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TAU-UNIVERSALITY VIOLATION WITH LIGHT NEUTRALINOS

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ABSTRACT

In a supersymmetric model with the lightest supersymmetric particle (LSP) χ in the range of a few hundred MeV's, the decay $\tau \rightarrow \mu \chi \chi$ is going to be allowed. We investigate the departure from tau-universality caused by this decay. It is found that the universality violation in this way can be greater than both non-universal electroweak radiative corrections and supersymmetric one-loop corrections over a considerable region of the parameter space allowed by experiments so far. Thus it suggests a method of constraining the parameter space with light LSP's using data from tau-factories.

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The search for supersymmetry (SUSY) [1] has been an active area for quite some time now. Results from the Large Electron-Positron (LEP) collider at CERN have put a lower mass bound of $m_Z/2$ on most supersymmetric particles except for the gluino and the lightest supersymmetric particle (LSP) [2]. Also, the Fermilab Tevatron experiments imply lower bounds in the range of 150-200 GeV on strongly interacting superparticles like the squarks and the gluino [3]. However, it is widely held that a region in the parameter space containing light gluinos (2.5-5 GeV) cannot be completely ruled out yet [4]. In such a case, a squark can also be considerably lighter (~ 70 GeV or so) while still evading experiments, since it will decay promptly into a quark and a (light) gluino, the latter being instrumental in degrading the missing transverse energy so that the corresponding events do not survive the cuts imposed in hadronic collision experiments. Motivations for a light gluino also come from the observation that it leads to a better agreement between theory and experiment in the running of the strong coupling constant α_s [5]. Theoretically, some attempts have been made in recent times to justify scenarios involving light gauginos in models of radiative SUSY breaking where dimension-3 terms are absent [6]. Also, efforts have been made to constrain light superparticles from various phenomenological considerations [7].

Evidently, a light LSP is always present in the scenario described above. In most SUSY searches, relations among the various parameters are used to simplify the picture by postulating the SUSY to be embedded in a Grand Unified Theory (GUT). This has an added incentive in the demonstration that the three coupling constants can be made to unify exactly at the energy scale of 10^{16} GeV if the theory is supersymmetric [8]. Under a GUT hypothesis, a light gluino in the range 2.5-5 GeV normally implies an LSP with mass between 0.4-1.0 GeV. It is also seen that under such circumstances, all observables are consistent with the LEP data provided that one is in a region of the parameter space where $-50 \text{ GeV} \geq \mu \geq -100 \text{ GeV}$, and $1.5 \leq \tan\beta \leq 2.0$, μ and $\tan\beta$ being respectively the Higgsino mass parameter and the ratio of the vacuum expectation values of the two Higgs doublets. Side by side, some

models like those involving radiative SUSY breaking have suggested LSP's as light as about 100 MeV [6]. It has also been claimed that, contrary to earlier conclusions, a light LSP in the range of a few hundred MeV's *can* be reconciled with the dark matter content of the universe [9]. Thus it is desirable to have as many model-independent criteria as possible to explore a light LSP in the laboratory. Some such studies have recently been conducted by us in the light of B-decay experiments [10]. Here we would like to emphasize that the precise measurement of weak universality violation in τ -decays can also yield useful information in this context.

Weak universality has been found to hold rather accurately in the $e - \mu$ sector, as is seen from a comparison of the results from pion-decay with theoretical predictions. Similarly, the universality of charged current interactions involving the τ can be subjected to accurate tests in the decays such as $\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$ and $\tau \rightarrow e \bar{\nu}_e \nu_\tau$, as also from $W \rightarrow \tau \bar{\nu}_\tau$ and $\tau \rightarrow \pi \nu_\tau$ [11]. Precise determination of the mass, lifetime and the various branching ratios of the τ in a τ -factory can further check the standard model predictions in this respect [12].

Let us now consider the various ways in which τ -decay may exhibit departure from universality in the measurements of the leptonic decay modes. To be specific, let us talk about the decay $\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$, and call the corresponding effective Fermi coupling constant $G_{\tau\mu}$. The total decay width in the above channel, including QED corrections, is given by [13]

$$\Gamma^0 = \frac{G_{\tau\mu}^2 m_\tau^5}{192\pi^3} \left[1 + \frac{\alpha}{2\pi} (25/4 - \pi^2) \right] \left[1 + \frac{3m_\tau^2}{5m_W^2} \right] f(x) \quad (1)$$

with

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \quad (2)$$

The last two factors above correspond to the effects of the τ -momentum in the W-propagator and the final state muon mass respectively. Here $G_{\tau\mu}$ is assumed to include the one-loop electroweak radiative corrections [14] comprising W-boson self-energy, box and triangle diagrams. Thus $G_{\tau\mu}$ is related to the corresponding quantity $G_{\mu e}$ by

$$\frac{G_{\tau\mu}}{G_{\mu e}} = 1 + \Delta r_\tau - \Delta r_\mu \quad (3)$$

where

$$\Delta r_l = -\frac{\Pi_{WW}^T(0)}{m_W^2} + \text{box} + \text{triangle} \quad (4)$$

in the on-shell renormalisation scheme. Thus the deviation of $\frac{G_{\tau\mu}}{G_{\mu e}}$ from unity depends on the cancellation between one-loop corrections to τ - and μ -decay, and is of the order of $\frac{\alpha}{4\pi} \frac{m_\tau^2}{m_W^2} \sim 10^{-6}$.

In a SUSY scenario, one-loop graphs involving superparticles further contribute to $\frac{G_{\tau\mu}}{G_{\mu e}}$. The resulting departures from universality have been studied in reference [15] where the potential contributions from charged-Higgs mediated tree graphs have also been taken into account. We shall return to comment upon them later.

Our purpose is to point out at this juncture that in the presence of a light LSP χ , the tree-level decay $\tau \rightarrow \mu \chi \chi$ is also possible. Because of the invisibility of the LSP, this leads to the same observed final state as $\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$. As a result, the effective value of $G_{\tau\mu}$ as measured from $\tau \rightarrow \mu + \text{nothing}$ receives an additional positive contribution. This contribution is absent in the case of muon decays if $m_\chi \geq m_\mu/2$. If we label the width for $\tau \rightarrow \mu \chi \chi$ as Γ^{SUSY} , then, neglecting one-loop effects for the time being, we obtain

$$\frac{G_{\tau\mu}^2}{G_{\mu e}^2} = 1 + \frac{\Gamma^{SUSY}}{\Gamma^0} \quad (5)$$

or

$$\frac{G_{\tau\mu}}{G_{\mu e}} - 1 = \sqrt{1 + \frac{\Gamma^{SUSY}}{\Gamma^0}} - 1 \quad (6)$$

Γ^{SUSY} can receive tree-level contributions because, in a SUSY model, the lepton and slepton mass matrices are not in general simultaneously diagonal. This is plausible if one assumes the SUSY to be embedded in a higher symmetry which is broken at a high energy scale [16]. (One standard way to envision this while at the same time providing a rather logical method of breaking SUSY is to work with a model based on N=1 supergravity (SUGRA), the SUGRA being broken at the GUT scale, leaving as its artifacts soft SUSY breaking terms at the electroweak scale.) The scalar masses in the resulting theory undergo quantum corrections as they evolve from the high scale to the electroweak energy. Thus, if the neutrinos have non-vanishing masses, the charged slepton mass matrix in the left sector is given by

$$M_{\tilde{l}}^2 = \mu^2 + M_l M_l^\dagger + c_0 M_\nu M_\nu^\dagger \quad (7)$$

where the last term arises from the Yukawa couplings of left-sleptons with charged Higgsinos, c_0 being a model-dependent parameter. It is the presence of this term which causes a mismatch between M_l and $M_{\tilde{l}}$ [17]. Consequently, the lepton-slepton-neutralino interactions in general do violate flavour. Since the neutrino mass parameters that occur in the Yukawa couplings correspond to the Dirac mass terms, see-saw type scenarios with large Majorana masses entail the possibility of such parameters being of the order of the tau-mass itself [18]. Consequently, the flavour-changing interactions, particularly those involving the third generation, are also at their strongest in such cases.

The tree-level flavour violating lepton-slepton-LSP coupling allows the decay $\tau \rightarrow \mu \chi \chi$

through the diagrams shown in figure 1. With m_χ in the range of a few hundred MeV's, assuming χ to be dominantly a photino [19], the flavour-violating interaction is given by

$$\mathcal{L}_{l_i \tilde{l}_j \chi} = -\sqrt{2} e c_{ij} \tilde{l}_j^\dagger \bar{\chi} \left[\frac{1 - \gamma_5}{2} \right] l_i + h.c. \quad (8)$$

\tilde{l} being a left slepton. Here c_{ij} is the parameter characterizing the amount of flavour violation, and is a function of the parameter c_0 and the leptonic mixing matrix. We treat the c_{ij} 's as phenomenological inputs here. The best experimental constraints on them are obtained from limits on decays like $\mu \rightarrow e \gamma$ and $\tau \rightarrow \mu \gamma$ [20]. It can be seen by suitably translating the limits given in reference [20] and using the current bounds on these rare decays [2] that while radiative μ -decay leads to the constraint $\left(\frac{c_{12} \Delta m_{\tilde{l}}^2}{m_{\tilde{l}}^2} \right)_{max} \approx 10^{-3}$, the restriction on the τ -sector is much less severe, namely $\left(\frac{c_{23} \Delta m_{\tilde{l}}^2}{m_{\tilde{l}}^2} \right)_{max} \approx 0.2 - 0.3$ (absolute values implied). For our purpose here the latter is important. Thus, from a model-independent point of view there is the possibility of relatively large values of the flavour-changing transition between the third and the second generations of leptons in a SUSY scenario.

The squared matrix element for $\tau(p_0) \rightarrow \mu(p_3) \chi(p_1) \chi(p_2)$ is

$$\mathcal{M}^2 = \left(\frac{64 g^4 \text{Sin}^2 \theta_W c^2}{m_{\tilde{l}}^4} \right) \left[(p_0 \cdot p_1)(p_2 \cdot p_3) + (p_0 \cdot p_2)(p_1 \cdot p_3) - m_\chi^2 (p_0 \cdot p_3) \right] \quad (9)$$

where

$$c = c_{23} \frac{\Delta m_{\tilde{l}}^2}{m_{\tilde{l}}^2} \quad (10)$$

$m_{\tilde{l}}$ and $\Delta m_{\tilde{l}}^2$ being respectively the average slepton mass and the mass-squared difference between the left smu and stau.

The branching ratios for this decay as well as the observed departure from universality, parametrized by $\frac{G_{\tau\mu}}{G_{\mu e}} - 1$, can be directly computed using equations (6) and (9). Both these

quantities are presented as functions of the LSP mass in figures 2 and 3 respectively. It is obvious from equation (6) that to the leading order, $\left(\frac{G_{\tau\mu}}{G_{\mu e}} - 1\right) \approx (\Gamma^{SU\!SY}/2\Gamma^0) \sim c^2 m_{\tilde{l}}^{-4}$. Thus its dependence on c and the slepton mass can be studied from Figure 3 itself by suitable scaling.

Figure 2. gives us an idea of the order of magnitude of the branching ratio for the tau decaying into a pair of LSP's. The curve corresponds to $m_{\tilde{l}} = 60 \text{ GeV}$ and a 20 per cent slepton mass-squared splitting. The experimental constraints discussed above allow this region of the parameter space even upto $c_{23} \approx 1$.

Figure 3. uses two values of the average slepton mass, and $c = 0.01$ in magnitude. From the standpoint of experimental limits this is again a quite conservative choice of parameters. It is found that the departure from universality due to $\Gamma^{SU\!SY}$ can be greater than that from any other source so long as $m_{\chi} \leq 0.5\text{GeV}$, $m_{\tilde{l}} \leq 100 \text{ GeV}$ and $c \leq 0.1$ approximately. This immediately suggests the feasibility of limiting a rather large and hitherto unconstrained area of the parameter space in a scenario with light LSP's. This should be possible with the accumulation of about 10^{7-8} τ 's in a τ -factory. The important point to note here is that the analysis performed here is essentially *model-independent* in nature; even the GUT assumptions are not used. Therefore, any constraints obtained by this method pertain to non-minimal versions of SUSY as well.

A few comments are in order concerning the one-loop SUSY effects vis-a-vis the tree-level effects discussed here. Firstly, for the choice of parameters, if we use the guidelines available from a GUT-inspired scenario, then a light LSP (and gluino) should correspond to $\tan\beta \leq 2$. Also, it can be easily verified that the charged Higgs mass has to be about a hundred GeV so that the LEP limits on the Higgs sector are obeyed. In such a case, as has been shown in reference [15], the Higgs-mediated one-loop corrections to $\tau \rightarrow \mu \bar{\nu}_{\mu} \nu_{\tau}$ tend to be small. In a similar way, the Higgs mediated tree-level diagram gives a very

small ($O(10^{-8})$) contribution to $\left(\frac{G_{\tau\mu}}{G_{\mu e}} - 1\right)$. The remaining part of the one-loop SUSY effect consists in diagrams mediated by charginos and neutralinos. There, too, the important quantity is $\Delta r_{\tau}^{SUSY} - \Delta r_{\mu}^{SUSY}$ *i.e.* the difference between the nonuniversal parts of the two contributions. The net effect is thus controlled by $\frac{\Delta m_i^2}{m_i^2}$ and $\frac{\Delta m_{\tilde{\nu}}^2}{m_{\tilde{\nu}}^2}$. The enhancements due to a light LSP in the loop mostly contribute to the universal part of the correction [21] and cancel out in $\left(\frac{G_{\tau\mu}}{G_{\mu e}} - 1\right)$. It is thus estimated that the loop contributions to leptonic tau-decay with a light LSP is at best of the order of 10^{-4} , and that, too, with a rather large (more than 50 per cent) slepton mass splitting. On the other hand, our calculations show that the tree level contributions to departure from universality can be as large as, and perhaps larger than, 10^{-4} even for much smaller splitting between slepton masses. This is evident if one notes that, for example, $|c| = 0.01$ (the value used in Figure 3) is achievable even with $\left|\frac{\Delta m_i^2}{m_i^2}\right| = 0.2$ and $|c_{23}| = 0.05$, which is well within the region of the parameter space allowed by current experimental limits. Thus the tree-level flavour-changing decay should give more useful clues in restricting the parameter space with light LSP's using departure from τ - universality at the level of reference [15].

A lower limit of about 5 GeV on the LSP mass has been claimed earlier using the process $e^+e^- \rightarrow \gamma\tilde{\gamma}\tilde{\gamma}$, so long as the selectron is lighter than 55 GeV [22]. However, the study of tau decays can improve this limit in a model-independent manner for either the smuon or the stau having a lower mass.

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Figure Captions

Figure 1:

The tree-level contributions to $\tau \rightarrow \mu\chi\chi$. In addition there will be crossed diagrams where the four-momenta of the LSP's are interchanged.

Figure 2:

The branching ratio for $\tau \rightarrow \mu\chi\chi$ scaled by the parameter c_{23} , plotted against the LSP mass, for $|\frac{\Delta m_l^2}{m_l^2}| = 0.2$ and $m_{\tilde{l}} = 60 \text{ GeV}$.

Figure 3:

The quantity $\frac{G_{\tau\mu}}{G_{\mu e}} - 1$ plotted against the LSP mass, for $|c| = |c_{23} \left(\frac{\Delta m_l^2}{m_l^2}\right)| = 0.01$. The solid and dashed lines correspond to $m_{\tilde{l}} = 45 \text{ GeV}$ and $m_{\tilde{l}} = 60 \text{ GeV}$ respectively.