# New physics prospects in semileptonic $\Lambda_b \to \Lambda_c^*$ decays

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**Abstract.** Observations of flavor anomalies in the $b$-sector, particularly the deviations in the measurements of the lepton flavor universality ratios in the $b \to c\tau\nu_\tau$ transitions from the standard model (SM) predictions, suggest the existence of possible new physics beyond the SM. In the pursuit of new physics in similar decays involving $b \to c\ell\nu_\ell$ transitions, we scrutinize the decay modes $\Lambda_b \to \Lambda_c^*(2595, 2625)\tau^-\bar{\nu}_\tau$ beyond the SM. In particular, we examine the impact of the presence of leptoquarks in these decay modes, within the framework of the vector leptoquark $U_1$ model. We employ form factors obtained from lattice QCD (LQCD) calculations to predict various $q^2$-dependent observables. Some of these observables include the differential branching fraction, the ratio of branching fractions and the forward-backward asymmetry of the charged lepton. The new couplings are constrained using current $b \to c\ell\nu_\ell$ experimental data.

## 1 Introduction

The disagreements between the experimental measurements and the standard model (SM) predictions of several $b$-decay observables and the violation of the lepton flavor universality (LFU) property of the SM hint the existence of new physics (NP) beyond the SM. In the flavor changing neutral current $b \to s\ell^+\ell^-$ transitions, the angular observable $P_5'$ of $B \to K^*\mu^+\mu^-$, branching ratio and angular observables in $B_s \to \phi\mu^+\mu^-$ and $\mathcal{B}(B \to K\mu^+\mu^-)$ have tensions with the SM predictions at about $2-4\sigma$ [1–4]. To address these anomalies, various NP models involving a $Z'$ boson or a leptoquark (LQ) are proposed. In the flavor changing charged current transitions $b \to c\ell^-\bar{\nu}_\ell$, the current world average values of the LFU ratios, $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$ reported by the HFLAV group [5], $R_D^{expt} = 0.342 \pm 0.026$ and $R_{D^*}^{expt} = 0.287 \pm 0.012$ are at a combined tension of about $3.3\sigma$ from the SM predictions. The average of the LHCb [6] and CMS measurements [7] of $R_{J/\psi} = \mathcal{B}(B_c \to J/\psi\tau\nu_\tau)/\mathcal{B}(B_c \to J/\psi\mu\nu_\mu) = 0.52 \pm 0.20$ [8] is consistent with the SM prediction [9] at $1.3\sigma$. Again, several NP models involving a $W'$ boson, a charged Higgs boson or a LQ are proposed to explain the observed discrepancies in these decays.

The LQs which are color triplet bosons couple to both quarks and leptons and are widely considered as potential candidates for addressing the anomalies in both $b \to c$ and $b \to s$ transitions. These hypothetical particles carry both baryon and lepton numbers and can have a spin of either 0 (scalar) or 1 (vector) along with a fractional electric charge. They naturally arise in various extensions of the SM, such as the technicolor model, grand unified theories, Pati-Salam models and the quark and lepton composite model. In this work, we investigate

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the $\Lambda_b \to \Lambda_c^* \tau^- \bar{\nu}_\tau$ decay modes mediated by $b \to c\tau^-\bar{\nu}_\tau$ transition in the $U_1(\bar{\mathbf{3}}, \mathbf{1}, 2/3)$ vector leptoquark (LQ) model. Here, the final hadron state $\Lambda_c^*$ denotes the lightest charm baryons, $\Lambda_c(2595)$ and $\Lambda_c(2625)$ with $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively.

## 2 Theoretical Framework

### 2.1 Effective Hamiltonian and $U_1$ leptoquark contribution

The $b \to c\ell\nu_\ell$ process can be described by the following effective Hamiltonian [10],

$$\mathcal{H}_{eff}^{b\to c\ell\nu} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big[O_{V_L} + \sum_i C_i O_i\Big], \tag{1}$$

where $G_F$ and $V_{cb}$ are the Fermi constant and the CKM matrix element, respectively. $O_i$ denote the fermionic operators $O_{V_{L,R}} = (\bar{c}\gamma^\mu b_{L,R})\left(\bar{\ell}_L\gamma_\mu\nu_{\ell_L}\right), O_{S_{L,R}} = (\bar{c}b_{L,R})\left(\bar{\ell}_R\nu_{\ell_L}\right)$ and $O_T = (\bar{c}\sigma^{\mu\nu}b_L)\left(\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell_L}\right)$ with their corresponding vector, scalar and tensor Wilson coefficients as $C_{V_{L,R}}$, $C_{S_{L,R}}$ and $C_T$.

The $U_1$ interaction Lagrangian with the SM fermions can be described by [11],

$$\mathcal{L}_{U_1} = h_L^{ij}\bar{Q}_i\gamma_\mu U_1^\mu L_j + h_R^{ij}\bar{d}_{Ri}\gamma_\mu U_1^\mu \ell_{Rj} + h.c. \tag{2}$$

where $h_{L,R}^{ij}$ are $3\times 3$ complex matrices describing the couplings of $U_1$ LQ with SM fermions. $Q_i$ and $L_j$ are the SM left-handed quark and lepton doublets, and $d_R$ and $\ell_R$ are the right-handed quark and lepton singlets, respectively. The indices $i, j$ stand for generation indices.

On rotating the down-type quarks in Eq.2 into the mass eigenstate basis and applying Fierz tranformations, the couplings contributing to $b \to c\tau\bar{\nu}_\tau$ are found to be

$$C_{V_L}(\mu_{\rm LQ}) = \frac{1}{2\sqrt{2}G_F V_{cb}}\sum_{k=1}^{3} V_{k3}\frac{h_L^{23}h_L^{k3*}}{M_{U_1}^2} = \frac{1}{2\sqrt{2}G_F V_{cb}}V_{33}\frac{h_L^{23}h_L^{33*}}{M_{U_1}^2}, \tag{3}$$

$$C_{S_R}(\mu_{\rm LQ}) = \frac{-1}{\sqrt{2}G_F V_{cb}}\sum_{k=1}^{3} V_{k3}\frac{h_L^{23}h_R^{k3*}}{M_{U_1}^2} = \frac{-1}{\sqrt{2}G_F V_{cb}}V_{33}\frac{h_L^{23}h_R^{33*}}{M_{U_1}^2}, \tag{4}$$

where $V_{k3}$ denotes the CKM matrix elements and $M_{U_1}$ denotes mass of the LQ, which we have taken to be 2 TeV in our analysis. Here, we have neglected the Cabibbo-suppressed terms $V_{13}$ and $V_{23}$ to obtain the final expressions.

### 2.2 Differential decay rate for $\Lambda_b \to \Lambda_c^*(2595, 2625)\tau^-\bar{\nu}_\tau$

The expression for the differential decay rate for the considered decay processes in our work is given by [12],

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cb}|^2 q^2|\mathbf{p}_2|}{192\pi^3 m_{B_1}^2}\left(1 - \frac{m_l^2}{q^2}\right)^2 H_{\frac{1}{2}\to\frac{1}{2}(\frac{3}{2})}, \tag{5}$$

where

$$\begin{aligned} H_{\frac{1}{2}\to\frac{1}{2}} = {} & \left(H^2_{\frac{1}{2}0}\right) + \left(H^2_{-\frac{1}{2}0}\right) + \left(H^2_{\frac{1}{2}1}\right) + \left(H^2_{-\frac{1}{2}-1}\right) + \frac{m_l^2}{2q^2}\Big[\left(H^2_{\frac{1}{2}0}\right) + \left(H^2_{-\frac{1}{2}0}\right) \\ & + \left(H^2_{\frac{1}{2}1}\right) + \left(H^2_{-\frac{1}{2}-1}\right) + 3\left(H^2_{\frac{1}{2}t} + H^2_{-\frac{1}{2}t}\right)\Big] + \frac{3}{2}\Big[\left(H^{SP}_{\frac{1}{2}0}\right)^2 + \left(H^{SP}_{-\frac{1}{2}0}\right)^2\Big] \\ & + \frac{3m_l}{\sqrt{q^2}}\Big[H_{\frac{1}{2}t}H^{SP}_{\frac{1}{2}0} + H_{-\frac{1}{2}t}H^{SP}_{-\frac{1}{2}0}\Big] \end{aligned} \tag{6}$$

and

$$\begin{aligned} H_{\frac{1}{2}\to\frac{3}{2}} &= \left(H^2_{\frac{1}{2}0}\right) + \left(H^2_{-\frac{1}{2}0}\right) + \left(H^2_{\frac{1}{2}1}\right) + \left(H^2_{-\frac{1}{2}-1}\right) + \left(H^2_{\frac{3}{2}1}\right) + \left(H^2_{-\frac{3}{2}-1}\right) \\ &\quad + \frac{m_l^2}{2q^2}\Big[\left(H^2_{\frac{1}{2}0}\right) + \left(H^2_{-\frac{1}{2}0}\right) + \left(H^2_{\frac{1}{2}1}\right) + \left(H^2_{-\frac{1}{2}-1}\right) + \left(H^2_{\frac{3}{2}1}\right) \\ &\quad + \left(H^2_{-\frac{3}{2}-1}\right) + 3\left(H^2_{\frac{1}{2}t} + H^2_{-\frac{1}{2}t}\right)\Big] + \frac{3}{2}\Big[\left(H^{SP}_{\frac{1}{2}0}\right)^2 + \left(H^{SP}_{-\frac{1}{2}0}\right)^2\Big] \\ &\quad + \frac{3m_l}{\sqrt{q^2}}\Big[H_{\frac{1}{2}t}H^{SP}_{\frac{1}{2}0} + H_{-\frac{1}{2}t}H^{SP}_{-\frac{1}{2}0}\Big] \end{aligned} \tag{7}$$

Eqs. 6 and 7 give the total helicity amplitudes for a 1/2 → 1/2 and 1/2 → 3/2 transitions, respectively. These helicity amplitudes are expressed in terms of the Wilson coefficients and form factors. We use the form factors obtained from recent lattice QCD calculations [13] in our analysis. We give predictions for various $q^2$-dependent observables such as the differential branching fraction $DBR(q^2)$, ratio of branching fractions $R_{\Lambda_c^*}(q^2)$ and forward-backward asymmetry of the charged lepton $A^{\tau}_{FB}(q^2)$ as defined in [14].

## 3 Constraints on LQ couplings and $q^2$-dependence

The new couplings are constrained using the current experimental measurements of $R_{D^{(*)}}$, $R_{J/\psi}$, $F_L^{D^*}$ and $P_\tau^{D^*}$ [5, 8, 15]. We also consider an upper bound of $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau) < 30\%$ [16] in constraining the couplings. Performing a $\chi^2$ analysis with the $\chi^2$ function defined as

$$\chi^2(C_k) = \sum_{ij}^{N_{obs}} [O_i^{exp} - O_i^{th}(C_k)]\mathcal{V}_{ij}^{-1}[O_j^{exp} - O_j^{th}(C_k)], \tag{8}$$

we obtain the best-fit values of the product of the LQ couplings which appear in Eqs. 3 and 4. These results are shown in Table 1. In Eq. 8, $O_i^{th}$ are the theoretical predictions [8] of the observables in terms of the new couplings $C_k$ and $O_i^{exp}$ denotes their corresponding experimentally measured values. $\mathcal{V}$ is the covariance matrix where the correlation of $R_D$ and $R_{D^*}$ is taken into account. Fig.1 displays the 1$\sigma$ allowed parameter space obtained for the leptoquark couplings.

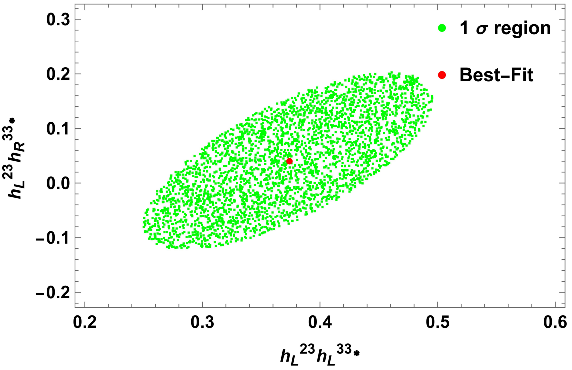

**Figure 1.** 1$\sigma$ allowed parameter space for the Leptoquark couplings

**Table 1.** Best-fit values of the new couplings

| | Best-fit value | $\chi^2_{\text{min}}$ |
|---|---|---|
| SM | $C_k = 0$ | 16.842 |
| $U_1$ | $(h_L^{23}h_L^{33*}, h_L^{23}h_R^{33*}) = (0.374, 0.040)$ | 1.569 |

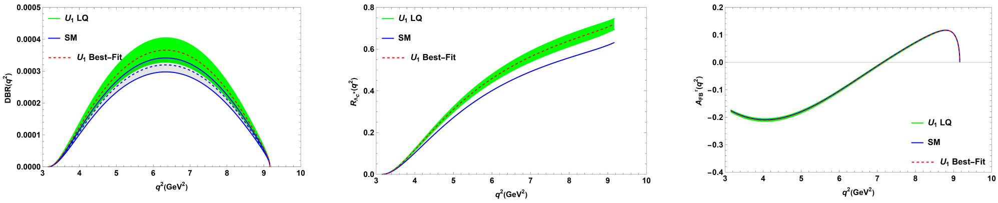

**Figure 2.** $q^2$- dependence of $DBR(q^2)$, $R_{\Lambda_c^*}(q^2)$ and $A_{FB}^{\tau}(q^2)$ in SM and in $U_1$ LQ scenario for $\Lambda_b \to \Lambda_c^*(2595)\tau^-\bar{\nu}_\tau$ decay.

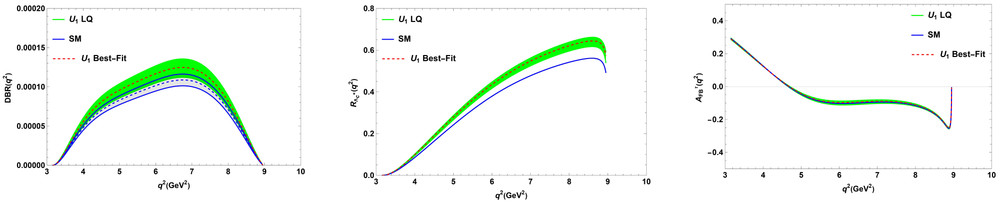

**Figure 3.** $q^2$- dependence of $DBR(q^2)$, $R_{\Lambda_c^*}(q^2)$ and $A_{FB}^{\tau}(q^2)$ in SM and in $U_1$ LQ scenario for $\Lambda_b \to \Lambda_c^*(2625)\tau^-\bar{\nu}_\tau$ decay.

The $q^2$-variation of the observables of interest in the SM and in the $U_1$ LQ scenario for $\Lambda_b \to \Lambda_c^*(2595, 2625)\tau^-\bar{\nu}_\tau$ decays is illustrated in Figs. 2 and 3. In the presence of $U_1$ LQ, the $DBR(q^2)$ is enhanced over the entire $q^2$ range. The LFU ratio $R_{\Lambda_c^*}(q^2)$ displays a prominent sensitivity to NP in the higher $q^2$ region. On the other hand, $A_{FB}^{\tau}(q^2)$ is mostly consistent with SM predictions for both decay modes as the NP dependency largely cancels out in this ratio.

## 4 Conclusion

In this work, we have scrutinized the $\Lambda_b \to \Lambda_c^*(2595, 2625)\tau^-\bar{\nu}_\tau$ decay modes beyond the SM, within the framework of $U_1$ leptoquark model. We obtained the allowed parameter space for the LQ couplings using the currently available experimental measurements in $b \to c$ sector. We found that the observables of interest are sensitive to $U_1$ LQ effects. For the LFU ratio $R_{\Lambda_c^*}(q^2)$, a distinct deviation from the SM prediction is observed in the higher $q^2$ region. Measurement of this observable can substantiate the observed anomalies in $b$-decays. Thus, the study of $\Lambda_b \to \Lambda_c^*\tau^-\bar{\nu}_\tau$ decay channels can provide insights on LFU violation in the $b \to c$ sector.

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