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Benchmarks in Quark Flavor Physics

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Flavor – why do we (still) care?

For decades quark flavor physics has attracted a lot of attention starting with kaon decays in the late 60s and 70s. Many important predictions could be obtained, like the presence of the charm quark in 1970 in order to explain the data on $K_L \to \mu^+\mu^-$ or the observation that CP violation in neutral kaon mixing requires a third quark generation. Only subsequently have these predictions been confirmed by direct production of the new heavy particles.

With the discovery of the three quark generations and measurements of their masses, flavor in the Standard Model (SM) has evolved to a much more complete picture, with flavor violation being governed exclusively by the 3×3 CKM matrix. The smallness of its mixing angles together with the absence of flavor changing neutral currents (FCNCs) at the tree level and their suppression via the GIM mechanism at the loop level lead to very small rates for FCNC processes in the SM and therefore the potential for large beyond the SM (BSM) contributions.

Since then a lot of effort has been put in the theoretical understanding and measurement of flavor violation in the K, B and D meson systems, with the results so far in strong support of the SM contribution to FCNC processes being the dominant contribution to many flavor violating observables. In fact the constraints from the flavor sector, in particular from $K^0 - \bar{K}^0$ mixing, constrain the scale of generic BSM operators to be at least $\mathcal{O}(10^5)$ TeV, not only well beyond the reach of the LHC, but also orders of magnitude larger than bounds obtained from electroweak precision tests and electric dipole moments.

Facing this situation one might be drawn to conclude that the flavor physics era is essentially over and the SM has been proven to yield the correct description. This conclusion however is, at best, premature for various reasons:

1. *Lack of a fundamental theory of flavor.* SM quark flavor introduces 10 parameters (6 quark masses, 3 mixing angles and 1 CP-violating phase) – a larger number than in any other sector of the SM. Furthermore the very hierarchical pattern of quark masses and CKM mixings suggests the presence of some flavor symmetry. Information on the underlying theory will most likely be accessible in flavor violating decays, thus asking for further and more precise measurements.

2. *Tensions in the SM fit.* While so far all flavor data are in quite good agreement with the SM prediction, small tensions in the data persist, like the $\varepsilon_K - \sin 2\beta$ tension, just to name one example. In order to turn these hints into conclusive evidence for BSM physics – or to resolve the tensions and reconcile the SM – more accurate measurements are required in conjunction with improved theory predictions.

3. *Unexplored territory.* Finally despite the impressive number of measurements that have already been done, there is still a lot of flavor territory left almost completely unexplored, like rare K decays or angular observables in semi-leptonic B decays, and still quite weakly constrained fields like CP-violation in the B_s system, leptonic B and B_s decays, charm decays etc.

While each of these three taken by itself provides already strong motivation to pursue the flavor physics program, it is the interplay of all three of them that makes flavor physics to be an outstanding opportunity to identify the nature of physics beyond the SM realized in nature.

Interplay and complementarity of K, B and D physics

Having stressed the importance of pursuing the flavor physics program, let us now address the question where to best look for new physics. Should we try to explore the yet unknown territory, or should we rather focus on improving the precision of measurements which have already been done? Is it best to focus on K, B, B_s or D physics? Are there single benchmark channels which would make other measurements obsolete?

Unfortunately there is no single best answer to any of these questions. The new physics sensitivity of various channels depends strongly on the concrete BSM physics under consideration. At first this sounds like very bad news, as it means that maybe many of the observables we attempt to measure will eventually turn out to be compatible with the SM prediction. One should be aware however that *not* finding signs of BSM physics in certain benchmark channels does not only yield strong constraints, but will also serve as an essential ingredient to discriminate between various BSM scenarios.

In order to identify benchmark channels which can be affected by BSM contributions in a significant manner, it is instructive to first consider the hierarchical structure of flavor violating effects in the SM which are determined by the hierarchy in the CKM matrix. The various meson systems are governed by

$$\underbrace{V_{ts}^*V_{td}}_{K\text{ system}} \sim 5\cdot 10^{-4} \ll \underbrace{V_{tb}^*V_{td}}_{B_d\text{ system}} \sim 10^{-2} < \underbrace{V_{tb}^*V_{ts}}_{B_s\text{ system}} \sim 4\cdot 10^{-2}\,,$$

and we see that in the SM generally rare K decays are the most suppressed ones. Since many BSM scenarios introduce new sources of flavor violation that have a priori nothing to do with the CKM matrix, this hierarchical pattern gets reversed for the relative size of possible BSM effects. I. e. in many models the largest effects are to be expected in kaon decays, while the deviations in the B_d and B_s systems are more modest.

K physics program

An additional argument in favor of K physics is that many branching ratios can be predicted with an impressive prediction within the SM. Outstanding in this respect are certainly the rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$, with an intrinsic theory error at the few percent level (given a precise determination of the relevant CKM elements), but also the decays $K_L \to \pi^0\ell^+\ell^-$ ($\ell = \mu, e$) whose theoretical predictions could be significantly improved by a more precise measurement of the decays $K_S \to \pi^0\ell^+\ell^-$. Since these decays are all sensitive to different BSM contributions (CP-conserving vs. CP-violating, presence vs. absence of scalar contributions), studying their branching ratios in a correlated manner will not only allow for clear signals of BSM physics but also for a clean way to distinguish among various BSM scenarios.

Another benchmark observable is the CP-violating parameter ε_K in $K^0 - \bar{K}^0$ mixing. While it is measured to very high precision, the accuracy of the theoretical prediction has for a long time been limited by hadronic uncertainties. Only recently significant progress in the relevant lattice calculations has been achieved so that at present the uncertainty of the SM prediction is dominated by parametric uncertainties, in particular stemming from the determination of $|V_{cb}|$. The better theoretical understanding of ε_K turned out to be particularly important, as it revealed a tension with the measured value of $\sin 2\beta$, the CP-violating phase of $B_d - \bar{B}_d$ mixing.

B and B_s physics program

While generically one expects largest BSM signatures in K decays, there exist also many well-motivated scenarios in which new physics is primarily connected to the third quark generation. In such scenarios clearly B physics observables will serve as a more useful tool to identify the underlying BSM theory.

Out of the very large number of interesting observables, for the sake of brevity only very few examples shall be mentioned here. First of all, the CP-violating phase of $B_s - \bar{B}_s$ mixing is theoretically very clean and very suppressed in the SM, therefore allowing for potentially large BSM signatures which can be obtained in many new physics models. A precise measurement of the time-dependent CP-asymmetry in $B_s \to J/\psi\phi$ and the semi-leptonic asymmetry $A^s_{\rm SL}$ is therefore desirable.

Second, measuring $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ can either reveal or severely constrain the presence of scalar contributions to FCNC processes. In fact strong constraints of supersymmetric models with large $\tan\beta$ have already been obtained from the recent LHCb and CMS data.

Furthermore, the semi-leptonic B decays $B \to K^*\ell^+\ell^-$ and $B \to X_s\ell^+\ell^-$ offer a plethora of angular observables which allow to disentangle the BSM contributions to the Wilson coefficients of various effective operators. Again a correlated study of many observables is the best way to distinguish among various BSM scenarios.

Finally, a precise determination of the CKM matrix and the unitarity triangle will not only be helpful in finding possible tensions in the SM fit, but, being rather insensitive to BSM contributions, is also crucial in order to identify which flavor observables are affected by BSM physics.

D physics program

Last but not least also the D meson sector offers potentially interesting opportunities. Due to the strong suppression of short-distance effects in the SM by the GIM mechanism, these decays are dominated by long-distance dynamics making theoretical predictions a very challenging task. The most interesting observables are then related to CP-violating transitions in the charm sector, since the SM is expected to yield very small contributions here leaving a lot of room for BSM physics to enter. Still in order to be able to convincingly disentangle new physics from the SM background, a major theoretical effort will be required.

Complementarity of the various meson systems

The above discussion does not attempt to give an extensive review of all important flavor physics channels, but rather focuses on a few selected benchmark observables. Already from this rough overview some quite general statements on the complementarity of K, B and D physics can be deduced which we collect in the following.

- Considering BSM physics with a generic flavor structure, the hierarchy of CKM suppression factors together with their theoretical cleanness results in rare K decays being sensitive to the highest scales. In fact many concrete models of BSM physics predict much larger effects in K decays than in B physics observables.

- Nevertheless in many other known BSM scenarios, due to specific well-motivated flavor structures, effects in rare K decays turn out to be rather small while the effects in B decays can be much more pronounced. In addition the B systems offer a much larger number of potentially interesting observables, thus facilitating the identification of the specific BSM physics at work.

- Finally it is conceivable that new flavor violating effects appear dominantly in the up quark sector, as happens e.g. in alignment models. In such cases the D meson sector will be the only one where one can hope to find deviations from the SM.

- From the above discussion it is obvious that it is impossible to make a case in favor of one meson system over the others concerning their ability to detect BSM interactions. This will remain true also after we have found new particles in direct searches at the LHC, since the flavor structure of BSM interactions is extremely hard to access in those experiments.

- On the contrary it is the pattern of deviations from the SM not only within the various meson systems, but in particular also the complementary information obtained from the different systems, which will provide the information necessary to distinguish among various BSM frameworks.

Last but not least it should be stressed that the flavor physics program is largely complementary to direct search experiments. While new particles will most likely be identified in high energy experiments, many of their interactions can not be probed in a straightforward manner. In order to understand the underlying flavor structure and possibly obtain experimental insights on the origin of flavor, precision studies of FCNC observables in all the various meson systems are mandatory.