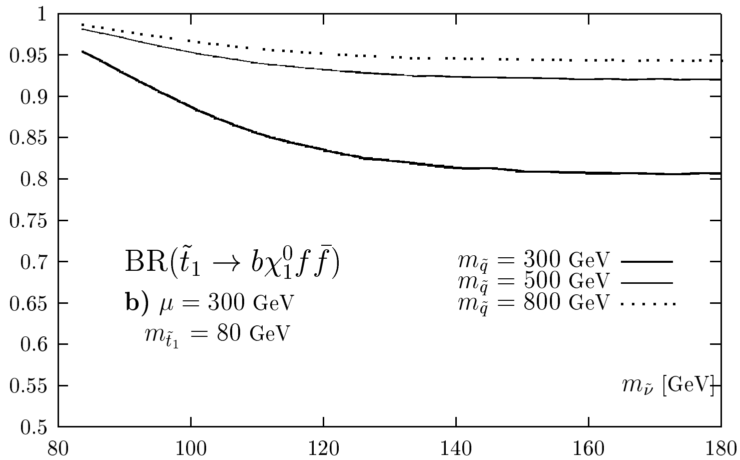

Figure 3: The branching ratio BR($\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$) as a function of $m_{\tilde{\nu}}$ for $m_{\tilde{t}_1} = 80$ GeV.

Let us now turn to the three–body decay modes. If the lightest top squark has a mass $m_{\tilde{t}_1}$ smaller than $m_t + m_{\chi_1^0}$ and $m_b + m_{\chi_1^+}$ but larger than $m_{\chi_1^0} + M_W$, the decay channel $\tilde{t}_1 \to bW^+\chi_1^0$ opens up kinematically and would dominate. For large values of μ where the lightest charginos and neutralinos are gaugino–like with masses $m_{\chi_1^0} \sim m_{\chi_1^+}/2$, this would occur for $m_{\chi_1^0}$ values larger than M_W and thus $\tilde{t}_1$ masses in excess of ~ 200 GeV. This is also the case for the channel $\tilde{t}_1 \to bH^+\chi_1^0$, which though has a less favorable phase space due the larger $H^\pm$ mass expected in the MSSM: $M_{H^\pm}^2 = M_W^2 + M_A^2$ which leads, with the LEP2 bound $M_A \gtrsim 90$ GeV [2], to $M_{H^\pm} \gtrsim 120$ GeV. If the $\tilde{t}_1$ is heavier than charged sleptons and/or sneutrinos, the decay channels $\tilde{t}_1 \to bl^+\tilde{\nu}$ and $\tilde{t}_1 \to b\tilde{l}^+\nu$, would also occur. Since these three–body decay modes are of $\mathcal{O}(\alpha^2)$, they can compete with the $\tilde{t}_1 \to c\chi_1^0)$ mode which is of $\mathcal{O}(\alpha^3)$ modulo the large logarithm $\log(\Lambda_{\rm GUT}/M_W^2)$.

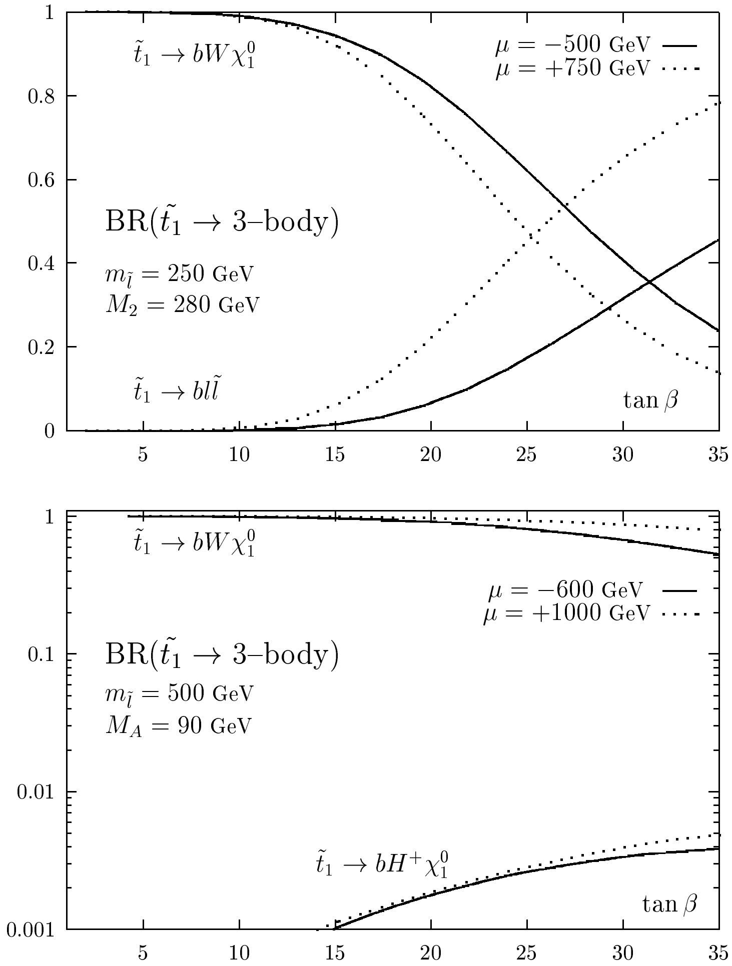

Figure 4: The branching ratios as a function of $\tan\beta$ for the three–body modes $\tilde{t}_1 \to bW\chi_1^0,\ bl\tilde{l}$ (a) and $bW\chi_1^0,\ bH^+\chi_1^0$ (b) for a set of $\mu, m\tilde{l}$ and M_A values; $m_{\tilde{t}_1} = 250$ GeV.

This is shown in Fig. 4 where we display the branching ratios for these modes for a stop mass $m_{\tilde{t}_1} = 250$ GeV as a function of $\tan\beta$. In Fig. 4a, where a relatively small common slepton mass $m_{\tilde{l}} = 250$ GeV is assumed, BR($\tilde{t}_1 \to bW^+\chi_1^0$) dominates for small $\tan\beta$ values and BR($\tilde{t}_1 \to b\tilde{l}l'$) for very large values: in the latter case, the mixing in the $\tilde{\tau}$ sector is very strong leading to light $\tilde{\tau}_1$ states with enhanced Yukawa couplings. In Fig. 4b, where the $\tilde{t}_1 \to b\tilde{l}l'$ is kinematically closed because of the choice $m_{\tilde{l}} = 500$ GeV, only the modes $\tilde{t}_1 \to bW^+\chi_1^0$ and $\tilde{t}_1 \to c\chi_1^0$ are in competition: because the $H^\pm$ boson has a relatively large mass, $M_{H^\pm} \sim 120$ GeV, and tiny Yukawa couplings to light fermions [even the couplings to τ leptons are not strong enough in this case], BR($\tilde{t}_1 \to bH^+\chi_1^0$) does not reach the percent level.

5. Conclusions

We have analyzed the four–body decay mode of the lightest top squark into the lightest neutralino, a bottom quark and two massless fermions, $\tilde{t}_1 \to b\chi_1^0 f\bar{f}'$, in the MSSM. We have shown that it can dominate over the loop–induced decay into a charm quark and the LSP, $\tilde{t}_1 \to c\chi_1^0$, if charginos and sleptons have masses not too much larger than the $\tilde{t}_1$ mass. In particular, for top squarks with masses of the order of 100–200 GeV which can be thus produced at a future e^+e^- linear collider with a center of mass energy $\sqrt{s} \sim 500$ GeV, this decay mode should be taken into account in the search for this particle.

We have also discussed the three–body decay modes of the lightest top squark: $\tilde{t}_1 \to Wb\chi_1^0$, $H^+b\chi_0^1$ and $bl^+\tilde{\nu}$, $b\tilde{l}^+\nu$, which possibly open up for relatively larger $\tilde{t}_1$ mass values. Some of these processes, in particular the ones with W bosons and slepton final states if kinematically allowed, can also largely dominate over the loop induced decay into a charm quark and the LSP.

These decay modes lead to final states with b–quarks, multi–leptons and/or multi–jets and a large amount of missing energy due to the escaping LSPs. These signals would be rather easy to detect in the clean environment of e^+e^- colliders [10].

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