A Closer Look at R_D and R_{D^*} Anomalies

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Based on arXiv:1610.03038 (submitted to JHEP)
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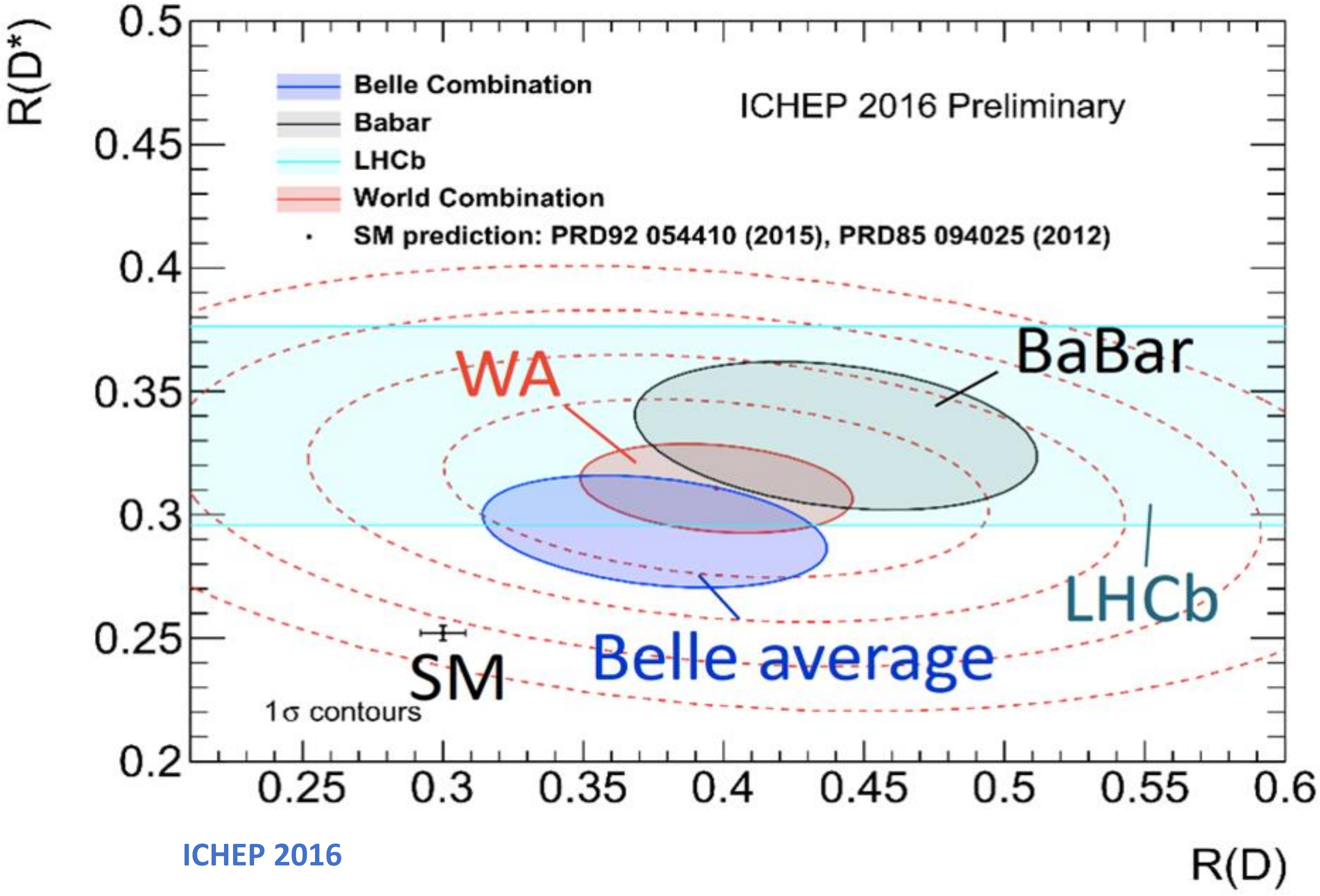
Motivation



ICHEP 2016

$$R_{D^{(*)}} = \frac{\mathcal{B}\left(\overline{B} \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathcal{B}\left(\overline{B} \to D^{(*)}l\bar{\nu}_l\right)}$$

$$R_{D^*}^{Exp} = 0.316 \pm 0.016 \pm 0.010$$

$$R_{D^*}^{SM} = 0.252 \pm 0.003$$

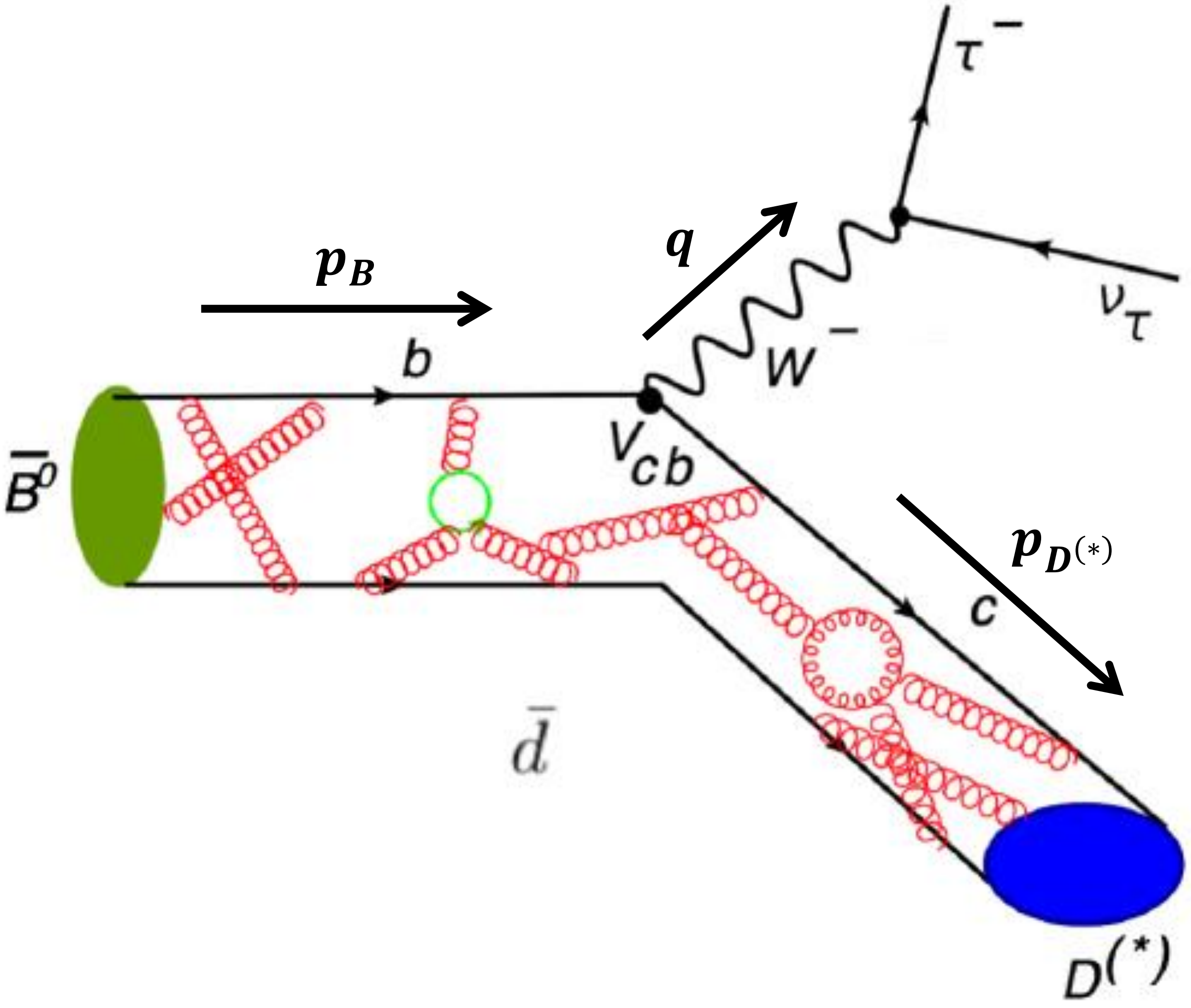
$$R_{D}^{Exp} = 0.397 \pm 0.040 \pm 0.028$$

$$R_{D}^{SM} = 0.300 \pm 0.008$$

Combined significance of the deviation : 4σ

Talk by **Thomas Browder**

The Kinematics



$$\mathcal{M} = \langle D^{(*)}(p_{D^{(*)}}, m_{D^{(*)}}) | \mathcal{H}_{had} | B(p_B, m_B) \rangle \times M_{lep}$$

$q = p_B - p_{D^{(*)}}$

q^2 : invariant mass of the leptonic state

- Parameterise the hadronic part with form factors
- Form factors calculated either in lattice or in Heavy Quark Effective Theory.

Observables

Branching Ratio

$$\frac{d^2\mathcal{B}_\ell^{D^{(*)}}}{dq^2\, d(\cos\theta)} = \mathcal{N}\, |p_{D^{(*)}}| \left(a_\ell^{D^{(*)}} + b_\ell^{D^{(*)}} \cos\theta + c_\ell^{D^{(*)}} \cos^2\theta\right)$$

$$\mathcal{B}_\ell^{D^{(*)}} = \int \mathcal{N}\, |p_{D^{(*)}}| \left(2a_\ell^{D^{(*)}} + \frac{2}{3} c_\ell^{D^{(*)}}\right) dq^2$$

$$\mathcal{N} = \frac{\tau_B\, G_F^2 |V_{cb}|^2 q^2}{256\pi^3 M_B^2} \left(1 - \frac{m_\ell^2}{q^2}\right)^2$$

$$|p_{D^{(*)}}| = \frac{\sqrt{\lambda(M_B^2, M_{D^{(*)}}^2, q^2)}}{2M_B}$$

R_D & R_{D^*}

$$R_{D^{(*)}} = \frac{\mathcal{B}\left(\overline{B} \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathcal{B}\left(\overline{B} \to D^{(*)} l\bar{\nu}_l\right)}$$

$$R_{D^{(*)}}[q^2\, \text{bin}] = \frac{\mathcal{B}_\tau^{D^{(*)}}[q^2\, \text{bin}]}{\mathcal{B}_l^{D^{(*)}}[q^2\, \text{bin}]}$$

Tau Polarisation

$$P_\tau(D^{(*)}) = \frac{\Gamma_\tau^{D^{(*)}}(+) - \Gamma_\tau^{D^{(*)}}(-)}{\Gamma_\tau^{D^{(*)}}(+) + \Gamma_\tau^{D^{(*)}}(-)}$$

Forward-Backward Asymmetry

$$\mathcal{A}_{FB}^{D^{(*)}} = \frac{\int_0^{\pi/2} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta - \int_{\pi/2}^{\pi} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta}{\int_0^{\pi/2} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta + \int_{\pi/2}^{\pi} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta} = \frac{\int b_\tau^{D^{(*)}}(q^2) dq^2}{\Gamma^{D^{(*)}}}$$

Summary of Experimental Results & Theoretical Predictions

List of Observables			
Observable	Experimental Results		SM Prediction
	Experiment	Measured value	
R_D	Belle	$0.375 \pm 0.064 \pm 0.026$	0.299 ± 0.011
	BaBar	$0.440 \pm 0.058 \pm 0.042$	0.300 ± 0.008
	HFAG average	$0.397 \pm 0.040 \pm 0.028$	$\mathbf{0.300^{+0.012}_{-0.011}}$
R_{D^*}	Belle	$0.293 \pm 0.038 \pm 0.015$	
	Belle	$0.302 \pm 0.030 \pm 0.011$	
	BaBar	$0.332 \pm 0.024 \pm 0.018$	
	LHCb	$0.336 \pm 0.027 \pm 0.030$	0.252 ± 0.003
	HFAG average	$0.316 \pm 0.016 \pm 0.010$	$\mathbf{0.254 \pm 0.004}$
	Belle	$0.276 \pm 0.034 \,^{+0.029}_{-0.026}$	
	Our average	0.310 ± 0.017	
$\mathcal{B}\left(\overline{B} \to D\tau\bar{\nu}_\tau\right)$	BaBar	$1.02 \pm 0.13 \pm 0.11$ %	$\mathbf{0.633 \pm 0.016}$ %
$\mathcal{B}\left(\overline{B} \to D^*\tau\bar{\nu}_\tau\right)$	BaBar	$1.76 \pm 0.13 \pm 0.12$ %	$\mathbf{1.27 \pm 0.09}$ %
$\mathcal{B}\left(\overline{B} \to Dl\bar{\nu}_l\right)$	HFAG average	$2.13 \pm 0.03 \pm 0.09$ %	$\mathbf{2.11^{+0.09}_{-0.11}}$ %
$\mathcal{B}\left(\overline{B} \to D^*l\bar{\nu}_l\right)$	HFAG average	$4.93 \pm 0.01 \pm 0.11$ %	$\mathbf{5.04^{+0.44}_{-0.35}}$%
$P_\tau\left(\overline{B} \to D\tau\bar{\nu}_\tau\right)$			0.325 ± 0.009
			$\mathbf{0.325^{+0.013}_{-0.014}}$
$P_\tau\left(\overline{B} \to D^*\tau\bar{\nu}_\tau\right)$	Belle	$-0.44 \pm 0.47 \,^{+0.20}_{-0.17}$	-0.497 ± 0.013
			$\mathbf{-0.497 \pm 0.008}$
$\mathcal{A}_{FB}^{D}$			$\mathbf{-0.360^{+0.002}_{-0.001}}$
$\mathcal{A}_{FB}^{D^*}$			$\mathbf{0.064 \pm 0.014}$

New Measurement

Discrepancy only in tau

No discrepancy

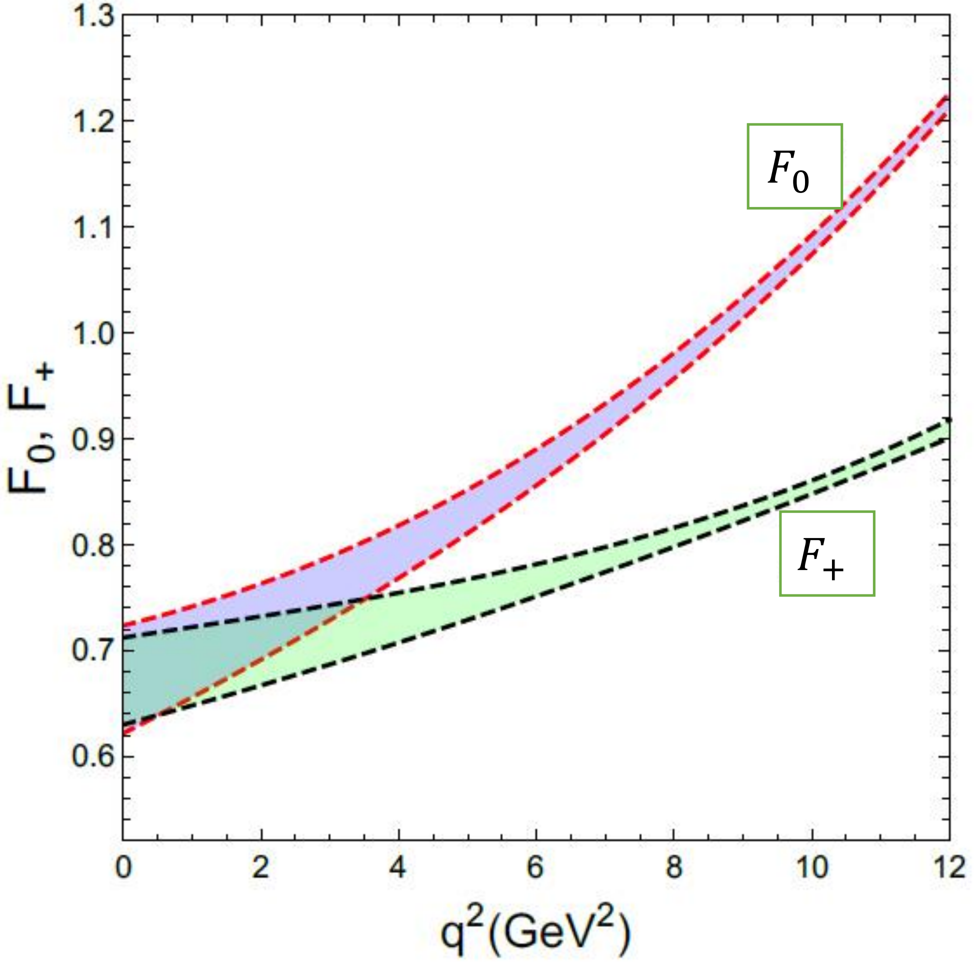
First measurement

$B \to D$ Form Factors: Definition

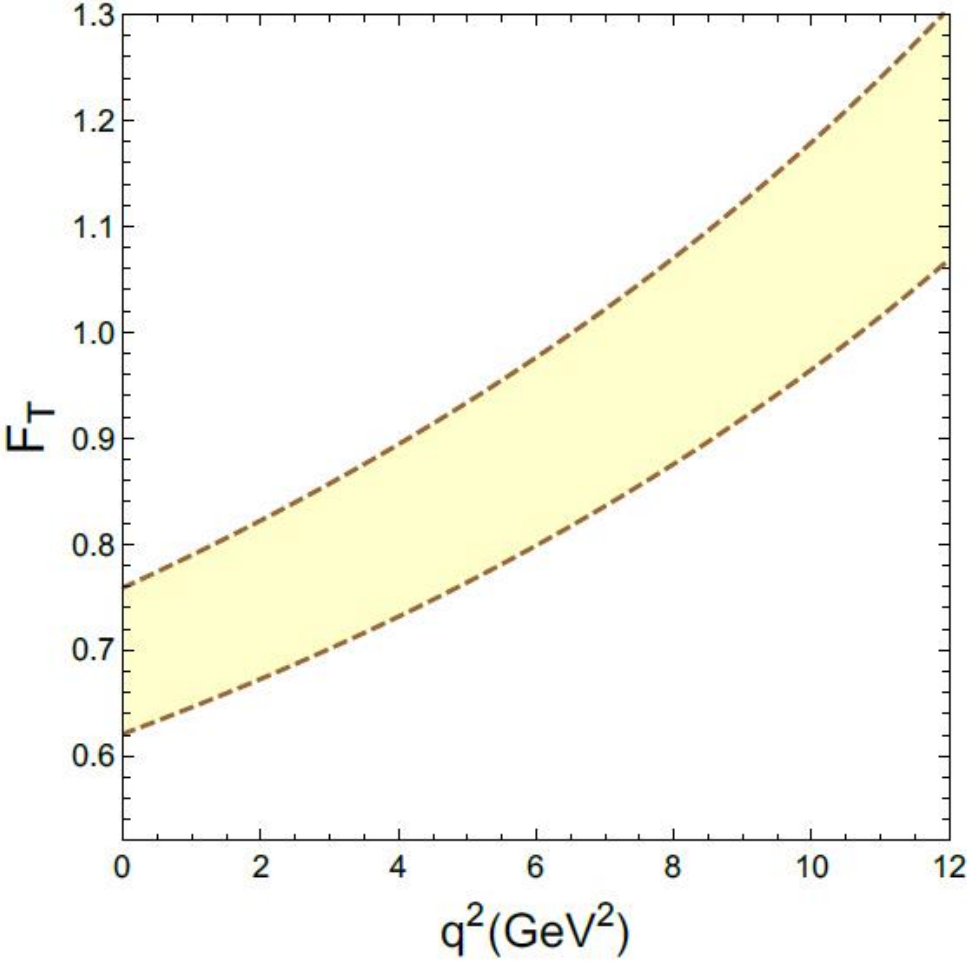
$$\begin{aligned}
\langle D(p_D, M_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B, M_B)\rangle &= F_+(q^2)\left[(p_B + p_D)^\mu - \frac{M_B^2 - M_D^2}{q^2} q^\mu\right] \\
&\quad + F_0(q^2)\frac{M_B^2 - M_D^2}{q^2} q^\mu \\
\langle D(p_D, M_D)|\bar{c}\gamma^\mu \gamma_5 b|\bar{B}(p_B, M_B)\rangle &= 0 \\
\langle D(p_D, M_D)|\bar{c} b|\bar{B}(p_B, M_B)\rangle &= F_0(q^2)\frac{M_B^2 - M_D^2}{m_b - m_c} \\
\langle D(p_D, M_D)|\bar{c}\gamma_5 b|\bar{B}(p_B, M_B)\rangle &= 0 \\
\langle D(p_D, M_D)|\bar{c}\sigma^{\mu\nu} b|\bar{B}(p_B, M_B)\rangle &= -i(p_B^\mu p_D^\nu - p_B^\nu p_D^\mu)\frac{2F_T(q^2)}{M_B + M_D} \\
\langle D(p_D, M_D)|\bar{c}\sigma^{\mu\nu}\gamma_5 b|\bar{B}(p_B, M_B)\rangle &= \varepsilon^{\mu\nu\rho\sigma} p_{B\rho} p_{D\sigma}\frac{2F_T(q^2)}{M_B + M_D}
\end{aligned}$$

$B \to D$ Form Factors: Plot

Lattice Calculation



Empirical Formula



MILC collaboration arXiv:1503.07237

$B \to D^*$ Form Factors: Definition

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\gamma_\mu b|\bar{B}(p_B, M_B)\rangle = i\varepsilon_{\mu\nu\rho\sigma}\epsilon^{\nu *} p_B^\rho p_{D^*}^\sigma \frac{2V(q^2)}{M_B + M_{D^*}}$$

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\gamma_\mu\gamma_5 b|\bar{B}(p_B, M_B)\rangle = 2M_{D^*}\frac{\epsilon^*.q}{q^2}q_\mu A_0(q^2) + (M_B + M_{D^*})\left[\epsilon_\mu^* - \frac{\epsilon^*.q}{q^2}q_\mu\right]A_1(q^2) - \frac{\epsilon^*.q}{M_B + M_{D^*}}\left[(p_B + p_{D^*})_\mu - \frac{M_B^2 - M_{D^*}^2}{q^2}q_\mu\right]A_2(q^2)$$

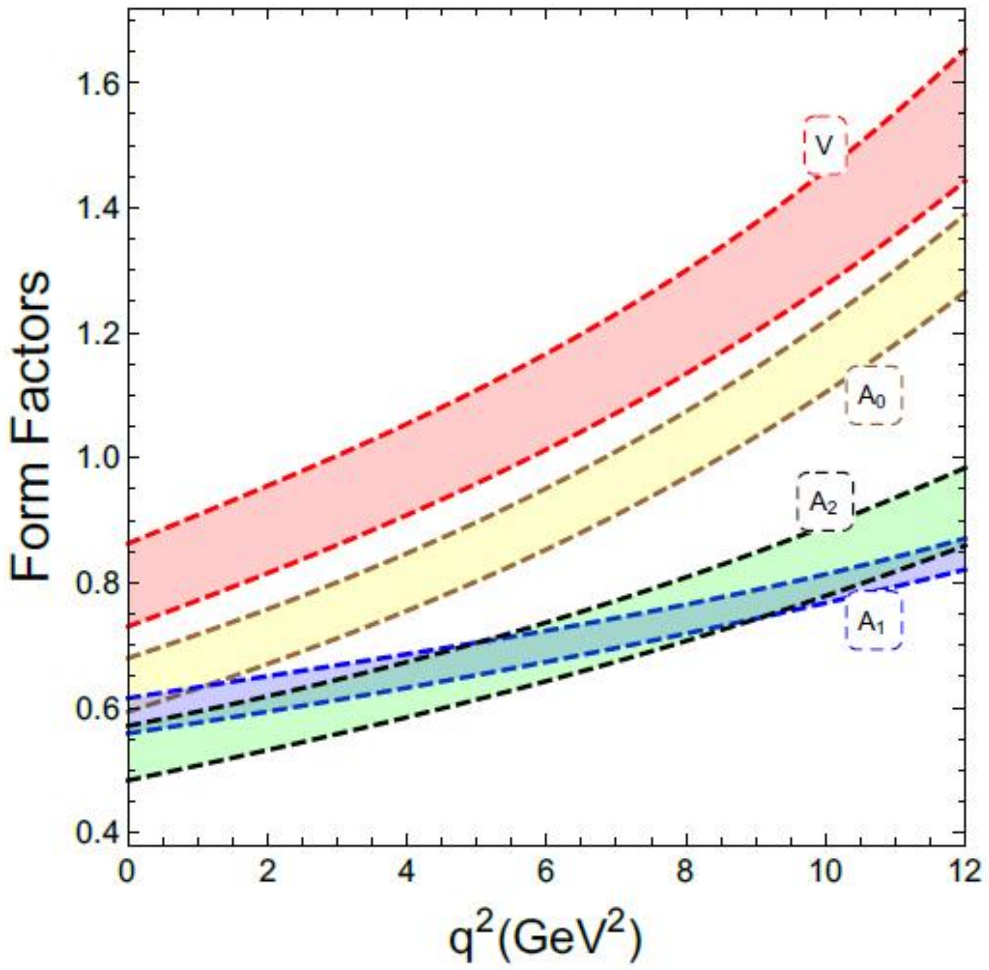
$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}b|\bar{B}(p_B, M_B)\rangle = 0$$

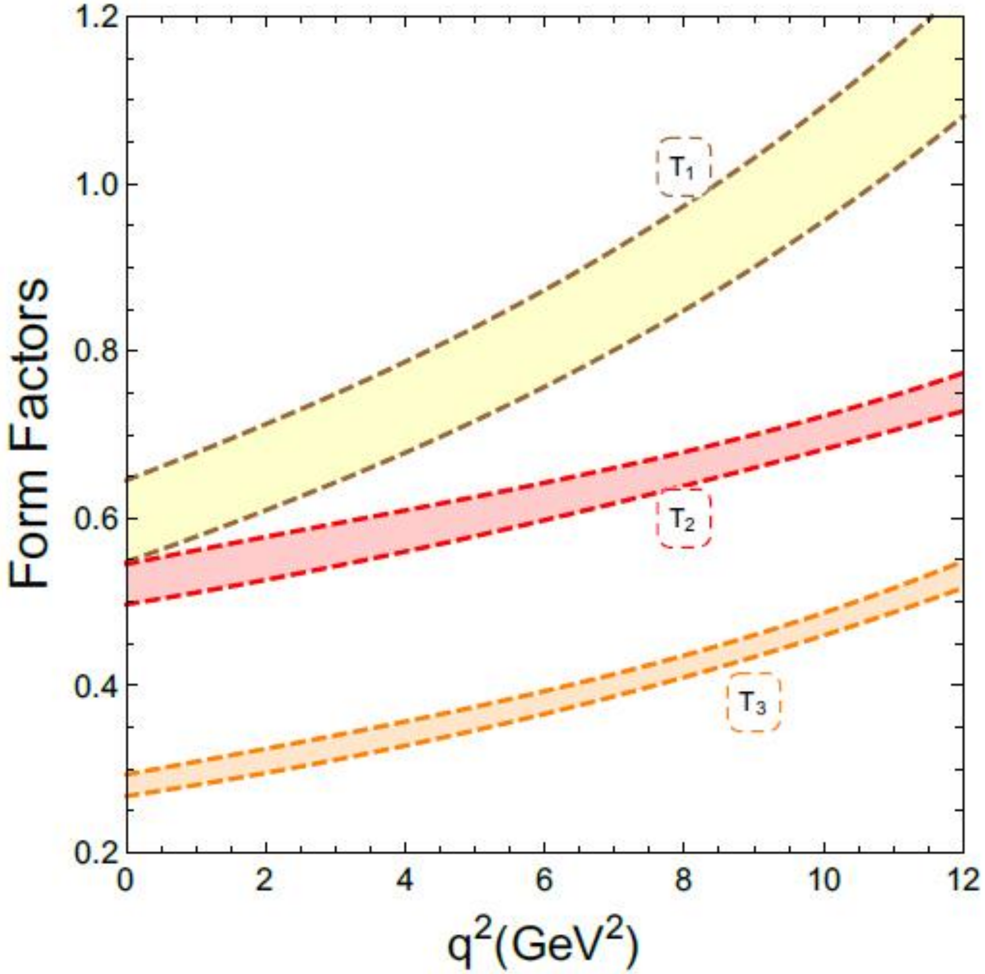
$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\gamma_5 b|\bar{B}(p_B, M_B)\rangle = -\epsilon^*.q\,\frac{2M_{D^*}}{m_b + m_c}A_0(q^2)$$

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\sigma_{\mu\nu} b|\bar{B}(p_B, M_B)\rangle = -\varepsilon_{\mu\nu\alpha\beta}\Big[-\epsilon^{\alpha *}(p_{D^*} + p_B)^\beta T_1(q^2) + \frac{M_B^2 - M_{D^*}^2}{q^2}\epsilon^{*\alpha}q^\beta\left(T_1(q^2) - T_2(q^2)\right) + 2\frac{\epsilon^*.q}{q^2}p_B^\alpha p_{D^*}^\beta\left(T_1(q^2) - T_2(q^2) - \frac{q^2}{M_B^2 - M_{D^*}^2}T_3(q^2)\right)\Big]$$

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\sigma_{\mu\nu}q^\nu b|\bar{B}(p_B, M_B)\rangle = -2\varepsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p_B^\rho p_{D^*}^\sigma T_1(q^2)$$

$B \to D^*$ Form Factors: Plot





arXiv:1309.0301 [hep-ph]

- Used Heavy Quark Effective Theory

Operator Basis

$$\mathcal{O}^{cb\ell}_{\rm VL} = [\bar{c}\,\gamma^\mu\, b][\bar{\ell}\,\gamma_\mu\, P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm AL} = [\bar{c}\,\gamma^\mu\,\gamma_5\, b][\bar{\ell}\,\gamma_\mu\, P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm SL} = [\bar{c}\, b][\bar{\ell}\, P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm PL} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm TL} = [\bar{c}\,\sigma^{\mu\nu}\, b][\bar{\ell}\,\sigma_{\mu\nu}\, P_L\,\nu]$$

$$\mathcal{O}^{cb\ell}_{\rm VR} = [\bar{c}\,\gamma^\mu\, b][\bar{\ell}\,\gamma_\mu\, P_R\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm AR} = [\bar{c}\,\gamma^\mu\,\gamma_5\, b][\bar{\ell}\,\gamma_\mu\, P_R\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm SR} = [\bar{c}\, b][\bar{\ell}\, P_R\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm PR} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_R\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm TR} = [\bar{c}\,\sigma^{\mu\nu}\, b][\bar{\ell}\,\sigma_{\mu\nu}\, P_R\,\nu]$$

- Only take these!
- Consistent with the SM gauge symmetry

- Tensor operators not taken in the account
- (Appears in the appendix)

- Not taken into account

SM: $C_{VL} = 1$, $C_{AL} = -1$

We provide the analytical expressions for all operators

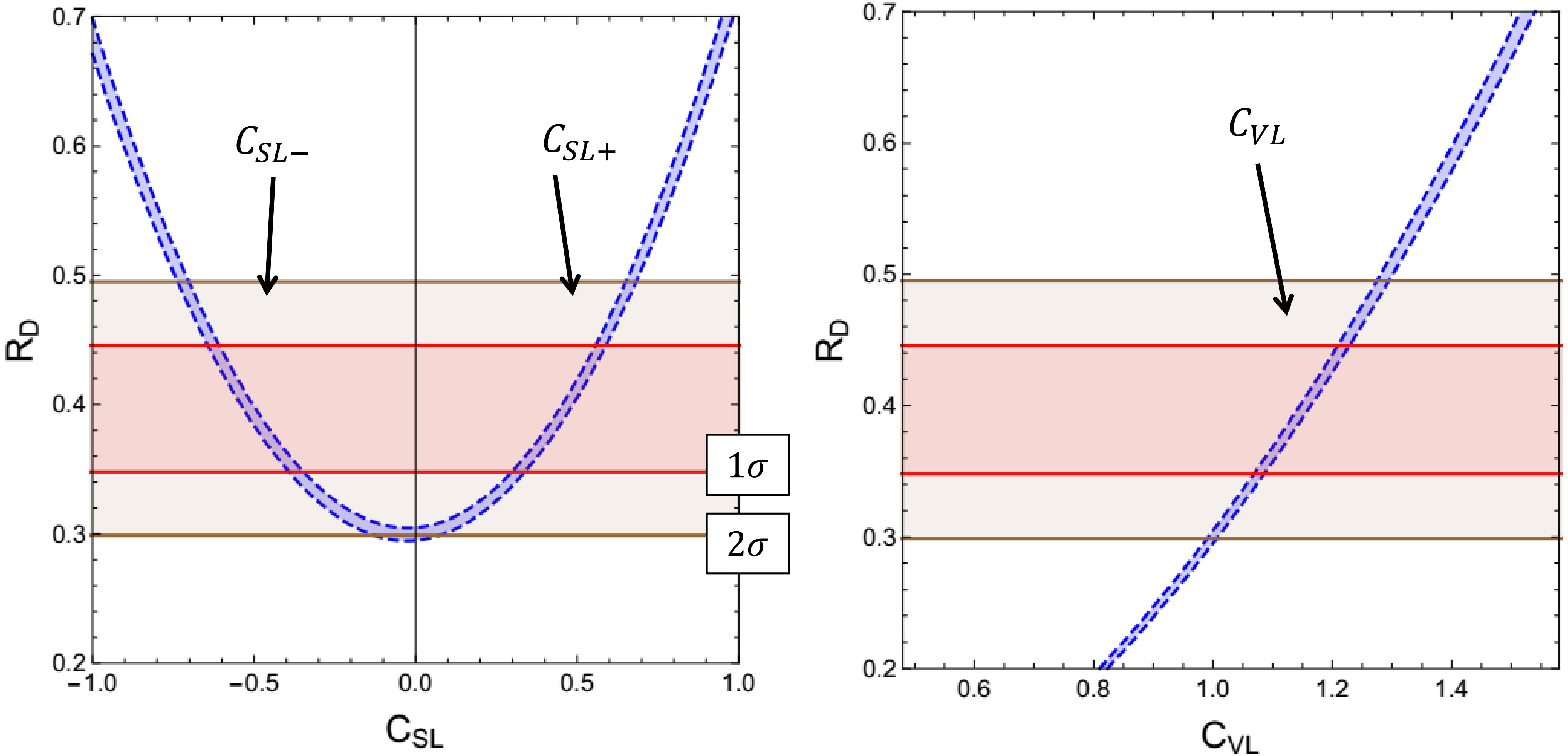
Independence of R_D and R_{D^*}

$\mathcal{O}^{cb\ell}_{\rm VL} = [\bar{c}\,\gamma^\mu\, b][\bar{\ell}\,\gamma_\mu\, P_L\,\nu]$	$B \to D$	$B \to D^*$
$\mathcal{O}^{cb\ell}_{\rm AL} = [\bar{c}\,\gamma^\mu\,\gamma_5\, b][\bar{\ell}\,\gamma_\mu\, P_L\,\nu]$		$B \to D^*$
$\mathcal{O}^{cb\ell}_{\rm SL} = [\bar{c}\, b][\bar{\ell}\, P_L\,\nu]$	$B \to D$	
$\mathcal{O}^{cb\ell}_{\rm PL} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_L\,\nu]$		$B \to D^*$
$\mathcal{O}^{cb\ell}_{\rm TL} = [\bar{c}\,\sigma^{\mu\nu}\, b][\bar{\ell}\,\sigma_{\mu\nu}\, P_L\,\nu]$	$B \to D$	$B \to D^*$

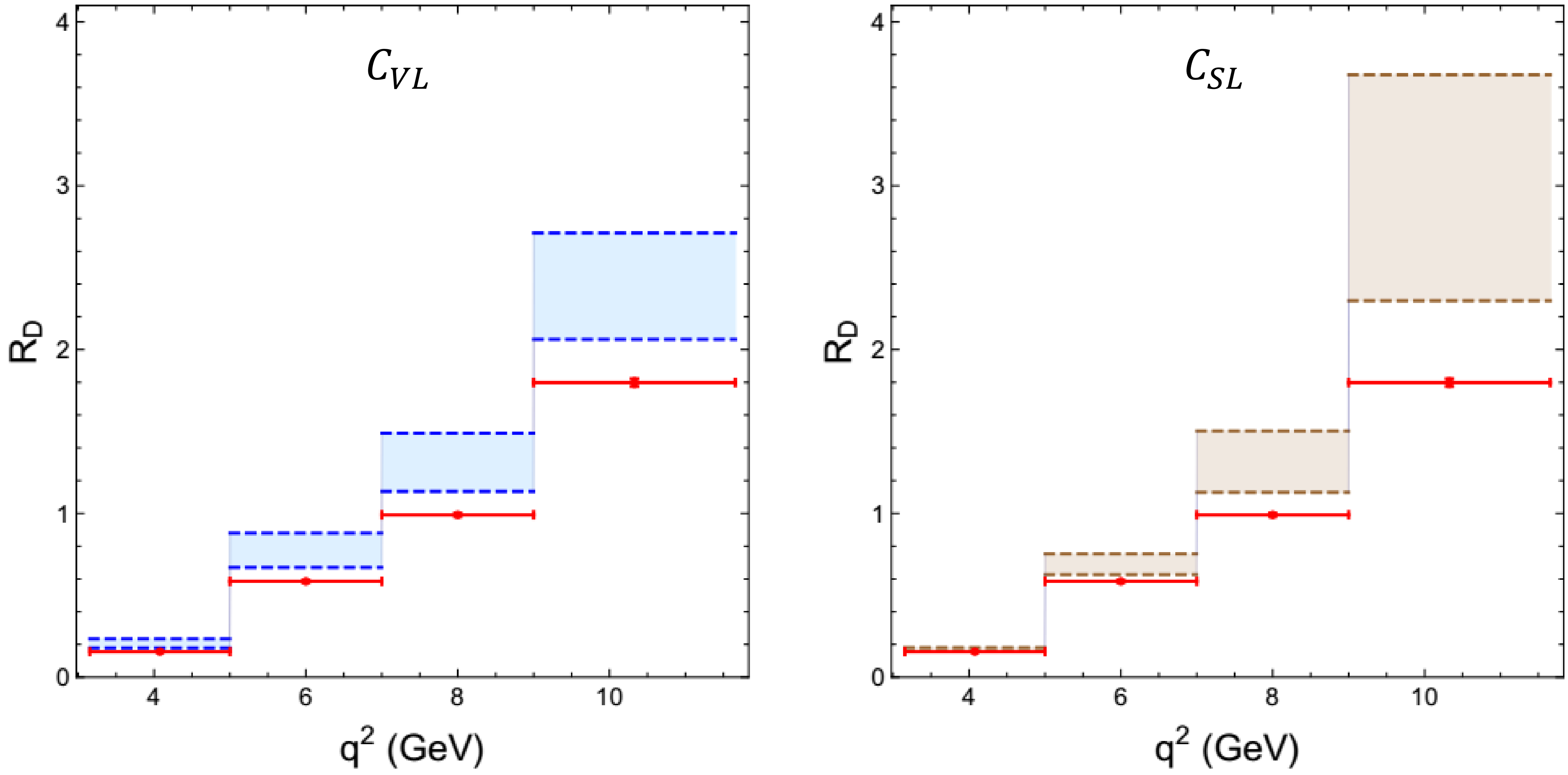
- R_D & R_{D^*} are independent observations
- Attempt to explain one at a time

Explaining R_D

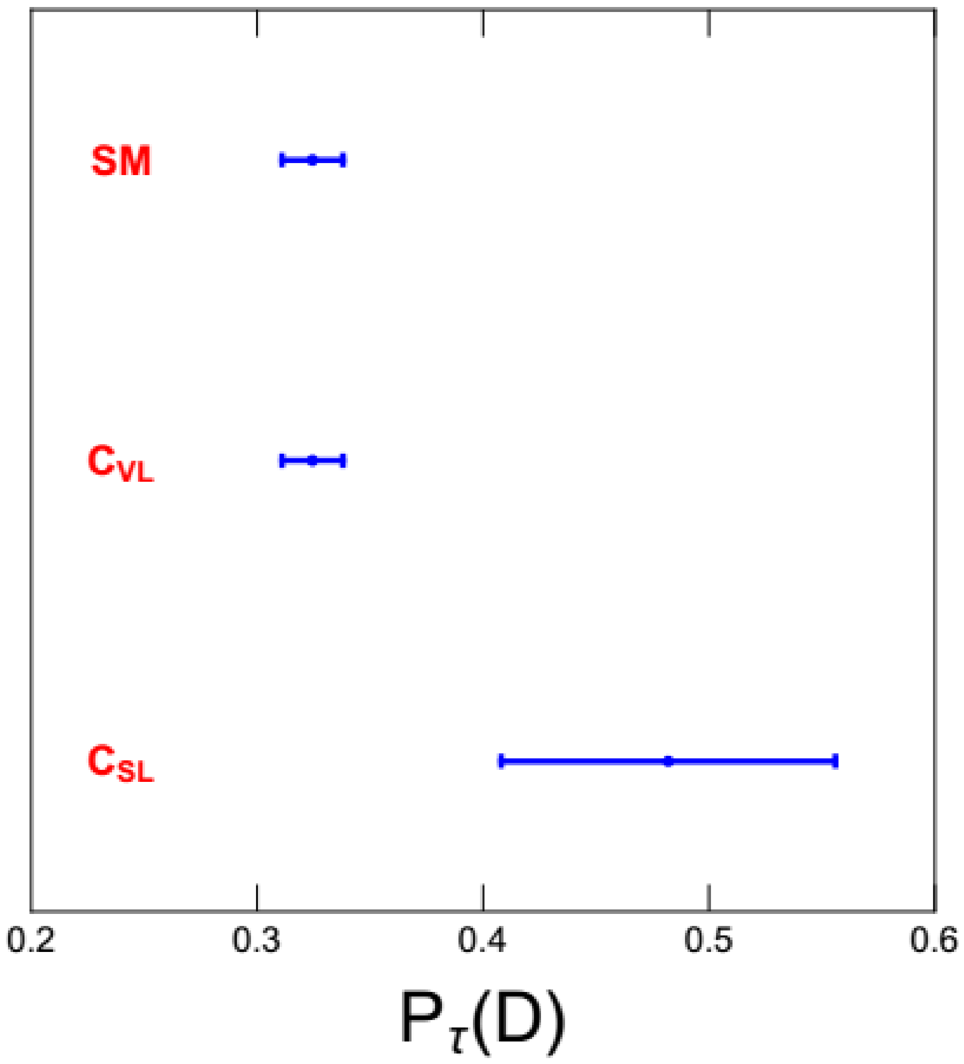
- R_D dependent on : C_{VL}^{τ} and C_{SL}^{τ}

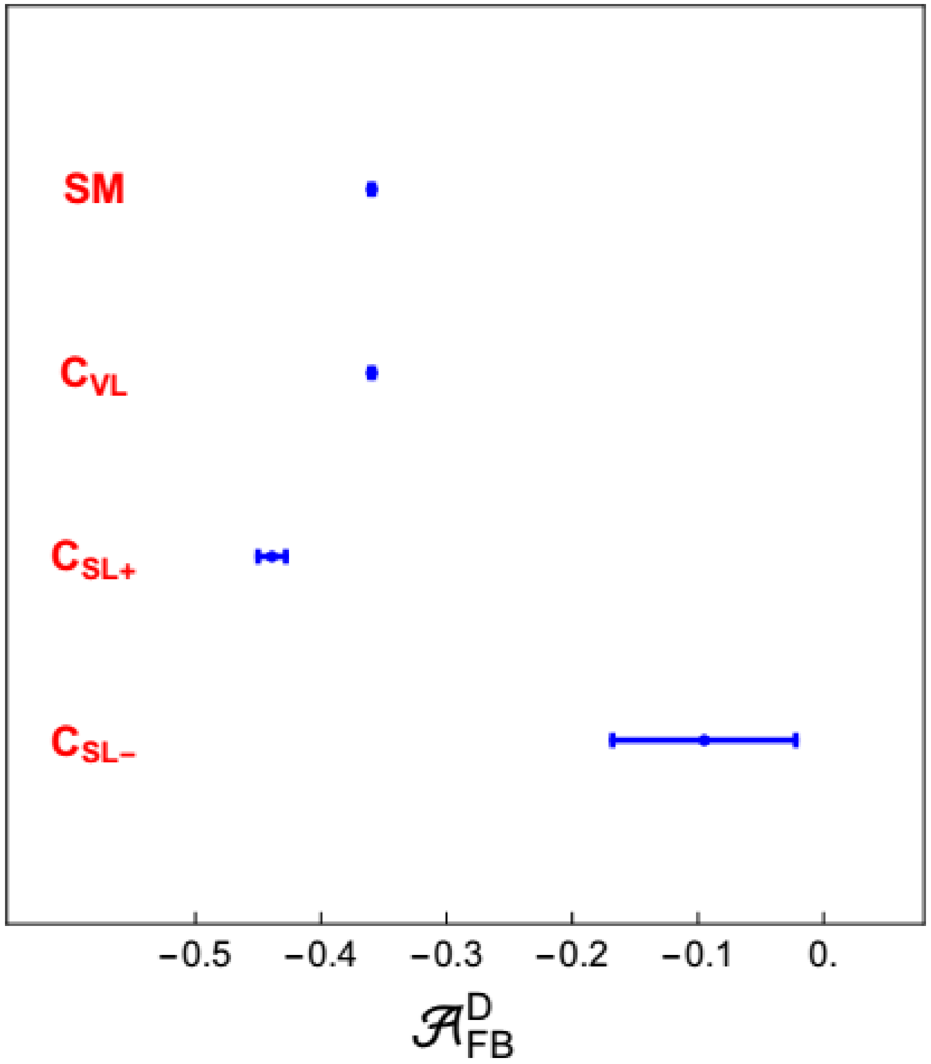


Binned R_D : Prediction



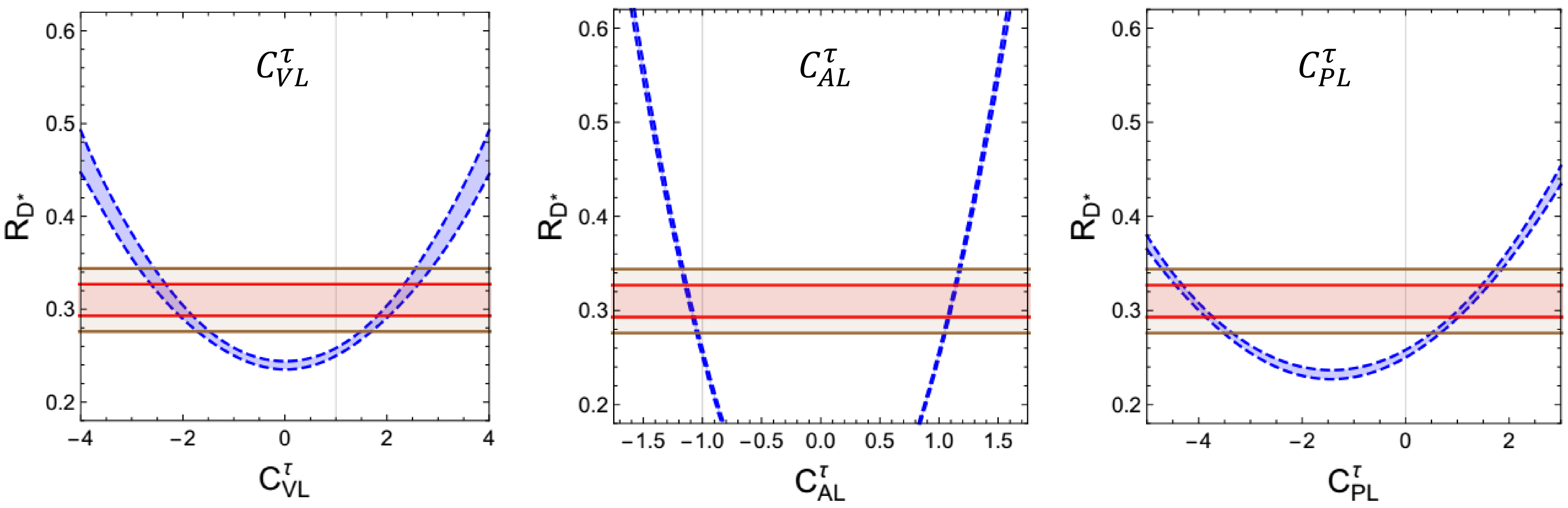
Tau Polarisation and FB Asymmetry



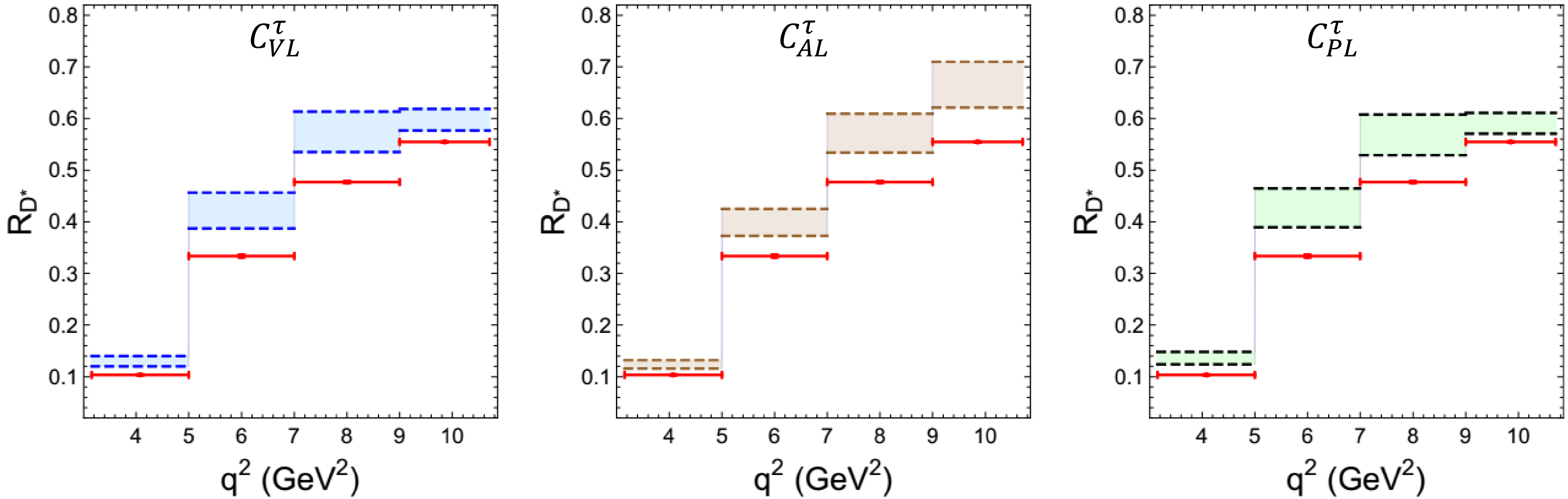


Explaining R_{D^*}

- R_{D^*} dependent on : $C^{\tau}_{VL}, C^{\tau}_{AL}$ and C^{τ}_{PL}

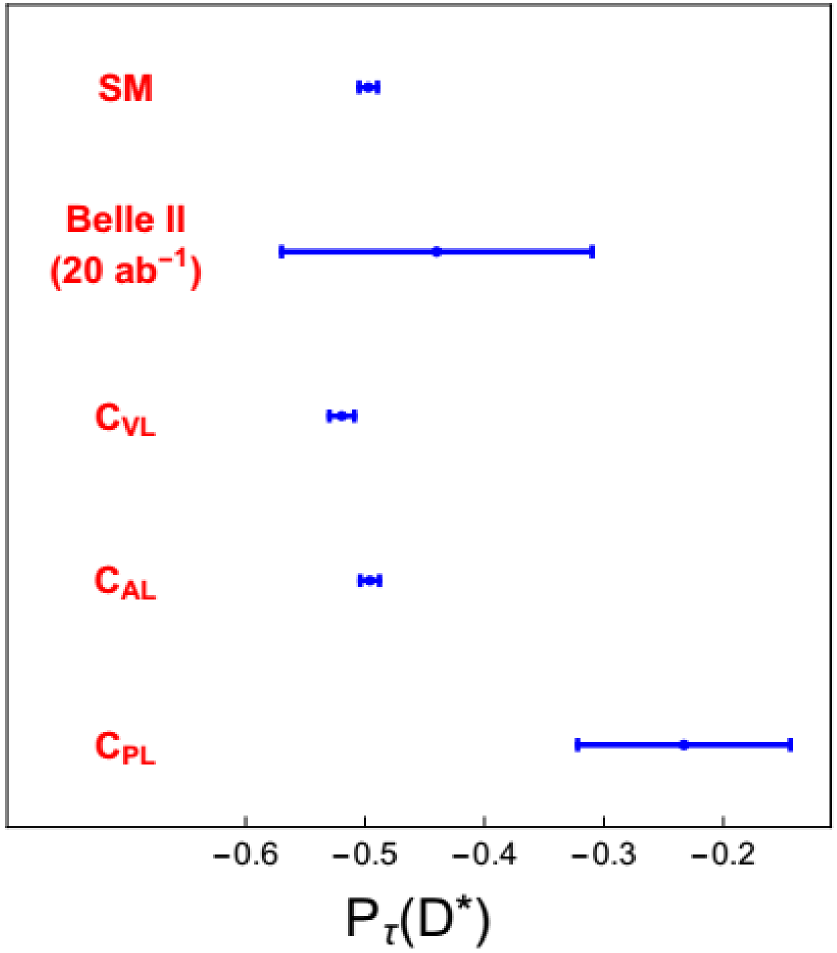


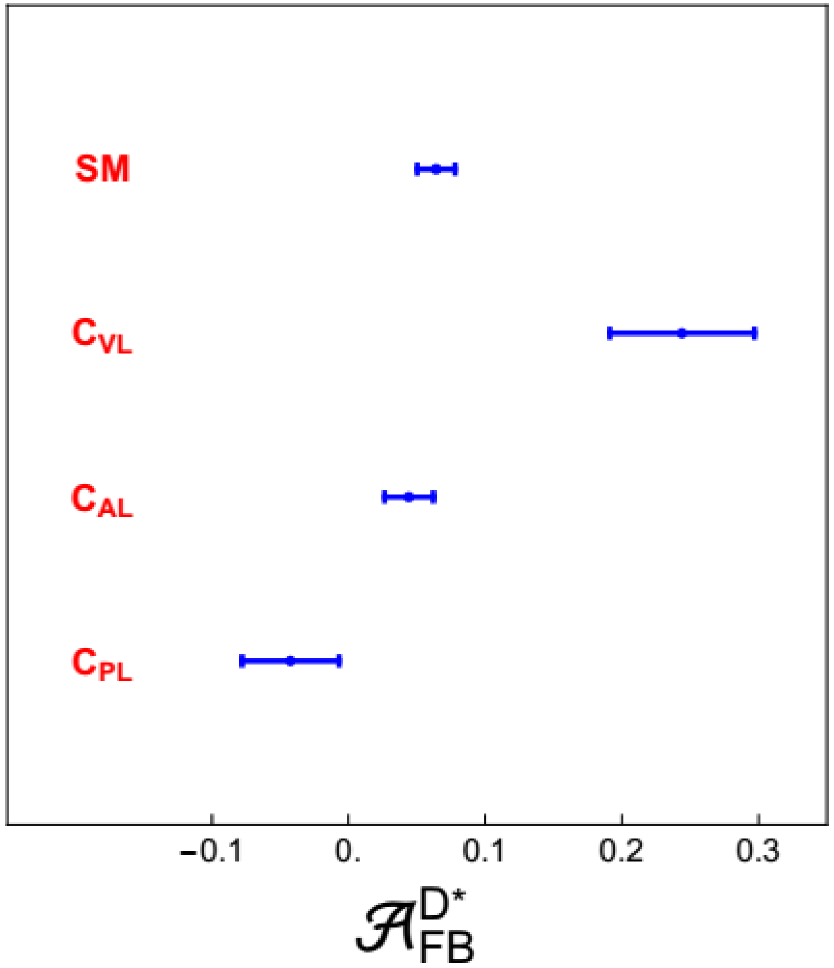
Binned R_{D^*} : Prediction



- Note the value in the last bin!

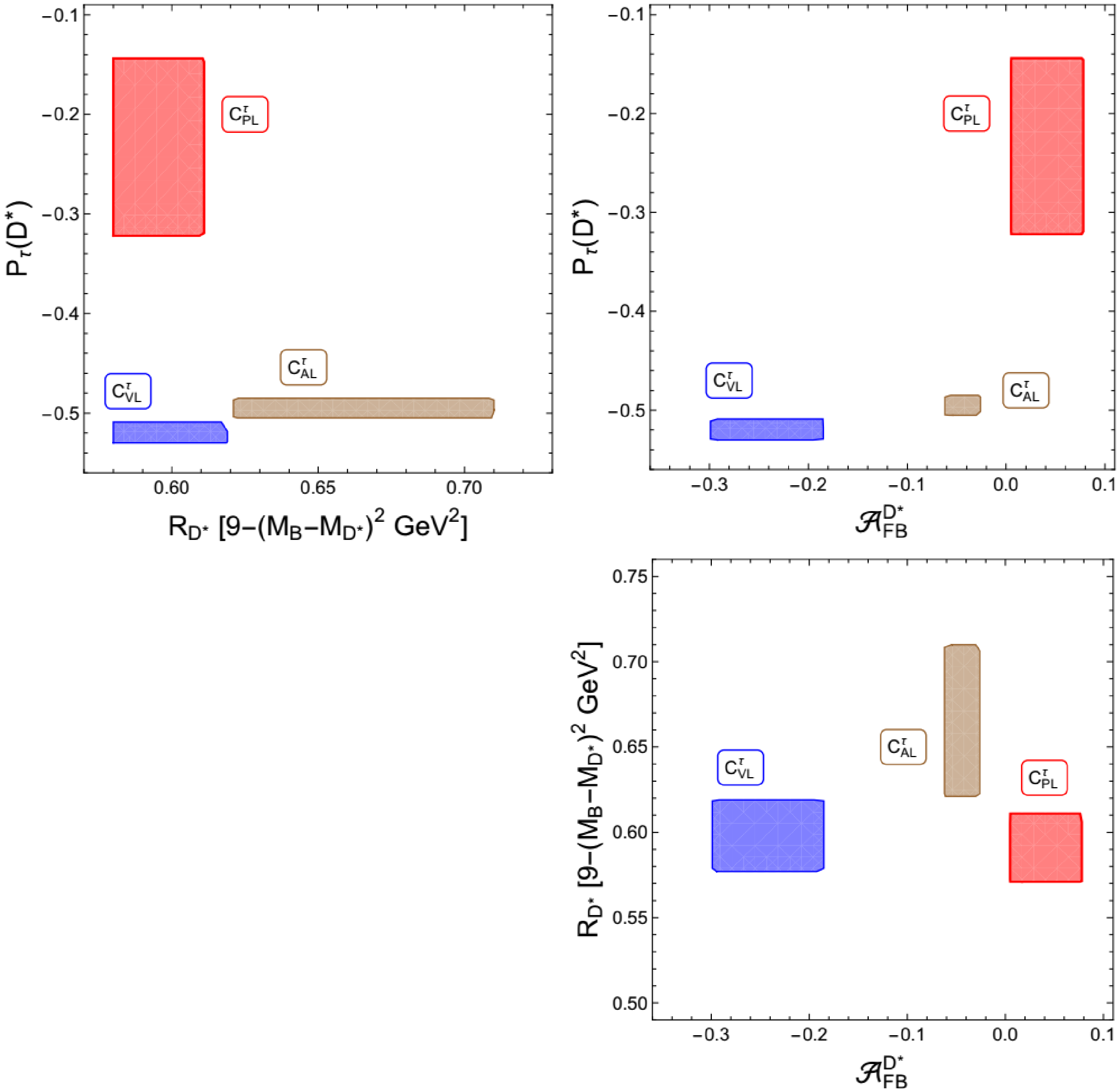
Tau Polarisation and FB Asymmetry





- Belle measurement plotted – projection at 20 ab^{-1}

Tau polarisation result: arXiv:1608.06391

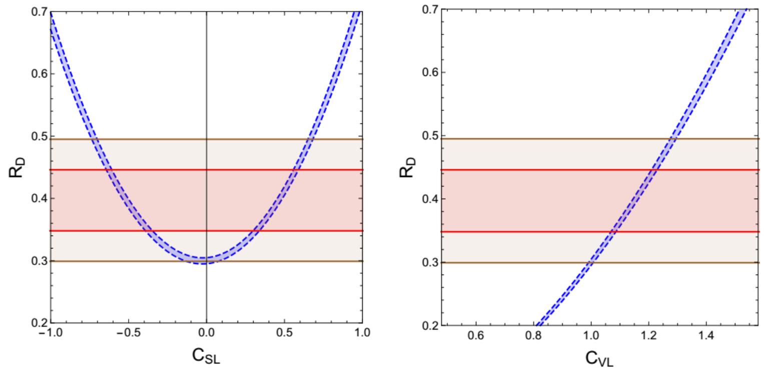


Differentiating Between the Scenarios

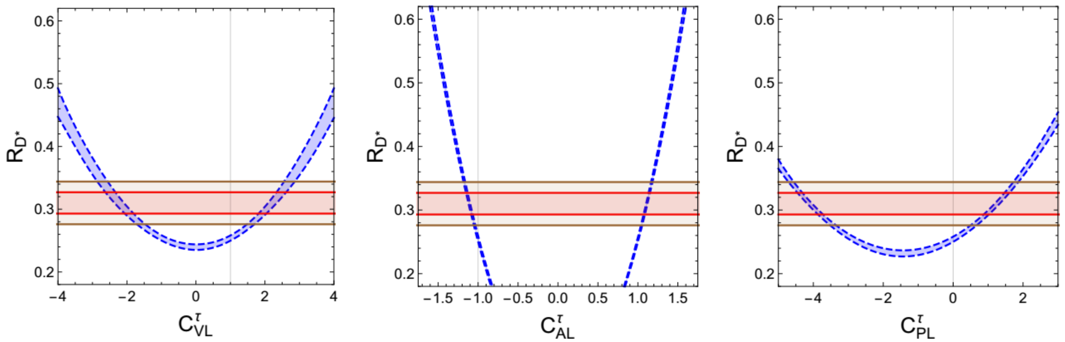
- Can differentiate between the different Wilson coefficients
- Urged experimentalists to make this measurement

Summary

- R_D and R_{D^*} - long standing anomaly with the SM

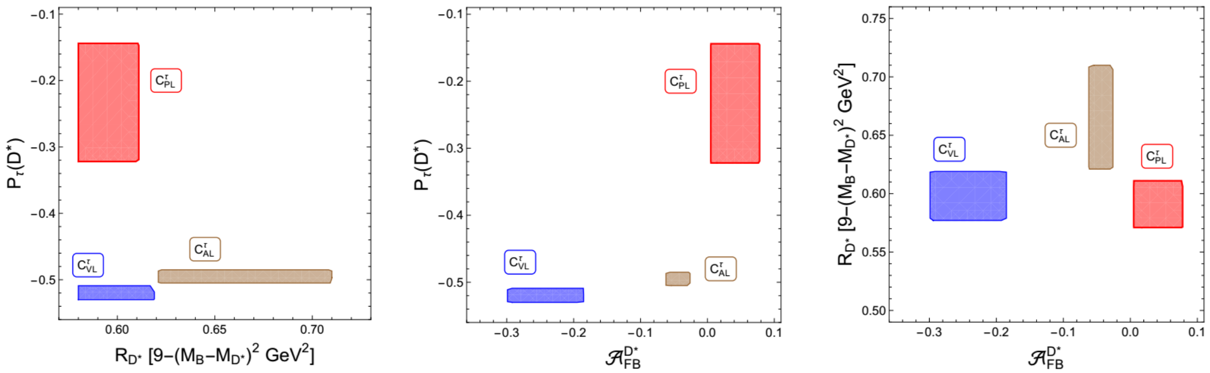


- Model independent analysis using six-dimensional operators



- Independent explanations

- P_τ, binned $\mathrm{R_{D^*}}$ and forward-backward asymmetry:



BACKUP SLIDES

'Old' and 'new' operator basis

$$\mathcal{L}_{\rm eff}^{b\to c\,\ell\,\nu} = \frac{2G_F V_{cb}}{\sqrt{2}} \Big(C_9^{cb\ell}\,\mathcal{O}_9^{cb\ell} + C_9^{cb\ell\,\prime}\,\mathcal{O}_9^{cb\ell\,\prime} + C_{10}^{cb\ell}\,\mathcal{O}_{10}^{cb\ell} + C_{10}^{cb\ell\,\prime}\,\mathcal{O}_{10}^{cb\ell\,\prime} + C_s^{cb\ell}\,\mathcal{O}_s^{cb\ell} + C_s^{cb\ell}\,\mathcal{O}_s^{cb\ell\,\prime}$$
$$+ \; C_p^{cb\ell}\,\mathcal{O}_p^{cb\ell} + C_p^{cb\ell\,\prime}\,\mathcal{O}_p^{cb\ell\,\prime} + C_T^{cb\ell}\,\mathcal{O}_T^{cb\ell} + C_{T5}^{cb\ell}\,\mathcal{O}_{T5}^{cb\ell} \Big) \qquad (2)$$

$$C_{\rm VL}^{cb\ell} = \frac{1}{2}\left(C_9^{cb\ell} - C_{10}^{cb\ell} + C_9^{cb\ell\,\prime} - C_{10}^{cb\ell\,\prime}\right)$$
$$C_{\rm AL}^{cb\ell} = \frac{1}{2}\left(-C_9^{cb\ell} + C_{10}^{cb\ell} + C_9^{cb\ell\,\prime} - C_{10}^{cb\ell\,\prime}\right)$$
$$C_{\rm SL}^{cb\ell} = \frac{1}{2}\left(C_s^{cb\ell} - C_p^{cb\ell} + C_s^{cb\ell\,\prime} - C_p^{cb\ell\,\prime}\right)$$
$$C_{\rm PL}^{cb\ell} = \frac{1}{2}\left(-C_s^{cb\ell} + C_p^{cb\ell} + C_s^{cb\ell\,\prime} - C_p^{cb\ell\,\prime}\right)$$
$$C_{\rm TL}^{cb\ell} = \left(C_T^{cb\ell} - C_{T5}^{cb\ell}\right)$$

$$C_{\rm SR}^{cb\ell} = \frac{1}{2}\left(C_s^{cb\ell} + C_p^{cb\ell} + C_s^{cb\ell\,\prime} + C_p^{cb\ell\,\prime}\right)$$
$$C_{\rm PR}^{cb\ell} = \frac{1}{2}\left(-C_s^{cb\ell} - C_p^{cb\ell} + C_s^{cb\ell\,\prime} + C_p^{cb\ell\,\prime}\right)$$
$$C_{\rm VR}^{cb\ell} = \frac{1}{2}\left(C_9^{cb\ell} + C_{10}^{cb\ell} + C_9^{cb\ell\,\prime} + C_{10}^{cb\ell\,\prime}\right)$$
$$C_{\rm AR}^{cb\ell} = \frac{1}{2}\left(-C_9^{cb\ell} - C_{10}^{cb\ell} + C_9^{cb\ell\,\prime} + C_{10}^{cb\ell\,\prime}\right)$$
$$C_{\rm TR}^{cb\ell} = \left(C_T^{cb\ell} + C_{T5}^{cb\ell}\right)$$

Expressions: $B \to D$

$$
\begin{aligned}
a_\ell^D(+) &= \frac{2\left(M_B^2-M_D^2\right)^2}{(m_b-m_c)^{\,2}}\,|\mathbf{C_{SL}^\ell}|^{\mathbf{2}}\mathbf{F_0^2} \\
&\quad + m_\ell\left[\frac{4(M_B^2-M_D^2)^2}{q^2\,(m_b-m_c)}\mathcal{R}\left(\mathbf{C_{VL}^\ell C_{SL}^{\ell *}}\right)\mathbf{F_0^2}\right] \\
&\quad + m_\ell^2\left[\frac{2\left(M_B^2-M_D^2\right)^2}{q^4}\,|\mathbf{C_{VL}^\ell}|^{\mathbf{2}}\mathbf{F_0^2}\right] \\
b_\ell^D(+) &= -m_\ell\left[\frac{8|p_D|M_B\left(M_B^2-M_D^2\right)}{q^2\,(m_b-m_c)}\mathcal{R}\left(\mathbf{C_{SL}^\ell C_{VL}^{\ell *}}\right)\mathbf{F_0F_+}\right] \\
&\quad - m_\ell^2\left[\frac{8|p_D|M_B\left(M_B^2-M_D^2\right)}{q^4}|\mathbf{C_{VL}^\ell}|^{\mathbf{2}}\mathbf{F_0F_+}\right] \\
c_\ell^D(+) &= m_\ell^2\left[\frac{8|p_D|^2M_B^2}{q^4}|\mathbf{C_{VL}^\ell}|^{\mathbf{2}}\mathbf{F_+^2}\right]
\end{aligned}
$$

$$
\begin{aligned}
a_\ell^D(-) &= \frac{8M_B^2|p_D|^2}{q^2}\,|\mathbf{C_{VL}^\ell}|^{\mathbf{2}}\mathbf{F_+^2} \\
b_\ell^D(-) &= 0 \\
c_\ell^D(-) &= -\frac{8M_B^2|p_D|^2}{q^2}|\mathbf{C_{VL}^\ell}|^{\mathbf{2}}\mathbf{F_+^2}
\end{aligned}
$$

Expressions: $B \to D^*$

$$
\begin{aligned}
a_\ell^{D^*}(-) &= \frac{8M_B^2\,|p_{D^*}|^2}{(M_B+M_{D^*})^2}\left|\mathbf{C}_{\mathbf{VL}}^\ell\right|^{\mathbf{2}}\mathbf{V}^{\mathbf{2}} + \frac{(M_B+M_{D^*})^2\,(8M_{D^*}^2q^2+\lambda)}{2M_{D^*}^2q^2}\left|\mathbf{C}_{\mathbf{AL}}^\ell\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{1}}^{\mathbf{2}} \\
&+\frac{8M_B^4|p_{D^*}|^4}{M_{D^*}^2\,(M_B+M_{D^*})^2\,q^2}\left|\mathbf{C}_{\mathbf{AL}}^\ell\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{2}}^{\mathbf{2}} \\
&-\frac{4\,|p_{D^*}|^2\,M_B^2\,(M_B^2-M_{D^*}^2-q^2)}{M_{D^*}^2q^2}\left|\mathbf{C}_{\mathbf{AL}}^\ell\right|^{\mathbf{2}}(\mathbf{A_1A_2})
\end{aligned}
$$

$$
b_\ell^{D^*}(-) = -16|p_{D^*}|M_B\mathcal{R}\left(\mathbf{C}_{\mathbf{VL}}^\ell\mathbf{C}_{\mathbf{AL}}^{\ell*}\right)(\mathbf{VA_1})
$$

$$
\begin{aligned}
c_\ell^{D^*}(-) &= \frac{8\,|p_{D^*}|^2\,M_B^2}{(M_B+M_{D^*})^2}\left|\mathbf{C}_{\mathbf{VL}}^\ell\right|^{\mathbf{2}}\mathbf{V}^{\mathbf{2}} - \frac{(M_B+M_{D^*})^2\,\lambda}{2M_{D^*}^2q^2}\left|\mathbf{C}_{\mathbf{AL}}^\ell\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{1}}^{\mathbf{2}} \\
&-\frac{8|p_{D^*}|^4M_B^4}{(M_B+M_{D^*})^2\,M_{D^*}^2q^2}\left|\mathbf{C}_{\mathbf{AL}}^\ell\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{2}}^{\mathbf{2}} \\
&+\frac{4\,|p_{D^*}|^2\,M_B^2\,(M_B^2-M_{D^*}^2-q^2)}{M_{D^*}^2q^2}\left|\mathbf{C}_{\mathbf{AL}}^\ell\right|^{\mathbf{2}}(\mathbf{A_1A_2})
\end{aligned}
$$

Expressions: $B \to D^*$ (contd.)

$$a_\ell^{D^*}(+) = \frac{8\left|p_{D^*}\right|^2 M_B^2}{\left(m_b+m_c\right)^2}\left|\mathbf{C}_{\mathbf{PL}}^{\ell}\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{0}}^{\mathbf{2}} - m_\ell\left[\frac{16\left|p_{D^*}\right|^2 M_B^2}{\left(m_b+m_c\right)q^2}\mathcal{R}\left(\mathbf{C}_{\mathbf{AL}}^{\ell}\mathbf{C}_{\mathbf{PL}}^{\ell *}\right)\mathbf{A}_{\mathbf{0}}^{\mathbf{2}}\right] + m_\ell^2\left[\frac{8\left|p_{D^*}\right|^2 M_B^2}{q^4}\left|\mathbf{C}_{\mathbf{AL}}^{\ell}\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{0}}^{\mathbf{2}} + \frac{8\left|p_{D^*}\right|^2 M_B^2}{\left(M_B+M_{D^*}\right)^2 q^2}\left|\mathbf{C}_{\mathbf{VL}}^{\ell}\right|^{\mathbf{2}}\mathbf{V}^{\mathbf{2}} + \frac{2\left(M_B+M_{D^*}\right)^2}{q^2}\left|\mathbf{C}_{\mathbf{AL}}^{\ell}\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{1}}^{\mathbf{2}}\right]$$

$$b_\ell^{D^*}(+) = m_\ell\left[\frac{4|p_{D^*}|M_B\left(M_B+M_{D^*}\right)\left(M_B^2-M_{D^*}^2-q^2\right)}{M_{D^*}\left(m_b+m_c\right)q^2}\mathcal{R}\left(\mathbf{C}_{\mathbf{AL}}^{\ell}\mathbf{C}_{\mathbf{PL}}^{\ell *}\right)\mathbf{A_0A_1} - \frac{16}{\left(m_b+m_c\right)}\frac{|p_{D^*}|^3 M_B^3}{\left(M_B+M_{D^*}\right)M_{D^*}q^2}\mathcal{R}\left(\mathbf{C}_{\mathbf{AL}}^{\ell}\mathbf{C}_{\mathbf{PL}}^{\ell *}\right)\mathbf{A_0A_2}\right] + m_\ell^2\left[-\frac{4|p_{D^*}|M_B\left(M_B+M_{D^*}\right)}{M_{D^*}q^4}\left(M_B^2-M_{D^*}^2-q^2\right)\left|\mathbf{C}_{\mathbf{AL}}^{\ell}\right|^{\mathbf{2}}\mathbf{A_0A_1} + \frac{16|p_{D^*}|^3 M_B^3}{\left(M_B+M_{D^*}\right)M_{D^*}q^4}\left|\mathbf{C}_{\mathbf{AL}}^{\ell}\right|^{\mathbf{2}}\mathbf{A_0A_2}\right]$$

$$c_\ell^{D^*}(+) = m_\ell^2\left[-\frac{8\left|p_{D^*}\right|^2 M_B^2}{\left(M_B+M_{D^*}\right)^2 q^2}\left|\mathbf{C}_{\mathbf{VL}}^{\ell}\right|^{\mathbf{2}}\mathbf{V}^{\mathbf{2}} + \frac{\left(M_B+M_{D^*}\right)^2\lambda}{2M_{D^*}^2 q^4}\left|\mathbf{C}_{\mathbf{AL}}^{\ell}\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{1}}^{\mathbf{2}} + \frac{8|p_{D^*}|^4 M_B^4}{M_{D^*}^2\left(M_B+M_{D^*}\right)^2 q^4}\left|\mathbf{C}_{\mathbf{AL}}^{\ell}\right|^{\mathbf{2}}\mathbf{A}_{\mathbf{2}}^{\mathbf{2}} - \frac{4\left|p_{D^*}\right|^2 M_B^2}{M_{D^*}^2 q^4}\left(M_B^2-M_{D^*}^2-q^2\right)\left|\mathbf{C}_{\mathbf{AL}}^{\ell}\right|^{\mathbf{2}}\left(\mathbf{A_1A_2}\right)\right]$$

Errors in $B \to D$ Formfactors

$$F_+(z) = \frac{1}{\phi_+(z)} \sum_{k=0}^{3} a_k^+ z^k$$

$$F_0(z) = \frac{1}{\phi_0(z)} \sum_{k=0}^{3} a_k^0 z^k$$

	a_0^+	a_1^+	a_2^+	a_3^+	a_0^0	a_1^0	a_2^0	a_3^0
Values	0.01261	-0.0963	0.37	-0.05	0.01140	-0.0590	0.19	-0.03
Uncertainties	0.00010	0.0033	0.11	0.90	0.00009	0.0028	0.10	0.87

	a_0^+	a_1^+	a_2^+	a_3^+	a_0^0	a_1^0	a_2^0	a_3^0
a_0^+	1.00000	0.24419	−0.08658	0.01207	0.00000	0.23370	0.03838	−0.05639
a_1^+		1.00000	−0.57339	0.25749	0.00000	0.80558	−0.25493	−0.15014
a_2^+			1.00000	−0.64492	0.00000	−0.44966	0.66213	0.05120
a_3^+				1.00000	0.00000	0.11311	−0.20100	0.23714
a_0^0					1.00000	0.00000	0.00000	0.00000
a_1^0						1.00000	−0.44352	0.02485
a_2^0							1.00000	−0.46248
a_3^0								1.00000

$\chi^2(\mathbf{x}) = (\mathbf{x}-\mathbf{x_0})^T\,\mathbf{V}^{-1}\,(\mathbf{x}-\mathbf{x_0})$ where $\mathbf{x} = (a_0^+, a_1^+, a_2^+, a_3^+, a_0^0, a_1^0, a_2^0, a_3^0)$

$V_{ij} = \sigma_i(\mathbf{x})\rho_{ij}\sigma_j(\mathbf{x})$

$$\chi^2 \leq 1.646$$

HQET Parameterisation

$$h_V(w) = R_1(w) h_{A_1}(w)$$

$$h_{A_2}(w) = \frac{R_2(w) - R_3(w)}{2\, r_{D^*}} h_{A_1}(w)$$

$$h_{A_3}(w) = \frac{R_2(w) + R_3(w)}{2} h_{A_1}(w)$$

$$h_{T_1}(w) = \frac{1}{2(1 + r_{D^*}^2 - 2r_{D^*}w)} \left[\frac{m_b - m_c}{M_B - M_{D^*}}(1 - r_{D^*})^2 (w+1)\, h_{A_1}(w) - \frac{m_b + m_c}{M_B + M_{D^*}}(1 + r_{D^*})^2 (w-1)\, h_V(w)\right]$$

$$h_{T_2}(w) = \frac{(1 - r_{D^*}^2)(w+1)}{2(1 + r_{D^*}^2 - 2r_{D^*}w)} \left[\frac{m_b - m_c}{M_B - M_{D^*}}\, h_{A_1}(w) - \frac{m_b + m_c}{M_B + M_{D^*}}\, h_V(w)\right]$$

$$h_{T_3}(w) = -\frac{1}{2(1 + r_{D^*})(1 + r_{D^*}^2 - 2r_{D^*}w)} \left[2\frac{m_b - m_c}{M_B - M_{D^*}} r_{D^*}(w+1)\, h_{A_1}(w) - \frac{m_b - m_c}{M_B - M_{D^*}}(1 + r_{D^*}^2 - 2r_{D^*}w)(h_{A_3}(w) - r_{D^*} h_{A_2}(w)) - \frac{m_b + m_c}{M_B + M_{D^*}}(1 + r_{D^*})^2\, h_V(w)\right]$$

$$h_{A_1}(w) = h_{A_1}(1)[1 - 8\rho_{D^*}^2 z + (53\rho_{D^*}^2 - 15)z^2 - (231\rho_{D^*}^2 - 91)z^3]$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

$$R_3(w) = 1.22 - 0.052(w-1) + 0.026(w-1)^2$$

$$w(q^2) = (M_B^2 + M_{D^*}^2 - q^2)/2M_B M_{D^*}$$

$$z = \frac{\sqrt{\omega + 1} - \sqrt{2}}{\sqrt{\omega + 1} + \sqrt{2}}$$

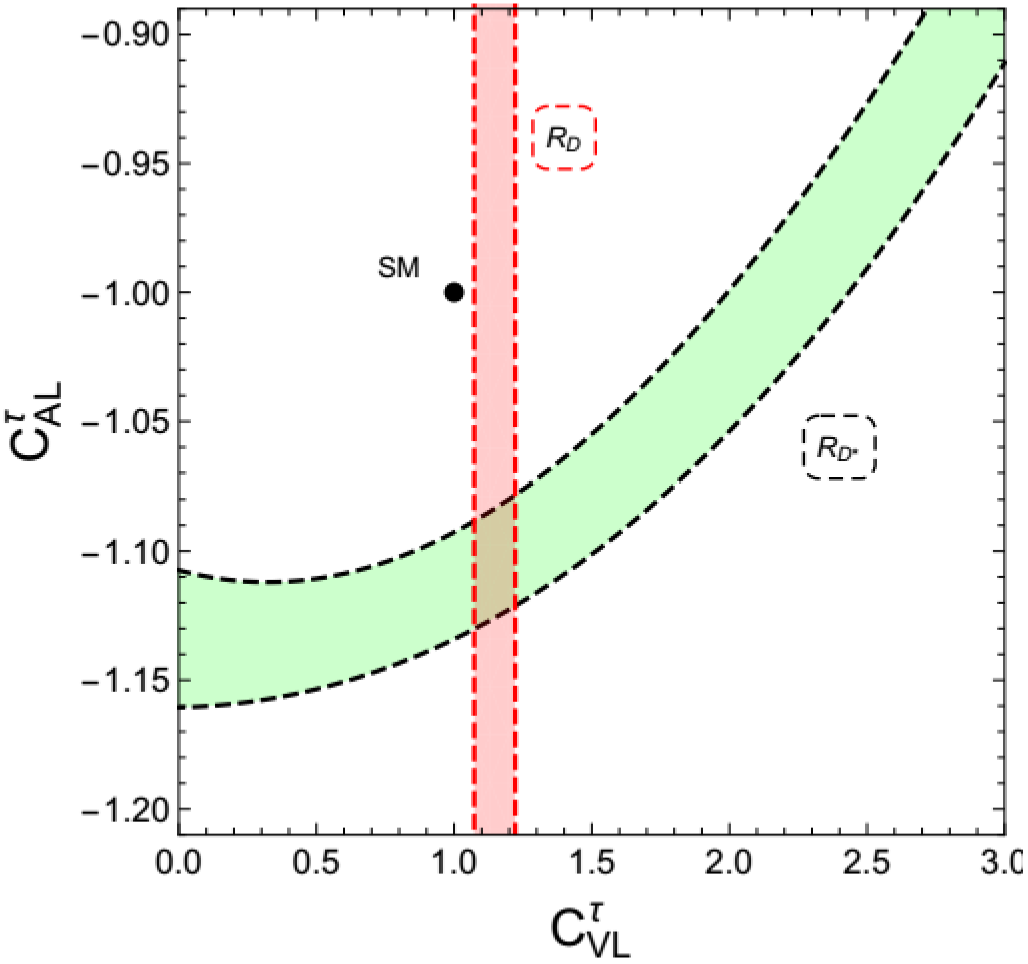
$$R_1(1) = 1.406 \pm 0.033$$

$$R_2(1) = 0.853 \pm 0.020$$

$$\rho_{D^*}^2 = 1.207 \pm 0.026$$

$$h_{A_1}(1) = 0.906 \pm 0.013$$

Both decays simultaneously



- Choose the $C_{VL} - C_{AL}$ plane

$$C^{\tau}_{VL} \in [1.073,\ 1.222]$$

$$C^{\tau}_{AL} \in [-1.144,\ -1.067]$$

To explain both, need

$$C_{VL} = -C_{AL} \approx 1.07$$

OP: $\frac{g_{NP}^2}{\Lambda^2}[\bar{c}\gamma^{\mu}P_L b][\bar{\ell}\gamma_{\mu}P_L\nu_{\ell}]$

$\Rightarrow \Lambda \approx g_{NP} \times 2.25$ TeV