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# New physics effect on $B_c \to J/\psi\tau\bar{\nu}$ in relation to the $R_{D^{(*)}}$ anomaly

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ABSTRACT

We study possible new physics (NP) effects on $B_c \to J/\psi\tau\bar{\nu}$, which has been recently measured at LHCb as the ratio of $R_{J/\psi} = \mathcal{B}(B_c \to J/\psi\tau\bar{\nu})/\mathcal{B}(B_c \to J/\psi\mu\bar{\nu})$. Combining it with the long-standing $R_{D^{(*)}}$ measurements, in which the discrepancy with the prediction of the standard model is present, we find possible solutions to the anomaly by several NP types. Then, we see that adding the $R_{J/\psi}$ measurement does not improve NP fit to data, but the NP scenarios still give better $\chi^2$ than the SM. We also investigate indirect NP constraints from the lifetime of $B_c$ and NP predictions on the $\tau$ longitudinal polarization in $\bar{B} \to D^*\tau\bar{\nu}$.



## 1. Introduction

On recent years, discrepancies with the predictions of the Standard Model (SM) have started to emerge in semi-tauonic decays of $B$ meson, $\bar{B} \to D^{(*)}\tau\bar{\nu}$. Measurements have been done in the lepton-universality ratios,

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu})}\,, \tag{1}$$

for $\ell = e$ or $\mu$. The world average of the BaBar [1,2], Belle [3–5], and LHCb [6,7] results shows $\sim 4\sigma$ deviation from the SM prediction. Then, many theorists have tried to address this anomaly in different new physics (NP) models; as in Refs. [8–23] for model-independent approaches, Refs. [24–36] for charged Higgs, Refs. [37–40] for lepton flavor violation, Refs. [8,41–53] for leptoquarks (in relation to $B \to K^{(*)}\mu^+\mu^-$), and Refs. [54–56] for others. When we start with the low-energy effective field theory, NP effects are described by the four fermion operators of $(bc\tau\nu)$:

$$\begin{aligned}-\mathcal{L} = \frac{4G_F}{\sqrt{2}}V_{cb}\big[&(1+C_{V_1})(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)\\ &+C_{V_2}(\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_L)+C_{S_1}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L)\\ &+C_{S_2}(\bar{c}_R b_L)(\bar{\tau}_R\nu_L)+C_T(\bar{c}_R\sigma^{\mu\nu}b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_L)\big]\,,\end{aligned} \tag{2}$$

where NP effects are encoded in the Wilson coefficients $C_X$. At the present stage, NP contributions with nonzero $C_X$ from single operators in (2) are possible solutions to the $R_{D^{(*)}}$ anomaly except for $C_{S_1}$,[1] according to the previous studies, *e.g.*, as in Refs. [8,9]. The $V_1$ scenario has an advantage such that a similar $V-A$ current in the $bs$ system can also explain the anomalies in $B \to K^{(*)}\mu^+\mu^-$ (*e.g.*, see Refs. [41,48,51]). The $V_2$ scenario requires $C_{V_2}$ to be pure imaginary and the $S_2$ scenario needs a large negative $C_{S_2}$, to address the $R_{D^{(*)}}$ anomaly [13,28].

Some leptoquark (LQ) models contribute to $\bar{B} \to D^{(*)}\tau\bar{\nu}$ with scalar-tensor operators so that $C_{S_2} \simeq \pm 7.8 C_T$ at the $m_b$ scale.[2] Then, they also explain the $R_{D^{(*)}}$ anomaly. For a dedicated study, see Ref. [8].

In Ref. [57], this anomaly has been investigated by looking at the lifetime of $B_c$ meson along with the decay $B_c \to \tau\bar{\nu}$. As $C_X \neq 0$ (for $X \neq T$) also contributes to $B_c \to \tau\bar{\nu}$, it is necessary that the contribution does not exceed the fraction of the total decay width of $B_c$, which has been experimentally measured and theoretically calculated. Indeed, this could allow us to exclude a large contribution from $C_{S_i} \neq 0$. In Ref. [58], a stronger limit on the scalar contribution has been suggested with using LEP1 data for $B_c \to \tau\bar{\nu}$.

In September 2017, the LHCb collaboration reported a new measurement regarding $b \to c\tau\nu$ in $B_c$. To be specific, the ratio

$$R_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu})}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu})} = 0.71 \pm 0.17 \pm 0.18\,, \tag{3}$$

[1] The $S_1$ type operator $(\bar{c}_L b_R)(\bar{\tau}_R\nu_L)$ never accommodates the experimental values of $R_D$ and $R_{D^*}$ at the same time. Henceforth, we skip the $S_1$ scenario in this paper from the beginning.

[2] At the scale where LQ models are defined, the corresponding relations are $C_{S_2} = \pm 4C_T$. These relations are realized for the scalar leptoquark bosons ($R_2$ and $S_1$) that transform as $(\mathbf{3}, \mathbf{2}, 7/6)$ and $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$, respectively.

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has been obtained with dataset of run 1 ($3\,\mathrm{fb}^{-1}$) [59,60]. Thus, this new measurement enables us to develop explanations for the anomaly with the above NP scenarios, which will be shown in this paper. We will also revisit the constraints with use of the lifetime of $B_c$ and put some predictions on the $\tau$ longitudinal polarization.

This letter is then organized as follows. In Sec. 2, we obtain a formula for the decay rate of $B_c \to J/\psi\tau\bar{\nu}$ in the presence of the NP operators. A description of form factors for the $B_c \to J/\psi$ transition is also given. In Sec. 3, we proceed to numerical analysis and obtain possible solutions to the $R_D$, $R_{D^*}$, and $R_{J/\psi}$ measurements by the NP scenarios. We also investigate NP effect on the lifetime of $B_c$, associated with $B_c \to \tau\bar{\nu}$, and the $\tau$ longitudinal polarization in $\bar{B} \to D^*\tau\bar{\nu}$. The Sec. 4 is devoted to summary.

## 2. Description of hadronic amplitude and form factors

The hadronic transition of $B_c \to J/\psi$ can be written in analogy with that of $\bar{B} \to D^*$. Namely, we can obtain the formula for the decay rate of $B_c \to J/\psi\tau\bar{\nu}$ as follows [8],

$$
\begin{aligned}
\frac{d\Gamma}{dq^2} =& \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_{B_c}^3} q^2 \sqrt{\lambda_{J/\psi}(q^2)} \left(1-\frac{m_\tau^2}{q^2}\right)^2 \times \\
& \Bigg\{ (|1+C_{V_1}|^2 + |C_{V_2}|^2) \left[ \left(1+\frac{m_\tau^2}{2q^2}\right)\left(H_{V_+}^2 + H_{V_-}^2 + H_{V_0}^2\right) \right. \\
& \left. + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V_t}^2 \right] - 2\mathrm{Re}[(1+C_{V_1})C_{V_2}^*] \\
& \times \left[ \left(1+\frac{m_\tau^2}{2q^2}\right)\left(H_{V_0}^2 + 2H_{V_+}\cdot H_{V_-}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V_t}^2 \right] \\
& + \frac{3}{2}|C_{S_1} - C_{S_2}|^2 H_S^2 \\
& + 8|C_T|^2 \left(1+\frac{2m_\tau^2}{q^2}\right)\left(H_{T_+}^2 + H_{T_-}^2 + H_{T_0}^2\right) \\
& + 3\mathrm{Re}[(1+C_{V_1}-C_{V_2})(C_{S_1}^* - C_{S_2}^*)] \frac{m_\tau}{\sqrt{q^2}} H_S \cdot H_{V_t} \\
& - 12\mathrm{Re}[(1+C_{V_1})C_T^*] \\
& \times \frac{m_\tau}{\sqrt{q^2}} \left(H_{T_0}\cdot H_{V_0} + H_{T_+}\cdot H_{V_+} - H_{T_-}\cdot H_{V_-}\right) \\
& + 12\mathrm{Re}[C_{V_2}C_T^*] \\
& \times \frac{m_\tau}{\sqrt{q^2}} \left(H_{T_0}\cdot H_{V_0} + H_{T_+}\cdot H_{V_-} - H_{T_-}\cdot H_{V_+}\right) \Bigg\},
\end{aligned} \tag{4}
$$

where $H$s are hadronic helicity amplitudes given by

$$
H_{V_\pm}(q^2) = (m_{B_c} + m_{J/\psi}) A_1^c(q^2) \mp \frac{\sqrt{\lambda_{J/\psi}(q^2)}}{m_{B_c} + m_{J/\psi}} V^c(q^2), \tag{5}
$$

$$
\begin{aligned}
H_{V_0}(q^2) =& \frac{m_{B_c} + m_{J/\psi}}{2m_{J/\psi}\sqrt{q^2}} \left[ -(m_{B_c}^2 - m_{J/\psi}^2 - q^2) A_1^c(q^2) \right. \\
& \left. + \frac{\lambda_{J/\psi}(q^2)}{(m_{B_c}+m_{J/\psi})^2} A_2^c(q^2) \right],
\end{aligned} \tag{6}
$$

$$
H_{V_t}(q^2) = -\sqrt{\frac{\lambda_{J/\psi}(q^2)}{q^2}} A_0^c(q^2), \tag{7}
$$

$$
H_S(q^2) = -\frac{\sqrt{\lambda_{J/\psi}(q^2)}}{m_b + m_c} A_0^c(q^2), \tag{8}
$$

$$
H_{T_\pm}(q^2) = \frac{1}{\sqrt{q^2}} \left[ \pm(m_{B_c}^2 - m_{J/\psi}^2) T_2^c(q^2) + \sqrt{\lambda_{J/\psi}(q^2)} T_1^c(q^2) \right], \tag{9}
$$

$$
\begin{aligned}
H_{T_0}(q^2) =& \frac{1}{2m_{J/\psi}} \left[ -(m_{B_c}^2 + 3m_{J/\psi}^2 - q^2) T_2^c(q^2) \right. \\
& \left. + \frac{\lambda_{J/\psi}(q^2)}{m_{B_c}^2 - m_{J/\psi}^2} T_3^c(q^2) \right],
\end{aligned} \tag{10}
$$

and $\lambda_{J/\psi}(q^2) = [(m_{B_c} - m_{J/\psi})^2 - q^2][(m_{B_c} + m_{J/\psi})^2 - q^2]$. The functions $V^c$, $A_i^c$, and $T_i^c$ are form factors (FFs) for the $B_c \to J/\psi$ transition whose definitions are given in Appendix A. The scalar hadronic amplitude is obtained as in eq. (8) using the quark-level equation of motion.

The FFs for the vector and axial-vector currents have been investigated in Ref. [61] with the use of perturbative QCD [62,63] and then the following parameterizations are given:

$$
V^c(q^2) = V^c(0) \exp\left[0.065\, q^2 + 0.0015\, (q^2)^2\right], \tag{11}
$$

$$
A_0^c(q^2) = A_0^c(0) \exp\left[0.047\, q^2 + 0.0017\, (q^2)^2\right], \tag{12}
$$

$$
A_1^c(q^2) = A_1^c(0) \exp\left[0.038\, q^2 + 0.0015\, (q^2)^2\right], \tag{13}
$$

$$
A_2^c(q^2) = A_2^c(0) \exp\left[0.064\, q^2 + 0.0041\, (q^2)^2\right], \tag{14}
$$

where the values for the $q^2 = 0$ point are obtained by the fit; $V^c(0) = 0.42 \pm 0.01 \pm 0.01$, $A_0^c(0) = 0.52 \pm 0.02 \pm 0.01$, $A_1^c(0) = 0.46 \pm 0.02 \pm 0.01$, and $A_2^c(0) = 0.64 \pm 0.02 \pm 0.01$ [61]. As for the tensor FFs, we simply adopt the quark-level equation of motion (see Ref. [8]). That is,

$$
T_1^c(q^2) = \frac{m_b + m_c}{m_{B_c} + m_{J/\psi}} V^c(q^2), \tag{15}
$$

$$
T_2^c(q^2) = \frac{m_b - m_c}{m_{B_c} - m_{J/\psi}} A_1^c(q^2), \tag{16}
$$

$$
\begin{aligned}
T_3^c(q^2) =& -\frac{m_b - m_c}{q^2} \Big[ m_{B_c}\left(A_1^c(q^2) - A_2^c(q^2)\right) \\
& + m_{J/\psi}\left(A_2^c(q^2) + A_1^c(q^2) - 2A_0^c(q^2)\right) \Big].
\end{aligned} \tag{17}
$$

Therefore, we are now ready to calculate the decay rate in any type of NP model.

## 3. Numerical analysis

For numerical evaluation on $R_{J/\psi}$, we take the following values for input; $m_{B_c} = 6.275\,\mathrm{GeV}$, $m_{J/\psi} = 3.096\,\mathrm{GeV}$, $m_\tau = 1.777\,\mathrm{GeV}$, $m_b + m_c = 6.2\,\mathrm{GeV}$, and $m_b - m_c = 3.45\,\mathrm{GeV}$ [64]. Then, the SM predicts

$$
R_{J/\psi}^{\mathrm{SM}} = 0.283 \pm 0.048, \tag{18}
$$

where the uncertainty comes from the inputs of $V^c(0)$, $A_0^c(0)$, $A_1^c(0)$, and $A_2^c(0)$. The result is consistent with Refs. [65,66]. This is compared with (3) and thus, one finds that there exists a $1.7\sigma$ deviation from the SM, i.e., $[\chi^2]_{J/\psi}^{\mathrm{SM}} \simeq 2.9$. Note that the $R_{J/\psi}$ measurement still include a large uncertainty. Combined with the $R_D$ and $R_{D^*}$ measurements [60,67], it turns out $[\chi^2]_{J/\psi+D+D^*}^{\mathrm{SM}} \simeq 22$.

In Fig. 1, we show correlation between $R_{D^*}$ and $R_{J/\psi}$ in the presence of one NP operator ($V_1$, $V_2$, $S_2$, or $T$) and LQ specific operators ($\mathrm{LQ}_\pm : C_{S_2} = \pm 7.8 C_T$), where the NP type is denoted in the