Leptoquark models for the $B$–physics anomalies

Olcyr Sumensari

Laboratoire de Physique Théorique (Bât. 210), CNRS and Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay cedex, France.

Instituto de Física, Universidade de São Paulo, C.P. 66.318, 05315-970 São Paulo, Brazil.

The $B$-physics experiments at LHCb, BaBar and Belle hint towards deviations from Lepton Flavor Universality in both the tree-level and loop-induced $B$ meson semileptonic decays. We propose a leptoquark model with light right-handed neutrinos which can accommodate both $R^{\text{exp}}_K < R^{\text{SM}}_K$ and $R^{\text{exp}}_D (\ast) > R^{\text{SM}}_D (\ast)$. We discuss several of its predictions which can be tested in modern day experiments. We also comment on the recent finding at LHCb, namely $R^{\text{exp}}_{K^*} < R^{\text{SM}}_{K^*}$.

1 Introduction

Even though no signal of New Physics appeared so far in the direct searches at the LHC, the $B$-physics experiments (BaBar, Belle and LHCb) hint at very intriguing deviations from lepton flavor universality (LFU). More specifically, the LHCb Collaboration measured the partial branching fractions of $B^+ \rightarrow K^+ \ell\ell$ in the bin $q^2 \in [1,6]$ GeV$^2$ and found

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu\mu)}{\mathcal{B}(B^+ \rightarrow K^+ ee)} = 0.745 \pm 0.090 \pm 0.074 \pm 0.036,$$

which lies 2.4$\sigma$ below the Standard Model (SM) prediction, $R^{\text{SM}}_K = 1.00(1)$.

Furthermore, another intriguing indication of LFU violation appeared in the tree-level processes, mediated by the charged currents,

$$R_D = \frac{\mathcal{B}(B \rightarrow D\tau\nu)}{\mathcal{B}(B \rightarrow D\ell\nu)} \bigg|_{\ell \in \{e,\mu\}} = 0.41 \pm 0.05,$$

which is obtained by combining several experimental values. This value appears to be 2.2$\sigma$ above the SM prediction, $R^{\text{SM}}_D = 0.286 \pm 0.012$, obtained by solely relying on the lattice QCD (LQCD) data for the form factors, recently computed in Ref.\(^4\). That result is corroborated by the experimentally established $R^{\text{exp}}_D = 0.310(15)(8)$, also confirmed by LHCb,\(^5\) which appears to be 3.3$\sigma$ larger than the SM prediction, $R^{\text{SM}}_D = 0.252 \pm 0.003$.\(^6\) Note, however, that the theoretical estimate of $R^{\text{SM}}_D$ relies strongly on experimental information extracted from the differential distribution of $d\Gamma(B \rightarrow D^*\ell\nu)/dq^2$ (with $\ell = e, \mu$). The LQCD result for the full set of $B \rightarrow D^*$ form factors is still not available, and those are mandatory to consistently consider NP scenarios with couplings to both $\mu$ and $\tau$ (and not only to $\tau$-leptons), as suggested by current data.

Several models have been proposed to simultaneously accommodate $R_K$ and $R_D(\ast)$, see Ref.\(^7\) and references therein. While many authors considered effective scenarios, very few viable
solutions to the puzzle of $B$-physics anomalies have been proposed. Among those, the models containing leptoquark (LQ) states are of particular interest as we will discuss in the following.

2 Leptoquark models for $b \to s\ell\ell$

Starting with the $R_K$ puzzle, the LQ states can be fully specified by their SM representation $(SU(3)_c, SU(2)_L)_{Y}$, where the hypercharge $Y$ is normalized by $Q = Y + T_3$. Among the LQ scenarios, the ones invoking vector LQs are not renormalizable and become problematic when computing the loop-induced processes, such as $\tau \to \mu\gamma$ and the $B_s \to \bar{B}_s$ mixing amplitude.\(^8\) In Table 1, we list the scalar LQ states that can modify $R_K$ through tree-level contributions to $b \to s\mu\mu$.\(^9\)

| $(SU(3)_c, SU(2)_L)_{U(1)_{Y}}$ | BNC | Interaction | Eff. Coefficients | $R_K/R_K^\text{SM}$ |
|-------------------------------|-----|-------------|-------------------|---------------------|
| $(3,3)_{1/3}$                 | $\times$ | $\overline{Q}C_{ij}T_2 \tau \cdot \Delta L$ | $C_9 = -C_{10}$ | $< 1$ |
| $(3,1)_{4/3}$                 | $\times$ | $d_R \Delta \ell_R$ | $(C_9)' = (C_{10})'$ | $\approx 1$ |
| $(3,2)_{7/6}$                 | $\checkmark$ | $\overline{Q}\Delta \ell_R$ | $C_9 = C_{10}$ | $> 1$ |
| $(3,2)_{1/6}$                 | $\checkmark$ | $\overline{d}_R \Delta \ell \gamma$ | $(C_9)' = -(C_{10})'$ | $< 1$ |

Table 1: List of LQ states which can modify $B(B \to K\mu^+\mu^-)$ at tree-level. The conservation of baryon number (BNC), the interaction term and the corresponding Wilson coefficients are also listed along with the prediction for $R_K$. Couplings to electrons are set to zero.

From this Table we see that only the states $(3,2)_{1/6}$ and $(3,3)_{1/3}$ can consistently accommodate $R_K^\text{exp} < R_K^\text{SM}$ at tree-level. Notice, however, that the latter state violates baryon number via the dangerous diquark couplings, which can induce the proton decay at tree-level.\(^10\) In the following we discuss how the scenario $(3,2)_{1/6}$, originally proposed in Ref.\(^11\), can be consistently extended to accommodate $R_K$ and $R_D$ without contradictions with other flavor physics constraints.

3 A leptoquark model to explain $R_K$ and $R_D$

In Ref.\(^7\), it was pointed-out that the inclusion of light right-handed (RH) neutrinos to the model $(3,2)_{1/6}$ induces new contributions to charged current processes. The Lagrangian of the model then becomes

$$L_{\Delta(1/6)} = Y^{ij}_L \overline{d}_R \Delta \gamma^\mu \gamma_{\mu} \frac{1}{2} L_{j} + Y^{ij}_R \overline{Q} \Delta_{i\gamma} \nu_{R,j} + \text{h.c.},$$

(3)

where $i, j$ stand for flavor indices and $y_{L,R}$ are two generic Yukawa matrices. The LQ doublet is denoted by $\Delta$ and we define the left-handed doublets as $Q_i = [(V^\dagger u_L)_i \ d_L)_j]^T$ and $L_j = [(U_{\nu L})_i \ \ell_{Li}]^T$, where $V$ and $U$ are the Cabibbo-Kobayashi-Maskawa (CKM) and Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrices, respectively. We reiterate that the novelty of this model is the introduction of the second term in Eq. (3) which induces the LQ interaction with up-type quarks.

In the following we assume that the two LQ are mass-degenerate, $m_\Delta \approx 1$ TeV, and that the RH neutrinos are massless in comparison with the hadronic scale. The transitions $b \to s\ell\ell$ and $b \to c\ell\nu$ can then be described by a low-energy effective theory with interaction terms

$$L_{\text{eff}}^{d_k \to d,\ell\ell} = \frac{Y^{ij}_L Y^{*kl}_L}{2 m_\Delta^2} \overline{d}_i \gamma_{\mu} P_R d_k \overline{\ell}_j \gamma^\mu P_L \ell_j + \text{h.c.},$$

(4)

and

$$L_{\text{eff}}^{d_k \to a\nu\tau} = \frac{(V \cdot Y_R)^{ij}_L Y^{*kl}_L}{2 m_\Delta^2} \left[ \overline{u}_i P_R d_k \overline{\ell}_j P_R \nu_j + \frac{1}{4} \overline{u}_i \sigma_{\mu\nu} P_R d_k \overline{\ell}_j \sigma^{\mu\nu} P_R \nu_j \right] + \text{h.c.},$$

(5)
which will be used in the phenomenological discussions below. Notice that the contributions to the charged processes (and to $b \to c\ell\nu$ in particular) depend on the existence of RH neutrinos.

4 Constraints and predictions

For simplicity, the couplings to the first generation are set to zero to avoid the potential problems with the atomic parity violation experiments,\(^{10}\) as well as the experimental limits on $\mathcal{B}(K \to \pi\nu\nu)$ and $\mathcal{B}(B_s \to \mu e)$.\(^7\) The couplings are varied within the perturbativity limit, $|\langle y_L \rangle_{ij}| \leq 4\pi$, and are confronted with several constraints of which the most relevant ones are: (i) the experimentally established $\mathcal{B}(B_s \to \mu \mu)$, and $\mathcal{B}(B \to K \mu \mu)$ in the [15, 19] GeV\(^2\) bin, (ii) $B_s - \overline{B}_s$ mixing, (iii) bounds on the lepton flavor violating $\tau$ decays, such as $\mathcal{B}(\tau \to \mu \phi)$ and $\mathcal{B}(\tau \to \mu \gamma)$, (iv) (semi–)leptonic meson decays, (v) the ratio $R_D^{\mu/e} = \mathcal{B}(B \to D\mu\nu)/\mathcal{B}(B \to D\nu)$, and (vi) limits on $\mathcal{B}(B \to K\nu\nu)$, cf. Ref.\(^7\) for details.

After applying the constraints described above, we find that this model can not only predict $R_K = 0.88(8)$, compatible with the experimental finding, but also accommodate the excess in $R_D$ at the 1$\sigma$ level. In other terms, our model can satisfactorily explain the anomalies $R_K$ and $R_D$. Notice that we only focus on $R_D$ because all the needed form factors have been computed on the lattice.\(^7\) We cannot provide the accurate statement concerning $R_{D^*}$ because the full set of $B \to D^*$ form-factors is not available from LQCD simulations. We can only make a qualitative observation that $R_{D^*} > R_{D^*}^{SM}$ in our model. Our main predictions are shown in Fig. 1 and summarized below:\(^7\)

- We computed the LFV decay $\mathcal{B}(B \to K\mu\tau)$, which is found to be
  \[ 2.1 \times 10^{-10} \leq \mathcal{B}(B \to K\mu\tau) \leq 6.7 \times 10^{-6}, \]
  also shown in Fig. 1. The predictions for the other LFV modes can be inferred bound given above via the relations $\mathcal{B}(B_s \to \mu\tau) \approx 0.9 \times \mathcal{B}(B \to K\mu\tau)$ and $\mathcal{B}(B \to K^*\mu\tau) \approx 1.8 \times \mathcal{B}(B \to K\mu\tau)$ derived in Ref.\(^{12}\).

- A distinctive prediction of the model is that the ratio $R_{\eta\ell} = \mathcal{B}(B_c \to \eta\ell\nu)/\mathcal{B}(B_c \to \eta\ell\nu)$ and the leptonic decay mode $\mathcal{B}(B_c \to \tau\nu)$ can be considerably larger than the SM predictions. We found that
  \[ 1.02 \leq R_{\eta\ell}/R_{\eta\ell}^{SM} \leq 1.21, \quad \text{and} \quad 5.5 \leq \mathcal{B}(B_c \to \tau\nu) \leq 16.1, \]
  as shown in Fig. 1, which offer an alternative experimental test of the validity of our model.

Can the $R_K$ hints be explained by scalar leptoquarks?

A preliminary result for $R_K$ has been presented by LHCb which indicates another deviation from LFU. The ratio $R_K = \mathcal{B}(B \to K^*\mu\mu)/\mathcal{B}(B \to K^*\mu\mu)$ in two different $q^2$ bins appears to be $2.2 - 2.4$ below the SM prediction.\(^{13}\) If confirmed, this result would exclude the model discussed above, since it predicts $R_K$ to be slightly larger than $R_K^{SM}$. The only LQ state that can explain both $R_K^{exp} < R_K^{SM}$ and $R_{D^*}^{exp} < R_{D^*}^{SM}$ at tree-level is the $SU(2)_L$ triplet (3, 3)\(^{14}\). Nonetheless, as discussed above, an additional symmetry is needed to forbid dangerous diquark couplings from destabilizing the proton.\(^{10}\) Another possibility recently proposed is to consider the doublet LQ (3, 2)\(_{7/6}\) amended with a symmetry to forbid the tree-level contribution to $b \to s\ell\ell$.\(^{15}\) This latter scenario generates the Wilson coefficients $C_9 = -C_{10} < 0$ through loops and it has the great advantage of not disturbing the proton stability.

5 Conclusions

In this proceeding we discussed a LQ model which can explain the LFU anomalies in both charged and neutral $B$-meson decays, namely $R_K^{exp} < R_K^{SM}$ and $R_{D^*}^{exp} > R_{D^*}^{SM}$. Our model offer
Figure 1 – The blue points are obtained by subjecting the Yukawa couplings of our model to the constraints discussed in Sec. 4, and the red ones are selected from the blue ones after requiring the compatibility with $R_{\text{exp}}$ to $2\sigma$. We plot our predictions for three selected quantities: $B(B \to K_{\mu\tau})$, the ratio between $R_{\eta_c} = B(B_c \to \eta_c\tau\bar{\nu})/B(B_c \to \eta_c\ell\bar{\nu})$ predicted by our model and its SM value, and a similar ratio of $B(B_c \to \tau\bar{\nu})$.

several predictions which can be tested in the near future: (i) branching ratios for the exclusive $b \to s\mu\tau$ modes can be as large as $\mathcal{O}(10^{-6})$, being also bounded from below; (ii) the LFUV effects in $R_{\eta_c} = B(B_c \to \eta_c\tau\nu)/B(B_c \to \eta_c\ell\nu)$ can be larger than predicted in the SM, and (iii) $B(B_c \to \tau\nu)$ is predicted to be enhanced by a factor of $5 \div 16$ with respect to the SM value. Furthermore, we devise a scalar LQ model which can explain $R_{K^{(*)}} < R_{K^{(*)}}^{\text{SM}}$ through loop effects.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreements No. 690575 and No. 674896.

References

1. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 113, 151601 (2014).
2. M. Bordone, G. Isidori and A. Pattori, Eur. Phys. J. C 76, no. 8, 440 (2016); G. Hiller and F. Kruger, Phys. Rev. D 69, 074020 (2004).
3. J. P. Lees et al. [BaBar Collaboration], Phys. Rev. Lett. 109 (2012) 101802; M. Huschle et al. [Belle Collaboration], Phys. Rev. D 92 (2015) no.7, 072014; A. Abdesselam et al. [Belle Collaboration], arXiv:1603.06711.
4. J. A. Bailey et al. [MILC Collaboration], Phys. Rev. D 92 (2015) no.3, 034506.
5. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, no. 11, 111803 (2015).
6. S. Fajfer, J. F. Kamenik, I. Nisandzic and J. Zupan, Phys. Rev. Lett. 109, 161801 (2012).
7. D. Bećirević, S. Fajfer, N. Košnik and O. Sumensari, Phys. Rev. D 94, no. 11, 115021 (2016).
8. S. Fajfer and N. Košnik, Phys. Lett. B 755, 270 (2016).
9. D. Bećirević, N. Košnik, O. Sumensari and R. Z. Funchal, JHEP 1611, 035 (2016).
10. I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Košnik, Phys. Rept. 641, 1 (2016).
11. D. Bećirević, S. Fajfer and N. Košnik, Phys. Rev. D 92, no. 1, 014016 (2015).
12. D. Bećirević, O. Sumensari and R. Z. Funchal, Eur. Phys. J. C 76, no. 3, 134 (2016).
13. S. Bifani, CERN Seminar, April 18, 2017.
14. A. Crivellin, D. Miller and T. Ota, arXiv:1703.09226 [hep-ph].
15. D. Bećirević and O. Sumensari, arXiv:1704.05835 [hep-ph].