Flavour Physics: Now and in the LHC era*

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We present an overview of what we learned so far from low-energy flavour observables, concerning physics beyond the Standard Model, and what we could still learn from further studies in flavour physics in the next few years.

I. INTRODUCTION: THE MAIN LESSONS OF FLAVOUR PHYSICS

In the last few years there has been a great experimental progress in quark and lepton flavour physics. In the quark sector, the validity of the Standard Model (SM) has been strongly reinforced by a series of challenging tests. As summarised by the plots shown in Fig. 1, all the relevant SM parameters controlling quark-flavour dynamics (the quark masses and the angles of the Cabibbo-Kobayashi-Maskawa matrix [1]) have been determined with good accuracy. More important, several suppressed observables (such as ΔM_{B_d}, ΔM_{B_s}, $\mathcal{A}^{\rm CP}_{K\Psi}$, $B \to X_s\gamma$, ϵ_K, ...) potentially sensitive to New Physics (NP) have been measured with good accuracy, showing no deviations from the SM. The situation is somehow similar to the flavour-conserving electroweak precision observables (EWPO) after LEP: the SM works very well and genuine one-loop electroweak effects have been tested with relative accuracy in the 10%–30% range. Similarly to the EWPO case, also in the quark flavour sector NP effects can only appear as a small correction to the leading SM contribution.

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, in agreement with the expectations of Grand Unified Theories (GUT).

If the SM is not a complete theory, it is natural to expect new degrees of freedom around or slightly above the electroweak scale (the energy domain that will be fully explored for the first time at the LHC). Indeed we cannot extend the validity of the SM above the TeV range without a serious fine-tuning problem in the Higgs sector (see e.g. Ref. [4]). In constructing a realistic SM extension we should then try to reconcile three apparently conflicting requirements:

i. new degrees of freedom around the electroweak scale,

ii. no significant deviations for the SM in the quark sector (as well as no significant effects in EWPO);

iii. non-standard flavour structures in the lepton sector.

The rest of this talk is devoted to discuss how these three points can be reconciled, and why they imply that a few specific measurements in the flavour sector will still be very interesting also in the LHC era.

II. WHAT WE LEARNED SO FAR ABOUT NEW PHYSICS

We can follow three main strategies to describe and quantify what we learned so far about NP from quark-flavour observables.

I. *Generic EFT approach.*
As long as we are interested in processes occurring well below the electroweak scale (such as B, D and K decays), we can integrate out the new degrees of freedom and describe NP effects –in full

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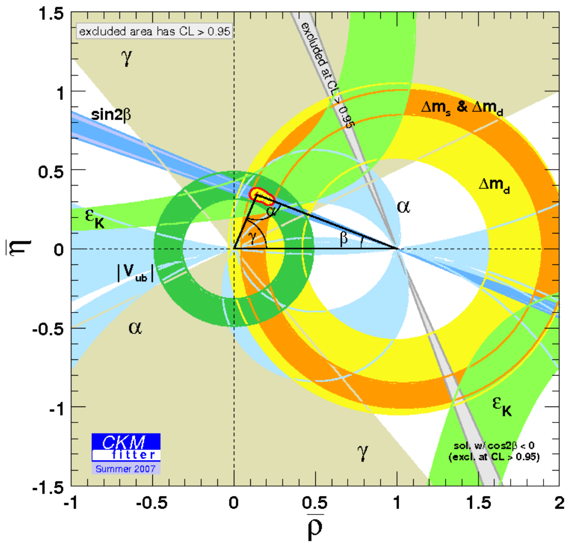

FIG. 1: Fit of the CKM unitarity triangle within the SM [2] (see also [3]).

generality– by means of an Effective Field Theory (EFT) approach. The SM Lagrangian becomes the renormalizable part of a more general local Lagrangian which includes an infinite tower of higher-dimensional operators, constructed in terms of SM fields and suppressed by inverse powers of a scale $\Lambda_{\rm NP} > v = 174$ GeV. This general bottom-up approach allows us to analyse all realistic extensions of the SM in terms of a limited number of parameters (the coefficients of the higher-dimensional operators). The disadvantage of this strategy is that it does not allow us to establish correlations of New Physics (NP) effects at low and high energies (the scale $\Lambda_{\rm NP}$ defines the cut-off of the EFT). The number of correlations among different low-energy observables is also very limited, unless some restrictive assumptions about the structure of the EFT are employed.

II. *Explicit NP models.*
The generic EFT approach is somehow the opposite of the standard top-bottom strategy toward NP, where a given theory –and a specific set of parameters– are employed to evaluate possible deviations from the SM. The top-bottom approach usually allows to establish several correlations, both a low-energies and between low- and high-energy observables. However, the price to pay is the loss of generality. This is quite a high price given our limited knowledge about the physics above the electroweak scale.

III. *EFT with explicit flavour symmetries.*
An interesting compromise between these two extreme strategies is obtained implementing specific symmetry restrictions on the EFT. The extra constraints increase the number of correlations in low-energy observables. The experimental tests of such correlations allows us to test/establish general features of the NP model (possibly valid both at low- and high-energies). In particular, B, D and K decays are extremely useful in determining the flavour-symmetry breaking pattern of the NP model. The EFT approaches based on the Minimal Flavour Violation (MFV) hypothesis and its variations (MFV at large $\tan\beta$, n-MFV, ...) have exactly this goal.

A. Generic EFT approaches and the flavour problem

The NP contributions to the higher-dimensional operators of the EFT should naturally induce large effects in processes which are not mediated by tree-level SM amplitudes, such as meson-antimeson mixing ($\Delta F = 2$ amplitudes) or flavour-changing neutral-current (FCNC) rare decays. On the other hand, it is usually a good approximation to neglect non-standard effects in processes which are mediated by tree-level SM amplitudes. A general analyses of $\Delta F = 2$ observables based on the latter assumption has recently been performed by the UTfit Collaboration [3] (earlier studies can be found also in Ref. [2]). The results are summarised by the plots in Fig. 2.

First of all, it is interesting to note that present data, in particular the determination of γ and $|V_{ub}|$, allow a rather precise determination of the CKM matrix using tree-level processes only (Fig. 2 left). This allows a model-independent comparison of the experimental data on meson-antimeson mixing with the corresponding theoretical SM predictions. NP effects in $\Delta F = 2$ amplitudes can simply be parametrized in terms of a modulo and a phase for each meson-antimeson amplitude,

$$\frac{\langle M | H_{\rm eff}^{\rm full} | \bar{M} \rangle}{\langle M | H_{\rm eff}^{\rm SM} | \bar{M} \rangle} = C_M e^{2i\phi_M} \qquad (1)$$

such that the SM is recovered for $C_M = 1$ and

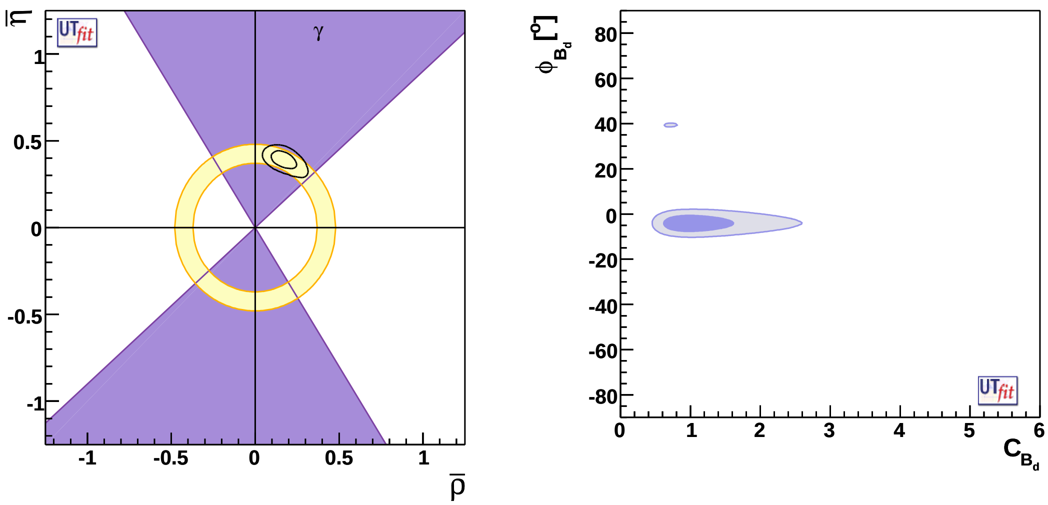

FIG. 2: Left: Constraints on the $\bar{\rho}$–$\bar{\eta}$ plane using tree-level observables only. Right: Constraints on the effective parameters encoding NP effects in the B_d–$\bar{B}_d$ mixing amplitude (magnitude and phase) [3].

$\phi_M = 0$. The main conclusions which can be drawn form the present analyses can be summarized as follows:

- In all the three accessible amplitudes (K^0–$\bar{K}^0$, B_d–$\bar{B}_d$, and B_s–$\bar{B}_s$) the magnitude of the new-physics amplitude cannot exceed, in size, the SM short-distance contribution. The latter is suppressed both by the GIM mechanism and by the hierarchical structure of the CKM matrix ($|V_{td}|, |V_{ts}| \ll 1$):

$$\mathcal{A}_{\rm SM}^{\Delta F=2} \sim \frac{G_F^2 M_W^2}{2\pi^2} (V_{ti}^* V_{tj})^2 \times \times \langle \bar{M} | (\bar{Q}_L^i \gamma^\mu Q_L^j)^2 | M \rangle \qquad (i,j=d,s) \quad (2)$$

  Therefore, new-physics models with TeV-scale flavored degrees of freedom and $\mathcal{O}(1)$ flavour-mixing couplings are essentially ruled out: denoting by C_{ij} the flavour-mixing coupling in the NP model,

$$\mathcal{A}_{\rm NP}^{\Delta F=2} \sim \frac{C_{ij}}{2\Lambda^2} \langle \bar{M} | (\bar{Q}_L^i \gamma^\mu Q_L^j)^2 | M \rangle \qquad (3)$$

  the condition $|\mathcal{A}_{\rm NP}^{\Delta F=2}| < |\mathcal{A}_{\rm SM}^{\Delta F=2}|$ implies

$$\Lambda < \frac{3.4 \text{ TeV}}{|V_{ti}^* V_{tj}|/|C_{ij}|^{1/2}} < \left\{ \begin{array}{l} 9 \times 10^3 \text{ TeV} \times |C_{sd}|^{1/2} \\ 4 \times 10^2 \text{ TeV} \times |C_{bd}|^{1/2} \\ 7 \times 10^1 \text{ TeV} \times |C_{bs}|^{1/2} \end{array} \right.$$

- As clearly shown in Fig. 2, in the B_d–$\bar{B}_d$ case there is still room for a new-physics contribution up to $\sim 50\%$ of the SM one (C_{B_d} can be substantially different from unity). However, this is possible only if the new-physics contribution is aligned in phase with respect to the SM amplitude (ϕ_{B_d} close to zero). A similar conclusion holds also for the K^0–$\bar{K}^0$ amplitude.

- Contrary to B_d–$\bar{B}_d$ and K^0–$\bar{K}^0$ amplitudes, at present there is only a very loose bound on the CPV phase of the B_s–$\bar{B}_s$ mixing amplitude. This leaves open the possibility of observing a large $\mathcal{A}_{\rm CP}(B_s \to J/\Psi\phi)$ at LHCb, which would be a clear signal of physics beyond the SM.

The strong bounds on Λ in models with generic flavour structure ($C_{ij} \sim 1$) 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 hypothesis [5, 6, 7, 8]. Under this assumption, which will be discussed below, the first two items listed above find a natural explanation.

B. Minimal Flavour Violation

The main idea of MFV is that 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 [6, 7]. This allows us to establish general and unambiguous correlations among NP effects in various rare decays. These falsifiable predictions are a key ingredient to identify in a model-independent way the flavour structure of the new-physics model.

In a more quantitative way, the MFV construction consists in identifying the flavour symmetry and symmetry-breaking structure of the SM and enforce it the EFT. In the quark sector this procedure is unambiguous: the largest group of flavour-changing field transformations commuting with the gauge group is $\mathcal{G}_q = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$, and this group is broken only by the two $3 \times \bar{3}$ structures of the Yukawa interaction:

$$\begin{aligned} \mathcal{L}_{\rm Y}^{\rm quark} &= \bar{Q}_L^i (Y_U)_{ij} U_R^j H_U + \\ &+ \bar{Q}_L^i (Y_D)_{ij} D_R^j H_D + \text{h.c.} \end{aligned} \qquad (4)$$

The invariance of the SM Lagrangian under $\mathcal{G}_q$ can be formally recovered elevating the Yukawa matrices to spurion fields with appropriate transformation properties under $\mathcal{G}_q$. The hypothesis of MFV states that these are the only spurions breaking $\mathcal{G}_q$ also beyond the SM. Within the effective theory formulation, this implies that all the higher dimensional operators constructed from SM and Yukawa fields must be (formally) invariant under $\mathcal{G}_q$.

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 $(Y_U Y_U^\dagger)_{ij} \approx y_t^2 V_{3i}^* V_{3j}$, with $y_t = m_t/v \approx 1$ (in the down-quark mass-eigenstate basis). As a result, within this framework the coefficients of the higher-dimensional operators have the same CKM suppression of the corresponding SM amplitudes and the bounds on the new-physics scale are in the few TeV range. This is already clear from Eq.(3), once we set $C_{ij} = y_t^2 V_{3i}^* V_{3j}$; statistically well defined and updated bounds can be in Ref. [3]. Moreover, the flavour structure of $Y_U Y_U^\dagger$ implies a well-defined link among possible deviations from the SM in FCNC transitions of the type $s \to d$, $b \to d$, and $b \to s$ (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 is a concept that has been implemented and discussed in several works, especially after the first results of the B factories (see e.g. Ref. [9]). 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 TeV-scale effective theories where new degrees of freedoms, such as extra scalar fields (see e.g. [10]) or SUSY partners of the SM fields (see e.g. [11, 12]), are included. Finally, this symmetry and symmetry-breaking pattern can explicitly be implemented in well-motivated UV completions of the SM valid up to very high energy scales (see e.g. [13, 14]).

As shown in Fig. 3, 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. 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

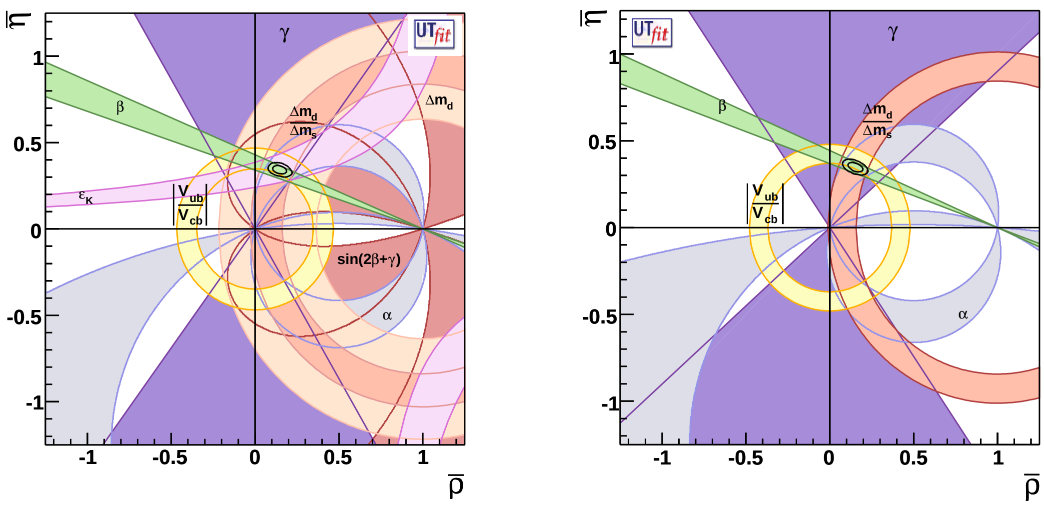

FIG. 3: Fit of the CKM unitarity triangle within the SM (left) and in generic extensions of the SM satisfying the MFV hypothesis (right) [3].

MFV assumption [6]. So far we have only bounds on NP effects in the flavour sector, and it could well be that the new theory includes non-minimal sources of flavour symmetry breaking with specific flavour structures, such as those discussed in Ref. [15]. It is also conceivable that there is not an underlying flavour symmetry, and the suppression of FCNCs is of dynamical origin. This happens for instance in scenarios with hierarchical fermion wave functions [16], which are well motivated by models with warped extra-dimensions [17].

Last but not least, it is worth to stress that even within the pessimistic MFV framework the lepton sector could still be very exciting. The implementation of the MFV hypothesis in the lepton sector is not as straightforward as for the quark sector [7]. But if the breaking of lepton flavour and total lepton number are decoupled, rare LFV decays such as $\mu \to e\gamma$ could be within the reach of the next generation of experiments even in a MFV framework [7].

C. Flavour constraints in explicit models

In all explicit NP scenarios the constraints of flavour physics play a very important role. This is obvious in cases where the model allow the existence of new sources of flavour symmetry breaking. A typical example is the MSSM with generic flavour structures [18]: here each flavour observable is used to set a limit on a specific combination of non-diagonal entries of the sfermion mass matrices (see e.g. Ref. [19] for a recent discussion).

The importance of flavour observables is less obvious in constrained models, such as MSSM scenarios with MFV. The situation here turns out to be even more interesting than in generic models: the number of free parameters is substantially reduced and a given observable put constrains which are relevant for several other processes (even beyond the flavour sector). As a result, the consistency of the model is probed to a deep level.

An illustration of this fact in the context of the mSUGRA scenario has been presented in Ref. [20]: the information derived by $B \to X_s\gamma$ poses a significant constraint on the model, which is compatible with those derived from flavour conserving processes. In particular, the heavy stop mass required by $B \to X_s\gamma$ is one of the main ingredients which pushes the mass of the light Higgs boson above the LEP bound [21].

As recently shown in Ref. [22], there are also specific supersymmetric MFV frameworks which are essentially ruled out by the recent results of flavour physics. In particular, the present constraints from $\mathcal{B}(B \to \tau\nu)$, $\mathcal{B}(B_s \to \mu^+\mu^-)$ and $\mathcal{B}(B \to X_s\gamma)$, puts in serious difficulties the $SO(10)$ GUT model of Dermisek and Raby [23], a specific example of MFV scenario with large $\tan\beta$.

III. FLAVOUR PHYSICS IN THE LHC ERA

If new particles or, more generally, new degrees of freedom, are present in the TeV energy range, there are good chances that part of them will be discovered at the LHC. This does not mean that the complete structure of the new model can easily be determined at the LHC: the direct discovery of new particles is only one of the ingredients necessary to achieve this goal. As already discussed in the previous section, some of the parameters of the model (in particular its flavour structure) can only be determined with improved measurements in the flavour sector. A brief survey of the most interesting low-energy flavour observables in this perspective, focusing on MSSM scenarios with MFV (or approximate MFV), is presented in the following.

A. Helicity-suppressed observables and the large $\tan\beta$ scenario

The Higgs sector of the MSSM consists of two $SU(2)_L$ scalar doublets, coupled separately to up- and down-type quarks

$$\begin{aligned} \mathcal{L}_{\rm H}^{\rm tree} &= \bar{Q}_L Y_U U_R H_U + \bar{Q}_L Y_D D_R H_D + \\ &+ \bar{L}_L Y_E E_R H_D + V(H_U, H_D) + \text{h.c.} \end{aligned} \quad (5)$$

A key parameter of this sector is the ratio of the two Higgs vevs: $\tan\beta = \langle H_U\rangle / \langle H_D\rangle$. Varying $\tan\beta$ leads to modify the overall normalization of the two Yukawa couplings and, for $\tan\beta \sim 40$–50, we can achieve the interesting unification of top and bottom Yukawa couplings.

The variation of $\tan\beta$ do not change the misalignment in flavour space of the two Yukawa couplings. This implies that flavour-changing observables not suppressed by powers of down-type quark masses (i.e. most of the experimentally accessible observables) are not sensitive to the value of $\tan\beta$. If the model has a MFV structure, the phenomenological consequences of $\tan\beta \gg 1$ show up only in the few observables sensitive to helicity-suppressed amplitudes. These are confined to the B-meson system (because of the large b-quark Yukawa coupling), with the notable exception of $K \to \ell\nu$ decays. We can divide the most interesting observables in three classes: the charged-current processes $B(K) \to \ell\nu$, the rare decays $B_{s,d} \to \ell^+\ell^-$, and the FCNC transition $B \to X_s\gamma$.

It is worth to stress that, beside the theoretical interest, the large $\tan\beta$ regime of the MSSM could also provide a natural explanation of the $a_\mu = (g-2)_\mu/2$ anomaly, which is now a solid 3σ effect: $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} \approx (2.9 \pm 0.9) \times 10^{-9}$ [24]. The size of this discrepancy is large compared to the electroweak SM contribution ($\Delta a_\mu^{\rm e.w.} \approx 1.5 \times 10^{-9}$). This large discrepancy can easily be explained by the fact that a_μ is a(flavour-conserving) helicity suppressed observable, whose non-standard contribution can be enhanced compared to the SM one by increasing the value of $\tan\beta$:

$$\Delta a_\mu^{\rm MSSM} \approx \tan\beta \times \Delta a_\mu^{\rm e.w.} \times \left(\frac{M_W}{\widetilde{M}_{\rm slept}} \right)^2 \quad (6)$$

For values of $\tan\beta \gtrsim 10$ the $M_W/\widetilde{M}_{\rm slept}$ suppression can easily be compensated for sleptons well above the W mass, in prefect agreement with the constraints of electroweak precision tests.

1. $B(K) \to \ell\nu$

The charged-current processes $P \to \ell\nu$ are the simplest flavour-violating helicity suppressed observables. Here both SM and Higgs-mediated contributions (sensitive to $\tan\beta$) appear already at the tree level. The $H^\pm$ contribution is proportional to the Yukawa couplings of quarks and leptons, but it can compete with the $W^\pm$ exchange thanks to the helicity suppression of $P \to \ell\nu$ [25]. Taking into account the resummation of the leading $\tan\beta$ corrections to all orders, the $H^\pm$ contributions to the $P \to \ell\nu$ amplitude within a MFV supersymmetric framework leads to the following ratio [26, 27]:

$$\begin{aligned} R_{P\ell\nu} &= \frac{\mathcal{B}(P\ell\nu)}{\mathcal{B}^{\rm SM}(P\ell\nu)} \\ &\stackrel{\rm SUSY}{=} \left[1 - \left(\frac{m_P^2}{m_{H^\pm}^2} \right) \frac{\tan^2\beta}{(1+\epsilon_0 \tan\beta)} \right]^2 \end{aligned} \quad (7)$$

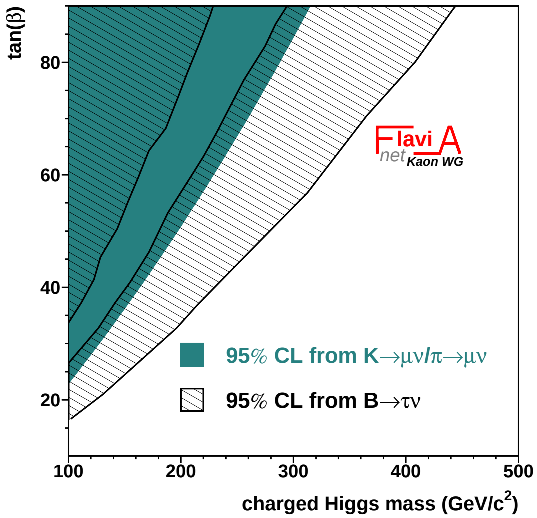

FIG. 4: Present constraints in the M_H–$\tan\beta$ plane from $\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(K \to \mu\nu)$ [32].

where ϵ_0 denotes the effective coupling which parametrizes the non-holomorphic corrections to the down-type Yukawa interaction [28, 29]. For a natural choice of the MSSM parameters, Eq. (7) implies a suppression with respect to the SM in B decays of few$\times$10% (but an enhancement is also possible for very light $M_{H^\pm}$) and an effect 100 times smaller in K decays (where the branching ratio is necessarily smaller than $\mathcal{B}^{\rm SM}$).

In the B case only the τ modes has been observed: $\mathcal{B}(B \to \tau\nu)^{\rm exp} = (1.41 \pm 0.43) \times 10^{-4}$ [30]. In the Kaon system the precision of $\mathcal{B}(K \to \mu\nu)$ is around 0.3% [31]. In the limit of negligible theoretical errors, we should therefore expect similar bounds in the M_H–$\tan\beta$ plane from B and K decays. This limit is far from being realistic, due to the sizable errors on f_P (determined from Lattice QCD) and V_{uq} (which must be determined without using the information on $P \to \ell\nu$ decays). But again the present level of precision is such that the B and K decays set competitive bounds in the M_H–$\tan\beta$ plane (see Fig. 4). Both channels have interesting possibility of improvement in the near future.

2. $B \to \ell^+\ell^-$

The important role of $\mathcal{B}(B_{s,d} \to \ell^+\ell^-)$ in the large $\tan\beta$ regime of the MSSM has been widely discussed in the literature (see e.g. Ref. [26, 33, 34, 35] for a recent discussion). Similarly to $P \to \ell\nu$ decays, the leading non-SM contribution in $B \to \ell^+\ell^-$ decays is generated by a single tree-level type amplitude: the neutral Higgs exchange $B \to A, H \to \ell^+\ell^-$. Since the effective FCNC coupling of the neutral Higgs bosons appears only at the quantum level, in this case the amplitude has a strong dependence on other MSSM parameters in addition to M_H and $\tan\beta$. In particular, a key role is played by μ and the up-type trilinear soft-breaking term (A_U), which control the strength of the non-holomorphic terms. The leading parametric dependence of the scalar FCNC amplitude from these parameters is given by

$$\mathcal{A}_{\rm Higgs}(B \to \ell^+\ell^-) \propto \frac{m_b m_\ell}{M_A^2} \frac{\mu A_U}{M_{\tilde{q}}^2} \tan^3\beta \times f_{\rm loop}$$

For $\tan\beta \sim 50$ and $M_A \sim 0.5$ TeV the neutral-Higgs contribution to $\mathcal{B}(B_{s,d} \to \ell^+\ell^-)$ can easily lead to an $\mathcal{O}(100)$ enhancement over the SM expectation. This possibility is already excluded by experiments: the upper bound $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ [36] is only about 15 times higher that the SM prediction of 3.5×10^{-9} [37]. This limit poses interesting constraints on the MSSM parameter space, especially for light M_H and large values of $\tan\beta$ (see e.g. Fig. 5). However, given the specific dependence on A_U and μ, the present $\mathcal{B}(B_s \to \mu^+\mu^-)$ bound does not exclude the large $\tan\beta$ effects in $(g-2)_\mu$ and $P \to \ell\nu$ already discussed. The only clear phenomenological conclusion which can be drawn for the present (improved) limit on $\mathcal{B}(B_s \to \mu^+\mu^-)$ is the fact that the neutral-Higgs contribution to ΔM_{B_s} [38] is negligible.

3. $B \to X_s\gamma$

The radiative decay $B \to X_s\gamma$ is one of the observables most sensitive to non-standard contributions, not only in the large $\tan\beta$ regime of the MSSM. Contrary to pure leptonic decays discussed before, $B \to X_s\gamma$ does not receive effective tree-level contributions from the Higgs sector.

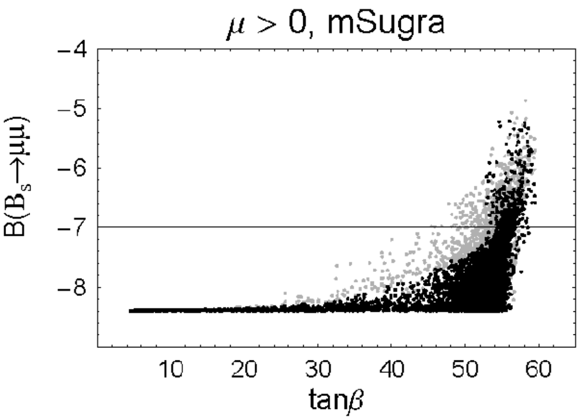

FIG. 5: $\mathcal{B}(B_s \to \mu^+\mu^-)$ as a function of $\tan\beta$ in the mSUGRA scenario [34].

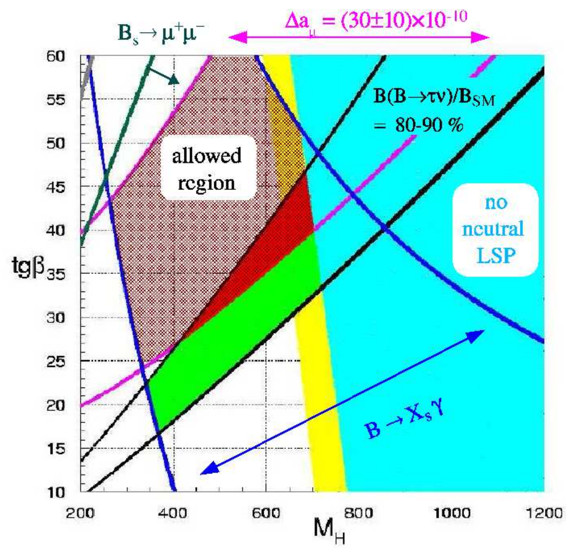

FIG. 6: Combined bounds from low-energy observables in the $\tan\beta$–M_H plane assuming heavy squarks and dark-matter constraints in the A-funnel region [41] ($M_{\tilde{q}} = 1.5$ TeV, $A_U = -1$ TeV, $\mu = 0.5$ TeV, $M_{\tilde{\ell}} = 0.4$ TeV, $1.01 < R_{Bs\gamma} < 1.24$; the light-blue area is excluded by the dark-matter conditions).

The one-loop charged-Higgs amplitude, which increases the rate compared to the SM expectation, can be partially compensated by the chargino-squark amplitude, giving rise to delicate cancellations. As a result, the extraction of bound in the M_H–$\tan\beta$ plane from $\mathcal{B}(B \to X_s\gamma)$ (within the MSSM) is a non trivial task.

Despite the complicated interplay of various non-standard contributions, $B \to X_s\gamma$ is particularly interesting given the good theoretical control of the SM prediction and the small experimental error. According to the recent NNLO analysis of Ref. [39], the SM prediction is

$$\mathcal{B}(B \to X_s\gamma)^{\rm SM}_{E_\gamma > 1.6~{\rm GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$

to be compared with the experimental average [40]:

$$\mathcal{B}(B \to X_s\gamma)^{\rm exp}_{E_\gamma > 1.6~{\rm GeV})} = (3.55 \pm 0.24) \times 10^{-4}$$

These results allow a small but non negligible positive non-standard contribution to $\mathcal{B}(B \to X_s\gamma)$ (as expected if the charged-Higgs amplitude would dominate over the chargino-squark one), which represents one of the most significant constraint in the MSSM parameter space.

An illustration of the typical correlations of the low-energy flavour constraints in the M_H–$\tan\beta$, in a generic scenario with heavy squarks and dark-matter conditions satisfied in the A-funnel region, is shown in Fig. 6. One of the most interesting aspects of this scenario is the fact that a supersymmetric contribution to a_μ of $\mathcal{O}(10^{-9})$ is both compatible with the present constraints from $\mathcal{B}(B \to X_s\gamma)$ and it implies a suppression of $\mathcal{B}(B \to \tau\nu)$ with respect to its SM prediction of at least 10% [41]. A more precise determination of $\mathcal{B}(B \to \tau\nu)$ is therefore a key element to test this scenario.

B. Rare K decays

Among the many rare K and B decays, the $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ modes are unique since their SM branching ratios can be computed to an exceptionally high degree of precision, not matched by any other FCNC processes involving quarks. It is then not surprising that $K \to \pi\nu\bar{\nu}$ decays continue to raise a strong theoretical interest, both within and beyond the SM (see e.g. Ref. [42]).

Because of the strong suppression of the $s \to d$ short-distance amplitude in the SM [$V_{td}V^*_{ts} = \mathcal{O}(10^{-4})$], rare K decays are the most sensitive probes of possible deviations from the strict MFV

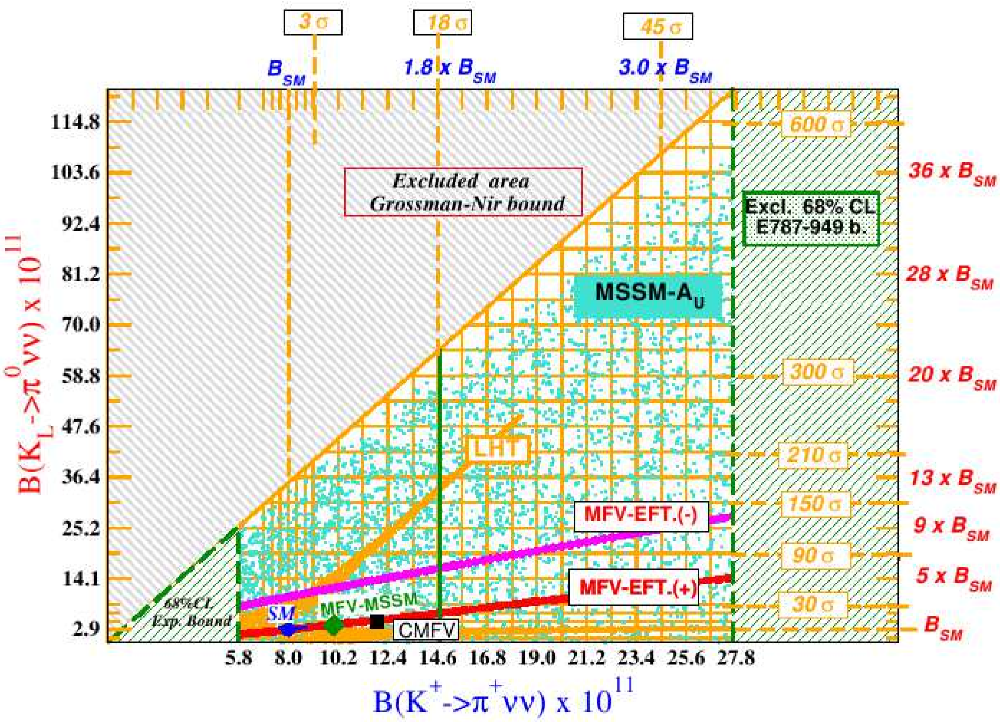

FIG. 7: Predictions of different NP models for $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ and $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ [courtesy of F. Mescia]. The 95% C.L. exluded areas of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ refer to the result of the BNL-E787/949 experiment [50].

ansatz. Several recent NP analyses confirm the high discovery potential of these channels (see Fig. 7 and Ref. [42]). The latter has also improved thanks three significant improvements on the SM predictions of $K \to \pi\nu\bar{\nu}$ rates: i) the NNLO calculation of the dimension-six charm-quark contribution to $K^+ \to \pi^+\nu\bar{\nu}$ [43]; ii) the first complete analysis of dimension-eight and long-distance (up-quark) contributions relevant to $K^+ \to \pi^+\nu\bar{\nu}$ [44]; iii) a new comprehensive analysis of matrix-elements and isospin-breaking effects, relevant to both channels [45]. Thanks to these recent works, the irreducible theoretical uncertainties on both branching ratios are at the few % level.

It is worth stressing that if a deviation from the SM is seen in one of the two $K \to \pi\nu\bar{\nu}$ channels, a key independent information about the nature of NP can be obtained also from the two $K_L \to \pi^0\ell^+\ell^-$ ($\ell = e, \mu$) modes. The latter are not as clean as the neutrino modes, but are still dominated by SD dynamics and very sensitive to NP [46, 47, 48, 49].

C. Lepton Flavour Violation and LF non-universality

LFV couplings naturally appear in the MSSM once we extend it to accommodate the non-vanishing neutrino masses and mixing angles by means of a supersymmetric seesaw mechanism [51]. In particular, the renormalization-group-induced LFV entries appearing in the left-handed slepton mass matrices have the following form [51]: $\delta^{ij}_{LL} = c_\nu (Y^\dagger_\nu Y_\nu)_{ij}$, where Y_ν are the neutrino Yukawa couplings and c_ν is a numerical coefficient of $\mathcal{O}(0.1–1)$. The information from neutrino masses is not sufficient to determine in a model-independent way all the seesaw parameters relevant to LFV rates and, in particular, the neutrino Yukawa couplings. To reduce the number of free parameters specific SUSY-GUT models and/or flavour symmetries need to be employed.

Two main roads are often considered in the literature: the case where the charged-lepton LFV couplings are linked to the CKM matrix (the quark mixing matrix) and the case where they are connected to the PMNS matrix (the neutrino mixing matrix) [52].

Once non-vanishing LFV entries in the slepton mass matrices are generated, LFV rare decays are naturally induced by one-loop diagrams with the exchange of gauginos and sleptons. For large values of $\tan\beta$ the radiative decays $\ell_i \to \ell_j \gamma$, mediated by dipole operators, are linearly enhanced, in close analogy to the $\tan\beta$-enhancement of $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$. A strong link between these two observable naturally emerges [53]. We can indeed write

$$\frac{\mathcal{B}(\ell_i \to \ell_j \gamma)}{\mathcal{B}(\ell_i \to \ell_j \nu_{\ell_i} \bar{\nu_{\ell_j}})} = \frac{48\pi^3 \alpha}{G_F^2} \left[\frac{\Delta a_\mu}{m_\mu^2}\right]^2 \times \\ \times \left[\frac{f_{2c}\left(M_2^2/M_{\tilde\ell}^2, \mu^2/M_{\tilde\ell}^2\right)}{g_{2c}\left(M_2^2/M_{\tilde\ell}^2, \mu^2/M_{\tilde\ell}^2\right)}\right]^2 \left|\delta_{LL}^{ij}\right|^2 \qquad (8)$$

where f_{2c} and g_{2c} are $\mathcal{O}(1)$ loop functions. In the limit of a degenerate SUSY spectrum, this implies

$$\mathcal{B}(\ell_i \to \ell_j \gamma) \approx \left[\frac{\Delta a_\mu}{20 \times 10^{-10}}\right]^2 \times \\ \times \begin{cases} 1 \times 10^{-4} \left|\delta_{LL}^{12}\right|^2 & [\mu \to e] \\ 2 \times 10^{-5} \left|\delta_{LL}^{23}\right|^2 & [\tau \to \mu] \end{cases} \qquad (9)$$

The strong correlation between Δa_μ and the rate of the LFV transitions $\ell_i \to \ell_j \gamma$ holds well beyond the simplified assumptions used to derive these equations (see Fig. 8). The normalization $|\delta_{LL}^{12}| = 10^{-4}$ used in Fig. 8 for $\mathcal{B}(\mu \to e\gamma)$ corresponds to the MFV hypothesis in the lepton sector with $M_\nu \gtrsim 10^{12}$ GeV [7]. As can be seen, for such natural choice of δ_{LL} the $\mu \to e\gamma$ branching ratio is in the 10^{-12} range, i.e. well within the reach of the MEG experiment [54].

Ratios of similar LFV decay rates, such as $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma)$, are much more easy to be predicted, being free from the overall normalization uncertainty. These predictions depend essentially only on the flavour structure of the LFV couplings. The search for $\mathcal{B}(\tau \to \mu\gamma)$ is thus a key element in trying to determine the structure of flavour symmetry breaking in the lepton sector. In particular, $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma)$ ranges from to 10^2 in the case of a PMNS hierarchy, to

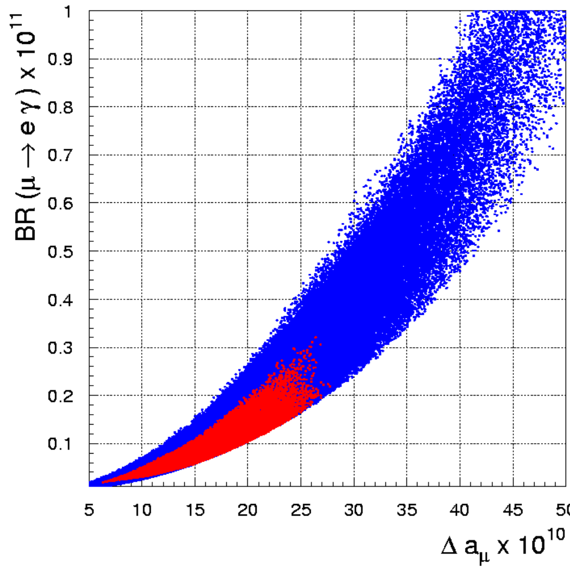

FIG. 8: $\mathcal{B}(\mu \to e\gamma)$ vs. $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$ in the MSSM assuming $|\delta_{LL}^{12}| = 10^{-4}$ [26].

10^4 in the case of a CKM-type hierarchy. In the latter case $\mathcal{B}(\tau \to \mu\gamma)$ can exceed 10^{-9} and be within the reach of a super-B factory. The enhancement of $\mathcal{B}(\tau \to \mu\gamma)$ can be even larger in non-supersymmetric frameworks, such as the one recently discussed in Ref. [55].

An independent and potentially large class of LFV contributions to rare decays in the large $\tan\beta$ regime of the MSSM comes from Higgs-mediated amplitudes. Similarly to the quark sector, non-holomorphic couplings can induce an effective FCNC Higgs coupling also in the lepton sector [56]. Gauge- and Higgs-mediated amplitudes leads to very different correlations among LFV processes [52, 57, 58] and their combined study can reveal the underlying mechanism of LFV.

Finally, as recently pointed out in Ref. [59], Higgs-mediated LFV effects at large $\tan\beta$ can also induce visible deviations of lepton-flavour universality in charged-current processes. If the slepton sector contains sizable (non-minimal) sources of LFV, we could hope to observe deviations from the SM predictions in the $\mathcal{B}(P \to \ell\nu)/\mathcal{B}(P \to \ell'\nu)$ ratios. The deviations can be $\mathcal{O}(1\%)$ in $\mathcal{B}(K \to e\nu)/\mathcal{B}(K \to \mu\nu)$ [59], and can reach

$\mathcal{O}(1)$ and $\mathcal{O}(10^3)$ in $\mathcal{B}(B \to \mu\nu)/\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(B \to e\nu)/\mathcal{B}(B \to \tau\nu)$, respectively [26].

D. Other observables

The observables mentioned so far are only a subset of those which is still worth to improve, or to search for, in the LHC era. They have been selected mainly because they are interesting also in MFV scenarios, or in the most pessimistic case for flavour physics. Going beyond MFV –as stressed above, this possibility is certainly open– the list of potentially interesting measurements is much longer. Extensive studies can be found in the recent reports [60, 61, 62]. Mentioning only a few examples, a key observable to falsify MFV is the time-dependent CP asymmetry in $B_s \to \psi\phi$ (or the measurement of the CPV phase of B_s–$\bar{B}_s$ mixing), one of the golden channels of the LHCb experiment. It is also very important, both within and beyond MFV, trying to improve the measurements of CKM elements from tree-level dominated processes (namely $|V_{us}|$ from $K_{\ell 3}$, $|V_{ub}|$ and $|V_{cb}|$ from semileptonic B decays, and γ from CP asymmetries in penguin-free modes). These measurements are not directly sensitive to NP, but are the key ingredient to improve the SM predictions in processes which are sensitive to NP.

On general grounds, a key issue in planning future experiments in the quark sector is the control of theoretical uncertainties, or the control over long-distance dynamics. From this point of view, leptonic and semileptonic B and K decays (both charged and neutral currents, either fully inclusive or with at most one stable meson in the final state), are the potentially most interesting channels. In the B case we should also add CP asymmetries in penguin-free modes and some radiative decays (most notably $B \to X_s\gamma$). On the other hand, some of the observables which have received a lot of attention in the recent past, such as time-dependent CP asymmetries in penguin dominated modes, are less interesting: the present level of accuracy is not far from the level of irreducible theoretical uncertainties, and no sizable deviation from the SM has been identified yet.

Last but not least, we comment about D–$\bar{D}$ mixing, whose evidence reported by B-factory experiments is one of the highlights of this conference [63]. Such evidence is a very useful information about the interplay of weak and strong interactions. However, the impact about physics beyond the SM is rather limited. The observed values of the D–$\bar{D}$ mixing parameters are in the ball park of the SM expectations. This allows us to exclude models which predict a too large Δm_D (see e.g. [64]), but the bounds are not very precise given the sizable long-distance contributions to this quantity. In a future perspective, only the measurement of CP violation in D–$\bar{D}$ mixing could provide a significant new information about physics beyond the SM.

IV. CONCLUSIONS

The absence of significant deviations from the SM in quark flavour physics is a key information about new physics. Only models with highly non generic flavour structures can both stabilise the electroweak sector and be compatible with flavour observables. In such models we expect new particles within the LHC reach. This does not mean that the complete structure of the new theory can easily be determined at the LHC. Virtually in all cases interesting aspects of the models can be determined only from future high-precision studies in the flavour sector.

As briefly illustrated in this talk, the set of low-energy observables to be measured with higher precision, and the rare transitions to be searched for is limited (if we are interested only on physics beyond the SM). However, there is not a single experimental set up where we can study all of them. The set of interesting observables includes μ, K, τ, and B decays. Ideally, their precision study would require several different types of facilities and experiments.

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