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Flavour Physics: Theory

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We review the recent progress in our theoretical understanding of flavour-changing processes. The overall excellent agreement with the corresponding measurements allows to derive severe constraints on possible extensions of the Standard Model. Theory implications of the few open experimental flavour puzzles are briefly discussed.

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1. Why flavour matters in the LHC era?

In the past three decades, the standard model (SM) has withstood severe experimental scrutiny and emerged as a phenomenologically extremely successful theory. Nonetheless, theoretical arguments to consider it merely as an effective field theory (EFT) remain relevant even after the recent discovery of the Higgs-like scalar at the LHC, completing the SM predicted particle content. In this context it is instructive to decompose the SM Lagrangian (including possible neutrino mass operators) in terms of the relevant gauge-kinetic terms and the effective potential

$$\mathscr{L}_{\nu\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_a,\psi_i) + D_\mu\phi^\dagger D^\mu\phi - V_{\mathrm{eff}}(\phi,A_a,\psi_i)\,, \tag{1.1}$$

where A_a, ψ_i and ϕ stand for the SM gauge fields, fermions and the Higgs field, respectively. Three of the most important SM theoretical puzzles concern the structure of V_{eff}

$$V_{\mathrm{eff}} = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + Y^{ij}\psi_L^i\psi_R^j\phi + \frac{y^{ij}}{\Lambda}\psi^{iT}\psi_L^j\phi^T\phi + \dots\,, \tag{1.2}$$

namely the electroweak (EW) hiearchy problem, i.e. why $|\mu^2| \ll \Lambda^2$ where Λ is the EFT cut-off scale; the SM flavor puzzle: why Y^{ij} are aligned (in the quark sector) and hierarchical (in both the quark and charged lepton sectors); and finally the mechanism of neutrino mass generation, i.e. the existence of the y^{ij}/Λ term. In absence of new light degrees of freedom, the outstanding task of high energy physics in general and flavour physics in particular is to understand and constrain the size of additional terms in the series (suppressed by increasing powers of $1/\Lambda$) with the hope of gaining new insights on these issues.

2. (Over)constraining the flavour sector of SM and new physics

In the SM quark sector (in absence of any additional terms in (1.2)), the relevant Yukawa matrices Y_u, Y_d are the only sources of the global quark flavour symmetry breaking which can be parametrized completely in terms of 10 physical parameters: 6 quark masses (given by the eigenvalues of the diagonal mass matrices $m_u \equiv vV_L^uY_uV_R^{u\dagger}$ and $m_d \equiv vV_L^dY_dV_R^{d\dagger}$, where $v\equiv\langle\phi\rangle$ and $V_{L,R}^{u,d}$ are unitary matrices), 3 CKM mixing angles and a single CP odd phase (all parametrized within a single physical unitary matrix $V\equiv V_L^uV_L^{d\dagger}$). The utility of flavour physics in constraining possible new effects in precision experiments is due to the fact, that (in principle) the above few parameters determine all the flavor phenomena in quark sector. Throughout the continuing improvement over the past few decades, the experimental measurements have generally exhibited excellent consistency with SM predictions. This is perhaps best exemplified by the two-dimensional projection of a recent compendulum of experimental constraints onto the SM quark flavour parameter space in the complex plane of $\bar\rho + i\bar\eta \equiv -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$ as performed by the UTFit [1] and the CKM-Fitter [2] collaborations in Fig. 1.

Theoretically, the flavour programme relies heavily on the powerful tools of Wilsonian operator product expansion (OPE) and renormalization group equations (RGEs), where weak scale operators in $\mathscr{L}_{\nu\mathrm{SM}}$ are matched onto a cascade of effective field theories defined below the relevant particle $(t,h,Z,W\dots)$ thresholds. Schematically

$$\mathscr{L}_{\nu\mathrm{SM}} \to \mathscr{L}^{\mathrm{eff}}_{\mathrm{weak}}(\sim G_F\sum_i c_i\mathscr{Q}_i) + \mathscr{L}_{QCD\times QED}\,, \tag{2.1}$$

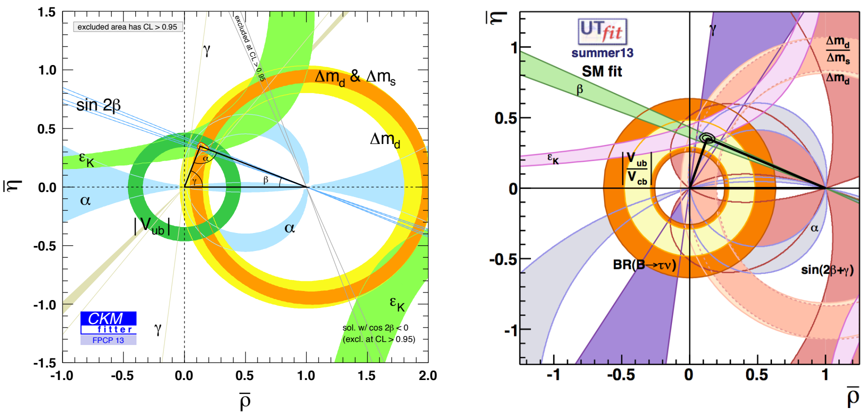

Figure 1: Result of the SM CKM fit projected onto the $\bar\rho - \bar\eta$ plane, as obtained by the UTFit (left) [1] and CKMfitter (right) [2] collaborations. Shown shaded are the 95% C.L. regions selected by the given observables.

where $G_F \sim 1/v^2$ is the Fermi constant, while c_i and $\mathscr{Q}_i$ are the effective Wilson coefficients and local operators, respectively. Such matching and RGE evolution are systematically improvable via perturbative QCD, QED and EW corrections and is currently known to N^{2}LO in QCD and NLO in EW expansion for several of the most interesting and most precisely measured observables. Most recent improvements include the NLO EW contributions to the rare $K^+ \to \pi^+ \nu\bar\nu$ decay [3] and N^{2}LO $c\bar c$ contributions to the neutral kaon oscillation observables (ε_K and Δm_K) [4].

In order to interpret results of experimental measurements involving hadronic initial and final states, a final step needs to involve non-perturbative matching to an effective description involving QCD bound states $\mathscr{L}^{\rm eff}_{\rm weak} \to \mathscr{L}^{\rm eff}(\pi, N, K, D, B, \ldots)$, i.e. the computation of hadronic $\langle \mathscr{Q}_i \rangle$ matrix elements. It has predominantly been due to the tremendous improvements in lattice QCD approaches to such calculations that propelled the field into the era of precision flavour constraints (for discussion on recent progress see [5]).

Given the multitude of complementary experimental results over-constraining the SM quark flavour sector, it has become possible to complete the above sketched programme even in presence of new sources of SM flavour symmetry breaking, i.e. flavour changing transitions among SM quarks mediated by new heavy degrees of freedom with masses $m_{NP} \gtrsim v$ and described by a Lagrangian $\mathscr{L}_{\rm BSM}$. At scales μ below the new particle thresholds but above the EW breaking scale ($v < \mu < m_{NP}$), any such effects can be described in complete generality in terms of local operators involving only SM fields [6] via the matching procedure[1]

$$\mathscr{L}_{\rm BSM} \to \mathscr{L}_{\nu\rm SM} + \sum_{d>4} \frac{\mathscr{Q}_i^{(d)}}{\Lambda^{d-4}}\,, \tag{2.2}$$

where d is the canonical operator dimension. Below the EW breaking scale, these new contributions can lead to (a) shifts in the Wilson coefficients corresponding to $\mathscr{Q}_i$ present in $\mathscr{L}^{\rm eff}_{\rm weak}$ already within the SM; (b) the appearance of new effective local operators. In both cases, the resulting effects on the measured flavour observables can be computed systematically. Given the overall good

[1] A simple generalization of such matching applies even in presence of weakly coupled new light (neutral) particles with masses well below the weak scale [7].

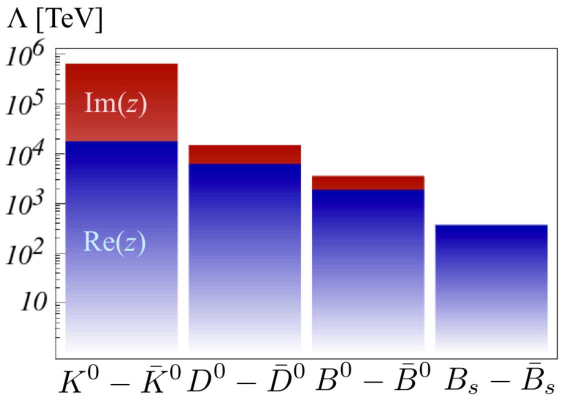

Figure 2: Current constraints of neutral meson oscillation measurements on new $\Delta F = 2$ dimension six operator contributions, given in terms of the effective operator scale (see text for details). Bounds on the CP conserving and CP violating contributions are shown in blue and red, respectively.

agreement of SM predictions with current experimental measurements, such procedure typically results in severe bounds on the underlying new physics (NP) flavour breaking sources in $\mathscr{L}_{\rm BSM}$.

Let us consider the canonical example of NP in $\Delta F = 2$ processes associated with oscillations of neutral mesons (for recent extended discussion see [8]). The leading ($d = 6$) NP operators are of the form $\mathscr{Q}^{(6)}_{AB} \sim z^{ij}[\bar{q}_i\Gamma^A q_j]\otimes[\bar{q}_i\Gamma^B q_j]$, where q_i denote the SM quark fields, while $\Gamma^{A,B}$ denote the Clifford algebra generators. Assuming z^{ij} to be generic $\mathscr{O}(1)$ complex numbers, $z \sim \exp(i\phi_{\rm NP})$, the reach of current constraints in terms the probed NP scales Λ are shown in Fig. 2. It is important to stress that most of these constraints are currently limited by theory uncertainties, both related to SM contributions, as well as concerning the size of NP effects. In particular, many of the observables are already sensitive to NLO QCD effects in the NP matching procedure (2.2) [9].

The current severe flavour bounds could be interpreted as a requirement on BSM degrees of freedom to exhibit a large mass gap with respect to the EW scale (if the NP flavour and CP breaking sources are of order one and not aligned with $Y_{u,d}$). Conversely, TeV scale NP can only be reconciled with current experimental results, provided it exhibits sufficient flavor symmetry or structure, such that $|z^{ij}| \ll 1$ (the extreme case being minimal flavour violation (MFV) [10], where one requires $Y_{u,d}$ to be the only sources of flavour breaking even BSM) . It is however interesting to note that even flavour trivial NP is not completely safe from flavour constraints. An excellent example is provided by the measurements of the first row CKM matrix elements V_{ui}, which can be combined to probe the corresponding CKM unitarity condition [11]

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0008\left({}^{+7}_{-6}\right) . \tag{2.3}$$

Such constraints are significant in presence of new weak currents coupling to quark bilinears, e.g. $\mathscr{Q}^{(6)}_{\phi Q} \sim z^{ij}\bar{Q}^i_L\tau^a\gamma^\mu Q^j_L\phi^\dagger\tau_a\overleftrightarrow{D}_\mu\phi$, where τ^a are Pauli matrices and $\overleftrightarrow{D}_\mu \equiv \overrightarrow{D}_\mu - \overleftarrow{D}_\mu$. In general, such operators generate flavour changing neutral currents (FCNCs) as well as modifications of weak charged currents among quarks. Enforcing flavour triviality, $z^{ij} = \delta^{ij}$, efficiently suppresses FCNCs and the effect of $\mathscr{Q}^{(6)}_{\phi Q}$ is reduced to a universal contribution to quark weak charged currents. It can be parametrized as a shift in the effective Fermi constant as measured in semileptonic processes, compared to the value extracted from the muon lifetime

$$G_F^{(\mathrm{sl})} = G_F^{(\mu)} \left[1 + \frac{v^2}{2\Lambda^2} \right] . \tag{2.4}$$

Using (2.3) and $G_F^{(\mu)}$ from [12] leads to a bound on the effective $\mathscr{Q}_{\phi Q}^{(6)}$ scale of $\Lambda > 5.5$ TeV .

3. Flavour probes of EW and Higgs sectors

The previous example demonstrates how flavour measurements can be reinterpreted as competitive constraints on the EW and scalar (Higgs) sectors of the theory. In this context the rare leptonic decays $B_{s,d} \to \mu^+\mu^-$ represent new powerful probes. These modes are theoretically very clean, with negligible long distance contributions. Consequently, within the SM, their rates are currently predicted to better than 10% accuracy [13]

$$\mathscr{B}_{d,SM} = (1.07 \pm 0.10) \times 10^{-10} , \qquad \overline{\mathscr{B}}_{s,SM} = (3.56 \pm 0.18) \times 10^{-9} , \tag{3.1}$$

where the dominant sources of error are due to parametric uncertainties in $|V_{ts,td}^* V_{tb}|$, m_t and the relevant meson decay constants $f_{B_{s,d}}$. At this level of precision, an important B_s oscillation effect due to a sizable width difference ($\Delta\Gamma_s$) of the two B_s mass eigenstates needs to be taken into account [14] when comparing with experimental measurements, which probe the flavour-averaged time-integrated distribution

$$\langle \Gamma(B_s \to f) \rangle_{[t]} = \frac{1}{2} \int_0^t dt' \left[\Gamma(B_s(t') \to f) + \Gamma(\bar{B}_s(t') \to f) \right] , \tag{3.2}$$

where $\Gamma(B_s(t') \to f)$ denotes the decay rate (as a function of the proper time t') of a B_s flavor eigenstate at initial time (and correspondingly for $\bar{B}_s$). The experiments measure approximately $\overline{\mathscr{B}}_s \equiv \tau_{B_s} \langle \Gamma(B_s \to \mu^+\mu^-) \rangle_{[t\to\infty]}$, where τ_{B_s} refers to the inverse of the average decay width of both B_s mass eigenstates. In this limit Eq. (3.2) yields for the SM prediction

$$\langle \Gamma(B_s \to \mu^+\mu^-) \rangle_{[t \gg \tau_{B_s}]}^{SM} \simeq \frac{1}{1-y_s} \langle \Gamma(B_s \to \mu^+\mu^-) \rangle_{[t=0]}^{SM} , \tag{3.3}$$

where $y_s \equiv \tau_{B_s} \Delta\Gamma_s/2 = 0.088(14)$. The recent first experimental evidences of the $B_{s,d}$ di-muonic decays [15]

$$\overline{\mathscr{B}}_d^{(\mathrm{exp})} = (3.6^{+1.9}_{-1.2}) \times 10^{-10} , \qquad \overline{\mathscr{B}}_s^{(\mathrm{exp})} = (2.9^{+0.8}_{-0.6}) \times 10^{-9} , \tag{3.4}$$

are in good agreement with the above SM expectations, although they cannot yet match the theoretical precision.

The $B_{s,d} \to \mu^+\mu^-$ decays are particularly sensitive to scalar mediated FCNCs (in addition to Z penguin contributions). As such they represent clean probes of the Yukawa interactions beyond the tree level. A well studied example is the MFV minimal supersymmetric standard model (MSSM) at large $\tan\beta \equiv v_d/v_u$, where $v_{u,d}$ are the condensate values of the two Higgs doublets in the model and $v_u^2 + v_d^2 = v^2$. Here the dominant NP contribution to the rates is enhanced by three powers of $\tan\beta$ at the amplitude level. The resulting $\overline{\mathscr{B}}_s$ constraints on the extra Higgs-like states in the

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model are already competitive with direct LHC searches for such particles [16]. Within the context of flavour general MSSM (at small to moderate $\tan\beta$) on the other hand, $\overline{\mathscr{B}}_{s,d}$ are also sensitive to the third generation trilinear supersymmetry breaking (A) terms. In particular, combined with the measured value of the observed Higgs boson mass (requiring large $|A_{33}|$), the current $\overline{\mathscr{B}}_{s,d}$ measurements already provide relevant constraints on $|A_{23,13}|$ below bounds imposed by vacuum stability requirements (absence of colour breaking vacua, i.e. $|A_{23,13}A_{33}| < 3m^2_{\tilde{t}_L}$) for scalar top quark masses below the TeV as preferred by naturalness considerations [17]. Finally, when combined, the latest $\overline{\mathscr{B}}_{s,d}$ results are also beginning to test a possible $\mathscr{B}_d/\overline{\mathscr{B}}_s$ enhancement predicted in non-MFV models (c.f. [18]). Conversely they constitute a new nontrivial test of MFV [19].

The sensitivity of rare (semi)leptonic $B_{s,d}$ decays to non-standard Z penguin contributions can perhaps best be illustrated by comparing the effects of flavour violation in these processes to flavour non-universality constraints from measurements at the Z pole at LEP [20]. Obviously, such a comparison can only be performed within explicit flavour models correlating both types of effects. In MFV, for example, the leading two operators in operator dimension and flavour breaking expansion affecting (predominantly) Z boson couplings to down-type quarks are $\mathscr{Q}_L^{(6)} \sim (Y_u Y_u^\dagger)^{ij} \bar{Q}_L^i \gamma^\mu Q_L^j \phi^\dagger \overleftrightarrow{D}_\mu \phi$ and $\mathscr{Q}_R^{(6)} \sim Y_d^i (Y_u Y_u^\dagger)^{ij} Y_d^j \bar{d}_R^i \gamma^\mu d_R^j \phi^\dagger \overleftrightarrow{D}_\mu \phi$. Parametrizing the effective deviations in the Z boson couplings to down-type quarks as

$$\mathscr{L}^Z_{\rm eff} = Z_\mu \bar{d}^i \gamma^\mu \left[(g^{ij}_{L,SM} + \delta g^{ij}_L) P_L + (g^{ij}_{R,SM} + \delta g^{ij}_R) P_R \right] d^j \,, \tag{3.5}$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$, while $g^{ij}_{L,R,SM}$ and $\delta g^{ij}_{L,R}$ refer to the effective SM and NP contributions, respectively, within MFV one obtains the relations $\delta g_L^{bs} = (V_{tb} V_{ts}^*/|V_{tb}|^2)\delta g_L^{bb}$ and $\delta g_R^{bs} = (m_s V_{tb} V_{ts}^*/m_b |V_{tb}|^2)\delta g_R^{bb}$. Consequently at current precision, rare (semi)leptonic $B_{s,d}$ decays are already competitive with the LEP measurements in constraining δg_L^{bb} at the permille level.

4. Signs of NP in flavour?

Despite the overall excellent agreement of flavour measurements with SM predictions, a few experimental flavour puzzles have recently received considerable attention.

4.1 $B \to K^* \ell^+ \ell^-$ angular observables

Observables related to the rare $b \to s(\gamma, \ell^+\ell^-)$ transitions offer a wealth of information on potential non-standard contributions to the corresponding effective weak Lagrangian $\mathscr{L}^{\rm eff}_{\rm weak}$. In particular, one can define theoretically clean complementary observables, sensitive to different manifestations of NP in $b \to s$ semileptonic transitions. These include angular observables in $B \to K^{(*)}\ell^+\ell^-$ decays [21], time dependent decay observables in the $B_s \to \mu^+\mu^-$ mode [22], as well as CP violating asymmetries in $b \to s(\gamma, \ell^+\ell^-)$ decays [23]. Combining all of this information, including the recent new experimental results from the LHCb collaboration already allows to efficiently disentangle and constrain possible non-standard effects from global fits [24] (see also [25]).

Recently, such fits of angular $B \to K^* \ell^+\ell^-$ observables binned in the low leptonic invariant mass region ($q^2 \equiv (p_{\ell^+} + p_{\ell^-})^2 \in [0.1, 8.68]\,{\rm GeV}^2$) have been exhibiting a tension between some of the LHCb measurements and the corresponding theoretical predictions within the SM [26]. Starting from a fully differential $\bar{B}^0 \to (\bar{K}^{0*} \to K^-\pi^+)\ell^+\ell^-$ decay rate distribution $d^4\Gamma/d\cos\theta_\ell d\cos\theta_K d\phi dq^2$

(where θ_ℓ is the angle between the flight direction of the ℓ^- and the $\bar{B}^0$ meson in the dimuon rest frame, θ_K is the angle between the flight direction of the charged kaon from $\bar{K}^{0*}$ decay and the $\bar{B}^0$ meson in the $\bar{K}^{0*}$ rest frame, and ϕ is the angle between the decay planes of the $\bar{K}^{0*}$ and the dimuon system in the $\bar{B}^0$ meson rest frame), one can define a number of angular asymmetries by folding the distributions with respect to judiciously chosen axes, such that the leading theoretical uncertainties related to the reduced hadronic form factors (see below) cancel out. These observables are mostly sensitive to the contributions of $\mathscr{Q}_7 \sim m_b[\bar{s}\sigma_{\mu\nu}(1+\gamma_5)b]eF^{\mu\nu}$ and $\mathscr{Q}_9 \sim [\bar{s}\gamma_\mu(1-\gamma_5)b][\bar{\ell}\gamma^\mu\ell]$ (and the corresponding chirally flipped operators) entering $\mathscr{L}^{\rm eff}_{\rm weak}$ and the current ($\sim 3\sigma$) tension seems to be most economically reconciled via a $\sim 40\%$ reduction in the contribution of $\mathscr{Q}_9$ [27].

Before interpreting such an effect in terms of possible NP contributions, it is crucial to reevaluate the corresponding SM theory estimates based on QCD factorisation at large hadronic recoil. The resulting reduction in the number of independent hadronic form factors is broken be computable perturbative (in α_s) and non-perturbative ($1/m_b$ power) corrections. The later are estimated using naive dimensional analysis and parametrized relative to to the factorized contributions. It has been pointed out recently [28] that such treatment may underestimate the non-perturbative effects, especially the effective long distance (LD) contributions to the hadronic matrix element $\langle\mathscr{Q}_9\rangle$ due to the hadronic substructure of the photon $\langle\mathscr{Q}_9\rangle_{LD} \sim \int d^4x \exp(-iq\cdot x)\langle\bar{K}^{0*}|T\{j^{\rm em}_\mu(x),\mathscr{H}^{\rm had}_{\rm eff}(0)\}\bar{B}^0\rangle$, where $\mathscr{H}^{\rm had}_{\rm eff}$ contains contributions of four-quark operators of the form $[\bar{q}\Gamma_A b]\otimes[\bar{s}\Gamma_B q]$. Consequently, a first principles evaluation of $\langle\mathscr{Q}_9\rangle_{LD}$ would certainly contribute significantly to resolving the issue (see [29] for recent progress in this direction).

In the meantime, a number of experimental tests could possibly shed light on the puzzle and help to disentangle its origin. For example, more inclusive observables integrated over larger q^2 bins defined away from known intermediate resonances (i.e. $q^2 \in [1,6]$ GeV^2) should be less sensitive to non-local LD contributions. Conversely, fine q^2 binning could enhance the experimental sensitivity to (resonant) QCD effects. Another possibility is to consider the high $q^2 > 14\,\text{GeV}^2$ (low hadronic recoil) region, where the SM theory predictions (based on heavy quark effective theory OPE) and their uncertainties are dominated by different systematics compared to the low q^2 region [30]. However, the recent LHCb observation of an unexpected resonant structure at high q^2 in the $B^+ \to K^+\mu^+\mu^-$ decays [31] indicates that a better understanding of the high q^2 region is needed before the angular $B \to K^*\ell^+\ell^-$ fit puzzle can be confronted reliably using high q^2 data. Finally, there are several related rare semileptonic decay modes of b-flavored hadrons which are sensitive to a deviation in $\langle\mathscr{Q}_9\rangle$ (or in the corresponding short distance Wilson coefficient c_9), i.e. $B_s \to \phi\ell^+\ell^-$, $B \to K\ell^+\ell^-$, $\Lambda_b \to \Lambda\ell^+\ell^-$ and the inclusive modes $B_q \to X_s\ell^+\ell^-$. Since these processes are subject to different long distance hadronic effects, they offer the possibility to disentangle possible short distance contributions to c_9 from QCD effects in $\langle\mathscr{Q}_9\rangle$. For example, if the observed discrepancy is due to short distance physics reducing c_9, one would expect reduced rates compared to SM predictions for all these modes.

Assuming the $B \to K^*\ell^+\ell^-$ anomaly is due to NP contributions affecting predominantly c_9, one can easily identify the corresponding effective weak operator above the EW breaking scale $\mathscr{Q}_9 \to \mathscr{Q}^{(6)}_{Q\ell} \sim z_{ij}\bar{Q}^i\gamma_\mu Q^j(\bar{L}\gamma^\mu L + \bar{\ell}_R\gamma^\mu\ell_R)$. In particular, such NP should couple (almost) universally to both lepton chiralities. Consequently, the effect cannot be due to an anomalous $\bar{s}\not{Z}b$ interaction in (3.5), since the SM Z boson has very different couplings to left and right-handed leptons. The simplest model examples that could be compatible with the data thus possibly involve new Z'

bosons [27, 32]. Another immediate consequence of $\mathscr{Q}^{(6)}_{Q\ell}$ are deviations in $B \to (K, K^*, X_s)\bar{\nu}\nu$ decays. These processes are especially interesting since they are free from LD non-local QCD contributions (but precise knowledge of the relevant form factors is still needed in order to make reliable predictions). On the other hand, if the leptonic chiral alignment behind $\mathscr{Q}^{(6)}_{Q\ell}$ is not perfect, one expects also contributions from other EW operators matching onto $\mathscr{Q}_{10} \sim [\bar{s}\gamma_\mu(1-\gamma_5)b][\bar{\ell}\gamma^\mu\gamma_5\ell]$ below the EW breaking scale. Interestingly, such effects are just starting to be significantly constrained by $B_s \to \mu^+\mu^-$ (see Sec. 3).

4.2 CP violation in charm decays

CP violation in the neutral D meson decays to CP eigenstates f is probed with time-integrated CP asymmetries

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \,. \tag{4.1}$$

These can arise from interferences between decay amplitudes with non-zero CP odd (ϕ_f) and even (δ_f) phase differences $a_f^{\rm dir} \simeq -2r_f \sin\delta_f \sin\phi_f$, where $r_f \ll 1$ is the ratio of magnitudes of the interfering amplitudes. Recently a non-zero value of the difference $\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-}$ has been reported by several experiments leading to the present world average [33] $\Delta a_{CP} = (-0.329 \pm 0.121)\%$. This value is larger in magnitude than naïve SM estimates based on QCD factorisation in the $m_c \gg \Lambda_{QCD}$ limit $|\Delta a_{CP}^{\rm SM}| \sim |{\rm Im}(V_{cs}^* V_{us}/V_{cd}^* V_{ud})|(\alpha_s/\pi) \ll 0.1\%$ [34]. In general, the SM contribution can be factorized as $\Delta a_{CP}^{\rm SM} \simeq (0.13\%){\rm Im}(\Delta R^{\rm SM})$, where the first numerical factor is determined completely in terms of the relevant CKM elements. On the other hand, ΔR denotes the sum of ratios of the relevant hadronic matrix elements. While $|\Delta R| \gg 1$ is not what we expect for $m_c \gg \Lambda_{QCD}$, the $\Delta I = 1/2$ rule in $K \to 2\pi$ decays teaches us that such an enhancement may not be impossible treating charm quark as light [35]. Arguably, it might even help to address the apparent sizable flavor $SU(3)$ violation in the observed D decay rates [36].

On the other hand, a NP explanation of the observed size of Δa_{CP} in the form of four quark operators $\mathscr{Q}^{(6)}_{ABq} \sim \exp(i\phi_{NP})[\bar{u}\Gamma_A c] \otimes [\bar{q}\Gamma_B q]$ would require an effective NP scale of $\Lambda \lesssim 15$ TeV [37]. Such NP would be subject to important constraints from D oscillations, CPV in kaon decays and nuclear electric dipole moments (EDMs). In particular, one can show that the ε'/ε measurement alone requires that any $\mathscr{Q}^{(6)}_{ABq}$ addressing the Δa_{CP} puzzle must involve right-handed u and/or c quark fields [38]. Interestingly, chromo-dipole operators $\mathscr{Q}_8^{(\prime)} \sim \bar{u}T^a\sigma_{\mu\nu}(1\pm\gamma_5)cG_a^{\mu\nu}$ which easily satisfy current flavour bounds can be generated in well-motivated NP models like the MSSM [39] or composite Higgs / warped extra-dimensional models [40].

In this situation, a key question to address is how to distinguish between possible NP and SM explanations of the Δa_{CP} puzzle. While explicit NP models may predict several related signatures (i.e. collider signals at high p_T or effects in EDMs), a lot of information can be obtained model-independently using charm data alone. For example, one can construct isospin sum rules accurately preserved by SM, which are however violated in certain models of NP (like $a_{CP}(D^+ \to \pi^+\pi^0) = 0$) [41]. Similarly, effects of NP chromo-dipole operators could be tested using CPV asymmetries in radiative and rare semileptonic D decays $D \to (P^+P^-)_V\gamma$ [42] and $D \to (P^+P^-)_V\ell^+\ell^-$ [43], respectively. Finally, it is important to constrain or measure CPV in other non-leptonic D decays in order to constrain a possible QCD enhancement of ΔR, which is not expected to translate universally to other modes [44].

4.3 CP violation in semileptonic b decays

Given the good consistency of the global CKM fits, CPV in B_s mixing is predicted precisely within the SM. In particular, time-dependent CP asymmetries in B_s decays to CP eigenstates (f) are given by

$$a^s_{CP}(t) = \frac{\Gamma(\bar{B}_s(t) \to f) - \Gamma(B_s(t) \to f)}{\Gamma(\bar{B}_s(t) \to f) + \Gamma(B_s(t) \to f)} = -\eta_{CP} \sin(\phi_s) \sin(\Delta m_s t) \tag{4.2}$$

where $\eta_{CP} = \pm 1$ for CP even (odd) f, Δm_s is the B_s eigenstates' mass difference, while in the SM $\phi_s \equiv \mathrm{Arg}[-(V_{ub}V^*_{us})/(V_{cb}V^*_{cs})] = -0.036 \pm 0.002$ [45]. So far, no signs of deviations from these expectations have been observed by the LHCb [46]. On the other hand, the D0 experiment at the Tevatron has measured an anomalously large di-muon CP asymmetry [47]

$$A^b_{sl} \equiv \frac{N(\bar{b}b \to X\mu^+\mu^+) - N(\bar{b}b \to X\mu^-\mu^-)}{N(\bar{b}b \to X\mu^+\mu^+) + N(\bar{b}b \to X\mu^-\mu^-)} = (-0.787 \pm 0.172 \pm 0.093)\%\,. \tag{4.3}$$

If the above measured value is due to CP violation in $B_{s,d}$ mixing it can be related to the corresponding flavour-specific wrong-sign (time-integrated) semileptonic asymmetries

$$a^q_{sl} \equiv \frac{\Gamma(\bar{B}_q \to \mu^+ X) - \Gamma(B_q \to \mu^- X)}{\Gamma(\bar{B}_q \to \mu^+ X) + \Gamma(B_q \to \mu^- X)}\,, \tag{4.4}$$

as $A^b_{sl} = f_d a^d_{sl} + f_s a^s_{sl}$, where $f_{d,s}$ are the corresponding production fragmentation fractions, leading to the SM prediction $A^{b,\mathrm{SM}}_{sl} = (-0.20 \pm 0.03) \times 10^{-3}$ [45] . While deviating from this SM expectation by more than 3σ, currently the D0 measurement in (4.3) is still marginally consistent with the measurements of flavour-specific semileptonic CP asymmetries in (4.4) at the B factories and recently at LHCb [48] . However, any heavy NP accommodating A^b_{sl} by generating a new CPV phase in B_s mixing would be in conflict with the measured value of ϕ_s from $a^s_{CP}(t)$ in $B_s \to J/\psi(\phi, f_0)$ decays (a similar argument applies to CPV NP contributions to dispersive B_d mixing amplitudes) [49].

An alternative possibility for accommodating the A^b_{sl} anomaly within NP models is to consider new CPV contributions to absorptive B_q mixing amplitudes via new or anomalously enhanced decay modes, common to B_q and $\bar{B}_q$ mesons. In the B_s system, any sizable effects of this kind are excluded by the measurements of $\Delta\Gamma_s$ and Δm_s. In the B_d case on the other hand, while being severely constrained by $\Delta B = 1$ FCNC decay measurements, some improvement in the fit to B_q mixing data and A^b_{sl} can be obtained using for example $(\bar{d}\Gamma_A b) \otimes (\bar{\tau}\Gamma_B \tau)$ type of operators [50].

Finally, a non-zero value of A^b_{sl} can also be induced by direct CP asymmetries in semileptonic B_q (and also D_q) decays [51]. In particular, $\mathscr{O}(0.1\%)$ asymmetries in B_q decays or $\mathscr{O}(1\%)$ asymmetries in D_q decays would fully reconcile the D0 result. Unfortunately, such effects are completely negligible within the SM and also difficult to obtain in NP models. Experimentally at least, the idea could possibly be tested at the LHC using b's from t decays [52] or alternatively at the B factories.

4.4 Lepton flavour universality in B decays

Flavour universality of charged current weak interactions is one of the key predictions of the SM. It has been well tested directly at colliders via W decays. On the other hand, additional charged interactions could induce lepton flavour universality (LFU) violation in processes at low energies. The relevant observables can be predicted accurately within the SM even in processes involving hadrons, since most QCD uncertainties cancel in LFU ratios. Consequently, pion, kaon and D processes have been found to be well consistent with LFU expectations at the $\mathscr{O}(0.1-1)\%$ level [53].

In the B sector on the other hand, in the last few years an apparent tension in the global CKM unitarity fits has been linked to the discrepancy between the various $|V_{ub}|$ determinations. Being most pronounced in taunic B decays, the tension has been somewhat reduced with the inclusion of the latest Belle measurement [54]. Incidentally, current measurements of semi-taunic B decays also exhibit an anomalous enhancement compared to SM expectations [55]. These are indications that the "$|V_{ub}|$ puzzle" may not be a CKM issue at all. One can definine the following LFU ratios

$$\Delta R^{\pi}_{\tau/\ell} \equiv \frac{\tau_{B^0}}{\tau_{B^+}} \frac{\mathscr{B}(B^- \to \tau^- \bar{\nu})}{\Delta\mathscr{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu})}\,, \quad R_{\tau/\ell} \equiv \frac{\mathscr{B}(B \to D\tau\nu)}{\mathscr{B}(B \to D\ell\nu)}\,, \quad R^*_{\tau/\ell} \equiv \frac{\mathscr{B}(B \to D^*\tau\nu)}{\mathscr{B}(B \to D^*\ell\nu)}\,, \tag{4.5}$$

where $\Delta\mathscr{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu})$ [56] refers to the corresponding decay branching fraction integrated over only the part of phase-space $(p_B - p_\pi)^2 > 16\,\mathrm{GeV}^2$ where Lattice QCD provides reliable theoretical estimates of the relevant hadronic form factors. Two key benefits of the observables in (4.5) are that (1) they are free from CKM parametric uncertainties; and (2) that the corresponding SM predictions are very robust. In particular, the dominant hadronic form factor dependence cancels in the ratios $R^{(*)}_{\tau/\ell}$, while the remaining corrections can be computed systematically [57, 58]. At present the measured ratios $\Delta R^{\pi}_{\tau/\ell}$ and $R^{(*)}_{\tau/\ell}$ exhibit a 1.6σ and (combined) 3.4σ tension, respectively, when compared to SM expectations.

Any NP addressing the above LFU violation puzzle in B decays would need to satisfy severe constraints from the measurements of down quark and charged lepton FCNC processes, as well as from precise tests of LFU in the pion and kaon sectors. Together these lead to a requirement on the relevant NP being flavour aligned with the third generation in both the quark and charged lepton sectors. The size of the apparent discrepancies then points towards a relatively low effective NP scale of $\Lambda \lesssim 100$ GeV for operators of the form $\mathscr{Q}^{(6)}_{b\tau,AB} \sim V_{qb}[\bar{b}\Gamma_A q] \otimes [\bar{\nu}\Gamma_B \tau]$ [59] . A number of explicit NP model possibilities has been suggested satisfying these requirements including general two Higgs doublet models, leptoquarks and 3rd generaton compositeness [59, 60]. At least in the case of $R^{(*)}_{\tau/\ell}$, the various possibilities can in principle be disentangled using the differential rate information once it becomes more precise [58, 61]. At the same time the required low effective NP scale opens the possibility for probing such NP directly at the LHC. Generic high-p_T predictions include anomalous (possibly resonant) production of $pp \to t + E_T^{\rm miss}, \tau + E_T^{\rm miss}$ or $t\bar{b}$.

5. Conclusions

The success of the SM in describing flavor-changing processes implies that large new sources of flavor symmetry breaking at the TeV scale are mostly excluded. At the same time, if present, they could still significantly affect NP searches at high p_T (c.f. [62]). However, there are sectors of the theory that are just starting to be tested. The current measurements of $B_{s,d} \to \mu^+\mu^-$ for example are probing the Yukawa interactions at the loop level with a precision no better than 30%. At the same time, the recent Higgs discovery offers a new direct probe of flavor dynamics (see [63]).

If confirmed at higher significance, the few open experimental flavour puzzles have several interesting implications: The LHCb angular fit of $B \to K^* \mu^+ \mu^-$ decays exhibits deviations from theoretical predictions within SM and signifies the importance of understanding the origin of the apparent Q_9 suppression (whether due to QCD or NP); If due to NP, the observation of a sizable Δa_{CP} points towards new flavor sources in the u_R sector, something that could be verified in other charm decay modes; At face value, the D0 measured A_{sl}^b is inconsistent with the measured CPV in $B_{s,d}$ mixing. This leads to interesting implications for (direct) semileptonic B (and D) asymmetries; Finally, if confirmed, the observed LFU violations in B decays point towards new charged current interactions of 3rd generation matter fields with potentially interesting top and tau physics implications at the LHC.

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