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Rare Leptonic Decays

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I shortly review implications of the absence and especially of a possible discovery of lepton flavor violation in the charged sector. This is done in an effective approach and for some specific new physics models.

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1. Introduction

In this decade several neutrino oscillation experiments have been performed which uniformly can be explained by the existence of small neutrino masses. Thereby, lepton flavor violation (LFV) has been proved. On the other hand searches for LFV in the charged lepton sector (i.e. cLFV) failed so far which at first sight is not contradictory: Extending the Standard Model (SM) only with a dimension 5 operator in order to parametrize the neutrino masses, the predicted rate of cLFV processes is negligible compared to the experimental sensitivity.

But as such an extension is non-renormalizable, a more fundamental model should be found. This new model might introduce particles at some heavy scale but there is a priori no reason why it should include strong suppression of cLFV. In particular if there is new physics (NP) around the electroweak scale which violates lepton flavor, sizeable cLFV rates can be expected.

The present experimental situation is twofold: First there had been a lot of progress testing the τ flavor conservation in B-factories. The present bounds can be summarized [1]:

$$\mathrm{BR}(\tau \to \mu\,\gamma) < 4.5\,10^{-8} \tag{1.1}$$

$$\mathrm{BR}(\tau \to e\,\gamma) < 1.1\,10^{-7} \tag{1.2}$$

$$\mathrm{BR}(\tau \to 3l) \lesssim 3\,10^{-8} \tag{1.3}$$

$$\mathrm{BR}(\tau \to l\,\mathrm{mesons}) \lesssim 3\,10^{-8} - 10^{-7} \tag{1.4}$$

Further improvements down to 10^{-8} in near future can be achieved from the analysis of more data [2]. Future experiments could be Super B-factories which can lower these bounds down to several 10^{-9} [3]. Secondly, the μ–e flavor transitions are experimentally strongly restricted already since years. But in this decade so far only some bound on μ conversion could be lowered [1]:

$$\mathrm{BR}(\mu \to e\,\gamma) < 1.2\,10^{-11} \tag{1.5}$$

$$\mathrm{BR}(\mu \to 3e) < 1.0\,10^{-12} \tag{1.6}$$

$$\mathrm{R}(\mu\,\mathrm{Au} \to e\,\mathrm{Au}) < 7\,10^{-13} \tag{1.7}$$

This situation should change very soon. MEG at PSI started end of last year and is expected to provide data on $\mu \to e\gamma$ with a sensitivity of 10^{-13} within few years [4][1]. While this search is limited by the sensitivity of the detectors and new technologies had to be developed, searches for μ conversion are limited by the currently available muon beam intensities. Hence plans for new experiments exist. Mu2e at Fermilab [6] as well as COMET at J-PARC [7] aim a sensitivity of 10^{-16}. The ultimate plan is the PRISM/PRIME project at J-PARC. Therefor the FFAG muon storage ring will provide the beam which is clean enough for a sensitivity of 10^{-18} [8].

2. General treatment

Given our ignorance about cLFV it is best treated with an effective Lagrangian. Depending on

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[1] See also [5] which appeared after the conference.

the experiment one of the following three terms might be relevant:

$$\mathscr{L} \supset \frac{a_{Dij}}{\Lambda^2} e m_{l_j} (\bar{l}_i \sigma^{\mu\nu} l_j) F_{\mu\nu} + \tag{2.1}$$

$$\sum_\Gamma \frac{a_{L\Gamma,ijk}}{\Lambda^2} (\bar{l}_i \Gamma^\alpha l_j)\, (\bar{l}_k \Gamma_\alpha l_k) + \tag{2.2}$$

$$\sum_\Gamma \frac{a_{Q\Gamma,ijk}}{\Lambda^2} (\bar{l}_i \Gamma^\alpha l_j)\, (\bar{q}_k \Gamma_\alpha q_k) \tag{2.3}$$

Here Λ is the mass scale of lepton flavor violating new physics, a are some coupling constants and $\Gamma^\alpha \in \{1, \gamma^\mu, \sigma^{\mu\nu}\}$. Generically only the vector coupling is relevant as scalar and tensor couplings are chirality suppressed. Accordingly, in the dipole operator a factor of m_{l_j} has been extracted which can be expected from chirality suppression. A possible chirality dependence of the couplings has been omitted. With present bounds, eqs. (1.1)-(1.7), NP with unsuppressed flavor violation ($a \sim 1$) can be excluded up to $\Lambda \sim 10^{2-3}$ TeV. A loop suppression can relax this bound by one order of magnitude. Hence a GIM suppression or non-maximal flavor mixing is necessary in order to have NP at the electroweak scale, corresponding to $a \sim 10^{-6}$.

The dipole operator induces $l_i \to l_j\gamma$ at tree level, the four fermi couplings $l \to 3l$ and μ conversion (or $\tau \to l$ mesons). From model building point of view it is not clear which of these operators should be leading. The dipole induces the four fermi couplings at tree level but the four fermi couplings the dipole only at one loop. Hence the coupling constants can differ by a few order of magnitudes.

Any detection of cLFV would be interesting as evidence for new physics and a confirmation of LFV in the charged sector. The next step is to try to discriminate among different models. In most models this should be possible more directly at LHC but in any case it is worthwile to launch into the problem on different ways. In principle each term in eqs. (2.1)-(2.3) can be determined separately by experiment, providing us with a lot of information about the underlying model. In practice the following observations could be done:

1. (Non-)observation of cLFV. Only the leading ratio $\frac{a}{\Lambda^2}$ can be constrained. Hence the bare observation of one process (as well as the present non-observation) can only exclude models with maximal (minimal) values for $\frac{a}{\Lambda^2}$. Examples are the SM (the anarchic Randall-Sundrum model, chapter 3.2).

2. Observation of rare τ decays. Some models predict relations between transitions of different flavors (e.g. the triplet Higgs model, chapter 3.1). Given the strong experimental bounds on μ–e transitions, in these models rare τ decays can hardly be close to their present exclusion bounds.

3. Observation of the same flavor transition but in different processes. The ratios of the dipole to the four fermi coupling constants are not arbitrary in a given model. Hence this is a powerful tool for model discrimination. In the case of only μ conversion it has been pointed out that the use of different atoms might be enough to disentangle the dipole from the 2 lepton-2 quark operator [9].

4. Observation of $\mu \to e\gamma$. Here it is possible to study the dependence on the chirality of the ingoing muon [10].

Further information can be obtained by a combination with other experiments. For example, the measurement of the muon anomalous magnetic moment provides the ratio of flavor violating to conserving couplings. Searches for lepton EDMs and universality can also constrict the parameter space. If LHC succeeds finding and identifying the new physics model, low energy cLFV experiments provide a complementary tool. They make it possible to confirm the model and to measure the flavor mixing parameters.

3. Examples of new physics models

In the last decades a lot of models with cLFV have been invented, many of them in order to solve other physical problems. One of these problems is the existence of neutrino masses which cannot be explained in the SM. Already the inclusion of neutrino masses as an effective operator in the SM Lagrangian leads to non-vanishing cLFV. But due to a GIM suppression it is proportional to $(m_\nu/m_W)^4$ [11] and therefore vanishing for all practical purposes. In the most straightforward extension, the see-saw (type I) [12], this conclusion does not change as long as the mass of the right-handed neutrino is very large.

3.1 The triplet Higgs model

This correspondence between smallness of neutrino masses and cLFV is broken in the triplet Higgs model (see-saw type II) [13]. There the new ingredient to the SM is a $\mathrm{SU}(2)$ triplet Δ leading to a new term in the Lagrangian:

$$\mathscr{L} \supset -\frac{1}{2} Y_{ij} \bar{L}_i^c \Delta L_j + \text{h.c.}$$

From that one can easily infer the tree level relations for the neutrino mass, $m_{\nu ij} = Y_{ij} \left\langle \Delta^0 \right\rangle$ and for cLFV, $\mathrm{BR}(l_i \to l_j \bar{l}_k l_k) \propto G_F^{-2} |Y_{ij} Y_{kk}^*|^2 M_{\Delta^0}^{-4}$. Thus the smallness of the neutrino masses can be explained by a tiny vacuum expectation value $\left\langle \Delta^0 \right\rangle$ while the Yukawa couplings might be sizeable and the mass scale M_{Δ^0} small enough for detectable cLFV.

The flavor dependence of $l \to 3l$ is directly connected to the neutrino mass matrix. Therefore, given the strong experimental bound on $\mu \to 3e$, the processes $\tau \to 3l$ should not be observed with upcoming experiments. This holds also for other cLFV τ decays which are mediated by one loop.

Another unambiguous prediction is that only left-handed leptons participate in cLFV processes. But due to ignorance of some parameters of the neutrino mass matrix (namely the mass of the lightest neutrino and the MNS matrix element U_{e3}) the ratios of the rates of different μ decay processes cannot be predicted [14]. In particular, if $m_{\nu 12} m_{\nu 11}^*$ is very small, the dipole can overcome the tree level process $\mu \to 3e$, cf. fig. 1.

3.2 The anarchic Randall-Sundrum model

Other models try to solve the hierarchy problem. One of them which is particularly interesting for cLFV studies, is the anarchic Randall-Sundrum model [15]. In this model there exists a 5th dimension and the metric depends on the position in this dimension (warped geometry). The Higgs is confined to a brane and by the warped geometry protected from large contributions to its mass coming from particles confined at another brane. The fermions are not confined and therefore the

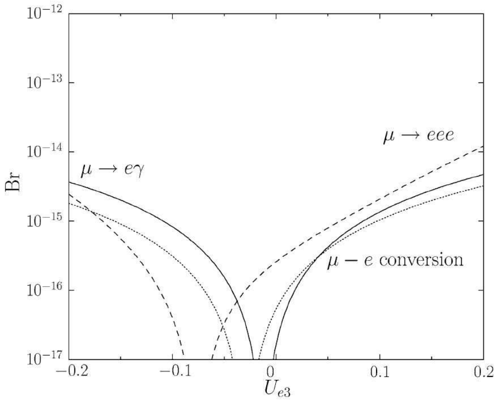

Figure 1: Branching ratios for rare μ decays/μ conversion in the triplet Higgs model as a function of the MNS matrix element U_{e3}. A hierarchical spectrum of light neutrinos, a triplet mass of 200 GeV and $\langle\Delta^0\rangle = 9.5$ eV have been assumed [14].

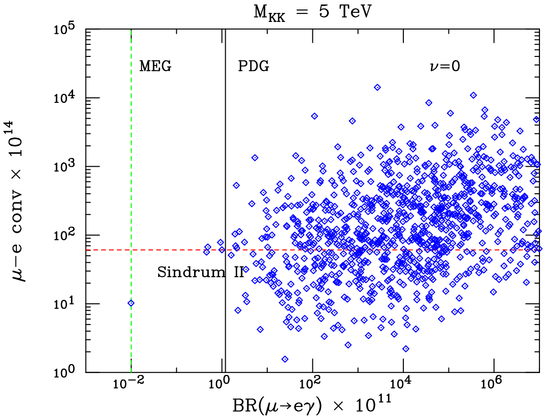

Figure 2: Possible values for $\mathrm{BR}(\mu \to e\gamma)$ and $\mathrm{R}(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti})$ in the anarchic Randall-Sundrum model with Kaluza-Klein masses of 5 TeV. If MEG can lower the bound to 10^{-13}, this scenario is excluded [16].

hierarchy of the Yukawas can be explained by the overlap of the fermion with the Higgs field even with "anarchic" localizations in the 5th dimension and Yukawas of order 1. Also the gauge bosons can propagate in the 5th dimension. Because the Kaluza-Klein modes have different overlap to different fermions, their interaction strength is flavor dependent. Most importantly, the Z boson mass eigenstate has contributions from Kaluza-Klein modes. Thus the Z boson generates the 4 fermi couplings already at tree level. The peculiar property of this model is that it cannot evade cLFV constraints: The Kaluza-Klein modes cannot be made arbitrarily heavy as the model should solve the hierarchy problem, the flavor changing interactions are related to the localizations of the fermions in the 5th dimension which are assumed to be "anarchic". Again, although slightly suppressed, the bounds on μ–e transitions are more stringent than the ones from τ decays and probe already the naturalness of this model (fig. 2). Due to a "tension" between small μ conversion and $\mu \to e\gamma$ this probe holds even for higher Kaluza-Klein masses [16].

3.3 Supersymmetric models

The new physics model most often considered is Supersymmetry (SUSY). Flavor violation arises from the soft SUSY breaking terms. The leptonic part of the simplest model with R-Parity, the MSSM reads:

$$-\mathscr{L} \supset \tilde{L}_i^* m^2_{L\,ij} \tilde{L}_j + \tilde{e}^*_{Ri} m^2_{e\,ij} \tilde{e}_{Rj} + \left(\tilde{e}^*_{Ri} A_{e\,ij} \tilde{L}_j H_d + \mathrm{h.c.}\right)$$

As flavor violation is only due to the superpartners, it appears at one loop. The process $l_i \to l_j\gamma$ is proportional to only three coupling constants and therefore dominant. It can be estimated:

$$\mathrm{BR}(l_i \to l_j\gamma) \sim \frac{\alpha^3}{G_F^2} \left| \frac{m^2_{L,e\,ij}}{m_S^4} \right|^2 \tan^2\beta\, \mathrm{BR}(l_i \to l_j \nu_i \bar{\nu}_j) \tag{3.1}$$

where it is assumed that either m_L^2 or m_e^2 gives the leading contribution as A_e has no $\tan\beta$ enhancement. It turns out that the four fermi operators (usually) are dominated by the penguin diagrams

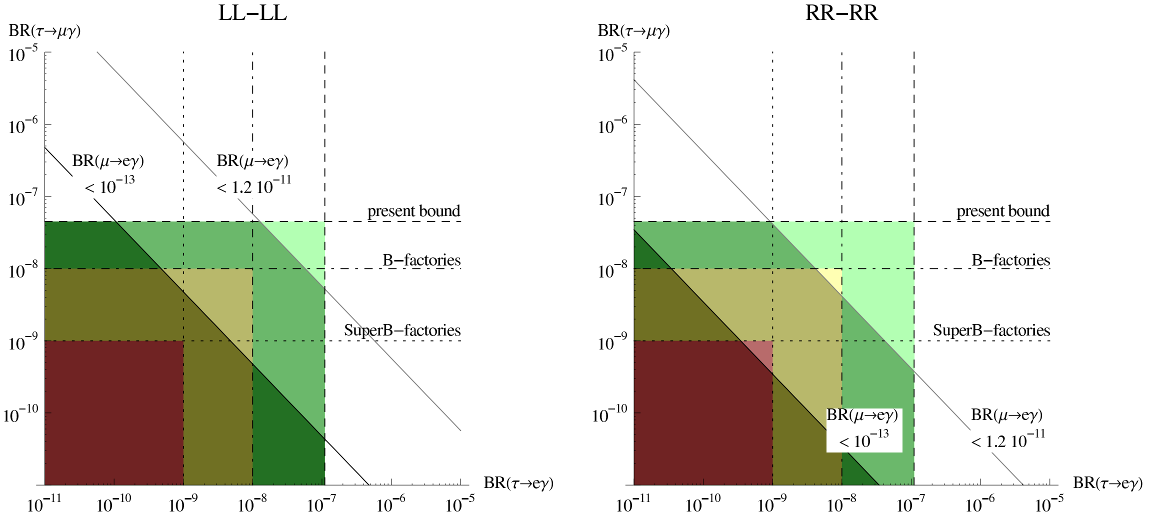

Figure 3: Allowed values for the rates of the rare τ decays. The diagonal exclusion lines come from present and future bounds on $\mu \to e\gamma$ assuming the MSSM and masses from SPS1a [21]. In the left (right) figure dominance of m_L^2 (m_e^2) has been assumed [20].

which leads to a simple relation to the dipole. For μ–e transitions it holds [17]:

$$\mathrm{BR}(\mu \to 3e) \sim \mathrm{R}(\mu\mathrm{Ti} \to e\mathrm{Ti}) \sim \alpha\, \mathrm{BR}(\mu \to e\gamma)$$

The general one-loop expressions can be found in [18]. While the prediction for $\mu \to 3e$ is stable, the rate for μ conversion can deviate in the case of small $\tan\beta$ or when two loop Higgs mediation dominates [19].

To derive correlations between rare τ and μ decays is difficult as in general $m^2_{L\tau j}$, $m^2_{L\mu e}$ are unrelated. The only restrictions can therefore be inferred from the mechanism which generates cLFV. Looking at second order in the flavor mixing soft masses, again for m_L^2 or m_e^2 dominance [20]:

$$\mathrm{BR}(\mu \to e\gamma) \gtrsim \frac{\alpha^3}{G_F^2} \left| \frac{m^2_{L,e\,\mu\tau} m^2_{L,e\,\tau e}}{m_S^6} \right|^2 \tan^2\beta \tag{3.2}$$

In the absence of cancellations with the term proportional to $m^2_{L\mu e}$, this second order contributon can be seen as a lower bound for $\mathrm{BR}(\mu \to e\gamma)$. Following eq. (3.1) for the τ flavor transitions this leads to a constraint of the form $\mathrm{BR}(\mu \to e\gamma) \gtrsim C\,\mathrm{BR}(\tau \to \mu\gamma)\mathrm{BR}(\tau \to e\gamma)$, cf. fig. 3.

The absolute size of cLFV instead is not predicted by SUSY. Though, making the naive assumption that flavor mixing terms could be of the order of flavor diagonal soft masses, i.e. the assumption of maximal flavor mixing, the absence of $\mu \to e\gamma$ requires the soft masses to be bigger than 1 TeV. This fact (as well as the absence of some other processes in the quark sector) is usually referred to as the SUSY flavor problem. It can be completely evaded by imposing the condition of minimal flavor violation [22] which means that the Yukawas are the only source of flavor violation. If the MSSM is extended to include neutrino masses, this definition cannot be generalized unambigously. Simple attempts can be found in [23] but they fail already to describe the see-saw.

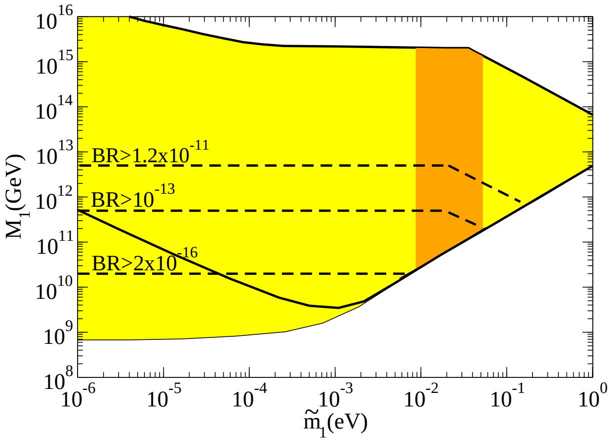

Figure 4: The yellow band is the allowed parameter region for successful (unflavored) leptogenesis [29], the dashed lines are the upper exclusion limits derived from the absence of $\mu \to e\gamma$ in present and future experiments. Assumed are soft masses of 200 GeV and $\tan\beta = 10$ [27].

In any case – even if the soft masses and $\tan\beta$ could be determined, or the deviation of the μ anomalous magnetic moment was taken seriously [24] – in order to get predictions about the rate of rare decays additional assumptions are necessary.

3.3.1 The supersymmetric see-saw

As the MSSM does not explain neutrino masses, a sensible apposition is the most elegant solution, the see-saw (type I). Such as in the SM it consists in adding 3 right-handed neutrinos to the particle content. But there are two qualitative differences: First, the introduction of the heavy neutrinos does not lead to a hierarchy problem. Secondly, if the mass $M_{\rm mes}$ of the messenger particles which transmit SUSY breaking, is larger than the mass of the right-handed neutrinos, this modifies the soft masses via the RG equations:

$$m^2_{Lij} \approx -\frac{1}{8\pi^2}\left(m^2_{L}+m^2_{\nu}+m^2_{H_u}+|A_\nu|^2\right)Y^*_{\nu\,ki}\log\left(\frac{M_{\rm mes}}{M_k}\right)Y_{\nu\,kj} \qquad (i \neq j) \tag{3.3}$$

Here M is the diagonal mass matrix of right-handed neutrinos, Y_ν the neutrino Yukawa coupling and it has been assumed that the soft masses m_i are proportional to unity at $M_{\rm mes}$, the trilinear proportional to the Yukawa. Again A_{eij} is usually disregarded as the corresponding amplitude is not $\tan\beta$ enhanced, m^2_{eij} turns out to be negligible. Thus it is expected that in the SUSY see-saw only left-handed leptons participate in cLFV interactions.

It has been verified that this effect can bring rare decays close to present bounds [25]. However, because of the large number of parameters, the SUSY see-saw can accommodate any value for the rare decays [26]. Therefore, the absence of rare leptonic decays cannot exclude the SUSY see-saw.

But of course it is possible to constrain the see-saw parameters, i.e. in general the combination $Y^*_{\nu\,ki}\log(M_{\rm mes}/M_k)Y_{\nu\,kj}$ (cf. eq. (3.3)). Under the plausible assumptions of hierarchical Yukawas and the absence of cancellations this bound can be translated into upper bounds on the more intuitive smallest Yukawa coupling and lightest right-handed neutrino mass [27]. The latter is especially interesting as leptogenesis predicts a lower bound [28]. This might allow for an exclusion of supersymmetric leptogenesis, cf. fig. 4.

3.3.2 Supersymmetric GUTs

Another very widespread assumption is that of grand unification. Typically, quarks and leptons are members of the same multiplet. Then above the GUT breaking scale the mixing of the quarks is communicated to the lepton sector. For Planck scale SUSY breaking this becomes again manifest in the slepton soft masses via the RG equations, analogously to the the see-saw case. Contrary to the see-saw where the source of flavor mixing is the poorly constrained neutrino Yukawa matrix, in GUT scenarios it is the up-type quark Yukawa matrix. Nevertheless the predictions depend not only on SUSY parameters but also on the specific GUT realization. For soft SUSY masses close to the weak scale one expects cLFV at most a few orders of magnitude below present experiment [30].

4. Summary

In the SM lepton flavor is broken by the neutrino mixings. But the expected rate for rare leptonic decays is well below the achievable experimental sensitivity. Therefore any detection of rare leptonic decays is a clear evidence of new physics.

On the other hand new physics close to the electroweak scale generically is expected to introduce new sources of flavor violation. Hence present experiments already strongly constrain new physics. Namely we know that a strong suppression must be at work. With further data from B-factories and the results from MEG this suppression mechanism will be probed again. If a signal was found, it would be possible to discriminate among different models.

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