The Flavourful Road to New Physics

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Abstract. Flavour physics plays a prominent role in our quest to understand and constrain possible phenomena beyond the standard model. It directly relates to two of the outstanding issues of contemporary particle physics: the so-called standard model and new physics flavour puzzles. At the same time it indirectly probes new physics scales up to 10^5 TeV through virtual effects. On the other hand, nonstandard flavour phenomena, if observed, could help shed light and constrain the nature of the electroweak symmetry breaking and the Higgs sector of the theory. In particular, such effects could help reduce fine-tuning in models addressing the electroweak hierarchy in light of null LHC new physics search results. Finally, exotic flavour-violating processes, such as those involving missing energy signtures may turn out to be the portals to possible hidden BSM sectors.

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

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)\,, \tag{1}$$

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}

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

namely the electroweak (EW) hiearchy problem, i.e. why $|\mu^2| \ll \Lambda^2$ where Λ is the EFT cut-off scale; the SM flavour 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.

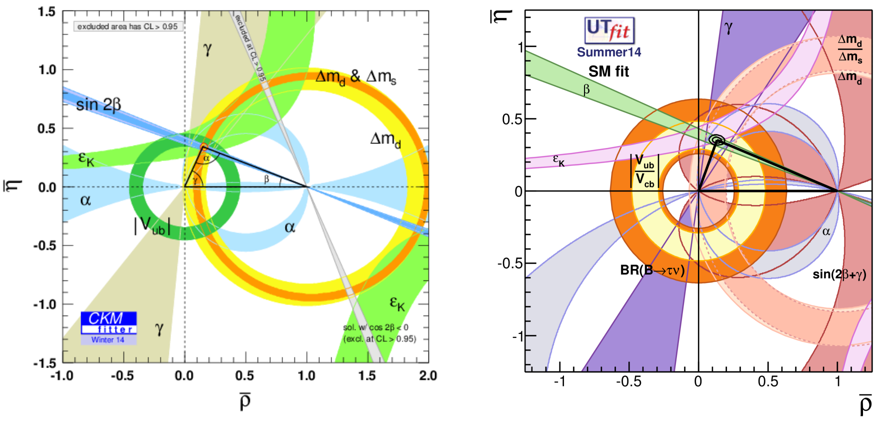

Figure 1. Result of the SM CKM fit projected onto the $\bar{\rho}-\bar{\eta}$ plane, as obtained by the UTFit (left) [1] and CKMfitter (right) [2] collaborations. Shown shaded are the 95% C.L. regions selected by the given observables.

2. Twofold role of flavour physics

In the SM quark sector (in absence of any additional terms in Eq. (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 $m_u \equiv v V_L^u Y_u V_R^{u\dagger}$ and $m_d \equiv v V_L^d Y_d V_R^{d\dagger}$, 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 $V \equiv V_L^u V_L^{d\dagger}$). 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 flavour phenomena in quark sector. This defines a twofold scope of flavour physics related to particle phenomena beyond SM: (1) It provides probes of new physics (NP) effects going well beyond the direct reach of high energy collider experiments; (2) It allows to test the sources of SM flavour symmetries and their violation.

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 CKMFitter [2] collaborations in Fig. 1.

In order to interpret results of experimental measurements involving hadronic initial and final states, the theoretical predictions need to involve non-perturbative matching to an effective description in terms of QCD bound states. 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 [3]).

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 $\mathcal{L}_{\rm BSM}$. 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

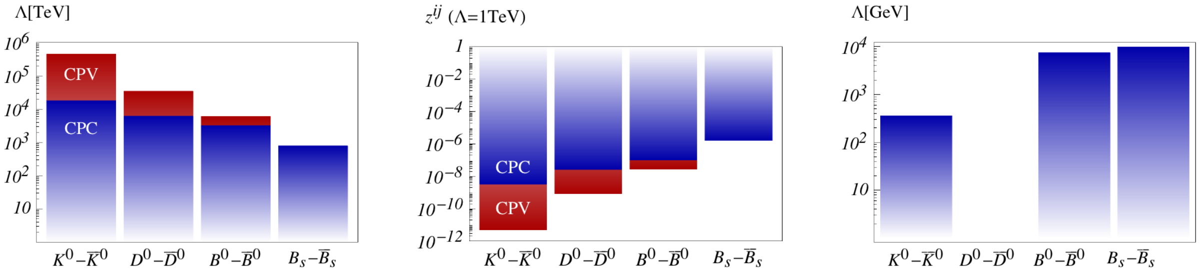

Figure 2. Current constraints of neutral meson oscillation measurements on new $\Delta F = 2$ dimension six operator contributions, given in terms of the effective operator scale (for generic flavour structures on the left and in the MFV limit on the right) or Wilson coefficients' size (in the centre). Bounds on the CP conserving and CP violating contributions are shown in blue and red, respectively (see text for details).

operators involving only SM fields [4] via the matching procedure

$$\mathcal{L}_{\text{BSM}} \to \mathcal{L}_{\nu\text{SM}} + \sum_{d>4} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}} \,, \tag{3}$$

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 $\mathcal{Q}_i$ present in $\mathcal{L}^{\text{eff}}_{\text{weak}}$ 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 agreement of SM predictions with current experimental measurements, such procedure typically results in severe bounds on the underlying NP flavour breaking sources in $\mathcal{L}_{\text{BSM}}$.

Let us consider the canonical example of NP in $\Delta F = 2$ processes associated with oscillations of neutral mesons (for recent extended discussion see [5]). The leading ($d = 6$) NP operators are of the form $\mathcal{Q}^{(6)}_{AB} \sim z^{ij}[\bar{q}_i\Gamma^A q_j] \otimes [\bar{q}_i\Gamma^B q_j]$, where q_i denote the SM quark fields, while $\Gamma^{A,B}$ denote the Clifford algebra generators. Assuming z^{ij} to be generic $\mathcal{O}(1)$ complex numbers, $z \sim \exp(i\phi_{\text{NP}})$, the reach of current constraints in terms the probed NP scales Λ are shown in Fig. 2 (left). It is important to stress that most of these constraints are currently limited by theory (i.e. lattice QCD inputs [6]) and parametric uncertainties. Consequently, significant future improvements will require a corroborative effort of mostly lattice QCD methods on the theory side, as well as improved experimental determinations of SM CKM parameters by flavour experiments, most notably LHCb and Belle II. Among the few $\Delta F = 2$ observables which remain largely free from theoretical uncertainties are those related to CP violation in D^0 and B_s oscillations. These are expected to remain effective experimental null-tests of the SM in the foreseeable future.

The current severe flavour bounds could be interpreted as a requirement on beyond SM (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 (c.f. Fig. 2 (center)) can only be reconciled with current experimental results, provided it exhibits sufficient flavour symmetry or structure, such that $|z^{ij}| \ll 1$ (the extreme case being minimal flavour violation (MFV) [7], where one requires $Y_{u,d}$ to be the only sources of flavour breaking even BSM) . However, even in this most minimalistic scenario, the suggestive pattern of masses and mixing observed in both the quark and lepton (neutrino) sectors remains largely unexplained. It thus remains as one of the ultimate goals of flavour physics to determine whether the observed hierarchies and structures of flavour parameters are purely accidental, or rather determined dynamically or from symmetry considerations. A particularly interesting hint is provided by the fact that within the SM, flavour is only broken by Higgs interactions. On the other hand, beyond SM sources of flavour breaking in general may or may not be related to EW scale generation. At least in the minimal realisations of models addressing the electroweak hierarchy problem, a part of this intrinsic connection remains. In the minimal supersymmetric SM for example, new flavour sources appear due to supresymmetry breaking in the form of both squark and slepton soft masses as well as trilinear couplings. One of the peculiar features of this setup is that starting with a positive quadratic term in the Higgs potential at a very high scale, electroweak symmetry breaking is triggered radiatively by renormalization group running of the potential parameters. Incidentally, this running is dominated by the large top (and stop) Yukawa couplings [8]. Conversely, in models of a composite pseudo-Goldstone Higgs boson the SM flavour symmetry is broken via the mechanism of partial compositeness – kinetic mixing of SM chiral fermions with their massive vector-like partners [9]. However also in this case electroweak symmetry and SM flavour symmetries are connected since the breaking of the Goldstone shift symmetry generating a nontrivial potential for the SM Higgs doublet receives the dominant contribution from the top quark Yukawa [10].

In contrast to the quark sector, flavour mixing in the lepton sector, as exhibited by the entries of the PMNS matrix, is large. However, lepton flavour violating observables are generically tied to the breaking of chiral symmetry (for Dirac neutrinos) or lepton number breaking (for Majorana neutrinos) and thus suppressed by the smallness of observed neutrino masses. A case of observable lepton flavour violation can nonetheless be easily made. Assuming that, as suggested by the smallness of neutrino masses, lepton number is broken by Majorana terms at a very high scale, one can still decouple this mechanism from the breaking of the leptonic flavour symmetry, which can be broken at a much lower scale. The resulting neutrino spectrum is of pseudo-Dirac type and sizable rates for lepton flavour violating processes can result [11]. Interesting lepton flavour violating phenomenology is of course also expected in models where the breaking of the SM lepton flavour symmetries is not directly linked to neutrino masses, such as in supersymmetric and partial compositeness models discussed above.

3. Reclaiming flavourful NP at EW scale

In the SM, the global flavour symmetry in the quark sector $\mathcal{G}_F^q \equiv SU(3)_Q \times SU(3)_U \times SU(3)_D$ is broken by the two quark Yukawas, formally transforming under $\mathcal{G}_F^q$ as $Y_u \sim (3,\bar{3},1)$ and $Y_d \sim (3,1,\bar{3})$. Since $Y_{u,d}$ alone preserve $SU(3)_{D,U}$, respectively, it is always possible to align any NP breaking of $SU(3)_{U,D}$ completely with the SM directions, leaving no observable effects. On the other hand, one can identify two unique sources of $SU(3)_Q$ breaking already in the SM given by $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\mathrm{tr}}}$ and $\mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\mathrm{tr}}}$, where $\not{\mathrm{tr}}$ denotes the traceless part. Since $[\mathcal{A}_u, \mathcal{A}_d] \neq 0$, it is not possible to hide sizable new $SU(3)_Q$ breaking contributions by aligning them in flavour space with either $\mathcal{A}_u$ or $\mathcal{A}_d$.

What is more, even starting with a UV theory of NP coupling to SM matter fields in a flavour trivial way, the RG running between the high scale and the EW scale will necessarily induce some NP breaking of $\mathcal{G}_F^q$. The relevant contributions will be proportional to $\int d^4x\, T\{\mathcal{Q}_{\mathrm{NP}}\, \mathcal{H}_{\mathrm{SM}}\}$, where $\mathcal{Q}_{\mathrm{NP}}$ are the relevant NP operators and $T\{\}$ denotes the time-ordering operator. Fortunately, for flavour trivial $\mathcal{Q}_{\mathrm{NP}}$ the resulting low energy theory will be minimally flavour violating [7], easily satisfying most stringent flavour constraints even for NP degrees of freedom at the TeV scale [5, 12]. Considering again the explicit example of $\Delta F = 2$ transitions, in this limit only the $SU(3)_Q$ breaking contributions remain relevant generating $\mathcal{Q}_{LL}^{(6)} \sim [z_Q^{ij}(\bar{Q}_L^i \gamma_\mu Q_L^j)]^2$, where $\mathbf{z}_Q = \mathbf{1} + a_1 \mathcal{A}_{\mathbf{u}} + a_2 \mathcal{A}_{\mathbf{d}} + \ldots$, and $a_{i>2} \lesssim a_{1,2} \lesssim 1$. For $a_1 = 1$ and $a_{i\neq 1} = 0$ the resulting experimental constraints on the effective NP scale Λ are shown in Fig. 2 (right). Note that in this case, since $\mathrm{tr}[z_Q \cdot J] = 0$, where $J = [\mathcal{A}_u, \mathcal{A}_d]$ and $\det[J]$ is proportional to the SM Jarlskog invariant, no new CP violating effects are generated (c.f. Refs. [13, 14, 15] for a more detailed

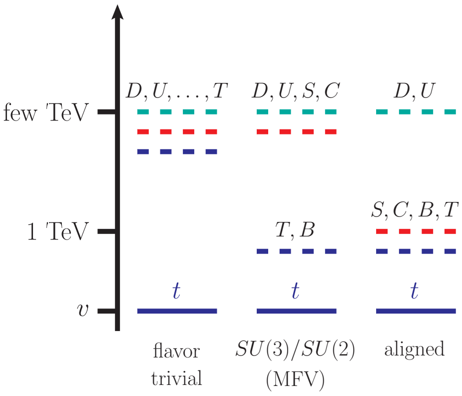

Figure 3. Schematic illustration of the current LHC direct search constraints on the masses of (SUSY) quark partners assuming different flavour structures: flavour triviality (left), respecting the approximate SM $SU(3)/SU(2)$ flavour breaking pattern (including MFV) (center), and in flavour alignment models (right). See text for details.

discussion).

The absence so far of observable NP flavour effects when combined with stringent constraints on direct production of new (especially colored) degrees of freedom at the LHC leads to important ramifications for the EW hierarchy problem. In the SM, the top Yukawa ($Y_t \equiv m_t/v$) imposes the largest fine-tuning in the Higgs potential, schematically parametrized as a UV sensitive shift in the μ^2 term in Eq. (2) ($\delta\mu^2 \sim Y_t^2\Lambda^2/16\pi^2$). Candidate NP theories hoping to address the SM naturalness problem introduce bosonic (in supersymmetric (SUSY) theories) or fermionic (in composite pseudo-Goldstone Higgs models) top quark partners (T), whose contributions are related by symmetry to cancel exactly the Y_t induced quadratic sensitivity of the EW scale to Λ. It is instead replaced by a logarithmic one

$$\delta\mu^2 \sim \frac{Y_t^2}{16\pi^2}\Lambda^2 \to \frac{Y_t^2}{16\pi^2} m_T^2 \log\frac{\Lambda}{m_T}\,. \tag{4}$$

Natural EW NP (keeping $\delta\mu^2 \lesssim \mu^2$) with a high ultra-violet (UV) cut-off $\Lambda \gg v$ should thus contain relatively light top partners ($m_T \lesssim 1$ TeV). Such light new degrees of freedom seem to be at odds with the high NP scales implied by indirect flavour constraints unless the associated flavour structures are highly non-generic. While flavour triviality is able to resolve this tension, it necessarily also predicts degeneracy in the NP spectra (see Fig. 3, left). In the case of natural NP specifically, this implies the presence of $u-$ and $d-$quark partners (U, D) with $m_{U,D} \sim m_T$. In the recent years, the ATLAS and CMS experiments at the LHC have already mostly excluded the possibility of $m_{U,D} \lesssim 1$ TeV [16], thus putting the idea of flavour trivial natural NP under severe pressure.

Fortunately flavour triviality is actually not necessary for meeting the most stringent flavour requirements. This is because the dominant flavour symmetry breaking in the SM is driven by the large Y_t and is thus characterized by a $SU(3)/SU(2)$ symmetry breaking pattern [13]. It turns out that any NP respecting such a pattern can avoid the most stringent (CP violating) FCNC constraints in the K and D meson sectors, while simultaneously allowing for observable effects in B meson and top quark physics [13, 17]. Finally, a reduced approximate $SU(2)$ flavour symmetry is compatible with split spectra where third generation partners can be much lighter than their first two generation counterparts, thus improving the naturalness of such models in light of negative LHC NP search results (see also Fig. 3, center).

An illustrative example of such models is the s.c. natural SUSY setup (c.f. [18]), where BSM flavour effects are mediated by 3rd generation squarks (and also sleptons). Together with the gaugino and higgsino sectors, these are also the only SUSY partners directly accessible at LHC energies. The key flavour observables constraining such scenarios have been identified to include meson mixing observables (ϵ_K, Δm_q, ϕ_q), rare (semi)leptonic B decays ($B \to (X)\ell^+\ell^-, \nu\bar{\nu}$), LFV as well as nuclear and leptonic EDMs [19]. In particular, the recently observed $B_s \to \mu^+\mu^-$ together with the first hints for $B_d \to \mu^+\mu^-$ [20] already represent a powerful probe of the MFV paradigm [12]. At the same time $B \to (X)\ell^+\ell^-$ sensitivity to SUSY Z-penguins is becoming competitive with direct LEP constraints on $Z \to b\bar{b}$ [21]. Finally, the best sensitivity to the slepton sector is possibly exhibited by leptonic dipole transitions. In particular, the recently improved experimental bound on the EDM of the electron [22] imposes non-trivial constraints on the Higgsino and sneutrino mass parameters in such models [19].

Another possibility is to align the directions (in flavour space) of SM and NP flavour breaking contributions [23]. This mechanism has several interesting features. In contrast to strict MFV-like structures [24], flavour alignment can easily be implemented within fundamental theories of flavour generation via (spontaneously broken) abelian horizontal symmetries [25], while offering comparable protection from dangerous right handed charged and neutral flavour changing currents (associated with the breaking of $SU(3)_{U,D}$). However as discussed in the beginning of this section, alignment is not possible in the case of $SU(3)_Q$ breaking and the most severe flavour constraints are then expected from measurements of CP violating FCNCs in the K and D sectors [14]. In the SM, light quark FCNCs are approximately CP conserving due to the smallness of both the masses of first two generation quarks as well as their mixings (CKM matrix elements) with the heavier third generation. It turns out that any new $SU(3)_Q$ breaking, which is sufficiently aligned with either $\mathcal{A}_u$ or $\mathcal{A}_d$ directions in the flavour (sub)space of the first two generations, inherits this CP protection, significantly relaxing the relevant flavour constraints [15]. Finally, since flavour alignment does not require non-abelian flavour symmetries, it allows for the possibility of split first two generation flavoured NP spectra.

In turn, NP close to the EW scale with significant (but sufficiently aligned) flavour breaking has several interesting implications for collider phenomenology. For example, in SUSY theories with not too heavy Majorana gluinos ($\tilde{g}$ with $m_{\tilde{g}} \lesssim$few TeV) the valence ($u-$ and $d-$) squark ($\tilde{u}$ and $\tilde{d}$) cross-sections at the LHC are significantly enhanced compared to non-valence contributions due to $t-$channel $\tilde{g}$ mediated $qq' \to \tilde{q}\tilde{q}'$ partonic processes (where $q^{(\prime)} = u, d$) [26, 27, 28]. Consequently, current severe LHC constraints on degenerate light generation squarks [16] are completely dominated by these first generation squark contributions. Conversely, in light of existing searches $s-$ and $c-$squarks ($\tilde{s}$ and $\tilde{c}$) could still be as light as $m_{\tilde{s},\tilde{c}} \gtrsim 500$ GeV (see also Fig. 3, right) [28]. The second intriguing possibility is that of large top and charm partner mixing. Such a scenario has been worked out in the context of the MSSM [29] pointing out that large flavour breaking can significantly affect the sensitivity of existing experimental searches and also results in some reduction of the EW scale fine-tuning. (see also [30] for a similar study in the context of composite Higgs models).

4. Flavour portals to the dark sector

Despite the overwhelming success of the SM in describing the observed physical phenomena below the EW scale, the notion that the SM particles are the only dynamical degrees of freedom within the electroweak energy range is far from established. Not only is the existence of new light particles not excluded, since they would evade direct detection when sufficiently weakly interacting, but their presence could even be welcome. Indeed, many NP models are built upon some spontaneously broken symmetries, and do often have remnants at low-energy in the form of massless or very light Goldstone bosons. More crucially, there are now very strong indications that the universe is filled with dark matter, so there should be at least one new electrically neutral colorless particle, possibly lighter than the electroweak scale. Once opening that door, it is not such a drastic step to imagine a whole dark sector, i.e. a full-fledged set of darkly interacting dark particles only loosely connected to our own visible sector. Further, it should be stressed that adjoining a dark sector to the SM is always possible, does not need to be directly related to dark matter (so one would rather speak of a hidden sector), and is actually quite generic in supersymmetric models (c.f. for a recent review [31]).

Assuming that there are new particles, neutral under the SM gauge group, one can write down the gauge invariant operators coupling such particles to SM fields and thus construct the lowest-dimensional effective interactions parametrizing low-scale departures from the SM particle content [32]. In order to probe such BSM physics experimentally, one usually needs to resort to some further simplifying assumptions. In particular, the new particles may not be stable on cosmological scales and thus avoid dark matter, cosmic microwave background, cosmic ray and big bang nucleosynthesis constraints. On the other hand, if they are sufficiently long-lived, they may escape from particle experiments as missing energy. Being sufficiently weakly coupled to SM fields, they would also not significantly affect SM processes. Baring these restrictions in mind, the main impact then is to open new decay and production channels. Among the suitable decay probes, FCNC and other non-standard processes with missing energy, such as LFV decays of charged leptons and rare decays of quarkonia, kaons and B mesons are especially powerful due to their extreme suppression in the SM. In this way, non-trivial constraints on particular dark sector realizations in terms of hidden photons (A') mixing kinetically with the hypercharge, $\mathcal{L} \ni \epsilon B^{\mu\nu} A'_{\mu\nu}$, have been recently obtained by BaBar [33]. In the future, existing and updated constraints and measurements of rare kaon and B meson decay modes with missing energy, such as $K \to \pi E_{\text{miss}}$ and $B \to K^{(*)} E_{\text{miss}}$ might constitute unique windows into NP scenarios with light neutral long-lived particles [32]. Among the analogue flavour changing processes at high p_T, monotop production [34] currently seems to be most promising.

5. Conclusions

Success of SM in describing flavour-changing processes implies that large new sources of flavour symmetry breaking at TeV scale are mostly excluded. However, NP at TeV scale need not be flavour trivial. If (properly aligned) new sources of flavour breaking are present, precision flavour observables may still hide NP signals at the few 10% level in well motivated NP models (e.g. natural SUSY). At the same time, 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%. New flavour dynamics can also significantly affect and guide NP searches at high p_T and have implications for EW fine-tuning. Finally, it is well worth investing in searches of exotic flavour-violating effects, such as missing energy modes, as they may turn out to be the portals to possible hidden BSM sectors.

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