Pair production of the fourth family charged sleptons at $e^+e^-$ colliders

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Abstract – We study the pair production of $\bar{\nu}_4$, which is the supersymmetric partner of the fourth family charged lepton, at the $e^+e^-$ colliders. It is shown that the investigation of this process at ILC/CLIC will give the opportunity to differentiate the MSSM with three and four families. The ILC with $\sqrt{s} = 1$ TeV and $L_{int} = 1$ ab$^{-1}$ has the potential for the observation of the fourth family slepton with mass up to 420 GeV, if the fourth SM family neutrino has a Dirac nature. The CLIC with $\sqrt{s} = 3$ TeV and $L_{int} = 1$ ab$^{-1}$ will enlarge the observation region up to $m_{\tilde{l}_4} = 580$ GeV.

Recently, the fourth Standard Model (SM) family has attracted an increasing interest in the high-energy physics (HEP) community [1–8]. In some sense, we deal with SM4 “renaissance” (we denote the Standard Model with three and four families as SM3 and SM4, respectively). Actually, the existence of the fourth SM family follows from the SM basics [9–12]. Moreover, a former objection against SM4 based on electroweak precision data has disappeared [13–19]: new studies show that SM3 and SM4 have the same status [20]. The current limits on the masses of the fourth SM family leptons are [21]: $m_{\tilde{\nu}_4} > 100$ GeV, $m_{\nu_4} > 90$ (80) GeV for Dirac (Majorana) neutrinos. Recently, the Collider Detector at Fermilab (CDF) has constrained the masses of the fourth SM family quarks to $m_{\tilde{u}_4} > 335$ GeV at 95% CL [22], $m_{\tilde{d}_4} > 338$ GeV at 95% CL [23]. On the other hand, the partial-wave unitarity leads to an upper bound of 700 GeV for the fourth SM family fermion masses [24].

The SM, while describing almost all experimental HEP data well, has not yet answered a number of fundamental questions. For this reason, different approaches beyond the SM have been developed. Among them, the supersymmetry (SUSY) plays an important role. Below, we denote the minimal supersymmetric model as MSSM4 (MSSM3) in the case of four (three) SM families. Within the MSSM3 the low-mass eigenstate stop $\tilde{t}_1$ may be lighter than the top quark due to the large Yukawa coupling [25]. By analogy, within the MSSM4 the fourth family sfermions could be lighter than corresponding fermions. Because of the larger masses of the fourth family fermions (expected to be around 500 GeV) the fourth family sfermions indeed may be the lightest ones among the squarks and sleptons. Since the light superpartners of the third and fourth family squarks have almost the same decay chains it will be difficult to differentiate MSSM3 and MSSM4 at hadron colliders.

In this work, we consider the pair production of the supersymmetric fourth family charged slepton, which is expected to be the lightest one among the charged sleptons, at future linear colliders, namely ILC [26] with $\sqrt{s} = 1$ TeV and CLIC [27] with $\sqrt{s} = 3$ TeV. We present the results for pair production of the fourth family charged slepton $\tilde{l}_4$ (also called tau-prime) decaying to a fourth family neutrino $\nu_4$ and a chargino $\tilde{\chi}^\pm_1$ with the subsequent $\tilde{\chi}^0_1$ decay into a neutralino $\tilde{\chi}^0_1$ and a $W^-$-boson.

The inclusion of the fourth SM family into MSSM is straightforward [28]. In the ($\tilde{l}_{4L}, \tilde{l}_{4R}$) basis, the mass matrix of the fourth family charged sleptons is given by

$$ M^2_{\tilde{l}_4} = \left( \begin{array}{cc} m^2_{\tilde{l}_4 L} & a_{l_4} m_{\tilde{l}_4} \\ a_{l_4}^* m_{\tilde{l}_4} & m^2_{\tilde{l}_4 R} \end{array} \right), \quad (1) $$

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where \( m^2 = M^2 + m^2 - m^2 \cos 2\beta (\frac{1}{2} - \sin^2 \theta_W) \), \( m^2 = M^2 + m^2 - m^2 \cos 2\beta \sin^2 \theta_W \) and \( a_i = A_i - \mu \tan \beta \), \( A_4 \) is the trilinear Higgs fourth family charged lepton parameter (the notation of [29] is used, extension to MSSM4 is straightforward).

The mass eigenstates \( \tilde{l}_u \) and \( \tilde{l}_h \) are related to \( \tilde{l}_{4L} \) and \( \tilde{l}_{4R} \) by

\[
\begin{pmatrix}
\tilde{l}_u \\
\tilde{l}_h
\end{pmatrix}
= \begin{pmatrix}
\cos \theta_{\tilde{t}_4} & \sin \theta_{\tilde{t}_4} \\
-\sin \theta_{\tilde{t}_4} & \cos \theta_{\tilde{t}_4}
\end{pmatrix}
\begin{pmatrix}
\tilde{l}_{4L} \\
\tilde{l}_{4R}
\end{pmatrix}
\]  

(2)

with the eigenvalues

\[
m_{\tilde{l}_{4i(u,h)}}^2 = \frac{1}{2}(m_{\tilde{l}_{4L}}^2 + m_{\tilde{l}_{4R}}^2) \pm \frac{1}{2}\sqrt{(m_{\tilde{l}_{4L}}^2 - m_{\tilde{l}_{4R}}^2)^2 + 4a^2_{\tilde{t}_4}m_{\tilde{t}_4}^2}
\]  

(3)

and the mixing angle \( \theta_{\tilde{t}_4} \) given by

\[
\cos \theta_{\tilde{t}_4} = \frac{-a_{\tilde{t}_4}m_{\tilde{t}_4}}{\sqrt{(m_{\tilde{l}_{4L}}^2 - m_{\tilde{l}_{4R}}^2)^2 + a^2_{\tilde{t}_4}m_{\tilde{t}_4}^2}}
\]  

(4)

As seen from eq. (3), \( \tilde{l}_u \) is expected to be the lightest charged slepton because of the large value of \( m_{\tilde{t}_4} \).

The cross-section for the process \( e^+e^- \rightarrow \tilde{l}_4^{+}\tilde{l}_4^- \) is

\[
\sigma(e^+e^- \rightarrow \tilde{l}_4^{+}\tilde{l}_4^-) = \frac{\pi a^2}{3s} (s^2 - 4m_{\tilde{l}_{4u}}^2)^{3/2} 
\times \left( 1 + \frac{a_{\tilde{t}_4}v_e^2 s}{8\sin^2 \theta_W \cos^2 \theta_W \Re[D(Z)]} + \frac{a_{\tilde{t}_4}^2 (v_e^2 + a_E^2)s^2}{256\sin^2 \theta_W \cos^2 \theta_W |D(Z)|^2} \right),
\]  

(5)

where \( D(Z) = 1/[s - m_{\tilde{t}_4}^2 + i\Gamma_{\tilde{t}_4}m_{\tilde{t}_4}] \); \( v_e = -1 + 4 \sin^2 \theta_W \), \( a_{\tilde{t}_4} = -1 \) and \( a_{\tilde{t}_4} = 2(-\cos^2 \theta_{\tilde{t}_4} + 2\sin^2 \theta_{\tilde{t}_4}) \). It is clear that sleptons decouple from the Z-boson if \( \cos^2 \theta_{\tilde{t}_4} = 2 \sin^2 \theta_{\tilde{t}_4} \).

The cross-section has a minimum at

\[
\cos^2 \theta_{\tilde{t}_4} = 2\sin^2 \theta_W \left[ 1 + \frac{s - m_{\tilde{t}_4}^2}{s} \frac{4v_e}{v_e^2 + a_E^2} \cos^2 \theta_W \right].
\]  

(6)

There are two main decay modes of \( \tilde{l}_4^+ \), namely \( \tilde{l}_4^+ \rightarrow \nu_4\tilde{\chi}_1^- \) and \( \tilde{l}_4^+ \rightarrow \tilde{\nu}_4 W^- \). Here, we are interested in the first decay channel since it allows to differentiate the signal of \( \tilde{l}_4^+ \) from the lighter stau \( \tilde{\tau}_1 \). The chargino decays dominantly through \( \tilde{\chi}_1^+ \rightarrow \tilde{\nu}_4 W^- \); where we assume the \( \tilde{\chi}_1^0 \) to be the lightest supersymmetric particle (LSP). The \( \nu_4 \) decays are determined by the nature of the fourth family neutrino. In the Dirac case we deal with \( \nu_4 \rightarrow l^- W^+ \), while in the Majorana case we also have \( \nu_4 \rightarrow l^+ W^- \) in addition to \( \nu_4 \rightarrow l^- W^- \), with the branching ratios \( BR(\nu_4 \rightarrow l^+ W^-) = BR(\nu_4 \rightarrow l^- W^+) \).

In fig. 1, we present the cross-section depending on the mixing parameter for different masses at \( \sqrt{s} = 3 \) TeV. It is seen that the cross-section has a minimum at \( \cos \theta_{\tilde{t}_4} = 0.6 \) and maximum at \( \cos \theta_{\tilde{t}_4} = 1 \). Hereafter, we use the conservative value of \( \cos \theta_{\tilde{t}_4} = 0.6 \) for numerical calculations. The cross-sections depending on the mass \( m_{\tilde{t}_4} \) for two different values of center-of-mass energies are presented in fig. 2. Taking the fourth family charged slepton mass \( m_{\tilde{t}_4} = 300 \) GeV, we obtain the cross-section \( \sigma = 12.6 \) fb at ILCT with \( \sqrt{s} = 1 \) TeV. At CLIC with 3 TeV center-of-mass energy we obtain the cross-section \( \sigma = 2.3 \) fb for \( m_{\tilde{t}_4} = 500 \) GeV. As seen from fig. 2, ILCT is advantageous up to the mass \( m_{\tilde{t}_4} \approx 425 \) GeV.

If the fourth family neutrino has a Dirac nature we propose decay chains given in fig. 3 for the signal. This signal will be seen in detector as \( 3\mu^- + \mu^- + 4j + E_T \). The decays of the \( \nu_4 \) are governed by the leptonic \( 4 \times 4 \) mixing matrix. For numerical calculations we use the parametrization given in [30], which is compatible with the experimental data on the masses and mixings in leptonic sector. In this case, \( BR(\nu_4 \rightarrow \mu^- W^+) \approx 0.68 \) and \( BR(\nu_4 \rightarrow \tau^- W^+) \approx 0.32 \), which is the reason for choosing the muon channel for \( \nu_4 \) decays. Keeping in mind that \( BR(W^- \rightarrow l^- \nu_l) = 0.11 \) and \( BR(W^- \rightarrow hadrons) = 0.68 \), and assuming that \( BR(l_{4L} \rightarrow \nu_4 \tilde{\chi}_1^-) = 0.5 \), we obtain a resulting branching factor for the considered signal as \( 6.5 \times 10^{-4} \). This corresponds to 8 signal events for
$m_{\tilde{l}_4} = 300 \text{ GeV}$ at ILC with $\sqrt{s} = 1 \text{ TeV}$ and $L_{\text{int}} = 1 \text{ ab}^{-1}$. It should be noted that this signal is almost background- less. Furthermore, the number of signal events is doubled if we consider the charge-conjugated process. An additional factor 4 comes from counting the $W$-boson decays into the electron channel.

The CLIC with center-of-mass energy $\sqrt{s} = 3 \text{ TeV}$ and integrated luminosity $L_{\text{int}} = 1 \text{ ab}^{-1}$ will give the opportunity to investigate fourth family charged sleptons with masses up to 1 TeV. In the Dirac $\nu_4$ case, for the pair production of $\tilde{l}_4$ with 500 GeV mass we obtain 1.5 signal events in the channel $3\mu^- + \mu^+ + 4j + E_T$ and 3 events when the charge-conjugated process is added. The number of events becomes 12 if the $W \rightarrow e\nu$ channels are also considered.

An even more spectacular signature is expected if the $\nu_4$ has a Majorana nature. In this case, $\nu_4$ will decay into both $\mu^-W^+$ and $\mu^+W^-$ with the same branching ratio equal to 0.34. If $\nu_4$ in fig. 3 (right diagram) decays into the $\mu^-W^+$ channel (where $W^+ \rightarrow q\bar{q}'$), the signal will be seen in the detector as $3\mu^- + 6j + E_T$. This signal is almost free of background and has a resulting branching ratio equal to $1.0 \times 10^{-3}$. This corresponds to 12.5 signal events for $m_{\tilde{l}_4} = 300 \text{ GeV}$ at ILC with $\sqrt{s} = 1 \text{ TeV}$ and $L_{\text{int}} = 1 \text{ ab}^{-1}$. The number of events becomes 25 if the charge-conjugated process is added. Concerning the CLIC with $\sqrt{s} = 3 \text{ TeV}$ and $L_{\text{int}} = 1 \text{ ab}^{-1}$ integrated luminosity we obtain 5 signal events for $m_{\tilde{l}_4} = 500 \text{ GeV}$ when the charge-conjugated process is added, and 10 signal events if the $W \rightarrow e\nu$ channel is counted as well.

In table 1, we present the signal cross-sections for different masses of the fourth family slepton. In this table, we consider leptonically final states containing muons. When the electron final states are added one should multiply the corresponding numbers with a factor of 4 (2) for the Dirac (Majorana) neutrino case.

In order to estimate the discovery potential, we consider the Dirac neutrino case. The main background comes from the process $e^+e^- \rightarrow W^+W^-W^+W^-Z$, where $Z$ decays into the $\mu^+\mu^-$ channel, two same-sign $W$-bosons decay into muons, whereas the remaining $W$-bosons decay into hadrons. Taking into account corresponding branching fractions, we obtain the background cross-section for the $3\mu^\pm + \mu^\mp + 4j + E_T$ final state as 0.16 ab at the ILC and 1.74 ab at the CLIC.

For the statistical significance we use the following formula [31]:

$$SS = \sqrt{2(N_S + N_B)\ln(1 + N_S/N_B) - N_S},$$

where $N_S$ and $N_B$ are the number of signal and background events, respectively. For the ILC with 1 ab$^{-1}$, we obtain the statistical significance $SS = 7.3$ if $m_{\tilde{l}_4} = 300 \text{ GeV}$. This collider has the potential to discover (SS > 5) the fourth family slepton up to the mass of 370 GeV; the observation limit ($SS = 3$) is 420 GeV and the exclusion limit ($SS = 2$) is 440 GeV.

At CLIC with 1 ab$^{-1}$, we obtain $SS = 1.9$ if $m_{\tilde{l}_4} = 500 \text{ GeV}$. Inclusion of the electron channels for leptonic $W$ decays improves the statistical significance. In this case, both signal and background cross-sections are multiplied by a factor of 4 and we obtain $SS = 3.8$ for $m_{\tilde{l}_4} = 500 \text{ GeV}$.

The CLIC has the potential to observe the fourth family slepton up to the mass of 580 GeV and the exclusion limit is 990 GeV. It should be noted that the center-of-mass energy of the collider could be optimized for an actual mass value of the fourth family slepton. For example, in the case of $m_{\tilde{l}_4} = 500 \text{ GeV}$, decreasing the center-of-mass

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Mass (GeV) & $\sqrt{s} = 1 \text{ TeV}$ & $\sqrt{s} = 3 \text{ TeV}$ \\ \hline
200 & 24.6 (38.0) & 3.4 (5.4) \\ 300 & 16.4 (25.4) & 3.4 (5.2) \\ 400 & 7.0 (10.6) & 3.2 (5.0) \\ 450 & 2.6 (4.0) & 3.0 (4.8) \\ 500 & 0 (0) & 3.0 (4.6) \\ \hline
\end{tabular}
\caption{The signal cross-sections in ab for $3\mu^\pm + \mu^\mp + 4j + E_T$ (3$\mu^\pm$ + 6jets + $E_T$) final states.}
\end{table}
energy from 3 TeV to 1.5 TeV results in an increase of the signal cross-section by a factor of 2 and a decrease of the background by a factor of 3. The work on this subject is under progress.

In conclusion, it is quite possible that the first manifestation of the MSSM4 will come from the lepton colliders. This possibility should be considered in the framework of the ILC and CLIC physics search programs.

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