Role of the Right-Handed Neutrino in $B_c^+ \to B_s \mu^+ \nu_\mu$ Decay

Priyanka Boora
Malaviya National Institute of Technology Jaipur

In collaboration with
Dr. Kavita Lalwani and Dr. Dinesh Kumar

Conference on Falvor Physics and CP-Violation

28 May 2024

Table Of Content

Introduction

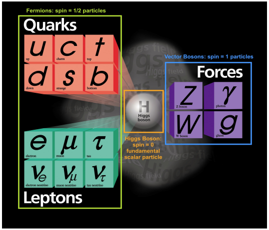
- In Particle Physics flavor refers to a species of elementary particles.

Introduction

- In Particle Physics flavor refers to a species of elementary particles.
- The Stadard Model includes six flavor of quarks and six flavor of leptons.

Introduction

- In Particle Physics flavor refers to a species of elementary particles.
- The Stadard Model includes six flavor of quarks and six flavor of leptons.
- The SM is based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$.



Hints for New Physics

- Neutrino masses
- Matter Anti-matter Asymmetry
- Lepton Flavor Universality Violation
- Dark Matter

- Right-Handed Neutrinos

- Right-Handed Neutrinos
- The inclusion of Right-Handed Neutrinos can play an important role in the search of new physics [JHEP 08 (2020) 022;JHEP10(2021)122].

- Right-Handed Neutrinos
- The inclusion of Right-Handed Neutrinos can play an important role in the search of new physics [JHEP 08 (2020) 022;JHEP10(2021)122].
- Our goal is to find the impact of RHN on exclusive semileptonic $B_c^+ \to B_s \mu^+ \nu$ decay induced at quark level by $c \to s \mu^+ \nu$.

- Right-Handed Neutrinos
- The inclusion of Right-Handed Neutrinos can play an important role in the search of new physics [JHEP 08 (2020) 022;JHEP10(2021)122].
- Our goal is to find the impact of RHN on exclusive semileptonic $B_c^+ \to B_s \mu^+ \nu$ decay induced at quark level by $c \to s\mu^+\nu$.
- The extension of the low-energy effective Hamiltonian with the inclusion of the dimension-six operator gives a platform to analyze the effects of New Physics.

Effective Hamiltonian

The low energy dimension-six effective Hamiltonian is

$$H_{\text{eff}} = \frac{4G_F V_{cs}}{\sqrt{2}}\left[O_{LL}^{V} + \sum_{\substack{i=S,V,T \\ A,B=L,R}} C_{AB}^{i} O_{AB}^{i}\right] \tag{1}$$

Effective Hamiltonian

The low energy dimension-six effective Hamiltonian is

$$H_{\text{eff}} = \frac{4G_F V_{cs}}{\sqrt{2}}\left[O_{LL}^V + \sum_{\substack{i=S,V,T\\ A,B=L,R}} C_{AB}^i O_{AB}^i\right] \quad (1)$$

with ten fermion operators

- $O_{AB}^V = (\bar{s}\gamma_\mu P_A c)(\bar{\nu}_\mu \gamma_\mu P_B \mu)$
- $O_{AB}^S = (\bar{s}P_A c)(\bar{\nu}_\mu P_B \mu)$
- $O_{AB}^T = \delta_{ij}(\bar{s}\sigma^{\mu\nu} P_A c)(\bar{\nu}_\mu \sigma_{\mu\nu} P_B \mu)$

Effective Hamiltonian

The low energy dimension-six effective Hamiltonian is

$$H_{\text{eff}} = \frac{4G_F V_{cs}}{\sqrt{2}} \left[O_{LL}^V + \sum_{\substack{i=S,V,T \\ A,B=L,R}} C_{AB}^i O_{AB}^i \right] \tag{1}$$

with ten fermion operators

- $O_{AB}^V = (\bar{s}\gamma_\mu P_A c)(\bar{\nu}_\mu \gamma_\mu P_B \mu)$
- $O_{AB}^S = (\bar{s} P_A c)(\bar{\nu}_\mu P_B \mu)$
- $O_{AB}^T = \delta_{ij}(\bar{s}\sigma^{\mu\nu} P_A c)(\bar{\nu}_\mu \sigma_{\mu\nu} P_B \mu)$

The Wilson Coefficients of New Physics are constrained by using the available experimental measurements of $D_{(s)}^{0(+)}$ mesons [Physical Review D, 103(7):075019, 2021].

Experimental Constraint

- To constrain the NP effect, we considered the six leptonic and semi-leptonic charm transitions.

Mode	SM	Experiment
$D_s^+ \to \mu^+\nu_\mu$	$(5.28 \pm 0.08) \times 10^{-3}$	$(5.50 \pm 0.23) \times 10^{-3}$
$D^0 \to K^-\mu^+\nu_\mu$	$(3.40 \pm 0.22) \times 10^{-2}$	$(3.41 \pm 0.04) \times 10^{-2}$
$D^+ \to \bar{K}^0\mu^+\nu_\mu$	$(8.70 \pm 0.73) \times 10^{-2}$	$(8.76 \pm 0.19) \times 10^{-2}$
$D^0 \to K^{*-}\mu^+\nu_\mu$	$(1.81 \pm 0.16) \times 10^{-2}$	$(1.89 \pm 0.24) \times 10^{-2}$
$D^+ \to \bar{K}^{*0}\mu^+\nu_\mu$	$(4.75 \pm 0.42) \times 10^{-2}$	$(5.27 \pm 0.15) \times 10^{-2}$
$D_s^+ \to \phi\mu^+\nu_\mu$	$(2.33 \pm 0.40) \times 10^{-2}$	$(1.90 \pm 0.50) \times 10^{-2}$

Table: Branching ratios of leptonic and semi-leptonic decays calculated in the SM [PRD, 96(5):054514, 2017; IJMPA, 21(30):6125–6172,2006] and comparison with the currently available experimental values [PDG, 2020(8):083C01, 2020]

χ^2 Minimization

- For best fit values of Wilson coefficients the χ^2 minimization [JHEP 09 (2018) 152] methodolgy is used:

χ^2 Minimization

- For best fit values of Wilson coefficients the χ^2 minimization [JHEP 09 (2018) 152] methodolgy is used:

$$\chi^2(C_i^{eff}) = \sum_n \frac{[\mathcal{O}_m^{th}(C_i^{eff}) - \mathcal{O}_m^{exp}]^2}{\sigma^2_{\mathcal{O}_m^{exp}}} \tag{2}$$

Here $\mathcal{O}^{th}(C_i^{eff})$ are the theoretical prediction value which depend upon the NP WCs C_i^{eff}. $\mathcal{O}^{exp}$ are the experimental measurement and $\sigma_{\mathcal{O}^{exp}}$ are the corresponding uncertainity.

χ^2 Minimization

- For best fit values of Wilson coefficients the χ^2 minimization [JHEP 09 (2018) 152] methodolgy is used:

$$\chi^2(C_i^{eff}) = \sum_n \frac{[\mathcal{O}_m^{th}(C_i^{eff}) - \mathcal{O}_m^{exp}]^2}{\sigma^2_{\mathcal{O}_m^{exp}}} \quad (2)$$

  Here $\mathcal{O}^{th}(C_i^{eff})$ are the theoretical prediction value which depend upon the NP WCs C_i^{eff}. $\mathcal{O}^{exp}$ are the experimental measurement and $\sigma_{\mathcal{O}^{exp}}$ are the corresponding uncertainity.

- To obtain the most likely value of WCs the minimization is done by MINUIT library [Comput. Phys. Commun. 10, 343 (1975)].

Wilson Coefficient Values

- The best fit values are:

Coefficient (s)	Value (s)	χ^2
C_{LL}^{V}	$(-3.95 \pm 4.69) \times 10^{-3}$	10.81
C_{RL}^{V}	$(-1.26 \pm 0.48) \times 10^{-2}$	04.44
C_{LR}^{V}	0.0 ± 0.07	11.53
C_{RR}^{V}	0.0 ± 0.07	11.53
C_{LL}^{S}	$(-0.53 \pm 0.77) \times 10^{-3}$	11.07
C_{RL}^{S}	$(-7.42 \pm 0.07) \times 10^{-2}$	11.53
C_{LR}^{S}	$(5.90 \pm 4.93) \times 10^{-3}$	11.18
C_{RR}^{S}	$(5.90 \pm 4.93) \times 10^{-3}$	11.18
C_{LL}^{T}	$(-3.66 \pm 0.97) \times 10^{-2}$	01.76
C_{RR}^{T}	$(6.35 \pm 1.41) \times 10^{-2}$	06.53

Table: Best fit values of Wilson coefficients.For the SM χ^2_{SM} = 11.534.

Differential Decay Width

The decay width in terms of angular dependence is given by

$$\frac{d\Gamma(B_c^+ \to B_s\mu^+\nu_\mu)}{dq^2\, d\cos\theta_\mu} = \frac{G_F^2 V_{cs}^2}{256 m_{B_c}^3 \pi^3} q^2 \lambda_{B_s}^{1/2}(q^2) \left(1 - \frac{m_\mu^2}{q^2}\right)^2 \times \left\{ J_0(q^2) + J_1(q^2)\cos\theta_\mu + J_2(q^2)\cos^2\theta_\mu \right\} \quad (3)$$

Differential Decay Width

The decay width in terms of angular dependence is given by

$$\frac{d\Gamma(B_c^+ \to B_s \mu^+ \nu_\mu)}{dq^2 d\cos\theta_\mu} = \frac{G_F^2 V_{cs}^2}{256 m_{B_c}^3 \pi^3} q^2 \lambda_{B_s}^{1/2}(q^2) \left(1 - \frac{m_\mu^2}{q^2}\right)^2 \times \left\{ J_0(q^2) + J_1(q^2)\cos\theta_\mu + J_2(q^2)\cos^2\theta_\mu \right\} \quad (3)$$

where, $q^2 = (p_{\mu^+} + p_\nu)$ the square momentum transferred to the muon pair, θ_μ is the polar angle of the muon momentum in the rest frame of the $\mu^+\nu$ pair, w.r.to the z-axis defined by the B_c meson momentum. The differential angular coefficients are given as

$$\begin{aligned} J_0\left(q^2\right) &= \left|\mathcal{W}_0^L - \frac{2m_\mu}{\sqrt{q^2}}\mathcal{W}_T^L\right|^2 + \frac{m_\mu^2}{q^2}\left|\mathcal{W}_t^L + \frac{\sqrt{q^2}}{m_\mu}\mathcal{W}_S^L\right|^2 + (L \leftrightarrow R), \\ J_1\left(q^2\right) &= \frac{2m_\mu^2}{q^2} Re\left[\left(\mathcal{W}_0^L - \frac{2\sqrt{q^2}}{m_\mu}\mathcal{W}_T^L\right)\left(\mathcal{W}_t^{L*} + \frac{\sqrt{q^2}}{m_\mu}\mathcal{W}_S^{L*}\right)\right] + (L \leftrightarrow R), \quad (4) \\ J_2\left(q^2\right) &= -\left(1 - \frac{m_\mu^2}{q^2}\right)\left(\left|\mathcal{W}_0^L\right|^2 - 4\left|\mathcal{W}_T^L\right|^2\right) + (L \leftrightarrow R), \end{aligned}$$

Hadronic Amplitudes

$$
\begin{aligned}
\mathcal{W}_0^L &= \left(1 + C_{LL}^V + C_{RL}^V\right) H_{V,0}^s, & \mathcal{W}_0^R &= \left(C_{LR}^V + C_{RR}^V\right) H_{V,0}^s, \\
\mathcal{W}_t^L &= \left(1 + C_{LL}^V + C_{RL}^V\right) H_{V,t}^s, & \mathcal{W}_t^R &= \left(C_{LR}^V + C_{RR}^V\right) H_{V,t}^s, \\
\mathcal{W}_S^L &= \left(C_{RL}^S + C_{LL}^S\right) H_S^s, & \mathcal{W}_S^R &= \left(C_{RR}^S + C_{LR}^S\right) H_S^s, \\
\mathcal{W}_T^L &= 2C_{LL}^T H_T^s, & \mathcal{W}_T^R &= 2C_{RR}^T H_T^s.
\end{aligned}
\tag{5}
$$

Hadronic Amplitudes

$$\begin{aligned}
\mathcal{W}_0^L &= \left(1 + C_{LL}^V + C_{RL}^V\right) H_{V,0}^s, & \mathcal{W}_0^R &= \left(C_{LR}^V + C_{RR}^V\right) H_{V,0}^s,\\
\mathcal{W}_t^L &= \left(1 + C_{LL}^V + C_{RL}^V\right) H_{V,t}^s, & \mathcal{W}_t^R &= \left(C_{LR}^V + C_{RR}^V\right) H_{V,t}^s,\\
\mathcal{W}_S^L &= \left(C_{RL}^S + C_{LL}^S\right) H_S^s, & \mathcal{W}_S^R &= \left(C_{RR}^S + C_{LR}^S\right) H_S^s,\\
\mathcal{W}_T^L &= 2C_{LL}^T H_T^s, & \mathcal{W}_T^R &= 2C_{RR}^T H_T^s.
\end{aligned} \tag{5}$$

The hadronic amplitudes in terms of F_0, F_+ and F_T form factors are:

$$\begin{aligned}
H_{V,0}^s(q^2) &\equiv H_{V_L,0}^s(q^2) = H_{V_R,0}^s(q^2) = \sqrt{\frac{\lambda_{B_s}(q^2)}{q^2}}F_+(q^2),\\
H_{V,t}^s(q^2) &\equiv H_{V_L,t}^s(q^2) = H_{V_R,t}^s(q^2) = \frac{m_{B_c}^2 - m_{B_s}^2}{\sqrt{q^2}}F_0(q^2),\\
H_S^s(q^2) &\equiv H_{S_L}^s(q^2) = H_{S_R}^s(q^2) \simeq \frac{m_{B_c}^2 - m_{B_s}^2}{m_c - m_s}F_0(q^2),\\
H_T^s(q^2) &= H_{T_L+-}^s = H_{T_L0t}^s = -H_{T_R+-}^s = H_{T_R0t}^s = -\frac{\sqrt{\lambda_{B_s}(q^2)}}{m_{B_c} + m_{B_s}}F_T(q^2),
\end{aligned} \tag{6}$$

Differential Decay Width

$$
\begin{aligned}
\frac{d\Gamma}{dq^2}(B_c^+ \to B_s \mu^+ \nu) = & \frac{G_F^2 V_{cs}^2}{192 m_{B_c}^3 \pi^3} q^2 \lambda_{B_s}^{1/2}\left(q^2\right)\left(1-\frac{m_\mu^2}{q^2}\right)^2 \\
& \times \Bigg\{ \left(\left|1 + C_{LL}^V + C_{RL}^V\right|^2 + \left|C_{LR}^V + C_{RR}^V\right|^2 \right) \\
& \left[\left(H_{V,0}^s\right)^2 \left(\frac{m_\mu^2}{2q^2} + 1\right) + \frac{3m_\mu^2}{2q^2} \left(H_{V,t}^s\right)^2 \right] \\
& + \frac{3}{2}\left(H_S^s\right)^2 \left(\left|C_{RL}^S + C_{LL}^S\right|^2 + \left|C_{RR}^S + C_{LR}^S\right|^2 \right) \\
& + 8\left(\left|C_{LL}^T\right|^2 + \left|C_{RR}^T\right|^2 \right) \left(H_T^s\right)^2 \left(1 + \frac{2m_\mu^2}{q^2}\right) \\
& + 3Re\left[\left(1 + C_{LL}^V + C_{RL}^V\right)\left(C_{RL}^S + C_{LL}^S\right)^* \right. \\
& \left. + \left(C_{LR}^V + C_{RR}^V\right)\left(C_{RR}^S + C_{LR}^S\right)^* \right] \frac{m_\mu}{\sqrt{q^2}} H_S^s H_{V,t}^s \\
& -12Re\left[\left(1 + C_{LLL}^V + C_{RL}^V\right) C_{LLL}^{T*} + \left(C_{RR}^V + C_{LR}^V\right) C_{RR}^{T*} \right] \frac{m_\mu}{\sqrt{q^2}} H_T^s H_{V,0}^s \Bigg\}.
\end{aligned}
\tag{7}
$$

Form Factor

- The computation of the form factors is evaluated over the full range of q^2; $0 < q^2 < (M_{B_c^+} - M_{B_s})^2$ by chain fit of the results from HISQ method and NQCD [Physical Review D, 102(1):014513, 2020]:

Form Factor

- The computation of the form factors is evaluated over the full range of q^2; $0 < q^2 < (M_{B_c^+} - M_{B_s})^2$ by chain fit of the results from HISQ method and NQCD [Physical Review D, 102(1):014513, 2020]:

$$\boxed{f(q^2) = P(q^2) \sum_{n}^{N} A_n z_p(q^2)^n} \tag{8}$$

Form Factor

- The computation of the form factors is evaluated over the full range of q^2; $0 < q^2 < (M_{B_c^+} - M_{B_s})^2$ by chain fit of the results from HISQ method and NQCD [Physical Review D, 102(1):014513, 2020]:

$$\boxed{f(q^2) = P(q^2) \sum_n^N A_n z_p(q^2)^n} \tag{8}$$

where, $z_p\left(q^2\right) = \frac{z\left(q^2\right)}{\left|z\left(M_p^2\right)\right|}$,
$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+}}{\sqrt{t_+ - q^2} + \sqrt{t_+}}$ with $t_+ = (m_{B_c} + m_{B_s})^2$
$P(q^2) = \left(1 - q^2/M_{\mathrm{res}}^2\right)^{-1}$ and A_n is the covariance matrix.

Scenarios

Spin	Q.N.	Nature	ν_L	ν_R
0	$S_1 \sim (\bar{3}, 1, 1/3)$	LQ	$C^V_{LL}, C^S_{LL}, C^T_{LL}$	$C^V_{RR}, C^S_{RR}, C^T_{RR}$
0	$\Phi \sim (1, 2, 1/2)$	SB	C^S_{LL}, C^S_{RL}	C^S_{LR}, C^S_{RR}
0	$R_2 \sim (3, 2, 1/6)$	LQ	-	C^S_{RR}, C^T_{RR}
1	$U^\mu_1 \sim (3, 1, 2/3)$	LQ	C^V_{LL}, C^S_{RL}	C^V_{RR}, C^S_{LR}
1	$V^\mu_2 \sim (\bar{3}, 2, -1/6)$	LQ	-	C^S_{LR}
1	$V^\mu \sim (1, 1, -1)$	VB	-	C^V_{RR}

Table: Spin, $SU(3)_C \times SU(2)_L \times U(1)_Y$ quantum numbers and nature (LQ = leptoquark, SB = scalar boson, VB = vector boson) of the possible candidates to mediate $c \to s$ transitions [JHEP 08 (2020) 022].

New Physics

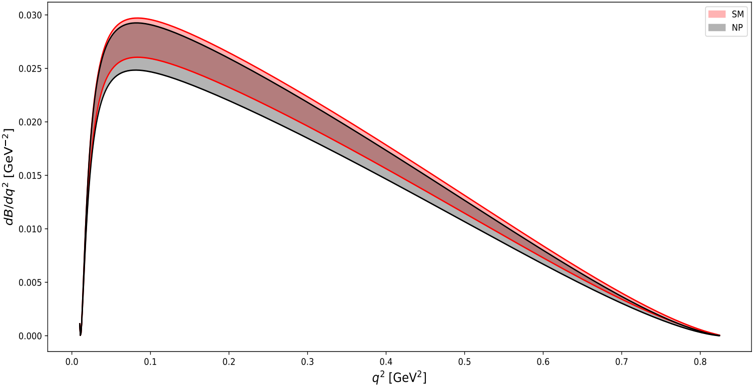


Figure: q^2 spectrum for all new physics contribution both the SM and NP includes the unceratinity of the form factors.

RHN sceanrio

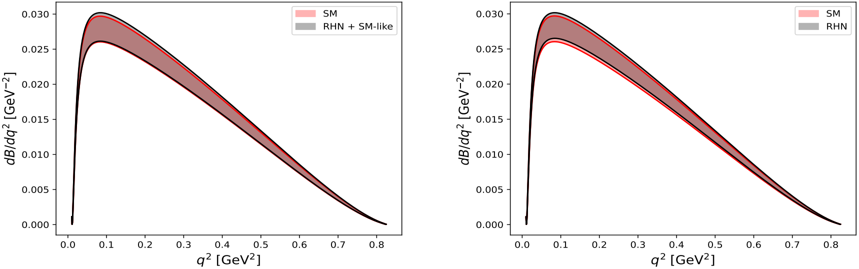


Figure: q^2 spectrum for the RHN + SM-like contribution: O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR} (left side), and RHN: O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR} (right side).

Vector Boson (1,1,-1) & Leptoquark ($\bar{3}$,2,-1/6) scenario

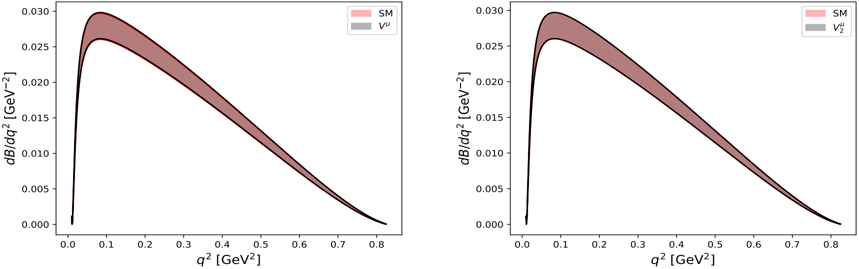
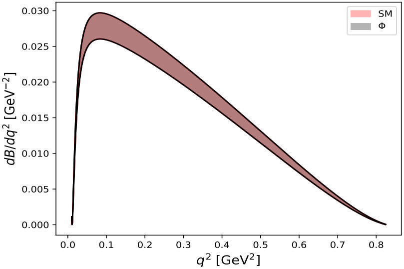


Figure: q^2 spectrum for the Vector Boson (V^μ): O^V_{RR} (left), and Leptoquark (V_2^μ): O^S_{LR} (right).

Scalar Boson (1,2,1/2) scenario



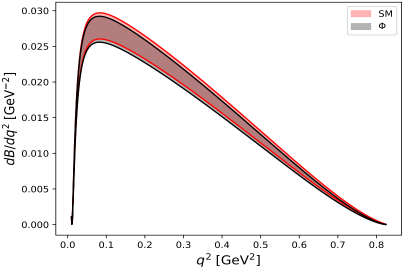


Figure: q^2 spectrum for Φ (1,2,1/2): O^S_{LR}, O^S_{RR} (left) included only right-handed operators; O^S_{LL}, O^S_{RL} and O^S_{RR}, O^S_{LR} (right) included both left and right-handed operators.

Leptoquark (3,1,2/3) scenario

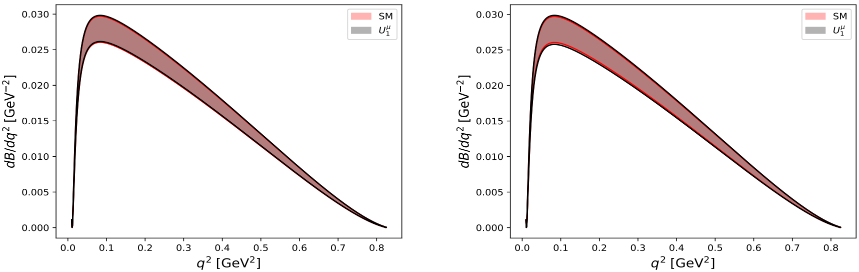


Figure: q^2 spectrum for U_1^μ (3,1,2/3): O^V_{RR}, O^S_{LR} (left) with right-handed operatos only; O^V_{LL}, O^S_{RL} and O^V_{RR}, O^S_{LR} (right) with both left and right-handed operators.

Leptoquark (3,2,1/6) scenario

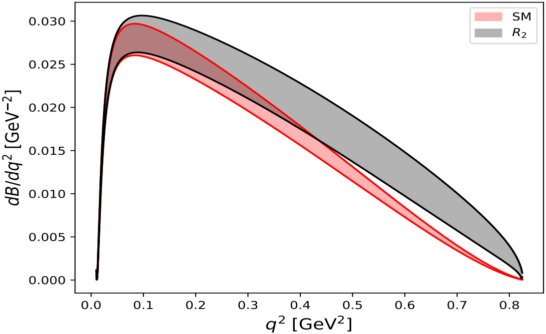


Figure: q^2 spectrum for R_2 (3,2,1/6): O^S_{RR}, O^T_{RR} with $C^S_{RR} = 4rC^T_{RR}$ where r = 2 at b-quark scale.

Leptoquark ($\bar{3}$,1,1/3) scenario

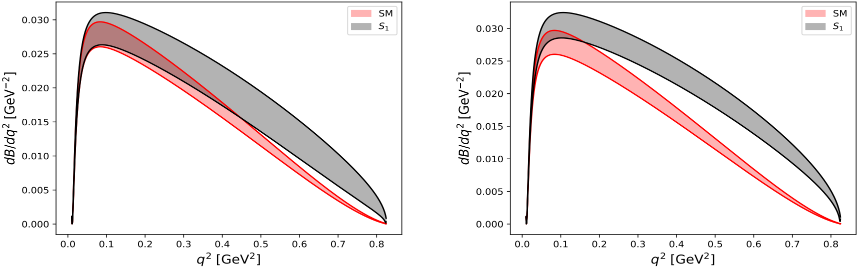


Figure: q^2 spectrum for S_1 ($\bar{3}$,1,1/3): $O^V_{RR}, O^S_{RR}, O^T_{RR}$ with $C^S_{RR} = -4rC^T_{RR}$ (left) for right-handed operators only; $O^V_{LL}, O^S_{LL}, O^T_{LL}$ and $O^V_{RR}, O^S_{RR}, O^T_{RR}$ with $C^S_{LL} = -4rC^T_{LL}$ and $C^S_{RR} = -4rC^T_{RR}$ (right) for both left and right-handed operators.

Conclusion

- Using the EFT approach, the impact of NP operator's on the $B_c^+ \to B_s\mu^+\nu_\mu$ decay is analyzed.

Conclusion

- Using the EFT approach, the impact of NP operator's on the $B_c^+ \to B_s \mu^+ \nu_\mu$ decay is analyzed.
- The NP Wilson Coefficients are constrained by using the leptonic and semileptonic charm decays.

Conclusion

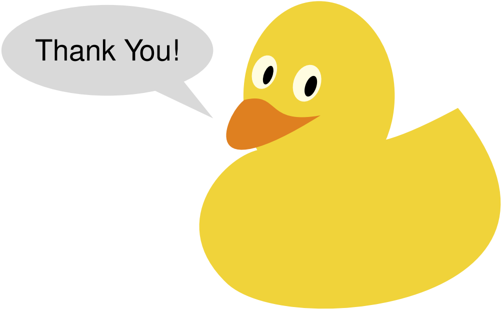
- Using the EFT approach, the impact of NP operator's on the $B_c^+ \to B_s \mu^+ \nu_\mu$ decay is analyzed.
- The NP Wilson Coefficients are constrained by using the leptonic and semileptonic charm decays.
- We have focused on the NP operators which can arise due to the presence of RHN.

Conclusion

- Using the EFT approach, the impact of NP operator's on the $B_c^+ \to B_s \mu^+ \nu_\mu$ decay is analyzed.
- The NP Wilson Coefficients are constrained by using the leptonic and semileptonic charm decays.
- We have focused on the NP operators which can arise due to the presence of RHN.
- Among all the scenarios, the scenario 6 and 7 gives a small deviation in Braching fraction from the SM.

Conclusion

- Using the EFT approach, the impact of NP operator's on the $B_c^+ \to B_s \mu^+ \nu_\mu$ decay is analyzed.
- The NP Wilson Coefficients are constrained by using the leptonic and semileptonic charm decays.
- We have focused on the NP operators which can arise due to the presence of RHN.
- Among all the scenarios, the scenario 6 and 7 gives a small deviation in Braching fraction from the SM.
- Other observable like A_{FB} should be investigated in order to see any effects of NP.


Thank You!

Backup Slides

Differential Decay Width

- Differential decay distribution can be written as

$$\frac{d\Gamma(B_c^+ \to B_s \mu^+ \nu_\mu)}{dq^2 d\cos\theta_\mu} = \frac{G_F^2 V_{cs}^2}{256 m_{B_c}^3 4\pi^3} q^2 \lambda_{B_s}^{1/2}(q^2)\left(1 - \frac{m_\mu^2}{q^2}\right)^2 L_{\mu\nu} H^{\mu\nu} \quad (9)$$

where the short-hand notation for the Kallen triangle function is

$$\lambda_{B_s}\left(q^2\right) \equiv \lambda\left(m_{B_c}^2, m_{B_s}^2, q^2\right) = m_{B_c}^4 + m_{B_s}^4 + q^4 - 2m_{B_c}^2 m_{B_s}^2 - 2m_{B_s}^2 q^2 - 2m_{B_c}^2 q^2$$

Leptonic Amplitude

The lepton helicity amplitudes are defined as

$$L^{\lambda_\mu, {}^L_R}_{V\mp A,\lambda}\left(q^2,\theta_\mu,\phi\right) = \epsilon_\alpha(\lambda)\left\langle \mu^+\left(\lambda_\mu\right)\nu\left(\lambda_\nu\right)\left|\bar{\nu}\gamma^\mu\left(1\mp\gamma_5\right)\mu\right|0\right\rangle$$

$$L^{\lambda_\mu, {}^L_R}_{S\mp P,\lambda}\left(q^2,\theta_\mu,\phi\right) = \left\langle \mu^+\left(\lambda_\mu\right)\nu\left(\lambda_\nu\right)\left|\bar{\nu}\gamma^\mu\left(1\mp\gamma_5\right)\mu\right|0\right\rangle$$

$$L^{\lambda_\mu, {}^L_R}_{T\mp T5,\lambda}\left(q^2,\theta_\mu,\phi\right) = -L^{\lambda_\mu, {}^L_R}_{T\mp T5,\lambda}\left(q^2,\theta_\mu,\phi\right) = -i\epsilon_\alpha(\lambda)\epsilon_\beta\left(\lambda'\right)\left\langle \mu^+\left(\lambda_\mu\right)\nu\left(\lambda_\nu\right)\right|$$

where λ_μ is the muon helicity and $\epsilon(\lambda)$ are the polarization vector of the intermediate vector boson.

Leptonic: $D_s^+ \to \mu^+ \nu_\mu$

The branching fraction for leptonic is

$$\mathcal{B} = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s^+}^2 M_{D_s^+} m_\mu^2$$

$$\Big[\Big| 1 + C_{LL}^V - C_{RL}^V + \frac{m_{D_s^+}^2}{m_\mu (m_c + m_s)} (C_{RL}^S - C_{LL}^S) \Big|^2 + \Big| C_{RR}^V - C_{LR}^V + \frac{m_{D_s^+}^2}{m_\mu (m_c + m_s)} \quad (10)$$

where $\tau_{D_s^+}$ is the lifetime of the D_s^+ meson, $M_{D_s^+}$ and m_μ are the masses of the D_s^+ meson and muon lepton respectively, and the decay constant is

$$f_{D_s^+} = (248.0 \pm 1.6) MeV$$

Semi-leptonic: $D \to P\mu^+\nu_\mu$

$$
\begin{aligned}
\frac{d\mathcal{B}}{dq^2}(D \to P\mu^+\nu) = & \frac{G_F^2 V_{cs}^2}{192 m_D^3 \pi^3} q^2 \lambda_P^{1/2}\left(q^2\right)\left(1-\frac{m_\mu^2}{q^2}\right)^2 \tau_D \\
& \times \Bigg\{ \left(\left|1 + C_{LL}^V + C_{RL}^V\right|^2 + \left|C_{LR}^V + C_{RR}^V\right|^2 \right) \\
& \left[\left(H_{V,0}^P\right)^2 \left(\frac{m_\mu^2}{2q^2} + 1\right) + \frac{3m_\mu^2}{2q^2}\left(H_{V,s}^P\right)^2 \right] \\
& + \frac{3}{2}\left(H_{S,s}^P\right)^2 \left(\left|C_{RL}^S + C_{LL}^S\right|^2 + \left|C_{RR}^S + C_{LR}^S\right|^2 \right) \\
& + 8\left(\left|C_{LL}^T\right|^2 + \left|C_{RR}^T\right|^2 \right)\left(H_T^P\right)^2 \left(1 + \frac{2m_\mu^2}{q^2}\right) \\
& + 3Re\left[\left(1 + C_{LL}^V + C_{RL}^V\right)\left(C_{RL}^S + C_{LL}^S\right)^* \right. \\
& \left. + \left(C_{LR}^V + C_{RR}^V\right)\left(C_{RR}^S + C_{LR}^S\right)^* \right] \frac{m_\mu}{\sqrt{q^2}} H_{S,s}^P H_{V,s}^P \\
& -12Re\left[\left(1 + C_{LLL}^V + C_{RL}^V\right) C_{LLL}^{T*} + \left(C_{RR}^V + C_{LR}^V\right) C_{RR}^{T*} \right] \frac{m_\mu}{\sqrt{q^2}} H_T^P H_{V,0}^P \Bigg\} .
\end{aligned}
\tag{11}
$$

Semi-leptonic: $D \to V\mu^+\nu_\mu$

$$\frac{d\mathcal{B}}{dq^2}(D \to V\mu^+\nu) = \frac{G_F^2 V_{cs}^2}{192 m_D^3 \pi^3} q^2 \lambda_V^{1/2}\left(q^2\right)\left(1 - \frac{m_\mu^2}{q^2}\right)^2 \tau_D$$
$$\times \Bigg\{ \left(\left|1 + C_{LL}^V\right|^2 + \left|C_{RL}^V\right|^2 + \left|C_{LR}^V\right|^2 + \left|C_{RR}^V\right|^2 \right)$$
$$\left[\left(H_{V,+}^2 + H_{V,-}^2 + H_{V,0}^2\right)\left(\frac{m_\mu^2}{2q^2} + 1\right) + \frac{3m_\mu^2}{2q^2}\left(H_{V,t}^2\right) \right]$$
$$+ \left(\left(1 + C_{LL}^V\right) C_{RL}^{V*} + C_{LR}^V C_{RR}^{V*} \right) \left[\left(H_{V,0}^2 + 2H_{V,+}H_{V,-}\right)\left(\frac{m_\mu^2}{2q^2} + 1\right) + \frac{3m_\mu^2}{2q^2}\left(H_{V,t}^2\right) \right]$$
$$+ \frac{3}{2} H_S^2 \left(\left|C_{RL}^S - C_{LL}^S\right|^2 + \left|C_{RR}^S - C_{LR}^S\right|^2 \right) \tag{12}$$
$$+ 8 \left(\left|C_{LL}^T\right|^2 + \left|C_{RR}^T\right|^2 \right) \left(H_{T,+}^2 + H_{T,-}^2 + H_{T,-}^2\right)\left(1 + \frac{2m_\mu^2}{q^2}\right)$$
$$+ 3Re\left[\left(1 + C_{LL}^V - C_{RL}^V\right)\left(C_{RL}^S - C_{LL}^S\right)^* + \left(C_{LR}^V - C_{RR}^V\right)\left(C_{RR}^S - C_{LR}^S\right)^* \right] \frac{m_\mu}{\sqrt{q^2}} H_S H_{V,t}$$
$$-12Re\left[\left(1 + C_{LL}^V\right) C_{LL}^{T*} + C_{RR}^V C_{RR}^{T*} \right] \frac{m_\mu}{\sqrt{q^2}} \left(H_{T,0}H_{V,0} + H_{T,+}H_{V,+} + H_{T,-}H_{V,-}\right)$$
$$+12Re\left[C_{RL}^V C_{LL}^{T*} + C_{LR}^V C_{RR}^{T*} \right] \frac{m_\mu}{\sqrt{q^2}} \left(H_{T,0}H_{V,0} + H_{T,+}H_{V,-} - H_{T,-}H_{V,+}\right) \Bigg\}$$

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: $O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}$

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: $O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}$
  2. RHN: $O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}$

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: $O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}$
  2. RHN: $O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}$
  3. Vector Boson nature: V^μ (1,1,-1): O^V_{RR}

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: $O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}$
  2. RHN: $O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}$
  3. Vector Boson nature: V^μ (1,1,-1): O^V_{RR}
  4. Scalar Boson nature
     1. φ (1,2,1/2): O^S_{LR}, O^S_{RR}
     2. φ (1,2,1/2): O^S_{LL}, O^S_{RL} and O^S_{LR}, O^S_{RR}

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  2. RHN: O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  3. Vector Boson nature: V^μ (1,1,-1): O^V_{RR}
  4. Scalar Boson nature
     1. φ (1,2,1/2): O^S_{LR}, O^S_{RR}
     2. φ (1,2,1/2): O^S_{LL}, O^S_{RL} and O^S_{LR}, O^S_{RR}
  5. Leptoquark nature
     1. U_1^μ (3,1,2/3): O^V_{RR}, O^S_{LR}
     2. U_1^μ (3,1,2/3): O^V_{LL}, O^S_{RL} and O^V_{RR}, O^S_{LR}

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  2. RHN: O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  3. Vector Boson nature: V^μ (1,1,-1): O^V_{RR}
  4. Scalar Boson nature
     1. φ (1,2,1/2): O^S_{LR}, O^S_{RR}
     2. φ (1,2,1/2): O^S_{LL}, O^S_{RL} and O^S_{LR}, O^S_{RR}
  5. Leptoquark nature
     1. U_1^μ (3,1,2/3): O^V_{RR}, O^S_{LR}
     2. U_1^μ (3,1,2/3): O^V_{LL}, O^S_{RL} and O^V_{RR}, O^S_{LR}
  6. Leptoquark nature: R_2 (3,2,1/6): O^S_{RR}, O^T_{RR} with $C^S_{RR} = 4rC^T_{RR}$

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  2. RHN: O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  3. Vector Boson nature: V^μ (1,1,-1): O^V_{RR}
  4. Scalar Boson nature
     1. φ (1,2,1/2): O^S_{LR}, O^S_{RR}
     2. φ (1,2,1/2): O^S_{LL}, O^S_{RL} and O^S_{LR}, O^S_{RR}
  5. Leptoquark nature
     1. U^μ_1 (3,1,2/3): O^V_{RR}, O^S_{LR}
     2. U^μ_1 (3,1,2/3): O^V_{LL}, O^S_{RL} and O^V_{RR}, O^S_{LR}
  6. Leptoquark nature: R_2 (3,2,1/6): O^S_{RR}, O^T_{RR} with $C^S_{RR} = 4rC^T_{RR}$
  7. Leptoquark nature
     1. S_1 ($\bar{3}$,1,1/3): O^V_{RR}, O^S_{RR}, O^T_{RR} with $C^S_{RR} = -4rC^T_{RR}$
     2. S_1 ($\bar{3}$,1,1/3): O^V_{LL}, O^S_{LL}, O^T_{LL} and O^V_{RR}, O^S_{RR}, O^T_{RR} with $C^S_{LL} = -4rC^T_{LL}$ and $C^S_{RR} = -4rC^T_{RR}$

Scenarios

- The following scenarios [JHEP 08 (2020) 022] are analyzed:
  1. RHN + SM-like contribution: O^V_{LL}, O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  2. RHN: O^V_{LR}, O^V_{RR}, O^S_{LR}, O^S_{RR}, O^T_{RR}
  3. Vector Boson nature: V^μ (1,1,-1): O^V_{RR}
  4. Scalar Boson nature
     1. φ (1,2,1/2): O^S_{LR}, O^S_{RR}
     2. φ (1,2,1/2): O^S_{LL}, O^S_{RL} and O^S_{LR}, O^S_{RR}
  5. Leptoquark nature
     1. U_1^μ (3,1,2/3): O^V_{RR}, O^S_{LR}
     2. U_1^μ (3,1,2/3): O^V_{LL}, O^S_{RL} and O^V_{RR}, O^S_{LR}
  6. Leptoquark nature: R_2 (3,2,1/6): O^S_{RR}, O^T_{RR} with $C^S_{RR} = 4rC^T_{RR}$
  7. Leptoquark nature
     1. S_1 ($\bar{3}$,1,1/3): O^V_{RR}, O^S_{RR}, O^T_{RR} with $C^S_{RR} = -4rC^T_{RR}$
     2. S_1 ($\bar{3}$,1,1/3): O^V_{LL}, O^S_{LL}, O^T_{LL} and O^V_{RR}, O^S_{RR}, O^T_{RR} with $C^S_{LL} = -4rC^T_{LL}$ and $C^S_{RR} = -4rC^T_{RR}$
  8. Leptoquark nature: V_2^μ ($\bar{3}$,2,-1/6): O^S_{LR}