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Excesses of muon $g-2$, $R_{D^{(*)}}$, and $R_{K^{(*)}}$ in a leptoquark model

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ABSTRACT

In this study, we investigate muon $g-2$, $R_{K^{(*)}}$, and $R_{D^{(*)}}$ anomalies in a specific model with one doublet, one triplet, and one singlet scalar leptoquark (LQ). When the strict limits from the $\ell' \to \ell\gamma$, $\Delta B = 2$, $B_s \to \mu^+\mu^-$, and $B^+ \to K^+\nu\bar{\nu}$ processes are considered, it is difficult to use one scalar LQ to explain all of the anomalies due to the strong correlations among the constraints and observables. After ignoring the constraints and small couplings, the muon $g-2$ can be explained by the doublet LQ alone due to the m_t enhancement, whereas the measured and unexpected smaller $R_{K^{(*)}}$ requires the combined effects of the doublet and triplet LQs, and the R_D and R_{D^*} excesses depend on the singlet LQ through scalar- and tensor-type interactions.

1. Introduction

Several interesting excesses in semileptonic B decays have been determined in experiments such as: (i) the angular observable P_5' of $B \to K^*\mu^+\mu^-$ [1], where a 3.4σ deviation due to the integrated luminosity of 3.0 fb^{-1} was found at the LHCb [2,3], and the same measurement with a 2.6σ deviation was also reported by Belle [4]; and (ii) the branching fraction ratios R_{D,D^*}, which are defined and measured as [5–10]:

$$R_D = \frac{\bar{B} \to D\tau\nu}{\bar{B} \to D\ell\nu} = \begin{cases} 0.375 \pm 0.064 \pm 0.026 & \text{Belle [5]}, \\ 0.440 \pm 0.058 \pm 0.042 & \text{BaBar [6,7]}, \end{cases}$$

$$R_{D^*} = \frac{\bar{B} \to D^*\tau\nu}{\bar{B} \to D^*\ell\nu} = \begin{cases} 0.302 \pm 0.030 \pm 0.011 & \text{Belle [8]}, \\ 0.270 \pm 0.035 \pm^{+0.028}_{-0.025} & \text{Belle [9]}, \\ 0.332 \pm 0.024 \pm 0.018 & \text{BaBar [6,7]}, \\ 0.336 \pm 0.027 \pm 0.030 & \text{LHCb [10]}, \end{cases} \quad (1)$$

where $\ell = (e, \mu)$, and these measurements can test the violation of lepton-flavor universality. The averaged results from the heavy flavor averaging group are $R_D = 0.403 \pm 0.040 \pm 0.024$ and $R_{D^*} = 0.310 \pm 0.015 \pm 0.008$ [11], and the standard model (SM) predictions are around $R_D \approx 0.3$ [12,13] and $R_{D^*} \approx 0.25$, respectively.

Further tests of lepton-flavor universality can be made using the branching fraction ratios $R_{K^{(*)}} = BR(B \to K^{(*)}\mu^+\mu^-)/BR(B \to K^{(*)}e^+e^-)$. The current LHCb measurements are $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$ [14] and $R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$ [15], which indicate a more than 2.5σ deviation from the SM results. In addition, a known anomaly is the muon anomalous magnetic dipole moment (muon $g-2$), where its latest measurement is $\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\rm SM} = (28.8 \pm 8.0) \times 10^{-10}$ [16]. If we assume that these results are correct, we need to extend the SM to explain these excesses. Inspired by these experimental observations, various solutions to the anomalies have been proposed [17–78].

In the SM, the $b \to c\ell'\bar{\nu}_{\ell'}$ decays ($\ell' = e, \mu, \tau$) arise from the W-mediated tree diagram, whereas the $b \to s\ell'^+\ell'^-$ decays are generated by W-mediated box and Z-mediated penguin diagrams. In the present study, based on our earlier study of muon $g-2$ and R_K anomalies [73], we attempt to establish a specific model that simultaneously explains the muon $g-2$, $R_{K^{(*)}}$, and $R_{D^{(*)}}$ anomalies when the experimental bounds involved are satisfied. The serious constraints include $\ell_i \to \ell_j\gamma$, $\Delta F = 2$, $B_s \to \mu^+\mu^-$, $B \to K\nu\bar{\nu}$, etc. To clarify the effects introduced, we do not scan all of the parameters involved, but instead we retain the relevant couplings that can satisfy or escape from the experimental bounds, whereas we directly neglect the constrained and smaller couplings.

To obtain the non-universal lepton-flavor effects, we consider the extension of the SM by including scalar leptoquarks (LQs), where the LQs are colored scalar particles that are coupled to a lepton and a quark at the same vertex, and the couplings to the quarks and leptons are flavor-dependent free parameters. LQs can

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couple to fermions and charge-conjugation of them at the same time, so in addition to the $SU(2)$ singlet, doublet, and triplet representations, the hypercharge of each representation may also have different choices depending on what quarks (leptons) or charge-conjugated quarks (leptons) couple to the LQs. Hence, in order to explain all of the excesses mentioned earlier in an actual model, we must decide what LQs are needed.

It is known that the effective interactions for the muon $g-2$ can be expressed as $\bar{\mu}\sigma_{\alpha\beta}P_\chi \mu F^{\alpha\beta}$, where $P_\chi = P_{R(L)}$ is the chiral projection operator and $F^{\alpha\beta}$ is the electromagnetic field strength tensor. The initial and final muons carry different chirality, so in order to enhance the Δa_μ and avoid suppression by the lepton mass, the introduced LQ must interact with the left-handed and right-handed leptons. Due to the gauge invariance, the LQ can be an $SU(2)$ doublet, and its hypercharge can be determined as $Y = 7/6$.

In addition to the muon $g-2$, the doublet LQ can also contribute to $b \to s\ell'^+\ell'^-$; thus, this LQ may help resolve the excesses in $B \to K^{(*)}\mu^+\mu^-$. Unfortunately, the corrections to the Wilson coefficients of C_9 and C_{10} for the $b \to s\ell^+\ell^-$ decays have the same sign, whereas we need an opposite sign to explain the measurements of the $R_{K^{(*)}}$, P'_5, and $B_s \to \mu^+\mu^-$ decays. Moreover, when combined with the experimental limits, the Yukawa couplings involved are too small to explain the R_D and R_{D^*} anomalies. Thus, we have to introduce more LQs.

Due to the SM neutrinos being left-handed particles, the extra LQs for the $b \to c\ell'\bar{\nu}_{\ell'}$ processes must couple to the doublet leptons. According to the gauge invariance, these LQs can be singlet, doublet, or triplet. The $b \to c$ transition involves up- and down-type quarks, so the doublet LQ is excluded as a candidate. A triplet LQ is a good candidate for the $b \to s\ell'^+\ell'^-$ processes because the associated values for C_9 and C_{10} have opposite signs. The triplet LQ can contribute to both $b \to s\ell'^+\ell'^-$ and $b \to c\ell'\bar{\nu}_{\ell'}$ decays at the tree level, but it can be shown that both processes share the same LQ couplings. Therefore, by considering the constraints on the $b \to s\ell^+\ell^-$ decays and $\Delta B = 2$ process, the R_D and R_{D^*} cannot be enhanced significantly. Thus, in addition to the triplet LQ, it is necessary to consider a singlet LQ [28,70]. Intriguingly, we show that such a singlet LQ can contribute to $b \to c\ell'\bar{\nu}_{\ell'}$ but not to $b \to s\ell'^+\ell'^-$ at the tree level, i.e., the couplings of the singlet LQ are not affected by the $b \to s\ell^+\ell^-$ constraints. The singlet LQ can induce $b \to s\mu^+\mu^-$ according to one-loop diagrams [70], but a previous analysis by [75] showed that it is not a viable approach when using a singlet scalar LQ to simultaneously explain $R_{D^{(*)}}$ and $R_{K^{(*)}}$. Hence, more LQs are necessary to explain the anomalies.

The remainder of this paper is organized as follows. In Section 2, we introduce our model and derive formulae for the numerical analysis. In Section 3, we present the numerical analysis to show the parameter regions that correspond with anomalies in semileptonic B decays. A summary is given in Section 4.

2. Model and formulae

In this section, we begin by formulating the model, before studying the relevant phenomena of interest. The three LQs introduced are $\Phi_{7/6} = (2, 7/6)$, $\Delta_{1/3} = (3, 1/3)$, and $S^{1/3} = (1, 1/3)$ under $(SU(2)_L, U(1)_Y)$ SM gauge symmetry, where the doublet and triplet representations can be taken as:

$$\Phi_{7/6} = \begin{pmatrix} \phi^{5/3} \\ \phi^{2/3} \end{pmatrix}, \quad \Delta_{1/3} = \begin{pmatrix} \delta^{1/3}/\sqrt{2} & \delta^{4/3} \\ \delta^{-2/3} & -\delta^{1/3}/\sqrt{2} \end{pmatrix}, \tag{2}$$

where the superscripts are the electric charges of the particles. Accordingly, the LQ Yukawa couplings to the SM fermions are expressed as:

$$\begin{aligned} -L_{LQ} = & \left[\bar{u}\,\mathbf{V}\mathbf{k}P_R\ell\phi^{5/3} + \bar{d}\,\mathbf{k}P_R\ell\phi^{2/3}\right] \\ & + \left[-\bar{\ell}\,\tilde{\mathbf{k}}P_R u\phi^{-5/3} + \bar{\nu}\,\tilde{\mathbf{k}}P_R u\phi^{-2/3}\right] \\ & + \left[\overline{u^c}\,\mathbf{V}^*\mathbf{y}P_L\nu\delta^{-2/3} - \frac{1}{\sqrt{2}}\overline{u^c}\,\mathbf{V}^*\mathbf{y}P_L\ell\delta^{1/3}\right. \\ & \left. - \frac{1}{\sqrt{2}}\overline{d^c}\,\mathbf{y}P_L\nu\delta^{1/3} - \overline{d^c}\,\mathbf{y}P_L\ell\delta^{4/3}\right], \\ & + \left(\overline{u^c}\,\mathbf{V}^*\tilde{\mathbf{y}}P_L\ell - \overline{d^c}\,\tilde{\mathbf{y}}P_L\nu + \overline{u^c}\mathbf{w}P_R\ell\right)S^{1/3} + h.c., \end{aligned} \tag{3}$$

where the flavor indices are suppressed, $\mathbf{V} \equiv U_L^u U_L^{d\dagger}$ denotes the Cabibbo–Kobayashi–Maskawa (CKM) matrix, $U_L^{u,d}$ are the unitary matrices used to diagonalize the quark mass matrices, and U_L^d and U_R^u have been absorbed into $\mathbf{k}$, $\tilde{\mathbf{k}}$, $\mathbf{y}$, $\tilde{\mathbf{y}}$, and $\mathbf{w}$. In the model, we cannot generate the neutrino masses. Therefore, we treat the neutrinos as massless particles and their flavor mixing effects are rotated away. There is no evidence for any new CP violation, so in the following, we treat the Yukawa couplings as real numbers.

The scalar LQs can also couple to the SM Higgs via the scalar potential, and the cross section for the Higgs to diphoton can be modified in principle. However, the couplings of the LQs to the Higgs are different parameters and irrelevant to the flavors, so by taking proper values for the parameters, the signal strength parameter for the Higgs to diphoton can fit the LHC data. Hence, we do not discuss this issue in the present study, but a detailed analysis was given by [73].

2.1. Effective interactions for semileptonic B-decay

According to the interactions in Eq. (3), we first derive the four-Fermi interactions for the $b \to c\ell'\bar{\nu}_{\ell'}$ and $b \to s\ell'^+\ell'^-$ decays. For the $b \to c\ell'\bar{\nu}_{\ell'}$ processes, the induced current-current interactions from $k_{3j}\tilde{k}_{i2}$ and $\tilde{y}_{3i}w_{2j}$ are $(S-P)\times(S-P)$ and those from $y_{3i}y_{2j}$ and $\tilde{y}_{3i}\tilde{y}_{2j}$ are $(S-P)\times(S+P)$, where S and P denote the scalar and pseudoscalar currents, respectively. After taking the Fierz transformations, the Hamiltonian for the $b \to c\ell'\bar{\nu}_{\ell'}$ decays can be expressed as:

$$\begin{aligned} \mathcal{H}_{b\to c} = & \left(-\frac{\tilde{y}_{3i}w_{2j}}{2m_S^2} + \frac{k_{3j}\tilde{k}_{i2}}{2m_\Phi^2}\right)\bar{c}P_L b\,\bar{\ell}_j P_L\nu_i \\ & + \left(\frac{\tilde{y}_{3i}w_{2j}}{2m_S^2} + \frac{k_{3j}\tilde{k}_{i2}}{2m_\Phi^2}\right)\frac{1}{4}\bar{c}\sigma_{\mu\nu}P_L b\,\bar{\ell}_j\sigma^{\mu\nu}P_L\nu_i \\ & - \sum_a V_{2a}\frac{y_{aj}y_{3i}}{4m_\Delta^2}\bar{c}\gamma_\mu P_L b\,\bar{\ell}_j\gamma^\mu P_L\nu_i \\ & + \sum_a V_{2a}\frac{\tilde{y}_{aj}\tilde{y}_{3i}}{2m_S^2}\bar{c}\gamma_\mu P_L b\,\bar{\ell}_j\gamma^\mu P_L\nu_i, \end{aligned} \tag{4}$$

where the indices i, j are the lepton flavors, and the LQs in the same representation are taken as degenerate particles. It can be seen that the interaction structure obtained from the triplet LQ is the same as that from the W-boson. The doublet LQ generates an $(S-P)\times(S-P)$ structure, but also a tensor structure. However, the singlet LQ can produce $(V-A)\times(V-A)$, $(S-P)\times(S-P)$, and tensor structures. Nevertheless, we show later that the singlet LQ makes the main contribution to the R_D and R_{D^*} excesses. It is difficult to explain R_{D,D^*} by only using the doublet or/and triplet LQs when the R_K excess and other strict constraints are satisfied.

Using the Yukawa couplings in Eq. (3), the effective Hamiltonian for the $b \to s\ell'^+\ell'^-$ decays mediated by $\phi^{2/3}$ and $\delta^{4/3}$ at the tree level can be expressed as: