Impact of leptoquarks in semileptonic B decays

Suchismita Sahoo[*][†]
School of Physics, University of Hyderabad,
Hyderabad-500046, India
E-mail: suchismita@uohyd.ac.in

Rukmani Mohanta
School of Physics, University of Hyderabad,
Hyderabad-500046, India
E-mail: rmsp@uohyd.ernet.in

Anjan K. Giri
Physics Department, IIT Hyderabad,
Kandi - 502285, India
E-mail: giria@iith.ac.in

We study the impact of vector leptoquarks on the recent anomalies in semileptonic B meson decays such as R_K and $R_{D^{(*)}}$ etc. We constrain the leptoquark couplings by using the existing data on the branching ratios of $B_s \to l^+ l^-$ and $\bar{B} \to X_s l^+ l^-$ processes, where $l = e, \mu, \tau$. We estimate the branching ratios of $\bar{B} \to D^{(*)} l \bar{\nu}_l$ processes using the constrained leptoquark parameter space. We also investigate the possibility of simultaneous explanation of $R_{D^{(*)}}$, R_K anomalies in this model.

---

[*]Speaker.

1. Introduction

Recently both BaBar [1] and Belle [2] experiments have measured the ratio of branching fractions of $\bar{B} \to D\tau\bar{\nu}_\tau$ over $\bar{B} \to Dl\bar{\nu}_l$ decays, where $l = e, \mu$ and the present average experimental result [3] is

$$R_D = \frac{\text{Br}\,(\bar{B} \to D\tau\bar{\nu}_\tau)}{\text{Br}\,(\bar{B} \to Dl\bar{\nu}_l)} = 0.397 \pm 0.040 \pm 0.028, \tag{1.1}$$

which has 1.9σ deviation from its standard model (SM) prediction $R_D^{\text{SM}} = 0.300 \pm 0.008$ [4]. Besides, both the B factories and LHCb [5] have reported 3.3σ discrepancy [3] in the measurement of R_{D^*}

$$R_{D^*} = \frac{\text{Br}\,(\bar{B} \to D^*\tau\bar{\nu}_\tau)}{\text{Br}\,(\bar{B} \to D^*l\bar{\nu}_l)} = 0.316 \pm 0.016 \pm 0.010, \tag{1.2}$$

from its SM result $R_{D^*}^{\text{SM}} = 0.252 \pm 0.003$ [6]. Analogously another interesting observable is the lepton nonuniversality (LNU) parameter (R_K) in $B^+ \to K^+l^+l^-$ process, which has recently been measured at LHCb, with value [7],

$$R_K = \frac{\text{Br}\,(B^+ \to K^+\mu^+\mu^-)}{\text{Br}\,(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036, \tag{1.3}$$

and corresponds to a 2.6σ deviation from its SM value $R_K = 1.0003 \pm 0.0001$ [8] in the dilepton invariant mass squared bin $\left(1 \leq q^2 \leq 6\right) \text{GeV}^2$.

In this paper, we would like to investigate the semileptonic $\bar{B} \to D^{(*)}l\bar{\nu}_l$ decay processes, mediated by the FCNC transitions $b \to cl\bar{\nu}_l$ in the vector leptoquark (LQ) model. We compute the branching ratios of $\bar{B} \to D^{(*)}l\bar{\nu}_l$ modes in this model. The simultaneous study of the lepton non-universality parameters $R_{D^{(*)}}$ and $R_{K^{(*)}}$ is the main objective of this work. LQs are color triplet hypothetical bosonic particles which allow quarks and leptons to interact simultaneously and carry both baryon and lepton numbers. LQs can have spin 0 (scalar) or spin 1 (vector) and are encountered in various extensions of the SM, such as technicolor model, GUT theories, Pati-Salam models and the quark and lepton composite model.

The outline of the paper is follows. In section 2, we discuss the effective Hamiltonians involving $b \to cl\bar{\nu}_l$ and $b \to sll$ transitions in the SM. We also present the new physics contribution due to the vector LQ exchange. The constraint on LQ parameter space by using the experimental limit on the branching ratios of the $B_s \to l^+l^-$ and $\bar{B} \to X_s l^+l^-$ decays and the numerical analysis for $\bar{B} \to D^{(*)}l\bar{\nu}_l$ processes are presented in section 3. Section 4 contains the conclusion.

2. Effective Hamiltonian and the new physics contribution from vector leptoquark exchange

In the SM, the effective Hamiltonian describing the processes mediated by the $b \to cl\bar{\nu}_l$ transition is given by [9]

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(\delta_{l\tau} + C_{V_1}^l \right) \left(\bar{c}_L \gamma^\mu b_L \right) \left(\bar{\tau}_L \gamma_\mu \nu_{lL} \right) \right], \tag{2.1}$$

where G_F is the Fermi constant, V_{cb} is the CKM matrix element and $q_{L(R)} = L(R)q$ are the chiral quark fields with $L(R) = (1 \mp \gamma_5)/2$ as the projection operators. The Wilson coefficient $C_{V_1}^l$ is zero in the SM and can only be generated by the new physics model.

The effective Hamiltonian for $b \to s l^+ l^-$ process in the SM is given by

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu) , \qquad (2.2)$$

where $\mathcal{O}_i$'s are the six dimensional operators and C_i's are the corresponding Wilson coefficients.

Models with vector LQs can modify the SM effective Hamiltonian (2.1, 2.2) due to the additional contributions arising from the LQs exchange and will give measurable deviations from the predictions of the SM in the beauty sector. Here we consider $U_3(3,3,2/3)$ vector LQ multiplet which is invariant under the SM $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group and does not allow proton decay. The interaction Lagrangian for U_3 LQ with the SM fermions is given by [9]

$$\mathcal{L}^{LQ} = h_{3L}^{ij} \bar{Q}_{iL} \boldsymbol{\sigma} \gamma^\mu L_{jL} \mathbf{U}_{3\mu}, \qquad (2.3)$$

where $Q(L)$ is the left handed quark (lepton) doublets, h_{3L}^{ij} are the LQ couplings and $\boldsymbol{\sigma}$ represents the Pauli matrices. After performing the Fierz transformation and comparing with (2.1), we obtain an additional Wilson coefficient as

$$C_{V_1}^l = -\frac{1}{2\sqrt{2} G_F V_{cb}} \sum_{k=1}^{3} V_{k3} \frac{h_{3L}^{2l} h_{3L}^{k3\,*}}{M_{U_3^{2/3}}^2}. \qquad (2.4)$$

Similarly the comparison of Eqn. (2.3) after Fierz transformation, with the SM effective Hamiltonian (2.2), one can obtain new Wilson coefficients $C_{9,10}^{NP}$

$$C_9^{NP} = -C_{10}^{NP} = \frac{\pi}{\sqrt{2} G_F V_{tb} V_{ts}^* \alpha} \frac{h_{3L}^{ni} h_{3L}^{mj\,*}}{M_{U_3^{2/3}}^2}. \qquad (2.5)$$

3. Constraint on leptoquark couplings and numerical analysis

After knowing the new physics contribution to the SM, we now proceed to constrain the new parameter space by using the experimental limit on the branching ratios of $B_s \to l^+ l^-$ and $\bar{B} \to X_s l^+ l^-$ processes. Including LQ model, the branching ratio of $B_s \to l^+ l^-$ process is given by

$$\text{Br}(B_s \to l^+ l^-) = \frac{G_F^2}{16\pi^3} \tau_{B_s} \alpha^2 f_{B_s}^2 |C_{10}^{SM}|^2 M_{B_s} m_l^2 |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_l^2}{M_{B_s}^2}} \left| 1 + \frac{C_{10}^{NP}}{C_{10}^{SM}} \right|^2. \qquad (3.1)$$

Now comparing the theoretical value of branching ratio with the 1σ range of the experimental data, the constraint on the real and imaginary part of the LQ couplings are given in Table 1.

The branching ratio of $\bar{B} \to X_s ll$ process in the LQ model is given by

$$\left(\frac{d\text{Br}}{ds_1}\right)_{LQ} = B_0 \Big[\frac{16}{3}(1-s_1)^2(1+2s_1)[\text{Re}(C_9^{eff} C_9^{NP*} + \text{Re}(C_{10} C_{10}^{NP*})]$$
$$+ \frac{8}{3}(1-s_1)^2(1+2s_1) \left[|C_9^{NP}|^2 + |C_{10}^{NP}|^2 \right] + 32(1-s_1)^2 \, \text{Re}(C_7 C_{10}^{NP*}) \Big], \qquad (3.2)$$

where $s_1 = q^2/m_b^2$ and B_0 can be found in [10]. The allowed region of corresponding LQ couplings which are compatible with the 1σ range of the experimental result in low q^2 are given in Table 1.

Now using the constrained LQ couplings from Table 1 and Eqns. (2.4, 2.5), we compute the bound on new Wilson coefficients $C_{V_1}^l$, $C_{9,10}^{NP}$. In Table II, we present the predicted values of branching ratios of $B \to D^{(*)}l\nu_l$ processes in both the SM and U_3 LQ model. In Fig. 1, we show the q^2 variation of LNU parameters, $R_D(q^2)$ (left panel) and $R_{D^*}(q^2)$ (right panel). The plots for $R_K(q^2)$ (left panel) and $R_{K^*}(q^2)$ (right panel) parameters in low q^2 region are shown in Fig. 2. The corresponding numerical values of LNU parameters are given in Table 2.

Table 1: Constraints on the real and imaginary parts of the leptoquark couplings (for $M_{LQ} = 1$ TeV) from $B_s \to l^+l^-$ and $\bar{B} \to X_s ll$ processes [10]

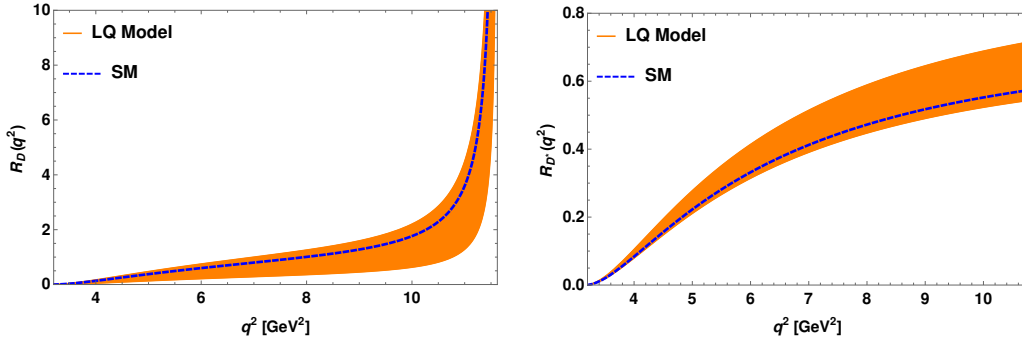| Deacy process	Leptoquark Couplings	Real part	Imaginary Part
$B_s \to l^+l^-$	$h_{3L}^{21} h_{3L}^{31*}$	$-13.0 \to 13.0$	$-13 \to 13$
	$h_{3L}^{22} h_{3L}^{32*}$	$-0.016 \to 0.0$	$-0.008 \to 0.008$
	$h_{3L}^{23} h_{3L}^{33*}$	$-0.4 \to 0.4$	$-0.4 \to 0.4$
$\bar{B} \to X_s l^+l^-$	$h_{3L}^{21} h_{3L}^{31*}$	$-0.01 \to 0.01$	$-0.01 \to 0.01$
	$h_{3L}^{22} h_{3L}^{32*}$	$-0.008 \to 0.008$	$-0.008 \to 0.008$

Figure 1: The q^2 variation of $R_D(q^2)$ (left panel) and $R_{D^*}(q^2)$ (right panel) parameters in LQ model.

4. Conclusion

In this work we have studied the rare semileptonic $\bar{B} \to D^{(*)}l\bar{\nu}_l$ decays and the lepton nonuniversalty parameters such as $R_{D^{(*)}}$ and $R_{K^{(*)}}$ in the $U_3(3,3,2/3)$ vector LQ model. The LQ parameter space is constrained by using the branching ratios of rare $B_s \to l^+l^-$ and $\bar{B} \to X_s l^+l^-$ decay processes. We computed the branching ratios and lepton nonuniversality in $\bar{B} \to D^{(*)}l\bar{\nu}_l$ processes in the U_3 vector LQ model. The anomaly in R_K observable is also studied. We found that the observed anomalies can be accommodated in this model.

References

[1] BaBar Collaboration, J. Lees et al., Phys. Rev. Lett. **109**, 101802 (2012); BaBar Collaboration, J. Lees et al., Phys. Rev. D **88**, 072012 (2013).

Table 2: The predicted values of branching ratios of $\bar{B} \to D^{(*)} l \bar{\nu}_l$ processes and the $R_{D^{(*)}}$, $R_{K^{(*)}}$ anomalies in vector leptoquark model [10, 11]

Observables	SM Predictions	Values in LQ Model
$\mathrm{Br}(\bar{B} \to D l \bar{\nu}_l)$	$(2.18 \pm 0.13) \times 10^{-2}$	$(2.13 - 2.25) \times 10^{-2}$
$\mathrm{Br}(\bar{B} \to D \tau \bar{\nu}_l)$	$(6.75 \pm 0.08) \times 10^{-3}$	$(2.48 - 8.2) \times 10^{-3}$
$\mathrm{Br}(\bar{B} \to D^* l \bar{\nu}_l)$	$(5.18 \pm 0.31) \times 10^{-2}$	$(5.04 - 5.32) \times 10^{-2}$
$\mathrm{Br}(\bar{B} \to D^* \tau \bar{\nu}_l)$	$(1.33 \pm 0.14) \times 10^{-2}$	$(1.3 - 1.6) \times 10^{-2}$
R_D	0.31	$0.11 - 0.386$
R_{D^*}	0.26	$0.243 - 0.32$
$R_{K \, q^2 \in [1,6]}$	1.006	$0.75 - 1.006$
$R_{K^* \, q^2 \in [1,6]}$	0.996	$0.725 - 0.996$
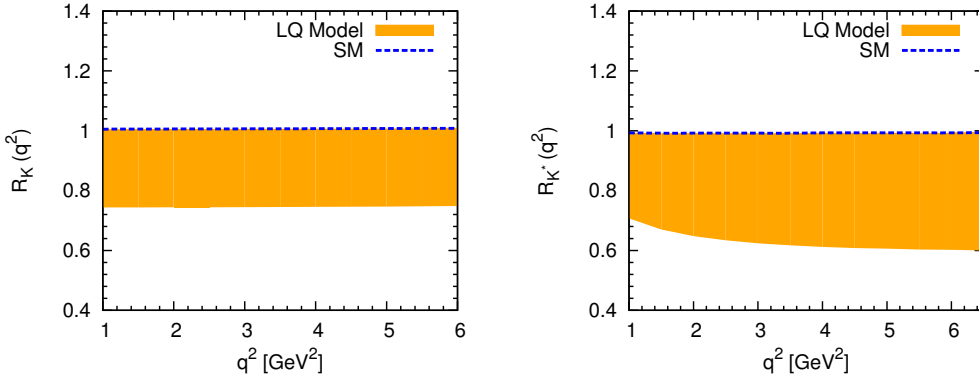
Figure 2: The plot for $R_K(q^2)$ (left panel) and $R_{K^*}(q^2)$ (right panel) in the low q^2 region in LQ model.

[2] Belle Collaboration, M. Huschle et al., Phys. Rev. D **92**, 072014 (2015); Belle Collaboration, A. Abdesselam et al., [arXiv:1603.06711].

[3] Heavy Flavour Averaging Group, http://www.slac.stanford.edu/xorg/hfag/semi/winter16/ winter16_dtaunu.html.

[4] H. Na et al., Phys. Rev. D **92**, 054410 (2015).

[5] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **115**, 111803 (2015) Addendum: Phys. Rev. Lett. **115**, 159901 (2015).

[6] S. Fajfer, J. F. Kamenik, and I. Nisandzic, Phys. Rev. D **85**, 094025 (2012).

[7] R. Aaij et al., [LHCb Collaboration], Phys. Rev. Lett. **113**, 151601 (2014).

[8] C. Bobeth, G. Hiller, G. Piranishvili, JHEP **12**, 040 (2007).

[9] Y. Sakaki, R. Watanabe, M. Tanaka and A. Tayduganov, Phys. Rev. D **88**, 094012 (2013).

[10] S. Sahoo, R. Mohanta and A. Giri, [arXiv:1609.04367].

[11] A. Giri, R. Mohanta and S. Sahoo, J.Phys.Conf.Ser. **770**, 012031 (2016).