I. $\mu \to e$ CONVERSION IN NUCLEI

A. Introduction [2 pages]

With the discovery of neutrino masses and lepton mixing, the fact that individual lepton-flavor numbers – electron-number, muon-number, and tau-number – are not conserved has been established. All such violating effects to date have been observed in the neutral lepton sector, through the phenomenon of neutrino oscillations. Charged-lepton flavor-violation (CLFV), on the other hand, has been the subject of intense experimental searching since the discovery of the muon but, to this date, no evidence for it has ever been uncovered.

The Standard Model augmented by new physics that leads to the experimentally observed neutrino masses predicts a non-zero rate for CLFV process, but expectations depend dramatically on the mechanism responsible for neutrino mass generation. For example, if the physics responsible for neutrino masses is very heavy (as in the case of a high mass scale seesaw mechanism) or very weakly coupled (as in the case of Dirac neutrinos), expectations for CLFV processes are around forty orders of magnitude smaller than current experimental bounds. The reason for this is that the active neutrino contribution is GIM suppressed, such that the amplitude for CLFV is proportional to the tiny neutrino mass-squared differences. For example, the massive neutrino contribution (Fig. 1) to $\mu \to e\gamma$ is

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}, \tag{1}$$

where $U_{\alpha i}$, $\alpha = e, \mu, \tau$ and $i = 1, 2, 3$, are the elements of the neutrino mixing matrix and M_W is the W-boson mass.

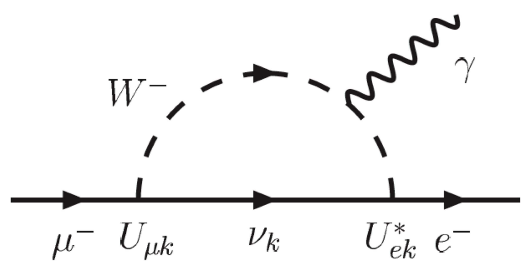

FIG. 1: Massive neutrino contribution to the charged lepton flavor-violating muon decay $\mu \to e\gamma$. ν_i are neutrino mass eigenstates, while $U_{\alpha k}$, $\alpha = e, \mu, \tau$ and $k = 1, 2, 3$, are the elements of the lepton mixing matrix.

On the other hand, certain neutrino mass generating mechanisms are already disfavored due to the fact that CLFV has yet to be observed. It is fair to say that searches for CLFV are bound to play a key role as far as uncovering the origin of neutrino masses. Moreover, like other flavor-changing neutral current processes, searches for CLFV are also among the most powerful and promising probes of new physics at or even above the TeV scale, regardless of its connection to neutrino masses. Concrete examples will be discussed in the next subsection.

Among the different CLFV channels, three rare muon processes stand out, thanks in part to the muon's small mass and long lifetime: $\mu \to e\gamma$, $\mu \to eee$ and $\mu \to e$-conversion in nuclei. Current experiments have been able to rule out, at the 90% confidence level, $\mu^+ \to e^+\gamma$ with branching ratios above 1.2×10^{-11} and $\mu^+ \to e^+e^-e^+$ with branching ratios above 1.0×10^{-12}, while the rate for $\mu^- + {}^{48}\mathrm{Ti} \to e^- + {}^{48}\mathrm{Ti}$ normalized to the capture rate ($\mu \to e$ conversion in titanium), is constrained to be less than 4.3×10^{-12}. [**other bounds here?**] The concurrent exploration of all three rare muon processes is of the utmost importance given that these are all state-of-the-art, extremely challenging experiments and the fact that the three process "feel" different types of new physics in distinct ways. If CLFV is observed in either one of these processes, results from other searches will play a fundamental role as far as establishing the nature of the lepton-flavor violating new physics.

Depending on the nature of the CLFV physics, one of the three bounds listed above turns out to be the most significant. For a particular class of models, including several of the standard supersymmetric ones, efforts to observe $\mu \to e\gamma$ prove to be most promising currently and in the immediate future. The MEG experiment, currently taking data at PSI, is aiming at being sensitive to $\mu \to e\gamma$ branching ratios larger than several times 10^{-14} [**check**]. However, given the existence of very intense future muon sources, $\mu \to e$-conversion will likely serve as the deepest probe of CLFV, superior to $\mu \to e\gamma$ in its new physics reach regardless of the nature of the new physics. Among other factors, it is this "feature," which will be discussed in more detail in the next subsection, that drives us to concentrate on the CLFV process where a nuclear-captured muon converts into an electron – $\mu \to e$-conversion in nuclei.

Negatively charged muons that stop in matter are quickly trapped and form muonic atoms, which undergo electromagnetic transitions until the muon is in the $1s$ orbital. Trapped muons either Michel-decay or convert into neutrinos in the field of the nucleus:

$$\mu^- + (A, Z) \to \nu_\mu + (A, Z-1), \tag{2}$$

where (A, Z) represents a nucleus with mass number A and atomic number Z.

Similarly, the $\mu \to e$-conversion process is characterized by

$$\mu^- + (A, Z) \to e^- + (A, Z). \tag{3}$$

Instead of discussing the rate Γ for this muon and electron number violating process, it is convenient to define the normalized capture rate

$$B(\mu \to e - \text{conv}) \equiv \frac{\Gamma(\mu^- + (A, Z) \to e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \to \nu_\mu + (A, Z-1))}, \tag{4}$$

to which we will often refer to as the '$\mu \to e$-conversion rate.'

B. Comparison to Current HEP Program [6 pages]

It is important to place searches for CLFV in general and $\mu \to e$-conversion in particular in the larger context of the current and near future developments of the high energy physics program. We will assume that next-generation neutrino oscillation experiments will take place and provide nontrivial information regarding lepton mixing and other new "neutrino physics." We will also assume that the LHC experiments will have taken enough data in order to provide a clearer picture of physics at around the TeV scale. Finally, we assume that one will either have observed $\mu \to e\gamma$ or constrained its branching ratio to be less than 10^{-14}. It appears unlikely that a future experiment will be able to significantly improve on this, regardless of whether very intense muon sources are available. This is *not* the case of future searches for $\mu \to e$-conversion, as will be discussed later.

1. *Model Independent Analysis: $\mu \to e$-conversion vs. $\mu \to e\gamma$*

One can estimate the sensitivity of CLFV processes to new physics in a model independent way by adding to the standard model effective operators that violate lepton flavor. For concreteness, consider the effect of the standard model augmented by the following CLFV effective Lagrangian:

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L\right), \tag{5}$$

where Λ is the scale of new physics and κ measures whether the dominant new physics contribution to CLFV comes in the form of a dimension-five, CLFV magnetic moment-type operator ($\kappa \ll 1$) or from a CLFV four-fermion interaction ($\kappa \gg 1$). The effective Lagrangian above will mediate both $\mu \to e\gamma$ and $\mu \to e$-conversion (and, at a less significant level, $\mu \to eee$, which will not be discussed). While there is a handful of other effective operators that may also contribute, the ones above contain qualitatively the predictions of most distinct new physics scenarios as far as $\mu \to e\gamma$ and $\mu \to e$-conversion are concerned. The sensitivity of different CLFV probes to Λ as a function κ is depicted in Fig. 2. Note that, regardless of the value of κ, a $\mu \to e$-conversion experiment sensitive to capture rates above 10^{-16} probes Λ values smaller than a few thousand TeV!

For $\kappa \ll 1$, the normalized $\mu \to e$-conversion is around several times 10^{-3} of the branching ratio for $\mu \to e\gamma$, while for $\kappa \gg 1$ the branching ratio for $\mu \to e\gamma$ is many orders of magnitude smaller than the normalized capture rate for $\mu \to e$-conversion. Hence, a $\mu \to e$-conversion experiment sensitive to normalized rates above 10^{-16} is at least as sensitive to new physics as a $\mu \to e\gamma$ experiment sensitive to branching ratios above a few $\times 10^{-14}$, regardless of the nature of the new physics. It is important to emphasize that while we are using Eq. (5) to make this point, this conclusion is very generic and applies to most new physics scenarios that have been explored in the literature to date.

In the case of a positive CLFV signal in either $\mu \to e\gamma$ or $\mu \to e$-conversion, combined results from different CLFV processes provide detailed information regarding the new physics. For example, should the world be properly described

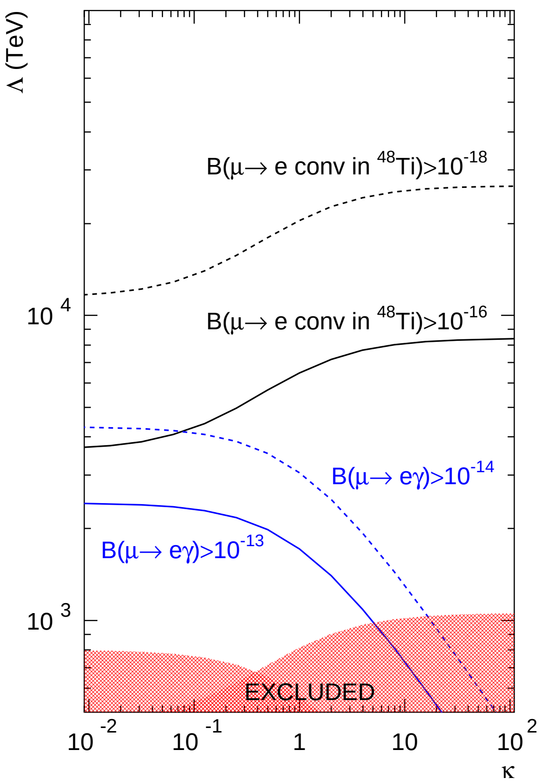

FIG. 2: Sensitivity of a $\mu \to e$-conversion in ^{48}Ti experiment that can probe a normalized capture rate of 10^{-16} and 10^{-18}, and of a $\mu \to e\gamma$ search that is sensitive to a branching ratio of 10^{-13} and 10^{-14}, to the new physics scale Λ as a function of κ, as defined in Eq. (5). The dimensionless parameter κ interpolates between a flavor-violating magnetic moment-type operator ($\kappa \ll 1$) and a flavor-violating four-fermion operator ($\kappa \gg 1$). Also depicted is the currently excluded region of this parameter space.

by Eq. (5), a measurement of $\mu \to e\gamma$ and $\mu \to e$-conversion allows one to determine both Λ and κ independently, while a single measurement can only determine a combination of the two new physics parameters. In general, it is well known that a comparison of $B(\mu \to e - \text{conv})$ and $B(\mu \to e\gamma)$ helps distinguish among models or even measure the value of new physics parameters. A concrete example is depicted in Fig. 3, where the ratio of branching ratios $C \equiv B(\mu \to e\gamma)/B(\mu \to e - \text{conv})$ is plotted as a function of $\tan\beta$ in the case of the MSSM with MSUGRA boundary conditions for the soft SUSY breaking parameters. One can see that a precise measurement of C can determine the sign of the MSSM μ-parameter, especially if $\tan\beta$ is not too large.

The effective Lagrangian that describes $\mu \to e$-conversion and $\mu \to e\gamma$ contains, in general, several dimension-six operators not included in Eq. (5), including those with different muon and electron chiralities and scalar–scalar four-fermion operators. Information regarding all the different parameters that describe CLFV can be obtained from the CLFV probes themselves. In the advent of a positive signal for $\mu \to e$-conversion, details of the effective Lagrangian can be obtained by comparing the rate for $\mu \to e$-conversion in different nuclei, since different nuclei are sensitive to new physics in distinct ways, as depicted in Fig. 4. This flexibility is not shared by $\mu \to e\gamma$ (where one can only hope to measure, in principle, the final state photon or electron polarizations). In the case of a positive signal in $\mu \to eee$, some detailed information regarding the underlying physics can also be obtained by analyzing in detail the kinematics of the three final state leptons.

2. CLFV and new physics at the TeV scale

By the end of 2008, we expect the LHC experiments to start accumulating data that will reveal the mechanism of electroweak symmetry breaking and explore the physics of the TeV scale. Several theoretically motivated scenarios predict the existence of new degrees of freedom with masses at or below 1 TeV and, if this is the case, one expects some of these new states to be discovered at the LHC.

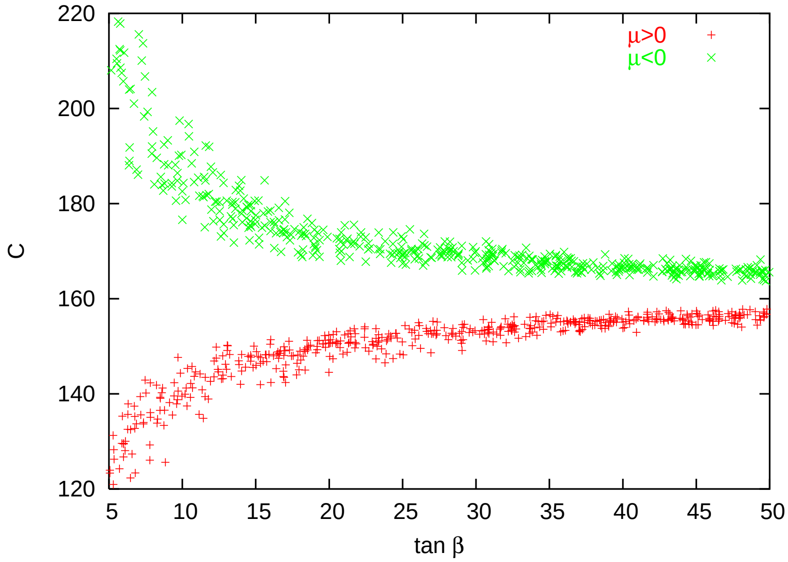

FIG. 3: $C \equiv B(\mu \to e\gamma)/B(\mu \to e-\text{conv})$ in the MSSM with MSUGRA boundary conditions for the soft parameters and neutrino masses induced by the seesaw mechanism, as a function of $\tan\beta$ for different signs of the μ-parameter. From C. E. Yaguna, Int. J. Mod. Phys. A **21**, 1283 (2006).

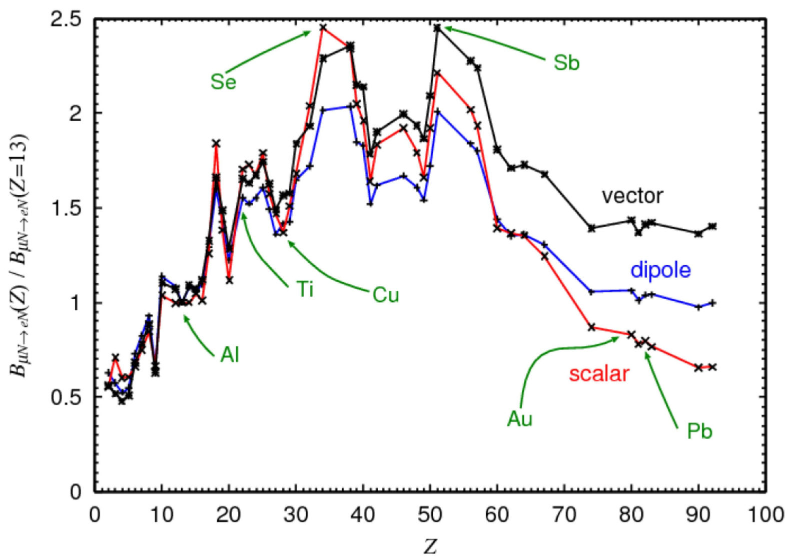

FIG. 4: $\mu \to e$-conversion rate for different nuclei, normalized to that for $\mu \to e$-conversion in aluminum. The different curves represent the contribution of different types of higher dimensional operators. From R. Kitano, M. Koike and Y. Okada, Phys. Rev. D **66**, 096002 (2002).

New physics at the TeV scale is expected to mediate CLFV processes. Expectations are model-dependent, but detailed computations in specific models lead to CLFV rates very close to current experimental bounds, as will be discussed in more detail shortly. We first conservatively assume that the new physics will predominantly induce flavor-violating magnetic-moment type effective interactions at the one-loop level. A concrete example is depicted in Fig. 5.

In this case, CLFV is given by Eq. (5) (potentially augmented by similar operators where the electron and muon chiralities are reversed) with $\kappa \ll 1$ and

$$\frac{1}{\Lambda^2} \sim \frac{eg^2}{16\pi^2}\frac{\theta_{e\mu}}{M_{\rm new}^2}, \tag{6}$$

where $M_{\rm new}$ are the masses of the new states that couple to standard model fields with coupling g and $\theta_{e\mu}$ is a

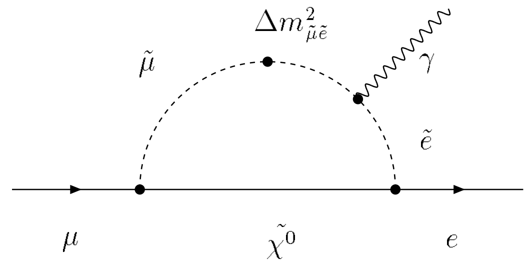

FIG. 5: MSSM slepton–neutralino contribution to $\mu \to e\gamma$. $\Delta m^2_{\tilde{e}\tilde{\mu}}$ stands for the insertion of an off-diagonal element of the slepton mass-matrix. From Y. Kuno and Y. Okada, Rev. Mod. Phys. **73**, 151 (2001).

flavor-violating factor, most likely inaccessible to the LHC. If one assumes g (henceforth assumed to be of order one) and $M_{\rm new}$ to be known, failure to observe CLFV translates into bounds on $\theta_{e\mu}$.

As a concrete example, consider the possibility that the currently observed three sigma [**check**] discrepancy between the standard model prediction and the measurement of the muon anomalous magnetic moment is due to new electroweak scale physics. In this case, the new physics contribution to the anomalous magnetic moment of the muon is capture by a flavor-conserving version of the magnetic moment-type operator that mediates CLFV. Current data on the muon anomalous magnetic moment translates into a measurement of a combination of the new physics scale $M_{\rm new}$ and the new coupling g, in which case currents bounds on CLFV are already quite severe and constrain $\theta_{e\mu} < 10^{-3}$ [**check**].

Similarly, if the LHC discovers new states with masses $M_{\rm new}$ around 1 TeV, current bounds from CLFV will already translate into $\theta_{e\mu} \lesssim 10^{-2}$. In this case, $\mu \to e$-conversion experiments sensitive to conversion rates greater than 10^{-16} will probe $\theta_{e\mu} \gtrsim 10^{-4}$ [**check**].

What are the expected values for $\theta_{e\mu}$? The answer to this is model dependent, but one can identify general categories. Generic new physics models predict $\theta_{e\mu} \sim 1$, in which case searches for CLFV already rule out $M_{\rm new} \sim 1$ TeV. Hence searches for CLFV, along with other flavor observables, already constrain any physics at the TeV scale to be flavor conserving at the leading order. For this reason, one often assumes that the only sources of lepton-flavor violation are the ones already present in the standard model, *i.e.*, the charged-lepton Yukawa couplings and the neutrino mass generating sector. In this case, $\theta_{e\mu}$ values can be computed on a case by case, and its value may or may not dependent on the unknown new physics responsible for neutrino masses and lepton mixing.

Several detailed analysis have been performed for the different independently motivated new physics scenarios, including models with weak scale supersymmetry, models with flat and warped extra-dimensions, and little Higgs models. Some results depend on details of the physics responsible for neutrino masses, about which we will discuss more shortly, but tend to lead to $\theta_{e\mu}$ values such that $\mu \to e$-conversion is "guaranteed" to happen with rates above 10^{-17} or so as long as the new physics is observable at the LHC.

Two examples are depicted in Figs. 6 and 7. Fig. 6 depicts the result of a scan of the MSSM parameter space for different SUSY-GUT scenarios where neutrino masses are generated via the seesaw mechanism. The GUT hypothesis fixes the values of the right-handed neutrino Majorana masses, while there remains the freedom to choose the off-diagonal structure of the neutrino Yukawa couplings. Here two different choices are made: the neutrino Yukawa coupling matrix is PMNS-like, *i.e.*, all its mixing angles are large, as in the physically observable lepton mixing matrix, or it is CKM-like, *i.e.*, all its mixing angles are small, as in the physically observable quark mixing matrix. While the different choices lead to $\mu \to e$-gamma rates that vary by more than four orders of magnitude, it is clear that a $\mu \to e$-conversion experiment sensitive to normalized rates above 10^{-17} or so should cover the majority of the LHC accessible parameter space.

Fig. 6 depicts the result of a scan of the parameter space of the littlest Higgs model with T-parity. The different colored (shaded) points refer to different ansatze for the structure of the mirror lepton mixing sector, not dissimilar from the choice of neutrino Yukawa matrices made in the SUSY example discussed briefly above. Also here, a $\mu \to e$-conversion experiment sensitive to normalized conversion rates above 10^{-16} should cover the parameter space explored in the figure. This is also true for a handful of points where the branching ratio for $\mu \to e\gamma$ is less than 10^{-14}. Note that in this case results do not depend on the mechanism responsible for neutrino masses, but do depend on the unknown mirror fermion mixing matrix.

It is also important to discuss the case where CLFV is generated by new physics at the tree-level, *i.e.*, it is a consequence of the simple exchange of a heavy new physics particle. An example is depicted in Fig. 8. Other than SUSY with R-parity violation, depicted in Fig. 8, several well-motivated new physics scenarios lead to similar CLFV effects including the models with lepto-quarks, neutrino mass models with Higgs triplets, and models with extra Z' gauge bosons.

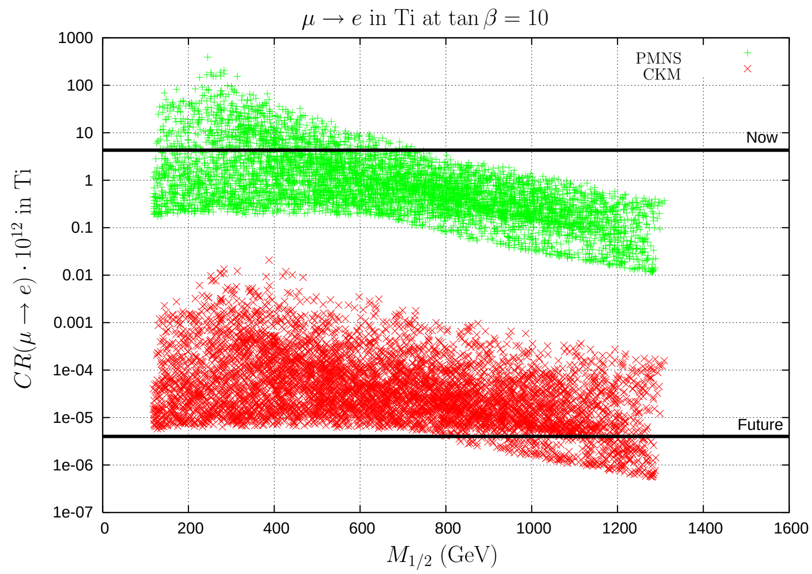

FIG. 6: $\mu \to e$-conversion rate in Ti for different SUSY–GUT scenarios. The plots are obtained by scanning the LHC accessible parameter space. The horizontal lines are the present (SINDRUM II) bound and the planned (Future) sensitivity to the process both at the proposed PRIME experiment in JPARC and at the porposed $\mu 2e$ experiment in FNAL. From L. Calibbi, A. Faccia, A. Masiero and S. K. Vempati, Phys. Rev. D **74**, 116002 (2006).

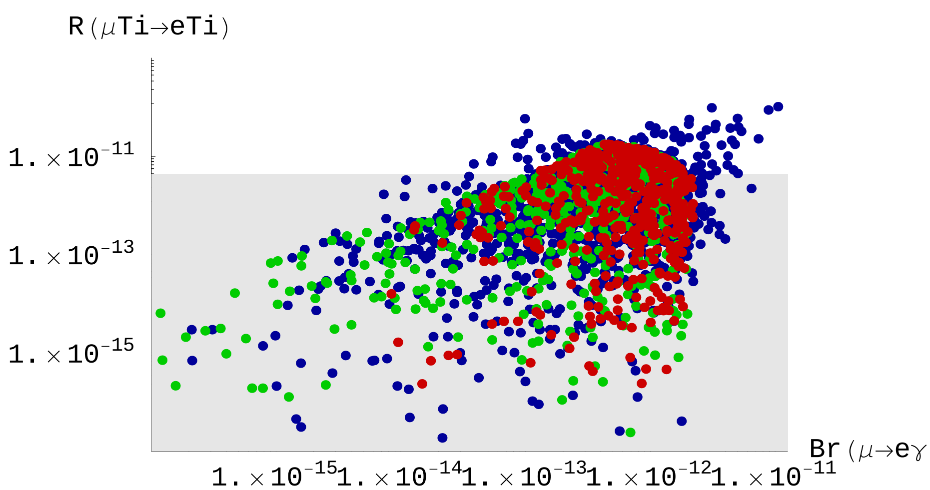

FIG. 7: $\mu \to e$-conversion rate in Ti versus $\mu \to e\gamma$ branching ratio for different littlest Higgs scenarios. The light grey region is allowed by current searches for CLFV. The different shaded points represent different ansatze for the mirror fermion mixing matrix. From M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP **0705**, 013 (2007).

In this case, CLFV is described by Eq. (5) (potentially augmented by, say, scalar–scalar four-fermion operators) with $\kappa \gg 1$ and

$$\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M_{\rm new}^2}. \tag{7}$$

Here, if $M_{\rm new}$ is measured at the LHC, current bounds from $\mu \to e$-conversion constrain $g^2\theta_{e\mu}$ to be tiny. In the example depicted in Fig. 8, $g^2\theta_{e\mu} \sim \lambda'_{221}\lambda'_{121}$, which is, not surprisingly, most severely constrained by searches for $\mu \to e$-conversion in nuclei.

To summarize the discussion so far: if the LHC discovers new states at the TeV scale, several distinct new physics

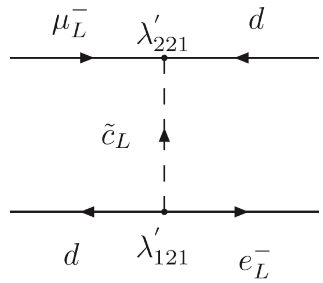

FIG. 8: MSSM tree-level R-partity violating contribution to $\mu \to e$-conversion. From A. de Gouvêa, S. Lola and K. Tobe, Phys. Rev. D **63**, 035004 (2001).

scenarios predict CLFV violating process to occur with rates that are close to current experimental bounds. In this case, a positive $\mu \to e$-conversion result (which may or may not be accompanied by a positive $\mu \to e\gamma$ or $\mu \to eee$ result) will tell us about the flavor structure of the new physics sector, and may even help distinguish among different new physics scenarios. It is important to emphasize that the information one will extract from the CLFV sector is complementary to the information one can hope to extract from LHC data.

Similarly, in the advent of new physics at the LHC, a negative $\mu \to e$-conversion result will also contribute to our understanding of the new TeV scale physics. It would reveal that (i) the new physics is indeed intrinsically lepton-flavor conserving and (ii) the flavor breaking effects induced by the known sources of flavor violation are smaller than naive expectations. Different physics may explain (ii). For example, in the case of SUSY, low-energy gauge-mediated scenarios usually lead to suppressed flavor-violating effects. Furthermore, as will be discussed in more detail shortly, some of the estimates above depend on the physics responsible for neutrino masses, which may be such that TeV-scale CLFV effects are smaller than naive expectations.

There remains, of course, the possibility that the LHC discovers no new degrees of freedom other than what appears to be a standard model Higgs boson. This will indicate that the new physics beyond the standard model is significantly heavier than the TeV scale. Under these circumstances, searches for CLFV violation remain extremely valuable, especially searches for $\mu \to e$-conversion (and, to a lesser extent, searches for $\mu \to eee$). The reason is that if the LHC fails to discover any beyond-the-standard-model effect, the gauge hierarchy problem will, most likely, prove to be a poor indicator for the new physics scale. In this case, progress in fundamental particle physics, including the answers for the open questions, will have to rely, at least for some time, on indirect new physics probes, *i.e.*, on the intensity frontier. These include precision studies of neutrinos and their properties, precision measurements of well-known standard model quantities (like the anomalous magnetic moment of the muon), and searches for forbidden or extremely suppressed processes, like CLFV muon processes. Under these circumstances, the intensity frontier would be the only game in town. Of the probes listed above, CLFV is the one capable of "directly" reaching out to several thousand TeV, especially – in the case of $\mu \to e$-conversion – if new flavor-violating effects are large (in the sense $\theta_{e\mu} \sim 1$) and strongly coupled ($g \sim 1$) and occur at the tree-level (see Eq. (7) and Fig. 2). While there are, by no means, any guarantees that this is the case, there are reasons to believe in such a scenario. Among other plausibility arguments is the fact that the only palpable evidence for new physics is the existence of non-zero neutrino masses. The tiny neutrino masses are potentially due to new, heavy physics and the large lepton mixing angles seem to indicate that flavor-numbers are not conserved in the neutrino sector. Hence, as long as the neutrino mass scale is not too heavy (above 10^4 TeV), there remains the possibility that $\mu \to e$-conversion will directly teach us about the physics responsible for non-zero neutrino masses.

3. CLFV, neutrino masses, and the matter–antimatter asymmetry of the Universe

As discussed in the introduction, massive neutrinos and lepton mixing imply that CLFV *must* occur at some level. While the active neutrino contribution to CLFV is known, as already discussed, to be tiny there remains the likely possibility that the new physics responsible for neutrino masses will induce CLFV at observable levels. Several examples of this have been mentioned in passing above.

Here we will discuss in detail the MSSM case in order to underline the potential importance of CLFV to understanding neutrino masses and other related phenomena, including leptogenesis. In the MSSM with MSUGRA boundary conditions large CLFV are generated if neutrino masses are a consequence of the seesaw mechanism. In more detail, a non-zero off-diagonal slepton mass-squared (see Fig. 5)

$$\Delta m^2_{\tilde{\mu}\tilde{e}} \simeq \sum_k \frac{M^2_{\rm SUSY}}{16\pi^2} y^*_{\mu k} y_{ek} \log\left(\frac{M_{\rm GUT}}{M_k}\right), \tag{8}$$

where $y_{\alpha k}$, $\alpha = e, \mu, \tau$ and $k = 1, 2, 3$, are the neutrino Yukawa couplings, M_k are the right-handed neutrino Majorana masses, $M_{\rm SUSY}$ is a typical supersymmetric mass and $M_{\rm GUT}$ is a typical ultraviolet cut-off, often equated with the GUT scale. In this case, the rate for muon CLFV is proportional to $(\Delta m^2_{\tilde{\mu}\tilde{e}})^2$ ($\theta_{e\mu} \sim \Delta m^2_{\tilde{\mu}\tilde{e}}/M^2_{\rm SUSY}$), such that it probes some combination of the neutrino Yukawa couplings and hence provides non-trivial information regarding the neutrino mass sector (this statement is very dependent on the physics of SUSY breaking, which we are assuming is well known).

Knowledge of the neutrino Yukawa couplings is also fundamental when it comes to determining whether leptogenesis is the mechanism responsible for the matter–antimatter asymmetry of the Universe. The amount of baryon number generated depends on a linear combination of neutrino Yukawa couplings and right-handed Majorana neutrino masses different from the one above ($\propto {\rm Im}[(y^\dagger y)^2_{j1}]$ in the case of thermal leptogensis), while a third linear combination determines the observed active neutrino masses:

$$m_{\alpha\beta} = \sum_k y_{\alpha k} \frac{v^2}{M_k} y_{\beta k}. \tag{9}$$

It has been shown that, given the right circumstances, neutrino oscillation measurements combined with positive results from CLFV, positive results from searches for neutrinoless double-beta decay, and information regarding the low-energy SUSY and SUSY breaking, can provide enough information in order to test leptogenesis. Hence, if thermal leptogenesis is ever to be tested experimentally, CLFV will certainly play a fundamental role.

It is important to emphasize that negative results from CLFV, combined with the discovery of SUSY at the LHC, may prove as important positive results. The reason is as follows. In the MSSM, standard thermal required the lightest right-handed neutrino Majorana mass to be larger than 10^9 GeV or so. This translates into a rough lower bound on the neutrino Yukawa couplings, using Eq. (9): $y^2 \gtrsim 10^{-5}$. This, in turn, implies that $\theta_{e\mu} \sim 10^{-6}$. Hence, if CLFV experiments can rule out $\theta_{e\mu} > 10^{-6}$, standard thermal leptogenesis would be severely disfavored. Such a sensitivity could only be obtained, if at all, in searches for $\mu \to e$-conversion fed by very intense muon sources [**check**].

One last topic, not sure worthwhile including– models where the rare for CLFV is directly related to the neutrino mixing parameters – example large extra dimensions.

C. Experimental Strategy [2 pages]