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Rare B Decays And Lepton Flavour Universality Tests at LHCb

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Abstract. In the lepton sector the Standard Model incorporates both lepton-flavour and lepton-number universality. In a generic New Physics scenario this is not necessarily the case and these symmetries need to be experimentally tested. Numerous searches have failed to find any signs of Lepton Flavour Violation (LFU) or Lepton Flavour Universality Violation (LFUV). New Physics could, however, generate LFUV in the heavy flavour sector where the existing experimental constraints are weaker. Recent searches at LHCb focus on precisely this unexplored territory by studying the B decays involving $b \to c\tau\nu$ and $b \to sl^+l^-$ transitions. Several theoretically and experimentally clean observables, such as $\mathcal{R}(D*)$ or $\mathcal{R}(K)$, diverge from the Standard Model predictions and could be the first signs of LFUV.

1. Introduction

The Standard Model (SM) is a Minimal Flavour Violating (MFV) model, where the flavour changing transitions in the quark sector are governed by the CKM matrix. The CKM matrix is non-diagonal and quarks from different generations are known to mix. Transitions between the lepton families (Lepton Flavour Violation, LFV) are not present in the SM, but known to exist in nature at least through neutrino mixing [1]. The expected LFV processes ($\mathcal{O}(10^{-40})$) are well below the current experimental reach. Many New Physics (NP) scenarios predict significantly larger and experimentally reachable LFV. LHCb has searched for LFV in many decay processes ($B_s \to e^{\pm}\mu^{\mp}$, $D^0 \to e^{\pm}\mu^{\mp}$). Thus far, no evidence of LFV has been seen.

Besides being lepton flavour conserving, the SM is also lepton favour universal (LFU) and the couplings of the different lepton families to the neutral and charged gauge bosons are identical. NP can violate LFU even if neutrino mixing is the only source of LFV.

The LFU assumption has been thoroughly tested at LEP, SLC, and many other colliders [2]. The most stringent limits on LFU Violation (LFUV) involve the first two generations. Thus, NP could easily evade the existing bounds from direct searches and still effect the third generation: many NP scenarios contain additional interactions and enhanced couplings only to the third generation. If NP is also MFV, the experimental limits on the kaon and pion decays need to be improved by an order of magnitude to be able to probe the same parameter space accessible to B decays [3]. Therefore, processes such as $b \to c\tau\nu$ and $b \to sl^+l^-$ transitions are well suited for LFU tests.

2. $\mathcal{R}(D^*)$

According to the LFU, leptonic branching fractions only differ due to effects related to different lepton masses: Higgs couplings, the available phase space and the helicity suppression. Semi-leptonic B decays are in general well understood and described within the SM. The theoretical uncertainties arising from the hadronic form factors and common SM parameters can be reduced by constructing ratios of branching fractions, such as the relative ratio of the two $B^0 \to D^{*-}l^+\nu_\tau$ decays[1] [4]:

$$\mathcal{R}(D^*)_{SM} = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\tau)} = 0.252(3). \tag{1}$$

Besides theoretical benefits the ratios can be also measured more precisely because the common detection uncertainties (D^* reconstruction, particle identification and tracking) cancel.

The $\mathcal{R}(D^*)$ ratio has been previously determined by BaBar and Belle at e^+e^- collisions [5, 6, 7]. The combined experimental result is in a significant tension with respect to the SM prediction at the 3.7σ level [8, 9]. The same quantity has been determined by the LHCb collaboration in a much more challenging hadronic environment which requires a different analysis strategy compared to what was used in Belle and BaBar.

In LHCb, the momentum of the signal B meson cannot be constrained by the "tagger" B from the other b-quark. Instead, the boost of the visible system is combined with the position information on the B and D decay vertices to reconstruct the B momentum. Only candidates where τ decays to a muon and two neutrinos are used to ensure the visible final state is the same for the nominator and denominator. The two decays are finally separated using mainly the three B rest frame variables: difference between the reconstructed B and the visible daughter candidate four-momenta (missing mass), squared four-momentum transfer to the lepton system (lepton pair recoil) and lepton energy.

The LHCb measurement on the full Run 1 dataset (integrated luminosity of 3 fb^{-1}) [10]

$$\mathcal{R}(D^*)_{LHCb} = 0.336 \pm 0.027(stat.) \pm 0.030(syst.), \tag{2}$$

compares well to the existing measurements in central value as well as in precision [5, 6, 7] - a remarkable achievement in a hadronic environment. It supports the tensions seen before and raises their significance to the level of 4σ (see Figure 1).

3. $\mathcal{R}(K)$

The $\mathcal{R}(D^*)$ is not the only observable where LHCb sees unexpected results. Another group of excellent LFU tests involves $b \to sl^+l^-$ type Flavour Changing Neutral Current (FCNC) transitions. FCNC's are highly suppressed in the SM and are therefore sensitive to a multitude of NP contributions (both at loop and tree level). The abundance of B decays to kaons and muons relative to the similar decays to kaons and electrons is precisely constrained to unity in the SM [11]:

$$\mathcal{R}(K)_{SM} = \frac{\mathcal{B}(B^+ \to K\mu^+\mu^+)}{\mathcal{B}(B^+ \to Ke^+e^+)} = 1 \pm \mathcal{O}(10^{-3}), \tag{3}$$

where small deviations arise from the lepton mass difference.

The $\mathcal{R}(K)$ ratio has been determined previously by the B factories, although with a meagre precision of 20-50% depending on the di-lepton mass squared (q^2) region [12, 13]. LHCb measures $\mathcal{R}(K)$ in the range $1 < q^2 < 6$ $\texttt{GeV}^2/c^4$. This excludes the resonant J/ψ and $\Psi(2S)$ regions and allows for more precise theoretical estimates. The measurement is in practice performed as a double ratio between the relative signal mode yields and the respective resonant $B^+ \to J/\psi(\to l^+l^-)K^+$ modes to reduce the experimental uncertainties.

[1] Charge conjugated modes are included throughout this paper, unless specified otherwise.

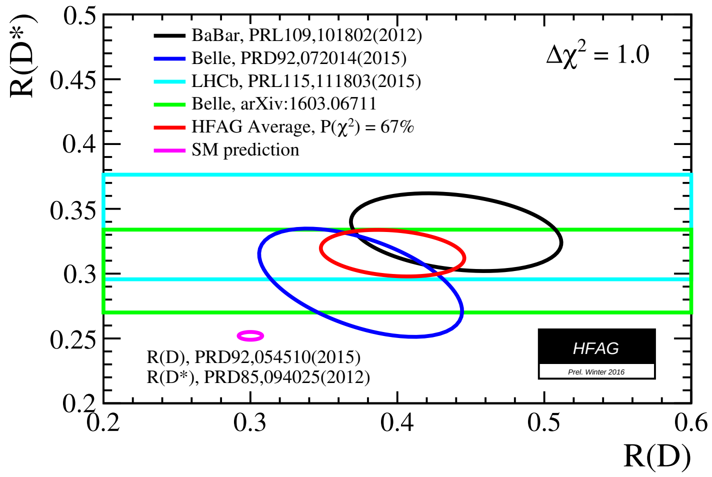

Figure 1. Experimental $\mathcal{R}(D*)$ and $\mathcal{R}(D)$ measurements from BaBar, Belle and LHCb, together with the latest SM predictions. The bands denote the confidence regions corresponding to one standard deviations around the central values. $\mathcal{R}(D*)$ and $\mathcal{R}(D)$ exceed the SM predictions by 1.9σ and 3.3σ respectively. Considering the correlation of -0.21 between the two, the resulting combined χ^2 is 19.73 for 2 degree of freedom, corresponding to a p-value of 5.2×10^{-5}. The difference with the SM predictions reported above is at 4.0σ level. Note, that the latest Belle $\mathcal{R}(D*)$ measurement [9] is not included. The effect of the new result on the combined significance is small.

The main uncertainties in this measurement are related to to the electron mode. The efficiency to detect an electron is around half of that of muons and the large radiative energy losses result in a broad mass distribution; the shape of which depends strongly on the number of associated photons in the detector and is thus difficult to simulate. The radiation also causes migration in the q^2 bins. All these effects, however, are well accounted for within the larger systematics of the electron mode.

The measured $\mathcal{R}(K)$ from LHCb's full Run 1 dataset [14]:

$$\mathcal{R}(K)_{LHCb} = 0.745^{+0.090}_{-0.074}(stat.) \pm 0.036(syst.), \tag{4}$$

is the most precise measurement of this quantity. It agrees well with the previous measurements in its di-lepton mass squared region and strengthens the claim for tensions in $b \to s$ transitions.

4. Individual leptonic B decays

The individual branching fractions measurements suggest that the tension in $\mathcal{R}(K)$ is caused by tensions in $B^+ \to K^+\mu^+\mu^-$ [15] rather than in $B^+ \to K^+e^+e^-$ [14]. Unfortunately the branching fraction of the electronic mode is not determined precisely enough to draw stronger conclusions.

Other LHCb branching fractions measurements of B decays that involve $b \to s$ FCNC transitions include $\mathcal{B}(B^0 \to K^*\mu^+\mu^-)$ [16, 17, 18], $\mathcal{B}(B^0 \to \phi\mu^+\mu^-)$ [19, 20, 21], and $\mathcal{B}(B_s \to \mu^+\mu^-)$ [22]. All these measurements are lower than their SM predicted values, especially in the low di-lepton mass squared region (in case of the semileptonic modes).

The physics involved in these transitions can additionally be studied with the angular observables of $B^0 \to K^*\mu^+\mu^-$ decays [23]. One of the theoretically cleanest observables (remapped to achieve a smaller form factor dependence) called P_5' differs from the SM predictions at (global) 3.4σ.

In the case of $B^0 \to K^*e^+e^-$ the analysis is again more difficult that that of the muon mode. Nevertheless, the latest results for the branching fraction and angular observables are in good agreement with the SM predictions [24]. All of these discrepancies could be explained by NP coupling differently to muons (and possibly tauons), but not electrons.

5. Summary

The tensions in the $\mathcal{R}(D^*)$, $\mathcal{R}(K)$ and individual $b \to s$ modes can not be ignored: the global $b \to sl^+l^-$ fits show global tensions with the SM at discovery $(4-5\sigma)$ level [25]. The situation is especially interesting because of the existing theoretical attempts able to explain many of the tensions simultaneously (e.g. leptoquarks, Z' models) [26, 27]. The case for the new analysis and better experimental precision in Run 2 is as strong as ever. In Run 2, LHCb is expected to record almost three times as many B decays as were recorded in Run 1. LHCb will update the present analysis as well as probe the tensions with additional measurements such as $\mathcal{R}(D^*)$ on hadronic τ decays, $\mathcal{R}(D)$, and extend the $\mathcal{R}$ measurements to other mesons and baryons $(D_s, \Lambda_c, \Lambda_c^*)$.

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