Effects of scalar leptoquarks in $b \to s$ transitions

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Abstract. We investigate the effect of scalar leptoquarks on the recent anomalies observed in rare semileptonic B meson decays involving the quark level transition $b \to s$. The leptoquark parameter space is constrained by using the measured branching ratio of $B_s \to \mu^+\mu^-$ process. We estimate the branching ratio of $B \to K^{(*)}\mu^+\mu^-(\nu\bar{\nu})$ processes, using the constraint leptoquark couplings. We also compute forward-backward asymmetry, polarization fractions of K^* and $P'_{4,5,6}$ observables in the $B \to K^*\mu^+\mu^-$ process. The R_K anomaly in the $B \to Kl^+l^-$ process is also studied. Furthermore, we predict the branching ratios of lepton flavour violating decays, such as $B_s \to l_i^+ l_j^-$, $B \to K^{(*)} l_i^+ l_j^-$ and $B_s \to \phi l_i^+ l_j^-$, which are found to be within the experimental reach of LHCb and the upcoming Belle II experiments.

1. Introduction

The study of rare semileptonic decays of B mesons involving flavour changing neutral current (FCNC) transition $b \to s$, plays an important role to critically test the standard model (SM) and to look for the possible existence of new physics (NP). Such rare processes are highly suppressed in the SM as they occur at one-loop level (penguin and box diagrams). Recently LHCb has reported 3σ discrepancy in $B \to K^*\mu^+\mu^-$ angular observables, mainly in the decay rate and P'_5. Furthermore, the lepton non-universality parameter in the $B \to Kl^+l^-$ decay is found to be $R_K^{\rm LHCb} = {\rm Br}(B^+ \to K^+\mu^+\mu^-)/{\rm Br}(B^+ \to K^+e^+e^-) = 0.745^{+0.09}_{-0.074} \pm 0.036$ [1] in the low q^2 bin $(1 \le q^2 \le 6)$ GeV^2, which has 2.6σ deviation from the SM prediction $R_K^{\rm SM} = 1.0003 \pm 0.0001$.

In this article, we intend to study the effect of scalar leptoquark (LQ) on the branching ratio as well as other asymmetry parameters of $B \to K^{(*)}\mu^+\mu^-(\nu\bar{\nu})$ processes. We also investigate the lepton flavour violating (LFV) decays, such as $B_s \to l_i^+ l_j^-$, $B^+_{(s)} \to K^{(*)+}(\phi) l_i^+ l_j^-$ mediated via the scalar LQ. Leptoquarks are color triplet bosonic particles which can couple to a quark and a lepton simultaneously and can occur in various extensions of the SM, e.g., grand unified theory, Pati Salam model, composite scenarios, etc. We consider the simple renormalizable scalar LQ model, for which the bounds from proton decays may not be relevant, and LQ may give signatures in other low-energy processes. In this work, we would like to see whether the scalar LQ model can accommodate some of the recent anomalies observed at LHCb.

The outline of the paper is follows. In section II we discuss the new physics contributions to the SM values due to the exchange of scalar LQ and the constraint on the leptoquark couplings from $B_s \to \mu^+\mu^-$ process. The branching ratios and other recent anomalies in $B \to K^{(*)}\mu^+\mu^-$ process are computed in section III. In section IV we estimate the branching ratio of $B \to K^{(*)}\nu\bar{\nu}$ process. The rare LFV decays are studied in section V and section VI contains the summary and conclusion.

2. New physics contributions due to leptoquark excahnge

In the SM, the effective Hamiltonian for processes involving $b \to s l^+ l^-$ quark level transition is given by [2]

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

where G_F is the Fermi constant, $V_{qq'}$ are the CKM matrix elements, α denotes the fine structure constant, $P_{L,R}$ are the projection operators and C_i's are the Wilson coefficients.

The SM effective Hamiltonian (1) can be modified in the scalar leptoquark model due to the exchange of LQ. Here we will consider two minimal renormalizable scalar leptoquark multiplets $X = (3, 2, 7/6)$ and $(3, 2, 1/6)$, which are invariant under the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ and do not allow proton decay. The interaction Lagrangian of $X = (3, 2, 7/6)$ leptoquark with the SM fermion bilinear is given by [2]

$$\mathcal{L} = -\lambda_u^{ij} \ \bar{u}^i_{\alpha R} (V_\alpha e^j_L - Y_\alpha \nu^j_L) - \lambda_e^{ij} \ \bar{e}^i_R \left(V_L^\dagger u^j_{\alpha L} + Y^\dagger_\alpha d^j_{\alpha L} \right) + h.c. \ , \tag{2}$$

which after performing the Fierz transformation and then comparing with the SM effective Hamiltonian (1) gives additional Wilson coefficients to the $b \to s l^+ l^-$ processes as

$$C_9^{NP} = C_{10}^{NP} = -\frac{\pi}{2\sqrt{2} G_F \alpha V_{tb} V_{ts}^*} \frac{\lambda_\mu^{32} \lambda_\mu^{22*}}{M_Y^2} \ . \tag{3}$$

Similarly the $X = (3, 2, 1/6)$ LQ also provide new primed Wilson coefficients ${C'_{9,10}}^{NP}$ corresponding to the semileptonic electroweak penguin operators $\mathcal{O}'_{9,10}$. These Wilson coefficients will give additional contributions to the leptonic decay rate $B_s \to \mu\mu$. Now comparing the SM predicted branching ratio of $B_s \to \mu^+\mu^-$ process from [3], with the corresponding experimental result [4], we obtain the constraint on the combination of leptoquark couplings. The detailed formalism of the constraints on leptoquark coupling can be found in [2]; therefore, here we will simply quote the results, as

$$0 \le \frac{|\lambda^{32} \lambda^{22*}|}{M_S^2} \le 5 \times 10^{-9} \ \text{GeV}^{-2} \qquad \text{for} \qquad \pi/2 \le \phi^{NP} \le 3\pi/2 \ , \tag{4}$$

where M_S is the mass of scalar leptoquark. Similarly for $B_s \to e^+e^-$ process, the bound on the product of leptoquark coupling is found as $|\lambda^{31}\lambda^{21*}|/M_S^2 \ < \ 2.54 \times 10^{-5}$.

3. $B \to K^{(*)} \mu^+\mu^-$ process

In this section, we study the anomalies in $B \to K^{(*)}\mu^+\mu^-$ process in the scalar leptoquark model. The differential decay distribution with respect to the lepton-pair invariant mass (q^2) after integration over all three angles (θ_{K^*}, θ_l and ϕ) is given by [5, 6]

$$\frac{d\Gamma}{dq^2} = \frac{3}{4} \Big(J_1 - \frac{J_2}{3} \Big), \tag{5}$$

where the coefficients $J_{1,2}$ are functions of the dilepton invariant mass.

The various combinations of J_i, for $i = 1, ..., 9$ coefficients will give additional interesting observables like forward-backward asymmetry, isospin asymmetry, polarisation fraction of K^* and $P'_{4,5,6}$ observables to look for new physics. The forward backward asymmetry (A_{FB}), longitudinal polarisation fraction of K^* (F_L) and the form-factor-independent (FFI) observable (P'_5) are defined as [5, 6, 7]

$$A_{FB}\left(q^2\right) = -\frac{3}{8}\frac{J_6}{d\Gamma/dq^2}\,, \qquad F_L\left(q^2\right) = \frac{3J_1^c - J_2^c}{4d\Gamma/dq^2}\,, \qquad P'_5\left(q^2\right) = \frac{J_5}{2\sqrt{-J_2^c J_2^s}}. \tag{6}$$

In Fig. 1, we show the q^2 variation of branching ratio (top left panel), A_{FB} (top right panel) and P'_5 observable (bottom panel) in the $(3, 2, 7/6)$ LQ model. The integrated values of branching ratio of $B \to K^*\mu^+\mu^-$ process in both SM and LQ model are found to be [5]

$$\mathrm{Br}(B \to K^*\mu^+\mu^-)|_{\mathrm{SM}} = (7.74 \pm 0.46) \times 10^{-7}, \quad \mathrm{Br}(B \to K^*\mu^+\mu^-)|_{\mathrm{LQ}} = (6.88 - 8.73) \times 10^{-7}. \tag{7}$$

and the predicted value of A_{FB}, F_L and P'_5 in the SM and LQ model are [5]

$$\begin{aligned} &\langle A_{FB}\rangle|_{\mathrm{SM}} = -(0.09 \pm 0.005),\ \langle F_L\rangle_{\mathrm{SM}} = 0.71 \pm 0.043,\ \langle P'_5\rangle_{\mathrm{SM}} = -0.204 \pm 0.012, \\ &\langle A_{FB}\rangle|_{\mathrm{LQ}} = -0.11 \to 0.004, \quad \langle F_L\rangle_{\mathrm{LQ}} = 0.7 \to 0.8, \quad \langle P'_5\rangle_{\mathrm{LQ}} = -0.42 \to 0.13. \end{aligned} \tag{8}$$

Another interesting observable is the lepton non-universality parameter (R_K) in $B \to K l^+ l^-$ process, which is the ratio of branching fraction of $B \to K l^+ l^-$ decays into dimuons over dielectrons. In Fig. 2, we show the variation of lepton non-universality with respect to low q^2 (left panel) and high q^2 (right panel) in leptoquark model. The predicted values of R_K in $q^2 \in [1, 6]\mathrm{GeV}^2$ bin is $(0.62 - 0.96)$ [2] and in high q^2 bin ($q^2 \geq 14.18$) GeV^2 is $(0.75 \to 1.0)$ [8].

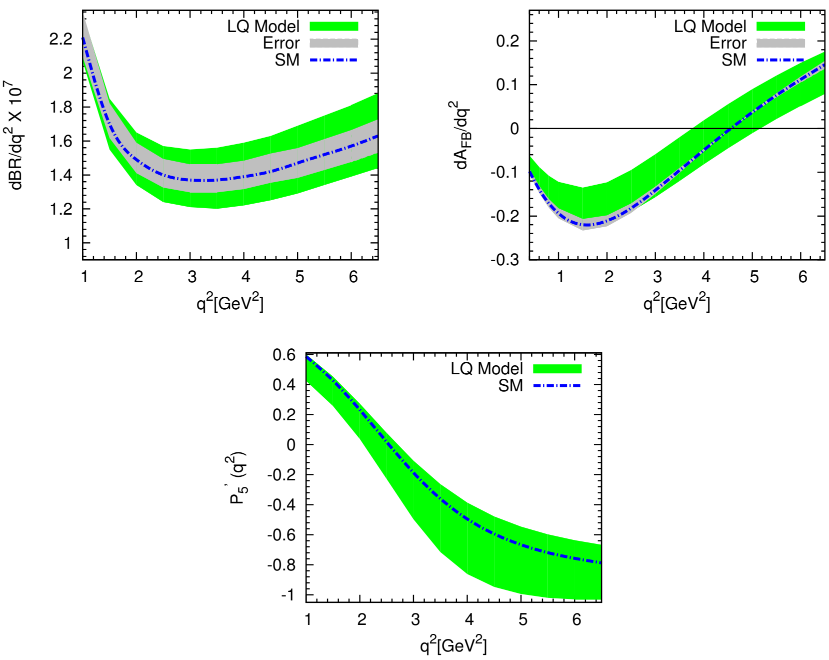

Figure 1. The q^2 variation of branching ratio (top left panel), forward-backward asymmetry (top right panel) and P'_5 observable (bottom panel) of $B \to K^*\mu^+\mu^-$ process in the scalar leptoquark model [5].

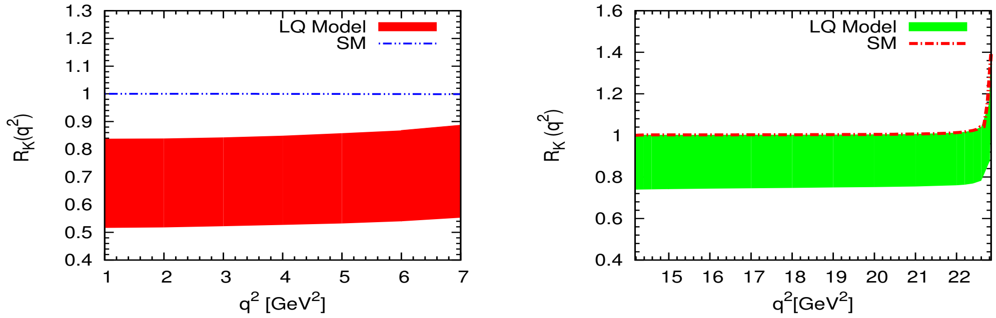

Figure 2. The variation of lepton non-universality parameter (R_K) with respect to low q^2 (left panel) and high q^2 (right panel) in the scalar leptoquark model [2].

4. $B \to K^{(*)}\nu\bar{\nu}$ process

The $B \to K^{(*)}\nu\bar{\nu}$ process is mediated by $b \to s\nu\bar{\nu}$ transition and the effective Hamiltonian in the SM is given by [9, 8]

$$\mathcal{H}_{eff} = \frac{-4G_f}{\sqrt{2}} V_{tb}V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu\right) + h.c.. \tag{9}$$

In the SM, the C_R^ν Wilson coefficient is zero and can only be generate by the new physics. The new contribution to the SM effective Hamiltonian (9) due to the exchange of $(3, 2, 1/6)$ scalar leptoquark is given by [8]

$$\mathcal{H}_{LQ} = \frac{\lambda_\mu^{32}\lambda_\mu^{22*}}{M_Y^2} (\bar{s}\gamma^\mu P_R b)(\bar{\nu}\gamma_\mu(1-\gamma_5)\nu) , \tag{10}$$

which contributes C_R^ν Wilson coefficient as

$$C_R^\nu|_{LQ} = -\frac{\pi}{2\sqrt{2}G_F \alpha V_{tb}V_{ts}^*} \frac{\lambda_d^{22}\lambda_d^{32*}}{M_V^2} . \tag{11}$$

The decay distribution of $B \to K\nu\bar{\nu}$ process with the di-neutrino invariant mass is given by

$$\frac{d\Gamma}{ds_B} = \frac{G_f^2\alpha^2}{256\pi^5} |V_{ts}^* V_{tb}|^2 m_B^5 \lambda^{3/2}(s_B, \tilde{m}_K^2, 1) |f_+^K(s_B)|^2 |C_L^\nu + C_R^\nu|^2, \tag{12}$$

where $\tilde{m}_i = m_i/m_B$ and $s_B = s/m_B^2$. The differential decay rate for $B \to K^*\nu\bar{\nu}$ process is

$$\frac{d^2\Gamma}{ds_B d\cos\theta} = \frac{9}{4} m_B^2 (|A_\perp|^2 + |A_\parallel|^2) \sin^2\theta + \frac{9}{2} m_B^2 |A_0|^2 \cos^2\theta, \tag{13}$$

where the transitivity amplitude $A_{\perp,\parallel,0}$ are given in [9, 8].

Now using the constraint LQ coupling from Eqn. (4), the predicted branching ratios of $B \to K^{(*)}\nu\bar{\nu}$ processes (in units of 10^{-6}) both in the SM and LQ model respectively are [8]

$$\mathrm{Br}(B_d \to K\nu\bar{\nu})|_{\mathrm{SM}} = (4.9 \pm 0.29), \qquad \mathrm{Br}(B_d \to K\nu\bar{\nu})|_{\mathrm{LQ}} = (3.6 - 5.2), \tag{14}$$

$$\mathrm{Br}(B_d \to K^*\nu\bar{\nu})|_{\mathrm{SM}} = (9.54 \pm 0.57), \qquad \mathrm{Br}(B_d \to K^*\nu\bar{\nu})|_{\mathrm{LQ}} = (7.0 - 10.13), \tag{15}$$

and the variation of branching ratio of $B \to K\nu\bar{\nu}$ (left panel) and $B \to K^*\nu\bar{\nu}$ (right panel) with s_B in the leptoquark model is shown in Fig. 3.

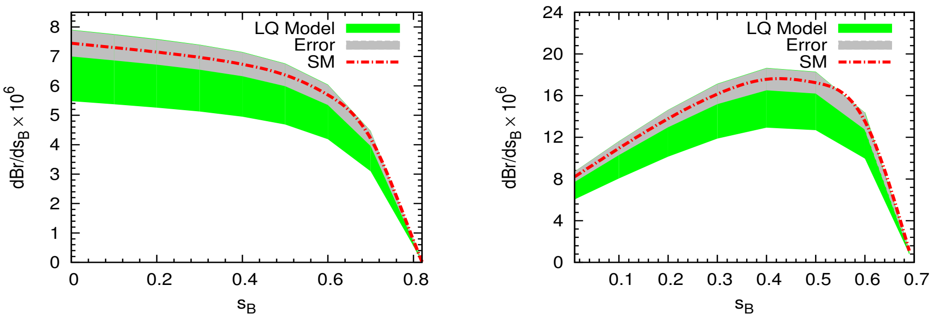

Figure 3. The variation of branching ratio of $B \to K\nu\bar{\nu}$ (left panel) and $B \to K^*\nu\bar{\nu}$ (right panel) with respect to s_B in the scalar leptoquark model [8].

5. Lepton flavour violating decays

In this section, we will discuss the lepton flavour violating B meson decays mediated through the exchange of scalar leptoquarks. The LFV processes are extremely rare in the SM as they are either proceed through box diagram or two-loop suppressed with tiny neutrino masses in one of the loop. However, in the LQ model they can occur at tree level. The effective Hamiltonian for $b \to s l_i^{\mp} l_j^{\pm}$ LFV decays in the LQ model is given by [10]

$$\mathcal{H}_{LQ} = \left[G_{LQ}\,(\bar{q}\gamma^{\mu}P_L b)\,(\bar{l}_i\gamma_{\mu}(1+\gamma_5)l_j) + H_{LQ}\,(\bar{q}\gamma^{\mu}P_L b)\,(\bar{l}_j\gamma_{\mu}(1+\gamma_5)l_i)\right] , \tag{16}$$

where the constant coefficient G_{LQ} and H_{LQ} are

$$G_{LQ} = \frac{\lambda^{3i}\lambda^{kj*}}{8M_Y^2}, \qquad H_{LQ} = \frac{\lambda^{ki}\lambda^{3j*}}{8M_Y^2} . \tag{17}$$

Now, in order to compute the required leptoquark coupling, we used the the coupling given in Eqn. (4) as basis value and assumed that the leptoquark couplings between different generation of quarks and leptons follow the simple scaling law, i.e. $\lambda^{ij} = (m_i/m_j)^{1/4}\lambda^{ii}$ with $j>i$. Using this ansatz we compute the branching ratio of LFV decays, such as $B_s \to l_i^+ l_j^-$, $B^+ \to {K^{(*)}}^+ l_i^+ l_j^-$ and $B_s \to \phi l_i^+ l_j^-$, and the predicted values are listed in Table-I, which are consistent with present experimental upper limits [4]. We show the plot for branching ratio of $B^+ \to K^+\mu^+e^-$ (left panel), $B^+ \to K^+\tau^+e^-$ (middle panel) and $B^+ \to K^+\tau^+\mu^-$ (right panel) decays in Fig. 4.

6. Conclusion

In this paper we have studied the recent anomalies in rare semileptonic B meson decays in scalar leptoquark model. We constrained the new LQ parameter space using the recent measurements on $B_s \to \mu^+\mu^-$ process. Using such constrained LQ couplings, we computed the branching ratio of $B \to K^{(*)}\mu^+\mu^-(\nu\bar{\nu})$ processes. We also estimated the forward-backward asymmetry, polarization fractions of K^* and the FFI observables in the full physical region except for the intermediate region of q^2. We found that the observed R_K anomaly can be explained in the LQ model. We then predicted the branching ratio of LFV decays such as $B_s \to l_i^+ l_j^-$, $B_{(s)}^+ \to {K^{(*)}}^+(\phi) l_i^+ l_j^-$, which are found to be well below the experimental limit.

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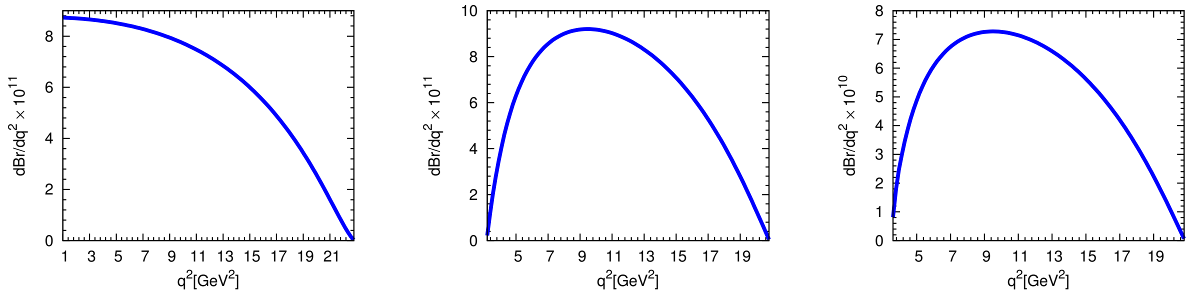

Figure 4. The variation of branching ratio of $B^+ \to K^+\mu^+e^-$ (left panel), $B^+ \to K^+\tau^+e^-$ (middle panel), and $B^+ \to K^+\tau^+\mu^-$ (right panel) with respect to q^2 in the scalar leptoquark model [10].

Table 1. The predicted branching ratios for $B_s \to l_i^+ l_j^-$, $B_{(s)}^+ \to K^{(*)^+}(\phi) l_i^+ l_j^-$ lepton flavour violating decays, where $l = e, \mu, \tau$ in the leptoquark model [10].

Decay process	Predicted Br	Expt. limit [4]
$B_s \to \mu^\pm e^\mp$	$< 1.5 \times 10^{-11}$	$< 1.1 \times 10^{-8}$
$B_s \to \mu^\pm \tau^\mp$	$< 1.2 \times 10^{-8}$	...
$B_s \to e^\pm \tau^\mp$	$< 8.5 \times 10^{-10}$	...
$B^+ \to K^+\mu^+e^-$	$< 1.36 \times 10^{-9}$	$< 1.3 \times 10^{-7}$
$B^+ \to K^+\tau^+\mu^-$	$< 8.8 \times 10^{-9}$	$< 2.8 \times 10^{-5}$
$B^+ \to K^+\tau^+e^-$	$< 1.12 \times 10^{-9}$	$< 1.5 \times 10^{-5}$
$B^+ \to K^{*+}\mu^+e^-$	$<1.4 \times 10^{-9}$	$< 9.9 \times 10^{-7}$
$B^+ \to K^{*+}\tau^+\mu^-$	$<1.56 \times 10^{-8}$	...
$B^+ \to K^{*+}\tau^+e^-$	$< 2 \times 10^{-9}$	...
$B_s \to \phi\mu^+e^-$	$< 8.2 \times 10^{-10}$	...
$B_s \to \phi\tau^+\mu^-$	$< 1.1 \times 10^{-8}$	...
$B_s \to \phi\tau^+e^-$	1.42×10^{-9}	...

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