Model independent analysis of new physics effects on $B_c \rightarrow (D_s, D_s^*)\mu^+\mu^-$ decay observables

Rupak Dutta*

National Institute of Technology Silchar, Silchar 788010, India

(Received 14 June 2019; published 21 October 2019)

Motivated by the anomalies present in $b \rightarrow s l^+ l^-$ neutral current decays, we study the corresponding $B_c \rightarrow (D_s, D_s^*)\mu^+\mu^-$ decays within the standard model and beyond. We use a model independent effective theory formalism in the presence of vector and axial vector new physics operators and study the implications of the latest global fit to the $b \rightarrow s l^+ l^-$ data on various observables for the $B_c \rightarrow (D_s, D_s^*)\mu^+\mu^-$ decays. We give predictions on several observables such as the differential branching ratio, ratio of branching ratios, forward backward asymmetry, and the longitudinal polarization fraction of the D_s^* meson within standard model and within several new physics scenarios. These results can be tested at the Large Hadron Collider and, in principle, can provide complementary information regarding new physics in $b \rightarrow s l^+ l^-$ neutral current decays.

DOI: [10.1103/PhysRevD.100.075025](https://doi.org/10.1103/PhysRevD.100.075025)

I. INTRODUCTION

Although standard model (SM) of particle physics is successful in explaining various experimental observations, it, however, cannot accommodate several longstanding issues such as dark matter, dark energy, neutrino mass, matter antimatter asymmetry in the universe etc. It indirectly confirms the existence of a more global theory beyond the SM. There are two ways to determine the nature of new physics (NP). One is direct detection of new particles and their interactions and another is indirect detection through their effects on various low energy processes. In this respect, flavor physics can, in principle, be the ideal platform to look for indirect evidences of NP. In fact, various anomalies with the SM prediction have been reported by dedicated experiments such as *BABAR*, *Belle*, and more recently by LHCb. In particular, measurement of various observables in $b \rightarrow c \tau \nu$ charged current interactions and in $b \rightarrow s l^+ l^-$ neutral current interactions already provided hints of NP. We will focus here on anomalies present in B meson decays mediated via $b \rightarrow s l^+ l^-$ neutral current interactions. The most important observables are the lepton flavor universality (LFU) ratios R_K and R_{K^*} , various angular observables in $B \rightarrow K^* \mu^+ \mu^-$ decays, and the branching ratio of $B_s \rightarrow \phi \mu^+ \mu^-$ decays.

The experimental results confirming these anomalies are listed below.

A significant deviation from the SM expectation is observed in the LFU ratios R_K and R_{K^*} defined as

$$R_K^{(*)} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu \mu)}{\mathcal{B}(B \rightarrow K^{(*)} e e)}. \quad (1)$$

The first LHCb measurement of $R_K = 0.745_{-0.074}^{+0.090} \pm 0.036$ [1] in the low q^2 bin $1 < q^2 < 6 \text{ GeV}^2$ deviates from the SM prediction $R_K \approx 1$ [2–4] at 2.6σ level. Very recently, the earlier measurement was superseded by LHCb Collaboration and it is reported to be $R_K = 0.846_{-0.054-0.014}^{+0.060+0.016}$ [5]. Although it moves closer to the SM value, the deviation with the SM prediction still stands at 2.5σ level. Similarly, the measured value of $R_{K^*} = 0.66_{-0.07}^{+0.11} \pm 0.03$ and $0.69_{-0.07}^{+0.11} \pm 0.05$ in the dilepton invariant mass $q^2 = [0.045, 1.1] \text{ GeV}^2$ and $[1.1, 6.0] \text{ GeV}^2$ [6] deviate from the SM prediction of $R_{K^*} \approx 1$ [7,8] at approximately 2.1σ and 2.4σ , respectively. Very recently, Belle collaboration has reported the values of R_{K^*} in multiple q^2 bin but with a much larger uncertainties [9]. The other notable deviation is the deviation observed in the angular observable P'_5 in $B \rightarrow K^* \mu^+ \mu^-$ decays [10,11]. LHCb [12,13] and ATLAS [14] have measured the value of the angular observable P'_5 in the q^2 range $4.0 < q^2 < 6.0 \text{ GeV}^2$ and the deviation from the SM prediction is found to be more than 3σ [15]. Belle [16] and CMS [17] have also measured this observable in the q^2 bin $4.3 < q^2 < 8.68 \text{ GeV}^2$ and $4.3 < q^2 < 6.0 \text{ GeV}^2$, respectively. Although the Belle measured value differs from the SM expectation at 2.6σ

*rupak@phy.nits.ac.in

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

level, the measured value by CMS is consistent with the SM expectation at 1σ level. Similarly, there is a systematic deficit in the measured value of branching ratio of $B_s \rightarrow \phi\mu^+\mu^-$ [18,19] decays as compared to the SM prediction [15,20]. Currently the deviation with the SM prediction stands at around 3.7σ . If it persists and is confirmed by future experiments, it could unravel new flavor structure beyond the SM physics. Various global fits [21–31] to the $b \rightarrow sl^+l^-$ data have been performed and it was suggested that some of these anomalies can be resolved by modifying the Wilson coefficients (WCs).

It should be noted that, if these anomalies are due to NP, this will show up in other similar decay modes as well. There are various similar decay channels with same underlying quark level transition and the LFU violation can be explored in these decay modes as well. In this context, $B \rightarrow K_2^*\mu^+\mu^-$ and $B \rightarrow K_1\mu^+\mu^-$ decay modes have been analyzed very recently in Ref. [32] and Ref. [33], respectively. In this paper, we analyze $B_c \rightarrow (D_s, D_s^*)\mu^+\mu^-$ decays mediated via $b \rightarrow sl^+l^-$ neutral current transitions within the SM and in several NP scenarios. LHCb has already measured the ratio of branching ratio $R_{J/\psi}$ in $B_c \rightarrow J/\psi l\bar{l}$ decays. Detection and measurement of various observables pertaining to B_c meson decaying to other mesons via $b \rightarrow sl^+l^-$ neutral current interactions will be feasible once more and more data will be accumulated by LHCb. It is worth mentioning that the study of such modes is complimentary to the study of $B \rightarrow (K, K^*)\mu^+\mu^-$ decays and it can, in principle, provide useful information regarding different NP Lorentz structures. Moreover, study of these decay modes both theoretically and experimentally can act as a useful ingredient in maximizing future sensitivity to NP.

Within the SM, $B_c \rightarrow (D_s, D_s^*)\mu^+\mu^-$ decays have been studied previously using the relativistic constituent quark model [34], light-front quark model [35,36], QCD sum rules [37,38], and relativistic quark model [39]. In this paper, we use the relativistic quark model of Ref. [39] and supplement the previous analysis by analyzing the effect of several NP on these decay modes in a model independent way. We use an effective theory formalism in the presence of new vector and axial vector couplings that couples only to the muon sector. We give prediction of several observables such as the ratio of branching ratios, lepton side forward backward asymmetry, and the longitudinal polarization fraction of the D_s^* meson within the SM and within various NP scenarios.

Our paper is organized as follows. In Sec. II, we start with the effective weak Hamiltonian for $b \rightarrow sl^+l^-$ decays in the presence of new vector and axial vector operators. We also discuss the hadronic matrix elements of $B_c \rightarrow D_s$ and $B_c \rightarrow D_s^*$ and their parametrization in terms of various meson to meson transition form factors. In Sec. III, we write down the helicity amplitudes for the $B_c \rightarrow D_s\mu^+\mu^-$ and $B_c \rightarrow D_s^*\mu^+\mu^-$ decay modes and construct several

observables. In Sec. IV, we give predictions of all the observables in the SM and in several NP cases obtained from the global fit. We conclude with a brief summary of our results in Sec. V.

II. FORMALISM

The most general effective weak Hamiltonian in the presence of new vector and axial vector operators for the $|\Delta B| = |\Delta S| = 1$ transition can be written as

$$\begin{aligned} \mathcal{H}_{\text{eff}} = & -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{\alpha_e}{4\pi}\left[C_9^{\text{eff}}\bar{s}\gamma^\mu P_L b\bar{l}\gamma_\mu l + C_{10}\bar{s}\gamma^\mu P_L b\bar{l}\gamma_\mu\gamma_5 l \right. \\ & -\frac{2m_b}{q^2}C_7^{\text{eff}}\bar{s}iq_\nu\sigma^{\mu\nu}P_R b\bar{l}\gamma_\mu l + C_9^{\text{NP}}\bar{s}\gamma^\mu P_L b\bar{l}\gamma_\mu l \\ & + C_{10}^{\text{NP}}\bar{s}\gamma^\mu P_L b\bar{l}\gamma_\mu\gamma_5 l + C_9'\bar{s}\gamma^\mu P_R b\bar{l}\gamma_\mu l \\ & \left. + C_{10}'\bar{s}\gamma^\mu P_R b\bar{l}\gamma_\mu\gamma_5 l\right], \end{aligned} \quad (2)$$

where G_F is the Fermi coupling constant, α_e is the electromagnetic coupling constant, V_{tb} and V_{ts} are the relevant Cabibbo Kobayashi Maskawa (CKM) matrix elements, and $P_{R,L} = (1 \pm \gamma_5)/2$ are the chiral projectors. All the WCs are evaluated at a renormalization scale of $\mu = m_b^{\text{pole}} = 4.8$ GeV. The b quark mass associated with C_7^{eff} is considered to be running mass in the $\overline{\text{MS}}$ scheme. In principle, there can be several NP Lorentz structures such as vector, axial vector, scalar, pseudoscalar, and tensor. The scalar, pseudoscalar and the tensor NP operators are severely constrained by $B_s \rightarrow \mu\mu$ and $b \rightarrow s\gamma$ measurements [40–42]. Hence, we consider NP in the form of vector and axial vector operators only. Again, we do not consider NP in the dipole operator as these are well constrained by radiative decays. The non factorizable corrections coming from electromagnetic corrections to the matrix elements of purely hadronic operators in the weak effective Hamiltonian are ignored in our analysis. These corrections, however, are expected to be significant at low q^2 [43,44]. All the NP WCs C_9^{NP} , C_{10}^{NP} , C_9' , and C_{10}' are assumed to be real for our analysis. In the SM, $C_9^{\text{NP}} = C_{10}^{\text{NP}} = C_9' = C_{10}' = 0$. The effective WCs C_7^{eff} and C_9^{eff} are defined as

$$\begin{aligned} C_7^{\text{eff}} &= C_7 - \frac{1}{3}C_5 - C_6, \\ C_9^{\text{eff}} &= C_9 + y(q^2) + y_{\text{BW}}(q^2), \end{aligned} \quad (3)$$

where the contributions coming from the one loop matrix elements of the four quark operators are contained in [45]

$$y(q^2) = h\left(\frac{m_c}{m_b}, \frac{q^2}{m_b^2}\right)(3C_1 + C_2 + 3C_3 + C_4 + 3C_5 + C_6) - \frac{1}{2}h\left(1, \frac{q^2}{m_b^2}\right)(4C_3 + 4C_4 + 3C_5 + C_6) - \frac{1}{2}h\left(0, \frac{q^2}{m_b^2}\right)(C_3 + 3C_4) + \frac{2}{9}(3C_3 + C_4 + 3C_5 + C_6). \quad (4)$$

Here

$$h(z, s) = -\ln \frac{m_b}{\mu} - \frac{8}{9} \ln z + \frac{8}{27} + \frac{4}{9}x - \frac{2}{9}(2+x)|1-x|^{1/2} \begin{cases} \ln \left| \frac{\sqrt{1-x}+1}{\sqrt{1-x}-1} \right| - i\pi & \text{for } x = \frac{4z^2}{s} < 1 \\ 2 \arctan \frac{1}{\sqrt{x-1}} & \text{for } x = \frac{4z^2}{s} > 1 \end{cases}$$

$$h(0, s) = \frac{8}{27} - \ln \frac{m_b}{\mu} - \frac{4}{9} \ln s + \frac{4}{9} i\pi. \quad (5)$$

The phenomenological parameter $y_{\text{BW}}(q^2)$ involves the long distance effects coming from the $c\bar{c}$ resonance contributions coming from J/Ψ , Ψ' etc. In particular, these resonances provide large peaked contributions in the q^2 bins that are close to these charmonium resonance masses. The corresponding q^2 bins are not considered in our analysis. The values of masses of charm and bottom quark in these expressions are defined in pole mass scheme. The WCs that contains the short distance contribution can be

calculated perturbatively, whereas, for the calculation of the long distance contributions contained in the matrix elements of local operators between initial and final hadron states, it requires a nonperturbative approach. The hadronic matrix elements can be expressed in terms of various meson to meson transition form factors.

The hadronic matrix elements for the $B_c \rightarrow D_s \mu^+ \mu^-$ decays can be parametrized in terms of three invariant form factors. Those are

$$\langle D_s | \bar{s} \gamma^\mu b | B_c \rangle = f_+(q^2) \left[p_{B_c}^\mu + p_{D_s}^\mu - \frac{M_{B_c}^2 - M_{D_s}^2}{q^2} q^\mu \right] + f_0(q^2) \frac{M_{B_c}^2 - M_{D_s}^2}{q^2} q^\mu,$$

$$\langle D_s | \bar{s} \sigma^{\mu\nu} q_\nu b | B_c \rangle = \frac{if_T(q^2)}{M_{B_c} + M_{D_s}} [q^2(p_{B_c}^\mu + p_{D_s}^\mu) - (M_{B_c}^2 - M_{D_s}^2)q^\mu]. \quad (6)$$

Similarly, for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays, the hadronic matrix elements can be parametrized in terms of seven invariant form factors, i.e.,

$$\langle D_s^* | \bar{s} \gamma^\mu b | B_c \rangle = \frac{2iV(q^2)}{M_{B_c} + M_{D_s^*}} \epsilon^{\mu\nu\rho\sigma} \epsilon_\nu^* p_{B_c\rho} p_{D_s^*\sigma},$$

$$\langle D_s^* | \bar{s} \gamma^\mu \gamma_5 b | B_c \rangle = 2M_{D_s^*} A_0(q^2) \frac{\epsilon^* \cdot q}{q^2} q^\mu + (M_{B_c} + M_{D_s^*}) A_1(q^2) \left(\epsilon^{*\mu} - \frac{\epsilon^* \cdot q}{q^2} q^\mu \right) - A_2(q^2) \frac{\epsilon^* \cdot q}{M_{B_c} + M_{D_s^*}} \left[p_{B_c}^\mu + p_{D_s^*}^\mu - \frac{M_{B_c}^2 - M_{D_s^*}^2}{q^2} q^\mu \right],$$

$$\langle D_s^* | \bar{s} i \sigma^{\mu\nu} q_\nu b | B_c \rangle = 2T_1(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\nu^* p_{B_c\rho} p_{D_s^*\sigma},$$

$$\langle D_s^* | \bar{s} i \sigma^{\mu\nu} \gamma_5 q_\nu b | B_c \rangle = T_2(q^2) [(M_{B_c}^2 - M_{D_s^*}^2) \epsilon^{*\mu} - (\epsilon^* \cdot q)(p_{B_c}^\mu + p_{D_s^*}^\mu)] + T_3(q^2) (\epsilon^* \cdot q) \left[q^\mu - \frac{q^2}{M_{B_c}^2 - M_{D_s^*}^2} (p_{B_c}^\mu + p_{D_s^*}^\mu) \right], \quad (7)$$

where $q^\mu = (p_B - p_{D_s, D_s^*})^\mu$ is the four momentum transfer and ϵ_μ is polarization vector of the D_s^* meson. For the $B_c \rightarrow D_s$ and $B_c \rightarrow D_s^*$ transition form factors we follow the relativistic quark model adopted in Ref. [39]. It was mentioned in Ref. [39] that in the limit of infinitely heavy quark mass and large energy of the final meson, the form factor results obtained in this approach are consistent with all the model independent symmetry relations [46,47]. We refer to Ref. [39] for all the omitted details.

III. HELICITY AMPLITUDES AND DECAY OBSERVABLES

For the helicity amplitudes, we pattern our analysis after that of Ref. [39] and, indeed, adopt a common notation. We

use the helicity techniques of Refs. [48,49] and write the hadronic helicity amplitudes for $B_c \rightarrow D_s l^+ l^-$ decays in the presence of vector and axial vector NP operators as follows:

$$\begin{aligned}
 H_{\pm}^{(i)} &= 0, \\
 H_0^{(1)} &= \sqrt{\frac{\lambda}{q^2}} \left[(C_9^{\text{eff}} + C_9^{\text{NP}} + C'_9) f_+(q^2) + C_7^{\text{eff}} \frac{2m_b}{M_{B_c} + M_{D_s}} f_T(q^2) \right] \\
 H_0^{(2)} &= \sqrt{\frac{\lambda}{q^2}} (C_{10} + C_{10}^{\text{NP}} + C'_{10}) f_+(q^2), \\
 H_t^{(1)} &= \frac{M_{B_c}^2 - M_{D_s}^2}{q^2} (C_9^{\text{eff}} + C_9^{\text{NP}} + C'_9) f_0(q^2), \\
 H_t^{(2)} &= \frac{M_{B_c}^2 - M_{D_s}^2}{q^2} (C_{10} + C_{10}^{\text{NP}} + C'_{10}) f_0(q^2)
 \end{aligned} \tag{8}$$

Similarly, for $B_c \rightarrow D_s^* l^+ l^-$ decays, the hadronic helicity amplitudes are

$$\begin{aligned}
 H_{\pm}^{(1)} &= -(M_{B_c}^2 - M_{D_s^*}^2) \left[(C_9^{\text{eff}} + C_9^{\text{NP}} - C'_9) \frac{A_1(q^2)}{M_{B_c} - M_{D_s^*}} + \frac{2m_b}{q^2} C_7^{\text{eff}} T_2(q^2) \right] \\
 &\quad \pm \sqrt{\lambda} \left[(C_9^{\text{eff}} + C_9^{\text{NP}} + C'_9) \frac{V(q^2)}{M_{B_c} + M_{D_s^*}} + \frac{2m_b}{q^2} C_7^{\text{eff}} T_1(q^2) \right], \\
 H_{\pm}^{(2)} &= (C_{10} + C_{10}^{\text{NP}} - C'_{10}) [-(M_{B_c} + M_{D_s^*}) A_1(q^2)] \pm (C_{10} + C_{10}^{\text{NP}} + C'_{10}) \frac{\sqrt{\lambda}}{M_{B_c} + M_{D_s^*}} V(q^2), \\
 H_0^{(1)} &= -\frac{1}{2M_{D_s^*} \sqrt{q^2}} \left\{ (C_9^{\text{eff}} + C_9^{\text{NP}} - C'_9) \left[(M_{B_c}^2 - M_{D_s^*}^2 - q^2)(M_{B_c} + M_{D_s^*}) A_1(q^2) - \frac{\lambda}{M_{B_c} + M_{D_s^*}} A_2(q^2) \right] \right. \\
 &\quad \left. + 2m_b C_7^{\text{eff}} \left[(M_{B_c}^2 + 3M_{D_s^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{M_{B_c}^2 - M_{D_s^*}^2} T_3(q^2) \right] \right\} \\
 H_0^{(2)} &= -\frac{1}{2M_{D_s^*} \sqrt{q^2}} (C_{10} + C_{10}^{\text{NP}} - C'_{10}) \left[(M_{B_c}^2 - M_{D_s^*}^2 - q^2)(M_{B_c} + M_{D_s^*}) A_1(q^2) - \frac{\lambda}{M_{B_c} + M_{D_s^*}} A_2(q^2) \right] \\
 H_t^{(1)} &= -\sqrt{\frac{\lambda}{q^2}} (C_9^{\text{eff}} + C_9^{\text{NP}} - C'_9) A_0(q^2), \\
 H_t^{(2)} &= -\sqrt{\frac{\lambda}{q^2}} (C_{10} + C_{10}^{\text{NP}} - C'_{10}) A_0(q^2),
 \end{aligned} \tag{9}$$

where

$$\lambda = M_{B_c}^4 + M_{D_s, D_s^*}^4 + q^4 - 2(M_{B_c}^2 M_{D_s, D_s^*}^2 + M_{D_s, D_s^*}^2 q^2 + M_{B_c}^2 q^2). \tag{10}$$

Using the helicity amplitudes, the three body $B_c \rightarrow D_s l^+ l^-$ and $B_c \rightarrow D_s^* l^+ l^-$ differential decay rate can be written as [39]

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{(2\pi)^3} \left(\frac{\alpha_e |V_{tb} V_{ts}^*|}{2\pi} \right)^2 \frac{\lambda^{1/2} q^2}{48M_{B_c}^3} \sqrt{1 - \frac{4m_l^2}{q^2}} \left[H^{(1)} H^{\dagger(1)} \left(1 + \frac{4m_l^2}{q^2} \right) + H^{(2)} H^{\dagger(2)} \left(1 - \frac{4m_l^2}{q^2} \right) + \frac{2m_l^2}{q^2} 3H_t^{(2)} H_t^{\dagger(2)} \right], \tag{11}$$

where m_l denotes the mass of lepton and

$$H^{(i)} H^{\dagger(i)} = H_+^{(i)} H_+^{\dagger(i)} + H_-^{(i)} H_-^{\dagger(i)} + H_0^{(i)} H_0^{\dagger(i)}. \tag{12}$$

We define the differential ratio of branching ratio as follows:

$$R_{D_s, D_s^*}(q^2) = \frac{d\Gamma/dq^2(B_c \rightarrow (D_s, D_s^*)\mu^+\mu^-)}{d\Gamma/dq^2(B_c \rightarrow (D_s, D_s^*)e^+e^-)}. \quad (13)$$

$$A_{FB}(q^2) = \frac{3}{4} \sqrt{1 - \frac{4m_l^2}{q^2}} \left\{ \frac{\text{Re}(H_+^{(1)} H_+^{\dagger(2)}) - \text{Re}(H_-^{(1)} H_-^{\dagger(2)})}{H^{(1)} H^{\dagger(1)} (1 + \frac{4m_l^2}{q^2}) + H^{(2)} H^{\dagger(2)} (1 - \frac{4m_l^2}{q^2}) + \frac{2m_l^2}{q^2} 3H_t^{(2)} H_t^{\dagger(2)}} \right\}. \quad (14)$$

Similarly, the longitudinal polarization fraction of the D_s^* meson can be written as [39]

$$F_L(q^2) = \frac{H_0^{(1)} H_0^{\dagger(1)} (1 + \frac{4m_l^2}{q^2}) + H_0^{(2)} H_0^{\dagger(2)} (1 - \frac{4m_l^2}{q^2}) + \frac{2m_l^2}{q^2} 3H_t^{(2)} H_t^{\dagger(2)}}{H^{(1)} H^{\dagger(1)} (1 + \frac{4m_l^2}{q^2}) + H^{(2)} H^{\dagger(2)} (1 - \frac{4m_l^2}{q^2}) + \frac{2m_l^2}{q^2} 3H_t^{(2)} H_t^{\dagger(2)}} \quad (15)$$

It should be noted that the forward backward asymmetry observable $A_{FB}(q^2)$ for the $B_c \rightarrow D_s \mu^+ \mu^-$ decay mode is zero in the SM as the helicity amplitudes $H_{\pm}^i = 0$. It is worth mentioning that it can have a nonzero value only if it receives contribution from scalar, pseudoscalar, or tensor NP operators. Since we consider NP in vector and axial vector operators only, we do not discuss $A_{FB}(q^2)$ for the $B_c \rightarrow D_s \mu^+ \mu^-$ decay mode in Sec. IV.

IV. RESULTS AND DISCUSSION

A. Inputs

For definiteness, we first report all the inputs that are used for the computation of all the decay observables. We employ a renormalization scale of $\mu = 4.8$ GeV throughout our analysis. For the meson masses, we use $M_{B_c} = 6.2751$ GeV, $M_{D_s} = 1.968$ GeV, and $M_{D_s^*} = 2.1122$ GeV, as given in Ref. [50]. For the lepton masses, we use $m_e = 0.5109989461 \times 10^{-3}$ GeV and $m_\mu = 0.1056583715$ GeV

We also construct observables such as the forward backward asymmetry of the lepton pair A_{FB} and the longitudinal polarization fraction of the D_s^* meson F_L as a function of dilepton invariant mass q^2 . The forward backward asymmetry $A_{FB}(q^2)$ is given by [39]

from Ref. [50]. Similarly, the mean life time of B_c meson and the Fermi coupling constant are taken to be $\tau_{B_c} = 0.507 \times 10^{-12}$ s and $G_F = 1.1663787 \times 10^{-5}$ GeV⁻², as reported in Ref. [50]. For the quark masses, we use $m_b(\overline{\text{MS}}) = 4.2$ GeV, $m_c(\overline{\text{MS}}) = 1.28$ GeV, and $m_b^{\text{pole}} = 4.8$ GeV [51]. For the electromagnetic coupling constant, we use $\alpha_e^{-1} = 133.28$. We use $|V_{tb} V_{ts}| = 0.0401 \pm 0.0010$ as given in Ref. [52]. The WCs in our numerical estimates, taken from Refs. [53], are reported in Table. I. A relativistic quark model based on quasipotential approach was adopted in Ref. [39] to determine various $B_c \rightarrow D_s$ and $B_c \rightarrow D_s^*$ transition form factors. Various form factors at $q^2 = 0$ and the fitted parameters σ_1 and σ_2 , taken from Ref. [39], are reported in Table II. It was shown in Ref. [39] that the q^2 dependence of the form factors can be well parametrized and reproduced in the form:

$$F(q^2) = \frac{F(0)}{(1 - \frac{q^2}{M^2}) (1 - \sigma_1 \frac{q^2}{M_{B_s^*}^2} + \sigma_2 \frac{q^4}{M_{B_s^*}^4})} \quad (16)$$

for $F(q^2) = f_+(q^2), f_T(q^2), V(q^2), A_0(q^2), T_1(q^2)$. Whereas, for $F(q^2) = f_0(q^2), A_1(q^2), A_2(q^2), T_2(q^2), T_3(q^2)$, it can be well approximated by

$$F(q^2) = \frac{F(0)}{(1 - \sigma_1 \frac{q^2}{M_{B_s^*}^2} + \sigma_2 \frac{q^4}{M_{B_s^*}^4})}, \quad (17)$$

TABLE I. Wilson coefficients evaluated at renormalization scale of $\mu = 4.8$ GeV from Ref. [53].

C_1	C_2	C_3	C_4	C_5	C_6	C_7^{eff}	C_9	C_{10}
-0.248	1.107	0.011	-0.026	0.007	-0.031	-0.313	4.344	-4.669

TABLE II. $B_c \rightarrow D_s$ and $B_c \rightarrow D_s^*$ form factors at $q^2 = 0$ and the fitted parameters σ_1 and σ_2 from Ref. [39].

	f_+	f_0	f_T	V	A_0	A_1	A_2	T_1	T_2	T_3
F_0	0.129	0.129	0.098	0.182	0.070	0.089	0.110	0.085	0.085	0.051
σ_1	2.096	2.331	1.412	2.133	1.561	2.479	2.833	1.540	2.577	2.783
σ_2	1.147	1.666	0.048	1.183	0.192	1.686	2.167	0.248	1.859	2.170

TABLE III. q^2 bin (in GeV^2) averaged values of various observables of $B_c \rightarrow D_s \mu^+ \mu^-$ and $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays in the SM. The uncertainties in each observable corresponds to the uncertainties associated with the meson to meson transition form factors and the CKM matrix elements.

Observable/ q^2 bin	[0.045–1.0]	[1.0–2.0]	[2.0–3.0]	[3.0–4.0]	[4.0–5.0]	[5.0–6.0]	[1.0–6.0]
$10^7 \times \mathcal{B}(B_c \rightarrow D_s \mu \mu)$	0.025 ± 0.001	0.030 ± 0.002	0.034 ± 0.002	0.038 ± 0.002	0.043 ± 0.003	0.049 ± 0.004	0.194 ± 0.013
R_{D_s}	1.006 ± 0.008	1.007 ± 0.002	1.005 ± 0.001	1.004 ± 0.001	1.003 ± 0.001	1.003 ± 0.001	1.004 ± 0.001
$10^7 \times \mathcal{B}(B_c \rightarrow D_s^* \mu \mu)$	0.024 ± 0.001	0.011 ± 0.001	0.014 ± 0.002	0.020 ± 0.002	0.028 ± 0.003	0.039 ± 0.004	0.113 ± 0.012
$\langle A_{FB}^{D_s^*} \rangle$	-0.064 ± 0.002	-0.076 ± 0.012	0.033 ± 0.006	0.110 ± 0.009	0.160 ± 0.011	0.194 ± 0.013	0.123 ± 0.009
$\langle F_L^{D_s^*} \rangle$	0.266 ± 0.033	0.711 ± 0.034	0.662 ± 0.032	0.566 ± 0.035	0.488 ± 0.036	0.430 ± 0.037	0.526 ± 0.035
$R_{D_s^*}$	0.999 ± 0.005	0.993 ± 0.002	0.992 ± 0.001	0.993 ± 0.001	0.994 ± 0.001	0.995 ± 0.001	0.994 ± 0.001

where $M = M_{B_s}$ for $A_0(q^2)$ and $M = M_{B_s^*}$ for all other form factors. We use $M_{B_s} = 5.36689 \text{ GeV}$ and $M_{B_s^*} = 5.4154 \text{ GeV}$ from Ref. [50]. The form factors describe the hadronization of quarks and gluons: these involve QCD in the nonperturbative regime and are a significant source of theoretical uncertainties. To gauge the effect of the form factor uncertainties on various observables, we have used $\pm 5\%$ uncertainty in $F(0)$, σ_1 and σ_2 .

B. SM prediction of $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decay observables

Now let us proceed to discuss our results in the SM. In Table III, we report our q^2 bin averaged values of various observables for the $B_c \rightarrow D_s \mu^+ \mu^-$ and $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays. We restrict our analysis to low dilepton invariant mass region and consider seven q^2 bins ranging from (0.045–6.0) GeV^2 . The central values are obtained using the central values of all the input parameters. For the uncertainties, we have performed a naive χ^2 analysis defined as

$$\chi^2 = \sum_i \frac{(\mathcal{O}_i - \mathcal{O}_i^0)^2}{\Delta_i^2}, \quad (18)$$

where $\mathcal{O}_i = (|V_{tb} V_{ts}^*|, F(0), \sigma_1, \sigma_2)$. Here $\mathcal{O}_i^0$ represents the central values of all the parameters and Δ_i represents 1σ uncertainty associated with each parameter. To find out the uncertainties in each observable, We impose $\chi^2 \leq 2.156$ for the $B_c \rightarrow D_s \mu^+ \mu^-$ decays and $\chi^2 \leq 8.643$ for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays. In the SM, we find the branching ratios of $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decays to be of $\mathcal{O}(10^{-8})$ which might be within the experimental sensitivity of LHCb because of the large number of B_c mesons that are being produced at the LHC. We also obtain the LFU ratios to be $R_{D_s, D_s^*} \approx 1$ in the SM. It is observed that in the q^2 bin ranging from (0.045–2) GeV^2 , the $\langle A_{FB}^{D_s^*} \rangle$ observable assumes negative values, whereas, for $q^2 > 2 \text{ GeV}^2$, it assumes positive values. It should be noted that the uncertainty associated with the LFU ratios R_{D_s} and $R_{D_s^*}$ are quite negligible in comparison to the uncertainties present in the branching ratio, the forward backward asymmetry $\langle A_{FB}^{D_s^*} \rangle$ and the longitudinal polarization

fraction of the D_s^* meson $\langle F_L^{D_s^*} \rangle$. Measurements of these ratios in future will be crucial in determining various NP Lorentz structures.

We have shown in Fig. 1 the q^2 dependence of differential branching ratios, forward backward asymmetry, and longitudinal polarization fraction of D_s^* meson in the low q^2 region $0.045 \leq q^2 \leq 6 \text{ GeV}^2$. The line corresponds to the central values of all the input parameters, whereas, the band corresponds to the uncertainties associated with the CKM matrix element and the form factor inputs. In the SM, we find the zero crossing in $A_{FB}(q^2)$ of $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays at $q^2 = 2.2 \pm 0.2 \text{ GeV}^2$. Our results are quite similar to the values reported in Ref. [39]. Slight deviations may occur due to different choices of input parameters.

C. New physics analysis

Our main objective is to determine the effect of NP on $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decay observables in a model independent way. To this end, we use an effective theory formalism in the presence of new vector (V) and axial vector (A) couplings in our analysis. Although there can be other NP Lorentz structures such as scalar (S), pseudoscalar (P), and tensor (T), they are severely constrained by $B_s \rightarrow \mu \mu$ and $b \rightarrow s \gamma$ data. Hence we omit any discussion regarding these NP operators. Global fits of NP to the $b \rightarrow s l^+ l^-$ data have been carried out by several groups [21–31]. In Ref. [30], the authors perform a global fit of C_9^{NP} , C_{10}^{NP} , C_9' , and C_{10}' by using the constraints coming not only from R_K , R_{K^*} , P_5' , and $\mathcal{B}(B_s \rightarrow \phi \mu^+ \mu^-)$ but also from $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$, differential branching ratios of $B^{0,+} \rightarrow K^{0,+} \mu^+ \mu^-$, $B^{0,+} \rightarrow K^{0,+} \mu^+ \mu^-$, and $B \rightarrow X_s \mu^+ \mu^-$, angular observables in $B^0 \rightarrow K^{0*} \mu^+ \mu^-$ and $B_s \rightarrow \phi \mu^+ \mu^-$ decays. Two different scenarios were considered in Ref. [30]. In 1D scenario, the best solutions to these anomalies were obtained for C_9^{NP} , C_{10}^{NP} , $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ and $C_9^{\text{NP}} = -C_9'$. Similarly, for 2D scenario, where NP contributes to two WCs, the best solutions were obtained for $(C_9^{\text{NP}}, C_{10}^{\text{NP}})$, (C_9^{NP}, C_9') , and $(C_9^{\text{NP}}, C_{10}')$. There are other possibilities with different WCs exist that give rise to similar fits. We, however, consider only seven of them: four from 1D scenario and three from 2D scenario. The best fit

FIG. 1. Differential branching ratio dB/dq^2 , forward backward asymmetry of lepton pair $A_{FB}(q^2)$ and longitudinal polarization fraction of D_s^* meson $F_L(q^2)$ for the $B_c \rightarrow D_s \mu^+ \mu^-$ and $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays in the SM. The band corresponds to the uncertainties in the transition form factors and the CKM matrix elements as discussed in the text.

values and the corresponding $\Delta\chi^2$ values of all these NP WCs for 1D and 2D scenarios, taken from Ref. [30], are reported in Table IV. It should be noted that NP contributions to (C_9^{NP}, C'_9) and $(C_9^{\text{NP}}, C'_{10})$ are the most favored ones from the 2D scenario and NP in $C_9^{\text{NP}} = -C'_9$ is the most favored one from 1D scenario.

In Appendix, we report q^2 bin averaged values of various observables such as the branching ratio, ratio of branching ratio, forward backward asymmetry, and longitudinal polarization fraction of the D_s^* meson for the $B_c \rightarrow D_s \mu^+ \mu^-$ and $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays in the presence of these NP WCs. In each q^2 bin, the branching ratio of $B_c \rightarrow D_s \mu^+ \mu^-$ is smaller in each NP scenarios than in the SM except for $C_9^{\text{NP}} = -C'_9$. It remains SM like for $C_9^{\text{NP}} = -C'_9$. A similar conclusion can be made for the ratio of branching ratio R_{D_s} as well. For the $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay, the bin averaged branching ratio and the ratio of branching ratio $R_{D_s^*}$ in each q^2 bin for each NP scenarios are smaller than the corresponding SM value. However, the A_{FB} and F_L values can be either smaller or larger in NP cases than the SM central value. It should be mentioned that the deviation of R_{D_s} , $R_{D_s^*}$, and A_{FB} from the SM prediction can be quite large in some q^2 bins.

In Fig. 2, we show various q^2 dependent observables for the $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decays in the presence of various NP WCs in 1D scenario. Our observations are as follows:

- (i) The differential branching ratio for the $B_c \rightarrow D_s \mu^+ \mu^-$ decays is reduced at all q^2 for C_9^{NP} , C_{10}^{NP} , and $C_9^{\text{NP}} = -C'_{10}$, whereas, it remains SM like for $C_9^{\text{NP}} = -C'_9$. This could very well be understood from Eq. (8) that $H_0^{(1)}$ and $H_t^{(1)}$ helicity amplitudes for the $B_c \rightarrow D_s \mu^+ \mu^-$ decay mode depend on the combination $C_9^{\text{NP}} + C'_9$. Hence the NP contribution cancels. It should be noted that, except for $C_9^{\text{NP}} = -C'_9$, all the other NP scenarios are distinguishable from the SM prediction at slightly more than 1σ significance. Moreover, the deviation from

TABLE IV. Best fit and the corresponding $\Delta\chi^2$ values of different new vector and axial vector Wilson coefficients in 1D and 2D scenarios taken from Ref. [30].

Wilson coefficients	Best fit values	$\Delta\chi^2$
C_9^{NP}	-1.07	37.6
C_{10}^{NP}	+0.78	27.0
$C_9^{\text{NP}} = -C'_{10}$	-0.52	36.3
$C_9^{\text{NP}} = -C'_9$	-1.11	40.5
$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	(-0.94, +0.23)	41.8
(C_9^{NP}, C'_9)	(-1.27, +0.68)	49.4
$(C_9^{\text{NP}}, C'_{10})$	(-1.36, -0.46)	52.8

FIG. 2. Differential branching ratio $d\mathcal{B}/dq^2$, forward backward asymmetry of lepton pair $A_{FB}(q^2)$ and longitudinal polarization fraction of D_s^* meson $F_L(q^2)$ for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ and $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays in the SM (red) and for the best fit values of new VA couplings in 1D scenario. Green, blue, purple, and yellow lines correspond to the best fit values of $C_9^{\text{NP}} = -1.07$, $C_{10}^{\text{NP}} = 0.78$, $C_9^{\text{NP}} = -C_{10}^{\text{NP}} = -0.52$, and $C_9^{\text{NP}} = -C'_9 = -1.11$, respectively. The SM error band is shown with grey.

the SM prediction is more pronounced in case of $C_9^{\text{NP}} = -C_{10}^{\text{NP}} = -0.52$ NP scenario.

- (ii) The differential branching ratio for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays is reduced at all q^2 for C_9^{NP} , C_{10}^{NP} , $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$, and $C_9^{\text{NP}} = -C'_9$. The deviation with the SM prediction increases as q^2 increases for each NP WCs. It should be mentioned that the differential branching ratio obtained in each of these NP scenarios, however, lies within the SM error band.
- (iii) For all the NP couplings, the zero crossing in the forward backward asymmetry observable $A_{FB}^{D_s^*}$ is shifted to the higher values of q^2 than in the SM. There is, however, one exception. For $C_{10}^{\text{NP}} = 0.78$, the zero crossing coincides with the SM prediction although the shape of $A_{FB}^{D_s^*}$ may slightly vary. Maximum deviation from the SM prediction is observed for C_9^{NP} and $C_9^{\text{NP}} = -C'_9$. We observe the zero crossing of $A_{FB}^{D_s^*}$ at $q^2 \approx 2.8 \text{ GeV}^2$ in case of C_9^{NP} and $C_9^{\text{NP}} = -C'_9$ NP scenarios which are clearly distinguishable from the SM prediction $q^2 \approx 2.2 \pm 0.2 \text{ GeV}^2$ at 3σ significance. Similarly, for $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$ scenario, the zero crossing appears at $q^2 \approx 2.4 \text{ GeV}^2$ and it is distinguishable from the SM case at 1σ significance.

- (iv) The peak of the longitudinal polarization fraction of D_s^* meson may shift toward a higher values of q^2 than in the SM. Although the longitudinal polarization fraction F_L is reduced at all q^2 for C_9^{NP} , $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$, and $C_9^{\text{NP}} = -C'_9$, it may increase with C_{10}^{NP} for $q^2 > 1.2 \text{ GeV}^2$.

There are other combinations of VA couplings exist in the 1D scenario as reported in Ref. [30]. We, however, do not consider those cases because of their small $\Delta\chi^2$ values.

We now consider several NP WCs from the 2D scenarios having high $\Delta\chi^2$ values from the global fit [30]. The best fit values, taken from Ref. [30], are reported in Table IV. We show in Fig. 3 various observables such as differential branching ratio $d\mathcal{B}/dq^2$, forward backward asymmetry of lepton pair $A_{FB}(q^2)$, and longitudinal polarization fraction of D_s^* meson $F_L(q^2)$ as a function of dilepton invariant mass q^2 for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ and $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays in the presence of such NP. Our main observations are as follows:

- (i) The differential branching ratio for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay is reduced at all q^2 for each NP couplings. The deviation from the SM prediction is more pronounced in case of $(C_9^{\text{NP}}, C_{10}^{\text{NP}}) = (-0.94, +0.23)$. It should be noted that only $(C_9^{\text{NP}}, C_{10}^{\text{NP}})$ NP scenario can be

FIG. 3. Differential branching ratio dB/dq^2 , forward backward asymmetry of lepton pair $A_{FB}(q^2)$ and longitudinal polarization fraction of D_s^* meson $F_L(q^2)$ for the $B_c \rightarrow D_s \mu^+ \mu^-$ and $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays in the SM (red) and for the best fit values of new VA couplings in 2D scenario. Green, blue and purple lines correspond to the best fit values of $(C_9^{\text{NP}}, C_{10}^{\text{NP}}) = (-0.94, +0.23)$, $(C_9^{\text{NP}}, C'_9) = (-1.27, +0.68)$ and $(C_9^{\text{NP}}, C'_{10}) = (-1.36, -0.46)$, respectively. The SM error band is shown with grey.

distinguished from the SM case at around 2σ significance.

- (ii) Similar to $B_c \rightarrow D_s \mu^+ \mu^-$, the differential branching ratio for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ decay is also reduced at all q^2 . The deviation with the SM prediction, however, increases with increase in q^2 . It reaches maximum at $q^2 = 6 \text{ GeV}^2$. The deviation observed in each scenario, however, lies within the SM error band.
- (iii) The zero crossing in the forward backward asymmetry observable $A_{FB}(q^2)$ is shifted to higher values of q^2 than in the SM for each NP WCs. The maximum deviation from the SM prediction is observed for $(C_9^{\text{NP}}, C'_{10}) = (-1.36, -0.46)$ which is shown with a purple line in Fig. 3. The zero of A_{FB} is distinguishable from the SM case at more than 4σ significance in case of (C_9^{NP}, C'_9) and $(C_9^{\text{NP}}, C'_{10})$ NP scenarios, whereas, the significance is around 2.5σ for $(C_9^{\text{NP}}, C_{10}^{\text{NP}})$ NP scenario. Hence, a measurement of the zero of the A_{FB} will be a good candidate to probe new physics structures that is responsible for lepton flavor universality violation in $b \rightarrow sl^+ l^-$ sector.
- (iv) The longitudinal polarization fraction of the D_s^* meson $F_L(q^2)$ decreases once we include the NP

WCs. It is observed that the peak of the $F_L(q^2)$ distribution reduces and shifted toward slightly higher q^2 than in the SM. Maximum deviation from the SM prediction is observed for $(C_9^{\text{NP}}, C'_{10}) = (-1.36, -0.46)$ which is shown with a purple line in Fig. 3.

V. CONCLUSION

Motivated by the anomalies present in $B \rightarrow (K, K^*) \mu^+ \mu^-$ decays, we have analyzed $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decays mediated via $b \rightarrow sl^+ l^-$ neutral current transitions using the $B_c \rightarrow (D_s, D_s^*)$ transition form factors obtained in the relativistic quark model. We use a model independent effective theory formalism and include NP effects coming from new vector and axial vector operators only. We discard scalar, pseudoscalar, and tensor operators as they are severely constrained by $B_s \rightarrow \mu\mu$ and $b \rightarrow s\gamma$ data. Several authors have performed global fits to the $b \rightarrow sl^+ l^-$ data and proposed two types of NP scenarios, namely, 1D and 2D scenarios. In the 1D scenario, we chose four NP cases in which the NP contribution is coming from only one NP WCs at a time. In the 2D scenario, we chose three NP cases in which the NP contribution is coming from two NP WCs at a time.

We give predictions on several observables such as branching ratio, ratio of branching ratio, forward backward asymmetry, and the longitudinal polarization fraction of the D_s^* meson in the SM and in several NP cases. We observe that for most of the NP cases, the branching ratio for both the decay modes is reduced at all q^2 . In most cases, the zero of $A_{FB}(q^2)$ parameter is shifted to the higher value of q^2 than in the SM. However, with only C_{10}^{NP} , the zero crossing is SM like. Similarly, for the longitudinal polarization fraction of the D_s^* meson, the peak of the distribution is reduced at all q^2 and it is slightly shifted toward higher value of q^2 than in the SM. It is worth emphasizing that the zero of forward backward asymmetry parameter $A_{FB}(q^2)$ can be clearly distinguished from the SM case at more than 4σ significance for (C_9^{NP}, C_9') and $(C_9^{\text{NP}}, C_{10}')$ NP scenarios. Similarly, it can be distinguished from the SM case at 2.5σ and 3σ significance for $(C_9^{\text{NP}}, C_{10}^{\text{NP}})$, C_9^{NP} and $C_9^{\text{NP}} = -C_9'$ NP scenarios, respectively. These results are quite interesting because measurement of the zero of A_{FB} for the $B_c \rightarrow D_s^* \mu^+ \mu^-$ decays in future can put additional constraint on

the NP Lorentz structures that are responsible for lepton flavor universality violation in $b \rightarrow sl^+ l^-$ sector. Similarly, the lepton flavor universal ratios R_{D_s} and $R_{D_s^*}$ are exceptionally clean observables with theoretical errors being at the level of only 1% making them an ideal candidate to probe new physics.

Although there is a hint of NP in $b \rightarrow sl^+ l^-$ transition decays, NP is not yet established. Unlike $B \rightarrow (K, K^*) \mu^+ \mu^-$ decays which are rigorously studied both theoretically and experimentally, the $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decays mediated via same underlying quark level transition received significantly less attention. Measurement of various observables for the $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decays and at the same time improved estimates of various $B_c \rightarrow D_s$ and $B_c \rightarrow D_s^*$ transition form factors in future will be crucial in identifying the true nature of NP. Again, to enhance the significance of various measurements related to $b \rightarrow sl^+ l^-$ decays and to disentangle genuine NP effects from various statistical and systematic uncertainties, more data samples are needed.

APPENDIX: PREDICTION OF OBSERVABLES IN THE SM AND IN SEVERAL NP CASES

In Tables (V–X), we report, the q^2 bin averaged values of all the observables for the $B_c \rightarrow (D_s, D_s^*) \mu^+ \mu^-$ decays in the SM and in several NP cases.

TABLE V. q^2 bin averaged values of $10^7 \times \mathcal{B}(B_c \rightarrow D_s \mu^+ \mu^-)$ in the SM and in several NP cases from $1D$ and $2D$ scenarios.

q^2 bin (GeV^2)	SM	C_9^{NP}	C_{10}^{NP}	$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	$C_9^{\text{NP}} = -C_9'$	$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	(C_9^{NP}, C_9')	$(C_9^{\text{NP}}, C_{10}')$
[0.045, 1.0]	0.025	0.020	0.021	0.020	0.025	0.019	0.022	0.022
[1.0, 2.0]	0.030	0.024	0.025	0.023	0.030	0.023	0.026	0.026
[2.0, 3.0]	0.034	0.027	0.028	0.026	0.034	0.026	0.030	0.029
[3.0, 4.0]	0.038	0.030	0.032	0.030	0.038	0.029	0.033	0.033
[4.0, 5.0]	0.043	0.034	0.036	0.034	0.043	0.033	0.038	0.037
[5.0, 6.0]	0.049	0.039	0.042	0.039	0.049	0.038	0.043	0.042
[1.0, 6.0]	0.193	0.154	0.163	0.152	0.193	0.149	0.171	0.166

TABLE VI. q^2 bin averaged values of R_{D_s} in the SM and in several NP cases from $1D$ and $2D$ scenarios.

q^2 bin (GeV^2)	SM	C_9^{NP}	C_{10}^{NP}	$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	$C_9^{\text{NP}} = -C_9'$	$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	(C_9^{NP}, C_9')	$(C_9^{\text{NP}}, C_{10}')$
[0.045, 1.0]	1.006	0.798	0.846	0.788	1.006	0.770	0.884	0.859
[1.0, 2.0]	1.007	0.803	0.845	0.790	1.007	0.774	0.888	0.867
[2.0, 3.0]	1.005	0.802	0.844	0.788	1.005	0.773	0.886	0.865
[3.0, 4.0]	1.004	0.801	0.844	0.788	1.004	0.772	0.885	0.863
[4.0, 5.0]	1.003	0.800	0.845	0.789	1.003	0.772	0.884	0.861
[5.0, 6.0]	1.003	0.799	0.847	0.790	1.003	0.772	0.884	0.859
[1.0, 6.0]	1.004	0.801	0.845	0.789	1.004	0.773	0.885	0.863

TABLE VII. q^2 bin averaged values of $10^7 \times \mathcal{B}(B_c \rightarrow D_s^* \mu^+ \mu^-)$ in the SM and in several NP cases from 1D and 2D scenarios.

q^2 bin (GeV ²)	SM	C_9^{NP}	C_{10}^{NP}	$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	$C_9^{\text{NP}} = -C'_9$	$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	(C_9^{NP}, C'_9)	$(C_9^{\text{NP}}, C'_{10})$
[0.045, 1.0]	0.024	0.024	0.023	0.023	0.023	0.023	0.023	0.023
[1.0, 2.0]	0.011	0.010	0.009	0.009	0.009	0.010	0.010	0.009
[2.0, 3.0]	0.014	0.012	0.011	0.011	0.011	0.012	0.011	0.011
[3.0, 4.0]	0.020	0.017	0.016	0.015	0.016	0.016	0.016	0.015
[4.0, 5.0]	0.028	0.023	0.022	0.022	0.022	0.022	0.022	0.021
[5.0, 6.0]	0.039	0.032	0.031	0.030	0.030	0.030	0.030	0.028
[1.0, 6.0]	0.113	0.095	0.090	0.087	0.088	0.089	0.088	0.085

TABLE VIII. q^2 bin averaged values of $R_{D_s^*}$ in the SM and in several NP cases from 1D and 2D scenarios.

q^2 bin (GeV ²)	SM	C_9^{NP}	C_{10}^{NP}	$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	$C_9^{\text{NP}} = -C'_9$	$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	(C_9^{NP}, C'_9)	$(C_9^{\text{NP}}, C'_{10})$
[0.045, 1.0]	0.999	0.995	0.994	0.957	0.961	0.977	0.975	0.970
[1.0, 2.0]	0.993	0.915	0.801	0.815	0.834	0.860	0.855	0.830
[2.0, 3.0]	0.992	0.859	0.776	0.770	0.790	0.804	0.797	0.767
[3.0, 4.0]	0.993	0.834	0.781	0.760	0.778	0.783	0.774	0.744
[4.0, 5.0]	0.994	0.820	0.790	0.760	0.772	0.774	0.763	0.733
[5.0, 6.0]	0.995	0.812	0.799	0.763	0.768	0.769	0.756	0.726
[1.0, 6.0]	0.994	0.834	0.791	0.768	0.786	0.786	0.776	0.746

TABLE IX. q^2 bin averaged values of $\langle A_{FB}^{D_s^*} \rangle$ in the SM and in several NP cases from 1D and 2D scenarios.

q^2 bin (GeV ²)	SM	C_9^{NP}	C_{10}^{NP}	$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	$C_9^{\text{NP}} = -C'_9$	$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	(C_9^{NP}, C'_9)	$(C_9^{\text{NP}}, C'_{10})$
[0.045, 1.0]	-0.064	-0.069	-0.056	-0.062	-0.072	-0.066	-0.072	-0.072
[1.0, 2.0]	-0.076	-0.124	-0.079	-0.103	-0.138	-0.121	-0.141	-0.150
[2.0, 3.0]	0.033	-0.028	0.035	0.006	-0.033	-0.020	-0.043	-0.052
[3.0, 4.0]	0.110	0.055	0.117	0.092	0.055	0.065	0.043	0.037
[4.0, 5.0]	0.160	0.112	0.168	0.148	0.116	0.123	0.104	0.099
[5.0, 6.0]	0.194	0.153	0.201	0.186	0.159	0.164	0.147	0.144
[1.0, 6.0]	0.123	0.072	0.129	0.107	0.074	0.082	0.062	0.056

TABLE X. q^2 bin averaged values of $\langle F_L^{D_s^*} \rangle$ in the SM and in several NP cases from 1D and 2D scenarios.

q^2 bin (GeV ²)	SM	C_9^{NP}	C_{10}^{NP}	$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	$C_9^{\text{NP}} = -C'_9$	$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	(C_9^{NP}, C'_9)	$(C_9^{\text{NP}}, C'_{10})$
[0.045, 1.0]	0.266	0.213	0.232	0.215	0.181	0.208	0.186	0.177
[1.0, 2.0]	0.711	0.620	0.725	0.671	0.558	0.630	0.567	0.554
[2.0, 3.0]	0.662	0.613	0.697	0.661	0.548	0.627	0.566	0.558
[3.0, 4.0]	0.566	0.541	0.594	0.573	0.476	0.552	0.498	0.493
[4.0, 5.0]	0.488	0.475	0.508	0.496	0.413	0.482	0.435	0.432
[5.0, 6.0]	0.430	0.423	0.444	0.437	0.365	0.428	0.387	0.385
[1.0, 6.0]	0.526	0.503	0.546	0.529	0.440	0.511	0.461	0.457

- [1] R. Aaij *et al.* (LHCb Collaboration), Test of Lepton Universality Using $B^+ \rightarrow K^+\ell^+\ell^-$ Decays, *Phys. Rev. Lett.* **113**, 151601 (2014).
- [2] G. Hiller and F. Kruger, More model-independent analysis of $b \rightarrow s$ processes, *Phys. Rev. D* **69**, 074020 (2004).
- [3] C. Bobeth, G. Hiller, and G. Piranishvili, Angular distributions of $\bar{B} \rightarrow \bar{K}\ell^+\ell^-$ decays, *J. High Energy Phys.* **12** (2007) 040.
- [4] M. Bordone, G. Isidori, and A. Pattori, On the Standard Model predictions for R_K and R_{K^*} , *Eur. Phys. J. C* **76**, 440 (2016).
- [5] R. Aaij *et al.* (LHCb Collaboration), Search for Lepton-Universality Violation in $B^+ \rightarrow K^+\ell^+\ell^-$ Decays, *Phys. Rev. Lett.* **122**, 191801 (2019).
- [6] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality with $B^0 \rightarrow K^{*0}\ell^+\ell^-$ decays, *J. High Energy Phys.* **08** (2017) 055.
- [7] B. Capdevila, S. Descotes-Genon, J. Matias, and J. Virto, Assessing lepton-flavour non-universality from $B \rightarrow K^*\ell\ell$ angular analyses, *J. High Energy Phys.* **10** (2016) 075.
- [8] N. Serra, R. Silva Coutinho, and D. van Dyk, Measuring the breaking of lepton flavor universality in $B \rightarrow K^*\ell^+\ell^-$, *Phys. Rev. D* **95**, 035029 (2017).
- [9] A. Abdesselam *et al.* (Belle Collaboration), Test of lepton flavor universality in $B \rightarrow K^*\ell^+\ell^-$ decays at Belle, *arXiv:1904.02440*.
- [10] S. Descotes-Genon, J. Matias, M. Ramon, and J. Virto, Implications from clean observables for the binned analysis of $B \rightarrow K^*\mu^+\mu^-$ at large recoil, *J. High Energy Phys.* **01** (2013) 048.
- [11] S. Descotes-Genon, T. Hurth, J. Matias, and J. Virto, Optimizing the basis of $B \rightarrow K^*\ell\ell$ observables in the full kinematic range, *J. High Energy Phys.* **05** (2013) 137.
- [12] R. Aaij *et al.* (LHCb Collaboration), Measurement of Form-Factor-Independent Observables in the Decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$, *Phys. Rev. Lett.* **111**, 191801 (2013).
- [13] R. Aaij *et al.* (LHCb Collaboration), Angular analysis of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay using 3 fb⁻¹ of integrated luminosity, *J. High Energy Phys.* **02** (2016) 104.
- [14] M. Aaboud *et al.* (ATLAS Collaboration), Angular analysis of $B_d^0 \rightarrow K^*\mu^+\mu^-$ decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *J. High Energy Phys.* **10** (2018) 047.
- [15] J. Aebischer, J. Kumar, P. Stangl, and D. M. Straub, A global likelihood for precision constraints and flavour anomalies, *Eur. Phys. J. C* **79**, 509 (2019).
- [16] A. Abdesselam *et al.* (Belle Collaboration), Angular analysis of $B^0 \rightarrow K^*(892)^0\ell^+\ell^-$, *arXiv:1604.04042*.
- [17] CMS Collaboration, Measurement of the P_1 and P'_5 angular parameters of the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV, Report No. CMS-PAS-BPH-15-008.
- [18] R. Aaij *et al.* (LHCb Collaboration), Differential branching fraction and angular analysis of the decay $B_s^0 \rightarrow \phi\mu^+\mu^-$, *J. High Energy Phys.* **07** (2013) 084.
- [19] R. Aaij *et al.* (LHCb Collaboration), Angular analysis and differential branching fraction of the decay $B_s^0 \rightarrow \phi\mu^+\mu^-$, *J. High Energy Phys.* **09** (2015) 179.
- [20] A. Bharucha, D. M. Straub, and R. Zwicky, $B \rightarrow V\ell^+\ell^-$ in the Standard Model from light-cone sum rules, *J. High Energy Phys.* **08** (2016) 098.
- [21] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, Patterns of New Physics in $b \rightarrow s\ell^+\ell^-$ transitions in the light of recent data, *J. High Energy Phys.* **01** (2018) 093.
- [22] W. Altmannshofer, P. Stangl, and D. M. Straub, Interpreting hints for lepton flavor universality violation, *Phys. Rev. D* **96**, 055008 (2017).
- [23] G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre, and A. Urbano, Flavour anomalies after the R_{K^*} measurement, *J. High Energy Phys.* **09** (2017) 010.
- [24] G. Hiller and I. Nisandzic, R_K and R_{K^*} beyond the standard model, *Phys. Rev. D* **96**, 035003 (2017).
- [25] L. S. Geng, B. Grinstein, S. Jger, J. Martin Camalich, X. L. Ren, and R. X. Shi, Towards the discovery of new physics with lepton-universality ratios of $b \rightarrow s\ell\ell$ decays, *Phys. Rev. D* **96**, 093006 (2017).
- [26] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, On flavourful easter eggs for new physics hunger and lepton flavour universality violation, *Eur. Phys. J. C* **77**, 688 (2017).
- [27] A. Celis, J. Fuentes-Martin, A. Vicente, and J. Virto, Gauge-invariant implications of the LHCb measurements on lepton-flavor nonuniversality, *Phys. Rev. D* **96**, 035026 (2017).
- [28] A. K. Alok, B. Bhattacharya, A. Datta, D. Kumar, J. Kumar, and D. London, New physics in $b \rightarrow s\mu^+\mu^-$ after the measurement of R_{K^*} , *Phys. Rev. D* **96**, 095009 (2017).
- [29] A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, New physics in $b \rightarrow s\mu^+\mu^-$: Distinguishing models through CP -violating effects, *Phys. Rev. D* **96**, 015034 (2017).
- [30] A. K. Alok, A. Dighe, S. Gangal, and D. Kumar, Continuing search for new physics in $b \rightarrow s\mu\mu$ decays: Two operators at a time, *J. High Energy Phys.* **06** (2019) 089.
- [31] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, New physics in $b \rightarrow s\ell^+\ell^-$ confronts new data on lepton universality, *Eur. Phys. J. C* **79**, 719 (2019).
- [32] D. Das, B. Kindra, G. Kumar, and N. Mahajan, $B \rightarrow K_2^*(1430)\ell^+\ell^-$ distributions at large recoil in the Standard Model and beyond, *Phys. Rev. D* **99**, 093012 (2019).
- [33] Z. R. Huang, M. A. Paracha, I. Ahmed, and C. D. Lü, Testing leptoquark and Z' models via $B \rightarrow K_1(1270, 1400)\mu^+\mu^-$ decays, *arXiv:1812.03491*.
- [34] A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Korner, and V. E. Lyubovitskij, The exclusive rare decays $B \rightarrow K(K^*)\bar{\ell}\ell$ and $B_c \rightarrow D(D^*)\bar{\ell}\ell$ in a relativistic quark model, *Eur. Phys. J. direct A* **4**, 1 (2002).
- [35] C. Q. Geng, C. W. Hwang, and C. C. Liu, Study of rare $B_c^+ \rightarrow D_{d,s} +$ lepton anti-lepton decays, *Phys. Rev. D* **65**, 094037 (2002).
- [36] H. M. Choi, Light-front quark model analysis of the exclusive rare $B_c \rightarrow D_{(s)}(\ell^+\ell^-, \nu_\ell\bar{\nu}_\ell)$ decays, *Phys. Rev. D* **81**, 054003 (2010).
- [37] K. Azizi, F. Falahati, V. Bashiry, and S. M. Zebarjad, Analysis of the rare $B_c \rightarrow D_{s,d}^*l^+l^-$ decays in QCD, *Phys. Rev. D* **77**, 114024 (2008).

- [38] K. Azizi and R. Khosravi, Analysis of the rare semileptonic $B_c \rightarrow P(D, D_s)\ell^+\ell^-/\nu\bar{\nu}$ decays within QCD sum rules, *Phys. Rev. D* **78**, 036005 (2008).
- [39] D. Ebert, R. N. Faustov, and V. O. Galkin, Rare semileptonic decays of B and B_c mesons in the relativistic quark model, *Phys. Rev. D* **82**, 034032 (2010).
- [40] A. K. Alok, A. Datta, A. Dighe, M. Duraishamy, D. Ghosh, and D. London, New physics in $b \rightarrow s\mu^+\mu^-$: CP-conserving observables, *J. High Energy Phys.* **11** (2011) 121.
- [41] A. K. Alok, A. Datta, A. Dighe, M. Duraishamy, D. Ghosh, and D. London, New physics in $b \rightarrow s\mu^+\mu^-$: CP-violating observables, *J. High Energy Phys.* **11** (2011) 122.
- [42] D. Bardhan, P. Byakti, and D. Ghosh, Role of tensor operators in R_K and R_{K^*} , *Phys. Lett. B* **773**, 505 (2017).
- [43] M. Beneke, T. Feldmann, and D. Seidel, Systematic approach to exclusive $B \rightarrow V\ell^+\ell^-$, $V\gamma$ decays, *Nucl. Phys. B* **612**, 25 (2001).
- [44] M. Beneke, T. Feldmann, and D. Seidel, Exclusive radiative and electroweak $b \rightarrow d$ and $b \rightarrow s$ penguin decays at NLO, *Eur. Phys. J. C* **41**, 173 (2005).
- [45] A. J. Buras and M. Munz, Effective Hamiltonian for $B \rightarrow X_s e^+e^-$ beyond leading logarithms in the NDR and HV schemes, *Phys. Rev. D* **52**, 186 (1995).
- [46] J. Charles, A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Heavy to light form-factors in the heavy mass to large energy limit of QCD, *Phys. Rev. D* **60**, 014001 (1999).
- [47] D. Ebert, R. N. Faustov, and V. O. Galkin, Form-factors of heavy to light B decays at large recoil, *Phys. Rev. D* **64**, 094022 (2001).
- [48] J. G. Korner and G. A. Schuler, Exclusive semileptonic heavy meson decays including lepton mass effects, *Z. Phys. C* **46**, 93 (1990).
- [49] A. Kadeer, J. G. Korner, and U. Moosbrugger, Helicity analysis of semileptonic hyperon decays including lepton mass effects, *Eur. Phys. J. C* **59**, 27 (2009).
- [50] M. Tanabashi *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **98**, 030001 (2018).
- [51] W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub, and M. Wick, Symmetries and asymmetries of $B \rightarrow K^*\mu^+\mu^-$ decays in the Standard Model and beyond, *J. High Energy Phys.* **01** (2009) 019.
- [52] M. Bona *et al.* (UTfit Collaboration), The unitarity triangle fit in the standard model and hadronic parameters from lattice QCD: A reappraisal after the measurements of Δm_s and $\text{BR}(B \rightarrow \text{TV}_T)$, *J. High Energy Phys.* **10** (2006) 081.
- [53] A. Ali, P. Ball, L. T. Handoko, and G. Hiller, A comparative study of the decays $B \rightarrow (K, K^*)\ell^+\ell^-$ in standard model and supersymmetric theories, *Phys. Rev. D* **61**, 074024 (2000).