Flavour physics: quarks and leptons

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A brief overview of some topics in flavour physics is carried out, illustrating the probing power of flavour, and its role in shedding light on the NP model at work. Following a short discussion of flavour and CP violation in the lepton sector, the anomalous magnetic moments of charged leptons are revisited. Subsequently, several hadronic observables are discussed, with a particular focus on tensions related to B-meson decays. A few examples of ambitious NP models aiming at addressing the flavour problem(s) are also considered.

(The topics selected do not aim at providing a full comprehensive overview of quark and lepton flavour physics; they rather consist in a small subset, complying with time requirements, and reflect a personal viewpoint.)

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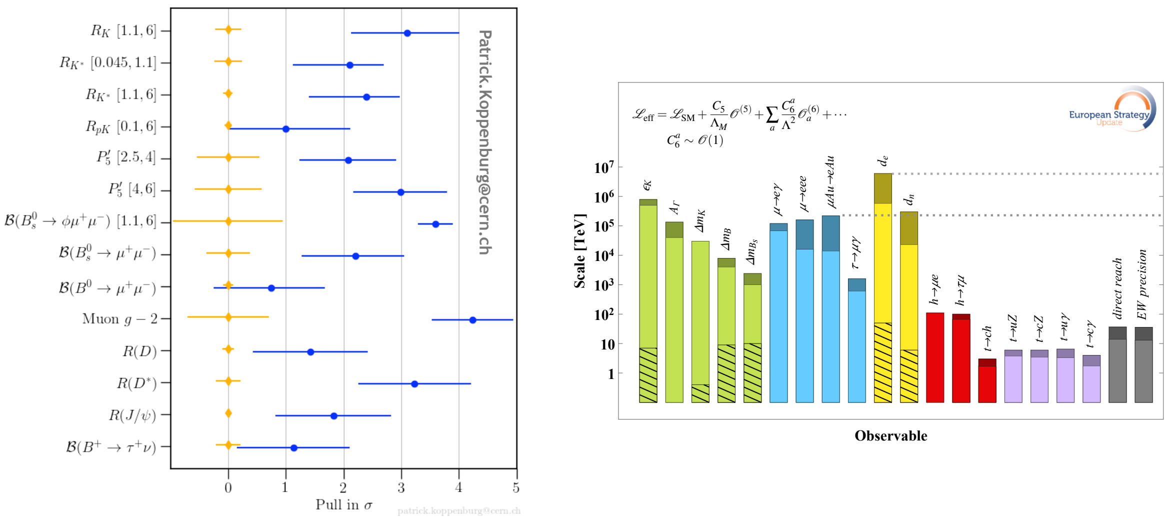

Figure 1: On the left, summary of several observables exhibiting a tension between the corresponding SM prediction and associated experimental data (from [1]). On the right, sensitivity to the NP scale of present and future flavour-dedicated facilities, inferred from generic EFT dimension-six operators (including meson, lepton, EDMs, Higgs and top flavoured couplings), compared with the reach of direct flavour-blind searches and EW precision measurements (grey). The effective coefficients are taken to be either $O(1)$ (plain columns) or suppressed by minimal flavour violation factors (hatched). Light (dark) colours correspond to present data (mid-term prospects); from [2].

1. The probing power of flavour observables

Flavour physics has played a key role in the very construction of the Standard Model (SM). Flavour violation in the quark sector is described by the so-called Cabibbo-Kobayashi-Maskawa (CKM) paradigm, which has so far provided a mostly successful description of flavour transitions, decays and CP violation. In addition to numerous theoretical caveats and three crucial observations that the SM cannot account for - the baryon asymmetry of the Universe (BAU), the lack of a viable dark matter (DM) candidate and neutrino oscillations - recent years have seen the emergence of several “flavoured” tensions between SM prediction and observation, mostly at the level of 2σ, or above. A synthetic (incomplete) summary [1] is offered in the left panel of Fig. 1.

Clearly New Physics (NP) is required - but which is then the SM extension (or entirely new framework) successfully accommodating all data? Although the LHC is yet to discover a new resonance, flavoured observables - arising from searches at the high-intensity frontier - offer numerous hints. While detailed comprehensive studies of well-motivated beyond the SM (BSM) constructions must be carried out, the so-called effective field theory (EFT) approach offers a model-independent tool allowing to identify and characterise generic classes of NP models in terms of the hints provided by data. In the EFT approach, an effective Lagrangian generalises the SM one, with the effects of unknown potentially heavy states encoded in new, high-order non renormalisable terms,

$$\mathcal{L}^{\rm eff} = \mathcal{L}^{\rm SM} + \sum_{n\geq 5} \frac{1}{\Lambda_{\rm NP}^{n-4}} C^n(g, Y, \ldots)\, O^n(\ell, q, H, \gamma, \ldots)\,, \qquad (1)$$

which are cast in terms of effective operators O^n and coefficients C^n, and of the NP scale, Λ_{NP}. Confronting the observables written in terms of the latter ingredients with data allows to infer bounds on the ratios $C^n/\Lambda_{\text{NP}}^{n-4}$; relying on simplicity (and naturality) arguments, one can set $C^n_{ij} = 1$, which thus allows inferring bounds on the scale of new physics to which the observables are sensitive to (in view of the experimental prospects). As visible from the right panel of Fig. 1, flavour observables as ε_K, charged lepton flavour violating (cLFV) muon decays and electric dipole moments (EDMs) can probe NP scales as high as 10^5 TeV (or above), well beyond the sensitivity of any collider [2].

In the following sections we will briefly overview some topics in flavour physics, illustrating the probing power of flavour, and its role in shedding light on the NP model at work.

2. Flavour and CP violation in the lepton sector

The (near) future experimental observation of any process violating lepton flavour (or total lepton number), or of a sizeable lepton EDM clearly constitutes a discovery of New Physics, revealing a departure from minimal BSM constructions in which the SM is extended via Dirac massive neutrinos.

In the lepton sector, the EFT approach has been extensively pursued: recent comprehensive analyses, focusing on complementary constraints on dimension 6 effective operators arising from current bounds (and future sensitivities) on $\mu \to e\gamma$ and $\mu \to 3e$ decays as well as $\mu - e$ conversion in nuclei, allowed to cast a clear picture on the most constraining observables, and also emphasised the relevance of taking into account all operators (indirect effects due to mixing and running) [3].

Specific cLFV signatures have been extensively investigated and highlighted as powerful means to disentangle (and further learn about) certain mechanisms of neutrino mass generation; as an example, recall that while in type I seesaw constructions one typically finds $\text{BR}(\mu \to e\gamma)/\text{BR}(\mu \to 3e) \sim 5 - 10$ (for masses of the propagators in the TeV-ballpark), for a type III seesaw one has $\text{BR}(\mu \to e\gamma)/\text{BR}(\mu \to 3e) \sim 10^{-3}$, a consequence of having the cLFV 3-body decay occurring at the tree-level (see, e.g. [4]). However, the presence of CP violating phases (Dirac and/or Majorana) in association to the new lepton mixings can strongly impact such predictive scenarios.

As shown in [5], in a minimal extension of the SM via two heavy Majorana sterile states (thus emulating a very minimal type I seesaw construction), CP violating phases can be at the source of a strong loss of correlation between (otherwise correlated) observables; this is shown on the left panel of Fig. 2, for the case of $\text{BR}(\mu \to e\gamma)$ versus $\text{CR}(\mu - e, \text{Al})$, under the hypothesis of heavy states with masses ≈ 1 TeV. The possible presence of such phases - which are a generic feature of mechanisms of neutrino mass generation - should be also taken into account upon interpretation of future data: regimes of large active-sterile mixings, which would be excluded due to conflict with cLFV bounds, could be rendered experimentally viable should CP violating phases be present.

Another illustrative example of the probing power of cLFV observables can be found in scotogenic models (in which the SM is extended via inert scalar doublets and right-handed neutrinos [6]). For instance, as shown in [7], cLFV rates, in particular $\text{BR}(\mu \to 3e)$ and $\text{BR}(\mu \to e\gamma)$, could shed light on the nature of the dark matter candidate (in this case, the inert scalar, as seen in the right panel of Fig. 2); a future measurement of the ratio of rates for the latter cLFV observables could further hint on the absolute neutrino mass scale.

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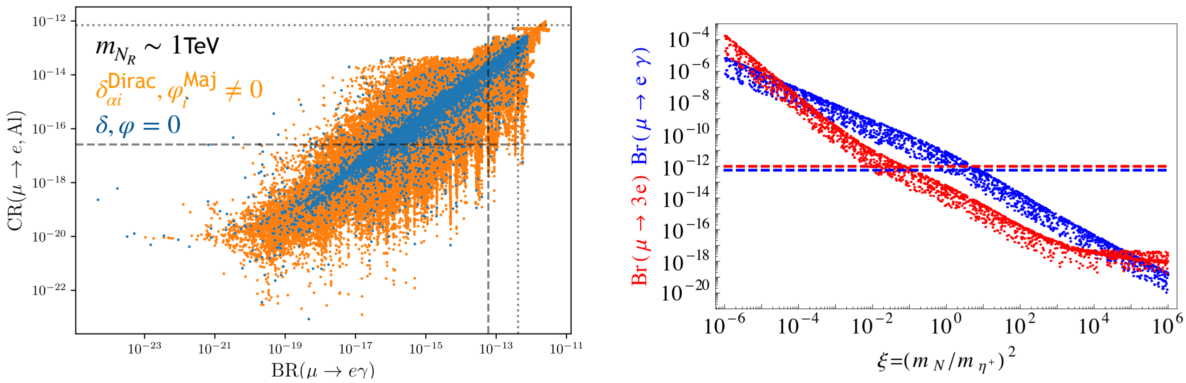

Figure 2: On the left, predictions for BR($\mu \to e\gamma$) and CR($\mu - e$, Al) in a "3+2 toy model", comparing the CP conserving case (blue points) with that in which Dirac and Majorana CP phases are non-vanishing (orange points); leading to the displayed results, all active-sterile mixing angles and phases were randomly varied. Dotted (dashed) lines denote current bounds (future sensitivity); from [5]. On the right, predictions for BR($\mu \to e\gamma$) and BR($\mu \to 3e$) in a scotogenic model as a function of $\xi = (m_N/m_{\eta^+})^2$ (ratio of right-handed neutrino and inert scalar masses), for a normal ordering of the light neutrino spectrum. The horizontal dashed lines show the current upper bounds; from [7].

3. Anomalous magnetic moments: muon and electron

As extensively discussed (see G. Colangelo contribution [8]), following the recent experimental and theoretical developments regarding the determination of the anomalous magnetic moment of the muon, no definitive picture can be drawn concerning a possible tension between prediction and observation; should Δa_μ remain around 4σ, NP must be called to provide a sizeable contribution, and this will have strong implications on the classes of models capable of saturating such a large discrepancy [9]. Many appealing SM extensions are capable of doing so (although LHC negative search results pushes the mass of the mediators to be increasingly heavier...); some viable examples include (minimal flavour-aligned) two-Higgs-doublet models [10], extensions via leptoquarks (see, e.g. [11]), or supersymmetric (SUSY) models, both minimal or "flavoured" realisations [12] (in the later case allowing to saturate Δa_μ for TeV-scale superpartners, and lower $\tan\beta$ regimes).

Following the determination of α from Caesium atoms, a new tension with the SM emerged concerning Δa_e, $\mathcal{O}(-2.3\sigma)$. Several attempts have been made to simultaneously explain both Δa_μ and $\Delta a_e^{\rm Cs}$: among (many) other examples, light Z' constructions (see, e.g. [13]), or scalar leptoquark extensions [14] have been explored. More recently, relying on α as extracted from Rubidium atoms, the SM prediction for a_e has become closer to the experimental value ($\Delta a_e \sim \mathcal{O}(+1.7\sigma)$) [15]. The situation regarding both the determination of α and the subsequent prediction for Δa_e must be clarified, hopefully leading to a more concrete picture of tensions concerning anomalous magnetic moments of charged leptons.

4. Hadron flavours: from the Cabibbo angle anomaly to B-meson decays

Before moving to the discussion of anomalous patterns in observables related to B-meson decays, we briefly comment on the so-called Cabibbo angle anomaly (CAA).

4.1 The Cabibbo angle anomaly

A recent tension in the determination of CKM matrix elements (V_{ud} and V_{us}, leading to the determination of the Cabbibo angle θ_C) has further suggested another potential manifestation of NP: a deficit in the unitarity of the CKM first row (around the 3σ level) has been identified, and appears to be a consequence of a tension between the value of V_{ud} (as extracted from super-allowed beta decays) and that of V_{us} as determined from kaon and tau decays. Interestingly, minimal SM extensions, relying only in the modification of $Z\nu\nu$ and $W\ell\nu$ couplings (flavour conserving but flavour non-universal) allow to reduce the discrepancies between direct and indirect determinations of V_{us}, leading to preferred scenarios [16].

4.2 Anomalies in B-meson decays

Rare B-meson decays have become the object of increasing attention in view of their role as probes of the SM paradigm of flavour; as seen in the synthesis displayed on the left panel of Fig. 1, numerous discrepancies between SM prediction and observation, typically at the level of 2σ (or above), have emerged in recent years, several suggesting the violation of lepton flavour universality (LFUV). The ratios $R_{K^{(*)}} = \text{BR}(B \to K^{(*)}\mu\mu)/\text{BR}(B \to K^{(*)}ee)$ and $R_{D^{(*)}} = \text{BR}(B \to D^{(*)}\tau\nu)/\text{BR}(B \to D^{(*)}\ell\nu)$ are examples of the latter. These B-meson decay "anomalies" could offer valuable - if not crucial - insight into the structure of the NP model which in addition to being at their source, could also possibly explain the other SM observational problems. Beginning from experimental data, the EFT approach allows identifying viable classes of NP models, thus paving the way to minimal BSM realisations, and possibly to complete constructions.

Several independent studies from distinct collaborations have identified key features allowing to explain the neutral current anomalies, $R_{K^{(*)}}$ (in agreement with available data): only vector/axial operators can satisfactorily succeed, with preferred (left-handed) NP couplings to muons. In particular, the hypothesis $C^V_{9\mu} = -C^V_{10\mu}$ together with non-vanishing flavour universal contributions C^U_9 (see, e.g. [17, 18]), lead to the best fits; this is visible on the left panel of Fig. 3. Resolving the charged current decay anomalies proves more challenging (especially in view of abundant related experimental constraints). Single operator fits (vector operators, C_{V_L}), or combinations of scalar and tensor operators (C_{S_L} and C_T) constitute viable options [19], see right panel of Fig. 3. Realising the above discussed requirements in concrete BSM constructions is not easy - especially since having a common NP scale for the charged and neutral current candidates suggests that the couplings of the latter should be significantly smaller (or then correspond to higher order contributions, in contrast to the charged current transitions which are naturally realised at the tree level). While many appealing solutions are already phenomenologically and/or experimentally ruled out, an $SU(2)$-singlet vector leptoquark (LQ), U_1, offers the only single-mediator solution to both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies [20] (noticing that such vector LQ constructions necessarily call upon some form of ultraviolet (UV) completion). Other successful possibilities call upon sets of NP mediators, in particular pairs of scalar LQs: R_2 and S_3 [21], or S_1 and S_3 [22].

In all cases, any BSM construction aiming at addressing $R_{K^{(*)}}$ and $R_{D^{(*)}}$ potentially opens the door to new contributions to numerous flavoured processes, be it at high intensities or even at colliders. It is important to notice that LFUV new interactions are expected to lead to (observable) effects in $K \to \pi\nu\nu$, $D \to \tau(\mu)\nu$, $K \to \mu\nu$, $B \to D\mu\nu$, $B \to K^{(*)}\nu\nu$, $B_{(c)} \to \tau\nu$, $B \to K\mu\tau(e)$,

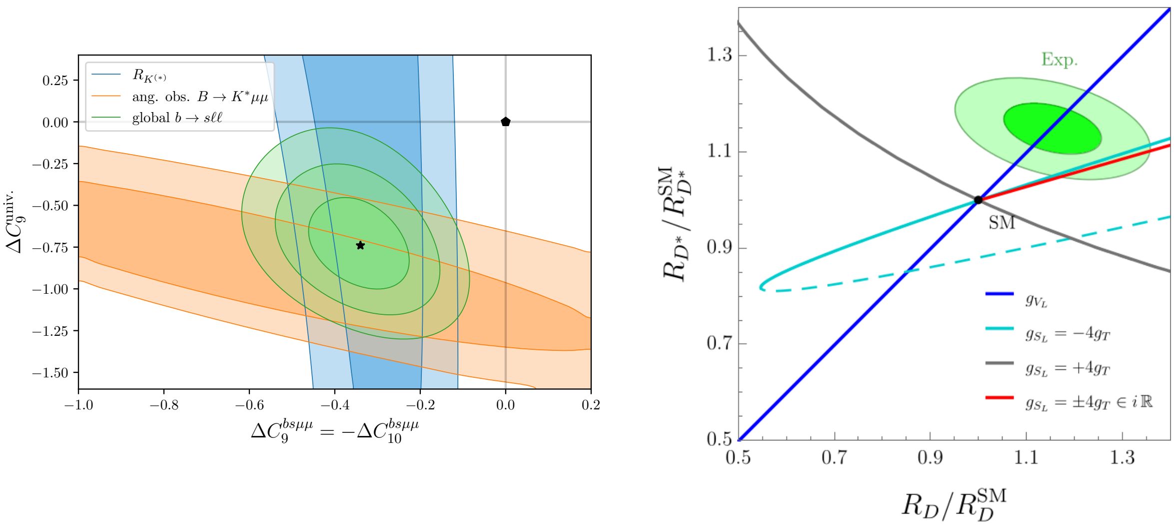

Figure 3: On the left, likelihood contours (1σ, 2σ (and 3σ for the global fit)) in the plane of weak-EFT and SM-EFT Wilson coefficients (fit of EFT coefficients (at 4.8 GeV) with the best fit point $\Delta C_9^{bs\mu\mu} = -0.34^{+0.08}_{-0.08}$ and $\Delta C_9^{\rm univ.} = -0.74^{+0.19}_{-0.17}$). Dashed contour lines denote the situation prior to the updated 2021 R_K data, a pentagon the SM prediction and a star the new best fit point (from [18]). On the right, predictions for $R_{D^{(*)}}/R^{\rm SM}_{D^{(*)}}$ in several EFT scenarios (see full discussion in [19]). Current 1σ and 2σ experimental constraints are depicted by the darker (lighter) green region (dashed lines correspond to couplings in tension with the BR($B_c \to \tau\nu$)< 0.3 constraint; from [19].

$K \to \mu e$, $\tau \to K(\pi)\ell$, $\tau \to \phi\mu$, $\tau \to 3\mu$, $\tau \to \mu\gamma$, $\mu \to e\gamma$, $\mu - e$ conversion in nuclei, among many others[1]... also possibly leading to (new) wide tails in the di-lepton invariant mass spectrum at high p_T (di-muon, di-tau and cLFV $\mu\tau$).

In what follows we illustrate two minimal BSM constructions, relying in vector and in scalar LQs. The first one consists in a SM extension via a single vector leptoquark and heavy vector-like leptons [23]; the mixings of the latter (required to be $SU(2)_L$ doublets to avoid conflict with data from $Z \to \ell\ell'$ decays) with the SM leptons lead to the desired pattern of non-universality in the $U_1 q\ell$ couplings, which would otherwise be flavour universal. The most stringent constraints arise from cLFV $\mu - e$ conversion in nuclei and $K_L \to e\mu$ decays, both processes occurring at tree-level. The viable regimes of the model (in agreement with all experimental constraints and accounting for both $R_{K^{(*)}}$ and $R_{D^{(*)}}$) lie within the future sensitivity of both Mu2e and COMET experiments (dedicated to searching for $\mu - e$ conversion in Aluminium). This is shown in the left panel of Fig. 4. A second illustrative example relies in a SM extension via two scalar leptoquarks, R_2 and S_3 [24]. Complex C_{S_L} couplings allow to accommodate the tensions in $R_{K^{(*)}}$ and $R_{D^{(*)}}$, with LQ masses around the TeV; as seen from the right panel of Fig. 4, the model is characterised by a significant enhancement of $B \to K^{(*)}\nu\nu$ decays (in comparison to the SM expectation), as well as

[1]It should be emphasised that the kaon sector will offer extensive opportunities to test and unveil NP constructions: in addition to the $K \to \pi\nu\nu$ modes, cLFV decays have been shown to be sensitive probes of many of the LFUV BSM constructions under scrutiny.

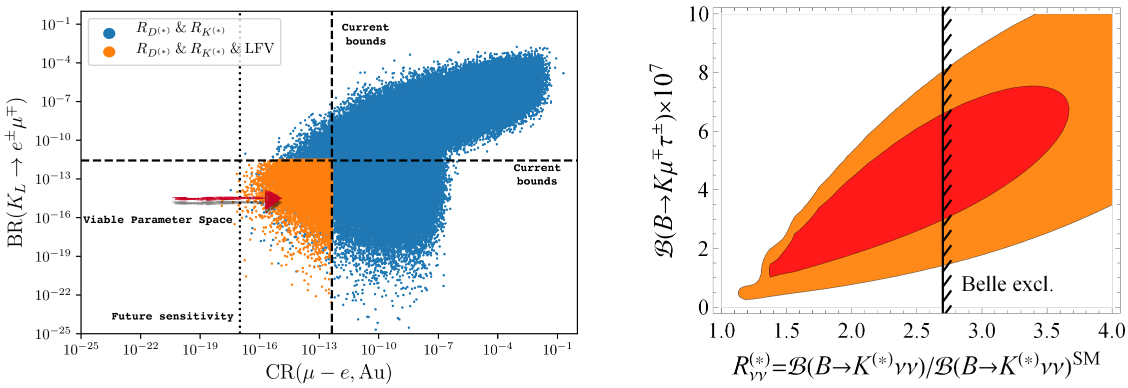

Figure 4: On the left, regions in the plane of a SM extension via a single vector LQ and heavy vector-like leptons, spanned by CR($\mu - e$, N) and BR($K \to \mu e$), accommodating both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ (blue) and regions further complying with cLFV constraints (yellow). Dashed (dotted) lines denote current bounds (future sensitivity); from [23]. On the right, BR($B \to K^{(*)}\nu\nu$)/BR($B \to K^{(*)}\nu\nu$)$^{\mathrm{SM}}$ versus BR($B \to K\mu\tau$) in a SM extension via two scalar leptoquarks, R_2 and S_3. The vertical black line denotes the associated current limit. From [24].

to lower bounds on cLFV $B \to K\mu\tau$ (and $\tau \to \mu\gamma$, not displayed). All these features render these constructions testable, and hence very appealing.

Before considering examples of more ambitious NP constructions, a few points must be highlighted in what concerns (model-independent) searches for such flavoured constructions at high-p_T. Notice that from an EFT point of view, and given the fact that at the LHC five quark flavours effectively play a role upon proton-proton collisions, the same 4-fermion operators at the origin of B-meson decays can mediate interesting phenomena, and can be henced probed by searches at high-p_T. As recently shown [25], LHC limits inferred from searches of $\mu\tau$ tails in the high-p_T regimes (especially in the high-luminosity runs) are expected to be very competitive, outperforming the high-intensity searches for quarkonia (charmonium and bottomonium) decays into $\mu\tau$. Likewise, di-tau tails ($pp \to \tau\tau$) have also been shown to lead to model-independent lower bounds on certain cLFV observables, as is the case of $B \to K\mu\tau$ [19].

5. New physics flavoured constructions

While numerous NP models successfully explain one or several SM problems and/or tensions with experiment, the ultimate goal is to identify constructions addressing *all* the SM caveats, and resolving its many tensions with observation[2]. Here, a very small set of examples is proposed, aiming at illustrating the different possibilities.

Scalar LQ constructions aiming at accounting for $R_{K^{(*)}}$ and $R_{D^{(*)}}$ do not in general allow to saturate the tensions in the anomalous magnetic moment of the muon [26]; however a coherent NP pattern appears to be emerging: a very minimal SM extension via two scalars (scalar LQ S_1, and a charged $SU(2)_L$ singlet ϕ^+) [27] allows to simultaneously explain Δa_μ and $R_{D^{(*)}}$ relying on S_1, the Cabibbo angle anomaly from contributions of ϕ^+, as well as $R_{K^{(*)}}$, from the interplay of the

[2]Notice that Δa_μ and the B-meson decay anomalies do not (in general) point towards compatible minimal NP models.

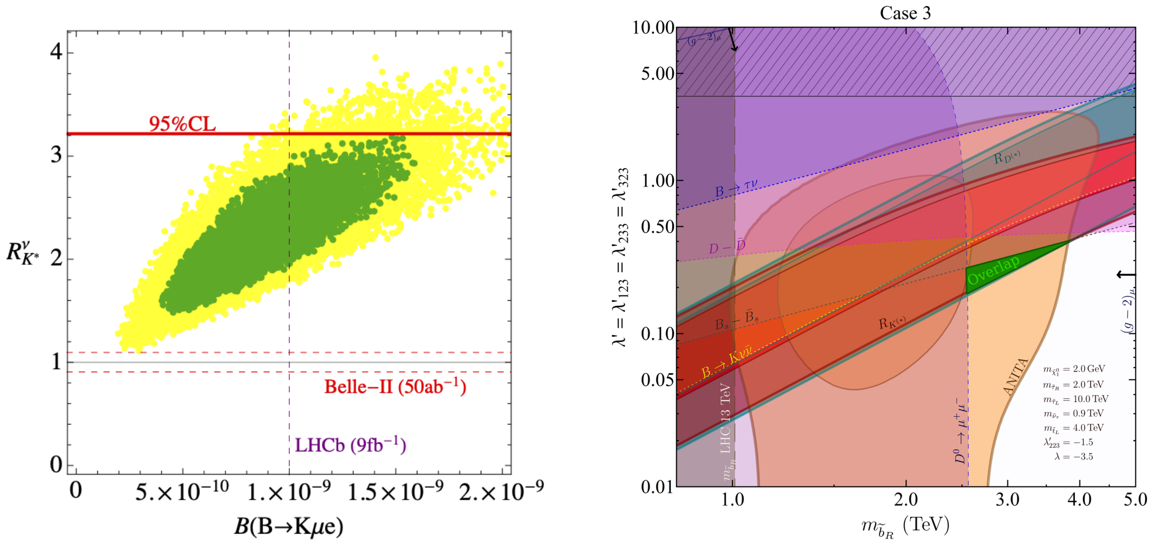

Figure 5: On the left, preferred values for BR($B \to K^{(*)}\nu\nu$) and BR($B \to K\mu e$) in a SM extension via two scalars (S_1 and ϕ^+, see [27]). Lines denote current (95% C.L.) limit and future prospects; from [27]. On the right, benchmark scenario for an R-parity violating SUSY case, displaying the viable regimes complying with all requirements in the plane spanned by the RpV coupling λ' and $m_{\tilde{b}_R}$ squark mass; from [28], to which we refer for complete details and discussion.

loop-level contributions of both scalars. As already encountered, this minimal construction leads to enhanced rates for $B \to K^{(*)}\nu\nu$ and $B \to K\mu e$ decays, as visible in the left panel of Fig. 5.

As recently shown, R-parity violating SUSY constructions (in particular realisations in which the third sfermion family is the lightest) [28] allow, in addition to addressing $R_{K^{(*)}}$ and $R_{D^{(*)}}$, accounting for neutrino mass generation (at the loop-level) and even to explain the ANITA balloon detector anomalous events. Once all constraints are taken into account, as manifest from the right panel of Fig. 5, the (small) viable region of the parameter space renders the model comparatively testable.

Finally, UV-complete models based on variants of the original Pati-Salam $SU(4) \times SU(2)_L \times SU(2)_R$ have been extensively explored to address the different anomalies and tensions; flavour non-universal Pati-Salam constructions, as is the case of the so-called “4321” flavoured models, are amongst the most successful attempts at UV completion, offering excellent prospects for model building and quark-lepton unification (see, e.g. [29]).

Finally, it must be mentioned that symmetries play a key role in addressing the flavour puzzle: discrete or continuous, gauge or flavoured, symmetries allow to reduce the arbitrariness of the flavour sources (couplings, etc.), also allowing to relate the quark and lepton sectors, further offering a “rationale” framework to parametrise Nature’s choices in flavour. The action of symmetries dramatically increases the predictive power of a given construction, rendering it in turn more testable.

6. Outlook and prospects

Other than paving the way to the very construction of the SM, recent years have seen flavour emerging as a powerful tool, pointing the way to going beyond the SM and offering valuable hints in the identification of the NP model at work. From the discovery of neutrino oscillations, high-intensity flavour probes have been steadily suggesting numerous tensions with the SM, from the anomalous magnetic moments of the muon (and electron) to several B-meson related observables.

While more data is being anxiously awaited for (on a_μ^{exp}, on B-meson as well as on beauty- and charmed-baryon decays from LHC and Belle II, from kaon experiments, cLFV dedicated searches...), a huge effort is also being currently carried on the theory front. Identifying "tensions" with SM predictions calls upon precise experimental data, as well as accurate theory predictions. Reducing theory uncertainties requires progress in many fields, from higher-order contributions, lattice QCD, computation of hadronic/nuclear matrix elements...

In addition to carefully following numerous observables where effects of NP might indirectly show up, a common goal is to identify further clean and/or optimised quantities, be them related to the baryon, meson or lepton sectors. Likewise, comprehensive, UV-complete models (possibly symmetry strengthened) must be explored, in a systematic approach to hopefully putting together - piece by piece - the flavour puzzle.

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