Global fit to $b \to c\tau\nu$ data

Implications of LHCb measurements and future prospects

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Based on arXiv:1904.09311

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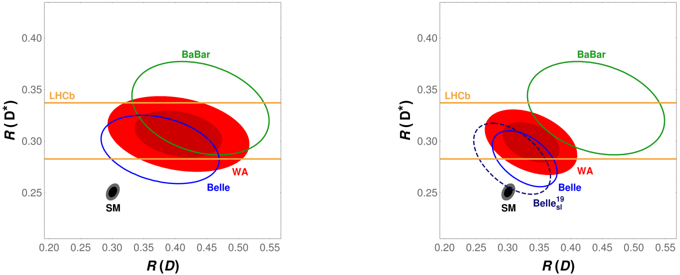
Introduction

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

4.4σ discrepancy
3.7σ discrepancy



pre-Moriond (HFLAV)   post-Moriond (our average)

$F_L^{D^*} = 0.60 \pm 0.08$ (stat) ± 0.04 (syst)   1.6σ discrepancy

[Belle 2019]

Theoretical framework - Effective Hamiltonian

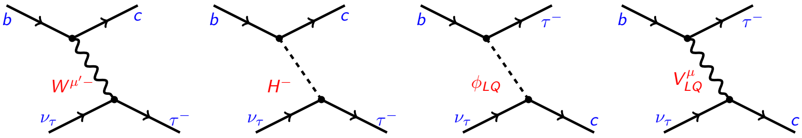
- Most general $SU(3)_C \otimes U(1)_Q$-invariant effective Hamiltonian at b scale, without light right-handed neutrinos

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[(1 + C_{V_L})\, \mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_R}\mathcal{O}_{S_R} + C_{S_L}\mathcal{O}_{S_L} + C_T\mathcal{O}_T \right] + \text{h.c.}$$

$$\mathcal{O}_{V_L} = (\bar{c}_L\gamma^\mu b_L)\left(\bar{\ell}_L\gamma_\mu\nu_{\ell L}\right), \qquad \mathcal{O}_{V_R} = (\bar{c}_R\gamma^\mu b_R)\left(\bar{\ell}_L\gamma_\mu\nu_{\ell L}\right),$$
$$\mathcal{O}_{S_R} = (\bar{c}_L b_R)\left(\bar{\ell}_R\nu_{\ell L}\right), \qquad \mathcal{O}_{S_L} = (\bar{c}_R b_L)\left(\bar{\ell}_R\nu_{\ell L}\right),$$
$$\mathcal{O}_T = (\bar{c}_R\sigma^{\mu\nu} b_L)\left(\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L}\right).$$

$$\boxed{C_{V_L}^{\text{SM}} = C_{V_R}^{\text{SM}} = C_{S_L}^{\text{SM}} = C_{S_R}^{\text{SM}} = C_T^{\text{SM}} = 0}$$

Theoretical framework - Effective Hamiltonian



C_{V_L} $\quad$ C_{S_L}, C_{S_R}, C_T $\quad$ C_{V_L}, C_{V_R}, C_T $\quad$ C_{V_L}, C_{S_R}

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

See Sumensari talk

Theoretical framework - Assumptions

- NP contributions, $C_i \neq 0$, **only in the third generation of leptons**
- **EWSB is linearly relarized** $\rightarrow C_{V_R}$ is flavour universal, i.e. $C_{V_R} = 0$
- **CP-conserving**: all Wilson coefficients C_i are assumed to be real
- **Form factors**: Heavy quark effective theory (HQET) parametrization, including corrections of order α_s, $\Lambda_{\text{QCD}}/m_{b,c}$ and $\Lambda^2_{\text{QCD}}/m_c^2$

See Jung talk

Theoretical framework - Observables in the fit

Our fit:

- The ratios $\mathcal{R}_{D^{(*)}}$
- Differential distributions of the decay rates $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
- The longitudinal polarization fraction $F_L^{D^*}$
- The leptonic decay rate $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\,(30)\%$

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

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

$\mathcal{B} < 30\%$ B_c lifetime

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

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 ...]

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 $\mathrm{d}\Gamma/\mathrm{d}q^2$ maximally conservative

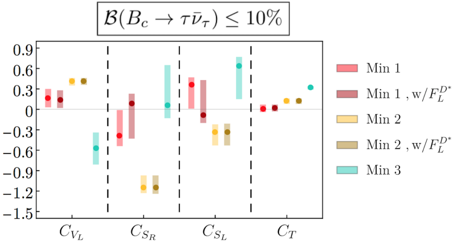
$$\chi^2_{\text{min},d\Gamma}/\text{d.o.f.} \sim 43/54$$

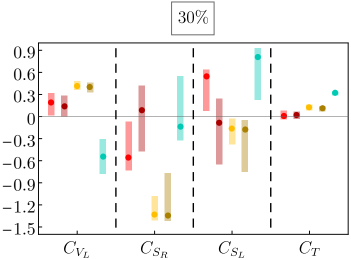
- $\mathcal{R}_D$ and $\mathcal{R}_{D^*}$

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

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

Fit and results





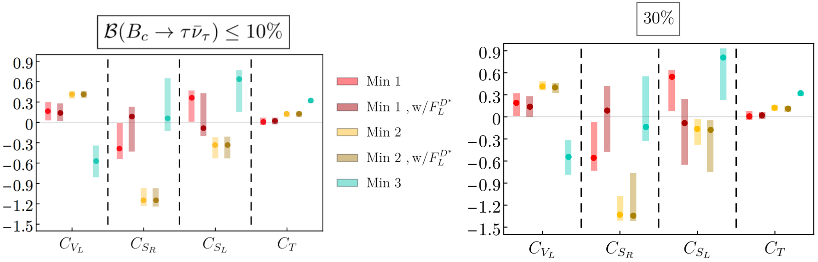
	Min 1	Min 2	Min 3	Min 1	Min 2	Min 3
$\mathcal{B}(B_c \to \tau\nu)$		10%			30%	
$\chi^2_{\rm min}$/d.o.f.	34.1/53	37.5/53	58.6/53	33.8/53	36.6/53	58.4/53
C_{V_L}	$0.17^{+0.13}_{-0.14}$	$0.41^{+0.05}_{-0.06}$	$-0.57^{+0.23}_{-0.24}$	$0.19^{+0.13}_{-0.17}$	$0.42^{+0.06}_{-0.06}$	$-0.54^{+0.23}_{-0.24}$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

	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_L}	$0.14^{+0.14}_{-0.12}$	$0.41^{+0.05}_{-0.05}$	$\mathbf{0.14^{+0.14}_{-0.14}}$	$0.40^{+0.06}_{-0.07}$
C_{S_R}	$0.09^{+0.14}_{-0.52}$	$-1.15^{+0.18}_{-0.09}$	$\mathbf{0.09^{+0.33}_{-0.56}}$	$-1.34^{+0.57}_{-0.08}$
C_{S_L}	$-0.09^{+0.52}_{-0.11}$	$-0.34^{+0.13}_{-0.19}$	$\mathbf{-0.09^{+0.68}_{-0.21}}$	$-0.18^{+0.13}_{-0.57}$
C_T	$0.02^{+0.05}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$\mathbf{0.02^{+0.05}_{-0.05}}$	$0.11^{+0.03}_{-0.04}$

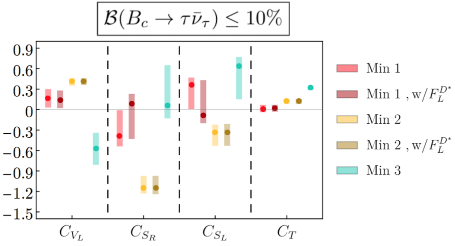
Min 1b compatible with minima found at M. Blanke et. al '18, R. Shi et. al '19, A. Kumar et. al '19 ...

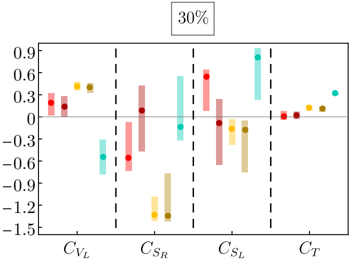
Fit and results



- Strong preference for New Physics: $\chi^2_{\mathrm{SM}} - \chi^2 = 31.4$
- 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

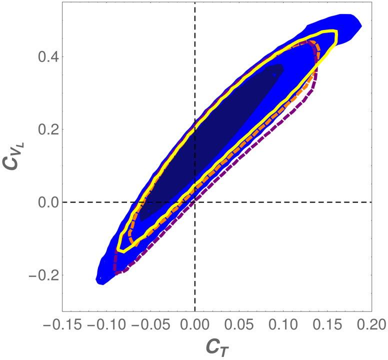




Global minimum (34.1/53)

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

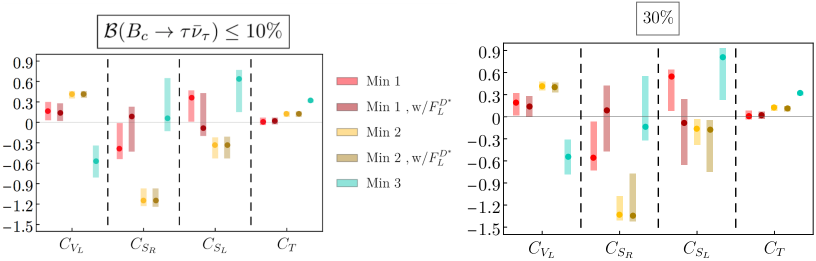
Fit and results



Global minimum (34.1/53)

- Requieres either C_{V_L} or C_T

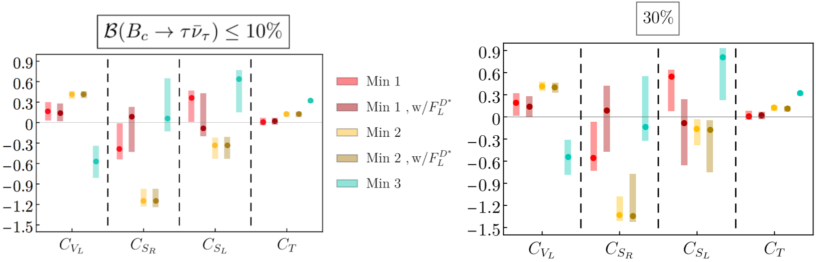
Fit and results



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 R_{D^*} and q^2 distributinos
- Min 3 fits R_{D^*} perfectly, disfavoured by q^2 ditributions

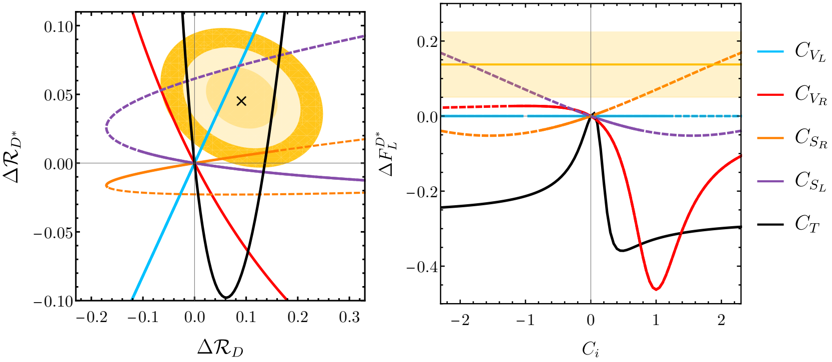
Fit and results



Adding $F_L^{D^*}$

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

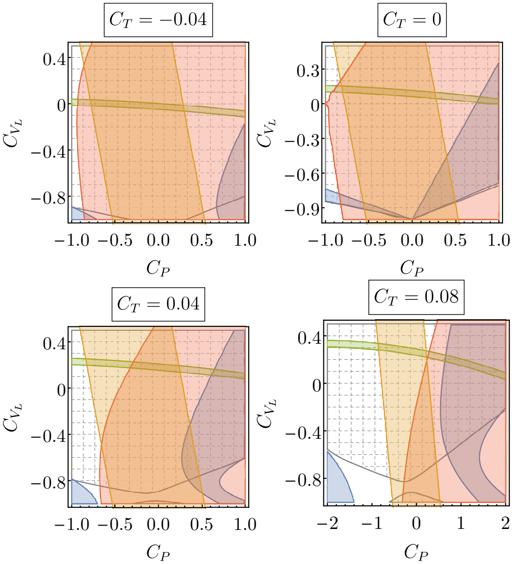
Interpretation of results



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

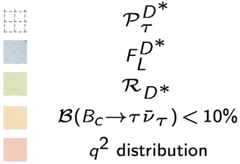
$$\Delta X = X - X_{SM}$$

Interpretation of results



$\mathbf{C_P \equiv C_{S_R} - C_{S_L}}$

D^* observables = f(C_{V_L}, 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_{V_R}
  - Additional degrees of freedom: ν_R...
- **Experimental side**: there is an unidentified of underestimated systematic uncertainty in experimental measurements

Interpretation of results

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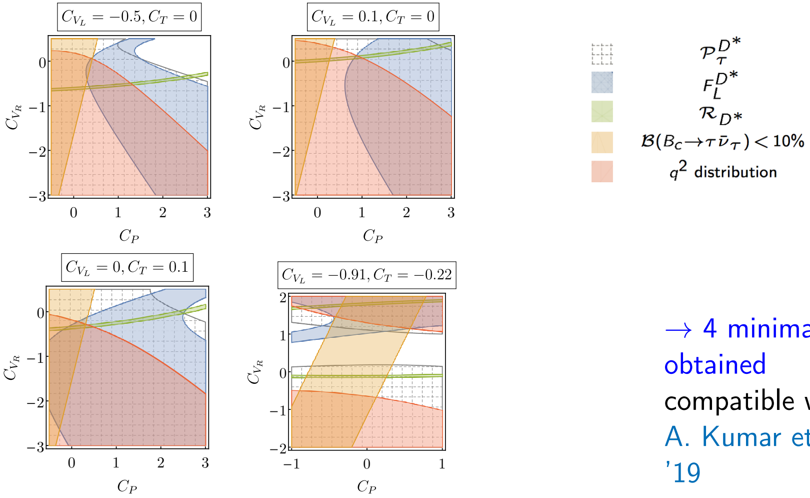
  - There is an insufficient gap between the electroweak and the NP scale
  - The electroweak symmetry breaking is non-linear: C_{V_R}
  - Additional degrees of freedom: ν_R...
- **Experimental side**: there is an unidentified of undersitmated systematic uncertainty in experimental measurements $\rightarrow$ upcoming experimental studies of LHCb and Belle II

Interpretation of results



→ 4 minima obtained compatible with A. Kumar et. al '19

- Including C_{V_R} slightly improves the fit $\chi^2/\text{d.o.f.} = 32.5/55$
- Two fine-tuned solutions $C_{V_L} \sim -0.9$

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_{V_R}: The tension disappears for fine-tuned solutions

Thank you!

Current status of B anoamlies

Series of anomalies in semileptonic B-meson decays

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

4.4σ discrepancy

4.0σ discrepancy

SM prediction

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

Experimental values pre-Moriond (HFLAV)

$$\mathcal{R}_D = 0.407 \pm 0.039 \pm 0.024 \quad \text{and} \quad \mathcal{R}_{D^*} = 0.306 \pm 0.013 \pm 0.007$$

Experimental values post-Moriond (our average)

$$\mathcal{R}_D = 0.337 \pm 0.030 \quad \text{and} \quad \mathcal{R}_{D^*} = 0.299 \pm 0.013$$

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Experimental values post-Moriond (HFLAV)

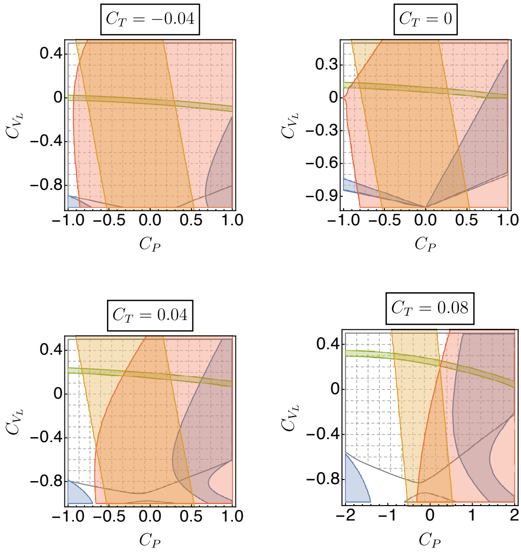
$$\mathcal{R}_D = 0.340 \pm 0.027 \pm 0.013 \quad \text{and} \quad \mathcal{R}_{D^*} = 0.295 \pm 0.011 \pm 0.008$$

New Belle measurements

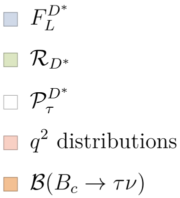
- Similar solutions as before
- Again, all Wilson coefficients compatible with zero at 1σ

	Min 1b	Min 2b	Min 1b	Min 2b
χ^2_{min}/d.o.f.	37.6/54	42.1/54	37.4 /54	40.1/54
C_{V_L}	$0.14^{+0.14}_{-0.12}$	$0.41^{+0.05}_{-0.05}$	$0.09^{+0.13}_{-0.11}$	$0.35^{+0.04}_{-0.07}$
C_{S_R}	$0.09^{+0.14}_{-0.52}$	$-1.15^{+0.18}_{-0.09}$	$0.14^{+0.06}_{-0.67}$	$-1.27^{+0.66}_{-0.07}$
C_{S_L}	$-0.09^{+0.52}_{-0.11}$	$-0.34^{+0.13}_{-0.19}$	$-0.20^{+0.58}_{-0.03}$	$-0.30^{+0.12}_{-0.51}$
C_T	$0.02^{+0.05}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$0.007^{+0.046}_{-0.044}$	$0.091^{+0.029}_{-0.030}$

Table: Black old data, blue with preliminary Belle data



$$C_P \equiv C_{S_R} - C_{S_L}$$



Results with Belle new measurement

Fit

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

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

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

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

$y_i \rightarrow$ 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 $\chi^2|_{y_i^{\text{min}}+\Delta y_i}$ varying all parameters that increase $\Delta\chi^2 = 1$

Form Factors

- Heavy quark effective theory (HQET) parametrization
- Corrections of order α_s, $\Lambda_{\text{QCD}}/m_{b,c}$ and $\Lambda^2_{\text{QCD}}/m^2_c$
- 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

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

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	$\mathcal{O}(1/m_{b,c})$
$\chi_2'(1)$	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	$\mathcal{O}(1/m_{b,c})$
$l_1(1)$	0.14 ± 0.23	$\mathcal{O}(1/m_c^2)$
$l_2(1)$	2.00 ± 0.30	$\mathcal{O}(1/m_c^2)$

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

Observables in the fit

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

vector contribution $C_V = 1 + C_{V_L} + C_{V_R}$

scalar contribution $C_S = C_{S_R} + C_{S_L}$

Observables in the fit

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

"almost" axial contribution $C_A = C_{V_R} - (1 + C_{V_L})$

pseudoscalar contribution $C_P = C_{S_R} - C_{S_L}$

2d plots

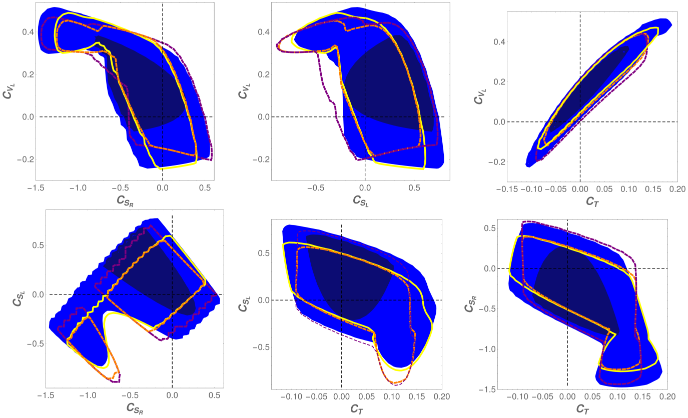


Figure: Blue areas (lighter 95% and darker 68% CL) show the minima without $F_L^{D^*}$ and with $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 30\%$. The yellow lines display how the 95% CL bounds change when $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$. The dashed lines show the effect of adding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

R_D and R_D^* predictions

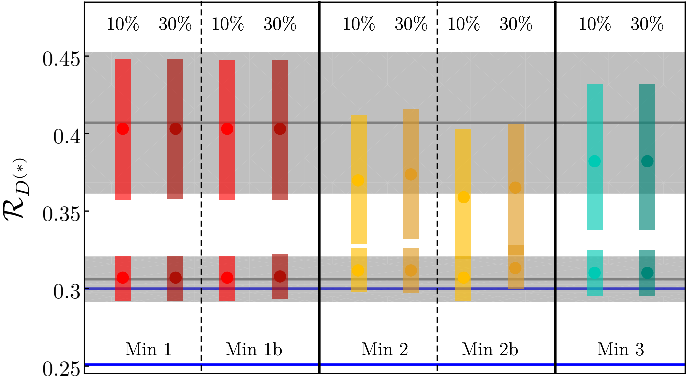
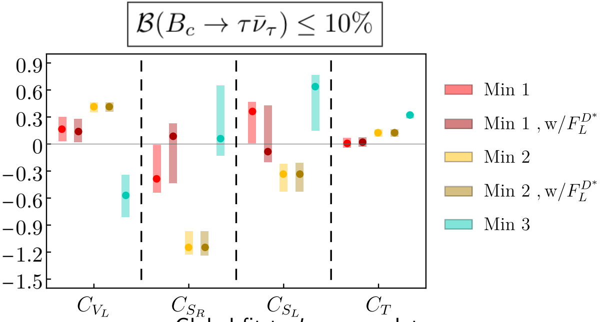
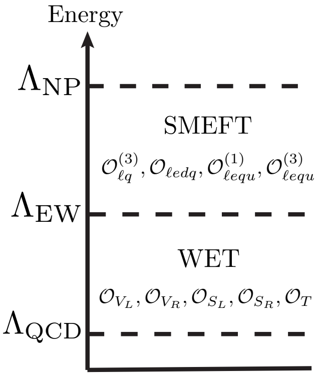


Figure: Predictions for $\mathcal{R}_D$ (higher numerical values) and $\mathcal{R}_{D^*}$ (lower numerical values) . The blue lines show the SM predictions, $\mathcal{R}_D = 0.300^{+0.005}_{-0.004}$ (upper blue line) and $\mathcal{R}_{D^*} = 0.251^{+0.004}_{-0.003}$ (lower blue line).

Fit and results



New Physics



$$
\begin{aligned}
C_{V_L}(\mu_b) &= -1.503\ \tilde{C}_{V_L}(\Lambda)\,, \\
C_{S_L}(\mu_b) &= -1.257\ \tilde{C}_{S_L}(\Lambda) + 0.2076\ \tilde{C}_T(\Lambda)\,, \\
C_{S_R}(\mu_b) &= -1.254\ \tilde{C}_{S_R}(\Lambda)\,, \\
C_T(\mu_b) &= 0.002725\ \tilde{C}_{S_L}(\Lambda) - 0.6059\ \tilde{C}_T(\Lambda)\,.
\end{aligned}
$$

$\mu_b = 5$ GeV

$\Lambda = 1$ TeV

New Physics

Spin	Q.N.	Nature	Allowed couplings	SMEFT	WET
0	$S_1 \sim (\bar{3}, 1, 1/3)$	LQ	$\overline{q_L^c}\ell_L$, $\overline{d_R}u_R^c$, $\overline{u_R^c}e_R$	$\tilde{C}_{V_L}$, $\tilde{C}_{S_L}$, $\tilde{C}_T$	C_{V_L}, C_{S_L}, C_T
0	$S_3 \sim (\bar{3}, 3, 1/3)$	LQ	$\overline{q_L^c}\ell_L$	$\tilde{C}_{V_L}$	C_{V_L}
0	$R_2 \sim (3, 2, 7/6)$	LQ	$\overline{u_R}\ell_L$, $\overline{q_L}e_R$	$\tilde{C}_{S_L}$, $\tilde{C}_T$	C_{S_L}, C_T
0	$H_2 \sim (1, 2, 1/2)$	SB	$\overline{q_L}d_R$, $\overline{\ell_L}e_R$, $\overline{u_R}q_L$	$\tilde{C}_{S_R}$, $\tilde{C}_{S_L}$	C_{S_R}, C_{S_L}, C_T
1	$V_2 \sim (\bar{3}, 2, 5/6)$	LQ	$\overline{d_R^c}\gamma_\mu\ell_L$, $\overline{e_R^c}\gamma_\mu q_L$	$\tilde{C}_{S_R}$	C_{S_R}
1	$U_1 \sim (3, 1, 2/3)$	LQ	$\overline{q_L}\gamma_\mu\ell_L$, $\overline{d_R}\gamma_\mu e_R$	$\tilde{C}_{V_L}$, $\tilde{C}_{S_R}$	C_{V_L}, C_{S_R}
1	$U_3 \sim (3, 3, 2/3)$	LQ	$\overline{q_L}\gamma_\mu\ell_L$	$\tilde{C}_{V_L}$	C_{V_L}
1	$W'_\mu \sim (1, 3, 0)$	VB	$\overline{\ell_L}\gamma_\mu\ell_L$, $\overline{q_L}\gamma_\mu q_L$	$\tilde{C}_{V_L}$	C_{V_L}

New Physics

Global minimum

$$\mathbf{C_{V_L}} = \mathbf{0.17^{+0.13}_{-0.14}}, \qquad C_{S_R} = -0.39^{+0.38}_{-0.15},$$
$$C_{S_L} = 0.36^{+0.11}_{-0.35}, \qquad C_T = 0.01^{+0.06}_{-0.05}.$$

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

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

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

ruled out by DS

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

New Physics

Min 2

$$\mathbf{C_{V_L}} = \mathbf{0.41^{+0.05}_{-0.06}}, \qquad \mathbf{C_{S_R}} = \mathbf{-1.15^{+0.18}_{-0.08}},$$
$$\mathbf{C_{S_L}} = \mathbf{-0.34^{+0.12}_{-0.19}}, \qquad \mathbf{C_T} = \mathbf{0.12^{+0.04}_{-0.04}}.$$

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

Min 3

$$C_{V_L} = -0.57^{+0.23}_{-0.24}, \qquad C_{S_R} = 0.06^{+0.59}_{-0.19},$$
$$\mathbf{C_{S_L}} = \mathbf{0.64^{+0.13}_{-0.49}}, \qquad \mathbf{C_T} = \mathbf{0.32^{+0.02}_{-0.03}}.$$

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