Studying the NP effects in semileptonic Ω_b and Σ_b decays

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Outline

1. Background and Motivation
2. Theoretical Framework
   - The form factors and helicity amplitudes
   - The observables for $\Omega_b \to \Omega_c l \bar{\nu}_l$
3. Numerical Analysis
   - Constraints on the NP parameters
   - Predictions for the Observables
4. Summary and Conclusive

Background and Motivation

B baryon semileptonic decays

1. Examination of SM

   (Texting the LFUV)

2. Provide valuable information about the CKM

   (For example: $|V_{cb}|$ of $B \to D^{(*)} l \nu_l$ decays)

3. Hints of new physics

   (Leptoquark model, 2HDM, SUSY model etc.)

Background and Motivation

1. The latest averaged results of R_D and R_{D^*} measured by HFLAV are

   $R_D^{\rm avg} = 0.339 \pm 0.026 \pm 0.014$, $R_{D^*}^{\rm avg} = 0.295 \pm 0.010 \pm 0.010$

   $R_D^{\rm SM} = 0.298 \pm 0.003$, $R_{D^*}^{\rm SM} = 0.252 \pm 0.005$

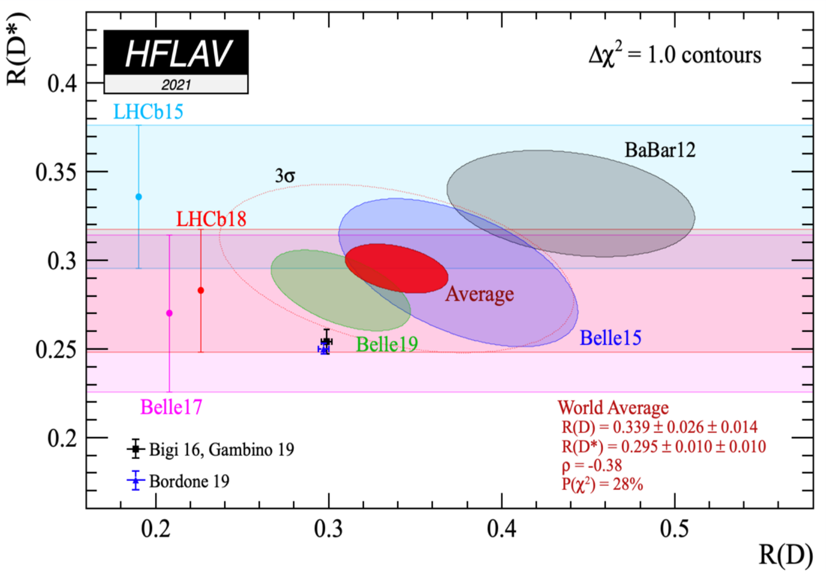
   1.4σ 2.9σ

   $R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\{e/\mu\}\bar{\nu})}$, Combined about 3.4σ deviation

2. Most recently LHCb reported the ratio $R_{J/\psi}$ has also been measured $R_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi\{e/\mu\}\bar{\nu})} = 0.71 \pm 0.17 \pm 018$

   This result deviates about 2σ away from its SM predictions.

$R(D^{(*)})$ Anomaly


R(D*)
HFLAV
2021
$\Delta\chi^2$ = 1.0 contours
LHCb15
BaBar12
3σ
LHCb18
Average
Belle15
Belle19
Belle17
World Average
R(D) = 0.339 ± 0.026 ± 0.014
R(D*) = 0.295 ± 0.010 ± 0.010
ρ = -0.38
P(χ²) = 28%
Bigi 16, Gambino 19
Bordone 19
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
R(D)

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Theoretical Framework

- The most general effective Lagrangian for $b \to c l \nu_l$ transition

$$\begin{aligned}\mathcal{L}_{eff} &= \frac{-4G_F}{\sqrt{2}} V_{cb}[(1+V_L)\,\bar{q}_L\gamma^\mu b_L \bar{l}_L\gamma_\mu\nu_L + V_R\,\bar{q}_R\gamma^\mu b_R \bar{l}_L\gamma_\mu\nu_L \\ &+ S_L\,\bar{q}_R b_L \bar{l}_R\nu_L + S_R\,\bar{q}_L b_R \bar{l}_R\nu_L + T_L\,\bar{q}_R\sigma^{\mu\nu} b_L \bar{l}_R\sigma_{\mu\nu}\nu_L + \text{h.c.}]\end{aligned}$$

We assume the neutrino to be always left chiral and neglect T_L. The four NP coupling parameters are assumed to be complex. In the SM, $V_{L,R} = S_{L,R} = 0$

The form factors

- The hadronic matrix elements of vector and axial vector current

$$\langle B_2,\lambda_2|\bar{c}\gamma_\mu b|B_1,\lambda_1\rangle = \bar{u}_2(p_2,\lambda_2)\left[f_1(q^2)\gamma_\mu + i f_2(q^2)\sigma_{\mu\nu}q^\nu + f_3(q^2)q_\mu\right]u_1(p_1,\lambda_1),$$

$$\langle B_2,\lambda_2|\bar{c}\gamma_\mu\gamma_5 b|B_1,\lambda_1\rangle = \bar{u}_2(p_2,\lambda_2)\left[g_1(q^2)\gamma_\mu + i g_2(q^2)\sigma_{\mu\nu}q^\nu + g_3(q^2)q_\mu\right]\gamma_5 u_1(p_1,\lambda_1),$$

where $q = p_1 - p_2, \sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu,\gamma_\nu]$,

$$\langle B_2,\lambda_2|\bar{c}\gamma_\mu b|B_1,\lambda_1\rangle = \bar{u}_2(p_2,\lambda_2)\left[F_1(w)\gamma_\mu + F_2(w)v_\mu + F_3(w)v'_\mu\right]u_1(p_1,\lambda_1),$$

$$\langle B_2,\lambda_2|\bar{c}\gamma_\mu\gamma_5 b|B_1,\lambda_1\rangle = \bar{u}_2(p_2,\lambda_2)\left[G_1(w)\gamma_\mu + G_2(w)v_\mu + G_3(w)v'^\mu\right]\gamma_5 u_1(p_1,\lambda_1),$$

where $w = v.v' = \left(m_{B_1}^2 + m_{B_2}^2 - q^2\right)/2m_{B_1}m_{B_2}$

- The hadronic matrix elements of scalar and pseudoscalar current

$$\langle B_2,\lambda_2|\bar{c}b|B_1,\lambda_1\rangle = \bar{u}_2(p_2,\lambda_2)\left[f_1(q^2)\frac{q}{m_b-m_c} + f_3(q^2)\frac{q^2}{m_b-m_c}\right]u_1(p_1,\lambda_1),$$

$$\langle B_2,\lambda_2|\bar{c}\gamma_5 b|B_1,\lambda_1\rangle = \bar{u}_2(p_2,\lambda_2)\left[-g_1(q^2)\frac{q}{m_b+m_c} - g_3(q^2)\frac{q^2}{m_b+m_c}\right]\gamma_5 u_1(p_1,\lambda_1),$$

(arXiv:1905.13468)

The form factors

The relationship of two sets of form factors

$$\begin{aligned}
f_1(q^2) &= F_1(q^2) + \left(m_{B_1} + m_{B_2}\right)\left[\frac{F_2(q^2)}{2m_{B_1}} + \frac{F_3(q^2)}{2m_{B_2}}\right], \\
f_2(q^2) &= \frac{F_2(q^2)}{2m_{B_1}} + \frac{F_3(q^2)}{2m_{B_2}}, \qquad f_3(q^2) = \frac{F_2(q^2)}{2m_{B_1}} - \frac{F_3(q^2)}{2m_{B_2}}, \\
g_1(q^2) &= G_1(q^2) - \left(m_{B_1} - m_{B_2}\right)\left[\frac{G_2(q^2)}{2m_{B_1}} + \frac{G_3(q^2)}{2m_{B_2}}\right], \\
g_2(q^2) &= \frac{G_2(q^2)}{2m_{B_1}} + \frac{G_3(q^2)}{2m_{B_2}}, \qquad g_3(q^2) = \frac{G_2(q^2)}{2m_{B_1}} - \frac{G_3(q^2)}{2m_{B_2}}.
\end{aligned}$$

with

$$F_1(w) = G_1(w) = -\frac{1}{3}\zeta_1(w), \qquad F_2(w) = F_3(w) = \frac{2}{3}\frac{2}{w+1}\zeta_1(w), \qquad G_2(w) = G_3(w) = 0.$$

♣ More details information from (hep-ph/0604017)

The helicity amplitudes

$$H^{V/A}_{\lambda_2\lambda_W} = M^{V/A}_{\mu}(\lambda_2)\epsilon^{\dagger\mu}(\lambda_W), \quad H_{\lambda_2\lambda_W} = H^{V}_{\lambda_2\lambda_W} - H^{A}_{\lambda_2\lambda_W}, \quad H^{SP}_{\frac{1}{2}0} = H^{S}_{\frac{1}{2}0} - H^{P}_{\frac{1}{2}0},$$

$$\begin{aligned}
H^V_{\frac{1}{2}0} &= (1+V_L+V_R)\frac{\sqrt{Q_-}}{\sqrt{q^2}}\left[\left(m_{B_1}+m_{B_2}\right)f_1(q^2) - q^2 f_2(q^2)\right], \\
H^A_{\frac{1}{2}0} &= (1+V_L-V_R)\frac{\sqrt{Q_+}}{\sqrt{q^2}}\left[\left(m_{B_1}-m_{B_2}\right)g_1(q^2) + q^2 g_2(q^2)\right], \\
H^V_{\frac{1}{2}1} &= (1+V_L+V_R)\sqrt{2Q_-}\left[-f_1(q^2) + \left(m_{B_1}+m_{B_2}\right)f_2(q^2)\right], \\
H^A_{\frac{1}{2}1} &= (1+V_L-V_R)\sqrt{2Q_+}\left[-g_1(q^2) - \left(m_{B_1}-m_{B_2}\right)g_2(q^2)\right], \\
H^V_{\frac{1}{2}t} &= (1+V_L+V_R)\frac{\sqrt{Q_+}}{\sqrt{q^2}}\left[\left(m_{B_1}-m_{B_2}\right)f_1(q^2) + q^2 f_3(q^2)\right], \\
H^A_{\frac{1}{2}t} &= (1+V_L-V_R)\frac{\sqrt{Q_-}}{\sqrt{q^2}}\left[\left(m_{B_1}+m_{B_2}\right)g_1(q^2) - q^2 g_3(q^2)\right], \\
H^S_{\frac{1}{2}0} &= (S_L+S_R)\frac{\sqrt{Q_+}}{m_b-m_c}\left[\left(m_{B_1}-m_{B_2}\right)f_1(q^2) + q^2 f_3(q^2)\right], \\
H^P_{\frac{1}{2}0} &= (S_L-S_R)\frac{\sqrt{Q_-}}{m_b+m_c}\left[\left(m_{B_1}+m_{B_2}\right)g_1(q^2) - q^2 g_3(q^2)\right].
\end{aligned}$$

The observables for $\Omega_b \to \Omega_c l\bar{\nu}_l(\Sigma_b \to \Sigma_c l\bar{\nu}_l)$

$$
\begin{aligned}
\frac{d\mathcal{B}(\Omega_b(\Sigma_b) \to \Omega_c(\Sigma_c) l\,\bar{\nu}_l)}{dq^2} &= \tau_{\Omega_b(\Sigma_b)} \frac{d\Gamma(\Omega_b(\Sigma_b) \to \Omega_c(\Sigma_c) l\,\bar{\nu}_l)}{dq^2}, \\
A^l_{\rm FB}(q^2) &= \left(\int_{-1}^{0} d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l} - \int_{0}^{1} d\cos\theta_l \frac{d^2\Gamma}{dq^2 d\cos\theta_l} \right) \Big/ \frac{d\Gamma}{dq^2} \\
C^l_F(q^2) &= \frac{1}{d\Gamma/dq^2} \frac{d^2}{d(\cos\theta_l)^2} \left(\frac{d^2\Gamma}{dq^2 d\cos\theta_l} \right), \\
P_L^{\Omega_c(\Sigma_c)}(q^2) &= \frac{\mathrm{d}\Gamma^{\lambda_2=1/2}/\mathrm{d}q^2 - \mathrm{d}\Gamma^{\lambda_2=-1/2}/\mathrm{d}q^2}{\mathrm{d}\Gamma/\mathrm{d}q^2}, \\
P_L^l(q^2) &= \frac{\mathrm{d}\Gamma^{\lambda_\tau=1/2}/\mathrm{d}q^2 - \mathrm{d}\Gamma^{\lambda_\tau=-1/2}/\mathrm{d}q^2}{\mathrm{d}\Gamma/\mathrm{d}q^2}, \\
\mathrm{R}_{\Omega_c(\Sigma_c)}(q^2) &= \frac{d\mathcal{B}(B_1 \to B_2 \tau\,\bar{\nu}_\tau)/dq^2}{d\mathcal{B}(B_1 \to B_2 l\,\bar{\nu}_l)/dq^2}.
\end{aligned}
$$

- ♣ $\frac{d\Gamma(\Omega_b(\Sigma_b)\to\Omega_c(\Sigma_c)l\,\bar{\nu}_l)}{dq^2}$, $\mathrm{d}\Gamma^{\lambda_2=\pm1/2}/dq^2$ and $\mathrm{d}\Gamma^{\lambda_l=\pm1/2}/dq^2$ are from (arXiv:1812.08314).
- ♣ $\langle\mathcal{B}\rangle$, $\langle A^l_{\rm FB}\rangle$, $\langle C^l_F\rangle$, $\langle P^l_L\rangle$, $\langle P_L^{\Omega_c(\Sigma_c)}\rangle$ and $\langle \mathrm{R}_{\Omega_c(\Sigma_c)}\rangle$.

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Constraints on the NP parameters

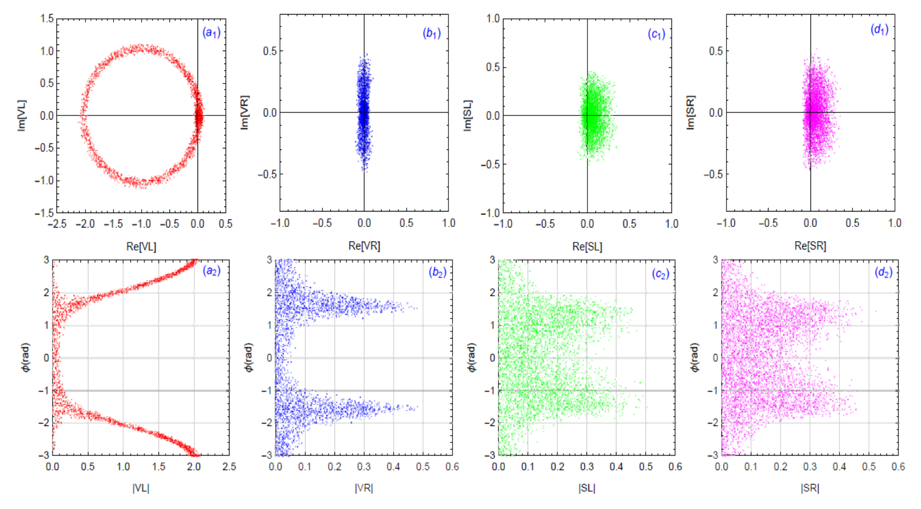
- Four NP coupling parameters are assumed to be complex and considered only one NP parameter one time.
- Four NP coupling parameters are constrained from the latest experimental values of $\mathcal{B}(B \to D^{(*)} l \bar{\nu}_l)$, $R_{D^{(*)}}$ and $R_{J/\psi}$.

(arXiv:1212.1878, arXiv:1309.0301)

Decay modes	NP coefficients	Min value	Max Value	Max of $\|V_i(S_i)\|(i = L.R)$
$b \to c l \bar{\nu}_l$	$(\mathrm{Re}[V_L], \mathrm{Im}[V_L])$	$(-2.116, -1.123)$	$(0.121, 1.109)$	2.118
	$(\mathrm{Re}[V_R], \mathrm{Im}[V_R])$	$(-0.105, -0.481)$	$(0.105, 0.479)$	0.482
	$(\mathrm{Re}[S_L], \mathrm{Im}[S_L])$	$(-0.111, -0.502)$	$(0.351, 0.451)$	0.502
	$(\mathrm{Re}[S_R], \mathrm{Im}[S_R])$	$(-0.094, -0.456)$	$(0.355, 0.519)$	0.524

Constraints on the NP parameters

The real-imaginary and modulus-phase of the four complex NP parameters

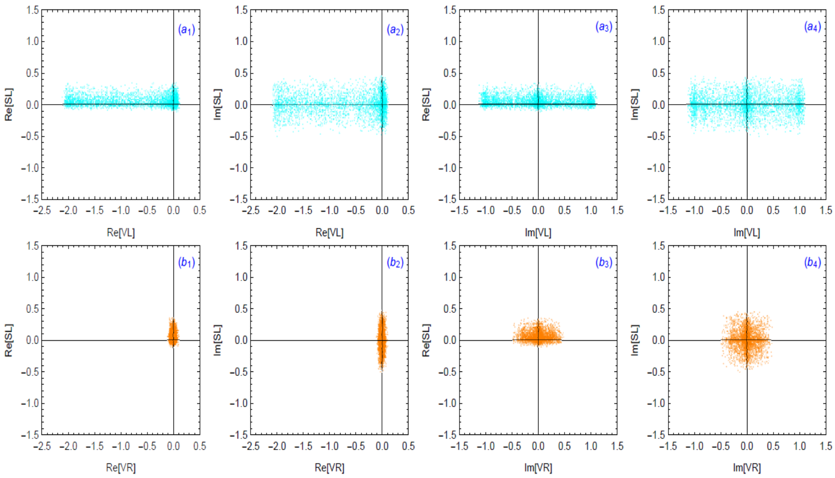


V_L V_R S_L S_R

Constraints on the NP parameters

$V_L - S_L$

$V_R - S_L$



Predictions for observables

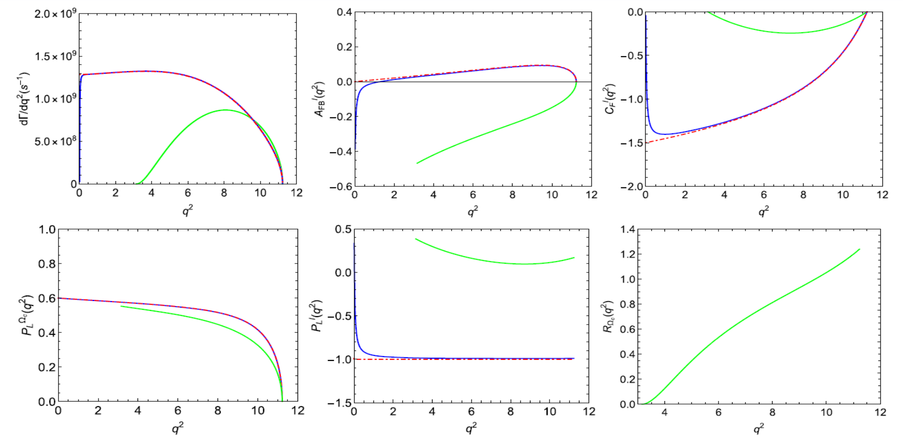
The SM central values for various observable of $\Omega_b \to \Omega_c l\bar{\nu}_l$ and $\Sigma_b \to \Sigma_c l\bar{\nu}_l$

	$\Omega_b \to \Omega_c l\nu$			$\Sigma_b \to \Sigma_c l\nu$		
	e mode	μ mode	τ mode	e mode	μ mode	τ mode
$\Gamma \times 10^{10}$ s^{-1}	1.295	1.292	0.529	1.610	1.641	0.540
$\langle P_L^l \rangle$	−1.123	−1.093	0.135	−1.135	−1.131	0.132
$\langle P_L^{\Omega_c(\Sigma_c)} \rangle$	0.586	0.585	0.354	0.582	0.582	0.355
$\langle A_{FB}^l \rangle$	0.062	0.052	−0.220	0.065	0.055	−0.220
$\langle C_F^l \rangle$	−1.170	−1.140	−0.135	−1.178	−1.148	−0.139
$\langle \mathrm{R}_{\Omega_c(\Sigma_c)} \rangle$		$\mathrm{R}_{\Omega_c} = 0.370$			$\mathrm{R}_{\Sigma_c} = 0.339$	

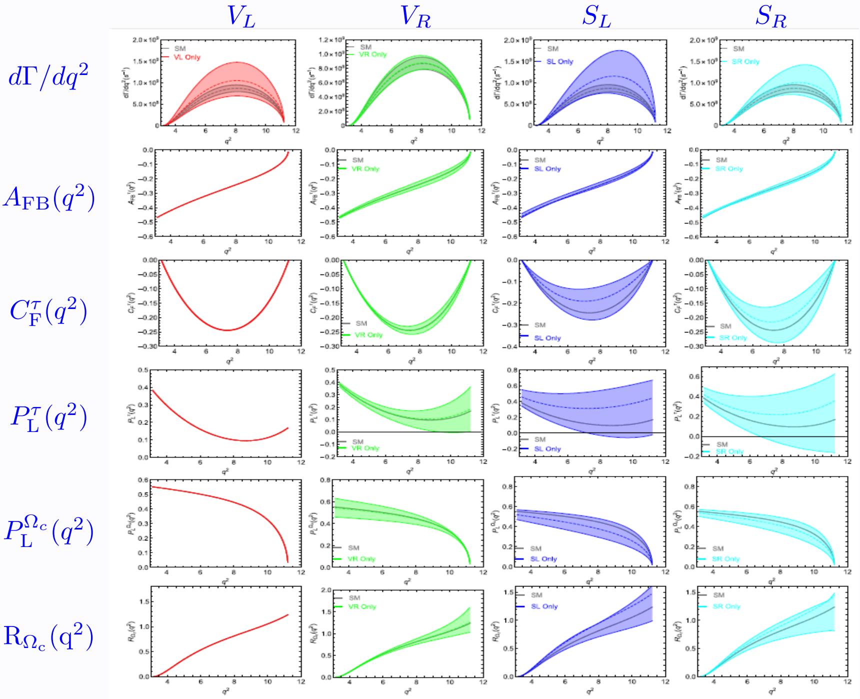
♣ The behaviors of each observable as a function of q^2 for $\Omega_b \to \Omega_c l\bar{\nu}_l$ and $\Sigma_b \to \Sigma_c l\bar{\nu}_l$ within SM and within various NP scenarios are similar to each other.

Predictions for observables

The q^2 dependent of various observables in the SM



♣ the red dot dash line, blue and green line represent the e, μ and τ.



V_L
V_R
S_L
S_R
$d\Gamma/dq^2$
$A_{\rm FB}(q^2)$
$C_{\rm F}^{\tau}(q^2)$
$P_{\rm L}^{\tau}(q^2)$
$P_{\rm L}^{\Omega_c}(q^2)$
$\mathrm{R}_{\Omega_c}(\mathrm{q}^2)$
SM
VL Only
VR Only
SL Only
SR Only
q^2

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Summary and Conclusive

Using the NP coupling parameters constrained from the latest experimental results of $B(B_c) \to D^{(*)}(J/\psi)l\nu_l$ processes, we have performed a model-independent analysis of the NP effects in the $\Omega_b \to \Omega_c l\nu_l$ and $\Sigma_b \to \Sigma_c l\nu_l$ decays. , we find

- The regions for the four NP coupling parameters of the vector and scalar operators are obtained from the latest experimental results within 2σ along with the limit $\mathcal{B}(B \to D^{(*)}l\bar{\nu})$, $\mathrm{R_{D^{(*)}}}$ and $\mathrm{R_{J/\psi}}$.
- The SM center values for observables and the behaviors of each observables as a function of q^2 for $\Omega_b \to \Omega_c l\bar{\nu}$ and $\Sigma_b \to \Sigma_c l\bar{\nu}$ are similar.

Summary and Conclusive

- In four NP scenarios, it is clear to find that $d\Gamma/dq^2$ including any kind of NP couplings are all enhanced largely and have significant deviations. In the V_L scenario, $A^{\tau}_{FB}(q^2)$, $C^{\tau}_{F}(q^2)$, $P^{\tau}_{L}(q^2)$, $P^{\Omega_c}_{L}(q^2)$ and $\mathrm{R}_{\Omega_c}(\mathrm{q}^2)$ are the same as their corresponding SM predictions. For other three NP scenarios, all angular observables have significant deviations from their SM predictions.

Thanks for your attention!

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