Examining Semileptonic Decays of $B_s \to D_s^{**}$ Mesons Beyond The Standard Model

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Introduction

- In $b \to c\tau\bar{\nu}_\tau$ transitions, anomalies as observed in the measured Lepton Flavor Universality (LFU) ratios $R_{D^{(*)}}$ have indicated the possible existence of new physics (NP) beyond the standard model (SM).
- The current combined tension of $R_{D^{(*)}}$ with the SM stands at about 3.3σ [1]. Other measured observables like the LFU ratio $R_{J/\psi}$, the D^* polarization $F_L^{D^*}$ and the τ polarization $P_\tau^{D^*}$ have also suggested the need to search for NP.
- It is, therefore, imperative that NP be probed in similar decay modes mediated by $b \to c\tau\bar{\nu}_\tau$ transitions. 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.

Effective Lagrangian

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

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

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

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

Observables

The two-fold angular decay distribution can be expressed as [2]

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

where $a(q^2), b(q^2), c(q^2)$ are q^2-dependent coefficients that are sensitive to NP contributions.
Integrating out $cos\theta_\ell$, we can obtain the differential decay rate $d\Gamma/dq^2$, from which we construct the LFU ratio $R_{D_s^{**}}$

$$R_{D_s^{**}} = \frac{d\Gamma(\tau)/dq^2}{d\Gamma(\ell)/dq^2}.$$

The forward-backward asymmetry is defined as

$$A_{FB}^\tau = \frac{\left(\int_0^1 - \int_{-1}^0\right)\frac{d^2\Gamma}{dq^2dcos\theta_\ell}dcos\theta_\ell}{\left(\int_0^1 + \int_{-1}^0\right)\frac{d^2\Gamma}{dq^2dcos\theta_\ell}dcos\theta_\ell} = \frac{b(q^2)}{d\Gamma/dq^2},$$

and the convexity as

$$C_F^\tau = \frac{\left(\int_{1/2}^1 - \int_{-1/2}^{1/2} + \int_{-1}^{-1/2}\right)\frac{d^2\Gamma}{dq^2dcos\theta_\ell}dcos\theta_\ell}{\left(\int_0^1 + \int_{-1}^0\right)\frac{d^2\Gamma}{dq^2dcos\theta_\ell}dcos\theta_\ell} = \frac{c(q^2)}{2(d\Gamma/dq^2)}.$$

Form Factors

The form factors for the $B_s \to D_s^{**}$ transitions are calculated within the Heavy Quark Effective Theory (HQET) framework [3], where they are parametrized by the leading order Isgur-Wise functions and given to linear order in $(w-1)$ as :

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

$$\zeta(\omega) \simeq \zeta(1)[1 + \zeta'(w-1)].$$

Following [3], we consider approximation C to obtain the values of the form factor parameters. The function $\zeta(w)$ determines the form factors for transitions involving D_{s0}^* and D_{s1}^*, whereas the function $\tau(w)$ determines the form factors for transitions involving D_{s1} and D_{s2}^*.

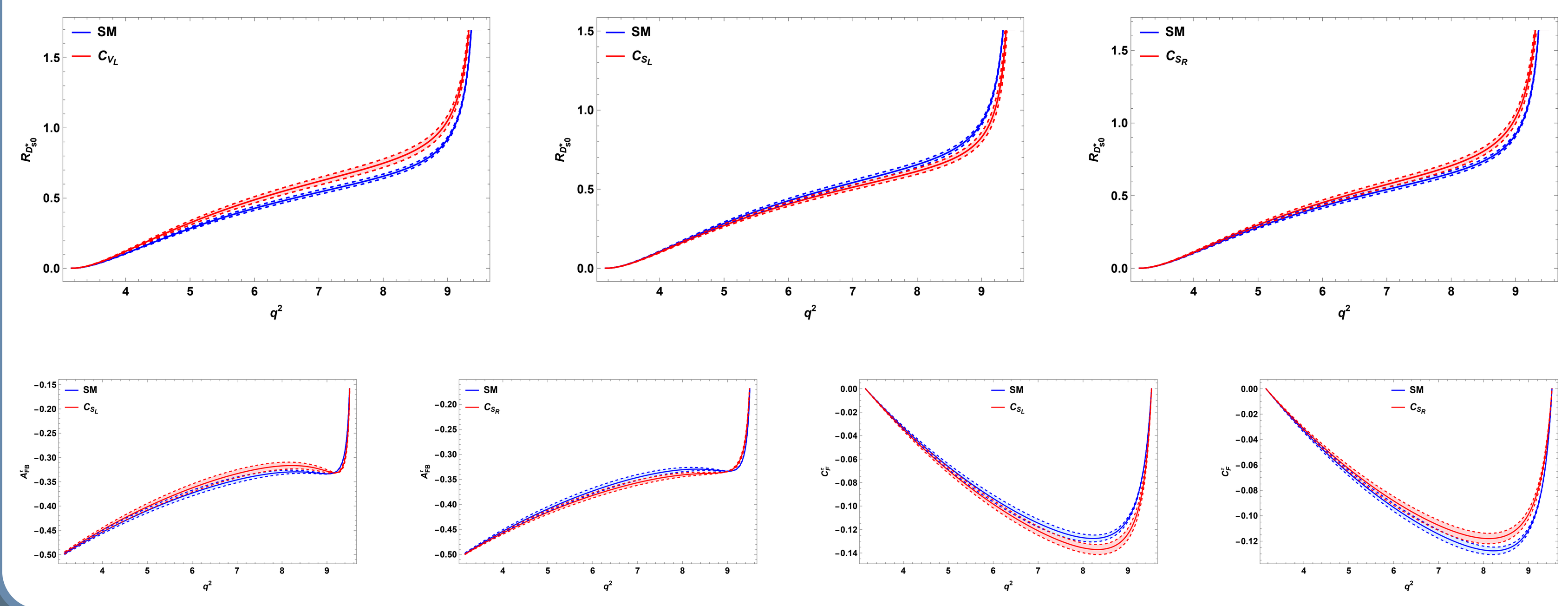
NP Couplings

The values of the new couplings $C_k (k = V_L, S_L, S_R)$ are taken from [4], where a χ^2 fit was performed 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 $\mathcal{B}(B_c^+ \to \tau\bar{\nu}_\tau)$. 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 :

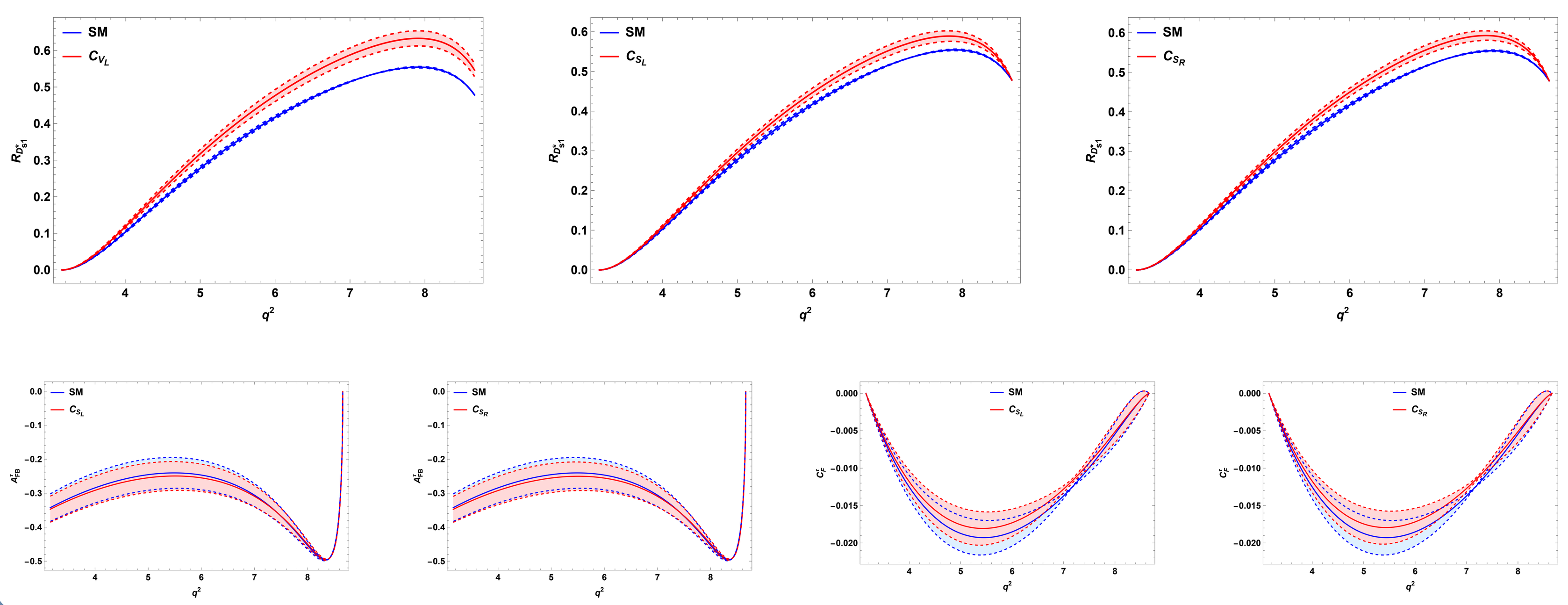
C_k	Best fit value	1σ range	Pull
C_{V_L}	0.0687	[0.0513, 0.0858]	3.8630
C_{S_L}	0.1348	[0.0879, 0.179]	2.7731
C_{S_R}	0.1483	[0.1068, 0.1877]	3.4043

Table 1: Best fit values of NP couplings

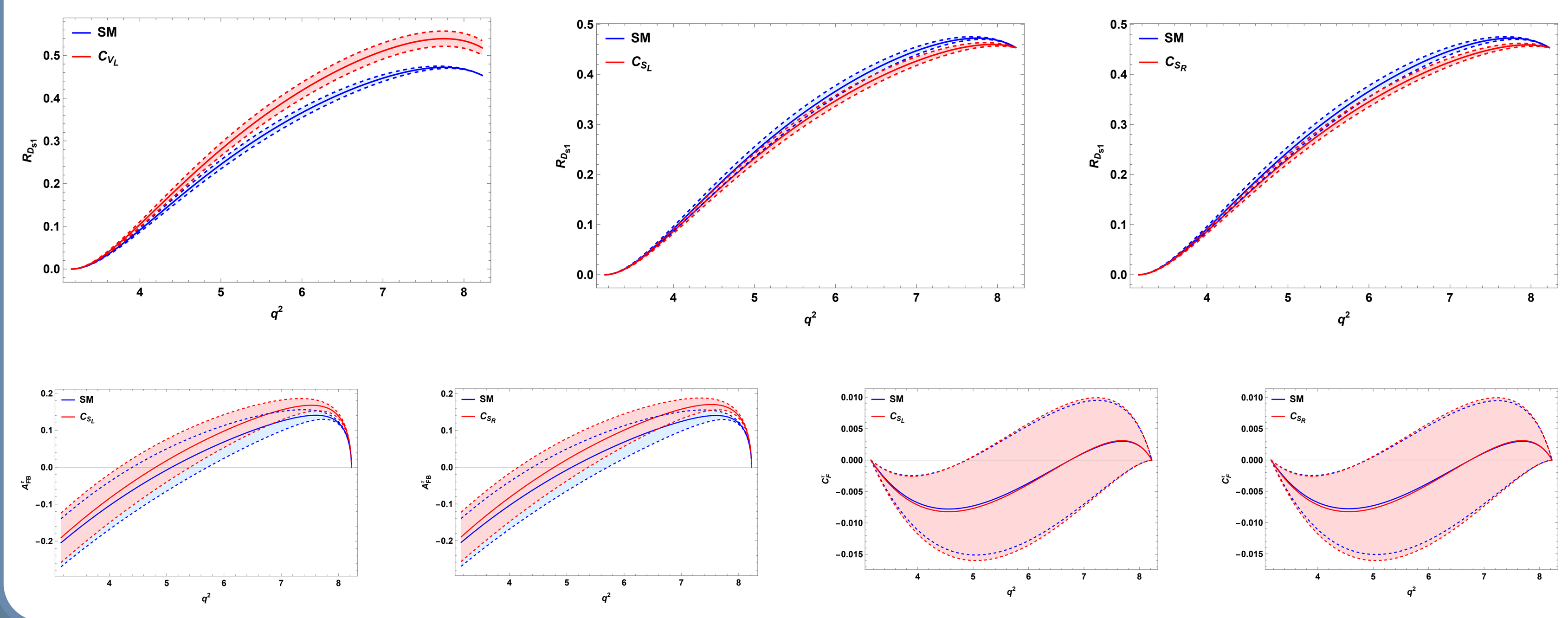
Result : q^2-dependence for the mode $B_s \to D_{s0}^*\tau\bar{\nu}_\tau$



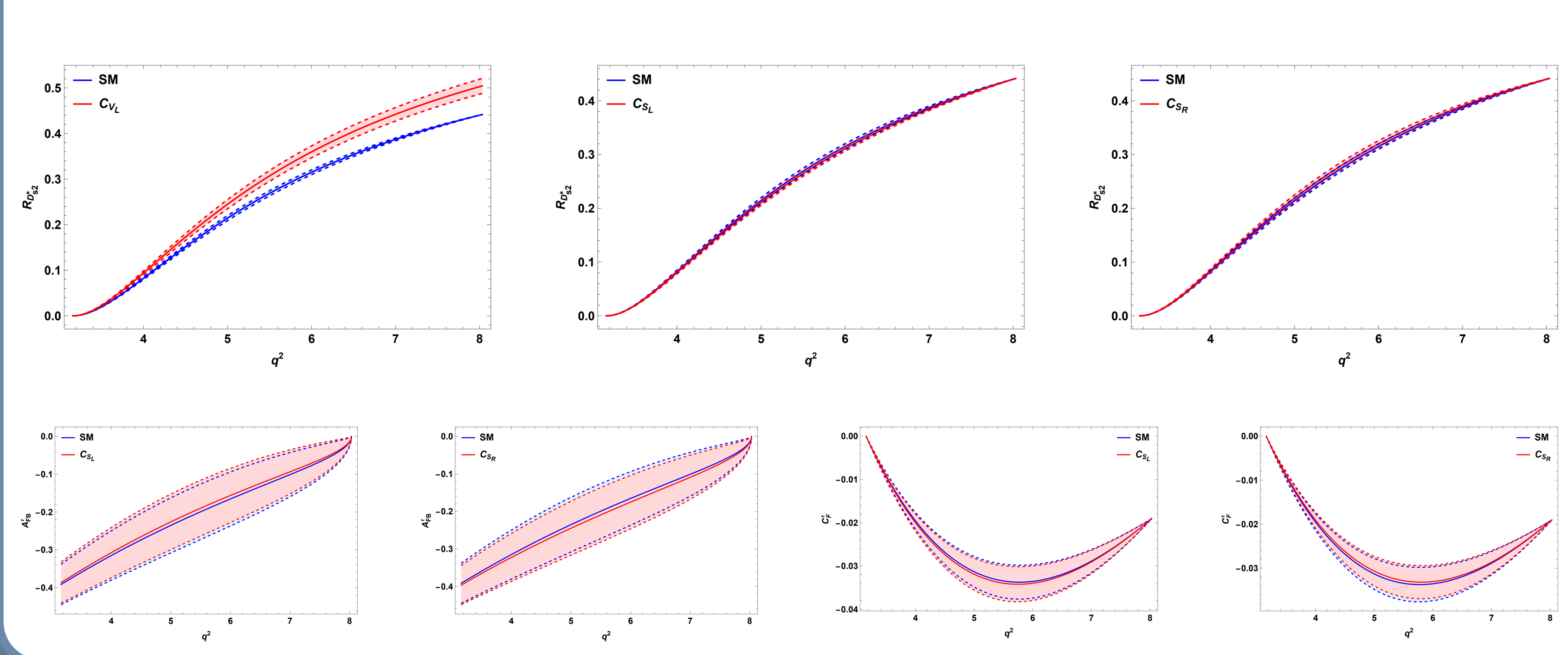
Result : q^2-dependence for the mode $B_s \to D_{s1}^*\tau\bar{\nu}_\tau$



Result : q^2-dependence for the mode $B_s \to D_{s1}\tau\bar{\nu}_\tau$



Result : q^2-dependence for the mode $B_s \to D_{s2}^*\tau\bar{\nu}_\tau$



Discussion and Conclusion

- For the considered decay modes, it is observed that the ratio $R_{D_s^{**}}$ is more sensitive to new physics compared to A_{FB}^τ and C_F^τ.
- $R_{D_s^{**}}$ displays maximum new physics effects 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 the SM. For A_{FB}^τ and C_F^τ, 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 comparison with the SM. 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, in comparison with the SM. The ratio $R_{D_{s2}^*}$ is in agreement with the SM for the scalar couplings.
- The observables considered here have shown a varied pattern in their dependence on NP interactions. Their precise measurements will help to substantiate or rule out various NP scenarios. This can be a crucial complementary information on the structure of NP in $b \to c\tau\bar{\nu}_\tau$ transitions.

References

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[2] D. Bečirević, F. Jaffredo, A. Peñuelas and O. Sumensari, JHEP 05, 175 (2021)
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[4] C. P. Haritha, K. Jain, and B. Mawlong, Nucl. Phys. B. 994, 116309 (2023).