Chargino Production at an $e^-e^-$ Collider

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Abstract

The chargino pair production in $e^-e^-$ collisions with their subsequent decays are considered within SUSY models with R-parity violation and with lepton number non-conservation. The production process ($\sqrt{s} = 1$ TeV) is predicted to be large in a wide range of both sneutrino and chargino masses. The influence of all virtual sneutrino states and their mixings with electrons are taken into account. Some specific situations are pointed out when significant suppressions of the cross section can take place. The chargino decays are discussed for either the chargino as LSP or the chargino as heavier sparticle. In both cases unique signals are possible with up to six charged fermions and without missing energy.

1 Introduction

Many problems connected with particle physics as well as with astrophysics and cosmology remain unsolved within the framework of the Standard Model (SM). The search for going beyond the SM is therefore a part of many research programs. Supersymmetric models are among them as one of the most attractive extensions of the SM.

In the Minimal Supersymmetric Standard Model (MSSM) we assume that lepton- as well as baryon-numbers are conserved by introducing the so called R-parity in order to avoid rapid proton decay. This number is given by $R = (-1)^{L + 3B + 2S}$, with lepton number $L$, baryon number $B$ and spin $S$ of the respective particle. Two important consequences arise by that: firstly, we may only produce an even number of supersymmetric particles and, secondly, the lightest supersymmetric particle (LSP) is stable (and it has to be the lightest neutralino $\tilde{\chi}_1^0$). But there is no fundamental principle to introduce this R-parity. As long as either the baryon- or the lepton-number remains conserved, we are free to violate R-parity. In models with broken R-parity the phenomenology will be changed significantly. Since the LSP is unstable in these models, events with missing energy are not typical, anymore. Therefore it is worthwhile to investigate these models more carefully. It was
done lately especially in the context of the recent HERA data [1] which can (also) be interpreted within this type of models [2]. In this paper we would like to consider possible R-parity violation signals from chargino production at an $e^+e^-$ collider. This option of a future linear collider is especially promising for non-standard physics as the SM activity is highly suppressed (doubly charged initial state with a finite lepton number) [3].

Since this process violates lepton number, we introduce an additional superpotential violating R-parity, allowed by supersymmetry and renormalization [4]. This superpotential leads to new couplings both between two leptons and a slepton and between two baryonic states and a leptonic one

$$\mathcal{L} = \lambda_{abc} \left\{ \tilde{\nu}_a L \tilde{e}_c R e_b L + \tilde{e}_b L \tilde{\nu}_a L \tilde{e}_c R + (\tilde{e}_c R)^* (\tilde{\nu}_a L) e_b L - (a \leftrightarrow b) \right\} + h.c. \quad (1)$$

$$\mathcal{L} = \lambda'_{abc} \left\{ \tilde{\nu}_a L \tilde{d}_c R d_b L + \tilde{d}_b L \tilde{\nu}_a L \tilde{d}_c R + (\tilde{d}_c R)^* (\tilde{\nu}_a L) d_b L - \tilde{e}_a L \tilde{d}_c R u_b L - \tilde{u}_b L \tilde{d}_c R e_a L + (\tilde{d}_c R)^* (\tilde{e}_a L) u_b L \right\} + h.c. \quad (2)$$

We also get additional mixing between leptons, gauginos and higgsinos ($e, \mu, \tau, \tilde{W}^-, \tilde{H}^-$) and ($\nu_e, \nu_\mu, \nu_\tau, \tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0$), charged sleptons and charged Higgs bosons ($\tilde{e}, \tilde{\mu}, \tilde{\tau}, H^-$) and sneutrinos and neutral Higgs bosons ($\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau, H_1^0, H_2^0$) (for details of these mixings see e.g. [5]). From experiments we know, that these additional couplings, though existing, are small compared to the gauge ones [6]. We have also strong restrictions for additional mixings except those between gauginos and higgsinos, and between two neutral Higgs states.

The number of processes, in which two particles are produced is, due to charge conservation, limited to

1. $e^- e^- \to e^- e^-$
2. $e^- e^- \to W^- W^-$
3. $e^- e^- \to l_i^- l_j^-$ \quad $l_(i,j) = \mu^-, \tau^-$
4. $e^- e^- \to \tilde{e}^- \tilde{e}^-$
5. $e^- e^- \to \tilde{l}_i^- \tilde{l}_j^- \quad \tilde{l}_i(j) = \mu^-, \tau^-$
6. $e^- e^- \to \tilde{\chi}_i^- \tilde{\chi}_j^- \quad i, j = 1, 2$

Process (i) is the only possible process allowed in the SM and already investigated [7]. Processes (ii) and (iii) violate lepton number, but they are also possible in models without supersymmetry and have been investigated [8]. Processes (iv)-(vi) are only possible in supersymmetric models, where process (iv) is the only one, which is also possible within the MSSM, because it does not violate lepton number. This process has also been considered in the literature [9]. Both processes (v) and (vi) violate lepton number. Since process (v) is limited by the couplings $\lambda_{abc}$, we will consider only process (vi) in this paper. Although this process was already discussed in [9], both sneutrino mixing effects and R-parity violating decays of the produced charginos were not taken into account. It was assumed that the LSP is still the lightest neutralino and stable (like in the MSSM with conserved both R-parity and lepton number). Consequently the signatures of the final states are quite different from those given there.
This paper is organized as follows: in the next section we will calculate and discuss the cross section for process (vi) and in the following section we shall investigate possible decay modes of the produced charginos and we will consider possible signatures. Some concluding remarks will be collected in the last section.

2 Chargino production by $e^-e^-$ scattering

The process $e^-e^- \to \tilde{\chi}_i^- \tilde{\chi}_j^-$ proceeds through two Feynman diagrams with exchanged sneutrinos (in t and u channels) so the sneutrino-chargino-electron coupling must be known. In supersymmetric models the charginos are in principle mixtures of a Wino and a charged Higgsino eigenstate. If the lepton number is violated, then also leptons may mix with the Wino and the Higgsino. However, as already mentioned before, this mixing is strongly restricted by experiments and therefore negligible for the considered production process. The remaining mixing may be written in the following way $\tilde{\chi}_i^- = V_{i1}\tilde{W}^- + V_{i2}\tilde{H}^-$. Since only the Wino contribution couples with an electron (in the limit of zero electron mass) we will assume normalization in which the produced chargino is a pure Wino state with $V_{i1} = 1$. For other mixings results given in this paper should be multiplied by a factor $V_{i1}^4$.

This assumption implies the chargino-sneutrino-electron gauge coupling to be

$$\mathcal{L} = \frac{g}{\sqrt{2}} \tilde{\chi}_i^- (1 - \gamma_5) e \tilde{K}_{em} \tilde{\nu}_m^* + h.c., \quad (3)$$

with $g$ defined by the SM charged Lagrangian

$$\mathcal{L} = \frac{g}{\sqrt{2}} \tilde{e} \gamma^\mu (1 - \gamma_5) K_{em} \nu_m W^-_{\mu} + h.c.. \quad (4)$$

These interactions are written in a physical basis. For simplicity we assume that only left-handed currents exist. If we do not introduce right-handed neutrino $SU(2)_L$ singlets to the SM then neutrinos are massless and $K = I$, otherwise we have a $(3+n_R) \times (3+n_R)$ neutrino mass matrix and consequently a $3 \times (3 + n_R)$ charged lepton-neutrino mixing matrix $K$ which is of course not equal to identity $K \neq I$ (for details see e.g. [10]). Similarly
a diagonalization of the sneutrino - neutral Higgs sector gives a $\tilde{K}$ mixing matrix of dimension $3 \times 5$. Due to unitarity of the matrix $\tilde{U}$ we have

$$\sum_{m=1}^{5} | \tilde{K}_{em} |^2 = 1. \quad \text{(5)}$$

In the following, when we become specific, we will only take into account the sneutrino mixing submatrix with dimension $3 \times 3$. This is mainly motivated by the fact that in the limit of zero electron mass only sneutrino-electron couplings are unequal to zero. Both, the Higgs mixing part and the sneutrino Higgs mixing part are of no interest, since the first does not lead to any coupling (this is also the reason why an appropriate part of the Lagrangian with the $\tilde{K}'$ submatrix does not appear in Eq.(3)) and the second is assumed to be small.

In the limit of zero electron mass only four nonzero helicity amplitudes exist which can be written in the following form ($\lambda_{i(j)} = \pm 1/2$ stands for the helicities of the produced charginos, $\Sigma \lambda = \lambda_i + \lambda_j$, $\Theta$ is a scattering angle of the chargino $\tilde{\chi}^-_i$ in the $e^- e^-$ CM energy frame)

$$M(\ldots; \lambda_i, \lambda_j) = \frac{g^2}{2} \sum_{m=1}^{3} \tilde{K}_{em}^2 s \sqrt{(E_i + 2\lambda_i p_i)(E_j + 2\lambda_j p_j)}$$

$$\left( \frac{1}{t - m_{\tilde{\nu}_m}^2} - \frac{1}{u - m_{\tilde{\nu}_m}^2} \right) D^{1,\Sigma \lambda}_{-1}(\Theta), \quad \text{(6)}$$

where

$$E_{i(j)} = \frac{s \pm m_{\tilde{\chi}^-_i}^2 + m_{\tilde{\chi}^-_j}^2}{2\sqrt{s}},$$

$$t(u) = m_{\tilde{\chi}^-_i}^2 - \sqrt{s}(E_i \mp 2p_i \cos \Theta).$$

Two factors influence the magnitude of the amplitude $M$ – the square of the mixing matrix elements $\tilde{K}_{me}$ and the sneutrino masses $m_{\tilde{\nu}_m}$. The interplay between different elements of the $\tilde{K}_{em}$ matrix and the sneutrino masses can be quite important and can impact on the magnitude of the cross section in a meaningful way as we will discuss now.

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1 To be more specific: Let’s denote sneutrino and neutral Higgs states by $\tilde{\nu}_i$, $i=1,\ldots,5$. Then introducing a unitary $5 \times 5$ matrix $\tilde{U} = \begin{pmatrix} \tilde{K} \\ \tilde{K}' \end{pmatrix}$, which diagonalizes the sneutrino-neutral Higgs mass matrix, we get also a transformation between physical and non-physical states $\tilde{\nu} = \tilde{U} \tilde{\nu}_{\text{phys}}$. Assuming that the neutral Higgs coupling with the chargino-electron pair is negligible, we get directly the matrix $\tilde{K}$ in Eq.(3).
Let’s assume that all sneutrinos are degenerate in mass and the matrix $\tilde{K}$ is real. Then the amplitude $M$ in Eq.(6) has the form

$$M \propto \sum_m \tilde{K}_{em}^2 f(m_{\tilde{\nu}_m}) = f(m_{\tilde{\nu}_m}) \sum_m \tilde{K}_{em}^2 = f(m_{\tilde{\nu}_m}),$$

where Eq.(5) has been used. That means that in this case, no matter whatever the mixing between the sneutrinos and the electrons is, we have effectively one sneutrino with maximal mixing $\tilde{K}_{em} = 1$. A similar situation happens when we have different masses of the sneutrinos but only with one dominate (maximal) mixing $\tilde{K}_{em} \approx 1$ (negligible contributions from the other ones).

Fig.1 shows results for these two cases when a pair of the same chargino is produced at CM energy equal to 1 TeV. The results are also sensitive to the free parameters of the neutralino-chargino sector. Instead of choosing parameters $M_1^2$, $\mu$ and $\tan \beta = \frac{v_2}{v_1}$ as it is usually done, we fix here the chargino parameters $200 \text{ GeV} \leq m_{\tilde{\chi}^-_1} \leq 500 \text{ GeV}$ and $V_{11} = 1$. Notice that this choice is always possible, since the chargino sector is described by three free parameters, but for our calculations we have to fix only two of them. The sneutrino mass is taken in the range $100 \text{ GeV} \leq m_{\tilde{\nu}} \leq 800 \text{ GeV}$.

Fig.1 Cross section for the process $e^- e^- \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^- \bar{\nu}$ as a function of the chargino mass and sneutrino masses (downwards) $m_{\tilde{\nu}} = 100, 200, 300, 500, 800 \text{ GeV}$ and $\sqrt{s} = 1 \text{ TeV}$, $\tilde{K}_{em} = 1$, $V_{11} = 1$ (see text for details).

We can see that for a large spectrum of both sneutrino and chargino masses significant (detectable) values of the cross section are possible.
But a different situation can arise when the mixing matrix element \( \tilde{K}_{em} \) is not the maximal one and consequently smaller cross sections will be achieved \( (\sigma(e^-e^- \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^-) \sim \tilde{K}_{em}^4) \).

Firstly, let’s assume that the sneutrinos have apparently different masses but the mixing elements have comparable values. Such a situation is possible. To make this point clearer let’s support this statement by recalling an example from neutrino physics. It was proposed lately that solar, atmospheric and LSND results can be explained with a neutrino mixing matrix of the form \( [11] \) (notations modified to our convention (Eq.(4)), \( l(m) \) stands for charged leptons (neutrinos), respectively)

\[
\begin{pmatrix}
0.700 & 0.700 & 0.140 \\
-0.714 & 0.689 & 0.124 \\
-0.010 & -0.187 & 0.982
\end{pmatrix}
\leq \tilde{K}_{lm} \leq
\begin{pmatrix}
0.764 & 0.630 & 0.140 \\
-0.645 & 0.754 & 0.124 \\
-0.028 & -0.185 & 0.982
\end{pmatrix}
\tag{7}
\]

Similarly, if some of the elements of the matrix \( \tilde{K} \) are comparable in magnitude then, because of kinematical reasons, only the lightest sneutrino would contribute to the cross section (see Eq.(6)) and there would be a possibility of results smaller by even one order of magnitude (e.g. \( \sim (0.7)^4 \)) compared with the situation in Fig.1. Secondly, until now we assume that the \( \tilde{K}_{em} \) elements are real. However, if some of them are imaginary then real and imaginary elements would give opposite contributions to the amplitude (Eq.(6)) causing that the cross section would also be smaller than that given in Fig.1. We could even imagine some dramatic cancelations in this case. Let’s invoke physics from the neutrino sector once more. Another possible solution to a few not fully understood neutrino experimental results have been postulated e.g. in \([12]\). It was found that almost degenerate three neutrinos can reconcile solar, atmospheric, dark matter and neutrinoless double-\( \beta \) decay results with a mixing matrix of the form

\[
K_{lm} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \\ 1 & 1 & 1 \end{pmatrix}, \quad (\omega = e^{\frac{2\pi i}{3}}).
\tag{8}
\]

For such a matrix we have \( \sum_m K_{em}^2 = 1 + \omega + \omega^2 = 0 \). If a similar situation exists in the sneutrino sector then a large suppression of the cross section could happen.

3 Decays and Signatures

In this section we shall discuss possible decays of the produced charginos in order to investigate possible signatures for the process \( e^- e^- \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^- \). Since the lightest supersymmetric particle LSP is in case of R-parity violation not necessarily the lightest neutralino \( \tilde{\chi}_0^0 \) but also the lighter chargino or the sneutrino \( \tilde{\nu} \) are possible candidates, we have to distinguish two possible scenarios:

(1) \( \tilde{\chi}_1^- \) is the LSP
(2) \( \tilde{\chi}_1^- \) is not the LSP
In case the chargino is the LSP, it decays R-parity violating. Two different modes are possible: In the first case all lepton components of $\tilde{\chi}_1^-$ are negligible. Then the chargino decays via t- and u-channel processes with a virtual sfermion

$$\tilde{\chi}_1^- \rightarrow e_i^- \nu_j \bar{\nu}_k (e_i^+ e_j^- e_k^-)$$

or

$$\tilde{\chi}_1^- \rightarrow e_i^- q_j \bar{q}_k (\nu_i \bar{u}_j d_k)$$

due to the couplings $\lambda_{abc}$ or $\lambda'_{abc}$ at the sfermion-fermion-fermion vertex respectively, where the $i, j, k = 1, 2, 3$ denote the families.

In the second case a non-vanishing lepton-wino and lepton-higgsino mixing exists. This mixing, although (as already discussed) negligible for the production process, may become important for the decays [5]. In this case, the lepton component of $\tilde{\chi}_1^-$ couples to a gauge boson and the respective lepton by a gauge coupling. Therefore the interesting decay modes are

$$\tilde{\chi}_1^- \rightarrow W^- \nu_i (Ze_i^-) (i = 1, 2, 3).$$

Therefore possible signatures contain up to six charged fermions, in some cases six charged leptons. In each case signatures without missing energy are possible.

In case the lighter chargino $\tilde{\chi}_1^-$ is not the LSP, we have to consider other candidates. Two possible candidates, discussed here, are the lightest neutralino $\tilde{\chi}_0^0$ or the sneutrino $\tilde{\nu}$.

In some scenarios the chargino, though not the LSP, still decays dominantly R-parity violating, into either three fermions [13] or a fermion and a gauge boson [5]. For these scenarios the modes and therefore the signatures are just the same as in case (i).

In many other scenarios the chargino decays R-parity conserving into the respective LSP and SM-particles [9]

$LSP = neutralino$

$$\tilde{\chi}_1^- \rightarrow \tilde{\chi}_0^0 \nu_i e_i^- (\tilde{\chi}_1^0 \bar{u}_i d_i)$$

$$\tilde{\chi}_1^- \rightarrow H^- \tilde{\chi}_1^0,$$

$$\tilde{\chi}_1^- \rightarrow W^- \tilde{\chi}_1^0$$

$LSP = sneutrino$

$$\tilde{\chi}_1^- \rightarrow \tilde{\nu}_i e_i^-.$$

The respective LSP subsequently decays R-parity violating. In the first case the $\tilde{\chi}_1^0$ decays by $\tilde{\chi}_1^0 \rightarrow e_i^+ e_j^- \nu_k (e_i^- u_j \bar{d}_k)$ or, if there is a non-vanishing neutrino-gaugino-higgsino mixing, also the decays $\tilde{\chi}_1^0 \rightarrow \nu_i Z (e_i \bar{W})$ are possible. In the latter case the sneutrino $\tilde{\nu}_i$ decays by $\tilde{\nu}_i \rightarrow e_j^+ e_k^- (d_j \bar{q}_k)$. The main result is that, for all different scenarios, signatures without missing energy are possible. Since missing energy is a typical part of a MSSM event, these signatures are obviously different from those for the process $e^- e^- \rightarrow e^- e^-$ within the MSSM.
Backgrounds from SM or non-SUSY models with lepton number violation are of higher order, since the basic processes $e^- e^- \rightarrow e^- e^-$ and $e^- e^- \rightarrow W^- W^-$ lead to signatures with at most four charged fermions. Therefore possible background processes are $e^- e^- \rightarrow l l B B$, where $l$ denotes a lepton and $B$ denotes a boson $B = H, W, Z$ [14]. These higher order processes should be compared with signatures considered in this paper as both of them predict 6 charged fermions in the final state (paper in preparation).

4 Conclusions

We have discussed chargino pair production in $e^- e^-$ collisions for supersymmetric models with R-parity violation and with lepton number non-conservation. The gauge nature of the appropriate couplings causes that the magnitude of the cross section is large enough for the process to be detected in a wide range of both sneutrino and chargino masses. However, it has been shown that the interplay between contributions from different sneutrino states can cause large suppression of the cross section. If this is not the case then the final signal from the decaying charginos is worth to study. It has been shown that final state with up to six charged fermions or even, in some cases, six charged leptons can be produced for both considered cases, e.g. the lighter chargino is the LSP or is not the LSP. These signatures are without missing energy.

We therefore conclude, that an $e^- e^-$-collider can be a very good tool in order to discover SUSY models with lepton number violation.

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