Exploring $b \to c\tau\nu$ mediated baryonic decay modes in SMEFT framework

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FPCP 2024

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Outline

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Introduction

The Standard Model (**SM**) is

- A gauge theory of 3 interactions excluding gravity.
- Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- With the **Higgs** discovery in 2012, it provides a quite successful theory.
- Despite spectacular success, it fails to explain:
  1. Why 3 generations of quarks and leptons.
  2. Hierarchy problem.
  3. Dark matter and dark energy.
  4. Matter antimatter asymmetry.

Motivation

- Several measurements on b hadron decay observables disagreed with SM prediction.
- These deviations have been seen particularly in decay mediated by $b \to s\ell^+\ell^-$, $b \to s\nu\nu$ and $b \to c\tau^-\bar{\nu_\tau}$.
- R_D, R_{D^*} and $R_{J/\psi}$ deviates from SM .
- Thus investigating semileptonic b baryon decay modes $\Xi_b \to \Xi_c\tau^-\bar{\nu}_\tau$ and $\Sigma_b \to \Sigma_c^{(*)}\tau^-\bar{\nu}_\tau$ is well motivated.
- Motivated by the interplay between the LEFT and SMEFT operators at the electroweak scale, we study the interrelation among the transitions $b \to c\tau\nu_\tau$, $b \to s\nu\bar{\nu}$ and $b \to s\tau^+\tau^-$.

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

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

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 $(l = e, \mu, \tau)$.

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

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

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

[1]

[1] arXiv:2306.09401

Continued...

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

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

The sum $i = L, R$ comprises the operators $\mathcal{O}_{L,R}$ with the corresponding WCs $C_{L,R}$ contributing to $b \to s\nu\bar{\nu}$ decays.

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

For $i = 9^{(\prime)}, 10^{(\prime)}$, the sum comprises the operators $\mathcal{O}_{9^{(\prime)},10^{(\prime)}}$ with the corresponding WCs $C_{9^{(\prime)},10^{(\prime)}}$ that contribute to $b \to s\,\ell^+\,\ell^-$ decays.

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

Interplay between $b \to c\ell\nu_\ell$, $b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$ process in SMEFT

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

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

where,

$$Q_{lq}^{(3)} = (\bar{l}_p \gamma_\mu \sigma_a l_r)(\bar{q}_s \gamma^\mu \sigma^a q_t), \qquad Q_{ledq} = (\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$$
$$Q_{lequ}^{(1)} = (\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t), \qquad Q_{lequ}^{(3)} = (\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$$
$$Q_{\phi q}^{(3)} = (\phi^\dagger i D_\mu^a \phi)(\bar{q}_p \sigma_a \gamma^\mu q_r), \quad Q_{lq}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$
$$Q_{\phi q}^{(1)} = (\phi^\dagger i D_\mu \phi)(\bar{q}_p \gamma^\mu q_r), \quad Q_{\phi ud} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u}_p \gamma^\mu d_r).$$

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[2] arXiv:**2306.09401**

Analysis in SMEFT formalism

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

$$C_{V_L}^{(l)} = -\frac{V_{ud}}{V_{ub}}\frac{v^2}{\Lambda^2}\left[C_{lq}^{(3)}\right] + \frac{V_{ud}}{V_{ub}}\frac{v^2}{\Lambda^2}\left[C_{\phi q}^{(3)}\right], \quad C_{V_R}^{(l)} = \frac{1}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[C_{\phi ud}\right], \tag{9}$$

$$C_{S_L}^{(l)} = -\frac{1}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[C_{lequ}^{(1)}\right]^*, \quad C_{S_R}^{(l)} = -\frac{V_{ud}}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[C_{ledq}\right]^*, \tag{10}$$

$$C_T^{(l)} = -\frac{1}{2V_{ub}}\frac{v^2}{\Lambda^2}\left[C_{lequ}^{(3)}\right]^*, \tag{11}$$

$$\begin{aligned} C_9 &= C_9^{\rm SM} + \tilde{c}_{ql}^{(1)} + \tilde{c}_{ql}^{(3)} - \zeta\tilde{c}_Z \\ C_{10} &= C_{10}^{\rm SM} - \tilde{c}_{ql}^{(1)} - \tilde{c}_{ql}^{(3)} + \tilde{c}_Z \\ C_L^{\nu} &= C_L^{\rm SM} + \tilde{c}_{ql}^{(1)} - \tilde{c}_{ql}^{(3)} + \tilde{c}_Z \\ C_R^{\nu} &= \tilde{c}_{dl} + \tilde{c}'_Z . \end{aligned} \tag{12}$$

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[3] Ref. **JHEP, vol. 02, p. 184, 2015.**

SM and experimental value of observables

Observables	SM Values	Expt. Value
R_D	0.299 ± 0.003	$0.357 \pm 0.029 \pm 0.014$
R_{D^*}	0.254 ± 0.005	$0.284 \pm 0.010 \pm 0.012$
$P_\tau(D^*)$	-0.497 ± 0.013	$-0.38 \pm 0.51^{+0.21}_{-0.16}$
$F_L(D^*)$	0.457 ± 0.010	$0.60 \pm 0.08 \pm 0.04$
$R(\Lambda_c)$	0.3328 ± 0.01	0.3379
$\mathcal{B}(B \to K^+\nu\bar{\nu})$	$(4.43 \pm 0.31) \times 10^{-6}$	5.5×10^{-5}
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	$(9.47 \pm 1.40) \times 10^{-6}$	2.3×10^{-5}
$\mathcal{B}(\bar{B}_s \to \tau^+\tau^-)$	$(7.73 \pm 0.49) \times 10^{-7}$	6.8×10^{-3}
$\mathcal{B}(\bar{B} \to K^+\tau^+\tau^-)$	$(1.42 \pm 0.2) \times 10^{-7}$	1.31×10^{-3}

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

Parameter space for SMEFT couplings from $b \to c\tau\nu_\tau$ process

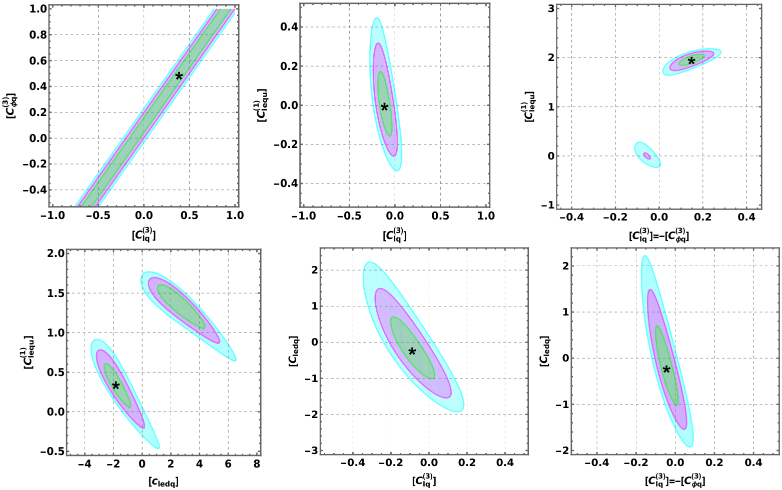

Figure: Parameter space for different combinations of WCs from $b \to c\tau\nu_\tau$ process.

Complementary constraints

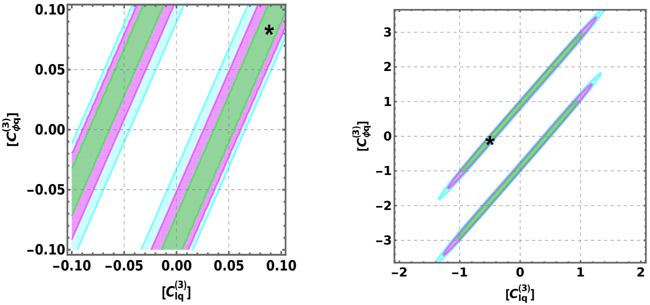

Figure: Complementary constraints from $b \to s\nu\bar{\nu}$ (Left) and $b \to s\tau^+\tau^-$ (Right) Process

1D and 2D Scenarios

Constraints	$b \to c\tau\nu_\tau$	$b \to s\tau^+\tau^-$	$b \to s\nu\bar{\nu}$
$C_{lq}^{(3)} = -C_{\phi q}^{(3)}$	0.0497	-0.298	-0.149
$C_{lq}^{(3)}$	-0.0995	-0.456	-0.092
$C_{lequ}^{(1)}$	-0.138	—	—
$(C_{lq}^{(3)}, C_{\phi q}^{(3)})$	(0.38, 0.49)	(-0.49, -0.078)	(0.08, 0.084)
$(C_{lq}^{(3)} = -C_{\phi q}^{(3)}, C_{lequ}^{(1)})$	(0.149, 1.96)	—	—
$(C_{lq}^{(3)}, C_{lequ}^{(1)})$	(-0.11, -0.0019)	—	—
$(C_{lq}^{(3)} = -C_{\phi q}^{(3)}, C_{ledq})$	(-0.0433, -0.21)	—	—
$(C_{lq}^{(3)}, C_{ledq})$	(-0.086, -0.21)	—	—
$(C_{lequ}^{(1)}, C_{ledq})$	(0.348, -1.819)	—	—

Table: Fit parameters corresponding to different 1d and 2d scenarios.

Interpretation of $B_b \to B_c^{(*)}\ell\nu$ decay

- Two fold angular distribution for $B_b \to B_c^{(*)}\ell\nu$ including NP given as:

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta} = N\left(1-\frac{m_l^2}{q^2}\right)^2\left[\mathcal{A}_1+\frac{m_l^2}{q^2}\mathcal{A}_2+2\mathcal{A}_3+\frac{4m_l}{\sqrt{q^2}}\mathcal{A}_4\right]. \qquad (13)$$

- Differential decay rate for $B_b \to B_c^{(*)}\ell\nu$ given as:

$$\frac{d\Gamma}{dq^2} = \frac{8N}{3}\left(1-\frac{m_l^2}{q^2}\right)^2\left[\mathcal{B}_1+\frac{m_l^2}{2q^2}\mathcal{B}_2+\frac{3}{2}\mathcal{B}_3+\frac{3m_l}{\sqrt{q^2}}\mathcal{B}_4\right], \qquad (14)$$

- Similarly ratio of branching fractions $R_{B_c^{(*)}}(q^2)$, forward-backward asymmetry $A_{FB}^L(q^2)$, polarization fraction of the charged lepton $P_l(q^2)$ defined as follows:

$$R_{B_c^{(*)}}(q^2) = \frac{\Gamma(B_b \to B_c^{(*)}\tau\nu)}{\Gamma(B_b \to B_c^{(*)}\,l\,\nu)}, \qquad A_{FB}^l(q^2) = \frac{\left(\int_{-1}^0 - \int_0^1\right) d\cos\theta\, \frac{d^2\Gamma}{dq^2\, d\cos\theta}}{\frac{d\Gamma}{dq^2}}.$$

$$P^l(q^2) = \frac{d\Gamma(+)/dq^2 - d\Gamma(-)/dq^2}{d\Gamma(+)/dq^2 + d\Gamma(-)/dq^2}. \qquad (15)$$

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[4] For detailed expression and form factors refer. EPJC(2023)83:136

Interpretation of $\Xi_b \to \Xi_c \tau^- \bar{\nu}_\tau$ decay

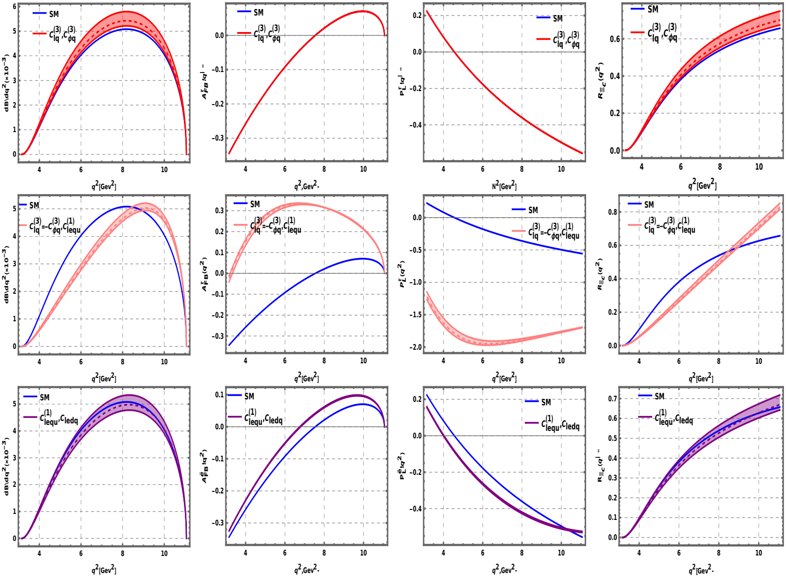

Figure: q^2 dependent DBR, A^l_{FB}, P^l and R_{Ξ_c}

Interpretation of $\Sigma_b \to \Sigma_c \tau^- \bar{\nu}_\tau$ decay

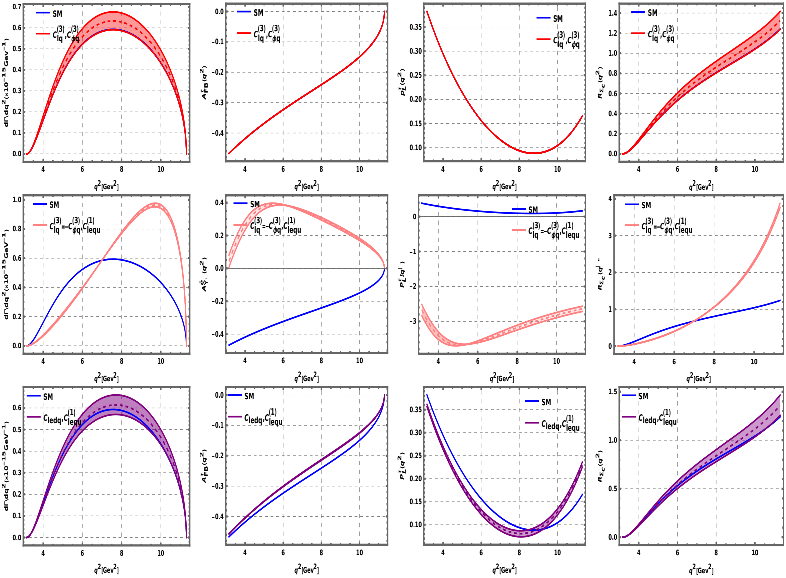

Figure: q^2 dependent $\frac{d\Gamma}{dq^2}$, A^l_{FB}, P^l and R_{Σ_c}

Interpretation of $\Sigma_b \to \Sigma_c^* \tau^- \bar{\nu}_\tau$ decay

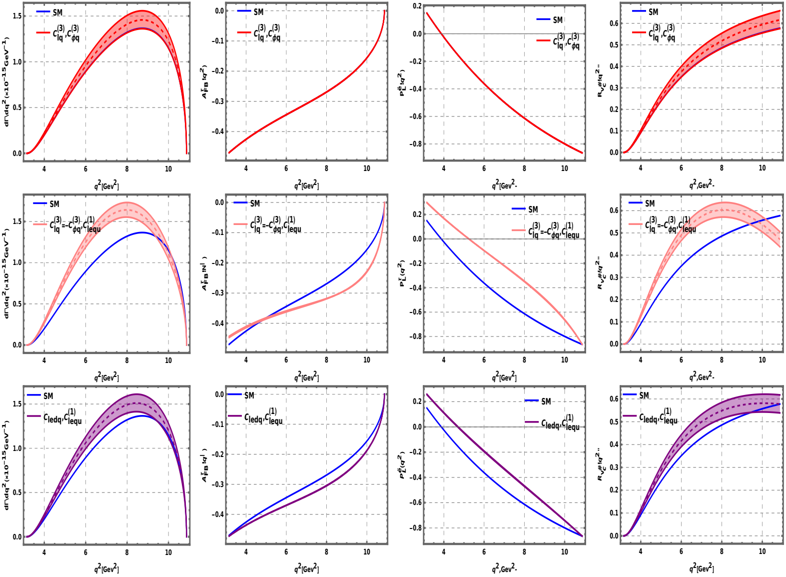

Figure: q^2 dependent $\frac{d\Gamma}{dq^2}$, A^l_{FB}, P^l and $R_{\Sigma_c^{(*)}}$

Interpretation using complementary constraints

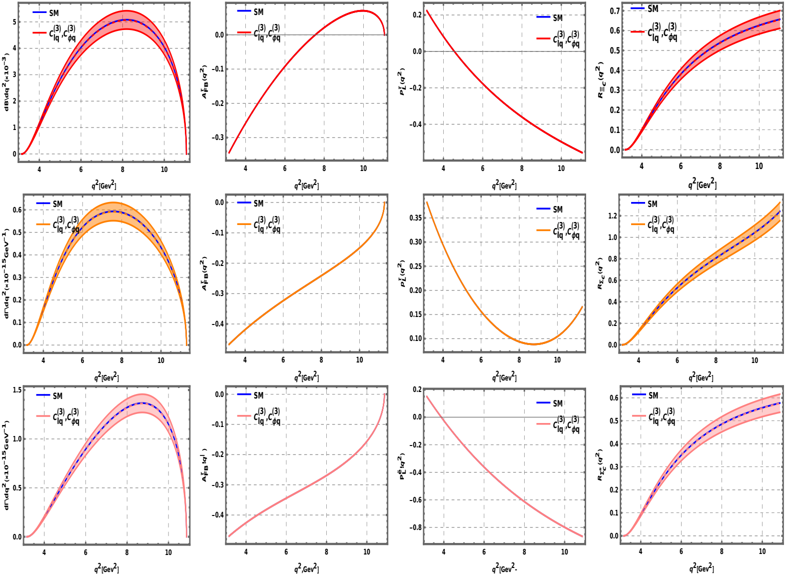

Figure: q^2 dependent $\frac{d\Gamma}{dq^2}$, A^l_{FB}, P^l and $R_{B_c^{(*)}}$

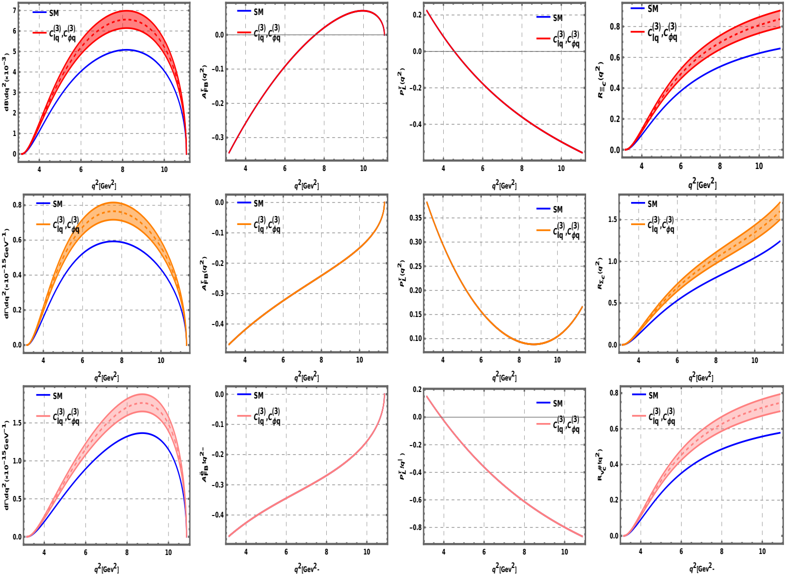

Figure: q^2 dependent $\frac{d\Gamma}{dq^2}$, A^l_{FB}, P^l and $R_{B_c^{(*)}}$

Conclusions

- $B_b \to B_c^{(*)} \ell\nu$ decay modes are analyzed within the SM and SMEFT scenario.
- We employ a least square method to impose constraints. The numerical results for the SMEFT Wilson coefficients obtained from χ^2 are given in the table.
- Utilizing these outcomes as input we reevaluate predictions for the pertinent observables, and visually depict them in various figures.
- The presence of $C_{\ell q}^{(3)}$,$C_{\phi q}^{(3)}$ and $C_{\ell equ}^{(1)}$ WCs modified the SM prediction significantly.
- $b \to s\tau^+\tau^-$ and $b \to s\nu\bar{\nu}$ can be act as complementary observable to constarin $b \to s\tau\nu_\tau$ process.

Thank You.