Global fits to $b \to c\tau\nu$ transitions

Mainz Prisma U.

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Based on arXiv:1904.09311 and arXiv:2004.06726

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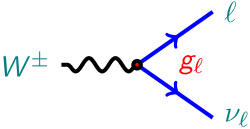
Mainz Institute for Theoretical Physics

Introduction

Lepton Flavour Universality → no difference between electroweak decays at high energy (negligible mass)



$$g_e = g_\mu = g_\tau$$

anomalies in	charged currents $b \to c$	$\left(\frac{\tau}{\mu,e}, \mathcal{R}_{D^{(*)}}\right)$
Lepton Universality	neutral currents $b \to s$	$\left(\frac{\mu}{e}, \mathcal{R}_{K^{(*)}}\right)$

Introduction

Discrepancies [$(2-4)\sigma$] in semileptonic B decays

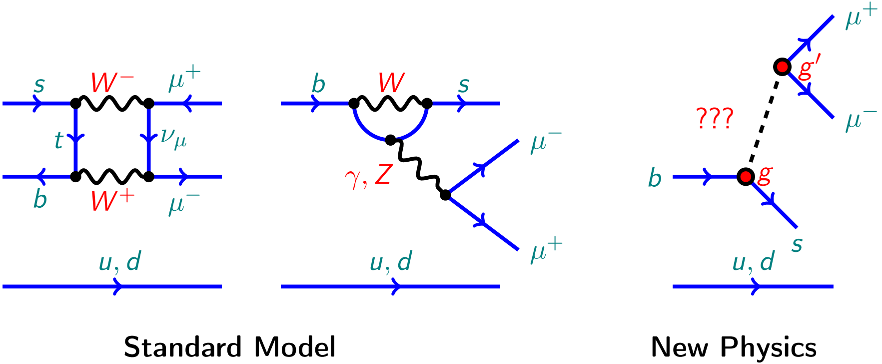
$$\mathcal{R}_{D^{(*)}} \equiv \left.\frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}\right|_{\ell=e,\mu} \qquad \mathcal{R}^{\text{exp}}_{D^{(*)}} > \mathcal{R}^{\text{SM}}_{D^{(*)}}$$

$$\mathcal{R}_{K^{(*)}} \equiv \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2\in[q^2_{\text{min}},q^2_{\text{max}}]} \qquad \mathcal{R}^{\text{exp}}_{K^{(*)}} < \mathcal{R}^{\text{SM}}_{K^{(*)}}$$

Introduction: $B \to K\mu^+\mu^-$

$B = B^-, B^0,$ $\quad B^- = b\,\bar{u},\ B^0 = \bar{b}\,d$

$K = K^0, K^+,$ $\quad K^+ = u\,\bar{s},\ K^0 = d\,\bar{s}$



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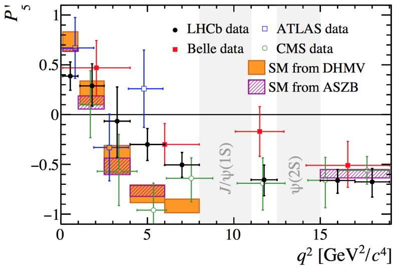
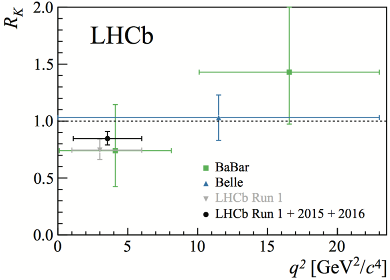


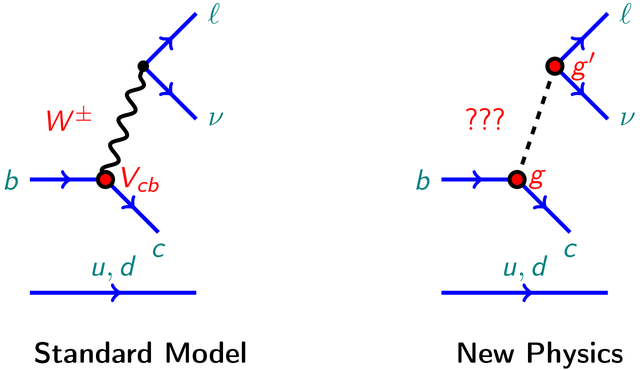


Also $B_d \to K^0\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_d \to \Lambda\mu^+\mu^-$...

Introduction: $B \to D\tau\nu$

$B = B^-, B^0,$ $B^- = b\,\bar{u},\ B^0 = \bar{b}d$

$D = D^0, D^+,$ $D^0 = c\bar{u},\ D^+ = c\bar{d}$



Current status of charged B anomalies

$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

2016 : 3.9σ discrepancy

2019 : 3.2σ discrepancy

SM prediction

$$\mathcal{R}_D^{\text{SM}} = 0.300^{+0.005}_{-0.004} \quad \text{and} \quad \mathcal{R}_{D^*}^{\text{SM}} = 0.251^{+0.004}_{-0.003}$$

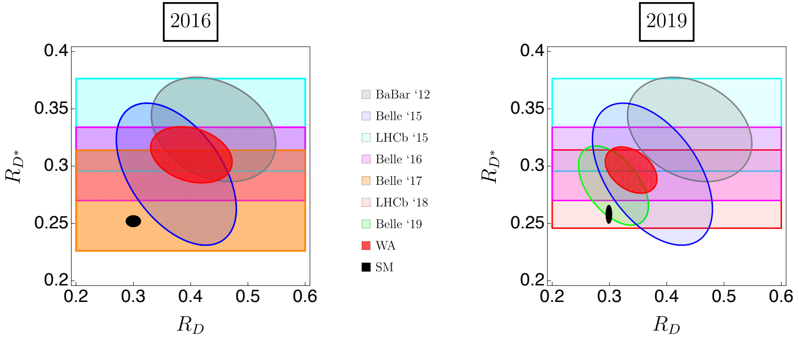
World average 2016 (HFLAV)

$$\mathcal{R}_D = 0.403 \pm 0.040 \pm 0.02 \quad \text{and} \quad \mathcal{R}_{D^*} = 0.310 \pm 0.015 \pm 0.008$$

World average 2019 (HFLAV)

$$\mathcal{R}_D = 0.340 \pm 0.027 \pm 0.013 \quad \text{and} \quad \mathcal{R}_{D^*} = 0.295 \pm 0.011 \pm 0.008$$

Current status of charged B anomalies



World average 2016 (HFLAV) World average 2019 (HFLAV)

Current status of charged B anoamlies

More measurements...

$\bar{F}_L^{D^*} = 0.60 \pm 0.08\ (\text{stat})\ \pm 0.04\ (\text{syst})$ 1.6σ discrepancy

[Belle '19]

Current status of charged B anoamlies

More measurements...

$$\bar{F}_L^{D^*} = 0.60 \pm 0.08 \text{ (stat) } \pm 0.04 \text{ (syst)}$$

1.6σ discrepancy

[Belle '19]

$$\mathcal{R}_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18, \quad \mathcal{R}_{J/\psi}^{SM} \approx 0.25 - 0.28$$

before October!

$$\mathcal{P}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}, \quad \mathcal{P}_\tau^{D^*\text{SM}} = -0.497 \pm 0.013$$

...

Large experimental uncertainties

Current status of charged B anoamlies

More measurements...

$$\bar{F}_L^{D^*} = 0.60 \pm 0.08\ (\text{stat})\ \pm 0.04\ (\text{syst})$$ 1.6σ discrepancy

[Belle '19]

$$\mathcal{R}_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi \tau \bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi \mu \bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18, \quad \mathcal{R}_{J/\psi}^{SM} = 0.2582 \pm 0.0038$$

[2007.06956]

$$\mathcal{P}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}, \quad \mathcal{P}_\tau^{D^*\text{SM}} = -0.497 \pm 0.013$$

...

Large experimental uncertainties

Theoretical framework - Effective Hamiltonian

- Most general $SU(3)_C \otimes U(1)_Q$-invariant effective Hamiltonian at b scale, without light right-handed neutrinos

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[\left(1 + C_{LL}^V\right) \mathcal{O}_{LL}^V + C_{RL}^V \mathcal{O}_{RL}^V + C_{RL}^S \mathcal{O}_{RL}^S + C_{LL}^S \mathcal{O}_{LL}^S + C_{LL}^T \mathcal{O}_{LL}^T \Big] + \text{h.c.}.$$

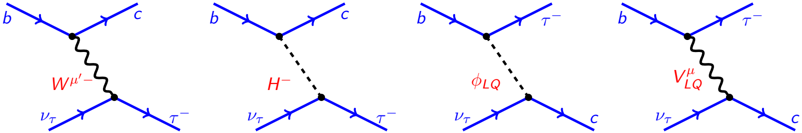
$$\mathcal{O}_{LL}^V = (\bar{c}_L \gamma^\mu b_L) \left(\bar{\ell}_L \gamma_\mu \nu_{\ell L}\right), \qquad \mathcal{O}_{RL}^V = (\bar{c}_R \gamma^\mu b_R) \left(\bar{\ell}_L \gamma_\mu \nu_{\ell L}\right),$$

$$\mathcal{O}_{RL}^S = (\bar{c}_L b_R) \left(\bar{\ell}_R \nu_{\ell L}\right), \qquad \mathcal{O}_{LL}^S = (\bar{c}_R b_L) \left(\bar{\ell}_R \nu_{\ell L}\right),$$

$$\mathcal{O}_{LL}^T = (\bar{c}_R \sigma^{\mu\nu} b_L) \left(\bar{\ell}_R \sigma_{\mu\nu} \nu_{\ell L}\right).$$

$$\boxed{C_{LL}^{V\,\text{SM}} = C_{RL}^{V\,\text{SM}} = C_{LL}^{S\,\text{SM}} = C_{RL}^{S\,\text{SM}} = C_{LL}^{T\,\text{SM}} = 0}$$

Theoretical framework - Effective Hamiltonian



C^V_{LL} $\quad$ $C^S_{LL}, C^S_{RL}, C^T_{LL}$ $\quad$ $C^V_{LL}, C^V_{RL}, C^T_{LL}$ $\quad$ C^V_{LL}, C^S_{RL}

Many analysis: usually with single operator/mediator and partial data information

[Freytsis et al, Bardhan et al, Cai et al, Hu et al, Celis et al, Datta et al, Bhattacharya et al, Alonso et al, . . .]

Theoretical framework - Assumptions

- NP contributions, $C_i \neq 0$, **only in the third generation of leptons**

  $\mathcal{B}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)/\mathcal{B}(\tau \to e\nu_\tau\bar{\nu}_e) \approx 1$
  analyses of $b \to c(e,\mu)\bar{\nu}_{(e,\mu)}$ transitions

- **EWSB is linearly relarized** $\to$ C_{RL}^V is flavour universal, i.e. $C_{RL}^V = 0$

  No new states up to 1 TeV
  Higgs couplings consistent with SM

- **CP-conserving**: all Wilson coefficients C_i are assumed to be real

Form Factors

- Heavy quark effective theory (HQET) parametrization
- Corrections of order α_s, $\Lambda_{\text{QCD}}/m_{b,c}$ and $\Lambda^2_{\text{QCD}}/m_c^2$
- Inputs from lattice QCD, light cone sum rules and QCD sum rules
- No experimental information used $\rightarrow$ FFs independent of NP scenario
- 10 form-factor parameters

$$\hat{h}(q^2) = h(q^2)/\xi(q^2)\,.$$

[M. Jung et. al '18, M. Bordrone et al, '19]

Form Factors

Parameter	Value	
ρ^2	1.32 ± 0.06	leading IW function
c	1.20 ± 0.12	leading IW function
d	-0.84 ± 0.17	leading IW function
$\chi_2(1)$	-0.058 ± 0.020	
$\chi_2'(1)$	0.001 ± 0.020	$\mathcal{O}(1/m_{b,c})$
$\chi_3'(1)$	0.036 ± 0.020	$\mathcal{O}(1/m_{b,c})$
$\eta(1)$	0.355 ± 0.040	$\mathcal{O}(1/m_{b,c})$
$\eta'(1)$	-0.03 ± 0.11	
$l_1(1)$	0.14 ± 0.23	$\mathcal{O}(1/m_c^2)$
$l_2(1)$	-2.00 ± 0.30	$\mathcal{O}(1/m_c^2)$

$$\xi(q^2) = 1 - 8\rho^2 z(q^2) + (64c - 16\rho^2)\, z^2(q^2) + (256c - 24\rho^2 + 512d) \ldots$$

Observables in the fit

$$
\begin{aligned}
\frac{d\Gamma(\bar{B} \to D\tau\bar{\nu}_\tau)}{dq^2} &= \frac{G_F^2 |V_{cb}|^2}{192\pi^3 m_B^3}\, q^2 \sqrt{\lambda_D(q^2)} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \\
&\times \Bigg\{ \left|1 + C_{LL}^V + C_{RL}^V\right|^2 \left[\left(1 + \frac{m_\tau^2}{2q^2}\right) H_{V,0}^{s,2} + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V,t}^{s2}\right] \\
&+ \frac{3}{2}\left|C_{RL}^S + C_{LL}^S\right|^2 H_S^s + 8\,|C_T|^2 \left(1 + \frac{2m_\tau^2}{q^2}\right) H_T^{s2} \\
&+ 3\,\mathcal{R}\mathrm{e}\left[\left(1 + C_{LL}^V + C_{RL}^V\right)\left(C_{RL}^S + C_{LL}^S\right)^*\right] \frac{m_\tau}{\sqrt{q^2}} H_S^s H_{V,t}^s \\
&- 12\,\mathcal{R}\mathrm{e}\left[\left(1 + C_{LL}^V + C_{RL}^V\right)\left(C_{LL}^T\right)^*\right] \frac{m_\tau}{\sqrt{q^2}} H_T^s H_{V,0}^s \Bigg\}
\end{aligned}
$$

vector contribution $C_V = 1 + C_{LL}^V + C_{RL}^V$
scalar contribution $C_S = C_{RL}^S + C_{LL}^S$

Observables in the fit

$$\frac{d\Gamma(\bar{B}\to D^*\tau\bar{\nu}_\tau)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3}\, q^2\sqrt{\lambda_{D^*}(q^2)}\left(1-\frac{m_\tau^2}{q^2}\right)^2$$

$$\times \left\{\left(\left|1+\left(C_{LL}^V\right)^2+\left|C_{RL}^V\right|\right|^2\right)\left[\left(1+\frac{m_\tau^2}{2q^2}\right)\left(H_{V,+}^2+H_{V,-}^2+H_{V,0}^2\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}H_{V,t}^2\right]\right.$$

$$-\ 2\,\mathcal{R}\mathrm{e}\left[\left(1+C_{LL}^V\right)\left(C_{RL}^V\right)^*\right]\left[\left(1+\frac{m_\tau^2}{2q^2}\right)\left(H_{V,0}^2+2H_{V,+}H_{V,-}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}H_{V,t}^2\right]$$

$$+\ \frac{3}{2}\left|C_{RL}^S-C_{LL}^S\right|^2 H_S^2 + 8\left|C_T\right|^2\left(1+\frac{2m_\tau^2}{q^2}\right)\left(H_{T,+}^2+H_{T,-}^2+H_{T,0}^2\right)$$

$$+\ 3\,\mathcal{R}\mathrm{e}\left[\left(1+C_{LL}^V-C_{RL}^V\right)\left(C_{RL}^S-C_{LL}^S\right)^*\right]\frac{m_\tau}{\sqrt{q^2}}H_S H_{V,t}$$

$$-\ 12\,\mathcal{R}\mathrm{e}\left[\left(1+C_{LL}^V\right)\left(C_{LL}^T\right)^*\right]\frac{m_\tau}{\sqrt{q^2}}\left(H_{T,0}H_{V,0}+H_{T,+}H_{V,+}-H_{T,-}H_{V,-}\right)$$

$$\left.+\ 12\,\mathcal{R}\mathrm{e}\left[C_{RL}^V\left(C_{LL}^T\right)^*\right]\frac{m_\tau}{\sqrt{q^2}}\left(H_{T,0}H_{V,0}+H_{T,+}H_{V,-}-H_{T,-}H_{V,+}\right)\right\}$$

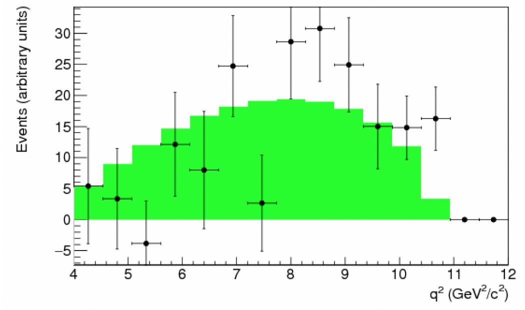
"almost" axial contribution $C_A = C_{RL}^V - (1 + C_{LL}^V)$

pseudoscalar contribution $C_P = C_{RL}^S - C_{LL}^S$

Observables in the fit

Observables included in the fit:

- The ratios $\mathcal{R}_{D^{(*)}}$
- Differential distributions of the decay rates $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
- The longitudinal polarization fraction $\bar{F}_L^{D^*}$



[Belle '15]

Observables in the fit

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- The ratios $\mathcal{R}_{D^{(*)}}$
- Differential distributions of the decay rates $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
- The longitudinal polarization fraction $\bar{F}_L^{D^*}$

$$F_L^{D^*}(q^2) = \frac{d\Gamma_{\lambda_{D^*}=0}}{dq^2} \bigg/ \frac{d\Gamma^{D^*}}{dq^2}$$

Theoretical framework - Observables in the fit

- The leptonic decay rate $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10(30)\%$

$$\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) = \tau_{B_c} \frac{m_{B_c} m_\tau^2 f_{B_c}^2 G_F^2 |V_{cb}|^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \times \left| (1 + C_{LL}^V) - C_{RL}^V + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} (C_{RL}^S - C_{LL}^S) \right|^2$$

$\mathcal{B} < 10\%$ LEP data at the Z peak
$\mathcal{B} < 30\%$ B_c lifetime

See also
M. Blanke et. al '18
for further discussion

Fit

$$\chi^2 = \chi^2_{\rm exp} + \chi^2_{\rm FF}$$

$\chi^2_{\rm exp} \rightarrow$ experimental contributions: 2 + 58 + 1 observables

$\chi^2_{\rm FF} \rightarrow$ 10 form factors

$$\chi^2(y_i) = F(y_i)^T V^{-1} F(y_i), \quad F(y_i) = f_{\rm th}(y_i) - f_{\rm exp}, \quad V_{ij} = \rho_{ij}\sigma_i\sigma_j$$

$y_i \rightarrow$ input parameters of the fit
$\rho_{ij} \rightarrow$ correlation between observable i and j
$\sigma_i \rightarrow$ uncertainity of observable i
Δy_i : determined minimizing $\chi^2|_{y_i^{\rm min}+\Delta y_i}$ varying all parameters that increase $\Delta\chi^2 = 1$

SM fit

- SM fit, $C_i = 0$

$$\chi^2_{\text{min}}/\text{d.o.f.} = 65.5/57 \rightarrow \text{ CL of } \sim 20\%$$

- Uncertainties in $\text{d}\Gamma/\text{d}q^2$ maximally conservative

$$\chi^2_{\text{min},d\Gamma}/\text{d.o.f.} \sim 43/54$$

- $\mathcal{R}_D$ and $\mathcal{R}_{D^*}$

$$\chi^2/\text{d.o.f} = 22.6/2 \rightarrow 4.4\sigma\text{-tension}$$

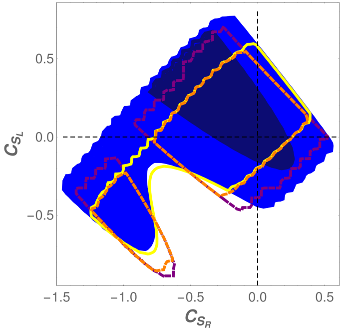
→ NP scenarios judged by the improvement when compared to the SM

Fit and results

- Always two minima with degenerate χ^2

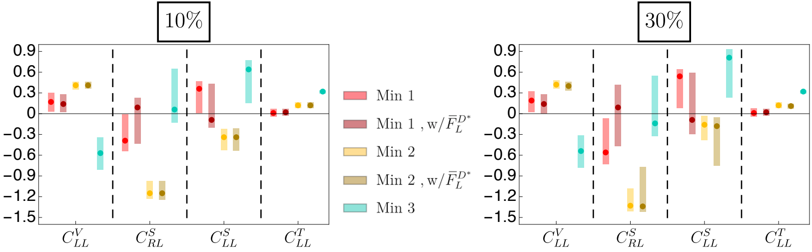
$$C_{LL}^{V'} = -2 - C_{LL}^{V} \quad \text{and} \quad C_i' = -C_i \quad \text{for} \quad i = {}^{S}_{RL},\ {}^{S}_{LL},\ {}^{T}_{LL}.$$

- Distributions highly non-gaussian



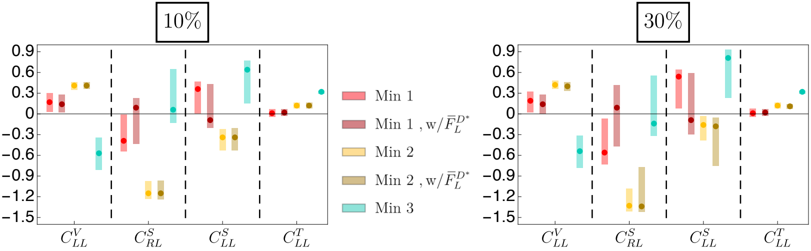
Example of the correlation between two Wilson coefficients ($C_{RL}^S - C_{LL}^S$). Blue areas (lighter 95% and darker 68% CL) minima without $\bar{F}_L^{D^*}$ and $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$.

Fit and results



	Min 1	Min 2	Min 3	Min 1	Min 2	Min 3
$\mathcal{B}(B_c \to \tau\nu)$		10%			30%	
$\chi^2_{\rm min}$/d.o.f.	34.1/53	37.5/53	58.6/53	33.8/53	36.6/53	58.4/53
C_{LL}^V	$0.17^{+0.13}_{-0.14}$	$0.41^{+0.05}_{-0.06}$	$-0.57^{+0.23}_{-0.24}$	$0.19^{+0.13}_{-0.17}$	$0.42^{+0.06}_{-0.06}$	$-0.54^{+0.23}_{-0.24}$
C_{RL}^S	$-0.39^{+0.38}_{-0.15}$	$-1.15^{+0.18}_{-0.08}$	$0.06^{+0.59}_{-0.19}$	$-0.56^{+0.49}_{-0.17}$	$-1.33^{+0.25}_{-0.08}$	$-0.14^{+0.69}_{-0.18}$
C_{LL}^S	$0.36^{+0.11}_{-0.35}$	$-0.34^{+0.12}_{-0.19}$	$0.64^{+0.13}_{-0.49}$	$0.54^{+0.10}_{-0.46}$	$-0.16^{+0.13}_{-0.22}$	$0.81^{+0.12}_{-0.58}$
C_{LL}^T	$0.01^{+0.06}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$0.32^{+0.02}_{-0.03}$	$0.01^{+0.07}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$0.32^{+0.02}_{-0.03}$

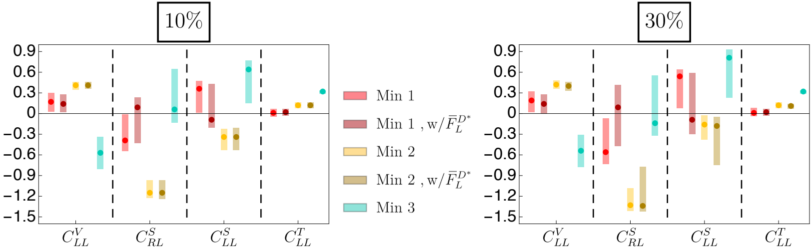
Fit and results



Fits **without** $\bar{F}_L^{D^*}$

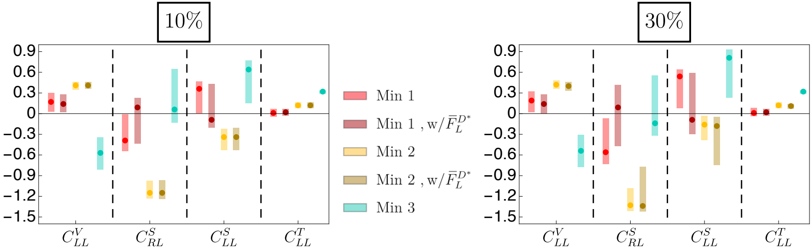
- One global minimum (34.1/53) and two local minima (37.5/53 and 58.6/53)

Fit and results



- Strong preference for New Physics: $\chi^2_{\text{SM}} - \chi^2 = 31.4$
- All minima saturate the constraint $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\,(30)\%$
- Complex C_i do not improve the χ^2, but open to many solutions

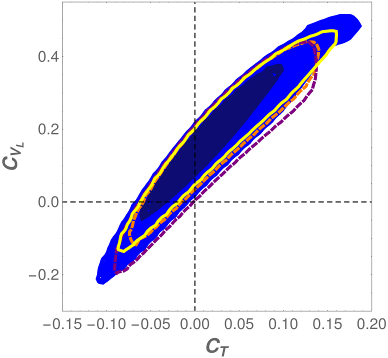
Fit and results



Global minimum (34.1/53)

- No absolute preference of a single Wilson coefficient
- Compatible with a global modification of the SM: adding C^V_{LL}: $\Delta\chi^2 = 1.4$

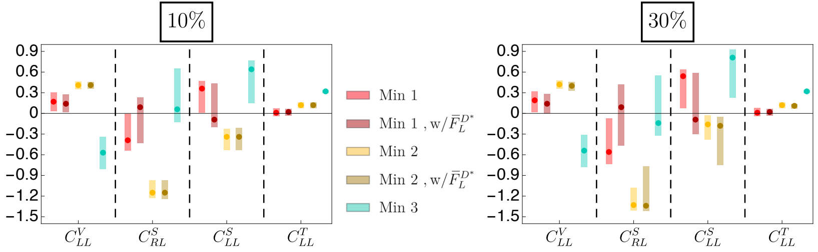
Fit and results



Global minimum (34.1/53)

- Requires either C_{LL}^{V} or C_{LL}^{T}

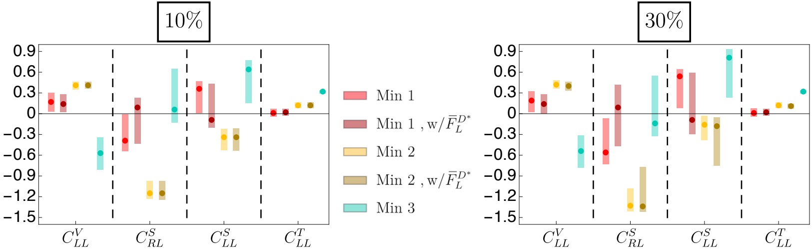
Fit and results



Local minima (Min 2 → 37.5/53 and Min 3 → 58.6/53)

- Further away from the SM and involves sizeable Wilson coefficients
- Min 2 fits slightly worse $\mathcal{R}_{D^*}$ and q^2 distributions
- Min 3 fits $\mathcal{R}_{D^*}$ perfectly disfavoured by q^2 distributions

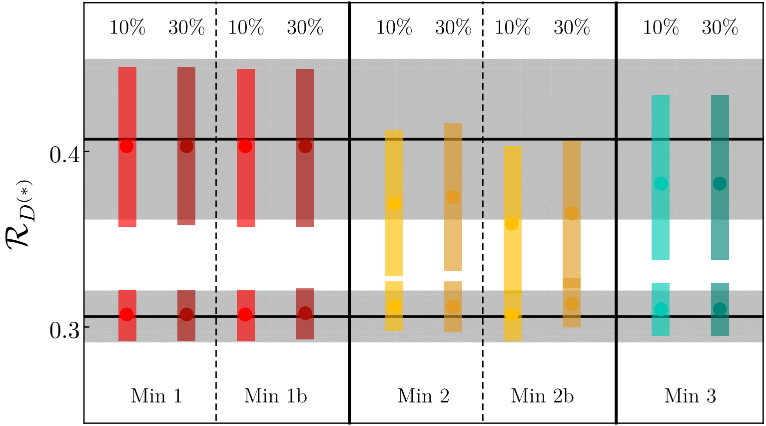
Fit and results



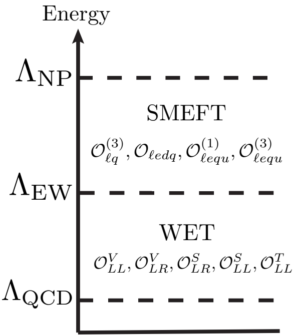
Adding $\bar{F}_L^{D^*}$

- Still no clear preference for a single coefficient
- Central values smaller, while 1σ regions almost constant
- Min 3 disappears

Fit and results



New Physics



$$
\begin{aligned}
C_{LL}^{V}(\mu_b) &= -1.503\, \tilde{C}_{LL}^{V}(\Lambda)\,, \\
C_{LL}^{S}(\mu_b) &= -1.257\, \tilde{C}_{LL}^{S}(\Lambda) + 0.2076\, \tilde{C}_{LL}^{T}(\Lambda)\,, \\
C_{RL}^{S}(\mu_b) &= -1.254\, \tilde{C}_{RL}^{S}(\Lambda)\,, \\
C_{LL}^{T}(\mu_b) &= 0.002725\, \tilde{C}_{LL}^{S}(\Lambda) - 0.6059\, \tilde{C}_{LL}^{T}(\Lambda)\,.
\end{aligned}
$$

$\mu_b = 5$ GeV

$\Lambda = 1$ TeV

New Physics

Spin	Q.N.	Nature	Allowed couplings	SMEFT	WET
0	$S_1 \sim (\bar{3}, 1, 1/3)$	LQ	$\overline{q_L^c}\ell_L$, $\overline{d_R}u_R^c$, $\overline{u_R^c}e_R$	$\tilde{C}_{LL}^V$, $\tilde{C}_{LL}^S$, $\tilde{C}_{LL}^T$	C_{LL}^V, C_{LL}^S, C_{LL}^T
0	$S_3 \sim (\bar{3}, 3, 1/3)$	LQ	$\overline{q_L^c}\ell_L$	$\tilde{C}_{LL}^V$	C_{LL}^V
0	$R_2 \sim (3, 2, 7/6)$	LQ	$\overline{u_R}\ell_L$, $\overline{q_L}e_R$	$\tilde{C}_{LL}^S$, $\tilde{C}_{LL}^T$	C_{LL}^S, C_{LL}^T
0	$H_2 \sim (1, 2, 1/2)$	SB	$\overline{q_L}d_R$, $\overline{\ell_L}e_R$, $\overline{u_R}q_L$	$\tilde{C}_{RL}^S$, $\tilde{C}_{LL}^S$	C_{RL}^S, C_{LL}^S, C_{LL}^T
1	$V_2 \sim (\bar{3}, 2, 5/6)$	LQ	$\overline{d_R^c}\gamma_\mu\ell_L$, $\overline{e_R^c}\gamma_\mu q_L$	$\tilde{C}_{RL}^S$	C_{RL}^S
1	$U_1 \sim (3, 1, 2/3)$	LQ	$\overline{q_L}\gamma_\mu\ell_L$, $\overline{d_R}\gamma_\mu e_R$	$\tilde{C}_{LL}^V$, $\tilde{C}_{RL}^S$	C_{LL}^V, C_{RL}^S
1	$U_3 \sim (3, 3, 2/3)$	LQ	$\overline{q_L}\gamma_\mu\ell_L$	$\tilde{C}_{LL}^V$	C_{LL}^V
1	$W'_\mu \sim (1, 3, 0)$	VB	$\overline{\ell_L}\gamma_\mu\ell_L$, $\overline{q_L}\gamma_\mu q_L$	$\tilde{C}_{LL}^V$	C_{LL}^V

New Physics

Global minimum

$$\mathbf{C_{LL}^V} = \mathbf{0.17^{+0.13}_{-0.14}}, \qquad C_{RL}^S = -0.39^{+0.38}_{-0.15},$$
$$C_{LL}^S = 0.36^{+0.11}_{-0.35}, \qquad C_{LL}^T = 0.01^{+0.06}_{-0.05}.$$

$$\boxed{W'_\mu \sim (1,3,0)}$$

$$\mathcal{L}_{\text{eff}} \supset -\frac{\tilde{g}_{\ell\nu_\ell}\tilde{g}^\dagger_{du}}{M^2_{W'}} (\bar{\ell}_L\gamma_\mu\nu_{\ell L})(\bar{u}_L\gamma^\mu d_L),$$

$$\frac{M_{W'}}{\left(\tilde{g}_{\ell\nu_\ell}\tilde{g}^\dagger_{du}\right)^{1/2}} \sim 2 \text{ TeV} \xrightarrow[\text{with SM couplings}]{\text{sequential } W'} M_{W'} \sim 0.2 \text{ TeV}$$

ruled out by DS

$$\boxed{U_3 \sim (3,3,1/3),\ S_3 \sim (\bar{3},3,1/3)}$$

New Physics

Min 2

$$\mathbf{C^{V}_{LL}} = 0.41^{+0.05}_{-0.06}, \qquad \mathbf{C^{S}_{RL}} = -1.15^{+0.18}_{-0.08},$$
$$\mathbf{C^{S}_{LL}} = -0.34^{+0.12}_{-0.19}, \qquad \mathbf{C^{T}_{LL}} = 0.12^{+0.04}_{-0.04}.$$

$$\boxed{S_1 \sim (\bar{3}, 1, 1/3) + H_2 \sim (1, 2, 1/3)}$$

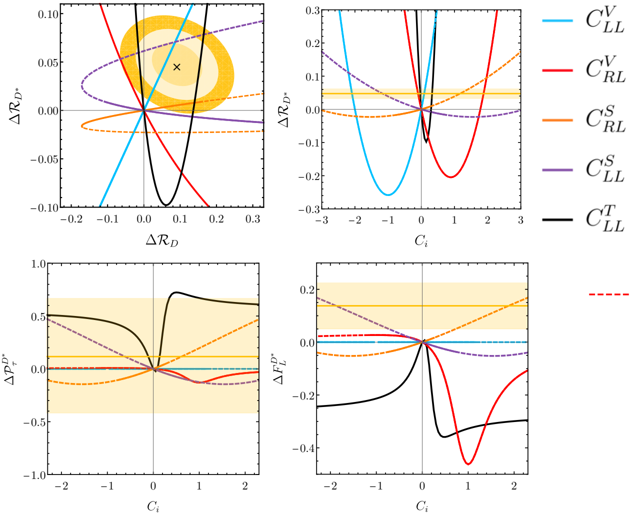
Min 3

$$C^{V}_{LL} = -0.57^{+0.23}_{-0.24}, \qquad C^{S}_{RL} = 0.06^{+0.59}_{-0.19},$$
$$\mathbf{C^{S}_{LL}} = 0.64^{+0.13}_{-0.49}, \qquad \mathbf{C^{T}_{LL}} = 0.32^{+0.02}_{-0.03}.$$

$$\boxed{R_2 \sim (3, 2, 7/6), S_1 \sim (\bar{3}, 1, 1/3)}$$

[A. Angelescue. al '18]

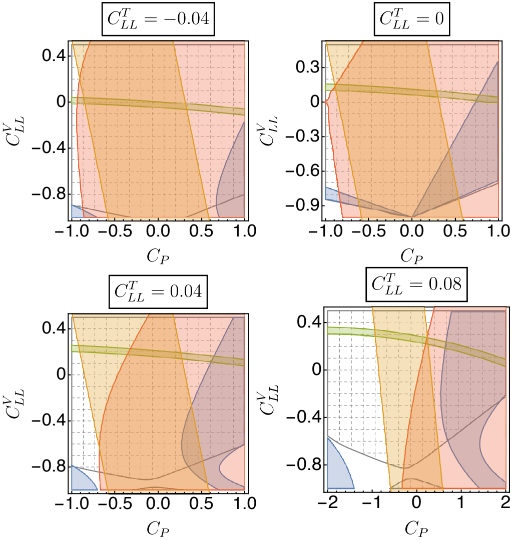
Interpretation of results



Excluded by $\mathcal{B}(B_c \to \tau\nu) \leq 10\%$

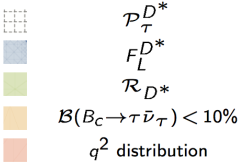
$$\Delta X \equiv X - X_{SM}$$

Interpretation of results



$$\mathbf{C_P \equiv C^S_{RL} - C^S_{LL}}$$

D^* observables = f(C^V_{LL}, C_P, C_T)



It is not possible to accommodate all D^* data at 1σ

Interpretation of results

Not possible to accommodate all experimental data at 1σ

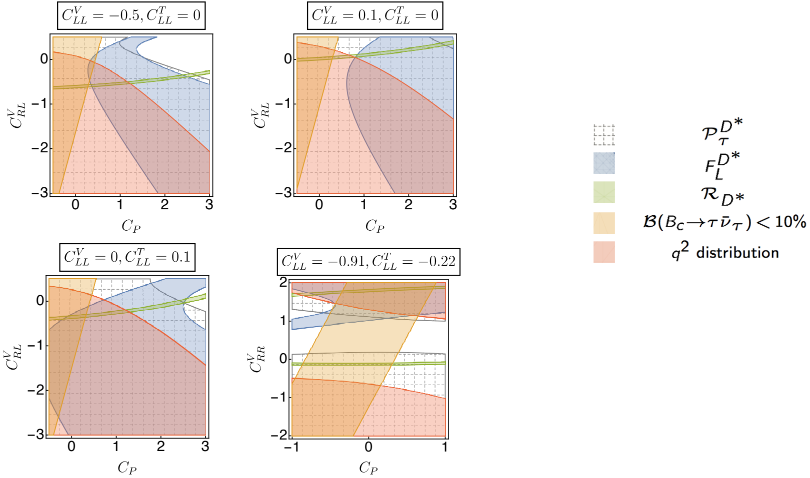
- **Theory side**: one of our assumptions is incorrect
  - There is an insufficient gap between the electroweak and the NP scale
  - The electroweak symmetry breaking is non-linear: C_{RL}^V
  - Additional degrees of freedom: light ν_R...
- **Experimental side**: there is an unidentified or underestimated systematic uncertainty in experimental measurements

Interpretation of results

Not possible to accommodate all experimental data at 1σ

- **Theory side**: one of our assumptions is incorrect
    - There is an insufficient gap between the electroweak and the NP scale
    - The electroweak symmetry breaking is non-linear: C_{RL}^{V}
    - Additional degrees of freedom: light ν_R...
- **Experimental side**: there is an unidentified or underestimated systematic uncertainty in experimental measurements $\rightarrow$ upcoming experimental studies of LHCb and Belle II

Adding C^V_{RL}



$C^V_{LL} = -0.5, C^T_{LL} = 0$
$C^V_{LL} = 0.1, C^T_{LL} = 0$
$C^V_{LL} = 0, C^T_{LL} = 0.1$
$C^V_{LL} = -0.91, C^T_{LL} = -0.22$
C^V_{RL}
C^V_{RR}
C_P
$\mathcal{P}_\tau^{D^*}$
$F_L^{D^*}$
$\mathcal{R}_{D^*}$
$\mathcal{B}(B_c \to \tau \bar{\nu}_\tau) < 10\%$
q^2 distribution

Adding C_{RL}^V

	Min 4	Min 5	Min 6	Min 7
$\chi^2_{\text{min}}/\text{d.o.f.}$	32.5/53	33.3/53	37.6/53	38.9/53
C_{LL}^V	$-0.91^{+0.10}_{-0.09}$	$-0.85^{+0.20}_{-0.10}$	$0.14^{+0.14}_{-0.12}$	$0.35^{+0.08}_{-0.08}$
C_{RL}^V	$1.89^{+0.19}_{-0.22}$	$-1.58^{+0.23}_{-0.22}$	$0.02^{+0.21}_{-0.24}$	$0.34^{+0.18}_{-0.18}$
C_{RL}^S	$-0.44^{+0.12}_{-0.45}$	$-0.33^{+0.52}_{-0.16}$	$0.10^{+0.15}_{-0.59}$	$-0.68^{+0.54}_{-0.14}$
C_{LL}^S	$-1.34^{+0.49}_{-0.12}$	$0.56^{+0.23}_{-0.54}$	$-0.12^{+0.65}_{-0.15}$	$-0.92^{+0.58}_{-0.11}$
C_{LL}^T	$-0.22^{+0.10}_{-0.11}$	$0.19^{+0.10}_{-0.10}$	$0.01^{+0.09}_{-0.07}$	$-0.02^{+0.08}_{-0.07}$

- Including C_{RL}^V slightly improves the fit $\chi^2/\text{d.o.f.} = 32.5/55$
- Global minimum $\rightarrow$ Min 6
- Two fine-tuned solutions (Min 4 and Min 5): $1 + C_{LL}^V \approx 0$

Including $\boldsymbol{\nu_R}$

$$\mathcal{H}_{\rm eff} = \frac{4 G_F V_{cb}}{\sqrt{2}} \left(\mathcal{O}_{LL}^V + \sum_{\substack{X=S,V,T \\ A,B=L,R}} C_{AB}^X \mathcal{O}_{AB}^X \right),$$

5 Wilson operators → 10 Wilson operators
→ difficult to fit all at the same time
→ focus on scenarios

$\bar{\mathcal{P}}_\tau^{D^*}$ included in the fits

Spin	Q.N.	Nature	ν_L-WET	N_R-WET
0	$S_1 \sim (\bar{3}, 1, 1/3)$	LQ	C_{LL}^V, C_{LL}^S, C_{LL}^T	C_{RR}^V, C_{RR}^S, C_{RR}^T
0	$\Phi \sim (1, 2, 1/2)$	SB	C_{LL}^S, C_{RL}^S	C_{LR}^S, C_{RR}^S
0	$\tilde{R}_2 \sim (3, 2, 1/6)$	LQ	-	C_{RR}^S, C_{RR}^T
1	$U_1^\mu \sim (3, 1, 2/3)$	LQ	C_{LL}^V, C_{RL}^S	C_{RR}^V, C_{LR}^S
1	$\tilde{V}_2^\mu \sim (\bar{3}, 2, -1/6)$	LQ	-	C_{LR}^S
1	$V^\mu \sim (1, 1, -1)$	VB	-	C_{RR}^V

Scenarios

1) RHN + SM-like contribution:
   $\mathcal{O}^V_{LL}\,,\mathcal{O}^V_{LR}\,,\mathcal{O}^V_{RR}\,,\mathcal{O}^S_{LR}\,,\mathcal{O}^S_{RR}\,,\mathcal{O}^T_{RR}\,,$
2) RHN: $\mathcal{O}^V_{LR}\,,\mathcal{O}^V_{RR}\,,\mathcal{O}^S_{LR}\,,\mathcal{O}^S_{RR}\,,\mathcal{O}^T_{RR}\,,$
3) V^μ: $\mathcal{O}^V_{RR}\,,$

4a) Φ: $\mathcal{O}^S_{LR}\,,\mathcal{O}^S_{RR}$ (b) $+\ \mathcal{O}^S_{LL}\,,\mathcal{O}^S_{RL}$

5a) U^μ_1: $\mathcal{O}^V_{RR}\,,\mathcal{O}^S_{LR}\,,$ (b) $+\ \mathcal{O}^V_{RL}\,,\mathcal{O}^S_{LL}$

6) $\tilde{R}_2$: $\mathcal{O}^S_{RR}\,,\mathcal{O}^T_{RR}$ with $C^S_{RR} = 4r\,C^T_{RR}\,,$

7a) S_1: $\mathcal{O}^V_{RR}\,,\mathcal{O}^S_{RR}\,,\mathcal{O}^T_{RR}$ (b)$+\ \mathcal{O}^V_{LL}\,,\mathcal{O}^S_{LL}\,,\mathcal{O}^T_{LL}$ with
   $C^S_{RR} = -4r\,C^T_{RR}\,,$ (b) and $C^S_{LL} = -4r\,C^T_{LL}$

8) $\tilde{V}^\mu_2$: $\mathcal{O}^S_{LR}\,.$

Quality of the fits

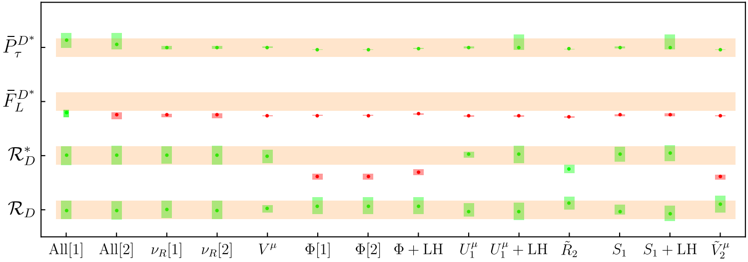
To measure the quality of our fits:

- Comparison with the SM: $\chi^2_{\text{SM}}/\text{d.o.f.} = 52.87/59$
- p-value: Larger p-values correspond to better explanations of the experimental data than lower ones

$$p(\chi^2_{\text{min}}, n) \equiv \int_{\chi^2_{\text{min}}}^{\infty} dz\, \chi^2(z, n) \quad \chi^2(z, n)$$

- Pull_{SM}: Compares any fitted solution with the SM results. Larger pulls $\rightarrow$ further from the SM
- Comparison with experimental data

Fit results



Scenario	$\mathcal{B}(B_c \to \tau\bar{\nu})$	χ^2/d.o.f	Pull$_{SM}$			Pull$_{SM}$	p-value
			$\bar{\mathcal{P}}_\tau^{D^*}$, $\bar{F}_L^{D^*}$	$\mathcal{R}_{D,D^*}$	$d\Gamma/dq^2$		
SM	2.16%	52.87/59					69.95%
Scenario 1, Min 1	$< 10\%$	37.26/53	0.007	2.08	0.0414	2.4	95.02%
Scenario 1, Min 2	$< 10\%$	38.86/53	0.001	2.08	0.0006	2.2	92.68%
Scenario 1, Min 1	$< 30\%$	36.42/53	0.022	2.08	0.0866	2.5	96.00%
Scenario 1, Min 2	$< 30\%$	38.54/53	0.011	2.08	0.000	2.2	93.21%
Scenario 2, Min 1	$< 10\%$	38.54/54	0.006	2.32	0.0113	2.5	93.20%
Scenario 2, Min 2	$< 10\%$	39.05/54	0.004	2.32	0.0003	2.4	93.73%
Scenario 2, Min 1	$< 30\%$	38.33/54	0.035	2.32	0.0023	2.5	94.73%
...	...	...	...	...	...	...	..

Fit results (RHN)

- Difficulty to reproduce longitudinal D^* polarization
- Scenarios involving only scalar (and tensor) operators can't reproduce $\mathcal{R}_{D^*}^{\text{exp}}$ (largest χ^2 value)
- Some scenarios disfavoured by the q^2 differential distributions of the $B \to D^{(*)}$ decay with respect to the SM (Pull$_{\text{SM}}$)
- Clear preference for NP (pulls 1.2 – 3.7)
- V^μ mediator (only C_{RR}^V) $\to$ similar to fit without RHN (C_{LL}^V) (largest pull)

Fit results (RHN)

Scenario	$\mathcal{B}(B_c \to \tau\bar{\nu})$	$\mathcal{R}_D$	$\mathcal{R}_{D^*}$	$\bar{F}_L^{D^*}$	$\bar{\mathcal{P}}_\tau^{D^*}$
Experiment	-	$0.340 \pm 0.027 \pm 0.013$	$0.295 \pm 0.011 \pm 0.008$	$0.60 \pm 0.08 \pm 0.04$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$
Scenario 1, Min 1	10%	0.339 ± 0.030 ✓	0.295 ± 0.014 ✓	$0.494^{+0.025}_{-0.045}$ ✓	$0.06^{+0.43}_{-0.45}$ ✓
Scenario 1, Min 2	10%	0.338 ± 0.030 ✓	0.296 ± 0.014 ✓	$0.472^{+0.023}_{-0.044}$ ✗	$-0.20^{+0.67}_{-0.30}$ ✓
Scenario 1, Min 1	30%	0.338 ± 0.030 ✓	0.295 ± 0.014 ✓	$0.510^{+0.014}_{-0.043}$ ✓	$0.08^{+0.32}_{-0.46}$ ✓
Scenario 1, Min 2	30%	0.338 ± 0.030 ✓	0.296 ± 0.014 ✓	$0.488^{+0.032}_{-0.050}$ ✓	$-0.24^{+0.64}_{-0.28}$ ✓
Scenario 2, Min 1	10%	$0.341^{+0.029}_{-0.028}$ ✓	0.296 ± 0.013 ✓	$0.474^{+0.010}_{-0.024}$ ✗	$-0.42^{+0.13}_{-0.07}$ ✓
Scenario 2, Min 2	10%	0.339 ± 0.030 ✓	0.296 ± 0.014 ✓	$0.471^{+0.012}_{-0.033}$ ✗	$-0.401^{+0.094}_{-0.064}$ ✓
Scenario 2, Min 1	30%	$0.341^{+0.029}_{-0.028}$ ✓	0.296 ± 0.013 ✓	$0.489^{+0.011}_{-0.048}$ ✗	$-0.47^{+0.15}_{-0.05}$ ✓
Scenario 2, Min 2	30%	0.340 ± 0.030 ✓	0.295 ± 0.014 ✓	$0.484^{+0.015}_{-0.045}$ ✗	$-0.45^{+0.13}_{-0.07}$ ✓
Scenario 3	2.5%	0.343 ± 0.012 ✓	0.294 ± 0.010 ✓	0.462 ± 0.004 ✗	$-0.377^{+0.031}_{-0.033}$ ✓
Scenario 4a, Min 1	10%	$0.353^{+0.028}_{-0.027}$ ✓	$0.2638^{+0.0034}_{-0.0049}$ ✗	$0.4662^{+0.0039}_{-0.0057}$ ✗	$-0.5028^{+0.0051}_{-0.0035}$ ✓
Scenario 4a, Min 2	10%	$0.353^{+0.028}_{-0.027}$ ✓	$0.2638^{+0.0034}_{-0.0049}$ ✗	$0.4662^{+0.0039}_{-0.0057}$ ✗	$-0.5028^{+0.0051}_{-0.0034}$ ✓
Scenario 4a, Min 1	30%	$0.348^{+0.028}_{-0.027}$ ✓	$0.2699^{+0.0032}_{-0.0058}$ ✗	$0.4792^{+0.0041}_{-0.0064}$ ✗	$-0.5144^{+0.0056}_{-0.0032}$ ✓
Scenario 4a, Min 2	30%	$0.348^{+0.028}_{-0.027}$ ✓	$0.2699^{+0.0032}_{-0.0058}$ ✗	$0.4792^{+0.0041}_{-0.0064}$ ✗	$-0.5144^{+0.0056}_{-0.0032}$ ✓
Scenario 4b	10%	0.353 ± 0.028 ✓	$0.2708^{+0.0032}_{-0.0052}$ ✗	$0.4815^{+0.0041}_{-0.0068}$ ✗	$-0.442^{+0.005}_{-0.026}$ ✓
Scenario 4b	30%	0.340 ± 0.028 ✓	$0.2866^{+0.0030}_{-0.0081}$ ✓	$0.5125^{+0.0044}_{-0.0126}$ ✓	$-0.356^{+0.006}_{-0.066}$ ✓
Scenario 5a	2.2%	$0.335^{+0.027}_{-0.017}$ ✓	$0.2966^{+0.0043}_{-0.0042}$ ✓	$0.4611^{+0.0056}_{-0.0070}$ ✗	$-0.364^{+0.048}_{-0.050}$ ✓
Scenario 5b	2.0%	0.334 ± 0.029 ✓	0.297 ± 0.013 ✓	$0.4609^{+0.0059}_{-0.0083}$ ✗	$-0.38^{+0.77}_{-0.16}$ ✓
Scenario 6	7.6%	$0.361^{+0.022}_{-0.021}$ ✓	$0.2748^{+0.0066}_{-0.0059}$ ✓	0.4522 ± 0.0050 ✗	$-0.4800^{+0.0078}_{-0.0076}$ ✓
Scenario 7a	4.6%	$0.335^{+0.021}_{-0.011}$ ✓	0.297 ± 0.011 ✓	$0.468^{+0.007}_{-0.011}$ ✗	$-0.377^{+0.033}_{-0.058}$ ✓
Scenario 7b	4.3%	$0.328^{+0.026}_{-0.025}$ ✓	0.299 ± 0.012 ✓	$0.471^{+0.014}_{-0.013}$ ✗	$-0.38^{+0.77}_{-0.12}$ ✓
Scenario 8	7.3%	$0.359^{+0.028}_{-0.027}$ ✓	0.2629 ± 0.0036 ✗	0.4644 ± 0.0043 ✗	-0.5012 ± 0.0039 ✓

Fit results (RHN)

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- Scenarios involving only scalar (and tensor) operators can't reproduce $\mathcal{R}_{D^*}^{\text{exp}}$ (largest χ^2 value)
- Some scenarios disfavoured by the q^2 differential distributions of the $B \to D^{(*)}$ decay with respect to the SM (Pull_{SM})
- Clear preference for NP (pulls $1.2 - 3.7$)
- V^μ mediator (only C_{RR}^V) $\to$ similar to fit without RHN (C_{LL}^V) (largest pull)

Fit results (RHN)

Scenario	$\mathcal{B}(B_c \to \tau\bar{\nu})$	χ^2/d.o.f	Pull$_{SM}$ $\bar{\mathcal{P}}_\tau^{D^*}$, $F_L^{D^*}$	Pull$_{SM}$ $\mathcal{R}_{D,D^*}$	Pull$_{SM}$ $d\Gamma/dq^2$	Pull$_{SM}$	p-value
SM	2.16%	52.87/59					69.95%
Scenario 1, Min 1	$< 10\%$	37.26/53	0.007	2.08	0.0414	2.4	95.02%
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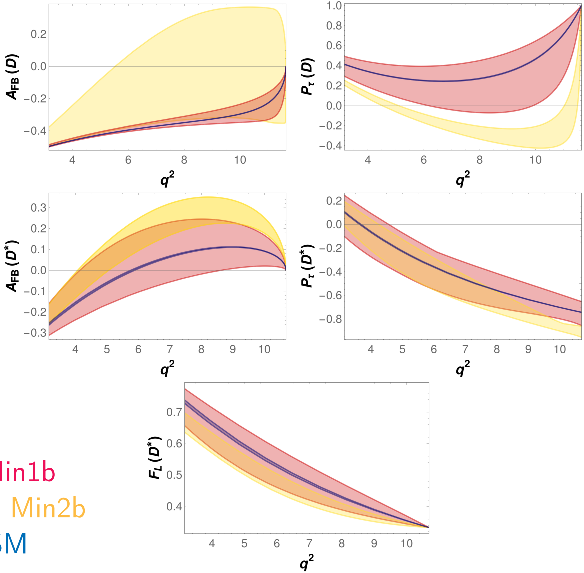
Scenario 1, Min 1	$< 30\%$	36.42/53	0.022	2.08	0.0866	2.5	96.00%
Scenario 1, Min 2	$< 30\%$	38.54/53	0.011	2.08	0.000	2.2	93.21%
Scenario 2, Min 1	$< 10\%$	38.54/54	0.006	2.32	0.0113	2.5	93.20%
Scenario 2, Min 2	$< 10\%$	39.05/54	0.004	2.32	0.0003	2.4	93.73%
Scenario 2, Min 1	$< 30\%$	38.33/54	0.035	2.32	0.0023	2.5	94.73%
Scenario 2, Min 2	$< 30\%$	38.80/54	0.025	2.32	0^*	2.4	94.09%
Scenario 3	$< 10\%$	39.50/58	0.150	3.65	0.0835	3.7	97.00%
Scenario 4a, Min 1	$< 10\%$	49.93/57	0.079	2.34	0^*	1.2	73.52%
Scenario 4a, Min 2	$< 10\%$	49.93/57	0.079	2.34	0^*	1.2	73.52%
Scenario 4a, Min 1	$< 30\%$	44.49/57	0.311	2.66	0^*	2.4	88.62%
Scenario 4a, Min 2	$< 30\%$	44.49/57	0.311	2.66	0^*	2.4	88.62%
Scenario 4b	$< 10\%$	43.56/55	0.054	2.07	0^*	1.9	86.70%
Scenario 4b	$< 30\%$	40.03/55	0.218	2.52	0^*	2.5	93.54%
Scenario 5a	$< 10\%$	39.39/57	0^*	3.22	0.0981	3.2	96.36%
Scenario 5b	$< 10\%$	39.37/55	0^*	3.34	0.0060	2.6	94.47%
Scenario 6	$< 10\%$	44.20/58	0^*	3.34	0^*	2.9	90.93%
Scenario 7a	$< 10\%$	39.21/57	0.126	3.22	0.0616	3.3	96.53%
Scenario 7b	$< 10\%$	39.06/55	0.014	2.56	0.0112	2.7	94.87%
Scenario 8	$< 10\%$	47.32/57	0.259	2.56	0^*	1.9	81.60%

Fit results (RHN)

- Scenarios with several operators: best fits correspond to solutions where all Wilson coefficients but one (*i.e.* C_{RR}^V) are compatible with zero
- Preference for solutions with all left-handed Wilson coefficients compatible with zero within 1σ
- Preferred solutions: V^μ, S_1, U_1^μ (cannot explain $\bar{F}_L^{D^*}$)
- Only RHN + SM and Φ with $\mathcal{B}(B_c \to \tau\nu) < 30\%$ can explain $\bar{F}_L^{D^*}$

Predictions for $B \to D^{(*)}\tau\bar{\nu}_\tau$ observables

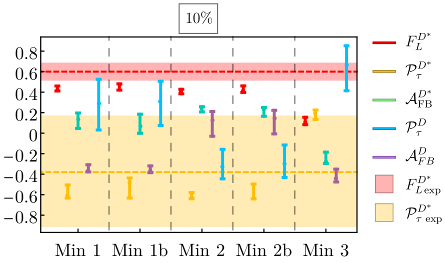


Red → Min1b

Yellow → Min2b

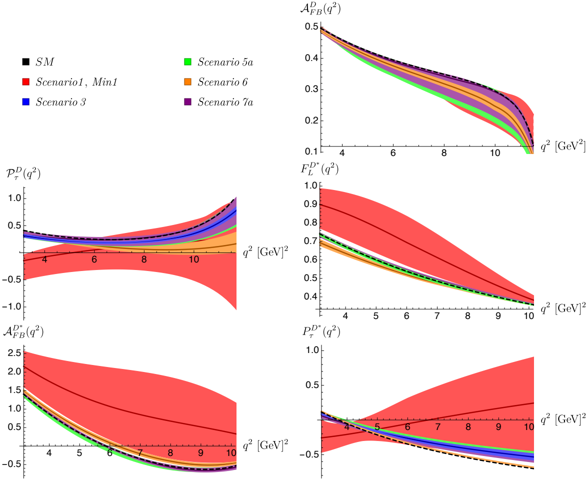
Blue → SM

Predictions for $B \to D^{(*)}\tau\bar{\nu}_\tau$ observables



$$\mathcal{R}_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell)} .$$

Other predictions

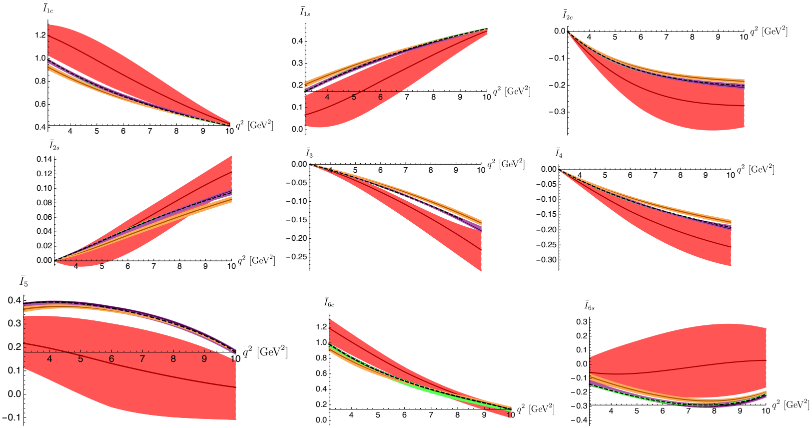


Other predictions

$$
\begin{aligned}
\frac{d^4\Gamma(B \to D^*\tau\bar{\nu})}{dq^2\, d\cos\theta_\tau\, d\cos\theta_D\, d\phi} &\equiv I(q^2, \theta_\tau, \theta_D, \phi) \\
&= \frac{9}{32\pi} \Big\{ I_1^s \sin^2\theta_D + I_1^c \cos^2\theta_D \\
&\quad + \left(I_2^s \sin^2\theta_D + I_2^c \cos^2\theta_D\right) \cos 2\theta_\tau \\
&\quad + \left(I_3 \cos 2\phi + I_9 \sin 2\phi\right) \sin^2\theta_D \sin^2\theta_\tau \\
&\quad + \left(I_4 \cos\phi + I_8 \sin\phi\right) \sin 2\theta_D \sin 2\theta_\tau \\
&\quad + \left(I_5 \cos\phi + I_7 \sin\phi\right) \sin 2\theta_D \sin\theta_\tau \\
&\quad + \left(I_6^s \sin^2\theta_D + I_6^c \cos^2\theta_D\right) \cos\theta_\tau \Big\}
\end{aligned}
$$

$$
\bar{I}_i(q^2) \equiv \frac{I_i(q^2)}{\Gamma_f(q^2)} .
$$

Other predictions



Conclusions

- Global fit to available data in $b \to c\tau\bar{\nu}_\tau$ transitions
- EFT approach with minima assumptions
  - NP enters only in 3rd generation of fermions
  - There is a sizeable gap between EW scale and NP
  - Operators are $SU(2)_L \otimes U(1)_Y$ invariant and electroweak symmetry breaking is linearly realized
  - All Wilson coefficients are real
- BaBar and Belle q^2 distributions included. Effect of $F_L^{D^*}$ analyzed
- Different fits performed
  - Main fit (without $F_L^{D^*}$): Three minima, one SM-like and two with stronger deviations from the SM
  - Fit with $F_L^{D^*}$: One minimum disappears , tension at 1σ
  - Fit with C_{RL}^V: The tension disappears for fine-tuned solutions
  - Several fits with RHN

Thank you!

2d plots

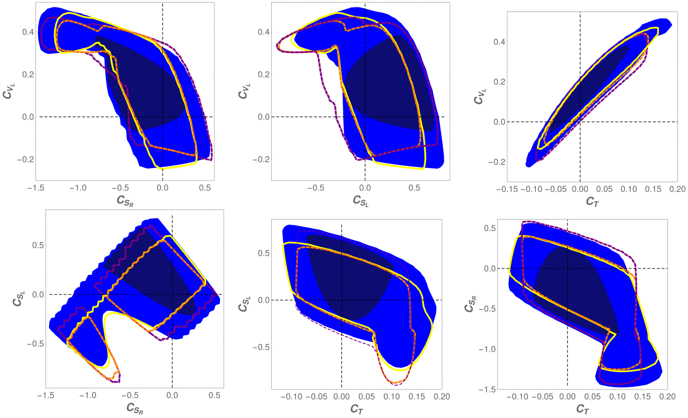


Figure: Blue areas (lighter 95% and darker 68% CL) show the minima without $F_L^{D^*}$ and with $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 30\%$. The yellow lines display how the 95% CL bounds change when $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$. The dashed lines show the effect of adding the observable $F_L^{D^*}$ for both $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 30\%$ (purple) and for $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$ (orange).

Form factors

Parameter	Value
ρ^2	1.32 ± 0.06
c	1.20 ± 0.12
d	-0.84 ± 0.17
$\chi_2(1)$	-0.058 ± 0.020
$\chi_2'(1)$	0.001 ± 0.020
$\chi_3'(1)$	0.036 ± 0.020
$\eta(1)$	0.355 ± 0.040
$\eta'(1)$	-0.03 ± 0.11
$l_1(1)$	0.14 ± 0.23
$l_2(1)$	2.00 ± 0.30

[M. Jung and D. Straub, 2019]

Form Factors

$$\omega(q^2) = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}} \qquad \text{and} \qquad z(q^2) = \frac{\sqrt{\omega(q^2)+1} - \sqrt{2}}{\sqrt{\omega(q^2)+1} + \sqrt{2}}\,.$$

$$\hat{h}_i(q^2) = h_i(q^2)/\xi(q^2)$$

[Bernlochner, 2017]

$$\hat{h}_+ = 1 + \hat{\alpha}_s\left[C_{V_1} + \frac{\omega+1}{2}\left(C_{V_2} + C_{V_3}\right)\right] + (\varepsilon_c + \varepsilon_b)\,\hat{L}_1\,,$$

$$\hat{h}_- = \hat{\alpha}_s\,\frac{\omega+1}{2}\left(C_{V_2} - C_{V_3}\right) + (\varepsilon_c - \varepsilon_b)\,\hat{L}_4\,,$$

$$\hat{h}_S = 1 + \hat{\alpha}_s C_S + (\varepsilon_c + \varepsilon_b)\left(\hat{L}_1 - \hat{L}_4\,\frac{\omega-1}{\omega+1}\right),$$

$$\hat{h}_T = 1 + \hat{\alpha}_s\left(C_{T_1} - C_{T_2} + C_{T_3}\right) + (\varepsilon_c + \varepsilon_b)\left(\hat{L}_1 - \hat{L}_4\right),$$

Form Factors

$$
\begin{aligned}
\hat{h}_V &= 1 + \hat{\alpha}_s C_{V_1} + \varepsilon_c \left(\hat{L}_2 - \hat{L}_5\right) + \varepsilon_b \left(\hat{L}_1 - \hat{L}_4\right), \\
\hat{h}_{A_1} &= 1 + \hat{\alpha}_s C_{A_1} + \varepsilon_c \left(\hat{L}_2 - \hat{L}_5 \frac{\omega - 1}{\omega + 1}\right) + \varepsilon_b \left(\hat{L}_1 - \hat{L}_4 \frac{\omega - 1}{\omega + 1}\right), \\
\hat{h}_{A_2} &= \hat{\alpha}_s C_{A_2} + \varepsilon_c \left(\hat{L}_3 + \hat{L}_6\right), \\
\hat{h}_{A_3} &= 1 + \hat{\alpha}_s \left(C_{A_1} + C_{A_3}\right) + \varepsilon_c \left(\hat{L}_2 - \hat{L}_3 + \hat{L}_6 - \hat{L}_5\right) + \varepsilon_b \left(\hat{L}_1 - \hat{L}_4\right), \\
\hat{h}_P &= 1 + \hat{\alpha}_s C_P + \varepsilon_c \left[\hat{L}_2 + \hat{L}_3 (\omega - 1) + \hat{L}_5 - \hat{L}_6 (\omega + 1)\right] + \varepsilon_b \left(\hat{L}_1 - \right. \\
\hat{h}_{T_1} &= 1 + \hat{\alpha}_s \left[C_{T_1} + \frac{\omega - 1}{2} \left(C_{T_2} - C_{T_3}\right)\right] + \varepsilon_c \hat{L}_2 + \varepsilon_b \hat{L}_1, \\
\hat{h}_{T_2} &= \hat{\alpha}_s \frac{\omega + 1}{2} \left(C_{T_2} + C_{T_3}\right) + \varepsilon_c \hat{L}_5 - \varepsilon_b \hat{L}_4, \\
\hat{h}_{T_3} &= \hat{\alpha}_s C_{T_2} + \varepsilon_c \left(\hat{L}_6 - \hat{L}_3\right),
\end{aligned}
$$

Angular observables

$$\frac{d^2\Gamma^{D^{(*)}}}{dq^2\, d\cos\theta_\ell} = a_\ell^{(*)}(q^2) - b_\ell^{(*)}(q^2)\cos\theta_\ell + c_\ell^{(*)}(q^2)\cos^2\theta_\ell\,,$$

$$\mathcal{A}_{\text{FB}}^{D^{(*)}}(q^2) \equiv b_\ell^{(*)}(q^2) \Bigg/ \frac{d\Gamma^{D^{(*)}}}{dq^2} = \left(\int_{-1}^{0} d\cos\theta_\ell\, \frac{d^2\Gamma^{D^{(*)}}}{dq^2\, d\cos\theta_\ell} - \int_{0}^{1} d\cos\theta$$

$$\mathcal{P}_\tau^{D^{(*)}}(q^2) = \left(\frac{d\Gamma^{D^{(*)}}_{\lambda_\tau=1/2}}{dq^2} - \frac{d\Gamma^{D^{(*)}}_{\lambda_\tau=-1/2}}{dq^2}\right) \Bigg/ \frac{d\Gamma^{D^{(*)}}}{dq^2}\,,$$

Angular observables

$$F_L^{D^*}(q^2) = \frac{d\Gamma_{\lambda_{D^*}=0}}{dq^2} \Bigg/ \frac{d\Gamma^{D^*}}{dq^2} \, .$$

$$\mathcal{O} \;=\; \frac{1}{\Gamma^{D^{(*)}}} \int_{m_\tau^2}^{q^2_{\rm max}} dq^2 \; \mathcal{O}(q^2) \, ,$$

$\mathcal{P}_\tau^{D^*} = -0.38 \pm 0.51 \text{ (stat) } {}^{+0.21}_{-0.16} \text{ (syst)}$
$F_L^{D^*} = 0.60 \pm 0.08 \text{ (stat) } \pm 0.04 \text{ (syst)}$

Theoretical framework - Observables in the fit

Other fits:

- The ratios $\mathcal{R}_{D^{(*)}}$
- ~~Differential distributions of the decay rates $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$~~ [M. Blanke et. al '18, R. Shi et. al '19, A. Kumar et. al '19 ...]
- The longitudinal polarization fraction $F_L^{D^*}$
- The leptonic decay rate $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 60\%$ [M. Blanke et. al '18]
- $\mathcal{P}_\tau^{D^*}$ and $\mathcal{R}_{J/\psi}$ included [M. Blanke et. al '18, R. Shi et. al '19, A. Kumar et. al '19 ...]

Fit and results

	Min 1b	Min 2b	**Min 1b**	Min 2b
$\mathcal{B}(B_c \to \tau\nu)$	10%		30%	
χ^2_{min}/d.o.f.	37.6/54	42.1/54	**37.6/54**	42.0/54
C^V_{LL}	$0.14^{+0.14}_{-0.12}$	$0.41^{+0.05}_{-0.05}$	$\mathbf{0.14^{+0.14}_{-0.14}}$	$0.40^{+0.06}_{-0.07}$
C^S_{RL}	$0.09^{+0.14}_{-0.52}$	$-1.15^{+0.18}_{-0.09}$	$\mathbf{0.09^{+0.33}_{-0.56}}$	$-1.34^{+0.57}_{-0.08}$
C^S_{LL}	$-0.09^{+0.52}_{-0.11}$	$-0.34^{+0.13}_{-0.19}$	$\mathbf{-0.09^{+0.68}_{-0.21}}$	$-0.18^{+0.13}_{-0.57}$
C^T_{LL}	$0.02^{+0.05}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$\mathbf{0.02^{+0.05}_{-0.05}}$	$0.11^{+0.03}_{-0.04}$

Min 1b compatible with minima found at M. Blanke et. al '18, R. Shi et. al '19, A. Kumar et. al '19 ...

Fit results

Scenario	$\mathcal{B}(B_c \to \tau\bar{\nu})$	χ^2/d.o.f	Pull$_{\text{SM}}$			Pull$_{\text{SM}}$	p-value
			$\bar{\mathcal{P}}_\tau^{D^*}$, $F_L^{D^*}$	$\mathcal{R}_{D,D^*}$	$d\Gamma/dq^2$		
SM	2.16%	52.87/59					69.95%
Scenario 1, Min 1	$< 10\%$	37.26/53	0.007	2.08	0.0414	2.4	95.02%
Scenario 1, Min 2	$< 10\%$	38.86/53	0.001	2.08	0.0006	2.2	92.68%
Scenario 1, Min 1	$< 30\%$	36.42/53	0.022	2.08	0.0866	2.5	96.00%
Scenario 1, Min 2	$< 30\%$	38.54/53	0.011	2.08	0.000	2.2	93.21%
Scenario 2, Min 1	$< 10\%$	38.54/54	0.006	2.32	0.0113	2.5	93.20%
Scenario 2, Min 2	$< 10\%$	39.05/54	0.004	2.32	0.0003	2.4	93.73%
Scenario 2, Min 1	$< 30\%$	38.33/54	0.035	2.32	0.0023	2.5	94.73%
Scenario 2, Min 2	$< 30\%$	38.80/54	0.025	2.32	0^*	2.4	94.09%
Scenario 3	$< 10\%$	39.50/58	0.150	3.65	0.0835	3.7	97.00%
Scenario 4a, Min 1	$< 10\%$	49.93/57	0.079	2.34	0^*	1.2	73.52%
Scenario 4a, Min 2	$< 10\%$	49.93/57	0.079	2.34	0^*	1.2	73.52%
Scenario 4a, Min 1	$< 30\%$	44.49/57	0.311	2.66	0^*	2.4	88.62%
Scenario 4a, Min 2	$< 30\%$	44.49/57	0.311	2.66	0^*	2.4	88.62%
Scenario 4b	$< 10\%$	43.56/55	0.054	2.07	0^*	1.9	86.70%
Scenario 4b	$< 30\%$	40.03/55	0.218	2.52	0^*	2.5	93.54%
Scenario 5a	$< 10\%$	39.39/57	0^*	3.22	0.0981	3.2	96.36%
Scenario 5b	$< 10\%$	39.37/55	0^*	3.34	0.0060	2.6	94.47%
Scenario 6	$< 10\%$	44.20/58	0^*	3.34	0^*	2.9	90.93%
Scenario 7a	$< 10\%$	39.21/57	0.126	3.22	0.0616	3.3	96.53%
Scenario 7b	$< 10\%$	39.06/55	0.014	2.56	0.0112	2.7	94.87%
Scenario 8	$< 10\%$	47.32/57	0.259	2.56	0^*	1.9	81.60%