Single chargino production with R-parity lepton number violation in e^-e^- collisions

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Abstract

We examine single chargino production in conjunction with R-parity lepton number violation in future electron-electron 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) [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. [2,3]).

Here we will explore the possibility of discovering the lepton number violating process of single chargino production at future lepton-lepton colliders. To our knowledge this process has not yet been discussed, though both lepton number violating charginos pair production in electron-electron collisions [4–6] and R-parity violating single chargino production in electron-positron collisions [3,7] have been considered.

As can be seen from Fig.1(I), the cross section for single chargino production is proportional to $\lambda^2 g^2$ where λ and g are couplings involved in the following Lagrangians ($\lambda_{abc} = -\lambda_{acb}$, a, b, c are family indices):

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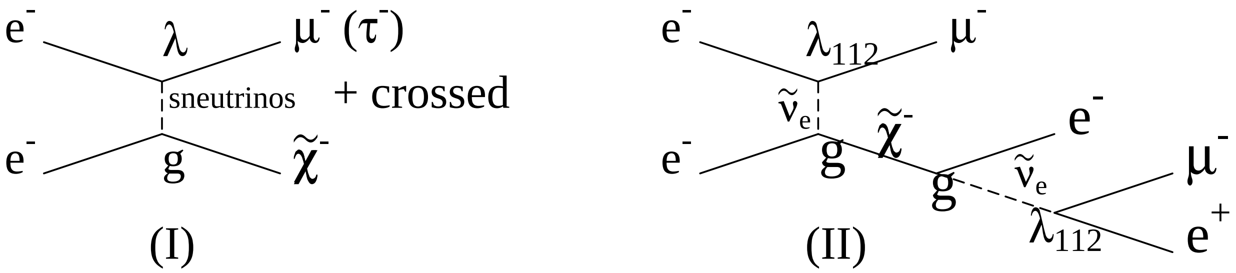

Fig. 1. On the left, single chargino production at an e^-e^- collider. λ and g are couplings specified in Eqs. (1,2). On the right, the lepton violating chargino decay for a scenario discussed in the paper.

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

$$\mathcal{L}_{\not R_p} = \lambda_{abc}\{\tilde{\nu}_{aL}\bar{l}_{cR}l_{bL} - (a \leftrightarrow b)\} + h.c. \tag{2}$$

The Lagrangian Eq. (1) is written in the physical basis. The matrix $\tilde{K}_{em}$ 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_1^0, H_2^0. 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 [8]. 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 $V_{i1} = 1$. Such a scenario can be relatively easily found in the parameter region $|\mu| \geq 100$ GeV, $M_2 \geq 100$ GeV for both small and large $\tan\beta$ (μ, M_2 being the higgsino and gaugino $SU(2)$ mass parameters, respectively, and $\tan\beta$ 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 $(e, \mu, \tau, \tilde{W}^-, \tilde{H}^-)_L$ exist, but are known to be smaller than the gauge ones [9].

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

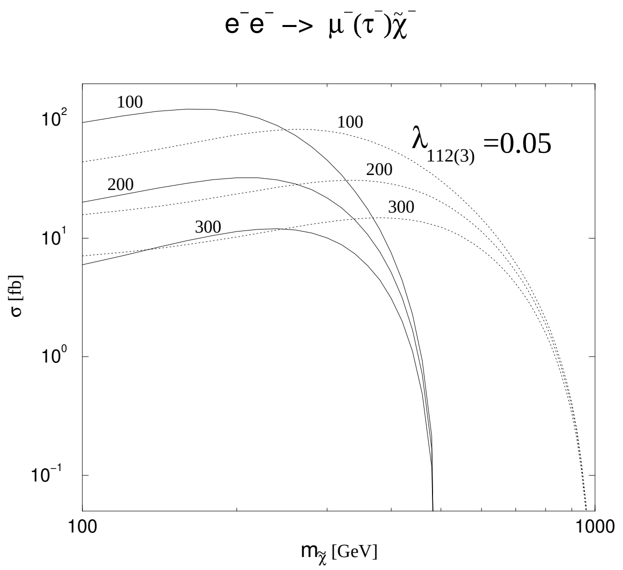

Fig. 2. Production of a single chargino in $e^-e^- \to \mu^-(\tau^-)\tilde{\chi}^-$ as function of its mass for both $\sqrt{s} = 500$ GeV (solid) and $\sqrt{s} = 1$ TeV (dashed) energies, $\lambda_{112(3)} = 0.05$. Sneutrino masses (in GeV) are shown above the curves. A 100% left-handed electron beam is assumed and the chargino is a pure wino state (see discussion in the introduction).

the chargino mass for different sneutrino masses [1]. For the R-parity violating coupling, we have used the most conservative available upper limit $\lambda_{112(3)}$, independently of the $\tilde{\nu}_e$ mass. 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 40 fb^{-1} yr^{-1} [11] and with a discovery limit at a level of 10 events per year ($\sigma = 0.25$ fb), the process is detectable for a wide range of sparticle masses.

With the R-parity violating production process Fig.1(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 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.1(II).

[1] Results (see Appendix) assume a $P^e_- = -100\%$ electron beam polarization. In reality we can expect that $P^e_- = -90\%$ can be achieved. Then the cross sections must be multiplied by a factor $\frac{1}{4}(1-P^{e_1}_-)(1-P^{e_2}_-) \simeq 0.9$.

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. $e^-e^- \to \mu^-\tilde{\chi}^-$ in Fig.2), we are interested in the situation where at least one, let us say λ_{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 λ_{112} coupling (the only possible decay channel, see Fig.1(II)).

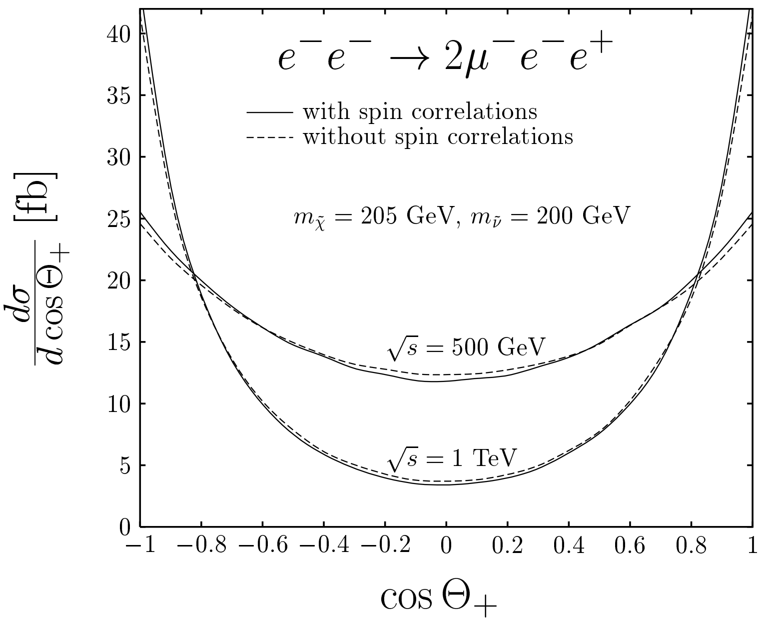

Fig. 3. Angular distribution of the final positron from Fig. 1 with spin correlations taken into account (solid line) and with factorization between its production and decay (dashed line). $\sqrt{s} = 1$ TeV, $m_{\tilde{\chi}} = 205$ GeV, $m_{\tilde{\nu}} = 200$ GeV, $\lambda = 0.05$.

In Fig.3, we show the final results for the angular distribution of the final positron (Fig.1(II)) 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

$$\left| \sum_{\tilde{\lambda}} M\left(--;-,\tilde{\lambda}\right) T\left(\tilde{\lambda}\right) \right|^2 \to \frac{1}{2} \sum_{\tilde{\lambda}} \left| M\left(--;-,\tilde{\lambda}\right) \right|^2 \sum_{\tilde{\lambda}} \left| T\left(\tilde{\lambda}\right) \right|^2 \tag{3}$$

We can see that spin correlations do not change the results substantially and are at most of the order of 2 % for considered c.m energies and the chargino mass. These effects are more important for energies below 350 GeV (up to 15 % in the range $250 \leq \sqrt{s} \leq 350$ GeV and the same chargino mass). Below $\sqrt{s} = 250$ GeV the production cross section decreases below 1 fb.

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] $e^-e^- \to e^-e^-Z$. With a possible Z boson decay to the lepton-antilepton pair, it does not coincide with the process under investigation ($e^-e^- \to 2\mu^-e^-e^+$). That means that we do not have to bother about the SM background contamination. However, this cross section is large enough ($\simeq 1$ 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 λ_{112} but also λ_{121} is not negligible and change the second coupling in the chargino decay channel (Fig.1(II)) from λ_{112} to λ_{121}. That means that we have now $(e^-e^- \to) e^-e^-\mu^-\mu^+$ 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, let us note that if the muon-muon collider were built then it would be sensitive to another set of R-parity lepton violating couplings, 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 λ value is large enough - in our discussion mainly λ_{112} - single chargino production in electron-electron collisions will be observable (Fig.2). If the chargino is the 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 $e^-e^- \to \mu^-(\tau^-)\tilde{\chi}^-$ is given by:

$$M(\sigma_1,\sigma_2;\lambda,\tilde{\lambda}) = g\lambda_{112}\Big[\bar{u}(p,\lambda)(1-\gamma_5)u(k_1,\sigma_1)\frac{1}{t-m^2_{\tilde{\nu}_e}}\bar{u}(\tilde{p},\tilde{\lambda})(1-\gamma_5)u(k_2,\sigma_2)$$
$$-\bar{u}(\tilde{p},\tilde{\lambda})(1-\gamma_5)u(k_1,\sigma_1)\frac{1}{u-m^2_{\tilde{\nu}_e}}\bar{u}(p,\lambda)(1-\gamma_5)u(k_2,\sigma_2)\Big], \tag{A.1}$$
$$t(u) = m^2_{\tilde{\chi}} - \sqrt{s}(\tilde{E} \mp 2\tilde{p}\cos\tilde{\Theta}) \tag{A.2}$$

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 λ denote momentum and helicity of the muon (tau) and $(\tilde{\Theta},\tilde{\phi})$ 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 Waerden spinor formalism [17] in which the 4–spinors can be written:

$$u(p,\lambda) = \begin{pmatrix} \sqrt{E-p\lambda}\,\chi(p,\lambda) \\ \sqrt{E+p\lambda}\,\chi(p,\lambda) \end{pmatrix}, \qquad v = \begin{pmatrix} \lambda\sqrt{E+p\lambda}\,\chi(p,-\lambda) \\ -\lambda\sqrt{E-p\lambda}\,\chi(p,-\lambda) \end{pmatrix}, \tag{A.3}$$

and the Weyl spinors are given by:

$$\chi(p,+1/2) = \begin{pmatrix} e^{-i\phi/2}\cos\theta/2 \\ e^{i\phi/2}\sin\theta/2 \end{pmatrix}, \qquad \chi(p,-1/2) = \begin{pmatrix} -e^{-i\phi/2}\sin\theta/2 \\ e^{i\phi/2}\cos\theta/2 \end{pmatrix}, \tag{A.4}$$

where Θ,ϕ denote the azimuthal and the polar angle of a particle with respect to the z axis.

In the limit of zero mass of all charged leptons we have only two non-vanishing helicity amplitudes $(\sigma_{1,2},\lambda=-1/2,\tilde{\lambda}=\pm1/2)$, namely:

$$M(-,-\to-,-) = g\sqrt{2s}\sqrt{(\tilde{E}-\tilde{p})(\tilde{E}-\tilde{p})}\lambda_{112}\left[\frac{\cos^2\frac{\tilde{\Theta}}{2}}{t-m^2_{\tilde{\nu}_e}} + \frac{\sin^2\frac{\tilde{\Theta}}{2}}{u-m^2_{\tilde{\nu}_e}}\right] \tag{A.5}$$
$$M(-,-\to-,+) = -g\sqrt{2s}\sqrt{(\tilde{E}+\tilde{p})(\tilde{E}-\tilde{p})}\cos\frac{\tilde{\Theta}}{2}\sin\frac{\tilde{\Theta}}{2}\lambda_{112}\left[\frac{1}{t-m^2_{\tilde{\nu}_e}} - \frac{1}{u-m^2_{\tilde{\nu}_e}}\right]. \tag{A.6}$$

The cross section is:

$$d\sigma = \frac{1}{2s} dLips\left(s, p, \tilde{p}\right) \sum_{\tilde{\lambda}} \left| M\left(-,-;-,\tilde{\lambda}\right)\right|^2 \tag{A.7}$$

where

$$dLips\left(s, p, \tilde{p}\right) = \frac{\tilde{p}}{16\pi^2 p} d\cos\tilde{\Theta} d\tilde{\phi}. \tag{A.8}$$

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

$$T(\tilde{\lambda}) = g\lambda_{112}\left[\bar{u}(p_1,\sigma_1)(1-\gamma_5)u(\tilde{p},\tilde{\lambda})\frac{1}{t - m^2_{\tilde{\nu}_e} + i\Gamma_{\tilde{\nu}} m_{\tilde{\nu}_e}}\bar{u}(p_2,\sigma_2)(1-\gamma_5)v(p_+,\sigma_+)\right], \tag{A.9}$$

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

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

$$T(\tilde{\lambda} = +1/2) = \Omega_t(+)\left[-e^{i/2(\phi_1-\tilde{\phi})}\sin\frac{\Theta_1}{2}\cos\frac{\tilde{\Theta}}{2} + e^{-i/2(\phi_1-\tilde{\phi})}\cos\frac{\Theta_1}{2}\sin\frac{\tilde{\Theta}}{2}\right]$$
$$\times\left[-e^{i/2(\phi_2-\phi_+)}\sin\frac{\Theta_2}{2}\cos\frac{\Theta_+}{2} + e^{-i/2(\phi_2-\phi_+)}\cos\frac{\Theta_2}{2}\sin\frac{\Theta_+}{2}\right] \tag{A.10}$$

$$T(\tilde{\lambda} = -1/2) = \Omega_t(-)\left[e^{i/2(\phi_1-\tilde{\phi})}\sin\frac{\Theta_1}{2}\sin\frac{\tilde{\Theta}}{2} + e^{-i/2(\phi_1-\tilde{\phi})}\cos\frac{\Theta_1}{2}\cos\frac{\tilde{\Theta}}{2}\right]$$
$$\times\left[-e^{i/2(\phi_2-\phi_+)}\sin\frac{\Theta_2}{2}\cos\frac{\Theta_+}{2} + e^{-i/2(\phi_2-\phi_+)}\cos\frac{\Theta_2}{2}\sin\frac{\Theta_+}{2}\right] \tag{A.11}$$

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

$$\Omega_t(\pm) = g\sqrt{8E_+E_1E_2}\sqrt{\tilde{E} \pm \tilde{p}\tilde{\lambda}}\lambda_{112}\frac{1}{t - m^2_{\tilde{\nu}_e} + i\Gamma_{\tilde{\nu}} m_{\tilde{\nu}_e}}. \tag{A.12}$$

The decay width can be written as

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

where

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

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 9 quantities describing the chargino 3–body–decay, four are eliminated by momentum conservation. These are chosen to be the angles Θ_1, ϕ_1 and the energies $E_{1,2}$, namely:

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

$$E_1 = \tilde{E} - E_2 - E_+ \qquad \text{(A.16)}$$

$$\cos\Theta_1 = \frac{\tilde{p}\cos\tilde{\Theta} - E_2\cos\Theta_2 - E_+\cos\Theta_+}{E_1}. \qquad \text{(A.17)}$$

The angle ϕ_1 is fixed by two relations:

$$E_1 \sin\Theta_1 \cos\phi_1 = \tilde{p}\sin\tilde{\Theta}\cos\tilde{\phi} - E_2\sin\Theta_2\cos\phi_2 - E_+\sin\Theta_+\cos\phi_+, \qquad \text{(A.18)}$$

$$E_1 \sin\Theta_1 \sin\phi_1 = \tilde{p}\sin\tilde{\Theta}\sin\tilde{\phi} - E_2\sin\Theta_2\sin\phi_2 - E_+\sin\Theta_+\sin\phi_+ \qquad \text{(A.19)}$$

We end up with 8 parameters for the full 4-particle phase space (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.3) only one decay channel to an $e^-\mu^+$ pair is open (for simplicity we assume that only one λ_{112} dominates):

$$\Gamma_{\tilde{\nu}} = \lambda_{112}^2 m_{\tilde{\nu}_e}/8\pi. \qquad \text{(A.20)}$$

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

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

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