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Signals for charginos/neutralinos in R-parity-violating Supersymmetric theory at a 500 GeV e^+e^- Collider

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Abstract

We investigate the production of charginos and neutralinos at a 500 GeV e^+e^- collider (NLC) and study their decays to the lightest neutralino, which then decays into multi-fermion final states through couplings which do not conserve R-parity. Detailed analyses are performed for five selected points in the parameter space.

Most search strategies for SUSY are based on the famous missing energy and momentum signature generated by undetected neutralino LSP(s). In the canonical form of the MSSM [1], the LSP is constrained to be stable (and weakly-interacting) because of conservation of R-parity [2], which is defined as $R = (-1)^{3B+L+2S}$. However, the gauge symmetry of the MSSM allows us to write terms in the superpotential which violate R-parity. The strongest constraint on these comes from the fact that the presence of *all* these terms can lead to catastrophically high rates for proton decay — a constraint which is easily avoided if we have R-parity-violating terms which violate only L or B, but not both. This leaves us only with rather weak phenomenological bounds on the individual L or B-violating couplings.

If we allow for non-conservation of R-parity, the LSP need no longer be stable and we can determine its decay modes. Since this can radically change the character of the missing energy signal for supersymmetry it is necessary to make a re-evaluation of supersymmetry signals assuming that the LSP *can* decay. While several such studies have been undertaken at the present generation of high-energy colliders [3], it is really to the clean environment of a 500 GeV linear e^+e^- collider (NLC) [4] that we must look if we wish to find unambiguous signals for R-parity-violating supersymmetry. What distinguishes our analysis from similar studies at LEP-2 is the higher collision energy, which opens up the possibility of copious production of the *heavier* chargino and neutralino states. Their cascade decays add to the signals, but also introduce additional complications because of the multiplicity of possible final states. We present here a first attempt to sort out these possibilities and obtain distinguishable signals.

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The particular scenario discussed in this work is the so–called *weak limit* of R-parity violation [5], where the R-parity-violating couplings are considerably smaller than the gauge couplings. As a result, most production and decay processes — apart from the LSP decay — in this analysis will take place along the lines expected in the R-parity-conserving case. However, we still require the couplings relevant for decay of the neutralino LSP to be large enough to ensure that it decays within the detector.

At a linear e^+e^- collider, in the weak R-parity-violation limit, the principal sparticle production channels are

1. production of a pair of similar/dissimilar charginos $e^+e^- \to \widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^{\mp}$ where $i,j = 1,2$;
2. production of a pair of similar/dissimilar neutralinos $e^+e^- \to \widetilde{\chi}_i^0\widetilde{\chi}_j^0$ where $i,j = 1,2,3,4$;
3. production of a pair of similar/dissimilar (charged) sleptons of the same flavour $e^+e^- \to \widetilde{\ell}_a\widetilde{\ell}_b^*$ where $a,b = L,R$;
4. production of a pair of sneutrinos of the same flavour $e^+e^- \to \widetilde{\nu}_\ell\widetilde{\nu}_\ell^*$ where $\ell = e,\mu,\tau$;
5. production of a pair of similar/dissimilar squarks of the same flavour $e^+e^- \to \widetilde{q}_a\widetilde{q}_b^*$ where $a,b = L,R$.

As a first exercise we concentrate on the first two, *i.e.* the production of gauginos only. The cross sections for gaugino production depend critically on the masses and mixing angles of charginos and neutralinos, which, in turn, depend on the parameters $M_2, \mu, \tan\beta$ of which the mass matrices are made up (assuming gaugino mass unification at a high scale) and on the selectron masses. At a 500 GeV machine, given the LEP-2 constraints [6] on the MSSM parameter space, it turns out to be rather difficult to produce the heavier charginos $\widetilde{\chi}_2^{\pm}$ or the heavier neutralinos $\widetilde{\chi}_3^0$ and $\widetilde{\chi}_4^0$, except in narrow regions of the parameter space where both the charginos or all the neutralinos are light. However, the lighter states, $\widetilde{\chi}_1^{\pm}, \widetilde{\chi}_1^0, \widetilde{\chi}_2^0$, can be freely produced.

Why is this? Part of the answer is given by kinematics: the current bounds[6] on the $\widetilde{\chi}_1^{\pm}$ mass from LEP-2 force the heavier states $\widetilde{\chi}_3^0$, $\widetilde{\chi}_4^0$ and $\widetilde{\chi}_2^{\pm}$ to have masses fairly close to the kinematic reach of a 500 GeV machine. This is illustrated in Fig. 1, where we have shown scatter plots of the heavier chargino and neutralino masses as M_2 varies over the range 0 to 600 GeV, μ varies from -600 to 600 GeV and $\tan\beta$ varies from 1.5 to 50. Clearly, when there is no experimental constraint on the MSSM, all the states are well within the kinematic reach of a 500 GeV machine (which corresponds to the 250 GeV box). Imposition of the LEP-2 constraint $\widetilde{\chi}_1^{\pm} > 91$ GeV[4] immediately drives the heaviest chargino and neutralino states (practically) out of the box, while the intermediate states $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_3^0$ are driven to heavier, but not kinematically inaccessible values. One can therefore, safely write off the $\widetilde{\chi}_4^0$ and $\widetilde{\chi}_2^{\pm}$ states. It only remains, therefore, to ask whether it is relevant to include the $\widetilde{\chi}_3^0$ in our analysis. For this, the *dynamics* of the production cross section(s) must be considered. It turned out that the production cross-section of $\widetilde{\chi}_3^0$ in association with a LSP, $\widetilde{\chi}_1^0$, is as severly suppressed compared to the lighter neutralino states as is the case of heavy chargino. Thus, we may feel justified in neglecting the $\widetilde{\chi}_3^0$ as well as the heavier $\widetilde{\chi}_4^0$ and $\widetilde{\chi}_2^{\pm}$ states.

[4]The present limit is 102 GeV

It is interesting to look at the graphs on the extreme right of Fig. 1. These would correspond to the (disappointing) situation when a 500 GeV e^+e^- collider has completed its run without finding any evidence of supersymmetry and has been able to push the lower bound on the mass of the lighter chargino to $\sim$ 250 GeV. It is likely that the machine would then be upgraded to 1 TeV in energy[4], kinematic limits for which correspond to the outer boxes in the figure. In this case, we see that the same pattern repeats itself, with the heavier states being pushed almost out of the picture. Thus the broad conclusions of this work would still hold in the newer context and almost identical studies can be made. Our analysis is, therefore, confined to these light states only.

Though our analysis is limited to gaugino prodution, a few comments about sneutrino and charged selectron production are in order. For our analysis we have chosen the selectron masses to be $M_{\widetilde{e}_L} = M_{\widetilde{e}_R} = 150$ GeV. It should be possible to pair-produce selectrons of this mass at the 500 GeV NLC. Each of these selectrons can have the following decays: (a) to an electron and a neutralino; (b) to a neutrino and a chargino (left selectron only); (c) to a lepton and a neutrino (if there are L-violating operators of the $LL\bar{E}$ form), or a pair of quarks (if there are L-violating operators of the $LQ\bar{D}$ form). Of these channels, in the weak R-parity-violation limit, we can neglect (c). For a right selectron, this means a unit branching ratio into electron and neutralino. For a pair of left selectrons, we can have in the final states:

$$e^+e^-\widetilde{\chi}^0\widetilde{\chi}^0, \qquad e^+\nu\widetilde{\chi}^0\widetilde{\chi}^-, \qquad e^-\bar{\nu}\widetilde{\chi}^0\widetilde{\chi}^+, \qquad \nu\bar{\nu}\widetilde{\chi}^+\widetilde{\chi}^-,$$

where all possible neutralinos and charginos allowed by kinematics will contribute. The first channel usually has the largest branching ratio and will have essentially the same signals as those which form the subject of this article, together with an extra electron–positron pair with large energies and transverse momenta. For the other signals, the chargino will decay through its gauge couplings to $\widetilde{\chi}^\pm_i \longrightarrow \widetilde{\chi}^0_j f\bar{f}'$ where f and f' are fermions differing by one unit in charge. Thus we will have a pair of neutralinos in the final state, accompanied by various combinations of electrons, jets and neutrinos contributing to missing energy. One possible difference between the leptons arising out of slepton decay and those arising out of neutralino decay is the existence of edges in the p_T spectrum. Another possibility which, in general, needs to be considered, is that of production of a pair of sneutrinos $\widetilde{\nu}_e$. The decay modes will be analogous to those of the selectron, with similar final states. A comprehensive discussion of all these signals is desirable, but is beyond the scope of this work, which concentrates on pair-production and decay of charginos and neutralinos. However, we can guess that the signals and analysis will be very similar.

We have chosen, for detailed analysis, five particular points in the MSSM parameter space which are allowed by the current LEP data and where the masses and mixings of the gaugino and higgsino states have different (but typical) features. These five points are

$$
\begin{array}{lllll}
(\mathbf{A}) & M_2 = 100 \text{ GeV}, & \mu = -200 \text{ GeV}, & \tan\beta = 2, & M_{\tilde{e}_L} = M_{\tilde{e}_R} = 150 \text{ GeV}, \\
(\mathbf{B}) & M_2 = 150 \text{ GeV}, & \mu = +150 \text{ GeV}, & \tan\beta = 20, & M_{\tilde{e}_L} = M_{\tilde{e}_R} = 150 \text{ GeV}, \\
(\mathbf{C}) & M_2 = 150 \text{ GeV}, & \mu = +250 \text{ GeV}, & \tan\beta = 2, & M_{\tilde{e}_L} = M_{\tilde{e}_R} = 150 \text{ GeV}, \\
(\mathbf{D}) & M_2 = 150 \text{ GeV}, & \mu = -250 \text{ GeV}, & \tan\beta = 20, & M_{\tilde{e}_L} = M_{\tilde{e}_R} = 200 \text{ GeV}, \\
(\mathbf{E}) & M_2 = 200 \text{ GeV}, & \mu = -250 \text{ GeV}, & \tan\beta = 20, & M_{\tilde{e}_L} = M_{\tilde{e}_R} = 200 \text{ GeV}.
\end{array}
$$

for which the masses of the gaugino states are given in Table 1.

Point	Particle	Mass	Particle	Mass
A	$\tilde{\chi}_1^\pm$	112.1 GeV	$\tilde{\chi}_1^0$	54.3 GeV
			$\tilde{\chi}_2^0$	111.9 GeV
	$\tilde{\chi}_2^\pm$	224.3 GeV	$\tilde{\chi}_3^0$	208.5 GeV
			$\tilde{\chi}_4^0$	224.4 GeV
B	$\tilde{\chi}_1^\pm$	99.9 GeV	$\tilde{\chi}_1^0$	63.4 GeV
			$\tilde{\chi}_2^0$	107.3 GeV
	$\tilde{\chi}_2^\pm$	218.8 GeV	$\tilde{\chi}_3^0$	163.6 GeV
			$\tilde{\chi}_4^0$	218.3 GeV
C	$\tilde{\chi}_1^\pm$	110.5 GeV	$\tilde{\chi}_1^0$	62.5 GeV
			$\tilde{\chi}_2^0$	117.7 GeV
	$\tilde{\chi}_2^\pm$	292.7 GeV	$\tilde{\chi}_3^0$	252.3 GeV
			$\tilde{\chi}_4^0$	297.6 GeV
D	$\tilde{\chi}_1^\pm$	135.2 GeV	$\tilde{\chi}_1^0$	73.7 GeV
			$\tilde{\chi}_2^0$	135.2 GeV
	$\tilde{\chi}_2^\pm$	282.1 GeV	$\tilde{\chi}_3^0$	262.0 GeV
			$\tilde{\chi}_4^0$	278.6 GeV
E	$\tilde{\chi}_1^\pm$	173.4 GeV	$\tilde{\chi}_1^0$	97.7 GeV
			$\tilde{\chi}_2^0$	173.6 GeV
	$\tilde{\chi}_2^\pm$	292.1 GeV	$\tilde{\chi}_3^0$	260.8 GeV
			$\tilde{\chi}_4^0$	290.1 GeV

Table 1. *Masses of the charginos and neutralinos at the five selected points (see text).*

Throughout this analysis, the soft supersymmetry-breaking squark masses have been set to the common value 500 GeV, and the trilinear couplings to $A_t = A_b = A_\tau = 0$. We also assume that the lightest neutralino is the LSP, and that it decays through a single dominant R-parity-violating coupling. The charginos and higher neutralinos will decay through various channels into final states containing the LSP, which will then decay into multi-fermion channels through R-parity-violating couplings. The decays of the LSP are summarized below, for the three types of (trilinear) R-parity-violating couplings

$$\widetilde{\chi}_1^0 \to \ell_1^+ \ell_2^- + \not{E}_T \quad (\text{for } LL\bar{E}), \qquad \widetilde{\chi}_1^0 \to \ell^\pm JJ \text{ or } JJ + \not{E}_T \quad (\text{for } LQ\bar{D}), \qquad \widetilde{\chi}_1^0 \to 3J \quad (\text{for } \bar{U}\bar{D}\bar{D}) \ ,$$

where J denotes a hadronic jet. Since the LSP has only R-parity-violating decay modes through a single coupling there is no dependence on the actual magnitude of the R-parity-violating coupling involved (subject, of course, to the condition that the decays take place within the detector).

A similar summary of the decay channels of charginos and higher neutralinos to LSP states is given below.

$$\begin{array}{lllll}
\widetilde{\chi}_2^0 & \to & \widetilde{\chi}_1^0 \ell^+ \ell^- & \text{or } \widetilde{\chi}_1^0 + \not{E}_T & \text{or } \widetilde{\chi}_1^0 JJ \\
 & \hookrightarrow & \widetilde{\chi}_j^\pm \ell^\mp + \not{E}_T & \text{or } \widetilde{\chi}_j^\pm JJ \quad (j=1,2) & \\
\widetilde{\chi}_3^0 & \to & \widetilde{\chi}_i^0 \ell^+ \ell^- & \text{or } \widetilde{\chi}_i^0 + \not{E}_T & \text{or } \widetilde{\chi}_i^0 JJ \quad (i=1,2) \\
 & \hookrightarrow & \widetilde{\chi}_j^\pm \ell^\mp + \not{E}_T & \text{or } \widetilde{\chi}_j^\pm JJ \quad (j=1,2) & \\
\widetilde{\chi}_4^0 & \to & \widetilde{\chi}_i^0 \ell^+ \ell^- & \text{or } \widetilde{\chi}_i^0 + \not{E}_T & \text{or } \widetilde{\chi}_i^0 JJ \quad (i=1,2,3) \\
 & \hookrightarrow & \widetilde{\chi}_j^\pm \ell^+ + \not{E}_T & \text{or } \widetilde{\chi}_j^\pm JJ \quad (j=1,2) & \\
\widetilde{\chi}_1^\pm & \to & \widetilde{\chi}_i^0 \ell^\pm + \not{E}_T & \text{or } \widetilde{\chi}_i^0 JJ \quad (i=1,2,3,4) & \\
\widetilde{\chi}_2^\pm & \to & \widetilde{\chi}_1^\pm \ell^+ \ell^- & \text{or } \widetilde{\chi}_1^\pm + \not{E}_T & \text{or } \widetilde{\chi}_1^\pm JJ \\
 & \hookrightarrow & \widetilde{\chi}_i^0 \ell^\pm + \not{E}_T & \text{or } \widetilde{\chi}_i^0 JJ \quad (i=1,2,3,4) &
\end{array}$$

This complex set of options is illustrated in Fig. 2, where a typical mass spectrum is chosen and possible decays are represented as transitions from a higher state to a lower. The left side shows the most general case, when all possible cascade decays are considered. It is straightforward to count that there are 15 possible decays when only the charginos and neutralinos are considered, and, if we include the fact that either leptonic or hadronic final states can occur, one has a total of 35 channels to consider. When this is combined with the fact that a *pair* of charginos or neutralinos is produced in e^+e^- collisions, with all sorts of combinations for the decays of each being possible, it is obvious that a complete study is a gigantic task and well beyond the scope of our present analysis. Fortunately, it proves possible to carry out a meaningful analysis using only a subset of these production and decay channels. The chief reason for this is that the heavier neutralino and chargino states can be ignored in a first analysis, as we have explained earlier. Moreover, it is well known that, for a large part of the parameter space, the next-to-lightest neutralino $\widetilde{\chi}_2^0$ is nearly degenerate with the lighter chargino $\widetilde{\chi}_1^\pm$, so that its decay modes to the charginos (or vice versa) are suppressed, if not forbidden. This certainly happens for the five points where we have performed our analysis. A similar phenomenon occurs with the heavier chargino and the heaviest neutralino. The corresponding decay modes have very little available phase space and may be ignored without much loss of generality.

We now concentrate on the final states which could be of interest at a 500 GeV e^+e^- collider. As we have explained before, these involve only the lowest three states in Fig. 2, and correspond, on the left of Fig. 2, to the three decays denoted by solid lines. If we take into account the approximate degeneracy of the $\widetilde{\chi}_2^0$ and the $\widetilde{\chi}_1^\pm$, this is reduced, on the right of Fig. 2, to just two decay modes.

Of course, these two lines really denote five decay modes, since $\widetilde{\chi}_2^0 \longrightarrow \widetilde{\chi}_1^0 + (\ell^+\ell^- \text{ or } \nu\bar{\nu} \text{ or } q\bar{q})$ and $\widetilde{\chi}_1^+ \longrightarrow \widetilde{\chi}_1^0 + (\ell^+\nu \text{ or } \; q\bar{q}')$. However, this number is manageable, even when all the combinatorics are taken into account, and we shall consider all these channels in the subsequent analysis.

We then concentrate on the final states which involve only the lowest three gaugino states $\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_1^\pm$, and if, further, we take into account the approximate degeneracy of the $\widetilde{\chi}_2^0$ and the $\widetilde{\chi}_1^\pm$, we need to consider just five decay modes, namely $\widetilde{\chi}_2^0 \longrightarrow \widetilde{\chi}_1^0 + (\ell^+\ell^- \text{ or } \nu\bar{\nu} \text{ or } q\bar{q})$ and $\widetilde{\chi}_1^+ \longrightarrow \widetilde{\chi}_1^0 + (\ell^+\nu \text{ or } \; q\bar{q}')$. We further assume that the R-parity violating couplings are such that the direct decay of $\widetilde{\chi}_1^+$ through R-parity violating coupling can be neglected.

Our studies were done using a parton-level Monte Carlo event generator, which does not yield high-quality results so far as hadronic jets are concerned, but which does enable us to get a quick and more-or-less correct picture of the signals that might be visible at the NLC.

We first focus on the case when R-parity is violated by $LL\bar{E}$ couplings. The $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ state will lead to *four* charged leptons and missing energy, *i.e.* $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \rightarrow \ell_1^+\ell_2^-\ell_3^+\ell_4^- + \not{E}_T$. The flavour of these leptons will be determined by the coupling responsible and cannot be predicted á priori. A final state with four hard charged leptons and missing energy is sufficiently spectacular to permit easy detection. The Standard Model backgrounds, *e.g.* WWZ production where all the gauge bosons decay through leptonic channels, turn out to be rather small.

If some of the heavier states are produced, then there will be additional leptons or jets in the final state from cascade decays. These lead to the following signals:

$$
\begin{array}{lcll}
e^+e^- \longrightarrow \widetilde{\chi}_1^0 + \widetilde{\chi}_2^0 & \rightarrow & \widetilde{\chi}_1^0 + \widetilde{\chi}_1^0\nu\bar{\nu} & \longrightarrow \; 4\ell + \not{E}_T \\
 & \hookrightarrow & \widetilde{\chi}_1^0 + \widetilde{\chi}_1^0\ell^+\ell^- & \longrightarrow \; 6\ell + \not{E}_T \\
 & \hookrightarrow & \widetilde{\chi}_1^0 + \widetilde{\chi}_1^0 JJ & \longrightarrow \; 4\ell + \not{E}_T + 2 \text{ jets} \\
e^+e^- \longrightarrow \widetilde{\chi}_2^0 + \widetilde{\chi}_2^0 & \rightarrow & \widetilde{\chi}_1^0\nu\bar{\nu} + \widetilde{\chi}_1^0\nu\bar{\nu} & \longrightarrow \; 4\ell + \not{E}_T \\
 & \hookrightarrow & \widetilde{\chi}_1^0\ell^+\ell^- + \widetilde{\chi}_1^0\nu\bar{\nu} & \longrightarrow \; 6\ell + \not{E}_T \\
 & \hookrightarrow & \widetilde{\chi}_1^0\ell^+\ell^- + \widetilde{\chi}_1^0\ell^+\ell^- & \longrightarrow \; 8\ell + \not{E}_T \\
 & \hookrightarrow & \widetilde{\chi}_1^0\nu\bar{\nu} + \widetilde{\chi}_1^0 JJ & \longrightarrow \; 4\ell + \not{E}_T + 2 \text{ jets} \\
 & \hookrightarrow & \widetilde{\chi}_1^0\ell^+\ell^- + \widetilde{\chi}_1^0 JJ & \longrightarrow \; 6\ell + \not{E}_T + 2 \text{ jets} \\
 & \hookrightarrow & \widetilde{\chi}_1^0 JJ + \widetilde{\chi}_1^0 JJ & \longrightarrow \; 4\ell + \not{E}_T + 4 \text{ jets} \\
e^+e^- \longrightarrow \widetilde{\chi}_1^+ + \widetilde{\chi}_1^- & \rightarrow & \widetilde{\chi}_1^0\ell^+\nu + \widetilde{\chi}_1^0\ell^-\bar{\nu} & \longrightarrow \; 6\ell + \not{E}_T \\
 & \hookrightarrow & \widetilde{\chi}_1^0\ell^+\nu + \widetilde{\chi}_1^0 JJ & \longrightarrow \; 5\ell + \not{E}_T + 2 \text{ jets} \\
 & \hookrightarrow & \widetilde{\chi}_1^0 JJ + \widetilde{\chi}_1^0\ell^-\bar{\nu} & \longrightarrow \; 5\ell + \not{E}_T + 2 \text{ jets} \\
 & \hookrightarrow & \widetilde{\chi}_1^0 JJ + \widetilde{\chi}_1^0 JJ & \longrightarrow \; 4\ell + \not{E}_T + 4 \text{ jets}
\end{array}
$$

We have chosen the following criteria for observability of leptons/jets at a 500 GeV e^+e^- machine:

$$
p_T^\ell > 10 \text{ GeV} \;, \qquad |\eta_\ell| < 3 \;, \qquad p_T^J > 10 \text{ GeV} \qquad \text{and} \qquad |\eta_J| < 3 \;.
$$

Moreover, we assume that two partons with an angular separation of $\delta R_{JJ} \equiv \sqrt{\delta\eta_{JJ}^2 + \delta\phi_{JJ}^2} < 0.7$ are merged into a single jet. Similarly, a lepton will be assumed to be part of a jet if its angular separation $\delta R_{\ell J} < 0.4$. It turns out that a cut of 20 GeV on the minimum missing energy leaves the signal(s) practically unaffected and this can be used for background reduction.

Counting signals by the number of leptons, we classify the observable final states as having 0–8 leptons with or without jets and always accompanied by substantial missing energy. To get an idea of the strength of the signal available from the above analysis, we show, in Table 2, the cross sections for these signals (in the case of a λ-coupling) for different pair-production modes for the point A in the parameter space.

	Signal	$\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^+\tilde{\chi}_1^-$	**Total Signal** (fb)	**Background** (fb)
A	$1\ell + \not{E}_T$	1.1	0.4	0.2	1.5	3.2	8272.5
	$2\ell + \not{E}_T$	14.9	5.2	1.8	15.3	37.2	2347.4
	$3\ell + \not{E}_T$	91.7	25.3	7.2	71.6	195.8	1.5
	$4\ell + \not{E}_T$	212.8	49.6	13.6	152.8	428.8	0.4
	$5\ell + \not{E}_T$	0.0	37.8	19.3	113.5	170.6	–
	$6\ell + \not{E}_T$	0.0	39.6	21.6	26.9	88.0	–
	$7\ell + \not{E}_T$	0.0	0.0	11.9	0.0	11.9	–
	$8\ell + \not{E}_T$	0.0	0.0	8.0	0.0	8.0	–

Table 2. *Showing the contribution (in fb) of different (light) chargino and neutralino production modes to multi-lepton signals at the* NLC *in the case of* λ *couplings. The last column shows the SM background.*

In addition to this table, we present, in Fig. 3(a), the distribution in missing energy corresponding to the multi-lepton cases above for the point (A) in the parameter space. As expected, the missing energy grows progressively softer as more and more leptons are seen: this is partly because these correspond to states with less neutrinos and partly because there are fewer undetected leptons which might have contributed to the missing energy. It is clear that a cut of 20 GeV on the minimum missing energy would leave the signal(s) practically unaffected and this can be used for background reduction.

Similarly, in Fig. 3(b), we present histograms showing the distribution in the number of jets corresponding to each of the leptonic signals. Again, quite naturally, there are fewer jets as the number of observed leptons grows larger. The point (A) in the parameter space is chosen for these plots. Though our construction and treatment of jets is rather primitive, we do not expect the qualitative features of this figure to change when a more sophisticated analysis is performed.

One other question which can arise is what we expect from the MSSM in case R-parity is conserved. In this case, instead of getting $4\ell + \not{E}_T$ from the pair of LSP's, we will simply get missing energy. A rough estimate of the signals can be made by simply mapping signals with n leptons in Table 2 to signals with $n - 4$ leptons. Keeping the backgrounds in mind, this means that it should still be possible to see signals with three and four leptons, but generally at a lower level than what would be the case if R-parity is violated. The absence of signals with more than four leptons would be a clear sign of R-parity-conserving supersymmetry. Alternatively, one could say that an unambiguous signal for R-parity-violating supersymmetry would be large numbers of events with 4, 5 and 6 leptons. Another possibility is to consider dilepton invariant masses. For example, in the R-parity-conserving scenario, a $4\ell + \not{E}_T$ signal can arise from the process $e^+e^- \to \widetilde{\chi}_2^0 \ + \ \widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\ell^+\ell^- \ + \ \widetilde{\chi}_1^0\ell'^+\ell'^-$. However, the invariant mass spectrum of the dileptons (subject to proper combinatorics) should show an endpoint corresponding to the mass difference between parent and daughter states. No such endpoint is expected in the R-parity-violating case.

When we turn to the case of $LQ\bar{D}$ operators, the LSP has two decay modes leading to rather different signatures. The decay to a charged lepton and two jets will lead, for $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ production, to a signal with an observable dilepton and (up to) four jets. The other mode will lead to (up to) four jets with substantial missing energy and momentum. One can also have a situation with one neutralino $\widetilde{\chi}_1^0$ decaying into either channel, which leads to a single charged lepton, missing energy and (up to) four jets. Each signature will have large backgrounds. However, in the first case, because of the Majorana nature of the neutralinos, it may be possible to see like-sign dileptons (LSD's), which have very little background from SM processes, and these may be treated as smoking-gun signals for supersymmetry.

As in the previous section, we can analyze the signals in terms of the various pair-production modes and the cascade decays. The basic processes from pair-production of LSP's are

$$\begin{array}{lclclcl} e^+e^- & \longrightarrow & \widetilde{\chi}_1^0 + \widetilde{\chi}_1^0 & \to & \ell^\pm q\bar{q}' + \ell^\pm q\bar{q}' & \to & 2\ell + 4 \text{ jets} \\ & & & \hookrightarrow & \nu q\bar{q} + \ell^\pm q\bar{q}' & \to & \ell + \not{E}_T + 4 \text{ jets} \\ & & & \hookrightarrow & \nu q\bar{q} + \nu q\bar{q} & \to & \not{E}_T + 4 \text{ jets} \end{array}$$

and one can go on to detail the final states from cascade decays as in the case of $LL\bar{E}$ operators (except that now there are more options). As before, most of the MSSM (R-parity-conserving) backgrounds will show a chanracteristic endpoint in some of the lepton p_T spectra, which can be used to identify (bot not isolate) some of the R-parity-violating signals.

	Signal	$\widetilde{\chi}_1^0\widetilde{\chi}_1^0$	$\widetilde{\chi}_1^0\widetilde{\chi}_2^0$	$\widetilde{\chi}_2^0\widetilde{\chi}_2^0$	$\widetilde{\chi}_1^+\widetilde{\chi}_1^-$	**Total Signal** (fb)	**Background** (fb)
A	1ℓ + jets	126.7	48.8	14.1	142.4	332.0	8262.5
	2ℓ + jets	27.9	47.2	21.6	128.4	225.1	243.1
	3ℓ + jets	0.0	28.0	21.8	48.4	98.2	1.5
	4ℓ + jets	0.0	6.0	14.2	6.5	26.7	–
	5ℓ + jets	0.0	0.0	6.3	0.0	6.3	–
	6ℓ + jets	0.0	0.0	1.4	0.0	1.4	–

Table 3. *Showing the contribution (in fb) of different (light) chargino and neutralino production modes to multi-lepton signals at the* NLC *in the case of* λ' *couplings. The last column shows the SM background.*

We now come to the important issue of LSD signals. One-eighth of the $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ signal will consist of LSD's: this leads to 35, 0.1, 0.4, 12, 12 LSD events at the points (A)–(E) respectively, assuming an integrated luminosity of 10 fb^{-1} per year. Despite the strong variation in these numbers over the parameter space, one can actually make a rough estimate of the contribution from cascade decays using Table 3 (for the point A) and assuming that the decay widths of the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^\pm$ are dominated by the Z

and W-exchange channel respectively. In this case, we estimate that the actual numbers of LSD events with 10 fb^{-1} luminosity will be around 180, 10, 75, 83 and 53 respectively for the points (A)–(E). Thus, even with a charge detection efficiency of around 70%, we should see quite healthy numbers of LSD's in a year's running of the NLC.

Finally, we suggest a simple strategy to reconstruct the mass of the LSP from the multilepton plus jets data. We construct the invariant mass of the hardest lepton with all jets in the *same* hemisphere, where the direction of the lepton is taken to be the hemisphere axis. The invariant mass thus obtained shows a distinct peak at the LSP mass and a smaller one at the mass of the (near-degenerate) lightest chargino or next-to-lightest neutralino. The mass resolution is esstimted to be about 5-10 GeV; more precise statements will require a more sophisticated Monte Carlo simulation at the genrator level.

In case baryon number is violated through $\bar{U}\bar{D}\bar{D}$ operators, the LSP will simply decay into three hadronic jets. Thus the basic process with production of $\widetilde{\chi}^0_1\widetilde{\chi}^0_1$ will lead to a six-jet final state (with some jets lost through merging). This has a large SM background from $t\bar{t}$ production, where both the top quarks decay hadronically. Other backgrounds, such as those from WWZ production are not inconsiderable either. Thus, kinematic strategies are of paramount importance in this case.

When one includes the cascade decays of the higher gauginos, there are several possible final states with multijets and with or without leptons. Final states with such large numbers of jets will inevitably involve a great deal of jet merging, leading to states with (much) lower jet multiplicity. The question now arises: if we do indeed observe multi-jet signals, with or without leptons and/or missing energy, what strategy should we adopt in order to identify whether these arise from baryon-number-violating couplings, or from some other source? The most straightforward solution is to appeal to kinematics and carry out mass reconstructions. We use the following strategy: the hardest jet in the final state is identified and its invariant mass is constructed with all the other jets lying in the same hemisphere. The direction of the hardest jet is taken as the hemisphere axis. Then, we look for the hardest jet in the opposite hemisphere and again construct its invariant mass with all other jets lying in that hemisphere. We require these two invariant masses to lie within 10 GeV of each other, noting that if they are equal, or nearly equal, this is indicative of similar parentage. Once this criterion is satisfied, we plot the two invariant mass distributions to see if they show significant peaking.

Some of our results are shown in Fig. 4. Once again, we have chosen the point (A) in the parameter space. It is clear from the figure that we have a clear resonance in the bin 50–60 GeV at the mass of the lightest neutralino, with a sharp cutoff at the mass of the second neutralino or (light chargino) around 120 GeV. However, this cutoff may not be clearly observable because of the SM backgrounds, especially the one from $t\bar{t}$, which, though it peaks around m_t, will have a non-vanishing tail in the neighbourhood of 100–120 GeV.

To summarize, we have discussed gaugino pair production at a 500 GeV e^+e^- collider in the weak R-

parity-violation limit, where the production modes are solely through the R-parity-conserving couplings while the lightest supersymmetric particle (LSP) decays purely through R-parity-violating couplings. Our analysis shows that it is sufficient to consider production of the two lightest neutralinos and of the lightest chargino. This simplifies matters considerably, since the higher chargino and neutralino states can have very complicated cascade decays, which would render the book-keeping almost an impossible task. We have then discussed the decays of the lightest neutralino (LSP) through the three types of R-parity-violating couplings assuming the top quark plays no role in these decays. At the same time we have considered decays of the (relevant) higher states to the LSP, with accompanying fermions. These result in a wealth of final state topologies, which we have classified by the number of hard isolated leptons. The observability of these leptons has been analyzed using a simple parton-level Monte Carlo event generator. For λ-type couplings, the signal is basically an excess of multi-lepton states, together with substantial missing energy. For λ'-type couplings, the signal consists of leptons and multiple jets in the final state, but we utilize a rather simple-minded algorithm to reconstruct the LSP and higher neutralino masses (within some resolution). This actually works pretty well and enables us to predict that such signals, if seen, can be quite clearly identified as due to $\not{R}_p$ supersymmetry. We also show that if charge identification of final-state leptons can be carried out with reasonable efficiency, then like-sign dilepton (LSD) signals could be a very promising signal, insofar as they have practically no SM backgrounds. For λ'' couplings, a similar mass reconstruction is suggested: this shows a distinct resonance and could be again used to indicate $\not{R}_p$ supersymmetry. We have also discussed backgrounds and some simple strategies for their elimination, though a detailed simulation has not been attempted.

Our results have been written up in detail (hep-ph/9904233).

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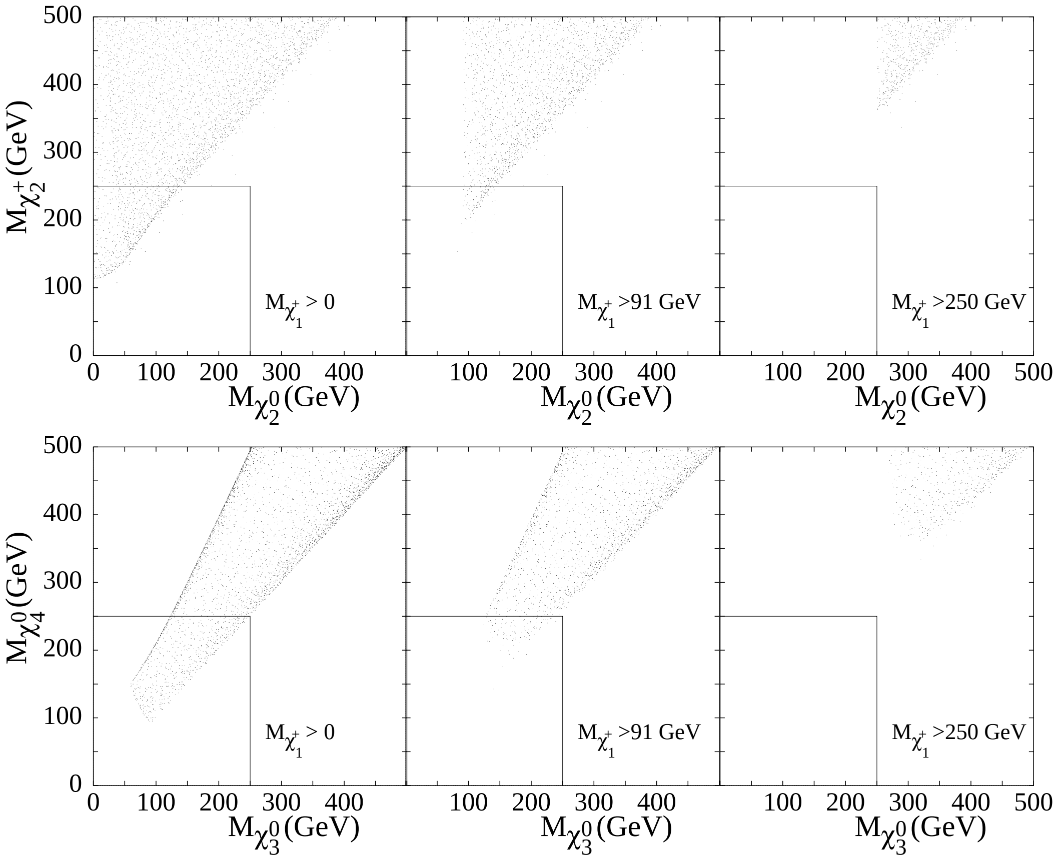

Figure 1. *Scatter plots for higher chargino and neutralino masses in the MSSM. The ranges of variation of the parameters are given in the text. The box represents the kinematic reach of a 500 GeV machine.*

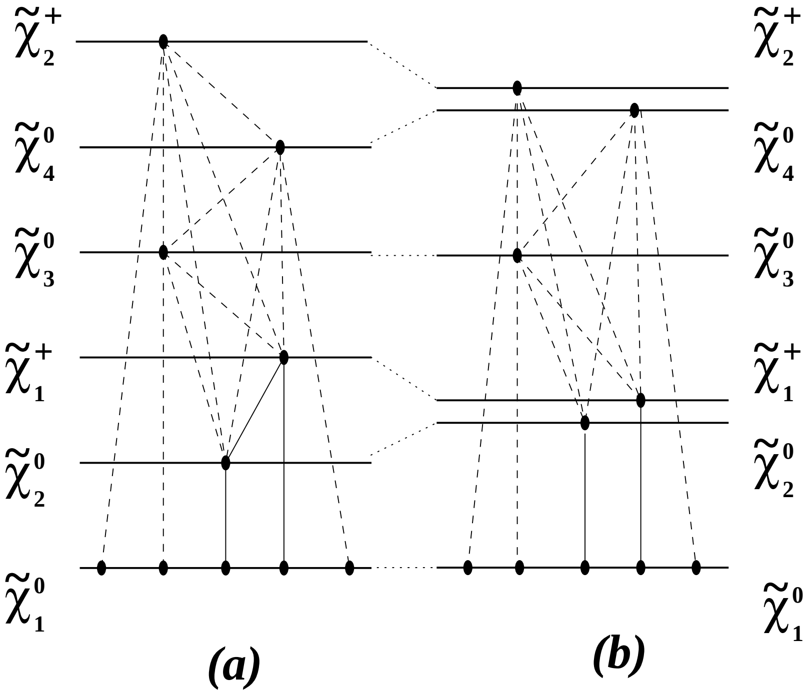

Figure 2. *Schematic diagram showing all possible cascade decays of higher charginos and neutralinos to the* LSP *in (a) the most general case, and (b) a simplified case where two pairs of states are almost degenerate. Broken lines indicate possible decays; solid lines indicate those which have been considered in this article.*

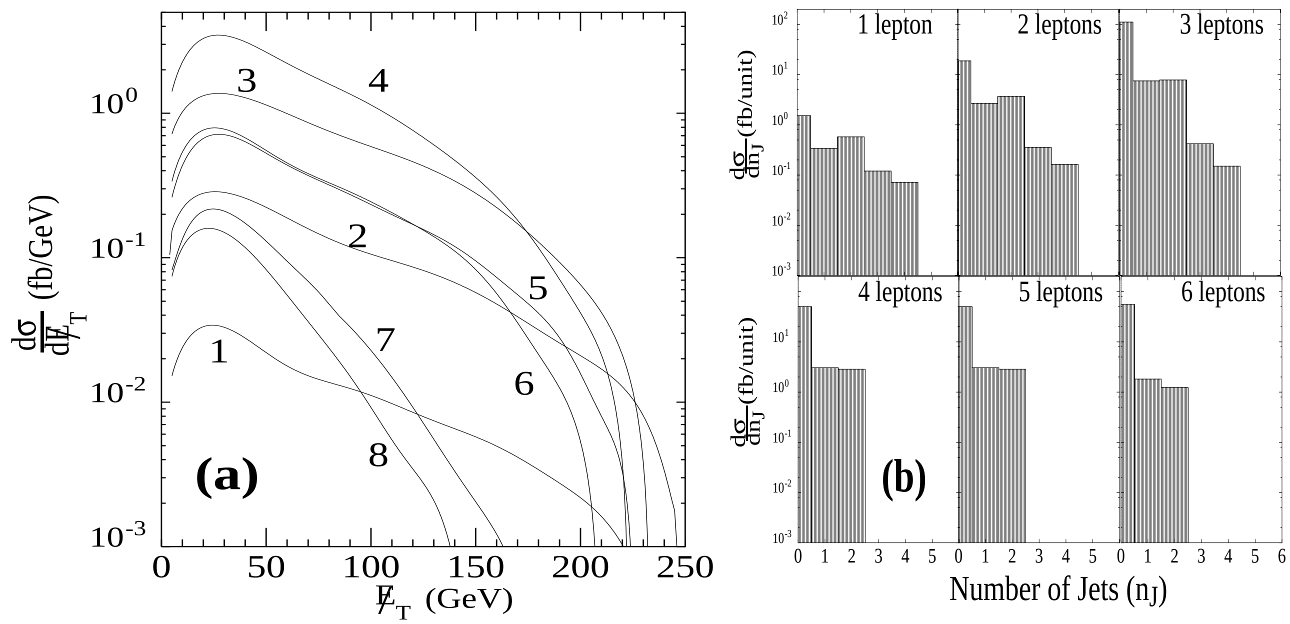

Figure 3. *Illustrating the distribution in (a) missing transverse energy ($\not{E}_T$) and (b) the number of jets (n_J) when the LSP decays through a λ coupling. In (a) the number of observable leptons is marked next to the relevant curve.*

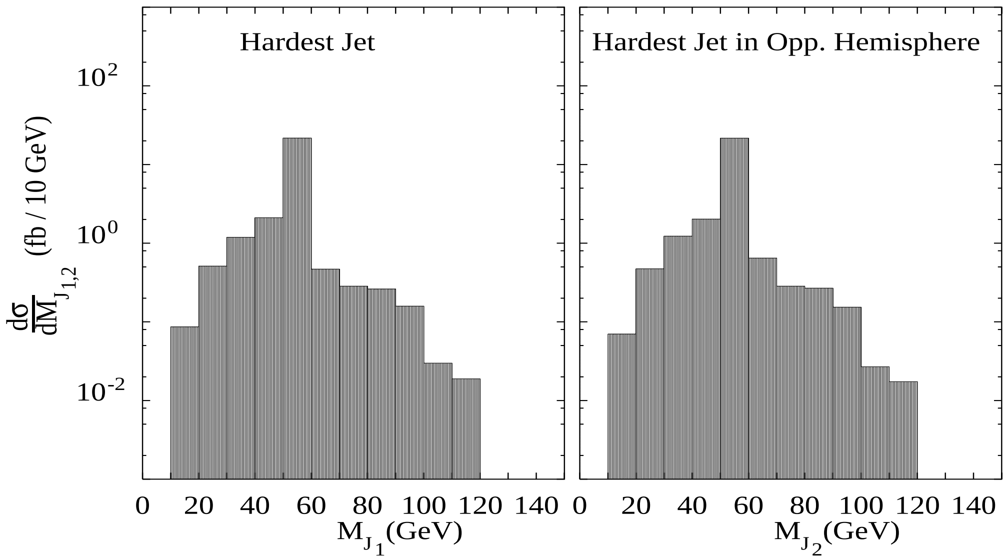

Figure 4. *Illustrating the distribution in invariant mass reconstructed from (a) the hardest jet and all jets in the same hemisphere, and (b) the hardest jet in the opposite hemisphere and all remaining hadronic jets, when all contributions are summed over (signal only). The point (A) in the parameter space is chosen.*