Effects of vector leptoquarks on $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$ decay

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Experimental data on $R(D^{(*)})$, $R(K^{(*)})$ and $R(J/\psi)$, provided by different collaborations, have shown sizable deviations from the SM predictions. To describe these anomalies many new physics scenarios have been proposed. One of them is leptoquark model with introducing the vector and scalar leptoquarks coupling simultaneously to the quarks and leptons. To look for similar possible anomalies in baryonic sector, we investigate the effects of a vector leptoquark $U_{3,3}^{(3,3,3)}$ on various physical quantities related to the tree-level $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$ decays ($\ell = \mu, \tau$), which proceed via $b \to c \ell \bar{\nu}_\ell$ transitions at quark level. We calculate the differential branching ratio and forward-backward asymmetry at $\mu$ and $\tau$ lepton channels in leptoquark model and compare their behavior with respect to $q^{2}$ with the predictions of the standard model (SM). In the calculations we use the form factors calculated in full QCD as the main inputs and take into account all the errors coming from the form factors and model parameters. It is observed that, at $\tau$ channel, the $R_\tau$ fit solution to data related to the leptoquark model sweeps some regions out of the SM band but it has a considerable intersection with the SM predictions. The $R_\mu$ type solution gives roughly the same results with the those of the SM on $DBR(q^2) - q^2$. At $\mu$ channel, the leptoquark model gives consistent results with the SM predictions on the behavior of $DBR(q^2)$ with respect to $q^2$. As far as the $q^2$ behavior of the $A_{FB}(q^2)$ is concerned, the two types of fits in leptoquark model for $\tau$ and the the predictions of this model for $\mu$ channel give exactly the same results as the SM. We also investigate the behavior of the popular parameter $R(q^2)$ with respect to $q^2$ and the value of $R(\Lambda_c)$ both in vector leptoquark and SM models. Both types fit solutions lead to results that deviate considerably from the SM predictions on $DBR(q^2) - q^2$ as well as $R(\Lambda_c)$. The experimental data on $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$, which is one of the important baryonic channels, will be very helpful. Any experimental deviations from the SM predictions in this channel will strengthen the importance of the tree-level hadronic weak transitions as good probes of the new physics effects beyond the SM (BSM).

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I. INTRODUCTION

The search for new physics (NP) effects BSM is done by two different ways: Direct search at hadron colliders and indirect search in hadronic decays. The direct search for NP effects and the predicted new particles have received null results so far and these effects have been excluded up to a few TeV. However, recently, there were recorded some significant deviations of the experimental data on some parameters of the weak decays of some hadrons with the SM predictions. These deviations may be considered as signs for the NP effects and are in agenda of many experimental and theoretical groups. Hence, the weak and semileptonic hadronic decays are receiving special attention. Among these decays are the semileptonic mesonic $B \to D^{(*)}(\bar{\tau})$ and $B_c \to J/\psi(h_c)(\bar{\tau})$ tree-level decays as well as the loop-level $B \to K^{(*)}\ell^+\ell^-$ transitions. These channels provide major contributions to both re-test the SM and the investigation of NP effects. In the SM, these decays occur by coupling to $W^\pm, Z$ and $\gamma$ which are assumed to be universal for all leptons. Normally, different masses of the charged leptons lead to different results in the branching fractions of the semileptonic decays including these leptons. Extra discrepancies with the SM predictions on parameters of these decays suggest lepton flavor universality violation (LFUV), which may be considered as the presence of the new particles BSM. In particular the $\tau$ channel, because of the larger mass of $\tau$, is highly sensitive to the contributions of hypothetical new particles like charged Higgs boson, which appear in leptoquark (LQ) or other NP models.

Over the past two decades, the experimental measurements on different parameters related to the aforementioned decay channels have greatly improved at B factories. The branching ratio of $B \to D^{(*)}\ell^-\bar{\nu}_\ell$ decay, which is very sensitive to the NP scenarios, is considered as one of the major sources of the LFUV. The parameters $R(D)$ and $R(D^{(*)})$ defined as

$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\ell^-\bar{\nu}_\ell)}{B(B \to D^{(*)}\ell^-\bar{\nu}_\ell)},$$

with the average values measured by BaBar, Belle and LHCb Collaborations [1]

$$R(D) = 0.340 \pm 0.027 \pm 0.013,$$  \hspace{1cm} (2)

and

$$R(D^{*}) = 0.295 \pm 0.011 \pm 0.008,$$  \hspace{1cm} (3)
indicate respectively 1.4σ and 2.5σ deviations from the related SM predictions. Another source is

$$R_{K^{(*)}} = \frac{BR(B \rightarrow K^{(*)} \mu^+ \mu^-)}{BR(B \rightarrow K^{(*)} e^+ e^-)}.$$  \hfill (4)

The LHCb collaboration measured

$$R_K = 0.745^{+0.090}_{-0.074} \text{(stat)} \pm 0.036 \text{(syst)},$$  \hfill (5)

in the interval $q^2 \epsilon[1, 6] \text{GeV}^2$ \textsuperscript{3},

$$R_{K^*} = 0.66^{+0.11}_{-0.07} \text{(stat)} \pm 0.03 \text{(syst)},$$  \hfill (6)

in the region $q^2 \epsilon[0.045, 1.1] \text{GeV}^2$ and

$$R_{K^*} = 0.69^{+0.11}_{-0.06} \text{(stat)} \pm 0.05 \text{(syst)},$$  \hfill (7)

for $q^2 \epsilon[1.1, 6] \text{GeV}^2$ \textsuperscript{3}, indicating the deviations from SM expectations by $(2.2-2.6)\sigma$  \textsuperscript{13}. The recent LHCb data on $R(J/\psi)$ for decay of $B_c \rightarrow J/\psi \ell \nu_\ell$ \textsuperscript{3}:

$$R(J/\psi) = 0.71 \pm 0.17 \text{(stat)} \pm 0.18 \text{(syst)}$$  \hfill (8)

shows serious deviations from the SM predictions \textsuperscript{6-12}. A recent more precise SM prediction made in \textsuperscript{13}, $R(J/\psi) = 0.25 \pm 0.01$, supports the existing tension between the SM theory prediction and the experimental data. In this study, authors calculated $R(\eta_c)$ in $B_c \rightarrow J/\psi \ell \nu_\ell$ as well, which may be in agenda of different experiments in near future. Any deviations of the measured result from the SM prediction will increase the importance of the tree-level charged weak decays as possible probes of the NP effects (for further related studies see \textsuperscript{14-21}).

Experiments have mainly focused on the tree-level mesonic transitions based on $b \rightarrow c \ell \ell \nu_\ell$ whilst similar discrepancies may be detected at tree-level baryonic transitions proceed via $b \rightarrow c \ell \ell \nu_\ell$. The semileptonic $\Lambda_b \rightarrow \Lambda_c \ell \nu_\ell$ channel is one of the important ones that is expected to be in focus of much attention both experimentally and theoretically. The form factors of this transition as the main inputs to theoretically analyze this mode in SM and BSM are available using some methods and approaches. In Ref. \textsuperscript{22}, as an example, the related form factors were calculated in full QCD. Using these form factors, $R(\Lambda_c) = 0.31 \pm 0.11$ was obtained, which needs to be checked in the experiment.

Many models of new physics have been proposed to explain the above mentioned experiment-SM anomalies. One of the most popular and on the agenda new physics models that can play an important role to solve these anomalies is the LQ model \textsuperscript{23, 24}. LQs that naturally appear in several new physics model such as extended technicolor model \textsuperscript{25}, compositeness \textsuperscript{26}, Pati-Salam model \textsuperscript{27}, grand unification theories with $SU(5)$ \textsuperscript{28} and $SO(10)$ \textsuperscript{29} are hypothetical color-triplet bosons. LQs can carry both lepton (L) and baryon (B) quantum numbers with electric and color charges. These particles couple to both the leptons and quarks simultaneously and, as a result, modify the amplitudes of the transitions that they are contributed. According to their properties under the Lorentz transformations, they are divided into two main categories: The spin 0 scalar leptoquarks as well as the spin 1 vector leptoquarks. In this study, we consider a single vector leptoquark $U_3(3, 3, \frac{2}{3})$ which can provide a simultaneous explanation to the anomalies in $b \rightarrow c$ and $b \rightarrow s$ transitions. The numbers inside the bracket represent the SM gauge group $SU(3) \times SU(2) \times U(1)$ transformation properties: They refer to the color, weak and hyper-charge representations, respectively. The vector leptoquarks were theoretically studied in \textsuperscript{31-37}. Using the vector LQ, $U_3(3, 3, \frac{2}{3})$, we calculate several observables such as the differential branching ratio, the lepton forward-backward asymmetry and ratio of differential branching ratios in $\tau$ and $\mu(\ell)$ channels, $R(\Lambda_c)$, in the $\Lambda_b \rightarrow \Lambda_c \ell \nu_\ell$ transition. Using the form factors calculated in full theory, we numerically analyze the physical quantities both in SM and vector LQ model and compare the obtained results with each other. Any future experimental data and their comparisions with the predictions of the present study will help us check whether their exists any discrepancy with the SM predictions in the channel under question or not and, if this is the case, whether the anomalies can be described by the vector LQs or not?

The outline of the paper is as follows. In next section, we present the effective Hamiltonian responsible for the transitions under considerdation both in the standard and LQ models. In section III, we depict the transition amplitude and matrix elements defining the transition under study. In section IV, we calculate some physical quantities related to the baryonic $\Lambda_b \rightarrow \Lambda_c \ell \nu_\ell$ channel and numerically analyze the results obtained. We compare the LQ model predictions with those of the SM in this section. We reserve the last section for the summary and conclusions.

II. THE EFFECTIVE HAMILTONIAN

The hadronic transition of $\Lambda_b \rightarrow \Lambda_c \ell \nu_\ell$ proceeds via $b \rightarrow c \ell \nu_\ell$ at tree-level. The low-energy effective Hamiltonian defining this transition in SM can be written as

$$H_{SM}^{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \bar{c} \gamma_\mu (1 - \gamma_5) b \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell,$$  \hfill (9)

where $G_F$ is the Fermi weak coupling constant and $V_{cb}$ is one of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Considering the LQ contributions of the exchange of vector multiplet $U_3^\mu$ at tree level, the effective Hamiltonian including the SM contributions and LQ corrections can be written as \textsuperscript{31, 32}

$$H_{SM+LQ}^{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \bar{c} \gamma_\mu (1 - \gamma_5) b \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \left[ C_V \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell (\bar{c} \gamma_\mu \gamma_5 b) - C_A \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell (\bar{c} \gamma_\mu \gamma_5 b) \right],$$  \hfill (10)
where $C_V$ and $C_A$ represent the Wilson coefficients including the SM contributions as well as those of the operators coming from vector and pseudo-vector type of LQ interactions, respectively. At the $\mu = M_U$ scale, $C_V$ and $C_A$ are written as

$$C_V = C_A = 1 + \frac{\sqrt{2} g_{\nu}^e (\nu_g)_{ct}}{4 G_F V_{cb} M_U^2}. \quad (11)$$

In $\tau$, channel we use two optimal solutions, called $R_A$ and $R_B$, obtained by the fitting of the parameters on the data in $B \to D(*)$ \cite{31,38}: 

$$g_{\nu}^e (\nu_g)_{ct} = \left\{ \begin{array}{c} 0.18 \pm 0.04 \quad R_A \vspace{1mm} \\ -2.88 \pm 0.04 \quad R_B \end{array} \right., \quad (12)$$

where in obtaining these values the mass of the vector LQ has been used as $M_U = 1 TeV$ at the scale $\mu = M_U$ by taking into account the constraints on the vector LQ mass provided by CMS collaboration \cite{39,40}. In Ref. \cite{32}, by attributing the difference between the experimental and indirect determinations of $\tau$ and $R$ to the leptoquark contribution, the following constraint in $\mu$ channel is obtained, which we use in our calculations:

$$| V_{cb} | Re \left( \frac{g_{\nu}^e (\nu_g)_{ct}}{V_{cb}} \right) \in [-0.1, -0.01] \times 10^{-3} \left( \frac{M_U}{TeV} \right)^2, \quad (13)$$

which will be used in our analyses.

III. THE TRANSITION AMPLITUDE AND FORM FACTORS

The amplitude of the decay $\Lambda_b \to \Lambda_c \ell \overline{\nu}_\ell$ is obtained by sandwiching the effective Hamiltonian between the initial and final baryonic states:

$$\mathcal{M}_{\Lambda_b \to \Lambda_c \ell \overline{\nu}_\ell}^{\Lambda_c \to \Lambda_b \ell \overline{\nu}_\ell} = \langle \Lambda_c, \lambda_2 | \mathcal{H}_{SM+LQ}^{eff} | \Lambda_b, \lambda_1 \rangle, \quad (14)$$

where $\lambda_1$ and $\lambda_2$ are the helicities of the parent and daughter baryons, respectively. The hadronic matrix elements of the axial and vector currents, inside the Hamiltonian, are parameterized by six hadronic form factors ($f_{1,2,3}$ and $g_{1,2,3}$) \cite{41,42}:

$$\mathcal{M}_{\mu}^{\Lambda_b \to \Lambda_c \ell \overline{\nu}_\ell} = \langle \Lambda_c, \lambda_2 | V^\mu | \Lambda_b, \lambda_1 \rangle = \bar{u}_{\Lambda_c}(p_2, \lambda_2) \left[ \gamma_\mu f_1(q^2) 
+ i \sigma_{\mu \nu} q^\nu f_2(q^2) + q^\mu f_3(q^2) \right] u_{\Lambda_b}(p_1, \lambda_1), \quad (15)$$

and

$$\mathcal{M}_{\mu}^{A} = \langle \Lambda_c, \lambda_2 | A^\mu | \Lambda_b, \lambda_1 \rangle = \bar{u}_{\Lambda_c}(p_2, \lambda_2) \left[ \gamma_\mu f_1(q^2) 
+ i \sigma_{\mu \nu} q^\nu f_2(q^2) + q^\mu f_3(q^2) \right] u_{\Lambda_b}(p_1, \lambda_1),$$

where $\sigma_{\mu \nu} = i \frac{1}{2} [\gamma_\mu, \gamma_\nu]$ and $q^\mu = (p_1 - p_2)^\mu$ is the four momentum transfer. Here, $V^\mu = \bar{c} \gamma_\mu b$ and $A^\mu = \bar{c} \gamma_\mu \gamma_5 b$ represent the vector and axial vector parts of the transition current, respectively and $u_{\Lambda_c}(p_2, \lambda_2)$ and $u_{\Lambda_b}(p_1, \lambda_1)$ are the corresponding Dirac spinors for the final and initial baryonic states. The transition matrix elements can be parameterized in terms of the four-vector velocities $v_\mu$ and $v'_\mu$, as well:

$$\mathcal{M}_{\mu}^{V} = \langle \Lambda_c, \lambda_2 | V^\mu | \Lambda_b, \lambda_1 \rangle = \bar{u}_{\Lambda_c}(p_2, \lambda_2) \left[ \gamma_\mu F_1(q^2) 
+ F_2(q^2) v_\mu + F_3(q^2) v'_\mu \right] u_{\Lambda_b}(p_1, \lambda_1), \quad (17)$$

and

$$\mathcal{M}_{\mu}^{A} = \langle \Lambda_c, \lambda_2 | A^\mu | \Lambda_b, \lambda_1 \rangle = \bar{u}_{\Lambda_c}(p_2, \lambda_2) \left[ \gamma_\mu G_1(q^2) 
+ G_2(q^2) v_\mu + G_3(q^2) v'_\mu \right] u_{\Lambda_b}(p_1, \lambda_1). \quad (18)$$

As we previously mentioned, the form factors $F_{1,2,3}$ and $G_{1,2,3}$ have been calculated in full QCD and are available \cite{22}. The following relations describe the two sets of form factors in terms of each other (see also \cite{22,31,41,42}):

$$f_1(q^2) = F_1(q^2) + (m_{\Lambda_c} + m_{\Lambda_b}) \left[ \frac{F_2(q^2)}{2m_{\Lambda_b}} + \frac{F_3(q^2)}{2m_{\Lambda_c}} \right],$$

$$f_2(q^2) = \frac{F_2(q^2)}{2m_{\Lambda_b}} + \frac{F_3(q^2)}{2m_{\Lambda_c}},$$

$$f_3(q^2) = \frac{F_2(q^2)}{2m_{\Lambda_b}} - \frac{F_3(q^2)}{2m_{\Lambda_c}},$$

$$g_1(q^2) = G_1(q^2) + (m_{\Lambda_c} - m_{\Lambda_b}) \left[ \frac{G_2(q^2)}{2m_{\Lambda_b}} + \frac{G_3(q^2)}{2m_{\Lambda_c}} \right],$$

$$g_2(q^2) = \frac{G_2(q^2)}{2m_{\Lambda_b}} + \frac{G_3(q^2)}{2m_{\Lambda_c}},$$

$$g_3(q^2) = \frac{G_2(q^2)}{2m_{\Lambda_b}} - \frac{G_3(q^2)}{2m_{\Lambda_c}}. \quad (19)$$
We would like to introduce the helicity amplitudes in terms of the various form factors and the NP couplings:

\[ H_{\lambda_2, \lambda_W}^{V(A)} = e^{i\mu}(\lambda_W)(\lambda_1, \lambda_2 | V(A)| \Lambda_b, \Lambda_c), \]

and

\[ H_{\lambda_2, \lambda_W} = H_{\lambda_2, \lambda_W}^{V} - H_{\lambda_2, \lambda_W}^{A}. \] (20)

\[
\begin{align*}
H_{1/2,0}^V &= C_V \sqrt{(m_{\Lambda_b} - m_{\Lambda_c})^2 - q^2} \left[ (m_{\Lambda_b} + m_{\Lambda_c}) f_1(q^2) - q^2 f_2(q^2) \right], \\
H_{1/2,0}^A &= C_A \sqrt{(m_{\Lambda_b} + m_{\Lambda_c})^2 - q^2} \left[ (m_{\Lambda_b} - m_{\Lambda_c}) g_1(q^2) + q^2 g_2(q^2) \right], \\
H_{1/2,1}^V &= C_V \sqrt{2[(m_{\Lambda_b} - m_{\Lambda_c})^2 - q^2]} \left[ -f_1(q^2) + (m_{\Lambda_b} + m_{\Lambda_c}) f_2(q^2) \right], \\
H_{1/2,1}^A &= C_A \sqrt{2[(m_{\Lambda_b} + m_{\Lambda_c})^2 - q^2]} \left[ -g_1(q^2) + (m_{\Lambda_b} - m_{\Lambda_c}) g_2(q^2) \right], \\
H_{1/2,t}^V &= C_V \sqrt{(m_{\Lambda_b} + m_{\Lambda_c})^2 - q^2} \left[ (m_{\Lambda_b} - m_{\Lambda_c}) f_1(q^2) + q^2 f_2(q^2) \right], \\
H_{1/2,t}^A &= C_A \sqrt{(m_{\Lambda_b} - m_{\Lambda_c})^2 - q^2} \left[ (m_{\Lambda_b} + m_{\Lambda_c}) g_1(q^2) - q^2 g_2(q^2) \right],
\end{align*}
\] (21)

where \( H_{\lambda_2, \lambda_W}^{V} = H_{\lambda_2, -\lambda_W}^{V} \) and \( H_{\lambda_2, \lambda_W}^{A} = -H_{\lambda_2, -\lambda_W}^{A} \). We will use these helicity amplitudes to calculate the desired physical quantities in terms of hadronic form factors.

IV. PHYSICAL OBSERVABLES

Using the helicity amplitudes in terms of the hadronic transition form factors discussed in the previous section, we would like to introduce some physical observables defining the transition under consideration such as the differential decay width and branching ratio, the lepton forward-backward asymmetry and \( R(\Lambda_c) \). Using the form factors from full QCD, we discuss the behavior of these quantities with respect to \( q^2 \) and compare the SM predictions with those of the SM+LQ to search for possible shifts.

A. The Differential Decay Width

Making use of the amplitude and the standard prescriptions, the differential angular distributions for \( \Lambda_b \rightarrow \Lambda_c \ell \pi_\ell \) decay channel can be written as

\[
\frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c \ell \pi_\ell)}{dq^2 d\cos \Theta_\ell} = \frac{G_F^2 |V_{cb}|^2 q^2 |\vec{p}_{\Lambda_b}|}{512 \pi^3 m_{\Lambda_b}^2} \left[ \frac{m_{\Lambda_b}}{q^2} \right]^2 \left[ A_1 + \frac{m_{\Lambda_b}^2}{q^2} A_2 \right],
\] (22)

where

\[
\begin{align*}
A_1 &= 2 \sin^2 \Theta_\ell (H_{1/2,0}^2 + H_{-1/2,0}^2) + (1 - \cos \Theta_\ell) \left( H_{1/2,1}^2 + \left( 1 + \cos \Theta_\ell \right) H_{-1/2,-1}^2 \right), \\
A_2 &= 2 \cos^2 \Theta_\ell (H_{1/2,0}^2 + H_{-1/2,0}^2) + \sin^2 \Theta_\ell \left( H_{1/2,1}^2 + H_{-1/2,-1}^2 \right) + 2 \left( H_{1/2,1}^2 + H_{1/2,-1}^2 \right) + 2 \left( H_{-1/2,1}^2 + H_{-1/2,-1}^2 \right), \\
|\vec{p}_{\Lambda_b}| &= \frac{\sqrt{\Delta}}{2 m_{\Lambda_b}}, \\
\Delta &= (m_{\Lambda_b}^2)^2 + (m_{\Lambda_c}^2)^2 + (q^2)^2 - 2 m_{\Lambda_b}^2 m_{\Lambda_c}^2 + m_{\Lambda_c}^2 q^2 + m_{\Lambda_b}^2 q^2.
\end{align*}
\] (23)

Here \( \Theta_\ell \) indicates the angle between momenta of the lepton and the baryon \( \Lambda_c \) in the \( q^2 \) rest frame.
B. The Differential Branching Ratio

In this subsection, we perform the numerical analysis of the differential branching ratio and discuss its dependence on $q^2$ at the $\mu$ and $\tau$ channels. To this end, we need the values of some input parameters presented in Table 1 [14]. Also, we need the fit functions of the form factors calculated via light cone QCD sum rules in full theory as the main inputs in SM and BSM. As we previously mentioned, these fits are available in Ref. [22]. They are given in terms of $q^2$ as

$$\mathcal{F}(q^2) = \frac{\mathcal{F}(0)}{(1 - \xi_1 \frac{q^2}{m_{\Lambda_b}^2} + \xi_2 \frac{q^4}{m_{\Lambda_b}^4} + \xi_3 \frac{q^6}{m_{\Lambda_b}^6} + \xi_4 \frac{q^8}{m_{\Lambda_b}^8})}$$  \hspace{1cm} (24)$$

where the $\xi_1$, $\xi_2$, $\xi_3$ and $\xi_4$ are fit parameters; and $\mathcal{F}(0)$ denotes the value of related form factor at $q^2 = 0$. The numerical values of these parameters are presented in Table II.

The differential branching ratio as a function of $q^2$ is obtained as

$$DBR(q^2) = \left( \int_{-1}^{1} \frac{d\Gamma(\Lambda_b \to \Lambda_c \ell \ell)}{dq^2 d\cos \Theta_l} d\cos \Theta_l \right) / \Gamma_{tot},$$  \hspace{1cm} (25)$$

where $\Gamma_{tot} = \frac{1}{\tau_{\Lambda_b}}$. In order to see how the predictions of the vector LQ model deviate from those of the SM, we plot the differential branching ratio of $\Lambda_b \to \Lambda_c \ell \ell$ transition at $\mu$ and $\tau$ channels in the SM and vector LQ models.

TABLE I: The values of some input parameters used in our calculations [14]. Note that in this table we show only the central values of the input parameters, while we take into account their uncertainties in the numerical calculations, as well.

| Some Input Parameters | Values |
|-----------------------|--------|
| $m_{\Lambda_b}$       | 5.6196 GeV |
| $m_{\Lambda_c}$       | 2.2864 GeV |
| $\tau_{\Lambda_b}$    | $1.47 \times 10^{-12}$ s |
| $G_F$                 | $1.166 \times 10^{-5}$ GeV$^{-2}$ |
| $|V_{cb}|$             | 0.0422 |
| $m_{\mu}$             | 0.1056 GeV |
| $m_{\tau}$            | 1.7768 GeV |

TABLE II: Parameters of the fit functions for different form factors for $\Lambda_b \to \Lambda_c$ decay [22].

| Form Factors | $\mathcal{F}(q^2 = 0)$ | $\xi_1$ | $\xi_2$ | $\xi_3$ | $\xi_4$ |
|--------------|------------------------|---------|---------|---------|---------|
| $F_1(q^2)$   | 1.220 \pm 0.293        | 1.03    | -4.60   | 28      | -53     |
| $F_2(q^2)$   | -0.256 \pm 0.061       | 2.17    | -8.63   | 51.40   | -85.2   |
| $F_3(q^2)$   | -0.421 \pm 0.101       | 2.18    | -1.02   | 18.12   | -32     |
| $G_1(q^2)$   | 0.751 \pm 0.180        | 1.41    | -3.30   | 21.90   | -40.10  |
| $G_2(q^2)$   | -0.156 \pm 0.037       | 1.46    | -6.50   | 41.20   | -74.82  |
| $G_3(q^2)$   | 0.320 \pm 0.077        | 2.36    | -2.90   | 28.20   | -45.20  |

As far as the $DBR(q^2) - q^2$ at $\tau$ channel is concerned, figure 2 shows that there are some regions related to $R_A$ type LQ model predictions that remain out of the SM band although the two models predictions have considerable intersections. The band of $R_B$ type LQ model, however, mainly lies inside the SM band and has very small deviations from the SM predictions at some regions.

![FIG. 1: The dependence of the $DBR$ on $q^2$ for the $\Lambda_b \to \Lambda_c \ell \ell$ transition in the SM and vector LQ models with all errors.](image)

![FIG. 2: The dependence of the $DBR$ on $q^2$ for the $\Lambda_b \to \Lambda_c \ell \ell$ transitions in the SM and vector LQ models with all errors.](image)
C. The Lepton Forward-Backward Asymmetry

In this subsection, we would like to deal with the lepton forward-backward asymmetry ($A_{FB}$), which is one of the important parameters sensitive to the new physics. It is defined as

$$A_{FB}(q^2) = \frac{\int_0^1 d\Gamma dq^2 d\cos\Theta_l d\cos\Theta_t - \int_0^{-1} d\Gamma dq^2 d\cos\Theta_l d\cos\Theta_t}{\int_0^1 d\Gamma dq^2 d\cos\Theta_l d\cos\Theta_t + \int_0^{-1} d\Gamma dq^2 d\cos\Theta_l d\cos\Theta_t}. \quad (26)$$

We plot the dependence of the lepton forward-backward asymmetry on $q^2$ at $\mu$ and $\tau$ channels both in the SM and vector LQ model in Figures 3 and 4 considering all the encountered errors in the calculations. From these figures, we conclude that the two models have predictions in a roughly good consistency for all the possible cases at all lepton channels. In the case of $\mu$, the $A_{FB}$ changes its sign at very small values of $q^2$, while this point is shifted to the average values of $q^2$ at $\tau$ case. Any future data on the values and signs of $A_{FB}$ at different lepton channels and their comparison with the predictions of the present study would help us get useful knowledge on the decay modes under study and the internal structures of the participated baryons as well as restrict the parameters of the models BSM.

D. The Popular Parameter $R(q^2)$

As the final task, we present the ratio of differential branching ratios in $\tau$ and $\mu$ channels, i. e.,

$$R(q^2) = \frac{DBR(q^2)(\Lambda_b \rightarrow \Lambda_c \tau \nu_{\tau})}{DBR(q^2)(\Lambda_b \rightarrow \Lambda_c \mu \nu_{\mu})}, \quad (27)$$

which is one of the most popular probes to search for new physics effects. The experiments have shown serious deviations from the SM predictions on this parameter in some mesonic channels and we are witnessing serious violations of the lepton flavor universality in mesonic channels. The $\Lambda_b \rightarrow \Lambda_c \ell \nu_{\ell}$ is one of the important tree-level baryonic
transitions, which is accessible in the experiments like LHCb. Testing the experimental data on $R(\Lambda_c)$ and their comparison with the theoretical predictions are of great importance. We plot the dependence of the $R(q^2)$ on $q^2$ in the SM and vector LQ model in Figure 5. From this figure, we see that the results obtained using both the $R_A$ and $R_B$ types fit solutions in LQ model deviate from the SM predictions, considerably. Only at higher values of $q^2$, the $R_B$ type fit solution shows some intersections with the SM predictions.

It will be instructive to give the values for $R(\Lambda_c)$ both in SM and LQ scenarios, as well. By performing the integrals over $q^2$ in the allowed limits we find

$$R(\Lambda_c) = \begin{cases} 
(0.314 - 0.339) & \text{SM} \\
(0.410 - 0.421) & \text{LQ } R_A \\
(0.335 - 0.445) & \text{LQ } R_B 
\end{cases}$$

From the obtained results we conclude that for both the $R_A$ and $R_B$ types solutions, LQ model predictions deviate from the SM prediction, considerably. The band related to the $R_B$ type LQ model shows only a very small overlap with the SM predictions. Future experimental data will tell us whether there are LFUV in $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$ channel or not.

V. SUMMARY AND CONCLUSIONS

The direct search for NP effects has ended up in null results so far. There is a hope to hunt these effects indirectly in some hadronic decay channels. The experimental data on $R(D^{(*)})$, $R(K^{(*)})$ and $R(J/\psi)$ have shown sizable deviations from the SM predictions, recently. The test of similar possible deviations in baryonic sector is of great importance. Different experiments may put in their agenda to answer this question in near future. In this situation, theoretical and phenomenological studies can play important roles before the experimental results. The anomalies between the data and SM predictions in the mentioned mesonic channels can be removed by introducing some NP scenarios BSM. Among these models are vector and scalar leptoquark models. We have investigated the tree-level $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$ in the SM and vector leptoquark models and compared the results with each other. Our aim is to provide results from different models, which may be compared with future experimental data.

In particular we calculated the differential branching ratios and forward-backward asymmetries at $\mu$ and $\tau$ lepton channels and saw no deviations of the LQ results from the SM predictions in $\mu$ channel. In the calculations we used the form factors calculated in full QCD as the main inputs and took into account all the errors coming from the form factors and model parameters. At $\tau$ channel, the results of both models on $A_{FB}$ are the same, as well. However, It is observed at $\tau$ channel that the $R_A$ type fit solution in leptoquark model sweeps some regions out of the SM band on $DBR(q^2) - q^2$ graph. The $R_B$ type solution gives roughly the same results with the those of the SM on $DBR(q^2) - q^2$.

We also investigated the behavior of $R(q^2)$ with respect to $q^2$ and extracted the values of the popular parameter $R(\Lambda_c)$ at different scenarios. We observed that the LQ predictions on $R(q^2) - q^2$ and $R(\Lambda_c)$ using both the $R_A$ and $R_B$ type fit solutions deviate considerably from the SM predictions. This makes the transition under consideration an important baryonic $b \to c$ based tree-level transition, which may be considered as a good probe to search for NP effects. Future data on the physical quantities considered in the present study will be very useful in this regard.

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