PROCEEDINGS OF SCIENCE

Scalar leptoquarks in flavour physics

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We reinvestigate contributions of scalar leptoquarks in $R_{D^{(*)}}$ anomalies and use constraints from the branching fractions of $B \to K^{(*)}\nu\bar{\nu}$ decays. Then, we update the constraints on parameter space and find which scalar leptoquarks remain viable and consistent with low- and high-energy flavour physics constraints. We comment on the implications of such selection.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

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1. Introduction

In the last twelve years, disagreement between theoretical predictions and the experimental results for observables in $B \to D^{(*)}\ell\nu$ transitions motivated many studies of the lepton flavour universality violation (LFUV). This resulted in the intensive analysis of the Standard Model (SM) contributions to the hadronic matrix elements. Many beyond SM models were suggested to explain the difference between the experimental results and the SM predictions. The extensions of the SM by one or more $O(1\text{ TeV})$ leptoquarks seemed to be the most successful in explaining the experimental signatures of such scenarios, as well as in figuring out the ultraviolet (UV) completion of the proposed models. It is known that at least two scalar leptoquarks [1, 2] can accommodate the former $R_{K^{(*)}}$ and still persistent $R_{D^{(*)}}$ anomalies. The simplest vector leptoquark, U_1, could accommodate both types of LFUV, but in contrast to the models with scalar leptoquarks, this scenario is not renormalisable. In this case, the loop processes depend explicitly on the cutoff requiring to specify the UV completion. Recently, the LHCb experiment revised the LFUV results in the $b \to s\ell\ell$ modes. Namely, the measured ratios $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee) < 1$, were reexamined and LHCb found $R_K = 0.949(47)$ and $R_{K^*} = 1.027(75)$, consistent with lepton universality [3]. The world average values of the charged current B meson puzzle $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}l\nu)$, with $l \in \{e, \mu\}$, remain $R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}$ and a model with one $O(1\text{ TeV})$ scalar leptoquark is still a viable option to accommodate that experimental deviation.

We reinvestigate a minimalistic setup of only one scalar leptoquark explaining $R_{D^{(*)}}$ [4]. Additionally, another observable indicated the deviation from its value predicted in the SM. The measured branching ratio $\mathcal{B}(B^\pm \to K^\pm\nu\bar{\nu}) = 2.40(67) \times 10^{-5}$ [7, 8]. We are not concerned to accommodate that deviation concerning the SM prediction. Still, we are careful that our model does not lead to $\mathcal{B}(B^\pm \to K^\pm\nu\bar{\nu})$ in disagreements with the experimental observations.

2. Theoretical framework

First, we write the low-energy effective theory (LEET) of $b \to c\tau\nu$ transitions. We extend the LEET Lagrangian by including a singlet fermion N_R (right-handed neutrino), which appears in the models involving the $\widetilde{R}_2$ leptoquark [4]. The relevant terms are

$$\begin{aligned}\mathcal{L}_{\text{b}\to\text{c}\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[&(1+g_{V_L})\,(\bar{c}_L\gamma^\mu b_L)\,(\bar{\tau}_L\gamma_\mu\nu_{\tau L}) + g_{V_R}\,(\bar{c}_R\gamma^\mu b_R)\,(\bar{\tau}_L\gamma_\mu\nu_{\tau L}) \\ &+ g_{S_L}\,(\bar{c}_R b_L)\,(\bar{\tau}_R\nu_{\tau L}) + g_T\,(\bar{c}_R\sigma^{\mu\nu}b_L)\,(\bar{\tau}_R\sigma_{\mu\nu}\nu_{\tau L}) + \\ &+ \widetilde{g}_{S_R}(\bar{c}_L b_R)(\bar{\tau}_L N_R) + \widetilde{g}_T(\bar{c}_L\sigma^{\mu\nu}b_R)(\bar{\tau}_L\sigma_{\mu\nu}N_R)\Big] + \text{h.c.}\,. \end{aligned} \tag{1}$$

After LEET at a low energy scale, we have to use the framework of the SM effective theory (SMEFT). To perform the matching from the high to low energy theory, we use the renormalisation group running between the SMEFT Wilson coefficients and the low-energy coefficients g_i of Eq. (1), defined at scale $\mu = m_b$. the SMEFT Lagrangian can be written as

$$\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2}\sum_i C_i\,O_i\,. \tag{2}$$

In models with a single leptoquark, a natural choice for the normalisation scale is $\Lambda = m_{\text{LQ}}$. For the semileptonic processes with the SM neutrino (see Refs. [14-15] and non-SM right-handed neutrino

N_R-SMEFT in Ref. [16] as we explained in Ref. [4]). The following operators are relevant:

$$\mathcal{O}^{(1)}_{\substack{lequ\\prst}} = (\bar{l}^a_p e_r)\epsilon^{ab}(\bar{q}^b_s u_t)\,, \qquad \mathcal{O}^{(3)}_{\substack{lequ\\prst}} = (\bar{l}^a_p \sigma^{\mu\nu} e_r)\epsilon^{ab}(\bar{q}^b_s \sigma_{\mu\nu} u_t)\,, \tag{3}$$

$$\mathcal{O}^{(1)}_{\substack{lq\\prst}} = (\bar{l}^j_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu u_t)\,, \qquad \mathcal{O}^{(3)}_{\substack{lq\\prst}} = (\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)\,, \tag{4}$$

$$\mathcal{O}^{(1)}_{\substack{Nldq\\rst}} = (\bar{N}_R l^a_r)\epsilon^{ab}(\bar{d}_s q^b_t)\,, \qquad \mathcal{O}^{(3)}_{\substack{Nldq\\rst}} = (\bar{N}_R \sigma^{\mu\nu} l^a_r)\epsilon^{ab}(\bar{d}_s \sigma_{\mu\nu} q^b_t)\,. \tag{5}$$

The vector Wilson coefficients $C^{(1),(3)}_{lq}$ in Eq. (1) do not run, while the scalar and tensor do run. In our paper [4] we found that $g_S(m_b) = \pm 8.8 g_T(m_b)$. The same holds for $\widetilde{g}_{S_R}$ and $\widetilde{g}_T$. The indices l and q denote the doublet lepton and quark fields, respectively, u and e are singlet up-quark and charged-lepton fields. Matrices τ^I are the Pauli-matrices ($I = 1,2,3$) acting on $SU(2)_L$, while $a, b = 1, 2$ are the indices of $SU(2)_L$ doublets. Finally, the flavour indices are $prst$. We use the diagonal basis for the left-handed down-type quarks and charged leptons. To determine the amplitudes for the $B \to D^{(*)}\ell\nu$, we rely on the knowledge of form factors for the $B \to D^{(*)}$ transitions coming from the quark operators in the Lagrangian in (1). The form factors we use are explained in detail in [4].

3. Experimental constraints

The most recent experimental averages (see Ref. [23] in our paper [4]), are $R_D^{\rm exp} = 0.344(26)$ and $R_{D^*}^{\rm exp} = 0.285(12)$. After collecting all the information on the form factors

$$\begin{aligned}\frac{R_{D^{(*)}}}{R^{\rm SM}_{D^{(*)}}} &= \left|1 + g_{V_L}\right|^2 + a_S^{D^{(*)}}\left(\left|g_{S_L}\right|^2 + \left|\widetilde{g}_{S_R}\right|^2\right) + a_T^{D^{(*)}}\left(|g_T|^2 + |\widetilde{g}_T|^2\right)\\ &\quad + a_{SV}^{D^{(*)}}\,\mathrm{Re}\left[(1+g_{V_L})\,g^*_{S_L}\right] + a_{TV}^{D^{(*)}}\,\mathrm{Re}\left[(1+g_{V_L})\,g^*_T\right]\,,\end{aligned} \tag{6}$$

where in the case of D in the final state (see discussion in [4]) $a_S^D = 1.08(1)$, $a_T^D = 0.83(5)$, $a_{SV}^D = 1.54(2)$, and $a_{TV}^D = 1.09(3)$. Instead, for the case of D^* in the final state, we find: $a_S^{D^*} = 0.037(4)$, $a_T^{D^*} = 8.56(35)$, $a_{SV}^{D^*} = -0.107(11)$, and $a_{TV}^{D^*} = -2.91(11)$. The same interactions of leptoquarks can be tested at LHC in modifying the high dilepton mass tails of $pp \to \tau\nu, \tau\tau$ processes. We used the HighPT package [5, 6], which enabled us to constrain the leptoquark couplings for each leptoquark. The recent deviation of the measured $\mathcal{B}(B \to K\nu\bar{\nu})$ [7] concerning the SM prediction [8, 9] might be approached by the leptoquark interactions too. We do not aim to explain it, but we are concerned that our scenarios do not conflict with the experimental bounds on $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$ [10]. We also considered constraints coming from loop-induced processes $Z \to \ell\ell, \nu\nu$ and $\tau \to l\nu\bar{\nu}$ [4].

4. Leptoquarks explanations

In our approach, we consider contributions of weak doublets $R_2 \equiv (3, 2, 7/6)$, $\tilde{R}_2 \equiv (3, 2, 1/6)$ and a weak singlet $S_1 \equiv (\bar{3}, 1, -1/3)$ (see Ref. [11]) interacting with the third lepton generations only.

4.1 R_2

The Yukawa interactions of the flavours entering in the $R_{D^{(*)}}$ are described in detail in [4]. We choose only following Yukawa coupling $y^R_{b\tau}$, $y^L_{c\tau} \neq 0$. In the right panel of Fig. 1, we present

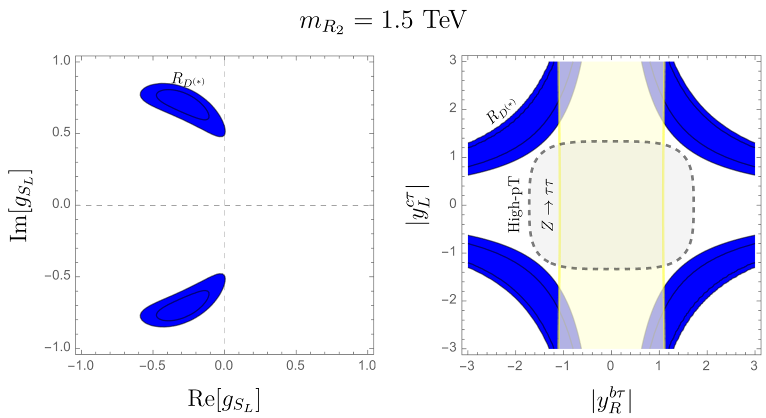

Figure 1: *R_2 bounds: In the left plot are shown the real and imaginary parts of $g_{S_L}(\mu = m_b)$ compatible with $R^{\rm exp}_{D^{(*)}}$ to 1 and 2σ ($m_{R_2} = 1.5$ TeV) Constraints on the Yukawa couplings are presented in the right plot but at the scale $\mu = m_{R_2}$.*

the constraints on the moduli of our Yukawa couplings ($|y^{b\tau}_R|$, $|y^{c\tau}_L|$). The 2σ constraints arising from experimental studies of the di-tau and mono-tau high-p_T tails at the LHC are in tension with the values of Yukawa couplings preferred by $R^{\rm exp}_{D^{(*)}}$. Since we rely on the down-quark mass, the tree-level flavour changing neutral semileptonic processes $b \to s$ or $b \to d$ are not allowed. Consequently, we do not expect significant effects in $b \to s\nu\bar{\nu}$ or $b \to s\ell^+\ell^-$ processes.

4.2 $\widetilde{R}_2$

We choose the nonzero couplings $\tilde{y}^{b\tau}_L$ and $\tilde{y}^{sN}_R$. This gives the scalar and tensorial contributions to $R_{D^{(*)}}$. The constraints are given in Fig. 2. The blue band corresponds to the constraint arising

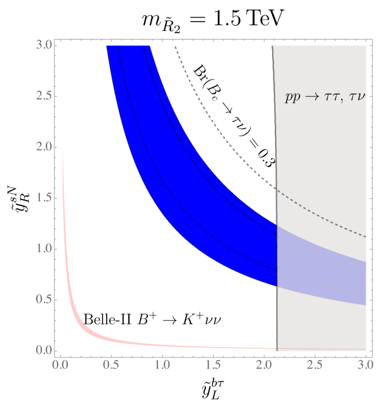

Figure 2: *$\widetilde{R}_2$ scenario at the high-energy scale $\mu = m_{\widetilde{R}_2} = 1.5$ TeV.*

from $R^{\rm exp}_{D^{(*)}}$, while the exclusion from the high-p_T tails corresponds to a shaded grey region. Limit on τ_{B_c} the requirement enforces $\mathcal{B}(B_c \to \tau\nu) \leq 30\%$, is below the dashed curve in the plot. The red curves correspond to the recently measured $\mathcal{B}(B \to K\nu\bar{\nu})$ [7].

4.3 S_1

The scalar singlet $S_1 \equiv (\bar{3}, 1, 1/3)$ is the last of the three possible scalar leptoquarks that can accommodate the experimental hint of LFUV with a minimal number of Yukawa couplings (two only). Ref. [4] explains that the two Yukawa couplings generate vector, scalar and tensor operator contributions, $g_{V_L} = \frac{v^2}{4V_{cb}} \frac{V_{cb}\,|y_L^{b\tau}|^2}{m_{S_1}^2}$, $g_{S_L}(m_{S_1}) = -\frac{v^2}{4V_{cb}} \frac{y_L^{b\tau}\, y_R^{c\tau *}}{m_{S_1}^2}$, with $g_{S_L}(m_b) = -8.8 \times g_T(m_b)$.

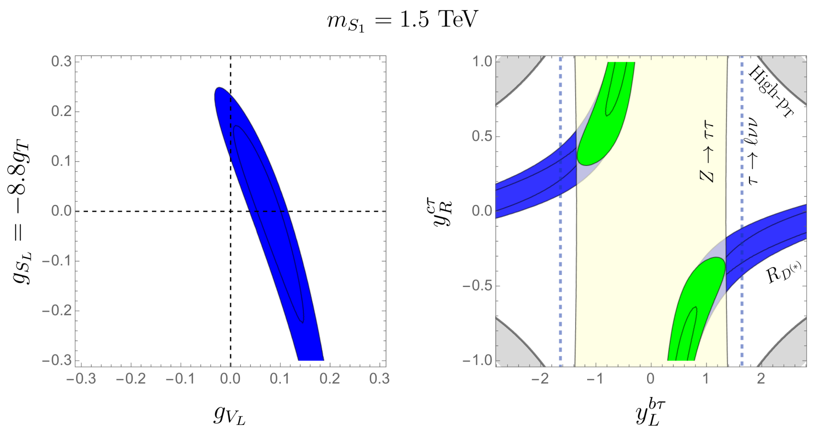

Figure 3: S_1 *bounds: In the left plot is shown the region of* g_{V_L} *and* $g_{S_L}(\mu = m_b) = -8.8 g_T(\mu = m_b)$ *compatible with* $R_{D^{(*)}}^{\rm exp}$ *to* 1σ *and* 2σ*. The constraints on the Yukawa couplings of the* S_1 *model are combined in the right plot.*

Our results in Fig. 3 contain blue and yellow regions respectively that depict the 2σ consistency with $R_{D^{(*)}}$ and $\mathcal{B}(Z \to \tau\tau)$. The latter is comparable with the constraint marked with dashed lines corresponding to the region allowed by $\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$ to 2σ. In this case, the grey regions are not allowed by the experimental studies of high-p_T tails of $pp \to \tau\nu, \tau\tau$ (to 2σ). Green regions result from the global fit at 1- and 2σ CL.

5. Conclusions

We reconsidered the explanation of the experimental indication of LFUV in $R_{D^{(*)}}^{\rm exp} > R_{D^{(*)}}^{\rm SM}$ by adding to the SM a single scalar leptoquark with the minimal number of Yukawa couplings. Among three leptoquarks R_2, $\tilde{R}_2$ and S_1 we find that only S_1, with Yukawa couplings to both left- and right-handed quark/lepton doublets, can explain the data $R_{D^{(*)}}^{\rm exp} > R_{D^{(*)}}^{\rm SM}$ without being in conflict with other constraints such as $\mathcal{B}(Z \to \tau\tau)^{\rm exp}$ and from the LHC studies of the tails of differential cross section of $pp \to \tau\tau, \tau\nu$ (+ soft jets) at high p_T. In our paper [4], we list several predictions that might support or invalidate the proposed model.

6. Acknowledgments

D.B.'s work is supported by the European Union's Horizon Europe research and innovation programme under the Marie Sklodowska-Curie Staff Exchange agreement No 101086085 -

ASYMMETRY and -Curie grant agreement No 860881-HIDDeN. S.F., N.K. and L.P. acknowledge financial support from the Slovenian Research Agency (research core funding No. P1-0035 and N1-0321).

References

[1] D. Bečirević, I. Doršner, S. Fajfer, N. Košnik, D. A. Faroughy and O. Sumensari, *Scalar leptoquarks from grand unified theories to accommodate the B-physics anomalies* Phys. Rev. D **98** (2018) no.5, 055003 doi:10.1103/PhysRevD.98.055003 [arXiv:1806.05689 [hep-ph]].

[2] D. Bečirević, I. Doršner, S. Fajfer, D. A. Faroughy, F. Jaffredo, N. Košnik and O. Sumensari, *Model with two scalar leptoquarks: R2 and S3*, Phys. Rev. D **106** (2022) no.7, 075023 doi:10.1103/PhysRevD.106.075023 [arXiv:2206.09717 [hep-ph]].

[3] R. Aaij *et al.* [LHCb], *Test of lepton universality in $b \to s\ell^+\ell^-$ decays*, Phys. Rev. Lett. **131** (2023) no.5, 051803 doi:10.1103/PhysRevLett.131.051803 [arXiv:2212.09152 [hep-ex]].

[4] D. Bečirević, S. Fajfer, N. Košnik and L. Pavičić, *RD(*) and survival of the fittest scalar leptoquark*, Phys. Rev. D **110** (2024) no.5, 055023 doi:10.1103/PhysRevD.110.055023 [arXiv:2404.16772 [hep-ph]].

[5] L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari and F. Wilsch, *HighPT: A tool for high-p_T Drell-Yan tails beyond the standard model,*, Comput. Phys. Commun. **289** (2023), 108749 doi:10.1016/j.cpc.2023.108749 [arXiv:2207.10756 [hep-ph]].

[6] L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari and F. Wilsch, *Drell-Yan tails beyond the Standard Model*, JHEP **03** (2023), 064 doi:10.1007/JHEP03(2023)064 [arXiv:2207.10714 [hep-ph]].

[7] I. Adachi *et al.* [Belle-II], *Evidence for $B+\to K+\nu\nu\,^{-}$ decays*, Phys. Rev. D **109** (2024) no.11, 112006 doi:10.1103/PhysRevD.109.112006 [arXiv:2311.14647 [hep-ex]].

[8] D. Bečirević, G. Piazza and O. Sumensari, *Revisiting $B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond*, Eur. Phys. J. C **83** (2023) no.3, 252 doi:10.1140/epjc/s10052-023-11388-z [arXiv:2301.06990 [hep-ph]].

[9] L. Allwicher, D. Becirevic, G. Piazza, S. Rosauro-Alcaraz and O. Sumensari, *Understanding the first measurement of $B \to K\nu\bar{\nu}$* , Phys. Lett. B **848** (2024), 138411 doi:10.1016/j.physletb.2023.138411 [arXiv:2309.02246 [hep-ph]].

[10] R. L. Workman *et al.* [Particle Data Group], *Review of Particle Physics*, PTEP **2022** (2022), 083C01 doi:10.1093/ptep/ptac097

[11] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Košnik, *Physics of leptoquarks in precision experiments and at particle colliders*, Phys. Rept. **641** (2016), 1-68 doi:10.1016/j.physrep.2016.06.001 [arXiv:1603.04993 [hep-ph]].

PoS(ICHEP2024)260