Sneutrino Factory

Yosuke Uehara

Department of Physics, University of Tokyo, Tokyo 113-0033, Japan

Abstract

We argue that future $e^+e^-$ linear colliders can produce many sneutrinos if lepton-number violating couplings $\lambda_{1j1}$ exist and enough beam polarization is obtained. The terms $\lambda_{ijk}L_iL_jE_k^c$ are allowed in a discrete $Z_3$-symmetry which is used to forbid rapid proton decay, and it is worthwhile to consider the possibility of the existence of such terms and their resultant. We study the process $e^+e^- \rightarrow \tilde{\nu} \rightarrow e^+e^-$ in detail, and show that if such resonance is not found, lepton-number violating couplings $\lambda_{1j1}$, will be strongly constrained. If we assume sneutrino mass $m_{\tilde{\nu}} = 500\text{GeV}$, beam polarization $P_{e^-} = 0.9, \ P_{e^+} = 0.6$, and integrated luminosity $L = 100\text{fb}^{-1}$, non-observation of $\tilde{\nu}$ resonance will lead to $\lambda_{1j1} \lesssim 0.02$ (if all charginos, and neutralinos, are lighter than the sneutrino), or $\lambda_{1j1} \lesssim 0.003$ (if all charginos, and neutralinos, are heavier than the sneutrino).
The Standard Model (SM) of particle physics explains many experimental facts excellently, but it is not considered as the ultimate theory. It is because Higgs sector of the SM receives divergent radiative corrections, and a fine-tuning is needed to make the SM valid up to high energy scale. Supersymmetry (SUSY) is considered as the most promising symmetry to solve this fine-tuning problem. If we assume SUSY, the superpartner of the SM particles cancels the divergent diagram and the Minimal Supersymmetric Standard Model (MSSM) can be valid up to high energy scale without any fine-tuning. Furthermore, the MSSM predicts the gauge coupling unification at very high energy scale $E \sim 2 \times 10^{16} \text{GeV}$, and thus it is very motivated.

However the naive MSSM includes very dangerous terms such as

$$W = \lambda_{ijk} L_i L_j \tilde{E}_k^c + \lambda'_{ijk} L_i Q_j \tilde{D}_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c,$$  \hspace{1cm} (1)

If these coefficients are $O(1)$, we have too rapid proton decay \footnote{1}. Thus, these coefficients must be extremely small.

The R-symmetry is a well-known symmetry to suppress the superpotential in Eq. (1). If one imposes R-parity invariance, superpotential in Eq. (1) vanishes and no such a dangerous phenomenon occurs. R-parity is defined as $R = (-1)^{(3B + L + 2S)}$. Here $B$ is baryon number of the particle, $L$ is the lepton number of the particle, and $S$ is the spin of the particle.

However, there is another interesting symmetry to suppress the dangerous operators in Eq. (1). A $Z_3$-symmetry forbids $\lambda''_{ijk} U_i^c D_j^c D_k^c$-term completely and it is anomaly-free \footnote{2}. Thus this $Z_3$-symmetry is interesting alternative to R-parity to suppress the dangerous rapid proton decay, since proton decay amplitude is mediated by the terms proportional to the product $\lambda' \lambda''$. The charge assignment of this $Z_3$ is shown in table 1.

| particle | $Q$ | $U_i^c$ | $D_j^c$ | $L$ | $E_k^c$ |
|----------|-----|---------|---------|-----|---------|
| charge   | 1   | $\alpha^2$ | $\alpha$ | $\alpha^2$ | $\alpha^2$ |

Table 1: charge assignment under the discrete gauge symmetry $Z_3$.

If we assume this $Z_3$-symmetry, $\lambda_{ijk} L_i L_j \tilde{E}_k^c$ and $\lambda'_{ijk} L_i Q_j \tilde{D}_k^c$ is allowed, and
hence it is interesting to consider the phenomena which \( \lambda_{ijk}L_iL_jE_k^c \) generates. In this paper, we consider the sneutrino-resonant production caused by this term. We assume \( \lambda'_{ijk} = \lambda''_{ijk} = 0 \) throughout this paper.

Constraints on the above lepton-number violating couplings \( \lambda_{ijk}L_iL_jE_k^c \) can be obtained from experiments. We show that the non-observation of superparticle in collider experiments can set upper bounds on couplings. ("direct" experiments) On the other hand, we have effects of virtual superparticles at the quantum level, and can set upper bounds on couplings. ("indirect" experiments)

First, let us consider "direct" experiments. LEP experiments searched for the lepton-number violating couplings \[ 3, 4, 5 \]. This direct search put strong constraints on \( \lambda_{1j1} \), which we will consider later, in the region \( m_{\tilde{\nu}} < \sim 200 \text{GeV} \) (LEP maximum energy).

Next, consider about "indirect" experiments \[ 6 \]. They include the EDM of fermions \[ 7 \], anomalous magnetic moment of the muon \[ 8 \], the decay width of the Z \[ 9, 10, 11 \] and of the W \[ 11 \] bosons, the strength of four-fermion interactions, with the subsequent production of lepton pairs at hadron \[ 12, 13 \] and lepton colliders \[ 14 \], rare processes such as \( \mu \rightarrow e\gamma \) \[ 15 \], \( e^- - \mu - \tau \) universality \[ 16, 11 \]. (For an extensive discussion, see \[ 17 \].)

The existence of \( \lambda \) coupling may wash-out the baryon-number asymmetry produced in the early universe \[ 18 \]. This is because spharelon processes violate \( B + L \), and \( \lambda \) couplings violate \( L \), and thus the combination violates \( B \). Nevertheless, we can avoid this difficulty if the baryon-number asymmetry in the universe is created after the electroweak phase transition, by the mechanism like Affleck-Dine baryogenesis \[ 19 \] or the electroweak baryogenesis \[ 20 \].

Thus lepton-number violating couplings \( \lambda_{ijk} \) are not severely constrained yet. In this paper, we consider a "direct" experiment and the expected constraints on the lepton-number violating couplings \( \lambda_{1j1} \) in the future collider experiments. The upper bounds of the lepton-number violating coupling \( \lambda_{ijk} \) from many "direct" and "indirect" experiments are shown in table 2.
Table 2: The upper bound of lepton-number violation and their origin. This is model independent constraint. Here we assume common SUSY scalar mass: $\tilde{m} = 100\text{GeV}$.

| $\lambda$ | upper bound | its origin                  |
|-----------|-------------|-----------------------------|
| $\lambda_{121}$ | $< 0.04$ | CC universality \[21\]. |
| $\lambda_{131}$ | $< 0.10$ | tau leptonic decay \[21\]. |

The “direct” experiment we consider is the sneutrino single production

$$e^+e^- \rightarrow \bar{\nu} \rightarrow e^+e^-.$$ (2)

It was previously studied in some articles \[6, 22, 23, 24\]. But \[6, 22, 23\] did not consider the interference between t-channel, \[22, 24\] did not calculate the decay width of sneutrino and they only assumed it, and all of them did not take into account the effect of beam polarization.

There are other articles which considered sneutrino resonant production. \[25\] considered sneutrino s-channel production, its decay into $b\bar{b}$, and their expected LEP signal. \[26, 27\] considered muon collider discovery potential of $\lambda$ and $\lambda'$ couplings.

The interference between resonant s-channel and t-channel smears the peak of cross section, and so we must take it into account. The decay width of sneutrino highly depends on the mass spectra of SUSY particles, and it is very important for setting upper limit on the lepton-number violating coupling from the experiments. Finally, in order to distinguish this sneutrino $e^+e^-$ resonance from usual $\gamma/Z$ resonance tail in the case that the sneutrino can decay into chargino and/or neutralino, we must use highly-polarized beam.

Sneutrino is produced as a s-channel resonance of $e^+e^-$ collision if the lepton-number violating superpotential

$$W = \lambda_{121}L_1L_2E_1^c + \lambda_{131}L_1L_3E_1^c,$$ (3)

exists. We do not distinguish $\lambda_{121}$ and $\lambda_{131}$, and simply write it as $\lambda$, hereafter.
Once produced, sfermion immediately decays into lighter particles. In the following, we show the relevant Lagrangian for the decay of sneutrino. Our convention is given in appendix A.

**Lepton-number violation:**

\[ \mathcal{L} = \lambda \tilde{\nu} e \tilde{e}. \]  

(4)

**Fermion-sfermion-chargino:**

\[ \mathcal{L} = -g \cos \phi_R (\tilde{\nu}^* \tilde{\chi}_1^+ l_L + \text{h.c.}) + g \epsilon_R \sin \phi_R (\tilde{\nu}^* \tilde{\chi}_2^+ l_L + \text{h.c.}). \]  

(5)

**Fermion-sfermion-neutralino:**

\[ \mathcal{L} = \sqrt{2} g_Z (-g^*_N \tilde{f}_L \tilde{\chi}_i^0 f_L + \text{h.c.}), \]  

(6)

\[ g^*_N = T_3 L \cos \theta_W (O_N)_{i2} + (Q - T_3 L) \sin \theta_W (O_N)_{i1}. \]

There are other Lagrangian which causes the decay of sneutrino, but their decay modes are highly suppressed mainly because of the multi-body phase space. So we do not write them.

The input parameters are described in table 3, and the mass spectra of neutralino and chargino are shown in table 4.

| parameter | mass(GeV) (case 1) | mass(GeV) (case 2) |
|-----------|---------------------|---------------------|
| $m_{\tilde{\nu}}$ | 500 | 500 |
| $M_1$ | 100 | 600 |
| $M_2$ | 200 | 1200 |
| $\mu$ | 100 | 600 |

Table 3: SUSY input parameters.

The decay modes

\[ \tilde{\nu} \to \tilde{\chi}_{1,2,3,4}^0 + \nu, \]  

(7a)

\[ \tilde{\nu} \to \tilde{\chi}_{1,2}^+ + l^+, \]  

(7b)
Table 4: Neutralino and chargino mass spectrum.

are kinematically allowed in the case 1 and dominates the decay modes. In the case 2, such decay mode cannot be allowed and only the lepton-number violating decay

\[ \tilde{\nu} \rightarrow e^+ e^- , \]  

dominates the decay. We will concentrate on this lepton-number violating decay mode.

We calculate the decay width for the case 1 and the case 2. The total decay width does not depend so much on \( \lambda \) in the case 1 because the decay mode is dominated by neutralino and chargino decay channel, and typically it is:

\[ \Gamma_{\tilde{\nu}} \sim 5.8 \text{ GeV. (for the case 1)} \]  

In the case 2, only the lepton-number violating decay is allowed and it highly depend on \( \lambda \). It is:

\[ \Gamma_{\tilde{\nu}} \sim 0.0020 \left( \frac{\lambda}{0.01} \right)^2 \text{ GeV. (for the case 2)} \]  

Now we consider the production of sneutrino. Since the sneutrino is spinless particle, beam polarization is extremely useful for its production. It is well described in figure 1, 2, 3, 4. By using beam polarization, we can improve the production cross section of spinless particle, \( \tilde{\nu} \). We cannot observe sharp peak in the case 1 if beam polarization is not enough. We can observe very sharp peak in the case 2 because in the case 2 sneutrino cannot decay into chargino and neutralino, and thus total decay width is very small. Here we selected the region \( \cos \theta < \frac{1}{\sqrt{2}} \) in order to avoid the divergent t-channel photon exchange process. And we use CIRCE \[28\] to take into account the effect of initial state radiation. For CIRCE, we assume TESLA data as an input.
Figure 1: Sneutrino resonance process $e^+e^- \rightarrow \gamma/Z/\tilde{\nu} \rightarrow e^+e^-$ cross section in case 1. Here we assume $\lambda = 0.05$ and beam polarization $P_{e^-} = 0.9$, $P_{e^+} = 0.6$. We can observe the peak of $\tilde{\nu}$ around its mass, $m_{\tilde{\nu}} = 500$GeV.

Figure 2: Sneutrino resonance process $e^+e^- \rightarrow \gamma/Z/\tilde{\nu} \rightarrow e^+e^-$ cross section in case 1. Here we assumed $\lambda = 0.05$ and beam polarization $P_{e^+} = P_{e^-} = 0.2$. We can see peak signal slightly.
Figure 3: Sneutrino resonance process $e^+e^- \rightarrow \gamma/Z/\tilde{\nu} \rightarrow e^+e^-$ cross section in case 2. Here we assume $\lambda = 0.05$ and beam polarization $P_{e^-} = 0.9$, $P_{e^+} = 0.6$. We can observe the extremely sharp peak of $\tilde{\nu}$ around its mass, $m_{\tilde{\nu}} = 500$GeV. The sharpness comes from the small decay width of sneutrino. In case 2, sneutrino cannot decay into chargino and neutralinos.

Figure 4: Sneutrino resonance process $e^+e^- \rightarrow \gamma/Z/\tilde{\nu} \rightarrow e^+e^-$ cross section in case 2. Here we assume $\lambda = 0.05$ and beam polarization $P_{e^-} = P_{e^+} = 0.2$. Here again we can observe the peak of $\tilde{\nu}$. This is because of the smallness of sneutrino decay width.
So with the help of beam polarization, we may be able to find the s-channel resonance of sneutrino even in the case 1. If sneutrino is lighter than charginos and neutralinos, we may be able to see resonance without beam polarization.

If such resonance cannot be found, lepton-number violating coupling $\lambda$ will be severely constrained. Here we assume integrated luminosity $100\text{fb}^{-1}$. Half of the experiment is done with beam polarization $P_{e^-} = 0.9$, $P_{e^+} = 0.6$ and other half of the experiment is done with beam polarization $P_{e^-} = 0.9$, $P_{e^+} = -0.6$. Then we can obtain the upper limit on $\lambda$ if we cannot see $e^+e^- \to \tilde{\nu} \to e^+e^-$ resonance. For a sneutrino mass of 500GeV,

$$\lambda \lesssim 0.021 \text{ (for the case 1)},$$

$$\lambda \lesssim 0.0030 \text{ (for the case 2)}.$$  

(11a)

(11b)

To summarize, we consider the process $e^+e^- \to \tilde{\nu} \to e^+e^-$ in the lepton-number braking models. Such processes are allowed in anomaly-free $Z_3$-symmetry which is imposed to protect the rapid proton decay $\exists$ instead of the $Z_2$-symmetry, "R-parity". We observe that using beam polarization is extremely useful to see the resonant peak of sneutrino in $e^+e^-$ system. Non-observation of such resonance will lead to a strong constraint on the lepton-number violating parameter $\lambda$.

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A Convention of Supersymmetric Interaction

I followed the convention of “Supersymmetric Standard Model for Collider Physicists” [29].

A.1 Chargino Sector

The chargino mass matrix $M_C$ can be written as:

$$M_C = \begin{pmatrix} M_2 & \sqrt{2}m_W \cos \beta \\ \sqrt{2}m_W \sin \beta & \mu \end{pmatrix},$$

(12)

here we assume $CP$ invariance and take all the entries in $M_C$ real. Then $M_C$ can be diagonalized by two orthogonal matrices:

$$O_R M_C O_L^T = \text{diag},$$

(13)

where

$$O_{L,R} = \begin{pmatrix} \cos \phi_{L,R} & \sin \phi_{L,R} \\ -\sin \phi_{L,R} & \cos \phi_{L,R} \end{pmatrix}.$$  

(14)

This diagonalization may leave negative eigenvalue in the diagonal entry. So we make every entry positive. First select the angle $\phi_L$ in the range $0 < \phi_L < \pi$, then $m_{\chi_1^-}$ can be made positive if we allow the full range for $\phi_R$: $-\pi < \phi_R < \pi$. Now $m_{\chi_2^-}$ can be either positive or negative depending on $\text{sgn}(M_2 \mu - m_W^2 \sin 2\beta)$.

We redefine $O_R$ as to allow for $\det O_R = -1$:

$$O_R = \begin{pmatrix} \cos \phi_R & \sin \phi_R \\ -\epsilon_R \sin \phi_R & \epsilon_R \cos \phi_R \end{pmatrix},$$

(15)

where $\epsilon_R = \text{sgn}(M_2 \mu - m_W^2 \sin 2\beta)$.

A.2 Neutrino Sector

The neutralino mass matrix can be written as:

$$M_N = \begin{pmatrix} M_1 & 0 & -m_Z \sin \theta_W \cos \beta & m_Z \sin \theta_W \sin \beta \\ 0 & M_2 & m_Z \cos \theta_W \cos \beta & m_Z \cos \theta_W \sin \beta \\ -m_Z \sin \theta_W \cos \beta & m_Z \cos \theta_W \cos \beta & 0 & -m_Z \cos \theta_W \sin \beta \\ m_Z \sin \theta_W \sin \beta & -m_Z \cos \theta_W \sin \beta & -\mu & 0 \end{pmatrix},$$

(16)
Hereafter we assume that all the entries in $M_N$ are real. In this case $M_N$ can be diagonalized by an orthogonal matrix $O_N$:

$$O_N M_N O_N^T = \text{real diagonal.} \quad (17)$$

However this procedure may leave some of the eigenvalues negative. The negative eigenvalues cannot be treated by introducing an extra sign factor, as in Section A.1, because the left and right neutralino fields are not independent. It is necessary to multiply the negative mass eigenstates by a factor of $i$. In practice, this is done by introducing an extra phase matrix in (17).

$$U_N^* M_N U_N^\dagger = \text{positive diagonal,} \quad (18)$$

where $U_N = \Phi_N O_N$ with $O_N$ given above, and $\Phi_N$ is a diagonal phase matrix $(\Phi_N)_{ij} = \delta_{ij} \eta_i$ with

$$\eta_i = \begin{cases} 1 & \text{if the mass eigenvalue is positive,} \\ i & \text{if the mass eigenvalue is negative.} \end{cases} \quad (19)$$

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