CERN-TH/20002-305
hep-ph/0210425

Three-body decays of $\tilde{\chi}_1^0$ in $R\!\!\!/_p$ models with dominant λ and λ' couplings *

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Decays of the lightest neutralino are studied in R_p-violating models, with operators $\lambda' LQD^c$ and λLLE^c involving third-generation matter fields and with dominant λ' and λ couplings. Decays with the top-quark among the particles produced are considered, in addition to those with an almost massless final state. Phenomenological analyses for examples of both classes of decays are presented. No specific assumption on the composition of the lightest neutralino is made. Our formulae can easily be generalized to study decays of heavier neutralinos. We also discuss effects of the $R\!\!\!/_p$ decays of the $\tilde{\chi}_1^0$ on the possible faking of the $H^{\pm}$ signal at the LHC by the recently pointed out $\tilde{\tau}\bar{b}t$ production through λ'_{333} coupling.

*Talk presented at the the 10th international conference on supersymmetry and unification of fundamental interactions, SUSY02, June 17-23, 2002, Hamburg (Germany).

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ABSTRACT

Decays of the lightest neutralino are studied in R_p-violating models with operators $\lambda' LQD^c$ and λLLE^c, involving third-generation matter fields and with dominant λ' and λ couplings. Decays with the top-quark among the particles produced are considered, in addition to those with an almost massless final state. Phenomenological analyses for examples of both classes of decays are presented. No specific assumption on the composition of the lightest neutralino is made. Our formulae can easily be generalized to study decays of heavier neutralinos. We also discuss effects of the $\not{R}_p$ decays of the $\tilde{\chi}_1^0$ on the possible faking of the $H^\pm$ signal at the LHC by the recently pointed out $\tilde{\tau}\bar{b}t$ production through λ'_{333} coupling.

Introduction

TeV scale Supersymmetry (SUSY) is theoretically the most attractive way of stabilizing the mass of the Higgs boson against radiative corrections, around the electroweak symmetry (EW) breaking scale. Hence, SUSY searches, along with those for the Higgs boson, form the focus of physics studies at the current and future colliders. In the simplest version of SUSY models one assumes conservation of a quantum number $R_p \equiv (-1)^{3B+L+2S}$, where S stands for the spin of the particle. The conservation of this quantum number is guaranteed only if the superpotential is invariant under the discrete R_p symmetry. However, there really is no deep theoretical reason for this symmetry. As a matter of fact, it is possible to have R_p-violating terms in the superpotential while respecting supersymmetry as well as invariance under the SM gauge transformation. These are given by

$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k + \kappa_i L_i H_2. \qquad (1)$$

Here L_i,Q_i are the doublet lepton, quark superfields, and E_i, U_i, D_i the singlet lepton, quark superfields, i being the generation index. The above necessarily mean non-conservation of the baryon number B and/or the lepton number L. The $\not{L}$ couplings allow the generation of ν masses in an economical way without introducing any new fields. The contribution from the trilinear λ, λ' comes at the one- or two-loop level and the bilinear

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κ_i generate it at tree level [1]. The Kamioka and SNO experiments now give an unambiguious evidence for ν masses. In SUSY models with $\not{R}_p$, there exists enough freedom to generate observed mass patterns with sparticle masses in the TeV range, and hence with clean predictions for collider searches. This interplay between indirect constraints, coming from ν physics and the collider signals of $\not{R}_p$ SUSY is a very interesting aspect of the $\not{R}_p$ SUSY studies. Of course the simultaneous existence of the λ' and λ'' couplings and TeV scale masses for the sfermions will mean a very rapid proton decay. This can be cured by adopting B conservation, i.e. $\lambda'' = 0$. This choice is actually preferred if $\not{R}_p$ terms are not to wash out baryogenesis. Unified string theories actually prefer models with B conservation and $\not{R}_p$ [2]. These models treat the lepton and the quark fields differently and have two discrete symmetries. B conservation and $\not{R}_p$ eliminate not just the dimension-4 operators for proton decay but also the dimension-5 operators. Needless to say that all this makes $\not{R}_p$ theoretically very interesting.

Of course the large number, 48 as per Eq. (1), of these essentially Yukawa-type couplings, with no theoretical indications about their sizes, is not a very satisfactory feature of $\not{R}_p$ SUSY. Luckily many of these unknown couplings are constrained by low energy processes such as p/μ decay, ν masses or cosmological arguments like generating the right amount of baryon asymmetry in the early Universe. There exist a host of constraints on $\not{R}_p$ couplings [3]. Most of the constraints come from virtual effects caused by sparticles in loops and some from direct collider searches. Many of these get less severe with increasing number of the third-generation indices of the involved couplings. The constraints on the $\not{L}$ couplings coming from ν masses can be particularly severe but may also depend on model assumptions. Hence a study of the *same* couplings in a collider environment, can certainly help to clarify model building.

R_p violation at the colliders

Effects of $\not{R}_p$ at colliders fall into qualitatively different classes, depending on the size of the $\not{R}_p$ couplings. The one effect that is always present is an unstable lightest supersymmetric particle (LSP), which need not even be the $\tilde{\chi}_1^0$. If at least one of the $\not{R}_p$, λ, λ' couplings is $> 10^{-6}$, the LSP will decay in the detector. In our work we consider the case of these $\not{L}, \not{R}_p$ couplings and take the $\tilde{\chi}_1^0$ to be the LSP. The decays of the LSP $\tilde{\chi}_1^0 \to f \bar{f}_1 f_2$ can give rise to strikingly different final states [4] as compared to the SUSY signal with R_p conservation. For masses of $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}$ of interest at the LHC and NLC, even a t in the final state will be allowed. For larger $\not{R}_p$ couplings, decays of particles and sparticles other than the LSP via $\not{R}_p$ interactions [5, 6, 7] can take place. For example, $\tilde{t} \to bl, t \to b\tilde{l}$. These then may compete with the R_p-conserving decays. The $\not{R}_p$ couplings can also give contributions to tree level processes due to virtual sparticle exchange, such as $pp \to \mu^+\mu^-$ [8, 7] or $pp(p\bar{p}) \to t\bar{t}X$. In the last case the interference terms give rise to non-vanishing t polarization [9], which can be probed by the decay lepton energy/angular distribution [10]. In addition, for large enough $\not{R}_p$ couplings, one also has resonant or non-resonant production of a single sparticle via the $\not{R}_p$ couplings [11, 12, 13]. For example, much as H^- produced via $t\bar{b}H^-$ coupling, one can also have $pp \to t\bar{b}\tilde{\tau}$ via λ'_{333} as shown in Figure 1. A few points are worth noting. The production cross-section is appreciable

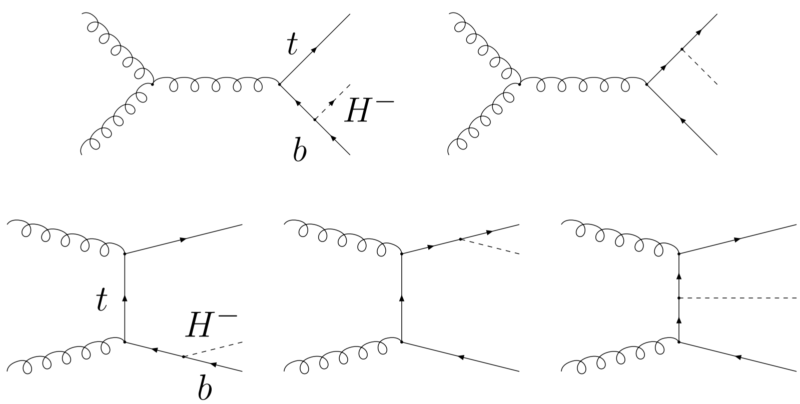

Figure 1: The different $2 \to 3$ subprocesses contributing to $H^+/\tilde{\tau}$.

even, for $m_{\tilde{t}} > m_t$ and for λ'_{333} as small as 0.05. $\tilde{\tau}$ so produced will have both $\not{R}_p$ and R_p-conserving decays. The latter will produce $\tilde{\chi}_1^0$, which will further decay through some $\not{R}_p$ coupling. Some of these decays can fake the charged Higgs signal. This can be seen in a little more detail as follows. For large $\lambda'_{333}, \tilde{\tau}'$s can have the R_p conserving decays, $\tilde{\tau} \to \tau\tilde{\chi}_1^0$ and $\tilde{\tau} \to \nu_\tau\tilde{\chi}_1^-$ for $m_t > m_{\tilde{\tau}}$, whereas for $m_t < m_{\tilde{\tau}}$, it can also have the $\not{R}_p$ decay $\tilde{\tau} \to b\bar{t}$. The net final state produced will then be decided by relative branching ratios of $\tilde{\chi}_1^0, \tilde{\chi}_1^+$ into different channels. Production of $\tilde{\tau}$ through $\not{R}_p$ couplings and its decay via the *same* will give rise to $pp \to t\bar{b}\tilde{\tau}X \to t\bar{b}t\bar{b}X$. Note that this is the same final state as the $H^\pm$. A comprehensive study of the H^+ signal at the LHC, in this case, will thus require full analysis of the three-body decays of the $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$. The R_p-conserving decays of the $\tilde{\tau}$ followed by the $\not{R}_p$ decays of the $\tilde{\chi}_1^0$ from the $\tilde{\tau}$ decay can also produce

$$\begin{aligned} pp \to t\bar{b}\tilde{\tau}X &\to (2t)(2b)(2\tau)X \\ &\to tb\ (2\bar{b})\ \tau\nu_\tau X, \end{aligned} \tag{2}$$

etc. These will then give rise to the characteristic $\not{L}$ signal of like-sign fermion pairs.

As mentioned already, of particular importance are the possibilities of testing the low energy constraints, in 'direct' signals at the colliders. Since the third generation sfermions are expected to be lighter, they may give rise to larger virtual effects. For $\tilde{\chi}_1^0, \tilde{\chi}_1^+$ with masses of interest at the LHC, NLC, final states with third-generation fermions including t are possible. One needs a study of the $\not{R}_p$ decays of $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$ retaining effects of the mass of the third-generation fermions, for $\not{L}$ coupling.

We therefore calculated three-body $\not{R}_p$ decays of the $\tilde{\chi}_1^0$ with dominant λ, λ' couplings involving at least two third-generation indices. We kept the mass effects of the third-generation fermions and the sfermion L–R mixing terms complex and analysed

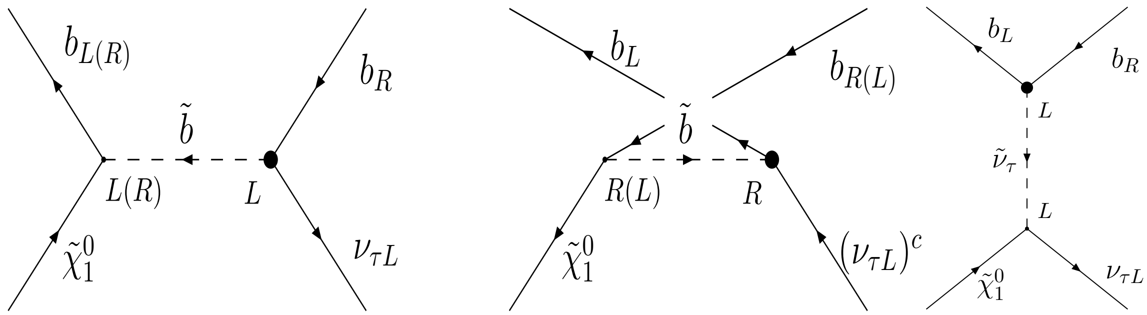

Figure 2: Diagrams contributing to the three body decay $\tilde{\chi}_1^0 \to b\bar{b}\nu_\tau$.

numerically for cases with unified/ununified gaugino masses, including the effect of subdominant λ, λ'.

Three-body decays of the $\tilde{\chi}_1^0$

In this section we present the results for the above-mentioned case of dominant λ'_{333} coupling. The calculation and the results can be trivially generalized [3] to cases of other couplings, dominant or subdominant. Figure 2 shows the diagrams contributing to the three-body decay $\tilde{\chi}_1^0 \to b\bar{b}\nu_\tau$. If $m_{\tilde{\chi}_1^0} > m_t$, then the decay into a massive final state containing t, viz. $\tilde{\chi}_1^0 \to \bar{b}t\nu_\tau$ + C.C., is also possible. Our expressions for the decay widths [3] are the most general in that they include the effect of the finite fermion masses and are applicable to the case of complex L–R mass term. In the limit of real L–R sfermion mass terms, these agree with the earlier calculations [14] with finite fermion mass and, in the limit of zero fermion mass, they agree with those of Refs. [15, 16] up to the corrections pointed out in Ref. [14].

The decay widths clearly depend on the L–R mixing in the sfermion sector as well as on the composition of the $\tilde{\chi}_1^0$. For example, for a Wino-like $\tilde{\chi}_1^0$, in the absence of L–R mixing, the second diagram with a $\tilde{b}_R$ exchange will not contribute. A substantial gaugino/higgsino mixing causes the width into the massive mode to be large at low $\tan\beta$, whereas for large $\tan\beta$ it is the massless mode that gets enhanced, compared to the corresponding widths for unmixed cases.

As an illustration, the results for the $\tilde{\chi}_1^0$ widths into massive and massless modes, for $\lambda'_{333} = 1$ and $M_{\tilde{\chi}_1^0} = 600$ GeV, are presented in Figure 3 as a function of m_*, the squark mass scale. We use two different choices of L–R mixing in the squark sector and different compositions of the $\tilde{\chi}_1^0$. The massive decay mode has a large width for low $\tan\beta$ and large higgsino–gaugino mixing. Otherwise the massless mode is larger, although the massive mode is non-negligible. From the left panel we see that, for a $\tilde{\chi}_1^0 \sim \tilde{W}$, the widths are enhanced by an order of magnitude with respect to the case of a $\tilde{\chi}_1^0 \sim \tilde{B}$. The right panel shows that with moderate L–R squark mixing, even for a $\tilde{\chi}_1^0 \sim \tilde{W}$, the $\tilde{b}$-mediated diagram contributes to the massive mode. Further the figures also show that smaller $\tilde{t}_1, \tilde{b}_1$,

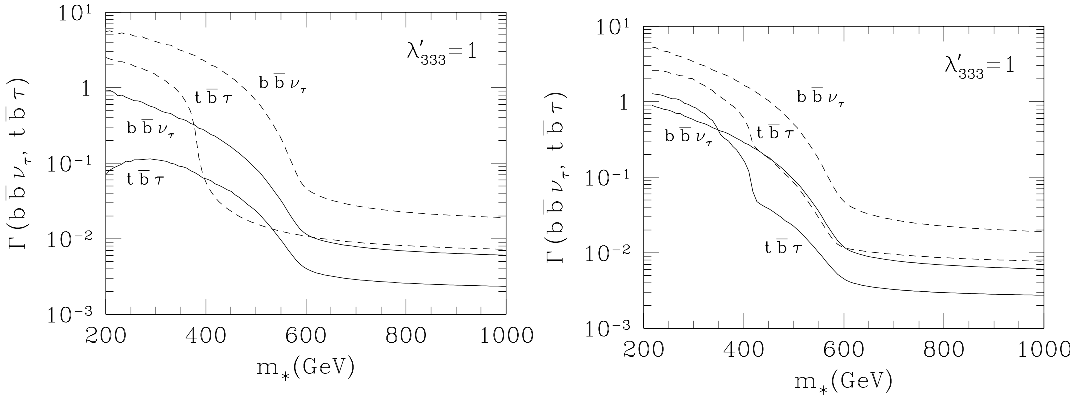

Figure 3: Left panel shows $\tilde{\chi}_1^0$ widths for no L–R squark mixing and the right one for moderate mixing. Dashed and solid lines are for a Wino-like and Bino-like $\tilde{\chi}_1^0$ respectively. In case of non-zero mixing, $A_t - \mu \cot\beta = 150$ GeV, $A_b - \mu \tan\beta = 2000$ GeV. m_* is a squark mass scale.

masses enhance the width for the massive mode for a $\tilde{B}$-like $\tilde{\chi}_1^0$. For the same reasons the widths into the massive and massless final state also depend on the value of $\tan\beta$.

Figure 4 shows the $b\bar{b}\nu_\tau, t\bar{b}\nu$ decay widths, as a function of the squark mass scale m_*. The massive mode dominates at lower $\tan\beta$ and the massless one for the higher values. Thus, to summarize, we find that with λ'_{333} dominant, the massive decay has a large width for low $\tan\beta$ and large higgsino–gaugino mixing. Otherwise the width for the massless mode is larger, though that for massive mode is also non-negligible. All the plots have been shown for $\lambda'_{333} = 1$. In the resonant sfermion region one finds very little dependence of the width on λ'_{333} and otherwise the widths for other values of the couplings simply scale down like λ'^2_{333}.

The analysis can be easily generalized to the case where there are more than one large $\not{R}_p$ couplings, and the results are shown in Figure 5. We notice that the widths into different final states are not too dissimilar, and more importantly the branching ratio into a final state with t is not too small.

Conclusions

It is important to have a collider probe of the $\not{R}_p$ λ and λ' couplings with more than one third-generation index. Further, single charged slepton production via the $\not{R}_p$ coupling λ'_{i33} can produce final states, which can be confused with the $H^\pm$ signal. Even for smaller but dominant $\not{R}_p$ λ and λ' couplings with more than one third-generation index, the three-body $\not{R}_p$ decays of $\tilde{\chi}_1^0, \tilde{\chi}_1^+$ can have important phenomenological consequences for new particle searches at the future colliders. If the $\tilde{\chi}_1^0$ is 'Wino'-like, its decay widths increase by over an order of magnitude. If the $\tilde{\chi}_1^0$ is lighter than the t, its $\not{R}_p$ decays will be dominantly into massless fermions: $b\bar{b}\nu_\tau$ for dominant λ'_{333} coupling, $c\bar{b}\tau, s\bar{b}\nu_\tau$ and the

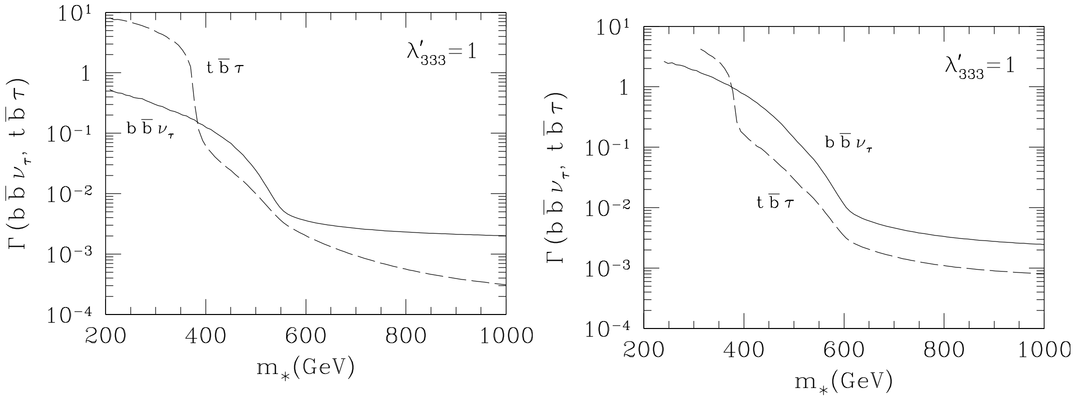

Figure 4: Solid lines show the $\tilde{\chi}_1^0$ decay width for the $b\bar{b}\nu_\tau$ channel and dashed lines for the $t\bar{b}\nu$ channel. The left panel is for $\tan\beta = 3$ with the trilinear soft term being 350 GeV whereas in the right panel $\tan\beta = 30$ and the trilinear soft term is 150 GeV. $m_{\tilde{B}}$, slepton mass and μ are all taken to be 600 GeV.

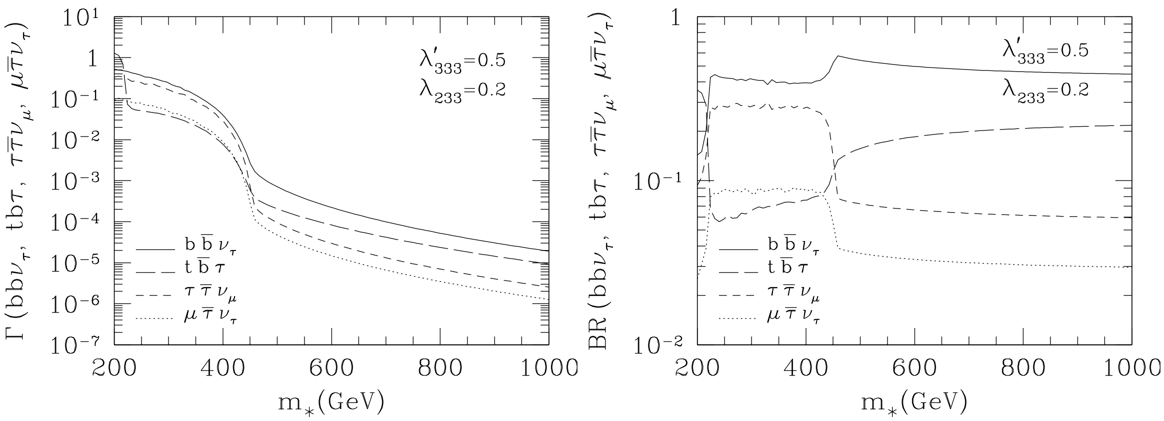

Figure 5: Left panel shows the decay widths of $\tilde{\chi}_1^0$ for $\lambda'_{333} = 0.5, \lambda_{233} = 0.2$ for various final states as indicated in the figure. The right panel shows branching ratios for the same. These are for no L–R mixing, $\mu = 500$ GeV, $\tan\beta = 3$ and $m_{\tilde{B}} = 500$ GeV.

charge conjugate modes $\bar{c}b\bar{\tau}, \bar{s}b\bar{\nu}_\tau$ for dominant λ'_{323}, and for λ_{233} into $\bar{\mu}\tau\nu_\tau$ and $\mu\bar{\tau}\bar{\nu}_\tau$. For a $\tilde{\chi}_1^0$ heavier than the t, the massive decay modes can become competitive for large L–R sfermion mass term and/or for substantial mixing in the higgsino/gaugino sector, at not too large $\tan\beta$. All the $\not{R}_p$ decays of the $\tilde{\chi}_1^0$ produce final states with like-sign dileptons as the tell-tale signature of the $\not{L}$, as long as the final state t decays hadronically.

Acknowledgements
I wish to thank my collaborators F. Borzumati, J.L. Kneur and F. Takayama for a nice collaboration, which resulted in the publication on which this talk is based.

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