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Examining semileptonic decays of B_s to D_s^{**} mesons beyond the standard model

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Deviations of the measured LFU ratios such as $R_{D^{(*)}}$ and $R_{J/\psi}$ from the standard model predictions by 3.3 σ and 1.8 σ, respectively, indicate the possible existence of new physics beyond the standard model. Precise measurements of other observables in decays involving $b \to c\ell\nu_\ell$ transitions in the future may substantiate or rule out the presence of new physics. Hence, it becomes important to analyze complementary $b \to c\ell\nu_\ell$ channels also, such as $B_s \to D_s^{**}\ell\nu_\ell$, where $D_s^{**} = \{D_{s0}^*, D_{s1}^*, D_{s1}, D_{s2}^*\}$. The measured ratios $R_{D^{(*)}}$ suggest an excess of taus, whereas the measured ratio R_{Λ_c} shows a deficit in taus. The complementary information obtained from the measurement of LFU ratios like $R_{D_s^{**}}$ may become crucial in the interpretation of the contributing new physics. In this work, we analyze various q^2-dependent observables pertaining to the $B_s \to D_s^{**}\ell\nu_\ell$ decay modes within a new physics approach. The new interactions are constrained using available experimental data of $b \to c\ell\nu_\ell$ transitions.

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1. Introduction

The anomalies in the Lepton Flavor Universality (LFU) ratios R_D and R_{D^*} persist as these ratios continue to exhibit deviations from the Standard Model (SM) by 3.3σ [1], hinting the presence of possible new physics (NP) beyond the SM. Measurements of other observables like $R_{J/\psi}$, $F_L^{D^*}$, $P_\tau^{D^*}$ and R_{Λ_c} additionally entails NP in $b \to c\tau\bar{\nu}_\tau$ transitions [2]. To obtain a more accurate picture of the new interactions which are driving these anomalies, it is therefore imperative to study observables in other decay modes mediated by the same underlying quark level transition. In this work, we focus on the complementary decay channels $B_s \to D_s^{**}\tau\bar{\nu}_\tau$, where $D_s^{**} = \{D_{s0}^*, D_{s1}^*, D_{s1}, D_{s2}^*\}$. The D_s^{**} states have narrow decay widths which may make their decays easier to measure in experimental colliders. Within a model-independent effective field theory approach, we analyze these decay modes, testing the sensitivity to NP of various q^2-dependent observables. In particular, we examine the LFU ratio $R_{D_s^{**}}$, the forward-backward asymmetry A_{FB}^τ and the convexity parameter C_F^τ.

2. Effective Lagrangian

The effective Lagrangian for $b \to c\ell\bar{\nu}_\ell$ transitions is written as

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V_L}^\ell) O_{V_L}^\ell + C_{V_R}^\ell O_{V_R}^\ell + C_{S_L}^\ell O_{S_L}^\ell + C_{S_R}^\ell O_{S_R}^\ell + C_T^\ell O_T^\ell \right] + h.c., \tag{1}$$

where $C_{V_{L,R}}, C_{S_{L,R}}, C_T$ are the vector, scalar and tensor type NP couplings, and the four-fermion operators are defined as

$$\begin{aligned} O_{V_L}^\ell &= (\bar{c}\gamma^\mu P_L b)(\bar{\nu}_\ell \gamma_\mu P_L \ell),\ O_{V_R}^\ell = (\bar{c}\gamma^\mu P_R b)(\bar{\nu}_\ell \gamma_\mu P_L \ell), \\ O_{S_L}^\ell &= (\bar{c} P_L b)(\bar{\nu}_\ell P_R \ell),\ O_{S_R}^\ell = (\bar{c} P_R b)(\bar{\nu}_\ell P_R \ell), \\ O_T^\ell &= (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\nu}_\ell \sigma_{\mu\nu} P_R \ell). \end{aligned} \tag{2}$$

In this work, we analyze new physics sensitivity only in the presence of C_{V_L}, C_{S_L} and C_{S_R} as in [2].

3. Observables

The two-fold angular decay distribution can be expressed as [3]

$$\frac{d^2\Gamma}{dq^2 dcos\theta_\ell} = a(q^2) + b(q^2)cos\theta_\ell + c(q^2)cos^2\theta_\ell, \tag{3}$$

where $a(q^2), b(q^2), c(q^2)$ are q^2-dependent coefficients that are sensitive to NP contributions, θ_ℓ is the angle between the charged lepton and the daughter meson in the rest frame of the virtual W boson. The relevant observables $R_{D_s^{**}}$, A_{FB}^τ and C_F^τ can be constructed using Eq. (3).

4. Form Factors

The form factors for the $B_s \to D_s^{**}$ transitions are calculated within the Heavy Quark Effective Theory (HQET) framework [4], where they are parametrized by the leading order Isgur-Wise functions and given to linear order in $(w - 1)$ as :

$$\zeta(\omega) \simeq \zeta(1)[1 + \zeta'(w-1)], \qquad \tau(\omega) \simeq \tau(1)[1 + \tau'(w-1)],$$

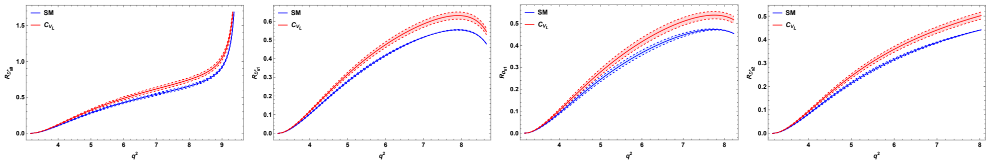

Figure 1: q^2-dependence of $R_{D_s^{**}}$ in the presence of C_{V_L}

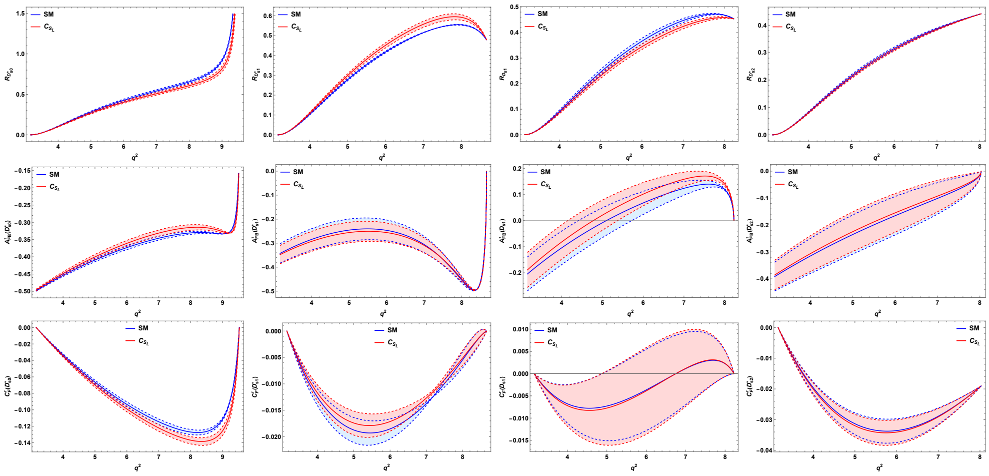

Figure 2: q^2-dependence of $R_{D_s^{**}}$ (top), A_{FB}^{τ} (middle) and C_F^{τ} (bottom) in the presence of C_{S_L}

where $\omega = (M_{B_s}^2 + M_{D_s^{**}}^2 - q^2)/2M_{B_s}M_{D_s^{**}}$. The function $\zeta(w)$ determines the form factors for $B_s \to \{D_{s0}^*, D_{s1}^*\}$ transitions, whereas $\tau(w)$ determines the form factors for $B_s \to \{D_{s1}, D_{s2}^*\}$ transitions. Following [4], we consider approximation C to obtain the form factor parameters.

5. Results

The values of the new couplings $C_k (k = V_L, S_L, S_R)$ are obtained by performing a χ^2-fit using the experimentally measured values of $R_{D^{(*)}}$, $R_{J/\psi}$, $F_L^{D^*}$ and $P_\tau^{D^*}$, and considering an upper bound 30% of $\mathcal{B}(B_c^+ \to \bar{\tau}\nu_\tau)$. We have used [5] to obtain theoretical expressions for the observables considered in the fit. The SM predictions of $R_{D^{(*)}}$ can be found in [1] and $R_{J/\psi}$ in [6] and references therein. Considering one new coupling at a time, the obtained best fit values of the couplings along with their 1σ range are given in the table below :

C_k	Best fit value	1σ range	Pull
C_{V_L}	0.0668	[0.0504, 0.0829]	4.2298
C_{S_L}	0.1543	[0.1000, 0.2052]	2.6631
C_{S_R}	0.1731	[0.1261, 0.2178]	3.4347

Table 1: Best fit values of NP couplings

The q^2-variations of $R_{D_s^{**}}$, A_{FB}^{τ} and C_F^{τ} in the presence of vector and scalar NP interactions are presented in Figs. (1-3).

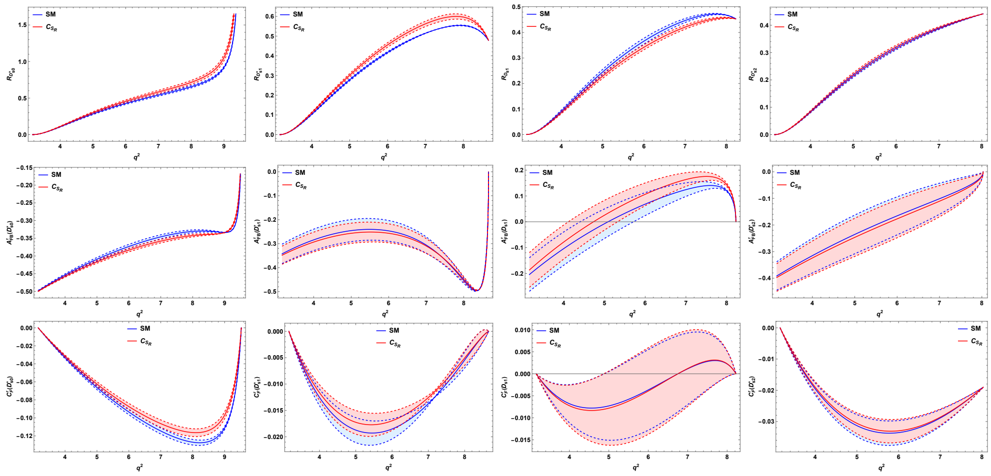

Figure 3: q^2-dependence of $R_{D_s^{**}}$ (top), A_{FB}^{τ} (middle) and C_F^{τ} (bottom) in the presence of coupling C_{S_R}

6. Discussion and Conclusion

For the considered decay modes, it is observed that $R_{D_s^{**}}$ is more sensitive to NP as compared to A_{FB}^{τ} and C_F^{τ}. $R_{D_s^{**}}$ displays maximum new physics sensitivity in the presence of the vector C_{V_L} coupling, rather than in the presence of the scalar $C_{S_{L(R)}}$ couplings. For all the decay modes, C_{V_L} effects tend to favour the tau mode in comparison with SM predictions. For A_{FB}^{τ} and C_F^{τ}, the NP effects of C_{V_L} cancel out in these ratios and are not presented here. In the presence of C_{S_L}, the ratios $R_{D_{s0}^*}$ and $R_{D_{s1}}$ indicate a deficit of taus, while $R_{D_{s1}^*}$ displays an excess of taus. In the presence of C_{S_R}, the ratio $R_{D_{s1}}$ indicate a deficit of taus, while $R_{D_{s0}^*}$ and $R_{D_{s1}^*}$ display excess of taus. The ratio $R_{D_{s2}^*}$ is in agreement with the SM prediction for the scalar couplings. The observables considered here have shown a varied pattern in their dependence on NP. Their precise measurements will help to substantiate or rule out various NP scenarios. This can furnish crucial complementary information on the structure of NP in $b \to c\tau\bar{\nu}_\tau$ transitions.

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