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

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Deviation from the standard model prediction is observed in many semileptonic $B$ decays mediated via $b \to c$ charged current interactions. In particular, current experimental measurements of the ratio of branching ratio $R_D$ and $R_{D^*}$ in $B \to D^{(*)} l\nu$ decays disagree with standard model expectations at the level of about 4.1σ. Moreover, recent measurement of the ratio of branching ratio $R_{J/\Psi}$ by LHCb, where $R_{J/\Psi} = B(B_c \to J/\Psi \tau\nu)/B(B_c \to J/\Psi \mu\nu)$, 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 $B_s \to D_s \tau\nu$ decays. We give prediction of several observables such as branching ratio, ratio of branching ratio, forward backward asymmetry parameter, $\tau$ polarization fraction, and the convexity parameter for the $B_s \to D_s \tau\nu$ decays within the standard model and within various new physics scenarios.

I. INTRODUCTION

Anomalies present in $R_D$, $R_{D^*}$ and $R_{J/\Psi}$ challenged the lepton flavor universality. At present the deviation in $R_D$ and $R_{D^*}$ from the standard model (SM) expectation [10] is at the level of 4.1σ [7][12]. A similar deviation of 1.3σ has been reported by LHCb in the ratio $R_{J/\Psi}$ [13] as well. Inspired by these anomalies we study the corresponding $B_s \to D_s \tau\nu$ decay mode within the SM and within various new physics (NP) scenarios by using the $B_s$ to $D_s$ transition form factors obtained in lattice QCD of Ref. [14]. The $B_s \to D_s \tau\nu$ decays serve as a complementary decay channel to similar $B$ decays mediated via $b \to cl\nu$ quark level transition. Again, in the limit of $SU(3)$ flavor symmetry $B \to Dl\nu$ and $B_s \to D_s l\nu$ decay modes should exhibit the similar properties.

Our main motivation here is to study the implication of $R_D$ and $R_{D^*}$ anomalies on $B_s \to D_s \tau\nu$ decay mode in a model independent way. We use the effective Lagrangian in the presence of NP couplings and give the predictions of various physical observables.

II. THEORY

The effective Lagrangian for $b \to cl\nu$ quark level transition decays consisting of the SM and beyond SM operators is given by [15][16]

$$L_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} V_{cb} \left\{ (1 + V_L) \bar{l}_L \gamma^\mu \nu_L \bar{c}_L \gamma^\mu b_L + V_R \tilde{\bar{l}}_L \gamma^\mu \nu_L \bar{c}_R \gamma^\mu b_R + \tilde{V}_L \tilde{\bar{l}}_R \gamma^\mu \nu_R \bar{c}_L \gamma^\mu b_L + \tilde{V}_R \tilde{\bar{l}}_R \gamma^\mu \nu_R \bar{c}_R \gamma^\mu b_R + S_L \tilde{\bar{l}}_R \nu_L \bar{c}_R b_L + \tilde{S}_R \tilde{\bar{l}}_R \nu_L \bar{c}_L b_R + \tilde{S}_R \tilde{\bar{l}}_R \nu_R \bar{c}_R b_L + \tilde{S}_R \tilde{\bar{l}}_R \nu_R \bar{c}_L b_R \right\} + \text{h.c.}, \quad (1)$$

where, $G_F$ is the Fermi coupling constant and $|V_{cb}|$ is the CKM matrix element and the couplings such as $V_L$, $V_R$, $S_L$, $S_R$ and $\tilde{V}_L$, $\tilde{V}_R$, $\tilde{S}_L$, $\tilde{S}_R$ denote the NP Wilson coefficients involving left handed and right handed neutrinos respectively. We investigate several $q^2$ dependent observables such as differential branching ratio DBR ($q^2$), ratio of branching ratio $R(q^2)$, lepton side forward backward asymmetry $A_{FB}(q^2)$, polarization fraction of the charged lepton.

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We also give predictions on the average values of these observable by separately integrating the numerator and the denominator over $q^2$. A detailed discussion is reported in the Ref. [17].

III. RESULTS AND DISCUSSIONS

We report in Table I the SM central values and the corresponding ranges of each observable for $B_s \rightarrow D_s l \nu$ decay mode. The SM central values are obtained by considering the central values of each input parameters and the ranges are obtained by including the uncertainties associated with $|V_{cb}|$ and the form factor inputs. The details are presented in the Ref. [17]. We notice that the branching ratio of $B_s \rightarrow D_s l \nu$ is of the order of $10^{-2}$ for the $e$ mode and the $\tau$ mode. In SM, the observables $A_{FB}^l, P_l, C_F^l$ for the $e$ mode are observed to be quite different from the corresponding $\tau$ mode.

![Image](image1.png)

**FIG. 1:** Allowed ranges of $(V_L, V_R)$, $(\tilde{V}_L, \tilde{V}_R)$, $(S_L, S_R)$ and $(\tilde{S}_L, \tilde{S}_R)$ NP couplings are shown in the top panel once $1\sigma$ constraint coming from the measured values of $R_D$ and $R_{D^*}$ are imposed. We show in the bottom panel the allowed ranges in $B(B_c \rightarrow \tau \nu)$ and $B(B_s \rightarrow D_s \tau \nu)$ in the presence of respective NP couplings.

| Observables | Central value | Range       | Observables | Central value | Range       |
|-------------|---------------|-------------|-------------|---------------|-------------|
| $B_s, \%$   | 2.238         | [2.013, 2.468] | $B_l, \%$   | 0.670         | [0.619, 0.724] |
| $P_e$       | -1.00         | -1.00       | $P_\tau$    | 0.320         | [0.273, 0.365]  |
| $A_{FB}^e$  | 0.00          | 0.00        | $A_{FB}^\tau$ | 0.360         | [0.356, 0.363]  |
| $C_F^e$     | -1.5          | -1.50       | $C_F^\tau$  | -0.271        | [-0.253, -0.289] |

**TABLE I:** SM prediction of various observables for the $e$ and the $\tau$ modes

We now proceed to discuss the various NP effects in $B_s \rightarrow D_s \tau \nu$ decay mode. We consider four different NP scenarios each containing two NP couplings at a time: $(V_L, V_R)$, $(S_L, S_R)$, $(\tilde{V}_L, \tilde{V}_R)$ and $(\tilde{S}_L, \tilde{S}_R)$. To get the allowed NP parameter space we impose the $1\sigma$ constraints coming from the measured ratio of branching ratio $R_D$ and $R_{D^*}$ as well as the requirement of $B(B_c \rightarrow \tau \nu) \leq 30\%$ from the LEP data [15]. In Fig. 1 we show the allowed ranges of each NP couplings and the corresponding $B(B_s \rightarrow D_s \tau \nu)$ and $B(B_c \rightarrow \tau \nu)$ allowed regions. It is observed that the $B(B_c \rightarrow \tau \nu)$ put a severe constraint on the scalar NP couplings and hence in our present analysis we omit the related discussions. Table II reports the allowed ranges of each observables for $B_s \rightarrow D_s \tau \nu$ decay mode when $(V_L, V_R)$ and $(\tilde{V}_L, \tilde{V}_R)$ NP couplings are present. We show the $q^2$ dependency of $R(q^2)$, $DBR(q^2)$, $A_{FB}^l(q^2)$, $P_l(q^2)$ using $(V_L, V_R)$ (top) and $(\tilde{V}_L, \tilde{V}_R)$ (bottom) NP couplings in Fig. 2. In the presence of $(V_L, V_R)$ NP couplings, we observe that...
$DBR(q^2)$ and $R(q^2)$ deviate considerably from the SM expectation whereas, no deviations are found in $A_{FB}^p(q^2)$, $P^r(q^2)$, $C_F^r(q^2)$. Similarly, in the presence of $(V_L, V_R)$ NP couplings the deviation is observed in $P^r(q^2)$ along with $DBR(q^2)$ and $R(q^2)$. Hence the polarization fraction of the charged lepton $P^r(q^2)$ can be used to distinguish between these two scenarios.

|          | $B\%$ | $R_D$ | $P^r$ | $A_{FB}$ | $C_F^r$ |
|----------|--------|-------|-------|----------|---------|
| $(V_L, V_R)$ | 0.733, 1.115 | 0.329, 0.496 | 0.234, 0.404 | 0.352, 0.364 | [-0.239, -0.305] |
| $(V_L, V_R)$ | 0.684, 1.174 | 0.307, 0.519 | 0.064, 0.276 | 0.356, 0.363 | [-0.253, -0.289] |

TABLE II: Allowed ranges of various observables with $(V_L, V_R)$ and $(\bar{V}_L, \bar{V}_R)$ NP couplings.

FIG. 2: $R(q^2)$, $DBR(q^2)$, $A_{FB}^p(q^2)$, $P^r(q^2)$ using $(V_L, V_R)$ (top) and $(\bar{V}_L, \bar{V}_R)$ (bottom) NP couplings (green band). The corresponding 1σ SM range is shown with the blue band.

IV. CONCLUSION

Based on the anomalies present in $R_D$ and $R_{D^*}$, we study their implication on $B_s \rightarrow D_s \tau\nu$ decay mode within the SM and within various NP scenarios. We find that only vector type NP couplings satisfy the $B(B_c \rightarrow \tau \nu)$ constraint whereas, the scalar type NP couplings are ruled out. Hence, studying the $B_s \rightarrow D_s \tau\nu$ decay mode will serve as an important stepping stone for $R_D$ and $R_{D^*}$ anomalies.

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