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SEARCH FOR FLAVOR LEPTON NUMBER VIOLATION IN SLEPTON DECAYS AT LHC

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We show that in supersymmetric models with explicit flavor lepton number violation due to soft supersymmetry breaking mass terms there could be detectable flavor lepton number violation in slepton decays. We estimate LHC discovery potential of the lepton flavor number violation in slepton decays.

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Supersymmetric electroweak models offer the simplest solution of the gauge hierarchy problem [1–4]. In real life supersymmetry has to be broken and the masses of superparticles have to be lighter than $O(1)$ Tev [4]. For the supersymmetric extension of the Weinberg–Salam model soft supersymmetry breaking terms usually consist of the gaugino mass terms, squark and slepton mass terms with the same mass at Planck scale and trilinear soft scalar terms proportional to the superpotential [4]. For such "standard" supersymmetry breaking terms the lepton flavor number is conserved in supersymmetric extension of Weinberg–Salam model. However, in general, squark and slepton soft supersymmetry breaking mass terms are not diagonal due to many reasons [5–15] (an account of stinglike or GUT interactions, nontrivial hidden sector, ..) and flavor lepton number is explicitly broken. As a consequence such models predict flavor lepton number violation in μ- and τ-decays [5–13]. In our previous papers [16–18] we proposed to look for flavor lepton number violation at LEP2 and NLC in slepton decays.

In this paper we investigate the "discovery potential" of LHC of flavor lepton number violation in slepton decays. We find that at LHC it would be possible to discover lepton number violation in slepton decays for slepton masses up to 300 GeV provided that the mixing between sleptons is closed to the maximal one.

In supersymmetric extensions of the Weinberg–Salam model supersymmetry is softly broken at some high energy scale M_{GUT} by generic soft terms:

$$\begin{aligned} -L_{soft} = m_{3/2}(A^u_{ij}\tilde{u}^j_R\tilde{q}^i_L H_u + A^d_{ij}\tilde{d}^j_R\tilde{q}^i_L H_d + \\ + A^l_{ij}\tilde{e}_R\tilde{l}_L H_d + \text{h.c.}) + (m^2_q)_{ij}\tilde{q}^i_L(\tilde{q}^i_L)^+ + (m^2_u)_{ij}\tilde{u}^i_R \times \\ \times(\tilde{u}^j_R)^+ + (m^2_d)_{ij}\tilde{d}^i_R(\tilde{d}^j_R)^+ + (m^2_l)_{ij}\tilde{l}^i_L(\tilde{l}^j_L)^+ + (m^2_e)_{ij}\tilde{e}^i_R \times \\ \times(\tilde{e}^j_R)^+ + m^2_1 H_u H^+_u + m^2_2 H_d H^+_d + \\ + (Bm^2_{3/2}H_u H_d + \frac{1}{2}m_a(\lambda\lambda)_a + \text{h.c.}) \ , \end{aligned} \qquad (1)$$

where i, j, a are summed over 1, 2, 3 and $\tilde{q}_L$, $\tilde{u}_R$, $\tilde{d}_R$ denote the left- (right-)handed squarks, $\tilde{l}_L$, $\tilde{e}_R$ the left- (right-)handed sleptons and H_u, H_d the two Higgs doublets; m_a are the three gaugino masses of $SU(3)$, $SU(2)$ and $U(1)$ respectively. In most analysis the mass terms are supposed to be diagonal at

M_{GUT} scale and gaugino and trilinear mass terms are also assumed universal at M_{GUT} scale. The renormalization group equations for soft parameters [19] allow to connect high energy scale with observable electroweak scale. The standard consequence of such analysis is that righthanded sleptons $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_R$ are the lightest sparticles among squarks and sleptons. In the approximation when we neglect lepton Yukawa coupling constants they are degenerate in masses.

In our analysis we assume that the lightest stable particle is gaugino corresponding to $U(1)$ gauge group that is now more or less standard assumption [20]. As it has been discussed in many papers [5-15] in general we can expect nonzero nondiagonal soft supersymmetry breaking terms in Lagrangian (1) that leads to additional contributions for flavor changing neutral currents and to flavor lepton number violation. From the nonobservation of $\mu \rightarrow e + \gamma$ decay ($Br(\mu \rightarrow e + \gamma) \leq 5 \cdot 10^{-11}$ [21]) one can find that [5,6-19]

$$\frac{(\Delta m^2{}_{e}\mu)_{RR}}{M^2_{av}} \equiv (\delta_{e\mu})_{RR} \leq 2k \cdot 10^{-1} M^2_{av}/(1 \text{ TeV})^2, \qquad (2)$$

where $k = O(1)$. For $m_{\tilde{e}_R} = 70\,\text{GeV}$ we find that $(\delta_{e\mu})_{RR} \leq 10^{-3}$. Analogous bounds resulting from the nonobservation of $\tau \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ decays are not very stringent [5,6-23].

The mass term for righthanded $\tilde{e}_R$ and $\tilde{\mu}_R$ sleptons has the form

$$-\delta L = m_1^2 \tilde{e}_R^+ \tilde{e}_R + m_2^2 \tilde{\mu}_R^+ \tilde{\mu}_R + m_{12}^2 (\tilde{e}_R^+ \tilde{\mu}_R + \tilde{\mu}_R^+ \tilde{e}_R) \qquad (3)$$

After the diagonalization of the mass term (3) we find that the eigenstates of the mass term (3) are

$$\tilde{e}_R^{'} = \tilde{e}_R \cos(\phi) + \tilde{\mu}_R \sin(\phi) \;, \qquad (4)$$

$$\tilde{\mu}_R^{'} = \tilde{\mu}_R \cos(\phi) - \tilde{e}_R^{'} \sin(\phi) \qquad (5)$$

with the masses

$$M^2_{1,2} = (1/2)[(m_1^2 + m_2^2) \pm ((m_1^2 - m_2^2)^2 + 4(m_{12}^2)^2)^{1/2}]. \qquad (6)$$

which practically coincide for small values of $m_1^2 - m_2^2$ and m_{12}^2. Here the mixing angle ϕ is determined by the formula

$$\tan(2\phi) = 2m_{12}^2(m_1^2 - m_2^2)^{-1} \qquad (7)$$

The crusial point is that even for small mixing parameter m_{12}^2 due to the smallness of the difference $m_1^2 - m_2^2$ the mixing angle ϕ is in general not small (at present state of art it is impossible to calculate the mixing angle ϕ reliably). For the most probable case when the lightest stable superparticle is superpartner of the $U(1)$ gauge boson plus some small mixing with other gaugino and higgsino, the sleptons $\tilde{\mu}_R$, $\tilde{e}_R^{'}$ decay mainly into leptons μ_R and e_R plus U(1) gaugino λ. The corresponding term in the Lagrangian responsible for slepton decays is

$$L_1 = \frac{2g_1}{\sqrt{2}}(\bar{e}_R \lambda_L \tilde{e}_R + \bar{\mu}_R \lambda_L \tilde{\mu}_R + \text{h.c.}), \qquad (8)$$

where $g_1^2 \approx 0.13$. For the case when mixing is absent the decay width of the slepton into lepton and LSP is given by the formula

$$\Gamma = \frac{g_1^2}{8\pi} M_{sl} \Delta_f \approx 5 \cdot 10^{-3} M_{sl} \Delta_f, \qquad (9)$$

$$\Delta_f = (1 - \frac{M^2_{LSP}}{M^2_{sl}})^2, \tag{10}$$

where M_{sl} and M_{LSP} are the masses of slepton and the lightest superparticle (U(1)-gaugino) respectively. For the case of nonzero mixing we find that the Lagrangian (11) in terms of slepton eigenstates reads

$$L_1 = \frac{2g_1}{\sqrt{2}}[\bar{e}_R\lambda_L(\tilde{e}'_R\cos(\phi) - \tilde{\mu}'_R\sin(\phi)) + \bar{\mu}_R\lambda_L(\tilde{\mu}'_R\cos(\phi) + \tilde{e}'_R\sin(\phi)) + \text{h.c.}] \tag{11}$$

At LEP2 and NLC in the neglection of slepton mixing $\tilde{\mu}_R$ and $\tilde{\tau}_R$ sleptons pair production occurs [22] via annihilation graphs involving the photon and the Z^0 boson and leads to the production of $\tilde{\mu}^+_R\tilde{\mu}^-_R$ and $\tilde{\tau}^+_R\tilde{\tau}^-_R$ pairs. For the production of righthanded selectrons in addition to the annihilation graphs we also have contributions from the t-channel exchange of the neutralino [23] .

An account of nonzero smuon-selectron mixing leads to the following formulae for the cross sections for LEP2 and NLC:

$$\begin{aligned}\sigma(e^+e^- \to e^+e^- + LSP + LSP) = k[(A + B\cos^2(\phi))^2\cos^4(\phi) + \\ +(A + B\sin^2(\phi))^2\sin^4(\phi) + B^2\sin^4(2\phi)/8],\end{aligned} \tag{12}$$

$$\begin{aligned}\sigma(e^+e^- \to \mu^+\mu^- + LSP + LSP) = k[(A + B\cos^2(\phi))^2\sin^4(\phi) + \\ +(A + B\sin^2(\phi))^2\cos^4(\phi) + B^2\sin^4(2\phi)/8],\end{aligned} \tag{13}$$

$$\begin{aligned}\sigma(e^+e^- \to \mu^\pm + e^\mp + LSP + LSP) = \frac{k\sin^2(2\phi)}{4}[(A + B\cos^2(\phi))^2 + \\ +(A + B\sin^2(\phi))^2 + B^2(\cos^4(\phi) + \sin^4(\phi))].\end{aligned} \tag{14}$$

Here A is the amplitude of s-exchange, B is the amplitude of t-exchange and k is the normalization factor. The corresponding formulae for A, B and k are contained in [23]. The reaction (14) proceeds with violation of flavor lepton number.

It should be noted that formulae (12)–(14) are valid only in the approximation of narrow decay width of sleptons

$$2\Gamma m_{\tilde{e}_R} \leq |m^2_{\tilde{\mu}_R} - m^2_{\tilde{e}_R}|. \tag{15}$$

For the case when the inequality (15) does not hold the effects due to the finite decay width are important and decrease the cross section with violation of flavor lepton number. The cross section for the reaction $e^+e^- \to e^+\mu^- + LSP + LSP$ is proportional to

$$\sigma \sim \sin^2(\phi)\cos^2(\phi)\int |D(p_1, m_{\tilde{e}}, \Gamma)D(p_2, m_{\tilde{e}}, \Gamma) - D(p_1, m_{\tilde{\mu}}, \Gamma)D(p_2, m_{\tilde{\mu}}, \Gamma)|^2 dp_1^2 dp_2^2, \tag{16}$$

where

$$D(p, m, \Gamma) = \frac{1}{p^2 - m^2 - i\Gamma m} \tag{17}$$

and $\Gamma_{\tilde{e}} \approx \Gamma_{\tilde{\mu}} = \Gamma$. The approximation (12)–(14) corresponds to the neglection of the interference terms in (16) and it is valid if the inequality (15) takes place.

For smaller slepton masses difference an account of the interference terms in (16) is very important [18, 25]. The integral (16) is approximately equal to

$$\sigma \sim \sin^2(\phi)\cos^2(\phi)\frac{2\pi^2}{b^2}(1 - \frac{b^2(b^2 - \frac{a^2}{4})}{(b^2 + \frac{a^2}{4})^2}), \qquad (18)$$

where $a = m^2_{\tilde{e}_R} - m^2_{\tilde{\mu}_R}$, $b = \Gamma(\frac{m_{\tilde{e}_R} + m_{\tilde{\mu}_R}}{2})$. An account of the interference effects leads to the decrease of the cross section (14) by factors 1, 0.82, 0.52, 0.17 for $|m^2_{\tilde{e}} - m^2_{\tilde{\mu}}| = 2\Gamma m_{\tilde{e}}$, $1.5\Gamma_{\tilde{e}}$, $\Gamma m_{\tilde{e}}$, $0.5\Gamma m_{\tilde{e}}$ respectively.

Consider now the possibility to discover lepton number violation in slepton decays at LHC. The possibility to discover sleptons at LHC have been discussed in refs.[26–28]. Here we shall use the results of ref.[28] where concrete estimates have been made for CMS detector. To be concrete we consider two points of the ref.[28].

Point A: $m(\tilde{l}_L) = 314$ GeV, $m(\tilde{l}_R) = 192$ GeV, $m(\tilde{\nu}) = 308$ GeV, $m(\tilde{\chi}^0_1) = 181$ GeV, $m(\tilde{\chi}^0_2) = 358$ GeV, $m(\tilde{g}) = 1036$ GeV, $m(\tilde{q}) = 905$ GeV, $\tan(\beta) = 2$, $\mathrm{sign}(\mu) = -$.

Point B: $m(\tilde{l}_L) = 112$ GeV, $m(\tilde{l}_R) = 98$ GeV, $m(\tilde{\nu}) = 93$ GeV, $m(\tilde{\chi}^0_1) = 39$ GeV, $m(\tilde{\chi}^0_2) = 87$ GeV, $m(\tilde{g}) = 254$ GeV, $m(\tilde{q}) = 234$ GeV, $\tan(\beta) = 2$, $\mathrm{sign}(\mu) = -$.

For point A the following cuts have been used: $p^l_T \geq 50$ GeV, $Isol \leq 0.1$, $|\eta| \leq 2.5$, $E^{miss}_T \geq 120$ GeV, $\Delta\phi(E^{miss}_T, ll) \geq 150^o$, jet veto - no jets with $E^{jet}_T \geq 30$ GeV in $|\eta| \leq 4.5$, Z-mass cut - $M_Z \pm 5$ GeV excluded, $\Delta\phi(l^+l^-) \leq 130^o$. With such cuts for the total luminosity $L_t = 10^5 pb^{-1}$ 91 events $e^+e^- + \mu^+\mu^-$ resulting from slepton decays have been found. The standard WS model background comes from WW, $t\bar{t}$, $Wt\bar{b}$, WZ, $\bar{\tau}\tau$ and gives 105 events. No SUSY background have been found. The significance for the slepton discovery at point A is 6.5. Using these results it is trivial to estimate the perspective for the discovery of flavour violation in slepton decays. Consider the most optimistic case of maximal slepton mixings and neglect the effects of destructive interference. For the case of maximal selectron-smuon mixing the number of signal events coming from slepton decays is $N_{sig}(e^+e^-) = N_{sig}(\mu^+\mu^-) = N_{sig}(\mu^\pm e^\mp) = 23$. The number of background events is $N_{back}(e^+e^-) = N_{back}(\mu^+\mu^-) = N_{back}(e^\pm\mu\mp) = 53$. The significance $S = \frac{Sleptons}{\sqrt{Background+Sleptons}}$ is 5.2 for all dilepton modes. For the case of maximal smuon-selectron mixing we have the same number of $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$ signal events, whereas in the case of the mixing absence we don't have $e^\pm\mu^\mp$ events. For the case of the maximal stau-smuon mixing we expect 23 $\mu^+\mu^-$ signal events and 46 e^+e^- signal events and 2 $\mu^\pm e^\mp$ signal events whereas the background is the same as for the case of maximal smuon-selectron mixing. The significance is: 4.6(e^+e^- mode), 2.6($\mu^+\mu^-$ mode), 5.2($e^+e^- + \mu^+\mu^-$ - mode). The case of selectron-stau mixing is the similar to the case of smuon-stau mixing the single difference consists in the replacement of $e \to \mu$, $\mu \to e$. For the case of maximal selectron-smuon-stau mixing we expect 46 $e^+e^- + \mu^+\mu^- + e^\pm\mu^\mp$ signal events and the significance is 2.8.

For the point B the cuts are similar to the point A, except $p^l_T \geq 20$ GeV, $E^{miss}_T \geq 50$ GeV, $\Delta\phi(E^{miss}_T, ll) \geq 160^o$ For the total luminosity $L_{tot} = 10^4 pb^{-1}$ the number of $e^+e^- + \mu^+\mu^-$ events resulting from direct slepton production has been found to be 323. The number of background events have been estimated equal to 989(standard model background) + 108(SUSY background)= 1092. The significance is 8.6. Our analysis for the point B is similar to the corresponding analysis for the point A. For the case of maximal selectron-smuon mixing we have found that the significance for all delepton modes is 6.4. For the case of the maximal smuon-stau mixing the significance for $e^+e^- + \mu^+\mu^-$ mode is 6.6 . The same significance is for the case of the maximal selectron-stau mixing. For the case of maximal selectron-smuon-stau mixing the significance for $e^+e^- + \mu^+\mu^- + e^\pm\mu^\mp$ mode is 3.0. For the total luminosity $L_{tot} = 10^5 pb^{-1}$ the significance is increased by factor ≈ 3.1. It is interesting to mention that at LHC the main mechanism of slepton pair production is the Drell-Yan mechanism and as a consequence for equal smuon and selectron masses the corresponding cross sections and the number of e^+e^- and $\mu^+\mu^-$ signal events coincide. The corresponding cross sections depend rather strongly on slepton masses. If smuon and selectron masses differ by 20 percent the corresponding cross sections and as a consequence the number of e^+e^- and $\mu^+\mu^-$ signal events will differ by factor ≈ 2 that as it has been demonstrated on the example of points A and B is detectable at LHC. However the effect of 20 percent smuon and selectron mass difference will imitate the effect of selectron-stau or smuon-stau mixings. So the situation could be rather complicated. At any rate by the neasurement of the difference in $\mu^+\mu^-$ and e^+e^- events it would be possible to measure the difference of smuon and selectron masses with the accuracy ≈ 20 percent that is very important because in MSSM smuon and selectron masses practically coincide for both righthanded and lefthanded sleptons.

Let us formulate the main result of this paper: in supersymmetric extension of standard Weinberg-Salam model there could be soft supersymmetry breaking terms responsible for flavor lepton number violation and slepton mixing. At LHC it would be possible to discover flavor lepton number violation in slepton decays for sleptons lighter than 300 GeV provided that the mixing among sleptons is closed to the maximal one. For the case of nonequal smuon and selectron masses the number of e^+e^- and $\mu^+\mu^-$ events will be different that imitate the effect of stau-smuon or stau-selectron mivings. At any rate the observation (or nonobservation) of the ($\mu^+\mu^-$ - e^+e^-) difference allows to conclude that smuon and selectron masses differ(coincide) at least with the accuracy 20 percent or to make conclusion about the discovery of slepton mixing. Unfortunately it is rather difficult to distinguish between these two possibilities. For the case of nonzero smuon-selectron mixing the number of $\mu^+\mu^-$ and e^+e^- events is predicted to be the same and moreover for the case of maximal smuon-selectron mixing the number of μ^+e^- and μ^-e^+ events coincide with the number of $\mu^+\mu^-$ and e^+e^- events. Of course, it is clear that at NLC or $\mu^+\mu^-$ collider the perspectives for the flavor lepton number violation discovery are the most promising but unfortunately now it is too far from reality.

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1. S.Dimopoulos and S.Raby, Nucl. Phys. **B192**, 353 (1981).
2. E.Witten, Nucl. Phys. **B185**,513 (1981).
3. S.Dimopoulos, S.Raby, and F.Wilczek, Phys. Rev. **D24**,1681 (1981).
4. For reviews and references, see H.P.Nilles, Phys. Rep. **110**, 3 (1984).
5. F.Gabbiani and A.Masiero, Nucl. Phys. **B322**, 235 (1989).
6. J.Hagelin, S.Kelley, and T.Tanaka, Nucl. Phys. **B415**, 293 (1994).
7. F.Barzumanti and A.Masiero, Phys. Rev. Lett. **57**, 961 (1986).

8. G.K.Leontaris, K.Tamvakis, and J.D.Vergados, Phys. Lett. **B171**, 412 (1986).
9. I.Antoniadis, J.Ellis, J.S.Hagelin, and D.V.Nanopoulos, Phys. Lett. **B231**, 65 (1989).
10. S.Kelley, J.L.Lopez, D.V.Nanopoulos, and H.Pois, Nucl. Phys. **B358**, 27 (1991).
11. L.Ibanez and D.Lust, Nucl. Phys.**B382**, 305 (1992).
12. V.Kaplunovsky and J.Louis, Phys. Lett. **B306**, 269 (1993).
13. R.Barbieri and L.J.Hall, Phys. Lett. **B338**, 212 (1995).
14. D.Choudhury et al., Phys. Lett. **B342**, 180 (1995).
15. N.V.Krasnikov, Mod. Phys. Lett. **A9**, 2825 (1994).
16. N.V.Krasnikov, Mod. Phys. Lett. **A9**, 791 (1994).
17. N.V.Krasnikov, Preprint INR-927-95, hep-ph/9511464.
18. N.V.Krasnikov, to be published in Phys. Lett.B
19. L.E.Ibanez and C.Lopez, Nucl. Phys.**B233**, 511 (1984).
20. For reviews, see: H.P.Nilles, Phys.Rep. **110**, 1 (1984); G.G.Ross, *Grand Unified Theories*, Benjamin, New York 1984; R.N.Mohapatra, *Unification and Supersymmetry*, Springer, New York 1992.
21. Particle Data Group, Review of particle properties, Phys. Rev. **D50**, ?? (1994).
22. Y.Nir and N.Seiberg, Phys. Lett. **B309**, 340 (1993).
23. M.Chen, C.Dionisi, M.Martinez, and X.Tata, Phys. Rep. **159**, 201 (1988).
24. H.Baer et al., *Low Energy Supersymmetry Phenomenology*, CERN-PRE/94-45.
25. Nima Arkani-Hamed, Hsin-Chia Cheng, Jonathan L. Feng and Lawerence J.Hall, Phys. Rev. Lett. **77**, 1937 (1996).
26. F.del Agulia and Ll.Ametller, Phys. Lett. **B261**, 326 (1991).
27. H.Baer, C.Chen, F.Paige, and X.Tata, Phys. Rev.**D49**, 3283 (1994).
28. D.Denegri, L.Rurua and N.Stepanov, *Detection of sleptons and instrumental requirements in CMS*, CMS Technical Note TN/96-059, October 1996.