

Lepton Flavor Universality tests in $b \rightarrow s\ell^+\ell^-$ decays at LHCb

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The electroweak sector of the Standard Model contains three generations of charged leptons $\ell^- \in \{e^-, \mu^-, \tau^-\}$ as exact replicas of each other, except for their Yukawa couplings to the Higgs that determine their masses. The Yukawas, and thereby, the masses, are not predicted but are parameters in the theory. A basic tenet in the formalism, known as lepton universality, is equality of the couplings to the electroweak gauge bosons $\{\gamma, Z, W^-\}$ among all three generations, and has mostly stood the test of time. However, precision tests in B decays have recently posed serious challenges to lepton flavor universality, potentially pointing to New Physics beyond the Standard Model. In this work we summarize the latest LHCb results on lepton flavor universality tests in the $b \rightarrow s\ell^+\ell^-$ electroweak penguin sector and mention further prospects with the upgraded LHCb detector.

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In the Standard Model (SM), the fact that there are three generations of flavors differing only in the masses, both in the quark and lepton sector, comes as an accidental feature without any real explanation – the so-called flavor problem. The masses are dictated by the corresponding Yukawa couplings to the Higgs, and are free parameters in the theory. On the other hand, the couplings to the electroweak gauge bosons, $\{\gamma, Z, W^\pm\}$, are the same for all three generations, referred to as lepton flavor universality. Many years of precision measurements in the flavor sector [1, 2] without any significant deviations has lent support to this picture. Yet, within the last couple of years, a pattern of anomalies in B -physics seems to challenge this notion. Both the charged and neutral electroweak currents, as well all three charged lepton, $\ell^- \in \{e^-, \mu^-, \tau^-\}$ seem to be involved.

In this article we focus on the recent anomalies in the electroweak penguin $b \rightarrow s\ell^+\ell^-$ sector in the double ratios, $R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu^-\mu^+)/\mathcal{B}(B \rightarrow K^{(*)}J/\psi)}{\mathcal{B}(B \rightarrow K^{(*)}e^-e^+)/\mathcal{B}(B \rightarrow K^{(*)}J/\psi)}$ measured by LHCb [3, 4], using $J/\psi \rightarrow \{e^+e^-, \mu^+\mu^-\}$ as control modes, on the 3 fb^{-1} Run 1 data sample collected between 2011-2012. These ratios, predicted to be $1 \pm \mathcal{O}(10^{-3})$ in the SM up to small corrections due to the e - μ mass difference, are very clean probes of the SM. Small corrections from QED are expected to be $\mathcal{O}(10^{-2})$ [5]. Experimentally, the measurements are challenging at LHCb due to complications related to trigger and large bremsstrahlung losses for the electron modes, compared to the muon, where much softer, low- p_T hardware triggers are achievable. For the electron modes, events triggered by high E_T electrons or hadrons or by particles not part of the signal candidate are used. They are characterized by different purities and resolutions and are studied separately and then combined. Correction for the electron bremsstrahlung depends on whether it occurs prior to or after the track traverses the bending magnet. For the former, the bremsstrahlung photon and the daughter electron correspond to different calorimeter cells, and bremsstrahlung recovery is harder.

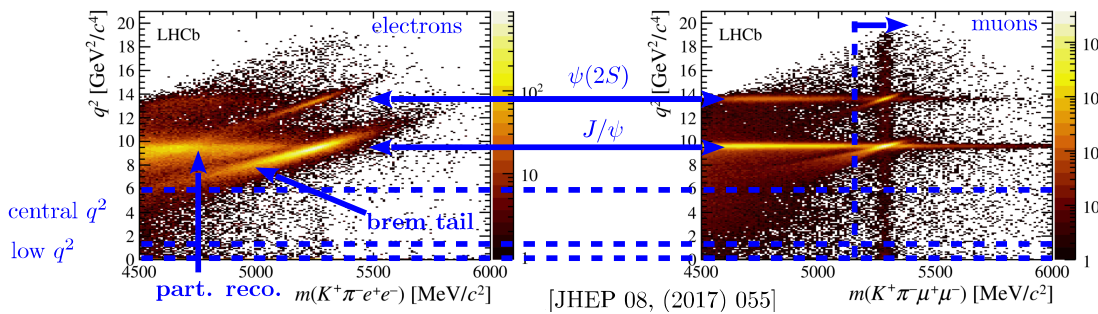


Figure 1: $B^0 \rightarrow K^*\ell^+\ell^-$ [4]: bremsstrahlung tails for electron (left) and muon (right).

The $q^2 \equiv m(\ell^+\ell^-)^2$ range for R_K is a single $[1, 6]\text{ GeV}^2$ bin, while for R_{K^*} , a low $[0.045, 1.1]\text{ GeV}^2$ region close to the photon pole, as well a central $[1.1, 6]\text{ GeV}^2$ bin most sensitive to the Wilson Coefficients $C_{9,10}$, are analyzed. Figure 1 shows the bremsstrahlung tails and partially reconstructed backgrounds for the e and μ cases. For the latter, most of the tails are gotten rid of by requiring the reconstructed B^0 mass to be greater than 5150 MeV. Figure 2 shows the results, summarized below, along with the tensions with the SM predictions, depending on the theory model:

- $R_{K^*}(0.045 < q^2 < 1.1\text{ GeV}^2) = 0.66_{-0.07}^{+0.11} \pm 0.03$ [2.1 – 2.3 σ tension]
- $R_{K^*}(1.1 < q^2 < 6.0\text{ GeV}^2) = 0.69_{-0.07}^{+0.11} \pm 0.05$ [2.4 – 2.5 σ tension]
- $R_K(1 < q^2 < 6.0\text{ GeV}^2) = 0.745_{-0.074}^{+0.090} \pm 0.036$ [2.6 σ tension]

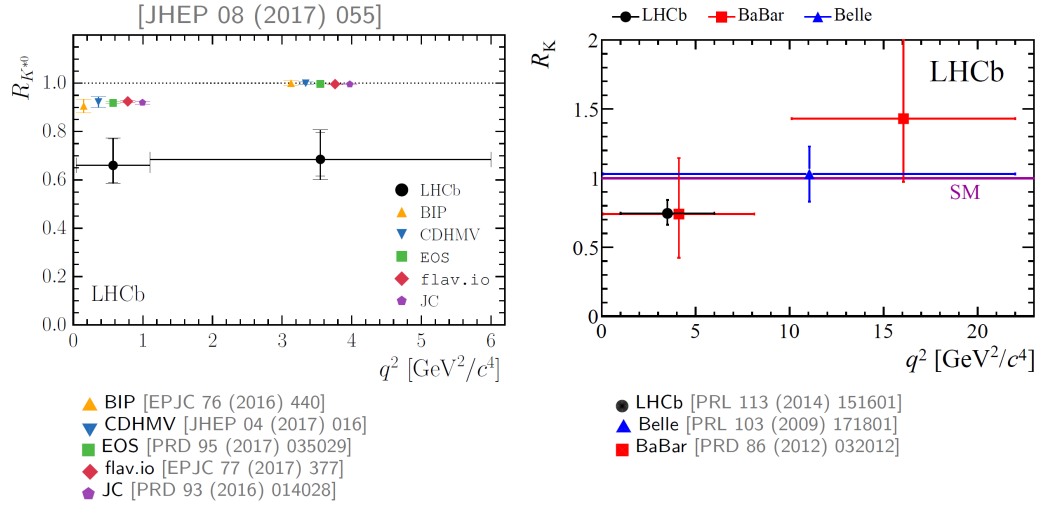


Figure 2: LHCb Run 1 results for R_{K^*} (left) and R_K (right), along with SM predictions from various models.

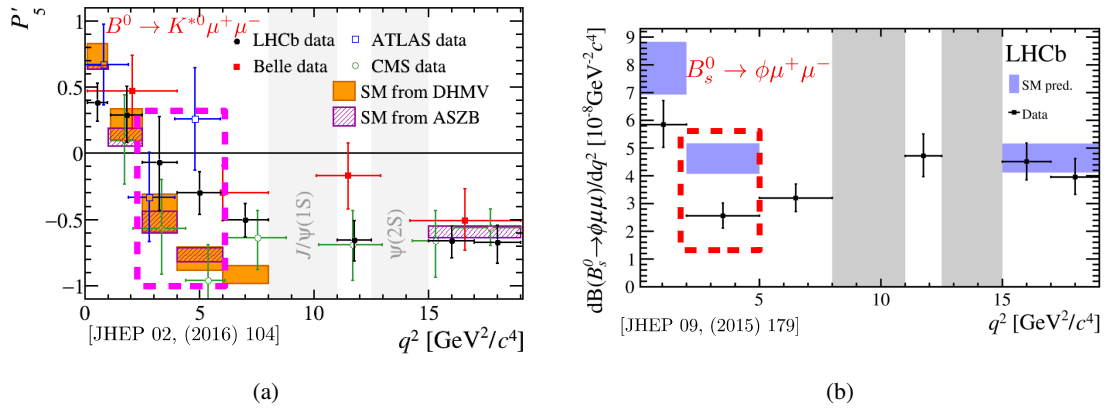


Figure 3: Tensions in the $b \rightarrow s\mu^+\mu^-$ sector for (a) P'_5 in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ [6] and (b) $B_s^0 \rightarrow \phi\mu^+\mu^-$ [7].

Several other tensions exist in the $b \rightarrow s\mu^+\mu^-$ sector, both in angular analyses (P'_5 observable in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ [6] as in Fig. 3a) and in the branching fractions being 1-3 σ lower than SM in several modes (shown for $B_s^0 \rightarrow \phi\mu^+\mu^-$ [7] in Fig. 3b). In fact, we note that the muonic modes are the ones responsible for the $R_{K^{(*)}}$ discrepancies. The perspective from global fits in the electroweak and radiative penguin sector [8, 9, 10], is that the Wilson coefficient C_9 is the safest bet where the tensions can be accommodated. Accounting for LFU violation, $\Delta C_{9\mu} \sim -1$ seems to be the viable path. In fact, the different parities of K and K^* allow to separate the effects from C_{9A} and C_{10V} [11, 12]. In terms of New Physics (NP), a tree level heavy Z' with non-trivial flavor structure coupling only to μ has been proposed [13, 14].

Looking forward, with Run 2 (2015-2018) just completing and over 9 fb⁻¹ of integrated luminosity collected by LHCb, significant amounts of additional data are on disk. Along with Run 2 $R_{K^{(*)}}$ updates, new R_ϕ , $R_{K\pi\pi}$ and R_{pK} results are in the pipeline. In 2019, LHC will enter a two year long shutdown when the LHCb will undergo the Phase I Upgrade. The hardware trigger will be replaced by a flexible software trigger from Run 3 onward [15]. Further still, sub-percent $R_{K^{(*)}}$

precision will be achievable after Upgrade II in the High-Luminosity LHC era. This will allow for clearer distinctions between different NP models. Figure 4 shows projections from the Upgrade II physics case document [15]. They do not include effects of an improved electromagnetic calorimeter for Upgrade II: higher granularity, fast-timing to reduce combinatorics.

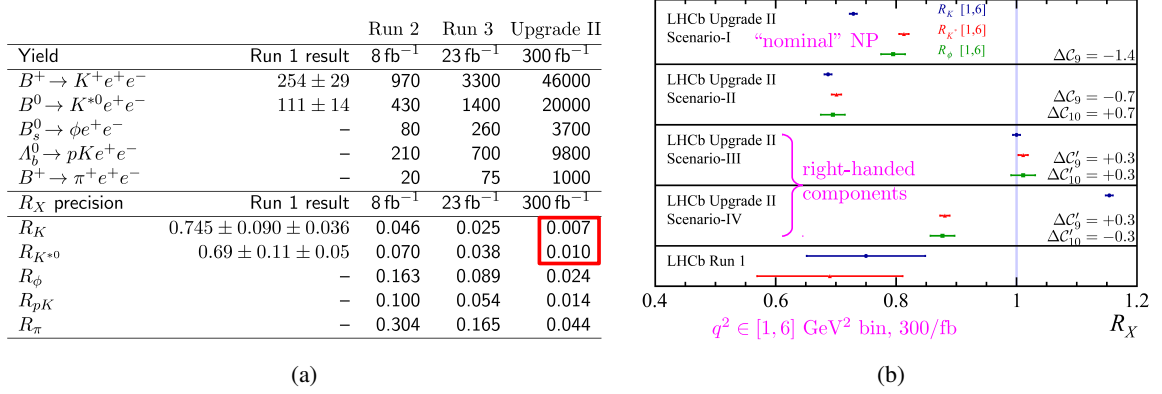


Figure 4: Projections for R_X measurements from the Upgrade II physics case document [15]: (a) sub-percent resolutions for $R_{K^{(*)}}$ and (b) distinguishing between different NP scenarios.

In summary, LHCb has seen some intriguing anomalies in the electroweak penguin sector, including hints of LFU violation. If these are confirmed in the LHCb Upgrade and Belle II era, it would be a truly remarkable discovery, reshaping our notions of particle physics.

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