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Vector leptoquark resolution of R_K and $R_{D^{(*)}}$ puzzles

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ABSTRACT

We propose that three recent anomalies in B meson decays, $R_{D^{(*)}}$, R_K, and P_5', might be explained by only one vector leptoquark weak triplet state. The constraints on the parameter space are obtained by considering $t \to b\tau^+\nu$ data, lepton flavor universality tests in the kaon sector, bounds on the lepton flavor violating decay $B \to K\mu\tau$, and $b \to c\mu^-\bar{\nu}$ decays. The presence of such vector leptoquark could be exposed in precise measurements of top semitauonic decays to b quark. The model predicts enhanced decay rate of $B \to K\bar{\nu}\nu$, approximate equality of lepton flavor universality ratios R_{K^*}, R_K, and suppressed branching fraction of $B_s \to \mu^+\mu^-$.

1. Introduction

Although LHC has not found yet any particles not present in the Standard Model (SM), low-energy precision experiments in B physics pointed out a few puzzling results. Namely, we are witnessing persistent indications of disagreement with the SM prediction of lepton flavor universality (LFU) ratio in the τ/μ and/or τ/e sector. In the case of ratio $R_{D^{(*)}} = \frac{\Gamma(B\to D^{(*)}\tau^-\bar{\nu})}{\Gamma(B\to D^{(*)}\ell^-\bar{\nu})}$ [1–6], the deviation from the SM is at 3.5σ level [7] and has attracted a lot of attention recently [8–12]. Since the denominator of these ratios are the well measured decay rates with light leptons in the final states, $\ell = e, \mu$, the most obvious interpretation of $R_{D^{(*)}}$ results are in terms of new physics affecting semileptonic $b \to c\tau^-\bar{\nu}$ processes [13].

The second group of observables, testing rare neutral current processes with flavor structure $(\bar{s}b)(\mu^+\mu^-)$, also indicate anomalous behaviour [14–27]. Decay $B \to K^*\mu^+\mu^-$ deviates from the SM in the by-now-famous P_5' angular observable at the confidence level of above 3σ [28–30]. If interpreted in terms of new physics (NP), all analyses point to modifications of the leptonic vector current, which is also subject to large uncertainties due to nonlocal QCD effects. However, several studies have shown that even with generous errors assigned to QCD systematic effects, the anomaly is not washed away [31]. Furthermore, the sizable violation of LFU in the ratio $R_K = \frac{\Gamma(B\to K\mu\mu)}{\Gamma(B\to Kee)}$ in the dilepton invariant mass bin 1 GeV$^2 \le q^2 \le 6$ GeV^2 has been established at 2.6σ level. This ratio, being largely free of theoretical uncertainties and experimental systematics, deviates in the muon channel consistently with the deviation in $B \to K^*\mu^+\mu^-$. Strikingly enough, all these disagreements were observed in the B meson decays to the leptons of the second and third generation. As pointed out in [13] the lepton flavour universality has been tested at percent level and is, in the case of pion and kaon, in excellent agreement with the SM predictions. It has been already suggested that scalar leptoquark might account for this anomalous behaviour in the recent literature [16,32–34,7,18,35].

Many models of NP [14,35,16,8,17,9,18–25,34] have been employed to explain either R_K and P_5' anomalies or $R_{D^{(*)}}$. It was suggested in Ref. [9] that R_K and P_5' can be explained if NP couples only to the third generation of quarks and leptons. Similarly, the authors of [36] suggested that both $R_{D^{(*)}}$ and R_K anomalies can be correlated if the effective four-fermion semileptonic operators consist of left-handed doublets. The model of [37] proposed existence of an additional weak bosonic triplet and falls in the category of weak doublet fermions coupling to the weak triplet bosons, which then can explain all three B meson anomalies. Among the NP proposals a number of them suggest that one scalar leptoquark accounts for either $R_D^{(*)}$ or R_K anomalies. However, in the recent paper [7] both deviations were addressed by a single scalar leptoquark with quantum numbers $(3, 1, -1/3)$ in such a way that $R_{D^{(*)}}$ anomalies are explained at the tree level, while R_K receives contributions at loop level. This scalar leptoquark unfortunately can couple to a diquark state too and therefore it potentially leads to proton decay. One may impose that this dangerous coupling vanishes, but such a scenario is not easily realised within Grand Unified Theories.

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In this paper, we extend the SM by a vector $SU(2)$ triplet leptoquark, which accomplishes both of the above requirements by generating purely left-handed currents with quarks and leptons. Furthermore, the triplet nature of the state connects the above mentioned anomalies with the rare decay modes of B mesons to a final states with neutrinos, and various charged lepton flavor violating decay modes. The considered state has no couplings to diquarks and has therefore definite baryon and lepton numbers and does not mediate proton decay. In [36] the same leptoquark state has been considered in a more restricted scenario with couplings to the third generation fermions in the weak basis.

The outline of this paper is the following: In Sec. 2 we describe how to accommodate $R_{D^{(*)}}$ and R_K within the scenario where vector triplet leptoquark mediates quark and lepton interactions. Sec. 3 discusses current constraints on the model and further experimental signatures of this model, while in the last section we present conclusions.

2. Signals

The vector multiplet U_3^μ that transforms under the SM gauge group as $(3,3,2/3)$ couples to a leptoquark current with $V-A$ structure:

$$\mathcal{L}_{U_3} = g_{ij}\,\bar{Q}_i\gamma^\mu\,\tau^A U^A_{3\mu}\,L_j + \text{h.c.}. \tag{1}$$

Here τ^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, respectively. The couplings g_{ij} are in general complex parameters, while for the sake of simplicity we will restrict our attention to the case where they are real. 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 destabilising the proton. The interaction Lagrangian (1) 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 ℓ_{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:

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

If ultraviolet origin of the U_3^μ 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 renormalisability, in contrast to the effective theory of Eq. (1). In this work 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:

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

$$\mathcal{V}g = \begin{pmatrix} 0 & \mathcal{V}_{us}g_{s\mu}+\mathcal{V}_{ub}g_{b\mu} & \mathcal{V}_{ub}g_{b\tau} \\ 0 & \mathcal{V}_{cs}g_{s\mu}+\mathcal{V}_{cb}g_{b\mu} & \mathcal{V}_{cb}g_{b\tau} \\ 0 & \mathcal{V}_{ts}g_{s\mu}+\mathcal{V}_{tb}g_{b\mu} & \mathcal{V}_{tb}g_{b\tau} \end{pmatrix}. \tag{3}$$

The rotated matrix $\mathcal{V}g$ determines the couplings of the LQ to the up-type quarks among which we also have a $U^{(2/3)}_{3\mu}$ coupling to $\bar{c}\nu$, required to explain $R_{D^{(*)}}$.

The leptoquark U_3 implements a combination of Wilson coefficients in the $b\to s\mu^+\mu^-$ effective Lagrangian [18,38],

$$C_9 = -C_{10} = \frac{\pi}{\mathcal{V}_{tb}\mathcal{V}^*_{ts}\alpha}\,g^*_{b\mu}g_{s\mu}\,\frac{v^2}{M_U^2}, \tag{4}$$

which has been shown to significantly improve the global fit of the $b\to s\mu^+\mu^-$ observables with the 1σ preferred region $C_9\in[-0.81,-0.50]$ [39], see also [40]. Here $v=246$ GeV is the electroweak vacuum expectation value. In this case we find

$$g^*_{b\mu}g_{s\mu}\in[0.7,1.3]\times10^{-3}\;(M_U/\text{TeV})^2\,. \tag{5}$$

Note that the effective coupling (4) also brings the LFU observable R_K in agreement with the experimental value [39].

On the other hand, the correction to the semileptonic decays $b\to c\tau^-\bar{\nu}$ also proceeds via exchange of the $U^{(2/3)}_{3\mu}$ state. The effective semileptonic Lagrangian in the SM complemented by the LQ correction is:

$$\begin{aligned}\mathcal{L}_{\text{SL}} = {} & -\left[\frac{4G_F}{\sqrt{2}}\mathcal{V}_{cb}\mathcal{U}_{\tau i} + \frac{g^*_{b\tau}(\mathcal{V}g\mathcal{U})_{ci}}{M_U^2}\right](\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L\nu_i) \\ & + \text{h.c.}\end{aligned} \tag{6}$$

The second term shifts the effective value of $|\mathcal{V}_{cb}|^2$ as measured in semitauonic decays summed over all neutrino species in the final state:

$$\left|\mathcal{V}^{(\tau)}_{cb}\right|^2 \simeq |\mathcal{V}_{cb}|^2\left[1+\frac{v^2}{M_U^2}\text{Re}\left(\frac{g^*_{b\tau}(\mathcal{V}g)_{c\tau}}{\mathcal{V}_{cb}}\right)\right]. \tag{7}$$

The above expression contains the interference term with the SM amplitude while the pure LQ contribution is rendered negligible compared to the interference term by an additional factor v^2/M_U^2. In the same manner the semimuonic decay widths $b\to c\mu^-\bar{\nu}$ are proportional to $|\mathcal{V}^{(\mu)}_{cb}|^2$ that is given by an analogous expression to Eq. (7). From the fit to the measured ratio $R_{D^{(*)}}$ done in Ref. [34] we learn that at 1σ we have the following constraint:

$$\text{Re}\left[g^*_{b\tau}(\mathcal{V}g)_{c\tau} - g^*_{b\mu}(\mathcal{V}g)_{c\mu}\right] = (0.18\pm0.04)\;(M_U/\text{TeV})^2\,. \tag{8}$$

We are allowing for LQ modifications to take place for both $\ell=\mu,\tau$ in $b\to c\ell^-\bar{\nu}$.

In summary, the data on $b\to s\mu^+\mu^-$ and $R_{D^{(*)}}$ points to a region in parameter space where

$$\begin{aligned} & g_{b\mu}g_{s\mu}\approx10^{-3}, \\ & \mathcal{V}_{cb}(g^2_{b\tau}-g^2_{b\mu}) - g_{b\mu}g_{s\mu}\approx0.18, \end{aligned} \tag{9}$$

is satisfied, 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, $|g_{s\mu}|,|g_{b\mu}|\gtrsim3\times10^{-4}$. The second equation can be simplified to

$$g^2_{b\tau}-g^2_{b\mu}\approx4.4, \tag{10}$$

which indicates $|g_{b\tau}|\gtrsim2$.

3. Additional constraints

3.1. LFU in the kaon sector

Potentially very severe constraints are the measurements of $|\mathcal{V}_{us}|$ in kaon muonic decays due to $U_{3\mu}$ contributions in $s \to u\mu^-\bar{\nu}$ but not in $s \to ue^-\bar{\nu}$, since first generation charged leptons are not affected by the studied LQ at tree level. Effects of this type are exposed by the lepton flavor universality ratios between decays involving the kaon and different charged leptons:

$$R^K_{e/\mu} = \frac{\Gamma(K^- \to e^-\bar{\nu})}{\Gamma(K^- \to \mu^-\bar{\nu})}, \qquad R^K_{\tau/\mu} = \frac{\Gamma(\tau^- \to K^-\nu)}{\Gamma(K^- \to \mu^-\bar{\nu})}. \tag{11}$$

Note that the value of $|\mathcal{V}_{us}|$ obtained from the global CKM fits relies on the data on semielectronic decays (cf. experimental inputs to $\mathcal{V}_{us}$ of the CKMfitter results [41] prepared for the EPS 2015 conference) that are not subject to the leptoquark amplitudes. The SM value of $|\mathcal{V}_{us}|$ is thus not a relevant constraint on the leptoquark couplings. The measured value of $R^K_{e/\mu}$ is due to the NA62 experiment [42] while the SM prediction has been calculated with negligible uncertainty [43] and is in good agreement with the experimental result:

$$\begin{aligned} R^{K(\mathrm{exp})}_{e/\mu} &= (2.488 \pm 0.010) \times 10^{-5}, \\ R^{K(\mathrm{SM})}_{e/\mu} &= (2.477 \pm 0.001) \times 10^{-5}. \end{aligned} \tag{12}$$

In the τ/μ sector, the SM prediction and the value obtained from the measured branching fractions [44] agree as well:

$$\begin{aligned} R^{K(\mathrm{exp})}_{\tau/\mu} &= (1.101 \pm 0.016) \times 10^{-2}, \\ R^{K(\mathrm{SM})}_{\tau/\mu} &= (1.1162 \pm 0.00026) \times 10^{-2}. \end{aligned} \tag{13}$$

From the Lagrangian (2) and couplings (3) one can derive the LQ modification of $\mathcal{V}_{us}$ as measured in $s \to u\mu^-\bar{\nu}$ decay:

$$\begin{aligned} \mathcal{V}^{(\mu)}_{us} &= \mathcal{V}_{us}\left[1 + \frac{v^2}{2M_U^2}\mathrm{Re}\left(\frac{g^*_{s\mu}(\mathcal{V}g)_{u\mu}}{\mathcal{V}_{us}}\right)\right] \\ &\equiv \mathcal{V}_{us}\left[1 + \delta^{(\mu)}_{us}\right]. \end{aligned} \tag{14}$$

Again, we have neglected the pure LQ terms which are proportional to v^4/M_U^4. The presence of LQ modifies both LFU ratios $R^K_{e/\mu}$, $R^K_{\tau/\mu}$ by a common factor

$$R^{K(\mathrm{SM})}_{\ell/\mu} \to R^{K(\mathrm{SM})}_{\ell/\mu}\left[1 - 2\delta^{(\mu)}_{us}\right], \qquad \ell = e, \tau. \tag{15}$$

We determine $\delta^{(\mu)}_{us} = (-2.2 \pm 2.2) \times 10^{-3}$ and $\delta^{(\mu)}_{us} = (6.7 \pm 7.1) \times 10^{-3}$ using the e/μ (12) and τ/μ (13) LFU ratios, respectively. Combining the two determinations of δ^{μ}_{us} results in average value $\delta^{(\mu)}_{us} = (-1.4 \pm 2.1) \times 10^{-3}$ and allows to put constraint on the LQ couplings:

$$\begin{aligned} &\mathrm{Re}\left(|g_{s\mu}|^2 + \frac{\mathcal{V}_{ub}}{\mathcal{V}_{us}} g^*_{s\mu} g_{b\mu}\right) \\ &\quad = (-4.6 \pm 6.9) \times 10^{-2} (M_U/\mathrm{TeV})^2. \end{aligned} \tag{16}$$

3.2. Semitauonic top decays

The eigencharge state $U^{(2/3)}_{3\mu}$ can have large effects also in semileptonic decays of the top quarks, in particular in the decay mode $t \to b\tau^+\nu$ being a purely third-generation transition. The correction to the tau-specific CKM element $\mathcal{V}_{tb}$ reads

$$\mathcal{V}^{(\tau)}_{tb} = \mathcal{V}_{tb}\left[1 + \delta^{(\tau)}_{tb}\right], \qquad \delta^{(\tau)}_{tb} = \frac{v^2}{2M_U^2}\,\mathrm{Re}\left(\frac{g^*_{b\tau}(\mathcal{V}g)_{t\tau}}{\mathcal{V}_{tb}}\right). \tag{17}$$

The correction $\delta^{(\tau)}_{tb}$ should be smaller than the relative error on $\mathcal{V}_{tb}$ as measured in decay $\mathcal{B}(t \to b\tau^+\nu) = 0.096 \pm 0.028$ by the CDF Collaboration [45]:

$$\frac{v^2}{M_U^2}\,\mathrm{Re}\left(\frac{g^*_{b\tau}(\mathcal{V}g)_{t\tau}}{\mathcal{V}_{tb}}\right) < 0.29. \tag{18}$$

This bound can be interpreted as

$$|g_{b\tau}| < 2.2\,(M_U/\mathrm{TeV}). \tag{19}$$

Recent analysis of the top decays in the $t\bar{t}$ production channel already probed $\mathcal{V}_{tb}$ in semitauonic decays of the top quark with competitive precision [46,47].

3.3. $b \to c\mu^-\bar{\nu}$ decay

For the rate of the semimuonic decays we are not aware, to our best knowledge, of an experimental measurement of $B \to D\ell^-\bar{\nu}$ quoting separate lepton-specific rates for $\ell = e$ and $\ell = \mu$. From the data on the semileptonic decays $b \to c\ell^-\bar{\nu}$ the average of inclusive and exclusive determinations is $|\mathcal{V}_{cb}|_{\mathrm{exp.}} = (41.00 \pm 1.07) \times 10^{-3}$, a value reported by the HFAG [48] and used by the CKMfitter group. On the other hand, CKMfitter performed a fit without using $|\mathcal{V}_{cb}|_{\mathrm{exp.}}$ as input and the preliminary result is then $|\mathcal{V}_{cb}|_{\mathrm{indirect}} = (42.99^{+0.36}_{-1.41}) \times 10^{-3}$ [41]. The difference between experimental and indirect determination of $\mathcal{V}_{cb}$ can then be assigned to the leptoquark contribution:

$$\begin{aligned} |\mathcal{V}_{cb}|_{\mathrm{exp.}} - |\mathcal{V}_{cb}|_{\mathrm{indirect}} &= (-2.0^{+1.7}_{-1.2}) \times 10^{-3} \\ &= \frac{v^2}{2M_U^2}|\mathcal{V}_{cb}|\mathrm{Re}\left(\frac{g^*_{b\mu}(\mathcal{V}g)_{c\mu}}{\mathcal{V}_{cb}}\right). \end{aligned} \tag{20}$$

The ensuing constraint is

$$|\mathcal{V}_{cb}|\mathrm{Re}\left(\frac{g^*_{b\mu}(\mathcal{V}g)_{c\mu}}{\mathcal{V}_{cb}}\right) \in [-0.1, -0.01] \times 10^{-3}\,(M_U/\mathrm{TeV})^2\,. \tag{21}$$

Notice that the considered leptoquark does not affect the semielectronic decays, and that the entire effect originates from semimuonic decays in our model. Although the presented bound includes intrinsic pollution from the semielectronic events, in lack of better constraint, we apply it as a bound on the LQ modification of semimuonic decays. It would be indeed very useful to have experimental results on the semileptonic rates for different leptons in the final states.

3.4. $B \to K\mu\tau$ decay

The observables that probe the LQ couplings with the b quark and violate lepton flavor are, at tree level, $B^- \to K^-\mu^+\tau^-$ and decays of bottomonium to $\tau\mu$. The branching ratio of the latter process is constrained at the level of 10^{-6} but taking into account large decay widths of bottomonia states, these bounds are not competitive with the bound $\mathcal{B}(B^- \to K^-\mu^+\tau^-) < 2.8 \times 10^{-5}$ at 90% CL [49]. We can estimate the decay width by adapting the bound from the very same process analysed in the case of scalar leptoquark in the representation $(\bar{3}, 1, 4/3)$ [50]:

$$|g_{b\tau}\, g_{s\mu}| \lesssim 0.09 (M_U/\mathrm{TeV})^2. \tag{22}$$

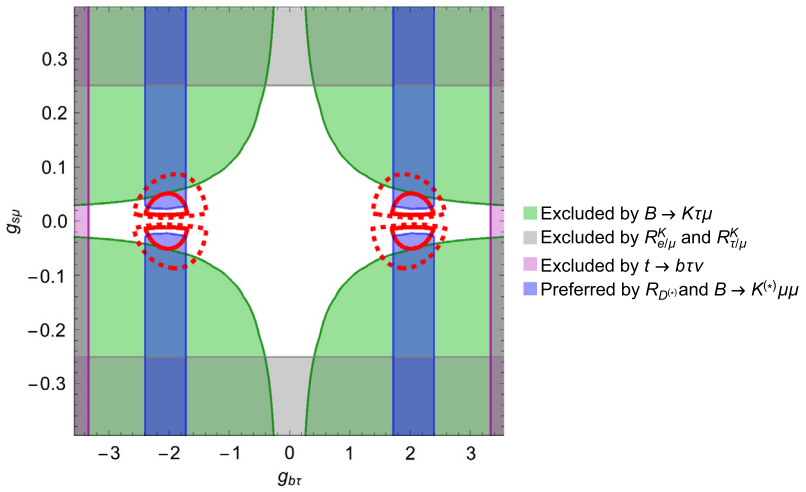

Fig. 1. Constraints of real parameters $g_{s\mu}$ and $g_{b\tau}$ in units M_U/TeV. The fitted regions are outlined in thick (1σ) and thick dashed (2σ).

3.5. Fitting the couplings

In Fig. 1 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 one to two orders of magnitude smaller, and is responsible, together with moderately large $g_{b\mu}$ ($0.1 \lesssim |g_{b\mu}| \lesssim 1$, not shown in Fig. 1), for the correction of the 1-loop SM effect in $b \to s\mu^+\mu^-$.

3.6. Further experimental signatures

The effect of the LQ triplet state in $B \to K^{(*)}\mu^+\mu^-$ directly implies an effect of similar size in $B \to K^{(*)}\bar{\nu}\nu$. Using the notation of Refs. [51,52] and extended in [33] to account for lepton flavor violation, we employ the effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{b\to s\bar{\nu}\nu} = \frac{G_F\alpha}{\pi\sqrt{2}}\mathcal{V}_{tb}\mathcal{V}_{ts}^* C_L^{ij}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j). \tag{23}$$

The effect of the U_3 leptoquark has been already studied in [52]. In the SM we have, for each pair of neutrinos, $C_L^{\text{SM}} = -6.38 \pm 0.06$ [51], while the vector LQ generates $C_L^{\mu\mu} = 2C_9$, where C_9 is defined in Eq. (4). The branching ratio is inclusive of all neutrino species and in this case the unitarity of the PMNS matrix U allows us to ignore neutrino mixing and we can set $\mathcal{U} = 1$ [53]. The relative modification of the decay rates of $B \to K^{(*)}\bar{\nu}\nu$ is equal for both K and K^* [52] and reads

$$1 + \frac{4}{3}\text{Re}(C_9/C_L^{\text{SM}}) + \frac{4}{3}|C_9/C_L^{\text{SM}}|^2. \tag{24}$$

The enhancement factor from the dominant interference term can reach up to 1.17 for $C_9 = -0.8$.

Consequences of the vector LQ for rare charm decays can be extracted from the couplings of the $U_3^{(5/3)}$ in Eq. (2). One can easily derive the contribution to the $c \to u\mu^+\mu^-$ effective Lagrangian. Following notation of Ref. [54], one can easily find that there is contribution to $C_{9,10}^{(\bar{u}c)}$ Wilson coefficients:

$$C_9^{(\bar{u}c)} = -C_{10}^{(\bar{u}c)} = \frac{2\pi(\mathcal{V}g)_{u\mu}(\mathcal{V}g)_{c\mu}^*}{\mathcal{V}_{ub}\mathcal{V}_{cb}^*\alpha}\frac{v^2}{M_U^2}. \tag{25}$$

We find $|\tilde{C}_9| \equiv |C_9^{(\bar{u}c)}/(\mathcal{V}_{ub}\mathcal{V}_{cb}^*)| \lesssim 0.05$, an order of magnitude below the currently allowed bound $|\tilde{C}_9| \leq 0.63$ [54].

One of the most sensitive channels to test this model is the decay $t \to b\tau^+\nu$ which was already used to constrain the couplings. The largest coupling $g_{b\tau}$ which drives this top decay is large, $|g_{b\tau}| \sim 2$, and according to Eq. (17) it increases the decay rate by 20%.

In addition, the U_3 leptoquark contributes to $R_{K^*} = \Gamma(B \to K^*\mu^+\mu^-)/\Gamma(B \to K^*e^+e^-)$. As already discussed in [55], in scenarios with left-handed currents the two LFU ratios, R_{K^*} and R_K, are predicted to be approximately equal, where the only difference between them originates from the small quadratic term of the LQ amplitude. Future LHCb measurements of R_{K^*} will definitely help in differentiation between different models. Another immediate consequence of positive LQ contribution to the C_{10}, ranging from 0.4 to 0.8 at 1σ CL, is destructive interference with the negative C_{10}^{SM}, which results in 20–35% smaller branching fraction compared to the SM face value for the time integrated branching fraction $\text{Br}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$ [56].

4. Conclusions

We propose that the simple extension of the SM by vector leptoquark that is a weak triplet can simultaneously explain all three recent B physics anomalies. This triplet contains massive vector states with electric charges 5/3, 2/3 and −1/3. The coupling of the charge 2/3 state with the second and third generation of down quarks and charged leptons introduces, via CKM and PMNS mixing, coupling of the 2/3 state to the up-type quarks and neutrinos, charge −1/3 state to the down-type quarks and neutrinos, and couplings of charge 5/3 state to up-type quarks and charged leptons. Our model is constrained by a number of tree level processes in addition to the B physics anomalies: tests of lepton flavor universality in K physics, semileptonic top decays $t \to b\tau^+\nu$, $b \to c\ell^-\bar{\nu}$ transition, and lepton flavor violating decay $B \to K\mu\tau$. We predict also that vector leptoquark affects $c \to u\mu^+\mu^-$ decays. The most stringent constraint comes from $D^0 \to \mu^+\mu^-$ decay as noticed in [54]. However, our prediction for the appropriate Wilson coefficients $C_{9,10}$ turned out to be much smaller than the ones allowed by the experimental data as discussed in [54]. We have also predicted moderate increases of decay $B \to K\bar{\nu}\nu$ and top decay $t \to b\tau^+\nu$. Our results are normalised to the mass of this states to be 1 TeV, which is in agreement with current direct searches of CMS/ATLAS limits on the leptoquark of the second/third generation [57,58]. Further efforts on both sides—theoretical and experimental—might help to understand better impact and perspective of this NP candidate.

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