Model independent analysis of $B^* \rightarrow P \ell \bar{\nu}_\ell$ decay processes

Atasi Ray$^{1,a}$, Suchismita Sahoo$^{2,b}$, Rukmani Mohanta$^{1,c}$

1 School of Physics, University of Hyderabad, Hyderabad 500046, India
2 Theoretical Physics Division, Physical Research Laboratory, Ahmedabad 380009, India

Received: 16 April 2019 / Accepted: 31 July 2019 / Published online: 9 August 2019 © The Author(s) 2019

Abstract Very compelling deviations in the recently observed lepton nonuniversality observables ($R_{D^{(*)}}, R_{K^{(*)}}, R_{J/\psi}$) of semileptonic $B$ meson decays from their Standard Model predictions hint towards the presence of some kind of new physics beyond it. In this regard, we investigate the effect of new physics in the semileptonic $B^*_d \rightarrow P \ell \bar{\nu}_\ell$ decay processes, where $P = D, \pi(D_\ell, K)$, in a model independent way. We consider the presence of additional vector and scalar type interactions and constrain the corresponding new couplings by fitting $\text{Br}(B^+_u \rightarrow \tau^+ \nu_\tau)$, $\text{Br}(B \rightarrow \pi \tau \bar{\nu}_\tau)$, $\text{Br}(B^+_d \rightarrow \tau^+ \nu_\tau)$, $R^d_{\tau}$, $R_{D^{(*)}}$, and $R_{J/\psi}$ data. Using the constrained new parameters, we estimate the branching ratios, forward-backward asymmetry, lepton-spin asymmetry and lepton non-universality observables of $B^*_d \rightarrow P \tau \bar{\nu}_\tau$ processes. We find that the branching ratios of these decay modes are sizeable and deviate significantly (for vector-type couplings) from their corresponding standard model values, which are expected to be within the reach of Run III of Large Hadron Collider experiment.

1 Introduction

In the last few years, several intriguing hints of new physics (NP) have been observed in the form of lepton flavour universality violating (LFUV) observables in semileptonic $B$ decays. In particular, the observables $R_{D^{(*)}} = \text{Br}(B \rightarrow D^{(*)} \ell \bar{\nu}_\ell)/\text{Br}(B \rightarrow D^{(*)} \ell \bar{\nu}_\ell)$, with $l = e, \mu$ in the charged-current transition $b \rightarrow c \ell \bar{\nu}_\ell$, measured by BaBar [1,2] Belle [3–6] and LHCb [7–9] Collaborations, with the following average values as determined by Heavy Flavour Averaging Group (HFLAV) [10]

$$R_D = 0.340 \pm 0.027 \pm 0.013, \quad R_{D^{*}} = 0.295 \pm 0.011 \pm 0.008,$$

with $R_D - R_{D^*}$ correlation of $-0.38$, indicate $\sim 3.08 \sigma$ discrepancy with their corresponding Standard Model (SM) predictions $R_{D^{SM}} = 0.299 \pm 0.003, \quad R_{D^{*}}^{SM} = 0.258 \pm 0.005$. (2)

The recently measured $R_{J/\psi}$ $= \text{Br}(B_c \rightarrow J/\psi \ell \bar{\nu}_\ell)/\text{Br}(B_c \rightarrow J/\psi \ell \bar{\nu}_\ell) = 0.71 \pm 0.17 \pm 0.184$ parameter by LHCb Collaboration [11] is in the same line and has nearly 2$\sigma$ deviation from its SM value $R_{J/\psi} = 0.289 \pm 0.01$ [12,13]. Similarly, in the semileptonic $B \rightarrow K^{(*)} \ell \bar{\nu}_\ell$ decay processes, mediated by the neutral current transition $b \rightarrow s \ell \nu$, and (2.2–2.4)$\sigma$ deviations have been observed in the measured values of $R_{K} = \text{Br}(B^+_c \rightarrow K^+ \ell^+ \ell^-)/\text{Br}(B^+_c \rightarrow K^+ \ell^+ \ell^-)$ [14] and $R_{K^*} = \text{Br}(B^0 \rightarrow K^{*+} \ell^+ \ell^-)/\text{Br}(B^0 \rightarrow K^{*+} \ell^+ \ell^-)$ [15] with values

$$R_{K}|_{q^2 \in [1.6] \text{ GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036,$$

$$R_{K^*}|_{q^2 \in [0.045,1.1] \text{ GeV}^2} = 0.66^{+0.11}_{-0.07} \pm 0.03,$$

$$R_{K^*}|_{q^2 \in [1.1,6] \text{ GeV}^2} = 0.69^{+0.11}_{-0.07} \pm 0.05,$$

from their corresponding SM predictions [16,17]

$$R_{K^{SM}}|_{q^2 \in [1.6] \text{ GeV}^2} = 1.003 \pm 0.0001,$$

$$R_{K^*|q^2 \in [0.045,1.1] \text{ GeV}^2} = 0.92 \pm 0.02,$$

$$R_{K^*}|_{q^2 \in [1.1,6] \text{ GeV}^2} = 1.00 \pm 0.01.$$ (4)

Recently, the LHCb experiment has announced its updated measurements on $R_{K}$ [18] and the Belle Collaboration has announced new $R_{K^*}$ [19] results. After combining the Run 1 and Run 2 data, though the updated experimental value of $R_{K} = 0.846^{+0.060}_{-0.054} \text{(stat)}^{+0.016}_{-0.014} \text{(syst)}$ [18] is closer to the SM prediction, the discrepancy still persists at the level of $\sim 2.5 \sigma$, due to the reduced errors. The errors in the new measurements on $R_{K^*} = 0.52^{+0.32}_{-0.26} \pm 0.005 (0.96^{+0.45}_{-0.29} \pm 0.11)$ observable in the $q^2 \in [0.045,1.1] \text{ GeV}^2$ ($q^2 \in [1.1,6] \text{ GeV}^2$) bin, reported by the Belle Collaboration [19] are quite a bit larger than the errors in the previous LHCb measurement. Additionally, a small discrepancy has also been
reported in the $b \to u \ell\bar{v}$ mediated process defined as $R_\pi^l = \frac{\tau^{\text{Exp}}}{\tau^{\text{SM}}} (\text{Br}(B^- \to \tau^- \bar{v}_\ell)/\text{Br}(B^0 \to \pi^+ l^- \bar{v}_l))$ [20]. As all these observables are ratios of branching fractions, the theoretical uncertainties due to the CKM matrix elements and hadronic form factors cancel out to a large extent, resulting in tight predictions with high accuracy. Therefore, the lepton flavor universality violating tests are considered to be the most powerful tools to probe new physics beyond the standard model. Tremendous effort has been made in the last few years to understand the nature of NP, which might be responsible for such deviations.

Being motivated by these observed anomalies in various $B$ meson decays, in this work we would like to investigate the impact of new physics on the differential decay rate and various other observables like forward–backward asymmetry, lepton spin asymmetry and lepton nonuniversality (LNU) observable of weakly decaying vector $B^*_d, q$ meson to a pseudoscalar $P(= D(D_s), \pi(K))$ meson mediated through the quark level transition $b \to (c,u)\bar{v}\ell\bar{v}$. Although such hadrons decay primarily through the electromagnetic process $B^*_d \to B_d \gamma$, and their weak decay channels are expected to be quite suppressed, the situation has improved considerably with the advent of the high luminosity Belle II experiment. For instance, as discussed in Ref. [21], using the production cross section of $\Upsilon(5S)$ in $e^-e^+$ collision as $\sigma(e^-e^+ \to \Upsilon(5S)) = 0.301 \text{nb}$ and $\text{Br}(\Upsilon(5S) \to B^* \bar{B}^*) = (38.1 \pm 3.4)\%$ [20], about $4 \times 10^9$ $B^*$ meson pairs ($B^*_d + \bar{B}^*_d$) are expected to be produced per year. This in turn implies that the rare $B^*$ decay modes with branching fraction $> \mathcal{O}(10^{-9})$ are likely to be observed at Belle II. Hence, Belle II experiment would be quite instrumental in search for the rare decay modes of the excited $B$ mesons. In addition the LHC experiment will also play a pivotal role in the search for $B^*$ decay channels, as the production cross section of $\Upsilon(5S)$ is much larger in $p\bar{p}$ collision compared to $e^-e^-$ collision. On the other hand, the study of $B^*$ meson decays has also received considerable attention in recent times. In the literature [22–25], the leptonic decay modes of $B^*_d, q$ mesons are investigated in SM and in the context of various new physics models. The analysis of semileptonic weak decays $B^* \to P \ell\bar{v}$ both in the SM and in the presence of NP are discussed in the Refs. [21,26,27].

The layout of the paper is as follows. In Sect. 2, we illustrate the theoretical framework required to analyse the decay processes $B^* \to P \ell\bar{v}$ in the effective theory formalism. The expressions for the differential decay rate and other observables like forward–backward asymmetry, lepton nonuniversality ($R_\pi^l$) and the lepton-spin asymmetry are presented in this section. The constraints on the new couplings using $\chi^2$ fit from $R_{\pi^+}, R_{J/P}, R_\pi, \text{Br}(B_{u,c} \to \tau\nu), \text{Br}(B \to \pi \ell\bar{v})$ observables are obtained in Sect. 3. Our results are discussed in Sect. 4 followed by the summary of our work in Sect. 5.

### 2 Theoretical framework

The most general effective Lagrangian for $B^* \to P \ell\bar{v}$ processes mediated by $b \to q \ell^-\bar{v}_{\ell} (q = u,c)$, in the effective field theory approach can be expressed as [28],

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2}G_F V_{qb} [ (1 + V_L) \bar{q}_L \gamma^{\mu} b_R \ell_L \gamma_{\mu} v_L$$

$$+ V_R \bar{q}_R \gamma^{\mu} b_R \ell_L \gamma_{\mu} v_L + S_L \bar{q}_R b_L \ell_R v_L$$

$$+ S_R \bar{q}_L b_R \ell_R v_L + T_L \bar{q}_R \gamma^{\mu} b_L \ell_R \gamma_{\mu} v_L + \text{h.c.}],$$

(5)

where $P$ is any pseudoscalar meson, $G_F$ is the Fermi constant, $V_{qb}$ is the CKM matrix element, $V_{L,R}, S_{L,R}, T_L$ are the new vector, scalar, and tensor type new physics couplings, which are zero in the standard model. All these new physics couplings are considered to be complex. Furthermore, we consider the neutrinos as left handed. We assume the NP effect is mainly through the third generation leptons and do not consider the effect of tensor operators in our analysis for simplicity. Here $(q, \ell)_{L,R} = P_{L,R}(q, \ell)$, where $P_{L,R} = (1 \pm \gamma_5)/2$ are the chiral projection operators.

We consider the kinematics of the decay process $B^* \to P \ell\bar{v}$ using helicity amplitudes. In this formalism, the decay process $B^* \to P \ell\bar{v}$ is considered to proceed through $B^* \to PW^{*-}$, where the off-shell $W^{*-}$ decays to $\ell^-\bar{v}_\ell$. One can write the amplitude from Eq. (5) as

$$\mathcal{M}(B^* \to P \ell\bar{v}) = \frac{G_F}{\sqrt{2}} V_{qb} \sum_k C_k(\mu) \langle P|\bar{q}\Gamma^k b|B^*\rangle \bar{u}_\ell \Gamma_k v_\ell,$$

(6)

where $C_k(\mu)$ represents the Wilson coefficient with values

$$C_k(\mu) = \begin{cases} 1 & \text{for SM}, \\ V_{L,R}, S_{L,R} & \text{for NP beyond SM}, \end{cases}$$

$\Gamma^k$ denotes the product of gamma matrices, which gives rise to different Lorentz structure of hadronic and leptonic currents of Eq. (5) i.e., $\Gamma^k = \gamma^{\mu}(1 \pm \gamma_5)$, and $(1 \pm \gamma_5)$. Hence, the square of the matrix element can be expressed as the product of leptonic ($L_{\mu\nu}$) and hadronic ($H^{\mu\nu}$) tensors (related to the corresponding helicity amplitudes)

$$|\mathcal{M}(B^* \to P \ell\bar{v})|^2 = \frac{G_F^2}{2} |V_{qb}|^2 \sum_{i,j} C_{ij}(\mu) (L_{\mu\nu} H^{\mu\nu})_{ij},$$

(7)

where the superscripts $i, j$ represent the combination of four operators ($V \mp A), (S \mp P)$ in the effective Lagrangian (5), $C_{ij}(\mu)$ denotes the product of Wilson coefficients $C_i$ and $C_j$. We omit these superscripts in the following discussion for convenience. It should be noted that, the polarization vector of the off-shell particle $W^*(\ell^-\bar{v}_\ell(m))$, satisfies the following orthonormality and completeness relations:
\[ \tilde{\epsilon}^{\ast \mu}(m') \tilde{\epsilon}_{\mu}(m') = g_{mm'} , \]
\[ \sum_{m'n'} \epsilon^{\ast \mu}(m) \epsilon^{\nu}(m') g_{mm'} g_{nn'} = g^{\mu \nu} , \]  
(8)

where \( g_{mm'} = \text{diag}(+, -, -, -) \) and \( m, m' = \pm, 0, t \) represent the transverse, longitudinal and time-like polarization components. Now inserting the completeness relation from Eq. (8) into (7), the product of \( L_{\mu \nu} \) and \( H^{\mu \nu} \) can be expressed as
\[ L_{\mu \nu} H^{\mu \nu} = \sum_{m, m', n, n'} L(m, n) H(m', n') g_{mm'} g_{nn'} , \]
(9)

where \( L(m, n) = L^{\mu \nu} \tilde{\epsilon}_{\mu}(m) \tilde{\epsilon}_{\nu}(n) \) and \( H(m, n) = H^{\mu \nu} \tilde{\epsilon}_{\mu}(m) \tilde{\epsilon}_{\nu}(n) \) are the Lorentz invariant parameters, and hence their values are independent of any specific reference frame. So for calculational convenience, we will evaluate \( H(m, n) \) in the \( B^* \) rest frame and \( L(m, n) \) in \( \ell - \bar{\nu}_\ell \) center of mass frame as discussed in [21, 26].

2.1 Hadronic helicity amplitudes

In the rest frame of \( B^* \) meson, we consider the pseudoscalar meson \( P \) to be moving along the positive \( z \)-direction. The polarization vector of the virtual \( W^* \) boson are chosen to be
\[ \tilde{\epsilon}^{\mu}(t) = \frac{1}{\sqrt{2}} \left( q_0, 0, 0, -|\vec{p}| \right) \]
\[ \tilde{\epsilon}^{\mu}(t) = \frac{1}{\sqrt{2}} \left( q_0, 0, 0, -|\vec{p}| \right) \]
\[ \tilde{\epsilon}(0) = \frac{1}{\sqrt{2}} \left( 0, \pm 1, -i, 0 \right) , \]
(10)

where \( q_0 = (m_{B^*}^2 - m_p^2 + q^2)/2m_{B^*}^2, |\vec{p}| = \lambda^{1/2}(m_{B^*}^2, m_p^2, q^2)/2m_{B^*}^2, q^2 = (p_B - p_P)^2 \), is the momentum transferred square and \( \lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca) \). The polarization vector of the on-shell \( B^* \) meson \( \epsilon^{\mu}(m = 0, \pm) \), takes the form
\[ \epsilon^{\mu}(0) = (0, 0, 0, 1) , \quad \epsilon^{\mu}(\pm) = \frac{1}{\sqrt{2}} \left( 0, \mp 1, -i, 0 \right) . \]
(11)

In order to calculate the hadronic helicity amplitudes, we use the following matrix elements of \( B^* \to P \) transition
\[ (p_P \tilde{q} \gamma_{\nu} b) \tilde{B}^*(\varepsilon, p_B^+) \]
\[ = \frac{2V(q^2)}{m_{B^*} + m_p} \epsilon^{\mu}_{\nu \rho \sigma} \epsilon^{\ast \mu} p_{\rho} p_{\sigma} , \]
\[ (p_P \tilde{q} \gamma_{\nu} \gamma_5 b) \tilde{B}^*(\varepsilon, p_B^+) = 2m_{B^*} A_0(q^2) \frac{\varepsilon \cdot q}{q^2} q_{\mu} \]
\[ + \left( m_p + m_{B^*} \right) A_1(q^2) \left( \epsilon_{\mu} - \frac{\varepsilon \cdot q}{q^2} q_{\mu} \right) \]
\[ + \left( m_p + m_{B^*} \right) A_2(q^2) \frac{\varepsilon \cdot q}{m_p + m_{B^*}} \left( p_{B^*} + p_{\mu} \right) - \frac{m_{B^*}^2 - m_p^2}{q^2} q_{\mu} , \]
(12)

where \( V(q^2) \), \( A_{0,1,2}(q^2) \) are the various form factors. The matrix elements for the scalar and pseudoscalar currents can be obtained by using the equation of motion
\[ i \partial_{\mu}(\bar{q} \gamma^\mu b) = (m_b - m_q) \bar{q} B, \]
\[ i \partial_{\mu}(\bar{q} \gamma^\mu \gamma_5 b) = -(m_b + m_q) \bar{q} B, \]
(13)

as
\[ (\bar{q} \gamma_{\mu} b \tilde{B}^*(\varepsilon, p_B^+)) = 0 , \]
\[ (\bar{q} \gamma_{\mu} \gamma_5 b \tilde{B}^*(\varepsilon, p_B^+)) = -(\varepsilon \cdot q) \frac{2m_{B^*}}{m_b + m_q} A_0(q^2) , \]
(14)

where the \( m_{b,q} \) represent the current quark masses evaluated at the \( b \)-quark mass scale. The helicity amplitudes are defined as
\[ H_{V_1}^{\ell\ell,\lambda_{W^*}}(q^2) = \tilde{\epsilon}^{\ast \mu}(\lambda_{W^*})(P(p_P \tilde{q} \gamma_{\mu} (1 - \gamma_5) b) \tilde{B}^*(\varepsilon, p_B^+) , \]
\[ H_{V_2}^{\ell\ell,\lambda_{W^*}}(q^2) = \tilde{\epsilon}^{\ast \mu}(\lambda_{W^*})(P(p_P \tilde{q} \gamma_{\mu} (1 + \gamma_5) b) \tilde{B}^*(\varepsilon, p_B^+) , \]
\[ H_{S_1}^{\ell\ell,\lambda_{W^*}}(q^2) = (P(p_P \tilde{q})(1 - \gamma_5) b) \tilde{B}^*(\varepsilon, p_B^+) , \]
\[ H_{S_2}^{\ell\ell,\lambda_{W^*}}(q^2) = (P(p_P \tilde{q})(1 + \gamma_5) b) \tilde{B}^*(\varepsilon, p_B^+) , \]
(15)

where for convenience, we use the notations \( \lambda_{W^*} = 0, \pm \) and \( \lambda_{W^*} = 0, \pm, t \) to represent the helicity states of the \( B^* \) and \( W^* \) boson. Thus, with Eqs. (12), (14) and (15), one obtains the following non-vanishing helicity amplitudes
\[ H_{N_0}^{\ell\ell}(q^2) = H_{00}^{\ell\ell}(q^2) = \frac{2m_{B^*} |\vec{p}|}{\sqrt{q^2}} A_0(q^2) , \]
\[ H_{00}^{\ell\ell}(q^2) = H_{00}^{\ell\ell}(q^2) = \frac{2m_{B^*} |\vec{p}|}{\sqrt{q^2}} A_0(q^2) , \]
(16)

2.2 Leptonic helicity amplitudes

The leptonic helicity amplitudes are defined as
\[ h_{\lambda,\lambda_{\ell}}^{\ell} = \frac{1}{2} \tilde{\epsilon}_{\mu}(\lambda_{W^*}) \bar{u}_{\ell}(\lambda_{\ell}) \Gamma^\mu \bar{v}_{\ell}(\lambda_{\ell}) , \]
(17)

where \( \lambda_{W^*} = \lambda_{\ell} - \lambda_{\bar{\nu}_\ell}, i = V_{L,R}, S_{L,R} \), and \( \Gamma^{V_{L,R}} = \gamma \mu (1 \mp \gamma_5), \Gamma^{S_{L,R}} = (1 \mp \gamma_5) \). In the center of mass frame of \( \ell - \bar{\nu}_\ell \), the four momenta of \( \ell \) and \( \bar{\nu}_\ell \) pair are expressed as
\[ p_{\ell \ell}^{\mu} = (E_{\ell}, |\vec{p}_{\ell}| \sin \theta, 0, |\vec{p}_{\ell}| \cos \theta) , \]
\[ p_{\bar{\nu}_\ell}^{\mu} = (|\vec{p}_{\ell}|, -|\vec{p}_{\ell}| \sin \theta, 0, -|\vec{p}_{\ell}| \cos \theta) . \]
(18)
where \( E_\ell = (q^2 + m_\ell^2)/2\sqrt{q^2} \), \( |\vec{p}_\ell| = (q^2 - m_\ell^2)/2\sqrt{q^2} \) and \( \theta \) is the angle between the three momenta of \( P \) and \( \ell \). The polarization vector of the virtual \( W^* \) boson in this frame is
\[
\vec{e}^\mu (t) = (1, 0, 0, 0), \quad \vec{e}^\mu (0) = (0, 0, 0, 1), \quad \vec{e}^\mu (\pm) = \frac{1}{\sqrt{2}} (0, \mp 1, i, 0).
\]
Thus, with Eqs. (17) and (19), one obtains the following non-vanishing contributions
\[
\begin{align*}
|h_{V_L/R}^{V_L/R}|^2 &= 8(q^2 - m_\ell^2), \\
|h_{V_L/R}^{V_L/R}|^2 &= 8m_\ell^2/2q^2(q^2 - m_\ell^2), \\
|\tilde{h}_{V_L/R}^{V_L/R}|^2 &= 4(q^2 - m_\ell^2), \\
|\tilde{h}_{V_L/R}^{V_L/R}| &= (8m_\ell^2/2q^2)(q^2 - m_\ell^2)^2.
\end{align*}
\]
(20)

2.3 Decay distribution and other observables

The double differential decay rate of \( B^* \to P \ell \tilde{\nu}_\ell \) decay process can be expressed as
\[
\frac{d^2\Gamma}{dq^2 d\cos \theta} = G_F^2 \frac{|\vec{p}|}{192\pi^3 m_B^2} |V_{qb}|^2 \frac{q^2}{2} \left( 1 - \frac{m_\ell^2}{q^2} \right) \times \frac{1}{M^2} |\vec{M}(\vec{B} \to P \ell \tilde{\nu}_\ell)|^2.
\]
(21)

Now, with Eqs. (16) and (20), one can obtain \( L_{\mu \nu} H^{\mu \nu} \) in terms of Wigner \( d \)-functions as
\[
L_{\mu \nu} H^{\mu \nu} = \frac{1}{8} \sum_{\lambda, \lambda', \lambda''} \epsilon_{\lambda \lambda' \lambda''} \epsilon_{\lambda' \lambda'' \lambda} 
\times d^j_{\lambda'' \lambda' \lambda} d^j_{\lambda' \lambda \lambda''} H^{j}_{\mu \lambda' \lambda''} H^{j}_{\nu \lambda' \lambda''},
\]
(22)

where \( J \) and \( J' \) take the values 0 and 1 and the various helicity components run over their allowed values. Thus, one can obtain the differential decay rate to particular leptonic helicity state \( (\lambda = \pm \frac{1}{2}) \) as
\[
\begin{align*}
\frac{d^2\Gamma}{dq^2 d\cos \theta} (\lambda = \pm \frac{1}{2}) &= G_F^2 \frac{|\vec{p}|}{768\pi^3 m_B^2} |V_{qb}|^2 q^2 \frac{q}{2} \left( 1 - \frac{m_\ell^2}{q^2} \right)^2 \\
&\times \left\{ |1 + V_L|^2[(1 - \cos \theta)^2 H_{++}^2 + (1 + \cos \theta)^2 H_{+-}^2] + 2\sin^2 \theta H_{00}^2 + |V_R|^2[(1 - \cos \theta)^2 H_{++}^2 \\
&+ (1 + \cos \theta)^2 H_{+-}^2 + 2\sin^2 \theta H_{00}^2] - 4\mathcal{R} \mathcal{E}[(1 + V_L) V_R^*] \right\} + 2(H_0 - \cos \theta H_{00})^2 \right\}. \\
&+ 4\mathcal{R} \mathcal{E}[1 + V_L - V_R)(H_0 - \cos \theta H_{00})^2] \\
&\times \left| H_0^2 (H_0 - \cos \theta H_{00}) \right| + 2|S_L - S_R|^2 H_{00}^2 \right\}.
\end{align*}
\]
(25)

From Eqs. (24) and (25), one can obtain the differential decay rate as
\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2}{288\pi^3 m_B^2} |V_{qb}|^2 q^2 \left( 1 - \frac{m_\ell^2}{q^2} \right)^2 \left[ |1 + V_L|^2 + |V_R|^2 \right] \\
\times \left[ (H_{++}^2 + H_{+-}^2 + H_{00}^2) \left( 1 + \frac{m_\ell^2}{2q^2} + \frac{3m_\ell^2}{2q^2} H_{00}^2 \right) \right] \\
- 2\mathcal{R} \mathcal{E}[1 + V_L V_R^*] \left[ 2H_0^2 + H_{00}^2 \right] \\
+ \mathcal{R} \mathcal{E}[1 + V_L - V_R)(H_0^2 - S_R^2)H_{00}^2 \right\}.
\]
(26)

where the values of the helicity amplitudes are given in Eq. (16).

Apart from the differential decay rate, the other NP sensitive observables, considered here are

- Lepton nonuniversality observable:
\[
R_{\ell\bar{\nu}}^P(q^2) = \frac{d\Gamma(B^* \to P \tau \tilde{\nu}_\tau)/dq^2}{d\Gamma(B^* \to P \ell \tilde{\nu}_\ell)/dq^2},
\]
(27)

where \( l \) denotes the light leptons \( l = e, \mu \).

- Forward–backward asymmetry:
\[
A_{FB}^{\ell\bar{\nu}}(q^2) = \frac{\int_{-1}^{1} d\cos \theta (d\Gamma(B^* \to P \ell \tilde{\nu}_\ell)/dq^2 d\cos \theta)}{\int_{-1}^{1} d\cos \theta (d\Gamma(B^* \to P \ell \tilde{\nu}_\ell)/dq^2 d\cos \theta)}.
\]
(28)

which can be expressed in terms of the helicity amplitudes as
\[
A_{FB}^{\ell\bar{\nu}}(q^2) = \frac{3X}{4Y},
\]
(29)

where the parameters \( X \) and \( Y \) are given as
\[
X = |1 + V_L|^2 - |V_R|^2(H_{++}^2 + H_{+-}^2) \\
+ 2H_0^2 |V_R|^2 + |V_R|^2 H_{00}^2
\]
+4\Re\{[(1 + V_L)\bar{V}_{R}^{\ast}] \left( H_{+\ldots} - \frac{m_{\ell}^2}{q^2} H_{00} \right) \}
+2\Re\{[(1 + V_L - V_R)(S_L^\ast - S_R^\ast)] \frac{m_{\ell}}{\sqrt{q^2}} H_{00} \}.

Y = \left[ (1 + V_L)^2 + |V_R|^2 \right] \left[ (H_{+}^2 + H_{++}^2) \right]
\times \left( \frac{1 + m_{\ell}^2}{2q^2} + \frac{3m_{\ell}^2}{2q^2} H_{00} \right)
-2\Re\{[(1 + V_L)\bar{V}_{R}^{\ast}] (2H_{-}H_{++} + H_{00}^2) \}
\times \left( \frac{1 + m_{\ell}^2}{2q^2} + \frac{3m_{\ell}^2}{2q^2} H_{00}^2 \right)
+3\frac{m_{\ell}}{\sqrt{q^2}} \Re\{[(1 + V_L - V_R)(S_L^\ast - S_R^\ast)] H_{00} H_{00} \}
+\frac{3}{2} |S_L - S_R|^2 H_{00}.

\text{(30)}

• Lepton-spin asymmetry:

\begin{equation}
A_L^{\ast}(q^2) = \frac{d\Gamma(\lambda_{\ell} = -1/2)/dq^2 - d\Gamma(\lambda_{\ell} = 1/2)/dq^2}{d\Gamma(\lambda_{\ell} = -1/2)/dq^2 + d\Gamma(\lambda_{\ell} = 1/2)/dq^2}.
\end{equation}

\text{(31)}

2.4 Form factors and their \( q^2 \) dependence

The main inputs required for the numerical analysis are the values of the form factors. As the first principle lattice calculation results of the form factors for \( B_{d,s}^+ \rightarrow D, D_{s}(\pi, K) \) transitions are not yet available, we use their values evaluated in the BSW model [29,30]. Their values at zero-momentum transfer are listed below:

\begin{align*}
A_0^{B^+\rightarrow D}(0) &= 0.71, \\
A_1^{B^+\rightarrow D}(0) &= 0.75, \\
A_2^{B^+\rightarrow D}(0) &= 0.62, \\
A_0^{\bar{B}^+\rightarrow D}(0) &= 0.66, \\
A_1^{\bar{B}^+\rightarrow D}(0) &= 0.69, \\
A_2^{\bar{B}^+\rightarrow D}(0) &= 0.59, \\
A_0^{\bar{B}^+\rightarrow \pi}(0) &= 0.34, \\
A_1^{\bar{B}^+\rightarrow \pi}(0) &= 0.38, \\
A_2^{\bar{B}^+\rightarrow \pi}(0) &= 0.30, \\
A_0^{\bar{B}^+\rightarrow K}(0) &= 0.28, \\
A_1^{\bar{B}^+\rightarrow K}(0) &= 0.29, \\
A_2^{\bar{B}^+\rightarrow K}(0) &= 0.26.
\end{align*}

\text{(32)}

The \( q^2 \) dependence of the form factors can be written as,

\begin{align*}
A_0(q^2) &\approx \frac{A_0(0)}{1 - q^2/m_{B_q}^2(H_{00}^0)}, \\
A_1(q^2) &\approx \frac{A_1(0)}{1 - q^2/m_{B_q}^2(1^+)} , \\
A_2(q^2) &\approx \frac{A_2(0)}{1 - q^2/m_{B_q}^2(1^+)} ,
\end{align*}

\begin{align*}
V(q^2) &\approx \frac{V(0)}{1 - q^2/m_{B_q}^2(1^+)}.
\end{align*}

\text{(33)}

where \( m_{B_q}(0^\pm) \) and \( m_{B_q}(1^\pm) \) are the pole masses whose values are presented in Table 1. In our analysis, we consider 10% uncertainty in the values of hadronic form factors at \( q^2 = 0 \).

3 Constraints on new couplings

In this analysis the new couplings are considered to be complex. Considering the contribution of only one coefficient at a time with all others set to zero, we perform the chi-square fitting for the individual complex couplings. The \( \chi^2 \) is defined as

\begin{equation}
\chi^2 = \sum_i \frac{(O_i^{\text{th}} - O_i^{\text{exp}})^2}{(\Delta O_i^2)^2},
\end{equation}

\text{(34)}

We use the theoretical expressions of these observables and their SM predictions from [32] and have listed them in Table 2.

Table 1 Values of pole masses in GeV

| Current | \( m(0^-) \) | \( m(0^+) \) | \( m(1^-) \) | \( m(1^+) \) |
|---------|--------------|--------------|--------------|--------------|
| \( \bar{c}b \) | 5.27 | 5.99 | 5.32 | 5.71 |
| \( \bar{c}b \) | 6.30 | 6.80 | 6.34 | 6.73 |

\text{Table 2 Values of the observables used in the fitting}

| Observables | Experimental value | SM prediction |
|-------------|--------------------|---------------|
| \( R_D \) | 0.340 \pm 0.027 \pm 0.013 | 0.299 \pm 0.003 |
| \( R_{D^*} \) | 0.295 \pm 0.011 \pm 0.008 | 0.258 \pm 0.005 |
| \( R_{J/\psi} \) | 0.71 \pm 0.251 | 0.289 \pm 0.01 |
| \( \text{Br}(B_c \rightarrow \tau \nu) \) | < 30% | (3.6 \pm 0.14) \times 10^{-2} |
| \( R_{\pi}^{L} \) | 0.699 \pm 0.156 | 0.583 \pm 0.055 |
| \( \text{Br}(B_d \rightarrow \tau \nu) \) | (1.09 \pm 0.24) \times 10^{-4} | (8.48 \pm 0.5) \times 10^{-5} |
| \( \text{Br}(B_{s} \rightarrow \pi^+ \tau \nu) \) | < 2.5 \times 10^{-4} | (9.40 \pm 0.75) \times 10^{-5} |
Fig. 1 Constraints on individual new complex coefficients associated with $b \to c\tau\bar{\nu}_\tau$ processes from the $\chi^2$ fit of $R_{D^{(*)}}$, $R_{J/\psi}$ and upper limit on $\text{Br}(B_s^+ \to \tau^+\nu_\tau)$. Here the red, blue and green colors stand for $1\sigma$, $2\sigma$ and $3\sigma$ contours respectively. The black dots represent the best-fit values.

In Fig. 1, we present the constraints on $V_L$ (top-left panel), $V_R$ (top-right panel), $S_L$ (bottom-left panel) and $S_R$ (bottom-right panel) coefficients of $b \to c$ mediated decay modes and the corresponding plots for the coefficients of $b \to u$ are shown in Fig. 2. It should be noted that, the best-fit values are degenerate in the presence of $V_L$, $S_L$ and $S_R$ couplings) for $b \to c$ ($b \to u$) processes and for each of these couplings, we have considered only benchmark values. The best-fit values and the corresponding $1\sigma$ ranges, which are obtained from the joint confidence regions of the real and imaginary planes of these new couplings, are presented in Table 3. The $\chi^2$/d.o.f, as well as the pull $\simeq \sqrt{\chi^2_{\text{SM}} - \chi^2_{\text{best-fit}}}$, for all the coefficients are also listed in this Table. One can notice that, the Wilson coefficient corresponding to $b \to c$ scalar operators have $\chi^2$/d.o.f $> 1$, which implies that the fit is not robust. However, the pull values of $V_{L,R}$ coefficients of $b \to c$ implicit that the measured data are consistent with our model in the presence of either $V_L$ or $V_R$ and can be a viable candidate for explaining the $b \to c\tau\bar{\nu}_\tau$ anomalies.

4 Effect of new coefficients on $B_{d,s}^* \to (D, D_s, \pi, K)\tau\bar{\nu}_\tau$ decay modes

After collecting all the theoretical expressions of required observables and getting knowledge on the allowed ranges of new parameters, we now proceed towards numerical analysis. The particles masses and the values of the CKM elements and the Fermi constant $G_F$ are taken from PDG [20].

The values of the current quark masses used in this analysis are $m_b = 4.2$ GeV, $m_c = 1.3$ GeV, and $m_u = 2.2$ MeV. The $q^2$ dependence of the form factors, required for numerical estimation are already discussed in section II. As the lifetimes of $B^*$ mesons are not yet measured, we impose the fact that for these mesons the electromagnetic transitions $B^* \to B\gamma$ are the dominant ones, and hence $\Gamma_{\text{tot}}(B^*) \simeq \Gamma(B^* \to B\gamma)$ and use the following results

$$\Gamma(B_d^+ \to B_d\gamma) = 0.148 \pm 0.002 \text{ KeV} \quad [31]$$
$$\Gamma(B_s^+ \to B_s\gamma) = 0.468^{+0.073}_{-0.075} \text{ KeV} \quad [31]$$
$$\Gamma(B_s^+ \to B_s\gamma) \simeq 0.07 \text{ KeV} \quad [32].$$

(36)
From Eq. (36), it should be noted that \( \Gamma_{\text{tot}}(B^{\pm} \rightarrow P_\ell \nu_\ell) \), so the branching fractions of \( B^{\pm} \rightarrow P_\ell \nu_\ell \) processes are roughly one-third of \( B^+ \rightarrow P_\ell \nu_\ell \). Hence, those results are not presented in this work. Furthermore, we assume that the new physics will couple only to third generation leptons, so the \( B^+_{d,s} \rightarrow P_\mu \nu_\mu \) processes will not be affected by the presence of new physics operators, and their standard model branching fractions are listed in Table 4, which are expected to be within the reach of LHC experiment.

Table 3 Best-fit values and corresponding 1σ ranges (for one benchmark set only) of the new complex coefficients

| Decay modes | New coefficients | Best-fit | 1σ range | \( \chi^2 / \text{d.o.f} \) | Pull |
|-------------|------------------|----------|----------|-----------------|------|
| \( b \rightarrow c \bar{\tau} \bar{\nu}_\tau \) | (Re\( [V_L] \), Im\( [V_L] \)) (Re\( [V_R] \), Im\( [V_R] \)) (Re\( [S_L] \), Im\( [S_L] \)) (Re\( [S_R] \), Im\( [S_R] \)) | \((-1.233, 1.045)\) \((-0.0034, -0.3783)\) \((0.097, 0)\) \((-0.695, -0.777)\) | \((-1.32, -1.075), [1.021, 1.067])\) \((-0.030, 0.025), [-0.438, -0.31])\) \((0.041, 0.15), [-0.257, 0.257])\) \((-0.93, -0.55), [-0.835, -0.72])\) | 1.151 | 2.982 |
| \( b \rightarrow u \bar{\tau} \bar{\nu}_\tau \) | (Re\( [V_L] \), Im\( [V_L] \)) (Re\( [V_R] \), Im\( [V_R] \)) (Re\( [S_L] \), Im\( [S_L] \)) (Re\( [S_R] \), Im\( [S_R] \)) | \((-0.915, 1.108)\) \((-0.116, 0)\) \((0.024, 0)\) \((-0.439, 0.005)\) | \((-1.45, -0.65), [1.02, 1.19])\) \((-0.205, -0.025), [-0.41, 0.41])\) \((-0.042, -0.004), [-0.092, 0.092])\) \((-0.457, -0.421), [-0.092, 0.092])\) | 0.131 | 1.160 |

From Eq. (36), it should be noted that \( \Gamma_{\text{tot}}(B^{\pm} \rightarrow P_\ell \nu_\ell) \), so the branching fractions of \( B^{\pm} \rightarrow P_\ell \nu_\ell \) processes are roughly one-third of \( B^+ \rightarrow P_\ell \nu_\ell \). Hence, those results are not presented in this work. Furthermore, we assume that the new physics will couple only to third generation leptons, so the \( B^+_{d,s} \rightarrow P_\mu \nu_\mu \) processes will not be affected by the presence of new physics operators, and their standard model branching fractions are listed in Table 4, which are expected to be within the reach of LHC experiment.

The \( B^+_{d,s} \rightarrow (D, D_s) \tau^- \bar{\nu}_\tau \) processes proceed through \( b \rightarrow c \) quark level transitions, so we use the constrained values of the new couplings obtained for \( b \rightarrow c \tau \bar{\nu}_\tau \) in order to calculate the associated observables of these processes. Similarly we use the allowed parameter space obtained for \( b \rightarrow u \tau \bar{\nu}_\tau \) process to compute the observables associated with \( B^+_{d,s} \rightarrow (\pi, K) \tau^- \bar{\nu}_\tau \) decay process as they are mediated by \( b \rightarrow u \) quark level transitions. In the following subsections, we discuss the effect of the presence of
Table 4 Branching fractions of \( B_{d,s}^+ \to P \mu \bar{\nu}_\mu \) processes in the Standard Model

| Decay processes                                    | SM branching fraction |
|----------------------------------------------------|-----------------------|
| \( Br(B_s^0 \to D^+ \mu^- \bar{\nu}_\mu) \)       | \((9.318 \pm 1.901) \times 10^{-8}\) |
| \( Br(B_s^+ \to D_s^+ \mu^- \bar{\nu}_\mu) \)    | \((1.709 \pm 0.349) \times 10^{-7}\) |
| \( Br(B_s^0 \to \pi^+ \mu^- \bar{\nu}_\mu) \)    | \((1.487 \pm 0.401) \times 10^{-9}\) |
| \( Br(B_s^+ \to K^+ \mu^- \bar{\nu}_\mu) \)      | \((1.618 \pm 0.437) \times 10^{-9}\) |

one Wilson coefficient at a time on various observables of \( B_{d,s}^+ \to (D, D_s, \pi, K) \tau \nu_\tau \) decay modes.

4.1 Effect of \( V_L \) only

Here we consider the case, where the additional contribution to the SM Lagrangian arising only from \( V_L \) coefficient and all other new coefficients are set to zero i.e., \((S_L = S_R = V_R = 0)\). Using the best-fit values and \( 1\sigma \) allowed parameter space of \( V_L \), obtained from the \( \chi^2 \) fit of \( R_{D^{(*)}V}, R_{J/\psi}, \)

| \( Br(B_s^0 \to \tau^- \nu_\tau) \) for \( b \to c \tau \nu \) transitions \( (R_\tau) \), \( Br(B^0 \to \pi^+ \tau^- \bar{\nu}_\tau) \), \( Br(B_s^+ \to \tau^+ \nu_\tau) \) for \( b \to u \tau \nu \) transitions. \( \) then calculate the differential decay rate, LNU observable, lepton spin asymmetry and forward–backward asymmetry of \( B^{(*)} \to D^{(*)} \tau \nu \) and \( B_s^+ \to D_s^+ \tau \nu \) (\( B^{(*)} \to \pi^+ \tau \nu \) and \( B_s^+ \to K^+ \tau \nu \)) decay processes. In the left panel of Fig. 3, we show the \( q^2 \) variation of decay rate (top) and \( R_D \) observable (bottom) of \( B^{(*)} \to D^{(*)} \tau \nu \) process and the corresponding plots for \( B^{(*)} \to \pi^+ \tau \nu \) channel are presented in the right panel of this figure. Here the blue dashed lines correspond to the SM prediction and the cyan bands represent the 1\sigma uncertainty, arising due to the errors in CKM matrix elements, hadronic form factors and the lifetime of \( B^+ \) meson. The solid black lines are obtained by using the best-fit values of the left handed vectorial new \( V_L \) coupling and the orange bands represent the 1\sigma allowed ranges, which includes the SM uncertainties as well as the uncertainties due to the new couplings. From the plots, one can notice significant deviation in the branching ratios and LNU observables from their SM predictions due to presence of additional \( V_L \) coefficient. To quantify these deviations, we define the pull metric at the observable level as

\[
\text{Pull}_i = \frac{C_{NP}^{i} - C_{SM}^{i}}{\sqrt{\Delta C_{NP}^{i2} + \Delta C_{SM}^{i2}}},
\]

where the index \( i \) runs over all observables, \( C_{SM}^{i} \) and \( C_{NP}^{i} \) denote the values of the observables in SM and NP scenarios and \( \Delta C_{SM}^{i}, \Delta C_{NP}^{i} \) are the corresponding 1\sigma uncertainties. We thus, obtain \( \text{Pull}_{Br}(R_D^+) = 0.530 \) (4.0) for \( B^+ \to D^+ \tau \nu \) process and \( \text{Pull}_{Br}(R_c^+) = 0.399 \) (1.239) for \( B^+ \to \pi^+ \tau \nu \) process. The Pull value for \( R_D^+ \) and \( R_c^+ \) are found to be large as the SM uncertainties cancel out in these observables, thus providing significantly large pull value. The plots for \( B^+ \to D^+ \tau \nu \) (\( B_s^+ \to K^+ \tau \nu \)) process follow the same form as \( B^{(*)} \to D^{(*)} \tau \nu \) (\( B^{(*)} \to \pi^+ \tau \nu \), and hence, are not included in this article. The numerical values of these observables are presented in Table 5. Furthermore, no deviation has been observed in the forward–backward asymmetry and lepton-spin asymmetry observables from their SM results, so we don’t provide the corresponding plots. The values of \( q^2 \) at which the forward–backward asymmetry vanishes are provided in Table 7.

4.2 Effect of \( V_R \) only

In this scenario, we explore the effect of only \( V_R \) coefficient on the decay rate and angular observables of \( B^+ \to (D^+, \pi^+) \tau \nu_\tau \) processes. Using the best-fit values and corresponding 1\sigma allowed ranges of \( V_R \) coefficients associated with \( b \to (c, u) \tau \nu_\tau \) transitions, we present the plots for the decay rate (left-top panel), \( R_D^+ \) (left-middle) and forward–backward asymmetry (left-bottom panel) of \( B^+ \to D^+ \tau \nu \) decay modes in Fig. 4. The corresponding plots for \( B^+ \to \pi^+ \tau \nu \) process are depicted in the right panel of Fig. 4. Here the solid black lines are obtained by using the best-fit values of new \( V_R \) couplings and the gray bands by including 1\sigma uncertainties of all input values. Reasonable deviation in all the observables (except the lepton-spin asymmetry) from their SM results are found due to the presence of additional \( V_R \) coefficient, with Pull values \( \text{Pull}_{Br}(R_D^+/\Delta q) = 0.429/3.21/3.391 \) for \( B^+ \to D^+ \tau \nu \) process and \( \text{Pull}_{Br}(R_c^+/\Delta q) = 0.368/1.203/1.323 \) for \( B^+ \to \pi^+ \tau \nu \). In Table 5, we present the numerical values of decay rates and all these parameters. Due to the additional contribution from \( V_R \) coefficient, we notice deviation in the zero crossing of the forward–backward asymmetry towards high \( q^2 \) and the \( q^2 \) values of the zero crossing point are given in Table 7.

4.3 Effect of \( S_L \) only

In this subsection, we consider the contribution of \( S_L \) new coefficient by assuming that all other new Wilson coefficients have vanishing values. As seen from Figs. 1 and 2, the \( S_L \) parameters are severely constrained by the current data. Within the allowed parameter space for \( S_L \) coefficient presented in Table 3, we show the \( q^2 \) variation of lepton-spin asymmetry (top) and forward–backward asymmetry (bottom) of \( B^+ \to D^+ \tau \bar{\nu}_\tau \) (\( B_s^+ \to \pi^+ \tau \nu \)) process on the left panel (right panel) of Fig. 5. Here the plots obtained from the best-fit values (1\sigma range) of \( S_L \) coupling are represented by dashed black lines (red bands). The numerical values of these observables are given in Table 6. With the additional \( S_L \) contribution, the deviation in the branching ratios and LNU observables from their SM predictions are found to be

\[ \text{Springer} \]
minimal. Though the lepton spin asymmetry and forward–backward asymmetry observables of $B^+ \to D^+ \tau^-\bar{\nu}_\tau$ provide slight deviation from their SM results, the deviation is negligible in the $B^* \to \pi^+\tau\bar{\nu}$ modes. The zero crossing point of the forward–backward asymmetry of $B^* \to D^+\tau\bar{\nu}$ process shifted sightly towards the low $q^2$ region. The $A^\tau_{FB}$ vanishing values of $q^2$ predicted from the best-fit values and $1\sigma$ range of new $S_L$ coefficient are presented in Table 7.

![Image](https://example.com/image.png)

Fig. 3  The $q^2$ variation of differential decay rates and LNU observables of $B^*_d \to D^+\tau^-\bar{\nu}_\tau$ (left panel) and $B^*_d \to \pi^+\tau\bar{\nu}_\tau$ (right panel) in presence of only $V_L$ new coefficient. Here the blue dashed lines represent the standard model predictions. The black solid lines and the orange bands are obtained by using the best-fit values and corresponding 1σ range of $V_L$ coefficient.

Table 5: Predicted numerical values of differential decay rate, LNU observables, lepton spin asymmetry and forward–backward asymmetry of $B^*_d \to D^+\tau^-\bar{\nu}_\tau$ and $B^*_d \to \pi^+(K^+)\tau\bar{\nu}_\tau$ decay processes in the SM and in the presence of $V_{L,R}$ coefficients.

| Observables | SM Predictions | Values with $V_L$ | Values with $V_R$ |
|-------------|----------------|-------------------|-------------------|
| $\text{Br}(B^{\ast \to D^+\tau^-\bar{\nu}_\tau})$ | $(2.786 \pm 0.568) \times 10^{-8}$ | $[2.646, 3.679] \times 10^{-8}$ | $[2.444, 4.019] \times 10^{-8}$ |
| $R^D_D$ | 0.299 | [0.328, 0.357] | [0.330, 0.358] |
| $A^D_D$ | 0.576 | 0.576 | 0.576 |
| $A^D_{FB}$ | $-0.054$ | $-0.054$ | [-0.027, -0.004] |
| $\text{Br}(B^{\ast \to D^+\tau^-\bar{\nu}_\tau})$ | $(5.074 \pm 1.035) \times 10^{-8}$ | $[4.818, 6.701] \times 10^{-8}$ | $[4.453, 7.320] \times 10^{-8}$ |
| $R^D_{D_c}$ | 0.297 | [0.326, 0.354] | [0.327, 0.356] |
| $A^D_{D_c}$ | 0.573 | 0.573 | 0.573 |
| $A^D_{FB}$ | $-0.053$ | $-0.053$ | [-0.025, -0.003] |
| $\text{Br}(B^{\ast \to K^+\tau^-\bar{\nu}_\tau})$ | $(1.008 \pm 0.272) \times 10^{-9}$ | $[0.771, 1.821] \times 10^{-9}$ | $[0.767, 1.781] \times 10^{-9}$ |
| $R^D_K$ | 0.678 | [0.710, 0.965] | [0.707, 0.943] |
| $A^D_K$ | 0.781 | 0.781 | 0.780, 0.781 |
| $A^D_{FB}$ | $-0.209$ | $-0.209$ | [-0.198, -0.127] |
| $\text{Br}(B^{\ast \to K^+\tau^-\bar{\nu}_\tau})$ | $(1.034 \pm 0.279) \times 10^{-9}$ | $[0.791, 1.869] \times 10^{-9}$ | $[0.787, 1.818] \times 10^{-9}$ |
| $R^K_K$ | 0.639 | [0.670, 0.910] | [0.666, 0.885] |
| $A^K_K$ | 0.747 | 0.747 | [0.745, 0.746] |
| $A^K_{FB}$ | $-0.207$ | $-0.207$ | [-0.196, -0.123] |
The $q^2$ variation of differential decay rate, lepton nonuniversality parameter and forward–backward asymmetry of $\bar{B}^*_d \to D^+\tau\bar{\nu}$ (left panel) and $\bar{B}^*_d \to \pi^+\tau\bar{\nu}$ (right panel) in presence of new $V_R$ coefficient. The black solid lines and the gray bands are obtained by using the best-fit values and corresponding $1\sigma$ range of $V_R$ coefficient.

4.4 Effect of $S_R$ only

Here we investigate the observables of $B^* \to (D^+, \pi^+)\tau\bar{\nu}$ decay modes by considering the presence of only additional $S_R$ coefficient. Using the available experimental data on $b \to (u, c)\tau\bar{\nu}$ transitions, we fit the corresponding $S_R$ coefficients, which is already discussed in section II. In the left panel of Fig. 6, we present the $q^2$ variation of decay rate (top), $R^*_D$ (second from top), lepton spin asymmetry (third from top) and forward–backward asymmetry (bottom) of $B^* \to D^+\tau\bar{\nu}$ and the corresponding plots for $B^* \to \pi^+\tau\bar{\nu}$ are shown in the right panel. Here the black dashed lines (magenta bands) are obtained from the best-fit values ($1\sigma$ range) of $S_R$ coupling and other input parameters. In this case also, the deviation in the lepton spin asymmetry and forward–backward asymmetry observables are comparatively large, whereas the deviations in the branching ratios and LNU observables are nominal. The numerical values are presented in Table 6. From Fig. 6, one can notice that the zero crossing point of the forward–backward asymmetry deviates significantly towards left (low $q^2$ region) and the corresponding $q^2$ values of the crossings are shown in Table 7.

5 Summary and conclusion

The rare decay modes of $B$ mesons have been extensively studied both theoretically and experimentally in order to crit-
the corresponding vector mesons i.e., the physics beyond it. In this regard, the rare decay channels of
are essential as they can provide complementary ways to go beyond the standard model. However, the weak decay
nels of $B^*$ vector mesons are not much explored experimen
tally as they decay dominantly through electromagnetic process $B^* \to B \gamma$. Recently, with the advent of high luminosity
LHCb experiment the sensitivity for the branching fractions of various rare decay modes is expected to reach the level
$\sim \mathcal{O}(10^{-9})$. Thus, the LHCb would be an ideal platform to explore the rare decay modes of $B^*$ mesons.

![Fig. 5](image-url) The $q^2$ variation of lepton spin asymmetry and forward–backward asymmetry of $\bar{B}^+_d \to D^+ \tau^+ \bar{\nu}_\tau$ (left panel) and $\bar{B}^+_s \to \pi^+ (K^+) \tau^+ \bar{\nu}_\tau$ (right panel) in presence of $S_L$ coefficient only. The black dashed lines and the red bands are obtained by using the best-fit values and corresponding 1σ range of $S_L$ coefficient.

### Table 6 Predicted numerical values of differential decay rate, LNU observables, lepton spin asymmetry and forward–backward asymmetry of $\bar{B}^+_d \to D^+ (D^*_\tau^+ \bar{\nu}_\tau$ and $\bar{B}^+_s \to \pi^+ (K^+) \tau^+ \bar{\nu}_\tau$ decay processes in presence of $S_{L,R}$ coefficients

| Observables | Values with $S_L$ | Values with $S_R$ |
|-------------|------------------|------------------|
| $\text{Br}(B^{*0} \to D^+ \tau^+ \bar{\nu}_\tau)$ | $[2.193, 3.344] \times 10^{-8}$ | $[2.180, 3.251] \times 10^{-8}$ |
| $R_D^\tau$ | $[0.296, 0.298]$ | $[0.290, 0.294]$ |
| $A_L^\tau$ | $[0.581, 0.594]$ | $[0.604, 0.626]$ |
| $A_{FB}^D$ | $[-0.066, -0.058]$ | $[-0.126, -0.096]$ |
| $\text{Br}(B^{*+} \to D_{s}^+ \tau^+ \bar{\nu}_\tau)$ | $[3.993, 6.089] \times 10^{-8}$ | $[3.968, 5.916] \times 10^{-8}$ |
| $R_{D_{s}}^\tau$ | $[0.293, 0.296]$ | $[0.287, 0.292]$ |
| $A_{L_{s}}^\tau$ | $[0.578, 0.591]$ | $[0.601, 0.624]$ |
| $A_{FB_{s}}$ | $[-0.065, -0.056]$ | $[-0.126, -0.095]$ |
| $\text{Br}(B^{*0} \to \pi^+ \tau^+ \bar{\nu}_\tau)$ | $[0.736, 1.285] \times 10^{-9}$ | $[0.719, 1.250] \times 10^{-9}$ |
| $R_\pi^\tau$ | $[0.678, 0.680]$ | $[0.662, 0.663]$ |
| $A_{L_{\pi}}^\tau$ | $[0.774, 0.780]$ | $[0.822, 0.823]$ |
| $A_{FB_{\pi}}$ | $[-0.208, -0.204]$ | $[-0.254, -0.251]$ |
| $\text{Br}(B^{*+} \to K^+ \tau^+ \bar{\nu}_\tau)$ | $[0.755, 1.320] \times 10^{-9}$ | $[0.732, 1.273] \times 10^{-9}$ |
| $R_K^\tau$ | $[0.640, 0.642]$ | $[0.619, 0.620]$ |
| $A_{L_{K}}^\tau$ | $[0.738, 0.746]$ | $[0.800, 0.802]$ |
| $A_{FB_{K}}$ | $[-0.207, -0.202]$ | $[-0.260, -0.256]$ |
Fig. 6 The $q^2$ variation of differential decay rate, LNU observable, lepton spin asymmetry and forward–backward asymmetry of $\bar{B}_d^* \to D^+ \tau^- \bar{\nu}_\tau$ (left panel) and $\bar{B}_d^* \to \pi^+ \tau^- \bar{\nu}_\tau$ (right panel) in presence of $S_R$ coefficient only. The black dashed lines and the magenta bands are obtained by using the best-fit values and corresponding 1$\sigma$ range of $S_R$ coefficient.

In view of the recently observed anomalies $R_{D^{(*)}}, R_{J/\psi}, R_{\pi}^l$ involving the charged current $b \to (c, u) l \nu$ transitions, we have performed a model independent analysis of the semileptonic decay process of $B^*$ vector meson decaying to a pseudoscalar meson $P$, where $P = D, D_s, \pi, K$, along with a charged lepton and corresponding antineutrino. We consid-
ered the generalized effective Lagrangian in the presence of vector and scalar type new physics operators. Considering only one new coefficient to be present at a time, we constrained the new parameters associated with $b \rightarrow c\tau\bar{\nu}_\tau$ processes by performing $\chi^2$ fit from $R_{D^{(*)}}, R_{J/\psi}$ parameters and the upper limit on $B^+_d \rightarrow \tau^+\nu_\tau$ branching fraction. The new couplings of $b \rightarrow u\tau\bar{\nu}_\tau$ processes are constrained by using experimental data on the branching ratios of $B_u \rightarrow \tau \nu_\tau$ and $B \rightarrow \pi \tau \nu_\tau$, and $R_{B}^\tau$ parameter. Using the best-fit values and the corresponding $1\sigma$ ranges of new individual complex Wilson coefficients, we computed the branching ratios, forward–backward asymmetry, lepton spin asymmetry and lepton non-universality observables of $B_{d(s)}^+ \rightarrow D^+ (D_{s}^{*+}) \tau^- \bar{\nu}_\tau$ and $B_{d(s)}^+ \rightarrow \pi^+(K^+) \tau^- \bar{\nu}_\tau$ decay processes. We have also shown the values of $q^2$ at which the forward–backward asymmetry vanishes. The branching fractions and LNU observables of these decay modes in the presence of additional $V_L$ coefficient have significant deviations from their corresponding standard model predictions, whereas no deviations have been found in the lepton spin asymmetry and forward–backward asymmetry observables. Due to the additional contributions from $V_R$ new coefficient, profound deviations have been observed in the decay rates, lepton nonuniversality and the forward–backward asymmetry of both $B^+ \rightarrow (D, \pi) \tau \bar{\nu}_\tau$ processes. Due to the presence of $V_R$ coupling, the zero crossing of forward–backward asymmetry has shifted towards high $q^2$ region for all decay modes. In the presence of $S_L$ coefficient, none of the observables are affected and there is practically no deviation from SM results. Only the lepton–spin asymmetry and forward–backward asymmetry observables of $B^+ \rightarrow D \tau \bar{\nu}_\tau$ show slight deviation due to additional $S_L$ coupling. On the other hand, in the presence of $S_R$ coupling, the lepton spin asymmetry and the forward–backward asymmetry show reasonable deviations from their SM predictions and the decay rate lepton nonuniversality observables remain unchanged. The zero crossing of forward–backward asymmetry of all decay modes in the presence of $S_R$ coefficient is found to be shifted towards low $q^2$ region. To conclude, we noticed significant deviations in some of the observables from their standard model predictions in presence of new couplings. The observation of these decay modes of vector $B^*$ mesons at LHC experiment will definitely shed light on the nature of new physics.

Acknowledgements RM and AR would like to thank Science and Engineering Research Board (SERB), Government of India for financial support through Grant no. EMR/2017/001448.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors’ comment: No additional data from any other sources has been used in this article.]

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP3.

References

1. J.P. Lees et al. (BaBar Collaboration), Phys. Rev. Lett. 109, 101802 (2012)
2. J.P. Lees et al. (BaBar Collaboration), Phys. Rev. D 88, 072012 (2013)
3. M. Huschle et al. (BaBar Collaboration), Phys. Rev. D 92, 072014 (2015)
4. Y. Sato et al. (BaBar Collaboration), Phys. Rev. D 94, 072007 (2016)
5. S. Hirose et al. (BaBar Collaboration), Phys. Rev. Lett. 118, 211801 (2017)
6. R. Abdesselam et al. (Belle Collaboration), arXiv:1904.08794 [hep-ex]
7. R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 115, 111803 (2015) [Erratum: Phys. Rev. Lett. 115, 159901 (2015)]
8. R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 120, 171802 (2018)
9. R. Aaij et al. (LHCb Collaboration), Phys. Rev. D 97, 072013 (2018)
10. Heavy Flavour Averaging Group, https://hfлав-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsGammaRDRDs.html
11. R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 120, 121801 (2018)
12. W.-F. Wang, Y.-Y. Fan, Z.-J. Xiao, Chin. Phys. C37, 093102 (2013)
13. M.A. Ivanov, J.G. Korner, P. Santorelli, Phys. Rev. D 71, 094006 (2005) [Erratum: Phys. Rev. D 75, 019901 (2007)]
14. R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 113, 151601 (2014)
15. R. Aaij et al. (LHCb Collaboration), JHEP 08, 055 (2017)
16. C. Bobeth, G. Hiller, G. Piranishvili, JHEP 12, 040 (2007)
17. B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, J. Virto, JHEP 01, 093 (2018)
18. T. Humair (for the LHCb Collaboration), “Lepton Flavor Universality tests with heavy flavour decays at LHCb,” talk given at Moriond, March 22 2019. See also R. Aaij et al. [LHCb Collaboration], “Search for lepton-universality violation in $B^+ \rightarrow K^+ l^+ l^-$ decays,” CERN-EP-2019-043, 22 March (2019)
19. M. Prim (for the Belle Collaboration), “Search for $B \rightarrow l\nu\gamma$ and $B \rightarrow \mu\nu\mu$ and Test of Lepton Universality with $R_{K^*}$ at Belle,” talk given at Moriond, March 22 (2019)
20. M. Tanabashi et al., (Particle Data Group), Phys. Rev. D 98, 030001 (2018)
21. Q. Chang, J. Zhu, X.-L. Wang, J.-F. Sun, Y.-L. Yang, Nucl. Phys. B 909, 921 (2016)
22. B. Grinstein, J.M. Camalich, Phys. Rev. Lett. 116, 141801 (2016)
23. S. Sahoo, R. Mohanta, J. Phys. G 44, 035001 (2017)
24. D. Kumar, J. Saini, S. Gangal, S.B. Das, Phys. Rev. D 97, 035007 (2018)
25. S. Kumbhakar, J. Saini, arXiv:1807.04055
26. Q. Chang, J. Zhu, N. Wang, R.-M. Wang, Adv. High Energy Phys. 2018, 7231354 (2018)
27. J. Zhang, Y. Zhang, Q. Zeng, Ruirui Sun, Euro Phys. J. C 79, 164 (2019)
28. M. Tanaka, R. Watanabe, Phys. Rev. D 87, 034028 (2013)
29. M. Wirbel, B. Stech, M. Bauer, Z. Phys. C 29, 637 (1985)
30. M. Bauer, B. Stech, M. Wirbel, Z. Phys. C 34, 103 (1987)
31. A.G. Akeroyd, C.-H. Chen, Phys. Rev. D 96, 075011 (2017). arXiv:1708.04072
32. A. Ray, S. Sahoo, R. Mohanta, Phys. Rev. D 99, 015015 (2019)
33. Chi-Yee Cheung, Chien-Wen Hwang, JHEP 04, 177 (2014). arXiv:1401.3917
34. A. Khodjamirian, T. Mannel, Alexey A. Petrov, JHEP 11, 142 (2015). arXiv:1509.07123