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Pair Production of Fourth Family Charged Sleptons at e^+e^- Colliders

V. Arı* and O. Çakır†

Ankara University, Faculty of Sciences,

Department of Physics, 06100, Tandogan, 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

We study the pair production of $\tilde{l}_4$, 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 opportunity to differentiate the MSSM with three and four families.

*Electronic address: vari@science.ankara.edu.tr

†Electronic address: ocakir@science.ankara.edu.tr

‡Electronic address: tcakir@mail.cern.ch

§Electronic address: ssultansoy@etu.edu.tr

Recently, the fourth Standard Model (SM4) family attracts an increasing interest of high energy physics (HEP) community [1, 2] (see also [3] and ref's therein). In some sense, we deal with SM4 "renaissance". Actually, the existence of the fourth SM family follows from the SM basics [4–6] (see also review [7] and ref's therein). Moreover, former objection against SM4 based on electroweak precision data is disappeared [8]: new studies show that SM3 and SM4 has the same status (see [9] and ref's therein). The current limits on the mass of the fourth SM family leptons are [10]: $m_{l_4} > 100$ GeV, $m_{\nu_4} > 90$ (80) GeV for Dirac (Majorana) neutrinos. Recently, the Collider Detector at Fermilab (CDF) has already constrained the masses of fourth family quarks: $m_{u_4} > 335$ GeV at 95% CL. [11], $m_{d_4} > 338$ GeV at 95% CL. [12]. On the other hand, the partial wave unitarity leads to an upper bound 700 GeV for fourth SM family fermion masses [13].

The SM, while well describing almost all experimental HEP data, has not answered a number of fundamental questions. For this reason, different approaches beyond the SM are developed. Among them, the supersymmetry (SUSY) plays an important role. Below, we denote this minimal supersymmetric model as MSSM4 (MSSM3) in the case of four (three) SM families. Within the MSSM3, for example the low mass eigenstate stop $\tilde{t}_1$ may be lighter than the top quark due to the large Yukawa coupling [14]. By analogy, within the MSSM4 the fourth family sfermions could be lighter than coresponding fermions. Because of the larger masses of the fourth family fermions (expected around 500 GeV) the fourth family sfermions quite may be the lightest ones among the squarks and sleptons. 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.

In this work, we consider pair production of supersymmetric fourth family charged sleptons, which is expected to be the lightest one among the charged sleptons, at future linear colliders, namely ILC with $\sqrt{s} = 1$ TeV [ILC] and CLIC with $\sqrt{s} = 3$ TeV [CLIC]. We present the results for pair production of the supersymmetric partner of the fourth family charged slepton $\tilde{l}_4$ (also called stau-prime) decaying to fourth family neutrino ν_4 and a chargino $\tilde{\chi}_1^-$ with a subsequent $\tilde{\chi}_1^-$ decay into a neutralino $\tilde{\chi}_1^0$ and W^- boson.

The inclusion of the fourth SM family into MSSM is straightforward [15]. Concerning the mass matrix of the fourth family sfermions, let us consider the charged sleptons case. In

the $(\tilde{l}_{4L}, \tilde{l}_{4R})$ basis, the mass matrix is given by

$$M^2_{\tilde{l}_4} = \begin{pmatrix} m^2_{\tilde{l}_{4L}} & a_{l_4} m_{l_4} \\ a_{l_4} m_{l_4} & m^2_{\tilde{l}_{4R}} \end{pmatrix} \tag{1}$$

where $m^2_{\tilde{l}_{4L}} = M^2_{\tilde{L}_4} + m^2_{l_4} - m^2_Z \cos 2\beta(\frac{1}{2} - \sin^2\theta_W)$, $m^2_{\tilde{l}_{4R}} = M^2_{\tilde{E}_4} + m^2_{l_4} - m^2_Z \cos 2\beta \sin^2\theta_W$ and $a_{l_4} = A_{l_4} - \mu \tan\beta$, A_{l_4} is trilinear Higgs-fourth family charged lepton parameter (the notation of [16] is used, extension to MSSM4 is straightforward).

The mass eigenstates $\tilde{l}_{4l}$ and $\tilde{l}_{4h}$ are related to $\tilde{l}_{4L}$ and $\tilde{l}_{4R}$ by

$$\begin{pmatrix} \tilde{l}_{4l} \\ \tilde{l}_{4h} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{l}_4} & \sin\theta_{\tilde{l}_4} \\ -\sin\theta_{\tilde{l}_4} & \cos\theta_{\tilde{l}_4} \end{pmatrix} \begin{pmatrix} \tilde{l}_{4L} \\ \tilde{l}_{4R} \end{pmatrix} \tag{2}$$

with the eigenvalues

$$m^2_{\tilde{l}_{4(l,h)}} = \frac{1}{2}(m^2_{\tilde{l}_{4L}} + m^2_{\tilde{l}_{4R}}) \mp \frac{1}{2}\sqrt{(m^2_{\tilde{l}_{4L}} - m^2_{\tilde{l}_{4R}})^2 + 4a^2_{l_4} m^2_{l_4}} \tag{3}$$

and the mixing angle $\theta_{\tilde{l}_4}$ is given by

$$\cos\theta_{\tilde{l}_4} = \frac{-a_{l_4} m_{l_4}}{\sqrt{(m^2_{\tilde{l}_{4L}} - m^2_{\tilde{l}_{4l}})^2 + a^2_{l_4} m^2_{l_4}}} \tag{4}$$

As seen from Eq. (3), $\tilde{l}_{4l}$ is expected to be the lightest charged slepton because of large value of m_{l_4}.

The cross section for the process $e^+e^- \to \tilde{l}^+_{4l}\tilde{l}^-_{4l}$ is:

$$\begin{aligned} \sigma(e^+e^- \to \tilde{l}^+_{4l}\tilde{l}^-_{4l}) &= \frac{\pi\alpha^2}{3s^4}(s^2 - 4sm^2_{\tilde{l}_{4l}})^{3/2} \\ &\times \left(1 + \frac{a_{ll} v_e s}{8\sin^2\theta_W \cos^2\theta_W} Re[D(Z)] + \frac{a^2_{ll}(v^2_e + a^2_e)s^2}{256\sin^4\theta_W \cos^4\theta_W}|D(Z)|^2\right) \end{aligned} \tag{5}$$

where $D(Z) = 1/[(s - m^2_Z + i\Gamma_Z m_Z]$; $v_e = -1 + 4\sin^2\theta_W$, $a_e = -1$ and $a_{ll} = 2(-\cos^2\theta_{\tilde{l}_4} + 2\sin^2\theta_W)$.

There are two main decay modes of $\tilde{l}_{4l}$, namely $\tilde{l}^-_{4l} \to \nu_4 \tilde{\chi}^-_1$ and $\tilde{l}^-_{4l} \to \tilde{\nu}_4 W^-$. Here, we are interested in the first decay channel since it allows to differentiate the signal of $\tilde{l}_{4l}$ from lighter stau $\tilde{\tau}_1$. The chargino decays dominantly through $\tilde{\chi}^-_1 \to \tilde{\chi}^0_1 W^-$ where we assume the $\tilde{\chi}^0_1$ to be the LSP. The ν_4 decays are determined by the nature of the fourth family neutrino. In the

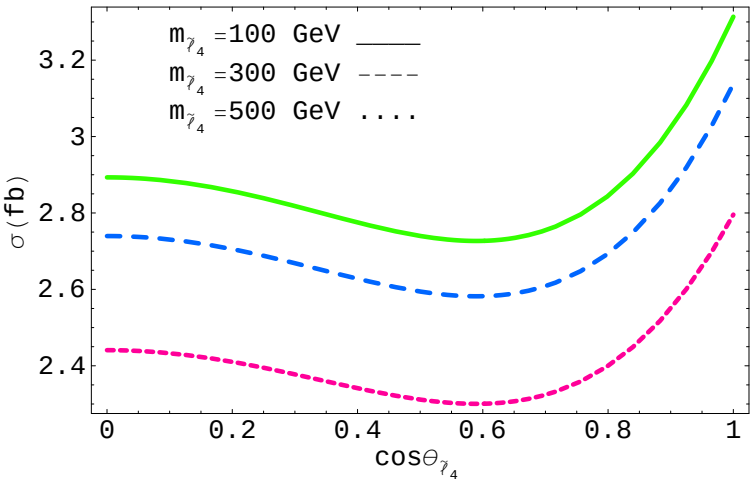

Figure 1: The cross section depending on the mixing parameter for different masses $m_{\tilde{l}_4}$ at $\sqrt{s} = 3$ TeV.

Dirac case we deal with $\nu_4 \to l^- W^+$, while in the Majorana case we also have $\nu_4 \to l^+ W^-$ in addition to $\nu_4 \to l^- W^+$, with the branchings $BR(\nu_4 \to l^+ W^-) = BR(\nu_4 \to l^- W^+)$.

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 $\cos\theta_{\tilde{l}_4} = 0.6$ and maximum at $\cos\theta_{\tilde{l}_4} = 1$. Hereafter, we use the conservative value of $\cos\theta_{\tilde{l}_4} = 0.6$ for numerical calculations. The cross sections depending on the mass $m_{\tilde{l}_4}$ for two different values of center of mass energies are presented in Fig. 2. Taking the fourth family charged slepton mass $m_{\tilde{l}_4} = 300$ GeV at ILC with $\sqrt{s} = 1$ TeV, we obtain the cross section $\sigma = 12.6$ fb. At CLIC with 3 TeV center of mass energy we obtain the cross section $\sigma = 2.3$ fb for $m_{\tilde{l}_4} = 500$ GeV. As seen from Fig. 2, ILC is advantageous up to the mass $m_{\tilde{l}_4} \simeq 450$ GeV.

We propose the following decay chains for the signal if the fourth family neutrino has the Dirac nature:

$$\tilde{l}_4^- \to \nu_4(\to \mu^- W^+(\to hadrons)) + \tilde{\chi}_1^-(\to \tilde{\chi}_1^0 W^-(\to \mu^- \nu)) \tag{6}$$

$$\tilde{l}_4^+ \to \bar{\nu}_4(\to \mu^+ W^-(\to \mu^- \nu)) + \tilde{\chi}_1^+(\to \tilde{\chi}_1^0 W^+(\to hadrons)) \tag{7}$$

This signal will be seen in detector as $3\mu^- + 1\mu^+ + 4j + E_T^{miss}$. The decays of the ν_4 are governed by the leptonic 4×4 mixing matrix. For numerical calculations we use the parametrization given in [17], which is compatible with the experimental data on the masses

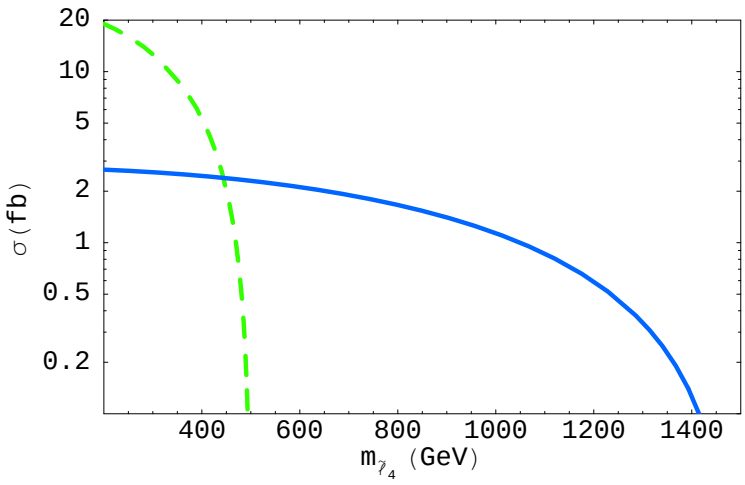

Figure 2: The cross sections depending on the mass of the fourth family charged lepton at 1 TeV (dashed) and 3 TeV (solid) center of mass energies.

and mixings in leptonic sector. In this case, $BR(\nu_4 \to \mu^- W^+) \simeq 0.68$ and $BR(\nu_4 \to \tau^- W^+) \simeq 0.32$, which is the reason for choosing the muon channel for ν_4 decays. Keeping in mind that $BR(W^- \to l^- \nu) = 0.11$ and $BR(W^- \to hadrons) = 0.68$ and assuming that $BR(\tilde{l}_{4l} \to \nu_4 \tilde{\chi}_1^-) = 0.5$, we obtain resulting branching for the considered signal as 6.5×10^{-4}. This corresponds to 8 signal events for $m_{\tilde{l}_4} = 300$ GeV at ILC with $\sqrt{s} = 1$ TeV and $L_{int} = 1$ ab^{-1}. It should be noted that this signal is almost backgroundless. Furthermore, the number of signal events is doubled if we consider the charge conjugated process. Additional factor 4 comes from counting the W- decays into electron channel.

The CLIC with the center of mass energy $\sqrt{s}$ =3 TeV and integrated luminosity $L_{int} = 1$ ab^{-1} will give opportunity to investigate fourth family charged slepton with masses up to 1 TeV. In the Dirac ν_4 case, for the pair production of $\tilde{l}_{4l}$ with 500 GeV mass, we obtain 2 signal events in the channel $3\mu^- + 1\mu^+ + 4j + E_T^{miss}$ and 4 events when charge conjugated process is added, and 16 events if the $W \to e\nu$ channels are also considered.

Even more spectacular signature is expected if the ν_4 has the Majorana nature. In this case, ν_4 will decay into both $\mu^- W^+$ and $\mu^+ W^-$ with the same branching ratio equal to 0.34. If $\bar{\nu}_4$ in Eq. (7) decays into $\mu^- W^+ (\to hadrons)$ channel, the signal will be seen in dedector as $3\mu^- + 6j + E_T^{miss}$. This signal is free of background and has resulting branching equal to 1.0×10^{-3}. This corresponds to 12 signal events for $m_{\tilde{l}_4} = 300$ GeV at ILC with $\sqrt{s} = 1$ TeV and $L_{int} = 1$ ab^{-1}. The number of events becomes 24 if charge conjugated process is addded.

Concerning the CLIC with $\sqrt{s} = 3$ TeV and $L_{int} = 1$ ab^{-1} integrated luminosity we obtain 5 signal events for $m_{\tilde{l}_4} = 500$ GeV when charge conjugated process is added, and 10 signal events if the $W^+ \to e^+\nu$ channel is counted as well.

In conclusion, it is quite possible that the first manifestation of MSSM4 will come from the lepton colliders. This case should be seriously analysed within the physics program of future lepton colliders.

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