Lepton flavor violating $\Lambda_b \rightarrow \Lambda \ell_1 \ell_2$ decay

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Inspired by the recent hints of lepton flavor universality violation in $b \rightarrow s \ell \ell$ and $b \rightarrow c \ell \nu$ transitions, we study lepton flavor violating exclusive $\Lambda_b \rightarrow \Lambda \ell_1 \ell_2$ ($\ell_1 \neq \ell_2$) decay, which is forbidden in the Standard Model. Starting from a general effective Hamiltonian for a $b \rightarrow s \ell_1^\pm \ell_2^\mp$ transition that includes vector and axial-vector operators, and scalar and pseudo-scalar operators, we derive a two-fold decay distribution of $\Lambda_b \rightarrow \Lambda \ell_1 \ell_2$. The distribution helps us to construct the differential branching ratio and the lepton side forward-backward asymmetry, which are studied in a vector leptoquark model. The parameter space of the vector leptoquark model is constrained by low energy observables.

I. INTRODUCTION

Though an $\mathcal{O}(1)$ signal of new physics (NP) is still at large, the recent results by the Belle and LHCb Collaborations in the neutral and charged current transitions of $b$-flavored mesons are intriguing hints of lepton flavor universality (LFU) violation, which is absent in the Standard Model (SM). In the flavor changing neutral current transition $b \rightarrow s \ell \ell$ the observables that probe LFU are

$$R_K^{(*)} = \frac{B(B \rightarrow K^{(*)}\mu^+\mu^-)}{B(B \rightarrow K^{(*)}e^+e^-)}.$$  \hfill (1)

The LHCb Collaboration has measured $R_K$ and the most recent result is

$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}, \quad 1 \leq q^2 \leq 6.0 \text{GeV}^2,$$  \hfill (2)

where $q^2$ is the invariant mass squared of the final state dilepton pair. This result is lower than the SM prediction $R_K^{SM} = 1.00 \pm 0.01$ by about $2.5\sigma$. On the other hand, the most recent measurements of $R_{K^{(*)}}$ by the LHCb in the two dilepton invariant mass squared bins

$$R_{K^{(*)}} = \begin{cases} 0.66^{+0.11}_{-0.17} \pm 0.03, & 0.045 \leq q^2 \leq 1.1 \text{GeV}^2, \\ 0.69^{+0.09}_{-0.07} \pm 0.05, & 1.1 \leq q^2 \leq 6.0 \text{GeV}^2, \end{cases}$$  \hfill (3)

deviate from the SM predictions $R_{K^{(*)}}^{SM} = 0.906 \pm 0.028$ and $R_{K^{(*)}}^{SM} = 1.00 \pm 0.01$ by $2.3\sigma$ and $2.5\sigma$, respectively. Belle has also presented their results of $R_K$ and $R_{K^{(*)}}$ which are closer to the SM predictions but has large uncertainties.

Independently of the results in the $b \rightarrow s \ell \ell$ transitions, hints of LFU violation have also been found in the charged current transition $b \rightarrow c \ell \nu$. The observables in which deviations from the SM predictions have been observed are $R_D$ and $R_{D^*}$,

$$R_{D^{(*)}} = \frac{B(B \rightarrow D^{(*)} \tau \nu)}{B(B \rightarrow D^{(*)} \ell \nu)}, \quad \ell = e, \mu.$$  \hfill (4)

$R_{D^*}$ has been measured by Belle $^{[5][7]}$, LHCb $^8$ and BaBar $^9$. The new measurement by Belle $^{[10]}$ using semi-leptonic tagging gives

$$R_D = 0.307 \pm 0.37 \pm 0.016,$$  \hfill (5)

$$R_{D^*} = 0.283 \pm 0.018 \pm 0.14.$$  \hfill (6)

HFLAV has combined the most recent results and their averages $^{[11]}$ exceed the SM predictions $R_D^{SM} = 0.299 \pm 0.003$ $^{[12]}$ and $R_{D^*}^{SM} = 0.258 \pm 0.005$ $^{[13]}$ by $2.3\sigma$ and $3.4\sigma$, respectively.

A number of NP models with new particle content has been constructed that can explain these deviations. Shortly after the first hints of LFU violation were announced $^{[14]}$, it was shown in Ref. $^{[15]}$ that LFU violation implies lepton flavor violating (LFV) interactions. Despite several counter examples to this observation $^{[16][17]}$, most models that generate LFU violation also generate LFV processes which are strictly forbidden in the SM. Therefore, the observation of LFV decay will be a smoking gun signal of NP. Some of the LFV processes that have been extensively looked for are lepton decays $\tau \rightarrow 3\mu$, $\mu \rightarrow 3e$ etc and $\ell \rightarrow \ell'M$ where $M$, is a meson, radiative decays $\mu \rightarrow e\gamma$ etc, and $\mu \rightarrow e$ conversion. Interestingly, in the Higgs sector $h \rightarrow \mu\tau$ was studied and an apparent excess was also reported by CMS $^{[18]}$, which disappeared in subsequent measurements.

In this paper we discuss LFV baryonic decay $\Lambda_b \rightarrow \Lambda \ell_1 \ell_2$, which proceeds through a $b \rightarrow s \ell_1^\pm \ell_2^\mp$ transition where $\ell_1^\pm$ and $\ell_2^\mp$ are charged leptons of different flavors. Though its SM counterpart $\Lambda_b \rightarrow \Lambda \ell \ell$ has been measured by the LHCb $^{[19][20]}$, to the best of our knowledge currently there are no experimental data on $\Lambda_b \rightarrow \Lambda \ell_1^\pm \ell_2^\mp$. Unlike $\Lambda_b \rightarrow \Lambda \ell \ell$, the decay width with $\Lambda_b \rightarrow \Lambda \ell_1^\pm \ell_2^\mp$ decay

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is that it does not suffer from long-distance QCD and charmonium resonance backgrounds. The $Λ_b \to Λℓ_1^± ℓ_2^−$ decay was earlier discussed in [21] in the context of scalar leptoquark model where only vector and axial-vector type effective operators were considered. In this paper we include in addition scalar and pseudo-scalar operators and present a double differential distribution. From this distribution we study the differential branching ratio and the forward-backward asymmetry. These observables are studied in a vector leptoquark model $U_1 \equiv (3,1)_{2/3}$. We use several low energy observables to constrain the model parameters.

The paper is organized as follows. We begin by describing in Sect. II the effective Hamiltonian for a $b \to s ℓ_1^± ℓ_2^−$ transition. The differential decay distribution of the exclusive $Λ_b \to Λℓ_1^± ℓ_2^−$ is calculated in Sect. III followed by a numerical analysis in Sect. IV. We summarize our discussions in Sect. V.

II. EFFECTIVE HAMILTONIAN

We start with the following effective Hamiltonian for the lepton flavor violating $b \to s ℓ_1^± ℓ_2^−$ transition:

$$H^{eff} = \frac{1}{2v^2} V_{tb} V^*_{ts} \frac{α_e}{4\pi} \sum_i \left( C_i O_i + C'_i O'_i \right),$$

where $v^2 = 1/\sqrt{2} G_F \approx 246$ GeV is the SM vacuum expectation value, and $i = V, A, S, P$ correspond to vector, axial-vector, scalar, and pseudo-scalar operators, which read

$$C_i^{(o)} = [s γ^μ P_{L(R)} b] [\bar{ℓ}_2γ_μℓ_1],$$

$$C_i^{(A)} = [s γ^μ P_{L(R)} b] [\bar{ℓ}_2γ_μγ_5ℓ_1],$$

$$C_i^{(s)} = [s P_{R(L)} b] [\bar{ℓ}_2ℓ_1], \quad C_i^{(P)} = [s P_{R(L)} b] [\bar{ℓ}_2γ_5ℓ_1].$$

III. EXCLUSIVE $Λ_b \to Λℓ_1^± ℓ_2^−$ DECAY

To set up the kinematics of the decay we assume that the $Λ_b$ is at rest while the $Λ$ and the dilepton pair travel along the +z- and −z-axis, respectively. We assign $p, k, q_1$ and $q_2$ as the momenta of the $Λ_b, Λ, ℓ_1$, and $ℓ_2$, and $s_p, s_k$ are the spins of $Λ_b, Λ$ on to the z-axis in their respective rest frames. We also introduce two kinematic variables; $q^μ = q_1^μ + q_2^μ$ is the four-momentum of the dilepton pair, and $θ_ℓ$ is the angle that the lepton $ℓ_1$ makes with respect to the z-axis in the dilepton rest frame. The decay amplitude can be written as

$$M^{λ_2,λ_1}(s_p, s_k) = -\frac{V_{tb}V^*_{ts}α_e}{2v^2} η_λ \sum_{i=L,R} \left[ η_λ H_{VA,λ}^{i,s_p,s_k} L_{i,λ}^{α_1,α_2} + H_{SP}^{i,s_p,s_k} L_{i,λ}^{α_1,α_2} \right].$$

Here $H_{VA,λ}^{i,s_p,s_k}$ and $H_{SP}^{i,s_p,s_k}$ are the hadronic helicity amplitudes corresponding to vector and axial-vector (VA), and scalar and pseudo-scalar (SP) operators, and the $L_{i,λ}^{α_1,α_2}$ are the leptonic helicity amplitudes. Here $i = L, R$ corresponds to the chiraldness of the lepton current and the $λ = t, ±1, 0$ are the helicity states of the virtual gauge boson that decay into the dilepton pair. The $λ_{1,2}$ are the helicities of the leptons and $η_λ = 1, η_{±1,0} = -1$. The definitions and the expressions of $H_{VA,λ}^{i,s_p,s_k}$ and $H_{SP}^{i,s_p,s_k}$ in terms of Wilson coefficients and form factors can be found in [29]. In the literature, instead of the hadronic helicity amplitudes, transversity amplitudes $A_{i,λ}^{||}(\parallel), A_{i,λ}^{⊥}(\perp)$ and $A_{SP,λ}(\perp), A_{SP,λ}(\parallel)$ are often used. Following [22] the expressions of the transversity amplitudes are collected in Appendix A.

The $L_{i,λ}^{α_1,α_2}$ and $L_{i,λ}^{α_2,α_1}$ amplitudes are defined as

$$L_{L,R}^{α_1,α_2} = \langle \bar{ℓ}_2(λ_2)ℓ_1(λ_1)|\bar{ℓ}_2(1+γ_5)ℓ_1|0⟩,$$

$$L_{L,R}^{α_2,α_1} = \bar{ε}^μ(λ)⟨\bar{ℓ}_2(λ_2)ℓ_1(λ_1)|\bar{ℓ}_2γ_μ(1+γ_5)ℓ_1|0⟩,$$

where $ε^μ$ is the polarization vector of the virtual gauge boson that decays in to the dilepton pair. The details of the calculations of $L_{L,R}^{α_1,α_2}$ and $L_{L,R}^{α_2,α_1}$ are given in Appendix B. Based on these calculations we obtain the differential branching ratio of $Λ_b \to Λℓ_1^± ℓ_2^−$ as

$$\frac{d\mathcal{B}}{dq^2d\cosθ_ℓ} = \frac{3}{2} \left( K_{1ss} \sin^2θ_ℓ + K_{1cc} \cos^2θ_ℓ + K_{1c} \cosθ_ℓ \right).$$

Each of the angular coefficients $K_{1ss,1cc,1c}$ can be written in the following way:

$$K_{1ss,1cc} = K_{1ss,1cc}^{VA} + K_{1ss,1cc}^{SP} + K_{1ss,1cc}^{int},$$

where

$$K_{1ss,1cc}^{VA} = K_{1ss,1cc}^{VA} + K_{1ss,1cc}^{SP} + K_{1ss,1cc}^{int}.$$
where $K_{1ss,1cc,1c}^{VA}, K_{1ss,1cc,1c}^{SP}$ are contributions from VA and SP operators, and $K_{1ss,1cc,1c}^{int}$ includes their interference terms. In terms of the transversity amplitudes the expressions of $K_{1ss,1cc,1c}^{VA}, K_{1ss,1cc,1c}^{SP}$ read

$$K_{1ss}^{VA} = \frac{1}{4} \left( 2 |A_R^||^2 + |A_L^||^2 + 2 |A_{L0}^||^2 + |A_{L1}^||^2 + \{ R \leftrightarrow L \} \right) - \frac{m_+^2 + m_0^2}{4q^2} \left( |A_R^||^2 + |A_L^||^2 + \{ R \leftrightarrow L \} \right)
$$

$$K_{1cc}^{VA} = \frac{1}{2} \left( |A_R^||^2 + |A_{L0}^||^2 + \{ R \leftrightarrow L \} \right) + \frac{m_+^2 + m_0^2}{4q^2} \times \left[ 2 |A_{L0}^||^2 + |A_{L1}^||^2 + \{ R \leftrightarrow L \} \right]
$$

$$K_{1c}^{VA} = -\beta_\ell \beta_\ell' \left( |A_R^||^2 + |A_{L1}^||^2 + \{ R \leftrightarrow L \} \right)
$$

$$K_{1ss}^{SP} = \frac{1}{4} \left( |A_S^||^2 + |A_P^||^2 + \{ \perp \leftrightarrow \parallel \} \right)
$$

$$K_{1cc}^{SP} = \frac{1}{4} \left( |A_P^||^2 + |A_S^||^2 + \{ \perp \leftrightarrow \parallel \} \right)
$$

$$K_{1c}^{SP} = 0 .
$$

The interference terms read

$$K_{1ss}^{int} = \frac{m_+ + m_0}{2\sqrt{q^2}} Re \left( A_{||} A^*_{P||} + A_{||} A^*_{P\perp} \right)
$$

$$K_{1cc}^{int} = \frac{m_+ + m_0}{2\sqrt{q^2}} Re \left( A_{||} A^*_{P||} + A_{||} A^*_{P\perp} \right) + \frac{m_- + m_0}{2\sqrt{q^2}} Re \left( A_{||} A^*_{S||} \right)
$$

IV. NUMERICAL ANALYSIS

Among many leptoquark models proposed to explain flavor anomalies, the vector leptoquark $U_1 \equiv (3,1)_{2/3}$ has emerged as an excellent candidate that can simultaneously alleviate the tensions between theory and experiments in both the charged and the neutral current sectors. In fact, $U_1$ can accommodate a large number of low energy data and high-$p_T$ searches without too much fine-tuning of the model parameters. Early works reconciling these anomalies by coupling the $U_1$ with the third generation quarks and leptons can be found in Refs. [17] [27]. The UV completion of this model has also recently been discussed in Ref. [28]. The SM gauge symmetry allows couplings of the $U_1$ leptoquark to both left- and right-handed fermions and the Lagrangian reads

$$\mathcal{L} \supset \frac{U_1^\mu}{\sqrt{2}} \left[ \beta_{L}^\mu Q_L \gamma_{\mu} L_L^\mu + \beta_{R}^\mu d_R^\mu \gamma_{\mu} \ell_R^\mu \right] .
$$
Here the $Q_L^i = (V_{ej}^* u_L^j, d_L^j)^T$ and $L_L^i = (\nu_L^j, \ell_L^j)^T$ are $SU(2)_L$ doublets, and the $\beta_L, \beta_R$ are $3 \times 3$ Yukawa matrices.

To address the flavor anomalies we assume the following flavor ansatz:

\[
\beta_L = \begin{pmatrix}
0 & 0 & 0 \\
0 & \beta_L^{\ell\mu} & \beta_L^{\ell\tau} \\
0 & \beta_L^{b\mu} & \beta_L^{b\tau}
\end{pmatrix}, \quad \beta_R = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & \beta_R^{b\tau}
\end{pmatrix}. \tag{26}
\]

With the couplings to the first generation set to zero the experimental limits on atomic parity violation, $\mu - e$ conversion on nuclei, and $B(K \to \pi\nu\nu)$ are evaded. An important feature of the vector leptoquark model is the absence of the tree level $b \to s\nu\bar{\nu}$ transition evading the current experimental constraints coming from $B \to K^\pm \nu\nu$ \[29\]. There is also a “flavor protection” mechanism in the $U_1$ loops due to which the purely leptonic processes $\tau \to 3\mu$, $\tau \to \mu\nu\bar{\nu}$ and $b \to s\nu\bar{\nu}$ have little phenomenological significance \[20\] \[30\] \[31\]. These processes aside, we consider a number of low energy flavor observables to constrain the flavor structure \[26\].

The Lagrangian \[25\] generates the following VA and SP operators for $b \to s\ell\ell$:

\[
C_s^{e\ell, \ell_2} = -C_A^{e\ell, \ell_2} = - \frac{\pi v^2}{2V_{tb}V_{ts}^* \alpha m^2_{1LQ}} \beta^{s\ell_1}(\beta^{b\ell_1})^* \tag{27}
\]

\[
C_A^{e\ell, \ell_2} = C_R^{e\ell, \ell_2} = - \frac{\pi v^2}{2V_{tb}V_{ts}^* \alpha m^2_{1LQ}} \beta^{s\ell_1}(\beta^{b\ell_1})^* \tag{28}
\]

\[
C_s^{b\ell, \ell_2} = -C_A^{b\ell, \ell_2} = \frac{\pi v^2}{V_{tb}V_{ts}^* \alpha m^2_{1LQ}} \beta^{b\ell_1}(\beta^{b\ell_1})^* \tag{29}
\]

\[
C_A^{b\ell, \ell_2} = C_R^{b\ell, \ell_2} = \frac{\pi v^2}{V_{tb}V_{ts}^* \alpha m^2_{1LQ}} \beta^{b\ell_1}(\beta^{b\ell_1})^*. \tag{30}
\]

For the given flavor ansatz \[26\] $R_K^{(\mu)}$ receives the following modifications \[32\] through the NP Wilson coefficients $C_{V,A}^{(\mu)}$:

\[
R_K^{(\mu)\text{GeV}^2} \approx 1 + 0.46C_{V,R}^{\mu}, \tag{31}
\]

\[
R_K^{(\mu)\text{GeV}^2} \approx 1 + 0.47C_{V,R}^{\mu}. \tag{32}
\]

Global fits to the most recent $b \to s\mu\mu$ data have been performed by several groups and we take the range $-0.59 \leq C^{\mu\mu}_V = -C^{\mu\mu}_A \leq -0.40$ \[33\] \[34\] in our analysis. For a large $\beta_L^{b\tau}$ there are additional flavor-universal contributions to the $\to s\ell\ell$ in the direction of $C_{V,A}^{\mu}$ due to the off-shell photon penguins \[31\].

\[
\Delta C_V \approx -\frac{v^2}{6m^2_{1LQ}V_{tb}V_{ts}^*} \frac{\beta^{b\tau}(\beta^{b\tau})^*}{m^2_{1LQ}} \log \left( \frac{m^2_{2LQ}}{m^2_{1LQ}} \right). \tag{33}
\]

Experiments yield $\Delta C_V = -0.73 \pm 0.23$ \[33\] \[34\].

While the contributions of $U_1$ leptoquark to $b \to s\mu\mu$ processes are through vector and axial-vector operators only, in the presence of a right-handed coupling $\beta_R^{b\tau}$ scalar and pseudo-scalar currents can contribute to $b \to s\tau\tau$ processes $B_s \to \tau^+\tau^-$ and $B \to K\tau^+\tau^-$. The $B_s \to \tau^+\tau^-$ branching ratio reads

\[
\frac{\mathcal{B}(B_s \to \tau^+\tau^-)}{\mathcal{B}(B_s \to \tau^+\tau^-)_{SM}} \times \left[ 1 + \frac{\pi v^2}{2V_{tb}V_{ts}^* \alpha m^2_{1LQ} C_{SM}^{10}} \left( \beta^{b\tau}_L - \frac{m^2_{B_s}}{m_r(m_s + m_b)(\beta^{b\tau}_R)^2} \right)^2 \right] \nonumber + \left( 1 - \frac{4m^2_{B_s}}{m^2_{B_s}} \right) \frac{\pi v^2}{2V_{tb}V_{ts}^* \alpha m^2_{1LQ} C_{SM}^{10}} \frac{m^2_{B_s}}{m_r(m_s + m_b)} \beta^{b\tau}_R (\beta^{b\tau}_R)^* . \tag{34}
\]

The present experimental upper limit is $\mathcal{B}(B_s \to \tau^+\tau^-) < 0.3(4.4) \times 10^{-3}$ \[35\] and the SM prediction read $\mathcal{B}(B_s \to \tau^+\tau^-) < (7.35 \pm 0.43) \times 10^{-7}$ \[36\]. The SM branching ratio of $B \to K\tau^+\tau^-$ is $\mathcal{B}(B \to K\tau^+\tau^-) = 1.44(0.28) \times 10^{-7}$ where we use hadronic inputs from \[37\]. and the experimental upper bound is $\mathcal{B}(B \to K\tau^+\tau^-) = (1.36 \pm 0.71) \times 10^{-3}$ \[38\].

The leptoquark also contributes to the LFV observables $\mathcal{B}(B^+ \to K^+\tau^+\mu^\mp)$ and $\mathcal{B}(\tau \to \mu\phi)$. Following the simplified expressions given in \[39\] we get

\[
\mathcal{B}(B^+ \to K^+\tau^+\mu^-) \approx \frac{v^4}{m^4_{1LQ}} \left( 0.50 |\beta^{\mu\mu}_L(\beta^{b\tau}_L)^*|^2 + 2.83 |\beta^{\mu\mu}_L(\beta^{b\tau}_L)^*|^2 - 1.39 \text{Re}[\beta^{\mu\mu}_L(\beta^{b\tau}_L)^*]) |\beta^{\mu\mu}_R|^2 \right), \tag{35}
\]

\[
\mathcal{B}(B^+ \to K^+\tau^-\mu^+) \approx \frac{v^4}{m^4_{1LQ}} 0.50 |\beta^{\mu\mu}_R(\beta^{b\tau}_R)^*|^2. \tag{36}
\]

The experimental upper limit is $\mathcal{B}(B^+ \to K^+\tau^+\mu^-) \leq 2.8 \times 10^{-5}$ and $\mathcal{B}(B^+ \to K^+\mu^+\tau^-) \leq 4.5 \times 10^{-5}$ \[40\]. For the $\tau \to \mu\phi$ decay, following \[41\] we get after neglecting the mass of the muon

\[
\mathcal{B}(\tau \to \mu\phi) = \frac{f^3_{\tau} m^3_{\tau}}{32\pi^4} \frac{1}{16 m^4_{1LQ}} \left( 1 - \frac{m^2_{\tau}}{m^2_{Z}} \right)^2 \left( 1 + 2 \frac{m^2_{\phi}}{m^2_{\tau}} \right) \times |\beta^{\mu\mu}_L(\beta^{b\tau}_L)^*|^2. \tag{37}
\]

The experimental upper limit from Belle \[42\] is $\mathcal{B}(\tau \to \mu\phi) \leq (0.0 \pm 5.1) \times 10^{-8}$. In the presence of right-handed coupling, $\tau \to \mu\gamma$ is also induced:

\[
\mathcal{B}(\tau \to \mu\gamma) = \frac{\alpha_e}{4\pi} \frac{m^3_{\tau}}{16 m^4_{1LQ}} \frac{1}{64 \pi^4} |\beta^{\mu\mu}_L(\beta^{b\tau}_R)|^2. \tag{38}
\]

The experimental upper bound is $\mathcal{B}(\tau \to \mu\gamma) = 0.0(3.0) \times 10^{-8}$ \[43\].

The charged current transition $b \to c\ell\ell$ also receives contributions from the vector leptoquark. Here the flavor of
the final state neutrino in general may be different from the flavor of the accompanying lepton. The most general effective Hamiltonian for this transition is

\[ H_{\text{eff}}^{b \rightarrow c \bar{e} \nu} = \frac{2V_{cb}}{\sqrt{2}} \left( (1 + C_{V_1}) O_{V_1} + C_{V_2} O_{V_2} + C_{S_1} O_{S_1} + C_{S_2} O_{S_2} + C_{T} O_{T} \right), \]

where the operators are given by

\[ O_{V_1} = (\bar{e}_L \gamma^\mu b_L)(\bar{\ell}_R \gamma^\mu \nu_L), \quad O_{V_2} = (\bar{e}_R \gamma^\mu b_R)(\bar{\ell}_R \gamma^\mu \nu_L), \]
\[ O_{S_1} = (\bar{e}_L b_R)(\bar{\ell}_R \nu_L), \quad O_{S_2} = (\bar{e}_R b_L)(\bar{\ell}_R \nu_L), \]
\[ O_{T} = (\bar{e}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_L). \]

In the SM all the Wilson coefficients \( C_i^L = 0 \). In the \( U_1 \) leptoquark model the only non-vanishing Wilson coefficients are

\[ C_{V_1}^L = \frac{v^2}{4m_{LQ}^2} (\beta^L)^* (\beta^L + \frac{V_{cs}}{V_{cb}} \beta^L); \]
\[ C_{S_1}^L = -\frac{v^2}{2m_{LQ}^2} (\beta^L)^* (\beta^L + \frac{V_{cs}}{V_{cb}} \beta^L). \]

The set of observables that we consider in this category are \( R_D, R_{D^*} \), and the branching ratio \( B(B_c \rightarrow \tau \nu) \). The expressions for \( R_D \) and \( R_{D^*} \) are [13]

\[ R_D \approx R_{D}^{\text{SM}} \left\{ |1 + C_{V_1}^L|^2 + 1.54 \text{Re}\left[ (1 + C_{V_1}^L)(C_{S_1}^L) \right] \right\} + 1.09|C_{S_1}^L|^2, \]
\[ R_{D^*} \approx R_{D^*}^{\text{SM}} \left\{ |1 + C_{V_1}^L|^2 + 0.13 \text{Re}\left[ (1 + C_{V_1}^L)(C_{S_1}^L) \right] \right\} + 0.05|C_{S_1}^L|^2. \]

The HFLAV averages that use the most recent measurements of these two observables are \( R_D = 0.340 \pm 0.030 \) and \( R_{D^*} = 0.295 \pm 0.013 \) [11]. The SM prediction of \( R_D^{\text{SM}} \) and \( R_{D^*}^{\text{SM}} \) are given in the Introduction section.

The \( B_c \rightarrow \tau \nu \) branching ratio reads

\[ B(B_c \rightarrow \tau \nu) = \frac{\tau_{B_c} m_{B_c} f_{B_c} |V_{cb}|^2}{16\pi^2 m_{B_c}} \left| 1 - \frac{m_{\tau}^2}{m_{B_c}^2} \right|^2 + \frac{v^2}{4m_{LQ}^2} \left( \beta^L - \frac{2m_{B_c}^2 \beta_{m_R}}{m_{\tau}(m_b + m_c)} \right)^* \left( \beta^L + \frac{V_{cs}}{V_{cb}} \beta^L \right)^2. \]

We now perform a \( \chi^2 \) analysis to find the parameter space allowed by the above low energy observables listed in Table [5]. The \( \chi^2 \) is defined as

\[ \chi^2 = \sum_i \left( \frac{O_i^{\text{exp}} - O_i^{\text{th}}}{\Delta O_i^{\text{exp}}} \right)^2, \]

where \( O_i^{\text{exp}} \) are the experimental (theoretical) values of the observables and \( \Delta O_i^{\text{exp}} \) are the experimental errors. We minimize the \( \chi^2 \) and choose a 2\( \sigma \) region about \( \chi^2_{\text{min}} \). In this analysis we set mass of the leptoquark \( m_{LQ} = 1.5 \) TeV. In Fig. 1 the obtained parameter space is shown. For this parameter space, the quark distribution of the differential branching ratio and the lepton-side forward-backward asymmetry is shown in Fig. 2.
The large branching ratios of the order $\mathcal{O}(10^{-5}, 10^{-6})$ are induced by large ranges of $\beta^{9\tau}$ allowed by the current data. Such large ranges arise due to poor experimental bounds on modes such as $B_s \to \tau^+\tau^-, B^+ \to K\tau^+\tau^-$. These branching ratios are accessible in the LHCb.

\[
\langle A_{FB}^\ell (\Lambda_b \to \Lambda\mu^+\tau^-) \rangle = -0.4040. \tag{51}
\]

The large branching ratios are strictly forbidden in the Standard Model and therefore any observation is a smoking gun signal of physics beyond the Standard Model. In recent years a number of lepton flavor universality violating decays has been observed albeit of low statistical significance. Many physics beyond the Standard Models that have been constructed to explain the origin of flavor universality violating couplings can also give rise to flavor violating decays. Motivated by these results, in this paper we have explored lepton flavor violating $b \to s\ell^+\ell^-$ transition in $\Lambda_b \to \Lambda\ell^+\ell^-$ decay. In this paper we have presented a double differential distribution of the decay in terms of dilepton invariant mass squared $q^2$ and lepton angle $\theta_L$. From this distribution we have obtained the differential branching ratio and the lepton-side forward-backward asymmetry. We have studied these two observables in the vector leptoquark model $U_1 \equiv (3,1)_{2/3}$. The parameter space of the model has been constrained by low energy observables. Our predicted range of the branching ratio in the vector leptoquark model may be accessible by the LHCb.
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Appendix A: Transversity amplitudes

Corresponding to the effective Hamiltonian \( \{7\} \) the expressions of the transversity amplitudes read \( \{22\} \)

\[
A_{\perp 1}^{L(R)} = -\sqrt{2}N \left( f_1^\perp \sqrt{2s_-}C_{VA+}^{L(R)} \right),
\]

\[
A_{\parallel 1}^{L(R)} = \sqrt{2}N \left( f_1^\parallel \sqrt{2s_-}C_{VA-}^{L(R)} \right),
\]

\[
A_{\perp 0}^{L(R)} = \sqrt{2}N \left( f_0^\perp (m_{L+} + m_{L}) \sqrt{q^2}C_{VA+}^{L(R)} \right),
\]

\[
A_{\parallel 0}^{L(R)} = -\sqrt{2}N \left( f_0^\parallel (m_{L+} - m_{L}) \sqrt{q^2}C_{VA-}^{L(R)} \right),
\]

\[
A_{\perp \ell} = -2\sqrt{2}N f_1^\ell (m_{L+} + m_{L}) \sqrt{q^2}C_{A,\ell}^{L(R)} - C_{A,\ell}'\),
\]

\[
A_{\parallel \ell} = 2\sqrt{2}N f_1^\ell (m_{L+} + m_{L}) \sqrt{q^2}C_{A,\ell} - C_{A,\ell}'\). \quad (A6)
\]

Here the normalization constant \( N(q^2) \) is given by

\[
N(q^2) = \frac{V_{tb}V_{ts}^* \alpha_s}{\sqrt{\tau_{L+}}} \sqrt{q^2} \left( \frac{\lambda(m_{L+}^2 - m_L^2)}{2\sqrt{q^2}C_{VA+}} \right) \beta_{\ell}\),
\]

\[
\beta_{\ell} = \left( 1 - \frac{(m_L + m_{L+})^2 - (m_L - m_{L+})^2}{q^2} \right), \quad \beta_{\ell}' = \left( 1 - \frac{(m_L + m_{L+})^2}{q^2} \right),
\]

where \( \lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca) \) and the Wilson coefficients are

\[
C_{VA+}^{L(R)} = (C_V + C_A) + (C_V' + C_A')\),
\]

\[
C_{VA-}^{L(R)} = (C_V + C_A) - (C_V' + C_A'), \quad (A8)
\]

The transversity amplitudes corresponding to the SP operators are \( \{22\} \)

\[
A_{S\perp} = 2\sqrt{2}N f_1^\ell \frac{m_{L+} - m_L}{m_b} \sqrt{s_+} \left( C_{S,\ell} + C_{S,\ell}' \right),
\]

\[
A_{S\parallel} = -2\sqrt{2}N f_1^\ell \frac{m_{L+} + m_L}{m_b} \sqrt{s_-} \left( C_{S,\ell} - C_{S,\ell}' \right),
\]

\[
A_{P\perp} = -2\sqrt{2}N f_1^\ell \frac{m_{L+} - m_L}{m_b} \sqrt{s_+} \left( C_{P,\ell} + C_{P,\ell}' \right),
\]

\[
A_{P\parallel} = 2\sqrt{2}N f_1^\ell \frac{m_{L+} + m_L}{m_b} \sqrt{s_-} \left( C_{P,\ell} - C_{P,\ell}' \right). \quad (A13)
\]

Appendix B: Spinors in dilepton rest frame

We assume that the lepton \( \ell^- \) is negatively charged and has four-momentum \( q_{\ell}^{\perp} = (E_{\ell}, -\hat{q}_\ell) \) while \( \ell^+ \) is positively charged and has four-momentum \( q_{\ell}^{\parallel} = (E_{\ell}, +\hat{q}_\ell) \)

\[
q_{\ell}^{\perp} = (E_{\ell}, -|q_{2\ell}| \sin \theta_{\ell}, 0, -|q_{2\ell}| \cos \theta_{\ell}) \quad \text{and} \quad q_{\ell}^{\parallel} = (E_{\ell}, |q_{2\ell}| \sin \theta_{\ell}, 0, |q_{2\ell}| \cos \theta_{\ell}),
\]

with

\[
|q_{2\ell}| = \frac{\lambda^{1/2}(q^2, m_{\ell+}^2, m_{\ell-}^2)}{2\sqrt{q^2}} \quad \text{and} \quad E_{\ell} = \frac{q^2 + m_{\ell+}^2 - m_{\ell-}^2}{2\sqrt{q^2}}.
\]

The explicit expressions of the lepton helicity amplitudes require us to calculate

\[
\bar{u}_{\ell\ell}(1 + \gamma_5)v_{\ell\ell}, \quad \bar{u}_\ell \gamma_\mu(1 + \gamma_5)v_{\ell\ell} \quad \text{for the lepton } \ell^+\]

Following \( \{17\} \) the explicit expressions of the spinor for the lepton \( \ell^+ \) is

\[
\begin{align*}
&u_{\ell\ell}(\lambda) = \frac{\sqrt{E_{\ell} + m_{\ell}\chi_{\ell}^u}}{2\sqrt{E_{\ell} + m_{\ell}\chi_{\ell}^u}} \left( \begin{array}{c}
\sin \frac{\theta_{\ell}}{2} \\
\cos \frac{\theta_{\ell}}{2}
\end{array} \right), \\
&\chi_{\ell}^u = \chi_{\ell}^v \left( 1 + \gamma_5 \right) - \chi_{\ell}^u \left( 1 - \gamma_5 \right)
\end{align*}
\]

For the lepton \( \ell^- \) which is moving in the opposite direction to \( \ell^+ \), the two component spinor \( \chi^v \) looks like

\[
\chi_{\ell}^v = \xi_{\ell}\chi_{\ell}^\perp, \quad \xi_{\ell} = 2\lambda e^{-2i\phi}.
\]

Hence we have

\[
\begin{align*}
&v_{\ell\ell}(\lambda) = \left( \begin{array}{c}
\sqrt{E_{\ell} - m_{\ell}\chi_{\ell}^v} \\
-2\sqrt{E_{\ell} + m_{\ell}\chi_{\ell}^v}
\end{array} \right), \\
&\chi_{\ell}^v = \chi_{\ell}^u \left( 1 - \gamma_5 \right) - \chi_{\ell}^v \left( 1 + \gamma_5 \right)
\end{align*}
\]

With these choices of lepton spinors we get the following expressions of the lepton helicity amplitudes \( L_{\lambda,\lambda_1} \) and

\[
\begin{align*}
&L_{\lambda,\lambda_1} = \left( \begin{array}{c}
\sin \frac{\theta_{\ell}}{2} \\
\cos \frac{\theta_{\ell}}{2}
\end{array} \right), \\
&\chi_{\ell}^v = \chi_{\ell}^u \left( 1 + \gamma_5 \right) - \chi_{\ell}^v \left( 1 - \gamma_5 \right)
\end{align*}
\]
\[ L_{R,0}^{\frac{1}{2}+\frac{1}{2}} = \frac{1}{\sqrt{2}} [m_1(\beta'_f - \beta_f) + m_2(\beta'_f + \beta_f)] \sin \theta_f, \]
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