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Summary Talk

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Shedding light on flavour symmetries with rare decays of quarks and leptons

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1 Introduction

In the last few years there has been a great experimental progress in quark and lepton flavour physics. On the quark side, the two B-factories have been very successful, both from the accelerator and the detector point of view. As a result, all the relevant parameters describing quark-flavour mixing within the Standard Model (quark masses and CKM angles) are now know with good accuracy. Despite this great progress, the overall picture of quark flavour physics is a bit frustrating as far as the search for physics beyond the Standard Model (SM) is concerned. The situation is somehow similar to the flavour-conserving electroweak physics after LEP: the SM works very well and genuine one-loop electroweak effects have been tested with relative accuracy in the 10%–30% range.

The situation of the lepton sector is more uncertain but also more exciting. The discovery of neutrino oscillations has two very significant implications: i) the SM is not complete; ii) there exists new flavour structures in addition to the three SM Yukawa couplings. We have not yet enough information to unambiguously determine how the SM Lagrangian should be modified in order to describe the phenomenon of neutrino oscillations. However, natural explanations point toward the existence of new degrees of freedom with explicit breaking of lepton number at very high energy scales ($\Lambda_{\rm LN} \sim 10^{10}$–$10^{15}$ GeV), in agreement with the expectations of Grand Unified Theories (GUT). As I will discuss in this talk, these insight about non-SM degrees of freedom from neutrino physics are likely to have non-trivial implications in other sectors of the model. In particular, in rare decays of charged leptons and, possibly, in a few rare B and K decays. Interestingly enough, these connections can be derived without specific dynamical assumptions about new physics, but only analysing the flavour-symmetry structure of the theory be means of general Effective Field Theory (EFT) approaches.

2 The SM as EFT and the flavour problem

The SM Lagrangian can be regarded as the renormalizable part of an effective field theory, valid up to some still undetermined cut-off scale Λ above the electroweak scale. Since the SM is renormalizable, we have no direct clues about the value of Λ; however, theoretical arguments based on a natural solution of the hierarchy problem suggest that Λ should not exceed a few TeV. As long as we are interested only in low-energy experiments, the EFT approach to physics beyond the SM is particularly useful. It allows us to analyse all realistic extensions of the model in terms of few unknown parameters (the coefficients of the higher-dimensional operators suppressed by inverse powers of Λ) and to compare the sensitivity to New Physics (NP) of different low-energy observables.

The non-renormalizable operators should naturally induce large effects in processes which are not mediated by tree-level SM amplitudes, such as flavour-changing neutral-current (FCNC) rare processes. Up to now there is no evidence of deviations from the SM in these processes and this implies severe bounds on the effective scale of various dimension-six operators. For instance, the good agreement between SM expectations and experimental determinations of K^0–$\overline{K}^0$ mixing leads to bounds above 10^4 TeV for the effective scale of $\Delta S = 2$ operators, i.e. well above the few TeV range suggested by the Higgs sector. Similar bounds are obtained for the scale of operators contributing to lepton-flavour violating (LFV) transitions in the lepton sector, such as $\mu \to e\gamma$.

The apparent contradiction between these two determinations of Λ is a manifestation of what in many specific frameworks (supersymmetry, technicolour, etc.) goes under the name of *flavour problem*: if we insist with the theoretical prejudice that new physics has to emerge in the TeV region, we have to conclude that the new theory possesses a highly non-generic flavour structure. Interestingly enough, this structure has not been clearly identified yet, mainly because the SM, i.e. the low-energy limit of the new theory, doesn't possess an exact flavour symmetry.

The most reasonable (but also most *pessimistic*) solution to the flavour problem is the so-called *Minimal Flavour Violation* (MFV) hypothesis [1–4]. Under this assumption, which will be discussed in detail in the next sections, flavour-violating interactions are linked to the known structure of Yukawa couplings also beyond the SM. As a result, non-standard contributions in FCNC transitions turn out to suppressed to a level consistent with experiments even for $\Lambda \sim$ few TeV. On the most interesting aspects of the MFV hypothesis is that it can easily be implemented within the general EFT approach to new physics [3, 4]. The effective theories based on this symmetry principle allow us to establish unambiguous correlations among NP effects in various rare decays. These falsifiable predictions are the key ingredients to identify in a model-independent way which are the irreducible sources of breaking of the flavour symmetry.

3 MFV in the quark sector

The pure gauge sector of the SM is invariant under a large symmetry group of flavour transformations: $\mathcal{G}_{\rm SM} = \mathcal{G}_q \otimes \mathcal{G}_\ell \otimes U(1)^5$, where

$$\mathcal{G}_q = {\rm SU}(3)_{Q_L} \otimes {\rm SU}(3)_{U_R} \otimes {\rm SU}(3)_{D_R}, \qquad \mathcal{G}_\ell = {\rm SU}(3)_{L_L} \otimes {\rm SU}(3)_{E_R} \tag{1}$$

nd three of the five $U(1)$ charges can be identified with baryon number, lepton number and hypercharge [1, 3]. This large group and, particularly the SU(3) subgroups controlling flavour-changing transitions, is explicitly broken by the Yukawa interaction

$$\mathcal{L}_Y = \overline{Q}_L \lambda_d D_R H + \overline{Q}_L \lambda_u U_R H_c + \overline{L}_L \lambda_e E_R H + {\rm h.c.} \tag{2}$$

Since $\mathcal{G}_{\rm SM}$ is broken already within the SM, it would not be consistent to impose it as an exact symmetry of the additional degrees of freedom present in SM extensions: even if absent a the tree-level, the breaking of $\mathcal{G}_{\rm SM}$ would reappear at the quantum level because of the Yukawa interaction. The most restrictive hypothesis we can make to *protect* the breaking of $\mathcal{G}_{\rm SM}$ in a consistent way, is to assume that λ_d, λ_u and λ_e are the only source of $\mathcal{G}_{\rm SM}$-breaking also beyond the SM.

To derive the phenomenological consequences of this hypothesis, it is convenient to treat $\mathcal{G}_{\rm SM}$ as an unbroken symmetry of the underlying theory, promoting the λ_i to be dynamical fields with non-trivial transformation properties under $\mathcal{G}_{\rm SM}$

$$\lambda_u \sim (3, \overline{3}, 1)_{{\rm SU}(3)^3_q}\ , \qquad \lambda_d \sim (3, 1, \overline{3})_{{\rm SU}(3)^3_q}\ , \qquad \lambda_e \sim (3, \overline{3})_{{\rm SU}(3)^2_\ell}\ . \tag{3}$$

f the breaking of $\mathcal{G}_{\rm SM}$ occurs at very high energy scales –well above the TeV region where the we expect new degrees of freedom– at low-energies we would only be sensitive to the background values of the λ_i, i.e. to the ordinary SM Yukawa couplings. Employing the EFT language, we then define that an effective theory satisfies the criterion of Minimal Flavour Violation if all higher-dimensional operators, constructed from SM and λ fields, are (formally) invariant under the flavour group $\mathcal{G}_{\rm SM}$ [3].

According to this criterion, one should in principle consider operators with arbitrary powers of the (adimensional) Yukawa fields. However, a strong simplification arises by the observation that all the eigenvalues of the Yukawa matrices are small, but for the top one, and that the off-diagonal elements of the CKM matrix (V_{ij}) are very suppressed. It is then easy to realize that, similarly to the pure SM case, the leading coupling ruling all FCNC transitions with external down-type quarks is [3]:

$$(\Delta^q_{\rm LL})_{i\neq j} = (\lambda_u \lambda_u^\dagger)_{ij} \approx y_t^2 (V_{\rm CKM})^*_{3i} (V_{\rm CKM})_{3j}\ , \qquad y_t = m_t/v \approx 1\ . \tag{4}$$

s a result, within this framework the bounds on the scale of dimension-six FCNC effective operators turn out to be in the few TeV range (see Ref. [5] for updated values). Moreover, the flavour structure of $\Delta^q_{\rm FC}$ implies a well-defined link among

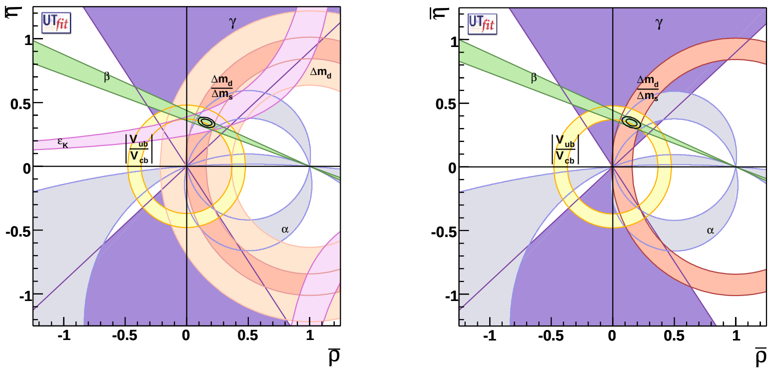

Figure 1: Fit of the CKM unitarity triangle within the SM (left) and in generic extensions of the SM satisfying the MFV hypothesis (right) [5].

possible deviations from the SM in FCNC transitions of the type $s \to d$, $b \to d$, and $b \to s$ (the only quark-level transitions where observable deviations from the SM are expected).

The idea that the CKM matrix rules the strength of FCNC transitions also beyond the SM has become a very popular concept in the recent literature and has been implemented and discussed in several works (see e.g. Ref. [2]). However, it is worth stressing that the CKM matrix represents only one part of the problem: a key role in determining the structure of FCNCs is also played by quark masses (via the GIM mechanism), or by the Yukawa eigenvalues. In this respect, the above MFV criterion provides the maximal protection of FCNCs (or the minimal violation of flavour symmetry), since the full structure of Yukawa matrices is preserved. Moreover, contrary to other approaches, the above MFV criterion is based on a renormalization-group-invariant symmetry argument, which can easily be extended to EFT approaches where new degrees of freedoms (such as extra Higgs doubles, or SUSY partners of the SM fields) are explicitly included.

As shown in Fig. 1, the MFV hypothesis provides a natural (a posteriori) justification of why no NP effects have been observed in the quark sector: by construction, most of the clean observables measured at B factories are insensitive to NP effects in this framework. However, it should be stressed that we are still very far from having proved the validity of this hypothesis from data. Non-minimal sources of flavour symmetry breaking with specific flavour structures, such as those discussed in Ref. [6], are still allowed (even with NP scales in the TeV range). A proof of the MFV hypothesis can be achieved only with a positive evidence of physics beyond the SM exhibiting the flavour pattern (link between $s \to d$, $b \to d$, and $b \to s$) predicted by the MFV assumption.

4 MFV in the lepton sector

Apart from arguments based on the analogy between quarks and leptons, the introduction of a MFV hypothesis for the lepton sector (MLFV) is demanded by a severe fine-tuning problem also in the lepton sector: within a generic EFT approach, the non-observation of $\mu \to e\gamma$ implies an effective NP scale above 10^5 TeV unless the coupling of the corresponding effective operator is suppressed by some symmetry principle.

Since the observed neutrino mass parameters are not described by the SM Yukawa interaction in Eq. (2), the formulation of a MLFV hypothesis is not straightforward. A proposal based on the assumption that the breaking of total lepton number (LN) and lepton flavour are decoupled in the underlying theory has recently been presented in Ref. [4], and further analysed in Ref. [7]. Two independent MLFV scenarios have been identified. They are characterized by the different status assigned to the effective Majorana mass matrix g_ν appearing as coefficient of the $|\Delta L| = 2$ dimension-five operator in the low energy effective theory [8]:

$$\mathcal{L}^{\nu}_{\rm eff} = -\frac{1}{\Lambda_{\rm LN}}\, g_\nu^{ij} (\overline{L}^{ci}_L \tau_2 H)(H^T \tau_2 L^j_L) + {\rm h.c.} \quad \longrightarrow \quad m_\nu = \frac{g_\nu v^2}{\Lambda_{\rm LN}} \tag{5}$$

n the truly minimal scenario (dubbed *minimal field content*), g_ν and the charged-lepton Yukawa coupling (λ_e) are assumed to be the only irreducible sources of breaking of $\mathcal{G}_\ell$, the lepton-flavour symmetry of the low-energy theory.

The irreducible character of g_ν does not hold in many realistic underlying theories with heavy right-handed neutrinos. For this reason, a second scenario (dubbed *extended field content*), with heavy right-handed neutrinos and a larger lepton-flavour symmetry group, $\mathcal{G}_\ell \times {\rm O}(3)_{\nu_R}$, has also been considered. In this extended scenario, the most natural and economical choice about the symmetry-breaking terms is the identification of the two Yukawa couplings, λ_ν and λ_e, as the only irreducible symmetry-breaking structures. In this context, $g_\nu \sim \lambda_\nu^T \lambda_\nu$ and the LN-breaking mass term of the heavy right-handed neutrinos is flavour-blind (up to Yukawa-induced corrections):

$$\begin{aligned} \mathcal{L}_{\rm heavy} &= -\frac{1}{2} M_\nu^{ij} \overline{\nu}^{ci}_R \nu^j_R + {\rm h.c.} \qquad M_\nu^{ij} = M_\nu \delta^{ij} \\ \mathcal{L}^{\rm ext}_Y &= \mathcal{L}_Y + i \lambda_\nu^{ij} \overline{\nu}^i_R (H^T \tau_2 L^j_L) + {\rm h.c.} \end{aligned} \tag{6}$$

n this scenario the flavour changing coupling relevant to $l_i \to l_j \gamma$ decays reads

$$(\Delta^\ell_{\rm LR})_{\rm MLFV} \;\propto\; \lambda_e \lambda_\nu^\dagger \lambda_\nu \to \frac{m_e}{v}\frac{M_\nu}{v^2} U_{\rm PMNS}\, (m_\nu^{1/2})_{\rm diag} H^2 (m_\nu^{1/2})_{\rm diag}\, U^\dagger_{\rm PMNS} \tag{7}$$

where H is an Hermitian-orthogonal matrix which can be parametrized in terms of three real parameters (ϕ_i) which control the amount of CP-violation in the right-handed sector [9]. In the CP-conserving limit, $H \to I$ and the phenomenological predictions for lepton FCNC decays turns out to be quite similar to the minimal field content scenario [4].

Once the field content of model is extended, there are in principle many alternative options to define the irreducible sources of lepton flavour symmetry breaking (see e.g. Ref. [10] for an extensive discussion). However, the specific choice discussed above has two important advantages: it is predictive and closely resemble the MFV hypothesis in the quark sector. The ν_R's are the counterpart of right-handed up quarks and, similarly to the quark sector, the symmetry-breaking sources are two Yukawa couplings.

The basic assumptions of the MLFV hypotheses are definitely less data-driven with respect to the quark sector. Nonetheless, the formulation of an EFT based on these assumptions is still very useful. As I will briefly illustrate in the following, it allows us to address in a very general way the following fundamental question: how can we detect the presence of new irreducible (fundamental) sources of LF symmetry breaking?

4.1 Phenomenological consequences on LFV decays

Using the MLFV-EFT approach, one can easily demonstrate that –in absence of new sources of LF violation– visible FCNC decays of μ and τ can occur only if there is a large hierarchy between Λ (the scale of new degrees of freedoms carrying LF) and $\Lambda_{\rm LN} \sim M_\nu$ (the scale of total LN violation) [4]. This condition is indeed realized within the explicit extensions of the SM widely discussed in the literature which predict sizable LF violating effects in charged leptons (see e.g. Ref. [11–14]).

More interestingly, the EFT allows us to draw unambiguous predictions about the relative size of LF violating decays of charged leptons (in terms of neutrino masses and mixing angles). At present, the uncertainty in the predictions for such ratios is limited from the poorly constrained value of the 1–3 mixing angle in the neutrino mass matrix (s_{13}) and, to a lesser extent, from the neutrino spectrum ordering and the CP violating phase δ. One of the clearest consequences from the phenomenological point of view is the observation that if $s_{13}0.1$ there is no hope to observe $\tau \to \mu\gamma$ at future accelerators (see Fig. 2). This happens because the stringent constraints from $\mu \to e\gamma$ already forbid too low values for the effective scale of LF violation. In other words, in absence of new sources of LF violation the most sensitive FCNC probe in the lepton sector is $\mu \to e\gamma$. This process should indeed be observed at MEG [15] for very realistic values of the new-physics scales Λ and $\Lambda_{\rm LN}$. Interestingly enough, this conclusion holds both in the minimal- and in the extended-field-content formulation of the MLFV framework.

The expectation of a higher NP sensitivity of $\mu \to \mu\gamma$ with respect to $\tau \to \mu\gamma$ (taking into account the corresponding experimental resolutions) is confirmed in several realistic NP frameworks. This happens for instance in the MSSM scenarios

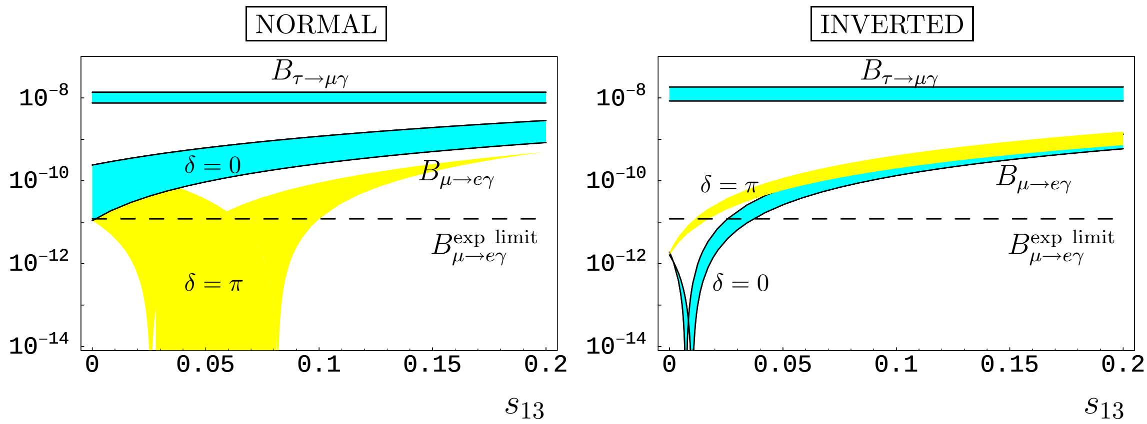

Figure 2: $B_{\tau\to\mu\gamma} = \Gamma(\tau \to \mu\gamma)/\Gamma(\tau \to \mu\nu\overline{\nu})$ compared to the $\mu \to e\gamma$ constraint within MLFV (minimal field content), as a function of the neutrino mixing angle s_{13} [4]. The shading corresponds to different values of the phase δ and the normal/inverted spectrum. The NP scales have been set to $\Lambda_{\rm LN}/\Lambda = 10^{10}$; their variation affects only the overall vertical scale.

analysed in Ref. [12–14] (see Fig. 3) with the exception of specific corners of the parameter space [12].

4.2 Leptogenesis

In the MLFV scenario with extended field content we can hope to generate the observed matter-antimatter asymmetry of the Universe by means of leptogenesis [16]. The viability of leptogenesis within the MLFV framework, which has recently been demonstrated in Ref. [17–19], is an interesting conceptual point: it implies that there are no phenomenological motivations to introduce new sources of flavour symmetry breaking in addition to the four λ_i (the three SM Yukawa couplings and λ_ν).

A necessary condition for leptogenesis to occur is a non-degenerate heavy-neutrino spectrum. Within the MLFV framework, the tree-level degeneracy of heavy neutrinos is lifted only by radiative corrections, which implies a rather predictive/constrained scenario. The most general form of the ν_R mass-splittings has the following structure:

$$\frac{\Delta M_R}{M_R} = c_\nu \left[\lambda_\nu\lambda_\nu^\dagger + (\lambda_\nu\lambda_\nu^\dagger)^T\right] + c_{\nu\nu}^{(1)} \left[\lambda_\nu\lambda_\nu^\dagger\lambda_\nu\lambda_\nu^\dagger + (\lambda_\nu\lambda_\nu^\dagger\lambda_\nu\lambda_\nu^\dagger)^T\right]$$
$$+ c_{\nu\nu}^{(2)} \left[\lambda_\nu\lambda_\nu^\dagger(\lambda_\nu\lambda_\nu^\dagger)^T\right] + c_{\nu\nu}^{(3)} \left[(\lambda_\nu\lambda_\nu^\dagger)^T\lambda_\nu\lambda_\nu^\dagger\right] + c_{\nu l} \left[\lambda_\nu\lambda_e^\dagger\lambda_e\lambda_\nu^\dagger + (\lambda_\nu\lambda_e^\dagger\lambda_e\lambda_\nu^\dagger)^T\right] + \ldots$$

Even without specifying the value of the c_i, this form allows us to derive a few general conclusions [17]:

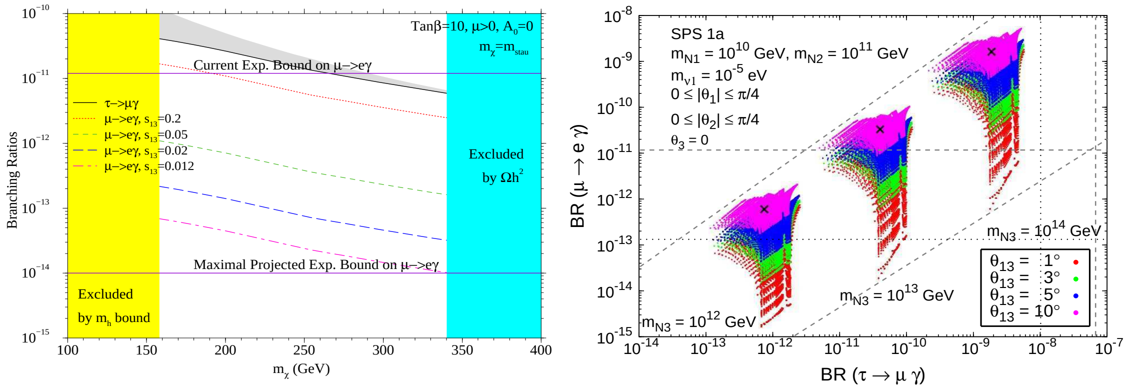

Figure 3: Left: Isolevel curves for $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ in the MSSM scenario of Ref. [13]. Right: $\mathcal{B}(\mu \to e\gamma)$ vs. $\mathcal{B}(\tau \to \mu\gamma)$ in the MSSM scenario of Ref. [14]

- The term proportional to c_ν does not generate a CPV asymmetry, but sets the scale for the mass splittings: these are of the order of magnitude of the decay widths, realizing in a natural way the condition of resonant leptogenesis.

- The right amount of leptogenesis can be generated even with $\lambda_e = 0$, if all the ϕ_i (the CP-violating parameters of H) are non vanishing. However, since $\lambda_\nu \sim \sqrt{M_\nu}$, for low values of M_ν ($\lesssim 10^{12}$ GeV) the asymmetry generated by the $c_{\nu l}$ term dominates. In this case η_B is typically too small to match the observed value and has a flat dependence on M_ν. At $M_\nu \gtrsim 10^{12}$ GeV the quadratic terms $c^{(i)}_{\nu\nu}$ dominate, determining an approximate linear growth of η_B with M_ν. These two regimes are illustrated in Fig.4.

As shown in in Fig.4, baryogenesis through leptogenesis is viable in MLFV models. In particular, assuming a loop hierarchy between the c_i (as expected in a perturbative scenario) and neglecting flavour-dependent effects in the Boltzmann equations (one-flavour approximation of Ref. [20]), the right size of η_B is naturally reached for $M_\nu \gtrsim 10^{12}$ GeV [17]. As shown in Ref. [18, 19], this lower bound can be weakened by the inclusion of flavour-dependent effects in the Boltzmann equations and/or by the $\tan\beta$-enhancement of λ_e occurring in two-Higgs doublet models.

From the phenomenological point of view, an important difference with respect to the CP-conserving case is the fact that non-vanishing ϕ_i change the predictions of the LFV decays, typically producing an enhancement of the $\mathcal{B}(\mu \to e\gamma)/\mathcal{B}(\tau \to \mu\gamma)$ ratio. The effect of the new phases is moderate and the CP-conserving predictions are recovered only for $M_\nu \gg 10^{12}$ GeV.

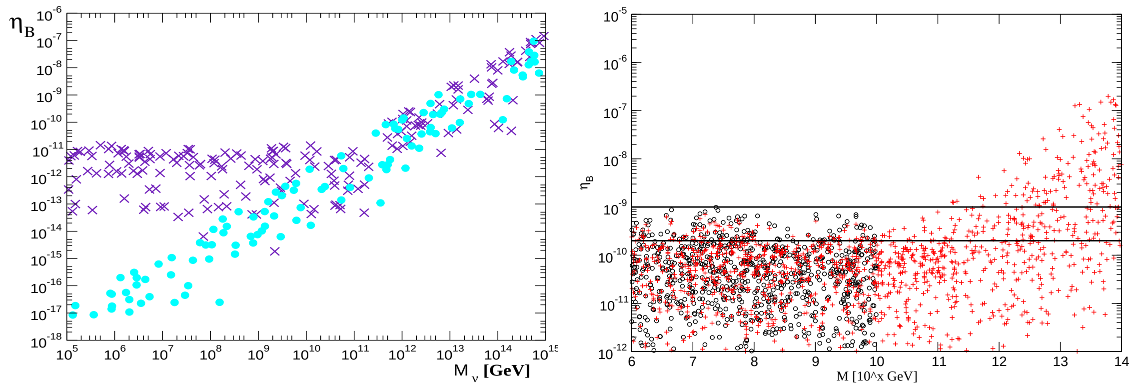

Figure 4: Left: Baryon asymmetry (η_B) as a function of the right-handed neutrino mass scale (M_ν) for $c_{\nu l} = 0$ (cyan circles) and $c_{\nu l} \neq 0$ (violet crosses) in the MLFV framework with extended field content [17]. Right: η_B as a function of M_ν with the inclusion of flavour-dependent effects [18].

5 MFV in Grand Unified Theories

Once we accept the idea that flavour dynamics obeys a MFV principle, both in the quark and in the lepton sector, it is interesting to ask if and how this is compatible with a grand-unified theory (GUT), where quarks and leptons sit in the same representations of a unified gauge group. This question has recently been addressed in Ref. [21], considering the exemplifying case of $\mathrm{SU}(5)_{\mathrm{gauge}}$.

Within $\mathrm{SU}(5)_{\mathrm{gauge}}$, the down-type singlet quarks (d^c_{iR}) and the lepton doublets (L_{iL}) belong to the $\bar{\mathbf{5}}$ representation; the quark doublet (Q_{iL}), the up-type (u^c_{iR}) and lepton singlets (e^c_{iR}) belong to the $\mathbf{10}$ representation, and finally the right-handed neutrinos (ν_{iR}) are singlet. In this framework the largest group of flavour transformation commuting with the gauge group is $\mathcal{G}_{\mathrm{GUT}} = \mathrm{SU}(3)_{\bar{5}} \times \mathrm{SU}(3)_{10} \times \mathrm{SU}(3)_1$, which is smaller than the direct product of the quark and lepton groups discussed before ($\mathcal{G}_q \times \mathcal{G}_l$). We should therefore expect some violations of the MFV+MLFV predictions, either in the quark sector, or in the lepton sector, or in both.

A phenomenologically acceptable description of the low-energy fermion mass matrices requires the introduction of at least four irreducible sources of $\mathcal{G}_{\mathrm{GUT}}$ breaking. From this point of view the situation is apparently similar to the non-unified case: the four $\mathcal{G}_{\mathrm{GUT}}$ spurions can be put in one-to-one correspondence with the low-energy spurions λ_u,λ_d, λ_e, and λ_ν. However, the smaller flavour group does not allow the diagonalization of λ_d and λ_e (which transform in the same way under $\mathcal{G}_{\mathrm{GUT}}$) in the same basis. As a result, two additional mixing matrices can appear in the expressions for flavour changing rates [21]. The hierarchical texture of the new mixing matrices is known since they reduce to the identity matrix in the limit $\lambda_e^T = \lambda_d$. Taking into account this fact, and analysing the structure of the allowed higher-dimensional operators, a number of reasonably firm phenomenological consequences can be deduced [21]:

- There is a well defined limit in which the standard MFV scenario for the quark sector is fully recovered: $M_\nu \ll 10^{12}$ GeV and small $\tan\beta$ (in a two-Higgs doublet case). For $M_\nu \sim 10^{12}$ GeV and small $\tan\beta$, deviations from the standard MFV pattern can be expected in rare K decays but not in B physics.[1] Ignoring fine-tuned scenarios, $M_\nu \gg 10^{12}$ GeV is excluded by the present constraints on quark FCNC transitions. Independently from the value of M_ν, deviations from the standard MFV pattern can appear both in K and in B physics for $\tan\beta m_t/m_b$ (see the next section).

- Contrary to the non-GUT MFV framework, the rate for $\mu \to e\gamma$ (and other LFV decays) cannot be arbitrarily suppressed by lowering the average mass M_ν of the heavy ν_R. This fact can easily be understood by looking at the flavour structure of the relevant effective couplings, which now assume the following form:
$$(\Delta^\ell_{\rm LR})_{\rm MFV-GUT} = \; c_1\; \lambda_e \lambda_\nu^\dagger \lambda_\nu \;+\; c_2\; \lambda_u \lambda_u^\dagger \lambda_e \;+\; c_3\; \lambda_u \lambda_u^\dagger \lambda_d^T \;+\; \ldots \qquad (8)$$
In addition to the terms involving $\lambda_\nu \sim \sqrt{M_\nu}$ already present in the non-unified case, the GUT group allows also M_ν-independent terms involving the quark Yukawa couplings. The latter become competitive for $M_\nu 10^{12}$ GeV and their contribution is such that for $\Lambda 10$ TeV the $\mu \to e\gamma$ rate is above 10^{-13} (i.e. within the reach of MEG [15]).

- Improved experimental information on $\tau \to \mu\gamma$ and $\tau \to e\gamma$ are a now a key tool: the best observables to discriminate the relative size of the MLFV contributions with respect to the GUT-MFV ones. In particular, if the quark-induced terms turn out to be dominant, the $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma)$ ratio could reach values of $\mathcal{O}(10^{-4})$, allowing $\tau \to \mu\gamma$ to be just below the present exclusion bounds.

6 The large $\tan\beta$ scenario

The conclusions discussed in the previous section are very general and holds in most GUT theories. The large $\tan\beta$ regime represents a more specific corner of GUT

[1] The conclusion that K decays are the most sensitive probes of possible deviations from the strict MFV ansatz follows from the strong suppression of the $s \to d$ short-distance amplitude in the SM [$V_{td}V_{ts}^* = \mathcal{O}(10^{-4})$], and goes beyond the hypothesis of an underlying GUT. This is the reason why $K \to \pi\nu\overline{\nu}$ decays, which are the best probes of $s \to d$ $\Delta F = 1$ short-distance amplitudes [22], play a key role in any extension of the SM containing non-minimal sources of flavour symmetry breaking, as confirmed by recent analyses performed in the framework of the Little Higgs model with T parity [23], and in the MSSM with non-minimal A terms [24].

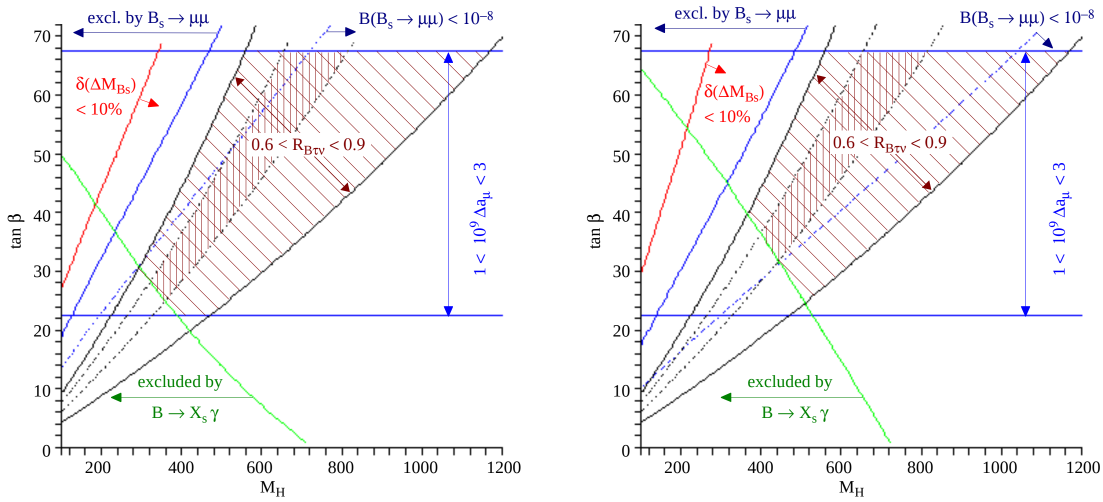

Figure 5: Correlations in the M_H–$\tan\beta$ plane within the MSSM for heavy squarks ($\mu = M_{\tilde{q}} = 2M_{\tilde{\ell}} = 3M_2 \approx 1$ TeV, $A_U = -/+\,1$ TeV in the left/right plot) [30]. $R_{B\tau\nu} = \mathrm{BR}(B \to \tau\nu)/\mathrm{BR}^{\mathrm{SM}}(B \to \tau\nu)$.

models, which is particularly interesting for flavour physics. Tan$\beta = v_u/v_d$, denotes the ratio of the two Higgs vacuum expectation values, which in many extensions of the SM are coupled separately to up- and down-type quarks (consistently with the MFV hypothesis). This parameter controls the overall normalization of the Yukawa couplings. The regime of large $\tan\beta$ [$\tan\beta = \mathcal{O}(m_t/m_b)$] has an intrinsic theoretical interest since it allows the unification of top and bottom Yukawa couplings, as predicted for instance in SO(10).

Since the b-quark Yukawa coupling become $\mathcal{O}(1)$, the large $\tan\beta$ regime is particularly interesting for B physics, even in absence of deviations from the MFV hypothesis. One of the most clear phenomenological consequences is the suppression of the $B \to \ell\nu$ decay rate with respect to its SM expectation [25]. Potentially measurable effects are expected also in $B \to X_s\gamma$, ΔM_{B_s} and, especially, in the helicity-suppressed FCNC decays $B_{s,d} \to \ell^+\ell^-$. The recent experimental evidence of $B \to \tau\nu$ at Belle [26] and Babar [28], the precise ΔM_{B_s} measurement by CDF [28], and the constantly improving bounds on $B_{s,d} \to \ell^+\ell^-$ by both CDF and D0 [29], make this scenario particularly interesting and timing from the phenomenological point if view.

Within the EFT approach where all the high degrees of freedom –but for the Higgs fields– are integrated out [3], we cannot establish well-defined correlations among these observables. However, the scenario becomes quite predictive within a more ambitious EFT: the MSSM with MFV. As recently shown in Ref. [30,31], in the MFV-MSSM with large $\tan\beta$ and heavy squarks, interesting correlations can be established among the B observables mentioned above and two flavour-conserving observables: the anomalous magnetic moment of the muon and the lower limit on the lightest Higgs boson mass. An illustration of these correlations is shown in Fig. 5.

Present data are far from having established a clear evidence for such scenario (as for any deviation from the SM). Nonetheless, it is interesting to note that this scenario can naturally solve the long-standing $(g-2)_\mu$ anomaly and explain in a natural why the lightest Higgs boson has not been observed yet. Moreover, it predicts visible deviations from the SM in $\mathrm{BR}(B \to \tau\nu)$ (most likely a suppression, of at least 10%) and $B_{s,d} \to \ell^+\ell^-$ (most likely a enhancement, up to a factor of 10), which could possibly be revealed in the near future. Finally, the parameter space which leads to these interesting effects can also naturally explain why $\mathrm{BR}(B \to X_s\gamma)$ and ΔM_{B_s} are in good agreement with the SM expectations [30].

The observables $\mathrm{BR}(B \to \tau\nu)$, $\mathrm{BR}(B_{s,d} \to \ell^+\ell^-)$ and $(g-2)_\mu$ can be considered as the most promising low-energy probes of the MSSM scenario with heavy squarks and large $\tan\beta$. Nonetheless, interesting consequences of this scenario could possibly be identified also in other observables. In particular, as pointed out in [32], if the slepton sector contains sizable sources of LFV, we could even hope to observe violations of lepton universality in the $\mathrm{BR}(P \to \ell\nu)/\mathrm{BR}(P \to \ell'\nu)$ ratios. Deviations from the SM can be $\mathcal{O}(1\%)$ in $\mathrm{BR}(K \to e\nu)/\mathrm{BR}(K \to \mu\nu)$ [32], and can reach $\mathcal{O}(1)$ and $\mathcal{O}(10^3)$ in $\mathrm{BR}(B \to \mu\nu)/\mathrm{BR}(B \to \tau\nu)$ and $\mathrm{BR}(B \to e\nu)/\mathrm{BR}(B \to \tau\nu)$, respectively [30].

7 Conclusions

Rare decays of quarks and leptons provide a unique opportunity to shed more light on the underlying mechanism of flavour mixing. The discovery of neutrino oscillations, which has opened a new era in flavour physics, gives us more hopes in this respect. As we have shown by means of a general EFT approach to physics beyond the SM, under rather general hypothesis (quark-lepton unification and new physics in the TeV range) neutrino oscillations imply the existence of interesting non-standard effects also in rare decays of charged leptons and, possibly, in a few rare B and K decay observables.

The most solid and exciting expectation is a $\mu \to e\gamma$ branching ratio exceeding 10^{-13}, i.e. within the reach of the MEG experiment. In more specific scenarios, we could also observe sizable non-standard effects in rare FCNC τ and K decays and –particularly in the large $\tan\beta$ regime of the MSSM– in the purely leptonic decays of both charged and neutral B mesons.

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Bibliography

[1] R. S. Chivukula and H. Georgi, 188198799; L. J. Hall and L. Randall, Phys. Rev. Lett. **65**, 2939 (1990).

[2] A. Ali and D. London, 91999687 [hep-ph/9903535]; A. J. Buras *et al.*, 5002001161 [hep-ph/0007085]; S. Laplace, Z. Ligeti, Y. Nir and G. Perez, 652002094040 [hep-ph/0202010]; A. J. Buras, Acta Phys. Polon. B **34** (2003) 5615 [hep-ph/0310208].

[3] G. D'Ambrosio, G. F. Giudice, G. Isidori and A. Strumia, 6452002155 [hep-ph/0207036].

[4] V. Cirigliano, B. Grinstein, G. Isidori and M. B. Wise, 7282005121 [hep-ph/0507001].

[5] M. Bona *et al.* [UTfit Collaboration], Phys. Rev. Lett. **97** (2006) 151803 [hep-ph/0605213].

[6] T. Feldmann and T. Mannel, hep-ph/0611095.

[7] V. Cirigliano and B. Grinstein, Nucl. Phys. B **752** (2006) 18 [hep-ph/0601111].

[8] S. Weinberg, Phys. Rev. Lett. **43**, 1566 (1979).

[9] S. Pascoli, S. T. Petcov and C. E. Yaguna, Phys. Lett. B **564**, 241 (2003) [hep-ph/0301095].

[10] S. Davidson and F. Palorini, Phys. Lett. B **642**, 72 (2006) [hep-ph/0607329].

[11] R. Barbieri, L. J. Hall and A. Strumia, 4451995219 [hep-ph/9501334].

[12] J. R. Ellis, J. Hisano, M. Raidal and Y. Shimizu, Phys. Rev. D **66** (2002) 115013 [hep-ph/0206110].

[13] A. Masiero, S. Profumo, S. K. Vempati and C. E. Yaguna, JHEP **0403** (2004) 046 [hep-ph/0401138].

[14] S. Antusch, E. Arganda, M. J. Herrero and A. M. Teixeira, JHEP **0611** (2006) 090 [hep-ph/0607263].

[15] M. Grassi [MEG Collaboration], Nucl. Phys. Proc. Suppl. **149** (2005) 369.

[16] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).

[17] V. Cirigliano, G. Isidori and V. Porretti, Nucl. Phys. B **763** (2007), 228 [hep-ph/0608123].

[18] G. C. Branco, A. J. Buras, S. Jager, S. Uhlig and A. Weiler, hep-ph/0609067.

[19] S. Uhlig, hep-ph/0612262.

[20] S. Blanchet and P. Di Bari, JCAP **0606**, 023 (2006) [hep-ph/0603107].

[21] B. Grinstein, V. Cirigliano, G. Isidori and M. B. Wise, Nucl. Phys. B **763** (2007) 35 [hep-ph/0608123].

[22] For recent reviews see: U. Haisch, hep-ph/0605170; D. Bryman, A. J. Buras, G. Isidori and L. Littenberg, Int. J. Mod. Phys. A **21**, 487 (2006) [hep-ph/0505171]; A. J. Buras, F. Schwab and S. Uhlig, hep-ph/0405132.

[23] M. Blanke *et al.*, JHEP **0701** (2007) 066 [hep-ph/0610298]; C. Tarantino, hep-ph/0702152 (these proceedings).

[24] G. Isidori *et al.*, JHEP **0608** (2006) 064 [hep-ph/0604074].

[25] W. S. Hou, Phys. Rev. D **48** (1993) 2342.

[26] K. Ikado *et al.*, Phys. Rev. Lett. **97** (2006) 251802 [hep-ex/0604018].

[27] B. Aubert *et al.* [BABAR Collaboration], hep-ex/0608019.

[28] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97** (2006) 062003 [hep-ex/0606027].

[29] R. Bernhard *et al.* [CDF Collaboration], hep-ex/0508058.

[30] G. Isidori and P. Paradisi, Phys. Lett. B **639** (2006) 499 [hep-ph/0605012].

[31] E. Lunghi, W. Porod and O. Vives, Phys. Rev. D **74**, 075003 (2006) [hep-ph/0605177].

[32] A. Masiero, P. Paradisi and R. Petronzio, Phys. Rev. D **74** (2006) 011701 [hep-ph/0511289].