

Snowmass2021 - Letter of Interest

Rare b Decays as Probes of New Physics

TF Topical Groups:

- TF6: Theory techniques for precision physics

RF Topical Groups:

- RF1: Weak decays of b and c quarks

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Abstract:

Rare b hadron decays are well recognized as important probes of the Standard Model (SM). However, in many cases, the poor knowledge of hadronic contributions limits their sensitivity to New Physics (NP). Robust analysis strategies are required to fully utilize rare decays in the search for physics beyond the SM. This is especially important in view of recent experimental results that show significant discrepancies with SM predictions and in view of the expected future sensitivities at existing and proposed colliders.

Robust Fits of Rare $b \rightarrow s\ell\ell$ Decay Data

The LHC is a b factory. The huge number of b quarks that are produced at the LHC gives for the first time access to a multitude of observables in rare b hadron decays. Prominent among them are observables in rare B meson and Λ_b baryon decays based on the flavor changing neutral current transition $b \rightarrow s\ell\ell$. In particular, the decay mode $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$ has received lots of attention since the start of LHC data taking, as it offers several new and important tests of the SM and its extensions¹.

The angular distribution of $B \rightarrow K^*\mu^+\mu^-$ measured by LHCb continues to show an intriguing $\sim 3\sigma$ discrepancy with the SM prediction². This anomaly is accompanied by a few other anomalies, among them the reduced branching ratio of $B_s \rightarrow \phi\mu^+\mu^-$ (a $\sim 3\sigma$ effect) and the hints for lepton flavor universality (LFU) violation in $B \rightarrow K\ell^+\ell^-$ ³ and $B \rightarrow K^*\ell^+\ell^-$ ⁴ ($\sim 2.5\sigma$ effects each). Various groups are performing global fits of the data, including a variety of different sets of observables and making use of different statistical methods (for the latest set of studies see^{5–11}). There is consensus that a NP effect in the form of a four fermion contact interaction $C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$ gives a consistent description of all $b \rightarrow s\ell\ell$ anomalies. However, apart from the theoretically clean LFU test, the relevant observables are affected by poorly known hadronic contributions, and the results of the fits have to be interpreted with caution.

The treatment of hadronic uncertainties is one of the most critical aspects of global fits. In exclusive b decays the main uncertainties in the theoretical predictions come from the hadronic form factors, but also from non-factorizable effects. The Non-factorizable effects can be calculated in the heavy quark limit using QCD factorization, but only partial estimates exist for effects beyond leading power^{12;13}. Assuming that

such estimates are sufficiently conservative, global fits find consistently strong evidence for NP. However, it is conceivable that unaccounted for hadronic effects could mimic lepton universal NP.

While improved theory estimates of hadronic effects are certainly welcome, this source of uncertainty can be largely eliminated by extracting hadronic effects directly from data in a global fit. Recent proposals in this direction^{14–17} provide the basis for such studies. As long as the hadronic contributions are parameterized in a sufficiently generic way, any missing standard physics can be accounted for. Studies are required to ascertain that the large amount of data from future LHCb runs will allow one to determine the hadronic effects directly from data and to simultaneously retain sensitivity to NP.

The Future of Rare b Decays

In the near future, Belle II will be able to make precision measurements of the inclusive processes $B \rightarrow X_s \ell^+ \ell^-$. Those decays are under very good theoretical control at low di-lepton invariant mass and will therefore be invaluable to scrutinize the anomalies observed by LHCb in the exclusive $b \rightarrow s \ell \ell$ counterparts.

It can be argued that the rare decays based on the $b \rightarrow d \ell \ell$ transition, like $B \rightarrow \pi \mu \mu$ or $B_s \rightarrow K^* \mu \mu$, have even better sensitivity to NP than $b \rightarrow s \ell \ell$ decays, as they are stronger suppressed in the SM. At the very least, the rare $b \rightarrow d \ell \ell$ decays give complementary information as they probe different NP flavor structures. It is thus highly motivated to analyse these decay modes for NP effects. The branching ratios of $b \rightarrow d \ell \ell$ decays are at the level of 10^{-8} or smaller, making them a challenging target for experiment. Nevertheless, LHCb already reported evidence for e.g. the $B_s \rightarrow K^* \mu \mu$ decay¹⁸. During the next runs of the LHC, the LHCb experiment will collect a sufficient amount of data which should allow them to measure a large set of interesting observables in the $b \rightarrow d \ell \ell$ decays, like angular observables in $B_s \rightarrow K^* \mu \mu$ or the LFU ratio $\text{BR}(B \rightarrow \pi \mu \mu)/\text{BR}(B \rightarrow \pi e e)$. This calls for an extension of global fit framework including a careful assessment of the long-distance hadronic effects in $b \rightarrow d \ell \ell$ decays.

In the long term, future circular electron-positron colliders like CEPC and FCC-ee offer unique sensitivities to rare decays that are not accessible at the LHC or Belle II^{19,20}. Running on the Z pole could produce up to 10^{12} b hadrons with a large boost in a clean environment. Among the most interesting processes that can be accessed at such experiments are rare b hadron decays with taus in the final state like $B \rightarrow K^* \tau \tau$ ²¹, as well as decays with neutrinos $B_s \rightarrow \phi \nu \bar{\nu}$, $\Lambda_b \rightarrow \Lambda \nu \bar{\nu}$. Studies that outline the complementary NP sensitivities are in progress.

If NP in rare decays exists at an experimentally detectable level, it is crucial to establish robust evidence for it. The discovery of NP in rare decays would transform the field. It would establish a completely new scale in particle physics and the existence of further new phenomena, in particular the existence of new particles that can be searched for and discovered directly at future particle colliders, will be guaranteed.

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