The effect of W' boson on the semileptonic $B_d^* \to D_d^+ \tau^- \bar{\nu}_\tau$ decay

S. Mahata[1] and S. Sahoo[2]
Department of Physics, National Institute of Technology Durgapur
Durgapur-713209, West Bengal, India
[1]*E-mail: supravatmahata3@gmail.com*, [2]*E-mail: sukadevsahoo@yahoo.com*

Introduction

In recent years, the flavour changing charged current (FCCC) transitions $b \to c l \bar{\nu}_l$ [1-4] have gained a special attention in theoretical and phenomenological studies to test the standard model (SM) and also for finding signal of new physics (NP) beyond the SM. Recently, lots of exciting results come out for this decay channel from experiments. BaBar, Belle and LHCb collaborations have estimated the lepton flavour universality (LFU) ratios $R_{D^{(*)}} = Br(B \to D^{(*)}\tau^- \bar{\nu}_\tau)/Br(B \to D^{(*)} l^- \bar{\nu}_l)$. Using their results, the world average experimental results of $R_D^{Exp} = 0.340 \pm 0.027 \pm 0.013$ and $R_{D^*}^{Exp} = 0.295 \pm 0.011 \pm 0.008$ measured by heavy flavour averaging group (HFAV) [5] are greater than their corresponding SM predictions ($R_D^{SM} = 0.299 \pm 0.003$, $R_{D^*}^{SM} = 0.258 \pm 0.005$) by 1.4σ and 2.5σ respectively. LHCb [6] also published the result $R_{J/\psi} = Br(B_c \to J/\psi \tau \bar{\nu}_\tau)/Br(B_c \to J/\psi l \bar{\nu}_l)$=0.71 $\pm$ 0.17 $\pm$ 0.18 which deviates from the SM prediction ($R_{J/\psi}^{SM} = 0.289 \pm 0.01$) by 2σ. So there exists some contradictions between the experimental results and the SM predictions, which are popularly known as $R_{D^{(*)}}$ and $R_{J/\psi}$ anomalies. Motivated by these anomalies, we are interested to investigate $B_d^* \to D_d^+ \tau^- \bar{\nu}_\tau$ decay in W' model. In this work, we have studied the impact of W' boson on the differential decay rate for this decay.

Theoretical Framework

The most general effective Lagrangian for the transition $b \to c l^- \bar{\nu}_l$ can be written as [7],

$$\begin{aligned}\mathcal{L}_{eff} = &-2\sqrt{2} G_F V_{cb} [(1+V_L)\bar{c}_L \gamma^\mu b_L \bar{l}_L \gamma_\mu \nu_L \\ &+ V_R \bar{c}_R \gamma^\mu b_R \bar{l}_L \gamma_\mu \nu_L + S_L \bar{c}_R b_L \bar{l}_R \nu_L \\ &+ S_R \bar{c}_L b_R \bar{l}_R \nu_L + T_L \bar{c}_R \sigma^{\mu\nu} b_L \bar{l}_R \sigma_{\mu\nu} \nu_L \\ &+ h.c], \end{aligned} \quad (1)$$

where G_F is the Fermi constant, V_{cb} is the CKM matrix element and $V_{L,R}$, $S_{L,R}$, T_L are the new vector, scalar and tensor type new physics couplings. In SM, all these new physics couplings are zero.

The differential decay rate of $B_d^* \to D_d^+ \tau^- \bar{\nu}_\tau$ decay can be expressed as [8]

$$\begin{aligned}\frac{d\Gamma}{dq^2} = &\frac{G_F^2}{288\pi^3} \frac{|\vec{P}|}{m_{B_d^*}^2} |V_{cb}|^2 q^2 \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \Big[(|1 + V_L|^2 + |V_R|^2) \Big[(H_{-+}^2 + H_{+-}^2 + H_{00}^2)\Big(1 + \frac{m_\tau^2}{2q^2}\Big) + \frac{3m_\tau^2}{2q^2} H_{0t}^2\Big] - 2\mathcal{R}e[(1 + V_L)V_R^*]\Big[(2H_{-+}H_{+-} + H_{00}^2)\Big(1 + \frac{m_\tau^2}{2q^2}\Big) + \frac{3m_\tau^2}{2q^2} H_{0t}^2\Big] \\ &+ 3\frac{m_\tau}{\sqrt{q^2}} \mathcal{R}e[(1 + V_L - V_R)(S_L^* - S_R^*)] H'_{0t} H_{0t} + \frac{3}{2}|S_L - S_R|^2 H'^2_{0t}\Big], \end{aligned} \quad (2)$$

where the detail expression with form factors of these helicity amplitudes (H_{00}, H_{0t}, $H_{\pm\mp}$ and H'_{0t}) can be found in ref. [8]. The form factors are the key inputs for numerical analysis. But the lattice calculation results of form factors for $B_d^* \to D_d$ transition are not yet available. We have taken the values of form factors calculated in the BSW model [9,10] from ref. [11]. In our analysis, we have considered 10% uncertainty in the values of form factors at $q^2 = 0$.

W' Model

The W' is a theoretically predicted beyond SM vector boson of charge ± 1. This particle arises from the simplest extension of the electroweak gauge group and it induces through the FCCC transitions. The most general effective Lagrangian for W' boson coupling to quarks and leptons through FCCC transition can be expressed as [3,4,12]

$$\mathcal{L}_{eff}^{W'} = \frac{W'_\mu}{\sqrt{2}} \Big[\bar{u}_i \gamma^\mu \left(\epsilon_{u_i d_j}^L P_L + \epsilon_{u_i d_j}^R P_R\right) d_j + \bar{l}_i \epsilon_{l_i \nu_j}^L \gamma^\mu P_L \nu_j\Big] + h.c , \quad (3)$$

where $P_{L(R)} = \frac{1 \mp \gamma_5}{2}$ is the left (right)-handed chirality projector; and the coefficient $\epsilon_{u_i d_j}^L$, $\epsilon_{u_i d_j}^R$ and $\epsilon_{l_i \nu_j}^L$ are the dimensionless flavour-dependent coupling parameter with $u_i \in$

(u, c, t), $d_j \in (d, s, b)$ and $l_i, l_j \in (e, \mu, \tau)$. Here, we have neglected the contribution of right-handed neutrino and consider that the W' boson couples only to the third-generation leptons.

Now comparing Eq. (3) with Eq. (1), one can get this W' contribution through these two new physics Wilson coefficients given below [3]

$$V_L \equiv \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\epsilon_{cb}^L \epsilon_{\tau\nu_\tau}^L}{M_{W'}^2}$$

$$V_R \equiv \frac{\sqrt{2}}{4G_F V_{cb}} \frac{\epsilon_{cb}^R \epsilon_{\tau\nu_\tau}^L}{M_{W'}^2}, \qquad (4)$$

where $M_{W'}$ is the mass of the W' boson. In our analysis, we have considered only the effect of the left-handed W' boson i.e $V_R = 0$. Because, the operator $\bar{c}_R \gamma^\mu b_R \bar{l}_L \gamma_\mu \nu_L$ does not contribute to the LFU violation at leading order [13].

To fix the W' coupling parameters, lots of work have been done from $R_{D^{(*)}}$ anomalies. The best fitted value $\epsilon_{cb}^L \epsilon_{\tau\nu_\tau}^L = 0.11$ with $M_{W'} = 1$ TeV have been constrained in the ref. [3]. In order to maximize the effects of NP, we have taken the range as [4]

$$\epsilon_{cb}^L \epsilon_{\tau\nu_\tau}^L = (0.12 \pm 0.03) \left(\frac{M_{W'}}{TeV}\right)^2. \qquad (5)$$

Results and Discussions

Using the above W' coupling parameters and all essential input parameters [14], we have investigated the differential decay rate of $B_d^* \to D_d^+ \tau^- \bar{\nu}_\tau$ decay in W' model and made a comparison with the SM to see the NP effect.

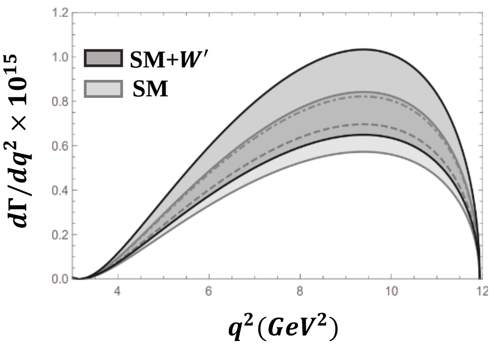

Fig. 1. The variation of differential decay rate with q^2. The dashed and dot dashed lines are the central variation in SM and W' model respectively.

In Fig.1, we have depicted the dependency of differential decay rate on q^2 in W' model as well as in SM. The sensitivity of the W' model have been observed at the middle q^2 region and become very less at the low q^2 and the high q^2region. We have also found a significant amount of deviation between the SM and the W' model. This deviation gives us a possible indication for the existence of NP. We can hope that this W' boson will be discovered in future upcoming collider experiment.

Acknowledgement

Mahata acknowledges NIT Durgapur for providing fellowship. Mahata thanks S. Biswas and M. Maji for useful discussions.

References

[1] M. Freytsis, Z. Ligeti and J. T. Ruderman, *Phys. Rev. D* **92**, 054018 (2017).
[2] X. Q. Li, Y. D. Yang and X. Zhang, *J. High Energy Phys.* **1608**, 054 (2016).
[3] J. D. Gomez, N. Quintero and E. Rojas, *Phys. Rev. D* **100**, 093003 (2019).
[4] X. L. Mu, Y. Li, Z. T. Zou and B. Zhu, *Phys. Rev. D* **100**, 113004 (2019).
[5] Y. Amhis et al. [Heavy Flavour Averaging Group], *Eur. Phys. J. C* **81**, 226 (2021) [arXiv:1909.12524 [hep-ex]].
[6] R. Aaij et al. [LHCb Collaboration], *Phys. Rev. Lett.* **120**, 121801 (2018).
[7] M. Tanaka and R. Watanabe, Phys. Rev. **D 87**, 034028 (2013).
[8] A. Ray, S. Sahoo and R. Mohanta, *Eur. Phys. J. C* **79**, 670 (2019).
[9] M. Wirbel, B. Stech, and M. Bauer, *Z. Phys. C* **29**, 637 (1985).
[10] M. Bauer, B. Stech, and M. Wirbel, *Z. Phys. C* **34**, 103 (1987).
[11] Q. Chang, J. Zhu, N. Wang and R.-M. Wang, *Adv. High Energy Phys.* **2018,** 7231354 (2018).
[12] S. Wang, *Int. J. Theor. Phys.* **60**, 982 (2021).
[13] O. Cat and M. Jung, *Phys. Rev. D* **92**, 055018 (2015).
[14] P. A. Zyla et al. [Particle Data Group], *Prog. Theor. Exp. Phys.* **2020**, 083C01 (2020) and 2021 update.