$R$-parity Violation in Neutralino Decays at an $e\gamma$ Collider

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ABSTRACT

At an $e\gamma$ collider, a selectron $\tilde{e}_{L,R}$ may be produced in association with a (lightest) neutralino $\tilde{\chi}_1^0$. Decay of the selectron may be expected to yield a final state with an electron and another $\tilde{\chi}_1^0$. If $R$-parity is violated, these two neutralinos will decay, giving rise to distinctive signatures, which are identified and studied.
For a variety of theoretical and phenomenological reasons, of which the unification of strong and electroweak couplings at a common scale is perhaps the most exciting [1], supersymmetry is currently the most popular option for going beyond the Standard Model (SM) of strong and electroweak interactions. Of course, even the minimal extension of the SM which incorporates supersymmetry (MSSM) predicts a large number of new particles and interactions which have not (yet) been seen. One of the major goals for particle physics is, thus, to study different strategies for the detection of these new particles. Many such analyses have already appeared in the literature [2]. It is apparent, however, that the current generation of high energy accelerators has already exhausted a certain part of its potential for new particle discovery and it is entirely possible that we will end up with a set of useful, but uninspiring, bounds. One would therefore have to achieve higher energies or alternative techniques if indeed the new physics — whether supersymmetry or something else — is to be found.

It is partly with this kind of future scenario in mind that several plans for new accelerators and accelerator techniques have been suggested, many of which are now under serious consideration. One of the most interesting of these is the suggestion of a high energy $e\gamma$ collider, which would be the first machine of its kind. The basic plan is to have a high energy $e^+e^-$ (or $e^-e^-$) collider (such as the 500 GeV NLC, for instance) and to direct a highly coherent laser beam at the positron (electron) beam at small angles; the back-scattered laser beam, which picks up most of the energy of the positron (electron) beam, could then be allowed to collide with the other electron (positron) beam, leading to $e\gamma$ interactions at high energies. This involves no new principle beyond inverse Compton scattering and detailed studies of the design and properties of such a machine have already appeared in the literature [3]. There have also been quite a few explorations of its physics possibilities, especially as a probe of low-energy supersymmetry [4].

One of the most interesting of these physics possibilities is the production of single selectrons through the process $e\gamma \rightarrow \tilde{e}_{L,R} + \tilde{\chi}^0_i (i = 1, 2, 3, 4)$. This can occur through an $s$-channel electron exchange or a $t$-channel selectron exchange. If the selectron decays to an electron (positron) and another neutralino, then we are left with an $e^-\tilde{\chi}^0_i \tilde{\chi}^0_j$ final state. We concentrate on the $e^-\tilde{\chi}^0_1 \tilde{\chi}^0_1$
state, which is kinematically favoured. In the canonical form of the MSSM, $R$-parity is conserved and the $\tilde{\chi}^{0}_1$ is the best candidate for the lightest supersymmetric particle (LSP), which does not decay and which escapes the detectors. The signal for this process is, then, a single hard electron and substantial missing energy and momentum. This process, together with its obvious SM background from $e\gamma \to e\nu \bar{\nu}$, has been discussed by several authors as a possible signal for supersymmetry\footnote{\textsuperscript{4-6}.}

Though it was pointed out long ago\footnote{\textsuperscript{7}} that $R$-parity conservation in the MSSM is not really demanded by any theoretical or experimental considerations, this rather less-than-elegant alternative was not taken very seriously during the first decade of studies in supersymmetry. Recently, in the wake of the announcement of an excess observed in high-$Q^2$ $ep$-scattering events at HERA\footnote{\textsuperscript{8}}, there has been a resurgence of interest in the possibility of $R$-parity violation, since this seems to provide a natural explanation of the excess in terms of a squark resonance\footnote{\textsuperscript{9}}. While the status of the HERA excess is still uncertain, what is certain is that $R$-parity violation is increasingly being recognised as an alternative scenario to the canonical form of the MSSM where $R$-parity is conserved. It is, thus, important to study the experimental consequences of $R$-parity violation, especially in the context of present and future high energy colliders, including the $e\gamma$ collider discussed above.

In this letter, we consider, therefore, the possibility that $R$-parity is not conserved and that the lightest neutralino (LSP) can, as a consequence, decay into three-fermion final states, whose flavour content depends on the nature of the $R$-parity-violating interactions. The selectron-neutralino production process will then lead to rather spectacular multi-fermion final states, which should have very little SM backgrounds. The observation of such states could be a clear signal for supersymmetry. We restrict our discussion to the so-called \textit{weak} limit, in which $R$-parity-violating couplings are small compared to gauge couplings and thus most production and decay mechanisms of supersymmetric particles occur exactly as in the canonical supersymmetric models, the only new feature being the decay of the neutralino LSP. If we were to allow somewhat larger $R$-parity-violating couplings — which are not experimentally disallowed\footnote{\textsuperscript{10}} — the scenario can change quite significantly. Even in the weak $R$-parity violation scenario, production of a selectron-neutralino pair is not the only
process at an $e\gamma$ collider where $R$-parity-violating effects could appear. One can also have such effects in the decays following production of a sneutrino-chargino pair. Moreover, in $R$-parity-violating models, it is also conceivable that the selectron, rather than the lightest neutralino, is the LSP, and can decay directly into two leptons (quarks) through the $R$-parity-violating $\lambda(\lambda')$ coupling. For larger $\lambda$ couplings, there is also the possibility of producing lepton-flavour-violating $\ell_i\tilde{\nu}_j$ final states directly. None of these signals are considered in this letter. A more comprehensive study of these processes is certainly called for and will be taken up in a forthcoming publication.

The basic processes leading to the production of a selectron-neutralino final state have already been discussed in the literature. Cross-sections have been listed in Ref. [6] for polarised beams. The photon flux and polarisation have been worked out by Ginzburg and his collaborators [3] and are quoted in Refs. [4, 5]. In the interests of brevity, we do not reproduce all these formulae here and refer the reader to the existing literature. We simply mention the assumptions we have made in our numerical analysis. Briefly, these are the following:

1. We assume that the laser back-scattering parameter $x = 2(1 + \sqrt{2}) \simeq 4.828$, its maximum value [3];

2. It is likely that the relatively low-energy photons in the beam would be lost [3] and thus the momentum fraction $y = E_\gamma/E_e$ of the photon beam lies between 0.5 and the maximum value $x/(1 + x) \simeq 0.828$ (this is identical with the choice of Ref. [5]);

3. The energy of the initial electron and positron beams are taken to be 250 GeV each (which is expected to be available at the NLC);

4. The polarisation of the initial laser beam ($P_l$), the initial positron beam ($\lambda_p$) which scatters the laser and the initial unscattered electron beam ($\lambda_e$) are taken to be $|P_l| = 1.0, |\lambda_p| = 0.4, \lambda_e = \pm 0.45$; the signs of $P_l, \lambda_p$ are consistent with the choices of Ref. [3].
5. With these more-or-less optimal choices of parameters, the luminosity expected for the $e\gamma$ collider would probably be of the same order as that of the parent $e^+e^-$ machine [5, 6]. We assume a representative value of 10 fb$^{-1}$.

Figure 1: Contours of cross-section (marked, in fb) for a left selectron of mass (a) 100 GeV, (b) 200 GeV and (c) 300 GeV. We choose the polarisation of the electron beam to be $\lambda_e = -0.45$. Larger cross-sections lie away from the origin for $\mu > 0$ and towards the origin for $\mu < 0$.

With the above assumptions we have incorporated the relevant formulae into a simple parton-level Monte Carlo event generator. In Fig. 1 we present contour plots of the total cross-section for $\tilde{e}_L\tilde{\chi}_1^0$ production in the $M_2 - \mu$ plane for $\tan\beta = 1.4$ and three different values of left-selectron mass $m_{\tilde{e}_L} = (a) 100$, (b) 200, and (c) 300 GeV respectively. We assume gaugino mass unification (at least in the electroweak sector) throughout this discussion. The cross-section (in fb) is marked next to the relevant contours. The region marked ‘Disallowed’ represents the region where either
(a) the production of a selectron-neutralino pair is kinematically disallowed, or (b) the selectron becomes the LSP and cannot decay to a neutralino. These contours are the same as those we would get in a model with conserved $R$-parity. The shaded region is ruled out by direct searches at LEP-2 for $R$-parity violation from an $LQ\bar{D}$-type operator, and agrees closely with the kinematic limit for chargino production. It is worth mentioning that the value of $\tan\beta$ chosen for this figure is at the edge of the allowed region (from the LEP Higgs search constraints) and is principally chosen because (a) this minimises the ruled-out region in the $M_2 - \mu$ plane, and (b) this is the common choice made by the LEP collaborations, so that the ruled-out region may be read off from their plots as well. We also note that our predictions of the cross-section agree well with those of Refs. 4, 5, 6.

It is immediately obvious that, for a projected luminosity of 10 fb$^{-1}$, one can obtain a few hundreds of left selectron events over a respectable range of parameter space, with negative values of $\mu$ being distinctly preferred. For a selectron mass of 100 GeV, the parameter space of interest is restricted by the requirement that the neutralino be the LSP, which forces it to be lighter than 100 GeV in this case. For $m_{\tilde{e}_L} = 300$ GeV, the parameter space is again restricted by the machine energy limitations, while the cross-section itself is limited by phase-space considerations. A left selectron mass in the range of 200 GeV, however, seems to be optimum for the $e\gamma$ collider, as Fig. 1(b) makes clear.

In Fig. 2, we present the analogue of Fig. 1 (with the same notations and conventions), for the right selectron. However, in determining these cross-sections, the sign of the electron beam polarisation has been reversed, since the earlier polarisation was designed specifically to produce the left selectron to the exclusion of the right. It is obvious that, other things being equal, the

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3 Of course, one could still look for $R$-parity violation in decays of the selectrons (for the neutralino produced in association with the selectron may decay into an additional selectron), but this interesting scenario is beyond the scope of this letter.

4 For $LL\bar{E}$-operators, care should be taken in reading off the results presented by the LEP collaborations [13], since they assume somewhat higher slepton masses than are considered in Figs. 1 and 2.
cross-sections are significantly larger than those of Fig. 1, primarily because the larger hypercharge of the right selectron couples it more strongly to the bino component of the neutralino (this is dominant over most of the parameter space for low values of $\tan \beta$). Thus a few thousand right selectrons could easily be produced in 10 fb$^{-1}$ of data, making detection a relatively simple matter.

![Figure 2](image)

**Figure 2:** Contours of cross-section (marked, in fb) for a right selectron of mass (a) 100 GeV, (b) 200 GeV and (c) 300 GeV. We choose the polarisation of the electron beam $\lambda_e = +0.45$. Larger cross-sections (marked, in fb) lie away from the origin for both $\mu < 0$ and $\mu > 0$.

The selectron can now decay in any one of the following *three* channels: (a) into an electron and a neutralino; (b) into a neutrino and a chargino (left selectron only); (c) into a neutrino and a charged lepton or into a pair of quarks (depending on the $R$-parity-violating coupling). For small values of $\lambda$ or $\lambda'$ (such as are assumed here) the last mode does not contribute much (except at the very edge of the parameter space where the electron-neutralino mode gets kinematically
suppressed) and will not be considered any further. The neutrino-chargino mode, is, however, important for the left selectron, and though we do not consider the corresponding final states in this letter, we must take into account the reduction in the branching ratio to electron-neutralino final states. In Fig. 3, we plot contours of the branching ratio of a left selectron of mass 200 GeV into the electron-neutralino channel in the $M_2 - \mu$ plane for $\tan \beta = 1.4$, assuming a vanishing contribution from the $R$-parity-violating channel(s). The parameters for Fig. 3 are chosen so that it is possible to convolute the branching ratio with production cross-sections read-off from Fig. 1(b). For the right selectron, under similar assumptions, we get a 100% branching ratio to the electron-neutralino mode. Apart from the branching ratio, the decay of the selectron into an electron and a neutralino should lead to a hard central electron which we identify by putting the following cuts: (a) pseudorapidity $|\eta_e| < 3$ and (b) transverse energy $E_T^e > 10$ GeV. These cuts, as may be expected, have very little effect on the cross-section, the reduction being by 1% or less.

![Figure 3: Contours of branching ratio for a left selectron to electron and neutralino.](image)

Till now, most of the results and discussions have not deviated from the $R$-parity-conserving
case. We now turn to the decay modes of the neutralinos (LSP’s) where much depends on the assumptions made about the $R$-parity-violating sector. The most general such interaction arises from the superpotential

$$\mathcal{W}_R = \lambda_{ijk} \epsilon_{\alpha\beta} \hat{L}_i^\alpha \hat{L}_j^\beta \hat{E}_k + \lambda'_{ijk} \epsilon_{\alpha\beta} \hat{Q}_i^\alpha \hat{D}_j^\beta \hat{D}_k + \mu_{ij} \epsilon_{\alpha\beta} \hat{L}_i^\alpha \hat{H}_j^\beta + \lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}_k$$

(1)

where $\hat{L}, \hat{Q}, \hat{H}$ are $SU(2)$ doublets containing lepton, quark and Higgs superfields respectively and all colour indices have been dropped. The $SU(2)$ structure demands that $\lambda$ be antisymmetric in the first two indices and $SU(3)_c$ invariance demands that $\lambda''$ be antisymmetric in the last two. The bilinear couplings can be absorbed in the corresponding trilinear ones by a redefinition of leptonic superfields and will play no further role in the subsequent discussion. The first three terms in the superpotential violate lepton number (but not baryon number) and the last one violates baryon number (but not lepton number).

One can now expand the $F$-term of the above superpotential to get the interaction vertices. We note that most (though not quite all) products of lepton-number-violating couplings of the $LQ\bar{D}$-type with baryon-number-violating couplings are severely constrained by the observed stability of the proton [10, 13]. A simple expedient to satisfy these constraints is to allow nonconservation of either lepton number, or of baryon number, but not of both. In most of the following discussion, we shall assume that only lepton number is violated. This option is, in fact, reasonably well-motivated from a theoretical point of view [14]. In fact, even for the lepton-number-violating couplings, we shall study signals assuming that one coupling at a time dominates. This is a rather naive assumption, but it is convenient and, at this exploratory stage of our study, seems a reasonable one to make. After all, one can argue that the situation is similar for the SM Yukawa couplings where the coupling of the top quark is overwhelmingly larger than the others.

We first concentrate on the $LL\bar{E}$ operators. In the presence of a $\lambda_{ijk}$ coupling, the neutralino LSP undergoes the three-body decays

$$\tilde{\chi}_1^0 \rightarrow \nu_i \ell^-_j \ell^+_k + \nu_j \ell^-_i \ell^+_k$$
through a virtual $\tilde{\nu}_{i(j)}$, $\tilde{\ell}_{L(i)}$, $\tilde{\ell}_{R(k)}$ exchange $^1$. Detailed formulae for these decays have appeared before $^1$ in the literature, and hence, are not presented here. It is adequate for our purposes to observe that the neutralino decay will yield a pair of charged leptons, not necessarily of the same flavour, and missing energy from the escaping neutrino. The Majorana nature of the $\tilde{\chi}^0_1$ also ensures that for every $\ell_j^-\ell_k^+$ pair, observed, there will be a $\ell_j^+\ell_k^-$ pair as well, with missing energy as before. The possible final states arising from a selectron and a neutralino together with the $\lambda$ coupling responsible are listed in Table 1. We have chosen, for illustration, a particular point in the parameter space ($M_2 = 180$ GeV, $\mu = -500$ GeV, $\tan\beta = 1.4$, $m_{\tilde{\ell}} = 200$ GeV) where the cross-sections are relatively large (46.14 fb and 114.83 fb for the left and right selectrons respectively) and the branching ratio of the left selectron to the neutralino decay mode is also large (0.89). Though the dependence of the kinematic distributions and hence the effect of the cuts on the sfermion mass spectrum is minimal, we have chosen, to be specific, all soft supersymmetry-breaking sfermion mass parameters to be 500 GeV, except the ones which directly enter into the analysis with different values (such as the selectron masses and hence the mass of the $\tilde{\nu}_e$ which is related to the $\tilde{e}_L$ mass). We also set all trilinear couplings to zero, which makes one stop rather lighter than 500 GeV, but still heavier than the neutralino LSP.

In Table 1, only the charged lepton content of the final state is shown. Such signals involving five charged leptons and substantial missing (transverse) energy ($E_T^\ell$) are rather distinctive and should be easily identifiable. For our parton-level analysis, we demand that all the charged leptons satisfy the criteria already imposed on the electron (arising from selectron decay), viz., $|\eta_\ell| < 3$ and $E_T^\ell > 10$ GeV. We further demand that if there are $\tau$ leptons in the final state, the other leptons should be isolated from the narrow jets arising from the $\tau$'s; for this we use a simple-minded cone algorithm with $\Delta R_{\ell\tau} > 0.2$, where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. It is also necessary to have a corresponding separation between the tau jets. We find that the effect of these selection criteria is to diminish the signal by about 35% (55% if there are $\tau$'s). We assume an efficiency of 80% for the identification $^5$

Since we assume the $\tilde{\chi}^0_1$ to be the LSP, the possibility of slepton resonances in the neutralino decay may be discounted.
of each \( \tau \) as contrasted to 95\% for the identification of an \( e \) or a \( \mu \). These efficiencies are based on LEP-2 estimates and may change slightly for the higher energies expected at an \( e\gamma \) collider. However, they are in the right ballpark\(^6\) and it is apparent from Table 1 that they should still lead to some tens of events per channel for a luminosity of 10 fb\(^{-1}\). Cross-sections in the last column of Table 1 include a combinatoric factor of 2 because the two neutralinos could decay either way.

| \( \lambda \) | leptons | C.S.(fb) | leptons | C.S.(fb) | leptons | C.S.(fb) |
|---|---|---|---|---|---|---|
| 121 | \( e^-e^+e^-e^+ \) | 5.56 (13.92) | \( e^-e^+\mu^+\mu^+ \) | 5.56 (13.92) | \( e^-e^+e^-\mu^+ \) | 11.11 (27.84) |
| 122 | \( e^-e^+\mu^-\mu^- \) | 5.56 (13.92) | \( e^-\mu^-\mu^-\mu^+ \) | 5.56 (13.92) | \( e^-e^+\mu^-\mu^- \) | 11.11 (27.84) |
| 123 | \( e^-e^+\tau^+e^-\tau^- \) | 3.86 (9.64) | \( e^-\mu^-\tau^+\mu^-\tau^- \) | 3.86 (9.64) | \( e^-e^+\tau^+\mu^-\tau^- \) | 7.72 (19.29) |
| 131 | \( e^-e^+e^-e^+ \) | 5.44 (13.56) | \( e^-e^+\tau^+e^-\tau^- \) | 3.87 (9.64) | \( e^-e^+e^-\tau^- \) | 9.18 (22.83) |
| 132 | \( e^-\mu^-\mu^-\mu^- \) | 5.44 (13.57) | \( e^-\mu^-\tau^+\mu^-\tau^- \) | 3.88 (9.63) | \( e^-e^+\mu^-\mu^- \) | 9.19 (22.84) |
| 133 | \( e^-e^+\tau^+e^-\tau^- \) | 3.58 (8.91) | \( e^-\tau^+\tau^-\tau^+\tau^- \) | 2.55 (6.35) | \( e^-e^+\tau^+\tau^-\tau^- \) | 6.05 (15.01) |
| 231 | \( e^-\mu^-\mu^-\mu^- \) | 5.44 (13.57) | \( e^-e^+\tau^+e^-\tau^- \) | 3.87 (9.64) | \( e^-e^+\mu^-\mu^- \) | 9.18 (22.84) |
| 232 | \( e^-\mu^-\mu^-\mu^- \) | 5.44 (13.57) | \( e^-\mu^-\tau^+\mu^-\tau^- \) | 3.88 (9.63) | \( e^-e^+\mu^-\mu^- \) | 9.18 (22.84) |
| 233 | \( e^-\mu^-\tau^+\mu^-\tau^- \) | 3.58 (8.92) | \( e^-\tau^+\tau^-\tau^+\tau^- \) | 2.55 (6.34) | \( e^-e^+\mu^-\mu^- \) | 6.06 (15.01) |

Table 1. Final states for different \( \lambda \) couplings with representative cross-sections for the left selectron in each channel. Numbers in parantheses show cross-sections for the right selectron. All (four) possible sign-combinations of the final state charges are taken into account. Parameter choices are explained in the text.

It is useful to note that (a) for a given selectron and a given coupling, the sum of the cross-sections in the three columns corresponds to the cross-sections shown in Figs. 1 and 2 (diminished by the application of cuts), hence it is trivial to calculate the branching ratios to the different channels; and (b) the above cross-sections have been calculated without any cuts on the missing \( E_T \). However, a cut of \( E_T > 20 \) GeV does not lead to any significant change (see below) in the cross-sections for this value of LSP mass (93.5 GeV), so these numbers may be considered representative. The principal SM background to these various signals will come from processes like \( e\gamma \rightarrow eZW^+W^-, \nu ZZW^- \),

\(^6\)In fact, if they err, it is on the conservative side.
followed by the leptonic decays of the $W, Z$ bosons. It is straightforward to estimate that such cross-sections are very small indeed (typically $\sim 1 \text{ fb} \times$ relevant leptonic branching ratios) and should not constitute a source of serious worry. We do not consider these backgrounds further in the current study.

![Graphs showing kinematic profiles for R-parity-violating signals.](image)

**Figure 4:** Kinematic profiles for the $R$-parity-violating signals. (a) Missing transverse energy distributions, and (b) variation of the average number of jets for a $\lambda'_{121}$ coupling and a final state with $e + E_T + \text{jets}$.  

As mentioned above, the charged leptons in the final state will always be accompanied by substantial missing energy and momentum. In Fig. 4(a), the solid line shows the missing (transverse) energy distribution for a $\lambda_{121}$ coupling and a 5-electron final state. Parameter choices coincide with Table 1. A substantial missing energy, say $E_T > 20$ GeV, should be considered an important part of the signal, and Fig. 4(a) shows that this would affect the signal only marginally. Of course,  

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7For example, the backgrounds presented in Ref. [6] would be further suppressed by the fine structure constant and then by the leptonic branching ratios.
the missing energy is rather sensitive to the neutralino mass, so that very light neutralino masses might then be excluded from this analysis. These, however, would be accessible to searches in $e^+e^-$ collisions at LEP and at the NLC itself.

We now turn to the case of $LQ\bar{D}$ operators and $\lambda'$ couplings, of which three ($\lambda'_{121}, \lambda'_{131}, \lambda'_{123}$) are of interest in possible explanations of the HERA excess \[9\]. In the presence of a $\lambda'_{ijk}$ coupling, the neutralino undergoes the three-body decays

$$\tilde{\chi}_1^0 \rightarrow \nu_i d_j \bar{d}_k + \ell_i^- u_j \bar{d}_k$$

provided they are kinematically allowed, through a virtual $\tilde{\nu}_{i,j}, \tilde{\ell}_{i,j}, \tilde{d}_{j,k}, \tilde{u}_j$ exchange. This leads to the set of final states listed in Table 2. Only the leptonic content of the final state is shown; this will always be accompanied by hadronic activity. As before, the last column contains a combinatoric factor of 2.

| $\lambda'$ | Final state | C.S.(fb) | Final state | C.S.(fb) | Final state | C.S.(fb) |
|------------|-------------|----------|-------------|----------|-------------|----------|
| $11k, 12k$ | $e^- + E_T$ | 7.03 (17.50) | $e^- + e^\pm e^\pm$ | 2.27 (5.60) | $e^- + e^\pm + E_T$ | 8.22 (20.47) |
| $i3k$      | $e^- + E_T$ | 44.45 (110.78) |             |          |             |          |
| $21k, 22k$ | $e^- + E_T$ | 7.02 (17.50) | $e^- + \mu^\pm \mu^\pm$ | 2.28 (5.60) | $e^- + \mu^\pm + E_T$ | 8.24 (20.46) |
| $31k, 32k$ | $e^- + E_T$ | 7.05 (17.58) | $e^- + \tau^\pm \tau^\pm$ | 2.71 (6.47) | $e^- + \tau^\pm + E_T$ | 8.24 (22.79) |

Table 2. Final states for different $\lambda'$ couplings with representative cross-sections for each channel. Notations and parameter choices are the same as in Table 1.

Each final state will, in fact, contain $n = 1, 2, 3, 4$ hadronic jets (depending on whether the jets merge or not). The cuts imposed in order to get the above cross-sections are (as before) $|\eta_\ell| < 3$ and $E_T^\ell > 10$ GeV for each charged lepton. These hardly affect the signal for a LSP mass as heavy as 93.5 GeV. For lower masses, of course, the $E_T$ cut would become significant. Since the final state is rather messy, with up to four hadronic jets, one has also to impose isolation criteria on all the leptons including narrow $\tau$-jets, for which we require $\Delta R_{\ell j} > 0.4$ (0.55 for $\tau$ jets). These further reduce the cross-section by about 37% (47% if there are $\tau$'s.) As before, we assume efficiencies of
95 (80)% in the identification of each $e, \mu(\tau)$. Despite these suppression factors, it seems clear that we still predict significant numbers of events for 10 fb$^{-1}$ luminosity.

For the jets, we demand $|\eta_j| < 3$ and $E_T^j > 15$ GeV and assume that jets with an angular separation $\Delta R_{jj} < 0.7$ merge into a single jet. The rapidity and minimum energy criteria add to the missing energy of the event, but this does not affect the numbers in Table 2, since no cut on missing energy was used in generating them. The missing (transverse) energy distribution for a final state with 3 electrons + jets is plotted as a dotted line in Fig. 4(a). Since there are no neutrinos in this final state the missing energy arises solely from jets and hence this may be taken as an indicator of the minimum missing energy required to identify neutrino final states.

One of the more spectacular possibilities in the case of $\lambda'$ couplings is the case of two or even three like-sign leptons in the final state. Though one has to pay a price of a factor of one-half (one-quarter) in cross-section to observe like-sign dilepton (trilepton) signals, the cross-sections are just about large enough and there is no SM background worth consideration. Such a signal is the surest sign of a Majorana particle in the decay chain and is likely to play a major role in the identification of neutralinos in a model with $R$-parity violation.

In the above we assume that the neutralino LSP cannot decay into a top quark, which accounts for the columns left blank in Table 2 and the fact that the branching ratio for neutralinos to neutrinos and jets is unity for $\lambda'_{i3k}$. This is certainly true for the parameter choice of Tables 1 and 2 for which the neutralino mass is 93.5 GeV. Should the LSP be heavier than the top quark, the final states for a $\lambda'_{i3k}$ coupling would involve the top quark and its decay products. For the energies assumed at the NLC, however, the production of neutralinos much heavier than the top quark is suppressed, so that neutralinos produced in $e\gamma$ collisions with any significant cross-section will have masses rather close to the top quark mass, in which case, the neutralino branching ratio to the top quark will be kinematically suppressed and this decay channel will not be competitive. The corresponding Cabibbo-Kobayashi-Maskawa-suppressed decay channel involving a charm quark is also negligible compared with the neutrino plus jets channel. The whole situation changes somewhat if a higher energy machine is contemplated, but that will not concern us in the present work.
Apart from the dramatic multilepton signals, the case of an electron accompanied by jets and missing energy is also worth serious consideration, since such signals are predicted irrespective of which $\lambda'$ coupling is involved. In fact, two of the couplings of interest for the HERA excess, viz., $\lambda'_{131}$ and $\lambda'_{132}$ can be accessed only through this mode. In this case signal cross-sections can be large for $\lambda'_{i3k}$ couplings, but we expect larger SM backgrounds too from processes like $e\gamma \rightarrow eZZ, \nuZW$, followed by hadronic decay of one of the $W, Z$ bosons (for which the branching ratios are higher) with gluon radiation making up the tally of jets. However, these backgrounds should be manageable with judicious cuts. The dashed line in Fig. 4(a) shows the missing (transverse) energy distribution for the signal assuming a $\lambda'_{121}$ coupling and a final state with $e^-$, jets and missing momentum. Parameter choices coincide with Table 2. As in the case of purely leptonic final states, a cut of $E_T^{miss} > 20$ GeV does not hurt the signal, though it must again be admitted that the missing energy will be rather soft if the neutralino is light.

In Fig. 4(b), we show a plot of the number of jets in the $e + E_T^{miss} +$ jets final state against neutralino mass for a left selectron with mass 200 GeV. The central value shows the mean number of jets and the bars show the statistical spread obtained in a simulation with 50000 events. The number of jets is determined almost wholly by the kinematics and has very little dependence on the other parameters of the model. It is apparent that for light neutralinos below 50 GeV, one would tend to have two jets, which is simply because the neutralinos are highly boosted and their decay products tend to lie in a narrow cone about the original direction. In this case, we will undoubtedly have a SM background from $e\gamma \rightarrow e\bar{q}q$ through a $Z$ resonance to worry about, and one would probably require a strong cut on the missing energy and maybe a cut on the invariant mass of the jets to remove the effect of the $Z$-resonance. The missing energy criterion alone should ensure that the background becomes negligible. Moreover, as the mass of the neutralino, increases, the final state would tend to have three to four jets. For the SM background, this requires radiation of at least one gluon and hence suppression of the cross-section by one or more powers of the strong coupling constant $\alpha_s$.

Finally, we briefly discuss the case when baryon-number is violated. In this case, each neutralino
(LSP) would decay into three jets, so that the final signal would be a hard, isolated electron and up to six hadronic jets. In the absence of multileptons in the final state it is essential to trigger on the sole electron which must then satisfy energy and angular criteria as defined above, and, in addition, must be isolated from all the hadronic jets. Given the wide spatial distribution of hadronic debris, this criterion would plainly lead to a significant reduction in the cross-section. Backgrounds from $e\gamma \to eZ \to eq\bar{q}$, followed by gluon radiation, can perhaps be controlled as before, though there is no simple criterion such as missing energy to distinguish signal from background. A detailed simulation of the multijet production and merging would be needed, therefore, and suitable cuts devised, in order to isolate the signal. Such an analysis is beyond the scope of the present work.

To conclude, then, we have explored the possibility that an $e\gamma$ collider can produce a selectron in association with a neutralino (LSP). Decay of the selectron can yield a final state with an electron and two neutralinos. We assume that $R$-parity is weakly violated and thus the neutralinos will decay into three-fermion states. Different possibilities have been considered and it seems that rather optimistic discovery limits can be set for lepton-number-violating couplings. Should an $e\gamma$ collider be built, therefore, one can look forward to significant advances in the study of supersymmetry, including the option of $R$-parity violation considered here.

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