Exploring $R_D$, $R_{D^*}$ and $R_{J/\Psi}$ anomalies

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Deviations from the standard model predictions have been reported in various observables concerned with the lepton flavor universality. At present, the deviation of the measured values of $R_D$ and $R_{D^*}$ from the standard model expectation is exceeded by 2.3σ and 3.4σ, respectively. Very recently LHCb has measured the ratio of branching ratio $R_{J/\Psi} = B(B_c \to J/\Psi \tau \nu)/B(B_c \to J/\Psi l \nu)$, where $l \in (e, \mu)$, to be 0.71 ± 0.17 ± 0.18 which is at more than 2σ away from the standard model prediction. We investigate the anomalies in $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ using a model independent framework with minimal number of new physics parameters. We find various new physics models that can explain these anomalies within 1σ.

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I. INTRODUCTION

Lepton flavor universality violation has been the center of attention due to the long standing anomalies that persisted in the ratio of branching ratios $R_D$ and $R_{D^*}$, where

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}, \quad l \in (e, \mu).$$

Unlike the individual branching ratio of these decay modes, $R_D$ and $R_{D^*}$ do not suffer from the uncertainties coming from the Cabbibo-Kobayashi-Mashakawa (CKM) matrix elements and the meson to meson form factors. The dependency on the CKM matrix elements exactly cancels in these ratios. Similarly, the uncertainties due to the form factors also largely cancel in these ratios and a clean prediction of dependency on the CKM matrix elements exactly cancels in these ratios. Similarly, the uncertainties due to the form factors also largely cancel in these ratios and a clean prediction of the CKM matrix elements exactly cancels in these ratios. 

Hence, any deviation from the SM prediction would clearly indicate the presence of new physics (NP). At present, combining the results of $R_D$ and $R_{D^*}$ measured by various experiments such as BABAR [1, 2], BELLE [3–5], and LHCb [6, 7], i.e., $R_D = 0.407 ± 0.039 ± 0.024$ and $R_{D^*} = 0.304 ± 0.013 ± 0.007$ exceed the SM predictions by 2.3σ and 3.4σ, respectively. Again, including the $R_D - R_{D^*}$ correlation, the discrepancy with SM prediction [8] currently stands at about 4.1σ [3]. Recently, LHCb [14, 15] has measured the value of the ratio of branching ratio

$$R_{J/\Psi} = \frac{B(B_c \to J/\Psi \tau \nu)}{B(B_c \to J/\Psi l \nu)} = 0.71 \pm 0.17 \pm 0.18,$$

where $l$ is either an electron or muon, which is at more than 2σ away from the standard model (SM) prediction [16, 17]. In Ref. [5], the $\tau$ polarization fraction in $B \to D^* \tau \nu$ decays has also been measured by BELLE Collaboration and it is reported to be $P_\tau^{D^*} = −0.38 ± 0.51^{+0.21}_{−0.16}$. All these measurements indicate an upward deviation from the SM expectation.

Various model-independent and model-dependent [18–41] approaches have been carried out to explore NP effects in $R_D$ and $R_{D^*}$. Very recently, NP effects on $B_c \to J/\Psi \tau \nu$ decays have also been studied by various authors [17, 42, 43]. In view of the new measurement of $R_{J/\Psi}$ made by LHCb, we investigate $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ anomalies within a model independent framework with minimal number of NP couplings. We use the most general effective Lagrangian in the presence of NP which is valid at renormalization scale $\mu = m_t$ and seek to find the minimal number of NP couplings that best fit the data. We have considered total 55 NP scenarios based on NP contributions from single operators as well as from two different operators and try to find the scenario that best explains $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ anomalies. Although this is not entirely a new idea, most efforts at explaining these anomalies consider only a subset of these 55 NP structures. We do not propose any NP model that can generate such NP structures in particular. Rather we study it from a purely phenomenological point of view. It was shown in Ref. [38] that lifetime of $B_c$ meson

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put a severe constraint on scalar type NP interactions. Based on various SM calculations [43, 46], it was inferred that $\mathcal{B}(B_c \to \tau \nu) \leq 5\%$ is necessary to comply with the current world average of the $B_c$ lifetime. However, the constraint can be relaxed up to 30% depending on the value of the total decay width of $B_c$ meson that is used as input for the SM calculation of various partonic transitions. Very recently, in Ref. [47], a more significant bound of $\mathcal{B}(B_c \to \tau \nu) \leq 10\%$ was obtained by taking the LEP data at the $Z$ peak. Our analysis also takes into account the indirect constraint coming from $\mathcal{B}(B_c \to \tau \nu)$ to rule out various NP scenarios. We, however, have not included the measured value of $P^{\tau \nu}$ reported by Belle in our fitting method since the uncertainties associated with it is rather large.

The paper is organized as follows. In section II, we present the most general effective weak Lagrangian for the $b \to c \tau R$, quark level transitions in the presence of NP, valid at renormalization scale $\mu = m_b$. We also present all the relevant formulas pertinent for our analysis. The results of our analysis are reported in section III. We conclude with a brief summary of our results in section IV.

II. THEORY FRAMEWORK

We begin with the most general effective Lagrangian for the $b \to c l \nu$ quark level transitions in the presence of NP. That is [48, 49]

$$\mathcal{L}_{\text{eff}} = - \frac{4G_F}{\sqrt{2}} V_{cb} \left\{ (1 + V_L) \bar{l}_L \gamma_{\mu} \nu_L c L \gamma^\mu b_L + V_R \bar{l}_L \gamma_{\mu} \nu_L c R \gamma^\mu b_R + \bar{V}_L l_R \gamma_{\mu} \nu_R c L \gamma^\mu b_L + \bar{V}_R l_R \gamma_{\mu} \nu_R c R \gamma^\mu b_R + S_L \bar{l}_R \nu_L c L b_R + S_R \bar{l}_R \nu_L c R b_R + \bar{S}_L l_R \nu_R c L b_R + \bar{S}_R l_R \nu_R c R b_R + T_L l_R \sigma_{\mu\nu} \nu_L c L \sigma_{\nu} b_R + T_R l_R \sigma_{\mu\nu} \nu_L c R \sigma_{\nu} b_R \right\} + \text{H.c.} ,$$

where $(V_L, V_R, S_L, S_R, T_L)$ represents NP couplings that involve left handed neutrino interactions and $(\bar{V}_L, \bar{V}_R, \bar{S}_L, \bar{S}_R, T_L)$ represents NP couplings that involve right handed neutrino interactions. We consider all the NP couplings to be real. In the presence of such NP, the three body differential branching ratios for $B_q \to (P, V) l \nu$ decays, where $P(V)$ represents pseudoscalar (vector) meson, can be written as [29, 32, 42]

$$\frac{d\Gamma^P}{dq^2} (+) = \frac{8N|\mathcal{F}_P|^2}{3} \left\{ \frac{m_S^2}{q^2} \left[ H_{T0}^2 + \frac{1}{2} H_{T0} H_{T1} + \frac{3}{2} H_{T2}^2 \right] \right\} , \quad \frac{d\Gamma^P}{dq^2} (-) = \frac{8N|\mathcal{F}_P|^2}{3} \left\{ \frac{m_S^2}{q^2} \left[ H_{T0}^2 + \frac{1}{2} H_{T0} H_{T1} + \frac{3}{2} H_{T2}^2 \right] \right\} ,$$

where

$$H_{T0} = H_T T_L + \sqrt{\frac{q^2}{m_1}} H_0 G_V , \quad \bar{H}_{T0} = H_T \bar{T}_L + \sqrt{\frac{q^2}{m_1}} H_0 \bar{G}_V , \quad H_{T1} = H_0 G_V + \sqrt{\frac{q^2}{m_1}} H_T T_L , \quad \bar{H}_{T1} = \bar{H}_0 \bar{G}_V + \sqrt{\frac{q^2}{m_1}} \bar{H}_T \bar{T}_L ,$$

$$H_{T2} = H_0 G_S + \sqrt{\frac{q^2}{m_1}} H_T \bar{T}_L , \quad \bar{H}_{T2} = \bar{H}_0 \bar{G}_S + \sqrt{\frac{q^2}{m_1}} \bar{H}_T \bar{T}_L ,$$

Similarly

$$\frac{d\Gamma^V}{dq^2} (+) = \frac{8N|\mathcal{F}_P|^2}{3} \left\{ \frac{m_S^2}{q^2} \left[ \tilde{A}^2_{TAV} + \frac{1}{2} \tilde{A}^2_{AVT} + \frac{3}{2} \tilde{A}^2_{TP} \right] \right\} , \quad \frac{d\Gamma^V}{dq^2} (-) = \frac{8N|\mathcal{F}_P|^2}{3} \left\{ \frac{m_S^2}{q^2} \left[ \tilde{A}^2_{TAV} + \frac{1}{2} \tilde{A}^2_{AVT} + \frac{3}{2} \tilde{A}^2_{TP} \right] \right\} ,$$

where

$$\tilde{A}^2_{TAV} = \left( A_{T0} T_L + \sqrt{\frac{q^2}{m_1}} A_0 G_A \right)^2 + \left( A_{T2} T_L + \sqrt{\frac{q^2}{m_1}} A_{||} G_A \right)^2 \left( A_{T3} T_L + \sqrt{\frac{q^2}{m_1}} A_{\perp} G_V \right)^2 ,$$

$$\tilde{A}^2_{TAV} = \left( A_{T0} \bar{T}_L + \sqrt{\frac{q^2}{m_1}} \bar{A}_0 \bar{G}_A \right)^2 + \left( A_{T2} \bar{T}_L + \sqrt{\frac{q^2}{m_1}} \bar{A}_{||} \bar{G}_A \right)^2 \left( A_{T3} \bar{T}_L + \sqrt{\frac{q^2}{m_1}} \bar{A}_{\perp} \bar{G}_V \right)^2 ,$$

$$\tilde{A}^2_{AVT} = \left( A_0 G_A + \sqrt{\frac{q^2}{m_1}} A_{T0} T_L \right)^2 + \left( A_{||} G_A + \sqrt{\frac{q^2}{m_1}} A_{T2} T_L \right)^2 \left( A_{\perp} G_V + \sqrt{\frac{q^2}{m_1}} A_{T3} T_L \right)^2 ,$$

$$\tilde{A}^2_{AVT} = \left( A_0 \bar{G}_A + \sqrt{\frac{q^2}{m_1}} \bar{A}_{T0} \bar{T}_L \right)^2 + \left( A_{||} \bar{G}_A + \sqrt{\frac{q^2}{m_1}} \bar{A}_{T2} \bar{T}_L \right)^2 \left( A_{\perp} \bar{G}_V + \sqrt{\frac{q^2}{m_1}} \bar{A}_{T3} \bar{T}_L \right)^2 ,$$

$$A_{TP} = A_t G_A + \sqrt{\frac{q^2}{m_1}} A_P G_P , \quad \tilde{A}_{TP} = A_t \bar{G}_A + \sqrt{\frac{q^2}{m_1}} \bar{A}_P \bar{G}_P$$

(7)
and
\[ A_\parallel = \frac{2(m_{B_q} + m_V)A_1(q^2)}{\sqrt{2}}, \quad A_\perp = -\frac{4m_{B_q}V(q^2)\vec{p}_V}{\sqrt{2}(m_{B_q} + m_V)}, \quad A_{T_L} = \frac{8\sqrt{2}m_{B_q}|\vec{p}_V|}{q^2} T_1, \]
\[ A_t = \frac{2m_{B_q}|\vec{p}_V|A_0(q^2)}{\sqrt{2}q^2}, \quad A_P = \frac{2m_{B_q}|\vec{p}_V|A_0(q^2)}{(m_b(\mu) + m_c(\mu))}, \quad A_{T_2} = -\frac{4\sqrt{2}(m_{B_q}^2 - m_c^2)}{q^2} T_2, \]
\[ A_0 = \frac{1}{2m_V q^2} \left[ \left(m_{B_q}^2 - m_V^2 - q^2\right)(m_{B_q} + m_V)A_1(q^2) - \frac{4m_{B_q}^2 |\vec{p}_V|^2}{m_{B_q}^2 + m_V^2} A_2(q^2) \right], \]
\[ A_{T_0} = \frac{2}{m_V} \left[ -\left(m_{B_q}^2 + 3m_V^2 - q^2\right)T_2(q^2) + \frac{2m_{B_q}|\vec{p}_V|}{m_{B_q}^2 - m_V^2} T_3(q^2) \right]. \quad (8) \]

Here we denote \( G_V = 1 + V_L + V_R, G_A = 1 + V_L - V_R, G_S = S_L + S_R, G_\rho = S_L - S_R, \bar{G}_V = V_L + V_R, \bar{G}_A = V_L - V_R, \bar{G}_S = S_L + S_R, \) and \( \bar{G}_\rho = S_L - S_R. \) Again, \(|\vec{p}_{\beta(V)}| = \sqrt{(m_{B_q}^2, m_V^2, q^2)/2m_{B_q}} \) denotes the three momentum vector of the outgoing meson. The ratio of branching ratios and \( \tau \) polarization fractions for these decay modes are
\[ R_M = \frac{B(B_q \to M\tau\nu)}{B(B_q \to M\nu)}, \quad P_M^\tau = \frac{\Gamma^M(+) - \Gamma^M(-)}{\Gamma^M(+) + \Gamma^M(-)}, \quad (9) \]
where \( l \) is either an electron or a muon and \( B_q \) is either a \( B \) meson or a \( B_s \) meson. Similarly, \( M \) refers to the outgoing pseudoscalar or vector meson. Again, \( \Gamma^+ ) \) and \( \Gamma^-(\) denote the decay widths of positive and negative helicity \( \tau \) lepton, respectively.

### III. NUMERICAL ANALYSES

For the numerical estimates of all the observables we first report all the input parameters. For the quark, lepton, and meson masses, we use \( m_u(m_b) = 4.18 \) GeV, \( m_c(m_b) = 0.91 \) GeV, \( m_e = 0.510998928 \times 10^{-5} \) GeV, \( m_u = 0.1056587151 \) GeV, \( m_\tau = 1.77682 \) GeV, \( m_j/\psi = 3.0969 \) GeV, \( m_b^- = 5.27931 \) GeV, \( m_{B_s} = 6.2751 \) GeV, \( m_{B_d^0} = 1.86483 \) GeV, and \( m_{D_s^0} = 2.00685 \) GeV [50]. Similarly, for the mean lifetime of \( B^- \) and \( B_s \) meson, we use \( \tau_{B^-} = 1.638 \times 10^{-12} \) s and \( \tau_{B_s} = 0.507 \times 10^{-12} \) s [70]. We use \( f_{B_s} = 0.434(0.015) \) GeV from Ref. [51]. The value of CKM matrix element is taken to be \( V_{cb} = 0.0490(0.0011) \) [60]. The uncertainty associated with \( f_{B_s} \) and \( V_{cb} \) are indicated by the number in parentheses.

In order to compute the branching fractions and other observables, we need information on various hadronic form factors that parametrize the hadronic matrix elements of vector, axial vector, scalar, pseudoscalar, and tensor currents between two mesons. For the \( B \to J/\Psi \) hadronic form factors, we follow ref. [16]. The relevant formula for \( V(q^2), \) \( A_0(q^2), A_1(q^2), \) and \( A_2(q^2) \) pertinent for our discussion, taken from ref. [16] is
\[ F(q^2) = F(0) \exp \left[ a q^2 + b (q^2)^2 \right], \quad (10) \]
where \( F \) stands for the form factors \( V, A_0, A_1, \) and \( A_2 \) and \( a, b \) are the fitted parameters. The numerical values of \( B \to J/\Psi \) form factors at \( q^2 = 0 \) and their fitted parameters \( a \) and \( b, \) calculated in perturbative QCD (PQCD) approach, are collected from ref. [16]. Similarly for the \( B \to J/\Psi \) tensor form factors, we follow Ref. [42]. The relevant formulas pertinent for our numerical computation are
\[ T_1(q^2) = \frac{m_b + m_c}{m_{B_s} + m_{J/\Psi}} V(q^2), \quad T_2(q^2) = \frac{m_b - m_c}{m_{B_s} - m_{J/\Psi}} A_1(q^2), \]
\[ T_3(q^2) = -\frac{m_b - m_c}{q^2} \left[ m_{B_s} \left( A_1(q^2) - A_2(q^2) \right) + m_{J/\Psi} \left( A_2(q^2) + A_1(q^2) - 2 A_0(q^2) \right) \right]. \quad (11) \]

A preliminary lattice calculation of \( B \to J/\Psi \) transition form factors is reported in Ref. [52] [53]. The \( B \to D \) transition form factors \( F_0(q^2) \) and \( F_+(q^2), \) calculated using lattice QCD techniques, are collected from Ref. [5]. For the tensor form factor \( F_T(q^2), \) we use Ref. [54]. That is
\[ F_T(q^2) = \frac{0.69}{\left( 1 - \frac{q^2}{6.4^2} \right) \left( 1 - 0.56 \frac{q^2}{6.4^2} \right)}. \quad (12) \]

Similarly, for \( B \to D^* \) form factors, we follow the heavy quark effective theory (HQET) approach of Ref. [55]. We refer to Ref. [54] for all the relevant equations.
We first perform a $\chi^2$ test to measure the disagreement of SM with the data. The $\chi^2$ is defined as

$$
\chi^2 = \sum_i \frac{(O_{i}^{\text{th}} - O_{i}^{\text{exp}})^2}{\Delta O_{i}^{\text{exp}}} ~ ,
$$

where $O_{i}^{\text{exp}}$ represents the measured central value of the observables and $\Delta O_{i}^{\text{exp}}$ represents corresponding 1σ uncertainty. Similarly, $O_{i}^{\text{th}}$ represents the theoretical prediction of the observables. We include a total of three measurements for the evaluation of $\chi^2$, namely, $R_D$, $R_{D^*}$, and $R_{J/\Psi}$. We have not included $P_{\tau}^{D^*}$ in our fit as the error associated with it is rather large. We have found $\chi_{\text{min}}^2 = 16.3$ in the SM. The $\chi_{\text{min}}^2$ in the SM is obtained by performing a random scan of all the theory input parameters such as CKM matrix elements, meson decay constant, and meson to meson form factors within 1σ of their central values. The corresponding best estimates for all the observables are listed in Table. II.

Let us now evaluate $\chi_{\text{min}}^2$ for various NP scenarios. First we consider that NP contributions are coming from an operator characterized by a single NP Wilson Coefficient (WC). We have considered total 10 such NP scenarios that involve left handed as well as right handed neutrino interactions. The $\chi^2_{\text{min}}$ obtained in each scenario and the corresponding best estimates of all the observables are listed in Table. II. We observe that we obtain the best fit to the data with $T_L$ NP coupling which corresponds to $\chi_{\text{min}}^2 = 1.7$ followed by $V_L$, $\bar{V}_L$, and $\bar{T}_L$ with $\chi_{\text{min}}^2 = 2.1$ each. The branching ratio of $B_c \rightarrow \tau\nu$ obtained in each of these scenarios is consistent with $B(B_c \rightarrow \tau\nu) \leq 5%$ obtained in the SM. With $T_L$ NP coupling, although the best estimates of $R_D$ and $R_{J/\Psi}$ lie inside the 1σ experimental range, the best estimate of $R_{D}$, however, lies outside 1σ of the experimental value. Similarly, with $V_L$ and $\bar{V}_{(L,R)}$ NP couplings although, the best estimates of $R_D$ and $R_{D^*}$ lie inside the 1σ experimental range, the best estimate of $R_{J/\Psi}$, however, lies outside 1σ of the experimental value. We show in Fig. I the 95% CL (blue band) allowed ranges in $(R_D, P_{\tau}^{D^*})$.

| Coefficients | Best fit value | $R_D$ | $R_{D^*}$ | $R_{J/\Psi}$ | $P_{\tau}^{D^*}$ | $B(B_c \rightarrow \tau\nu)\%$ | $\chi_{\text{min}}^2$ |
|--------------|---------------|-------|-----------|-------------|-----------------|-----------------------------|-------------|
| SM           |               | 0.334 | 0.225     | 0.291       | -0.501          | 2.3                        | 16.3        |
| $V_L$       | -2.11         | 0.398 | 0.307     | 0.356       | -0.494          | 2.9                        | 2.1         |
| $V_R$       | -0.09         | 0.276 | 0.295     | 0.345       | -0.496          | 2.5                        | 10.7        |
| $S_L$       | -1.51         | 0.365 | 0.330     | 0.418       | -0.140          | 121.5                      | 5.2         |
| $S_R$       | 0.31          | 0.427 | 0.266     | 0.308       | -0.431          | 12.1                       | 9.6         |
| $\bar{V}_L$ | 0.48          | 0.398 | 0.309     | 0.367       | -0.311          | 2.7                        | 2.1         |
| $\bar{V}_R$ | 0.48          | 0.398 | 0.309     | 0.367       | -0.311          | 2.7                        | 2.1         |
| $\bar{S}_L$ | 0.73          | 0.432 | 0.262     | 0.302       | -0.513          | 23.2                       | 11.2        |
| $\bar{S}_R$ | 0.73          | 0.432 | 0.262     | 0.302       | -0.513          | 23.2                       | 11.2        |
| $T_L$       | -0.08         | 0.309 | 0.302     | 0.457       | -0.467          | 2.0                        | 5.6         |
| $\bar{T}_L$ | 0.27          | 0.352 | 0.305     | 0.585       | -0.412          | 2.3                        | 1.7         |

TABLE I: Best estimates of $R_D$, $R_{D^*}$, $R_{J/\Psi}$, $P_{\tau}^{D^*}$, and $B(B_c \rightarrow \tau\nu)$ within the SM and within various NP scenarios.

$(R_{D^*}, P_{\tau}^{D^*})$, and $(R_{J/\Psi}, P_{\tau}^{D/\Psi})$ for NP scenarios with $V_L$, $\bar{V}_L$, and $\bar{T}_L$ NP couplings. We observe that, although, $V_L$ and $\bar{V}_L$ NP couplings can simultaneously explain the anomalies present in $R_D$ and $R_{D^*}$, these couplings, however, can not accommodate the $R_{J/\Psi}$ data within 1σ. We note that with $T_L$ NP coupling, the range obtained for $R_{J/\Psi}$ lies within the 1σ range of $R_{J/\Psi}$ data. However with $\bar{T}_L$ NP coupling, the range obtained for $R_D$ lies outside the 1σ experimental range. Again, we want to emphasise that the range in $\tau$ polarization fraction $P_{\tau}^{D^*}$ for each scenarios lies inside the 1σ allowed range reported by Belle Collaboration. However, with $\bar{T}_L$ and $V_L$ NP couplings, the central value lies inside the 95% (blue) CL allowed bands. We notice that with $V_L$ NP coupling, the central value of $P_{\tau}^{D^*}$ reported by Belle Collaboration lies much above the range obtained in this scenario. However, the uncertainty associated with $P_{\tau}^{D^*}$ is rather large. Precise determination of this parameter in the future will play a crucial role in identifying the exact nature of NP.

Now let us consider that NP contributions are coming from two different operators characterized by two NP WC. We consider total 45 such NP scenarios. In Table. II we show the best estimates of $R_D$, $R_{D^*}$, $R_{J/\Psi}$, $P_{\tau}^{D^*}$ and $B(B_c \rightarrow \tau\nu)$ for each of these scenarios. In that we have $\chi_{\text{min}}^2 = 0.43 \times 10^{-2}$ followed by $(V_R, \bar{T}_L)$, $(S_R, \bar{T}_L)$, and $(\bar{V}_L, \bar{T}_L)$ NP couplings with $\chi_{\text{min}}^2 = 0.013, 0.026$, and 0.11, respectively. However, with $(S_R, \bar{T}_L)$ NP couplings, the best estimates of $B(B_c \rightarrow \tau\nu) = 80.6%$ is much above the
FIG. 1: The allowed ranges in $\left( R_D, P_D^\tau \right)$, $\left( R_{D^*}, P_{D^*}^\tau \right)$, and $\left( R_{J/\Psi}, P_{J/\Psi}^\tau \right)$ at 95% CL are shown with blue bands. The experimental 1$\sigma$ range of $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ are shown with light red bands. The horizontal line in the leftmost panel represents the central value of $P_{D^*}^\tau$ reported by BELLE.

The upper bound of $\mathcal{B}(B_c \rightarrow \tau \nu) \leq 30\%$ estimated in the SM. Hence although, we get a much better fit with this NP structure, $(S_R, \tilde{T}_L)$ NP couplings can not accommodate the $B_c \rightarrow \tau \nu$ data.

We show in Fig. 2 the allowed range in $(\tilde{V}_R, \tilde{T}_L)$, $(\tilde{V}_R, \tilde{T}_L)$, and $(\tilde{V}_L, \tilde{T}_L)$ NP parameter space at 95% (blue) CL obtained from the measured values of $R_D$, $R_{D^*}$, and $R_{J/\Psi}$. We also show the allowed ranges in $\left( R_D, P_D^\tau \right)$, $\left( R_{D^*}, P_{D^*}^\tau \right)$, and $\left( R_{J/\Psi}, P_{J/\Psi}^\tau \right)$ for each of these NP scenarios. It is clear that with all these NP couplings, the allowed ranges in $R_D$, $R_{D^*}$, $R_{J/\Psi}$, and $P_{\tau}^D$ at 95% (blue) CL do overlap with the experimentally allowed values within 1$\sigma$. It should, however, be mentioned that with $(\tilde{V}_R, \tilde{T}_L)$ NP couplings, the value of $P_{D}^\tau$ can be negative depending on the value of the NP couplings. Similarly, we do not see much variation of $P_{\tau}^D$ with $(\tilde{V}_R, \tilde{T}_L)$ NP couplings. Measurement of $P_{D}^\tau$ and $P_{J/\Psi}^\tau$ in future will also play a crucial role.
FIG. 2: The allowed NP parameter space (leftmost panels) at 95% (blue) CL from $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ measurements. The corresponding allowed ranges in $(R_D, P_D^D)$, $(R_{D^*}, P_{D^*}^D)$, and $(R_{J/\Psi}, P_{J/\Psi}^{J/\Psi})$ are shown with blue dots. The experimental 1σ range of $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ are shown with light red bands. The horizontal line in the second panel represents the central value of $P_{D^*}^D$ reported by BELLE.

IV. CONCLUSION

In view of the recent result of $R_{J/\Psi}$, we investigate $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ anomalies using a model-independent framework. We consider total 55 NP models consisting of single as well as double NP coefficients and evaluate $\chi^2_{\text{min}}$ by including three measurements, namely, $R_D$, $R_{D^*}$, and $R_{J/\Psi}$. We find various NP models that can simultaneously explain $R_D$, $R_{D^*}$, and $R_{J/\Psi}$ anomalies within 1σ. We also give prediction on the $\tau$ polarization fraction parameter for all these decay modes in each NP scenarios. It should be noted that a more precise measurement on $P_{D^*}^{D^*}$ in future will be crucial to identify the true nature of NP. Again, in view of the immense importance of $R_D$, $R_{D^*}$, and $R_{J/\Psi}$, both experimentally and theoretically, it is important to ensure that theoretical calculations of various form factors are very precise. At the same time, measurement of $P_{\tau}^D$ and $P_{\tau}^{J/\Psi}$ in future will be crucial to rule out various NP scenarios.

[1] J. P. Lees et al. [BaBar Collaboration], “Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays,” Phys. Rev. Lett. 109, 101802 (2012) doi:10.1103/PhysRevLett.109.101802 [arXiv:1205.5442 [hep-ex]].
\[ B \rightarrow D^*\tau\bar{\nu}, \] \cite{PhysRevD.95.115038} doi:10.1103/PhysRevD.95.115038 [arXiv:1606.03164 [hep-ph]].

\[ M. A. Ivanov, J. G. Körner and C. T. Tran, “Exclusive decays \( B \rightarrow \ell^-\bar{\nu} \) and \( B \rightarrow D^{(*)}\ell^-\bar{\nu} \) in the covariant quark model,” Phys. Rev. D 92, no. 11, 114022 (2015) doi:10.1103/PhysRevD.92.114022 [arXiv:1508.02678 [hep-ph]].

\[ M. A. Ivanov, J. G. Krner and C. T. Tran, “Analyzing new physics in the decays \( B^0 \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau \) with form factors obtained from the covariant quark model,” Phys. Rev. D 94, no. 9, 094028 (2016) doi:10.1103/PhysRevD.94.094028 [arXiv:1607.02932 [hep-ph]].

\[ S. Nandi, S. K. Patra and A. Soni, “Correlating new physics signals in \( B \rightarrow D^{(*)}\tau\bar{\nu} \) with \( B \rightarrow \tau\nu \),” arXiv:1605.07191 [hep-ph].

\[ R. Dutta and A. Bhol, “\( b \rightarrow (c, u), \tau\nu \) leptonic and semileptonic decays within an effective field theory approach,” Phys. Rev. D 96, no. 3, 036012 (2017) doi:10.1103/PhysRevD.96.036012 [arXiv:1611.00231 [hep-ph]].

\[ R. Alonso, B. Grinstein and J. Martin Camalich, “Lifetime of \( B_c \): Constrains Explanations for Anomalies in \( B \rightarrow D^{(*)}\tau\nu \),” Phys. Rev. Lett. 118, no. 8, 081802 (2017) doi:10.1103/PhysRevLett.118.081802 [arXiv:1611.06676 [hep-ph]].

\[ A. Celis, M. Jung, X. Q. Li and A. Pich, “Scalar contributions to \( b \rightarrow c(u)\tau\nu \) transitions,” Phys. Lett. B 771, 168 (2017) doi:10.1016/j.physletb.2017.05.037 [arXiv:1612.07757 [hep-ph]].

\[ W. Altmannshofer, P. S. B. Dev and A. Soni, “\( R_{D^{*}} \) anomaly: A possible hint for natural supersymmetry with \( R \)-parity violation,” arXiv:1704.06659 [hep-ph].

\[ S. Iguro and K. Tobe, “\( R(D^{(*)}) \) in a general two Higgs doublet model,” arXiv:1708.06176 [hep-ph].

\[ R. Watanabe, “New Physics effect on \( B_c \rightarrow J/\psi\tau\bar{\nu} \) in relation to the \( R_{D^{(*)}} \) anomaly,” arXiv:1709.08644 [hep-ph].

\[ B. Chauhan and B. Kindra, “Invoking Chiral Vector Leptoquark to explain LFU violation in \( B \) Decays,” arXiv:1709.09989 [hep-ph].

\[ I. I. Y. Bigi, “Inclusive \( B(c) \) decays as a QCD lab,” Phys. Lett. B 371, 105 (1996) doi:10.1016/0370-2693(95)01574-4 [hep-ph/9601249].

\[ M. Beneke and G. Buchalla, “The \( B_c \) Meson Lifetime,” Phys. Rev. D 53, 4991 (1996) doi:10.1103/PhysRevD.53.4991 [hep-ph/9601249].

\[ C. H. Chang, S. L. Chen, T. F. Feng and X. Q. Li, “The Lifetime of \( B_c \) meson and some relevant problems,” Phys. Rev. D 64, 014003 (2001) doi:10.1103/PhysRevD.64.014003 [hep-ph/0007162].

\[ A. G. Akesson and C. H. Chen, “Constraint on the branching ratio of \( B_c \rightarrow \tau\bar{\nu} \) from LEP1 and consequences for \( R(D^{(*)}) \) anomaly,” Phys. Rev. D 96, no. 7, 075011 (2017) doi:10.1103/PhysRevD.96.075011 [arXiv:1708.04072 [hep-ph]].

\[ T. Bhattacharya, V. Cirigliano, S. D. Cohen, A. Filippuzzi, M. Gonzalez-Alonso, M. L. Graesser, R. Gupta and H. -W. Lin, “Probing Novel Scalar and Tensor Interactions from (Ultra)Cold Neutrons to the LHC,” Phys. Rev. D 85, 054512 (2012) doi:10.1103/PhysRevD.85.054512 [arXiv:1110.6448 [hep-ph]].

\[ V. Cirigliano, J. Jenkins and M. Gonzalez-Alonso, “Semileptonic decays of light quarks beyond the Standard Model,” Nucl. Phys. B 830, 95 (2010) arXiv:0908.1754 [hep-ph].

\[ C. Patrignani et al. [Particle Data Group], “Review of Particle Physics,” Chin. Phys. C 40, no. 10, 100001 (2016). doi:10.1088/1674-1137/40/10/100001.

\[ B. Colquhoun et al. [HPQCD Collaboration], “\( B \)-meson decay constants: a more complete picture from full lattice QCD,” Phys. Rev. D 91, no. 11, 114509 (2015) doi:10.1103/PhysRevD.91.114509 [arXiv:1503.05762 [hep-lat]].

\[ A. Lytle, B. Colquhoun, C. Davies, J. Koponen and C. McNeile, “Semileptonic \( B \) decays from full lattice QCD,” PoS BEAUTY 2016, 069 (2016) doi:10.22323/1.261.0069 [arXiv:1605.05645 [hep-lat]].

\[ B. Colquhoun et al. [HPQCD Collaboration], “\( B \) decays from highly improved staggered quarks and NRQCD,” PoS LATTICE 2016, 281 (2016) arXiv:1611.01987 [hep-lat].

\[ D. Melikhov and B. Stech, “Weak form-factors for heavy meson decays: An Update,” Phys. Rev. D 62, 014006 (2000) doi:10.1103/PhysRevD.62.014006 [hep-ph/0001113].

\[ I. Caprini, L. Lellouch and M. Neubert, “Dispersive bounds on the shape of anti-\( B \rightarrow D^{(*)} \) lepton anti-neutrino form-factors,” Nucl. Phys. B 530, 153 (1998) doi:10.1016/S0550-3213(98)00350-2 [hep-ph/9712417].
| Coefficients  | Best fit value | $R_D$ | $R_{D^*}$ | $R_{J/\psi}$ | $P_{D^*}$ | $\mathcal{B}(B_c \rightarrow \tau \nu)$% | $\chi^2_{min}$ |
|--------------|----------------|-------|-----------|-------------|-----------|-------------------------------|-------------|
| $(V_L, V_R)$ | $(-2.14, -0.04)$ | 0.406 | 0.308 | 0.357 | -0.500 | 2.7 | 2.1 |
| $(V_L, S_L)$ | $(-1.94, 1.62)$ | 0.403 | 0.308 | 0.383 | -0.092 | 137.3 | 1.8 |
| $(V_L, S_R)$ | $(0.09, 0.13)$ | 0.411 | 0.305 | 0.352 | -0.475 | 6.3 | 2.1 |
| $(V_L, T_L)$ | $(-2.13, -0.03)$ | 0.404 | 0.302 | 0.320 | -0.502 | 2.8 | 2.5 |
| $(V_L, \bar{V}_L)$ | $(-1.68, -0.87)$ | 0.397 | 0.306 | 0.356 | 0.121 | 2.7 | 2.1 |
| $(V_L, \bar{V}_R)$ | $(-1.68, -0.87)$ | 0.397 | 0.306 | 0.356 | 0.121 | 2.7 | 2.1 |
| $(V_L, \bar{S}_L)$ | $(-2.10, -0.29)$ | 0.403 | 0.305 | 0.353 | -0.498 | 5.9 | 2.1 |
| $(V_L, \bar{S}_R)$ | $(-2.10, -0.29)$ | 0.403 | 0.305 | 0.353 | -0.498 | 5.9 | 2.1 |
| $(V_R, T_L)$ | $(0.04, -0.23)$ | 0.361 | 0.312 | 0.534 | -0.439 | 2.3 | 1.8 |
| $(V_R, S_L)$ | $(0.08, -1.68)$ | 0.406 | 0.307 | 0.372 | -0.070 | 154.1 | 1.9 |
| $(V_R, S_R)$ | $(-0.09, 0.27)$ | 0.402 | 0.306 | 0.359 | -0.445 | 10.5 | 2.1 |
| $(V_R, \bar{V}_L)$ | $(0.25, -0.27)$ | 0.399 | 0.304 | 0.822 | -0.365 | 1.2 | 0.24 |
| $(V_R, \bar{V}_R)$ | $(0.06, 0.56)$ | 0.408 | 0.303 | 0.355 | -0.238 | 2.6 | 2.1 |
| $(V_R, \bar{S}_L)$ | $(-0.10, 0.72)$ | 0.410 | 0.306 | 0.359 | -0.507 | 22.9 | 2.0 |
| $(V_R, \bar{S}_R)$ | $(-0.10, 0.72)$ | 0.410 | 0.306 | 0.359 | -0.507 | 22.9 | 2.0 |
| $(\bar{S}_L, S_R)$ | $(0.08, 0.33)$ | 0.405 | 0.304 | 0.722 | -0.365 | 1.9 | $0.43 \times 10^{-2}$ |
| $(\bar{S}_L, T_L)$ | $(-0.49, 0.71)$ | 0.405 | 0.309 | 0.386 | -0.224 | 79.9 | 1.8 |
| $(\bar{S}_L, \bar{V}_L)$ | $(0.20, -0.10)$ | 0.413 | 0.303 | 0.512 | -0.486 | 0.04 | 0.66 |
| $(\bar{S}_L, \bar{V}_R)$ | $(0.06, -0.47)$ | 0.400 | 0.305 | 0.358 | -0.326 | 1.5 | 2.0 |
| $(\bar{S}_R, \bar{V}_R)$ | $(0.06, -0.47)$ | 0.400 | 0.305 | 0.358 | -0.326 | 1.5 | 2.0 |
| $(\bar{S}_L, \bar{S}_L)$ | $(1.08, 0.86)$ | 0.407 | 0.311 | 0.393 | -0.271 | 109.1 | 1.8 |
| $(\bar{S}_L, \bar{S}_R)$ | $(1.08, -0.86)$ | 0.407 | 0.311 | 0.393 | -0.271 | 109.1 | 1.8 |
| $(\bar{S}_R, \bar{T}_L)$ | $(0.18, -0.28)$ | 0.410 | 0.305 | 0.629 | -0.429 | 0.10 | 0.12 |
| $(\bar{T}_L, \bar{V}_L)$ | $(0.01, 0.48)$ | 0.394 | 0.308 | 0.345 | -0.310 | 2.5 | 2.3 |
| $(\bar{T}_L, \bar{V}_R)$ | $(0.01, 0.48)$ | 0.394 | 0.308 | 0.345 | -0.310 | 2.5 | 2.3 |
| $(\bar{T}_L, \bar{S}_L)$ | $(-0.08, -0.66)$ | 0.405 | 0.302 | 0.472 | -0.473 | 18.1 | 0.94 |
| $(\bar{T}_L, \bar{S}_R)$ | $(-0.08, -0.66)$ | 0.405 | 0.302 | 0.472 | -0.473 | 18.1 | 0.94 |
| $(\bar{T}_L, \bar{T}_L)$ | $(0.12, -0.38)$ | 0.392 | 0.307 | 0.741 | -0.345 | 2.3 | 0.16 |
| $(\bar{V}_L, \bar{V}_R)$ | $(-0.05, -0.52)$ | 0.413 | 0.308 | 0.362 | -0.313 | 2.5 | 2.1 |
| $(\bar{V}_L, \bar{S}_L)$ | $(0.37, -0.80)$ | 0.412 | 0.306 | 0.364 | -0.415 | 34.2 | 2.0 |
| $(\bar{V}_L, \bar{S}_R)$ | $(0.44, 0.15)$ | 0.405 | 0.304 | 0.358 | -0.342 | 4.9 | 2.0 |
| $(\bar{V}_R, \bar{T}_L)$ | $(0.34, -0.35)$ | 0.405 | 0.306 | 0.635 | -0.427 | 2.6 | 0.11 |
| $(\bar{V}_R, \bar{S}_L)$ | $(0.44, 0.15)$ | 0.405 | 0.304 | 0.358 | -0.342 | 4.9 | 2.0 |
| $(\bar{V}_R, \bar{S}_R)$ | $(0.37, -0.80)$ | 0.412 | 0.306 | 0.364 | -0.415 | 34.2 | 2.0 |
| $(\bar{V}_R, \bar{T}_L)$ | $(-0.68, 0.44)$ | 0.405 | 0.304 | 0.686 | -0.446 | 3.1 | $0.13 \times 10^{-1}$ |
| $(\bar{S}_L, \bar{S}_R)$ | $(1.36, -0.73)$ | 0.405 | 0.305 | 0.374 | -0.586 | 206.5 | 1.9 |
| $(\bar{S}_L, \bar{T}_L)$ | $(0.49, -0.27)$ | 0.399 | 0.307 | 0.619 | -0.418 | 12.1 | 0.22 |
| $(\bar{S}_R, \bar{T}_L)$ | $(0.49, -0.27)$ | 0.399 | 0.307 | 0.619 | -0.418 | 12.1 | 0.22 |

| Coefficients  | Best fit value | $R_D$ | $R_{D^*}$ | $R_{J/\psi}$ | $P_{D^*}$ | $\mathcal{B}(B_c \rightarrow \tau \nu)$% | $\chi^2_{min}$ |
|--------------|----------------|-------|-----------|-------------|-----------|-------------------------------|-------------|

TABLE II: Best estimates of $R_D$, $R_{D^*}$, $R_{J/\psi}$, $P_{D^*}$, and $\mathcal{B}(B_c \rightarrow \tau \nu)$ within various NP scenarios.