Pair Production of Tau Sneutrinos at Linear Colliders

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Abstract

The pair production of tau sneutrinos in $e^+e^-$ collisions and their subsequent decays are studied in a framework of the supersymmetric extension of the standard model. We present an analysis for the parameter space (BR vs. mass) which could be explored at the future high energy $e^+e^-$ colliders.

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The supersymmetry (SUSY) is considered to be a plausible candidate for physics beyond the Standard Model (SM). The minimal supersymmetric extension (MSSM) of the SM consists of the two-Higgs doublet extension and the corresponding supersymmetric partners of the SM, whose spin differs by one half unit. The SUSY and SM particles are distinguished by a quantum number, $R$-parity, with $R = (-1)^{3B+L+2s}$ where $B$ and $L$ are the baryon and lepton numbers and $s$ is the spin. It is commonly assumed that $R$-parity is conserved. As a consequence, SUSY particles are produced in pairs, and the decays (cascade) into SM particle plus SUSY particle ends with the lightest SUSY particle (LSP).

The Large Hadron Collider (LHC) has a great potential to search for supersymmetry, by virtue of its high beam energy and relatively large sparticle production cross sections. In the hadron collisions, the distribution of energy and momentum of the partons has a broad spectrum, for the LSP searches only the missing transverse momentum (MPT) or missing transverse energy (MET) become useful. Even some measurements of sparticles could be possible at the Large Hadron Collider (LHC), however, more precise determination \[1, 2\] of the underlying model parameters is necessary at future lepton colliders operating with polarized beams \[3, 4\]. Furthermore, being different from the hadron collisions, in the $e^+e^-$ collisions the missing energy can be directly inferred from the center of mass energy and the total energy of visible final state particles. In addition, the leptonic beams have very small spread to correlate the missing energy and momentum with the energy and momentum of the LSP’s. The spin-0 partners of the SM fermions (called sfermions) are the squarks, sleptons and sneutrinos. The sleptons and squarks of the third family are particularly interesting since their phenomenology is different from that of other two families. This is expected due to the mixing between the left-handed and right-handed components, and relatively their large Yukawa couplings. In future experiments, study of sneutrinos \[5, 6\] and their mixings might also be interesting \[7–9\].

The sneutrino mass limit is given from the direct searches $m_{\tilde{\nu}} > 94$ GeV \[10\], with the assumption of mass degeneracy and the presence of only the left handed sneutrinos $\tilde{\nu}_L$. From the results obtained by the LEP Collaborations on the invisible width of the $Z$ boson ($\Delta \Gamma_{inv.} < 2.0$ MeV) the limit on the sneutrino mass is given as $m_{\tilde{\nu}} > 44.7$ GeV.

In this work, we study the pair production of tau sneutrinos in $e^+e^-$ collisions, as well as their subsequent decays into tau lepton plus lighter chargino, and cascade ending with neutralinos (assuming LSP). We present an analysis for the parameter space (BR vs. mass)
which could be explored at the future high energy \(e^+e^-\) collider, namely the Compact Linear Collider (CLIC) in two beam acceleration technology allowing the preferable center of mass energy 3 TeV with \(L \approx 10^{35} \text{ cm}^{-2}\text{s}^{-1}\). \[1\]

The coupling of the tau sneutrinos with the \(Z\) boson is expressed by the interaction

\[
L = - \frac{i\sqrt{g^2 + g'^2}}{2} (\bar{\nu}_\tau \gamma\mu \nu_\tau - \partial^\mu \bar{\nu}_\tau \gamma^\mu \nu_\tau) Z_\mu
\]

where \(g\) and \(g'\) are the gauge coupling constants. For the sneutrino pair production the cross section is given by

\[
\sigma \left( e^+ e^- \rightarrow \bar{\nu}_\tau \nu_\tau \right) = \frac{\alpha^2 \pi}{192 \epsilon_w^4 s_w^4} s \left( \delta_e^2 + a_e^2 \right) \frac{m^2_{\nu_{\tau}}}{s - m^2_{\nu_{\tau}} + m^2_{\nu_{\tau}}}(1 - \frac{4m^2_{\nu_{\tau}}}{s})^{3/2}
\]

where \(\delta_e = -1 + 4s_w^2\) and \(a_e = -1\). The sneutrino mass is given by \(m^2_{\nu_{\tau}} = m^2_L - (m^2_Z/2) \cos 2\beta\). The tau sneutrino decays mainly to a chargino and a tau lepton. The interaction term for the tau sneutrino-chargino-tau vertex is given by

\[
L = -g_R (C_{i\tau}^L P_L + C_{i\tau}^R P_R) \tilde{\chi}_i^- \tilde{\nu}_\tau + h.c.
\]

where \(C_{i\tau}^L = V_{i\tau}^*\) and \(C_{i\tau}^R = -y_\tau U_{i2}\) and the Yukawa coupling \(y_\tau = m_\tau/\sqrt{2}m_W \cos \beta\). We use the matrices \(U\) and \(V\) to diagonalize chargino mass matrix. The chargino-neutralino-\(W\) boson interaction can be written as

\[
L = g W^- \tilde{\chi}_i^0 \gamma^\mu (D_{i\ell k}^L P_L + D_{i\ell k}^R P_R) \tilde{\chi}_k^+ + h.c.
\]

where couplings \(D_{i\ell k}^L = -Z_{i\ell} V_{k2}/\sqrt{2} + Z_{i\ell} V_{k1}\) and \(D_{i\ell k}^R = Z_{i\ell}^* U_{k2}/\sqrt{2} + Z_{i\ell} U_{k1}\), the interactions and notations can be found in \([12]\). Here, we use the \(4 \times 4\) matrices \(Z\) which diagonalize neutralino mass matrix.

We study the process \(e^+e^- \rightarrow \tilde{\nu}_\tau \bar{\nu}_\tau\) with subsequent SUSY decays \(\tilde{\nu}_\tau \rightarrow \tau^- \tilde{\chi}_1^+\) and \(\tilde{\chi}_1^+ \rightarrow W^+ \tilde{\chi}_1^0\). Benchmark points \(\alpha, \beta, \gamma, \delta\) and the mass spectra (in GeV) for third family sfermions, lightest chargino and neutralino, as calculated using SuSpect \([14]\) are given in Table II. Here, the scenarios \(\alpha, \beta, \gamma\) belongs to non-universal Higgs mass (NUHM) models, while \(\delta\) belongs to gravitino dark matter (GDM). The point \(\alpha\) has parameters \(m_0 = 210, m_{1/2} = 285, \tan \beta = 10\); point \(\beta\) has \(m_0 = 230, m_{1/2} = 360, \tan \beta = 10\); point \(\gamma\) has \(m_0 = 330, m_{1/2} = 240, \tan \beta = 20\); and point \(\delta\) has \(m_0 = 500, m_{1/2} = 750, \tan \beta = 10\). All these points have also the parameters \(\text{sign} \mu = +1\) and \(A_0 = 0\). At the points \(\alpha, \beta,\)
Figure 1: Cross sections for pair production of tau sneutrinos depending on the center of mass energy for different SUGRA points.

$\gamma$ and $\delta$, tau sneutrino has mass values 274.9 GeV, 324.6 GeV, 353.9 GeV and 695.2 GeV, respectively. The branching ratios for tau sneutrino into neutralino+tau and chargino+tau neutrino are given in Table [11] for a set of benchmark supersymmetric scenarios [13]. The tau sneutrino mostly decays to chargino and tau lepton for the $\alpha$ and $\gamma$ benchmark points. While it is comparable to the decay into neutralino for the points $\beta$ and $\delta$. The reaction is then observed as $e^+e^- \rightarrow \tau^+\tau^-W^-W^+ + E_T$ where $\tau$-leptons has an energy spectrum with two edges. An analysis on the sneutrino cascade decays as probe of the chargino spin properties and CP violation was studied in [15]. Above the threshold center of mass energy the tau sneutrinos are produced in the $e^+e^-$ collisions. A threshold scan for the energy could help to identify the model parameters. Fig. [3] shows the cross sections for tau sneutrino pair production depending on the center of mass energies covering relevant threshold regions. For the points $\alpha$, $\beta$, $\gamma$ and $\delta$ the cross sections show peaks at the center of mass energies 900 GeV, 1050 GeV, 1150 GeV and 2200 GeV, respectively. At the high energies, preferable energy of the CLIC ($\sqrt{s} = 3$ TeV), the cross sections for different benchmark points tend to converge around 1 fb, which will yield 100 events at a luminosity of $L_{\text{int}} = 10^5$ pb$^{-1}$.

Since the tau sneutrino has spin-0 it decays isotropically, and the boost of an isotropic distribution become a flat distribution in energy. Therefore, we expect the tau energy spectrum nearly flat between some kinematic endpoints [16]. The two endpoints energies
Table I: Benchmark points and the mass spectra (in GeV) for third family sfermions, lightest chargino and neutralino, as calculated using SuSpect [14].

| Model  | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ |
|-------|----------|---------|----------|---------|
| $m_{1/2}$ | 285      | 360     | 240      | 750     |
| $m_0$    | 210      | 230     | 330      | 500     |
| $\tan\beta$ | 10       | 10      | 20       | 10      |
| sign$(\mu)$ | +        | +       | +        | +       |
| $A_0$    | 0        | 0       | 0        | 0       |
| $m_t$    | 175.0    | 175.0   | 175.0    | 175.0   |

Masses

- $\tilde{\chi}^0_1$: 112.4, 144.7, 94.2, 315.8
- $\tilde{\chi}^\pm_1$: 208.9, 271.5, 174.4, 596.6
- $\tilde{\tau}_1$: 232.2, 262.4, 323.0, 564.0
- $\tilde{\tau}_2$: 288.9, 336.4, 369.6, 700.6
- $\tilde{\nu}_\tau$: 274.9, 324.6, 353.9, 695.2
- $\tilde{t}_1$: 481.2, 599.2, 443.4, 1214.0
- $\tilde{t}_2$: 659.6, 789.1, 607.2, 1484.0
- $\tilde{b}_1$: 602.5, 739.3, 551.6, 1459.0
- $\tilde{b}_2$: 637.1, 777.2, 600.4, 1525.0

Table II: Branching ratios for tau sneutrino at different supersymmetry parameter space.

| BR$(\tilde{\nu}_\tau \to \nu_\tau \tilde{\chi}^0_1)$ | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ |
|---------------------------------|----------|---------|----------|---------|
| [\%]                           | 31.5     | 41.5    | 16.1     | 39.1    |
| BR$(\tilde{\nu}_\tau \to \nu_\tau \tilde{\chi}^0_2)$ | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ |
| [\%]                           | 20.5     | 18.2    | 24.4     | 18.6    |
| BR$(\tilde{\nu}_\tau \to \tau^- \tilde{\chi}^+_1)$ | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ |
| [\%]                           | 48.0     | 40.3    | 59.6     | 37.9    |

$E_\pm$ of the spectrum are related to the tau sneutrino and chargino masses and the $\tilde{\nu}_\tau$ boost as

$$E_\pm = \frac{\sqrt{s}}{2m_{\tilde{\nu}}}(1 \pm \sqrt{1 - 4m_{\tilde{\nu}}^2/s}) \frac{m_{\tilde{\nu}}^2 - m_{\tilde{\chi}_1}^2}{2m_{\tilde{\nu}}}$$  (5)

where $\sqrt{s}$ is the collision center of mass energy for the process $e^+e^- \to \tilde{\nu}_\tau \tilde{\nu}_\tau \to \tau^+ \tilde{\chi}_1^- \tau^- \tilde{\chi}_1^+$.  

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Table III: Branching ratios for tau sneutrino at different supersymmetry parameter space.
This process provides a source of about fully polarized charginos, $\tilde{\chi}_1^+$ with negative helicity, and $\tilde{\chi}_1^-$ with positive helicity. Using the benchmark points we calculate the endpoint energies as: $E_-(E_+) = 6.3(656.9)$ for $\alpha$; $E_-(E_+) = 6.6(492.5)$ for $\beta$; $E_-(E_+) = 17.4(1121.4)$ for $\gamma$; $E_-(E_+) = 30.8(449.6)$ for $\delta$. The PYTHIA [22] is used for event generation and the energy distributions of the final state tau lepton, which are shown in Fig. 2 for different SUGRA points ($\alpha, \beta, \gamma, \delta$). We may determine the tau sneutrino mass by using the ratio of the two edge energies. If only the high energy edge is available, two-parameter fit can be used to obtain the required accuracy in the mass measurement.

The decay width of tau sneutrino is approximately determined by two-body problem as defined by
Table III: The unpolarized cross sections for signal and relevant background at $\sqrt{s}=3$ TeV.

| Benchmarks | Signal | Background |
|------------|--------|------------|
| $\sigma$(fb) | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ | $W^+W^-\tau^+\tau^-$ | $W^+W^-W^+W^-$ | $W^+W^-ZZ$ | $W^+W^-Z$ |
| 0.35 | 0.23 | 0.52 | 0.14 | 0.77 | 1.45 | 1.16 | 32.6 |

$$\Gamma(\tilde{\nu}_{\tau} \to \tau^- \tilde{\chi}_1^+) = \frac{g^2}{16\pi m_{\tilde{\nu}_{\tau}}} \sqrt{(1 - \frac{(m_{\tau} + m_{\tilde{\chi}_1})^2}{m_{\tilde{\nu}_t}^2})(1 - \frac{(m_{\tau} - m_{\tilde{\chi}_1})^2}{m_{\tilde{\nu}_t}^2})}$$

$$\times \left[ (|C_L|^2 + |C_R|^2) \left( \frac{m_{\tau}^2}{2\cos^2\beta m_W^2} \right) \left( 1 - \frac{m_{\tau}^2 + m_{\tilde{\chi}_1}^2}{m_{\tilde{\nu}_t}^2} \right) - 2\sqrt{2}C_LC_R^* \cos\beta m_W m_{\tilde{\nu}_t} \right]$$

(6)

The cross section for the process $e^+e^- \to \tilde{\nu}_{\tau}\tilde{\nu}_{\tau}$ has a special characteristics of scalar production proportional to $\beta^3$. For the pair production of tau sneutrinos, the required initial state has angular momentum $J_z = 1$ state, since the final state particles have spin-0, they must be produced in a $P$-wave, and the production cross section increases as $\beta^3$ near threshold (see Fig. [I], which is in contrast to fermion pair production, where the cross section increases as $\beta$. The measurement of this behaviour shows that sneutrinos are scalars, and may allow precise mass measurements at the 0.1 GeV level assuming at least a luminosity of 100 fb$^{-1}$. The sneutrino masses can be determined from a threshold scan.

The unpolarized cross sections for the signal and relevant background processes are given in Table III. Here, the cross section for the signal shows the resulting values after sneutrino and chargino decays ending the chain to neutralinos (LSP). While the background have the cross sections as given by the process, for further decays these values can be multiplied with the corresponding branching ratios to compare with the signal.

The total cross sections for pair production of tau sneutrinos at the energy range of $\sqrt{s} = 500 - 3000$ GeV are shown in Fig. [I] for the points $\alpha$, $\beta$, $\gamma$ and $\delta$. For point $\alpha$, the maximum of the cross section is about 7 fb for unpolarized beams at $\sqrt{s} \approx 900$ GeV. We obtain larger cross section 16 fb at maximum for the $e^+_Re^-_L$ polarization. At the other points $\beta$ and $\gamma$, the cross section show maximum around $\sqrt{s} \approx 1000$ GeV, but they are different in magnitude. Since the $\delta$ point has larger gaugino and scalar mass values, the cross section has maximum at $\sqrt{s} \approx 2300$ GeV. The machine operating at $\sqrt{s} = 3000$ GeV will produce tau sneutrino with a cross section 0.9 fb for unpolarized beams.

The distributions of the transverse momentum and rapidity of the $\tau$ lepton, and the
Figure 3: The cross section depending on the center of mass energy range for point $\alpha$. The lower curve denotes unpolarized case, while upper shows $RL$ and $LR$ polarization for positron and electron beams.

Figure 4: The same as Fig. 3 but for point $\beta$.

Invariant mass of two different sign $\tau$ leptons for the points $\alpha$, $\beta$, $\gamma$ and $\delta$ are shown in Figs. 7-10. It is shown that $p_T$ distributions of the $\tau$-lepton have an upper edge around 650 GeV, 500 GeV, 1100 GeV and 450 GeV for the points $\alpha$, $\beta$, $\gamma$ and $\delta$, respectively. The invariant mass distributions of two $\tau$-leptons have peaks between 300 GeV and 700 GeV, depending on the points. For a contributing background process $e^+e^- \rightarrow \tau^+\tau^-W^-W^+$, we find the $p_T$ distribution of tau lepton decreasing smoothly in the range $p_T > 50$ GeV. The rapidity of
tau lepton coming from this background shows a wide spectrum ($|\eta| < 3$) different from the signal expected, and the tau leptons originating from the $Z$ decays show an invariant mass spectrum around $m_Z$.

Concerning the benchmark points, the tau sneutrinos are heavier than the lightest chargino, the sneutrino can decay into a charged lepton and a chargino $\tilde{\nu}_\tau^* \rightarrow \tau^{-(+)} \tilde{\chi}_1^{+(--)}$, and chargino decays through lightest neutralino $\chi_1^{+(--)} \rightarrow \tilde{\chi}_1^0 W^{-(+)}$ followed by the $W^{-(+) -}$ boson decay to two jets or $l^{-(+)} + \not{E}_T$. The branching ratio can be identified for these decays. Here, we consider the hadronic decays of $W$-boson, then at the final state there
will be two opposite sign tau leptons, four jets and missing transverse energy (MET). The tau polarization can be measured from the energy distribution of the decay products of $\tau$. The degree of $\tau$ polarization can be used to determine the asymmetries and parameters in supersymmetric processes \[17–21\]. Analyzing tau polarization will also give some informa-
tion about the sneutrino interactions through the process $\tilde{\nu}_\tau \rightarrow \tau^- \tilde{\chi}_1^\pm$. Taking $\tau^-(\tau^+)$ has opposite polarization), we define the polarization in terms of the difference of the number $(N)$ of left- and right-handed $\tau^-$ produced for the signal:

$$P_{\tau} = \frac{N_L - N_R}{N_L + N_R} = \frac{|C_L|^2 - |C_R|^2 m_\tau^2 / 2 m_W^2 \cos^2 \beta}{|C_L|^2 + |C_R|^2 m_\tau^2 / 2 m_W^2 \cos^2 \beta}$$

(7)

If we calculate the number of tau events as $N = \sigma \cdot BR \cdot \epsilon \cdot L$, we find the degree of polarization for the signal. Here, we use the interaction term from Eq. 3 and find the tau polarization in terms of the chiral couplings $C_{L,R}$. Since the right-handed coupling is proportional to the mass ratio of $m_\tau/m_W$, which is negligible, therefore the left-handed polarization will dominate for the signal. We calculate $P_{\tau} = 0.96$ for the point $\gamma$, and $P_{\tau} = 0.99$ for other points. Due to the different aspects of the signal and background, an appropriate $p_T$ cut, pseudorapidity cut and the invariant mass $(m_{\tau\tau})$ cut will be useful to reduce the backgrounds.

In Fig. 11, we plot the contour lines in the plane of the branching ratio - tau sneutrino mass for the luminosities $L_{\text{int}} = 1000 \text{ fb}^{-1}$ (left) and $L_{\text{int}} = 200 \text{ fb}^{-1}$ (right) at the center of mass energy $\sqrt{s} = 3000$ GeV. The solid line corresponds to the unpolarised positron and electron beams, dashed lines show $e_R^+ e_L^-$ case and dotted line denotes $e_R^+ e_R^-$. The beam polarisation is helpful in the study of SUSY processes to improve the $S/\sqrt{B}$ (analyser). We consider here three options: unpolarised, LR and RL polarised positron/electron beams. For an integrated luminosity of $1 \text{ ab}^{-1}$, it is possible to cover four points even at the unpolarised case. In Table IV we present the integrated luminosity required to get $3\sigma$ signal significance at $\sqrt{s}=3$ TeV.
Figure 11: Contour plot for branching ratio depending on the tau sneutrino mass for the luminosities $L_{int} = 1000$ fb$^{-1}$ (left) and $L_{int} = 200$ fb$^{-1}$ (right) at the center of mass energy $\sqrt{s} = 3000$ GeV. The solid line corresponds to the unpolarized beams, dashed lines show $e_R^+e_L^-$ case and dotted lines denotes $e_L^+e_R^-$.  

Table IV: The luminosity (in fb$^{-1}$) required to obtain a $3\sigma$ signal significance at 3 TeV.

| Beams\points | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ |
|--------------|---------|---------|---------|---------|
| $e^+e^-$     | 191     | 443     | 86      | 1118    |
| $e^+_L e^-_R$ | 65      | 152     | 29      | 385     |
| $e^+_R e^-_L$ | 36      | 84      | 16      | 212     |

In conclusion, tau sneutrino pair production could give a valuable information about the sneutrino interactions. The LHC has the potential to measure the SUSY mass spectrum and a clue on the underlying scenarios with the exploitation of full high luminosity. A more precise determination of specific processes can be performed within the underlying model at future lepton colliders operating with polarized beams.

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