LEPTON FLAVOUR VIOLATION

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Abstract

After a summary of the motivations for searching flavour violating decays and electric dipole moments in the leptonic sector, I briefly sketch the present status of the limits on lepton-slepton misalignement and discuss the potentialities of the planned experimental improvements. Candidates for theories beyond the Standard Model have to satisfy all these experimental constraints; I will discuss in particular how the supersymmetric SM extended with the see-saw faces the flavour problem.

1 Motivations

There are many motivations for searching lepton flavour violating (LFV) decays - like $\tau \to \mu\gamma$, $\mu \to e\gamma$ -, fermion electric dipole moments (EDM) and additional contributions to fermion magnetic dipole moments:
1. lepton family number (L_i) violation is already a well established fact;
2. such observables, if measured - and there will be significant improvements in the experimental sensitivity in future - represent clean smoking guns for new physics;
3. they already are a severe test for theories beyond the Standard Model (SM), in particular for low energy supersymmetry.

Actually, to explain why such processes have not already been observed is one of the major problems of low energy supersymmetry: the *flavour problem*. In the following, I shall firstly briefly review the present constraints on the leptonic soft supersymmetry breaking terms and discuss the impact of the planned experimental improvements. It is convenient to encode such constraints on $\mathcal{L}_{soft}$ in the form of upper bounds on mass-insertion δ's.

In this way it is possible to test many extensions of the SM supplemented with low energy supersymmetry. The constraints from both the quark and leptonic sector of $\mathcal{L}_{soft}$ are so severe that the easiest way out is to consider the possibility of family blind soft terms. For the SM, then, all the above processes and their analog in the quark sector would be extremely suppressed. Nevertheless, even with universal soft terms, some extensions of the SM could give observable effects. This is the case for supersymmetric grand unified theories in the quark sector, as addressed by A. Masiero in his talk. In the leptonic sector, however, it is not even necessary to invoke a stage of grand unification to dispose of efficient beyond the SM interactions: it is quite likely that the desert below M_{GUT} suggested by gauge coupling unification is actually populated by three generations of right-handed neutrinos and their interactions: the see-saw mechanism. To estimate the prediction for LFV decays and EDM in the case that the SM is extended with the see-saw is an interesting task: it represents the minimal amount of contribution that could be present. If, in addition, there is a stage of grand unification, since there is no reason for a conspiracy between contributions of different nature, such processes should eventually be enhanced. In the following, I will develop this issue in some detail.

1.1 Basic Motivation n.1: L_i Violation

That L_i is violated at low energy we are pretty sure: it is even more violated than B_i. Indeed, neutrino oscillation experiments have shown that it is maximally violated because in the flavour basis where charged leptons are diagonal [1] the MNS matrix which diagonalises light neutrinos, thus expressing how much L_i is violated in the *effective* theory,

$$m_\nu^{eff} = U^*_{MNS} \hat{m}_\nu U^\dagger_{MNS} \tag{1}$$

has turn out to possess two large angles, $\theta_{23}, \theta_{12} \sim \pi/4$. Curiously enough, now the puzzle is to explain why the third angle is smaller than $\theta_C \approx .22$, which measures the amount of B_i violation at low energy.

The most elegant explanation of the smallness of neutrino masses is the see-saw mechanism [1]:

$$\mathcal{L}_{h.e.} \ni \frac{1}{2}\nu^{cT}\hat{M}\nu^c + \nu^{cT}\underbrace{V_R\hat{y}_\nu V_L}_{=y_\nu}\nu H_u^0 \tag{2}$$

$$l.e. \searrow$$

$$y_\nu^T \frac{1}{\hat{M}} y_\nu v_u^2 = m_\nu^{eff} \tag{3}$$

In the *fundamental* theory at high energy, the amount of L_i violation corresponds to the largeness of the mixing angles of V_R, V_L, the unitary matrices which diagonalise y_ν in the basis where M and charged leptons are diagonal. Notice that V_L (and not U_{MNS}) is the true analog of V_{CKM} in the leptonic sector. Clearly, L_i violation at low energy, i.e. $U_{MNS} \neq \mathbb{I}$, implies that V_R and V_L cannot both be $\mathbb{I}$, but we cannot guess the magnitude of their angles. So, the question "is V_L small like V_{CKM} or large like U_{MNS}?" is not academic.

It is not possible to find an answer by just looking at neutrino phenomenology, namely at m_ν^{eff}. As can be realised by simple parameter counting, one cannot extract V_R, V_L. It

[1] Here and in the following, diagonal matrices will be denoted with a hat.

is better to separate our ignorance from our knowledge by recognizing that the extraction of the combination

$$\frac{1}{\sqrt{\hat{M}}} V_R \hat{y} V_L v_u \tag{4}$$

from

$$m_\nu^{eff} = (U^*_{MNS} \sqrt{\hat{m}}_\nu R)(R^T \sqrt{\hat{m}}_\nu U^\dagger_{MNS}) = (\frac{1}{\sqrt{\hat{M}}} V_R \hat{y} V_L v_u)^T (\frac{1}{\sqrt{\hat{M}}} V_R \hat{y} V_L v_u) \tag{5}$$

is ambiguous up to R, an orthogonal complex matrix [2] . Thus, R parametrizes our ignorance in the sense that it encodes six physical informations that are present at high energy and that are subsequently lost when integrating out right-handed neutrinos [3]. To further disentangle the matrices in eq. (4), one should for example know $\hat{M}$. As also appears from the parameter counting, the two sets below are absolutely equivalent in describing the see-saw mechanism. However, as will be clarified in the following, the physical meaning of a certain quantity can be better interpreted using one set than the other.

$$\{ \underbrace{\hat{m}, \; U_{MNS}}_{\text{known}}, \; \underbrace{R, \; \hat{M}}_{\text{unknown}} \} \div \{ \underbrace{\hat{y}, \; V_L, \; V_R, \; \hat{M}}_{\text{fundamental}} \} \tag{6}$$

	$\hat{m}$	U_{MNS}	R	$\hat{M}$	$\hat{y}$	V_L	V_R	$\hat{M}$
real	3	3	3	3	3	3	3	3
phases		3	3			1	5	

It is interesting to wonder what is the physical meaning of the informations contained in R, which acts on ν and ν^c mass eigenstates at left and right respectively. It turns out that it is a dominance matrix [3]: its pattern reflects the way in which each heavy right-handed neutrino contributes in determining each light neutrino mass scale. Consider for instance the heaviest light neutrino mass scale, m_3. Due to the orthogonality of R,

$$m_3 = \sum_i R^2_{3i} m_3 \quad , \tag{7}$$

so that m_3 is determined by a sum of three contributions $\mathcal{C}_{3i} \equiv R^2_{3i} m_3$. It turns out that, once U_{MNS} is fixed, each $\mathcal{C}_{3i} = \mathcal{C}_{3i}(y^2_{ki}/M_i)$, i.e. is a function of M_i and its couplings to the light neutrinos y_{ki} only. R^2_{3i} thus represent the weights of the ν^c in determining m_3. Analogous considerations hold for the various m_j. So, if a certain ν^c gives the dominant contribution in determining a certain eigenvalue m_j, correspondingly this information is encoded in the structure of the jth row of R. For instance, if ν^c_k mostly determines the scale of m_j, we will have $R_{jk} >> R_{jh}$, where $h \neq k$. The interpretation in terms of weights is straightforward for the rotational part of R. One has however to be careful because of the possible presence of the three boosts (controlled by the three phases). In the latter case the weights R^2_{3i} are not necessarily positive nor smaller than 1. So, the situation is more subtle but, even including the phases of R, the interpretation in terms of dominance still holds. The presence of a structure in R is important. For hierarchical neutrinos for instance, if the third row of R, which determines m_{atm}, is structureless, one cannot account at same time for the large atmospheric mixing and the experimental value of $r \equiv (\Delta m^2_{sol}/\Delta m^2_{atm})^{1/2}$ without the introduction of a tuning between the Yukawas at the level of r. With a proper structure in the third row of R, the latter requirements are instead naturally fulfilled.

To proceed one needs other observables. Recently, a lot of attention has been given to the possibility of having baryogenesis through leptogenesis [4]. Here I will just make some comments. It is interesting to notice that, in the case of hierarchical right-handed neutrinos, say $M_1 < M_2 < M_3$, defining $R_{ij} = |R_{ij}|e^{i\phi_{ij}/2}$, the ϵ asymmetry can be written by using the first set of parameters in eq. (6) and it is simply given by [5]

$$\epsilon = \frac{3}{16\pi} \frac{-|R_{11}|^2 \Delta m^2_{sol} \sin\phi_{11} + |R_{31}|^2 \Delta m^2_{atm} \sin\phi_{31}}{|R_{11}|^2 m_1 + |R_{21}|^2 m_2 + |R_{31}|^2 m_3} \frac{M_1}{v^2} \quad . \tag{8}$$

With this parametrization, we can see mathematically what one would have expected by intuition, namely that the physical quantities involved in determining ϵ are just M_1, the spectrum of light-neutrinos, $\hat{m}$, and the first column of R, which expresses the composition of ν_1^c in terms of the light neutrino masses $\hat{m}_i$. Since there is not at all trace of U_{MNS}, from this formula one can immediately realise that ϵ (=leptogenesis) and m_ν^{eff} (=neutrino phenomenology) depend on two independent sets of CP violating phases [2], respectively those of R and those of U_{MNS}. Notice also that if $V_L \to U_{MNS}$, i.e. we postulate that low energy left mixings arise mostly from those at high energy, then $R \to \mathbb{I}$ and ϵ vanishes. Leptogenesis can however provide just one number. To proceed further one need other informations.

1.2 Basic Motivation n.2: New Physiscs "Smoking Guns"

Let's have a look at the SM as an effective theory: the operators of dimension $d > 4$ represent new physics and could be computed if we knew the fundamental theory beyond the SM. The only one which has been observed is the $d = 5$ operator responsible for neutrino masses, eq. (3); however, the $d = 6$ operator

$$\frac{1}{\Lambda^2} \bar{\psi} \sigma^{\mu\nu} (\gamma_5) \psi F_{\mu\nu} \phi \tag{9}$$

potentially induces LFV, EDM and additional contributions to MDM. Some upper limits on these observables and their probable future improvements are displayed in table 1. In the SM they are predicted to be much smaller than the present and future bounds. Observation of some of them would thus represent a very clean smoking gun for the presence of new physics beyond the SM.

1.3 Basic Motivation n.3: Test for Theories beyond the SM

The upper limits provide the third motivation, namely to test theories beyond the SM. Let me focus on the see-saw: in the non supersymmetric case, these operators are suppressed by powers of the scale of L violation and the effects are completely out of the

[2]See for instance [6] and references therein for different approaches to this subject.

	present [7]	planned [8]
d_e	$< 1.5\ 10^{-27}$ e cm	$< 10^{-29(-32)}$ e cm
d_μ	$< 10^{-18}$ e cm	$< 10^{-24(-26)}$ e cm
$\mathrm{BR}(\mu \to e\gamma)$	$< 1.2\ 10^{-11}$	$< 10^{-14}$
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 1.1\ 10^{-6}$	$< 10^{-9}(?)$

Table 1

future sensitivity; with low energy supersymmetry, on the contrary, these operators are suppressed by powers of m_{susy}, due to graphs with loops of virtual supersymmetric particles. The effects should be so large that the supersymmetric flavour problem arises: the only explanation of why such processes have not yet been found is to assume very specific patterns of soft supersymmetry breaking terms at high energy, namely that fermions and sfermions have to be nearly diagonal in the same basis.

2 Constraints on $\mathcal{M}^2_{\tilde{\ell}}$

In the basis where charged fermions are diagonalised, non observation of LFV, EDM and additional contributions to MDM in the leptonic sector, constrains the 6×6 hermitian matrix of soft sfermion masses, whose mixings represent the amount of fermion-sfermion misalignement. For practical purposes it is convenient to work in the mass insertion approximation (see for instance [9] and references therein): one assumes nearly degenerate sfermions so that the experimental upper bound on a certain observable can be directly translated into upper bounds on some of the δ's defined in this way

$$\mathcal{M}^2_{\tilde{\ell}} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^2_{RL} & m^2_{RR} \end{pmatrix} = \bar{m}^2_{\tilde{f}} \begin{pmatrix} \mathbb{I} + \delta^2_{LL} & \delta^2_{LR} \\ \delta^2_{RL} & \mathbb{I} + \delta^2_{RR} \end{pmatrix} \quad . \tag{10}$$

The constraints on the δ's are so many that, if one is patient enough to tackle them in a systematic way, one ends up with a sleptonarium [10], a catalogue of upper bounds on δ's. These bounds can be for instance represented in the $(M_1, m_{\tilde{e}_R})$ plane for fixed $\tan\beta$ values assuming for definiteness gaugino universality and μ from radiative electroweak symmetry breaking (deviations from these assumptions are easily estimated). Besides the encyclopedical motivation, such a collection is interesting because the combined analysis of all the limits allows to extract additional informations. In the following I will briefly sketch this issue (see [10] for more details).

Non observation of the decay $\ell_i \to \ell_j \gamma$ puts upper bounds on the absolute value of four δ_{ij}: $|\delta^{LL}_{ij}|$, $|\delta^{RR}_{ij}|$, $|\delta^{LR}_{ij}|$, $|\delta^{RL}_{ij}|$. There are two possible contributions to EDM: flavour conserving (FC) and flavour violating (FV). If no conspiracy between them is at work, the experimental bound can be put on each: $d_i^{exp} > d_i^{FC},\ d_i^{FV}$. The FC contribution bounds $\mathcal{I}m(\delta^{LR}_{ii})$. The FV contribution, which could be even bigger than the FC one if there is a fermion j heavier than the i, bounds the following four combinations of δ's:

$$\mathcal{I}m(\delta^{LL}_{ij}\delta^{LR}_{ji}) \quad , \quad \mathcal{I}m(\delta^{LR}_{ij}\delta^{RR}_{ji}) \quad , \quad \mathcal{I}m(\delta^{LL}_{ij}\delta^{LR}_{jj}\delta^{RR}_{ji}) \quad , \quad \mathcal{I}m(\delta^{LR}_{ij}\delta^{RL}_{jj}\delta^{LR}_{ji}) \quad . \tag{11}$$

Consider d_μ and let's have a look at the informations that can be obtained by combining the various bounds. Since the $|\delta_{23}|$ are independently constrained from $\tau \to \mu\gamma$, d_μ^{FV} cannot exceed a certain value. For instance, a bound at the level of 10^{-8} on the $BR(\tau \to \mu\gamma)$ would imply that the FV contribution to d_μ is not bigger then $\sim 10^{-23}$ e cm, well below the present experimental bound on d_μ but in the range of the planned sensitivity. So, if d_μ where observed above $\sim 10^{-23}$ e cm, we could conclude that we are measuring the FC contribution; if it where observed below, its origin - if FV or FC - would remain unknown. Similar remarks can be done for d_e.

3 δ's as Tests for Theories Beyond the SM

The interest of collecting the bounds on the δ's is that they can be easily compared with the prediction of theories. In general we can distinguish two contributions to the δ's: one already present at the scale Λ where boundary conditions are imposed and one which can be potentially developed when running from Λ to m_{susy}:

$$\delta_{ij} = \delta^{(0)}_{ij} + \delta^{(rad)}_{ij} \qquad . \tag{12}$$

Since there is no reason for contributions of such different origin to conspire, the above limits on the δ's can be applied to both.

It is well known that, even if $\delta^{(0)}$ vanishes, which is case for universal and real boundary conditions at Λ, $\delta^{(rad)}$ can be *generated from RGE* if below Λ there are new interactions beyond those of the SM [3]. It has been shown [13] that the see-saw (even without a stage of grandunification) could lead to observational consequences, due to a large Yukawa coupling in the Dirac term $y_3 = O(1)$. Fermion-sfermion misalignement reads

$$\bar{m}^2_{\tilde{f}}\delta^{LL}_{ij} = {m^2}^{LL}_{ij} = \frac{1}{8\pi^2}(3m_0^2 + 2A_0^2)\underbrace{(y_\nu^\dagger \ln(\frac{\Lambda}{\hat{M}})y_\nu)_{ij}}_{\equiv C_{ij}} \quad , \tag{13}$$

[3]In GUTs, for instance, $y_t = O(1)$ induces fermion-sfermion misalignement [11]: for $SU(5)$ it is however too small to lead to observable consequences, while for $SO(10)$ it could be sufficient [12].

where universality has been assumed and m_0, A_0 are respectively the soft scalar masses and the trilinear coupling. The bound on δ_{ij}^{LL} of the previous section is then translated into a bound on C_{ij} as displayed in fig. 1.

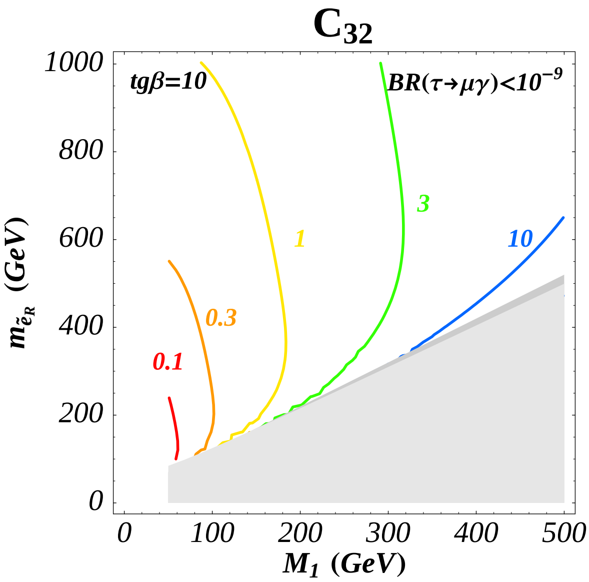

Figure 1: Upper limits on C_{32}, C_{21} in the plane $(M_1, m_{\tilde{e}_R})$, respectively the $\tilde{B}$ and right slepton masses. Gaugino and scalar universalities, μ from radiative electroweak symmetry breaking and $m_0 = A_0$ have been assumed.

It has been shown [14] that some simple realisations of the see-saw mechanism (for instance some models with $U(1)$ flavour symmetry, or with $R = \mathbb{I}$) lead to $\mu \to e\gamma$, $\tau \to \mu\gamma$ at hand, some models having been already ruled out by $\mu \to e\gamma$. It has been claimed that there exist a certain correlation between the solar solution and the rate of $\mu \to e\gamma$, which would be enhanced in the case of large solar mixing angle.

We addressed the question [15, 3] whether the prediction of high rates is or not a general feature of the see-saw. It turns out that this is not the case and that in general there is no connection between having a large solar angle and an enhancement of the $\mu \to e\gamma$ rate. Anyway, it is possible to link the $\tau \to \mu\gamma$ rate to physical characteristics of the see-saw: namely it is possible to have some indirect indications on the possible magnitude of the largeness of the 23 mixing angle of V_L, θ_{23}^L, which, as previously explained, is totally unaccessible from m_ν^{eff}. That C provide some access to V_L can be easily seen by noticing that, due to the mild effect of the logarithm, C is in first approximation diagonalised by V_L itself. The more the mixings in V_L are large, the more the rates will be enhanced. So, if $y_3 = O(1)$, which we assumed in all the following discussion, non observation of $\ell_i \to \ell_j\gamma$ can be translated into an upper bound on the combination $V_{Li3}V_{L3j}\ln(\Lambda/M_3)$.

Despite m_ν^{eff} provides no direct access to V_L, it is possible to establish an indirect correspondence by considering the following useful classification criterion for see-saw mechanisms [15]. Consider the hierarchical case for ν spectrum (for a discussion on the inverted hierarchical see [3]). One can classify every possible see-saw in three categories according to which right-handed neutrino dominates - in the sense explained previously - the scale m_{atm}. There are obviously three possibilities.

None: all the elements of the third row of R are of comparable magnitude. This class has the following features: $\theta_{atm} \sim \theta^L_{23}$; the scale of M_3, the heaviest ν^c has to be below $5 \cdot 10^{14}$ GeV; y_ν is "lopsided"; a tuning of the order of r is necessary in order to have at the same time large atmospheric mixing and hierarchical masses. All the see-saw models which follow from a $U(1)$ flavour symmetry with charges of the same sign belong to this class. Indeed, it is well known that in this case the actual values of the ν^c charges are not important because m^{eff}_ν depends only on those of ν. This physical information is well encoded in R: its elements are all of the same order but the absence of structure in R has to be payed by doing the tuning.

The heaviest, M_3**:** $rR_{33} \geq R_{31}, R_{32}$. In this case $\theta^L_{23} \approx \theta_{atm}$ with corrections at the level of r; again $M_3 < 5 \cdot 10^{14}$ GeV and y_ν is "lopsided", but now we have naturally large atmospheric mixing and large mass splittings, so that no tuning has to be introduced. These models necessitate of a richer flavour symmetry than those above, for instance a $U(1)_F$ flavour symmetry with positive and negative charges, which allow for holomorphic zeros in the textures.

One among the lightest, M_1 **or** M_2**:** $rR_{31(32)} \geq R_{33}, R_{32(31)}$. The relevant feature of this class is that θ^L_{23} is no more linked to θ_{atm}. On the contrary, y_ν can possess small mixings so that θ^L_{23} could even vanish. For this class $M_3 \geq r^{-1} 5 \cdot 10^{14}$ GeV - which is quite good for $SO(10)$ - large atmospheric mixing and large splitting is naturally realised. These interesting models necessitate of an even richer flavour symmetry than those above: models have been studied with several $U(1)_F$'s with positive and negative charges and with non-abelian flavour symmetries.

The remarkable fact that emerges from this classification is that the first two classes require $\theta^L_{23} \sim \pi/4$, so that $C_{32} \sim \ln(\Lambda/M_3) \sim 7$, while for the third class C_{32} can be much smaller. It is thus sufficient to give a look to fig. 1 to understand that future searches for $\tau \to \mu\gamma$ have the potentiality of discriminating between these categories. The present limit on $BR(\tau \to \mu\gamma)$ implies a limit on C_{32} weaker by a factor of 30 with respect to fig. 1, so that no conclusion can be drawn by now.

For $\mu \to e\gamma$ the situation is not so sharp: for the last two categories of models, dominance of the heaviest and of one among the lightest, the predictions are very model dependent. Instead, the models with only positive $U(1)_F$ charges of the first class predict $C_{21} \sim 7\ r$: if supersymmetry is somewhere at left of the green curve, such models are already excluded for r in the range of LMA. It is worth to stress that, if $\mu \to e\gamma$ were not found, this would be perfectly compatible with the two last categories, maybe slightly favouring the third one. Turning the argument around we can notice that $\mu \to e\gamma$ could test the product $V^L_{13} V^L_{23}$ up to the level of $\sim .005$, which corresponds the measured value of the analogous mixings in V_{CKM}. Notice also that anarchical models, for which $C_{21} \sim 7\ y^2$ (y being the common Yukawa), are already in crisis in all the supersymmetric plane.

It is also interesting to ask if the planned experimental improvement in the sensitivity to d_μ will imply significant progresses also from the model building point of view. This is the case because, even starting with universal and real boundary condition at Λ, $\delta^{(rad)}$ could induce an EDM. In the case of the see-saw, however, if $\hat{M} \propto \mathbb{I}$, the naive scaling $d_e/d_\mu \sim m_e/m_\mu$ - which, given the present bound on d_e, would imply $d_\mu < 10^{-25}$ e cm - cannot be avoided. On the contrary, in case of hierarchical ν^c, the naive scaling can be avoided due to the FC contribution [16]. In any case, the FV part is such that the phases in the four products of δ's in eq. (11) are very small [17]: this means that if the SM is extended to just the see-saw, then d_μ^{FV} is always smaller than the maximum value allowed from non observation of $\tau \to \mu\gamma$.

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