Impact of scalar leptoquarks on heavy baryonic decays

K. Azizi,1 A. T. Ölgün,2 and Z. Tavukoğlu2

1Department of Physics, Doğuş University, Acıbadem-Kadıköy, 34722 İstanbul, Turkey
2Vocational School Kadıköy Campus, Okan University, Hasanpaşa-Kadıköy, 34722 İstanbul, Turkey

We present a study on the impact of scalar leptoquarks on the semileptonic decays of Λb, Σb and Ξb. To this end, we calculate the differential branching ratio and lepton forward-backward asymmetry defining the processes Λb → Λℓ±ℓ∓, Σb → Σℓ±ℓ∓ and Ξb → Ξℓ±ℓ∓, with ℓ being μ or τ, using the form factors calculated via light cone QCD in full theory. In calculations, the errors of form factors in the standard model are also taken into account. We compare the results obtained in leptoquark model with those of the standard model as well as the existing experimental data.

PACS numbers: 12.60.-i, 14.80.Sv, 13.30.-a, 13.30.Ce, 14.20.Mr

I. INTRODUCTION

The physics of transitions based on b → sℓ±ℓ∓ at quark level constitutes one of the main directions of the research in high energy and particle physics both theoretically and experimentally as new physics effects can contribute to such decay channels. The flavor changing neutral current (FCNC) transitions of Λb → Λℓ±ℓ∓, Σb → Σℓ±ℓ∓ and Ξb → Ξℓ±ℓ∓ are among important baryonic decay channels that can be used as sensitive probes to indirectly search for new physics contributions. Especially, the rare Λb → Λℓ±ℓ∓ decay channel has been in the focus of much attention in recent years both theoretically and experimentally. The first measurement on the Λb → Λμ±μ∓ process has been reported by the CDF Collaboration [2] with 24 signal events and a statistical significance of 5.8 Gaussian standard deviations. Using the p̅p collisions data samples corresponding to 6.8 fb−1 and √s = 1.96 TeV collected by the CDF II detector, the differential branching ratio for the Λb → Λμ±μ∓ decay channel has been measured to be dBr(Λb → Λμ±μ∓)/dq2 = [1.73 ± 0.42(stat) ± 0.55(syst)] × 10−6 [1]. The differential branching fraction of Λb → Λμ±μ∓ decay channel has also been measured as dBr(Λb → Λμ±μ∓)/dq2 = (1.18 ± 0.08±0.03±0.27) × 10−7 GeV2/c4 at 15 GeV2/c4 ≤ q2 ≤ 20 GeV2/c4 region by the LHCb Collaboration [2].

The LHCb Collaboration has also measured the lepton forward-backward asymmetry associated to this transition as AFB = −0.05 ± 0.09(stat) ± 0.03(syst) at 15 GeV2/c4 ≤ q2 ≤ 20 GeV2/c4 region [2]. The orders of magnitude and matrix elements defining the above transitions.

In the light of progresses about LQs, we calculate the differential branching ratio and lepton forward-backward asymmetry corresponding to the Λb → Λℓ±ℓ∓, Σb → Σℓ±ℓ∓ and Ξb → Ξℓ±ℓ∓ processes in a scalar LQ model. In the calculations, we use the form factors as the main inputs calculated from the light cone QCD sum rules in full theory without any approximation. We also encounter the errors of the form factors to the calculations. We compare the regions swept by the LQ model with those of the SM and search for deviations of the LQ model predictions with those of the SM. We also compare the results with the available experimental data.

The outline of this article is as follow. In next section, we present the effective Hamiltonian responsible for the transitions under consideration both in the SM and LQ models. In section III, we present the transition amplitude and matrix elements defining the above transitions. In section IV, we calculate the differential decay rate and the lepton forward-backward asymmetry in the baryonic Λb → Λℓ±ℓ∓, Σb → Σℓ±ℓ∓ and Ξb → Ξℓ±ℓ∓ channels and numerically analyze the results obtained. We compare the LQ predictions with those of the SM and existing experimental data also in this section.
II. THE EFFECTIVE HAMILTONIAN AND WILSON COEFFICIENTS

At the quark level the effective Hamiltonian, defining the above mentioned \( b \rightarrow s \ell^+\ell^- \) based transitions, in terms of Wilson coefficients and different operators in SM is defined as \([22, 24, 27]\)

\[
\mathcal{H}^{\text{eff}}_{SM} = \frac{G_F \alpha_{em} V_{tb} V_{ts}^*}{2\sqrt{2}\pi} \left[ C_9^{\text{eff}} \bar{s}\gamma_\mu (1 - \gamma_5) b \bar{\ell}\gamma_\mu \ell + C_{10} \bar{s}\gamma_\mu (1 - \gamma_5) b \bar{\ell}\gamma_\mu \gamma_5 \ell - 2m_b C_7^{\text{eff}} \frac{1}{q^2} \bar{s}\sigma_{\mu\nu} q^{\nu} (1 + \gamma_5) b \bar{\ell}\gamma_\mu \ell \right],
\]

(1)

where \( G_F \) is the Fermi weak coupling constant, \( \alpha_{em} \) is the fine structure constant at \( Z \) mass scale, \( V_{tb} \) and \( V_{ts}^* \) are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, the \( C_9^{\text{eff}} \) and \( C_7^{\text{eff}} \) are the SM Wilson coefficients and \( q^2 \) is the transferred momentum squared. We collect the explicit expressions of the Wilson coefficients in SM in the Appendix: A. Considering the additional contributions arising from the exchange of scalar leptoquarks, the effective Hamiltonian for \( b \rightarrow s \ell^+\ell^- \) transition in the LQ model can be written as

\[
\mathcal{H}^{\text{eff}}_{LQ} = \frac{G_F \alpha_{em} V_{tb} V_{ts}^*}{2\sqrt{2}\pi} \left[ C_9^{\text{eff,LQ}} \bar{s}\gamma_\mu (1 - \gamma_5) b \bar{\ell}\gamma_\mu \ell + C_9^{\prime \text{eff,LQ}} \bar{s}\gamma_\mu (1 + \gamma_5) b \bar{\ell}\gamma_\mu \gamma_5 \ell + C_{10}^{\text{eff,LQ}} \bar{s}\gamma_\mu (1 + \gamma_5) b \bar{\ell}\gamma_\mu \gamma_5 \ell - 2m_b C_7^{\text{eff}} \frac{1}{q^2} \bar{s}\sigma_{\mu\nu} q^{\nu} (1 + \gamma_5) b \bar{\ell}\gamma_\mu \ell - 2m_b C_7^{\prime \text{eff}} \frac{1}{q^2} \bar{s}\sigma_{\mu\nu} q^{\nu} (1 - \gamma_5) b \bar{\ell}\gamma_\mu \ell \right],
\]

(2)

where \( C_9^{\text{eff,LQ}}, C_9^{\prime \text{eff,LQ}}, C_{10}^{\text{eff,LQ}} \) and \( C_{10}^{\prime \text{eff,LQ}} \) are new Wilson coefficients. These coefficients contain contributions from both the SM and LQ models, but the Wilson coefficients \( C_9^{\text{eff}} \) and \( C_7^{\text{eff}} \) remain unchanged compared to the SM. The Wilson coefficients \( C_9^{\text{eff,LQ}} \) and \( C_{10}^{\text{eff,LQ}} \) receive contributions from the exchange of the scalar leptoquarks \( X = (3, 2, 7/6) \) but the primed Wilson coefficients \( C_9^{\prime \text{eff,LQ}} \) and \( C_{10}^{\prime \text{eff,LQ}} \) pick up contributions from the exchange of the scalar leptoquarks \( X = (3, 2, 1/6) \). The Wilson coefficients in LQ model is given as (for more information about the Wilson coefficients of the LQ models see \([22, 24, 27]\))

\[
C_9^{\text{eff,LQ}} = C_9^{\text{eff}} + C_9^{LQ},
\]

\[
C_9^{\prime \text{eff,LQ}} = C_9^{\prime \text{eff}} + C_9^{LQ},
\]

\[
C_{10}^{\text{eff,LQ}} = C_{10}^{\text{eff}} + C_{10}^{LQ},
\]

\[
C_{10}^{\prime \text{eff,LQ}} = C_{10}^{\prime \text{eff}} + C_{10}^{LQ}.
\]

(3)

Here the new Wilson coefficients due to the exchange of the leptoquarks \( X = (3, 2, 7/6) \) are given by \([22, 24, 27]\)

\[
C_9^{LQ} = C_{10}^{LQ} = -\frac{\pi}{2\sqrt{2} G_F \alpha_{em} V_{tb} V_{ts}^*} \lambda_5^{23} \lambda_5^{22} \frac{\lambda_5^{23}}{M_Y^2},
\]

(4)

and the primed Wilson coefficients due to the exchange of the leptoquarks \( X = (3, 2, 1/6) \) are defined as \([22, 24, 27]\)

\[
C_9^{\prime \text{LQ}} = -C_{10}^{\prime \text{LQ}} = -\frac{\pi}{2\sqrt{2} G_F \alpha_{em} V_{tb} V_{ts}^*} \lambda_5^{22} \lambda_5^{32} \frac{\lambda_5^{22}}{M_Y^2},
\]

(5)

with

\[
0 \leq \frac{\lambda_5^{23} \lambda_5^{22}}{M_Y^2} = \frac{\lambda_5^{22} \lambda_5^{32}}{M_Y^2} \leq 5 \times 10^{-9} \text{ GeV}^{-2}, \]

(6)

where \( M_Y \) and \( M_Y \) denote masses of the scalar leptoquarks.

III. TRANSITION AMPLITUDE AND MATRIX ELEMENTS

Generally, the amplitude of the transition responsible for the \( \Lambda_b \rightarrow \Lambda b^+ \ell^- \), \( \Sigma_b \rightarrow \Sigma b^+ \ell^- \) and \( \Xi_b \rightarrow \Xi b^+ \ell^- \) baryonic decays is provided with sandwiching the effective Hamiltonian between the initial and final baryonic states,

\[
\mathcal{M}^{B_{Q} \rightarrow B b^+ \ell^-} = \langle B(p) \mid H^{\text{eff}} \mid B_Q(p + q, s) \rangle,
\]

(7)

where \( B \) represents \( \Lambda, \Sigma \) and \( \Xi \) baryons and \( Q \) corresponds to \( b \) quark. To get the transition amplitude, we need to consider the following transition matrix elements parametrized in terms of twelve form factors in full QCD:

\[
\langle B(p) \mid \bar{s}\gamma_\mu (1 - \gamma_5) b \mid B_Q(p + q, s) \rangle = \bar{u}_B(p) \left[ \gamma_\mu f_1(q^2) + i\sigma_{\mu\nu} q^{\nu} f_2(q^2) \right. + q^{\mu} f_3(q^2) - \gamma_\mu \gamma_5 g_1(q^2) - i\sigma_{\mu\nu} \gamma_5 g_2(q^2) \left. - q^\mu \gamma_5 g_3(q^2) \right] u_{B_Q}(p + q, s),
\]

(8)

\[
\langle B(p) \mid \bar{s}\gamma_\mu (1 + \gamma_5) b \mid B_Q(p + q, s) \rangle = \bar{u}_B(p) \left[ \gamma_\mu f_1(q^2) + i\sigma_{\mu\nu} q^{\nu} f_2(q^2) \right. + q^{\mu} f_3(q^2) + \gamma_\mu \gamma_5 g_1(q^2) + i\sigma_{\mu\nu} \gamma_5 g_2(q^2) \left. + q^\mu \gamma_5 g_3(q^2) \right] u_{B_Q}(p + q, s),
\]

(9)
\[ \langle B(p) | \bar{s}i\sigma_{\mu\nu}q'^{(1 + \gamma_5)b} | B_Q(p + q, s) \rangle = \\
\bar{u}_B(p) \left[ \gamma_\mu f_1^T(q^2) + i\sigma_{\mu\nu}q'' f_2^T(q^2) \right. \\
+ q'' f_3^T(q^2) \gamma_\mu \gamma_5 g_1^T(q^2) \gamma_\nu \\
\left. + i\sigma_{\mu\nu}q'' g_2^T(q^2) \right] u_{B_Q}(p + q, s), \]

and
\[ \langle B(p) | \bar{s}i\sigma_{\mu\nu}q'^{(1 - \gamma_5)b} | B_Q(p + q, s) \rangle = \\
\bar{u}_B(p) \left[ \gamma_\mu f_1^T(q^2) + i\sigma_{\mu\nu}q'' f_2^T(q^2) \right. \\
+ q'' f_3^T(q^2) - \gamma_\mu \gamma_5 g_1^T(q^2) \gamma_\nu \\
\left. - i\sigma_{\mu\nu}q'' g_2^T(q^2) \right] u_{B_Q}(p + q, s), \]

where the \( u_{B_Q} \) and \( u_B \) represent spinors of the initial and final states, respectively. The \( f_i^{(T)} \) and \( g_i^{(T)} \) (\( i \) running from 1 to 3) are transition form factors. In our calculations, we use these form factors calculated via light cone sum rules in full QCD. The values of these form factors corresponding to \( \Lambda_b \to \Lambda^{\ell^+\ell^-} \), \( \Sigma_b \to \Sigma^{\ell^+\ell^-} \) and \( \Xi_b \to \Xi^{\ell^+\ell^-} \) transitions are taken from [3], [4] and [5], respectively.

Using the above transition matrix elements in terms of form factors, we get the amplitude of the transitions \( \Lambda_b \to \Lambda^{\ell^+\ell^-}, \Sigma_b \to \Sigma^{\ell^+\ell^-} \) and \( \Xi_b \to \Xi^{\ell^+\ell^-} \) in the SM and LQ as

\[ M_{SM}^{B_Q \to B\ell^+\ell^-} = \frac{G_F^2 a_{\text{em}} V_{tb} V_{ts}^*}{2\sqrt{2}} \left\{ \bar{u}_B(p) (\gamma_\mu [A_1^{SM} R + B_1^{SM} L] + i\sigma_{\mu\nu} q'' [A_2^{SM} R + B_2^{SM} L]) \right. \\
+ q'' [A_3^{SM} R + B_3^{SM} L]) u_{B_Q}(p + q, s) \right\} (\bar{\ell}\gamma_\mu \ell) \\
+ \left[ \bar{u}_B(p) (\gamma_\mu [D_1^{SM} R + E_1^{SM} L] + i\sigma_{\mu\nu} q'' [D_2^{SM} R + E_2^{SM} L]) \right. \\
+ q'' [D_3^{SM} R + E_3^{SM} L]) u_{B_Q}(p + q, s) \right\} (\bar{\ell}\gamma_\mu \gamma_5 \ell), \]

and
\[ M_{LQ}^{B_Q \to B\ell^+\ell^-} = \frac{G_F^2 a_{\text{em}} V_{tb} V_{ts}^*}{2\sqrt{2}} \left\{ \bar{u}_B(p) (\gamma_\mu [A_1^{LQ} R + B_1^{LQ} L] + i\sigma_{\mu\nu} q'' [A_2^{LQ} R + B_2^{LQ} L]) \right. \\
+ q'' [A_3^{LQ} R + B_3^{LQ} L]) u_{B_Q}(p + q, s) \right\} (\bar{\ell}\gamma_\mu \ell) \\
+ \left[ \bar{u}_B(p) (\gamma_\mu [D_1^{LQ} R + E_1^{LQ} L] + i\sigma_{\mu\nu} q'' [D_2^{LQ} R + E_2^{LQ} L]) \right. \\
+ q'' [D_3^{LQ} R + E_3^{LQ} L]) u_{B_Q}(p + q, s) \right\} (\bar{\ell}\gamma_\mu \gamma_5 \ell), \]

where \( R = (1 + \gamma_5)/2 \) and \( L = (1 - \gamma_5)/2 \) and the calligraphic coefficients are collected in Appendix: B.

### IV. PHYSICAL OBSERVABLES

In this section we would like to calculate some physical observables such as the differential decay width,
the differential branching ratio and the lepton forward-backward asymmetry for the considered decay channels.

A. The differential decay width

Using the decay amplitudes and transition matrix elements in terms of form factors, we find the differential decay rate defining the transitions under consideration in the LQ model as

\[
\frac{d\Gamma_{LQ}}{dsdz}(z, \hat{s}) = \frac{G_F^2 \alpha^2_{em} m_B^2}{16384 \pi^5} |V_{tb} V_{ts}^*|^2 \sqrt{\lambda(1, r, \hat{s})} \left[ \mathcal{T}_0^{LQ}(\hat{s}) + \mathcal{T}_1^{LQ}(\hat{s}) z + \mathcal{T}_2^{LQ}(\hat{s}) z^2 \right],
\]

(14)

where \( v = \sqrt{1 - \frac{4m_B^2}{s}} \) is the lepton velocity, \( \lambda = \lambda(1, r, \hat{s}) = (1 - r - \hat{s})^2 - 4r\hat{s} \) is the usual triangle function, \( \hat{s} = \frac{q^2}{m_B^2} \), \( r = \frac{m^2_B - m^2_{B_Q}}{m^2_B} \) and \( z = \cos \theta \) with \( \theta \) being the angle between momenta of the lepton \( l^+ \) and the \( B_Q \) in the center of mass of leptons. The calligraphic \( \mathcal{T}_0^{LQ}(\hat{s}) \), \( \mathcal{T}_1^{LQ}(\hat{s}) \) and \( \mathcal{T}_2^{LQ}(\hat{s}) \) functions are given in Appendix: B.

B. The differential branching ratio

Using the expression of the differential decay width, in this subsection, we numerically analyze the differential branching ratio in terms of \( q^2 \) for the decay channels under consideration. For this aim, we present the values of some input parameters and the quark masses in \( \overline{MS} \) scheme used in the numerical analysis in Tables 1 and 2 [3]. As we previously said, we also use the values of form factors calculated via light cone QCD sum rules in full theory [3] [4] in numerical analysis. The differential branching ratios of decay channels under consideration on \( q^2 \), in the SM and LQ models, at \( \mu \) and \( \tau \) lepton channels are plotted in Figures 1-6. Note that, in these figures, the form factors are encountered with their uncertainties in SM that leads to some bands in this model. In LQ model we use the central values of the form factors. The bands in LQ model are due to the constrained regions of some parameters presented in Eq. (10). We do not present the results for \( e \) channel in the figures, because the predictions of \( \mu \) channel are very close to those of the \( e \) channel. In figure 1, we also show the experimental data provided by LHCb [2]. From these figures it is clear that,

- the differential branching ratios in terms of \( q^2 \) obtained in SM for all baryonic processes at both lepton channels include the bands of the LQ model except for \( \Sigma_b \rightarrow \Sigma^+ \mu^- \) and \( \Xi_b \rightarrow \Xi^+ \tau^- \) transitions. For latter we see some discrepancies between two models predictions at higher values of \( q^2 \), while in the case of \( \Sigma_b \rightarrow \Sigma^+ \mu^- \) although bands of two models have some intersections, the LQ band shows considerable discrepancies from that of the SM at whole physical region of \( q^2 \).

- The band of SM for \( \Lambda_b \rightarrow \Lambda^+ \mu^- \) channel encompasses the experimental data provided by the LHCb Collaboration in the intervals \( 15 \text{ GeV}^2/c^4 \leq q^2 \leq 18 \text{ GeV}^2/c^4 \), but these data cannot be described by LQ model. However, the predictions of SM and LQ models coincide with the experimental data in the region \( 18 \text{ GeV}^2/c^4 \leq q^2 \leq 20 \text{ GeV}^2/c^4 \). The experimental data at \( 0 \text{ GeV}^2/c^4 \leq q^2 \leq 15 \text{ GeV}^2/c^4 \) interval remain out of the regions swept by the two models predictions.

C. The lepton forward-backward asymmetry

In this subsection, we present the results of the lepton forward-backward asymmetry \( (A_{FB}) \) which is one of useful observables to search for NP effects. This quantity is defined as

\[
A_{FB}(\hat{s}) = \frac{\int_0^1 d\frac{d\Gamma}{dsdz}(z, \hat{s}) dz - \int_{-1}^0 d\frac{d\Gamma}{dsdz}(z, \hat{s}) dz}{\int_0^1 d\frac{d\Gamma}{dsdz}(z, \hat{s}) dz + \int_{-1}^0 d\frac{d\Gamma}{dsdz}(z, \hat{s}) dz}.
\]

(15)
FIG. 1: The dependence of the differential branching ratio on $q^2$ for the $\Lambda_b \to \Lambda \mu^+ \mu^-$ transition in the SM and LQ models. The experimental data are taken from the LHCb Collaboration Ref. [2].

FIG. 2: The dependence of the differential branching ratio on $q^2$ for the $\Lambda_b \to \Lambda \tau^+ \tau^-$ transition in the SM and LQ models.

FIG. 3: The dependence of the differential branching ratio on $q^2$ for the $\Sigma_b \to \Sigma\mu^+ \mu^-$ transition in the SM and LQ models.

In order to see how predictions of LQ scenario deviate from those of the SM, we plot the dependence of the lepton forward-backward asymmetry on $q^2$ for the channels under discussion in Figures 7-12. In figure 7, we also present the measured values of the leptonic forward backward-asymmetries by the LHCb Collaboration [2] in the $\Lambda_b \to \Lambda \mu^+ \mu^-$ decay channel. From these figures, we read that

- in all decay channels the LQ model predictions demonstrate considerable discrepancies from the SM predictions except for $\Sigma_b \to \Sigma\mu^+ \mu^-$ and $\Sigma_b \to \Sigma\tau^+ \tau^-$ transitions. In these two cases the SM bands include the areas swept by the LQ model

FIG. 4: The dependence of the differential branching ratio on $q^2$ for the $\Sigma_b \to \Sigma\tau^+ \tau^-$ transition in the SM and LQ models.

FIG. 5: The dependence of the differential branching ratio on $q^2$ for the $\Xi_b \to \Xi\mu^+ \mu^-$ transition in the SM and LQ models.

FIG. 6: The dependence of the differential branching ratio on $q^2$ for the $\Xi_b \to \Xi\tau^+ \tau^-$ transition in the SM and LQ models.

FIG. 7: The dependence of the $A_{FB}$ on $q^2$ for the $\Lambda_b \to \Lambda \mu^+ \mu^-$ transition in the SM and LQ models. The experimental data are taken from the LHCb Collaboration Ref. [2].
FIG. 8: The dependence of the $A_{FB}$ on $q^2$ for the $\Lambda_b \to \Lambda \tau^+\tau^-$ transition in the SM and LQ models.

FIG. 9: The dependence of the $A_{FB}$ on $q^2$ for the $\Sigma_b \to \Sigma \mu^+\mu^-$ transition in the SM and LQ models.

FIG. 10: The dependence of the $A_{FB}$ on $q^2$ for the $\Sigma_b \to \Sigma \tau^+\tau^-$ transition in the SM and LQ models.

FIG. 11: The dependence of the $A_{FB}$ on $q^2$ for the $\Xi_b \to \Xi \mu^+\mu^-$ transition in the SM and LQ models.

FIG. 12: The dependence of the $A_{FB}$ on $q^2$ for the $\Xi_b \to \Xi \tau^+\tau^-$ transition in the SM and LQ models.

- Ignoring from the small intersection of the SM narrow bands with errors of the experimental data at very low and high values of $q^2$, the LQ model, against the SM, can describe all data available in $\Lambda_b \to \Lambda \mu^+\mu^-$ channel.

V. CONCLUSION

In the present work, we have performed a comprehensive analysis of the semileptonic $\Lambda_b \to \Lambda \ell^+\ell^-$, $\Sigma_b \to \Sigma \ell^+\ell^-$ and $\Xi_b \to \Xi \ell^+\ell^-$ rare processes in the SM as well as the scalar leptoquark model. Using the parametrization of the matrix elements in terms of form factors calculated via light cone QCD sum rules in the full theory, we calculated the differential decay width and numerically analyzed the differential branching fraction and the lepton forward-backward asymmetry in terms of $q^2$ in different heavy baryonic decay channels for both the $\mu$ and $\tau$ leptons in both scenarios. We compared the predictions of the LQ model on the considered physical observables with those of the SM and the existing experimental data in $\Lambda_b \to \Lambda \mu^+\mu^-$ channel. We observed that the predictions of the LQ model on the differential decay width remain inside the bands of the SM except for $\Sigma_b \to \Sigma \mu^+\mu^-$ transition that we saw some deviations of the LQ model results from those of the SM. Both models describe some experimental data, available in $\Lambda_b \to \Lambda \mu^+\mu^-$ channel, at higher values of $q^2$. The data on the differential branching fraction of this channel can not be explained by the two models at lower values of $q^2$. In the case of lepton forward-backward asymmetry, the LQ model’s predictions, overall, demonstrate considerable deviations from the SM results. The experimental data existing in $\Lambda_b \to \Lambda \mu^+\mu^-$ channel, overall, are described by the LQ model but remain outside of the SM band.

More experimental data in $\Lambda_b \to \Lambda \tau^+\tau^-$ as well as $\Sigma_b \to \Sigma \ell^+\ell^-$ and $\Xi_b \to \Xi \ell^+\ell^-$ with both leptons are needed to compare with the theoretical predictions. We hope, with the RUN II data, it will be possible to measure different physical quantities related to such FCNC transitions at LHCb in near future. Comparison of the results.
experimental data with the theoretical predictions on different physical quantities in different decay channels can help us better explain some anomalies between the SM predictions and the experimental data in some channels and more important in the course of indirectly search for the new physics effects like leptoquarks.

**Note Added:** When providing this work we noticed that a part of our work, namely the \( A_b \rightarrow \Lambda \ell^+ \ell^- \) channel has been investigated in \[38, 39\] within the same framework. In these studies the authors use the form factors, as the main inputs, calculated in heavy quark effective theory while we use the form factors calculated via light cone QCD sum rules in full theory without using any approximation.

**ACKNOWLEDGEMENTS**

K. A. thanks Doğuş University for the financial support through the grant BAP 2015-16-D1-B04.

**Appendix: A**

The Wilson coefficient \( C_7^{eff} \) in leading logarithm approximation in the SM is written by \[34, 37\]

\[
C_7^{eff}(\mu_b) = \eta^{\frac{4}{3}} C_7(\mu_W) + \frac{8}{3} \left( \frac{n_s^{\frac{4}{3}}}{\eta^{\frac{4}{3}}} - \eta^{\frac{4}{3}} - \frac{4}{3} \right) C_8(\mu_W) + C_2(\mu_W) \sum_{i=1}^{s} h_i \eta^{a_i},
\]

(A.1)

where

\[
C_7(\mu_W) = -\frac{1}{2} D_0'(x_t),
\]

\[
C_8(\mu_W) = -\frac{1}{2} E_0'(x_t),
\]

\[
C_2(\mu_W) = 1.
\]

(A.2)

The functions \( D_0'(x_t) \) and \( E_0'(x_t) \) with

\[
x_t = \frac{m^2_{\tau W}}{m^2_{W}}
\]

are given as

\[
D_0'(x_t) = -\frac{(8x_t^3 + 5x_t^2 - 7x_t)}{12(1 - x_t)^3}
\]

\[
+ \frac{x_t^2(2 - 3x_t)}{2(1 - x_t)^4} \ln x_t,
\]

(A.3)

\[
E_0'(x_t) = -\frac{x_t(x_t^2 - 5x_t - 2)}{4(1 - x_t)^3}
\]

\[
+ \frac{3x_t^2}{2(1 - x_t)^4} \ln x_t.
\]

(A.4)

The parameter \( \eta \) in Eq.(A.1) is defined as

\[
\eta = \frac{\alpha_s(\mu_W)}{\alpha_s(\mu_b)},
\]

(A.5)

with

\[
\alpha_s(x) = \frac{\alpha_s(m_Z)}{1 - \beta_0 \frac{\alpha_s(m_Z)}{2\pi} \ln\left(\frac{m^2_{\tau W}}{m^2}\right)},
\]

(A.6)

where \( \alpha_s(m_Z) = 0.118 \) and \( \beta_0 = \frac{33}{3}. \) The coefficients \( h_i \) and \( a_i \) in Eq.(A.1) are also written by \[35, 36\]

\[
h_i = (2.2996, -1.0880, -\frac{3}{7}, -\frac{1}{7}, -0.6494, -0.0380, -0.0186, 0.0057),
\]

(A.7)

The Wilson coefficient \( C_9^{eff} \) in SM is given by \[35, 36\]

\[
C_9^{eff}(\hat{s}) = C_9^{NDR} \eta(\hat{s}) + h(z, \hat{s}) (3C_1 + C_2 + 3C_3 + 4C_4 + 3C_5 + C_6)
\]

\[
- \frac{1}{2} h(1, \hat{s}) (4C_3 + 4C_4 + 3C_5 + C_6)
\]

\[
- \frac{1}{2} h(0, \hat{s}) (C_3 + 3C_4)
\]

\[
+ \frac{2}{9} (3C_3 + C_4 + 3C_5 + C_6),
\]

(A.8)

where \( \hat{s} = s/m^2_{W} \) with \( 4m^2_{W} \leq q^2 \leq (m_{B_q} - m_{B})^2 \). The \( C_9^{NDR} \) in the naive dimensional regularizer (NDR) scheme is written as

\[
C_9^{NDR} = P_0^{NDR} + \frac{Y}{\sin \theta_W} \ln 4Z + P_E E,
\]

(A.9)

where \( P_0^{NDR} = 2.60 \pm 0.25, \sin^2 \theta_W = 0.23, Y = 0.98 \) and \( Z = 0.679 \pm 0.02 \). The last term in Eq.(A.9) is ignored due the negligible value of \( P_E \). In Eq.(A.8), the \( \eta(\hat{s}) \) is given as

\[
\eta(\hat{s}) = 1 + \frac{\alpha_s(\mu_W)}{\pi} \omega(\hat{s}),
\]

(A.10)

with

\[
\omega(\hat{s}) = \frac{2}{9} \pi^2 - \frac{4}{3} \text{Li}_2(\hat{s}) - \frac{2}{3} \ln \hat{s}^2 \ln(1 - \hat{s})
\]

\[
- \frac{5 + 4\hat{s}'}{3(1 + 2\hat{s}')} \ln(1 - \hat{s}'),
\]

\[
- \frac{2\hat{s}'(1 + \hat{s}')(1 - 2\hat{s}')}{}{3(1 - \hat{s})^2(1 + 2\hat{s})} \ln \hat{s}'
\]

\[
+ \frac{5 + 9\hat{s}' - 6\hat{s}'^2}{6(1 - \hat{s}')(1 + 2\hat{s}')},
\]

(A.11)
The function \( h(y, s') \) is written as

\[
h(y, s') = \frac{8}{9} \ln \frac{m_b}{\mu_b} - \frac{8}{9} \ln y + \frac{8}{27} + \frac{4}{9} x - \frac{2}{9} (2 + x) |1 - x|^{1/2}
\]

\[
\left\{ \begin{array}{ll}
\ln \left( \frac{\sqrt{x} - 1}{\sqrt{x} + 1} \right) - i \pi, & \text{for } x \equiv \frac{4s^2}{y} < 1 \\
2 \arctan \frac{1}{\sqrt{x} - 1}, & \text{for } x \equiv \frac{4s^2}{y} > 1,
\end{array} \right.
\]

(A.12)

where \( y = 1 \) or \( z = \frac{m_c}{m_b} \) and

\[
h(0, s') = \frac{8}{27} - \frac{8}{9} \ln \frac{m_b}{\mu_b} - \frac{4}{9} \ln s' + \frac{4}{9} i \pi.
\]

(A.13)

The coefficients \( C_j \) (\( j = 1, \ldots, 6 \)) at \( \mu_b = 5 \text{ GeV} \) scale are also written as

\[
C_j = \sum_{i=1}^{8} k_{ji} y^{n_i} \quad (j = 1, \ldots, 6),
\]

(A.14)

where the \( k_{ji} \) are defined as

\[
\begin{align*}
k_{11} &= (0, 0, 0, 0, \frac{1}{2}, -\frac{1}{2}, 0, 0), \\
k_{21} &= (0, 0, 0, 0, \frac{1}{2}, \frac{1}{2}, 0, 0), \\
k_{31} &= (0, 0, 0, 0, 0, 0, 0, 0), \\
k_{41} &= (0, 0, 0, 0, 0, 0, 0, 0), \\
k_{51} &= (0.0510, -0.1403, -0.0113, 0.0054), \\
k_{61} &= (0.0984, 0.1214, 0.0156, 0.0026), \\
k_{71} &= (-0.0397, 0.0117, -0.0025, 0.0304), \\
k_{81} &= 0.0335, 0.0239, -0.0462, -0.0112).
\end{align*}
\]

The Wilson coefficient \( C_{10} \) in the SM is given as:

\[
C_{10} = \frac{Y}{\sin^2 \theta_W}.
\]

(A.15)

Appendix: B

The calligraphic coefficients used in the transition amplitudes of the considered processes both in the SM and LQ models are find as

\[
\begin{align*}
A_1 &= f_1 C_9^{eff+} - g_1 C_9^{eff-} \\
&- 2m_b \frac{1}{q^2} \left[ f_1^T C_7^{eff+} + g_1^T C_7^{eff-} \right], \\
A_2 &= A_1(1 \to 2), \\
A_3 &= A_1(1 \to 3), \\
B_1 &= f_1 C_9^{eff+} + g_1 C_9^{eff-} \\
&- 2m_b \frac{1}{q^2} \left[ f_1^T C_7^{eff+} - g_1^T C_7^{eff-} \right], \\
B_2 &= B_1(1 \to 2), \\
B_3 &= B_1(1 \to 3), \\
D_1 &= f_1 C_{10}^{+} - g_1 C_{10}^{-}, \\
D_2 &= D_1(1 \to 2), \\
D_3 &= D_1(1 \to 3), \\
E_1 &= f_1 C_{10}^{+} + g_1 C_{10}^{-}, \\
E_2 &= E_1(1 \to 2), \\
E_3 &= E_1(1 \to 3),
\end{align*}
\]

(B.1)

with

\[
\begin{align*}
C_9^{eff+} &= C_9^{eff} + C'_9^{eff}, \\
C_9^{eff-} &= C_9^{eff} - C'_9^{eff}, \\
C_7^{eff+} &= C_7^{eff} + C'_7^{eff}, \\
C_7^{eff-} &= C_7^{eff} - C'_7^{eff}, \\
C_{10}^{+} &= C_{10} + C_{10}', \\
C_{10}^{-} &= C_{10} - C_{10}'.
\end{align*}
\]

The functions \( T_{LQ}^L(\hat{\bar{s}}) \), \( T_{LQ}^L(\hat{s}) \) and \( T_{LQ}^L(\hat{\bar{s}}) \) in the differential decay width are given as
\[ \mathcal{T}_0^{LQ}(\hat{s}) = 32m_{B_Q}^2 \hat{s}(1 + r - \hat{s}) \left( |D_3|^2 + |E_3|^2 \right) \\
+ 64m_{B_Q}^4 (1 - r - \hat{s}) \text{Re} \left[ D_1^* E_3 + D_3 E_1^* \right] \\
+ 64m_{B_Q}^2 \sqrt{r} (6m_{B_Q}^2 - m_{B_Q}^4 \hat{s}) \text{Re} \left[ D_1^* E_1 \right] \\
+ 64m_{B_Q}^2 \sqrt{r} \left\{ 2m_{B_Q} \hat{s} \text{Re} \left[ D_1^* E_3 \right] + (1 + r + \hat{s}) \text{Re} \left[ D_1^* D_3 + E_3^* E_3 \right] \right\} \\
+ 32m_{B_Q}^2 (2m_{B_Q}^2 + m_{B_Q}^4 \hat{s}) \left\{ (1 + r + \hat{s})m_{B_Q} \sqrt{r} \text{Re} \left[ A_1^* A_2 + B_1^* B_2 \right] \\
- m_{B_Q} (1 - r - \hat{s}) \text{Re} \left[ A_1^* B_2 + A_2^* B_1 \right] - 2\sqrt{r} \left( \text{Re} \left[ A_1^* B_1 \right] + m_{B_Q}^2 \hat{s} \text{Re} \left[ A_3^* B_2 \right] \right) \right\} \\
+ 8m_{B_Q}^2 \left\{ 4m_{B_Q}^2 (1 + r - \hat{s}) + m_{B_Q}^4 \left[ (1 - r)^2 - \hat{s}^2 \right] \right\} \left( |A_1|^2 + |B_1|^2 \right) \\
+ 8m_{B_Q}^2 \left\{ 4m_{B_Q}^2 \left[ \lambda + (1 + r - \hat{s}) \hat{s} \right] + m_{B_Q}^4 \hat{s} \left[ (1 - r)^2 - \hat{s}^2 \right] \right\} \left( |A_2|^2 + |B_2|^2 \right) \\
- 8m_{B_Q}^2 \left\{ 4m_{B_Q}^2 (1 + r - \hat{s}) - m_{B_Q}^4 \left[ (1 - r)^2 - \hat{s}^2 \right] \right\} \left( |D_1|^2 + |E_1|^2 \right) \\
+ 8m_{B_Q}^2 \hat{s} v^2 \left\{ - 8m_{B_Q} \hat{s} \sqrt{r} \text{Re} \left[ D_1^* E_2 \right] + 4(1 + r + \hat{s}) \sqrt{r} \text{Re} \left[ D_1^* D_2 + E_3^* E_2 \right] \\
- 4(1 - r - \hat{s}) \text{Re} \left[ D_1^* E_2 + D_2^* E_1 \right] + m_{B_Q} \left[ (1 - r)^2 - \hat{s}^2 \right] \left( |D_2|^2 + |E_2|^2 \right) \right\}, \]

(B.2)

\[ \mathcal{T}_1^{LQ}(\hat{s}) = -16m_{B_Q}^4 \hat{s} v \sqrt{\lambda} \left\{ 2 \text{Re} \left( A_1^* D_1 \right) - 2 \text{Re} \left( B_1^* E_1 \right) \right\} \\
+ 2m_{B_Q} \text{Re} \left( B_1^* D_2 - B_2^* D_1 + A_2^* E_1 - A_1^* E_2 \right) \right\} \\
+ 32m_{B_Q}^5 \hat{s} v \sqrt{\lambda} \left\{ m_{B_Q} (1 - r) \text{Re} \left( A_2^* D_2 - B_2^* E_2 \right) \\
+ \sqrt{r} \text{Re} \left( A_2^* D_1 + A_1^* D_2 - B_2^* E_1 - B_1^* E_2 \right) \right\}, \]

(B.3)

and

\[ \mathcal{T}_2^{LQ}(\hat{s}) = -8m_{B_Q}^4 v^2 \lambda \left( |A_1|^2 + |B_1|^2 + |D_1|^2 + |E_1|^2 \right) \\
+ 8m_{B_Q}^6 \hat{s} v^2 \lambda \left( |A_2|^2 + |B_2|^2 + |D_2|^2 + |E_2|^2 \right). \]

(B.4)
[37] A. J. Buras, “Weak Hamiltonian, CP violation and rare decays,” hep-ph/9806471.

[38] S. Sahoo and R. Mohanta, “Effects of scalar leptoquark on semileptonic $\Lambda_b$ decays,” arXiv:1607.04449 [hep-ph].

[39] S. w. Wang and Y. d. Yang, “Analysis of $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ decay in scalar leptoquark model,” arXiv:1608.03662 [hep-ph].