\tau - \mu - e \text{ Universality in } \tau \text{ Decays and Constraints on the Slepton Masses.}^* \\

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Abstract  

The leptonic \tau decays are calculated at the 1-loop level in the Minimal Supersymmetric Standard Model. The deviation from the \tau - \mu - e universality is studied as a function of the supersymmetric parameters and discussed in the context of the expected improvement of the experimental accuracy. 

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Studying the $\tau - \mu - e$ universality in the leptonic $\tau$ decays is an interesting laboratory for search for physics beyond the Standard Model.

In the Standard Model the $\tau$ decay partial width for the leptonic modes is:

$$\Gamma (\tau \rightarrow l\bar{\nu}_l\nu_\tau(\gamma)) = \frac{G_F^2 m_\tau^5}{192\pi^3} f(m_l^2/m_\tau^2) \times \left[ 1 + \frac{3}{5} \frac{m_\tau^2}{M_W^2} \left( 1 + \frac{\alpha(m_\tau)}{2\pi} \left( \frac{25}{4} - \pi^2 \right) \right) \left[ 1 + \frac{3}{5} \frac{m_\tau^2}{M_W^2} \right] \right]$$

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$ is the lepton mass correction and the last two factors are corrections from the nonlocal structure of the intermediate $W^\pm$ boson propagator and QED radiative corrections respectively.

The Fermi constant $G_F$ is determined by the muon life-time

$$G_F \equiv G_\mu = (1.16637 \pm 0.00002) \times 10^{-5} \text{GeV}^{-2} \quad (2)$$

and absorbs all the remaining electroweak radiative (loop) corrections:

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi \alpha}{2 M_W^2 (1 - M_W^2/M_Z^2)} \left( 1 - \Delta r(\alpha, M_W, M_Z, m_t, ...) \right)$$

In the on-shell renormalization scheme

$$\Delta r = -\frac{\hat{\Pi}_{WW}^T (0)}{M_W^2} + \Delta r' \quad (4)$$

where $\hat{\Pi}_{WW}^T$ is the renormalized $W^\pm$ boson self-energy calculated at zero momentum (process independent "oblique" correction) and $\Delta r'$ includes box and vertex corrections as well as the wave function renormalization factors for external neutrinos [1]. In the Standard Model the corrections $\Delta r'$ are universal for all the decays $l \rightarrow l' \nu_l \bar{\nu}_{l'}$ and hence follows the prediction (1) for the $\tau$ decays [2]. Any experimental deviation from these predictions would indicate the presence of physics beyond the Standard Model [1].

The purpose of this letter is to study the deviation from the $\tau - \mu - e$ universality in the leptonic $\tau$ decays in the framework of the Minimal Supersymmetric Standard Model (MSSM) (the quark-lepton non-universality in the MSSM has been studied in ref.[3]). The main source of non-universal contributions would be the tree level contribution from the charged Higgs boson (mass dependent couplings) and different slepton masses of the $\tilde{\mu}, \tilde{\tau}$ and $\tilde{e}$ sleptons exchanged in the loops. Thus the leptonic $\tau$ decays offer a unique possibility to establish some limits on the intergeneration mass

\footnote{Fermion mass dependence of the SM boxes and vertices as well as external momentum effects also give rise to small departure from strict universality of $\Delta r'$. This departure is, however, negligible being of order $\mathcal{O}(\alpha m_t^2/M_W^2)$.}
splitting for sleptons in absence of the intergeneration mixing. Those limits are complementary to the limits on the intergeneration mixing in the slepton mass matrix, which can be derived from the FCNC transitions [4].

With new, non-universal contributions the $G_\mu - \mu$on Fermi decay constant in eq.(1) has to be replaced by the process dependent constant

$$G_\mu \to G_{\tau,l}$$

with $G_\mu \equiv G_{\mu,e}$ in the present notation.

A new physics contribution to $G_{l,l'}$ can be classified as corrections to the strength of the effective $(V - A) \times (V - A)$ four-fermion interaction and corrections with another Lorentz structure of the effective four-fermion interaction. Supersymmetric particle exchange in the loops contributes mainly to the former whereas the tree level charged Higgs boson (and Goldstone boson) exchange contributes to the latter. Hence, the full contribution (say at 1-loop accuracy) to the $G_{l,l'}$ defined by eq.(1) can be written as [5]:

$$G^2_{l,l'} = \tilde{G}^2_{l,l'} \left( 1 + \frac{1}{32} H^2 \right) \left[ 1 - \frac{m_\mu}{m_\tau} \frac{H}{\sqrt{2} \left( 1 + \frac{1}{32} H^2 \right)} \right]$$

where

$$\tilde{G}_{l,l'} H = \frac{g_2^2 m_l m_{l'}}{2 M_W^2} \left( \frac{\tan^2 \beta}{M_{H^\pm}^2} + \frac{1}{M_W^2} \right)$$

and $\tilde{G}_{l,l'}$ is the one-loop corrected Fermi constant in the absence of the tree level Higgs contribution. It can be parameterized as:

$$\frac{\tilde{G}_{l,l'}}{\sqrt{2}} = \frac{\pi \alpha}{2 M_W^2 (1 - M_{W'}^2/M_Z^2) (1 - \Delta r) \left( 1 + \Delta' r_{l,l'} \right)}$$

where $\Delta r$ includes now all the SM corrections and the process independent ("oblique") supersymmetric corrections and $\Delta' r_{l,l'}$ contains only process dependent supersymmetric one-loop corrections.

The deviations from the $\tau - \mu - e$ universality can be conveniently discussed by studying the ratios $G_{\tau,e}/G_{\mu,e}$, $G_{\tau,\mu}/G_{\mu,e}$ and $G_{\tau,\mu}/G_{\tau,e}$, given by the ratios of the corresponding branching fractions. With the highly accurate experimental result for the $G_{\mu,e}$, the first two ratios are essentially a direct measure of non-universality in the corresponding tau decays. When the statistical error of future experiments will become negligible, the main problem for achieving maximum precision will be to reduce the systematic errors. One may expect that certain systematic errors will be cancelled in the ratio $G_{\tau,\mu}/G_{\tau,e}$.

In case the tree level Higgs exchange is negligible, i.e. for $\tau \to e\nu_{\tau}\bar{\nu}_e$ and $\mu \to e\nu_{\mu}\bar{\nu}_e$ (see below) we have $G_{l,l'} = \tilde{G}_{l,l'}$ and

$$G_{\tau,e}/G_{\mu,e} = 1 + \Delta' r_{\tau,e} - \Delta' r_{\mu,e}$$

$$G_{\tau,\mu}/G_{\mu,e} = 1 + \Delta' r_{\tau,\mu} - \Delta' r_{\mu,e}$$
For ratios involving $G_{r,\mu}$ the complete eq.(6) has to be used (in particular for large $\tan \beta$). [3]

We shall now discuss in more detail the new (supersymmetric) contributions and estimate their magnitude. The corrections $\Delta r'_{l,l'}$ contain the box, wave function renormalization and vertex contributions from the supersymmetric particle exchanges. The recent complete calculation of the $\mu$ decay in the MSSM [3] can be easily extended to study $\tau$ decays. For the details of the $G_\mu$ calculation we refer the reader to the ref. [2, 1, 6]. The extension to the case of $\tau$ decays requires the inclusion of the Higgs boson exchanges (neglected in the calculation of the $\mu$ decay width) as for large $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets, they can compete with the generic SUSY contributions. We remind that in the MSSM there are five physical Higgs bosons: one $CP$-odd $A^0$, two $CP$-even $H^0$ and $h^0$ and two charged $H^\pm$. The rough estimate of various contributions to the $\tau \to l\nu\bar{l}\nu$ decay amplitude is as follows. The tree level charged Higgs boson exchange is suppressed as compared to the dominant tree level $W^\pm$ exchange by the factor

$$\left(\frac{m_\tau m_l}{M_{H^\pm}^2}\right) \tan^2 \beta$$

(10)

Similar diagram generated by the charged Goldstone boson is much smaller (for $M_{H^\pm} \sim M_W$) since the couplings of the Goldstone bosons do not have the $\tan \beta$ amplification. The dominant diagrams containing one loop corrections to the $\tau W^\pm \nu$ vertex have the following suppression factors (compared to the dominant tree level graph):

- $\frac{g^2}{16\pi^2} \left(\frac{m_\tau^2}{M_W^2}\right) \tan \beta \left(\frac{M_{H^\pm}^2}{M_{H^0(h^0)}^2}\right)$ - for loops with $H^0(h^0)W^\pm \tau$ and $H^0(h^0)G^\pm \tau$ exchange,

- $\frac{g^2}{16\pi^2} \left(\frac{m_\tau^2}{M_W^2}\right) \tan^2 \beta \left(\frac{M_{H^\pm}^2}{M_{A^0}^2}\right)$ - for loops with $H^0(h^0)H^\pm \tau$ or $A^0H^\pm \tau$ exchange,

- $\frac{g^2}{16\pi^2} \left(\frac{M_W^2}{M_{SUSY}^2}\right)$ - for genuine SUSY loops generated by charginos/neutralinos and sleptons.

Other possible vertex diagrams do not contain $\tan \beta$. Similar estimates with $m_\tau \to m_l$ hold for the $lW^\pm \nu_l$ vertex. For dominant box contributions we have the following estimates:

\[\text{In many presentations the deviation from universality are parameterized in terms of the "effective" coupling constants } G_{l,l'} = g_l g_{l'}. \text{ However, as we see, the new physics contribution, in general, do not factorize and this parameterization is unnatural.}\]
- \frac{g^2}{16\pi^2} \left( \frac{m_{\tau}}{M_W} \right) \tan^2 \beta - (\text{where } M \text{ is the maximal mass circulating in the loop}) \text{ for boxes with } H^0(h^0)W^\pm, A^0W^\pm \text{ or } Z^0H^\pm \text{ exchange,}

- \frac{g^2}{16\pi^2} \left( \frac{m_{\tau}}{M_W^H} \right)^2 \tan^4 \beta - \text{ for boxes with } H^0(h^0)H^\pm \text{ or } A^0H^\pm \text{ exchange,}

- \frac{g^2}{16\pi^2} \left( \frac{M_W^2}{M_{\text{SUSY}}^2} \right) - \text{ (where } M_{\text{SUSY}} \text{ is the maximal SUSY mass circulating in the loop) \text{ for genuine SUSY loops generated by charginos/neutralinos and sleptons.}

From the above estimations, taking into account that \( \frac{g^2}{16\pi^2} \sim 2.5 \times 10^{-3} \) and \( \left( \frac{m_{\tau}^2}{M_W^2} \right) \sim 5 \times 10^{-4}, \left( \frac{m_\tau^2}{M_W^2} \right) \sim 1.5 \times 10^{-6} \) and \( \left( \frac{m_\tau^2}{M_W^2} \right) \sim 4 \times 10^{-11} \), it is clear that for the decay \( \tau \to e\nu_\tau \bar{\nu}_e \) the only contribution with the Higgs boson exchange which can be important is the one of the second type to the \( \tau \) vertex (and this is for large values of \( \tan \beta \), say, \( \tan \beta > 20 \)). Together with the corresponding contribution to the renormalized \( \nu_\tau \) self energy the following Higgs contribution to \( \Delta r'_{\tau,e} \) is obtained in the limit of large \( \tan \beta \):

\[
\delta(\Delta r'_{\tau,e}) = -\frac{g^2}{128\pi^2} \left( \frac{m_{\tau}}{M_W} \tan \beta \right)^2 \times \left[ -2 + I(A^0, H^\pm) + \cos^2 \alpha I(H^0, H^\pm) + \sin^2 \alpha I(h^0, H^\pm) \right]
\]

where \( I(1, 2) = \frac{1}{2} \frac{m_1^2 + m_2^2}{m_1^2 - m_2^2} \log \frac{m_1^2}{m_2^2} \) (12)

and \( \alpha \) is the mixing angle which diagonalizes the \( CP \)-even Higgs bosons mass matrix. The remaining new (supersymmetric) contribution to \( \Delta r'_{\tau,\mu} \) can be found in Appendix A of ref. [3].

Similar corrections have to be included for the decay \( \tau \to \mu\nu_\tau \bar{\nu}_\mu \), in the limit of large \( \tan \beta \). In addition, in this case, the tree level \( H^\pm \) exchange may become important (for a not too heavy \( H^\pm \)) and comparable with the genuine SUSY vertex and box corrections. The effective Fermi constant is then given by the formula (6).

For the sake of definiteness, we begin the discussion of the results with the ratio \( G_{\tau,e}/G_{\mu,e} \), which is given by eq.(9). The corrections \( \Delta r'_{L,V} \) depend, in general, on the chargino, neutralino and slepton masses and weakly (through the Higgs exchanges in the loop) on \( \tan \beta \) and \( M_{H^\pm} \) (the two parameters specify completely the Higgs sector). In case of no \( \text{Left} - \text{Right} \) mixing in the slepton mass matrix the results depend on the masses of the left-handed sfermions only. They can be parameterized by the sneutrino masses \( M_{\tilde{\nu}_I} \) (I=1,2,3) and are given by the relation:

\[
M_{\tilde{\nu}_I}^2 = M_{\tilde{e}_I}^2 + m_{\tilde{l}_I}^2 - M_W^2 \cos 2\beta
\]

(13)
It is natural to study the ratio $G_{\tau,e}/G_{\mu,e}$ as a function of the slepton masses (which can give the non-universal contribution), for several different sets of values of the "universal" variables: the chargino and neutralino masses, $\tan\beta$ and $M_{H^\pm}$. Furthermore, the considered ratio depends on four SUSY vertex corrections, one of them being common for both $G_{\tau,e}$ and $G_{\mu,e}$. We choose to fix the mass of the sneutrino corresponding to the "common" vertex and study the ratio $G_{\tau,e}/G_{\mu,e}$ as a function of:

$$x_{\tau,\mu} = \frac{M_{\tilde{\nu}_e}^2 - M_{\tilde{\nu}_\tau}^2}{M_{\tilde{\mu}_\mu}^2 + M_{\tilde{\nu}_e}^2}$$ (14)

The results are are shown in Figs. 1 and 2 where we plot the ratio $G_{\tau,e}/G_{\mu,e}$ as a function of $x_{\tau,\mu}$ for four different masses of the "same" $\tilde{\nu}$ sneutrino. Each point in the shadowed area correspond to a pair of values $(M_{\tilde{\nu}_e}, M_{\tilde{\nu}_\tau})$ (which we scanned in the range $50-500$ GeV) demonstrating the (weak) dependence on the variable complementary to $x_{\tau,\mu}$.

The pattern of those results can be understood as follows. For low value of the "same" sneutrino mass $M_{\tilde{\nu}_e}$ both $\Delta r'_{\tau,e}$ and $\Delta r'_{\mu,e}$ in eq.(7) receive similar corrections and $G_{\tau,e}/G_{\mu,e} \sim 1$. When both $M_{\tilde{\nu}_e}$ and $M_{\tilde{\nu}_\mu}$ are heavy, this happens because each of $\Delta r'$ in eq.(7) receives contribution only from the corrections to the "same" vertex $eW^\pm\tilde{\nu}_e$, the corrections to other vertices and boxes being suppressed by the inverse heavy mass squared according to the Appelquist-Carazzone decoupling theorem. If, e.g, the $\tau$ sneutrino becomes light (positive $x_{\tau,\mu}$) then $\Delta r'_{\tau,e}$ receives additional negative contribution from the $\tau W^\pm\tilde{\nu}_e$ vertex. However, at the same time there is also a substantial contribution from SUSY box diagram to $\Delta r'_{\tau,e}$ which is positive and as a result of the cancelation one gets again $G_{\tau,e}$ only slightly different from $G_{\mu,e}$. On the other hand, for a heavy "same" sneutrino mass $M_{\tilde{\nu}_e}$ only $\tau W^\pm\tilde{\nu}_\tau$ and $\mu W^\pm\tilde{\nu}_\mu$ vertices can give substantial negative contributions depending on which of the $\tau$ and $\mu$ sneutrino masses is light, thus explaining the pattern of the plots for heavy $M_{\tilde{\nu}_e}$.

For fixed $\tan\beta$ the effects vanish, of course, with increasing chargino and neutralino masses roughly as $M_W^2/M_{m_{\text{min}}(C,N)}^2$. This can be seen by comparing Figs. 1 and 2. The results depend also on $\tan\beta$, and are bigger for smaller values of $\tan\beta$, for fixed values of the physical chargino and neutralino masses. The $\tan\beta$ dependence is such, that it is small for fixed values of the $M_{gau}$ and $\mu$ parameters specifying the chargino and neutralino masses.

Exactly analogous results hold for the other two ratios $G_{\tau,\mu}/G_{\mu,e}$ and $G_{\tau,\mu}/G_{\tau,e}$ (with obvious interchange of $x_{\tau,\mu}$ into $x_{\tau,e}$ and $x_{\mu,e}$ respectively) for $\tan\beta < 15$, i.e. as long as the tree level Higgs exchange can be neglected.

Next we discuss the results for the ratio $G_{\tau,\mu}/G_{\mu,e}$ for large $\tan\beta$ values (and light charged Higgs boson). In that case, as can be seen from eq.(6) and Figure 3, the contribution of the tree level $H^\pm$ exchange lowers the predicted
value of the $G_{\tau,\mu}$. The effects of the Higgs boson 1-loop contributions to the vertices remain, however, unnoticeable.

Fig. 4 shows how in the large $\tan \beta$ case the non-universal effects decrease with the increasing chargino masses (this effect is similar as for the $G_{\tau,e}/G_{\mu,e}$) and increasing charged Higgs boson mass (a smaller overall shift of the whole plot toward negative values).

The mixing between the left and right-handed charged sleptons is proportional to the corresponding lepton mass and therefore is not expected to play a significant role for selectrons and smuons. For staus it can be significant and leads to a) lower values of the lighter $\tilde{\tau}$ slepton (for the same tau sneutrino mass), b) admixture to it of the right-handed component, which is not active in the vertex. Both effects tend to cancel each other. In order to demonstrate how the Left-Right mixing in the stau mass matrix changes the results described above we plot in Fig. 5 the ratio $G_{\tau,\mu}/G_{\mu,e}$ as a function of the lighter stau mass $M_{\tilde{\tau}_1}$ for $M_{\tilde{\nu}_\mu} = M_{\tilde{\nu}_e} = 500$ GeV. The numbers in the parentheses denote the masses of $\tilde{\nu}_\tau$ and $\tilde{\tau}_R$. At the right-most point of each curve the off-diagonal entry of the stau mass matrix vanishes. At those points the mass of $\tilde{\tau}_1$ (which for the values of the parameters shown in Fig. 5 corresponds then to $\tilde{\tau}_L$) is given by eq.(13). The Left-Right mixing increases from the right to the left of the plot until the lighter $\tilde{\tau}_1$ mass reaches $45$ GeV - the current experimental limit. As can be seen, with the Left-Right mixing the deviation of the ratio $G_{\tau,\mu}/G_{\mu,e}$ from unity slightly increases as compared to the case with no Left-Right mixing and the same value of $M_{\tilde{\nu}_e}$. Note also that with the Left-Right mixing the same value of $M_{\tilde{\nu}_e}$ may correspond to different predictions for $G_{\tau,\mu}/G_{\mu,e}$ (of course for different $M_{\tilde{\nu}_\mu}$).

For the future precision of $G_{\tau,\mu}$ and $G_{\tau,e}$ measurements [7, 8, 9, 10] of order 0.1% ($G_{\mu,e}$ is known with 0.002% precision) the only effect that eventually can be observed is the slightly smaller value of $G_{\tau,\mu}$ as compared to $G_{\tau,e}$ and $G_{\mu,e}$ (which, within this accuracy, should coincide in MSSM). If measured, such effect would mean a rather precise information about MSSM: large $\tan \beta > 20$, small $M_{H^\pm} \sim M_W$ (corresponding to small $M_{A^0}$), light charginos and neutralinos and large hierarchy in the slepton masses: $M_{\tilde{\nu}_e} \ll M_{\tilde{\nu}_\mu} \sim M_{\tilde{\nu}_e}$ This last point is in qualitative agreement with the tendency observed in the RGE evolution of the soft SUSY breaking terms from $M_{Planck}$ down to $M_W$: the large (in the case of large $\tan \beta$) Yukawa coupling of the tau drives its sneutrino mass to lower values than the masses of $\tilde{\nu}_\mu$ and $\tilde{\nu}_e$.

We remark also that the new evidence from CDF for the heavy top quark, $M_t = (174\pm20)$ GeV, is consistent with the minimal SO(10) Yukawa coupling unification $Y_t = Y_b$ and very large $\tan \beta$ values, $\tan \beta = 50 - 60$ [11]. For such values of $\tan \beta$, the tree level charge Higgs exchange effect seen in Fig. 3 and Fig. 4 is amplified by factor 4-5. The accuracy 0.1% for $G_{\tau,\mu}$ will be sufficient to confirm or rule out the large $\tan \beta$ scenario with $M_{H^\pm} = (100 - 200)$ GeV.

If the precision of the $G_{\tau,\mu}$ and $G_{\tau,e}$ measurements reaches 0.01% accuracy
then, as can be seen from our results, the sparticle (or in particular the slepton) masses become strongly constrained.

Finally we comment on the non-universal contributions to the decays $\pi \rightarrow \mu \nu_{\mu}$ and $\pi \rightarrow e \nu_{e}$. For heavy enough squarks, say $M_{\tilde{q}} > 300$ GeV, our results obtained for $G_{\tau,\mu}/G_{\tau,e}$ with $M_{\tilde{\nu}} > 300$ GeV apply directly to the pion decays, too. Indeed, in this case the only non-negligible source of non-universality in both $\pi$ and $\tau$ decays can be the supersymmetric contributions to the $\mu$ and $e$ vertices. The present experimental value $(g_{\mu}/g_{e})_{\pi} = 1.0014 \pm 0.0016$ is, however, not accurate enough to draw any firm conclusion (apart from the statement that $M_{\tilde{e}}$ cannot be much heavier than $M_{\tilde{\mu}}$). For lighter squarks a complete perturbative calculation of the effective four-Fermi lagrangian is necessary. As usual, at any given order, the results will depend on the cut-off separating the perturbative from non-perturbative regimes.

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FIGURE CAPTIONS

Figure 1. Departure from universality in the $\tau \rightarrow e \nu_\tau \bar{\nu}_e$ decay as a function of the variable $x_{\tau,\mu}$ defined in the text, for four different values of the $\bar{\nu}_e$ mass.

Figure 2. The same as in Figure 1 but for smaller chargino and neutralino masses.

Figure 3. Departure from universality in $\tau \rightarrow \mu \nu_\tau \bar{\nu}_\mu$ decay as a function of the variable $x_{\tau,e}$ defined in the text, for four different values of the $\bar{\nu}_\mu$ mass.

Figure 4. The same as in Figure 3 but for different charged Higgs boson mass $M_{H^\pm}$ and larger chargino and neutralino masses.

Figure 5. Effects of the Left-Right mixing in the $\tilde{\tau}_1, \tilde{\tau}_2$ mass matrix. The departure from universality is shown here as a function of the lighter $\tilde{\tau}$ mass. $M_{\bar{\nu}_e} = M_{\bar{\nu}_\mu} = 500$ GeV and the numbers in the parentheses correspond to the masses (in GeVs) $(M_{\bar{\nu}_e}, M_{\tilde{\tau}_\mu})$. At the rightmost points of each curve the mixing vanishes.
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