– SnowMass 2021: Letter of Interest –

Novel EFT connections between K and B physics and their tests

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Short Summary – This proposal underlines the importance of certain decays of K mesons as an avenue towards the discovery of new flavor dynamics, in particular effects *correlated* with the recent hints of lepton universality violation from B physics. Such correlated signals are established through arguments as general as possible, relying on the Standard Model Effective Field Theory (SMEFT) plus controlled flavor-sector assumptions. This proposal also emphasizes that many of the relevant K decays involve the K-short, a particle copiously produced at B-physics machines such as LHCb and Belle-II, and short lived enough that its decays can be accurately reconstructed in these experiments. K physics at LHCb and Belle-II turns out to offer very complementary avenues with respect to K machines at NA62 and KOTO.

Lepton Flavor Universality Violation – Recently observed discrepancies between measured and predicted quantities in B-meson decays brought considerable new interest in flavor physics. Several experiments found the ratios $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ in excess of the Standard Model (SM) predictions [1, 2, 3, 4, 5, 6, 7]. Besides, LHCb [8, 9, 10] found the ratios $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}\mu\mu)$ to be $\approx 2.6\sigma$ smaller than $R^{\rm SM}_{K^{(*)}} = 1.00(1)$ [11]. Being theoretically clean observables, the confirmation of these hints with more data at LHCb and Belle-II would be a clear indication of new physics (NP) around the TeV scale [12].

Current experiments at LHCb and Belle-II are working to improve these measurements, as well as to measure new quantities which could shed light into this puzzle. For instance, Belle-II aims at measuring the decays $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$ [13], which are necessarily modified by the viable NP explaining the B-meson discrepancies. Furthermore, LHCb and Belle-II are searching for forbidden modes in the SM, such as $\mathcal{B}(B_s \to \ell_i\ell_j)$ and $\mathcal{B}(B \to K^{(*)}\ell_i\ell_j)$, with $i \neq j$, which can also be significantly enhanced by the putative NP responsible for the above mentioned discrepancies [14].

Probing New Physics with K factories – In the coming years Kaon machines are expected to reach an unprecedented level of sensitivity to numerous observables that are highly correlated with those displaying the mentioned discrepancies. In particular, NA62 will measure for the first time the short-distance dominated decay $K^+ \to \pi^+\nu\bar{\nu}$ with $\mathcal{O}(10\%)$ accuracy [15]. NA62 and KOTO are also actively searching for the decays $K^+ \to \pi^+\mu e$ and $K_L \to \mu e$, respectively. An LHCb feasibility study [16] based on typical LHCb-upgrade assumptions [17] suggests that LHCb may well improve the limits on the latter decays thanks to the huge number of Kaons produced at LHC. All these observables provide precious constraints to scenarios explaining the B-meson discrepancies [16, 18, 19, 20], as exemplified below. Even aside these discrepancies, Kaon decays are probes of new effects at the highest scales attainable and thereby offer excruciating precision tests of the SM structure. An example of renewed recent interest is the test of first-row CKM-matrix unitarity, which currently shows a $\approx 3\sigma$ deviation from the SM expectations [21]. A crucial ingredient of this test is V_{us}, accurately measured through 2-body leptonic and 3-body semi-leptonic Kaon decays.

K decays as a probe of B anomalies and beyond – NP contributions to low-energy observables can be generically described by means of an effective Lagrangian,

$$\mathcal{L}_{\text{eff}} \supset \frac{C_{ijkl}^{(a)}}{\Lambda^2}\,\mathcal{O}_{ijkl}^{a}\,, \tag{1}$$

where C_{ijkl} denote the Wilson coefficients of the dimension-6 operators $\mathcal{O}_{ijkl}^{(a)} \sim \bar{Q}_i Q_j \bar{L}_k L_l$, with a labeling the operator, and i, j, k, l the flavor indices. Q and L denote schematically quark and lepton fields respectively, which may be electroweak doublets or singlets. Also, in the above expression we have omitted the Dirac structures between each fermion bilinear. Finally, $\Lambda \gg v_{\text{EW}}$ stands for the new-physics scale. The coupling C_{ijkl} encodes the flavor structure of NP, which can be typically of two kinds

(i) $C_{ijkl} \sim \lambda_{ij}^{(q)}\,\lambda_{kl}^{(\ell)}$ for new colorless bosons.

(ii) $C_{ijkl} \sim \lambda_{il}^{(q\ell)}\,\big(\lambda_{jk}^{(q\ell)}\big)^*$ if leptoquarks are exchanged at tree-level.

Connections between K- and B-meson observables can then arise in several ways. First, for the operators involving quark doublets, as suggested by the B-decay discrepancies [22], the same operator can contribute to different transitions via the misalignment between down- and up-type quarks, as described by the CKM matrix. More importantly, realistic flavor models predict specific patterns for C_{ijkl}. An example is the Minimal Flavor Violation (MFV) ansatz, which assumes that the only source of flavor violation are the SM Yukawa couplings [23]. A less restrictive possibility is to consider the global symmetry

$$U(2)^5 = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e\,,$$

which distinguishes the first two generations from the third one [24]. In particular, the latter approach has been proposed to explain the observed pattern of SM fermion masses and mixings. In both cases, correlations between Kaon and B-meson observables are predicted, which turn to be within reach of current Kaon facilities [20, 25]. More specifically, the so-called 'general MFV' ansatz [26], augmented with alternative scenarios in the – much less theoretically constrained – lepton sector, leads to striking correlations between $K \to \pi\nu\bar{\nu}$ and $B \to h_s\nu\bar{\nu}$ ($h_s = K, K^*, X_s$) that differ from the SM expectations and that could be probed at NA62 and Belle-II, respectively [20]. Besides, the scenario based on the $U(2)^5$ symmetry is well compatible with NP dominantly coupled to the 3rd generation of left-handed fermions, in turn suggested B-physics anomalies [14, 27]. In this case, $K \to \pi\nu\bar{\nu}$ decays are the only Kaon decays with third-generation leptons (the τ neutrinos) and thereby offer a unique Kaon-sector test of this hypothesis [25].

In short, Kaon decays – including all the LFV modes of the kind $K \to (\pi)\mu e$, that are null tests of the SM, as well as the short-distance dominanted $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ – offer a win-win set of observables in the search of beyond-SM effects. Theoretically, they offer valuable insights into scenarios aiming to explain the current B discrepancies. Independently of these discrepancies, they rank among the strongest SM tests one can obtain at colliders. Experimentally, such program can be pursued both at dedicated Kaon machines and at B-physics machines acting as Kaon ones.

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