Binwise scrutinization of $B_c \to D_s^{(*)} \mu^+ \mu^-$ decay in an EFT approach

Based on our paper arXiv:2409.01269v1 [hep-ph]

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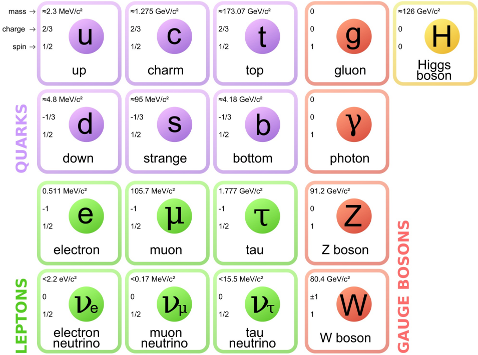
Outline

1. Introduction
2. Motivation
3. EFT Approach
4. Fit Analysis
5. Interpretation of $B_c \to D_s^{(*)} \mu^+ \mu^-$ decay
6. Results
7. Conclusion

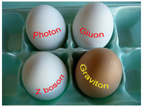
Table of Contents

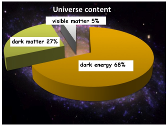
Introduction

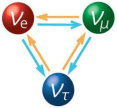
Standard Model

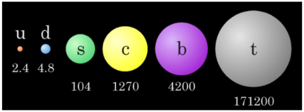


Limitations of SM









Matter dominated universe

Lepton Non-universality

Table of Contents

Motivation

Rare B Meson Decay

- **FCNC Processes:** Rare decays like $b \to s\ell^+\ell^-$ are highly suppressed in the SM, making them sensitive to New Physics (NP).
- Recent anomalies like $P_5^{'}$, $\mathcal{BR}(B \to \phi\mu^+\mu^-)$,$\mathcal{R}_{K_s^0}$ and $\mathcal{R}_{K^{*+}}$ reported by LHCb and Belle II suggest potential LFU violations in decays involving $b \to s\mu^+\mu^-$.

Why B_c Meson

1. The B_c meson is the lightest bound state with both b and c quarks.
2. Its mass lies between the charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) families.
3. It decays weakly, making it relatively long-lived, as it doesn't decay via strong or radiative modes.
4. Data on B_c mesons is scarce, and many excited states, including B_c^*'s ground state, are not yet determined.
5. B_c mesons are important for research due to their decays involving neutrinos.

Table of Contents

EFT Approach

- **Effective Hamiltonian**[1]**:**

$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}\, V_{ts}^* \Big[C_7^{eff}\, \mathcal{O}_7 + C_7'\, \mathcal{O}_7' + \sum_{i=9,10,P,S} \big((C_i + C_i^{NP})\, \mathcal{O}_i + C_i^{NP'}\, \mathcal{O}_i' \big) \Big],$$

where $\mathcal{O}_i^{(l)}$ are local effective operators, $C_i^{(l)}$ are WCs , V_{cb} is the CKM matrix element, G_F is the Fermi constant, and l represents the lepton flavor ($l = e, \mu, \tau$).

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{16\,\pi^2} m_b\,(\bar{s}\sigma_{\mu\,\nu} P_R\, b)\, F^{\mu\,\nu}, & \mathcal{O}_7' &= \frac{e}{16\,\pi^2} m_b\,(\bar{s}\sigma_{\mu\,\nu} P_L\, b)\, F^{\mu\,\nu} \\
\mathcal{O}_9 &= \frac{e^2}{16\,\pi^2} (\bar{s}\gamma_\mu P_L\, b)\,(\bar{\mu}\gamma^\mu\,\mu), & \mathcal{O}_9' &= \frac{e^2}{16\,\pi^2} (\bar{s}\gamma_\mu P_R\, b)\,(\bar{\mu}\gamma^\mu\,\mu), \\
\mathcal{O}_{10} &= \frac{e^2}{16\,\pi^2} (\bar{s}\gamma_\mu P_L\, b)\,(\bar{\mu}\gamma^\mu\,\gamma_5\,\mu), & \mathcal{O}_{10}' &= \frac{e^2}{16\,\pi^2} (\bar{s}\gamma_\mu P_R\, b)\,(\bar{\mu}\gamma^\mu\,\gamma_5\,\mu), \\
\mathcal{O}_S &= \frac{e^2}{16\,\pi^2} m_b\,(\bar{s} P_R\, b)\,(\bar{\mu}\mu), & \mathcal{O}_S' &= \frac{e^2}{16\,\pi^2} m_b\,(\bar{s} P_L\, b)\,(\bar{\mu}\mu), \\
\mathcal{O}_P &= \frac{e^2}{16\,\pi^2} m_b\,(\bar{s} P_R\, b)\,(\bar{\mu}\gamma_5\mu), & \mathcal{O}_P' &= \frac{e^2}{16\,\pi^2} m_b\,(\bar{s} P_L\, b)\,(\bar{\mu}\gamma_5\mu),
\end{aligned}$$

[1] arXiv:hep-ph/9910221

Table of Contents

Fit Analysis

- To find the best fit values of EFT coefficient, C_9^{NP} and C_{10}^{NP} in New Physics scenario, we performed χ^2 method.

$$\chi^2(C_i^{\rm NP}) = \sum_i \frac{\left[\mathcal{O}_i^{\rm th}(C_i^{\rm NP}) - \mathcal{O}_i^{\rm exp}\right]^2}{(\Delta\mathcal{O}_i^{\rm exp})^2 + (\Delta\mathcal{O}_i^{\rm th})^2}$$

$\mathcal{O}_i^{\rm th}(C_i^{\rm LQ})$ = Theoretical predictions for the observables used in this fit

$\Delta\mathcal{O}_i^{\rm th} = 1\sigma$ error from theory

Observables:

- BR($B_s \to \mu^+\mu^-$).
- BR($B \to K\mu^+\mu^-$) in different q^2 bins.
- BR($B \to K^*\mu^+\mu^-$) in different q^2 bins.
- BR($B_s \to \phi\mu^+\mu^-$) in different q^2 bins.
- Forward-backward asymmetry, Polarization asymmetry , $P_{1,2,3}$,$P'_{4,5,6,8}$ observables of $B \to K^*\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ decay modes.

1D Scenarios

Scenario	Coefficient	Best-fit value $[1\sigma]$	Pull	p-value (%)
S - I	$C_9^{\rm NP}$	$-1.227\ [^{-0.959}_{-1.363}]$	4.665	46.0
S - II	$C_{10}^{\rm NP}$	$0.456\ [^{0.555}_{0.252}]$	2.823	22.0
S - III	$C_9'^{\rm NP}$	$0.082\ [^{0.353}_{-0.252}]$	0.261	14.0
S - IV	$C_{10}'^{\rm NP}$	$-0.134\ [^{-0.050}_{-0.252}]$	1.085	13.0
S - V	$C_9^{\rm NP} = C_{10}^{\rm NP}$	$0.023\ [^{0.250}_{-0.050}]$	0.158	15.0
S - VI	$C_9^{\rm NP} = -C_{10}^{\rm NP}$	$-0.971\ [^{-0.757}_{-1.161}]$	4.921	53.0
S - VII	$C_9'^{\rm NP} = C_{10}'^{\rm NP}$	$-0.135\ [^{-0.052}_{-0.251}]$	1.003	14.0
S - VIII	$C_9'^{\rm NP} = -C_{10}'^{\rm NP}$	$0.109\ [^{0.147}_{0.048}]$	1.046	15.0
S - IX	$C_9^{\rm NP} = -C_9'^{\rm NP}$	$-0.835\ [^{-0.656}_{-0.959}]$	3.993	31.0
S - X	$C_9^{\rm NP} = -C_{10}^{\rm NP} = -C_9'^{\rm NP} = -C_{10}'^{\rm NP}$	$-0.374\ [^{-0.254}_{-0.451}]$	3.067	24.0
S - XI	$C_9^{\rm NP} = -C_{10}^{\rm NP} = C_9'^{\rm NP} = -C_{10}'^{\rm NP}$	$-0.281\ [^{-0.150}_{-0.454}]$	2.415	20.0

2D Scenarios

Scenario	Coefficient	Best fit value [1σ]	Pull	p-value (%)
S - I	$(C_9^{\rm NP}, C_{10}^{\rm NP})$	$(-1.398[^{-1.219}_{-1.578}], 0.694[^{0.855}_{0.480}])$	5.961	67.0
S - II	$(C_9^{\rm NP}, C_9^{\prime\rm NP})$	$(-1.206[^{-0.988}_{-1.428}], -0.020[^{0.325}_{-0.367}])$	4.640	47.0
S - III	$(C_9^{\rm NP}, C_{10}^{\prime\rm NP})$	$(-1.269[^{-1.079}_{-1.454}], -0.306[^{-0.158}_{-0.390}])$	5.239	53.0
S - IV	$(C_{10}^{\rm NP}, C_9^{\prime\rm NP})$	$(0.516[^{0.634}_{0.291}], -0.050[^{0.333}_{-0.341}])$	3.106	16.0
S - V	$(C_{10}^{\rm NP}, C_{10}^{\prime\rm NP})$	$(0.469[^{0.680}_{0.262}], 0.101[^{0.237}_{-0.088}])$	2.565	20.0
S - VI	$(C_9^{\prime\rm NP}, C_{10}^{\prime\rm NP})$	$(-0.033[^{0.283}_{-0.379}], -0.133[^{-0.008}_{-0.278}])$	1.059	13.0
S - VII	$(C_9^{\rm NP} = -C_9^{\prime\rm NP}, C_{10}^{\rm NP} = C_{10}^{\prime\rm NP})$	$(-0.811[^{0.636}_{-0.996}], 0.128[^{0.273}_{-0.018}])$	3.689	36.0
S - VIII	$(C_9^{\rm NP} = C_9^{\prime\rm NP}, C_{10}^{\rm NP} = -C_{10}^{\prime\rm NP})$	$(-1.121[^{-0.911}_{-1.330}], 0.302[^{0.365}_{0.198}])$	5.174	51.0
S - IX	$(C_9^{\rm NP} = C_9^{\prime\rm NP}, C_{10}^{\rm NP} = C_{10}^{\prime\rm NP})$	$(-0.838[^{-1.077}_{-0.600}], 0.015[^{-0.141}_{0.172}])$	4.032	31.0
S - X	$(C_9^{\rm NP} = -C_{10}^{\rm NP}, C_9^{\prime\rm NP} = C_{10}^{\prime\rm NP})$	$(-0.986[^{-0.783}_{-1.189}], 0.108[^{0.232}_{-0.015}])$	5.412	53.0
S - XI	$(C_9^{\rm NP} = -C_{10}^{\rm NP}, C_9^{\prime\rm NP} = -C_{10}^{\prime\rm NP})$	$(-1.008[^{-0.800}_{-1.217}], -0.089[^{0.033}_{-0.211}])$	4.922	49.0

Table of Contents

Interpretation of $B_c \to D_s^{(*)} \mu^+ \mu^-$ decay

The decay observables[2] :

- The q^2-dependent differential decay width as

$$\frac{d\Gamma}{dq^2} = \frac{1}{4}\left[3\, I_1^c + 6\, I_1^s - I_2^c - 2\, I_2^s\right],$$

- The lepton forward-backward asymmetry:

$$A_{FB}(q^2) = \frac{3\, I_6}{3\, I_1^c + 6\, I_1^s - I_2^c - 2\, I_2^s},$$

- The longitudinal and transverse polarization fractions of D_s^*:

$$F_L(q^2) = \frac{3\, I_1^c - I_2^c}{3\, I_1^c + 6\, I_1^s - I_2^c - 2\, I_2^s}, \qquad F_T(q^2) = 1 - F_L(q^2)$$

- The Lepton Flavor University (LFU) ratio:

$$R_{D_s^*}(q^2) = \frac{d\Gamma(B_c \to D_s^* \mu^+ \mu^-)/dq^2}{d\Gamma(B_c \to D_s^*\, e^+\, e^-)/dq^2}$$

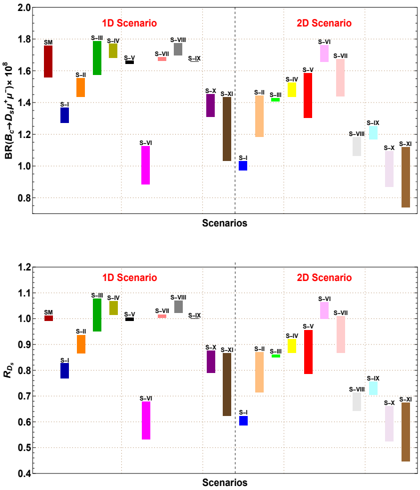
- P_5' clean observable:

$$P_5' = \frac{I_5}{2\sqrt{-I_2^c\, I_2^s}} \tag{1}$$

[2] arXiv:0811.1214

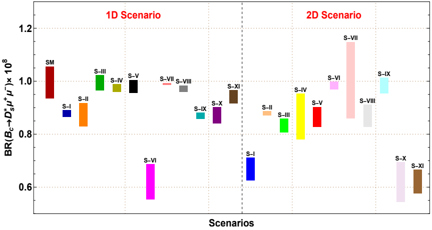
Table of Contents

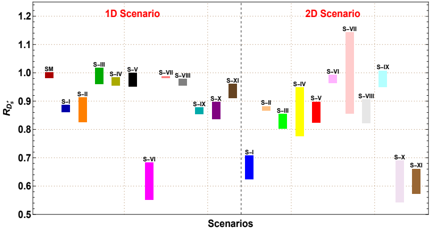
Results: $B_c \to D_s \mu^+ \mu^-$



	1D Scenario		2D Scenario	
Scenarios	$BR \times 10^8$	R_{D_s}	$BR \times 10^8$	R_{D_s}
SM	1.66	1.0006	1.66	1.0006
S - I	1.3	0.787	0.99	0.597
S - II	1.473	0.89	1.297	0.782
S - III	1.687	1.018	1.43	0.862
S - IV	1.71	1.036	1.433	0.864
S - V	1.66	0.9995	1.43	0.862
S - VI	0.994	0.6	1.71	1.03
S - VII	1.671	1.008	1.552	0.936
S - VIII	1.744	1.052	1.115	0.673
S - IX	1.659	1.0006	1.196	0.721
S - X	1.364	0.823	0.977	0.589
S - XI	1.253	0.756	0.92	0.555

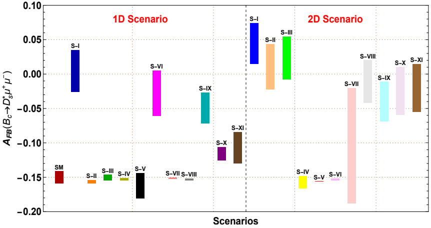
Results: $B_c \to D_s^* \mu^+ \mu^-$ $(BR \;\&\; R_{D_s^*})$

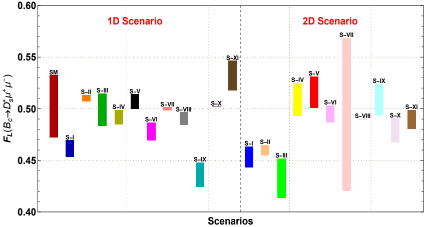




	1D Scenario		2D Scenario	
Scenarios	$BR \times 10^8$	$R_{D_s^*}$	$BR \times 10^8$	$R_{D_s^*}$
SM	0.996	0.991	0.996	0.991
S - I	0.872	0.868	0.659	0.656
S - II	0.858	0.854	0.877	0.872
S - III	0.988	0.983	0.826	0.822
S - IV	0.976	0.971	0.846	0.842
S - V	0.992	0.987	0.869	0.864
S - VI	0.613	0.61	0.979	0.975
S - VII	0.99	0.985	0.847	0.843
S - VIII	0.969	0.965	0.858	0.854
S - IX	0.866	0.861	0.981	0.976
S - X	0.863	0.859	0.615	0.612
S - XI	0.943	0.938	0.618	0.615

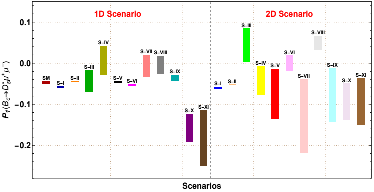
Results: $B_c \to D_s^* \mu^+\mu^-$ (A_{FB} & F_L)

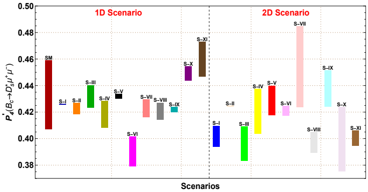


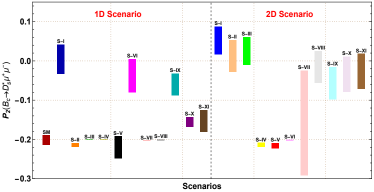


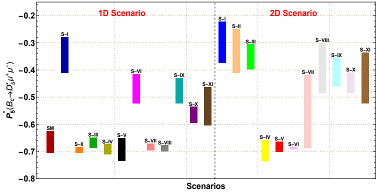
	1D Scenario		2D Scenario	
Scenarios	A_{FB}	F_L	A_{FB}	F_L
SM	−0.15	0.502	−0.15	0.502
S - I	0.0141	0.459	0.045	0.453
S - II	−0.157	0.511	0.011	0.462
S - III	−0.151	0.498	0.023	0.430
S - IV	−0.153	0.493	−0.157	0.515
S - V	−0.153	0.503	−0.156	0.518
S - VI	−0.028	0.479	−0.152	0.495
S - VII	−0.151	0.50	−0.053	0.446
S - VIII	−0.154	0.489	−0.011	0.489
S - IX	−0.046	0.434	−0.039	0.510
S - X	−0.113	0.502	−0.026	0.481
S - XI	−0.111	0.531	−0.021	0.490

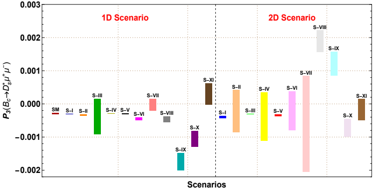
Results: $B_c \to D_s^* \mu^+ \mu^-$ $(P_{1,2,3}, P'_{4,5,8})$

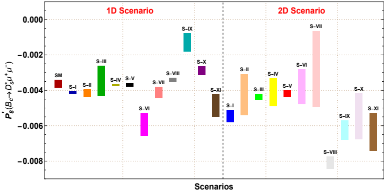












Results: $B_c \to D_s^* \mu^+ \mu^-$ $(P_{1,2,3}, P'_{4,5,8})$

1D Scenario						
Scenarios	$< P_1 >$	$< P_2 >$	$< P_3 > \times 10^3$	$< P_4^{'} >$	$< P_5^{'} >$	$< P_8^{'} > \times 10^2$
SM	-0.047	-0.20189	-0.289	0.433	-0.665	-0.362
S - I	-0.058	0.016	-0.304	0.426	-0.325	-0.413
S - II	-0.045	-0.215	-0.342	0.421	-0.698	-0.421
S - III	-0.04	-0.201	-0.435	0.431	-0.67	-0.34
S - IV	0.0006	-0.201	-0.29	0.42	-0.689	-0.37
S - V	-0.047	-0.206	-0.291	0.433	-0.671	-0.364
S - VI	-0.054	-0.037	-0.45	0.39	-0.47	-0.59
S - VII	-0.011	-0.202	-0.05	0.424	-0.681	-0.41
S - VIII	0.001	-0.2	-0.483	0.419	-0.691	-0.338
S - IX	-0.035	-0.055	-1.794	0.422	-0.47	-0.121
S - X	-0.165	-0.153	-1.101	0.45	-0.559	-0.285
S - XI	-0.174	-0.159	0.235	0.458	-0.546	-0.475
2D Scenarios						
SM	-0.047	-0.2	-0.289	0.433	-0.665	-0.362
S - I	-0.06	0.054	-0.399	0.4	-0.299	-0.55
S - II	-0.058	0.013	-0.205	0.426	-0.33	-0.043
S - III	0.055	0.026	-0.305	0.392	-0.358	-0.439
S - IV	-0.049	-0.217	-0.243	0.421	-0.698	-0.446
S - V	-0.083	-0.216	-0.343	0.431	-0.678	-0.416
S - VI	-0.003	-0.202	-0.231	0.421	-0.687	-0.379
S - VII	-0.08	-0.065	-1.83	0.43	-0.471	-0.132
S - VIII	0.055	-0.016	1.93	0.395	-0.397	-0.821
S - IX	-0.08	-0.054	1.24	0.438	-0.407	-0.629
S - X	-0.099	-0.035	-0.749	0.402	-0.448	-0.534
S - XI	-0.094	-0.029	-0.207	0.4	-0.434	-0.63

Table of Contents

Conclusion

- We have studied the $B_c \to D_s^{(*)}\ell\ell$ processes in model independent approach.
- We then constrained the NP parameter space using the (Axial)vector operators.
- Analyzed the observables such as branching ratio, the forward-backward asymmetry, lepton polarization asymmetries, etc.
- The discussed $B_c \to D_s^{(*)}\mu\mu$ decay observables deviate significantly from the SM contribution.

Thank you!

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