New Physics Prospects in the Rare $B_c \to D_s \ell^+ \ell^-$ Decay

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Ongoing work with Tarun Kumar, et al.

Outline

Anomalies

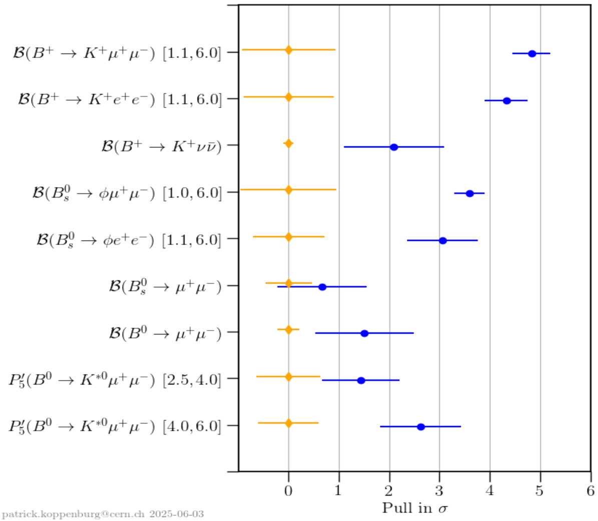
$B_c \to D_s \ell^+ \ell^-$

Theoretical Framework

Analysis and Results

Summary

Rare B Decays - Flavour Anomalies



https://www.koppenburg.ch/anomalies.html

Outline

$B_c \to D_s \ell^+ \ell^-$ Decay

- Rare $b \to s\ell\ell$ transitions are suppressed in the SM (only loop level) - ideal grounds for NP.
- $b \to s\ell\ell$: rich laboratory of information.
- We consider $B_c \to D_s \ell^+ \ell^-$ decay within the framework of the U_1 leptoquark (LQ) model.
- B_c mesons at LHCb: $\mathscr{O}(10^9 - 10^{10})$ B_c events per year. With luminosity $10^{34} cm^{-2} s^{-1}$, one could expect $\mathscr{O}(10^{10})$ B_c events per year [1].
- LHCb : $f_c/f_u \cdot \mathscr{B}(B_c^+ \to D_s^+ \mu^+ \mu^-) < 9.6 \times 10^{-8}$ (95% CL) [2]
- LQs : highly motivated NP candidates to explain flavor anomalies; couple to both quarks and leptons.
- NP in the muon channel only is considered.
- Observables such as branching fraction, CP asymmetry and LFU ratio of $B_c \to D_s \mu^+ \mu^-$ are analysed and predicted.

[1] Rev. Mod. Phys. 94, 015003 (2022), (arXiv:2101.08326)

[2] JHEP 02, 032 (2024), arXiv:2308.06162

Outline

Effective Hamiltonian

- The effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions including NP is

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

- We consider NP in vector (axial) operators only.
- Complex $C_9^{(\prime)\mathrm{NP}}, C_{10}^{(\prime)\mathrm{NP}}$: possible new CP violation sources.

U_1 Leptoquark

- U_1 interaction Lagrangian :

$$\mathscr{L} = x_{1\,ij}^{LL}\,\bar{Q}_{Li}\gamma_\mu U_1^\mu P_L L_j + x_{1\,ij}^{RR}\,\bar{d}_{Ri}\gamma_\mu U_1^\mu P_R \ell_j + \text{h.c.},$$

where

$$x_1^{LL} = \begin{pmatrix} \lambda_{11}^L & \lambda_{12}^L & \lambda_{13}^L \\ \lambda_{21}^L & \lambda_{22}^L & \lambda_{23}^L \\ \lambda_{31}^L & \lambda_{32}^L & \lambda_{33}^L \end{pmatrix}, \quad x_1^{RR} = \begin{pmatrix} \lambda_{11}^R & \lambda_{12}^R & \lambda_{13}^R \\ \lambda_{21}^R & \lambda_{22}^R & \lambda_{23}^R \\ \lambda_{31}^R & \lambda_{32}^R & \lambda_{33}^R \end{pmatrix}$$

- For $b \to s\mu^+\mu^-$, NP Wilson Coefficients (WCs) can be written as

$$C_9^{\rm NP} = -C_{10}^{\rm NP} = \frac{\pi}{\sqrt{2}G_F V_{tb}V_{ts}^*\alpha}\,\frac{\lambda_{s\mu}^L\left(\lambda_{b\mu}^L\right)^*}{M_{U_1}^2},$$

$$C_9' = C_{10}' = \frac{\pi}{\sqrt{2}G_F V_{tb}V_{ts}^*\alpha}\,\frac{\lambda_{s\mu}^R\left(\lambda_{b\mu}^R\right)^*}{M_{U_1}^2}.$$

NP Scenarios

1. NP1 : $C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}}$
2. NP2 : $C_9' = C_{10}'$

Observables

- Differential branching fraction is defined as

$$\frac{dBr}{dq^2} = \tau_{B_c}(2a_\ell + \frac{2}{3}c_\ell),$$

where

$$\begin{aligned} a_\ell &= \frac{G_F^2\alpha_{EW}^2|V_{tb}V_{ts}^*|^2}{2^9\pi^5 m_{B_c}^3}\beta_\ell\sqrt{\lambda}\Big[q^2|F_P|^2 + \frac{\lambda}{4}\left(|F_A|^2+|F_V|^2\right) \\ &+ 4m_\ell^2 m_{B_c}^2|F_A|^2 + 2m_\ell\left(m_{B_c}^2 - m_{D_s}^2 + q^2\right)\mathrm{Re}(F_P F_A^*)\Big], \\ c_\ell &= -\frac{G_F^2\alpha_{EW}^2|V_{tb}V_{ts}^*|^2}{2^9\pi^5 m_{B_c}^3}\beta_\ell\sqrt{\lambda}\frac{\lambda\beta_\ell^2}{4}\left(|F_A|^2+|F_V|^2\right). \end{aligned}$$

F_P, F_V and F_A : functions of FFs and WCs.

- For $B_c \to D_s$ FF : we adopt LQCD results. [3]

[3] (HPQCD Collab.), PRD 105, 014503 (2022) (arXiv:2108.11242))

- Direct CP asymmetry is defined as

$$A_{CP}(q^2) = \frac{\frac{d\Gamma}{dq^2}(B_c \to D_s \ell^+ \ell^-) - \frac{d\bar{\Gamma}}{dq^2}(\bar{B}_c \to \bar{D}_s \ell^+ \ell^-)}{\frac{d\Gamma}{dq^2}(B_c \to D_s \ell^+ \ell^-) + \frac{d\bar{\Gamma}}{dq^2}(\bar{B}_c \to \bar{D}_s \ell^+ \ell^-)}$$

- LFU ratio is defined as

$$R_{D_s} = \frac{\Gamma(B_c \to D_s \mu^+ \mu^-)}{\Gamma(B_c \to D_s e^+ e^-)}.$$

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Fits

- χ^2 fit - best fit values of $C_9^{(\prime)\mathrm{NP}}$ and $C_{10}^{(\prime)\mathrm{NP}}$.
- The χ^2 function is defined as

$$\chi^2 = (\mathcal{O}_{\mathrm{exp}} - \mathcal{O}_{\mathrm{th}})^T (\mathcal{C}_{\mathrm{exp}} + \mathcal{C}_{\mathrm{th}})^{-1} (\mathcal{O}_{\mathrm{exp}} - \mathcal{O}_{\mathrm{th}}),$$

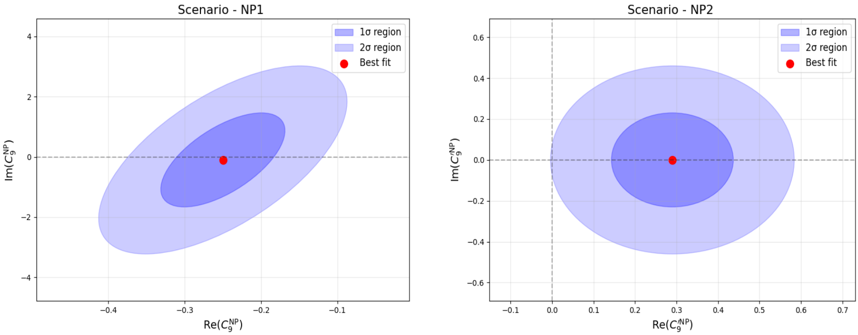
  where $\mathcal{O}_{\mathrm{exp}}$ and $\mathcal{O}_{\mathrm{th}}$ are experimental measurements and theoretical predictions. $\mathcal{C}_{\mathrm{th(exp)}}$ is the theoretical (experimental) covariance matrix.

- 194 $b \to s\mu\mu$ observables to constrain NP WCs :

  $R_{K^{(*)}}, Br(B \to K\mu\mu), Br(B_s \to \phi\mu\mu), F_L, A_{FB}, S_i, P_i^{(\prime)}(B \to K^*\mu\mu, B_s \to \phi\mu\mu)$ - LHCb, Belle, CMS, ATLAS.

Table: Fit results ($\chi^2_{\rm SM} = 214.41$)

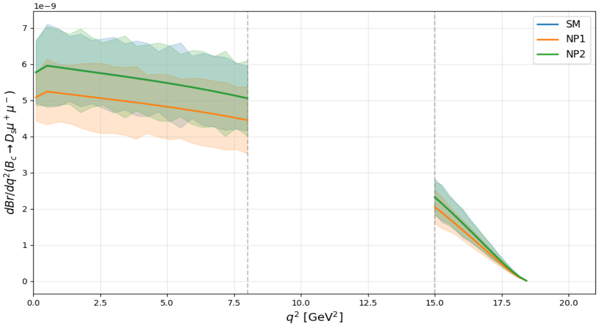
Scenario	$\chi^2_{\rm min}$	WC (1σ range)	p-value	Pull
NP1	197.8	$[(-0.33, -0.17), (-1.72, 1.48)]$	0.37	3.66σ
NP2	205.5	$[(0.14, 0.44), (-0.23, 0.23)]$	0.24	2.52σ



dBr/dq^2

Table: Differential branching fraction (10^{-9}) for $B_c \to D_s\mu^+\mu^-$

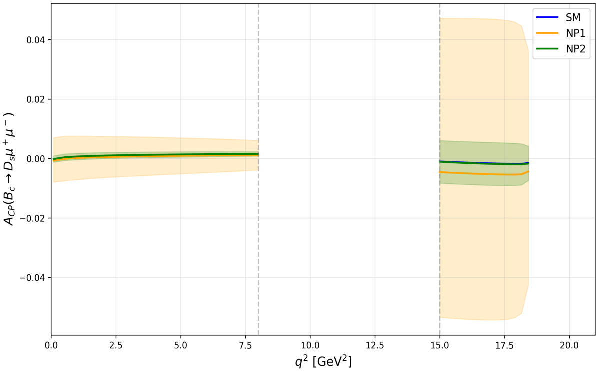
q^2-bin	SM	NP1	NP2
$0.10 - 0.98$	(5.92 ± 0.92)	(5.21 ± 0.89)	(5.92 ± 0.85)
$1.10 - 2.50$	(5.83 ± 1.18)	(5.13 ± 0.84)	(5.82 ± 1.07)
$2.50 - 4.00$	(5.68 ± 1.05)	(5.00 ± 0.87)	(5.67 ± 0.98)
$4.00 - 6.00$	(5.48 ± 1.02)	(4.82 ± 0.91)	(5.48 ± 0.97)
$6.0 - 8.0$	(5.21 ± 0.94)	(4.59 ± 0.77)	(5.22 ± 0.91)
$15 - 17$	(1.66 ± 0.35)	(1.47 ± 0.32)	(1.66 ± 0.35)
$17 - 18.55$	(0.41 ± 0.09)	(0.36 ± 0.07)	(0.41 ± 0.08)



A_{CP}

Table: Direct CP asymmetry (A_{CP}) (%) for $B_c \to D_s\mu^+\mu^-$

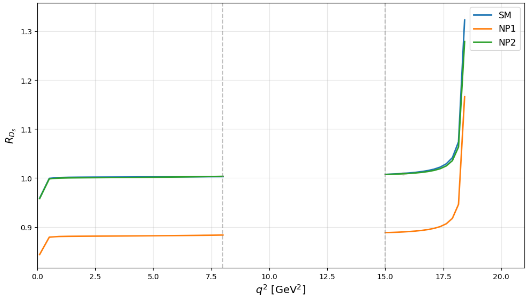
q^2-region	NP1 (1σ range)	NP2 (1σ range)
1.1 - 6	(-0.53, 0.72)	(-0.0, 0.17)
15 - 18.55	(-5.39, 4.70)	(-0.71, 0.48)



R_{D_s}

Table: R_{D_s} predictions

q^2-bin	NP1	NP2
$0.10 - 0.98$	(0.874 ± 0.017)	(0.992 ± 0.037)
$1.10 - 6.00$	(0.882 ± 0.008)	(1.001 ± 0.028)
$15 - 18.55$	(0.893 ± 0.020)	(1.012 ± 0.025)



Outline

Summary

- Anomalies in the flavour sector - indirect hints of NP. Rare decays - ideal places to look for NP.
- $B_c \to D_s \mu^+ \mu^-$ analyzed within a NP framework - U_1 leptoquark.
- NP scenarios involving vector currents only. Corresponding WCs $C_9^{(\prime)\mathrm{NP}}$ and $C_{10}^{(\prime)\mathrm{NP}}$ - complex.
- Predictions for branching fraction, LFU ratio and A_{CP} display sensitivity to NP scenario with only LH currents.
- A_{CP} can have sizeable enhancement with LH currents, particularly in the high-q^2 region - pattern seen in other $b \to s\ell\ell$ modes ($B \to K\ell\ell$, $\Lambda_b \to \Lambda\ell\ell$).
- At future LHC run, the mode can be potentially explored and tested for these observations.

THANK YOU