

Global fit to $b \rightarrow c\tau\nu$ transitions

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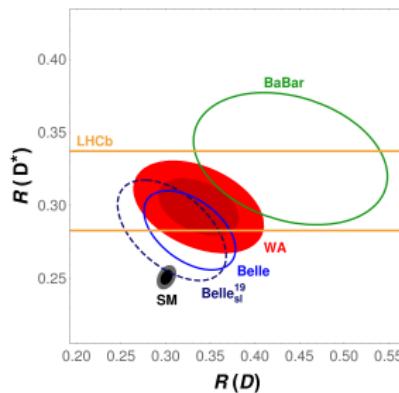
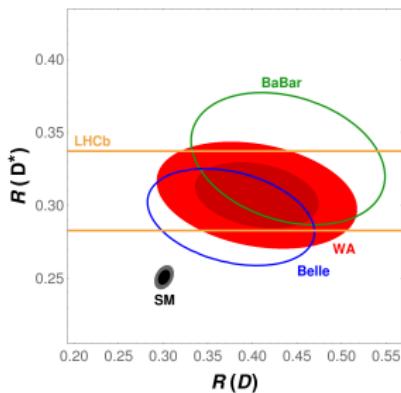
Based on arXiv:1904.09311



Introduction

- Series of anomalies in semileptonic B -meson decays

$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}\ell\bar{\nu})} \quad 4.4\sigma \text{ discrepancy}$$



$$F_L^{D^*} = 0.60 \pm 0.08 \text{ (stat)} \pm 0.04 \text{ (syst)} \quad 1.6\sigma \text{ discrepancy}$$

Theoretical framework - Effective Hamiltonian

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

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

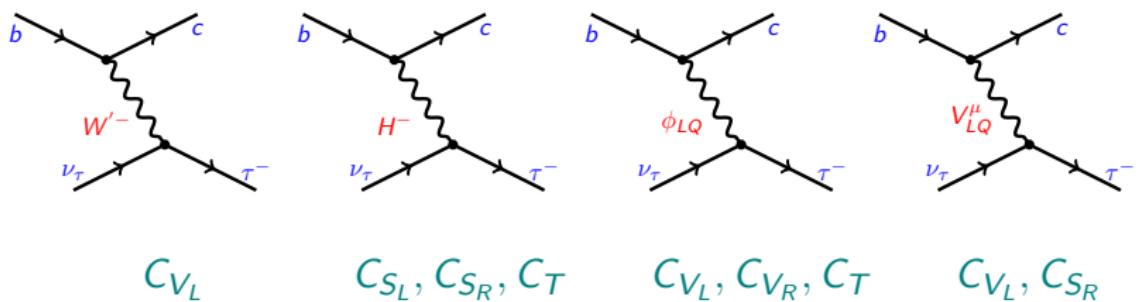
$$\mathcal{O}_{V_L} = (\bar{c}_L \gamma^\mu b_L) (\bar{\ell}_L \gamma_\mu \nu_{\ell L}), \quad \mathcal{O}_{V_R} = (\bar{c}_R \gamma^\mu b_R) (\bar{\ell}_L \gamma_\mu \nu_{\ell L}),$$

$$\mathcal{O}_{S_R} = (\bar{c}_L b_R) (\bar{\ell}_R \nu_{\ell L}), \quad \mathcal{O}_{S_L} = (\bar{c}_R b_L) (\bar{\ell}_R \nu_{\ell L}),$$

$$\mathcal{O}_T = (\bar{c}_R \sigma^{\mu\nu} b_L) (\bar{\ell}_R \sigma_{\mu\nu} \nu_{\ell L}).$$

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

Theoretical framework - Effective Hamiltonian



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

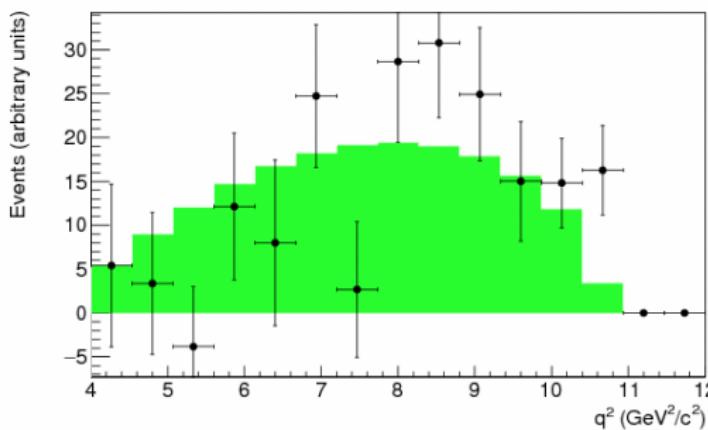
Theoretical framework - Assumptions

- NP contributions, $C_i \neq 0$, **only in the third generation of leptons**
- EWSB is linearly realized $\rightarrow C_{V_R}$ 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 $\Lambda_{\text{QCD}}^2/m_c^2$

Theoretical framework - Observables in the fit

Observables included in the fit:

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



[Belle '15]

Fit

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

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

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

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

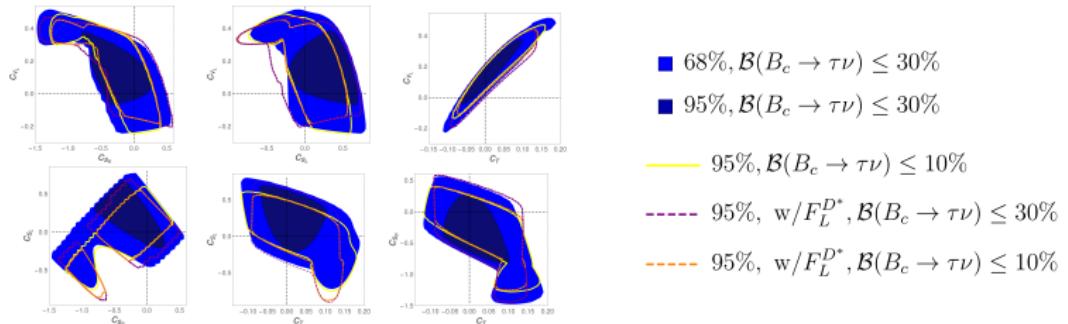
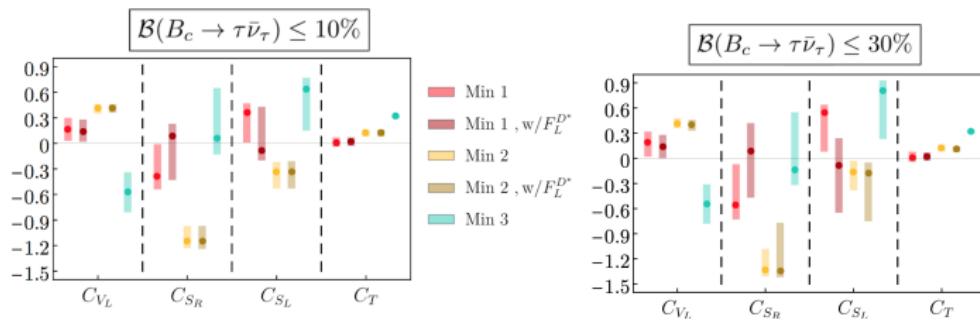
$y_i \rightarrow$ input parameters of the fit

$\rho_{ij} \rightarrow$ correlation between observable i and j

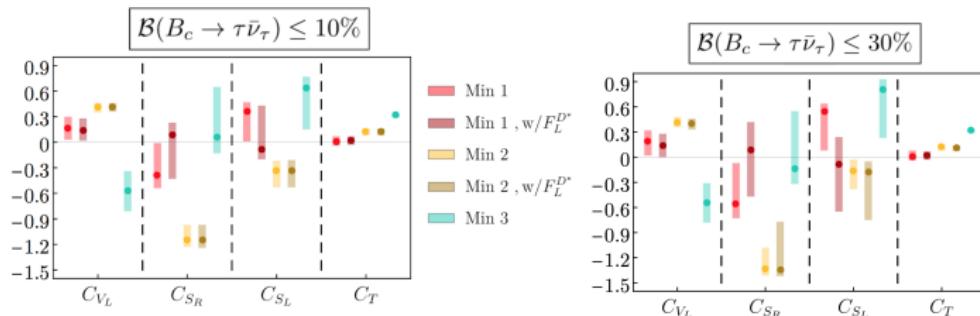
$\sigma_i \rightarrow$ uncertainty of observable *i*

Δy_i : determined minimizing $\chi^2|_{y_i^{\min} + \Delta y_i}$ varying all parameters
that increase $\Delta \chi^2 = 1$

Fit and results

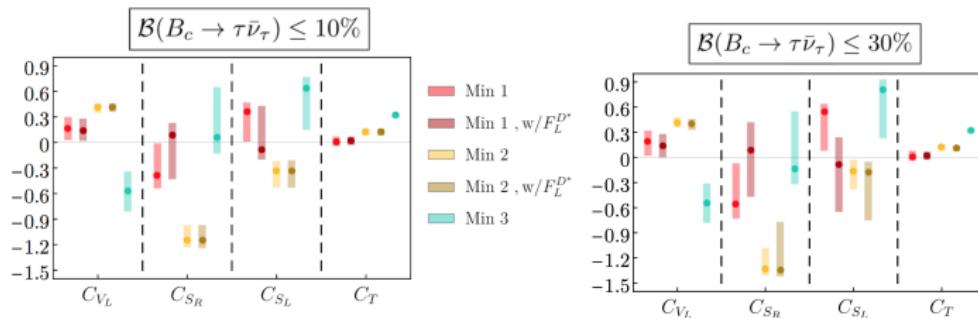


Fit and results



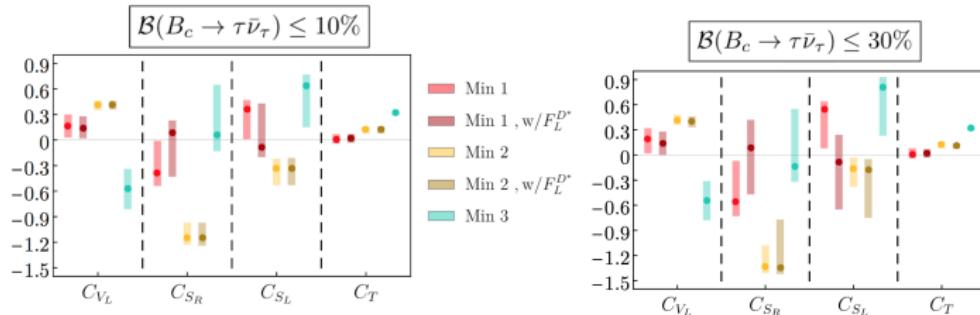
$\mathcal{B}(B_c \rightarrow \tau \nu)$	Min 1	Min 2	Min 3	Min 1	Min 2	Min 3
$\chi^2_{\text{min}}/\text{d.o.f.}$	34.1/53	37.5/53	58.6/53	33.8/53	36.6/53	58.4/53
C_{V_L}	$0.17^{+0.13}_{-0.14}$	$0.41^{+0.05}_{-0.06}$	$-0.57^{+0.23}_{-0.24}$	$0.19^{+0.13}_{-0.17}$	$0.42^{+0.06}_{-0.06}$	$-0.54^{+0.23}_{-0.24}$
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



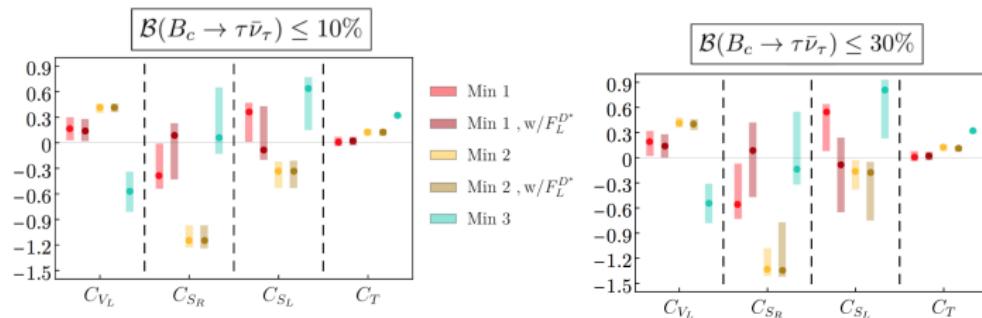
- Strong preference for New Physics: $\chi_{\text{SM}}^2 - \chi^2 = 31.4$
- No absolute preference of a single Wilson coefficient in the global minimum
- Min 1 compatible with a global modification of the SM:
adding C_{V_L} , $\Delta\chi^2 = 1.4$

Fit and results



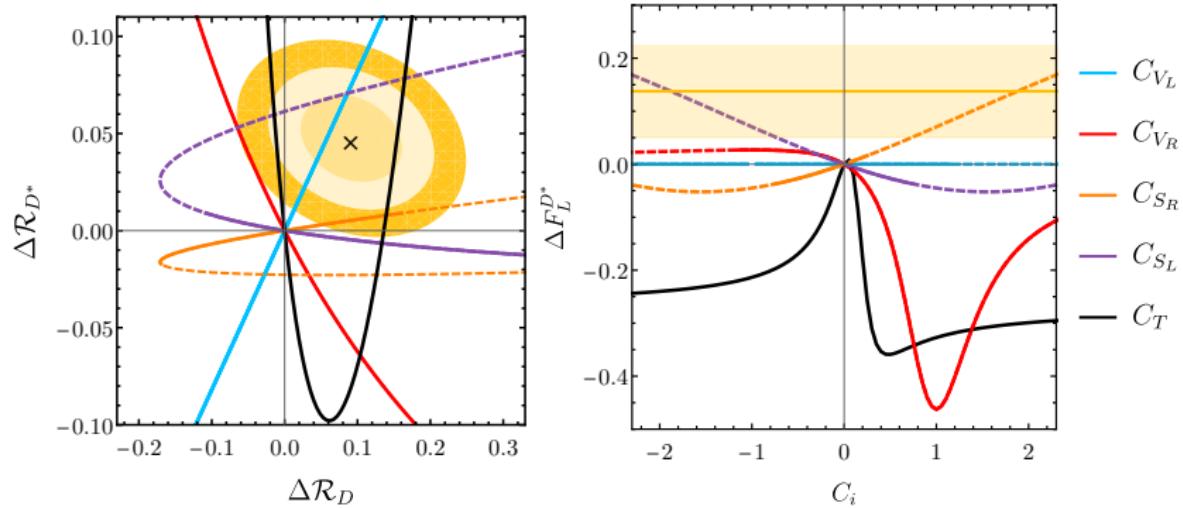
- Min 2 and Min 3 are further away from the SM and involves sizeable Wilson coefficients
- All minima saturate the constraint $\mathcal{B}(B_c \rightarrow \tau \bar{\nu}_\tau) \leq 10(30)\%$
- Complex C_i do not improve the χ^2 , but open to many solutions

Fit and results



- With $F_L^{D^*}$: still no clear preference for a single coefficient
- With $F_L^{D^*}$: Min 3 disappears

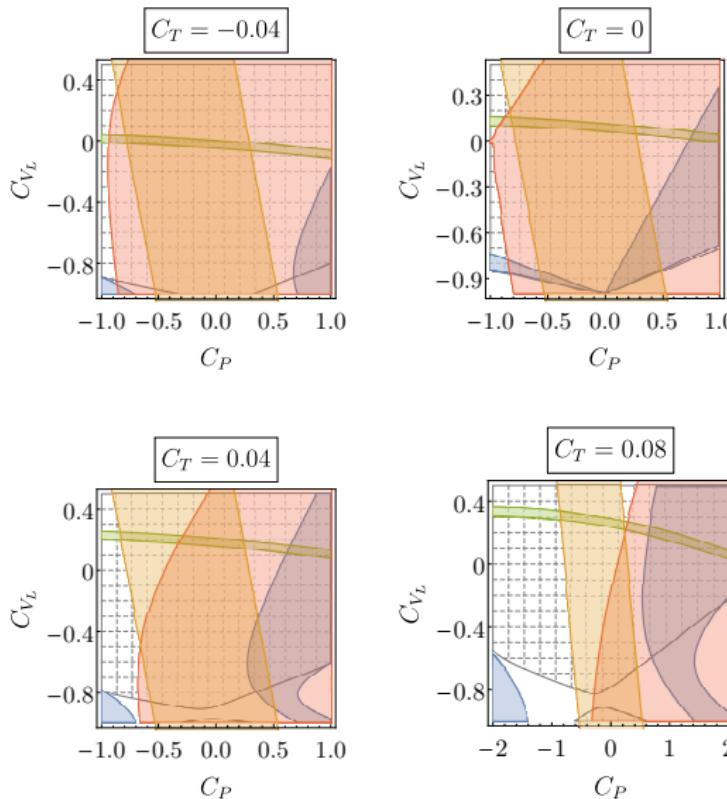
Interpretation of results



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

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

Interpretation of results



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

- \square $F_L^{D^*}$
- \square \mathcal{R}_{D^*}
- \square $\mathcal{P}_\tau^{D^*}$
- \blacksquare q^2 distributions
- \blacksquare $\mathcal{B}(B_c \rightarrow \tau\nu)$

Incompatibility
of the
experimental
data at 1σ

Interpretation of results

Incompatibility of the experimental data at 1σ

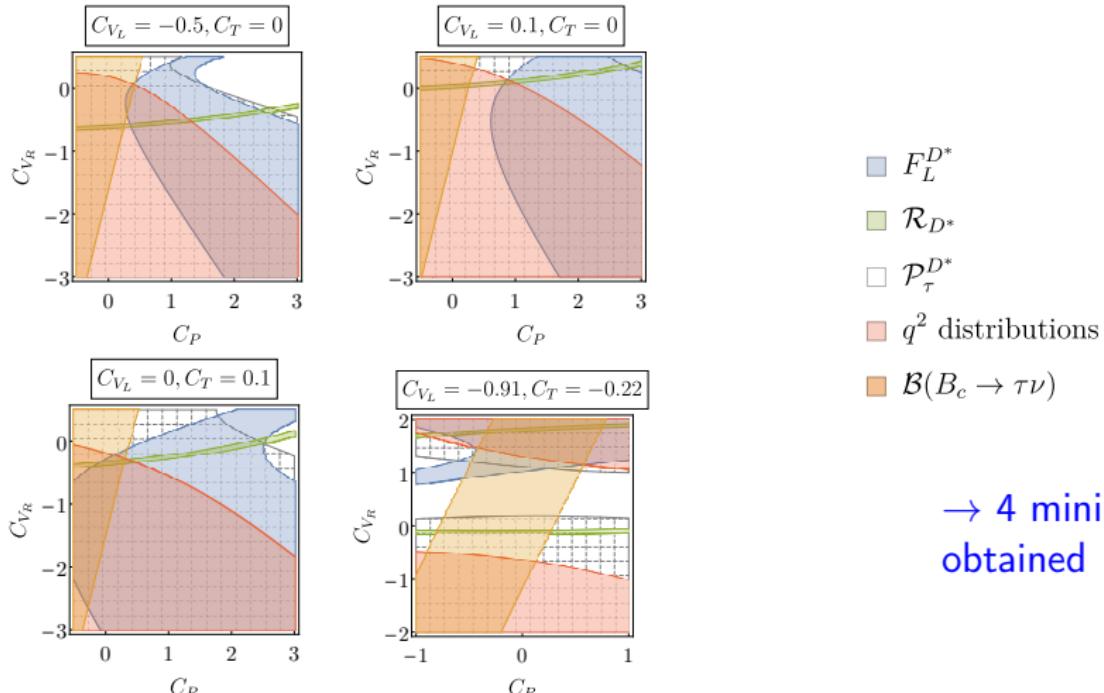
- **Theory side:** one of our assumptions is incorrect
 - There is an insufficient gap between the electroweak and the NP scale
 - The electroweak symmetry breaking is non-linear: C_{V_R}
 - Additional degrees of freedom: $\nu_R \dots$
- **Experimental side:** there is an unidentified or underestimated systematic uncertainty experimental measurements

Interpretation of results

Incompatibility of the 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: $\nu_R\dots$
- **Experimental side:** there is an unidentified or underestimated systematic uncertainty experimental measurements →
upcoming experimental studies of LHCb and Belle II

Interpretation of results



→ 4 minima obtained

- 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 $b \rightarrow c\tau\bar{\nu}_\tau$ 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

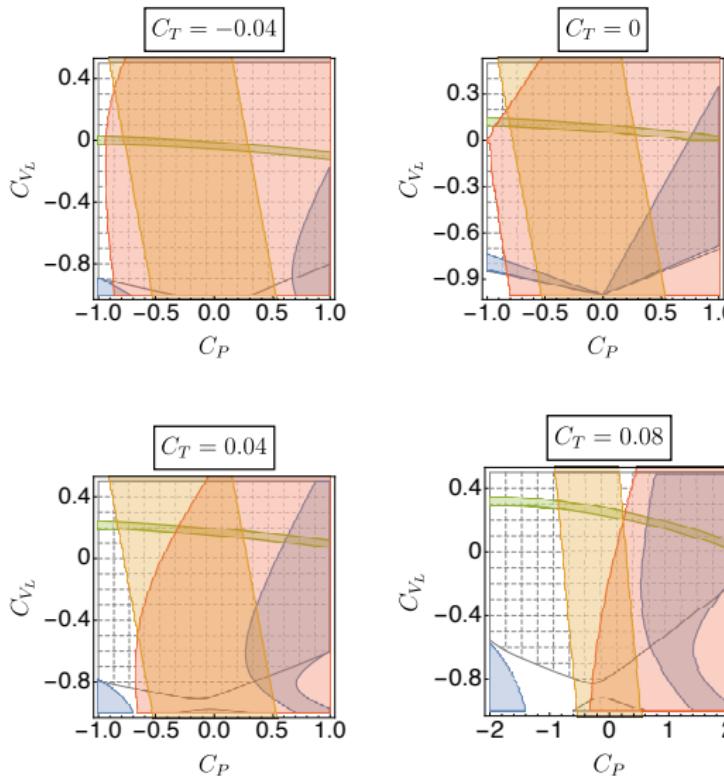
Back up

New Belle measurements (preliminary)

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

	Min 1b	Min 2b	Min 1b	Min 2b
$\chi^2_{\text{min}}/\text{d.o.f.}$	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



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

- $\square F_L^{D^*}$
- $\square \mathcal{R}_{D^*}$
- $\square \mathcal{P}_\tau^{D^*}$
- $\square q^2$ distributions
- $\blacksquare \mathcal{B}(B_c \rightarrow \tau\nu)$

Results with
Belle new
measurement

χ^2 minimization

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

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

SM fit

- SM, $C_i = 0$
- $\chi^2_{\min} = 65.5$ for 57 d.o.f $\rightarrow \text{CL} \sim 20\%$
- These numbers are misleading
 - Systematic uncertainties of q^2 distributions are chosen maximally conservative
- Contribution from R_{D^*} , $\chi^2 = 22.6$ for 2 d.o.f. $\rightarrow 4.4\sigma$ tension

2d plots

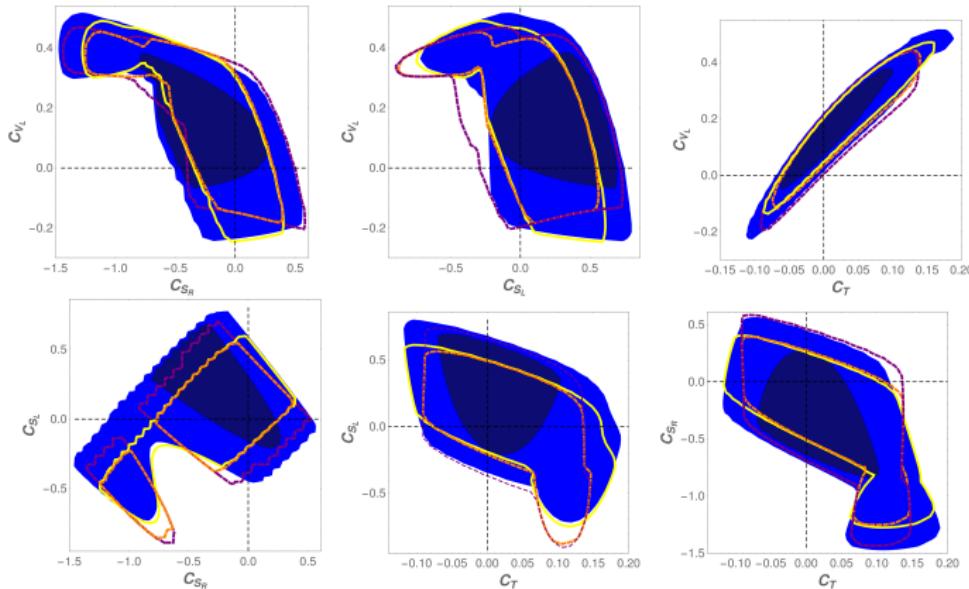


Figure: Blue areas (lighter 95% and darker 68% CL) show the minima without $F_L^{D^*}$ and with $\mathcal{B}(B_c \rightarrow \tau \bar{\nu}_\tau) \leq 30\%$. The yellow lines display how the 95% CL bounds change when $\mathcal{B}(B_c \rightarrow \tau \bar{\nu}_\tau) \leq 10\%$. The dashed lines show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

R_D and R_D^* predictions

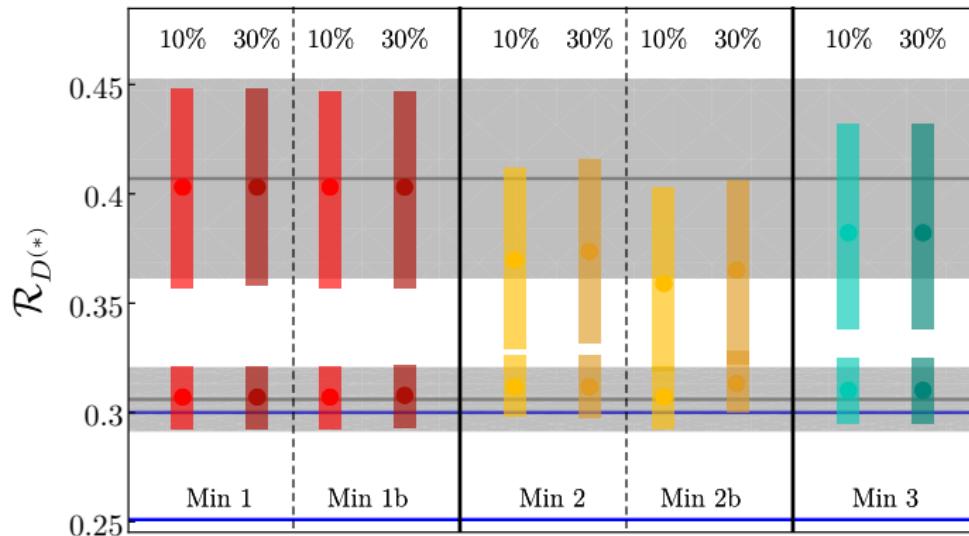
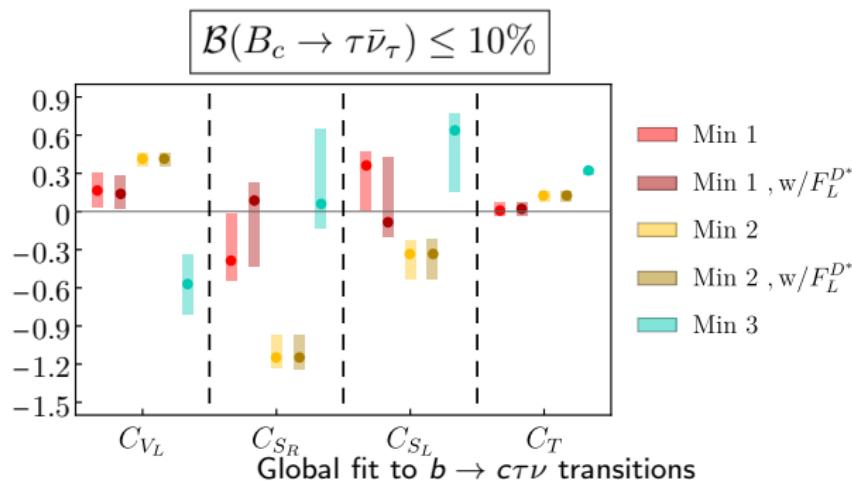


Figure: Predictions for \mathcal{R}_D (higher numerical values) and \mathcal{R}_{D^*} (lower numerical values). The blue lines show the SM predictions, $\mathcal{R}_D = 0.300^{+0.005}_{-0.004}$ (upper blue line) and $\mathcal{R}_{D^*} = 0.251^{+0.004}_{-0.003}$ (lower blue line).

Fit and results



Form factors

- Heavy quark effective theory (HQET) with corrections of order $\alpha_s, \Lambda_{\text{QCD}}/m_b, \Lambda_{\text{QCD}}/m_c^2$
- In the heavy-quark limit all FFs either vanish or reduce to a common functional form

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

$$\begin{aligned} \xi(q^2) &= 1 - \rho^2 [\omega(q^2) - 1] + c [\omega(q^2) - 1]^2 + d [\omega(q^2) - 1]^3 + \mathcal{O}([\omega - 1]^4) \\ &= 1 - 8\rho^2 z(q^2) + (64c - 16\rho^2) z^2(q^2) \\ &\quad + (256c - 24\rho^2 + 512d) z^3(q^2) + \mathcal{O}(z^4), \end{aligned}$$

Interpretation of results- Possible NP candidates

- Min 1 \mathcal{O}_{V_L}
 - W' boson, $M'_W \sim 0.2$ TeV **ruled out by direct searches**
 - Leptoquarks: $U_3 \sim (3, 3, 2/3)$
 - Scalar leptoquarks: $S_1 \sim (\bar{3}, 3, 1/3)$
- Min 2 $\mathcal{O}_{S_{L,R}}, \mathcal{O}_{V_L}, \mathcal{O}_T$
 - Combination of several candidates, e.g, leptoquark $S_1 \sim (\bar{3}, 3, 1/3)$ and scalar boson $H_2 \sim (1, 21/3)$
- Min 3 $\mathcal{O}_{S_L}, \mathcal{O}_T$
 - Scalar leptoquarks $R_2 \sim (3, 2, 7/6)$ or $S_1 \sim (\bar{3}, 1, 1/3)$

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]

Observables

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

Observables

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

Observables

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