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# $B_c \rightarrow D^{(*)} \tau \bar{\nu}_\tau$ processes in an effective field theory approach



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Anomalies 2021, IIT Hyderabad

November 11, 2021



# Outline of talk

- 1  $B_c$  Meson
- 2 Effective Hamiltonian
- 3 Numerical Fit
- 4  $B_c \rightarrow D^{(*)} \tau \nu_\tau$
- 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  $b \rightarrow (u, d, c, s)$  and  $c \rightarrow (u, d, s)$  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  $b \rightarrow u\tau\bar{\nu}_l$  transition:

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

where the six-dimensional effective operators are

$$\begin{aligned} \mathcal{O}_{V_L}^l &= (\bar{c}_L \gamma^\mu b_L) (\bar{\tau}_L \gamma_\mu \nu_{lL}), & \mathcal{O}_{V_R}^l &= (\bar{c}_R \gamma^\mu b_R) (\bar{\tau}_L \gamma_\mu \nu_{lL}), \\ \mathcal{O}_{S_L}^l &= (\bar{c}_L b_R) (\bar{\tau}_R \nu_{lL}), & \mathcal{O}_{S_R}^l &= (\bar{c}_R b_L) (\bar{\tau}_R \nu_{lL}), \\ \mathcal{O}_T^l &= (\bar{c}_R \sigma^{\mu\nu} b_L) (\bar{\tau}_R \sigma_{\mu\nu} \nu_{lL}), \end{aligned} \quad (2)$$



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

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

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.

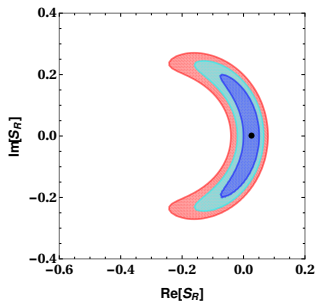
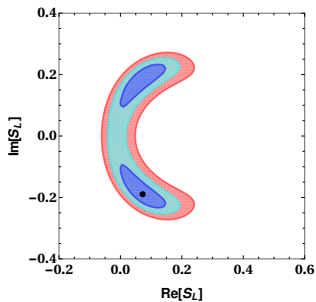
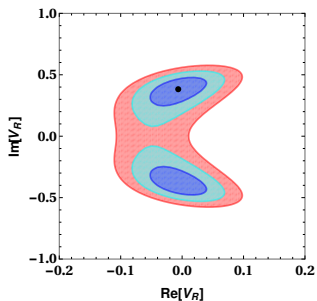
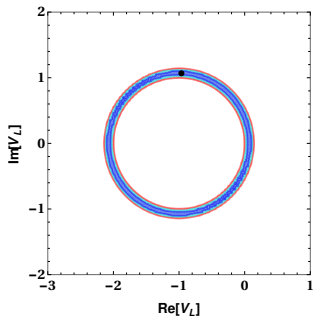
Table: Experimental and theoretical values of the observables used in the fitting

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

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

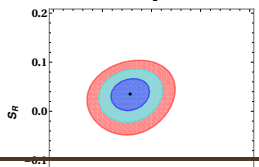
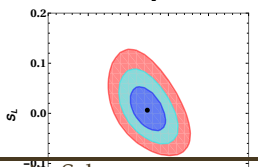
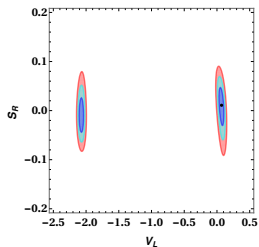
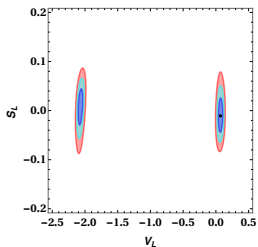
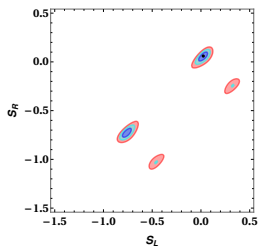
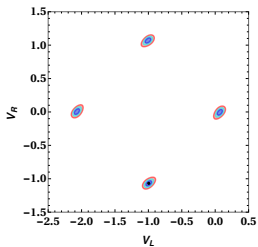




Table: Best-fit,  $\chi_{\min}^2/\text{d.o.f}$  and pull values of new Wilson coefficients.

Cases	New Wilson coefficients	Best-fit values	$\chi_{\min}^2/\text{d.o.f}$	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



$$B_c \rightarrow D^{(*)} \tau \bar{\nu}_\tau$$

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

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

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 helicity amplitudes.

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

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

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

- $\tau$  forward-backward asymmetry

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

- Lepton non-universality

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

- $\tau$  polarization asymmetry

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

- $D^*$  polarization asymmetry

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

- $\tau$  forward and backward fractions

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

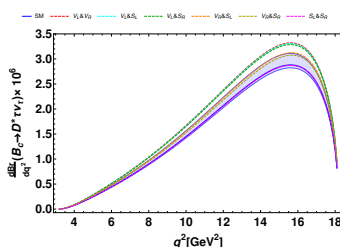
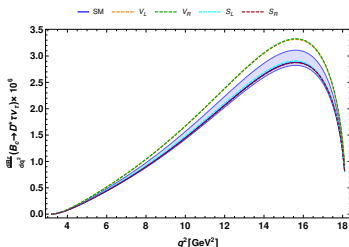
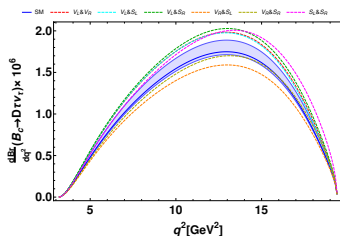
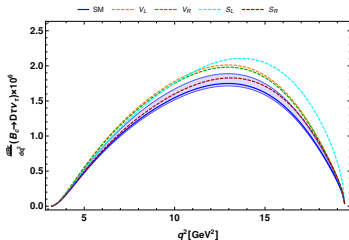
- $\tau$  spin 1/2 and  $-1/2$  fractions

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

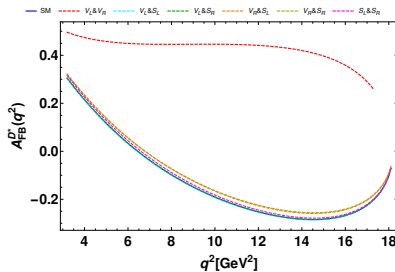
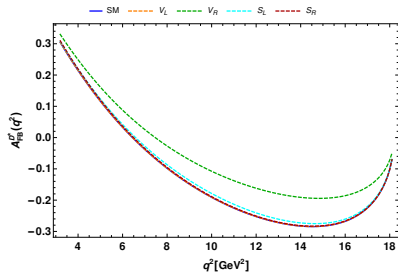
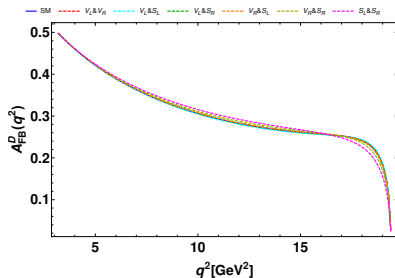
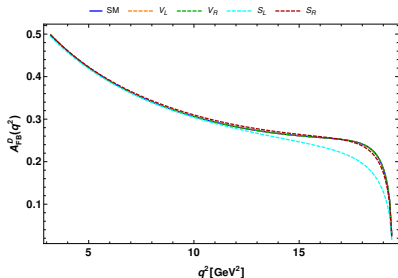
- $D^*$  longitudinal and transverse polarization fractions

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

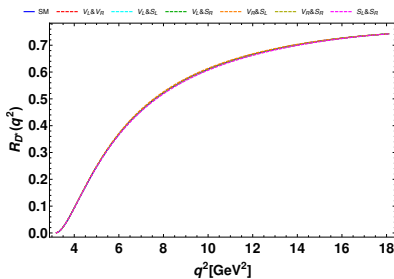
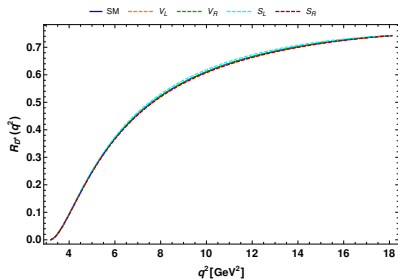
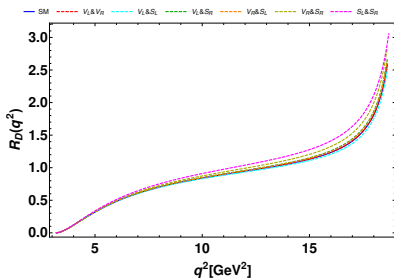
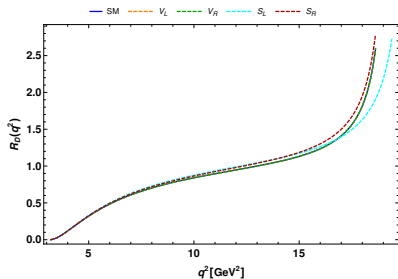
## Branching Ratio



# Forward-Backward Asymmetry

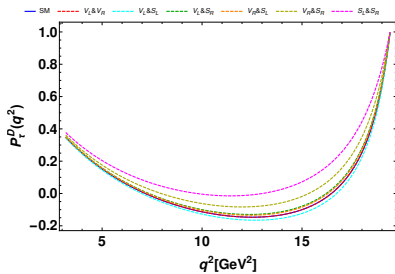
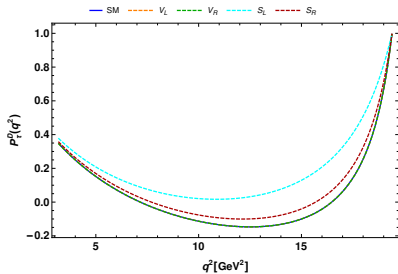


# Lepton Nonuniversality

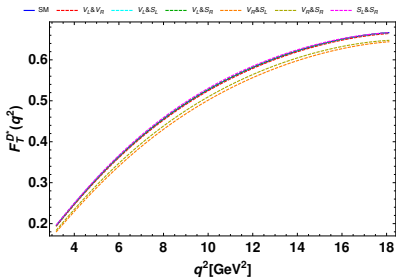
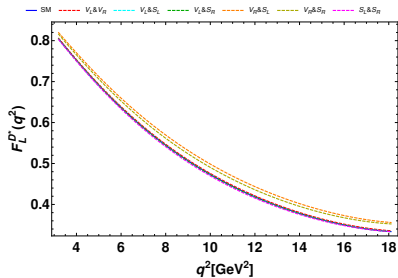




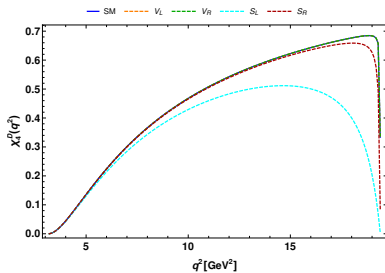
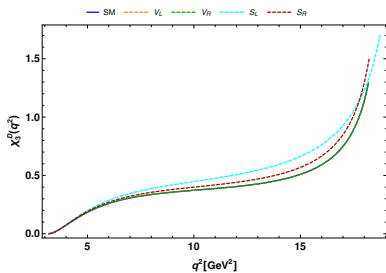
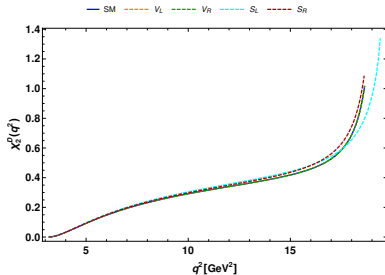
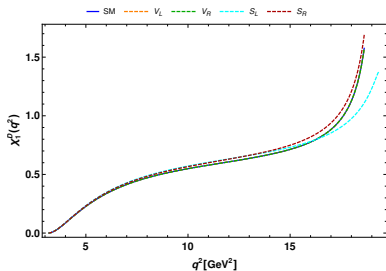
## $\tau$ Polarization Asymmetry



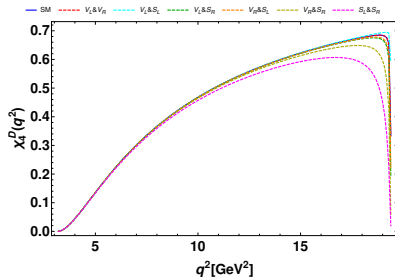
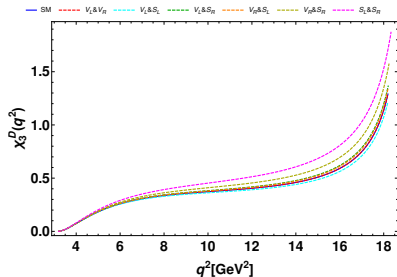
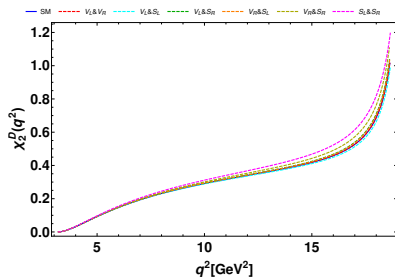
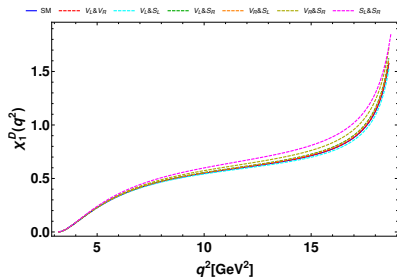
## $D^*$ Polarization Asymmetry



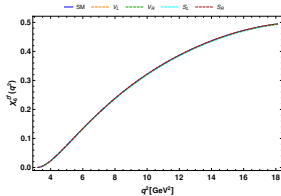
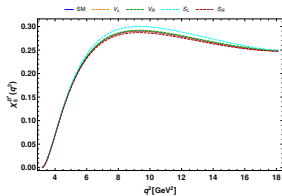
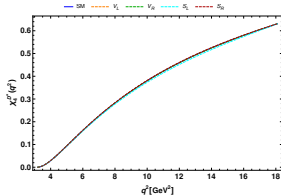
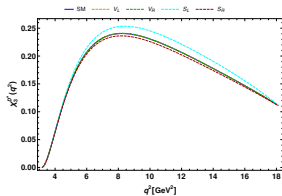
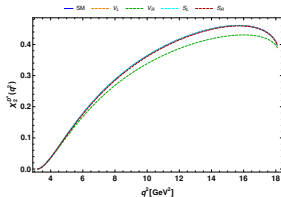
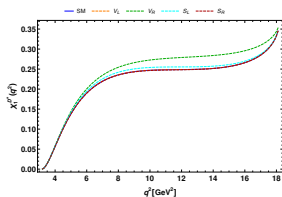
# $\chi_{1,2,3,4}^D$ Observables (Case A)



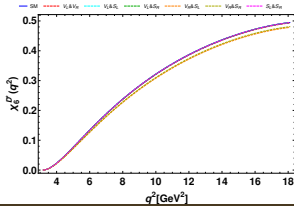
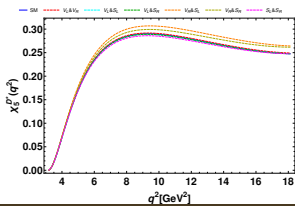
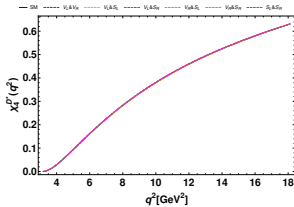
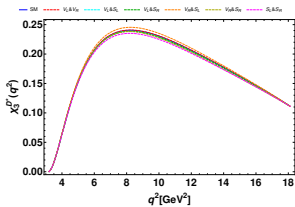
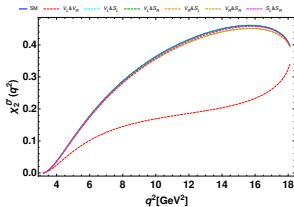
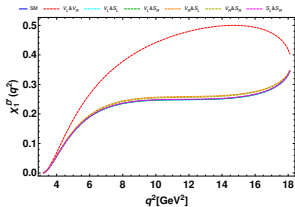
# $\chi_{1,2,3,4}^D$ Observables (Case B)



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



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





# Conclusion

- There exist a few measurements of  $B_c$  meson from LHCb and Tevatron.
- Investigated  $B_c \rightarrow D^{(*)} \tau \bar{\nu}_\tau$  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  $R_{D^{(*)}}, R_{J/\psi}, R_\pi^l, \text{Br}(B_{u,c} \rightarrow \tau \bar{\nu}_\tau)$  and  $\text{Br}(B \rightarrow \pi \tau \bar{\nu}_\tau)$  observables.
- Estimate the branching ratio,  $A_{\text{FB}}, R_{D^{(*)}}^{B_c}, P_\tau^{D^{(*)}}, F_{L,T}^{D^*}, \chi_{1,2,3,4}^{D^{(*)}}, \chi_{5,6}^{D^*}$  of  $B_c \rightarrow D^{(*)} \tau \bar{\nu}_\tau$  decay modes for both case A and case B

**THANK YOU !!!**