Signature of lepton flavor universality violation in $B_s \rightarrow D_s \tau \nu$ semileptonic decays

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Deviation from the standard model prediction is observed in many semileptonic B decays mediated via $b \rightarrow c$ charged current interactions. In particular, current experimental measurements of the ratio of branching ratio R_D and R_{D^*} in $B \rightarrow D^{(*)} l \nu$ decays disagree with standard model expectations at the level of about 4.1σ . Moreover, the recent measurement of the ratio of branching ratio $R_{J/\Psi}$ by LHCb, where $R_{J/\Psi} = \mathcal{B}(B_c \rightarrow J/\Psi \tau \nu) / \mathcal{B}(B_c \rightarrow J/\Psi \mu \nu)$, is more than 2σ away from the standard model prediction. In this context, we consider an effective Lagrangian in the presence of vector and scalar new physics couplings to study the implications of R_D and R_{D^*} anomalies in $B_s \rightarrow D_s \tau \nu$ decays. We give a prediction of several observables such as the branching ratio, ratio of branching ratio, forward backward asymmetry parameter, τ polarization fraction, and convexity parameter for the $B_s \rightarrow D_s \tau \nu$ decays within the standard model and within various new physics scenarios.

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I. INTRODUCTION

There are several reasons to believe that the standard model (SM) of particle physics is not a complete theory and thus there must be physics beyond the SM. It is therefore crucial to find the pattern of the new physics (NP) that is responsible for various long-standing anomalies. The underlying framework of the SM assumes that the charge and neutral leptons are universal in the weak interaction. However, various recent studies on semileptonic B decays such as $B \rightarrow D^{(*)} l \nu$, with l either e , μ , or τ , challenged the lepton flavor universality [1]. From the past few years, many experiments such as B factories have reported observables that are deviating from the SM prediction. In particular, the ratio of branching ratios R_D and R_{D^*} in $B \rightarrow D^{(*)} l \nu$ is measured to have a large discrepancy with respect to its SM counterpart.

A very precise SM prediction of the ratio of branching ratio R_D in $B \rightarrow D l \nu$ using the form factors obtained in lattice QCD is reported to be 0.300 ± 0.008 [2–5]. Although a full lattice calculation of various form factors for the $B \rightarrow D^*$ transition is not available, a precise prediction of $R_{D^*} = 0.252 \pm 0.003$ using heavy quark expansion including leading perturbative and power corrections [6] exists. Very

recently, in Ref [7], the authors predicted the value of R_{D^*} to be 0.260 ± 0.008 . Comparing with the current world averages of $R_D = 0.407 \pm 0.039 \pm 0.024$ and $R_{D^*} = 0.304 \pm 0.013 \pm 0.007$ from BABAR [8], Belle [9–11], and LHCb [12], the combined deviation currently stands at about 4.1σ . For definiteness, we report in Table I the current status of the experimentally measured ratio of branching ratios R_D and R_{D^*} [13]. Various studies in explaining the observed anomalies in B meson decays can be found in Refs. [14–44]. Very recently, LHCb measured the ratio of branching ratio $R_{J/\psi}$ to be $0.71 \pm 0.17 \pm 0.18$ [45]. Comparing with the SM prediction [46–48], we find the deviation to be at more than 2σ . Although a precise calculation of $B_c \rightarrow J/\Psi$ form factors is not available at present, preliminary results for the form factors are provided by the HPQCD Collaboration using lattice QCD [49].

Inspired by the anomalies present in $B \rightarrow (D, D^*) \tau \nu$ decays, we study the corresponding $B_s \rightarrow D_s \tau \nu$ semileptonic decays within SM and within various NP scenarios. A systematic study of $B_s \rightarrow D_s \tau \nu$ decays is important for

TABLE I. Current status of R_D and R_{D^*} [13].

Experiments	R_{D^*}	R_D
BABAR	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$
Belle	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$
Belle	$0.302 \pm 0.030 \pm 0.011$	...
LHCb	$0.336 \pm 0.027 \pm 0.030$	...
Belle	$0.270 \pm 0.035^{+0.028}_{-0.025}$	...
LHCb	$0.285 \pm 0.019 \pm 0.029$	...
Average	$0.304 \pm 0.013 \pm 0.007$	$0.407 \pm 0.039 \pm 0.024$

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several reasons. First, in the limit of SU(3) flavor symmetry, $B_s \rightarrow D_s \tau \nu$ and $B \rightarrow D \tau \nu$ decay modes should show similar properties. Second, since $B \rightarrow (D, D^*) \tau \nu$ and $B_s \rightarrow D_s \tau \nu$ decays are mediated via a $b \rightarrow c$ charged current interaction, anomalies present in $B \rightarrow (D, D^*) \tau \nu$ should show up in the $B_s \rightarrow D_s \tau \nu$ mode as well. Again, a combined analysis of B and B_s meson decays theoretically and experimentally may help us to determine $|V_{cb}|$ with higher precision, and this may also give some hints about our understanding of the inclusive and exclusive determination of $|V_{cb}|$.

The semileptonic $B_s \rightarrow D_s l \nu$ decays have been studied by various authors [50–61]. Within the SM, the branching ratio and ratio of the branching ratio have been calculated using the form factors obtained from perturbative QCD, the constituent quark meson model, the covariant light-front quark model, the light-cone sum rule, and more recently lattice QCD. Our main motivation here is to study the implications of R_D and R_{D^*} anomalies on $B_s \rightarrow D_s \tau \nu$ decays in a model-independent way. To this end, we use an effective theory formalism in the presence of NP to give prediction on various observables such as the decay rate, ratio of the branching ratio, lepton-side forward-backward asymmetry, longitudinal polarization fraction of the lepton, and convexity parameter for the $B_s \rightarrow D_s \tau \nu$ decays. We follow Ref. [62] for various $B_s \rightarrow D_s$ transition form factors. For our NP analysis, we impose 1σ constraint coming from the measured ratio of branching ratios R_D and R_{D^*} to obtain the allowed NP parameter space. This is to ensure that the resulting NP parameter space can simultaneously explain the anomalies present in R_D and R_{D^*} . We also use the constraint coming from the B_c meson lifetime in our analysis as it is shown in Ref. [38] that the lifetime of the B_c meson puts severe constraint on various NP couplings. Based on various SM calculations [63–65] of the B_c lifetime, it is found that $\mathcal{B}(B_c \rightarrow \tau \nu)$ cannot be more than 5%. However, this can be relaxed up to 30% depending on the input parameters that are used in the SM calculation. Very recently, in Ref. [66], a more stringent bound of $\mathcal{B}(B_c \rightarrow \tau \nu) \leq 10\%$ was obtained using the large electron-positron collider data at the Z peak.

The present discussion is organized as follows. In Sec. II, we start with a brief discussion of the most general effective Lagrangian in the presence of NP for the $b \rightarrow c l \nu$ quark-level transition decays. The three-body differential decay width formula obtained using the helicity formalism is also reported in Sec. II. Explicit formulas of various observables such as the ratio of the branching ratio, lepton-side forward-backward asymmetry, τ polarization fraction, and convexity parameter for the $B_s \rightarrow D_s \tau \nu$ decays in the presence of NP are reported. In Sec. III, we first report all the input parameters that are relevant for our numerical computation. Standard model results and the effects of NP couplings on various observables under various NP scenarios are reported in Sec. III. Finally, we conclude and summarize our results in Sec. IV.

II. PHENOMENOLOGY

The natural way to introduce NP effects in a model-independent approach is to construct an effective Lagrangian for the weak decays that includes both SM and the beyond-the-SM physics. We follow Refs. [67,68] and write the effective weak Lagrangian for the $b \rightarrow c \tau \nu$ quark-level transition decays in the presence of vector- and scalar-type NP interactions as

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & -\frac{4G_F}{\sqrt{2}} V_{cb} \left\{ (1 + V_L) \bar{l}_L \gamma_\mu \nu_L \bar{c}_L \gamma^\mu b_L \right. \\ & + V_R \bar{l}_L \gamma_\mu \nu_L \bar{c}_R \gamma^\mu b_R + \tilde{V}_L \bar{l}_R \gamma_\mu \nu_R \bar{c}_L \gamma^\mu b_L \\ & + \tilde{V}_R \bar{l}_R \gamma_\mu \nu_R \bar{c}_R \gamma^\mu b_R + S_L \bar{l}_R \nu_L \bar{c}_R b_L + S_R \bar{l}_R \nu_L \bar{c}_L b_R \\ & \left. + \tilde{S}_L \bar{l}_L \nu_R \bar{c}_R b_L + \tilde{S}_R \bar{l}_L \nu_R \bar{c}_L b_R \right\} + \text{H.c.}, \end{aligned} \quad (1)$$

where G_F is the Fermi coupling constant and $|V_{cb}|$ is the Cabibbo-Kobayashi-Mashkawa (CKM) matrix element. The effective Lagrangian of Eq. (1) is considered at renormalization scale $\mu = m_b$. The NP Wilson coefficients (WCs) denoted by V_L , V_R , S_L , and S_R involve left-handed neutrinos, whereas the WCs denoted by $\tilde{V}_L$, $\tilde{V}_R$, $\tilde{S}_L$, and $\tilde{S}_R$ involve right-handed neutrinos. Assuming all NP WCs to be real in the present analysis, we rewrite the above equation as [14]

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & -\frac{G_F}{\sqrt{2}} V_{cb} \left\{ G_V \bar{l} \gamma_\mu (1 - \gamma_5) \nu_l \bar{c} \gamma^\mu b \right. \\ & - G_A \bar{l} \gamma_\mu (1 - \gamma_5) \nu_l \bar{c} \gamma^\mu \gamma_5 b + G_S \bar{l} (1 - \gamma_5) \nu_l \bar{c} b \\ & - G_P \bar{l} (1 - \gamma_5) \nu_l \bar{c} \gamma_5 b + \tilde{G}_V \bar{l} \gamma_\mu (1 + \gamma_5) \nu_l \bar{c} \gamma^\mu b \\ & - \tilde{G}_A \bar{l} \gamma_\mu (1 + \gamma_5) \nu_l \bar{c} \gamma^\mu \gamma_5 b + \tilde{G}_S \bar{l} (1 + \gamma_5) \nu_l \bar{c} b \\ & \left. - \tilde{G}_P \bar{l} (1 + \gamma_5) \nu_l \bar{c} \gamma_5 b \right\} + \text{H.c.}, \end{aligned} \quad (2)$$

where

$$\begin{aligned} G_V &= 1 + V_L + V_R, & G_A &= 1 + V_L - V_R, \\ G_S &= S_L + S_R, & G_P &= S_L - S_R, \\ \tilde{G}_V &= \tilde{V}_L + \tilde{V}_R, & \tilde{G}_A &= \tilde{V}_L - \tilde{V}_R, \\ \tilde{G}_S &= \tilde{S}_L + \tilde{S}_R, & \tilde{G}_P &= \tilde{S}_L - \tilde{S}_R. \end{aligned} \quad (3)$$

The $B_s \rightarrow D_s l \nu$ decay amplitude depends on the non-perturbative hadronic matrix element, which can be parametrized in terms of $B_s \rightarrow D_s$ transition form factors as

$$\begin{aligned} & \langle D_s(P_{D_s}) | \bar{c} \gamma^\mu b | B_s(P_{B_s}) \rangle \\ &= f_+(q^2) \left[P_{B_s}^\mu + P_{D_s}^\mu - \frac{M_{B_s}^2 - M_{D_s}^2}{q^2} q^\mu \right] \\ & \quad + f_0(q^2) \frac{M_{B_s}^2 - M_{D_s}^2}{q^2} q^\mu, \\ & \langle D_s(P_{D_s}) | \bar{c} b | B_s(P_{B_s}) \rangle = \frac{m_{B_s}^2 - m_{D_s}^2}{m_b(\mu) - m_c(\mu)} f_0(q^2), \end{aligned} \quad (4)$$

where $q^\mu = P_{B_s}^\mu - P_{D_s}^\mu$ refers to the momentum transfer. It should be mentioned that we use the equation of motion to find the scalar matrix element. We follow Ref. [62] for the relevant form factors $f_0(q^2)$ and $f_+(q^2)$. The expressions pertinent for our discussion are [62]

$$P_0(q^2)f_0(q^2) = \sum_{j=0}^3 a_j^{(0)} z^j, \\ P_+(q^2)f_+(q^2) = \sum_{j=0}^3 a_j^{(+)} \left[z^j - (-1)^{j-J} \frac{j}{J} z^J \right], \quad (5)$$

where

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \\ t_+ = (M_{B_s} + M_{D_s})^2 \\ t_0 = (M_{B_s} - M_{D_s})^2 \\ P_{0,+}(q^2) = 1 - \frac{q^2}{M_{0,+}^2}. \quad (6)$$

Here, $P_{0,+}$ are Blaschke factors, and $M_0 = 6.42(10)$ GeV and $M_+ = 6.330(9)$ GeV are the resonance masses. We refer to Ref. [62] for all the omitted details.

The differential decay distribution for the $B_s \rightarrow D_s l \nu$ decays can be expressed as

$$\frac{d\Gamma}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2 |\vec{P}_{D_s}|}{(2\pi)^3 64 m_{B_s}^2} \left(1 - \frac{m_l^2}{q^2} \right) L_{\mu\nu} H^{\mu\nu}, \quad (7)$$

where $|\vec{P}_{D_s}| = \sqrt{\lambda(m_{B_s}^2, m_{D_s}^2, q^2)}/2m_{B_s}$ is the 3-momentum vector of the outgoing meson and $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$. Note that θ denotes the angle between the D_s meson and the lepton 3-momentum vector in the $(l\nu)$ rest frame. The covariant contraction $L_{\mu\nu} H^{\mu\nu}$ can be calculated using the helicity techniques of Refs. [69,70]. For completeness, we present here the final expression for the differential decay distribution of three-body $B_s \rightarrow D_s l \nu$ decays [14],

$$\frac{d\Gamma}{dq^2 d\cos\theta} = 2N |\vec{P}_{D_s}| \left\{ H_0^2 \sin^2\theta (G_V^2 + \tilde{G}_V^2) \right. \\ \left. + \frac{m_l^2}{q^2} [(H_0 G_V \cos\theta - H_{tS})^2 \right. \\ \left. + (H_0 \tilde{G}_V \cos\theta - \tilde{H}_{tS})^2] \right\}, \quad (8)$$

where

$$N = \frac{G_F^2 |V_{cb}|^2 q^2}{256\pi^3 m_{B_s}^2} \left(1 - \frac{m_l^2}{q^2} \right)^2, \quad H_0 = \frac{2m_{B_s} |\vec{P}_{D_s}|}{\sqrt{q^2}} f_+(q^2) \\ H_t = \frac{m_{B_s}^2 - m_{D_s}^2}{\sqrt{q^2}} f_0(q^2), \quad H_s = \frac{m_{B_s}^2 - m_{D_s}^2}{m_b(\mu) - m_c(\mu)} f_0(q^2), \\ H_{tS} = H_t G_V + \frac{\sqrt{q^2}}{m_l} H_s G_S, \quad \tilde{H}_{tS} = H_t \tilde{G}_V + \frac{\sqrt{q^2}}{m_l} H_s \tilde{G}_S. \quad (9)$$

By performing the $\cos\theta$ integration in Eq. (8), we get

$$\frac{d\Gamma}{dq^2} = \frac{8N |\vec{P}_{D_s}|}{3} \left\{ H_0^2 (G_V^2 + \tilde{G}_V^2) \left(1 + \frac{m_l^2}{2q^2} \right) \right. \\ \left. + \frac{3m_l^2}{2q^2} (H_{tS}^2 + \tilde{H}_{tS}^2) \right\}. \quad (10)$$

Setting $G_V = G_A = 1$ and all other NP couplings to zero, we obtain

$$\left(\frac{d\Gamma}{dq^2} \right)_{\text{SM}} = \frac{8N |\vec{P}_{D_s}|}{3} \left\{ H_0^2 \left(1 + \frac{m_l^2}{2q^2} \right) + \frac{3m_l^2}{2q^2} H_t^2 \right\}. \quad (11)$$

We define several q^2 -dependent observables such as the differential branching ratio $\text{DBR}(q^2)$, ratio of branching ratio $R(q^2)$, lepton-side forward-backward asymmetry $A_{FB}^l(q^2)$, polarization fraction of the charged lepton $P_l(q^2)$, and convexity parameter $C_F^l(q^2)$ for the $B_s \rightarrow D_s l \nu$ decays. Those are

$$\text{DBR}(q^2) = \frac{d\Gamma/dq^2}{\Gamma_{\text{Tot}}}, \quad R(q^2) = \frac{\mathcal{B}(B_s \rightarrow D_s \tau \nu)}{\mathcal{B}(B_s \rightarrow D_s l \nu)}, \\ A_{FB}^l(q^2) = \frac{(\int_{-1}^0 - \int_0^1) d\cos\theta \frac{d\Gamma}{dq^2 d\cos\theta}}{\frac{d\Gamma}{dq^2}}, \\ P_l(q^2) = \frac{d\Gamma(+)/dq^2 - d\Gamma(-)/dq^2}{d\Gamma(+)/dq^2 + d\Gamma(-)/dq^2}, \\ C_F^l(q^2) = \frac{1}{(d\Gamma/dq^2)} \left(\frac{d}{d\cos\theta} \right)^2 \left[\frac{d\Gamma}{dq^2 d\cos\theta} \right], \quad (12)$$

where $d\Gamma(+)/dq^2$ and $d\Gamma(-)/dq^2$ represent the differential decay width of positive and negative helicity leptons, respectively. In the presence of various NP, the explicit expressions for A_{FB}^l , $d\Gamma(+)/dq^2$, $d\Gamma(-)/dq^2$, and C_F^l are

$$\begin{aligned}
A_{FB}^l(q^2) &= \frac{3m_l^2}{2q^2} \frac{H_0 G_V H_{ts} + H_0 \tilde{G}_V \tilde{H}_{ts}}{H_0^2 (G_V^2 + \tilde{G}_V^2) (1 + \frac{m_l^2}{q^2}) + \frac{3m_l^2}{2q^2} (H_{ts}^2 + \tilde{H}_{ts}^2)}, \\
\frac{d\Gamma(+)}{dq^2} &= \frac{8N|P_{D_s}|}{3} \left[H_0^2 \tilde{G}_V^2 + \frac{m_l^2}{2q^2} (H_0^2 G_V^2 + 3H_{ts}^2) \right] \\
\frac{d\Gamma(-)}{dq^2} &= \frac{8N|P_{D_s}|}{3} \left[H_0^2 G_V^2 + \frac{m_l^2}{2q^2} (H_0^2 \tilde{G}_V^2 + 3\tilde{H}_{ts}^2) \right], \\
C_F^l &= \frac{3}{2} \frac{H_0^2 (G_V^2 + \tilde{G}_V^2) (\frac{m_l^2}{q^2} - 1)}{[H_0^2 (G_V^2 + \tilde{G}_V^2) (1 + \frac{m_l^2}{2q^2}) + \frac{3m_l^2}{2q^2} (H_{ts}^2 + \tilde{H}_{ts}^2)]} \quad (13)
\end{aligned}$$

The SM expressions are obtained by setting all the NP couplings to zero:

$$\begin{aligned}
[A_{FB}^l(q^2)]_{\text{SM}} &= \frac{3m_l^2}{2q^2} \left\{ \frac{H_0 H_t}{H_0^2 (1 + \frac{m_l^2}{q^2}) + \frac{3m_l^2}{2q^2} H_t^2} \right\}, \\
[P^l]_{\text{SM}} &= \frac{\frac{m_l^2}{2q^2} (H_0^2 + 3H_t^2) - H_0^2}{\frac{m_l^2}{2q^2} (H_0^2 + 3H_t^2) + H_0^2}, \\
[C_F^l]_{\text{SM}} &= \frac{3}{2} \frac{H_0^2 (\frac{m_l^2}{q^2} - 1)}{[H_0^2 (1 + \frac{m_l^2}{2q^2}) + \frac{3m_l^2}{2q^2} H_t^2]}. \quad (14)
\end{aligned}$$

The average values of the forward-backward asymmetry of the charged lepton $\langle A_{FB}^l \rangle$, the longitudinal polarization fraction of the lepton $\langle P^l \rangle$, and the convexity parameter $\langle C_F^l \rangle$ are obtained by separately integrating the numerators and denominators over q^2 .

III. NUMERICAL RESULTS AND DISCUSSIONS

A. Input parameters

Before proceeding with the analysis, we report in Table II all the input parameters that are relevant for our numerical computation. For the mass and lifetime parameter, we use the latest values reported in Ref. [71]. Similarly, for the CKM matrix element $|V_{cb}|$ and the Fermi coupling constant G_F , we use Ref. [71]. The lepton masses (m_e , m_τ) and meson masses (B_s , D_s) are in GeV units, whereas the Fermi coupling constant G_F is in GeV^{-2} units. The lifetime of the B_s meson (τ_{B_s}) is in seconds. The quark masses $m_b(m_b)$ and $m_c(m_b)$ evaluated at renormalization scale $\mu = m_b$ are in GeV units. For the relevant $B_s \rightarrow D_s$ form factor parameters, we follow the most recent lattice QCD calculation of Ref. [62]. The uncertainties associated with $|V_{cb}|$ and the form factors parameters are written within parentheses. We do not report the uncertainties associated with other input parameters as they do not play an important role in our analysis.

TABLE II. Theory inputs.

Inputs from PDG [71]		Form factor inputs [62]	
m_{B_s}	5.36689	$a_0^{(0)}$	0.658(31)
m_{D_s}	1.96827	$a_1^{(0)}$	-0.10(30)
$m_b(\mu)$	4.18	$a_2^{(0)}$	1.3(2.8)
$m_c(\mu)$	0.91	$a_0^{(+)}$	0.858(32)
m_e	$0.05109989461 \times 10^{-2}$	$a_1^{(+)}$	-3.38(41)
m_τ	1.77682	$a_2^{(+)}$	0.6(4.7)
$ V_{cb} $	0.0409(11)		
G_F	1.1663787×10^{-5}		
τ_{B_s}	1.505×10^{-12}		

We wish to determine the consequences of various NP couplings on various observables for the $B_s \rightarrow D_s \tau \nu$ decays in a model-independent way. It is therefore crucial to determine the size of the SM uncertainties in each observable that may come from various input parameters. Uncertainties in the theoretical prediction of various observables in $B_s \rightarrow D_s \tau \nu$ decays mainly come from two sources. First, they come from not very well-known CKM matrix element $|V_{cb}|$, and, second, they come from the nonperturbative hadronic form factor inputs ($a_0^{(0)}, a_1^{(0)}, a_2^{(0)}, a_0^{(+)}, a_1^{(+)}, a_2^{(+)}$). To gauge the effect of above-mentioned uncertainties on various observables, we perform a χ^2 test defined through

$$\chi^2 = \sum_{i=1}^7 \frac{(\mathcal{O}_i - \mathcal{O}_i^0)^2}{(\Delta \mathcal{O}_i)^2}, \quad (15)$$

where $\mathcal{O}_i = (|V_{cb}|, a_0^{(0)}, a_1^{(0)}, a_2^{(0)}, a_0^{(+)}, a_1^{(+)}, a_2^{(+)})$. Similarly, $\mathcal{O}_i^0$ and $\Delta \mathcal{O}_i$ represent the central value and the corresponding 1σ uncertainty given in Table II.

B. Standard model prediction

First, we wish to give a prediction of various observables for both the e and τ modes within the SM. We report in Table III the SM central values and the ranges of each observable for the e and the τ modes. Here, the central value of each observable corresponds to the central values of theory input parameters, whereas the uncertainty ranges of each observable correspond to a $\chi^2 \leq 1$ obtained using Eq. (15). The value of the ratio of branching ratio R_{D_s} in Table III is quite similar to the value reported in Ref. [62]. The slight difference may come from different choices of input parameters.

We notice that the SM prediction for the e mode is quite different from the τ mode. There is even a sign change in the polarization fraction P_l while going from the e to the τ mode. Again, the forward-backward asymmetry parameter for the e mode is zero, whereas it is nonzero positive for the τ mode. Similarly, the convexity parameter C_F^l for the e

TABLE III. SM prediction of various observables for the e and the τ modes.

Observables	Central value	Range	Observables	Central value	Range	Observables	Central value	Range
$\mathcal{B}(B_s \rightarrow D_s e \nu)\%$	2.238	[2.013, 2.468]	P^e	-1.00	-1.00	P^τ	0.320	[0.273, 0.365]
$\mathcal{B}(B_s \rightarrow D_s \tau \nu)\%$	0.670	[0.619, 0.724]	A_{FB}^e	0.00	0.00	A_{FB}^τ	0.360	[0.356, 0.363]
R_{D_s}	0.299	[0.277, 0.326]	C_F^e	-1.5	-1.50	C_F^τ	-0.271	[-0.253, -0.289]

mode is much larger in magnitude than for the τ mode. It is worth mentioning that the mass of the charged lepton plays an important role. In Fig. 1, we show the q^2 dependence of each observable for the e and the τ modes. We notice that the $A_{FB}^l(q^2)$, $P^l(q^2)$, and $C_F^l(q^2)$ observables remain constant in the entire q^2 region for the e mode. This could be very well understood from Eq. (14). In the massless limit, i.e, in the $m_l \rightarrow 0$ limit, the q^2 dependence gets canceled in the ratio for the $A_{FB}^l(q^2)$, $P^l(q^2)$, and $C_F^l(q^2)$ observables.

Now we proceed to discuss various NP effects in $B_s \rightarrow D_s \tau \nu$ decays.

C. New physics in $B_s \rightarrow D_s \tau \nu$ decays

The study of $B_s \rightarrow D_s \tau \nu$ decays both theoretically and experimentally is well motivated because of the long-standing anomalies present in R_D and R_{D^*} . We wish to study the implication of these existing anomalies on the $B_s \rightarrow D_s \tau \nu$ decays in a model-independent way. We consider four different NP scenarios based on NP contributions from two different operators. To determine the allowed NP parameter space, we impose 1σ constraint coming from the measured ratio of branching ratios R_D and R_{D^*} . We use the average values of R_D and R_{D^*} reported in Table I in our analysis. For the uncertainties, we added the statistical and systematic uncertainties in quadrature. Again, we assume that only the third-generation leptons get contribution from NP.

FIG. 1. q^2 dependence of various observables in the SM for the e (green) and the τ (blue) modes.

1. Scenario I: Only V_L and V_R NP couplings

In this scenario, we vary V_L and V_R and set all other NP couplings to zero. This is to ensure that the NP contribution to the $B_s \rightarrow D_s \tau \nu$ decay mode is coming only from vector-type NP couplings that involve left-handed neutrinos. In the presence of such NP, $d\Gamma/dq^2$, $R(q^2)$, $A_{FB}^\tau(q^2)$, $P^\tau(q^2)$, and $C_F^\tau(q^2)$ can be expressed as

$$\begin{aligned}
 \left[\frac{d\Gamma}{dq^2} \right]_{V_{L,R}} &= \left[\frac{d\Gamma}{dq^2} \right]_{\text{SM}} G_V^2, \\
 [R_{D_s}]_{V_{L,R}} &= [R_{D_s}]_{\text{SM}} G_V^2, \\
 [A_{FB}^l(q^2)]_{V_{L,R}} &= [A_{FB}^l(q^2)]_{\text{SM}}, \\
 [P^l]_{V_{L,R}} &= [P^l]_{\text{SM}}, \\
 [C_F^l]_{V_{L,R}} &= [C_F^l]_{\text{SM}}.
 \end{aligned} \tag{16}$$

It is evident from Eq. (16) that $d\Gamma/dq^2$ and $R(q^2)$ depend on V_L and V_R NP couplings and are proportional to G_V^2 , whereas $P^\tau(q^2)$, $A_{FB}^\tau(q^2)$, and $C_F^\tau(q^2)$ do not depend on these NP couplings since the contribution coming from V_L and V_R NP couplings gets canceled in the ratio. The allowed ranges of V_L and V_R after imposing the 1σ constraint coming from R_D and R_{D^*} are shown in the left panel of Fig. 2. In the right panel, we show the corresponding ranges in $\mathcal{B}(B_c \rightarrow \tau \nu)$ and $\mathcal{B}(B_s \rightarrow D_s \tau \nu)$. From the right panel of Fig. 2, we notice that the $\mathcal{B}(B_c \rightarrow \tau \nu)$ obtained in this scenario lies in the 2%–3% range. This is consistent with the upper limit of $\mathcal{B}(B_c \rightarrow \tau \nu) \leq 30\%$. We report in Table IV the allowed ranges of each observable for the $B_s \rightarrow D_s \tau \nu$ decays with (V_L, V_R) NP couplings of Fig. 2. We see a significant deviation in $\mathcal{B}(B_s \rightarrow D_s \tau \nu)$ and R_{D_s} from the SM prediction. As expected, the ranges of $P_{D_s}^\tau$, A_{FB}^τ , and C_F^τ do not vary at all with such NP couplings.

FIG. 2. Allowed ranges of V_L and V_R NP couplings are shown in the left panel once the 1σ constraint coming from the measured values of the ratio of branching ratios R_D and R_{D^*} is imposed. We show in the right panel the allowed ranges in $\mathcal{B}(B_c \rightarrow \tau \nu)$ and $\mathcal{B}(B_s \rightarrow D_s \tau \nu)$ in the presence of these NP couplings.

TABLE IV. Allowed ranges of various observables with V_L and V_R NP couplings of Fig. 2.

$\mathcal{B}(B_s \rightarrow D_s \tau \nu)\%$	R_{D_s}	P^τ	A_{FB}^τ	C_F^τ
[0.737, 1.098]	[0.332, 0.491]	[0.273, 0.365]	[0.356, 0.363]	[-0.253, -0.289]

We show in Fig. 3 the q^2 dependence of various observables with the allowed values of V_L and V_R NP couplings of Fig. 2. The SM range is shown with blue band, whereas the allowed range with V_L and V_R NP couplings is shown with the green band. It is evident from Fig. 3 that the differential branching ratio $\text{DBR}(q^2)$ and ratio of branching ratio $R(q^2)$ deviate considerably from the SM expectation. Again, as expected, we do not observe any deviation of $A_{FB}^\tau(q^2)$, $P^\tau(q^2)$, and $C_F^\tau(q^2)$ from the SM expectation in this NP scenario.

2. Scenario II: Only S_L and S_R NP couplings

In this scenario, we consider the effect of new scalar couplings only; i.e., $(S_L, S_R) \neq 0$, and all the other NP couplings are zero. In the presence of S_L and S_R NP couplings, the differential decay width, ratio of the branching ratio, forward-backward asymmetry, polarization fraction of the τ lepton, and convexity parameter can be expressed as

$$\begin{aligned}
 \left[\frac{d\Gamma}{dq^2} \right]_{S_{L,R}} &= \left[\frac{d\Gamma}{dq^2} \right]_{\text{SM}} + 8N|P_{D_s}| \left(\frac{1}{2} H_S^2 G_S^2 + \frac{m_l}{\sqrt{q^2}} H_l H_S G_S \right), \\
 [R_{D_s}]_{S_{L,R}} &= [R_{D_s}]_{\text{SM}} + \frac{8N|P_{D_s}| \left(\frac{1}{2} H_S^2 G_S^2 + \frac{m_l}{\sqrt{q^2}} H_l H_S G_S \right)}{\mathcal{B}(B_s \rightarrow D_s e \nu)}, \\
 A_{FB}^l(q^2)|_{S_{L,R}} &= \frac{3m_l^2}{2q^2} \left[\frac{H_0 H_l + H_0 \frac{\sqrt{q^2}}{m_l} H_S G_S}{H_0^2 (1 + \frac{m_l^2}{q^2}) + \frac{3m_l^2}{2q^2} H_l^2 + (3/2) H_S^2 G_S^2 + 3(m_l/\sqrt{q^2}) H_l H_S G_S} \right], \\
 [P^l]_{S_{L,R}} &= \frac{\frac{m_l^2}{2q^2} (H_0^2 + 3H_l^2) - H_0^2 + (3/2) H_S^2 G_S^2 + 3(m_l/\sqrt{q^2}) H_l H_S G_S}{\frac{m_l^2}{2q^2} (H_0^2 + 3H_l^2) + H_0^2 + (3/2) H_S^2 G_S^2 + 3(m_l/\sqrt{q^2}) H_l H_S G_S}, \\
 [C_F^l]_{S_{L,R}} &= \frac{3}{2} \frac{H_0^2 (\frac{m_l^2}{q^2} - 1)}{\{H_0^2 (1 + \frac{m_l^2}{2q^2}) + \frac{3m_l^2}{2q^2} H_l^2\} + (3/2) H_S^2 G_S^2 + 3(m_l/\sqrt{q^2}) H_l H_S G_S}.
 \end{aligned} \tag{17}$$

FIG. 3. q^2 dependence of various observables with the allowed ranges of V_L and V_R NP couplings of Fig. 2 are shown with the green band. The corresponding SM range is shown with the blue band.

FIG. 4. Allowed ranges of S_L and S_R NP couplings are shown in the left panel once the 1σ constraint coming from the measured values of the ratio of branching ratios R_D and R_{D^*} is imposed. We show in the right panel the allowed ranges in $\mathcal{B}(B_c \rightarrow \tau\nu)$ and $\mathcal{B}(B_s \rightarrow D_s\tau\nu)$ in the presence of these NP couplings. The pink constant line in the right panel corresponds to the upper bound of $\mathcal{B}(B_c \rightarrow \tau\nu) = 30\%$.

We impose a 1σ constraint coming from experimental values of R_D and R_{D^*} to determine the allowed values of S_L and S_R NP couplings. The resulting (S_L, S_R) allowed ranges are shown in the left panel of Fig. 4. In the right panel, we show the corresponding ranges in $\mathcal{B}(B_c \rightarrow \tau\nu)$ and $\mathcal{B}(B_s \rightarrow D_s\tau\nu)$ obtained using the allowed values of (S_L, S_R) NP couplings. It should be noted that the $\mathcal{B}(B_c \rightarrow \tau\nu)$ obtained in this scenario is rather large, more than 30%. Thus, although (S_L, S_R) NP couplings can simultaneously explain the anomalies present in R_D and R_{D^*} , they, however, fail to satisfy the upper bound of $\mathcal{B}(B_c \rightarrow \tau\nu) \leq 30\%$. Although this particular scenario is ruled out by the $\mathcal{B}(B_c \rightarrow \tau\nu)$ constraint, we nevertheless report in Table V the allowed ranges of all the observables obtained using the allowed values of S_L and S_R NP couplings of Fig. 4. The deviation from the SM prediction observed in this scenario is quite significant. We notice that the forward-backward asymmetry parameter can assume negative values within this scenario, which is quite distinct from the SM expectation.

TABLE V. Allowed ranges of various observables in the presence of S_L and S_R NP couplings.

$\mathcal{B}(B_s \rightarrow D_s\tau\nu)\%$	R_{D_s}	P^τ	A_{FB}^τ	C_F^τ
[0.688, 1.159]	[0.309, 0.511]	[0.350, 0.604]	[-0.276, 0.355]	[-0.158, -0.258]

We show the effect of NP on various q^2 -dependent observables in Fig. 5. We show with blue the SM band, whereas we show with green the allowed band once the NP is switched on. The deviation observed in this scenario is rather large, and it is, indeed, more pronounced than the deviation obtained with (V_L, V_R) NP couplings. Unlike scenario I, there is no cancellation of NP effects in $A_{FB}^\tau(q^2)$, $P^\tau(q^2)$, and $C_F^\tau(q^2)$. We notice that, although there is no zero crossing in the SM for the $A_{FB}^\tau(q^2)$ parameter, we may observe zero crossing depending on the values of S_L and S_R NP couplings. Similar conclusion can be drawn for the τ polarization fraction $P^\tau(q^2)$ as well. Moreover, depending on the values of the NP couplings, the shape of the q^2 distribution curve of each observable can be quite different from its SM counterpart.

3. Scenario III: Only $\tilde{V}_L$ and $\tilde{V}_R$ NP couplings

To study the effect of new vector-type NP couplings associated with right-handed neutrino interactions, we consider $(\tilde{V}_L, \tilde{V}_R)$ to be nonzero and all other NP couplings to be zero. In this scenario, the differential decay width, ratio of the branching ratio, forward-backward asymmetry, τ polarization fraction, and convexity parameter take the following simple form:

FIG. 5. q^2 dependence of various observables with the allowed ranges of S_L and S_R NP couplings of Fig. 4 is shown with the green band. The corresponding SM range is shown with the blue band.

FIG. 6. Allowed ranges of $\tilde{V}_L$ and $\tilde{V}_R$ NP couplings are shown in the left panel once the 1σ constraint coming from the measured values of the ratio of branching ratios R_D and R_{D^*} is imposed. We show in the right panel the allowed ranges in $\mathcal{B}(B_c \rightarrow \tau\nu)$ and $\mathcal{B}(B_s \rightarrow D_s\tau\nu)$ in the presence of these NP couplings.

$$\begin{aligned}
 \left[\frac{d\Gamma}{dq^2}\right]_{\tilde{V}_{L,R}} &= \left[\frac{d\Gamma}{dq^2}\right]_{\text{SM}} (1 + \tilde{G}_V^2), \\
 [R_{D_s}]_{\tilde{V}_{L,R}} &= [R_{D_s}]_{\text{SM}} (1 + \tilde{G}_V^2), \\
 [A_{FB}^l(q^2)]_{\tilde{V}_{L,R}} &= [A_{FB}^l(q^2)]_{\text{SM}}, \\
 [P^l]_{\tilde{V}_{L,R}} &= [P^l]_{\text{SM}} \frac{(1 - \tilde{G}_V^2)}{(1 + \tilde{G}_V^2)}, \\
 [C_F^l]_{\tilde{V}_{L,R}} &= [C_F^l]_{\text{SM}}.
 \end{aligned} \tag{18}$$

In the left panel of Fig. 6, we show the allowed region of $(\tilde{V}_L, \tilde{V}_R)$ NP couplings that is obtained once the 1σ R_D and R_{D^*} experimental constraint is imposed. Similarly, in the right panel, we show the corresponding ranges of $\mathcal{B}(B_c \rightarrow \tau\nu)$ and $\mathcal{B}(B_s \rightarrow D_s\tau\nu)$ obtained with the $(\tilde{V}_L, \tilde{V}_R)$ NP couplings. Similar to scenario I, we notice that $\mathcal{B}(B_c \rightarrow \tau\nu)$ obtained in this scenario lies within the (2–3)% range. This is, again, consistent with the upper bound of $\mathcal{B}(B_c \rightarrow \tau\nu) \leq 30\%$. In Table VI, we report the possible ranges of all the observables for the $B_s \rightarrow D_s\tau\nu$ decays.

TABLE VI. Allowed ranges of various observables in the presence of $\tilde{V}_L$ and $\tilde{V}_R$ NP couplings.

$\mathcal{B}(B_s \rightarrow D_s\tau\nu)\%$	R_{D_s}	P^τ	A_{FB}^τ	C_F^τ
[0.684, 1.174]	[0.307, 0.519]	[0.064, 0.276]	[0.356, 0.363]	[-0.253, -0.289]

The deviation from the SM prediction observed in this scenario is quite similar to the deviation observed in scenario I. However, there is one subtle difference. Unlike scenario I, a significant deviation from the SM prediction for the τ polarization fraction is observed in this scenario. This is evident from Eq. (18) that the NP effect does not get canceled for the τ polarization fraction P^τ .

In Fig. 7, we show the variation of various observables such as the differential branching ratio, ratio of the branching ratio, forward-backward asymmetry, τ polarization fraction, and convexity parameter as a function of q^2 . The deviation from the SM prediction observed in this scenario is quite similar to scenario I. As expected, we observe a significant deviation in the τ polarization parameter in this scenario. All the above-mentioned analyses for the observed deviations are clearly reflected in Eq. (18).

4. Scenario IV: Only $\tilde{S}_L$ and $\tilde{S}_R$ NP couplings

In this scenario, we wish to see the effect of new scalar-type NP couplings on various observables. To this end, we consider $(\tilde{S}_L, \tilde{S}_R)$ to be nonzero and all other NP couplings to be zero. In this scenario, the differential decay width, ratio of the branching ratio, forward-backward asymmetry, τ polarization fraction, and convexity parameter take the following form:

FIG. 7. q^2 dependence of various observables with the allowed ranges of $\tilde{V}_L$ and $\tilde{V}_R$ NP couplings of Fig. 6 is shown with the green band. The corresponding SM range is shown with the blue band.

FIG. 8. Allowed ranges of $\tilde{S}_L$ and $\tilde{S}_R$ NP couplings are shown in the left panel once the 1σ constraint coming from the measured values of the ratio of branching ratios R_D and R_{D^*} is imposed. The corresponding allowed ranges in $\mathcal{B}(B_c \rightarrow \tau\nu)$ and $\mathcal{B}(B_s \rightarrow D_s \tau\nu)$ in the presence of such NP couplings are shown in the right panel. The pink constant line denotes the upper bound of $\mathcal{B}(B_c \rightarrow \tau\nu) = 30\%$.

$$\begin{aligned}
 \left[\frac{d\Gamma}{dq^2} \right]_{\tilde{S}_{L,R}} &= \left[\frac{d\Gamma}{dq^2} \right]_{\text{SM}} + 4N|P_{D_s}|H_S^2\tilde{G}_S^2, [R_{D_s}]_{\tilde{S}_{L,R}} \\
 &= [R_{D_s}]_{\text{SM}} + \frac{(3/2)H_S^2\tilde{G}_S^2}{\mathcal{B}(B_s \rightarrow D_s e\nu)}, \\
 [A_{FB}^l(q^2)]_{\tilde{S}_{L,R}} &= \frac{3m_l^2}{2q^2} \left[\frac{H_0 H_t}{H_0^2(1 + \frac{m_l^2}{q^2}) + \frac{3m_l^2}{2q^2}H_t^2 + (3/2)H_S^2\tilde{G}_S^2} \right], \\
 [P^l]_{\tilde{S}_{L,R}} &= \frac{\frac{m_l^2}{2q^2}(H_0^2 + 3H_t^2) - H_0^2 - (3/2)H_S^2\tilde{G}_S^2}{\frac{m_l^2}{2q^2}(H_0^2 + 3H_t^2) + H_0^2 + (3/2)H_S^2\tilde{G}_S^2}, \\
 [C_F^l(q^2)]_{\tilde{S}_{L,R}} &= \frac{3}{2} \frac{H_0^2(\frac{m_l^2}{q^2} - 1)}{\{H_0^2(1 + \frac{m_l^2}{2q^2}) + \frac{3m_l^2}{2q^2}H_t^2\} + (3/2)H_S^2\tilde{G}_S^2}.
 \end{aligned} \tag{19}$$

TABLE VII. Allowed ranges of various observables in the presence of $\tilde{S}_L$ and $\tilde{S}_R$ NP couplings.

$\mathcal{B}(B_s \rightarrow D_s \tau\nu)\%$	R_{D_s}	P^τ	A_{FB}^τ	C_F^τ
[0.693, 1.159]	[0.308, 0.524]	[-0.200, 0.200]	[0.220, 0.331]	[-0.157, -0.260]

To determine the allowed ranges of $(\tilde{S}_L, \tilde{S}_R)$ NP couplings, we impose a 1σ constraint coming from experimentally measured values of R_D and R_{D^*} . The resulting NP parameter space, shown in the left panel of Fig. 8, can simultaneously explain the anomalies present in R_D and R_{D^*} . We show in the right panel the allowed ranges in $\mathcal{B}(B_c \rightarrow \tau\nu)$ and $B_s \rightarrow D_s \tau\nu$ with such NP. We notice that the $\mathcal{B}(B_c \rightarrow \tau\nu)$ obtained in this scenario is not compatible with the upper bound of $\mathcal{B}(B_c \rightarrow \tau\nu) \leq 30\%$. The numerical values written in the square brackets of Table VII represent the allowed ranges of observables obtained with the allowed values of $(\tilde{S}_L, \tilde{S}_R)$ of Fig. 8. Similar to scenario II, we see a significant deviation of all the observables from the SM expectation.

We show in Fig. 9 the q^2 distribution of various observables for the $B_s \rightarrow D_s \tau\nu$ decays. The blue band corresponds to the SM range, whereas the green band corresponds to the range of the observables once the $(\tilde{S}_L, \tilde{S}_R)$ NP couplings are switched on. The deviation observed in this scenario is rather large. We notice that, although, in the SM, there is no zero crossing in the τ polarization parameter, there may or may not be a zero crossing depending on the values of the NP couplings. For the differential branching ratio, the peak of the q^2 distribution may shift toward the high q^2 region.

FIG. 9. q^2 dependence of various observables with the allowed ranges of $\tilde{S}_L$ and $\tilde{S}_R$ NP couplings of Fig. 8 is shown with the green band. The corresponding SM range is shown with the blue band.

IV. CONCLUSION

In view of the long-standing anomalies in R_D and R_{D^*} , we study the corresponding $B_s \rightarrow D_s \tau \nu$ semileptonic decays in a model-independent framework. We use the helicity formalism to study the $B_s \rightarrow D_s \tau \nu$ semileptonic decays within the context of an effective Lagrangian in the presence of NP and explore four different NP scenarios based on contributions coming from two different NP operators. We give predictions on various observables such as the branching ratio, ratio of the branching ratio, forward-backward asymmetry, longitudinal polarization fraction of the charged lepton, and convexity parameter for this decay mode within SM and within four different NP scenarios.

We first report the central values and the ranges of each observable within the SM for both the e and the τ modes. We notice that all the observables change considerably while going from the e mode to the τ mode. The value of R_{D_s} is quite similar to the value reported in Ref. [62]. We

also give the first prediction of the longitudinal polarization fraction of the charged lepton, lepton-side forward-backward asymmetry, and convexity parameter for the $B_s \rightarrow D_s l \nu$ decays.

For our NP analysis, we assume that NP effects are coming from vector- and scalar-type NP couplings only. We notice that NP scenarios with (V_L, V_R) and $(\tilde{V}_L, \tilde{V}_R)$ NP couplings are compatible with the $\mathcal{B}(B_c \rightarrow \tau \nu)$ constraint. However, NP scenarios with (S_L, S_R) and $(\tilde{S}_L, \tilde{S}_R)$ NP couplings are ruled out due to the constraint coming from the lifetime of the B_c meson.

The study of $B_s \rightarrow D_s \tau \nu$ decays both theoretically and experimentally is crucial because it may provide new insights into the R_D and R_{D^*} anomaly as this decay mode is mediated via the same $b \rightarrow c$ charged-current interaction. Moreover, a precise determination of the branching fractions of this decay mode will allow an accurate determination of the CKM matrix element $|V_{cb}|$.

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