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Probing lepton flavor violation signal induced by R-violating minimal supersymmetric standard model at a linear collider*

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Abstract: The lepton-flavor violation (LFV) effect at an e^+e^- linear collider (LC), in the frame of R-parity violating minimal supersymmetric standard model is studied. We take the R-parity violating processes $e^+e^- \to e^\mp\mu^\pm$ as signal, and define the summation of the two processes as "experiment" observable. We find that the cross-section summation can reach $\mathcal{O}(10^1) fb$ in the parameter space without sneutrino resonance effect($\sqrt{s} \sim m_{\tilde{\nu}}$). The summation treatment manifests uniform differential distribution on $\cos\theta$, where θ denotes the polar angles of both outgoing e^+/e^- respectively to incoming electron beam in two signal processes. The uniform feature together with $e\mu$ collinearity would help to reduce the SM background dramatically. Consequently we conclude that at a 500 GeV LC with $480\, fb^{-1}$ annual luminosity, it's either possible to detect the distinctive R-violating LFV $e\mu$ signal, or exclude sneutrino to $m_{\tilde{\nu}} > 1.1$ TeV at 95% CL in the machine's biennial runtime interval.

Keywords: Discrete and Finite Symmetries, Supersymmetry Phenomenology, Beyond Standard Model.

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Contents

1. Introduction

Although the Standard Model (SM) is very successful, it's only an effective theory describing physics up to $\mathcal{O}(10^2)$GeV. Many experiments have been proposed in the past to find signals of new physics, and many new theoretical models have been developed to extend physics beyond the SM. Among these extensions of the SM, supersymmetric models are the most attractive ones, by offering an elegant way to solve the hierarchy problem and keep a consistent unification of gauge couplings.

In the SM the conservations of the baryon number B and lepton number L are automatic consequences of the gauge invariance and renormalizability. On the other hand, the lepton number conservation for individual generation has no strong theoretical basis. In addition, recent neutrino oscillation experiments [1, 2, 3] manifest that neutrinos strongly mix among flavors. Therefore, to accommodate the observation of neutrino oscillation which is apparently lepton flavor violating (LFV), the SM has to be extended. As the most general minimal supersymmetric extension of the SM, the R-parity violating minimal supersymmetric standard model ($\not{R}_p$-MSSM) contains all renormalizable terms which observe the $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_W \otimes \mathrm{U}(1)_Y$ gauge-symmetry, supersymmetry, and the most general superpotential with R-parity violation given by [4]

$$\mathcal{W}_{\not{R}_p} = \frac{1}{2}\epsilon_{ab}\lambda_{ijk}\hat{L}_i^a\hat{L}_j^b\hat{E}_k + \epsilon_{ab}\lambda^{'}_{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{D}_k + \frac{1}{2}\epsilon_{\alpha\beta\gamma}\lambda^{''}_{ijk}\hat{U}_i^\alpha\hat{D}_j^\beta\hat{D}_k^\gamma + \epsilon_{ab}\delta_i\hat{L}_i^a\hat{H}_2^b \qquad (1.1)$$

where $i,j,k = 1,2,3$ are generation indices, $a,b = 1,2$ are SU(2) isospin indices, and $\alpha,\beta,\gamma = 1,2,3$ are SU(3) color indices. $\lambda, \lambda^{'}, \lambda^{''}$ are dimensionless R-violating Yukawa couplings with $\lambda_{ijk} = -\lambda_{jik}$, $\lambda''_{ijk} = -\lambda''_{ikj}$. The last bilinear terms mix the lepton and the Higgs superfield which may generate masses of neutrinos.

Since the first two terms, $\hat{L}\hat{L}\hat{E}$ and $\hat{L}\hat{Q}\hat{D}$, in the R-parity violating superpotential may lead to single sneutrino production and sequential LFV final states, they are of special interest. Many authors studied these sneutrino s-channel production modes, both on- and off-mass-shell of sneutrino resonance [5]–[8]. Most of these works focused on how to probe the resonance effect on hadron colliders, such as Tevatron and LHC, where sneutrinos are produced via $\hat{L}\hat{Q}\hat{D}$ interactions and decay in R-parity conservation mode with high branch ratio, such as $\tilde{\nu} \to l\tilde{\chi}_i^{\pm}$. The signal of these sneutrino R-parity violating production and subsequential R-conserving decay modes, includes three leptons in final state, where two of the leptons are from chargino/neutrolino cascade decay. Obviously the analysis of these tri-lepton events is a good way to discover new physics beyond the SM. However, tri-lepton production can also be induced by some other new physics models, for example even in R-conserving MSSM, $\tilde{\chi}_i^{\pm}\tilde{\chi}_j^0$ association production may have the subsequential decay to three leptons plus two $\tilde{\chi}_1^0$ as the lightest supersymmetric particle (LSP). So, tri-lepton signal might not be able to distinguish R-violating interaction from other 'new physics background'.

In this paper, the possibility of detecting the di-lepton LFV processes $e^+e^- \to e^{\mp}\mu^{\pm}$ at an electron-positron linear collider(LC) is discussed in the framework of the minimal supersymmetric standard model(MSSM) with R-parity violation. We will demonstrate that with clean collision environment and high luminosity, an energetic e^+e^- LC machine will be a powerful tool to discover the R-parity violating LFV interactions.

2. The calculation of the processes $e^+e^- \to e^{\mp}\mu^{\pm}$ in R-violating MSSM

The R-violating interactions relevant to the calculations of the processes $e^+e^- \to e^{\mp}\mu^{\pm}$ at the leading order, are given by $\hat{L}\hat{L}\hat{E}$-type terms of the superpotential. By integrating eq. (1.1) over supercoordinates$(\theta, \bar{\theta})$, one obtains the tri-lepton lagrangian

$$\mathcal{L}_{\hat{L}\hat{L}\hat{E}} = \lambda_{ijk} \cdot (\bar{\nu}_i^c P_L l_j \tilde{l}_{Rk}^* + \bar{l}_k P_L \nu_i \tilde{l}_{Lj} + \bar{l}_k P_L l_j \tilde{\nu}_{Li}) + \text{h.c.} \tag{2.1}$$

where $P_{L/R} = (1 \mp \gamma_5)/2$ are left/right-hand project operator, and c refers to charge conjugation.

The Feynman diagrams of LFV signal processes $e^+e^- \to e^{\mp}\mu^{\pm}$ are depicted in figure 1.[1] From the experimental point of view, the charge measurement of high transverse momentum (p^T) tracks relies on many realistic factors, such as the configuration of the magnetic field surrounding tracker subdetector, the radius of outmost tracker system in transverse plane, and the spatial resolution of the tracker etc. The higher the track p_T is, the less accurate the lepton charge is determined. In order to get optimal efficiency on signal detection, we deliberately do not choose the criteria of using opposite charge veto in event selection, i.e. di-tracks of $e^-\mu^+$ final state won't be distinguished from those of $e^+\mu^-$. To reflect this 'non-signed' $e\mu$ experiment measurement, we use a consistent momentum notation to denote the two signal processes as:

$$e^-(p_1) + e^+(p_2) \to e^-(k_1) + \mu^+(k_2)\,, \tag{2.2}$$
$$e^-(p_1) + e^+(p_2) \to e^+(k_1) + \mu^-(k_2)\,, \tag{2.3}$$

[1] Here we do not present the diagrams which can be obtained by reversing the current arrow of $\tilde{\nu}$.

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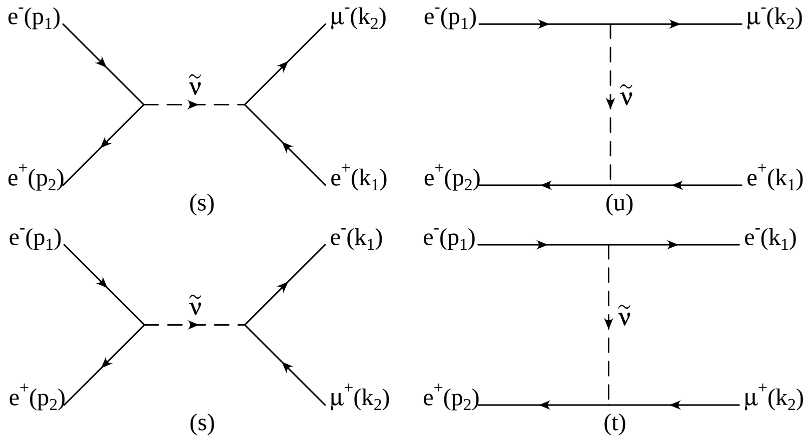

Figure 1: The relevant Feynman diagrams to the processes of $e^+e^- \to e^+\mu^-$ and $e^+e^- \to e^-\mu^+$. The upper two diagrams are corresponding to the $e^+\mu^-$ production, and the lower two are to the $e^-\mu^+$ production. With the definition of θ, $e^+\mu^-$ process is represented as "s" and "u" channel, while $e^-\mu^+$ as "s" and "t" channel.

where p_1 and p_2 are four-momenta of incoming electron and positron beams, k_1 represents outgoing $e^-(e^+)$ momenta in the two signal processes, and k_2 denotes that of $\mu^+(\mu^-)$ final particle correspondingly. The Mandelstam variables are defined accordingly, where electron and muon are taken as massless for simplicity.

$$\begin{aligned} s &= (p_1+p_2)^2 = (k_1+k_2)^2 \\ t &= (p_1-k_1)^2 = (p_2-k_2)^2 = -\frac{s}{2}(1-\cos\theta) \\ u &= (p_1-k_2)^2 = (p_2-k_1)^2 = -\frac{s}{2}(1+\cos\theta) \end{aligned} \tag{2.4}$$

where θ is defined to denote the polar angle of outgoing $e^-(e^+)$ of the individual signal process $e^+e^- \to e^-\mu^+$ $(e^+e^- \to e^+\mu^-)$ with respect to the incoming electron beam. We sum up the production events of the two signal processes given in eqs. (2.2)–(2.3), which have equal cross sections and asymmetric differential ones due to CP-conservation and the above θ definition. This summation treatment of the two signal processes is consistent with the 'non-signed' $e\mu$ experiment observation, where the charges of the final e and μ particles are not distinguished.

In this paper we assume that the sneutrino mass spectrum is degenerate, i.e.

$$m_{\tilde{\nu}_i} = m_{\tilde{\nu}} \qquad (i=1,2,3) \tag{2.5}$$

The amplitude of the $e^-\mu^+$ production process is denoted as

$$\mathcal{M}^{(-)} = \sum_{i=2,3} (\mathcal{M}^{(-)}_{s,i} - \mathcal{M}^{(-)}_{t,i}) \tag{2.6}$$

with

$$\begin{aligned} \mathcal{M}^{(-)}_{s,i} &= -i\,\lambda_{i11}\lambda_{i12}\cdot \bar{v}(p_2)P_L u(p_1)\cdot \mathcal{P}(s,m_{\tilde{\nu}})\cdot \bar{u}(k_1)P_R v(k_2) + (P_L \leftrightarrow P_R,\ \lambda_{i12}\to\lambda_{i21}) \\ \mathcal{M}^{(-)}_{t,i} &= -i\,\lambda_{i11}\lambda_{i12}\cdot \bar{v}(p_2)P_R v(k_2)\cdot \mathcal{P}(t,m_{\tilde{\nu}})\cdot \bar{u}(k_1)P_L u(p_1) + \\ &\quad +(P_L \leftrightarrow P_R,\ \lambda_{i12}\to\lambda_{i21})\,. \end{aligned} \tag{2.7}$$

Analogically, the amplitude of the $e^+\mu^-$ production process is given as

$$\mathcal{M}^{(+)} = \sum_{i=2,3} (\mathcal{M}^{(+)}_{s,i} - \mathcal{M}^{(+)}_{u,i}), \tag{2.8}$$

with

$$\begin{aligned}
\mathcal{M}^{(+)}_{s,i} &= -i\ \lambda_{i11}\lambda_{i21} \cdot \bar{v}(p_2)P_L u(p_1) \cdot \mathcal{P}(s, m_{\tilde{\nu}_i}) \cdot \bar{u}(k_2)P_R v(k_1) + \\
&\quad +(P_L \leftrightarrow P_R,\ \lambda_{i21} \to \lambda_{i12}) \\
\mathcal{M}^{(+)}_{u,i} &= -i\, \lambda_{i12}\lambda_{i11}\bar{v}(p_2)P_R v(k_1) \cdot \mathcal{P}(u, m_{\tilde{\nu}_i}) \cdot \bar{u}(k_2)P_L u(p_1) + \\
&\quad +(P_L \leftrightarrow P_R,\ \lambda_{i12} \to \lambda_{i21})\,.
\end{aligned} \tag{2.9}$$

Here, due to the coupling strength of sneutrino to the incoming electron and positron beam, only the generation index $i = 2, 3$ of the propagating sneutrino are considered. Under mass degeneration assumption, propagators of sneutrinos $\tilde{\nu}_{2,3}$ are given as

$$\begin{aligned}
\mathcal{P}(t, m_{\tilde{\nu}}) &= \frac{1}{t - m^2_{\tilde{\nu}}} \\
\mathcal{P}(u, m_{\tilde{\nu}}) &= \frac{1}{u - m^2_{\tilde{\nu}}} \\
\mathcal{P}(s, m_{\tilde{\nu}}) &= \frac{1}{s - m^2_{\tilde{\nu}} + is\Gamma_{\tilde{\nu}}/m_{\tilde{\nu}}}\,.
\end{aligned} \tag{2.10}$$

Here, to suppress resonance enhancement the sneutrino decay width $\Gamma_{\tilde{\nu}}$ is taken into account in the s-channel propagator.

Using eqs. (2.6)–(2.10), the summation of the differential cross sections of the two processes $e^+e^- \to e^-\mu^+$ and $e^+e^- \to e^+\mu^-$ can be written as

$$\begin{aligned}
\frac{d\sigma_{e\mu}}{d\cos\theta} &= \frac{1}{4}\frac{1}{32\pi s}\{|\mathcal{M}^{(-)}|^2 + |\mathcal{M}^{(+)}|^2\} \\
&= \frac{1}{4}\frac{1}{32\pi s}(\lambda^2_{211}\lambda^2_{212} + \lambda^2_{311}\lambda^2_{312} + \lambda^2_{311}\lambda^2_{321} + 2\lambda_{211}\lambda_{212}\lambda_{311}\lambda_{312}) \times \\
&\quad \times(2s^2 \cdot |\mathcal{P}(s, m_{\tilde{\nu}})|^2 + t^2 \cdot |\mathcal{P}(t, m_{\tilde{\nu}})|^2 + u^2 \cdot |\mathcal{P}(u, m_{\tilde{\nu}})|^2)
\end{aligned} \tag{2.11}$$

where the subscript $e\mu$ denotes the $(e^-\mu^+) + (e^+\mu^-)$ signal summation treatment. Due to the R-violating scalar-pseudoscalar(S-P) Yukawa couplings, the interference contribution among different topological diagrams vanishes as shown in the above equation. Another thing to be mentioned here is that the summation treatment of the $e^\pm\mu^\mp$ production processes doubles the 's'-channel contributions, while 't+u'-channel contributions cancel their individual forward-backward asymmetry on $\cos\theta$.

3. Numerical results and discussion

3.1 Signal

Required by superpotential eq. (1.1), λ_{iij} should be zero. For the other R-parity violating parameters, we refer to the experimental constraints presented in ref. [5], and take the

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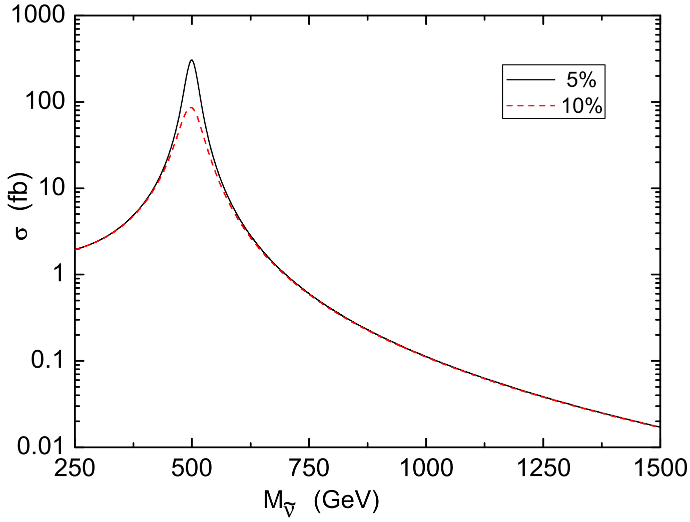

Figure 2: LFV cross section $\sigma_{e\mu}$ as function of $m_{\tilde{\nu}}$ at $\sqrt{s}$ = 500GeV. Solid and dashed line correspond to $\Gamma_{\tilde{\nu}} = 5, 10\%\ m_{\tilde{\nu}}$ respectively.

values of the λ_{ijk} coupling parameters as

$$\begin{aligned} \lambda_{12j} &= -\lambda_{21j} = 0.049\,, \qquad \lambda_{31j} = -\lambda_{13j} = 0.062 \\ \lambda_{23j} &= -\lambda_{32j} = 0.070\,, \end{aligned} \tag{3.1}$$

It should be stressed that these λ parameters are SUSY mass dependent, e.g. they could be scaled by a factor of $m_{\tilde{l}_j R}/100$[GeV]. In this work, a degenerate charged slepton spectrum of 100GeV is assumed, which could keep R-violating Yukawa couplings less than $\mathcal{O}(10^{-1})$.

To make our scenario consistent with available e^+e^- collision data, the degenerated sneutrino mass has to be constrained. For example, OPAL Experiment has set an upper limit on $\sigma(e^+e^- \to e\mu)$ as $22\,fb$ with $200 \leq \sqrt{s} \leq 209\,GeV$ at 95% CL [10]. To get a comparable value in this energy range by applying eq. (2.11) with the input R-violating parameters given in eq. (3.1), one can arrive at

$$m_{\tilde{\nu}} \geq 250\,\mathrm{GeV}\,.$$

Since linear colliders are running at fixed c.m.s energy, one can't expect to be so lucky that $\sqrt{s}$ will be so close to the sneutrino mass that real sneutrinos are produced or large resonance enhancement will occur. Therefore, in this work we mainly discuss the range of the sneutrino mass window that can be probed via off-resonance $e\mu$ LFV signal, at a LC collider running at 'moderate' energy such as TESLA Run1. Setting $\Gamma_{\tilde{\nu}} = 5\%$ and 10% of sneutrino mass $m_{\tilde{\nu}}$ to block on-resonance effect, we calculate the dependence of $\sigma_{e\mu}$ on $m_{\tilde{\nu}}$ at $\sqrt{s} = 500\,GeV$, and depict it in figure 2.

From figure 2 one can see that at a $500\,GeV$ LC machine, even without resonance enhancement the R-violating LFV cross-section of signal summation may reach $\mathcal{O}(1)\,fb$, which could be detected clearly at high luminosity linear colliders. However, if degenerated sneutrinos are heavier than 1 TeV, the signal will decrease to no more than $0.1\,fb$, which might

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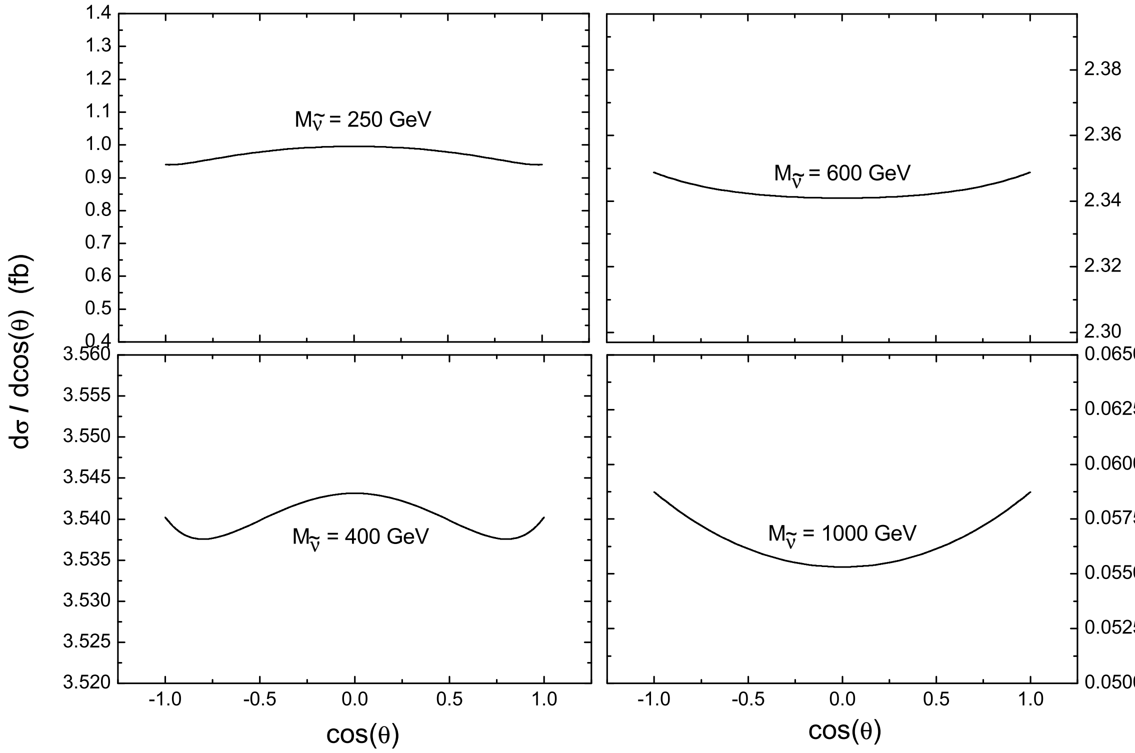

Figure 3: LFV differential cross section $\frac{d\sigma_{e\mu}}{d\cos\theta}$ at $\sqrt{s} = 500\text{GeV}$ for different sneutrino masses.

be overwhelmed by background. Now, the question is whether some event selection strategies can be developed to suppress background efficiently, so that off-resonance sneutrino LFV effect could be detected and sneutrino mass parameter limit would be extended up to $\mathcal{O}(\text{TeV})$. In the following discussion we will focus on the signal of $m_{\tilde{\nu}} = 1\,\text{TeV}$ contribution.

The angular distributions of four typical $m_{\tilde{\nu}}$ values are given in figure 3. The differential cross sections are nearly uniform versus $\cos\theta$ merely with trivial fluctuation. This uniformly distributing feature is mainly derived by the $e\mu$ summation treatment, namely though the two signal processes $e^+e^- \to e^+\mu^-$ and $e^+e^- \to e^-\mu^+$ tend to forward and backward respectively, the summation would erase the individual tendency. The cancellation determined by the summation treatment manifests itself clearly in figure 4, where the differential cross sections of both processes $e^+e^- \to e^+\mu^-$, $e^+e^- \to e^-\mu^+$ and the summation contribution at $m_{\tilde{\nu}} = 1\,\text{TeV}$ are plotted in the same frame.

Correspondingly, figure 5 shows the transverse momentum distribution of the signal. It is clear that the outgoing e and μ transverse momenta will rush to the beam energy E_{beam}, which is consistent with the uniform distribution of the differential cross section $\frac{d\sigma_{e\mu}}{d\cos\theta}$. It will be demonstrated below that the uniform distribution feature versus $\cos\theta$ of the LFV differential cross-section is very useful for extracting the signal from the background.

3.2 SM background and event selection

In the numerical calculation of physical background, the SM input parameters are taken as $m_\tau = 1776.99\,MeV$, $m_W = 80.423\,GeV$, $m_Z = 91.1876\,GeV$ and $\alpha = 1/128$ [9].

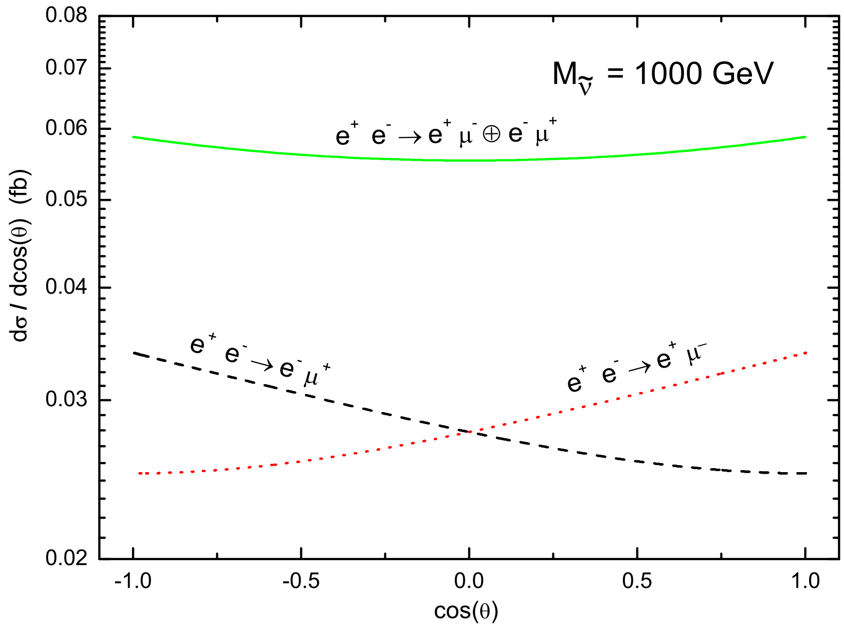

Figure 4: LFV differential cross section $\frac{d\sigma_{e\mu}}{d\cos\theta}$ at $\sqrt{s} = 500$GeV contributed by 1 TeV sneutrinos.

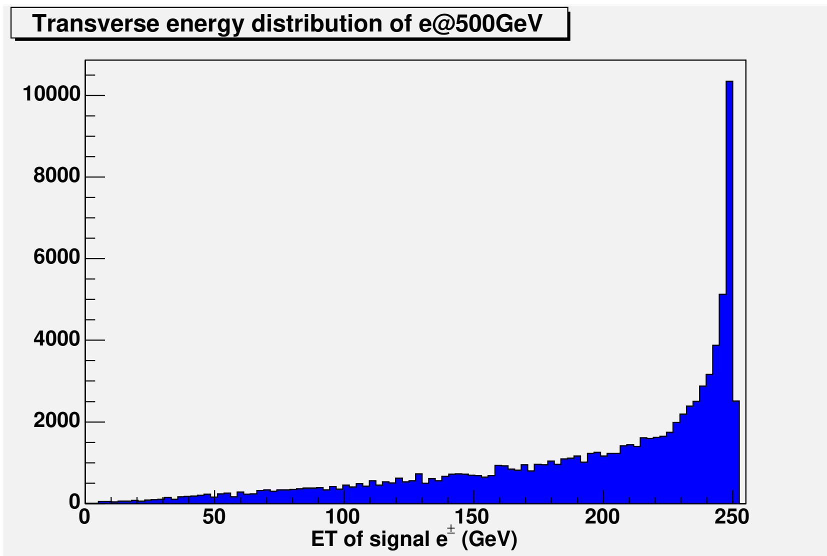

Figure 5: Transverse energy distribution of LFV signal of $m_{\tilde{\nu}} = 1$ TeV at $\sqrt{s} = 500$ GeV. Y-axis is arbitrary scale.

Due to its clean collision environment, LC is considered as powerful facility for precise studies on particle physics, which will complement and extend the physics program of hadron colliders such as Tevatron and LHC. One can expect that there will be an ideally good detector on LC, especially high performance central calorimeter and muon-tracker system with large angular coverage and good energy/transverse-momentum resolution. In such a capable detector, QCD instrumental background where two hadronic jets fake both energetic electron and muon candidate in same event, is negligible. Therefore, the main background to the LFV signal is from physical processes

$$e^+e^- \to W^+W^-, \tau\bar{\tau}, b\bar{b}, t\bar{t} \to e\mu + X$$

where X refers to decay products of W, τ, b and t other than $e\mu$. Among them, the last two ones can be removed easily: since the $e\mu$ from $b\bar{b}$ are very soft and always associated with jets as $b \to qW^* \to jl\nu$, one is able to eliminate this kind of background by some moderate calorimeter-based energy isolation cut on both $e\mu$ candidates. For $t\bar{t}$ events, they can be rejected by veto on high energy jets from two b-quarks. So, only WW and $\tau\bar{\tau}$ background have to be taken into account here. In this section, an event selection strategy will be introduced to reduce these two sorts of background, and its efficiency on the background is compared with that on the signal. The WW contribution at $\sqrt{s} = 500\,GeV$ is given by

$$\begin{aligned} \sigma_{WW} &= \sigma[e^+e^- \to W^+W^-] \times 2 \cdot \mathrm{Br}[W \to e\nu_e] \cdot \mathrm{Br}[W \to \mu\nu_\mu] \\ &\sim \mathbf{162.5}\,fb\,. \end{aligned}$$

Some MC distributions of $WW \to e\mu$ background generated by Pythia [11], are plotted in figure 6. The prominent feature of the WW background is the strong $\cos\theta$ dependence. The background from $\tau\tau$ is around $\mathbf{28}\,fb$, and MC distributions are plotted in figure 7. The final $e\mu$ from di-τ are much softer than those from WW and signal as well.

An "off-line" three-step event selection strategy is invented as follow:

1. $e\mu$ from WW production are almost forward-backward distributed, while those from signal incline perpendicular to the beam. So we define **CUT1** on polar angles as

$$0.55 \;\leq\; \theta_l \;\leq\; (\pi - 0.55) \qquad l = e, \mu \tag{3.2}$$

2. To have sensitivity to events produced at effective beam energy lower than the actual $\sqrt{s}/2$, we accept events which pass following loose **CUT2** on energy and momentum

$$\begin{aligned} E_e &\geq 85\% \cdot E_{\mathrm{beam}}\,, \\ p_\mu &\geq 75\% \cdot E_{\mathrm{beam}} \end{aligned} \tag{3.3}$$

   where for the electron the energy E_e is measured in calorimeter, and for the muon the momentum p_μ is determined by central tracker system within a magnetic field.

3. Assuming high spatial resolution on x-y plane vertical to the beam, we set a severe **CUT3** on $e\mu$ ϕ-difference to select back-to-back events as

$$|\pi - \Delta\phi_{e\mu}| \;\leq\; 0.01\,. \tag{3.4}$$

It's apparent that this three-step CUT strategy takes advantage of the uniform differential distribution and collinearity feature of LFV signal. Here considering relatively poor muon track p_μ^T resolution, we won't use missing transverse energy cut.

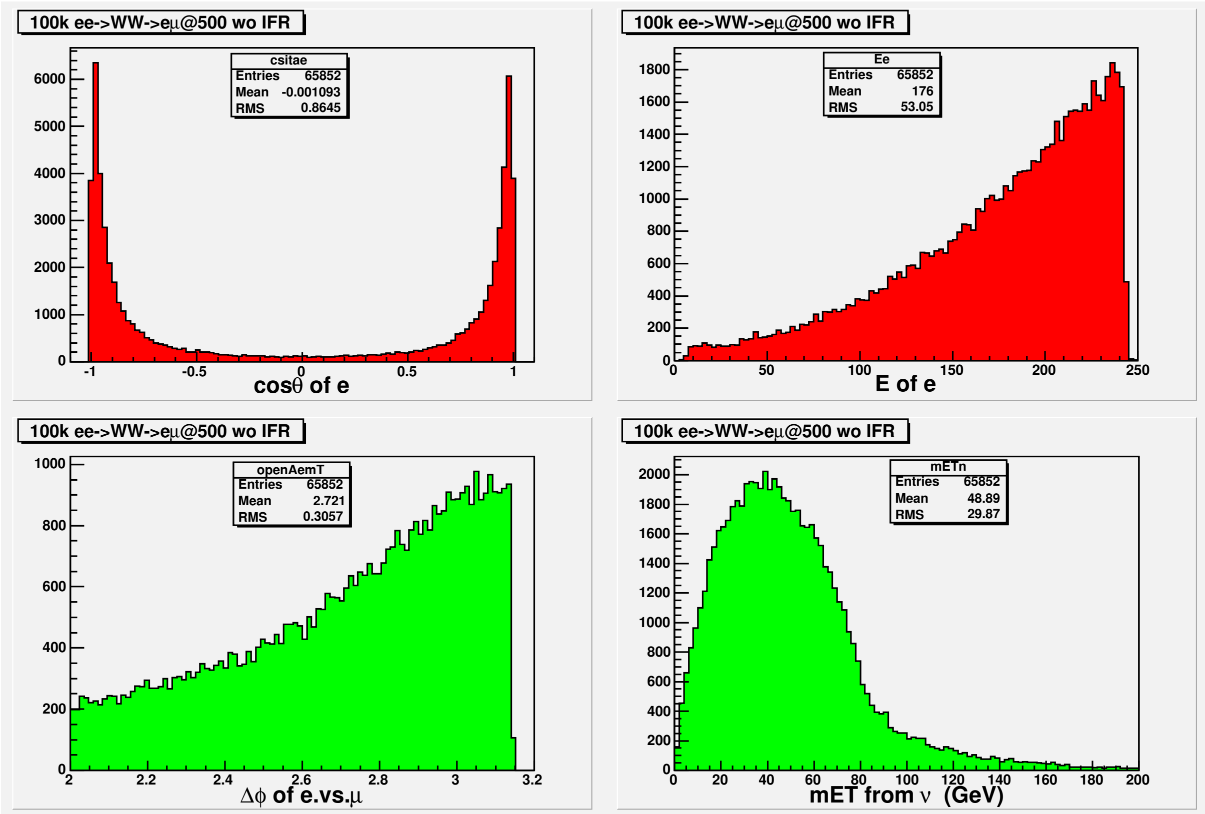

Figure 6: MC distributions of $e(\mu)$ from SM background $e^+e^- \to WW \to e\mu+X$ at $\sqrt{s} = 500$ GeV. $\cos\theta$ and energy of final e, ϕ separation of $e\mu$ and missing transverse energy are plotted.

	SM background $WW \to e\mu$	SM background $\tau\tau \to e\mu$	$e-\mu$ signal ($m_{\tilde{\nu}} = 1$ TeV)
no cut N_0 (at L fb^{-1})	65852 (4E2)	20000 (7E2)	90777 (8E5)
CUT1 N_1	15749	15864	76269
CUT2 N_2	2131	28	76269
CUT3 N_3	118	28	76269
efficiency ϵ	0.179%	0.14%	84.0%
σ before CUT	162.5 fb	28.1 fb	0.113 fb
σ after CUT	0.291 fb	0.039fb	0.095 fb

Table 1: Event selection efficiency on background and signal. The first 4 rows are numbers of events before and after individual CUT. The values of event selection efficiency on different samples are given in the 5th row.

Three sets of MC samples for WW, $\tau\tau$ and signal productions via e^+e^- collision at $\sqrt{s} = 500\,GeV$ are generated by Pythia with different assumed luminosities. Each process is simulated with the three-step event selection, and the numbers of events passing individual CUT are listed in table 1, respectively.

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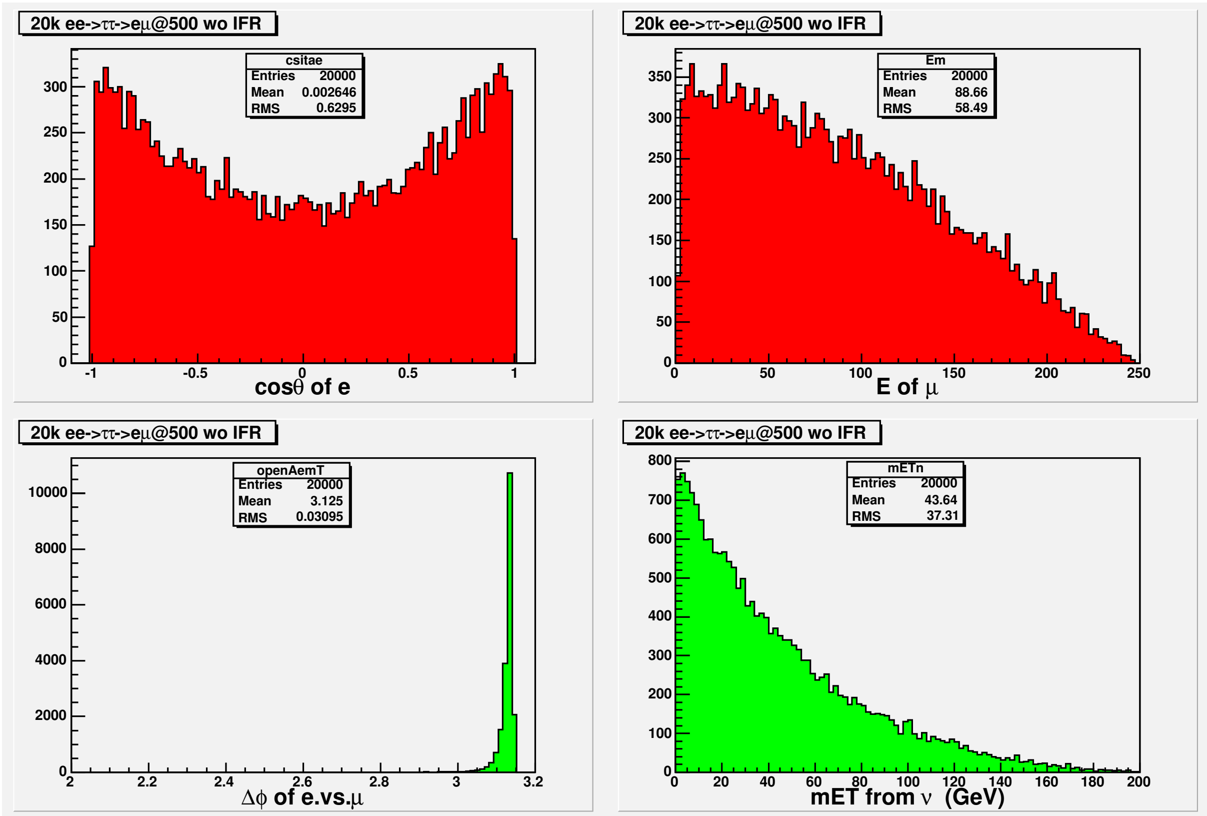

Figure 7: MC distributions of $e(\mu)$ from SM background $e^+e^- \to \tau\tau \to e\mu + X$ at $\sqrt{s} = 500\,\text{GeV}$.

Despite different integrated luminosities in generating the MC samples, we can define an unitary event selection efficiency on both background and signal as

$$\epsilon = \frac{N_3}{N_0} \,. \tag{3.5}$$

It's demonstrated that with the three-step strategy we are able to reduce the background by 3 orders, i.e. $\epsilon_{WW} \sim 0.18\%$ and $\epsilon_{\tau\tau} \sim 0.14\%$, while keeping the selection efficiency on the signal as high as 84%. The selection would result in an approximate $0.1\,fb$ signal cross section of 1 TeV sneutrino, which is about 3 factors smaller than the SM background. Since these CUTs have already left room for real beam at LCs and detector performance and are unbiased to both signal and background, we assume that the cross sections after CUTs are close to full efficiency with respect to a given luminosity.

At a 500 GeV e^+e^- collider with certain integrated luminosity L, the number of background events B and that of signal S contributed by sneutrinos with $m_{\tilde{\nu}} = 1\,\text{TeV}$ after selection are given by

$$\begin{aligned} \text{S} &= (\sigma_{e\mu} \cdot \epsilon_{e\mu}) \cdot L = \sigma_{e\mu}^{CUT} \cdot L \\ &= 0.095\,fb \cdot L \end{aligned} \tag{3.6}$$

$$\begin{aligned} \text{B} &= (\sigma_{WW} \cdot \epsilon_{WW} + \sigma_{\tau\tau} \cdot \epsilon_{\tau\tau}) \cdot L = \sigma_{SM}^{CUT} \cdot L \\ &= 0.33\,fb \cdot L \end{aligned} \tag{3.7}$$

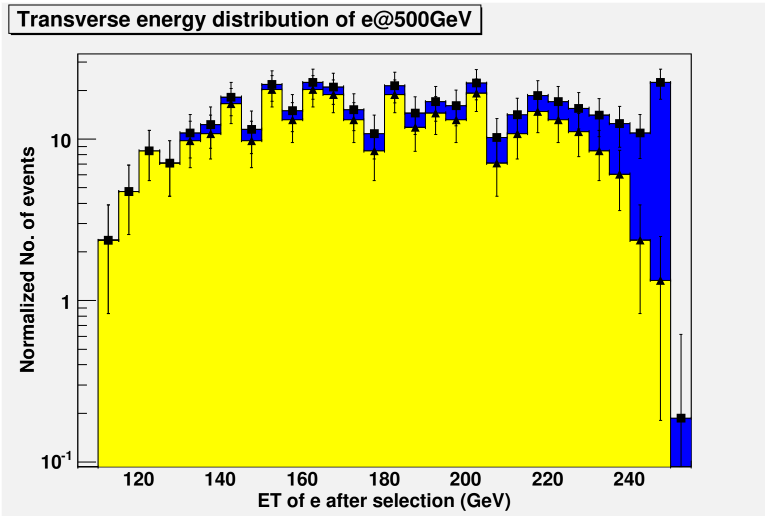

Figure 8: MC ET distributions of e candidates after event selection at $\sqrt{s} = 500\text{GeV}$. The number of events has been normalized by $960 fb^{-1}$ luminosity. YELLOW is for WW and $\tau\tau$ SM background; BLUE is for background plus $R\!\!\!/$-violating signal with $m_{\tilde{\nu}} = 1\,\text{TeV}$.

where σ_{SM}^{CUT} is the sum of WW and $\tau\tau$ contributions after CUTs, and $\sigma_{e\mu}^{CUT}$ is the cross-section of R-violating LFV signal respectively. The value of S/B is about 0.3 which is acceptable for a stable signal/background analysis. Sequentially, the significance of signal over background is defined as

$$\text{SB} = \frac{S}{\sqrt{B}} = \frac{\sigma_{e\mu}^{CUT}}{\sqrt{\sigma_{SM}^{CUT}}} \cdot \sqrt{L}\,. \tag{3.8}$$

Supposing a typical luminosity at a LC can reach $2 \times 10^{34} cm^{-2}s^{-1}$ [12], it's reasonable to presume a $480\,fb^{-1}$ annual data acquisition. Thereby, the biennial data accumulation on LC that is greater than $940\,fb^{-1}$, will provide a significance as large as 5 which is sufficient for the discovery of the R-violating LFV interaction. The transverse energy(E^T) distribution of electron candidates accumulated per year is simulated in figure 8. The high E^T tendency of the signal is obvious and distinctive from SM background. The significance varying with different sneutrino mass values at $\sqrt{s} = 500\text{GeV}$ is given in figure 9, which decreases with the increment of sneutrino mass and would drop to 2.5 at $m_{\tilde{\nu}} \sim 1.15\,\text{TeV}$, namely if no clue of signal is seen one can exclude sneutrinos up to this mass scale at 95% CL.

Finally, we want to say some words on potential backgrounds contributed by other non-SM physics. Even without R-parity violation, MSSM can induce large di-lepton LFV effect at LC collider [13, 14] too. Typical processes are heavily-mixed slepton pair production and cascade decay, $e^+e^- \to \tilde{l}_i^+\tilde{l}_i^- \to e\tilde{\chi}_1^0 + \mu\tilde{\chi}_1^0$. The character of these background is moderate e and μ associated with large missing E^T carried by LSP $\tilde{\chi}_1^0$, and these R-conservation LFV background can be removed from the $R\!\!\!/_p$ event samples by $e\mu$ energy CUT2 and colinearity CUT3. Some other interesting non-SM models predict a heavy $Z^{'}$ which could couple to $\mu\tau$, $e\tau$ or even $e\mu$ [15]. Due to V-A couplings of $Z^{'}$, the final e and μ from these background should be severely forward-backward, and would be cut off by the $\cos\theta$

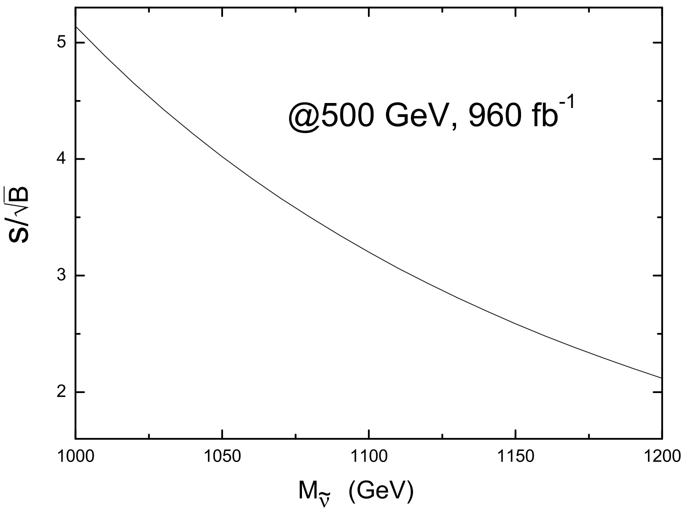

Figure 9: The dependence of R-violating signal significance on sneutrino masses.

CUT1. Even if a few background events survive the three-step off-line LFV selection, since the uniform differential distribution of the $\not{R}_p$-MSSM LFV will drive transverse momenta of outgoing e and μ peak at high energy very close to E_{beam} as shown in figure 8, this distinctive feature of R-violating signals will help to estimate the $Z^{'}$ contribution in the total selected samples.

4. Summary

We have studied the lepton flavor violating processes $e^+e^- \to e^{\mp}\mu^{\pm}$ in the MSSM with R-parity violation at an electron-positron LC with $2{\times}250\,GeV$ colliding energy. To be consistent with experimental measurement, we sum the two signal processes up and define an observable θ to denote both final e^- and e^+ polar angles with respect to the eletron beam. The summation cross-section measurement can reach $\mathcal{O}(10^1)fb$ without apparent sneutrino resonance enhancement.

Determined by scalar-pseudoscalar Yukawa couplings of sneutrino to leptons, and then enlarged by our $e^{\pm}\mu^{\mp}$ summation treatment, the R-violating LFV signal is characterized with a uniform differential distribution onto $\cos\theta$. Using this uniform distribution feature together with collinearity of $e\mu$ final states, we develop a three-step event selection strategy. Under this strategy, the SM background can be under control. Consequently, at a $500\,GeV$ LC machine running with annual luminosity $L_Y = 480\,fb^{-1}$, one can expect to extend R-violating interaction search to heavy off-mass-shell sneutrino contribution, namely in LC's two-year-run either detect $e\mu$ signal induced by sneutrino with $m_{\tilde{\nu}} = 1.0\,\text{TeV}$ at 99.99% CL discovery level, or exclude sneutrino to $m_{\tilde{\nu}} > 1.1\,\text{TeV}$ at 95% CL.

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References

[1] Super-Kamiokande collaboration, Y. Fukuda et al., *Evidence for oscillation of atmospheric neutrinos*, *Phys. Rev. Lett.* **81** (1998) 1562 [hep-ex/9807003]; *Solar b-8 and he p neutrino measurements from 1258 days of super-kamiokande data*, *Phys. Rev. Lett.* **86** (2001) 5651 [hep-ex/0103032]; *Constraints on neutrino oscillations using 1258 days of super-kamiokande solar neutrino data*, *Phys. Rev. Lett.* **86** (2001) 5656 [hep-ex/0103033].

[2] SNO collaboration, Q.R. Ahmad et al., *Measurement of the charged current interactions produced by b-8 solar neutrinos at the sudbury neutrino observatory*, *Phys. Rev. Lett.* **87** (2001) 071301 [nucl-ex/0106015].

[3] CHOOZ collaboration, M. Apollonio et al., *Limits on neutrino oscillations from the chooz experiment*, *Phys. Lett.* **B 466** (1999) 415 [hep-ex/9907037];
F. Boehm et al., *Search for neutrino oscillations at the Palo Verde nuclear reactors*, *Phys. Rev. Lett.* **84** (2000) 3764 [hep-ex/9912050].

[4] S. Weinberg, *Supersymmetry at ordinary energies, 1. Masses and conservation laws*, *Phys. Rev.* **D 26** (1982) 287;
N. Sakai and T. Yanagida, *Proton decay in a class of supersymmetric grand unified models*, *Nucl. Phys.* **B 197** (1982) 533.

[5] R. Barbier et al., *Report of the group on the R-parity violation*, hep-ph/9810232;
R parity Working Group collaboration, B. Allanach et al., *Searching for R-parity violation at run-II of the Tevatron*, hep-ph/9906224.

[6] G. Moreau, M. Chemtob, F. Deliot, C. Royon and E. Perez, *Resonant sneutrino production at Tevatron run II*, *Phys. Lett.* **B 475** (2000) 184 [hep-ph/9910341].

[7] G. Moreau, E. Perez and G. Polesello, *Resonant sneutrino production in supersymmetry with R-parity violation at the LHC*, *Nucl. Phys.* **B 604** (2001) 3 [hep-ph/0003012].

[8] S. Bar-Shalom, G. Eilam and B. Mele, *New scalar resonances from sneutrino Higgs mixing in supersymmetry with small lepton number (R-parity) violation*, *Phys. Rev.* **D 64** (2001) 095008 [hep-ph/0106053].

[9] Particle Data Group collaboration, K. Hagiwara et al., *Review of particle physics*, *Phys. Rev.* **D 66** (2002) 010001.

[10] OPAL collaboration, G. Abbiendi et al., *Search for lepton flavour violation in e^+e^- collisions at $\sqrt{s} = 189\ GeV - 209\ GeV$*, *Phys. Lett.* **B 519** (2001) 23 [hep-ex/0109011].

[11] T. Sjostrand et al., *High-energy-physics event generation with pythia 6.1*, *Comput. Phys. Commun.* **135** (2001) 238 [hep-ph/0010017].

[12] ECFA/DESY LC Physics Working Group collaboration, J.A. Aguilar-Saavedra et al., *Tesla technical design report part III: physics at an e^+e^- linear collider*, hep-ph/0106315;
Y. Nosochkov et al., *NLC luminosity as a function of beam parameters*, physics/0206044.

[13] W. Porod and W. Majerotto, *Large lepton flavor violating signals in supersymmetric particle decays at future e^+e^- colliders*, *Phys. Rev.* **D 66** (2002) 015003 [hep-ph/0201284];
ECFA/DESY LC Physics Working Group collaboration, J.A. Aguilar-Saavedra et al., *Tesla technical design report part III: physics at an e^+e^- linear collider*, hep-ph/0106315;
J. Hisano, M.M. Nojiri, Y. Shimizu and M. Tanaka, *Lepton flavor violation in the left-handed slepton production at future lepton colliders*, *Phys. Rev.* **D 60** (1999) 055008 [hep-ph/9808410].

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[14] M. Cannoni, S. Kolb and O. Panella, *Lepton flavour violation in $e^{\pm}e^{-} \to l^{\pm}e^{-}$ $(l = \mu, \tau)$ induced by r-conserving supersymmetry*, *Phys. Rev.* **D 68** (2003) 096002 [hep-ph/0306170].

[15] C. Yue, Y. Zhang and H. Li, *Lepton flavor violating signals of gauge bosons z' at future $e^{+}e^{-}$ colliders*, *J. Phys.* **G29** (2003) 737.