Implications of lepton nonuniversality in the beauty sector

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Abstract. The phenomenon of CP violation in the standard model (SM) framework and other observables have been established from the data obtained from the B factories and so far we have not seen anything new. Nevertheless, there have been instances of deviations in many measured observables in the flavor sector as far as the data and predictions are concerned. Here we will mention some deviations obtained in measurements related to lepton universality as seen from the data and try to understand their implications. To accommodate the observed data we will consider a leptoquark model, which seems to be one interesting model beyond the SM.

1. Introduction

The course of high energy physics is going through an interesting and exciting phase. We have in one hand many experiments, conducted in the last few decades, measured various observables which are in excellent agreement with the model proposed by Glashow, Salam and Weinberg, which is also known as the standard model in the literature. One exception being that of the observation of neutrino oscillation. At the same time there are many fundamental unsolved questions like the hierarchy problem, dark matter and baryon asymmetry of the Universe etc. which make ourselves believe that there is something beyond that of the SM. In fact, the resounding success of the SM has led us with no option but to believe that whatever may be the form of the new physics the low energy limit of the same is the SM. The $V - A$ current structure of the weak interactions has been established long ago and in the past has been very instrumental in providing many interesting and accurate results. It is interesting to note that we have observed, in the few years, some kind of unusual results involving lepton, in particular the heavy *tau* (or third generation leptons). The belief is that the couplings of third generation fermions to the electroweak symmetry breaking is comparatively stronger due to their large masses and therefore, sensitive to new physics that modifies the $V - A$ structure of the SM. From this point of view the study of $B^{(*)} \to \tau\bar{\nu}$ and $B \to D^{(*)}\tau\bar{\nu}$ charge current processes are really interesting. In recent measurements, BaBar [1] and Belle [2] have reported 3.5σ deviation in the ratio of branching fractions of $\bar{B} \to \bar{D}^{(*)}\tau\bar{\nu}$ over $\bar{B} \to \bar{D}^{(*)}l\bar{\nu}$, where $l = e, \mu$,

$$R_D = \frac{\text{Br}\left(\bar{B} \to D\tau\bar{\nu}\right)}{\text{Br}\left(\bar{B} \to Dl\bar{\nu}\right)} = 0.421 \pm 0.058, \quad R_{D^*} = \frac{\text{Br}\left(\bar{B} \to D^*\tau\bar{\nu}\right)}{\text{Br}\left(\bar{B} \to D^*l\bar{\nu}\right)} = 0.337 \pm 0.025,$$

from their corresponding SM predictions,

$$R_D^{\text{SM}} = 0.305 \pm 0.012, \qquad R_{D^*}^{\text{SM}} = 0.252 \pm 0.004. \tag{1}$$

The above results give us the impression that there might be providing us the indication of the violation of lepton universality. It should be noted here that the observales measured, as mentioned above, are ratio of two processes where in both the numerator and denominator both the initial state is the same whereas the final sates differ depending upon the kind of leptons involved. This actually helps us to reduce the theoretical uncertainties since most of the contributing terms are same and uncertainty actually cancels out. Since these decays occur at the tree level in the SM, the general expectation is that model with masses of the new particles near the TeV scale are required to explain the anomaly. The branching ratios of semileptonic $b \to c l \bar{\nu}$ processes can be computed precisely due to the light leptons mass, thus the deviation in $R_{D^{(*)}}$ is obviously from the new physics affecting the $\bar{B} \to \bar{D}^{(*)} \tau \bar{\nu}$ process. The branching ratios and $R_{D^{(*)}}$ anomaly in the SM and in various new physics models have been investigated in the literature. Similarly, another interesting observable, reported by LHCb [3], is the lepton non universality in $B \to K l^+ l^-$ process,

$$R_K = \frac{\text{Br}\left(\bar{B} \to K \mu^+ \mu^-\right)}{\text{Br}\left(\bar{B} \to K e^+ e^-\right)} = 0.745^{+0.090}_{-0.074} \pm 0.036, \tag{2}$$

which has 2.6σ deviation from the SM value, $R_K = 1.0003 \pm 0.0001$, in the dilepton invariant mass squared bin $\left(1 \leq q^2 \leq 6\right) \text{GeV}^2$. In the semileptonic decay rate of $B \to K^* \mu^+ \mu^-$ and the angular observables P_5' [4] have 3σ deviations from the SM prediction. The discrepancy of 3σ is also found in the decay rate of the $B_s \to \phi \mu^+ \mu^-$ process [5]

In this paper, we pursue the analysis of rare semileptonic decays of B meson to leptons of second and third generations and we extend the SM by an additional leptoquark model which is built based on the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetries. The study of famous $R_{D^{(*)}}$ anomaly and the lepton non-universality in the $b \to c \tau \bar{\nu}$ decay process are the main interests of this work. We calculate the branching ratio, forward-backward asymmetry and the τ-polarisations of $B \to D^{(*)} \tau \bar{\nu}$ processes in the leptoquark model. We estimate the branching ratio of rare leptonic $B^*_{u,c} \to \tau \bar{\nu}$ decay process of $B^*_{u,c}$ vector meson. In the leptoqaurk model, we also explore the possibility of lepton nonuniversality parameters in the $B^* \to \tau \bar{\nu}$ and $\Lambda_b \to \Lambda_c \tau \bar{\nu}$ processes. Leptoquarks can couple (decay) to a quark and lepton of the same generation simultaneously and carry both lepton and baryon number. They can have spin 0 (scalar leptoquarks) or spin 1 (vector leptoquarks) and can be characterized by their fractional electric charge and Fermion no $F = 3B + L$, where B and L are the baryon no. and lepton no. respectively. Such leptoquarks exist in some extended SM theories [6] such as grand unified theories based on $SU(5)$, $SU(10)$ etc., Pati-Salam model, technicolor model and composite model. To avoid rapid proton decay, we consider that the leptoquark does not couples to diquarks and therefore conserve baryon and lepton numbers. The leptoquark model in the context of B-physics anomalies has been taken up in the literature.

The outline of this paper is follows. In section II, we describe the effective Hamiltonian involving $b \to c \tau \bar{\nu}$ quark level transition in the SM. In section III we discuss the new physics contributions coming from vector leptoquarks and show how they can explain the observed anomalies in b-sector. Our results are presented in Section IV.

2. Effective Hamiltonian for $b \to c \tau \bar{\nu}_l$ and $b \to s l^+ l^-$ processes

In this section we write the relevant effective Hamiltonian in the SM as given by [7]

$$\mathcal{H}_{eff} = \frac{4 G_F}{\sqrt{2}} V_{cb} \Big[\left(\delta_{l\tau} + C^l_{V1}\right) \mathcal{O}^l_{V1} + C^l_{V2} \mathcal{O}^l_{V2} + C^l_{S1} \mathcal{O}^l_{S1} + C^l_{S2} \mathcal{O}^l_{S2} + C^l_T \mathcal{O}^l_T \Big], \tag{3}$$

where G_F is the Fermi constant, V_{cb} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element and the index l stands for neutrino flavour, $l = e, \mu, \tau$. The C^l_X's, where $X = V_{1,2}, S_{1,2}, T$ are

the Wilson coefficients and the corresponding operators are

$$
\begin{aligned}
\mathcal{O}_{V1}^{l} &= \left(\bar{C}_L \gamma^{\mu} b_L\right)\left(\bar{\tau}_L \gamma_{\mu} \nu_{lL}\right), \\
\mathcal{O}_{V2}^{l} &= \left(\bar{C}_R \gamma^{\mu} b_R\right)\left(\bar{\tau}_L \gamma_{\mu} \nu_{lL}\right), \\
\mathcal{O}_{S1}^{l} &= \left(\bar{C}_L b_R\right)\left(\bar{\tau}_R \nu_{lL}\right), \\
\mathcal{O}_{S2}^{l} &= \left(\bar{C}_R b_L\right)\left(\bar{\tau}_R \nu_{lL}\right), \\
\mathcal{O}_{T}^{l} &= \left(\bar{C}_R \sigma^{\mu\nu} b_L\right)\left(\bar{\tau}_R \sigma_{\mu\nu} \nu_{lL}\right),
\end{aligned}
\tag{4}
$$

where $L(R) = (1 \mp \gamma_5)/2$ are the projection operators. Since the flavour of neutrino is not observed at B-factories, all generations of neutrinos can be taken into the account to reveal the signature of new physics. In the SM, the contribution to the $b \to c l \bar{\nu}_l$ process is indicated as $\delta_{l\tau}$ and the Wilson coefficients (C_X^l) are zero, which can only be generated by new physics models. This new couplings can be bound experimentally, so that the effects of the new operators can be scrutinized in physical observables.

Similarly, the effective Hamiltonian describing the processes induced by $b \to s l^+ l^-$ transitions in the SM is given by [8]

$$
\begin{aligned}
\mathcal{H}_{eff} = & -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu) O_i + C_7 \frac{e}{16\pi^2}\left(\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R)b\right)F^{\mu\nu} \right. \\
& \left. + C_9^{eff}\frac{\alpha}{4\pi}(\bar{s}\gamma^{\mu}P_L b)\bar{l}\gamma_{\mu}l + C_{10}\frac{\alpha}{4\pi}(\bar{s}\gamma^{\mu}P_L b)\bar{l}\gamma_{\mu}\gamma_5 l \right],
\end{aligned}
\tag{5}
$$

where α is the fine structure constant, $V_{tb}V_{ts}^*$ is the product of CKM matrix element and C_i's are the Wilson coefficients evaluate at the renormalization scale $\mu = m_b$ [9]. In the following subsections we will explain the possible leptoquarks relevant for the $b \to c l \bar{\nu}_l$ and $b \to s l^+ l^-$ quark level transitions.

3. Vector leptoquarks and new Physics

Here we consider the new physics model in which the new particle interacts both with quarks and leptons simultaneously, called leptoquark, and carries both the baryon and lepton numbers. Leptoquarks have ten different multiplets [10] under the $SU(3)_c \times SU(2)_L \times U(1)_Y$ SM gauge symmetries with flavour non-diagonal couplings, half of them have scalar nature and other halves have vector nature under the Lorentz transformation. The scalar (vector) leptoquarks have spin 0 (1) and could potentially contribute to the FCNC processes involving the quark level transitions $b \to s l^+ l^-$ and $b \to c l^- \bar{\nu}$. Out of all possible leptoquark multiplets, six scalar and vector leptoquark bosons are relevant for the $b \to c l \bar{\nu}$ processes. Here $S_{1,3}$ and R_2 are the scalar leptoquark bosons, $U_{1,3}^{\mu}$ and V_2^{μ} are the vector leptoquark bosons. The vector leptoquarks with charge$= 2/3$ and fermion no.$=0$ can mediate both $b \to s l^+ l^-$ and $b \to c l^- \bar{\nu}$ quark level transitions. Therefore, $U_1^{\mu} = (3,3,2/3)$ and $U_3^{\mu} = (3,1,2/3)$ are only valid vector leptoquarks to study both $R_{K(*)}$ and $R_{D(*)}$ anomaly. In this work we investigate the $U_1^{\mu} = (3,3,2/3)$ and $U_3^{\mu} = (3,1,2/3)$ vector leptoquark, which have charge$=2/3$, fermion no $=0$ and can mediate both $b \to s l^+ l^-$ and $b \to c l^- \bar{\nu}$ quark level transitions. In order to avoid rapid proton decay we do not consider diquark interactions, as the presence of both leptoquark and diquark interactions will violate baryon and lepton number.

The interaction Lagrangian of $U_{1,3}^{\mu}$ leptoquarks with the SM fermion bilinear is given as [7, 10]

$$
\mathcal{L}^{LQ} = \left(h_{1L}^{ij}\bar{Q}_{iL}\gamma^{\mu}L_{jL} + h_{1R}^{ij}\bar{d}_{iR}\gamma^{\mu}l_{jR}\right)U_{1\mu} + h_{3L}^{ij}\bar{Q}_{iL}\boldsymbol{\sigma}\gamma^{\mu}L_{jL}U_{3\mu},
\tag{6}
$$

where $Q_L(L_L)$ is the left handed quark (lepton) doublet, $u_R(d_R)$ and l_R are the right-handed up (down) quark and lepton singlet respectively and $\psi^c = C\bar{\psi}^T = C\gamma^0\psi^*$ is the charge-conjugated fermion field of ψ. The leptoquark couplings are represented by h^{ij}, where i,j are the generation indices of quarks and leptons respectively.

Here the fermions are stated in the gauge eigen basis in which Yukawa couplings of the up type quarks and the charge leptons are diagonal, where as the down-type quark fields are rotated into the mass eigenstate basis by the CKM matrix. Now performing the Fierz transformations, we obtain additional Wilson coefficients to the $b \to c\tau\bar{\nu}_l$ process as [10],

$$C_{V_1}^l = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^3 V_{k3} \left[\frac{h_{1L}^{2l} h_{1L}^{k3\,*}}{2M_{U_1^{2/3}}^2} - \frac{h_{3L}^{2l} h_{3L}^{k3\,*}}{2M_{U_3^{2/3}}^2} \right], \tag{7a}$$

$$C_{V_2}^l = 0, \tag{7b}$$

$$C_{S_1}^l = -\frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^3 V_{k3} \frac{2h_{1L}^{2l} h_{1R}^{k3\,*}}{M_{U_1^{2/3}}^2}, \tag{7c}$$

where V_{k3} denotes the CKM matrix element and $M_{U_{1(3)}^{2/3}}$ is the mass of the leptoquark.

After expanding the $SU(2)$ indices of Eqn. (6), one can notice that $U_{1,3}$ vector leptoquarks also contributes additional Wilson coefficients to the $b \to sl^+l^-$ processes as

$$C_9^{NP} = -C_{10}^{NP} = \frac{1}{2\sqrt{2}G_F V_{tb} V_{ts}^*} \left[\frac{h_{1L}^{2l} h_{1L}^{k3\,*}}{M_{U_1^{2/3}}^2} + \frac{h_{3L}^{2l} h_{3L}^{k3\,*}}{M_{U_3^{-1/3}}^2} \right]. \tag{8a}$$

$$C_9'^{NP} = C_{10}'^{NP} = \frac{1}{2\sqrt{2}G_F V_{tb} V_{ts}^*} \frac{h_{1R}^{2l} h_{1R}^{k3\,*}}{M_{U_1^{2/3}}^2}, \tag{8b}$$

$$-C_P^{NP} = C_S^{NP} = \frac{1}{\sqrt{2}G_F V_{tb} V_{ts}^*} \frac{h_{1L}^{2l} h_{1R}^{k3\,*}}{M_{U_1^{2/3}}^2}, \tag{8c}$$

$$C_P'^{NP} = C_S'^{NP} = \frac{1}{\sqrt{2}G_F V_{tb} V_{ts}^*} \frac{h_{1R}^{2l} h_{1L}^{k3\,*}}{M_{U_1^{2/3}}^2}. \tag{8d}$$

4. Results and Discussion

First using the scenario of vector leptoquarks we constrain the parameter space in terms of the couplings from the existing data and thereafter use the same values to explore to explain the anomalies, as mentioned above [11]. Looking at the graphs it may be concluded that the possibility of vector types of leptoquark can be thought of as an alternative option at least in the context of the subject matter discussed here.

The deviations in the observables R_D and R_{D^*} in comparison to that of the SM predictions have been reported sometime ago by both Belle and BaBar. With the announcement of new result from LHCb the situation has not changed anyhow and as a matter of fact the combined deviation from all three experiments is still more than 3σ away from the SM expectation. At the same time we have also noticed the lepton nonuniversality in the form of R_K, where both first and second generation of leptons are involved. Past studies in the literature have indicated many scenarios for the possible reason behind such discrepancies. In a model independent analysis it was shown that new physics in the form vector type of couplings could be a possible candidate option for such a discrepancy. In this report we have considered the vector leptoquark
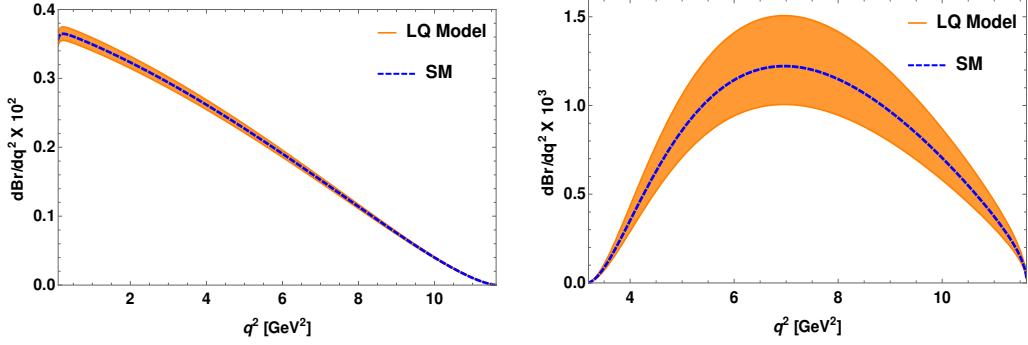
Figure 1. The variation of branching ratio of $B \to D \mu \bar{\nu}_l$ process (left panel) and $B \to D \tau \bar{\nu}_l$ process (right panel) with respect to q^2 in the leptoquark model. Here blue dashed line is for SM and orange bands represent leptoquark model.
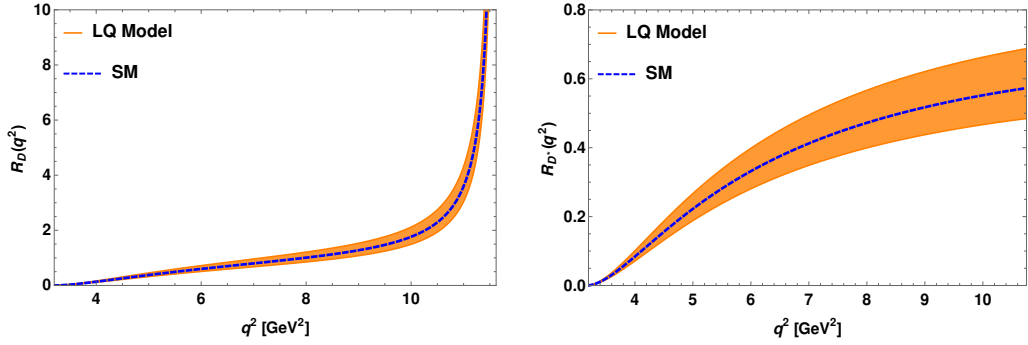

Figure 2. The q^2 variation of lepton non-universality $R_D(q^2)$ (left panel) and $R_{D^*}(q^2)$ (right panel) in leptoquark model.
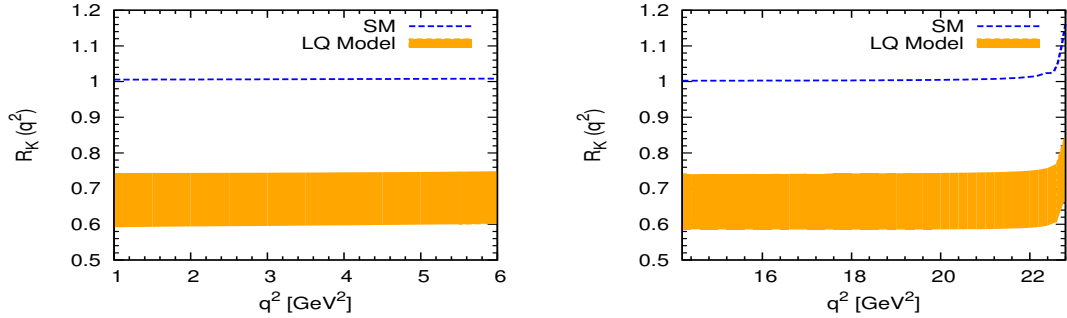

Figure 3. The plot for $R_K^{\mu e}(q^2)$ in low q^2 (left panel)and high q^2 (right panel) in the leptoquark model.

model to explain the discrepancies obtained in the so-called R_D and R_{D^*} problems and also the lepton nonuniversality observable R_K. It is interesting to note that we can simultaneously explain both these anomalies, one in the tree level and another in the loop suppressed process, using the vector leptoquarks. Therefore, using the scenario of vector leptoquarks as the possible new physics candidature one can attempt to understand the current discrepancies in the beauty sector related to lepton non-universality and we hope more refined measurements will resolve these puzzles in the next few years (using data obtained from LHCb and Belle II) or else will
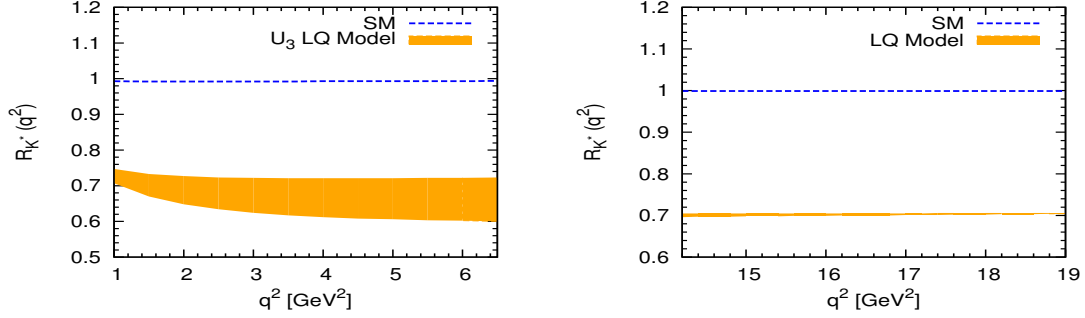
Figure 4. The plot for $R_{K^*}^{\mu e}(q^2)$ in low q^2 (left panel) and high q^2 (right panel) in the leptoquark model.

give some smoking gun signal for physics beyond the SM.

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