Single production of fourth family sneutrino via RPV couplings at linear colliders

O. Çakır and S. Kuday

Department of Physics, Ankara University,
Faculty of Sciences, Ankara, Turkey

İ.T. Çakır

Department of Physics, CERN, Geneva, Switzerland

S. Sultansoy

Physics Division, TOBB University of Economics and Technology, Ankara, Turkey and
Institute of Physics, Academy of Sciences, Baku, Azerbaijan

Abstract

The single production of fourth family sneutrino \( \tilde{\nu}_4 \) via R-parity violating interactions in electron-positron collisions has been investigated. We study the decays of \( \tilde{\nu}_4 \) into different flavor dilepton \( e^\pm \mu^\mp \) via R-parity violation. We discuss the constraints on the R-parity violating couplings \((\lambda_{411}, \lambda_{412})\) of the fourth family sneutrino at the linear collider energies.

\*Electronic address: ocakir@science.ankara.edu.tr
\dag Electronic address: kuday@science.ankara.edu.tr
\ddagger Electronic address: tckir@mail.cern.ch
\S Electronic address: ssultansoy@etu.edu.tr
The addition of fourth family fermions (see recent reviews [1] and [2]) to three families of the Standard Model (SM) can be followed by the extension of minimal supersymmetric standard model (MSSM) with the fourth family superpartners [3] (we denote minimal supersymmetric standard model with three and four families as MSSM3 and MSSM4, respectively). Concerning precision electroweak data the parameter space of the MSSM4 is tightly constrained [4, 5] if the neutrino has Dirac nature. However, this statement may be relaxed if the neutrino has Majorana nature (as in the SM4 case [6],[7]).

A search for supersymmetry (SUSY) is significant part of the physics program of TeV scale colliders. As mentioned in [8], it is difficult to differentiate MSSM3 and MSSM4 at hadron colliders, because the light superpartners of the third and fourth family quarks has almost the same decay chains if the R-parity is conserved. However, the rich phenomenology of the MSSM becomes even richer if R-parity is violated (see [9] and references therein). The R-parity is defined as $R = (-1)^{3(B-L)-2s}$, where $B, L$ and $s$ are the baryon number, lepton number and spin, respectively. Recently, searches for lepton flavor violating decays of third family sneutrinos into different flavor dileptons have been performed by the CDF and ATLAS experiments (see [10] and [11], respectively).

The baseline energy options for the linear colliders are assumed to be $\sqrt{s} = 0.5$ TeV for International Linear Collider (ILC) [12] and $\sqrt{s} = 3$ TeV for Compact Linear Collider (CLIC) [13]. An energy option $\sqrt{s} = 1$ TeV is also considered corresponding either to the early stage of the CLIC or to an upgraded version of the ILC. They have been designed to meet the requirements for planned physics search programs [14–16].

In this work, we consider the process $e^+e^- \rightarrow e^\pm \mu^\mp$ for linear collider energies $\sqrt{s} = 1$ TeV and 3 TeV. There are contributions to the cross section from both $s$-channel and $t$-channel diagrams, which were not studied previously for the production of fourth family sneutrino. The production cross section will depend on the mixture of RPV couplings $\lambda_{411}$ and $\lambda_{412}$.

The R-parity violating extension of the MSSM superpotential is given by

$$W_{RPV} = \frac{1}{2} \lambda_{ijk} \epsilon^{ab} L_a^i L_j^b E_k^i + \lambda'_{ijk} \epsilon^{ab} L_a^i Q_j^b D_k^i + \frac{1}{2} \lambda''_{ijk} \epsilon^{\alpha\beta\gamma} U_\alpha^i D_\beta^j D_\gamma^k$$

where $i, j, k = 1, 2, 3, 4$ are the family indices; $a, b = 1, 2$ are the $SU(2)_L$ indices and $\alpha, \beta, \gamma$ are the $SU(3)_C$ indices. $L_i(Q_i)$ are lepton (quark) $SU(2)$ doublet superfields; $E_i(D_i, U_i)$ are the charged lepton (down-type and up-type quark) $SU(2)$ singlet superfields. The couplings $\lambda_{ijk}$ and $\lambda''_{ijk}$ correspond to the lepton number violating and baryon number violating inter-
teractions, respectively. Clearly, the coupling constants $\lambda_{ijk}$ are antisymmetric under the exchange of the first two indices, while the $\lambda'_{ijk}$ are antisymmetric in last two indices. The first term in Eq. \[1\] leads to resonant production of sneutrinos in lepton-lepton collisions, while the second term allows slepton and sneutrino resonances in hadron-hadron collisions \[17\]. The squark resonances can also be produced in the lepton-hadron collisions \[18\]. Finally, the third term allows resonant squark production in the hadron-hadron collisions.

The magnitudes of the RPV couplings are arbitrary, and they are restricted only from the phenomenological considerations. A survey of the existing constraints on the RPV couplings (for three families) can be found in Refs. \[9, 19\].

The single production of fourth family sneutrino at the ILC and CLIC proceeds via the interaction terms in the Lagrangian written in terms of the component fields

\[
L_{RPV} = -\lambda_{4jk}\tilde{\nu}_{4L}\ell_{jL}\ell_{kR} + \lambda_{i4k}\tilde{\nu}_{4L}\ell_{iL}\ell_{kR} + H.c. \tag{2}
\]

where $\tilde{\nu}_{4L}$ is the fourth family sneutrino field and $\ell_{L(R)}$ is the left-handed (right-handed) lepton field, respectively. Once produced in $e^+e^-$ collisions the fourth family sneutrino $\tilde{\nu}_4$ can decay through different modes \[17\]: RPV decays $\tilde{\nu}_4 \rightarrow \ell_j^+\ell_k^-$ and $\tilde{\nu}_4 \rightarrow \bar{d}_j d_k$, supersymmetric decay $\tilde{\nu}_4 \rightarrow \nu_4\chi^0$, gauge decay $\tilde{\nu}_4 \rightarrow \ell_4^+\bar{\chi}^+$, weak decay $\tilde{\nu}_4 \rightarrow \ell_4^- W^+$ and Higgs decay $\tilde{\nu}_4 \rightarrow \ell_4^- H^+.$

Let us consider the signal from the decay $\tilde{\nu}_4 \rightarrow e^+\mu^-$ with different flavor charged leptons, both of which are well isolated and have high transverse momentum. The study is performed under the hypothesis that only the fourth family sneutrino ($\tilde{\nu}_4$) is produced and the sneutrino decay is determined by the $e^\pm\mu^\mp$ and $e^+e^-$ modes.

The cross section for the process $e^+e^- \rightarrow e^-\mu^+$, as shown in Fig.1, is given by

\[
\sigma = \frac{(\lambda_{411}\lambda_{412})^2}{32\pi s^2} \left[ \frac{s^3}{(s - m_{\tilde{\nu}_4}^2)^2 + m_{\tilde{\nu}_4}^2 \Gamma_{\tilde{\nu}_4}} + \frac{s(s + 2m_{\tilde{\nu}_4}^2)}{s + m_{\tilde{\nu}_4}^2} + 2m_{\tilde{\nu}_4}^2 \log\left(\frac{m_{\tilde{\nu}_4}^2}{s + m_{\tilde{\nu}_4}^2}\right) \right] \tag{3}
\]

where $m_{\tilde{\nu}_4}$ and $\Gamma_{\tilde{\nu}_4}$ are the mass and decay width of fourth family sneutrino, respectively.

We calculate the decay width of fourth family sneutrino depending on its mass and the RPV
couplings with the assumption of the relevant coupling dominance

$$\Gamma_{\tilde{\nu}_4} = (\lambda_{411}^2 + 2\lambda_{412}^2)m_{\tilde{\nu}_4}/16\pi$$

Assuming the couplings $\lambda_{412} = 0.1(0.05)$, $\lambda_{411} = 0.1(0.01)$ and the mass $m_{\tilde{\nu}_4} = 1$ TeV we calculate the decay width $\Gamma_{\tilde{\nu}_4} = 0.597$ (0.101) GeV. It can also be scaled for other mass values. The cross section for resonance production of the fourth family sneutrino for different RPV couplings is shown in Fig. 2.

For numerical calculations we implement the vertices from interaction Lagrangian (Eq. 2) into CalcHEP [20], and we take into account the effects from initial state radiation (ISR) and beamstrahlung (BS) using the beam parameters as shown in Table I.

Table I: The collider beam parameters of the ILC and CLIC needed to calculate the ISR+BS effects.

|                     | ILC       | CLIC      |
|---------------------|-----------|-----------|
| Horizontal beam size (nm) | 640       | 45        |
| Vertical beam size (nm)   | 5.7       | 1         |
| Bunch length (mm)         | 0.3       | 0.044     |
| Number of particles in the bunch (N) | $2 \times 10^{10}$ | $3.72 \times 10^{9}$ |
| Design luminosity (cm$^{-2}$s$^{-1}$) | $2 \times 10^{34}$ | $5.9 \times 10^{34}$ |
Table II: The production cross section of the fourth family sneutrino for different mass values. Here, we assume RPV couplings $\lambda_{412} = \lambda_{411} = 0.1$. The cross sections $\sigma_{ISR+BS}$ include initial state radiation (ISR) and beamstrahlung (BS), in $e^+e^-$ collisions at $\sqrt{s} = 1$ TeV.

| Mass (GeV) | $\sigma$(pb) | $\sigma_{ISR+BS}$(pb) |
|------------|--------------|------------------------|
| 200        | $7.21 \times 10^{-4}$ | $1.70 \times 10^{-1}$ |
| 400        | $7.43 \times 10^{-4}$ | $1.93 \times 10^{-1}$ |
| 600        | $1.06 \times 10^{-3}$ | $2.82 \times 10^{-1}$ |
| 800        | $3.06 \times 10^{-3}$ | $8.58 \times 10^{-1}$ |
| 1000       | $1.08 \times 10^{3}$  | $1.70 \times 10^{2}$  |

By fixing the RPV couplings $\lambda_{412} = \lambda_{411} = 0.1$, the signal cross sections for the fourth family sneutrino production for different mass values are presented in Tables II and III, where the cross sections $\sigma_{ISR+BS}$ include initial state radiation (ISR) and beamstrahlung (BS) in $e^+e^-$ collisions at $\sqrt{s} = 1$ TeV and $\sqrt{s} = 3$ TeV. For smaller RPV couplings such as $\lambda_{412} = \lambda_{411} = 0.01$, assuming $m_{\tilde{\nu}_4} = 400$ GeV we calculate the signal cross sections as $4.30 \times 10^{-3}$ pb and $1.38 \times 10^{-2}$ pb for $\sqrt{s} = 1$ and 3 TeV, respectively.

The main contributions to the background comes from the pair production of $W^+W^-$ and $\tau^+\tau^-$. The cross section for top-pair production $1.73 \times 10^{-1}(2.03 \times 10^{-1})$ pb at $\sqrt{s} = 1$ TeV and $1.98 \times 10^{-2}(1.81 \times 10^{-1})$ pb at $\sqrt{s} = 3$ TeV without (with) ISR+BS effects, respectively. This background is an order smaller than the $W^+W^-$ background and it can be removed by veto on high energy jets from two $b$-quarks. The cross sections for the $W^+W^-$ and $\tau^+\tau^-$ backgrounds as calculated with PYTHIA [21] including the ISR effects are given in Table IV for the center of mass energies $\sqrt{s} = 1$ and 3 TeV.

The contributions from these backgrounds to the final state $e^\pm \mu^\mp + X$ are estimated in the invariant mass distribution. In order to make the analysis with the signal and background it is required that electron and muon have transverse momentum $p_T^{e,\mu} > 25$ GeV and pseudorapidity $|\eta_{e,\mu}| < 2.5$.

The invariant mass distributions of $e\mu$ system are shown in Fig. 3 at $\sqrt{s} = 1$ TeV and in Fig. 4 at 3 TeV for both background and signal (assuming $\lambda_{411} = \lambda_{412} = 0.1$). From these figures we see that background remains almost at the same level for interested mass region. Therefore, we examined the invariant mass intervals for the existence of a fourth family.
Table III: The same as Table II but for $\sqrt{s} = 3$ TeV.

| Mass (GeV) | $\sigma$(pb) | $\sigma_{\text{ISR+BS}}$(pb) |
|------------|--------------|-------------------------------|
| 200        | $8.45 \times 10^{-5}$ | $2.23 \times 10^0$ |
| 400        | $8.21 \times 10^{-5}$ | $1.42 \times 10^0$ |
| 600        | $8.01 \times 10^{-5}$ | $1.11 \times 10^0$ |
| 800        | $7.91 \times 10^{-5}$ | $7.69 \times 10^{-1}$ |
| 1000       | $7.97 \times 10^{-5}$ | $4.96 \times 10^{-1}$ |
| 1200       | $8.26 \times 10^{-5}$ | $3.28 \times 10^{-1}$ |
| 1400       | $8.87 \times 10^{-5}$ | $2.22 \times 10^{-1}$ |
| 1600       | $9.96 \times 10^{-5}$ | $1.56 \times 10^{-1}$ |
| 1800       | $1.18 \times 10^{-4}$ | $1.14 \times 10^{-1}$ |
| 2000       | $1.50 \times 10^{-4}$ | $8.81 \times 10^{-2}$ |
| 2200       | $2.11 \times 10^{-4}$ | $7.13 \times 10^{-2}$ |
| 2400       | $3.39 \times 10^{-4}$ | $6.15 \times 10^{-2}$ |
| 2600       | $7.01 \times 10^{-4}$ | $5.82 \times 10^{-2}$ |
| 2800       | $2.59 \times 10^{-3}$ | $6.69 \times 10^{-2}$ |
| 3000       | $1.21 \times 10^2$ | $4.06 \times 10^0$ |

Table IV: Calculated backgrounds for the pair production of $W^+W^-$ and $\tau^+\tau^-$ at linear colliders. The numbers in the paranthesis correspond to the cross sections with the ISR effects.

| $\sqrt{s}$(TeV) | $\sigma(W^+W^-)$(pb) | $\sigma(\tau^+\tau^-)$(pb) |
|----------------|----------------------|----------------------------|
| 1              | $2.67 \times 10^0(3.17 \times 10^0)$ | $1.12 \times 10^{-1}(3.36 \times 10^{-1})$ |
| 3              | $4.63 \times 10^{-1}(4.07 \times 10^0)$ | $1.25 \times 10^{-2}(1.29 \times 10^0)$ |

sneutrino signal. The search region in the invariant mass spectrum is divided into mass bins $\Delta m$ for specific $m_{\tilde{\nu}_4}$, which is defined to be $(m_{\tilde{\nu}_4} \pm 3\sigma)$, where $\sigma$ is the mass resolution.

In Tables V and VI we present the cross sections $\Delta \sigma$ for signal and background within the mass intervals centered at each mass values. The statistical significance $SS = S/\sqrt{B}$ for signal observation is presented in the last column of these tables.

In Figs. 5 and 6 we present contour plots in the $(m_{\tilde{\nu}_4} - \lambda_{411})$ plane for an integrated luminosity of 200 fb$^{-1}$ at $\sqrt{s} = 1$ TeV and for an integrated luminosity 600 fb$^{-1}$ at $\sqrt{s} = 3$ TeV.
Figure 3: The $e\mu$ invariant mass distribution for background and signal at $\sqrt{s} = 1$ TeV (ISR and BS are included).

Figure 4: The $e\mu$ invariant mass distribution for background and signal at $\sqrt{s} = 3$ TeV (ISR and BS are included).
Figure 5: Attainable limits for the mass and RPV couplings of fourth family sneutrino at $\sqrt{s} = 1$ TeV (assuming $\lambda_{412} = \lambda_{411}$).

Figure 6: Attainable limits for the mass and RPV couplings of fourth family sneutrino at $\sqrt{s} = 3$ TeV (assuming $\lambda_{412} = \lambda_{411}$).
Table V: The cross sections for the signal and background calculated within the mass intervals at the center of mass energy $\sqrt{s} = 1$ TeV. Here, we assume the RPV couplings $\lambda_{411} = \lambda_{412} = 0.005$. The statistical significance is calculated for an integrated luminosity $200 \text{ fb}^{-1}$.

| $m_{\tilde{\nu}_4}$ (GeV) | $\Delta m$ (GeV) | $\Delta \sigma_s$ (fb) | $\Delta \sigma_B$ (fb) | $SS$ |
|-------------------------|-----------------|------------------------|------------------------|-----|
| 200                     | 20              | $4.22 \times 10^{-1}$  | $8.34 \times 10^{-1}$  | 6.5 |
| 400                     | 30              | $4.82 \times 10^{-1}$  | $1.60 \times 10^{0}$   | 5.4 |
| 600                     | 40              | $6.99 \times 10^{-1}$  | $2.23 \times 10^{0}$   | 6.6 |
| 800                     | 50              | $2.14 \times 10^{0}$   | $3.56 \times 10^{0}$   | 16.1|
| 1000                    | 60              | $6.57 \times 10^{4}$   | $7.35 \times 10^{-2}$  | $5.6 \times 10^{3}$ |

TeV, respectively. The regions above the curve denotes the range of RPV coupling $\lambda_{411}$ values that can be reached in the linear collider experiments. It is seen that even for $m_{\tilde{\nu}_4} < \sqrt{s}$ values the RPV couplings well below 0.01 are reachable.

In conclusion, the resonance production of fourth family sneutrino through R-parity violating couplings at the linear collider energies have been studied. The sensitivity to RPV couplings can be measured with better level compared to the information derived from indirect measurements. The results show that RPV couplings of fourth family sneutrino in the high mass region can be explored at linear collider experiments as complementary to the LHC results.

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Table VI: The same as Table V, but for $\sqrt{s} = 3$ TeV and $L_{int} = 600 \text{ fb}^{-1}$.

| $m_{\tilde{\nu}}$ (GeV) | $\Delta m$ (GeV) | $\Delta\sigma_s$ (fb) | $\Delta\sigma_B$ (fb) | SS |
|--------------------------|------------------|----------------------|----------------------|----|
| 200                      | 20               | $5.73 \times 10^0$   | $2.79 \times 10^0$   | 84.0 |
| 400                      | 30               | $3.60 \times 10^0$   | $2.32 \times 10^0$   | 57.9 |
| 600                      | 40               | $2.79 \times 10^0$   | $2.77 \times 10^0$   | 41.1 |
| 800                      | 50               | $1.92 \times 10^0$   | $3.20 \times 10^0$   | 26.3 |
| 1000                     | 60               | $1.24 \times 10^0$   | $4.50 \times 10^0$   | 14.3 |
| 1200                     | 70               | $8.30 \times 10^{-1}$ | $3.95 \times 10^0$   | 10.2 |
| 1400                     | 80               | $5.50 \times 10^{-1}$ | $4.82 \times 10^0$   | 6.1  |
| 1600                     | 90               | $3.80 \times 10^{-1}$ | $5.71 \times 10^0$   | 3.9  |
| 1800                     | 100              | $2.90 \times 10^{-1}$ | $5.81 \times 10^0$   | 2.9  |
| 2000                     | 110              | $2.10 \times 10^{-1}$ | $5.81 \times 10^0$   | 2.1  |
| 2200                     | 120              | $1.70 \times 10^{-1}$ | $6.68 \times 10^0$   | 1.6  |
| 2400                     | 130              | $1.50 \times 10^{-1}$ | $7.12 \times 10^0$   | 1.4  |
| 2600                     | 140              | $1.40 \times 10^{-1}$ | $4.71 \times 10^0$   | 1.6  |
| 2800                     | 150              | $1.60 \times 10^{-1}$ | $2.96 \times 10^0$   | 2.3  |
| 3000                     | 160              | $1.61 \times 10^0$   | $5.50 \times 10^{-1}$ | $5.3 \times 10^4$ |

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