## Lepton flavour non-universality in $b \to s\ell^+\ell^-$ processes

N. Košnik
*Jozef Stefan Institute, Jamova 39, P. O. Box 3000, 1001 Ljubljana, Slovenia*
*and*
*Department of Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia*

We describe the current situation of lepton flavor univesality tests in $B$ meson decays. We primarily focus on explanation of the observed deviation from 1 in neutral current processes observable $R_K = \mathcal{B}(B \to K\mu\mu)/\mathcal{B}(B \to K\mu\mu)_{[1,6]\mathrm{GeV}^2}$. Demonstrating the broad requirements of any NP scenario in the framework of effective theory we focus on concrete models with scalar or vector leptoquark playing the role of tree-level mediator of $B \to K\mu^+\mu^-$.

## 1 Introduction

The universality of lepton couplings has been a subject of continuous testing ever since the discovery of a muon. In the context of Fermi theory of weak interactions it was experimentally observed in weak decays (e.g. beta decays) that the effective couplings are insensitive to lepton flavor, $G_e \approx G_\mu$. Later on, with the advent of the Standard Model (SM) the universality of leptonic gauge couplings was built into the theory by providing three copies of matter with same quantum numbers. With neutrinos being (approximately) massless, one can work in the flavor basis of neutrinos where all the charged leptons have equal gauge couplings. The only property that distinguishes leptonic flavors are disparate mass scales stemming from non-universal Yukawa couplings to the SM Higgs boson. Thus the ratios of weak decay widths will differ from 1 only due to different leptons masses affecting kinematics. In such lepton flavor universality (LFU) ratios many of the theoretical as well as experimental uncertainties cancel out and can serve to test validity of the SM.

Experimental tests of lepton flavor universality span from low energy weak interactions to tests in highest achievable energies in colliders. In charged currents the most notable are LFU ratios in leptonic decays $R^P_{e/\mu} = \Gamma(P \to e\bar\nu)/\Gamma(P \to \mu\bar\nu)$ where $P$ stands for a pseudoscalar meson $\pi$ or $K$. On the other hand, for the weak neutral currents the LEP measurements of the $Z$-boson partial decay widths agree very well with the SM LFU predictions.

However, recent experimental advance of LFU tests to the sector of third generation quarks and/or involving the $\tau$ lepton has given as a hint of possible LFU violation in both charged and neutral current processes. For the former, the LFU ratio $R_{D^{(*)}} = \frac{\Gamma(B\to D^{(*)}\tau^-\bar\nu)}{\Gamma(B\to D^{(*)}\ell^-\bar\nu)}$ [1,2,3,4,5,6] deviates from the SM is at $3.5\sigma$ level and has attracted a lot of attention recently [7,8,9,10,11]. Since the denominator of these ratios are the well measured decay rates with light leptons in the final states, $\ell = e, \mu$, the simplest conceivable NP scenario would affect semileptonic $b \to c\tau^-\bar{\nu}$ processes [12].

Rare neutral current processes with flavor structure $(\bar{s}b)(\mu^+\mu^-)$ also persistently indicate anomalous behaviour [13,14,15,16,17,18,19,20,21,22,23,24,25,26]. Thesizable violation of LFU in the ratio

$$R_K = \frac{\Gamma(B \to K\mu\mu)_{q^2\in[1,6]\mathrm{GeV}^2}}{\Gamma(B \to Kee)_{q^2\in[1,6]\mathrm{GeV}^2}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036 \qquad (1)$$

has been found by the LHCb experiment [27] and is $2.6\sigma$ below the SM prediction 1.0003 [28]. It seems that this ratio, being largely free of theoretical uncertainties and experimental systematics, is smaller than 1 due to downward deviation of the muonic mode rate relative to the SM as indicated by differential rates of $B \to K^{(*)}\mu^+\mu^-$ processes [29]. Furthermore, in this case $R_K$ is consistent with the deviation in $B \to K^*\mu^+\mu^-$. Namely, the decay $B \to K^*\mu^+\mu^-$ deviates from the SM in the widely discussed angular observable $P_5'$ at the confidence level of above $3\sigma$ [30,31,32]. In terms of new physics (NP), global analyses point to modifications of the operator with leptonic vector current $\bar{\mu}\gamma^\nu\mu$, which is unfortunately also a subject of large uncertainties due to nonlocal QCD effects. Several studies have shown that even with generous errors assigned to QCD systematic effects, the anomaly is not washed away [33].

## 2 Effective theory analysis

The SM can be extended at or above the electroweak scale by heavy degrees of freedom representing a particular New Physics (NP) scenario. Once the NP states are integrated out we are left with the effective theory consisting of SM complemented by dimension-6 operators at the electroweak scale (SMEFT), schematically represented by the effective Lagrangian $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \Lambda^{-2}\sum_i C_i Q_i$. The following effective operators are important for rare processes in the down-quark sector: $(\bar{H}D_\mu H)(\bar{q}\gamma^\mu q)$, $H(\bar{q}\sigma_{\mu\nu}V^{\mu\nu}q)$, $(\bar{\ell}\ell)(\bar{q}q)$. Evolving the effective Lagrangian down to the scale of $b$ quark we find

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)\right)\right], \qquad (2)$$

with the operators

$$\begin{aligned}
\mathcal{O}_7^{(\prime)} &= \frac{e}{(4\pi)^2} m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \\
\mathcal{O}_9^{(\prime)} &= \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell), \qquad \mathcal{O}_{10}^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell), \\
\mathcal{O}_S^{(\prime)} &= \frac{e^2}{(4\pi)^2}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma^\mu\ell), \qquad \mathcal{O}_P^{(\prime)} = \frac{e^2}{(4\pi)^2}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell).
\end{aligned} \qquad (3)$$

Starting from the SMEFT and assuming that electroweak gauge symmetry is realized linearly, already imposes some features on the low energy theory of Eq. (2) [34,35]. First, tensor operators are not allowed. [a] Second, correlations arise in the (pseudo)scalar sector: $C_S = -C_P$, $C_S' = C_P'$.

The global fit of the $(\bar{s}b)(\bar{\mu}\mu)$ observables guides us to invoke intervening NP that decreases muonic decay rates instead of having increased electronic rates as a means to have $R_K$ smaller than 1. While $\mathcal{O}_7^{(\prime)}$ is clearly blind to leptons, (pseudo)scalar operators' contributions would be too amplified in $B_s \to \mu^+\mu^-$ if they were to explain the $R_K$ deviation. Finally, some combinations of (axial)vector operators $\mathcal{O}_9^{(\prime)}$, $\mathcal{O}_{10}^{(\prime)}$ are suited to explain the $R_K$ puzzle, while

[a] In similar charge-2/3 quark processes, e.g. $c \to u\ell^+\ell^-$, tensor operators are allowed.

global agreement with the $\bar{s}b\mu^+\mu$ observables can be much improved by assigning large negative contribution to $C_9$, $C_9 \in [-0.81, -0.50]$ [36]. Such scenario is implemented by a $Z'$ model where only $\mu$ and $\tau$ are charged under $L_\mu - L_\tau$ number [14,37] and in turn contribute to $C_9$ and $C_9'$ coefficients with opposite signs for $\mu$ and $\tau$, respectively. Among the preferred scenarios is also one involving left-handed fermions, $C_9 = -C_{10}$, which will be discussed in the following, where we will focus on the leptoquark models.

## 3 Leptoquarks

Leptoquarks are color triplet bosons that switch between quarks and leptons. They typically appear in model of unifications, e.g., Pati-Salam models or $SU(5)$ GUTs.

### *3.1 Scalar leptoquark* $\tilde{R}_2(3, 2, 1/6)$

There are 4 scalar leptoquark states potentially contributing to $R_K$ at tree level: (i) $(3, 2, 7/6)$ that increases $B \to K\mu^+\mu^-$, (ii) $(3, 2, 1/6)$ which can explain $R_K$, and, (iii) proton destabilizing states $(\bar{3}, 3, 1/3)$ and $(\bar{3}, 1, 4/3)$. Thus $\tilde{R}_2(3, 2, 1/6)$ is the most suitable candidate state. Its interactions to fermions are described by a renormalizable Lagrangian [38]

$$\begin{aligned}\mathcal{L} &= Y_{ij}\overline{L}_i\, i\tau^2 \tilde{R}_2^* d_{Rj} + \text{h.c.}\\ &= Y_{ij}\left(-\bar{\ell}_{Li} d_{Rj} \tilde{R}_2^{(2/3)*} + \bar{\nu}_{Lk}(V^{\text{PMNS}})^\dagger_{ki} d_{Rj} \tilde{R}_2^{(-1/3)*}\right) + \text{h.c.},\end{aligned} \tag{4}$$

with $Y$ a $3 \times 3$ complex matrix, $L_i$ and $d_{Rj}$ are the lepton doublet and down-quark singlet. Degenerate charge eigenstates of the leptoquark doublet are denoted with $\tilde{R}_2^{(2/3)}$ and $\tilde{R}_2^{(-1/3)}$. The last line in the above equation is written in the fermion mass basis. The scalar LQ exchange generates (axial)vector current operators [39]:

$$C_{10}' = -C_9' = \frac{\pi}{2\sqrt{2} G_F V_{tb} V_{ts}^* \alpha} \frac{Y_{\mu b} Y_{\mu s}^*}{m_{\tilde{R}_2}^2}\,. \tag{5}$$

We will assume other elements of $Y$ are negligibly small. The same state also contributes at loop level to operator $\mathcal{O}_7'$, where the corresponding coefficient will be suppressed by loop factor and electromagnetic coupling $\alpha/(4\pi)$, which turns out to be completely negligible. In $R_K$ the uncertainties of the hadronic form factors cancel out to a large extent in the ratio and the formula for the scenario $C_9' = -C_{10}'$ boils down to [38]:

$$R_K(C_{10}') = 1.001(1) - 0.46\ \text{Re}[C_{10}'] - 0.094(3)\ \text{Im}[C_{10}'] + 0.057(1)|C_{10}'|^2. \tag{6}$$

Remaining uncertainties are indicated by the numbers in parentheses. Fig. 1 shows on the right hand side contours of constant $R_K$ in the $C_{10}'$ plane using the formula (6). Dark gray region corresponds to the measured value of $R_K$. In the left hand side we plot the $1\sigma$ prediction of $C_{10}'$ after we take into account rate of $B_s \to \mu^+\mu^-$ and high-$q^2$ partial width of $B \to K\mu^+\mu^-$ [38]. We see an appreciable overlap with the measured $R_K$. Mapping the fitted region (green) to $R_K$ we obtain good agreement with $R_K^{\text{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$ [27]:

$$R_K^{\text{pred.}} = 0.88 \pm 0.08. \tag{7}$$

The considered leptoquark $\tilde{R}_2$ couples to the neutrinos with the same couplings as to the charged leptons, only modified by a PMNS rotation matrix. Namely, the charge $-1/3$ state will generate $(\bar{s}b)(\bar{\nu}\nu)$ operators while the box diagrams will lead to modification of $B_s - \bar{B}_s$ mixing frequency. The latter constraint also implies, in principle, an upper mass bound on $\tilde{R}_2$, since

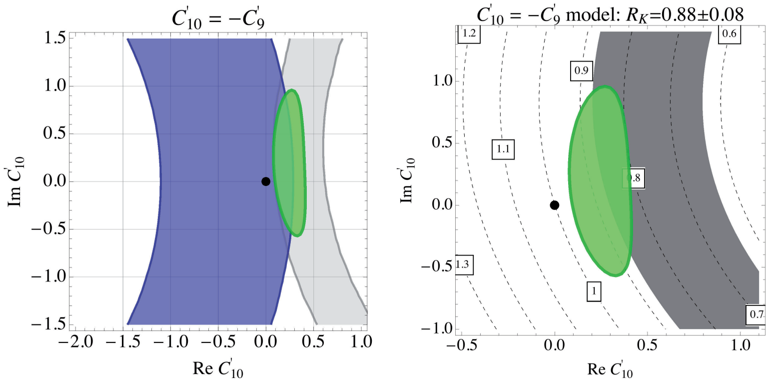


Figure 1 – Left: Regions in the complex $C'_{10}$ plane that are in $1\sigma$ agreement with $B_s \to \mu^+\mu^-$ (blue), $B \to K\mu^+\mu^-$ (gray). Green area corresponds to the $1\sigma$ coverage of $R_K$ from fit to both observables. Black dot is the SM. Right: Contours of constant $R_K$ are indicated by dashed lines. Gray region represents the $1\sigma$ measured range of $R_K$ projected onto the $C'_{10}$ plane, whereas green contour denotes the region allowed by $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$.

the modification of the $\Delta B = 2$ matrix element scales with $m^2_{\tilde{R}_2}$ for fixed value of $C'_{10}$ [38]:

$$\Delta m_{B_s} = \underbrace{\frac{G_F^2 m_W^2}{6\pi^2} |V_{tb}^* V_{ts}|^2 f_{B_s}^2 m_{B_s} B_{B_s} \eta_B S_0(x_t)}_{\Delta m_{B_s}^{\rm SM}} \left| 1 - \frac{1}{2\pi^2} \frac{\alpha^2}{S_0(x_t)} (C'^*_{10})^2 \frac{m^2_{\tilde{R}_2}}{m_W^2} \right|. \tag{8}$$

Currently the $\Delta m_s$ bound would be sensitive at $m_{\tilde{R}_2} \approx 100\,\mathrm{TeV}$.

## 4 Vector leptoquark $U_3(3,3,2/3)$

In this section, we extend the SM by a vector $SU(2)$ triplet leptoquark, which generates purely left-handed currents with quarks and leptons. One can address with this state also the charged LFU violation in $R_{D^{(*)}}$. The couplings to the SM matter are

$$\mathcal{L}_{U_3} = g_{ij} \bar{Q}_i \gamma^\mu \tau^A U^A_{3\mu} L_j + \text{h.c.}. \tag{9}$$

Here $\tau^A, A = 1,2,3$ are the Pauli matrices in the $SU(2)_L$ space whereas $i,j = 1,2,3$ count generations of the left-handed lepton and quark doublets, $L$ and $Q$. The couplings $g_{ij}$ are assumed to be real, for the sake of simplicity. The absence of any other term at mass dimension 4 of the operators ensures the conservation of baryon and lepton numbers and this allows the leptoquark $U_3$ to be close to the TeV scale without destabilizing the proton. The interaction Lagrangian (9) is written in the mass basis with $g_{ij}$ entries defined as the couplings between the $Q = 2/3$ component of the triplet, $U^{(2/3)}_{3\mu}$, to $\bar{d}_{Li}$ and $\ell_{Lj}$. Remaining three types of vertices to eigencharge states $U^{(2/3)}_{3\mu}$, $U^{(5/3)}_{3\mu}$, and $U^{(-1/3)}_{3\mu}$ are then obtained by rotating the $g$ matrix, where necessary, with the Cabibbo-Kobayashi-Maskawa (CKM) matrix $\mathcal{V}$ from the left or with the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix $\mathcal{U}$ from the right:

$$\begin{aligned} \mathcal{L}_{U_3} = {} & U^{(2/3)}_{3\mu} \left[ (\mathcal{V} g \mathcal{U})_{ij}\, \bar{u}_i \gamma^\mu P_L \nu_j - g_{ij}\, \bar{d}_i \gamma^\mu P_L \ell_j \right] \\ & + U^{(5/3)}_{3\mu} (\sqrt{2} \mathcal{V} g)_{ij}\, \bar{u}_i \gamma^\mu P_L \ell_j \\ & + U^{(-1/3)}_{3\mu} (\sqrt{2} g \mathcal{U})_{ij}\, \bar{d}_i \gamma^\mu P_L \nu_j + \text{h.c.}. \end{aligned} \tag{10}$$

If ultraviolet origin of the $U_3^\mu$ LQ is a gauge boson field of some higher symmetry group (e.g. Grand Unified Theory), then the coupling matrix $g$ in the mass basis should be unitary. Furthermore, in such theories the ability to choose gauge and the presence of additional Goldstone degrees of freedom would ensure renormalizability, in contrast to the effective theory of Eq. (9). In this section we limit ourselves to the tree-level constraint for which the details of the underlying ultraviolet completion are irrelevant.

The $b \to s\mu^+\mu^-$ processes are affected by the product $g_{b\mu}^* g_{s\mu}$ whereas the crucial parameter for $b \to c\tau^-\bar{\nu}$ is $g_{b\tau}$. We do not insist on a particular flavor structure of the matrix $g$ but note that the explanation of the LFU puzzles in the neutral and charged currents involves parameters $g_{s\mu}$, $g_{b\mu}$, and $g_{b\tau}$, which will be our tunable flavor parameters of the model. We assume the remaining elements $g_{ij}$ are negligibly small:

$$g = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{s\mu} & 0 \\ 0 & g_{b\mu} & g_{b\tau} \end{pmatrix}. \tag{11}$$

The leptoquark $U_3$ implements a combination of Wilson coefficients in the $b \to s\mu^+\mu^-$ effective Lagrangian [17,39],

$$C_9 = -C_{10} = \frac{\pi}{\mathcal{V}_{tb}\mathcal{V}_{ts}^*\alpha}\, g_{b\mu}^* g_{s\mu}\, \frac{v^2}{M_U^2}, \tag{12}$$

which has been shown to significantly improve the global fit of the $b \to s\mu^+\mu^-$ observables with the $1\sigma$ preferred region $C_9 \in [-0.81, -0.50]$ [36], see also [35]. Here $v = 246$ GeV is the electroweak vacuum expectation value. In this case we find

$$g_{b\mu}^* g_{s\mu} \in [0.7, 1.3] \times 10^{-3}\ (M_U/\mathrm{TeV})^2\,. \tag{13}$$

Note that the effective coupling (12) also brings the LFU observable $R_K$ in agreement with the experimental value [36]. Nonzero $g_{b\tau}$ is required to address the $R_{D^{(*)}}$ puzzle.

In order to address $R_K$, global $\bar{s}b\mu^+\mu^-$ fit, as well as $R_{D^{(*)}}$ the couplings have to satisfy the following conditions:

$$\begin{aligned} g_{b\mu} g_{s\mu} &\approx 10^{-3}, \\ \mathcal{V}_{cb}(g_{b\tau}^2 - g_{b\mu}^2) - g_{b\mu} g_{s\mu} &\approx 0.18, \end{aligned} \tag{14}$$

if $M_U = 1$ TeV. From the first equation we learn that, once we impose perturbativity condition ($|g_{s\mu}, g_{b\mu}, g_{b\tau}| < \sqrt{4\pi}$), that both $|g_{s\mu}|$ and $|g_{b\mu}|$ are also bounded from below, $|g_{s\mu}|, |g_{b\mu}| > 3 \times 10^{-4}$. The second equation can be simplified to

$$g_{b\tau}^2 - g_{b\mu}^2 \approx 4.4, \tag{15}$$

which indicates $|g_{b\tau}| \sim 2$.

However additional constraints may not allow for the above conditions to be satisfied. See Ref. [40] for a thorough analysis of constraints posed by LFU in the kaon sector, $t \to b\tau^+\nu$, $B \to K\tau\mu$, and $B \to K\bar{\nu}\nu$. In Fig. 2 we show the effect of the constraints projected onto $g_{s\mu}$-$g_{b\tau}$ space; $g_{b\mu}$ is free parameter of the fit. The best fit point with all the constraints and signals included is obtained at $\chi^2 \simeq 3$ and is much favoured over the SM situation. Clearly there is preference for large $g_{b\tau}$ to correct the large SM tree-level effect in $b \to c\tau^-\bar{\nu}$. On the other hand, $g_{s\mu}$ is two orders of magnitude smaller, and is responsible, together with moderately large $g_{b\mu}$ ($0.1 < |g_{b\mu}| < 1$, not shown in Fig. 2), for the correction of the 1-loop SM effect in $b \to s\mu^+\mu^-$.

Quite interestingly, the most stringent constraint in this model comes from the $B \to K\nu\bar{\nu}$, which also probes the coupling combinations responsible for lepton flavor violating $B \to K\mu\tau$ albeit with significantly better sensitivity.

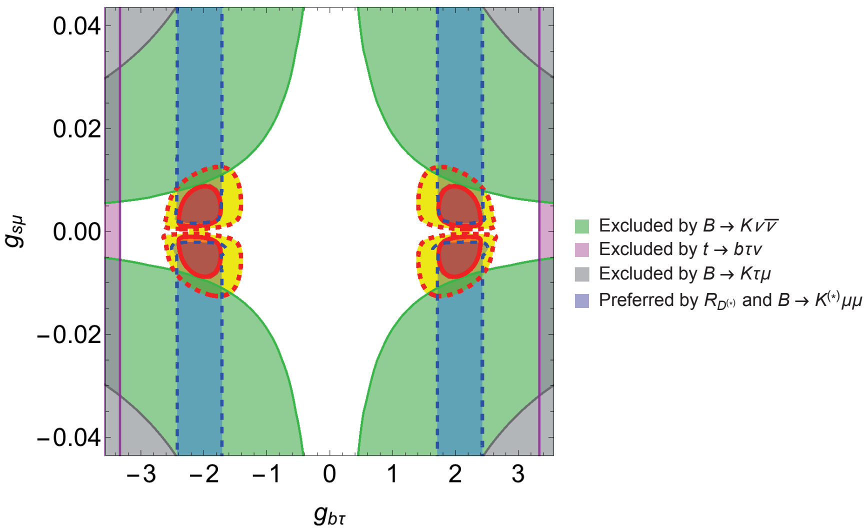


Figure 2 – Constraints of real parameters $g_{s\mu}$ and $g_{b\tau}$ in units $M_U$/TeV. The fitted regions are outlined in red ($1\sigma$) and red dashed ($2\sigma$). The region preferred by $R_{D^{(*)}}$ and $b \to s\mu^+\mu^-$ data is enclosed by blue dashed contour.

## 5 Conclusion

We have presented the current status of the LFU tests in $B$ meson decays. We have focused on the neutral current transitions driven by $b \to s\mu^+\mu^-$, and discussed how to explain the value of lepton flavor universality observable $R_K$. A scalar leptoquark $(3, 2, 1/6)$ can explain $R_K$ at tree level and could be exposed by further improvements in $B \to K^{(*)}\nu\bar{\nu}$[38]. For the vector leptoquark $(3, 3, 2/3)$ which couples to the left-handed fermions one can even attack simultaneously $R_K$ and $R_{D^{(*)}}$ puzzles. This scenario will ultimately be probed by improved sensitivity in $B \to K^{(*)}\nu\bar{\nu}$. Improved measurements of $R_K$ and related observables, e.g. $R_K^*$, will help to settle the issue of whether New Physics is at work in $B$ decays or not.

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