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Rare B and D decays: a theoretical overview

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After a brief introduction to the open problems in flavour physics we discuss the role of B and D decays in shedding light on physics beyond the Standard Model.

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1. Introduction

To a large extent the origin of flavour is still a mystery. We have very little clues about the nature of the underlying dynamics giving rise to the different masses of quarks and leptons, and responsible for their mixing. More precisely, our "ignorance" can be summarized by the following two open questions: i) What determines the observed pattern of masses and mixing angles of quarks and leptons? ii) Which are the sources of flavour symmetry breaking accessible at low energies? Is there anything else beside the Standard Model (SM) Yukawa couplings and the neutrino mass matrix?

The attempts to answer the first question are typically based on the introduction of a non-trivial flavour dynamics at some high scale. The new dynamics can be associated to Abelian or non-Abelian continuous symmetries or, as suggested by the neutrino sector, to a discrete symmetry. Alternatively, in models with extra space-time dimensions, the flavour hierarchy could be an infrared-property associated to the different localization of the fermion profiles in extra dimensions. In all cases it is quite easy to reproduce the observed mass matrices in terms of a reduced number of free parameters, while it is difficult to avoid problems with Flavour Changing Neutral Currents (FCNCs) unless some amount of fine-tuning is introduced. Most important, it is not easy to make progress in answering this question without knowing the ultraviolet completion of the model.

Answering the second question is more easy: it is mainly a question of precision, both on the theory and on the experimental side, and here is where rare decays play a key role. Despite the phenomenological success of the SM, we have clear indications that this theory needs an ultraviolet completion. The most realistic proposals point toward the existence of new degrees of freedom at the TeV scale, possibly accessible at the high-p_T experiments at the LHC. In this perspective the second question above is related to the flavour structure of these new degrees of freedom: is flavour symmetry breaking at the TeV scale fully controlled by the SM Yukawa couplings and the neutrino mass matrix? As far as the effects in low-energy observables are concerned, this question can be formulated within a general effective theory approach and, to a large extent, it is independent from the ultraviolet dynamics (see e.g. Ref. [1]). Following this approach we have already learned a lot about the possible flavour structure of physics beyond the SM. As I will illustrate in the rest of this talk, we could learn even more improving the precision (or the sensitivity) in specific measurements (or searches) for rare decays.

2. Recent developments in quark flavour mixing

The good overall consistency of the experimental constraints appearing in the so-called CKM fits (see [2, 3] for updated results) indicate that there is not much room for new sources of flavour symmetry breaking accessible at low energies. The success of the SM in describing flavour mixing is also confirmed by a series of other observations. Two notable examples are: i) the agreement between the SM prediction and the experimental determination of $\mathscr{B}(B \to X_s \gamma)$, where both theory and experimental errors are below the 10% level [4]; ii) the test of the CKM unitarity relation $|V_{id}|^2 + |V_{us}|^2 + |V_{Yb}|^2 = 1$, which is presently probed below the per-mil level [5]. All these precise tests can be translated into stringent bounds on physics beyond the SM [6]. These bounds allow

PoS(HQL 2010)067

us to conclude that new flavor-breaking sources comparable and not aligned to the SM Yukawa couplings are excluded for new degrees of freedom at the TeV scale.

The absence of large deviations form the SM in flavour-changing processes, together with the need of new degrees of freedom at the TeV scale to stabilize the SM Higgs sector, is the main motivation for the so-called Minimal Flavour Violation (MFV) hypothesis. Under this assumption, the SM Yukawa couplings are the only flavour symmetry breaking terms also beyond the SM [7]. More precisely, in the limit of vanishing quark Yukawa couplings the effective Lagrangian describing both SM and new degrees of freedom is invariant under the global quark flavour symmetry $SU(3)_{Q_L} \times SU(3)_{D_R} \times SU(3)_{U_R}$ [8]. Employing this hypothesis non-standard contributions in flavour-violating transitions turn out to be suppressed to a level consistent with experiments even for New Physics (NP) in the TeV range [7, 9]. The MFV hypothesis provides the technical tool to address the second question listed in the Introduction: if MFV holds, then there are no other sources of flavour symmetry breaking accessible at low energies. Two comments are in order:

- The MFV ansatz is quite successful on the phenomenological side; however, it is unlikely to be an exact property of the model valid to all scales. Despite some recent attempts to provide a dynamical justification of this symmetry-breaking ansatz (see e.g. [10]), the most natural possibility is that MFV is only an accidental low-energy property of the theory [11]. It is then very important to search for possible deviations (even if tiny) from the MFV predictions.

- Even if the MFV ansatz holds, it does not necessarily imply small deviations from the SM predictions in all flavour-changing phenomena. The MFV ansatz can be implemented in different ways. For instance, in models with two Higgs doublets we can change the relative normalization of the two Yukawa couplings [7], we can decouple the breaking of CP invariance from the breaking of the $SU(3)_{Q_L} \times SU(3)_{D_R} \times SU(3)_{U_R}$ quark-flavour group [12] and, in models with strong dynamics at the TeV scale, we can consider operators with a large number of Yukawa insertions [12]. All these variations leads to different and well defined patterns of possible deviations from the SM that we have just started to investigate.

3. Selected rare B decays

Despite the overall picture of quark flavour mixing shows a good consistency with the SM predictions, looking more closely there are a few cases where the agreement is not so good. The most interesting "anomalies" that have emerged in the last few years are: i) the $\sin 2\beta$ tension in the CKM fit; ii) CP violation (CPV) in B_s mixing; iii) the determination of $|V_{ub}|$ and the $B \to \tau\nu$ branching ratio (see Ref. [13] for an updated discussion). These (minor) deviations from the CKM picture are particularly interesting since NP contributions are small and compatible with the absence of large NP signals in other observables, as outlined above. It is then tempting to interpret some of these effects as the first signals of new physics at the TeV scale. The rare B decay observables I will discuss in the following are a key tool to understand if this is the case and, eventually, to discriminate among different extensions of the SM which could explain these effects.

PoS(HQL 2010)067

3.1 $B \to \ell\nu$ and $B \to D\tau\nu$

The purely leptonic $B \to \ell\nu$ decays are particularly interesting for two main reasons. On the one hand they are theoretically very clean: all hadronic uncertainties are confined to the B meson decay constant (f_B), which can be computed reliably using Lattice QCD. On the other hand, the strong helicity suppression makes them particularly sensitive probes of physics beyond the SM, especially of a non-standard Higgs sector.

The τ channel is the only decay mode of this type observed so far. The SM expectation for the branching ratio is $\mathscr{B}(B \to \tau\nu)^{\rm SM} = (G_F^2 m_B m_\tau^2)/(8\pi)(1 - m_\tau^2/m_B^2)^2 f_B^2 |V_{ub}|^2 \tau_B$. Using the best fit value of $|V_{ub}|$ from global CKM fits, and combining both direct lattice QCD constraints and indirect constrains from global CKM fits on f_B [14], the UTfit collaboration obtains [2] $\mathscr{B}(B \to \tau\nu)^{\rm SM} = (0.79 \pm 0.07) \times 10^{-4}$. This is substantially lower with respect to the current experimental world average, $\mathscr{B}(B \to \tau\nu)^{\rm exp} = (1.68 \pm 0.31) \times 10^{-4}$, with a statistical significance of a deviation from the SM close to 3σ. Even taking into account the more conservative estimate of the SM error quoted in [15], the deviation exceed the 2σ level.

Beside possible experimental improvements on $B \to \tau\nu$, an important ingredient to improve the significance of this SM test is the determination of $|V_{ub}|$ (that is relevant also for the $\sin 2\beta$ problem discussed before). Both these goals are possible at super-B factories. As far as $|V_{ub}|$ is concerned, this could be systematically improved in the future with more precise experimental data on $B \to \pi\ell\nu$ combined with Lattice QCD results on the $B \to \pi$ form-factor. Similarly to the approach presently adopted for the determination of $|V_{us}|$, the most promising strategy is the experimental determination of the kinematical dependence of the $B \to \pi$ form-factor combined with Lattice data to fix its overall normalization (see e.g. [16]).

One of the most interesting non-standard explanation the present "anomaly" in $B \to \tau\nu$ is obtained introducing of an effective $b \to u$ right-handed (RH) charged-current:

$$\mathscr{L}_{\rm eff}^{b\to u} = -\frac{4G_F}{\sqrt{2}} \left[V_{ub}\bar{u}_L\gamma^\mu b_L + \varepsilon_R \widetilde{V}_{ub}\bar{u}_R\gamma^\mu b_R\right] (\bar{\ell}_L\gamma_\mu\nu_L) + \text{h.c.} \qquad (\ell = e,\mu\tau)\,. \tag{3.1}$$

As pointed out in particular in [17], the presence of this RH current could accommodate a large $\mathscr{B}(B \to \tau\nu)$ and, at the same time, could explain the present tension between exclusive and inclusive determinations of $|V_{ub}|$. If this effect is there, RH currents should be visible also in other flavour-changing processes. As pointed out in Ref. [18], RH currents could indeed solve also the present anomaly in B_s mixing and, as discussed below, could induce sizable deviations from the SM in the rare FCNC decays $B \to \{X_s, K, K^*\}\nu\bar{\nu}$.

Another interesting proposal to explain the the large value of $\mathscr{B}(B \to \tau\nu)$ is related to the introduction of non-standard scalar currents, possibly associated to a non-standard Higgs sector. Assuming the strength of the scalar currents to be proportional to the Yukawa couplings of quarks and leptons involved, we can easily have a sizable impact in $B \to \tau\nu$ without significant effects in the helicity-allowed modes $B \to X_u\ell\nu$ ($\ell = e,\mu$). However, in this case some effect is expected also in $B \to D\tau\nu$: this mode is not helicity suppressed, but the large Yukawa coupling of the τ lepton implies a non-negligible sensitivity to scalar currents ($\sim 30\%$ of the non-standard contribution to $B \to \tau\nu$). The $B \to D(D^*)\tau\nu$ decays have just been observed at B factories. Contrary to $B \to \tau\nu$, $B \to D\tau\nu$ could possibly be accessible also at hadronic machines. In principle the theoretical errors

PoS(HQL 2010)067

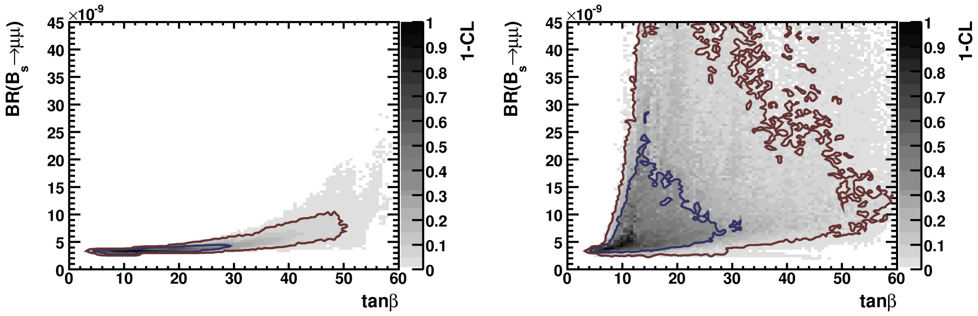

Figure 1: The correlation between $\mathscr{B}(B_s \to \mu^+\mu^-)$ and $\tan\beta$ in the constrained MSSM (left panel) and in the MSSM with non-universal Higgs soft-mass terms (right panel) [27]. In both panels the CL is obtained combining all the available (indirect) constraints on the model [27].

of the $B \to D$ hadronic form factors imply a sizable error in the prediction of $B \to D\tau\nu$. However, as pointed out in [19], this could be substantially reduced normalizing this decay mode to $B \to De\nu$.

3.2 $B_{s,d} \to \ell^+\ell^-$

The purely leptonic decays constitute a special case among exclusive FCNC transitions. Within the SM only the axial-current operator induces a non-vanishing contribution to these decays; as a result, they are totally dominated by short-distance dynamics. Moreover, the hadronic matrix element involved is the simplest we can consider, namely the B-meson decay constant.

The price to pay for this theoretically-clean amplitude is a strong helicity suppression for $\ell = \mu$ (and $\ell = e$), or the channels with the best experimental signature. Following Ref. [24] the SM predictions for the various branching ratios can be written as

$$\mathscr{B}(B_s \to \mu^+\mu^-)^{\rm SM} = 3.1 \times 10^{-9} \left(\frac{|V_{ts}|}{0.04}\right)^2 \times \left(\frac{f_{B_s}}{0.21\ \text{GeV}}\right)^2 = (3.2 \pm 0.2) \times 10^{-9}\ , \tag{3.2}$$

$$\frac{\mathscr{B}(B_s \to \tau^+\tau^-)^{\rm SM}}{\mathscr{B}(B_s \to \mu^+\mu^-)^{\rm SM}} = 215\ , \qquad \frac{\mathscr{B}(B_s \to e^+e^-)^{\rm SM}}{\mathscr{B}(B_s \to \mu^+\mu^-)^{\rm SM}} = 2.4 \times 10^{-5}\ . \tag{3.3}$$

The corresponding B_d modes are both suppressed by an additional factor $|V_{td}/V_{ts}|^2 f^2_{B_d}/f^2_{B_s} \approx 1/30$.

The present experimental bound closest to SM expectations is $\mathscr{B}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$, by CDF [25], that is is less than 20 times the SM expectation.

The strong helicity suppression and the theoretical cleanness make these modes excellent probes of several new-physics models and, particularly, of scalar FCNC amplitudes. Scalar FCNC operators, such as $\bar{b}_R s_L \bar{\mu}_R \mu_L$, are present within the SM but are negligible because of the smallness of down-type Yukawa couplings. However, these amplitudes could be non-negligible in models with an extended Higgs sector, such as the minimal supersymmetric extension of the SM (MSSM). As pointed out in Ref. [26], Higgs-mediated FCNC amplitudes in a MFV framework with flavour-blind phases could provide a simple explanation of the present anomalies in B_S and B_d mixing. A clean prediction of this framework is $B_s \to \ell^+\ell^-$ very close to its present experimental bound.

Even in the most restricted versions of the MSSM (with MFV and with no new CPV phases), $B \to \ell^+\ell^-$ decays could be largely enhanced over the SM expectations if $\tan\beta$ (the ratio of the

PoS(HQL 2010)067

two Higgs vacuum expectation values) is large. The leading non-SM amplitude contributing to $B \to \ell^+\ell^-$ is generated by the heavy neutral Higgs exchange ($B \to A, H \to \ell^+\ell^-$). However, since the effective FCNC coupling of the neutral Higgs bosons is generated at the quantum level, the amplitude has a strong dependence on other MSSM parameters in addition to $M_{A,H}$ 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 this effective vertex. The leading parametric dependence of the scalar FCNC amplitude from these parameters is

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

For $\tan\beta \gtrsim 30$ and $M_A \lesssim 0.5$ TeV the neutral-Higgs contribution can easily lead to $\mathscr{O}(10)$ enhancements of $\mathscr{B}(B_{s,d} \to \ell^+\ell^-)$ over the SM expectations. Most important, these decays represent a very useful tool to determine a combination of MSSM parameters that would help in discriminating different versions of the model (see Fig. 1).

3.3 $B \to K^*\ell^+\ell^-$

Theoretical predictions for exclusive FCNC decays are not easy. Even if the final state involve only one hadron, in most of the kinematical region re-scattering effects of the type $B \to K^*H\bar H \to K^*\ell^+\ell^-$ are possible, making difficult to estimate precisely the decay rate. However, the largest source of uncertainty is typically the normalization of the hadronic form factors. The theoretical error can be substantially reduced in appropriate ratios or differential distributions. A clean example of this type is the normalized forward-backward asymmetry in $B \to K^*\ell^+\ell^-$.

The observable is defined as

$$\mathscr{A}_{FB}(s) = \frac{1}{d\Gamma(B \to K^*\mu^+\mu^-)/ds} \int_{-1}^{1} d\cos\theta \, \frac{d^2\Gamma(B \to K^*\mu^+\mu^-)}{ds\, d\cos\theta} \mathrm{sgn}(\cos\theta) \,, \tag{3.4}$$

where θ is the angle between the momenta of μ^+ and $\bar B$ in the dilepton center-of-mass frame. Assuming that the leptonic current has only a vector (V) or axial-vector (A) structure (as in the SM), the FB asymmetry provides a direct measure of the A–V interference. Indeed, at the lowest-order one can write

$$\mathscr{A}_{\rm FB}(q^2) \propto {\rm Re}\left\{ C_{10A}^* \left[\frac{q^2}{m_b^2} C_{9V}^{\rm eff} + r(q^2) \frac{m_b C_{7\gamma}}{m_B} \right] \right\} ,$$

where $r(q^2)$ is an appropriate ratio of $B \to K^*$ vector and tensor form factors [20]. There are three main features of this observable that provide a clear and independent short-distance information:

1. The position of the zero (q_0) of $\mathscr{A}_{\rm FB}(q^2)$ in the low-q^2 region [20]: as shown by means of a full NLO calculation [21], the experimental measurement of q_0^2 could allow a determination of C_7/C_9 at the 10% level.

2. The sign of $\mathscr{A}_{\rm FB}(q^2)$ around the zero. This is fixed unambiguously in terms of the relative sign of C_{10} and C_9: within the SM one expects $\mathscr{A}_{\rm FB}(q^2 > q_0^2) > 0$ for $|\bar B\rangle \equiv |b\bar d\rangle$ mesons.

3. The relation $\mathscr{A}[\bar B]_{\rm FB}(q^2) = -\mathscr{A}[B]_{\rm FB}(q^2)$. This follows from the CP-odd structure of $\mathscr{A}_{\rm FB}$ and holds at the 10^{-3} level within the SM [22], where C_{10} has a negligible CP phase.

PoS(HQL 2010)067

The best experimental determination of the FB asymmetry has been obtained by BELLE [23]. Similarly to B_s–$\bar{B}_s$ mixing, also in this case the agreement with the SM is not good, leaving open the room for speculations about sizable non-standard effects. However, the errors are clearly too large to draw definite conclusions.

3.4 $B \to \{X_s, K, K^*\}\nu\bar{\nu}$

The FCNC decays with a pair of neutrinos in the final state rare extremely challenging from the experimental point of view but are among the most clean probes of non-standard scenarios. Following the analysis of Ref. [28], the branching ratios of the $B \to \{X_s, K, K^*\}\nu\bar{\nu}$ modes in generic extensions of the SM can be written as

$$\begin{aligned}
\mathscr{B}(B \to K\nu\bar{\nu}) &= \mathscr{B}(B \to K\nu\bar{\nu})_{\rm SM} \times [1-2\eta]\,\varepsilon^2 \,, && (3.5)\\
\mathscr{B}(B \to K^*\nu\bar{\nu}) &= \mathscr{B}(B \to K^*\nu\bar{\nu})_{\rm SM} \times [1+1.31\eta]\,\varepsilon^2 \,, && (3.6)\\
\mathscr{B}(B \to X_s\nu\bar{\nu}) &= \mathscr{B}(B \to X_s\nu\bar{\nu})_{\rm SM} \times [1+0.09\eta]\,\varepsilon^2 \,, && (3.7)
\end{aligned}$$

where we have introduced the variables

$$\varepsilon^2 = \frac{|X_{\rm LL}|^2 + |X_{\rm RL}|^2}{|X_{\rm LL}^{\rm SM}|^2}\,, \qquad \eta = \frac{-{\rm Re}\,(X_{\rm LL}^* X_{\rm RL})}{|X_{\rm LL}|^2 + |X_{\rm RL}|^2}\,, \tag{3.8}$$

in terms of the Wilson coefficient of the effective Hamiltonian

$$\mathscr{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi s_W^2} V_{tb}^* V_{ts} \times \left[X_{LL}(B_s)(\bar{b}_L\gamma^\mu s_L) + X_{RL}(B_s)(\bar{b}_R\gamma^\mu s_R)\right] \times (\bar{\nu}_L\gamma_\nu\nu_L)\,, \tag{3.9}$$

The updated predictions for the SM branching ratios [33, 32, 28] and corresponding experimental bounds [34] are

$$\begin{aligned}
\mathscr{B}(B \to K\nu\bar{\nu})_{\rm SM} &= (3.64 \pm 0.47) \times 10^{-6}\,, && \mathscr{B}_{\rm exp} < 1.4 \times 10^{-5}\,,\\
\mathscr{B}(B \to K^*\nu\bar{\nu})_{\rm SM} &= (7.2 \pm 1.1) \times 10^{-6}\,, && \mathscr{B}_{\rm exp} < 8.0 \times 10^{-5}\,,\\
\mathscr{B}(B \to X_s\nu\bar{\nu})_{\rm SM} &= (2.7 \pm 0.2) \times 10^{-5}\,, && \mathscr{B}_{\rm exp} < 6.4 \times 10^{-4}\,. && (3.10)
\end{aligned}$$

The expressions in Eqs. (3.5)–(3.7) are valid for wide class of NP model. A specific and well-motivated framework where sizable effects in these modes can be expected is the SM extended with RH flavour-violating currents (as already discussed in the case of $B \to \tau\nu$). The effect of RH currents in various low-energy observables have been analysed in Ref. [18] by means of a generic effective-theory approach. As far as $B \to \{X_s, K, K^*\}\nu\bar{\nu}$ decays are concerned, the predictions for the exclusive branching ratios can be enhanced by more than a factor of two over the corresponding SM estimates. On the contrary, the enhancement in the inclusive mode does not exceed 50%. Most important, a clear prediction of RH currents is the anti-correlation of the two exclusive modes: if $\mathscr{B}(B \to K\nu\bar{\nu})$ is enhanced then $\mathscr{B}(B \to K^*\nu\bar{\nu})$ is suppressed, and viceversa. Not surprisingly, the pattern of these three modes is very similar to what observed in the three modes relevant for the determination of $|V_{ub}|$. However, in the rare modes the deviations from the SM can in principle be larger than in the charged-current decays.

PoS(HQL 2010)067

Model	$\mathcal{B}(D^0 \to \mu^+\mu^-)$
Exp. bound	$\leq 1.3 \times 10^{-6}$
Standard Model	$\sim$ several $\times\, 10^{-13}$
$Q = +2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q = -1/3$ Fourth Family	$1 \times 10^{-11}\ (m_S/500\ \text{GeV})^2$
RPV-SUSY	$4.8 \times 10^{-9}\ (300\ \text{GeV}/m_{\tilde{d}_k})^2$

Table 1: $\mathcal{B}(D^0 \to \mu^+\mu^-)$ in various NP frameworks, assuming D^0–$\bar{D}^0$ mixing is dominated by NP [37].

PoS(HQL 2010)067

4. Rare *D* decays

In most conservative extensions of the SM rare D decays are not particularly interesting: in most cases the large long-distance contributions tend to “obscure” possible NP effects. The most promising observable for NP searches in the D-meson systems is the CPV phase of D^0–$\bar{D}^0$ mixing: a clean null test of the SM and a very sensitive probe of several NP frameworks (see e.g. Ref. [35] and references therein).

However, we should be open also to more exotic possibilities. In this respect rare D decays offer some other interesting null-tests beside CPV in mixing, such as $D \to \mu^+\mu^-$ or $D \to \mu e$. An exhaustive compilation of the most interesting modes can be found in [36]. In Table 1 we show the expectations for $D \to \mu^+\mu^-$ in various non-standard frameworks, assuming large NP contributions to D^0–$\bar{D}^0$ mixing (within the the present experimental bounds) [37]. As can be seen, only in the case of R-parity violating supersymmetry the rate could be within the reach of future experiments.

5. Conclusions

The origin of flavour remains, to a large extent, an open problem. However, a significant progress has been achieved in the phenomenological investigation of the sources of flavour symmetry breaking accessible at low energies. This investigation has allowed to set very stringent constraints on various extensions of the SM, ruling out models with significant misalignments from the SM Yukawa couplings at the TeV scale.

What we learned so far does not imply we cannot see some deviation from the SM in low-energy process in the near future. A few interesting anomalies in the CKM picture have started to emerge. Some of them will go away with more data, but others may well be the first signals of new physics at the TeV scale. Some clean rare B decay observables, such as $\mathcal{B}(B \to \ell^+\ell^-)$, $\mathcal{B}(B \to \tau\nu)$, and the FB asymmetry in $B \to K^*\ell^+\ell^-$, are powerful tools understand if these anomalies are signals of NP and, if this is the case, to discriminate among different SM extensions.

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