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Lepton Flavour Violation in charged leptons within SUSY-seesaw

E. Arganda[a], M. Herrero[b] *, J. Portolés[c], A. Rodriguez-Sanchez[b] and A.Teixeira[d]

[a] Departamento de Física Atómica, Molecular y Nuclear, Facultad de Ciencias Fí sicas,
Universidad Complutense de Madrid, Avda. Complutense s/n, E-28040 Madrid, Spain

[b]Departamento de Física Teórica C-XI and Instituto de Física Teórica C-XVI,
Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain

[c]IFIC, Universitat de Valencia-CSIC, Apt. Correus 22085, E-46071, Valencia,Spain

[d]Laboratoire de Physique Theorique, UMR 8627, Pris-Sud XI, Bat.210, F-91405 Orsay Cedex,France

In this paper we review our main results for Lepton Flavour Violating (LFV) semileptonic tau decays and muon-electron conversion in nuclei within the context of two Constrained SUSY-Seesaw Models, the CMSSM and the NUHM. The relevant spectrum is that of the Minimal Supersymmetric Standard Model extended by three right handed neutrinos, ν_{R_i} and their corresponding SUSY partners, $\tilde{\nu}_{R_i}$, $(i = 1, 2, 3)$. We use the seesaw mechanism for neutrino mass generation and choose a parameterisation of this mechanism that allows us to incorporate the neutrino data in our analysis of LFV processes. In addition to the full one-loop results for the rates of these processes, we will also review the set of simple formulas, valid at large $\tan\beta$, which are very useful to compare with present experimental bounds. The sensitivity to SUSY and Higgs sectors in these processes will also be discussed. This is a very short summary of the works in Refs. [1] and [2] to which we refer the reader for more details.

1. Framework for LFV in charged leptons

From the present neutrino data on neutrino oscillations, we know that Lepton Flavour Violation (LFV) occurs in the neutral lepton sector. However, we do not know yet if this LFV occurs in the charged lepton as well. Even if it occurs, we do not know either if these two violations are related or not. Within the Standard Model with mass less neutrinos there is not LFV. Futhermore, it is extremely suppressed even with massive neutrinos. In contrast, in supersymmetric (SUSY) models with Majorana neutrinos LFV can be sizeable. In particular, we consider here the spectrum of the Minimal Supersymmetric Standard Model (MSSM) extended with three rigth handed neutrinos, ν_{R_i}, and their SUSY partners, $\tilde{\nu}_{R_i}$ $(i = 1, 2, 3)$, and with the seesaw mechanism implemented to generate the neutrino masses, where it is known that large LFV rates occur. These are induced by the soft SUSY breaking slepton masses and are transmitted to the lepton sector by means of the Yukawa neutrino couplings, which can be large if the neutrinos are of Majorana type, and via loops of SUSY particles. Therefore, in the context we work within of SUSY-seesaw models the LFV in both the neutral and the charged lepton are closely related.

Regarding the seesaw mechanism we use the parameterisation proposed in [3], which is very useful to implement the neutrino data into our analysis of LFV. With this parameterisation, the 3×3 Yukawa coupling and Dirac mass matrices are set by $m_D = Y_\nu v_2 = \sqrt{m_N^{\rm diag}} R \sqrt{m_\nu^{\rm diag}} U_{\rm MNS}^\dagger$, with the 3×3 orthogonal matrix R defined by three complex angles θ_i $(i = 1, 2, 3)$ which represent the additional mixing introduced by the right handed neutrinos. The other quantities in this formula are $v_{1(2)} = v \cos(\sin)\beta$, $v = 174$ GeV; $m_\nu^{\rm diag} =$

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diag $(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$ denotes the three light neutrino masses, and $m_N^{\rm diag} = {\rm diag}\,(m_{N_1}, m_{N_2}, m_{N_3})$ the three heavy ones. $U_{\rm MNS}$ is given by the three (light) neutrino mixing angles θ_{12}, θ_{23} and θ_{13}, and three phases, δ, ϕ_1 and ϕ_2. With this parameterisation it is easy to accommodate the neutrino data, while leaving room for extra neutrino mixings (from the right handed sector). It further allows for large Yukawa couplings $Y_\nu \sim \mathcal{O}(1)$ by choosing large entries in $m_N^{\rm diag}$ and/or θ_i.

Here we focus in the particular LFV processes: 1) semileptonic $\tau \to \mu PP$ ($PP = \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0\bar{K}^0$), $\tau \to \mu P$ ($P = \pi, \eta, \eta'$), $\tau \to \mu V$ ($V = \rho, \phi$) decays and 2) $\mu - e$ conversion in heavy nuclei. The predictions in the following are for two different constrained MSSM-seesaw scenarios, with universal and non-universal Higgs soft masses. The respective parameters (in addition to the previous neutrino sector parameters) are: 1) CMSSM-seesaw: M_0, $M_{1/2}$, A_0 $\tan\beta$, and sign(μ), and 2) NUHM-seesaw: M_0, $M_{1/2}$, A_0 $\tan\beta$, sign(μ), $M_{H_1} = M_0(1+\delta_1)^{1/2}$ and $M_{H_2} = M_0(1+\delta_2)^{1/2}$.

The predictions presented here include a full one-loop computation of the SUSY diagrams contributing to these LFV processes and do not use the Leading Logarithmic (LLog) nor the mass insertion approximations. In the case of semileptonic tau decays we have not included the boxes which are clearly subdominant, but we have included correspondingly: the γ, Z and Higgs bosons, h^0 and H^0, mediated diagrams in $\tau \to \mu PP$, and the Z boson and A^0 Higgs boson mediated diagrams in $\tau \to \mu P$. The hadronisation of quark bilinears in all these semileptonic channels is performed within the chiral framework, using Chiral Perturbation Theory [4] to order and Resonance Chiral Theory [5] whenever the resonances like the ρ, etc., play a relevant role. The predictions for the $\mu - e$ conversion rates include the full set of SUSY one-loop contributing diagrams, mediated by γ, Z and Higgs bosons, as well as boxes. In this case we have followed very closely the general parameterisation and approximations of ref. [6].

2. Results and discussion

Here we present the predictions for BR($\tau \to \mu PP$) ($PP = \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0\bar{K}^0$), BR($\tau \to \mu P$) ($P = \pi, \eta, \eta'$), BR($\tau \to \mu V$) ($V = \rho, \phi$) and CR($\mu - e$, Nuclei) within the previously described framework and compare them with the following experimental bounds: BR($\tau \to \mu\pi^+\pi^-$) $< 4.8 \times 10^{-7}$, BR($\tau \to \mu K^+K^-$) $< 8 \times 10^{-7}$, BR($\tau \to \mu\pi$) $< 5.8 \times 10^{-8}$, BR($\tau \to \mu\eta$) $< 5.1 \times 10^{-8}$, BR($\tau \to \mu\eta'$) $< 5.3 \times 10^{-8}$, BR($\tau \to \mu\rho$) $< 2 \times 10^{-7}$, BR($\tau \to \mu\phi$) $< 1.3 \times 10^{-7}$, CR($\mu - e$, Au) $< 7 \times 10^{-13}$ and CR($\mu - e$, Ti) $< 4.3 \times 10^{-12}$. As a general result in LFV processes that can be mediated by

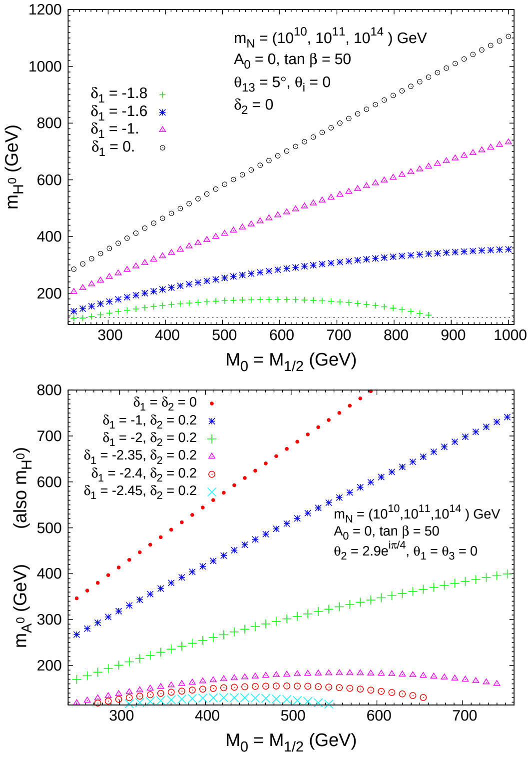

Figure 1. Predictions of the Higgs boson masses as a function of $M_{\rm SUSY}$ in the CMSSM ($\delta_1 = \delta_2 = 0$) and NUHM ($\delta_1 \neq 0$ and/or $\delta_2 \neq 0$) scenarios.

Higgs bosons we have found that the H^0 and A^0 contributions are relevant at large $\tan\beta$ if the Higgs masses are light enough. It is in this aspect where the main difference between the two considered scenarios lies. Within the CMSSM, light Higgs H^0 and A^0 bosons are only possible for low M_{SUSY} (here we take $M_{\text{SUSY}} = M_0 = M_{1/2}$ to reduce the number of input parameters). In contrast, within the NUHM, light Higgs bosons can be obtained even at large M_{SUSY}. In Fig. 1 it is shown that some specific choices of δ_1 and δ_2 lead to values of m_{H^0} and m_{A^0} as low as 110-120 GeV, even for heavy M_{SUSY} values above 600 GeV. Therefore, the sensitivity to the Higgs sector is higher in the NUHM. We start by presenting the results for the semileptonic tau decays. The mentioned sensitivity to the Higgs sector within the NUHM scenario can be seen in Fig. 2. Concretely, the BRs of the channels $\tau \to \mu K^+K^-$, $\tau \to \mu K^0\bar{K}^0$, $\tau \to \mu\pi^0\pi^0$, $\tau \to \mu\pi$, $\tau \to \mu\eta$ and $\tau \to \mu\eta'$ present a growing behaviour with M_{SUSY}, in the large M_{SUSY} region, due to the contribution of light Higgs bosons, which is non-decoupling. The decays involving Kaons and η mesons are particularly sensitive to the Higgs contributions because of their strange quark content, which has a stronger coupling to the Higgs bosons. On the other hand, the largest predicted rates are for $\tau \to \mu\pi^+\pi^-$ and $\tau \to \mu\rho$, dominated

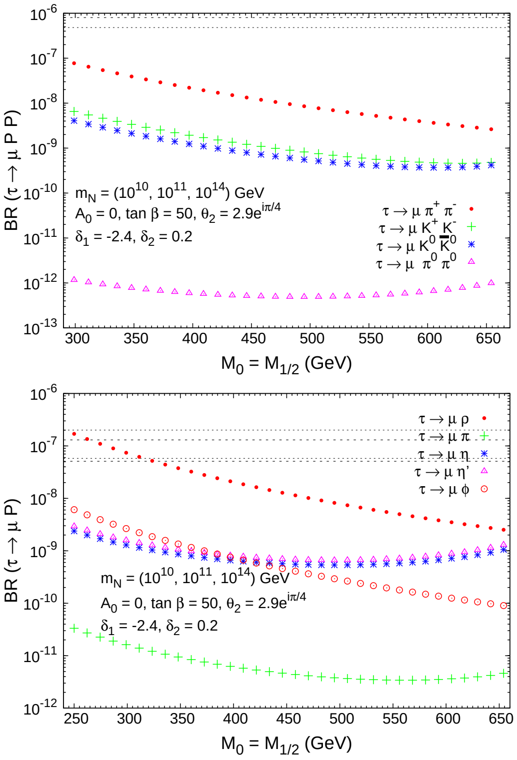

Figure 2. Present sensitivity to LFV in semileptonic τ decays within the NUHM scenario. The horizontal lines denote experimental bounds.

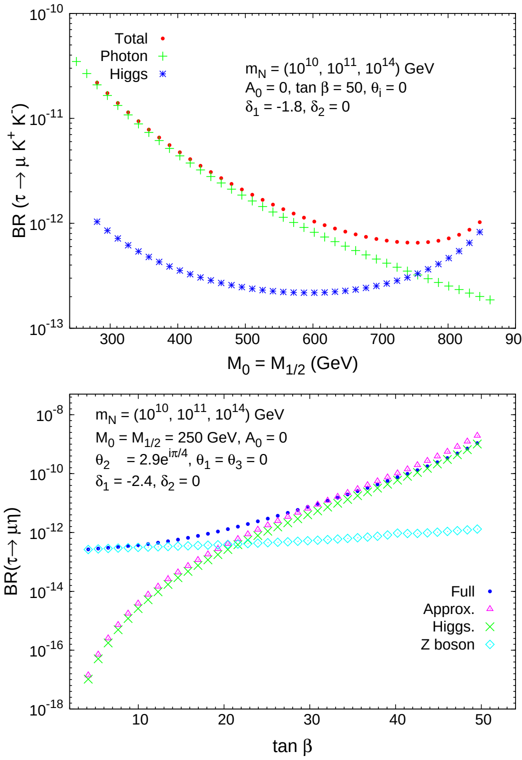

Figure 3. Comparison between the various contributions to the semileptonic LFV tau decays in the NUHM scenario: BR($\tau \to \mu K^+K^-$) plot above, BR($\tau \to \mu\eta$) plot below. In this later case, the aproximate result is also shown for comparison.

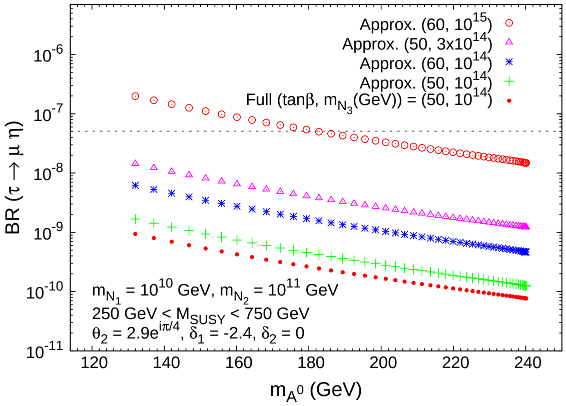

Figure 4. Sensitivity to Higgs sector in $\tau \to \mu\eta$ decays.

by the photon contribution, which are indeed at the present experimental reach in the low $M_{\rm SUSY}$ region.

The comparison between the various contributions to the semileptonic LFV tau decays in the NUHM scenario for BR($\tau \to \mu K^+K^-$) and BR($\tau \to \mu\eta$) can be seen in Fig. 3. It is clear from this figure, that $\tau \to \mu K^+K^-$ is dominated by the photon contribution, except in the large $M_{\rm SUSY}$ region , say $M_{\rm SUSY} > 750$ GeV, and large $\tan\beta$ region, say $\tan\beta \geq 50$, where the Higgs boson contribution plays an important role. Similar results are found for $\tau \to \mu K^0\bar{K}^0$. In contrast, in $\tau \to \mu\pi^+\pi^-$, the photon contribution dominantes largely the rates in all the studied region of the parameter space and therefor it is not sensitive at all to the Higgs sector. In the $\tau \to \mu\pi^0\pi^0$ channel, only the Higgs boson contributes, but the rates are extremely small. They are indeed much smaller that decays into kaons due to the fact that the Higgs couplings to the pions are proportional to m_π^2 whereas the the Higgs couplings to the pions are proportional to m_K^2. On the other hand, the $\tau \to \mu\eta$ channel is dominated by the A^0 Higgs boson contribution for all $M_{\rm SUSY}$ values, and for moderate and large $\tan\beta$, say $\tan\beta > 22$. Notice that for smaller values of $\tan\beta$ it is, however, dominated by the Z boson contribution.

A set of useful formulae for all these channels, within the mass insertion approximation which are valid at large $\tan\beta$, have also being derived by us in [1]. We include the most relevant of these aproximate formulas here, for completeness. The approximate results for the H^0-mediated contributions and the γ-mediated contributions are shown separately for comparison,

$$\begin{aligned}
&{\rm BR}(\tau \to \mu\eta)_{H_{\rm approx}} = \\
&\quad 1.2\times 10^{-7}\,|\delta_{32}|^2 \left(\frac{100}{m_{A^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
&{\rm BR}(\tau \to \mu\eta')_{H_{\rm approx}} = \\
&\quad 1.5\times 10^{-7}\,|\delta_{32}|^2 \left(\frac{100}{m_{A^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
&{\rm BR}(\tau \to \mu\pi)_{H_{\rm approx}} = \\
&\quad 3.6\times 10^{-10}\,|\delta_{32}|^2 \left(\frac{100}{m_{A^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
&{\rm BR}(\tau \to \mu\pi^0\pi^0)_{H_{\rm approx}} = \\
&\quad 1.3\times 10^{-10}\,|\delta_{32}|^2 \left(\frac{100}{m_{H^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
&{\rm BR}(\tau \to \mu\pi^+\pi^-)_{H_{\rm approx}} = \\
&\quad 2.6\times 10^{-10}\,|\delta_{32}|^2 \left(\frac{100}{m_{H^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
&{\rm BR}(\tau \to \mu K^+K^-)_{H_{\rm approx}} = \\
&\quad 2.8\times 10^{-8}\,|\delta_{32}|^2 \left(\frac{100}{m_{H^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
&{\rm BR}(\tau \to \mu K^0\bar{K}^0)_{H_{\rm approx}} = \\
&\quad 3.0\times 10^{-8}\,|\delta_{32}|^2 \left(\frac{100}{m_{H^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
&{\rm BR}(\tau \to \mu\pi^+\pi^-)_{\gamma_{\rm approx}} = \\
&\quad 3.7\times 10^{-5}\,|\delta_{32}|^2 \left(\frac{100}{M_{\rm SUSY}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \\
&{\rm BR}(\tau \to \mu K^+K^-)_{\gamma_{\rm approx}} = \\
&\quad 3.0\times 10^{-6}\,|\delta_{32}|^2 \left(\frac{100}{M_{\rm SUSY}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \\
&{\rm BR}(\tau \to \mu K^0\bar{K}^0)_{\gamma_{\rm approx}} = \\
&\quad 1.8\times 10^{-6}\,|\delta_{32}|^2 \left(\frac{100}{M_{\rm SUSY}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2
\end{aligned} \qquad (1)$$

We have shown that the predictions with these formulae agree with the full results within a factor of about 2. In the case of $\tau \to \mu\eta$ this comparison is shown in Figs. 3 and 4. It is also clear, from Fig. 3 that the approximation works much better in the large $\tan\beta$ region, $\tan\beta > 22$ where the H^0 boson dominates. Similar conclusions are found for $\tau \to \mu\eta'$. The next relevant channel in sensitivity to the Higgs sector is $\tau \to \mu K^+K^-$, but it is still below the present experimental bound. To our knowledge, there are not experimental bounds yet available for $\tau \to \mu K^0 \bar{K}^0$ and $\tau \to \mu\pi^0\pi^0$.

Finally, the maximum sensitivity to the Higgs sector is found for $\tau \to \mu\eta$ and $\tau \to \mu\eta'$ channels, largely dominated by the A^0 boson exchange. Fig. 4 shows that $\mathrm{BR}(\tau \to \mu\eta)$ reaches the experimental bound for large heaviest neutrino mass, large $\tan\beta$, large θ_i angles and low m_{A^0}. For the choice of input parameters in this figure, it occurs at $m_{N_3} = 10^{15}$ GeV, $\tan\beta = 60$, $\theta_2 = 2.9e^{i\pi/4}$ and $m_{A^0} = 180$ GeV.

Next we comment on the results for $\mu - e$ conversion in nuclei. Fig. 5 shows our predictions of the conversion rates for Titanium as a function of M_{SUSY} in both CMSSM and NUHM scenarios. As in the case of semileptonic tau decays, the sensitivity to the Higgs contribution is only manifest in the NUHM scenario. The predictions for $\mathrm{CR}(\mu - e, \mathrm{Ti})$ within the CMSSM scenario are largely dominated by the photon contribution and present a decoupling behaviour at large M_{SUSY}. In this case the present experimental bound is only reached at low M_{SUSY}. The perspectives for the future are much more promising. If the announced sensitivity by PRISM/PRIME of 10^{-18} is finally attained, the full studied range of M_{SUSY} will be covered.

Fig. 5 also illustrates that within the NUHM scenario the Higgs contribution dominates at large M_{SUSY} for light Higgs bosons. The predicted rates are close to the present experimental bound not only in the low M_{SUSY} region but also for heavy SUSY spectra. As in the previous semileptonic tau decays, we have also found a simple formula for the conversion rates, within the mass insertion approximation, which is valid at large $\tan\beta$ [2] and can be used for further analysis. This is dominated by the Higgs H^0 contribution and is given by,

$$\mathrm{CR}(\mu - e, \mathrm{Nucleus})|_{H\mathrm{approx}} \simeq \frac{m_\mu^5\, G_F^2\, \alpha^3\, Z_{\mathrm{eff}}^4\, F_p^2}{8\pi^2\, Z}\, (Z+N)^2 \left| g_{LS}^{(0)} \right|^2 \frac{1}{\Gamma_{\mathrm{capt}}},$$

$$g_{LS}^{(0)} = \frac{g^2}{48\pi^2} G_S^{(s,p)} \frac{m_\mu m_s}{m_{H^0}^2} \delta_{21} (\tan\beta)^3 \qquad (2)$$

It shows clearly the relevant features: the $\tan^6\beta$ enhacement of the rates, the Higgs mass dependence, $\propto 1/m_{H^0}^4$, and the strange quark mass dependence, $\propto m_s^2$.

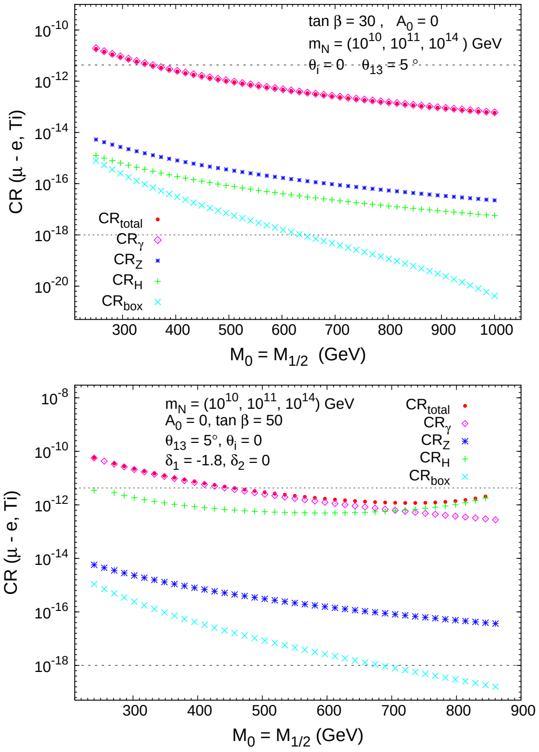

Figure 5. Predictions of $\mathrm{CR}(\mu - e,\ \mathrm{Ti})$ as a function of M_{SUSY} in the CMSSM (above) and NUHM (below) scenarios.

The predictions of the $\mu - e$ conversion rates for several nuclei are collected in Fig. 6. We can see again the growing behaviour with M_{SUSY} in the large M_{SUSY} region due to the non-decoupling of the Higgs contributions. At present, the most competitive nucleus for LFV searches is Au where, for the choice of input parameters in this figure, all the predicted rates are above the experimental bound. We have also shown in [2] that $\mu - e$ conversion in nuclei is extremely sensitive to θ_{13}, similarly to $\mu \to e\gamma$ and $\mu \to 3e$ and, therefore, a future measurement of this mixing angle can help in the searches of LFV in the $\mu - e$ sector.

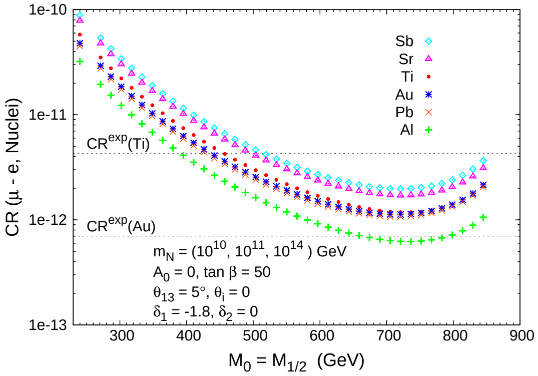

Figure 6. Present sensitivity to LFV in $\mu - e$ conversion for several nuclei within NUHM.

In conclusion, we have shown that semileptonic tau decays nicely complement the searches for LFV in the $\tau - \mu$ sector, in addition to $\tau \to \mu\gamma$. The future prospects for $\mu - e$ conversion in Ti are the most promising for LFV searches. Both processes, semileptonic tau decays and $\mu - e$ conversion in nuclei are indeed more sensitive to the Higgs sector than $\tau \to 3\mu$.

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