Measuring Lepton Flavour Violation at LHC with Long-Lived Slepton in the Coannihilation Region

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Abstract. When the mass difference between the lightest slepton, the NLSP, and the lightest neutralino, the LSP, is smaller than the tau mass, the lifetime of the lightest slepton is extraordinarily long and strongly dependent on lepton flavor violation. Therefore the long-lived slepton scenario offers an excellent opportunity to study lepton flavor violation at ATLAS and CMS detectors in the LHC. This is based on the work [1]

1. Introduction
Cosmological observations have confirmed the existence of the non-baryonic dark matter. The observed dark matter relic abundance is $\Omega_{DM}h^2 \simeq 0.11$ and points to the existence of a stable and weakly interacting particle with a mass $m = 100 - 1000$ GeV. In supersymmetric (SUSY) models with conserved R-parity, the Lightest Supersymmetric Particle (LSP), usually the lightest neutralino, is stable and it is a perfect candidate for the dark matter. In this case the mechanisms ,called coannihilation [2] is employed. In the coannihilation region, the Next to Lightest Supersymmetric Particle (NLSP) has a mass nearly degenerate to the LSP. The degeneracy required for the coannihilation to occur is generally $\delta m/m_{LSP} < \text{a few } \%$, where $\delta m = m_{NLSP} - m_{LSP}$.

Furthermore, it was pointed out in [3, 4, 5] that if staus are the NLSP and its mass difference with the LSP is less than the tau mass, they destroy $^7\text{Li}/^7\text{Be}$ nucleus through the internal conversion. With this small mass difference, staus become long-lived, they survive until Big-Bang Neucleosynthesis (BBN) starts and form bound states with nucleus. The stau-nucleus bound states decay immediately by virtual exchange of the hadronic current. In this way, it was shown that the relic abundance of the light elements is lowered effectively and the discrepancy between the observed value of $^7\text{Li}/^7\text{Be}$ abundance [6, 7] and the predicted value from the standard BBN [8] with WMAP data [9, 10] can be solved. Thus, a scenario with stau NLSP and neutralino LSP...
with $\delta m \leq m_{\tau}$ could explain the relic abundance of the light elements as well as the abundance of the dark matter. As shown in [3], if the mass difference, $\delta m$, between neutralino and stau is less than the tau mass, the two-body decay is forbidden and the lifetime of stau increases by more than 10 orders of magnitude.

Strictly speaking the previous discussion is correct only in the framework of the MSSM without intergenerational mixing in the slepton sector. In general, we expect that the lightest slepton, $\tilde{l}_1$, is not a pure stau, but there is some mixing with smuon and selectron. In the presence of this small intergenerational mixing, even with $\delta m \leq m_{\tau}$, other two-body decay channels like $\tilde{l}_1 \rightarrow \tilde{\chi}^0_1 + e(\mu)$, are still open [3]. In this case, given that the flavor conserving two-body decay channel is closed, the slepton lifetime will have a very good sensitivity to small Lepton Flavor Violation (LFV) parameters.

Long-lived charged-particles are very interesting since they provide a clear experimental signature at the LHC [11, 12, 13]. In Ref. [14] they conclude that even if the lifetime of the decaying particle is much longer than the size of the detector, some decays always take place inside the detector and it is possible to measure lifetimes as long as $10^{-5} - 10^{-3}$ seconds in a particular gauge mediation scenario.

2. mass spectrum and long-lived stau in MSSM

We found mass range which were obtained in the CMSSM parameter space by requiring the mass difference, $\delta m$, between the lightest neutralino mass, $m_{\tilde{\chi}^0_1}$, and the lighter stau mass, $m_{\tilde{\tau}_1}$, be smaller than tau mass, $m_{\tau}$. Here we also imposed the constraints from the relic density of the dark matter abundance, the anomalous magnetic moment of the muon, the bound on $\text{Br}(b \rightarrow s\gamma)$.

In Table 1, we show the SUSY mass spectrum for the interesting region at $\tan \beta = 30$ and $A_0 = 600$ GeV. As can be seen in this table, masses of the lightest neutralino and the lightest...
slepton are around 300 GeV. The lightest neutralino is mainly bino and the second lightest neutralino is wino with a small admixture of higgsino. The second lightest neutralino and the lightest chargino have masses \( \sim 550 \) GeV. The right-handed sleptons are in the range 300–390 GeV and the left-handed sleptons have masses of 510–570 GeV. The squarks are in the range 1150–1560 GeV while gluinos are heavier than the squarks and about 1540 – 1680 GeV.

The decay chain of the NLSP stau into two, three and four bodies are shown in Fig. 1. The exact decay rates are given in Appendix of [1]. Notice that when \( \delta m \gg m_\tilde{\tau}_1 \) the two-body decay is open and the lifetime of the stau, \( \tau_\tilde{\tau}_1 \), is \( \sim 10^{-22} \) sec. However, for \( \delta mm_\tau \) this decay is closed and the three or four-body decays are suppressed at least by an additional \( (\delta m)^4 G_F^2 (f_\pi/m_\tau)^2 / (30(2\pi)^2) \approx 10^{-13} \) with \( \delta m \sim 2 \) GeV. Therefore the stau becomes long-lived and the phenomenology of the MSSM changes dramatically.

3. LFV and long-lived slepton
In the previous section we have seen that \( \delta m \leq m_\tau \) is indeed possible in the framework of a CMSSM without LFV couplings. The lifetime of the NLSP stau in this scenario is increased by many orders of magnitude. However, once a new source of LFVs is introduced, the NLSP two-body decay channels into electron and/or muon can open again. In this case, the lifetime is inversely proportional to the square of the mixing of selectron and smuon with stau and therefore the measurement of the lifetime shows a strong sensitivity to LFV parameters.

To understand the dependence of lifetimes on LFV parameters, it is convenient to introduce the so-called Mass Insertions (MI), \( (\delta e_{RR/LL})_{\alpha\beta} \), defined

\[
(\delta e_{RR/LL})_{\alpha\beta} = \frac{\Delta M^e_{RR/LL\alpha\beta}}{M^e_{R/L\alpha} M^e_{R/L\beta}},
\]

where \( \alpha, \beta \) denote the lepton flavors. \( M^e_{R/L\alpha} \) and \( M^e_{R/L\beta} \) are diagonal elements of the slepton mass matrix, and \( \Delta M^e_{RR/LL\alpha\beta} \) are off-diagonal elements we introduced. In terms of these mass insertions, the two-body decay rate is approximately given by

\[
\Gamma_{2\text{-body}} = \frac{g^2}{2\pi m_\tilde{\tau}_1} (\delta m)^2 (|g^L_{\alpha\alpha_1}|^2 + |g^R_{\alpha\alpha_1}|^2),
\]
Figure 2. MI Feynman diagrams of two-body slepton decay: The diagram on the left side depicts two-body decay in the presence of $\delta_{RR}^e$ and the diagram on the right side in the presence of $\delta_{LL}^e$. The circle-crosses represent mass insertions for flavor and left-right chirality changes. Propagators for intermediate states are shown below corresponding scalar lines.

Table 2. Table of the mass difference and the lightest slepton, neutralino masses. $m_0$, $A_0$ and $\tan \beta$ are fixed to 260 GeV, 600 GeV and 30, respectively. The values of neutralino abundance and $a_\mu$ are shown for the reference.

| No. | $\delta m$ (GeV) | $m_{\tilde{\chi}_1^0}$ (GeV) | $m_{\tilde{l}_1}$ (GeV) | $\Omega_{\tilde{\chi}_1^0} h^2$ | $a_\mu \times 10^{-10}$ |
|-----|-----------------|-----------------|-----------------|------------------|------------------|
| A   | 2.227           | 323.1549        | 325.3817        | 0.110            | 10.32            |
| B   | 1.650           | 325.5601        | 326.2147        | 0.102            | 10.25            |
| C   | 0.407           | 327.6294        | 328.0365        | 0.085            | 10.09            |
| D   | 0.092           | 328.4060        | 328.4981        | 0.081            | 10.06            |

where $\alpha = e, \mu$. $g_{101}^{L,R}$ can be approximated in the mass insertion as shown in Fig. 2. In the case of right-handed slepton mixing, we have,

$$g_{101}^L \simeq 0, \quad g_{101}^R \simeq \tan \theta_W \frac{M_{\tilde{R}_\tau}^2 M_{\tilde{R}_\alpha}^2}{M_{\tilde{R}_\tau}^2 - M_{\tilde{R}_\alpha}^2} (\delta_{RR}^e)_{\alpha \tau},$$

while in the left-handed slepton mixing case, these couplings are given

$$g_{101}^L \simeq \frac{1}{2} \tan \theta_W \frac{m_\tau (A_0 - \mu \tan \beta)}{M_{\tilde{R}_\tau}^2 - M_{\tilde{R}_\alpha}^2} \frac{M_{\tilde{R}_\tau}^2 M_{\tilde{R}_\alpha}^2}{M_{\tilde{R}_\tau}^2 - M_{\tilde{R}_\alpha}^2} (\delta_{LL}^e)_{\alpha \tau}, \quad g_{101}^R \simeq 0.$$ (4)

To analyze the effects of the presence of a non-vanishing leptonic mass insertion on the NLSP lifetime we choose four points with different mass differences as shown in Table 2. In Fig. 3 (a), we show the lifetime of the lightest slepton, $\tilde{\tau}_{l_1}$, as a function of $(\delta_{RR}^e)_{\tau \tau}$, encoding the right-handed selectron-stau mixing, that we vary from $10^{-10}$ to $10^{-2}$ [15, 16]. We can see that the lifetime for $\delta m > m_\tau$ (case A in Table 2) does not change, because the decay of slepton to tau and neutralino is always the dominant decay mode and the lifetime is insensitive to $\delta_{RR}^e \leq 10^{-2}$. On the other hand, for $\delta m < m_\tau$, the lifetime grows more than 13 orders of magnitude in the limit $(\delta_{RR}^e)_{\tau \tau} \rightarrow 0$, where the three- or four-body decay processes are dominant. Then, the two-body decay into $\tau$ and $\tilde{\chi}_1^0$ is forbidden but those into $e$ (or $\mu$ for $(\delta_{RR}^e)_{\mu \tau} \neq 0$) and $\tilde{\chi}_1^0$ are allowed through LFV couplings. The lifetime decreases proportionally to $| (\delta_{RR}^e)_{\tau \tau} |^{-2}$ when the two-body decay dominates total decay width.

Figs. 4 (a) and (b) show the lifetime of the lightest slepton as a function of $(\delta_{LL}^e)_{\tau \tau}$ and $(\delta_{LL}^e)_{\mu \tau}$, respectively. The different curves correspond to the same mass differences used in
Figure 3. The lifetime of the lightest slepton as a function of $\delta e_{RR}$. The left panel, (a), is the lifetime of the lightest slepton with the right-handed selectron and stau mixing, and the right panel, (b), is the one with the right-handed smuon and stau mixing. In both panel, the solid (red), dashed (green), dotted (blue), dotted-dashed (pink) line correspond to $\delta m = 2.23$ (A), 1.65 (B), 0.41 (C), 0.09 (D) GeV, respectively. These lifetimes are calculated with the exact formulas in the Appendix of [1].

Figure 4. The lifetime of the lightest slepton as a function of $\delta e_{LL}$. The lines and the parameters are the same as Fig. 3.

Fig. 3. The dependence on these mass insertions in these figures is completely analogous to the behavior observed in Fig. 3. In fact, both figures would be identical if we replace $(\delta e_{LL})$ by $10 \times (\delta e_{RR})$. This is due to the fact that in this case, the lightest slepton decays into the electron or the muon through the left-handed stau component. The mixing of right and left-handed staus, Eq. (4), is proportional to $m_r (A_0 - \mu \tan \beta) / (M_{Rr}^2 - M_{Lr}^2)$. In the region of parameter space we are considering this factor is approximately 0.1. Thus, we can see that, also in the case of $(\delta e_{LL})$, the lifetime is sensitive to the presence of very small lepton flavor violating couplings and therefore to the presence of mass insertions orders of magnitude smaller than the present bounds.
detector. Almost all of them escape from the detector when $\tau$ of the order of 10 decays inside the detector for $\tau_1$ half of them decay inside the inner detector and nearly all of them decay within the detector. If $10^{-12}$ integrated luminosity, $\mathcal{L}_{\text{int}} = 30 \text{ fb}^{-1}$ is 4290.

### 4. LHC phenomenology

In this section, we discuss the expected phenomenology at LHC experiments, focusing mainly on the ATLAS detector [17, 18], of the long-lived slepton scenario. The lightest slepton is the NLSP, and therefore a large number of sleptons is expected to be produced via cascade decays of heavier SUSY particles, say, $\tilde{q}_L \rightarrow \tilde{\chi}_1^\pm + q$, $\tilde{\chi}_1^\pm \rightarrow \tilde{l}_1 + \nu_\tau$  \hspace{1cm} (5)

where $q$, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ denote the SM quarks, the lighter charginos and the second lightest neutralinos and $\nu_\tau$, $W$ and $\tilde{\nu}_\tau$ denote tau neutrino, weak boson and tau sneutrino, respectively. The 3rd generation squarks have many different decay chains.

When the long-lived sleptons have lifetimes between $10^{-5}$ and $10^{-12}$ sec., we will have a chance to observe decays of the slepton inside the detector.

The total cross section of SUSY pair production in our scenario is given in [19],

$$\sigma_{\text{SUSY}} = 130 \text{ fb}$$  \hspace{1cm} (6)

and we assume the integrated luminosity, $\mathcal{L}_{\text{int}} = 30 \text{ fb}^{-1}$. Then the number of lightest sleptons produced, $N_{\tilde{l}_1}$, is estimated as 4290. Therefore we would have 4290 long-lived sleptons produced in ATLAS that could decay inside the detector depending on the lifetime.

In Table 3, we show the expected number of slepton decays in each detector, assuming the integrated luminosity, $\mathcal{L}_{\text{int}} = 30 \text{ fb}^{-1}$ and $\beta\gamma = 2$. As can be seen, when the lifetime, $\tau_{\tilde{l}_1}$, is below $10^{-9}$ sec., most of the sleptons decay inside the pixel detector. When $\tau_{\tilde{l}_1} \sim 10^{-8}$ sec., almost half of them decay inside the inner detector and nearly all of them decay within the detector. If $\tau_{\tilde{l}_1}$ is between $10^{-8}$ and $10^{-6}$ sec., several hundreds of slepton decays occur inside the ATLAS detector. Almost all of them escape from the detector when $\tau_{\tilde{l}_1} > 10^{-5}$ sec., although we expect of the order of 10 decays inside the detector for $\tau_{\tilde{l}_1} \sim 10^{-5}$ sec.

If we can fix the mass difference between the lightest slepton and neutralino, we can determine the value of the mass insertion parameters from Figs. 3 and 4. In the case of right-handed slepton mixing case, lifetimes between $10^{-10}$ and $10^{-8}$ sec. would correspond to $(\delta_{RR})_{e\tau}$ between $10^{-7}$ and $10^{-4}$ with the mass difference, $m_e < \delta m < m_\tau$, and $(\delta_{RR})_{\mu\tau}$ between $10^{-7}$ and $10^{-5}$ with $m_\mu < \delta m < m_\tau$. Similarly, in the case of left-handed slepton mixing, the same lifetimes would

| $\tau$ (sec.) | 5 cm | 50 cm | 3.1 m | 5.8 m | 25.0 m |
|--------------|------|------|-------|-------|--------|
| $10^{-9}$    | 0.04 | 0.36 | 2.2   | 4.1   | 17.8   |
| $10^{-10}$   | 0.36 | 3.6  | 22.1  | 41.3  | 175.1  |
| $10^{-11}$   | 3.6  | 35.6 | 216.0 | 395.3 | 1461.9 |
| $10^{-12}$   | 35.6 | 343.0| 1731.0| 2658.3| 4225.5 |
| $10^{-13}$   | 343.0| 2425.6| 4265.5| 4289.7| 4290.0 |
| $10^{-14}$   | 2425.6| 4289.0| 4290.0| 4290.0| 4290.0 |

Table 3. The expected number of slepton decay in the ATLAS detector. The lifetime is varied from $10^{-12}$ to $10^{-5}$ seconds. The number of sleptons produced at LHC assuming the integrated luminosity, $\mathcal{L}_{\text{int}} = 30 \text{ fb}^{-1}$ is 4290.
correspond to \((\delta m_{LL})_{e\tau}\) between \(4 \times 10^{-6}\) and \(10^{-3}\) with \(m_e < \delta m < m_\tau\), and \((\delta m_{RR})_{e\tau, \mu\tau}\) between \(4 \times 10^{-6}\) and \(10^{-4}\) with \(m_\mu < \delta m < m_\tau\). For \(\tau_{\tilde{\tau}} \sim 10^{-8} \text{ sec.}\), about half of sleptons would decay inside the inner detector and the rest would decay inside the calorimeters and/or muon spectrometer.

5. summary

In this work, we have studied lepton flavor violation in a long-lived slepton scenario where the mass difference between the NLSP, the lightest slepton, and the LSP, the lightest neutralino, is smaller than the tau mass. This small \(\delta m\) is possible even in the framework of the CMSSM.

Then, we have analyzed the dependence of the lightest slepton lifetimes on different mass insertions, \((\delta m_{RR/LL})_{e\tau, \mu\tau}\) for values of \(\delta m\) from 2.23 to 0.09 GeV. We found that the lifetimes are proportional to \(|\delta m|^{-2}\) until three- or four-body decays become comparable. There is a difference of approximately a factor of 10 in the sensitivity of the lifetime on \(\delta m_{RR}\) and \(\delta m_{LL}\). This is due to the different proportion of left-handed and right-handed staus in the lightest slepton. We can see that, in this scenario, the lifetimes are sensitive to much smaller values of these \(\delta m\)s.

Finally, we have discussed the expected phenomenology at LHC experiments, mainly concentrating on the ATLAS detector. We have estimated the number of slepton decays in the different detectors, assuming an integrated luminosity \(L_{\text{int}} = 30 \text{ fb}^{-1}\) and \(\beta\gamma = 2\) (Table. 3). We have seen that the ATLAS detector can observe lifetimes in the range of \(10^{-11} \text{ to } 10^{-6} \text{ sec.}\,\) and these lifetime would correspond to \((\delta m_{RR})_{e\tau, \mu\tau}\) between \(10^{-7}\) and \(10^{-3}\) and \((\delta m_{LL})_{e\tau, \mu\tau}\) between \(4 \times 10^{-6}\) and \(10^{-3}\). Therefore we have shown that in the long-lived slepton scenario, the LHC offers a very good opportunity to study lepton flavor violation.

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