Study of the rare decays $B_{s,d}^* \rightarrow \mu^+ \mu^-$

Suchismita Sahoo* and Rukmani Mohanta†

School of Physics, University of Hyderabad, Hyderabad - 500046, India
suchismita@uohyd.ac.in*, rukmani98@gmail.com†

Abstract. We study rare leptonic decays of vector $B$ mesons in the scalar leptoquark and family non-universal $Z'$ models. We constrain these new couplings by using the measured branching fractions of $B_{s,d} \rightarrow \mu^+ \mu^-$ processes and the existing $B_{s,d}^0 - \bar{B}_{s,d}^0$ mixing data. We estimate the branching fractions of $B_{s,d}^* \rightarrow \mu^+ \mu^-$ in both the models, which are found to be reasonably enhanced from their corresponding standard model values and within the reach of Run 2-3 of LHC.

Keywords: rare $B$ decays, leptoquark model

1 Introduction

In recent times, the rare $B$ meson decays mediated by flavour changing neutral current (FCNC) $b \rightarrow s,d$ transitions have been providing crucial information in our search for new physics (NP) beyond the standard model (SM). The LHCb Collaboration has reported several anomalies in semileptonic $B$ decays at the level of few standard deviations. The rare $B_{s,d} \rightarrow \mu^+ \mu^-$ processes are highly suppressed in the SM as they proceed through one loop and box diagrams. These decays also encounter additional helicity suppression. Their theory branching fractions are given by [1]

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)|_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9},$$
$$\text{BR}(B_d \rightarrow \mu^+ \mu^-)|_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}. \quad (1)$$

In this work, we investigate the $B_{s,d}^* \rightarrow \mu^+ \mu^-$ processes in the context of leptoquark (LQ) and $Z'$ model. These processes don’t suffer from helicity suppression like $B_{s,d} \rightarrow \mu^+ \mu^-$ processes and the only non-perturbative quantity involved is the decay constant of $B_{s,d}^*$ mesons, which can be precisely calculated from lattice. LQs are color triplet bosons that couples to both quarks and leptons. The baryon and lepton number violating LQs have mass near the grand unification scale to avoid rapid proton decay. Thus we consider the baryon and lepton number conserving LQs, which do not induce proton decay and could be light enough to be accessible in accelerator searches. On the other hand, $Z'$ is a color singlet boson, which could be naturally derived from the extension of electroweak symmetry of the SM by adding additional $U(1)'$ gauge symmetry. The family non-universal $Z'$ model [2] is the simplest one to explore the inconsistency between the observed experimental data and the corresponding SM...
predicted values in some of the observables associated with $b \rightarrow s l^+ l^-$ decays. The popular $\pi K$ puzzle in the hadronic $B \rightarrow \pi K$ decays [3] and other anomalies associated with $b \rightarrow s \mu^+ \mu^-$ transitions observed at LHCb could be explained in the $Z'$ model.

The paper is organised as follows. In section 2, we discuss the effective Hamiltonian of $b \rightarrow s, d$ transitions in the SM. We then compute the $B^*_{s,d} \rightarrow \mu^+ \mu^-$ processes in the SM as well as LQ and $Z'$ model. Section 3 contains the conclusion.

## 2 $B^*_{s,d} \rightarrow \mu^+ \mu^-$ processes

In the SM, the effective Hamiltonian of rare processes involving the quark-level transitions $b \rightarrow q l^+ l^-$, where $q = d, s$ is given by [4]

$$H_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[ \lambda_k^{(q)} H_{\text{eff}}^{(q)} + \lambda_u H_{\text{eff}}^{(u)} \right] + h.c., \quad (2)$$

where

$$H_{\text{eff}}^{(u)} = C_1 (O_1^u - O_2^u) + C_2 (O_3^u - O_4^u),$$

$$H_{\text{eff}}^{(t)} = C_1 O_1^t + C_2 O_2^t + \sum_{i=3}^{10} C_i O_i,$$  \quad (3)

$G_F$ is the Fermi constant, $\lambda_k^{(q)} = V_{kb} V_{kq}^*$ and $C_i$'s are the Wilson coefficients.

The decay widths of $B^*_q \rightarrow \mu^+ \mu^-$ processes are given by [5]

$$\Gamma(B^*_q \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha^2}{96 \pi^3} |V_{tb} V_{tq}|^2 f_{B^*_q}^2 m_{B^*_q}^2 \sqrt{m_{B^*_q}^2 - 4m_l^2} \times$$

$$\left| \left[ C_9^{\text{eff}} + \frac{2m_b}{m_{B^*_q}} C_7^{\text{eff}} \right]^2 + C_{10}^2 \right|,$$  \quad (4)

where $\alpha$ is the fine structure constant, $f_{B^*_q}$ and $m_{B^*_q}$ are the decay constant and mass of $B^*_q$ meson respectively and $m_l$ is the mass of lepton. These processes are sensitive to the $C_7^{\text{eff}}$ Wilson coefficients, i.e., $O_7$ and $O_9$ operators, whereas the contributions from these operators vanish in the case of $B_{s,d} \rightarrow \mu^+ \mu^-$ processes. In order to calculate the branching fractions, we need to know the total decay widths of $B^*_s,d$ vector bosons. However, these are neither measured nor precisely known theoretically except for the decay widths of $B_{s,d} \rightarrow B_{s,d} \gamma$ decays. Now using the particle masses from Ref. [6] and taking the decay widths of radiative $B^*_{s,d}$ bosons from Ref. [7], the branching fractions are found to be

$$\text{BR}(B^*_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.7 \pm 0.2) \left( \frac{0.07 \text{ KeV}}{\Gamma_{\text{tot}}^{B^*_s}} \right) \times 10^{-11},$$

$$\text{BR}(B^*_d \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.86 \pm 0.21) \left( \frac{0.2 \text{ KeV}}{\Gamma_{\text{tot}}^{B^*_d}} \right) \times 10^{-13}. \quad (5)$$
These predicted branching fractions are sizable, about two order lower than the branching fractions of the corresponding pseudoscalar mesons decay.

The effective Hamiltonian in Eq. (2) can be modified in the both the LQ and Z' model. We consider $S_1(3, 2, 7/6)$ and $S_2(3, 2, 1/6)$ scalar LQ multiplets, which are invariant under the SM $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group. These will contribute new $C_{9,10}^{LQ}$ coefficients to the SM. In the NP model, the Wilson coefficients in Eq. (2) will be replaced by $C_{9,10} \to C_{9,10} + C_{9,10}^{NP}$. Now comparing the branching fraction of $B_{s,d} \to \mu^+\mu^-$ with the 1$\sigma$ uncertainty of experimental data, the constraints on the LQ couplings ($\lambda$) for $M_{LQ} = 1$ TeV are found to be [8]

$$0 \leq \left| \frac{\lambda^{32} \lambda^{22*}}{M_S^2} \right| \leq 5 \times 10^{-3}, \quad 1.5 \times 10^{-3} \leq \left| \frac{\lambda^{32} \lambda^{12*}}{M_S^2} \right| \leq 3.9 \times 10^{-3} . \quad (6)$$

Using the constrained couplings, we predict the branching fractions of $B_{s,d}^* \to \mu^+\mu^-$ in both $S_{1,2}$ LQ model and the corresponding values are listed in Table 1.

Similar to the LQ model, the presence of $Z'$ boson will also provide $C_{9,10}^{Z'}$ new coefficients. Varying the mass difference of $B_{s,d}^0 - \bar{B}_{s,d}^0$ mixing within the 2$\sigma$ allowed range of experimental value, the constraints on $\rho_{Lq}$ parameters are [4]

$$0 \leq \rho_{Ls} \leq 0.5 \times 10^{-3}, \quad 1 \times 10^{-4} \leq \rho_{Ld} \leq 1.25 \times 10^{-4}, \quad (7)$$

where $\rho_{Lq} = \frac{g_2 B_{qL}^{L}}{g_1 M_S}$ and $B_{qL}^{L}$ are the left handed FCNC $b_L - q_L - Z'$ couplings [9]. We consider the coupling of $Z'$ with the leptons as SM like. Using the above constrained couplings, the predicted branching fractions are given in Table 1. The detailed calculation of these processes in the SM as well as in both the LQ and Z' model can be found in Ref. [5] and [4], respectively.

### Table 1. Predicted branching fractions of $B_{s,d}^* \to l^+l^-$ decays in the LQ and $Z'$ model.

| Decay processes | Values in $Y = 1/6$ LQ model | Values in $Y = 7/6$ LQ model | Values in $Z'$ model |
|-----------------|-----------------------------|-----------------------------|---------------------|
| $B_s^* \to \mu^+\mu^-$ | $(1.7 - 3.19) \times 10^{-14}$ | $(1.7 - 1.93) \times 10^{-14}$ | $(1.7 - 2.2) \times 10^{-14}$ |
| $B_d^* \to \mu^+\mu^-$ | $(2.38 - 8.99) \times 10^{-13}$ | $(2.47 - 5.4) \times 10^{-13}$ | $(1.67 - 2.23) \times 10^{-13}$ |

## 3 Conclusions

We have studied the rare leptonic decays of $B_{s,d}^*$ bosons in both the scalar LQ and the family nonuniversal $Z'$ model. We constrain the NP parameters using the measured branching fractions of $B_{s,d} \to \mu^+\mu^-$ processes and the $B_{s,d}^0 - \bar{B}_{s,d}^0$
mixing data. We then estimated the branching fractions of $B_{s,d}^* \to \mu^+ \mu^-$ processes, which are found to be sizable and within the reach of LHC experiments.

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