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Analysis of $B_c \to D^{(*)}\tau\overline{\nu_\tau}$ decay processes

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Outline of talk

1. B_c Meson
2. Effective Hamiltonian
3. Numerical Fit
4. $B_c \to D^{(*)} \tau \nu_\tau$
5. Numerical Analysis

B_c Meson

- First observed by the CDF Collaboration at Fermilab.
- Only known heavy meson consisting of two heavy quarks: bottom (b) and charm (c) of different flavors and charges.
- Accessible kinematic range is broader in the decays of B_c meson: decay via $b \to (u, d, c, s)$ and $c \to (u, d, s)$ transition decays.
- Provide complimentary decay channels to similar decays in the other B mesons and the possibility to extract the CKM parameter V_{ub} as well.
- The lifetime of B_c meson put severe constraint on scalar new physics couplings.

Effective Hamiltonian

- The most general effective Hamiltonian responsible for $b \to u \tau \bar{\nu}_l$ transition:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[\left(\delta_{l\tau} + V_L\right) \mathcal{O}^l_{V_L} + V_R \mathcal{O}^l_{V_R} + S_L \mathcal{O}^l_{S_L} + S_R \mathcal{O}^l_{S_R} + T \mathcal{O}^l_T \Big], \qquad (1)$$

where the six-dimensional effective operators are

$$\begin{aligned} \mathcal{O}^l_{V_L} &= \left(\bar{c}_L \gamma^\mu b_L\right) \left(\bar{\tau}_L \gamma_\mu \nu_{lL}\right), \qquad & \mathcal{O}^l_{V_R} &= \left(\bar{c}_R \gamma^\mu b_R\right) \left(\bar{\tau}_L \gamma_\mu \nu_{lL}\right), \\ \mathcal{O}^l_{S_L} &= \left(\bar{c}_L b_R\right) \left(\bar{\tau}_R \nu_{lL}\right), & \mathcal{O}^l_{S_R} &= \left(\bar{c}_R b_L\right) \left(\bar{\tau}_R \nu_{lL}\right), \\ \mathcal{O}^l_T &= \left(\bar{c}_R \sigma^{\mu\nu} b_L\right) \left(\bar{\tau}_R \sigma_{\mu\nu} \nu_{lL}\right), \end{aligned} \qquad (2)$$

Numerical Fit

- With the assumption that the coupling of $b \to u$ and $b \to c$ transitions are same, we χ^2 fit the new coefficients to $R_{D^{(*)}}$, $R_{J/\psi}$, R_π^l, $\text{Br}(B_{u,c} \to \tau\bar{\nu}_\tau)$ and $\text{Br}(B \to \pi\tau\bar{\nu}_\tau)$ observables, defined as

$$\chi^2(C) = \sum_i \frac{(\mathcal{O}_i^{\text{th}}(C) - \mathcal{O}_i^{\text{Expt}})^2}{(\Delta\mathcal{O}_i^{\text{Expt}})^2 + (\Delta\mathcal{O}_i^{\text{SM}})^2} \,. \tag{3}$$

where
$\mathcal{O}_i^{\text{th}}(C)$: theoretical predictions of observables,
$\mathcal{O}_i^{\text{Expt}}$: respective experimental central values
$\Delta\mathcal{O}_i^{\text{Expt}}$ ($\Delta\mathcal{O}_i^{\text{SM}}$): corresponding experimental (SM) uncertainties.

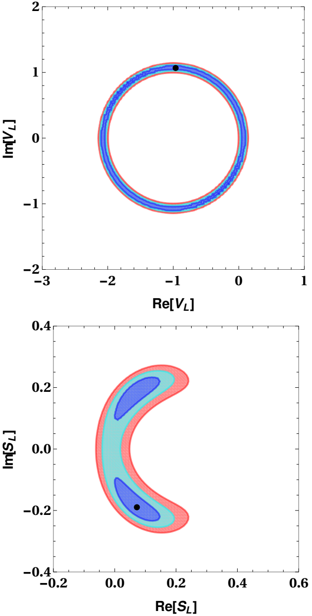
Table: Experimental and theoretical values of the observables used in the fitting

Observables	Experimental values	SM Predictions
R_D	$0.340 \pm 0.027 \pm 0.013$	0.299 ± 0.003
R_{D^*}	$0.295 \pm 0.011 \pm 0.008$	0.258 ± 0.005
$R_{J/\psi}$	0.71 ± 0.251	0.289 ± 0.01
$\mathrm{Br}(B_c \to \tau\nu)$	$< 30\%$	$(3.6 \pm 0.14) \times 10^{-2}$
R_π^l	0.699 ± 0.156	0.583 ± 0.055
$\mathrm{Br}(B_u \to \tau\nu)$	$(1.09 \pm 0.24) \times 10^{-4}$	$(8.48 \pm 0.5) \times 10^{-5}$
$\mathrm{Br}(B^0 \to \pi^+\tau\nu)$	$< 2.5 \times 10^{-4}$	$(9.40 \pm 0.75) \times 10^{-5}$

We consider new coefficients which are classified as

- **Case A**: Existence of only individual new complex coefficient.
- **Case B:** Existence of only two new real coefficients.

Case A



Case B

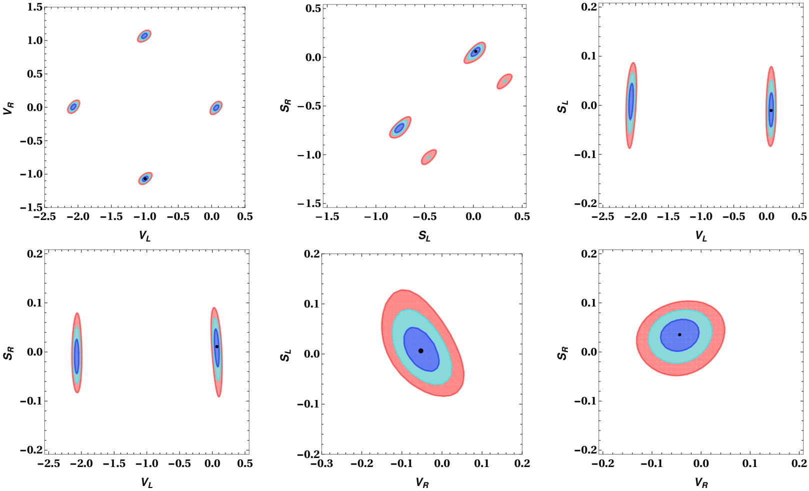


Table: Best-fit, χ^2_{min}/d.o.f and pull values of new Wilson coefficients.

Cases	New Wilson coefficients	Best-fit values	χ^2_{min}/d.o.f	Pull
Case A	$(\text{Re}[V_L], \text{Im}[V_L])$	$(-0.9671, 1.0723)$	0.549	3.171
	$(\text{Re}[V_R], \text{Im}[V_R])$	$(-0.0062, 0.3815)$	0.543	3.1755
	$(\text{Re}[S_L], \text{Im}[S_L])$	$(0.0736, -0.188)$	1.749	2.0134
	$(\text{Re}[S_R], \text{Im}[S_R])$	$(0.027, 0)$	2.1413	1.447
Case B	(V_L, V_R)	$(-0.995, -1.07)$	0.5425	3.176
	(V_L, S_L)	$(0.072, -0.011)$	0.506	3.205
	(V_L, S_R)	$(0.069, 0.01)$	0.518	3.196
	(V_R, S_L)	$(-0.052, 0.0065)$	1.886	1.836
	(V_R, S_R)	$(-0.044, 0.036)$	1.409	3.0
	(S_L, S_R)	$(0.0236, 0.0575)$	1.8415	1.9

- The branching ratio of $\bar{B} \to D l \bar{\nu}_l$:

$$\begin{aligned}\frac{d\mathcal{BR}}{dq^2} &= \tau_B \frac{G_F^2 |V_{cb}|^2}{192\pi^3 M_B^3} q^2 \sqrt{\lambda_D(q^2)} \left(1 - \frac{m_l^2}{q^2}\right)^2 \\ &\times \left\{ \left|1 + V_L + V_R\right|^2 \left[\left(1 + \frac{m_l^2}{2q^2}\right) H_0^2 + \frac{3}{2}\frac{m_l^2}{q^2} H_t^2\right] \right. \\ &\left. + \frac{3}{2} \left|S_L + S_R\right|^2 H_S^2 + 3\mathrm{Re}\left[(1 + V_L + V_R)(S_L^* + S_R^*)\right] \frac{m_l}{\sqrt{q^2}} H_S H_t \right\} \quad (4)\end{aligned}$$

where

$$\lambda_D = \lambda(M_B^2, M_D^2, q^2), \quad \text{with} \quad \lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)\,, \quad (5)$$

and $H_{i,\lambda}^s$'s ($\lambda = 0, \pm, t$) are the heicity amplitudes.

- The branching ratio of $\bar{B} \to D^* l \bar{\nu}_l$:

$$
\begin{aligned}
\frac{d\mathcal{BR}}{dq^2} \quad & = \tau_B \frac{G_F^2 |V_{cb}|^2}{192\pi^3 M_B^3} q^2 \sqrt{\lambda_{D^*}(q^2)} \left(1 - \frac{m_l^2}{q^2}\right)^2 \times \\
& \Bigg\{ \left(|1 + V_L|^2 + |V_R|^2\right) \left[\left(1 + \frac{m_l^2}{2q^2}\right) \left(H_{V,+}^2 + H_{V,-}^2 + H_{V,0}^2\right) + \frac{3}{2} \frac{m_l^2}{q^2} H_V^2 \right. \\
& -2\mathrm{Re}\left[(1 + V_L) V_R^*\right] \left[\left(1 + \frac{m_l^2}{2q^2}\right) \left(H_{V,0}^2 + 2H_{V,+}H_{V,-}\right) + \frac{3}{2} \frac{m_l^2}{q^2} H_{V,t}^2 \right] \\
& + \frac{3}{2} |S_L - S_R|^2 H_S^2 + 3\mathrm{Re}\left[(1 + V_L - V_R)(S_L^* - S_R^*)\right] \frac{m_l}{\sqrt{q^2}} H_S H_{V,t} \Bigg\},
\end{aligned}
$$

where $\lambda_{D^*} = \lambda(M_B^2, M_{D^*}^2, q^2)$ $H_{i,\lambda}$'s are the helicity amplitudes.

- τ forward-backward asymmetry

$$A_{\rm FB}^{D^{(*)}} = \frac{\int_0^1 \frac{d\Gamma}{d\cos} d\cos - \int_{-1}^0 \frac{d\Gamma}{d\cos} d\cos}{\int_{-1}^1 \frac{d\Gamma}{d\cos} d\cos} . \qquad (7)$$

- Lepton non-universality

$$R_{D^{(*)}}^{B_c} = \frac{\mathcal{BR}(B_c \to D^{(*)} \tau \bar{\nu}_\tau)}{\mathcal{BR}(B_c \to D^{(*)} l \bar{\nu}_l)}, \quad l = e, \mu. \qquad (8)$$

- τ polarization asymmetry

$$P_\tau^{D^{(*)}}(q^2) = \frac{d\Gamma(\lambda_\tau = 1/2)/dq^2 - d\Gamma(\lambda_\tau = -1/2)/dq^2}{d\Gamma(\lambda_\tau = 1/2)/dq^2 + d\Gamma(\lambda_\tau = -1/2)/dq^2} . \qquad (9)$$

- D^* polarization asymmetry

$$F_{L,T}^{D^*}(q^2) = \frac{d\Gamma_{L,T} \left(B_c \to D^* \tau \bar{\nu}\right)/dq^2}{d\Gamma \left(B_c \to D^* \tau \bar{\nu}\right)/dq^2} . \qquad (10)$$

- τ forward and backward fractions

$$\chi_{1,2}^{D^{(*)}} = \frac{1}{2} R_{D^{(*)}} \left(1 + A_{FB}^{D^{(*)}}\right) . \tag{11}$$

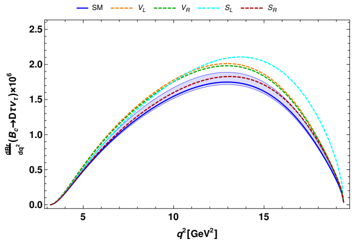
- τ spin $1/2$ and $-1/2$ fractions

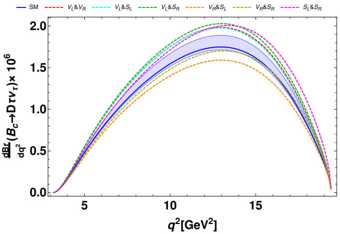
$$\chi_{3,4}^{D^{(*)}} = \frac{1}{2} R_{D^{(*)}} \left(1 + P_{\tau}^{D^{(*)}}\right) . \tag{12}$$

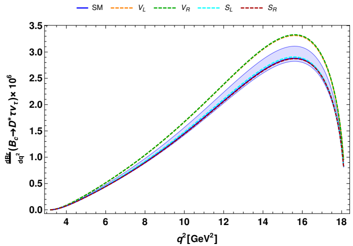
- D^* longitudinal and transverse polarization fractions

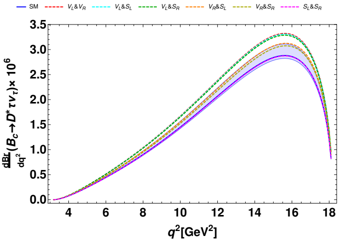
$$\chi_{5,6}^{D^*} = R_{D^*} F_{L,T}^{D^*} . \tag{13}$$

Branching Ratio

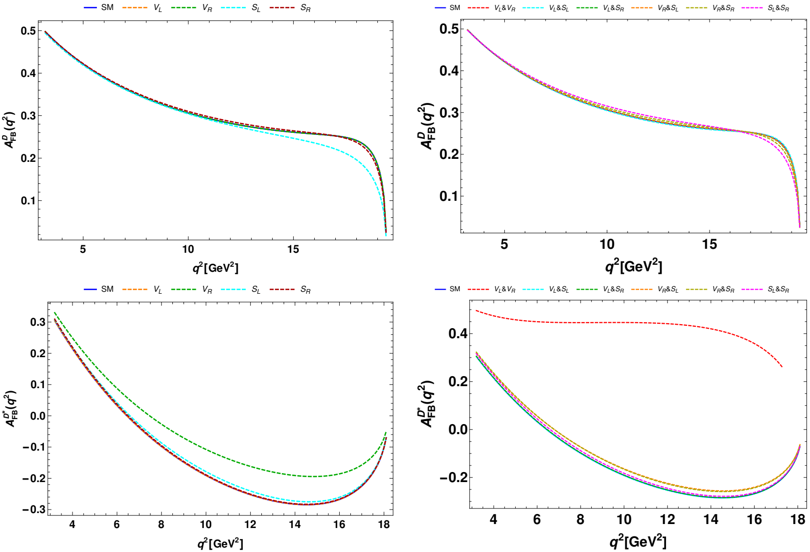




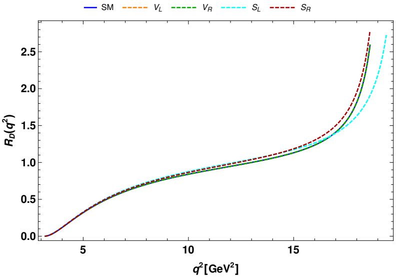


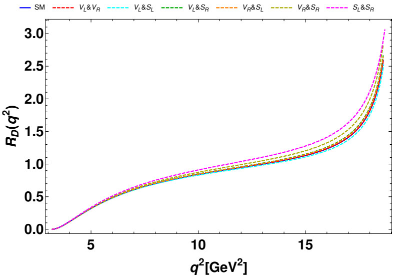


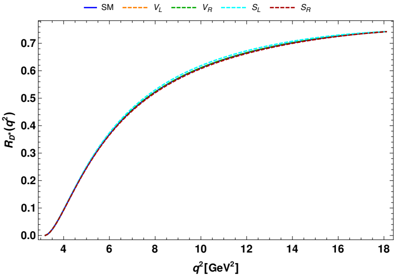
Forward-Backward Asymmetry

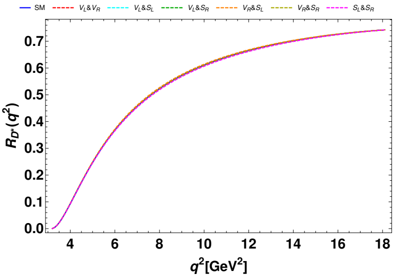


Lepton Nonuniversality

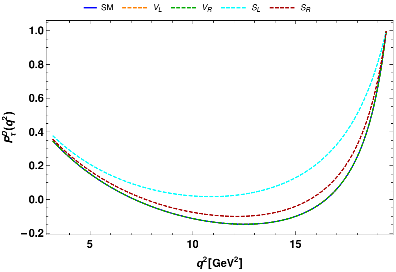


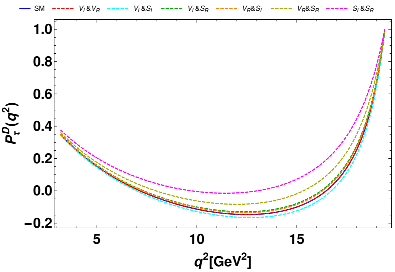




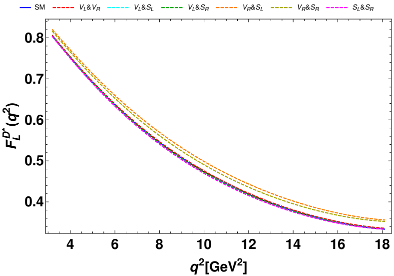


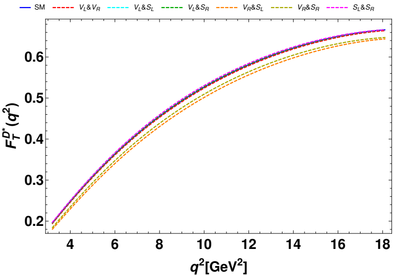
τ Polarization Asymmetry



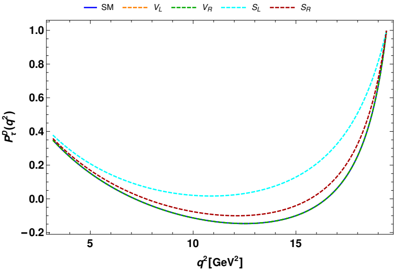


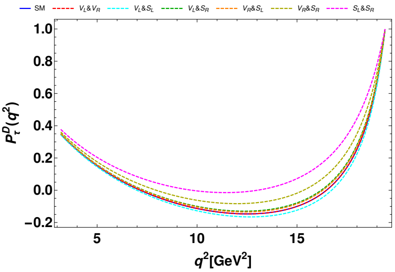
D^* Polarization Asymmetry



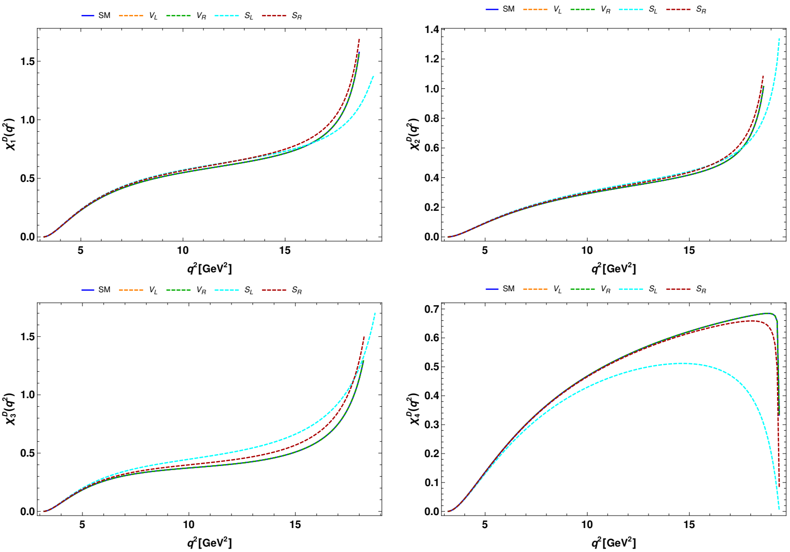


τ Polarization Asymmetry

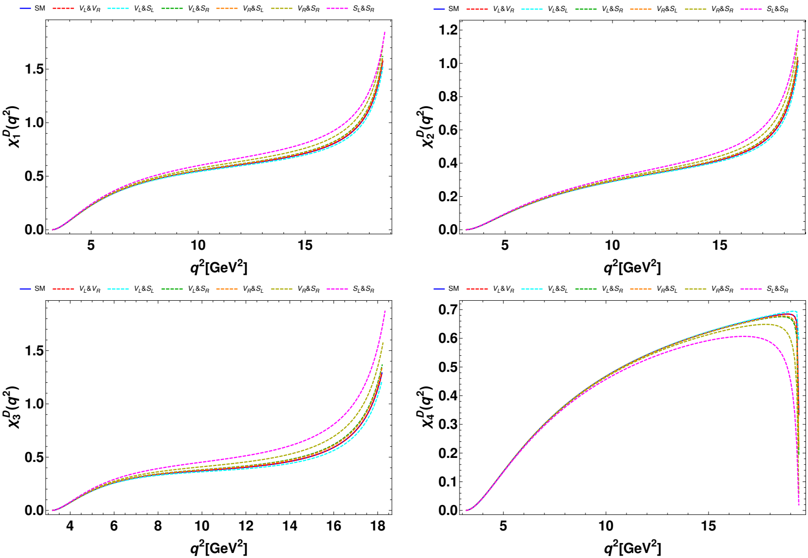




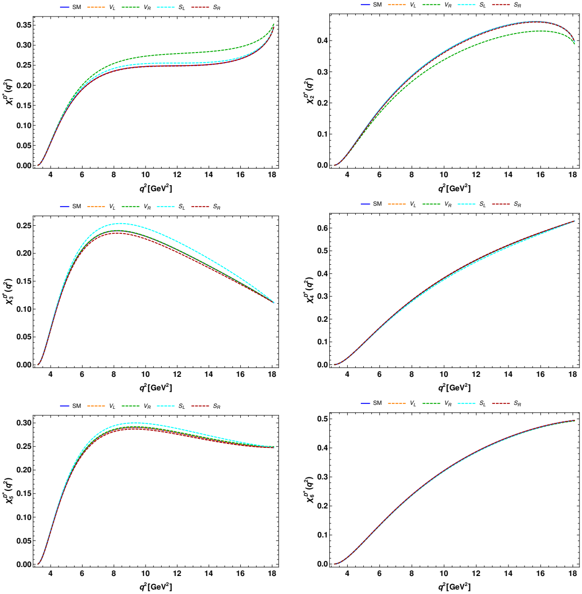
$\chi^D_{1,2,3,4}$ Observables (Case A)



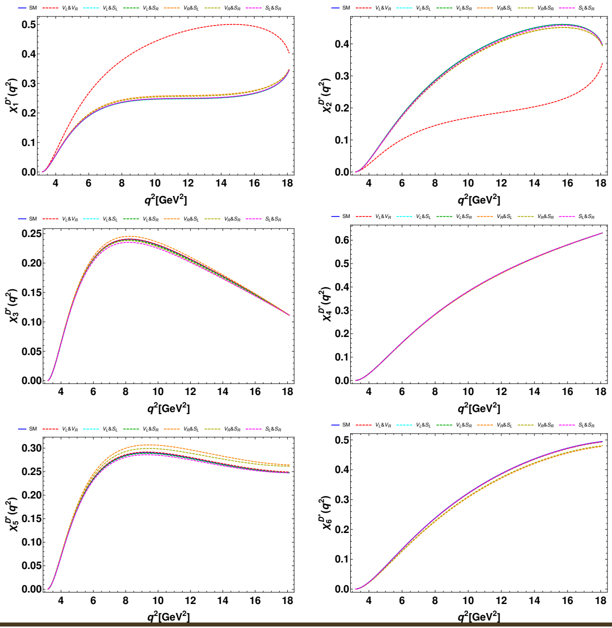
$\chi^D_{1,2,3,4}$ Observables (Case B)



$\chi^{D^*}_{1,2,3,4,5,6}$ Observables (Case A)



$\chi^{D^*}_{1,2,3,4,5,6}$ Observables (Case B)



Conclusion

- There exist a few measurements of B_c meson from LHCb and Tevatron.
- Investigated $B_c \to D^{(*)}\tau\bar{\nu}_\tau$ decays in an effective field theory approach.
- Case A: Existence of only individual new complex coefficient
  Case B: Existence of only two new real coefficients
- Chi-square fit to $R_{D^{(*)}}$, $R_{J/\psi}$, R_π^l, Br$(B_{u,c} \to \tau\bar{\nu}_\tau)$ and Br$(B \to \pi\tau\bar{\nu}_\tau)$ observables.
- Estimate the branching ratio, $A_{\rm FB}$, $R_{D^{(*)}}^{B_c}$, $P_\tau^{D^{(*)}}$, $F_{L,T}^{D^*}$, $\chi_{1,2,3,4}^{D^{(*)}}$, $\chi_{5,6}^{D^*}$ of $B_c \to D^{(*)}\tau\bar{\nu}_\tau$decay modes for both case A and case B

THANK YOU !!!