Understanding $b \to c\tau\nu$ mediated baryonic decays in SMEFT

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PPC 2024
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Motivation

- Measurements on b hadron decays show an interesting avenue for the Standard Model and beyond it.
- The deviations are present in the quark level transitions, particularly in
  - $b \to s\ell\ell$: BR$(B_s \to \phi\mu\mu) \sim 3.3\sigma$, $P_5'(B \to K^*\mu\mu) \sim 3.3\sigma$
  - $b \to s\nu\bar{\nu}$: BR $(B \to K^+\nu\bar{\nu}) \sim 2.8\sigma$
  - $b \to c\ell\bar{\nu}$: $R_{D^{(*)}} \sim 2\sigma$, $R_{J/\psi} \sim 2\sigma$, $P_\tau^{D^*}, F_L^{D^*} \sim (1.5-2)\sigma$
- Probing the $b-$baryon decays offers valuable insights into the weak interaction and the underlying dynamics.
- In this regard, we investigate semileptonic b baryon decay modes such as $\Xi_b \to \Xi_c \tau^- \bar{\nu}_\tau$ and $\Sigma_b \to \Sigma_c^{(*)} \tau^- \bar{\nu}_\tau$.
- W adopt the SMEFT framework, assuming that the scale of new physics exceeds the electroweak scale and that no additional light particles exist below this scale.

LEFT: Physics below EW scale

- For $b \to cl\nu$ transition, we employ the following weak effective Hamiltonian as

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \frac{4G_F}{\sqrt{2}} V_{cb} \sum_{i,l} C_i \mathcal{O}_i^l + \text{h.c.}\,, \tag{1}$$

where V_{cb}: CKM matrix element,
G_F: Fermi constant,
l: lepton flavors ($l = e, \mu, \tau$).

- The C_i and $\mathcal{O}_i^l$ are the Wilson coefficients and the local effective operators, respectively.
- The relevant 4-fermion operators are as follows,

$$\mathcal{O}_{V_L}^l = (\bar{c}_L \gamma^\mu b_L)(\bar{l}_L \gamma_\mu \nu_{lL})\,, \qquad \mathcal{O}_{V_R}^l = (\bar{c}_R \gamma^\mu b_R)(\bar{l}_L \gamma_\mu \nu_{lL})\,, \tag{2}$$

$$\mathcal{O}_{S_L}^l = (\bar{c}_R b_L)(\bar{l}_R \nu_{lL})\,, \qquad \mathcal{O}_{S_R}^l = (\bar{c}_L b_R)(\bar{l}_R \nu_{lL})\,, \tag{3}$$

$$\mathcal{O}_T^l = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{l}_R \sigma_{\mu\nu} \nu_{lL})\,. \tag{4}$$

- Similarly, the effective Hamiltonian governing both $b \to s\nu\bar{\nu}$ and $b \to s\,\ell^+\,\ell^-$ decays can be written as

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i\, \mathcal{O}_i\, + h.c. \tag{5}$$

- $b \to s\nu\bar{\nu}$:
  The effective operators $\mathcal{O}_i$ (where $i = L, R$) are

$$\mathcal{O}_L = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu), \quad \mathcal{O}_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu), \tag{6}$$

  where C_L and C_R are the associated Wilson coefficients.
- $b \to s\ell\ell$:
  The relevant effective operators are expressed as follows

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu l), \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu \gamma_5 l) \tag{7}$$

with $\mathcal{C}_9^{(\prime)}$ and $\mathcal{C}_{10}^{(\prime)}$, the vector and axial-vector couplings, respectively.

Contd...

SMEFT: Physics above EW scale

- The SMEFT effective Lagrangian at mass dimension six is given as follows:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{Q_i = Q_i^\dagger} \frac{C_i}{\Lambda^2} Q_i + \sum_{Q_i \neq, Q_i^\dagger} \left(\frac{C_i}{\Lambda^2}, Q_i + \frac{C_i^*}{\Lambda^2} Q_i^\dagger \right) . \quad (8)$$

- The relevant operators are provided below,

$$Q_{lq}^{(3)} = (\bar{l}_p \gamma_\mu \sigma_a l_r)(\bar{q}_s \gamma^\mu \sigma^a q_t), \qquad Q_{ledq} = (\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$$

$$Q_{lequ}^{(1)} = (\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t), \qquad Q_{lequ}^{(3)} = (\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$$

$$Q_{\phi q}^{(3)} = (\phi^\dagger i D_\mu^a \phi)(\bar{q}_p \sigma_a \gamma^\mu q_r), \qquad Q_{\phi ud} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u}_p \gamma^\mu d_r).$$

- In the presence of dimension six SMEFT operators, the WCs get modified

$$C_{V_L} = -\frac{v^2}{\Lambda^2} \frac{V_{cs}}{V_{cb}} (C_{\ell q}^{(3)ll23} - C_{\phi q}^{(3)23}), \qquad C_{V_R} = \frac{v^2}{2\Lambda^2 V_{cb}} C_{\phi ud}^{23},$$

$$C_{S_L} = -\frac{v^2}{2\Lambda^2} \frac{V_{cs}}{V_{cb}} C_{\ell edq}^{ll32}, \qquad C_{S_R} = -\frac{v^2}{2\Lambda^2} \frac{V_{tb}}{V_{cb}} C_{\ell equ}^{(1)ll32},$$

$$C_T = -\frac{v^2}{2\Lambda^2} \frac{V_{tb}}{V_{cb}} C_{\ell equ}^{(3)ll32}. \quad (9)$$

Measurements used in our analysis

Observables	Expt. Value	Deviation
R_D	$0.357 \pm 0.029 \pm 0.014$	1.98σ
R_{D^*}	$0.284 \pm 0.010 \pm 0.012$	2.15σ
$R_{J/\psi}$	$0.284 \pm 0.010 \pm 0.012$	$\sim 2\sigma$
$P_\tau(D^*)$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$	$\sim 1.5\sigma$
$F_L(D^*)$	$0.60 \pm 0.08 \pm 0.04$	$\sim 1.6\sigma$
$\mathcal{B}(B \to K^+ \nu\bar{\nu})$	$(2.4 \pm 0.7) \times 10^{-5}$	$\sim 2.8\sigma$
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	2.3×10^{-5}	–
$\mathcal{B}(\bar{B}_s \to \tau^+\tau^-)$	6.8×10^{-3}	–
$\mathcal{B}(\bar{B} \to K^+\tau^+\tau^-)$	1.31×10^{-3}	–

Table: Experimental results of various $b \to c\tau\nu_\tau$, $b \to s\nu\bar{\nu}$ and $b \to s\tau^+\tau^-$ observables.

Constraint on SMEFT couplings

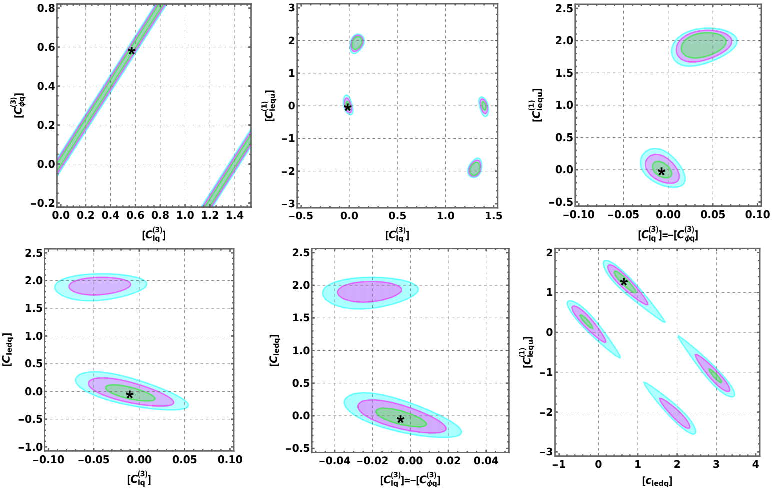

Figure: Allowed region with best-fit value for different combinations of WCs from $b \to c\tau\nu_\tau$ process.

Best-fit values

- We perform the naive chi-square analysis and is given as

$$\chi^2 = \sum_i \frac{\left(\mathcal{O}_i^{\rm Th}(C^{\rm NP}) - \mathcal{O}_i^{\rm Exp}\right)^2}{(\Delta\mathcal{O}_i^{\rm Exp})^2 + (\Delta\mathcal{O}_i^{\rm SM})^2}.$$

SMEFT couplings	$b \to c\tau\nu_\tau$	$b \to s\tau^+\tau^-$	$b \to s\nu\bar{\nu}$
$(C_{lq}^{(3)}, C_{\phi q}^{(3)})$	(0.572, 0.587)	(-0.49, -0.078)	(0.08, 0.084)
$(C_{lq}^{(3)} = -C_{\phi q}^{(3)}, C_{lequ}^{(1)})$	(-0.007, -0.004)	—	—
$(C_{lq}^{(3)}, C_{lequ}^{(1)})$	(-0.014, -0.0038)	—	—
$(C_{lq}^{(3)} = -C_{\phi q}^{(3)}, C_{ledq})$	(-0.0051, -0.033)	—	—
$(C_{lq}^{(3)}, C_{ledq})$	(-0.0102, -0.033)	—	—
$(C_{lequ}^{(1)}, C_{ledq})$	(1.290, 0.650)	—	—

Table: Best-fit values corresponding to different 2D scenarios.

Analysis of $B_b \to B_c^{(*)} \ell \nu$ processes

- Differential decay rate:

$$\frac{d\Gamma}{dq^2} = \frac{8N}{3}\left(1 - \frac{m_l^2}{q^2}\right)^2 \left[\mathcal{B}_1 + \frac{m_l^2}{2q^2}\mathcal{B}_2 + \frac{3}{2}\mathcal{B}_3 + \frac{3m_l}{\sqrt{q^2}}\mathcal{B}_4\right], \qquad (10)$$

- Forward-backward asymmetry:

$$A_{FB}^l(q^2) = \frac{\left(\int_{-1}^0 - \int_0^1\right) d\cos\theta \, \frac{d^2\Gamma}{dq^2\, d\cos\theta}}{\frac{d\Gamma}{dq^2}} \qquad (11)$$

- Longitudinal Polarization of charged lepton:

$$P^l(q^2) = \frac{d\Gamma(+)/dq^2 - d\Gamma(-)/dq^2}{d\Gamma(+)/dq^2 + d\Gamma(-)/dq^2} \qquad (12)$$

- Lepton non-universal observable:

$$R_{B_b} = \frac{d\Gamma^{B_b \to B_c^{(*)} \tau\nu}/dq^2}{d\Gamma^{B_b \to B_c^{(*)} e/\mu)\nu}/dq^2} \qquad (13)$$

Complete picture of q^2-dependency of the decay observables

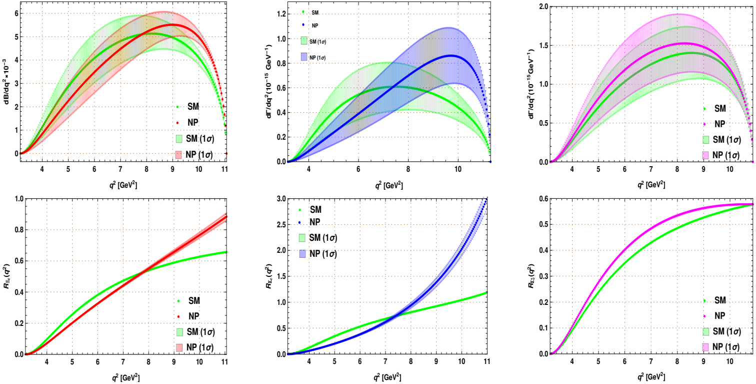

Figure: q^2-dependency of differential decay rate and lepton non-universality of $\Xi_b \to \Xi_c \ell\nu$ (left panel), $\Sigma_b \to \Sigma_c \ell\nu$ (middle panel) and $\Sigma_b \to \Sigma_c^* \ell\nu$ (right panel)

Complete picture of q^2-dependency of the decay observables

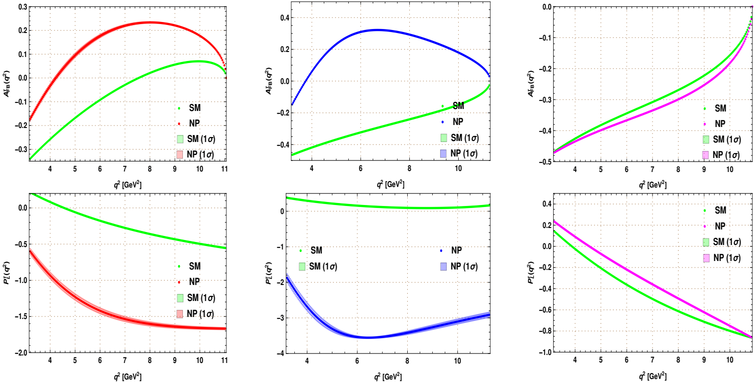

Figure: q^2-dependency of forward-backward asymmetry and polarisation asymmetry of $\Xi_b \to \Xi_c \ell \nu$ (left panel), $\Sigma_b \to \Sigma_c \ell \nu$ (middle panel) and $\Sigma_b \to \Sigma_c^* \ell \nu$ (right panel)

Conclusions

- Analyzed the baryonic $B_b \to B_c^{(*)} \ell\nu$ decay modes in the SM and SMEFT formalism.
- Employed the naive χ^2 analysis to constraint the SMEFT Wilson coefficients.
- Utilizing the best-fit outcomes, we analyzed the decay observables such as differential decay rate, forward-backward asymmetry, polarisation asymmetry and the lepton non-universal observables.
- The presence of $(C_{lequ}^{(1)}, C_{ledq})$ WCs allows significant deviations in the observables of the decay observables of $B_b \to B_c^{(*)} \ell\nu$ processes.
- $b \to s\tau^+\tau^-$ and $b \to s\nu\bar{\nu}$ can be act as complementary observable to constrain $b \to c\tau\nu_\tau$ process.

Thank You