# R-parity Violation at a 500 GeV $e^+e^-$-Collider [1]

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## 1 Introduction

Given only the particle content of the minimal supersymmetric standard model (MSSM)[1], the most general gauge and supersymmetric invariant Lagrangian includes the following Yukawa interactions *beyond* those of the MSSM [2]:

$$[\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k]_F \tag{1}$$

where $L$ and $\bar{E}$ ($Q$ and $\bar{U}, \bar{D}$) are the left-handed components of the doublet and singlet superfields respectively. If lepton-number violating couplings ($\Delta L \neq 0$; the first two sets of operators above) and baryon-number violating couplings ($\Delta B \neq 0$; the last set of operators) are simultaneously present in the Lagrangian, they generate proton decay at an unacceptable level. In the MSSM all the terms of Eq.(1) are eliminated by imposing a multiplicative symmetry called R-parity ($R_p$); all supersymmetric particles have $R_p = -1$, while all states of the Standard Model (SM) have $R_p = +1$. However there is no theoretical bias as to whether $R_p$ is conserved or not [3], thus it is important to study the possibility of having either $\Delta L \neq 0$ or $\Delta B \neq 0$ operators in the Lagrangian, but not both.

In this report we study the phenomenology of the Yukawa couplings (1) at a $500\,GeV$ $e^+e^-$ collider. It differs from that of the MSSM in two important aspects:

1. The lightest supersymmetric particle (LSP) is no longer protected by a symmetry and can decay to the conventional particles of the SM.

2. Beyond the MSSM pair production of sparticles, we now also have single sparticle production directly through the operators of Eq.(1).

The produced supersymmetric particles can now decay either directly, or through the LSP to an $R_p$-even final state. The possible dominant signals can thus be summarized as

$$\begin{array}{llll} (1) & (\text{MSSM pairproduction}) & \oplus & (\not{R}_p - \text{decay}), \\ (2) & (\not{R}_p \text{ single susy production}) & \oplus & (\not{R}_p - \text{decay}), \end{array} \tag{2}$$

which we in turn discuss in the next section.[3] We thereby no longer have the standard missing $\not{p}_T$ signals of the MSSM. In our analysis of the $\not{R}_p$ phenomenology we make the following assumptions which are discussed in detail in Ref.[4]:

1. Of the 45 couplings in Eq.(1), one coupling dominates. For example $\lambda_{121} \neq 0$, and the rest are set equal to zero. We thus consider 45 separate cases.

2. The LSP is the photino.

3. The LSP decays inside the detector, i.e. [5, 4] $\lambda > 5\gamma \cdot 10^{-2} \left(\frac{M_{\tilde{f}}}{100\ GeV}\right)^2 \left(\frac{1\ GeV}{M_{\tilde{\gamma}}}\right)^{5/2}$, where $\gamma$ is the Lorentz boost factor.

Present experimental constraints on the couplings (1) are summarized in Refs.[4, 7]. The most relevant bounds for are analysis are those on the operators $L_1 L_i \bar{E}_1$, $i = 1, 2$, and are given by $\lambda_{1i1} < 0.1(\frac{\tilde{m}}{100\,GeV})$, where $\tilde{m}$ refers to the supersymmetric mass relevant in the process. Cosmological bounds have been discussed elsewhere [6, 3].

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[3] We do not consider $2 \to 2$ processes via 2 $\not{R}_p$-operator insertions as we expect them to be strongly suppressed by the extra powers of the small coupling.

## 2 Cross sections and Signals

### 2.1 Pair Production of S-Particles

The cross-sections for the MSSM pair production of supersymmetric particles have been presented in Ref.[8]. As an example we consider here the case $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$, for which we have plotted the total cross-section in Fig.1 as a function of the scalar muon (s-muon, $\tilde{\mu}$) mass ($m_{\tilde{\mu}}$). The s-muon will dominantly decay to the LSP [4]: $\tilde{\mu} \to \tilde{\gamma}\mu$, provided the dominant coupling is not large compared to the gauge coupling or does not involve the s-muon. The decays of the photino $\tilde{\gamma}$ depend on the nature of the dominant operator

$$\begin{array}{ll} a)\,\tilde{\gamma} \to l_i^{\pm} l_k^{\mp} \nu_j, & \mathcal{O} = [L_i L_j \bar{E}_k]_F \\ b)\,\tilde{\gamma} \to l_i^{\pm} + 2\,jets, & \mathcal{O} = [L_i Q \bar{D}]_F \\ c)\,\tilde{\gamma} \to 3\,jets, & \mathcal{O} = [\bar{U}\bar{D}\bar{D}]_F \end{array} \tag{3}$$

The charges of the leptons can vary due to the Majorana nature of the photino. Combining the scalar muon production with its dominant decay and using the photino decays above we arrive at three sets of signals

$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^- + \begin{cases} l_i^+ l_i^+ l_k^- l_k^- + \not{p}_T & (a) \\ l_i^+ l_i^+ + 4\,jets & (b) \\ 6\,jets & (c) \end{cases} \tag{4}$$

The case ($c$) leads to no visible signal and thus to no experimental bound on $m_{\tilde{\mu}}$. The cases ($a$) and ($b$) however lead to clearly visible lepton-number violating signals for which the SM background should be small; particularly in case (a) where we obtain six charged leptons! We have estimated that 15-20 events per year should suffice to discover the s-muon in these scenarios. For a luminosity of $\mathcal{L} = 10^{33} cm^{-2} sec^{-1}$ this translates into a lower bound on the $\tilde{\mu}$ pair-production cross-section of $\sigma > 5 \cdot 10^{-4}\,pb$, which however is more than an order of magnitude too small to appear in the figure. We thus conclude that for dominant lepton-number violating operators we can discover the smuon right upto the kinematic limit of $250\,GeV$.

### 2.2 Single S-particle Production

The possible $2 \to 2$ single sparticle production mechanisms at an $e^+e^-$-collider are given by

$$e^+e^- \to \begin{cases} l_i^{\pm}\tilde{\chi}^{\mp}, & (a) \\ \tilde{l}_i^{\pm} W^{\mp}, & (b) \\ \nu_i \tilde{\chi}^0, & (c) \\ \tilde{\nu}_i(\gamma, Z^0), & (d) \end{cases} \tag{5}$$

where we have used conventional SUSY notation.[4] The processes (5) all employ the $\not{R}_p$-operator $\mathcal{O} = [L_1 L_i \bar{E}_1]_F$ and involve (among other diagrams) an s-channel resonance $\tilde{\nu}$-production. We have calculated the total production cross-section for all four processes[5]

$$\sigma_{\tilde{\chi}^{\pm}} = \frac{\alpha\lambda^2 X^2}{2 s_W^2 s}\left(X_1(m_{\tilde{\chi}^{\pm}}) + X_2(m_{\tilde{\chi}^{\pm}}) + X_3(m_{\tilde{\chi}^{\pm}})\right) \tag{6}$$

$$\sigma_{\tilde{\chi}^0} = \frac{\alpha\lambda^2 \tilde{X}(1-2s_W^2)^2}{4 c_W^2 s_W^2 s}\left(X_1(m_{\tilde{\chi}^0}) + 2X_2(m_{\tilde{\chi}^0}) + 2X_3(m_{\tilde{\chi}^0}) - X_4(m_{\tilde{\chi}^0})\right) \tag{7}$$

$$\sigma_{\tilde{l}} = \frac{\alpha\lambda^2}{8 s_W^2 s}\frac{1-L^2-W^2}{K(L,Z)}\left(Y_1(L,Z) + Y_2(L,Z) + Y_3(L,Z)\right) \tag{8}$$

$$\sigma_{\tilde{\nu}} = \frac{\alpha\lambda^2}{8 c_W^2 s_W^2 s}\frac{1-N^2-Z^2}{K(N,Z)}\left(Y_1(N,Z) + 2Y_2(N,Z) + 2Y_3(N,Z) - Y_4(N,Z)\right). \tag{9}$$

[4] $\tilde{l}$: s-leptons; $\tilde{\nu}$: s-neutrinos; $\tilde{\chi}^{\pm}$: charginos; $\tilde{\chi}^0$: neutralinos.

[5] The processes ($b$) and ($d$) have also been previously calculated in Ref[7] for $s = m_{\tilde{\nu}}^2$, as well as their analogs at hadron colliders in Ref[9].

Here $N = \frac{m_{\tilde{\nu}}}{\sqrt{s}}$, $L = \frac{m_{\tilde{l}}}{\sqrt{s}}$, $W = \frac{m_W}{\sqrt{s}}$, $Z = \frac{m_Z}{\sqrt{s}}$, are the normalized masses, and $c_W = \cos\theta_W$, $s_W = \sin\theta_W$, where $\theta_W$ is the electroweak mixing angle. The functions are given in the appendix. $X$, $m_{\tilde{\chi}^\pm}$, $\tilde{X}$, $m_{\tilde{\chi}^0}$ are given as functions of the fundamental parameters of the MSSM in Eqs(C19), (C18), (C40), and (C42) of Ref.[10] respectively. As an example we focus on the process of Eq.(9), or $\sigma_{\tilde{\nu}}$, for which we have plotted in Fig.2 the total cross-section as a function of the s-neutrino mass $m_{\tilde{\nu}}$, for the minimal coupling[6] $\lambda_{1i1} = 2\cdot 10^{-2}$. The signal in this case consists of four charged leptons as well as $\not{p}_T$ from one neutrino. We have used the same estimate as in the previous sub-section for the discovery limit and have included it as a dashed line in Fig.2.

## 3 Conclusions

In conclusion, for the case of supersymmetry with broken R-parity, we have analyzed both pair and single production of sparticles and shown that they can lead to distinctive signals. Pair production of sleptons should be observable upto the kinematic limit for dominant lepton number violating $\not{R}_p$-operators. Single sneutrino production should be observable for $m_{\tilde{\nu}}$ as large as $405\,GeV$ and for $\lambda > 10^{-3}$. This is a unique access to large susy masses.

## 4 Appendix

$$X_1(m) = \frac{(1-m^2)^2}{2((1-N^2)^2 + N^2 + (\lambda^2 N^2/(16\pi))} \tag{10}$$

$$X_2(m) = \frac{1}{2}((m^2 - 2N^2)\Psi + 1 - m^2 + \frac{(m^2-1)(N^2-m^2)}{8(m^2-N^2-1)}) \tag{11}$$

$$X_3(m) = \frac{(N^2\Psi + m^2 - 1)(N^2-1)}{(1-N^2)^2 + N^2 + \lambda^2 N^2/(16\pi)} \tag{12}$$

$$X_4(m) = \frac{2N^2(m^2-N^2-1)\Psi + (m^2-N^2-1)^2 - N^4}{m^2 - 2N^2 - 1} \tag{13}$$

$$Y_1(m_1,m_2) = \frac{K(-m_1^2 + (1-m_1^2-m_2^2)^2}{m_2^2((1-N^2)^2 + N^2 + (\lambda^2N^2/(16\pi))} \tag{14}$$

$$Y_2(m_1,m_2) = (m_1^2 + m_2^2 - 2)\Theta + \frac{K^2(1-2m_2^2-2m_2^2K^2-K^2) + 2m_1^2m_2^4}{m_2^2K(1-K^2)} \tag{15}$$

$$Y_3(m_1,m_2) = \frac{(1-N^2)(m_1^2m_2^2\Theta - (m_1^2+m_2^2-1)K)}{m_2^2((1-N^2)^2 + N^2 + N^2\lambda^2/(16\pi))} \tag{16}$$

$$Y_4(m_1,m_2) = \frac{2\left(N^2((Z^2-1)(\Omega-\Theta) + 2K - \frac{K}{Z^2}) + 2KZ^2 + \frac{K}{Z^2} - 3K\right)}{Z^2 + N^2 - 1} \tag{17}$$

And $\Psi = \ln(\frac{1+N^2-m^2}{N^2})$, $\Omega(m_1,m_2) = \ln\frac{1-N^2-Z^2+2K}{1-N^2-Z^2+2K}$, $K(m_1,m_2) = \frac{1}{2}\sqrt{(1+m_1^2-m_2^2) - 4m_1^2}$, and $\Theta = \ln\frac{K-1}{K+1}$.

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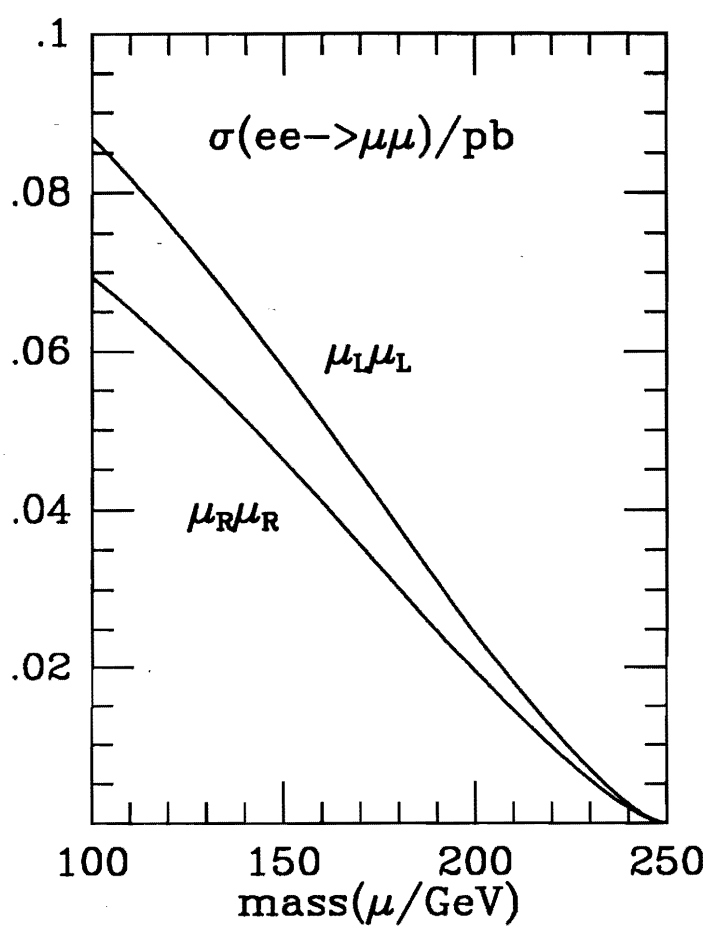


Fig. 1

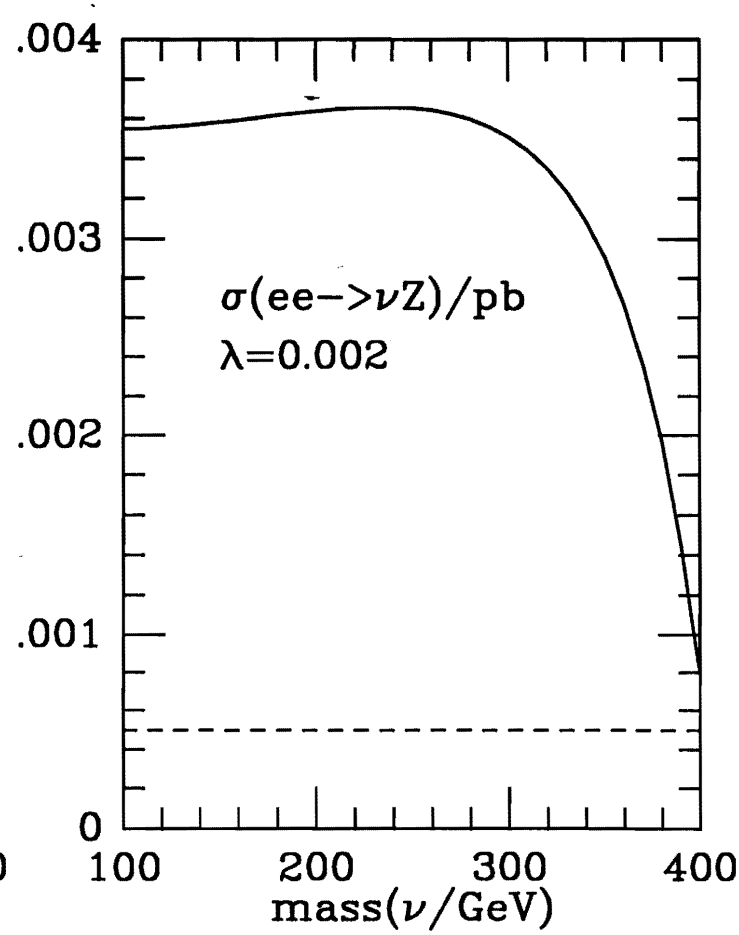


Fig. 2