Research Article

Analysis of $\Lambda_b \to \Lambda\mu^+\mu^-$ Decay in Scalar Leptoquark Model

Shuai-Wei Wang[1,2] and Ya-Dong Yang[1]

[1]*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei 430079, China*
[2]*Department of Physics, Nanyang Normal University, Nanyang, Henan 473061, China*

Correspondence should be addressed to Shuai-Wei Wang; shuaiweiwang@sina.com

We analyze the baryonic semilepton decay $\Lambda_b \to \Lambda\mu^+\mu^-$ in the scalar leptoquark models with $X(3,2,7/6)$ and $X(3,2,1/6)$ states, respectively. We also discuss the effects of these two NP models on some physical observables. For some measured observables, like the differential decay width, the longitudinal polarization of the dilepton system, the lepton-side forward-backward asymmetry, and the baryon-side forward-backward asymmetry, we find that the prediction values of SM are consistent with the current data in most q^2 ranges, where the prediction values of these two NP models can also keep consistent with the current data with 1σ. However, in some q^2 ranges, the prediction values of SM are difficult to meet the current data, but the contributions of these two NP models can meet them or keep close to them. For the double-lepton polarization asymmetries, P_{LT}, P_{TL}, P_{NN}, and P_{TT} are sensitive to the scalar leptoquark model $X(3,2,7/6)$ but not to $X(3,2,1/6)$. However, P_{LN}, P_{NL}, P_{TN}, and P_{NT} are not sensitive to these two NP models.

1. Introduction

The current data have hinted at several anomalies in *B* decays induced by the flavor-changing neutral current (FCNC) processes $b \to sl^+l^-$, which have been recognized as very important probes of the Standard Model (SM) and new physics (NP). For the baryonic semilepton decays, experimentally, $\Lambda_b \to \Lambda\mu^+\mu^-$ decay has been observed by the CDF collaboration [1] and measured by the LHCb collaboration at CERN [2]. Theoretically, studies on the $\Lambda_b \to \Lambda\mu^+\mu^-$ decay have been investigated in the SM and beyond the SM [3–16]. Their results showed that some observables of these processes are sensitive to the contributions of NP.

The leptoquark models have many kinds of states, not only vector ones, but also scalar ones. In regard to different decay processes, the different leptoquark states may produce different effects. For $b \to s\mu^+\mu^-$ processes, model independent constrains on leptoquarks are obtained in [17], where scalar leptoquark states with $X = (3,2,7/6)$ and $X = (3,2,1/6)$ have visible effects on the $b \to s\mu^+\mu^-$ processes of B meson decays. For $\Lambda_b \to \Lambda\mu^+\mu^-$ decay, their quark level transitions are also $b \to s\mu^+\mu^-$; therefore, in this paper, we try to examine the effects of scalar leptoquark models on some observables of $\Lambda_b \to \Lambda\mu^+\mu^-$ decay, such as the differential decay width, the longitudinal polarization of the dilepton system, the lepton-side forward-backward asymmetry, and the baryon-side forward-backward asymmetry and double-lepton polarization asymmetries.

The outline of this paper is as follows. In the next section we present the SM theoretical framework for $\Lambda_b \to \Lambda\mu^+\mu^-$ transitions. In Section 3, we introduce the employed scalar leptoquark models; the transition form factors are given in Section 4. In Section 5, we present the physical observables and numerical analyses. Finally, we will have a concluding section.

2. $\Lambda_b \to \Lambda\ell^+\ell^-$ Transitions

At quark level, the rare decay $\Lambda_b \to \Lambda\ell^+\ell^-$ is governed by the $b \to s\ell^+\ell^-$ transition; its effective Hamiltonian in the SM can be written as

$$\mathcal{H}^{\text{eff}} = \frac{G_F \alpha_{em} V_{tb} V_{ts}^*}{2\sqrt{2}\pi} \left[C_9^{\text{eff}} \bar{s}\gamma_\mu (1-\gamma_5) b \bar{\ell}\gamma^\mu\ell \right.$$
$$\left. + C_{10} \bar{s}\gamma_\mu (1-\gamma_5) b \bar{\ell}\gamma^\mu\gamma_5\ell \right.$$

$$-2m_b C_7^{\text{eff}} \frac{1}{q^2} \bar{s} i \sigma_{\mu\nu} q^\nu \left(1 + \gamma_5\right) b \bar{\ell} \gamma^\mu \ell \Big], \tag{1}$$

where G_F is the Fermi constant, $\alpha_{em} = e^2/4\pi$ is the fine-structure constant, and $V_{qq'}$ denote the CKM matrix elements.

Following [18], the effective Wilson coefficients in the high q^2 region are given by

$$C_7^{\text{eff}}\left(q^2\right)$$
$$= C_7 - \frac{1}{3}\left(C_3 + \frac{4}{3}C_4 + 20C_5 + \frac{80}{3}C_6\right)$$
$$- \frac{\alpha_s}{4\pi}\left[\left(C_1 - 6C_2\right) F_{1,c}^{(7)}\left(q^2\right) + C_8 F_8^{(7)}\left(q^2\right)\right],$$

$$C_9^{\text{eff}}\left(q^2\right)$$
$$= C_9 + \frac{4}{3}C_3 + \frac{64}{9}C_5 + \frac{64}{27}C_6 \tag{2}$$
$$+ h\left(0, q^2\right)\left(-\frac{1}{2}C_3 - \frac{2}{3}C_4 - 8C_5 - \frac{32}{3}C_6\right)$$
$$+ h\left(m_b, q^2\right)\left(-\frac{7}{2}C_3 - \frac{2}{3}C_4 - 38C_5 - \frac{32}{3}C_6\right)$$
$$+ h\left(m_c, q^2\right)\left(\frac{4}{3}C_1 + C_2 + 6C_3 + 60C_5\right)$$
$$- \frac{\alpha_s}{4\pi}\left[C_1 F_{1,c}^{(9)}\left(q^2\right) + C_2 F_{2,c}^{(9)}\left(q^2\right) + C_8 F_8^{(9)}\left(q^2\right)\right],$$

where the explicit expressions of these functions $F_8^{(7,9)}(q^2)$, $h(m_q, q^2)$, $F_{1,c}^{(7,9)}(q^2)$, and $F_{2,c}^{(7,9)}(q^2)$ can be found in [19–21]. However, in the low q^2 region, nonfactorizable hadronic effects are expected to have the sizeable corrections; these have not been calculated for the baryonic decay [21, 22]. According to [18], we use the effective Wilson coefficients $C_7^{\text{eff}}(q^2)$ and $C_9^{\text{eff}}(q^2)$ in (2) both in the low q^2 region and in the high q^2 region by increasing the 5% uncertainty.

3. Scalar Leptoquark Models

Here we consider two kinds of the minimal renormalizable scalar leptoquark models [17], containing one single additional representation of $SU(3) \times SU(2) \times U(1)$ where baryon number violation cannot be allowed in perturbation theory. There are only two such models which are represented as $X(3, 2, 7/6)$ and $X(3, 2, 1/6)$ under the $SU(3) \times SU(2) \times U(1)$ gauge group.

The interaction Lagrangian for the scalar leptoquark $X(3, 2, 7/6)$ couplings to the fermion bilinear can be written as

$$\mathscr{L} = -\lambda_u^{ij} \bar{u}_R^i X^T \epsilon L_L^j - \lambda_e^{ij} \bar{e}_R^i X^\dagger Q_L^j + \text{h.c.}, \tag{3}$$

where $i, j = 1, 2, 3$ are the generation indices, the couplings λ are in general complex parameters, $u_R(e_R)$ is the right-hand up-type quark (charged lepton) singlet, X is the scalar

leptoquark doublet, $\epsilon = i\sigma_2$ is a 2×2 matrix, and $Q_L(L_L)$ is the left-hand quark (lepton) doublet.

After performing Fierz transformation, the contribution to the interaction Hamiltonian for $b \to s\mu^+\mu^-$ is

$$\mathscr{H} = \frac{\lambda_\mu^{32} \lambda_\mu^{22*}}{8M_{(7/6)}^2}\left[\bar{s}\gamma^\mu\left(1 - \gamma_5\right) b\right]\left[\bar{\mu}\gamma_\mu\left(1 + \gamma_5\right)\mu\right]$$
$$= \frac{\lambda_\mu^{32} \lambda_\mu^{22*}}{4M_{(7/6)}^2}\left(O_9 + O_{10}\right), \tag{4}$$

which can be written in the style of the SM effective Hamiltonian as

$$\mathscr{H} = -\frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left(C_9^{\text{NP}} O_9 + C_{10}^{\text{NP}} O_{10}\right). \tag{5}$$

Then we obtain the new Wilson coefficients

$$C_9^{\text{NP}} = C_{10}^{\text{NP}} = -\frac{\pi}{2\sqrt{2}G_F V_{tb} V_{ts}^* \alpha} \frac{\lambda_\mu^{32} \lambda_\mu^{22*}}{M_{(7/6)}^2}. \tag{6}$$

The interaction Lagrangian for the scalar leptoquark $X = (3, 2, 1/6)$ couplings to the fermion bilinear can be written as

$$\mathscr{L} = -\lambda_d^{ij} \bar{d}_R^i X^T \epsilon L_L^j + \text{h.c.} \tag{7}$$

After performing Fierz transformation, the contribution to the interaction Hamiltonian for the $b \to s\mu^+\mu^-$ is

$$\mathscr{H} = \frac{\lambda_s^{22} \lambda_b^{32*}}{8M_{(1/6)}^2}\left[\bar{s}\gamma^\mu\left(1 + \gamma_5\right) b\right]\left[\bar{\mu}\gamma_\mu\left(1 - \gamma_5\right)\mu\right]$$
$$= \frac{\lambda_s^{22} \lambda_b^{32*}}{4M_{(1/6)}^2}\left(O_9' - O_{10}'\right), \tag{8}$$

where O_9' and O_{10}' are six-dimensional operators obtained from O_9 and O_{10} by the replacement $P_L \leftrightarrow P_R$. Writing in the style of the SM effective Hamiltonian, we obtain the new Wilson coefficients:

$$C_9'^{\text{NP}} = -C_{10}'^{\text{NP}} = \frac{\pi}{2\sqrt{2}G_F V_{tb} V_{ts}^* \alpha} \frac{\lambda_s^{22} \lambda_b^{32*}}{M_{(1/6)}^2}. \tag{9}$$

In [23], comparing the bounds on NP coupling parameters obtained from $B_s \to \mu^+\mu^-$, $\bar{B}_d^0 \to X_s\mu^+\mu^-$, and $B_s - \bar{B}_s$ mixing, respectively, the authors obtain the following results:

$$0 \le \frac{\left|\lambda_\mu^{32} \lambda_\mu^{22*}\right|}{M_{(7/6)}^2} = \frac{\left|\lambda_s^{22} \lambda_b^{32*}\right|}{M_{(1/6)}^2} = \frac{\left|\lambda_s^{32} \lambda_b^{22*}\right|}{M_S^2}$$
$$\le 5 \times 10^{-9}\,\text{GeV}^{-2}, \quad \text{for } \frac{\pi}{2} \le \phi^{\text{NP}} \le \frac{3\pi}{2}, \tag{10}$$

where the bounds will be used in the process of our calculations.

4. Transition Form Factors

For $\Lambda_b \to \Lambda\mu^+\mu^-$ decay, these form factors have been calculated in the framework of QCD light-cone sum rules (LCSR) in the low q^2 region [22] and lattice QCD in the high q^2 region [18], respectively. All of them use the helicity-based definition of the form factors [24]:

$$\langle \Lambda(p',s') |\bar{s}\gamma^\mu b| \Lambda_b(p,s)\rangle = \bar{u}_\Lambda(p',s')\Big[f_0(q^2)$$

$$\cdot (m_{\Lambda_b} - m_\Lambda)\frac{q^\mu}{q^2} + f_+(q^2)$$

$$\cdot \frac{m_{\Lambda_b} + m_\Lambda}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)$$

$$+ f_\perp(q^2)\left(\gamma^\mu - \frac{2m_\Lambda}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}p'^\mu\right)\Big]u_{\Lambda_b}(p,s),$$

$$\langle \Lambda(p',s') |\bar{s}\gamma^\mu\gamma_5 b| \Lambda_b(p,s)\rangle = -\bar{u}_\Lambda(p',s')$$

$$\cdot \gamma_5\Big[g_0(q^2)(m_{\Lambda_b} + m_\Lambda)\frac{q^\mu}{q^2} + g_+(q^2)$$

$$\cdot \frac{m_{\Lambda_b} - m_\Lambda}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)$$

$$+ g_\perp(q^2)\left(\gamma^\mu + \frac{2m_\Lambda}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}p'^\mu\right)\Big]u_{\Lambda_b}(p,s), \quad (11)$$

$$\langle \Lambda(p',s') |\bar{s}i\sigma^{\mu\nu}q_\nu b| \Lambda_b(p,s)\rangle = -\bar{u}_\Lambda(p',s')$$

$$\cdot \Big[h_+(q^2)\frac{q^2}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)$$

$$+ h_\perp(q^2)(m_{\Lambda_b} + m_\Lambda)$$

$$\cdot \left(\gamma^\mu - \frac{2m_\Lambda}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}p'^\mu\right)\Big]u_{\Lambda_b}(p,s),$$

$$\langle \Lambda(p',s') |\bar{s}i\sigma^{\mu\nu}q_\nu\gamma_5 b| \Lambda_b(p,s)\rangle = -\bar{u}_\Lambda(p',s')$$

$$\cdot \gamma_5\Big[\tilde{h}_+(q^2)\frac{q^2}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)$$

$$+ \tilde{h}_\perp(q^2)(m_{\Lambda_b} - m_\Lambda)$$

$$\cdot \left(\gamma^\mu + \frac{2m_\Lambda}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}p'^\mu\right)\Big]u_{\Lambda_b}(p,s),$$

where $q = p - p'$ and $s_\pm = (m_{\Lambda_b} \pm m_\Lambda)^2 - q^2$. The fit functions of helicity-based form factors can be found in equations (133)–(135) of [22] and equation (49) of [18].

5. Physical Observables and Numerical Analyses

5.1. Some Measured Observables. According to [25], the Λ_b polarization at the LHC has been measured to be small and compatible with zero, and polarization effects will average out for the symmetric ATLAS and CMS detectors, so we consider the initial baryon Λ_b as unpolarized. The fourfold differential rate of the $\Lambda_b \to \Lambda(\to a(1/2^+), b(0^-))\ell^+\ell^-$ can be written as [26]

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi}$$

$$= \frac{3}{8\pi}\Big[\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right)$$

$$+ \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_\Lambda \quad (12)$$

$$+ \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi$$

$$+ \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi\Big],$$

where the angles θ_ℓ and θ_Λ denote the polar directions of ℓ^- and $a(1/2^+)$, respectively. ϕ is the azimuthal angle between the $\ell^+\ell^-$ and $a(1/2^+)b(0^-)$ decay planes, and the explicit expressions of the coefficients K_i can be found in [26].

(a) The differential decay width is

$$\frac{d\Gamma}{dq^2} = 2K_{1ss} + K_{1cc}. \quad (13)$$

(b) The longitudinal polarization of the dilepton system is

$$F_L = \frac{2K_{1ss} - K_{1cc}}{2K_{1ss} + K_{1cc}}. \quad (14)$$

(c) The lepton-side forward-backward asymmetry is

$$A_{FB}^\ell = \frac{3}{2}\frac{K_{1c}}{2K_{1ss} + K_{1cc}}. \quad (15)$$

(d) The baryon-side forward-backward asymmetry is

$$A_{FB}^\Lambda = \frac{1}{2}\frac{2K_{2ss} + K_{2cc}}{2K_{1ss} + K_{1cc}}. \quad (16)$$

In the process of numerical analyses, we consider the theoretical uncertainties of all input parameters. For the form factors, we use the results of QCD light-cone sum rules (LCSR) in the low q^2 region [22] and lattice QCD in the high q^2 region [18]. Comparing to the current data which have been measured by LHCb collaboration [27], we plot the dependence of four observables mentioned above on the full physical region except the intermediate region of q^2 in Figure 1.
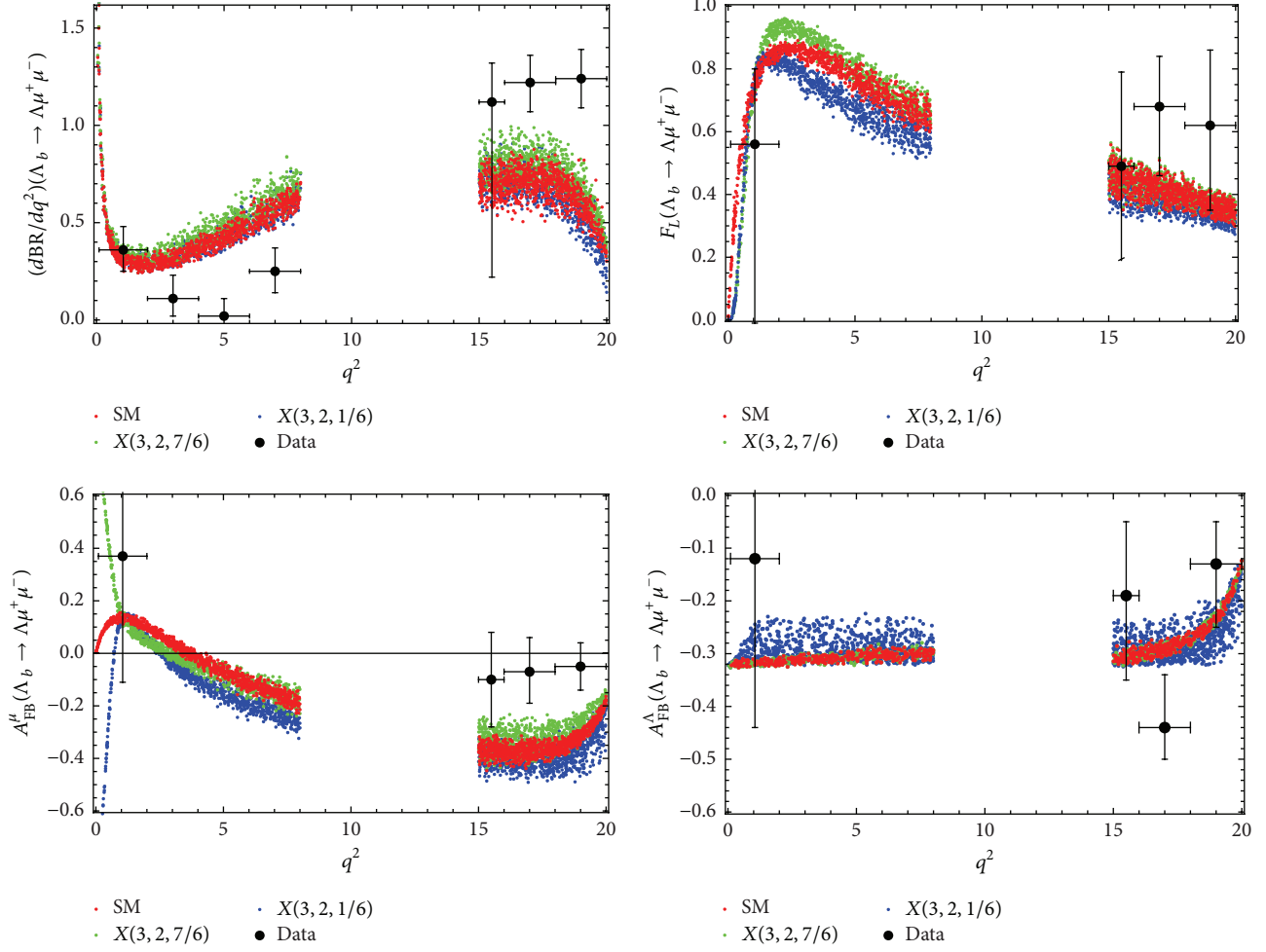
FIGURE 1: The dependence of $d\Gamma/dq^2$, F_L, A_{FB}^{μ}, and A_{FB}^{Λ} on q^2, respectively.

From Figure 1, we obtain the following results:

(i) For the differential decay width $d\Gamma/dq^2$, its prediction values of SM are consistent with the current data in the ranges of $0.1 < q^2 < 1\,\mathrm{GeV}^2/c^2$ and $15 < q^2 < 16\,\mathrm{GeV}^2/c^2$. When we consider the effects of these two NP models, the theoretical predictions are still consistent with the experimental results with 1σ in these ranges. However, in the remaining ranges, its prediction values of SM and these two NP models are difficult to meet the current data. But in the large q^2 region, the prediction values of the scalar leptoquark $X(3, 2, 7/6)$ are more closer to the current data.

(ii) For the longitudinal polarization F_L of the dilepton system, its prediction values of SM and these two NP models are consistent with the current data both in the low q^2 region and in the high q^2 region, respectively. In the low q^2 region, the prediction value of the scalar leptoquark $X(3, 2, 7/6)$ enhances that of SM, but the opposite result happens in the scalar leptoquark $X(3, 2, 1/6)$. There are not obvious

difference results between the SM and these two NP models in the high q^2 region.

(iii) For the lepton-side forward-backward asymmetry A_{FB}^{μ}, in the range of $0.1 < q^2 < 1\,\mathrm{GeV}^2/c^2$, its prediction value of SM is consistent with the current data with 1σ, but the result of the scalar leptoquark $X(3, 2, 7/6)$ is more closer to the central value of the current data than that of SM. In the high q^2 region, its prediction value of SM is lower than the current data. But the result of the scalar leptoquark $X(3, 2, 7/6)$ can meet the current data in the range of $15 < q^2 < 16\,\mathrm{GeV}^2/c^2$.

(iv) For the baryon-side forward-backward asymmetry A_{FB}^{Λ}, except in the range of $16 < q^2 < 18\,\mathrm{GeV}^2/c^2$, the current data in the remaining ranges can be met both in the SM and in these two NP models, respectively. When we consider the NP effects, this observable shows strong dependence on the scalar leptoquark $X(3, 2, 1/6)$. However, there are not obvious difference results between the SM and scalar leptoquark $X(3, 2, 7/6)$.

5.2. Double-Lepton Polarization Asymmetries. The definition of the double-lepton polarization asymmetry can be written as

$$\mathscr{P}_{ij} = \frac{\left(d\Gamma\left(\vec{s}_i^-, \vec{s}_j^+\right)/d\hat{s} - d\Gamma\left(-\vec{s}_i^-, \vec{s}_j^+\right)/d\hat{s}\right) - \left(d\Gamma\left(\vec{s}_i^-, -\vec{s}_j^+\right)/d\hat{s} - d\Gamma\left(-\vec{s}_i^-, -\vec{s}_j^+\right)/d\hat{s}\right)}{\left(d\Gamma\left(\vec{s}_i^-, \vec{s}_j^+\right)/d\hat{s} + d\Gamma\left(-\vec{s}_i^-, \vec{s}_j^+\right)/d\hat{s}\right) + \left(d\Gamma\left(\vec{s}_i^-, -\vec{s}_j^+\right)/d\hat{s} + d\Gamma\left(-\vec{s}_i^-, -\vec{s}_j^+\right)/d\hat{s}\right)}, \tag{17}$$

where $\vec{s}_{i(j)}^{-(+)}$ is the orthogonal unit vector in the rest frame of the leptons; its explicit explanation and nine double-lepton polarization asymmetries are presented in [28].

In [28], the form factors are defined as follows:

$$\left\langle \Lambda\left(p\right)\left|\bar{s}\gamma_\mu\left(1-\gamma_5\right)b\right|\Lambda_b\left(p+q\right)\right\rangle = \bar{u}_\Lambda\left(p\right)$$
$$\cdot\left[\gamma_\mu f_1\left(q^2\right) + i\sigma_{\mu\nu}q^\nu f_2\left(q^2\right) + q^\mu f_3\left(q^2\right)\right.$$
$$\left. - \gamma_\mu\gamma_5 g_1\left(q^2\right) - i\sigma_{\mu\nu}\gamma_5 q^\nu g_2\left(q^2\right) - q^\mu\gamma_5 g_3\left(q^2\right)\right]$$
$$\cdot u_{\Lambda_b}\left(p+q\right),$$
$$\left\langle \Lambda\left(p\right)\left|\bar{s}i\sigma_{\mu\nu}q^\nu\left(1+\gamma_5\right)b\right|\Lambda_b\left(p+q\right)\right\rangle = \bar{u}_\Lambda\left(p\right) \tag{18}$$
$$\cdot\left[\gamma_\mu f_1^T\left(q^2\right) + i\sigma_{\mu\nu}q^\nu f_2^T\left(q^2\right) + q^\mu f_3^T\left(q^2\right)\right.$$
$$\left. + \gamma_\mu\gamma_5 g_1^T\left(q^2\right) + i\sigma_{\mu\nu}\gamma_5 q^\nu g_2^T\left(q^2\right) + q^\mu\gamma_5 g_3^T\left(q^2\right)\right]$$
$$\cdot u_{\Lambda_b}\left(p+q\right),$$

where u_{Λ_b} and u_Λ are spinors of Λ_b and Λ baryons, respectively.

The form factors $f_i^{(T)}$ and $g_i^{(T)}$ in (18) are related to the helicity form factors $f_{+,\perp,0}$, $g_{+,\perp,0}$, $h_{+,\perp}$, and $\tilde{h}_{+,\perp}$ in (11) as follows:

$$f_+ = f_1 - \frac{q^2}{m_{\Lambda_b} + m_\Lambda}f_2,$$

$$f_\perp = f_1 - \left(m_{\Lambda_b} + m_\Lambda\right)f_2,$$

$$f_0 = f_1 + \frac{q^2}{m_{\Lambda_b} - m_\Lambda}f_3,$$

$$g_+ = g_1 + \frac{q^2}{m_{\Lambda_b} - m_\Lambda}g_2,$$

$$g_\perp = g_1 + \left(m_{\Lambda_b} - m_\Lambda\right)g_2,$$

$$g_0 = g_1 - \frac{q^2}{m_{\Lambda_b} + m_\Lambda}g_3,$$

$$h_+ = f_2^T - \frac{m_{\Lambda_b} + m_\Lambda}{q^2}f_1^T,$$

$$h_\perp = f_2^T - \frac{f_1^T}{m_{\Lambda_b} + m_\Lambda},$$

$$\tilde{h}_+ = g_2^T + \frac{m_{\Lambda_b} - m_\Lambda}{q^2}g_1^T,$$

$$\tilde{h}_\perp = g_2^T + \frac{g_1^T}{m_{\Lambda_b} - m_\Lambda}. \tag{19}$$

The amplitude for $\Lambda_b \to \Lambda\mu^+\mu^-$ decay can be written in terms of twelve form factors in (18), and we find that

$$\mathcal{M} = \frac{G\alpha}{8\sqrt{2}\pi}V_{tb}V_{ts}^* \left\{\bar{l}\gamma^\mu\left(1-\gamma_5\right)l\,\bar{u}_\Lambda\left(p\right)\right.$$
$$\cdot\left\{\left(A_1 - D_1\right)\gamma_\mu\left(1+\gamma_5\right) + \left(B_1 + E_1\right)\gamma_\mu\left(1-\gamma_5\right)\right.$$
$$+ i\sigma_{\mu\nu}q^\nu\left[\left(A_2 - D_2\right)\left(1+\gamma_5\right) + \left(B_2 - E_2\right)\left(1-\gamma_5\right)\right]$$
$$\left. + q_\mu\left[\left(A_3 - D_3\right)\left(1+\gamma_5\right) + \left(B_3 - E_3\right)\left(1-\gamma_5\right)\right]\right\}$$
$$\cdot u_{\Lambda_b}\left(p+q\right) + \bar{l}\gamma_\mu\left(1+\gamma_5\right)l\,\bar{u}_\Lambda\left(P\right) \tag{20}$$
$$\cdot\left\{\left(A_1 + D_1\right)\gamma_\mu\left(1+\gamma_5\right) + \left(B_1 + E_1\right)\gamma_\mu\left(1-\gamma_5\right)\right.$$
$$+ i\sigma_{\mu\nu}q^\nu\left[\left(A_2 + D_2\right)\left(1+\gamma_5\right) + \left(B_2 + E_2\right)\left(1-\gamma_5\right)\right]$$
$$\left. + q_\mu\left[\left(A_3 + D_3\right)\left(1+\gamma_5\right) + \left(B_3 + E_3\right)\left(1-\gamma_5\right)\right]\right\}$$
$$\cdot u_{\Lambda_b}\left(p+q\right)\right\},$$

where

$$A_1 = -\frac{2m_b}{q^2}C_7^{\text{eff}}\left(f_1^T + g_1^T\right) + \left(C_9^{\text{eff}} + C_9^{\text{NP}}\right)\left(f_1 - g_1\right)$$
$$+ C_9^{\prime\text{NP}}\left(f_1 + g_1\right),$$

$$A_2 = A_1\left(1 \longrightarrow 2\right),$$

$$A_3 = A_1\left(1 \longrightarrow 3\right),$$

$$B_i = A_i\left(g_i \longrightarrow -g_i; g_i^T \longrightarrow -g_i^T\right), \tag{21}$$

$$D_1 = \left(C_{10}^{\text{eff}} + C_{10}^{\text{NP}}\right)\left(f_1 - g_1\right) + C_{10}^{\prime\text{NP}}\left(f_1 + g_1\right),$$

$$D_2 = D_1\left(1 \longrightarrow 2\right),$$

$$D_3 = D_1\left(1 \longrightarrow 3\right),$$

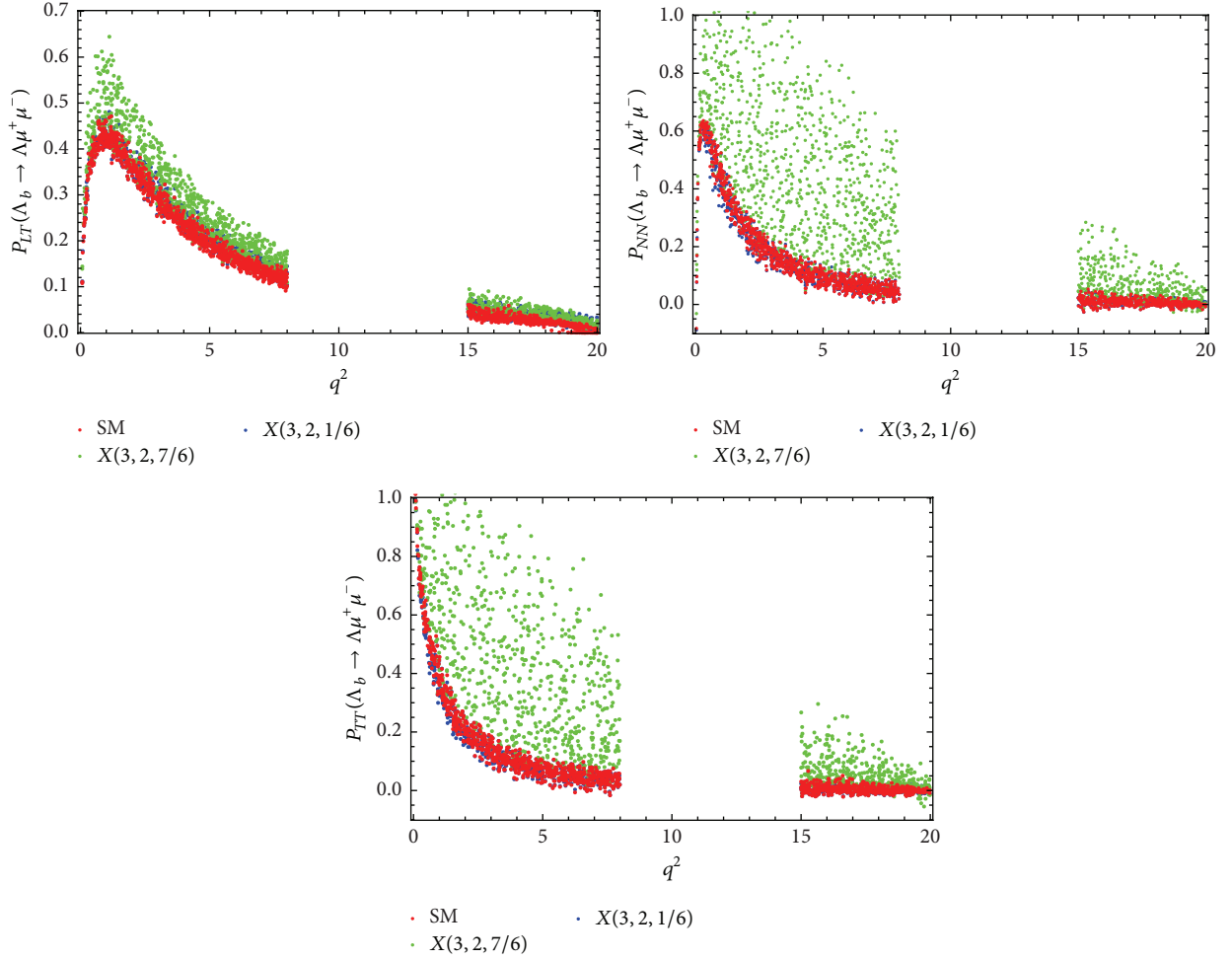$$E_i = D_i\left(g_i \longrightarrow -g_i\right).$$

FIGURE 2: The dependence of double-lepton polarization asymmetries P_{LT}, P_{NN}, and P_{TT} on q^2, respectively.

Because the vector and axial vector currents are not renormalized, we neglect the anomalous dimensions of coefficients $C_9^{(\prime)\mathrm{NP}}$ and $C_{10}^{(\prime)\mathrm{NP}}$ [29].

We also plot the dependence of the double-lepton polarization asymmetries on the full physical region except the intermediate region of q^2 in Figure 2 and find the following:

(i) Double-lepton polarization asymmetries P_{LT}, P_{TL}, P_{NN}, and P_{TT} of this decay process are sensitive to the contribution of the scalar leptoquark $X(3, 2, 7/6)$ but not to that of the scalar leptoquark $X(3, 2, 1/6)$.

(ii) For double-lepton polarization asymmetry P_{LT} of $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ decay, the contribution of the scalar leptoquark $X(3, 2, 7/6)$ can enhance its maximum value of SM prediction from 0.48 to 0.65 in the low q^2 region. For this decay process, these effects of these two NP models on P_{TL} which is not presented in this paper are similar to P_{LT}, respectively.

(iii) For double-lepton polarization asymmetry P_{NN} of $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ decay, when we consider the contribution of the scalar leptoquark $X(3, 2, 7/6)$, its value of SM prediction can be enhanced quite a lot both in the low q^2 region and in the high q^2 region. For this decay

process, the contribution of the scalar leptoquark $X(3, 2, 7/6)$ to P_{TT} is similar to P_{NN}, respectively.

(iv) For double-lepton polarization asymmetries P_{LN}, P_{NL}, P_{NT}, and P_{TN}, their values of SM prediction are almost zero, and the effects of these two NP models are not significant on them.

6. Conclusions

We calculate the differential decay width, the longitudinal polarization of the dilepton system, the lepton-side forward-backward asymmetry, and the baryon-side forward-backward asymmetry and double-lepton polarization asymmetries of $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ decay in the scalar leptoquark model $X(3, 2, 7/6)$ and $X(3, 2, 1/6)$, respectively. Using the constrained parameter spaces from $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow X_s\mu^+\mu^-$ decays, we depict the correlative figures between these observables and the momentum transfer q^2, respectively. We find, for the differential decay width, the longitudinal polarization of the dilepton system, the lepton-side forward-backward asymmetry, and the baryon-side forward-backward asymmetry, which have been measured by LHCb

collaboration; most of their current data can be met both in the SM and in these two NP models. However, some of their current data still cannot be met in the SM. When we consider the effects of these two NP models, like the lepton-side forward-backward asymmetry A^{μ}_{FB} in the range of $0.1 < q^2 < 1 \, \text{GeV}^2/c^2$, its current data with 1σ can be met. For the double-lepton polarization asymmetries, P_{LT}, P_{TL}, P_{NN}, and P_{TT} show strong dependence on the scalar leptoquark model $X(3, 2, 7/6)$ but not on $X(3, 2, 1/6)$, respectively. However, the prediction values of P_{LN}, P_{NL}, P_{TN}, and P_{NT} in the SM are almost zero, and they also show weak dependence on these two NP models.
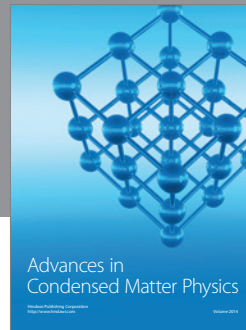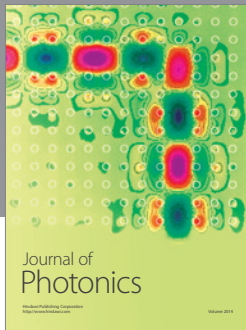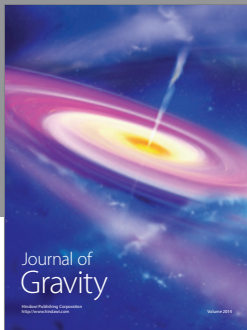
Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

References

[1] T. Aaltonen, B. Álvarez-González, S. Amerio et al., "Observation of the baryonic flavor-changing neutral current decay $\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$," *Physical Review Letters*, vol. 107, no. 20, Article ID 201802, 2011.

[2] R. Aaij, B. Adeva, M. Adinolfi et al., "Measurement of the differential branching fraction of the decay View the MathML source $\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$," *Physics Letters B*, vol. 725, no. 1–3, pp. 25–35, 2013.

[3] C. H. Chen and C. Q. Geng, "Lepton asymmetries in heavy baryon decays of $\Lambda_b \rightarrow \Lambda l^+ l^-$," *Physics Letters B*, vol. 516, no. 3-4, pp. 327–336, 2001.

[4] C. H. Chen, C. Q. Geng, and J. N. Ng, "T violation in $\Lambda_b \rightarrow \Lambda l^+ l^-$ decays with a polarized Λ," *Physical Review D*, vol. 65, Article ID 091502, 2002.

[5] G. Turan, "The exclusive $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ decay in the general two Higgs doublet model," *Journal of Physics G: Nuclear and Particle Physics*, vol. 31, no. 5, pp. 525–537, 2005.

[6] G. Turan, "The exclusive $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ decay with the fourth generation," *Journal of High Energy Physics*, vol. 2005, no. 5, article 008, 2005.

[7] A. K. Giri and R. Mohanta, "Study of FCNC mediated Z boson effect in the semileptonic rare baryonic decays $\Lambda_b \rightarrow \Lambda l^+ l^-$," *The European Physical Journal C: Particles and Fields*, vol. 45, no. 1, pp. 151–158, 2006.

[8] B. B. Şirvanli, "Semileptonic $\Lambda_b \rightarrow \Lambda\nu\bar{\nu}$ decay in the Leptophobic Z' model," *Modern Physics Letters A*, vol. 23, no. 5, pp. 347–358, 2008.

[9] V. Bashiry and K. Azizi, "The effects of fourth generation on the total branching ratio and the lepton polarization in $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ decay," *Journal of High Energy Physics*, vol. 2007, no. 7, p. 64, 2007.

[10] F. Zolfagharpour and V. Bashiry, "Double lepton polarization in $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ decay in the Standard Model with fourth generations scenario," *Nuclear Physics B*, vol. 796, no. 1-2, pp. 294–319, 2008.

[11] Y.-M. Wang, Y. Li, and C.-D. Lü, "Rare decays of $\Lambda_b \rightarrow \Lambda + \gamma$ and $\Lambda_b \rightarrow \Lambda + l^+ l^-$ in the light-cone sum rules," *The European Physical Journal C*, vol. 59, no. 4, pp. 861–882, 2009.

[12] M. J. Aslam, Y. M. Wang, and C. D. Lu, "Exclusive semileptonic decays of $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ in supersymmetric theories," *Physical Review D*, vol. 78, no. 11, Article ID 114032, 2008.

[13] S. Sahoo, C. K. Das, and L. Maharana, "Effect of both Z and Z' mediated flavor-changing neutral currents on the baryonic rare decay $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$," *International Journal of Modern Physics A*, vol. 24, no. 32, pp. 6223–6235, 2009.

[14] F. Li and C.-X. Yue, "Rare decays $\Lambda_b \rightarrow \Lambda l^+ l^-$ in the 331 models," *Europhysics Letters*, vol. 106, no. 6, Article ID 61001, 2014.

[15] T. M. Aliev, A. Ozpineci, and M. Savci, "Exclusive $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ decay beyond standard model," *Nuclear Physics B*, vol. 649, no. 1-2, pp. 168–188, 2003.

[16] T. M. Aliev and M. Savci, "Polarization effects in exclusive semileptonic $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ decay," *Journal of High Energy Physics*, vol. 2006, no. 5, p. 1, 2006.

[17] N. Košnik, "Model independent constraints on leptoquarks from $b \rightarrow s\ell^+\ell^-$ processes," *Physical Review D*, vol. 86, no. 5, Article ID 055004, 10 pages, 2012.

[18] W. Detmold and S. Meinel, "$\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ form factors, differential branching fraction, and angular observables from lattice QCD with relativistic b quarks," *Physical Review D*, vol. 93, Article ID 074501, 2016.

[19] D. Du, A. X. EI-Khadra, S. Gottlieb et al., "Phenomenology of semileptonic B-meson decays with form factors from lattice QCD," *Physical Review D*, vol. 93, no. 3, Article ID 034005, 2016.

[20] D. Seidel, "Analytic two-loop virtual corrections to $b \rightarrow d\ell^+\ell^-$," *Physical Review D*, vol. 70, Article ID 094038, 2004.

[21] M. Beneke, Th. Feldmann, and D. Seidel, "Systematic approach to exclusive $B \rightarrow V\ell^+\ell^-$, $V\gamma$ decays," *Nuclear Physics B*, vol. 612, no. 1-2, pp. 25–58, 2001.

[22] Y. M. Wang and Y. L. Shen, "Perturbative corrections to $\Lambda_b \rightarrow \Lambda$ form factors from QCD light-cone sum rules," *Journal of High Energy Physics*, vol. 2016, article179, 2016.

[23] S. Sahoo and R. Mohanta, "Study of the rare semileptonic decays $B^0_d \rightarrow K^* l^+ l^-$ in scalar leptoquark model," *Physical Review D*, vol. 93, no. 3, Article ID 034018, 20 pages, 2016.

[24] T. Feldmann and M. W. Yip, "Form factors for $\Lambda_b \rightarrow \Lambda$ transitions in the soft-collinear effective theory," *Physical Review D*, vol. 85, no. 1, Article ID 014035, 2012.

[25] R. Aaij, C. Abellan Beteta, B. Adeva et al., "Measurements of the View the $\Lambda^0_b \rightarrow J/\psi\Lambda$ decay amplitudes and the Λ^0_b polarisation in $\rho\rho$ collisions at $\sqrt{s} = 7$ TeV," *Physics Letters B*, vol. 724, no. 1–3, pp. 27–35, 2013.

[26] P. Böer, T. Feldmann, and D. V. Dyk, "Angular analysis of the decay $\Lambda_b \rightarrow \Lambda(\rightarrow N\pi)\ell^+\ell^-$," *Journal of High Energy Physics*, vol. 2015, article 155, 2015.

[27] R. Aaij, B. Adeva, M. Adinolfi et al., "Differential branching fraction and angular analysis of $\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$ decays," *Journal of High Energy Physics*, vol. 2015, article 115, 2015.

[28] T. M. Aliev, M. Savcı, and B. B. Şirvanlı, "Double-lepton polarization asymmetries in $\Lambda_b \rightarrow \Lambda\ell^+\ell^-$ - decay in universal extra dimension model," *The European Physical Journal C*, vol. 52, no. 2, pp. 375–382, 2007.

[29] C. Bobeth, P. Gambino, M. Gorbahn, and U. Haisch, "Complete NNLO QCD analysis of $\bar{B} \rightarrow X_S\ell^+\ell^-$ and higher order electroweak effects," *Journal of High Energy Physics*, vol. 2004, no. 4, p. 71, 2004.