Single chargino production with R-parity lepton number violation in electron-electron and muon-muon collisions

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Abstract

We examine single chargino production in conjunction with R-parity lepton number violation in future lepton-lepton collisions. Present bounds on R-parity violating couplings allow for a production cross section of the order of $\mathcal{O}(10 \text{ fb})$ for a wide range of sneutrino and chargino masses. Scenarios of chargino decay which lead to purely leptonic signals in the final state and without missing energy are also discussed.

1 Introduction

R-parity is a discrete symmetry defined by assigning to every field the number $R = (-1)^{3B+L+2S}$ ($B(L)$ - baryon (lepton) number, $S$ - spin of the particle) \cite{1}. If it is conserved then baryon and lepton number violating transitions are forbidden. In that case, the theory guarantees both proton stability and lepton universality. However, in supersymmetric extensions of the Standard Model, gauge invariance and renormalizability, the two main principles of any gauge theory, do not assure R-parity conservation. At present, wide phenomenological investigations of R-parity violating processes have been undertaken (for reviews see e.g. \cite{2,3}).

Here we will explore the possibility of discovering the lepton number violating process of single chargino production at future lepton-lepton colliders (see Fig.1(I) for an electron-electron collision). To our knowledge this process has not yet been discussed, though lepton number violating charginos pair production in electron-electron collisions (Fig.1(II)) has been considered \cite{4–6}.

Let us start with electron-electron collisions. The analysis of the muon option is analogous and will be shortly discussed whenever needed. As can be seen from Fig.1(I), the cross
The section for single chargino production is proportional to $\lambda^2 g^2$ where $\lambda$ and $g$ are couplings involved in the following Lagrangians ($\lambda_{abc} = -\lambda_{acb}$, $a, b, c$ are family indices):

$$L = g\bar{\tilde{\chi}}_i V_{i1} (1 - \gamma_5) e \tilde{K}_{em} \tilde{\nu}_m^* + h.c.,$$  \hspace{1cm} (1)

$$L_{\bar{R}_p} = \lambda_{abc} \{ \bar{\tilde{\nu}}_a L_c R_b L - (a \leftrightarrow b) \} + h.c. \hspace{1cm} (2)$$

These Lagrangians are written in physical basis. The matrix $\tilde{K}_{em}$ in Eq. (1) comes from the sneutrino mass matrix diagonalization. If R-parity is violated, we have to take into account the mixing between the sneutrinos $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$ and the neutral Higgs bosons $H^0_1$, $H^0_2$. We shall, however, assume that this mixing is negligible and does not affect the results, at least at the stage of chargino production. In what follows we shall also assume that the exchange of the lightest (electron) sneutrino dominates (which is equivalent to some hierarchy assumption in the sneutrino sector) and neglect the contribution of the heavier $\tilde{\nu}$'s. We therefore set ($e$ stands for electron) $\tilde{K}_{em} = \delta_{em}$ in Eq. (1). For more complicated cases where the interplay between sneutrino masses in propagators and appropriate elements of the $\tilde{K}$ matrix matters we refer to [5].

The second mixing matrix, namely $V_{i1}$ in Eq. (1) is connected with the chargino sector and describes the weights of the wino component of the chargino fields [7]. Since this is the only component of the charginos that couples to the electron and the sneutrino (the charged higgsino coupling is neglected in the limit of zero electron mass) we set for simplicity $V_{i1} = 1$. This is further justified by the analysis [8] (in the parameter region $|\mu| \geq 100$ GeV, $M_2 \geq 100$ GeV for both small and large $\tan \beta$, with $\mu, M_2$ being the higgsino and gaugino $SU(2)$ mass parameters, respectively, and $\beta$ a ratio of two vacuum expectation values involved in MSSM). In general the results should be multiplied by $V_{i1}^2$. Furthermore, with R-parity violation, additional couplings between leptons, gauginos and higgsinos ($e, \mu, \tau, \tilde{W}^-, \tilde{H}^-$) exist, but are known to be smaller than the gauge ones [9].
Fig. 2. Production of a single chargino in $e^-e^- \rightarrow \mu^- (\tau^-) \tilde{\chi}^-$ as function of its mass for both $\sqrt{s} = 500$ GeV (solid) and $\sqrt{s} = 1$ TeV (dashed) energies, $\lambda_{112(3)} = 0.05$. In both cases, curves corresponding to sneutrino masses $m_{\tilde{\nu}} = 100, 200, 300$ GeV are given. A 100% left-handed electron beam is assumed and the chargino is a pure wino state (see discussion in the introduction).

2 Single chargino production and decays: results

In Fig. 2 we gather the cross sections for single chargino production at future electron-electron colliders with c.m. energies $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV as functions of the chargino mass for different sneutrino masses $m_{\tilde{\nu}}$. For the R-parity violating coupling, we have used the most conservative available upper limit $\lambda_{112(3)} \equiv \lambda = 0.05$ [10], independently of the $\tilde{\nu}_e$ mass (in the case of muon-muon collisions the $\lambda_{212(3)}$ couplings would be involved). For sneutrino masses larger than 100 GeV this limit becomes weaker [10].

As can be deduced from Fig. 2, with a planned annual luminosity of some 50 fb$^{-1}$ yr$^{-1}$ [11] and with a discovery limit at a level of 10 events per year ($\sigma = 0.2$ fb), the process is detectable for a wide range of sparticle masses.

With the R-parity violating production process (I) we are already definitely out of the SM physics. It is therefore interesting to investigate the possible detector signals. With R-parity non-conservation, the collider phenomenology is quite different from the MSSM case and depends especially on the nature of the LSP (Lightest Supersymmetric Particle). In the MSSM, the stable LSP must be charge and color neutral for cosmological reasons [12]. With R-parity violation there are no hints about the unstable LSP. It can be among others a sneutrino, gluino or even a chargino [2,13]. Here we give an example of nonstandard

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1 Results (see Appendix) assume a $P_{e^-} = -100\%$ electron beam polarization. In reality we can expect that $P_{\mu^-} = -90\%$ can be achieved. Then the cross sections must be multiplied by a factor $rac{1}{2}(1 - P_{\mu^-})(1 - P_{e^-}) \approx 0.9$. 
phenomenology but restrict ourselves to a scenario in which charginos decay uniquely (via sneutrino exchange) to charged leptons. Final leptonic signals with lepton number violation and without missing energy could be detected, an interesting situation from the point of view of nonstandard physics, as there is no SM background (see further discussion). These two conditions (charged leptons without missing energy in the final state) require the chargino to be the second lightest supersymmetric particle (NLSP) with sneutrino the LSP. This situation is schematically summarized in Fig. 3. If the chargino were the LSP its lifetime should be long enough so that it would be seen in the detector. In other cases (i.e. when the chargino is neither NLSP nor LSP) the chargino would also have cascade decays to final jet states [14]. Then, the situation would be more complicated but at least we can expect that for kinematical reasons a decay to the R-parity lepton violating LSP sneutrino would still be important and the final signal with four charged leptons could be observed (work in progress).

Let us discuss the scenario with NLSP chargino. First, we should notice that, to get substantial chargino production (e.g. $e^-e^- \rightarrow \mu^-\tilde{\chi}^-$ in Fig.2), we are interested in the situation where at least one, let us say $\lambda_{112}$ coupling is large. Then the decay of chargino to three charged leptons must be observed in the detector, as it can undergo uniquely through the same large $\lambda_{112}$ coupling (the only possible decay channel, see Fig.3).

In Fig.4, we show the final results for the angular distribution of the final positron (Fig.3) for two different energies ($\sqrt{s} = 500(1000)$ GeV). We have taken $m_{\tilde{\chi}} = 205$ GeV and $m_{\tilde{\nu}} = 200$ GeV. Results have been obtained using the VEGAS procedure. Four particles in the final state give us an 8 dimensional integration. We have also applied the narrow width approximation where $\Gamma_{\tilde{\chi}} << m_{\tilde{\chi}}$ (see Appendix for details). The solid line describes results based on Eq. (A.21), when interferences between production and decay of charginos with $\tilde{\lambda} = \pm 1/2$ are taken into account. The dashed line describes results with factorization assumed [15], which means the following replacement in Eq. (A.21) is done

$$\sum_{\lambda} |M (- -; - , \tilde{\lambda}) T (\tilde{\lambda})|^2 \rightarrow \frac{1}{2} \sum_{\tilde{\lambda}} |M (- -; - , \tilde{\lambda})|^2 \sum_{\lambda} |T (\tilde{\lambda})|^2$$

(3)
We can see that spin correlations do not change the results substantially (≤ 2 % for considered c.m energies and the chargino mass). It is important that the positron angular distributions are not so strongly peaked in the beam directions, even for $\sqrt{s} = 1$ TeV collider energy. With assumed cuts ($|\cos \Theta_+| \leq 0.95$) enough events will be detected to investigate the process.

The only SM process, which gives a four charged lepton signal without missing energy is [16] $e^-e^- \rightarrow e^-e^-Z$. With a possible $Z$ boson decay to the lepton-antilepton pair, it does not coincide with the process under investigation ($e^-e^- \rightarrow 2\mu^-e^-e^+$). That means that we do not have to bother about the SM background contamination. However, this cross section is large enough ($\approx 1$ pb for $0.5 \leq \sqrt{s} \leq 2$ TeV energies) to cover some other scenarios. As an example let us assume that not only $\lambda_{112}$ but also $\lambda_{121}$ is not negligible and change the second coupling in the chargino decay channel (Fig.3) from $\lambda_{112}$ to $\lambda_{121}$. That means that we have now $(e^-e^- \rightarrow)e^-e^-\mu^-\mu^+$ in the final state, and this scenario will be dominated by the SM process given above with the $Z$ decay to the muon antimuon pair. In this way we can find that $\mu^-\mu^-e^-e^+(\tau^+), \mu^-\tau^-e^-e^+(\mu^+)$ and $\tau^-\tau^-e^-e^+$ charged lepton signals are testable (meaning sensitivity to the products $\lambda_{112} \cdot \lambda_{112}(\lambda_{113}), \lambda_{112} \cdot \lambda_{113}(\lambda_{123})$ and $\lambda_{113} \cdot \lambda_{113}$, respectively).

Finally, our results can be easily applied to the muon-muon collider where another set of R-parity lepton violating couplings can be tested, namely: $\lambda_{221} \cdot \lambda_{212}$ ($e^-e^-\mu^-\mu^+$ in the final state), $\lambda_{221} \cdot \lambda_{213}$ ($e^-e^-\mu^-\tau^+$) and $\lambda_{221} \cdot \lambda_{231}$ ($e^-\mu^-e^+\tau^-$).
3 Conclusions

Present experimental limits on R-parity violating couplings do not exclude large and detectable lepton number violating signals in lepton-lepton collisions. We discuss such a possibility in conjunction with single chargino production and its subsequent leptonic decay. If at least one $\lambda$ value is large enough - in our discussion mainly $\lambda_{112}$ - single chargino production in electron-electron collisions will be observable (Fig. 2). If the chargino is NLSP and sneutrino the LSP, a unique lepton number violating signal of four charged leptons without missing energy could be observed.

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A Appendix

The helicity amplitude for single chargino production $e^- e^- \rightarrow \mu^- (\tau^-) \tilde{\chi}^-$ is given by:

$$M(\sigma_1, \sigma_2; \lambda, \tilde{\lambda}) = g\lambda_{112} \left[ \bar{u}(p, \lambda)(1 - \gamma_5)u(k_1, \sigma_1) \frac{1}{t - m_{\chi}^2} \bar{u}(\tilde{p}, \tilde{\lambda})(1 - \gamma_5)u(k_2, \sigma_2) ight.$$

$$\left. - \bar{u}(\tilde{p}, \tilde{\lambda})(1 - \gamma_5)u(k_1, \sigma_1) \frac{1}{u - m_{\nu_e}^2} \bar{u}(p, \lambda)(1 - \gamma_5)u(k_2, \sigma_2) \right], \quad (A.1)$$

$$t(u) = m_{\chi}^2 - \sqrt{s}(\hat{E} \mp 2\tilde{p}\cos\tilde{\Theta}) \quad (A.2)$$

where $(\tilde{p}, \tilde{\lambda})$ denotes the momentum and helicity of the chargino, $(k_{1(2)}, \sigma_{1(2)})$ are the corresponding quantities for the incoming electrons, $p$ and $\lambda$ denote momentum and helicity of the muon (tau) and $(\hat{\Theta}, \hat{\phi})$ label the c.m. azimuthal and polar angles of a chargino with respect to the direction of the initial electron $e_1^-$. To work out the helicity amplitudes, we use the Weyl–van der Waarden spinor formalism [17] in which the 4–spinors can be written:

$$u(p, \lambda) = \begin{pmatrix} \sqrt{E - p\lambda} \chi(p, \lambda) \\ \sqrt{E + p\lambda} \chi(p, \lambda) \end{pmatrix}, \quad v = \begin{pmatrix} \lambda \sqrt{E + p\lambda} \chi(p, -\lambda) \\ -\lambda \sqrt{E - p\lambda} \chi(p, -\lambda) \end{pmatrix}, \quad (A.3)$$
and the Weyl spinors are given by:

\[
\chi(p, +1/2) = \left( e^{-i\phi/2} \cos \theta/2 \right), \quad \chi(p, -1/2) = \left( -e^{-i\phi/2} \sin \theta/2 \right),
\]

where \( \Theta, \phi \) denote the azimuthal and the polar angle of a particle with respect to the \( \hat{z} \) axis.

In the limit of zero mass of all charged leptons we have only two non-vanishing helicity amplitudes \((\sigma_{1,2}, \lambda = -1/2, \tilde{\lambda} = \pm 1/2)\), namely:

\[
M(-, - \rightarrow -, -) = g\sqrt{2s} \sqrt{(\tilde{E} - \tilde{p})(\tilde{E} - \tilde{p})} \lambda_{112} \left[ \frac{\cos^2 \frac{\tilde{\Theta}}{2} + \frac{\sin^2 \frac{\tilde{\Theta}}{2}}{u - m^2_{\tilde{\nu}_e}}}{t - m^2_{\tilde{\nu}_e}} \right],
\]

\[
M(-, - \rightarrow -, +) = -g\sqrt{2s} \sqrt{(\tilde{E} + \tilde{p})(\tilde{E} - \tilde{p})} \cos \frac{\tilde{\Theta}}{2} \sin \frac{\tilde{\Theta}}{2} \lambda_{112} \left[ \frac{1}{t - m^2_{\tilde{\nu}_e}} - \frac{1}{u - m^2_{\tilde{\nu}_e}} \right].
\]

The cross section is:

\[
d\sigma = \frac{1}{2s} dLips (s, p, \tilde{p}) \sum_{\tilde{\lambda}} \left| M(-, -; -, \tilde{\lambda}_j) \right|^2
\]

where

\[
dLips (s, p, \tilde{p}) = \frac{\tilde{p}}{16\pi^2 p} d\cos \tilde{\Theta} d\tilde{\phi}.
\]

In Fig. 3 we study the R-parity violating chargino decays via sneutrino exchange in the t-channel: \( \tilde{\chi} \rightarrow e^- e^+ \mu^- \). Analogously to the production the amplitude is:

\[
T(\tilde{\lambda}_i) = g\lambda_{112} \left[ \bar{u}(p_1, \sigma_1)(1 - \gamma_5)u(\tilde{p}, \tilde{\lambda}) \frac{1}{t - m^2_{\tilde{\nu}_e} + i\Gamma_{\tilde{\nu}} m_{\tilde{\nu}_e}} \bar{u}(p_2, \sigma_2)(1 - \gamma_5)\nu(p_+, \sigma_+) \right],
\]

where \(((p^i_{1(2)}, \sigma^i_{1(2)})\) denote the momenta and helicities of the electron and muon, \((p_+, \sigma_+)\) are analogous quantities for the final positron.

Using Eqs. (A.3,A.4) we get

\[
T(\tilde{\lambda} = +1/2) = \Omega_t(+) \left[ -e^{i/2(\phi_1 - \tilde{\phi})} \sin \frac{\Theta_1}{2} \cos \frac{\tilde{\Theta}}{2} + e^{-i/2(\phi_1 - \tilde{\phi})} \cos \frac{\Theta_1}{2} \sin \frac{\tilde{\Theta}}{2} \right]
\]
\[
\times \left[-e^{i/2(\phi_2-\phi_+)} \sin \frac{\Theta_2}{2} \cos \frac{\Theta_+}{2} + e^{-i/2(\phi_2-\phi_+)} \cos \frac{\Theta_2}{2} \sin \frac{\Theta_+}{2}\right]
\]

where \((\Theta_{+(1,2)}, \phi_{+(1,2)})\) denote azimuthal and polar angles of the final positron (electron (1), muon (2)) which are defined with respect to the direction of the initial electron beam \(e_1\) and \(\Omega_t(\pm)\) is given by

\[
\Omega_t(\pm) = g \sqrt{8E_+ E_2} \sqrt{\tilde{E} \pm \tilde{p} \lambda} \sum_{\tilde{\nu} \nu_n \lambda} \lambda_{n12} \frac{1}{l - m_{\tilde{\nu} n}^2 + i \Gamma_{\tilde{\nu} m} \nu_n}. \tag{A.12}
\]

The decay width can be written as

\[
d\Gamma = \frac{1}{2m_{\tilde{\chi}}} dLips (\tilde{m}, p_1, p_2, p_+) \sum_{\lambda} |T(\tilde{\lambda})|^2 \tag{A.13}
\]

where

\[
dLips (\tilde{m}, p_1, p_2, p_+) = \frac{1}{(2\pi)^5 8} \int dE_+ \int d \cos \Theta_+ \int d \phi_+ \int d \cos \Theta_2 \int d \phi_2. \tag{A.14}
\]

Formulae Eq. (A.13) describe the 3–body–decay of a chargino with energy \(\tilde{E}\) and angles \(\tilde{\Theta}, \tilde{\phi}\). The angles of the chargino and of the particles produced by chargino decay are defined with respect to the direction of the initial electron beam \(e_1\). Angles of the decaying particles are also defined with respect to the initial CM system of colliding electrons. We have left quantities connected with \(e^+\) as independent parameters to be integrated over. From the 12 quantities describing the chargino 3–body–decay, four are eliminated by momentum conservation. These are chosen to be the angles \(\Theta_1, \phi_1\) and the energies \(E_{1,2}\), namely:

\[
E_2 = \frac{1}{2} \frac{\tilde{m}_i - 2\tilde{E}E_+ + 2\tilde{p}E_+ \cos (\tilde{p}, p_+)}{\tilde{E} - E_+ - \tilde{p} \cos (\tilde{p}, p_2) + 2E_+ \cos (p_2, p_+)} \tag{A.15}
\]

\[
E_1 = \tilde{E} - E_2 - E_+ \tag{A.16}
\]

\[
\cos \Theta_1 = \frac{\tilde{p} \cos \tilde{\Theta} - E_2 \cos \Theta_2 - E_+ \cos \Theta_+}{E_1}. \tag{A.17}
\]

The angle \(\phi_1\) is fixed by two relations:

\[
E_1 \sin \Theta_1 \cos \phi_1 = \tilde{p} \sin \tilde{\Theta} \cos \tilde{\phi} - E_2 \sin \Theta_2 \cos \phi_2 - E_+ \sin \Theta_+ \cos \phi_+, \tag{A.18}
\]

\[
E_1 \sin \Theta_1 \sin \phi_1 = \tilde{p} \sin \tilde{\Theta} \sin \tilde{\phi} - E_2 \sin \Theta_2 \sin \phi_2 - E_+ \sin \Theta_+ \sin \phi_+. \tag{A.19}
\]
We end up with the 8 parameters (these are given by Eq. (A.14) and $\tilde{E}, \tilde{\Theta}, \tilde{\phi}$).

For completeness, it is trivial to compute the sneutrino decay width. For $m_{\tilde{\nu}} \leq m_{\tilde{\chi}}$ (the scenario discussed in the text, see Fig.4) only one decay channel to an $e^-\mu^+$ pair is open (for simplicity we assume that only one $\lambda_{112}$ dominates):

$$\Gamma_{\tilde{\nu}} = \frac{\lambda_{112}^2 m_{\tilde{\nu}}}{8\pi}. \quad (A.20)$$

Finally for the combined process of production and decay we obtain in the narrow width approximation:

$$d\sigma(e^-e^- \rightarrow 2\mu^-e^+) = \frac{1}{2s} d\text{Lips} \left( s, p, \tilde{p} \right) d\text{Lips} \left( \tilde{m}, p_1, p_2, p_+ \right) \frac{1}{2\pi} \sum_{\tilde{\lambda}} \left| M \left( --, -, \tilde{\lambda} \right) T \left( \tilde{\lambda} \right) \right|^2 \left( \frac{\pi}{m_T} \right) \Gamma \left( \tilde{\lambda} \right). \quad (A.21)$$

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