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Minimal scalar leptoquark model for $R_{D^{(*)}}$

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Motivated by the long-standing discrepancy in lepton flavor universality ratios R_D and R_{D^*} we assess the status of scalar leptoquark states R_2, $\tilde{R}_2$, and S_1 which can in principle provide a desired enhancement of $\mathcal{B}(B \to D^{(*)}\tau\nu)$ in a minimal setup with two Yukawa couplings only. We consider unavoidable low-energy constraints, Z-pole measurements as well as high-p_T constraints. After setting mass of each leptoquark to 1.5 TeV we find that of all considered states only S_1 leptoquark, coupled to both chiralities of leptons and quarks, is still a completely viable solution. On the other hand, the scenario with R_2 is in growing tension with $\Gamma(Z \to \tau\tau)$ and with the LHC constraints on the di-tau tails at high-p_T while the $\tilde{R}_2$ scenario is excluded by the $\mathcal{B}(B \to K^{(*)}\nu\nu)$ observable. We comment on the future experimental tests of S_1 scenario. Furthermore, a scenario of the S_1 leptoquark coupled exclusively to right-handed SM fermions and a right-handed neutrino N_R is also investigated as a potential solution for the $R_{D^{(*)}}$ with possible effects also in $\mathcal{B}(B \to K\nu\nu)$.

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1. Introduction

During the last twelve years, the experimental observations indicating the lepton flavor universality violation (LFUV) in $b \to c\ell\nu$ transitions motivated numerous studies of the BSM physics potentially leading to it. Specifically, the observable $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\nu)/(B \to D^{(*)}\ell\nu)$ is measured to be larger than its Standard Model (SM) prediction, with the combined deviation of $3.2\,\sigma$, given the HFLAV average [1]. Among different SM extensions, the low scale leptoquarks seem to be the most successful in providing the effect in $R_{D^{(*)}}$ while being consistent with numerous other low- and high-energy observables. In the past the different leptoquark solutions were proposed in order to accommodate for the two anomalies - $R_{K^{(*)}}$ and $R_{D^{(*)}}$ [2, 3], but since then the LHCb collaboration has reexamined the results in the $b \to s\ell\ell$ modes [4] finding the observable to completely agree with the SM. However, the anomaly in the $b \to c\ell\nu$ persists, and the one $O(1)$ TeV leptoquark model coupled to the third generation leptons remains the viable option to accommodate for the experimental excess. We reexamine the minimal leptoquark setup in [5]. Specifically, we investigate three different minimal leptoquark scenarios to find that only the S_1 scenario with both left- and right-handed interactions accommodates the anomaly and is still consistent with other observables.

In addition to the puzzle in the $b \to c\ell\nu$ transitions, the Belle II collaboration recently measured an excess in the branching ratio $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = 2.35(67) \times 10^{-5}$ [6], $2.7\,\sigma$ larger than the SM prediction. While the minimal leptoquark setup presented in [5] does not accommodate for the newly measured excess, we propose one additional minimal setup in [7] that accommodates for both excesses, namely the S_1 leptoquark coupled to the right-handed neutrinos.

2. EFT framework for $R_{D^{(*)}}$

The part of the low energy effective theory (LEFT) Lagrangian responsible for the $b \to c\ell\nu$ transition is

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

where we list only the subset that is relevant after matching the minimal models discussed in Sections 3. The important assumption through the paper is that the new physics is coupled only to the third generation leptons. We also added one singlet fermion N_R, also referred to as right-handed neutrino (RHN), since we consider the case of a light $\tilde{R}_2$ leptoquark coupling to the RHN on tree level. After calculating the amplitudes and accounting for the proper form factors (see the discussion in [5]), we find that the expression for $R_{D^{(*)}}$ is

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

where for the case of D meson in the final state, the coefficients are

$$a_S^D = 1.08(1), \quad a_T^D = 0.83(5), \quad a_{SV}^D = 1.54(2), \quad a_{TV}^D = 1.09(3), \tag{3}$$

and for the case of the D^* meson

$$a_S^{D^*} = 0.037(4), \quad a_T^{D^*} = 8.56(35), \quad a_{SV}^{D^*} = -0.107(11), \quad a_{TV}^{D^*} = -2.91(11)\,. \tag{4}$$

We have to stress that in this case the RHN is massless.

3. Leptoquark models for $R_{D^{(*)}}$

In the following section, we present three different scalar leptoquark models that provide the enhancing effect in the $R_{D^{(*)}}$ and study the constraints coming the other low- and high-energy observables, such as direct searches at colliders, high-p_T tails in $pp \to \tau\tau$ and $pp \to \tau\nu$ (using HighPT package [8, 9]), $Z \to \tau\tau$, $\tau \to \ell\nu\nu$ and B_s-meson mixing. As for $B \to K\nu\nu$, for these models, we use it as a constraint, rather than trying to accommodate the excess. We set all leptoquark masses in this section to 1.5 GeV.

3.1 R_2 and $\tilde{R}_2$

First we consider the R_2 leptoquark, whose quantum numbers are $(3, 2, 7/6)$ [10] and the model is described via

$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i^a\, e_j R_2^a \;+\; y_L^{ij}\,\overline{u}_{Ri} R_2^{T,a} \epsilon^{ab} L_j^b + \text{h.c.}\,, \tag{5}$$

and we consider the minimal coupling texture of only two non-zero Yukawa couplings, namely $y_R^{b\tau}$ and $y_L^{c\tau}$ in the down-quark mass basis. The results are shown on the left side of Figure 1 and we can see that the effects in $R_{D^{(*)}}$, the high-p_T tails and the $Z \to \tau\tau$ are incompatible with each other, rendering the model unviable.

The second model is $\tilde{R}_2$ leptoquark with the quantum numbers $(3, 2, 1/6)$ and is described by

$$\mathcal{L}_{\tilde{R}_2} = -\widetilde{y}_L^{ij}\overline{d}^i \widetilde{R}_2^a \epsilon^{ab} L^{j,b} + \widetilde{y}_R^{iN}\overline{Q}^{i,a}\widetilde{R}_2^a N_R + \text{h.c.} \tag{6}$$

where on top of the SM fermions we added a singlet state N_R , i.e. the right-handed neutrino. Once again, we consider a minimal texture of two non-zero Yukawa couplings - $\widetilde{y}_L^{b\tau}$ and $\widetilde{y}_R^{sN}$. The results are shown on the right side of the Figure 1 where we can see that the model can accommodate for the excess in $R_{D^{(*)}}$ but the effect in $\mathcal{B}(B \to K\nu\nu)$ is too large, also making the model not viable.

3.2 Left- and right-handed S_1

The S_1 leptoquark quantum numbers are $(\overline{3}, 1, 1/3)$ and its Lagrangian is the following:

$$\mathcal{L}_{S_1} = y_L^{ij}\,\overline{Q_i^C}^a\,\epsilon^{ab}\,L_j^b\,S_1 + y_R^{ij}\,\overline{u_i^C}\,e_j\,S_1 + \text{h.c.} \tag{7}$$

For the minimal setup of Yukawa couplings we choose $y_L^{b\tau}$ and $y_R^{c\tau}$ defined in the mass basis of the down-type quarks, as before. The results are shown on the Figure 2 and we can see that in this case the model can provide the desired effect in $R_{D^{(*)}}$ and at the same time it is consistent with other observables.

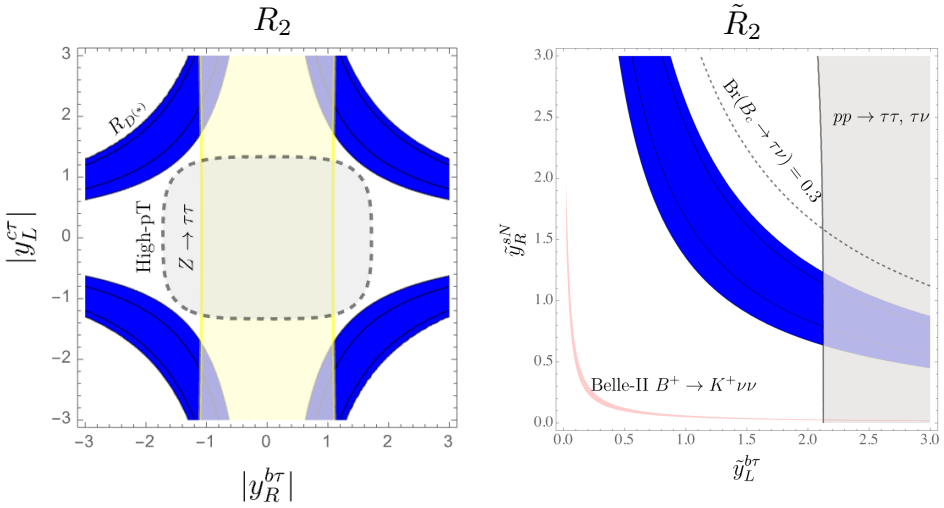

Figure 1: Left - the R_2 scenario where blue, yellow and gray region represent the regions allowed up to 2σ by $R_{D^{(*)}}$, $Z \to \tau\tau$ and high-p_T tails, respectively. Right - the $\tilde{R}_2$ scenario where blue and red region represent the allowed region up to 2σ by $R_{D^{(*)}}$ and $B \to K\nu\nu$, respectively and the gray region is excluded by the high-p_T tails. The dashed line represents the upper limit where the branching ratio for the $B_c \to \tau\nu$ would exceed the 30%.

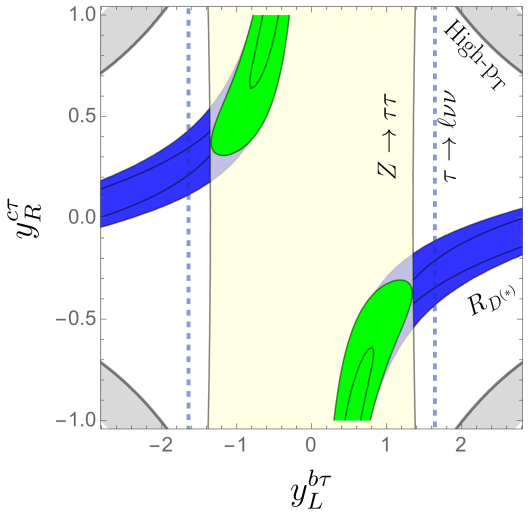

Figure 2: Plot showing combined constraints on the Yukawa couplings of the S_1 model specified in Eqs. (7): Blue and yellow regions respectively depict the 2σ consistency with $R_{D^{(*)}}$ and $\mathcal{B}(Z \to \tau\tau)$. The latter is comparable with the constraint marked with dashed lines corresponding to the region allowed by $\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$ to 2σ. Note that in this case the gray regions are not allowed by the experimental studies of high-p_T tails of $pp \to \tau\nu, \tau\tau$ (to 2σ as well). Green regions are the result of the global fit at 1- and 2σ CL.

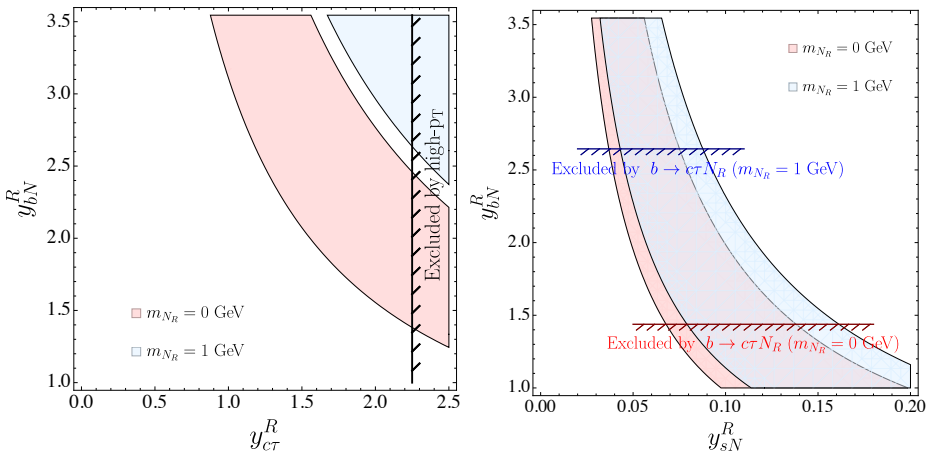

Figure 3: In the left plot we show y^R_{bN} vs $y^R_{c\tau}$ as obtained from the requirement of 2σ consistency with $R^{\text{exp}}_{D^{(*)}}$, for two values of m_{N_R}. Similarly, in the right one we show y^R_{bN} vs y^R_{sN} deduced from the consistency with $R_K^{\nu\nu\ (\text{exp})}$. The lower limit on y^R_{bN} from the left plot is indicated in the right one.

Given the allowed region on the Figure 2, one can make a series of predictions. More specifically, we have $\frac{\mathcal{B}(B_c\to\tau\nu)^{S_1}}{\mathcal{B}(B_c\to\tau\nu)^{\text{SM}}} \in [1.13, 1.48]$, $\frac{\mathcal{B}(B_s\to\tau\tau)^{S_1}}{\mathcal{B}(B_s\to\tau\tau)^{\text{SM}}} \in [0.73, 0.98]$, $\frac{\mathcal{B}(B\to K\tau\tau)^{S_1}}{\mathcal{B}(B\to K\tau\tau)^{\text{SM}}} \in [0.73, 0.98]$ and $\frac{\mathcal{B}(B\to K^{(*)}\nu\nu)^{S_1}}{\mathcal{B}(B\to K^{(*)}\nu\nu)^{\text{SM}}} \in [1.001, 1.02]$ at 2σ level. Also for the angular observables

$$F_L^{D^*} = 0.44(1)\,, \quad P_\tau^{D^*} = -0.53(3)\,, \quad A_{\text{fb}}^{D^*} = -0.05(1)\,, \quad A_{\text{fb}}^{D} = 0.33(1)\,, \tag{8}$$

that should be compared to the SM predictions $F_L^{D^*,\text{SM}} = 0.46(1)$, $P_\tau^{D^*,\text{SM}} = -0.51(2)$, $A_{\text{fb}}^{D,\text{SM}} = 0.3600(4)$, and $A_{\text{fb}}^{D^*,\text{SM}} = -0.06(1)$.

4. Right-handed S_1 in $R_{D^{(*)}}$ and $B \to K\nu\nu$

Finally, we consider the S_1 leptoquark that has only right-handed interactions and couples to the right-handed neutrino N_R. The Lagrangian with the minimal texture is the following:

$$\mathcal{L} \supset y^R_{c\tau}\, \overline{c^c} P_R \tau\, S_1 + y^R_{sN}\, \overline{s^c} P_R N_R\, S_1 + y^R_{bN}\, \overline{b^c} P_R N_R\, S_1 + \text{h.c.}\,, \tag{9}$$

where there are only three non-zero Yukawa couplings. In this model we let the RHN to be massive. The results are shown on the Figure 3 where it can be seen that there is a region in parameter space in which we successfully accommodate for both $R_{D^{(*)}}$ and $\mathcal{B}(B \to K\text{'inv'})$ for RHN masses up to 1 GeV.

Very few observables are affected by such minimal model, but massive RHN leaves a couple of very specific signatures. Most notably, in the angular observables that differentiate between lepton polarizations, such as τ-polarization asymmetry

$$\begin{aligned} &P_\tau^{D,\text{SM}} = 0.325(3)\,, \quad && P_\tau^{D}(m_{N_R} = 0\,\text{GeV}) = 0.25(2)\,, \quad && P_\tau^{D}(m_{N_R} = 1\,\text{GeV}) = 0.28(2) \\ &P_\tau^{D^*,\text{SM}} = -0.51(2)\,, \quad && P_\tau^{D^*}(m_{N_R} = 0\,\text{GeV}) = -0.39(4)\,, \quad && P_\tau^{D^*}(m_{N_R} = 1\,\text{GeV}) = -0.43(3), \end{aligned} \tag{10}$$

and also in observables that are directly proportional to RHN mass, such as $\mathcal{B}(B_s \to \text{'inv'})$ which is exactly 0 in the SM, but $(3 \pm 1) \times 10^{-6}$ for right-handed neutrino mass of 1 GeV.

5. Conclusion

In this work we revisited some possibilities of explaining the hint of LFUV in the $R_{D^{(*)}}$ by extending the SM by one scalar leptoquark with minimal setup. We explored three different scenarios and found that only the S_1 scenario with both right- and left-handed interactions provide the desired effect in $R_{D^{(*)}}$ while being consistent with other observables. In addition, we have presented one more scenario in order to explain both the excess in $R_{D^{(*)}}$ and $\mathcal{B}(B \to K\nu\nu)$. Namely, the S_1 leptoquark with only right-handed interactions. The model affects very few observables, but we find it has a specific signature in angular observables. More specifically, the presence of the right-handed neutrino can be inferred from precise measurements of tau polarizations in semileptonic decays, specifically the P_τ observable.

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