Flavor Physics with light quarks and leptons

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The impact of rare K decays and lepton-flavor violating processes in shedding light on physics beyond the Standard Model is reviewd. To this purpose, I first recall the formulation of the Minimal Flavor Violation hypothesis –both in the quark and in the lepton sector– and then use it as guiding principle in comparing the new-physics sensitivity of different rare processes. On the phenomenological side, the discussion is focused mainly on the impact of $K \to \pi\nu\bar{\nu}$, $\mu \to e\gamma$, and lepton-flavor universality tests with $K_{\ell 2}$ and $\pi_{\ell 2}$ decays.

1. Introduction

Despite the great phenomenological success of the Standard Model (SM), it is natural to consider this theory only as the low-energy limit of a more general model. More precisely, the SM Lagrangian can be regarded as the renormalizable part of an effective field theory (EFT), valid up to some still undetermined cut-off scale Λ ($\Lambda > M_W$). Since the SM is renormalizable, we have no clear 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. A key experimental test of this hypothesis will soon be performed at the LHC, with the direct exploration of the TeV energy scale.

The direct search for new degrees of freedom at the TeV scale (the so called *high-energy frontier*) is not the only tool at our disposal to shed light on physics beyond the SM. A complementary and equally important source of information about the underlying theory is provided by high-precision low-energy experiments (the so called *high-intensity frontier*). The latter are particularly interesting in determining the symmetry properties of the new degrees of freedom. As I will discuss in this talk, flavor-changing neutral-current (FCNC) transitions in K and μ decays, and lepton-flavor (LF) universality tests in $K_{\ell 2}$ and $\pi_{\ell 2}$ decays, offer a unique opportunity to study the flavour structure of physics beyond the SM.

1.1. The flavor problem

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 new-physics (NP) sensitivity 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 FCNC processes. Up to now there is no evidence of these effects and this implies severe bounds on the effective scale of dimension-six FCNC operators. For instance, the good agreement between SM expectations and experimental determinations of K^0–$\bar{K}^0$ 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 LF-violating operators contributing to FCNC 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, techincolour, etc.) goes under the name of *flavor 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 flavor 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 flavor symmetry.

The most reasonable (but also most *pessimistic*) solution to the flavor problem is the so-called *Minimal Flavor Violation* (MFV) hypothesis [1–4]. Under this assumption, which will be discussed in detail in the next sections, flavor-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 the possibility to formulate it within the general EFT approach to physics beyond the SM [2, 3]. The effective theories based on this symmetry principle allow us to establish unambiguous correlations among NP effects in different FCNC transitions. These falsifiable predictions are the key ingredient to identify in a model-independent way which are the irreducible sources of breaking of the flavor symmetry.

2. MFV in the quark sector

The pure gauge sector of the SM is invariant under a large symmetry group of flavor transformations: $G_F \equiv \mathrm{SU}(3)_q^3 \otimes \mathrm{SU}(3)_\ell^2 \otimes U(1)^5$, where $\mathrm{SU}(3)_q^3 =$

$\mathrm{SU}(3)_{Q_L} \otimes \mathrm{SU}(3)_{U_R} \otimes \mathrm{SU}(3)_{D_R}$, $\mathrm{SU}(3)_\ell^2 = \mathrm{SU}(3)_{L_L} \otimes \mathrm{SU}(3)_{E_R}$ and three of the five $U(1)$ charges can be identified with baryon number, lepton number and hypercharge [1, 2]. This large group and, particularly the SU(3) subgroups controlling flavor-changing transitions, is explicitly broken by the Yukawa interaction

$$\mathcal{L}_Y = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + \bar{L}_L Y_E E_R H \ + \ \text{h.c.} \tag{1}$$

Since G_F 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 G_F would reappear at the quantum level because of the Yukawa interaction. The most restrictive hypothesis we can make to *protect* the breaking of G_F in a consistent way, is to assume that Y_D, Y_U and Y_E are the only source of G_F-breaking also beyond the SM.

To implement and interpret this hypothesis in a natural way, we can assume that G_F is indeed a good symmetry, promoting the Y to be dynamical fields with non-trivial transformation properties under G_F:

$$Y_U \sim (3, \bar{3}, 1)_{\mathrm{SU}(3)_q^3}\ , \qquad Y_D \sim (3, 1, \bar{3})_{\mathrm{SU}(3)_q^3}\ , \\ Y_E \sim (3, \bar{3})_{\mathrm{SU}(3)_\ell^2}\ . \tag{2}$$

If the breaking of G_F occurs at very high energy scales –well above the TeV region where the we expect new degrees– at low-energies we would only be sensitive to the background values of the Y, i.e. to the ordinary SM Yukawa couplings. Employing the EFT language, we then define that an effective theory satisfies the criterion of Minimal Flavor Violation if all higher-dimensional operators, constructed from SM and Y fields, are (formally) invariant under the flavor group G_F [2].

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:

$$(\lambda_{\mathrm{FC}})_{ij} = \begin{cases} \left(Y_U Y_U^\dagger\right)_{ij} \approx \lambda_t^2 V_{3i}^* V_{3j} & i \neq j\ , \\ 0 & i = j\ . \end{cases} \tag{3}$$

As 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 (3) implies a well-defined link among possible deviations from the SM in FCNC transitions of the type $s \to d$, $b \to d$, and $b \to s$.[1]

Channel	short-distance contribution (rate %)	irreducible th. error on s.d. contrib.	SM BR (central value)
$K_L \to \pi^0 \nu\bar{\nu}$	$> 99\%$	$\sim 1\%$	3×10^{-11}
$K^+ \to \pi^+ \nu\bar{\nu}$	88%	$\sim 3\%$	8×10^{-11}
$K_L \to \pi^0 e^+ e^-$	38%	$\sim 15\%$	3.5×10^{-11}
$K_L \to \pi^0 \mu^+ \mu^-$	28%	$\sim 30\%$	1.5×10^{-11}

Table I Summary of the short-distance sensitivity of the four most-interesting rare K decays. The second column denotes the contribution to the total rate determined by electroweak dynamics (top-quark loops). The third column indicates the irreducible (non-parametric) error on the short-distance amplitude, as extracted from the corresponding rate measurement (in the limit of negligible exp. error).

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. [4]). However, it is worth stressing that the CKM matrix represent 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 flavor symmetry), since the full structure of Yukawa matrices is preserved. We finally emphasize that, contrary to other approaches, the above MFV criterion is based on a renormalization-group-invariant symmetry argument, which is independent from the specific new-physics framework.

3. Rare K decays

In the kaon sector is often difficult to control long-distance effects to a level sufficient to perform precise test of short-distance dynamics. This happens in the four golden modes $K_L \to \pi^0 \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 e^+ e^-$, and $K_L \to \pi^0 \mu^+ \mu^-$, which represent a unique window on $s \to d$ FCNC transitions. As shown in Table I, the theoretical cleanness of these four modes is not the same. The two neutrino channels are exceptionally clean: their decay rates can be computed to a degree of precision not matched by any other FCNC process in the B and K systems [6].

[1] Within the MFV framework, these three types of FCNC processes are the only quark-level transitions where observable deviations from the SM are expected.

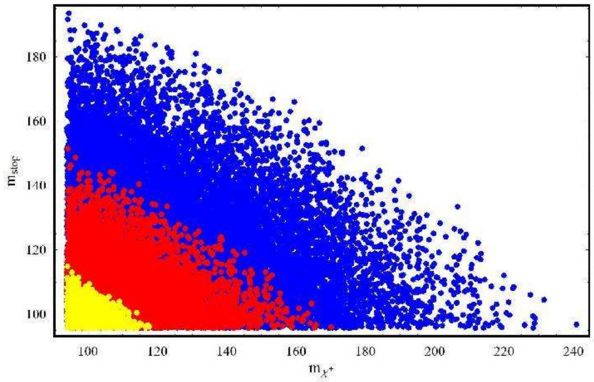

Figure 1: Regions in the $m_{\tilde{t}} - m_{\tilde{\chi}}$ plane (lightest stop and chargino masses) allowing enhancements of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ of more than 11% (yellow/light gray), 8.5% (red/medium gray) and 6% (blue/dark gray) in the MFV-MSSM scenario [24], for $\tan\beta = 2$ and $M_{H^+} > 1$ TeV [the corresponding enhancements for $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ are 15%, 12.5% and 10%, respectively].

3.1. SM predictions

$\underline{K \to \pi\nu\bar{\nu}}$ The main reason for the exceptional theoretical cleanness of $K \to \pi\nu\bar{\nu}$ decays is the fact that –within the SM– these processes are mediated by electroweak amplitudes of $O(G_F^2)$ which exhibit a power-like GIM mechanism and are largely dominated by top-quark loops. This property implies a severe suppression of non-perturbative effects [7–9]. By comparison, it should be noted that typical loop-induced amplitudes relevant to meson decays are of $O(G_F\alpha_s)$ (gluon penguins) or $O(G_F\alpha_{\rm em})$ (photon penguins), and have only a logarithmic-type GIM mechanism (which implies a much less severe suppression of long-distance effects).

A related important virtue, is the fact that the leading contributions to $K \to \pi\nu\bar{\nu}$ amplitudes can be described in terms of a single dimension-six effective operator,

$$Q_{sd}^{\nu\nu} = \bar{s}\gamma^\mu(1-\gamma_5)d \; \bar{\nu}\gamma_\mu(1-\gamma_5)\nu \;, \qquad (4)$$

both in the SM and in MFV models. The hadronic matrix elements of $Q_{sd}^{\nu\nu}$ relevant to $K \to \pi\nu\bar{\nu}$ amplitudes can be extracted directly from the well-measured $K \to \pi e\nu$ decays, including isospin breaking corrections [10].

The dominant theoretical error in estimating the $K^+ \to \pi^+\nu\bar{\nu}$ rate within the SM is due to the sub-leading, but non-negligible, charm contribution. A significant step forward in the reduction of this error has recently been achieved in Ref. [11], where the charm contribution to the Wilson coefficient of Q_{sd} has been evaluated at the NNLO accuracy in QCD. Thanks to this work, the intrinsic theoretical error in the perturbative charm contribution turns out to be safely negligible: the dominant uncertainty is the parametric error induced by the knowledge of m_c [11], which induces a $\sim \pm 5\%$ error in the total rate. Recently, the error associated to non-perturbative effects around and below the charm scale (dimension-eight operators and light-quark loops) has also been quantified and reduced [8]: this residual uncertainty induces a $\sim \pm 3\%$ error on the rate. As shown in Ref. [12], this error could possibly be reduced in the future by means of appropriate lattice calculations. Putting all the ingredients together, taking into account the sizable parametric uncertainty on the CKM matrix elements, the present updated prediction for the charged channel reads:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.2 \pm 1.0) \times 10^{-11} \qquad (5)$$

The case of $K_L \to \pi^0\nu\bar{\nu}$ is even cleaner from the theoretical point of view [13]. The CP structure of Q_{sd} implies that only the CP-violating part of the dimension-six effective Hamiltonian –where the charm contribution is absolutely negligible– contributes to $K_2 \to \pi^0\nu\bar{\nu}$. As a result, the dominant direct-CP-violating component of the $K_L \to \pi^0\nu\bar{\nu}$ amplitude is completely saturated by the top contribution (which receives tiny QCD corrections). Intermediate and long-distance effects in this process are confined only to the indirect-CP-violating contribution [14] and to the CP-conserving one [9], which are both extremely small. This allows us to write an expression for the $K_L \to \pi^0\nu\bar{\nu}$ rate in terms of short-distance parameters, namely

$$\begin{aligned} \mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\rm SM} &= 4.16 \times 10^{-10} \\ &\times \left[\frac{\overline{m}_t(m_t)}{167\ \mathrm{GeV}}\right]^{2.30} \left[\frac{\Im(V_{ts}^* V_{td})}{\lambda^5}\right]^2 , \end{aligned} \qquad (6)$$

which has a theoretical error below 3%.

$\underline{K \to \pi\ell^+\ell^-}$ The GIM mechanism of the $s \to d\gamma^*$ amplitude is only logarithmic. As a result, the $K \to \pi\gamma^* \to \pi\ell^+\ell^-$ amplitude is completely dominated by long-distance dynamics and provides a large contribution to the CP-allowed transitions $K^+ \to \pi^+\ell^+\ell^-$ and $K_S \to \pi^0\ell^+\ell^-$.

The situation is very different for the very-suppressed $K_L \to \pi^0\ell^+\ell^-$ modes. The decay amplitudes of these processes have three main ingredients: i) a clean direct-CP-violating component determined by short-distance dynamics; ii) an indirect-CP-violating term due to K_L-K_S mixing and the CP-allowed $K_S \to \pi^0\gamma^*$ transition; iii) a long-distance CP-conserving component due to two-photon intermediate states. Although generated by very different dynamics, these three components are of comparable size within the SM. The precise knowledge about their magnitude and sign (particularly of ii and iii) has substantially improved in the last few years [15–17]. This

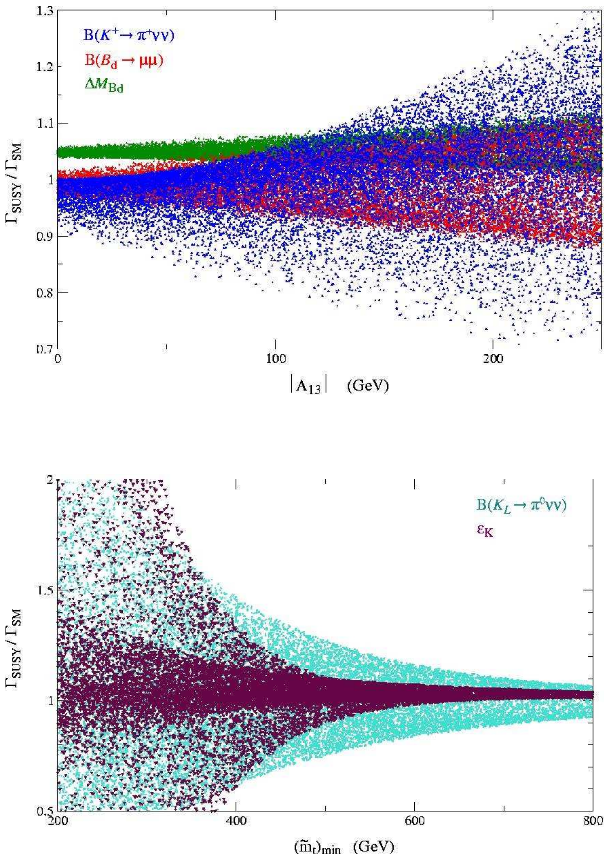

Figure 2: Dependence of various FCNC observables (normalized to their SM value) on the up-type trilinear terms (A_{13}) and on squark masses in the general MSSM [24] Upper plot: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ (blue/dark gray), $\mathcal{B}(B_d \to \mu^+\mu^-)$ (red/gray lower-region), ΔM_{B_d} (green/gray upper-region) as a function of A_{13}. Lower plot: ϵ_K (bordeaux/dark gray) and $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ (light blue/light gray) as a function of the lightest up-type squark mass.

improvement has been made possible by the observation of the $K_S \to \pi^0\ell^+\ell^-$ decays [18] and also by precise experimental studies of the $K_L \to \pi^0\gamma\gamma$ diphoton spectrum [19]. As a result of these new experimental results, and the related theoretical analyses in Ref. [15–17], we finally have a good control on all the components of $K_L \to \pi^0\ell^+\ell^-$ amplitudes (see Table I).

In both cases the short-distance component represent a sizable fraction of the branching ratios. Moreover, electron and muon modes have different sensitivity to short-distance dynamics (with different relative weights of vector- and axial-current contributions already within the SM). This provides a very powerful tool to distinguish among different new-physics scenarios [16, 20].

3.2. Rare K decays beyond the SM

As already mentioned, the short distance nature of the $s \to d\nu\bar{\nu}$ transition implies a strong sensitivity of $K \to \pi\nu\bar{\nu}$ decays to possible SM extensions [21]. Observable deviations from the SM predictions are expected in many specific frameworks. In particular, large effects are expected in models with non-MFV structures, such as scenarios with enhanced Z-penguins [22], the MSSM with non-MFV soft-breaking terms [23–25] or with R-parity violation [26]. The effects are much smaller in models which respect the MFV criterion, such as the low-energy supersymmetric scenarios analysed in Ref. [24, 27], or the little-Higgs and large-extra-dimension models discussed in Ref. [29] and Ref. [28]. Present experimental data do not allow yet to fully explore the high-discovery potential of these modes. Nonetheless, it is worth to stress that the evidence of the $K^+ \to \pi^+\nu\bar{\nu}$ transition obtained at BNL [30] already provides highly non-trivial constraints on the realistic scenarios with large new sources of flavour mixing.

As illustrated in Fig. 1, within the pessimistic framework of MFV the possible deviations from the SM in $K \to \pi\nu\bar{\nu}$ are highly correlated to the spectrum of the new degrees of freedom. For this reason, even within MFV models precise measurements of these modes would be very valuable (allowing for very stringent tests of the theory). In presence of non-MFV structures, the two $K \to \pi\nu\bar{\nu}$ modes are usually the most sensitive probes of new sources of flavor symmetry breaking which also violates the $SU(2)_L$ gauge symmetry (such as the up-type trilinear terms in the MSSM, see Fig. 2). Within these general frameworks, significant new information can also be extracted from the $K_L \to \pi^0\ell^+\ell^-$ modes [22, 24].

In summary, it is fair to say that the four rare K decay modes in Table I, and particularly the two neutrino modes, are a mandatory ingredient for a deeper and model-independent study of the flavor problem in the quark sector.

4. Minimal Lepton Flavor Violation

Since the observed neutrino mass parameters are not described by the SM Yukawa interaction in Eq. (1), the formulation of a MFV hypothesis for the lepton sector is not straightforward. A proposal based on the assumption that the breaking of total lepton number (LN) and lepton flavor are decoupled in the underlying theory has recently been presented in Ref. [3], and further analysed in Ref. [31].

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 [32]:

$$\mathcal{L}^{\nu}_{\rm eff} = -\frac{1}{\Lambda_{\rm LN}}\, g_{\nu}^{ij} (\bar{L}^{ci}_L \tau_2 H)(H^T \tau_2 L^j_L) \;+\; {\rm h.c.} \qquad (7)$$

In the truly minimal scenario (dubbed *minimal field content*), g_ν and the charged-lepton Yukawa coupling (Y_E) are assumed to be the only irreducible sources of breaking of $SU(3)_{L_L} \times SU(3)_{E_R}$, the lepton-flavor symmetry of the low-energy theory. This strong assumption 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-flavor symmetry group, $SU(3)_{L_L} \times SU(3)_{E_R} \times O(3)_{\nu_R}$, 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, Y_ν and Y_E, as the only irreducible symmetry-breaking structures (in close analogy with the quark sector). In this context, $g_\nu \sim Y_\nu^T Y_\nu$ and the LN-breaking mass term of the heavy right-handed neutrinos is flavor-blind (up to Yukawa-induced corrections):

$$\begin{aligned}\mathcal{L}_{\rm heavy} &= -\frac{1}{2} M_\nu^{ij} \bar{\nu}^{ci}_R \nu^j_R \;+\; {\rm h.c.} \qquad M^{ij}_\nu = M_\nu \delta^{ij} \\ \mathcal{L}^{\rm ext}_Y &= \mathcal{L}_Y + i Y^{ij}_\nu \bar{\nu}^i_R (H^T \tau_2 L^j_L) \;+\; {\rm h.c.} \qquad (8)\end{aligned}$$

The basic assumptions of these scenarios are more arbitrary are less phenomenologically-driven than in the quark sector. Nonetheless, the formulation of an EFT based on these assumptions is still very useful. As I will briefly illustrate in the next section, 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?

5. LF violation: μ vs τ 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) [3]. 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. [33]).

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

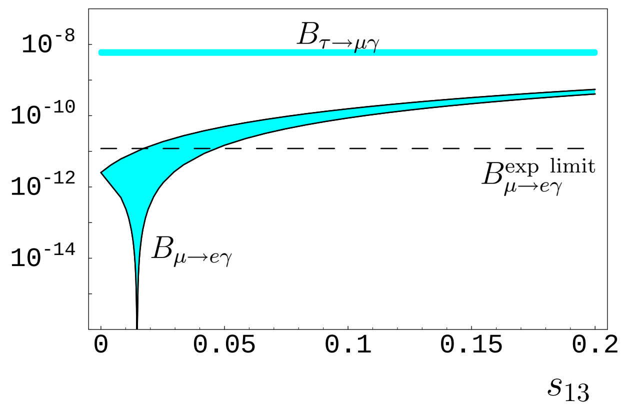

Figure 3: $B_{\tau\to\mu\gamma} = \Gamma(\tau \to \mu\gamma)/\Gamma(\tau \to \mu\nu\bar{\nu})$ compared to the $\mu \to e\gamma$ constraint within MLFV (minimal field content), as a function of the neutrino mixing angle s_{13} [3]. The shading corresponds to different values of the phase δ and the normal/inverted spectrum. The NP scales have been set to $\Lambda_{\rm LN}/\Lambda = 10^{10}$; their variation affects only the overall vertical scale.

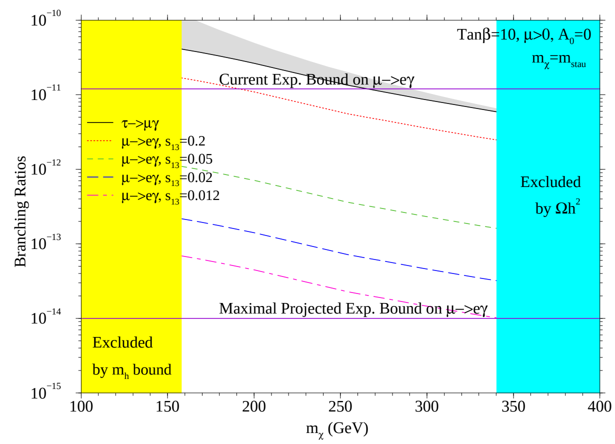

Figure 4: Isolevel curves for $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ in the MSSM (for $\tan\beta = 10$, $\mu > 0$ and $A_0 = 0$) compared with the present and future experimental resolution on $\mathcal{B}(\mu \to e\gamma)$ [35].

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 $s_{13} \gtrsim 0.1$ there is no hope to observe $\tau \to \mu\gamma$ at future accelerators (see Fig. 3). 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 [34] for very realistic values of the new-physics scales Λ and $\Lambda_{\rm LN}$.

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 (see Fig. 4) with the exception of specific corners of the parameter space [36].

6. LF universality tests in $K_{\ell 2}$ and $\pi_{\ell 2}$

An alternative phenomenological tool to search for new sources of LF violation is provided by precise LF universality tests in charged-current meson decays. In particular, the ratios

$$R_P^{\mu/e} = \frac{\mathcal{B}(P \to \mu\nu)}{\mathcal{B}(P \to e\nu)} \quad (9)$$

can be predicted with excellent accuracies in the SM, both for $P = \pi$ (0.02% accuracy [37]) and $P = K$ (0.04% accuracy [37]), allowing for some of the most significant tests of LF universality.

Within MLFV models, it is easy to realise that these ratios cannot be modified at appreciable levels: the presence of the charged-lepton Yukawa coupling (Y_E) in the operators involving the right-handed lepton fields makes their contribution safely negligible. However, as recently pointed out in Ref. [38], this suppression can be avoid in realistic non-MFV scenarios which can occur in specific supersymmetric frameworks.

The key ingredients which allows visible non-SM contributions in $R_P^{\mu/e}$ within the MSSM are:

i) large values of $\tan\beta$ (the ratio of the two Higgs vacuum expectation values), such that the overall normalization of Y_E –and correspondingly the $H^\pm$-exchange contribution to $P \to \ell\nu$– is enhanced;

ii) large mixing angles in the right-slepton sector, such that the $P \to \ell_i \nu_j$ rate (with $i \neq j$) becomes non negligible.

In the most favorable scenarios, the deviations from the SM could reach $\sim 1\%$ in the $R_K^{\mu/e}$ case [38] (not far from the present experimental resolution [39]) and $\sim$ few $\times 10^{-4}$ in the $R_\pi^{\mu/e}$ case. In the pion case the effect is quite below the present experimental resolution [40], but could well be within the reach of the new generation of high-precision $\pi_{\ell 2}$ experiments planned at TRIUMPH and at PSI.

In principle, larger violations of LF universality are expected in $B \to \ell\nu$ decays, with $\mathcal{O}(10\%)$ deviations from the SM in $R_B^{\mu/\tau}$ and even order-of-magnitude enhancements in $R_B^{e/\tau}$ [41]. However, the difficulty of precision measurements of the highly suppressed $B \to e/\mu\ \nu$ modes makes these non-standard effects undetectable (at least at present).

Similarly to the FCNC decays discussed in the previous sections, also for the LF universality tests the low-energy systems ($K_{\ell 2}$ and $\pi_{\ell 2}$) offer a unique opportunity in shedding light on physics beyond the Standard Model: the smallness of NP effects is more than compensated (in terms of NP sensitivity) by the excellent experimental resolution and the good theoretical control.

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