Caltech

# Current anomalies in semileptonic B decays into charm: Global EFT analysis

Clara Murgui

In collaboration with Martin Jung, Rusa Mandal, Ana Peñuelas and Antonio Pich

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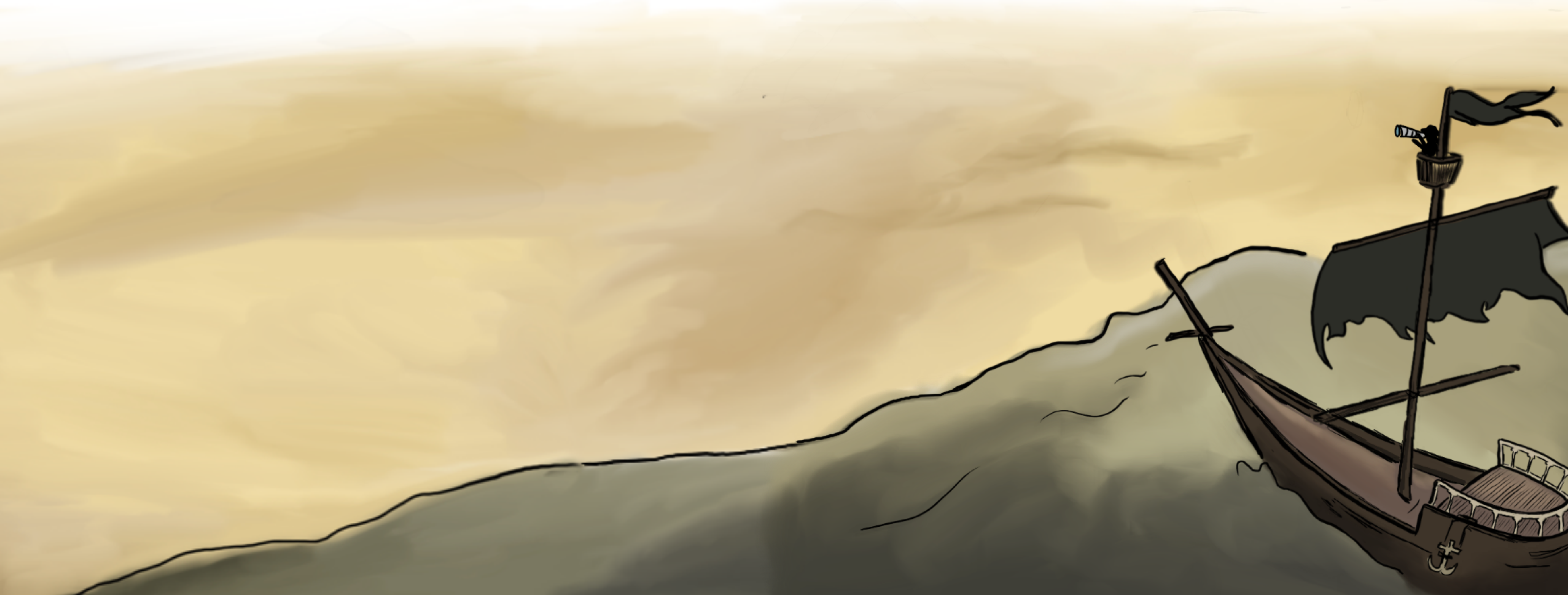
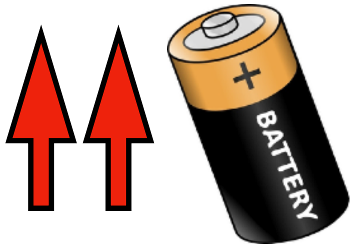


# Accessing High Energies

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{O}\left(\frac{\mathrm{Energy}}{\Lambda_{\mathrm{NP}}}\right)^n$$

Construction of Super colliders



ilc

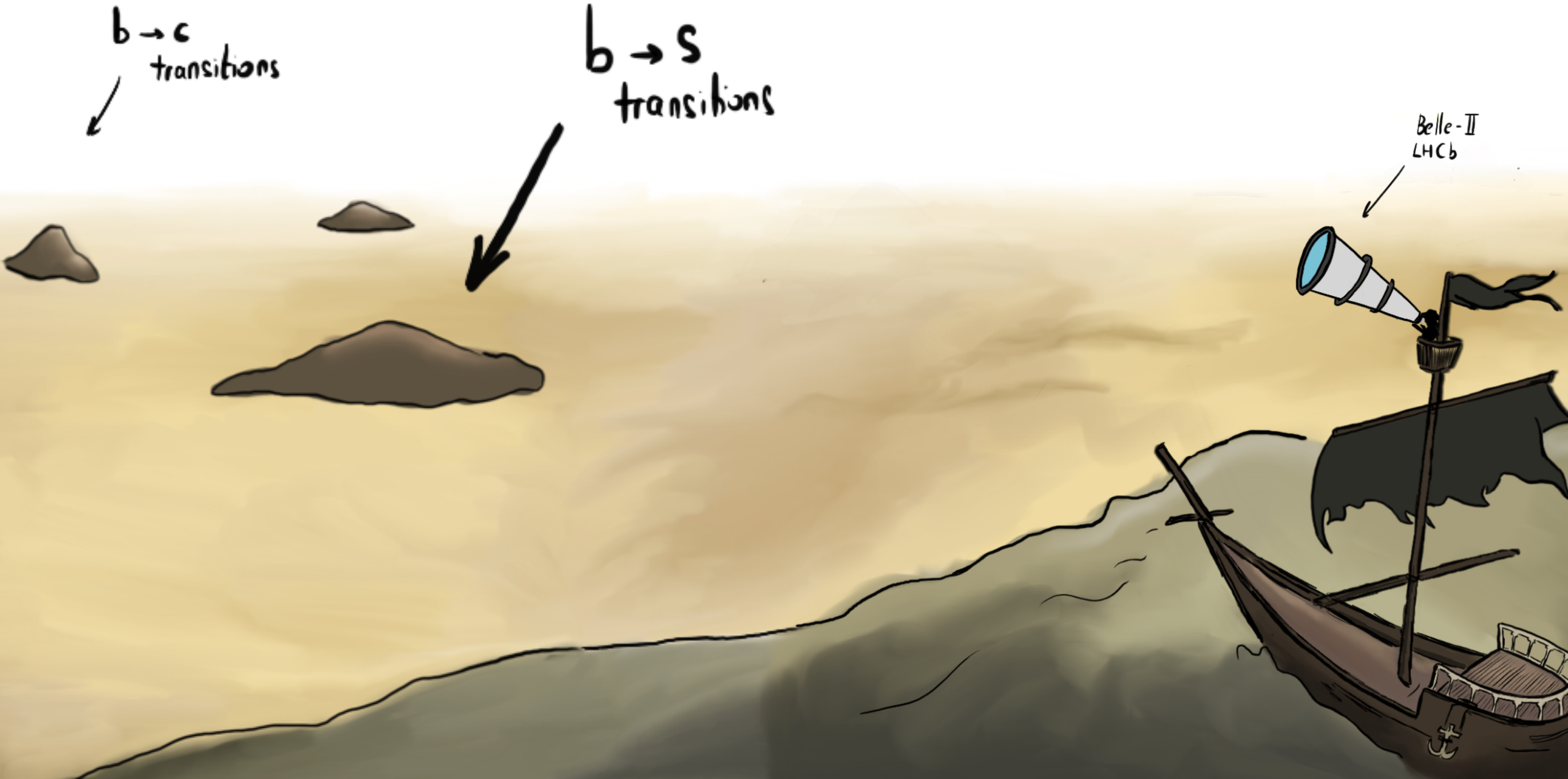
clic

Precision Physics

BaBar

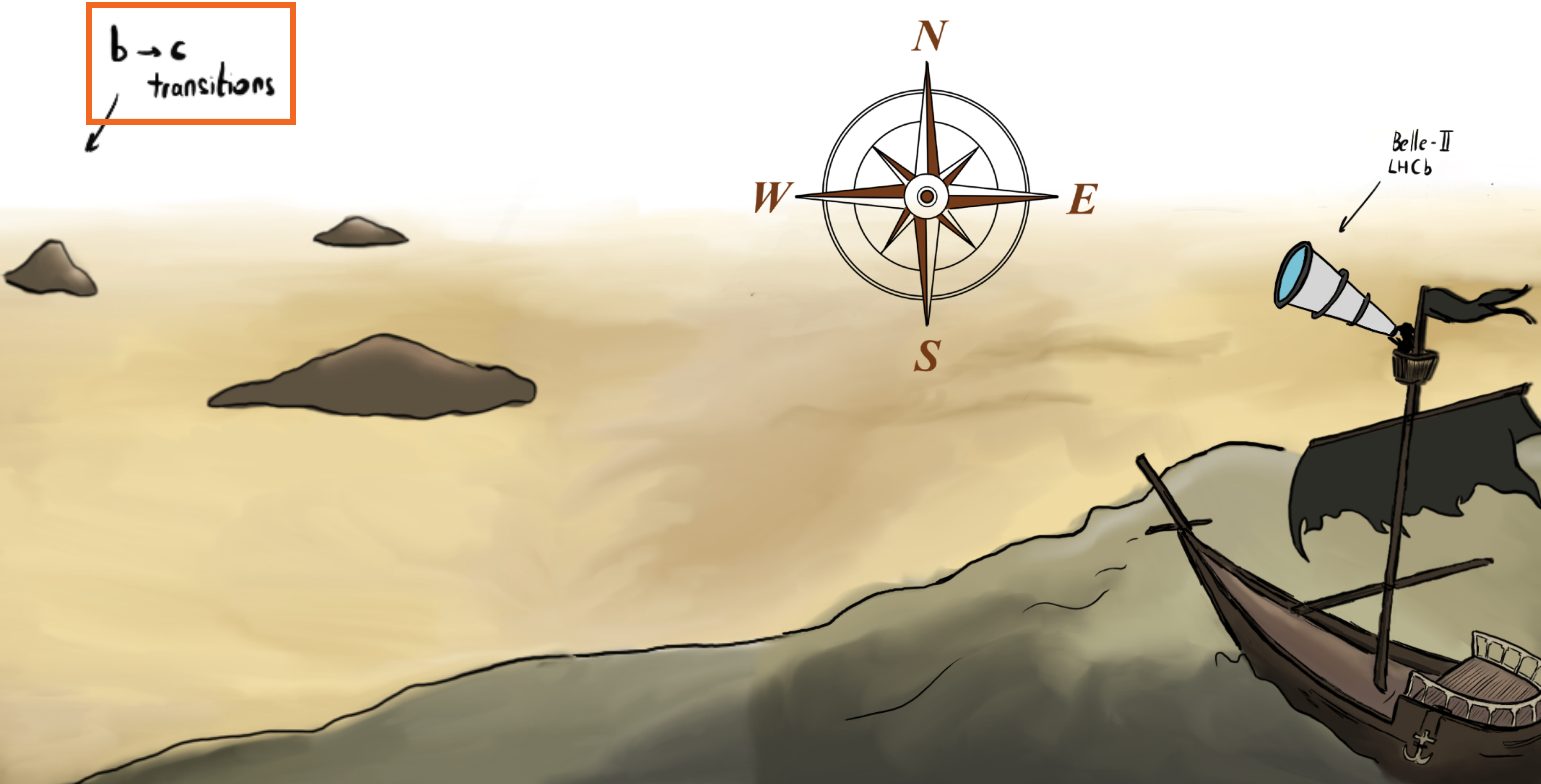
LHCb

Belle II


b → c transitions
b → s transitions
Belle-II
LHCb

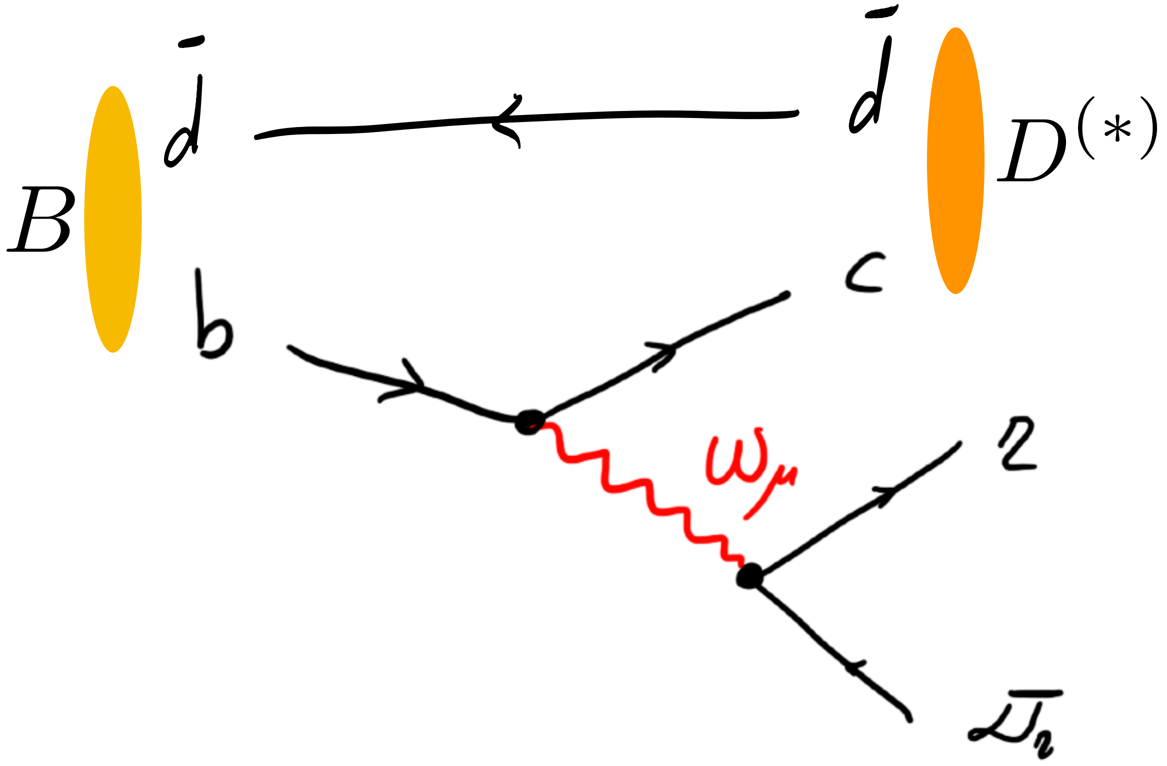
# Anomalies in $b \to c$ transitions

[Based on Refs. 1904.09311 and 2004.06726, in collaboration with Martin Jung, Rusa Mandal, Ana Peñuelas and Antonio Pich.]



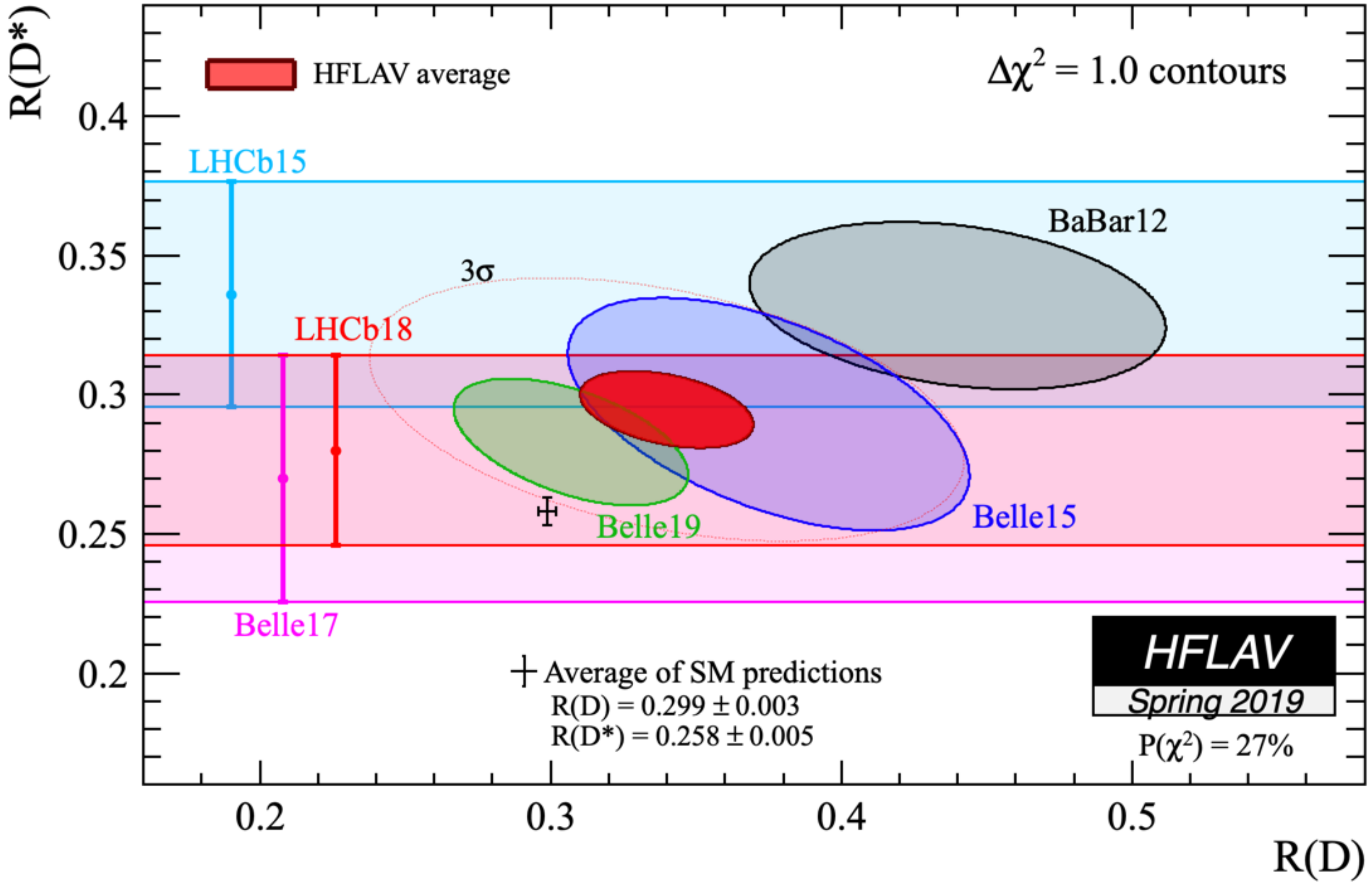
# Anomalies in $b \to c$ transitions

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



# Anomalies in $b \to c$ transitions

**Status 2021**



| | | | | |
|---|---|---|---|---|
| $3.9\,\sigma$ | $4.0\,\sigma$ | $3.9\,\sigma$ | $3.6\,\sigma$ | $3.1\,\sigma$ |
| 2015 | 2016 | 2017 | 2018 | 2019 |

[LHCb, 1506.08614, 1708.08856, 1711.02505]

[Belle, 1507.03233, 1607.07923, 1612.00529, 1709.00129, 1904.02440]

[BaBar, 1205.5442, 1303.0571]

# Anomalies in $b \to c$ transitions

Pattern of deviations in B-meson decays involving b to c transitions pointing to "the same direction"

- $\mathcal{R}_{D^{(*)}} \equiv \dfrac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)}$ **3.1 $\sigma$**

  HFLAV, up to date

- $\mathcal{R}_{J/\Psi} \equiv \dfrac{\mathcal{B}(B_c \to J/\Psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\Psi\mu\bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18$

  LHCb, 2017 **1.7 $\sigma$**

  $R_{J/\Psi\,SM} \sim 0.25 - 0.28$

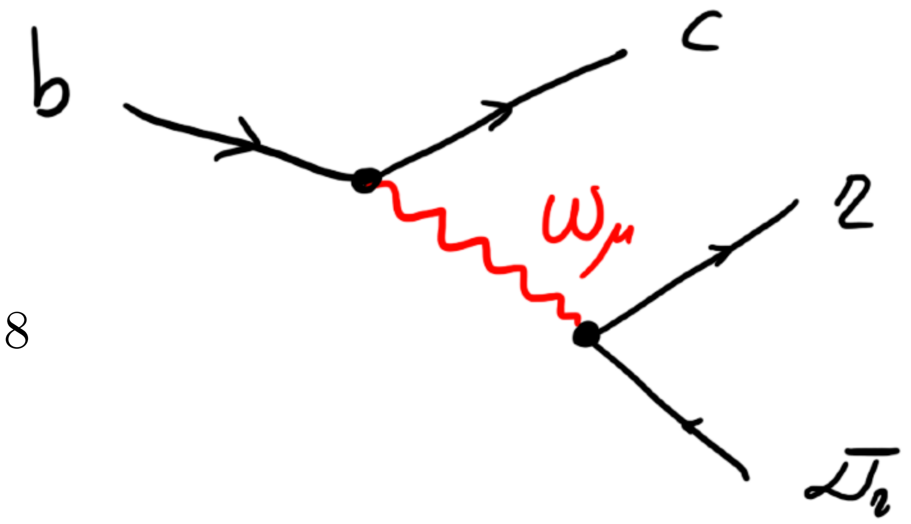
- $\bar{\mathcal{P}}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}$

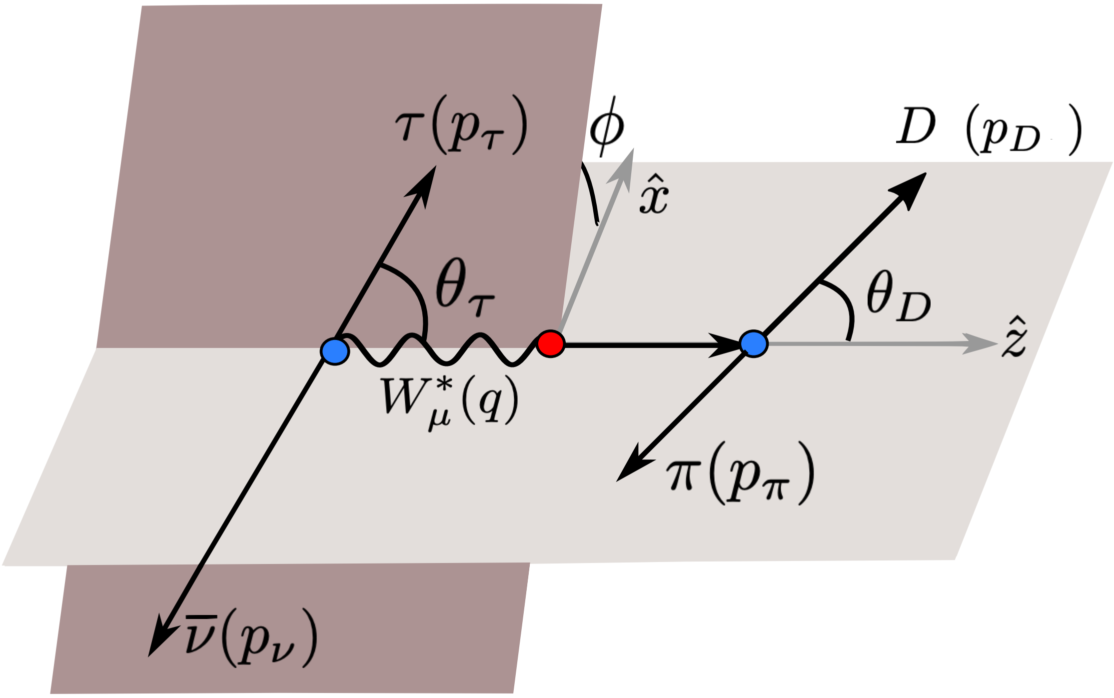
  Belle, 2016

  $\mathcal{P}_\tau(D^*)_{SM} = -0.499 \pm 0.003$

- $\bar{F}_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$ **1.6 $\sigma$**

  Belle, 2019

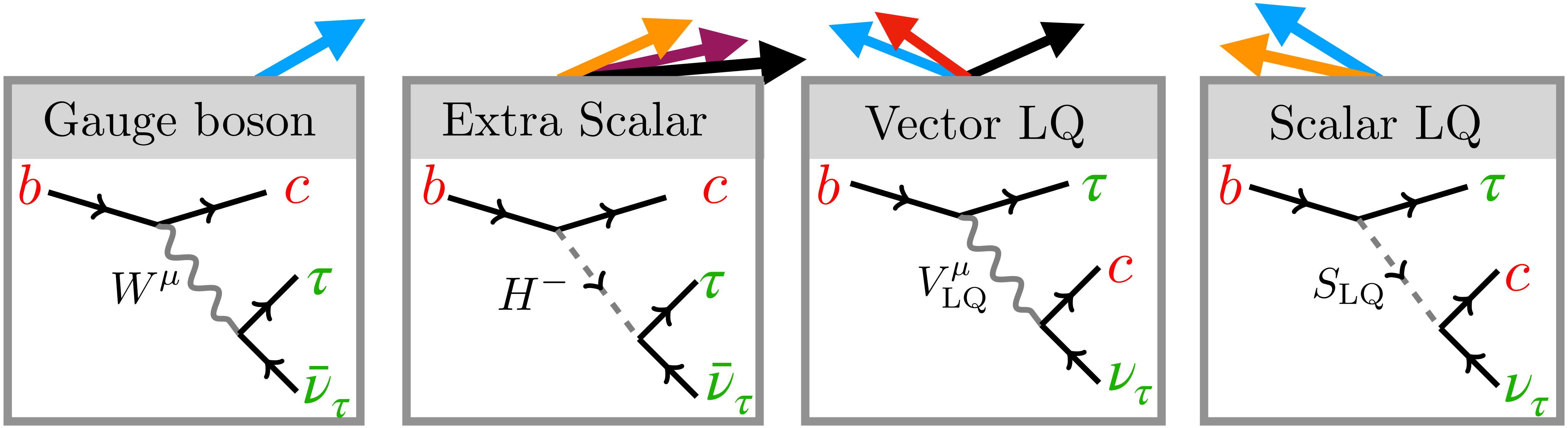




# Bottom-up approach

- Most general effective dim 6 Hamiltonian:

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



$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell),$$

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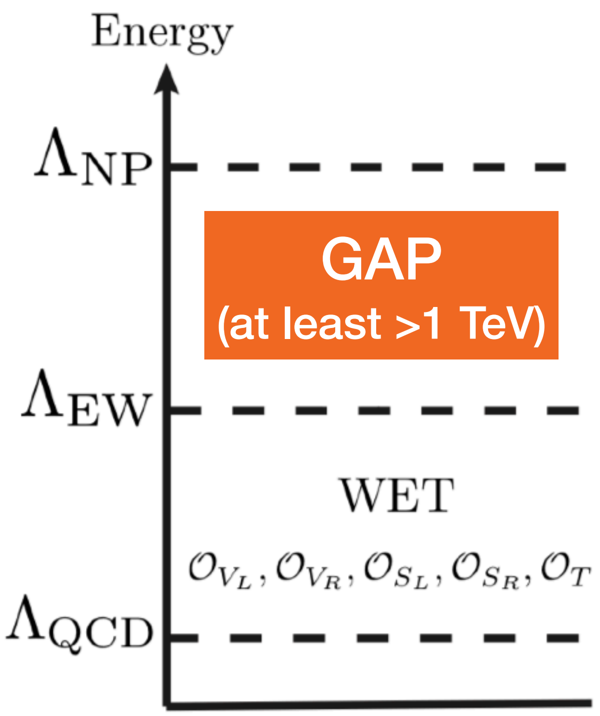
- Assumptions:

⇨ EFT ✓



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- Assumptions:

  - EFT ✓
  - New physics only in the third generation

NP effects negligible in $b \to c(e,\mu)\bar{\nu}_{(e,\mu)}$ analysis [Jung, Straub, 1801.01112]

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau),$$

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- Assumptions:
  - ⇨ EFT ✓
  - ⇨ New physics only in the third generation,
  - ⇨ $C_{V_R}$ lepton flavour universal $\Rightarrow C_{V_R}^{\tau} \sim 0$

$$C_{V_R}^{\ell} \equiv C_{V_R} + \mathcal{O}\left(\frac{v^4}{\Lambda_{\text{NP}}^4}\right)$$

Assuming SMEFT and no significant effect from NP in $b \to c(e,\mu)\bar{\nu}_{(e,\mu)}$ [Jung, Straub, 1801.01112]

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^{\mu}P_L b)(\bar{\tau}\,\gamma_{\mu}P_L\nu_{\tau}),$$

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- Assumptions:
    - EFT ✓
    - New physics only in the third generation,
    - $C_{V_R}$ lepton flavour universal $\Rightarrow C_{V_R}^{\tau} \sim 0$
    - CP conserving W.C.

      Fitted complex W.C. without significant improvement

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^{\mu} P_L b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^{\mu} P_R b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}),$$

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- Assumptions:

  - ⇨ EFT ✓
  - ⇨ New physics only in the third generation,
  - ⇨ $C_{V_R}$ lepton flavour universal $\Rightarrow C^{\tau}_{V_R} \sim 0$
  - ⇨ CP conserving W.C.

$\}$ $\boxed{\text{4 d.o.f.}}$

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau),$$

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- Inputs:

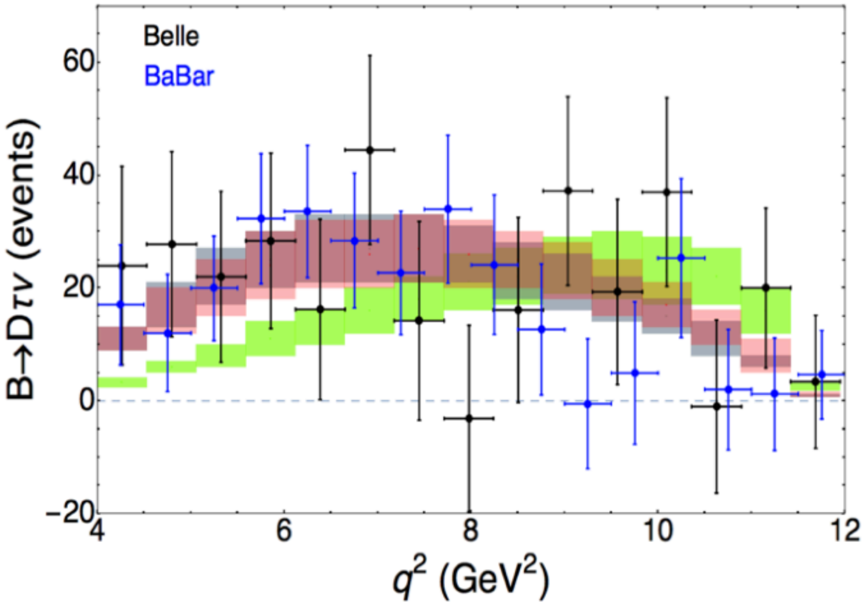
  ⇨ $\mathcal{R}_D$

  ⇨ $\mathcal{R}_{D^*}$

  ⇨ $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$

$$\tilde{\Gamma}(B \to D^{(*)}\tau\bar{\nu}_\tau) = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)_{\text{bin}}}{\sum_{\text{all bins}}\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)_{\text{bin}}}$$

[Belle, 1507.03233]



[BaBar, 1303.0571]

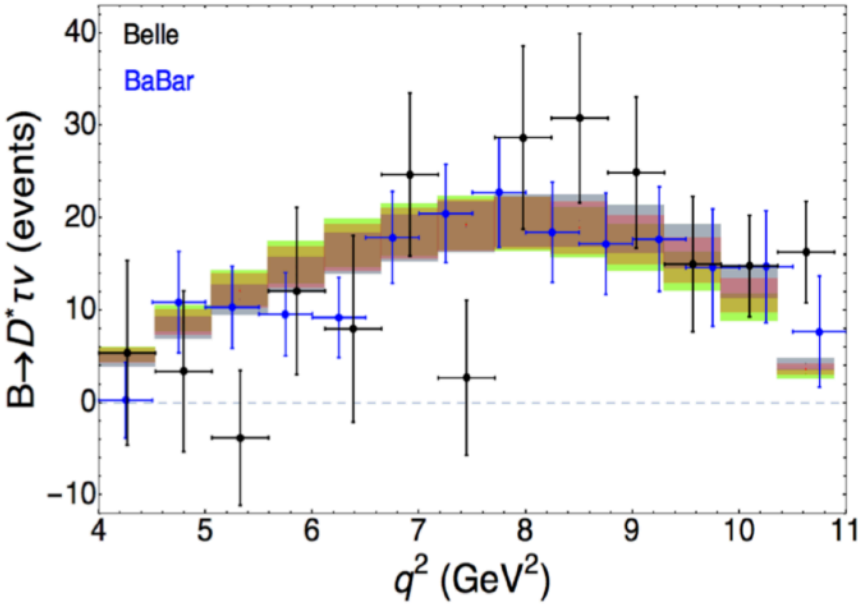


Image borrowed from [Celis et al., 2016]

# Bottom-up approach

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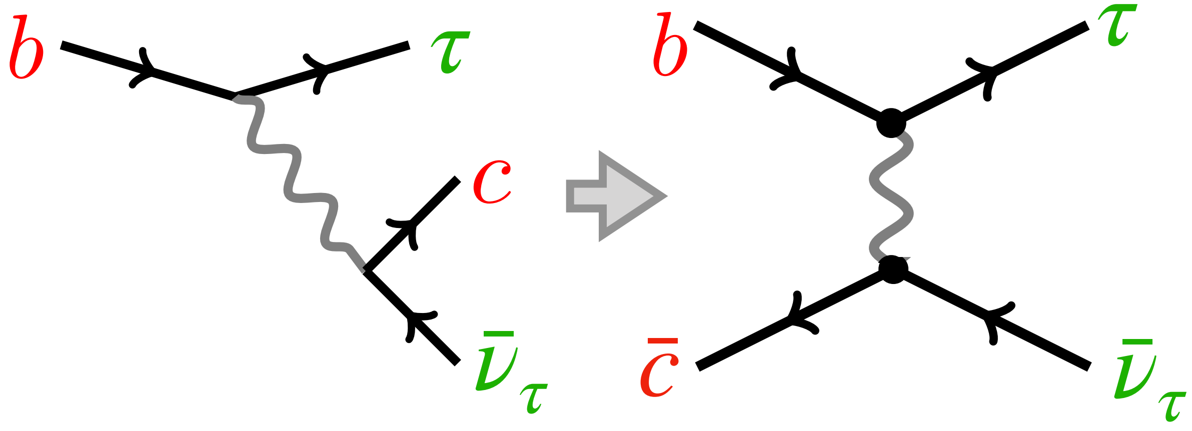
- Inputs:
  - $\mathcal{R}_D$
  - $\mathcal{R}_{D^*}$
  - $\Gamma(B\to D^{(*)}\tau\bar{\nu}_\tau)$
  - $B_c\to\tau\bar{\nu}_\tau$

$B\to D^{(*)}\tau\bar{\nu}$

$B_c\to\tau\bar{\nu}$



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

# Bottom-up approach

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- Inputs:

  - $\mathcal{R}_D$
  - $\mathcal{R}_{D^*}$
  - $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
  - $B_c \to \tau\bar{\nu}_\tau$

- Bc lifetime:

$\Rightarrow \text{Br}(B_c \to \tau\bar{\nu}_\tau) \leq 30 - 40\%$

[Alonso et al., 2016]

- Bound LEP Z peak:

[Akeroyd et al., 2017]

$\Rightarrow \text{Br}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$

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

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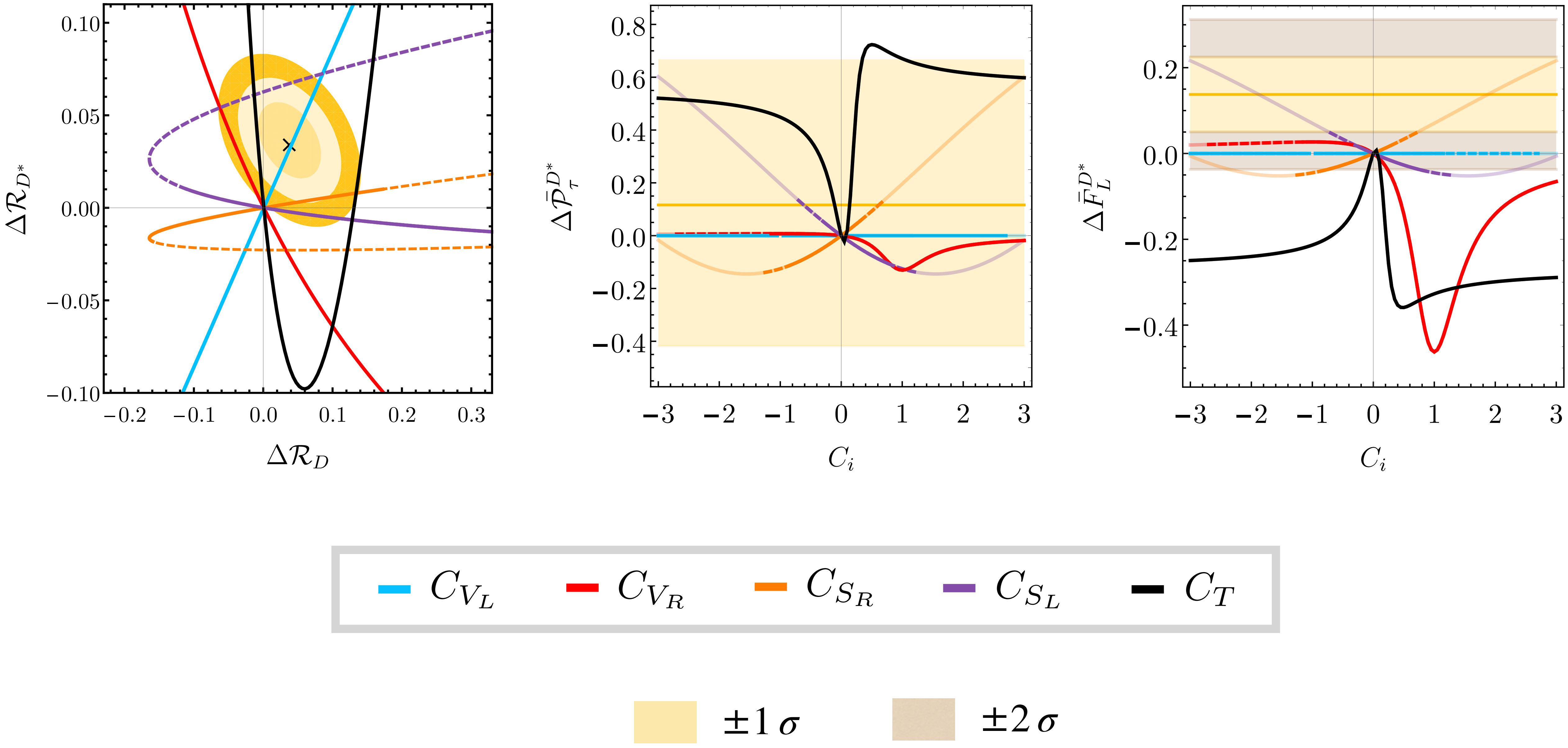
- Inputs:

  - ⇨ $\mathcal{R}_D$
  - ⇨ $\mathcal{R}_{D^*}$
  - ⇨ $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
  - ⇨ $B_c \to \tau\bar{\nu}_\tau$
  - ⇨ $F_L^{D^*}$

# Fit-independent analysis



# Fit-independent analysis

$$\Rightarrow \mathcal{R}_{D^*} = \mathcal{R}_{D^*}[\underbrace{(1 + C_{V_L} - C_{V_R})}_{\text{axial}\equiv C_A}, \underbrace{(C_{S_R} - C_{S_L})}_{\text{pseudo-scalar}\equiv C_P}, C_T]$$

- Inputs:

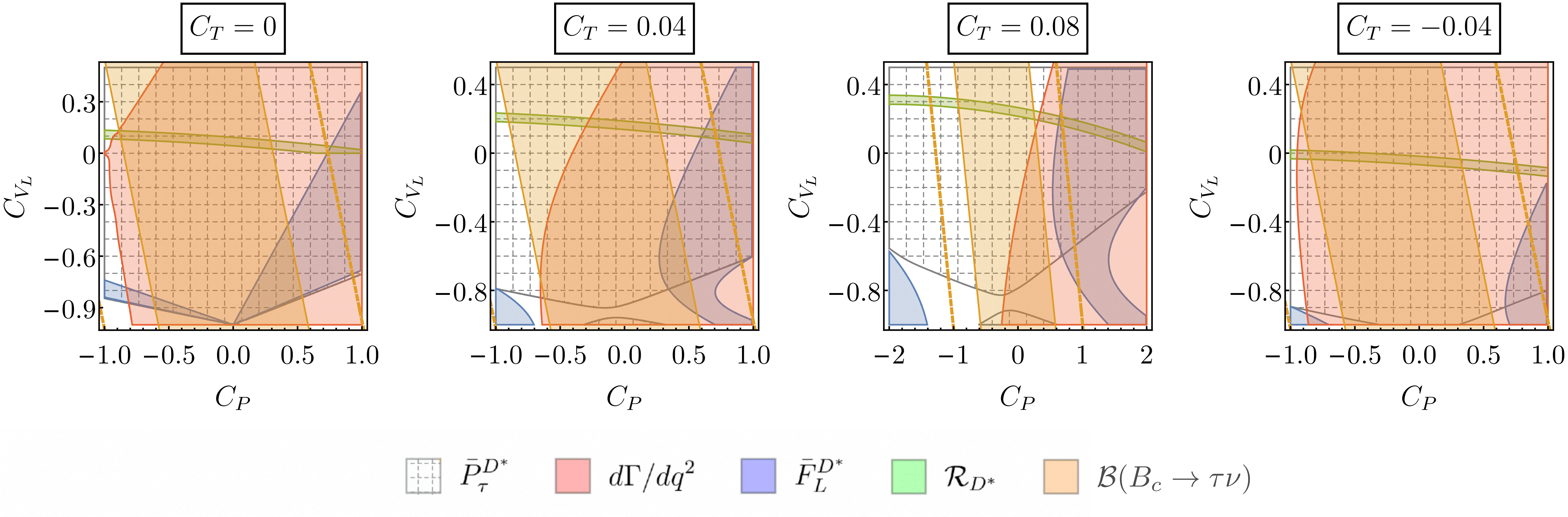
⇨ $\mathcal{R}_{D^*}$ ( $C_A$ ) $C_P$ $C_T$

⇨ $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$

⇨ $B_c \to \tau\bar{\nu}_\tau$ $C_A$ $C_P$

⇨ $F_L^{D^*}$ $C_A$ $C_P$ $C_T$

# Fit-independent analysis



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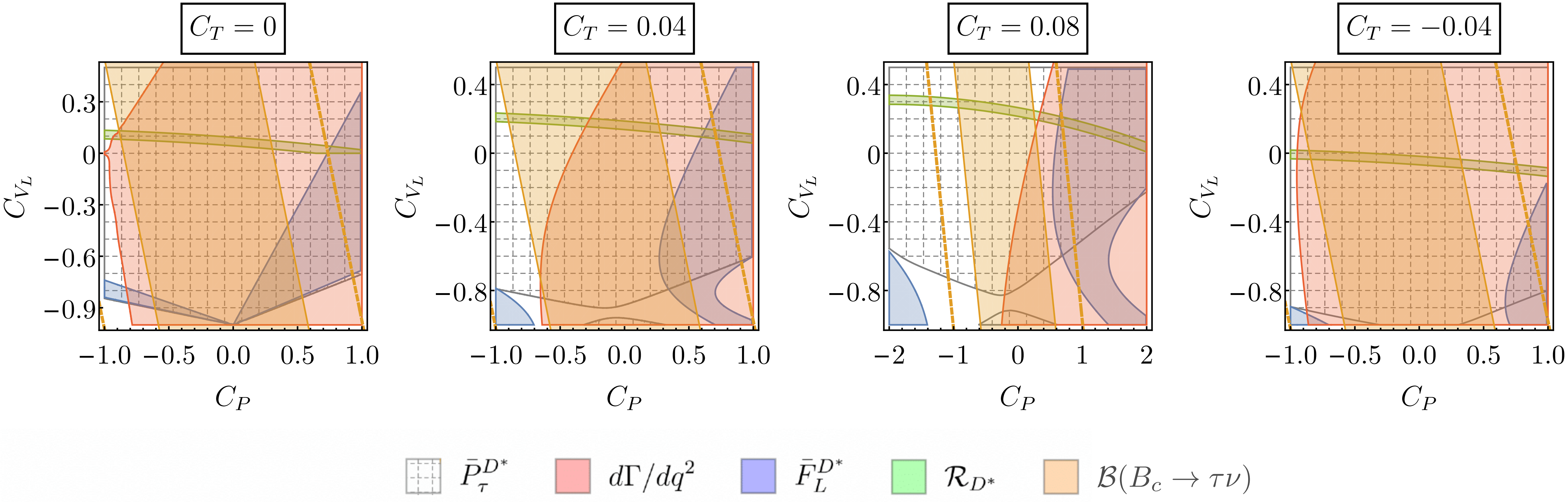

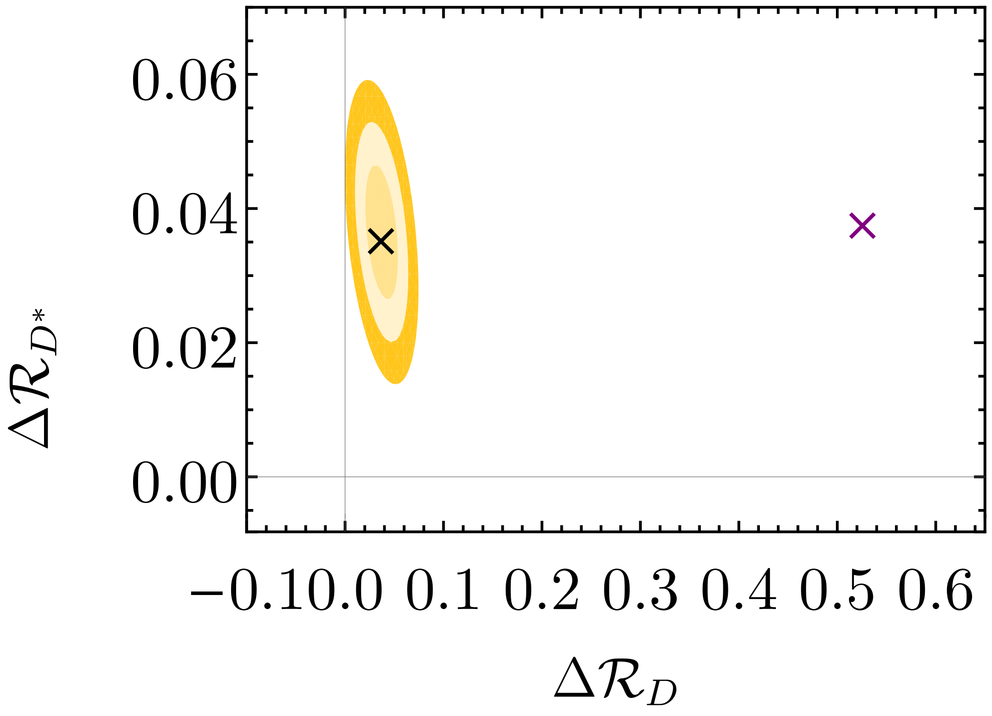

# Global Fit: inputs

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- Inputs:

⇨ $\mathcal{R}_D$

⇨ $\mathcal{R}_{D^*}$

⇨ $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$

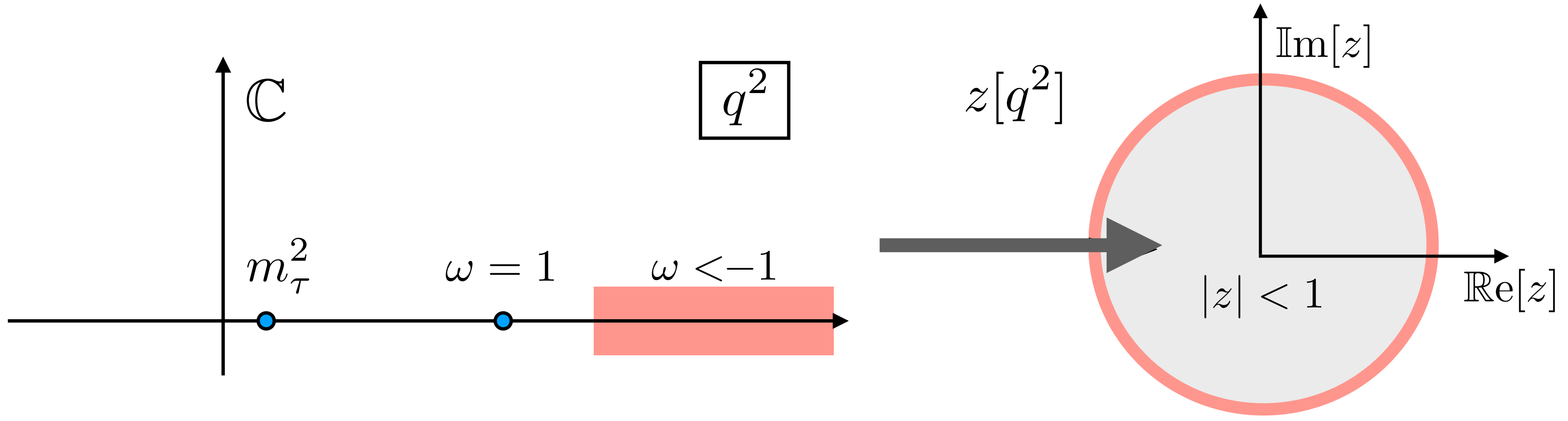
⇨ $B_c \to \tau\bar{\nu}_\tau$

⇨ $F_L^{D^*}$

$$\chi^2 = \underbrace{\chi^2_{\text{exp}}}_{\substack{\mathscr{R}_D,\,\mathscr{R}_{D^*}\ 2\text{ d.o.f.} \\ \Gamma(B\to D^{(*)})\ 58\text{ d.o.f.} \\ F_L^{D^*}\ 1\text{ d.o.f.}}} + \underbrace{\chi^2_{FF}}_{10\text{ d.o.f.}}$$

# Global fit: Form Factors

$$\mathcal{O}(\alpha_s,\ 1/m_{b,c},\ \text{and partially } 1/m_c^2)$$



Model-independent inputs
(No use of experimental data)

- Light-Cone Sum-Rules
- QCD Sum-Rules
- Lattice QCD

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

$\rho^2, c, d$: $\xi(q^2) \supset \mathcal{O}(z^4)$

$\chi_2(1), \chi_2'(1), \chi_3'(1), \eta(1), \eta'(1)$: $\mathcal{O}(1/m_{c,b})$

$l_1(1), l_2(1)$: $\mathcal{O}(1/m_c^2)$

# Global Fit: Goodness of the fit

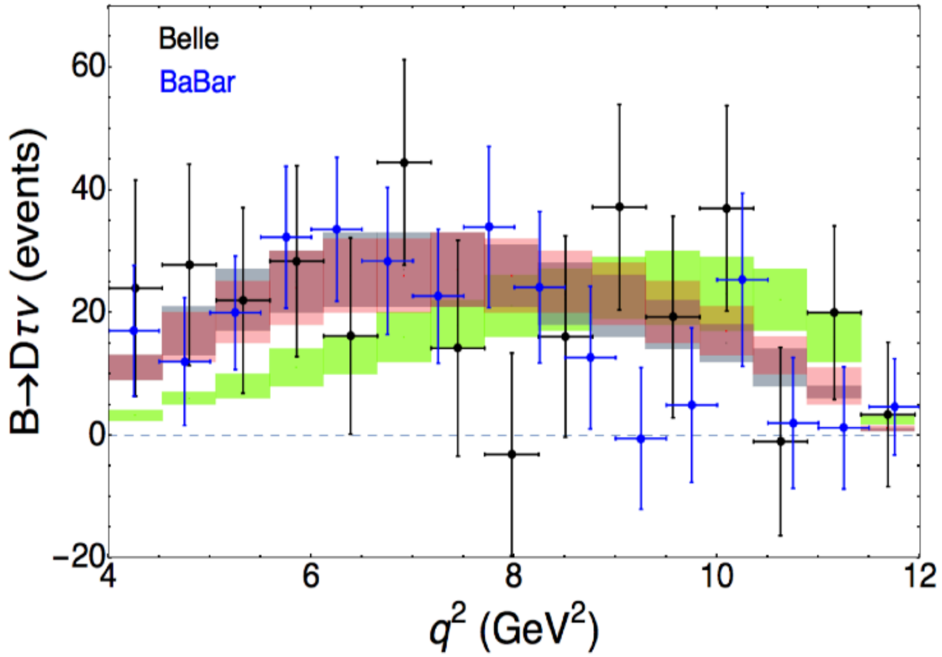
- Standard Model $(\forall C_i = 0)$ $\chi^2_{SM} = 65.5/57$ d.o.f.

⇨ $\chi^2_{R_D,R_{D^*}} = 22.6/2$ → Reproduce the well-known tension!

⇨ $\chi^2_{\Gamma[q^2]} = 43/54$

Conservative uncertainties

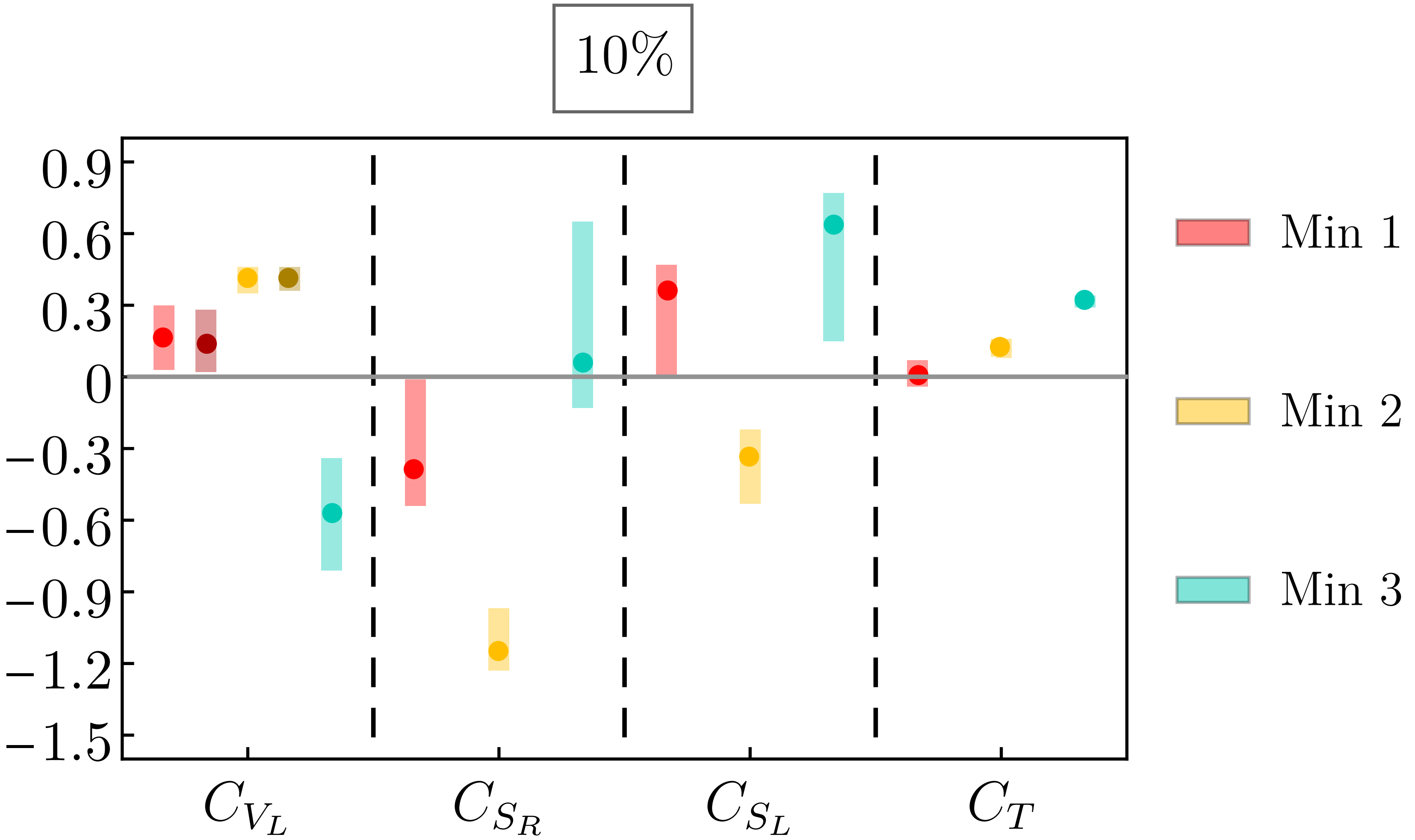
Misleading $\chi^2$ contribution



Quality of the fit: Pull w.r.t. the SM

# Global Fit: Results

- SM: $\chi^2_{SM} = 65.5\,/\,57$ d.o.f.
- New Physics: $\chi^2_{min1} = 34.1\,/\,53$ d.o.f. $\chi^2_{min2} = 37.5\,/\,53$ d.o.f. $\chi^2_{min3} = 58.6\,/\,53$ d.o.f.



# Global Fit: Results

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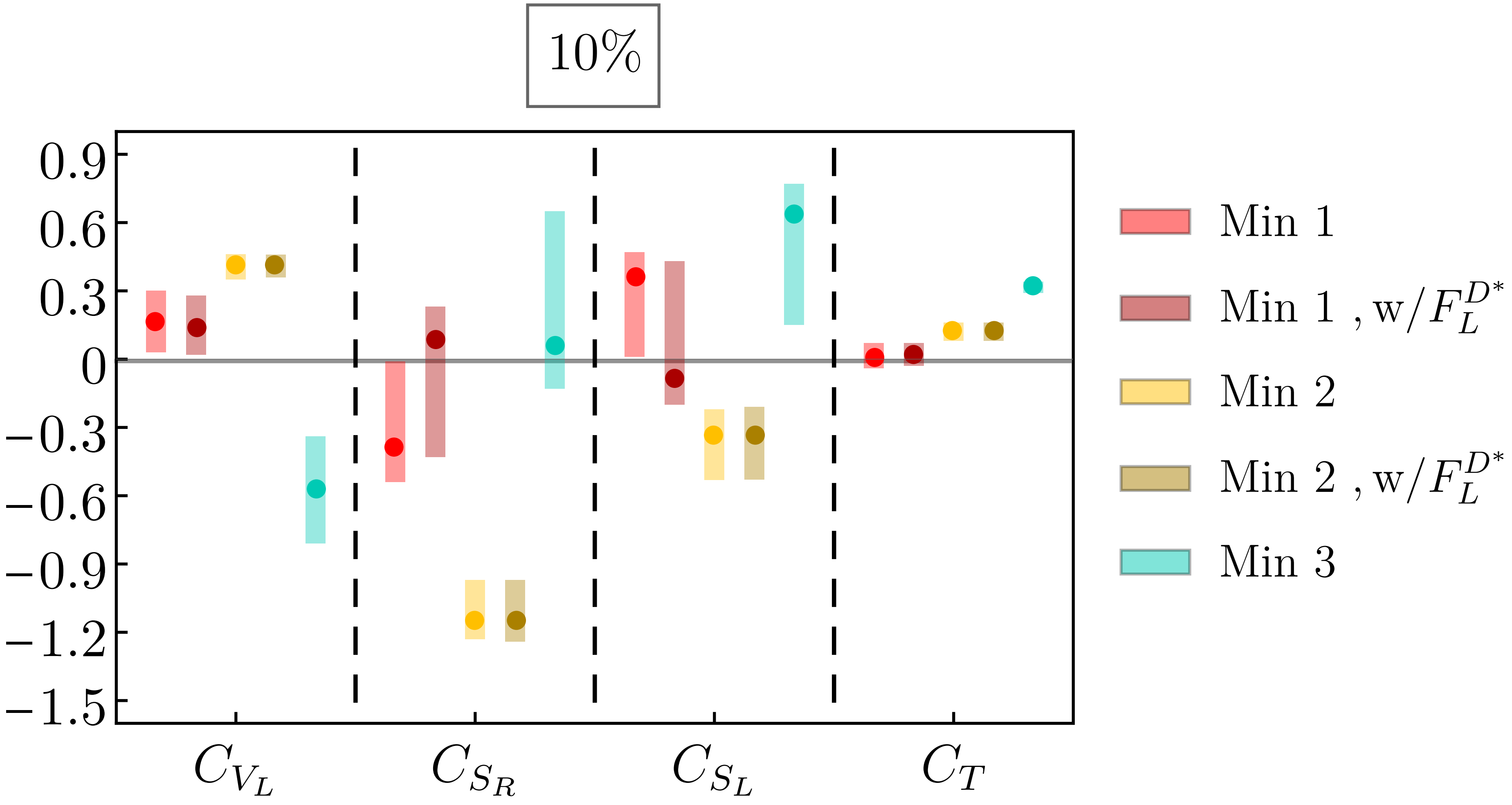
- New Physics: $\chi^2_{min1} = 34.1\,/\,53$ d.o.f. $\qquad$ $\chi^2_{min2} = 37.5\,/\,53$ d.o.f. $\qquad$ ~~$\chi^2_{min3} = 58.6\,/\,53$ d.o.f.~~

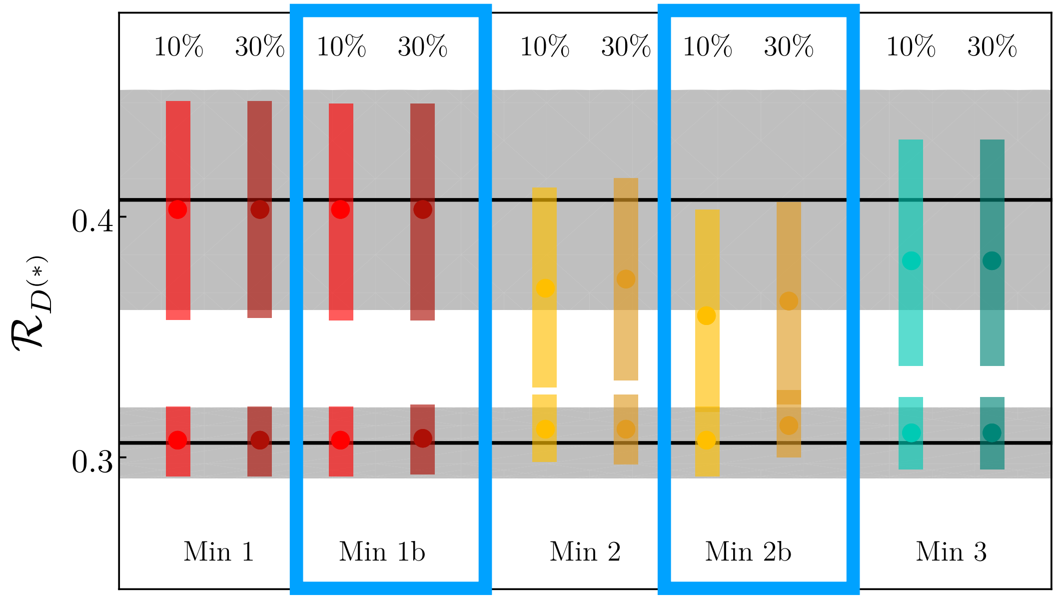
$$\chi^2_{min1} = 34.1\,/\,53 \text{ d.o.f.} \Downarrow \chi^2_{min1b} = 37.4\,/\,54 \text{ d.o.f.}$$

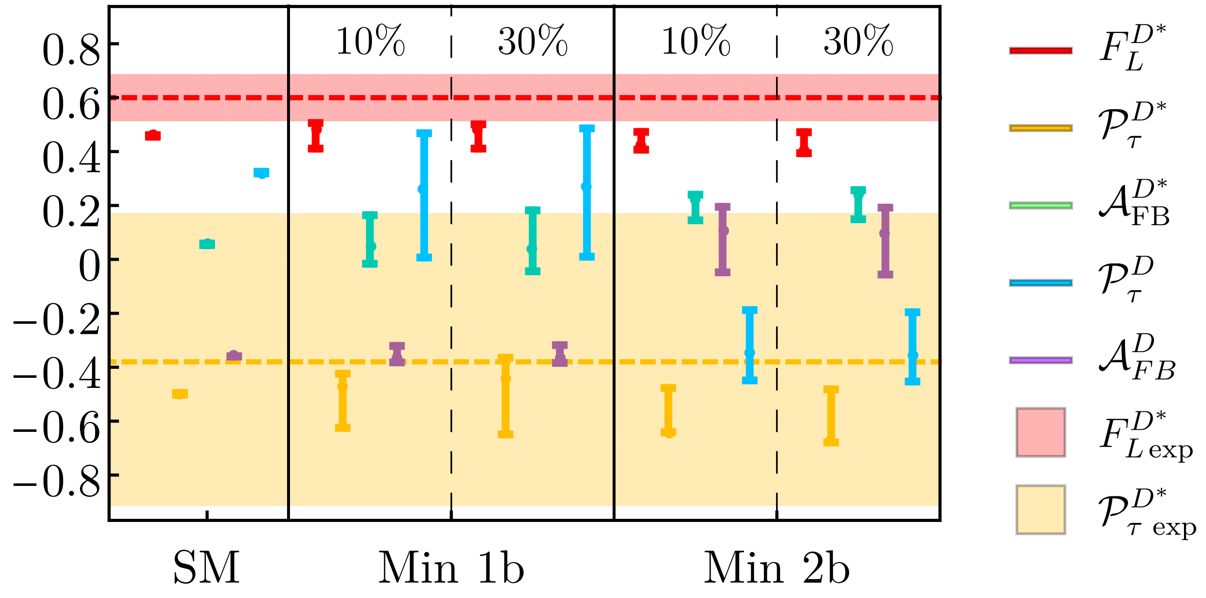
$$\chi^2_{min2} = 37.5\,/\,53 \text{ d.o.f.} \Downarrow \chi^2_{min2b} = 40.1\,/\,54 \text{ d.o.f.}$$

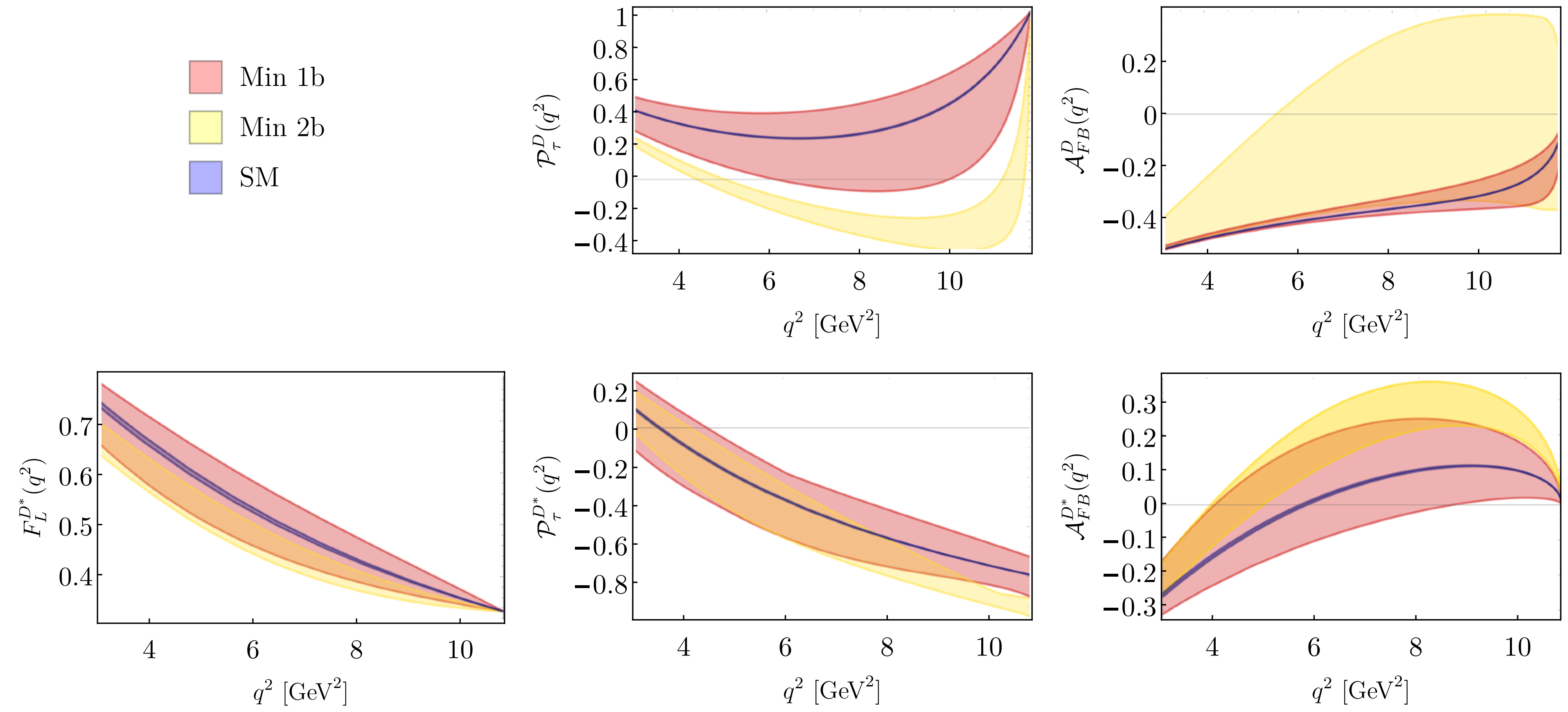


# Global Fit: Predictions

Integrated observables

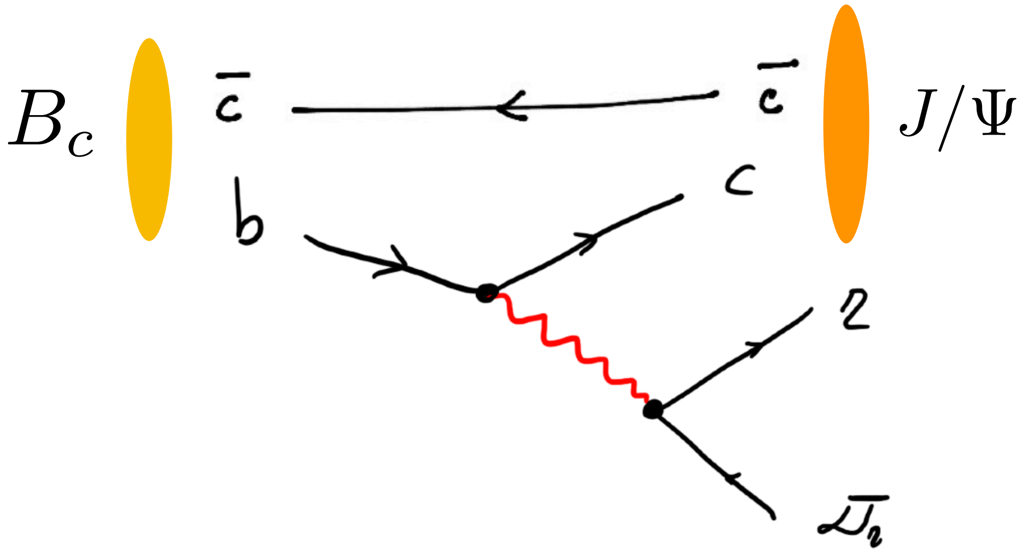


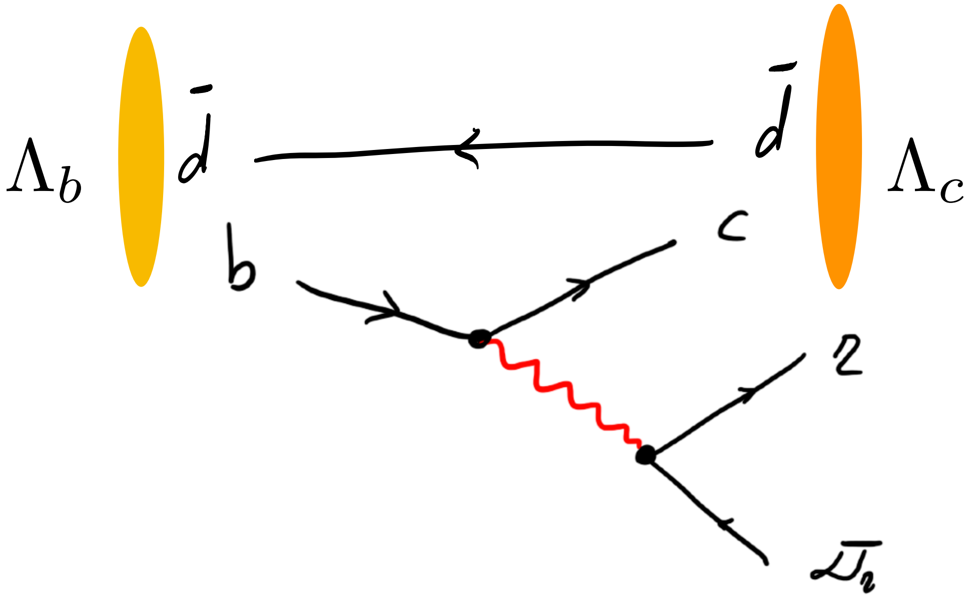




Differential angular observables

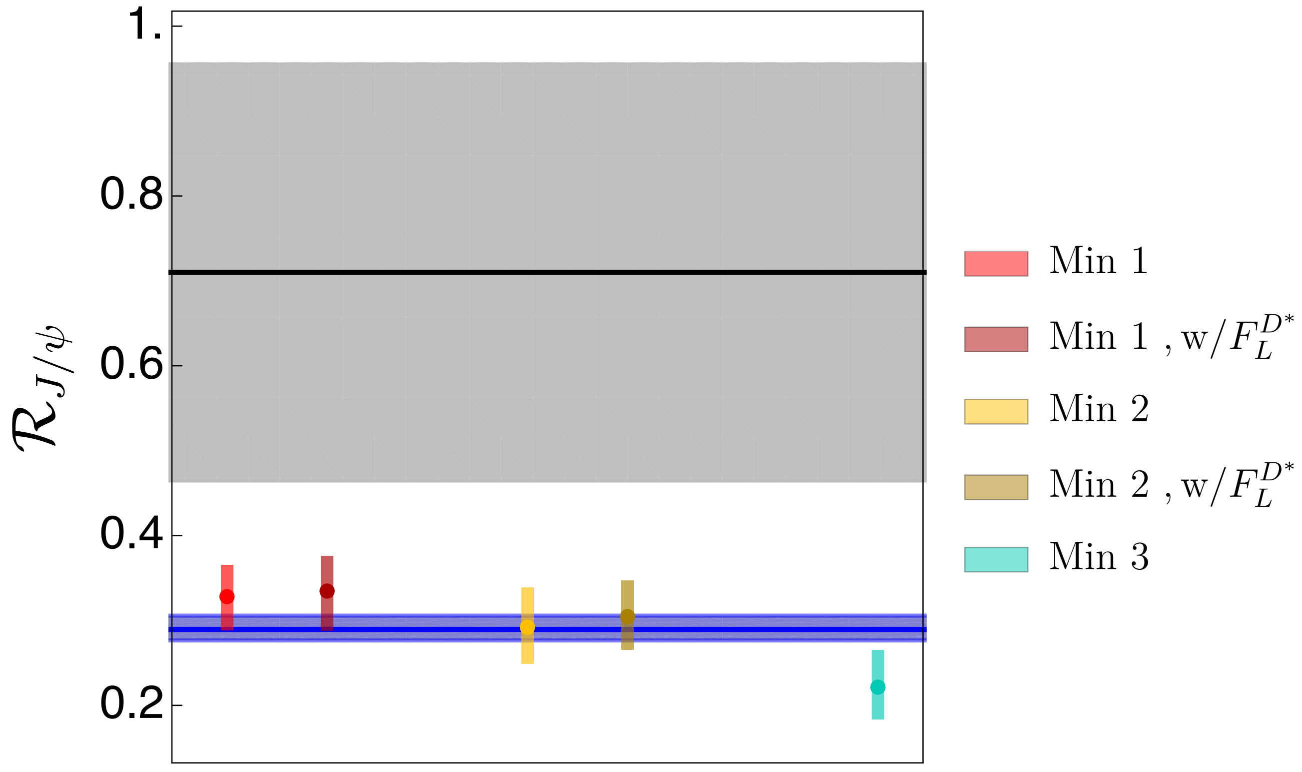
# Global Fit: Predictions

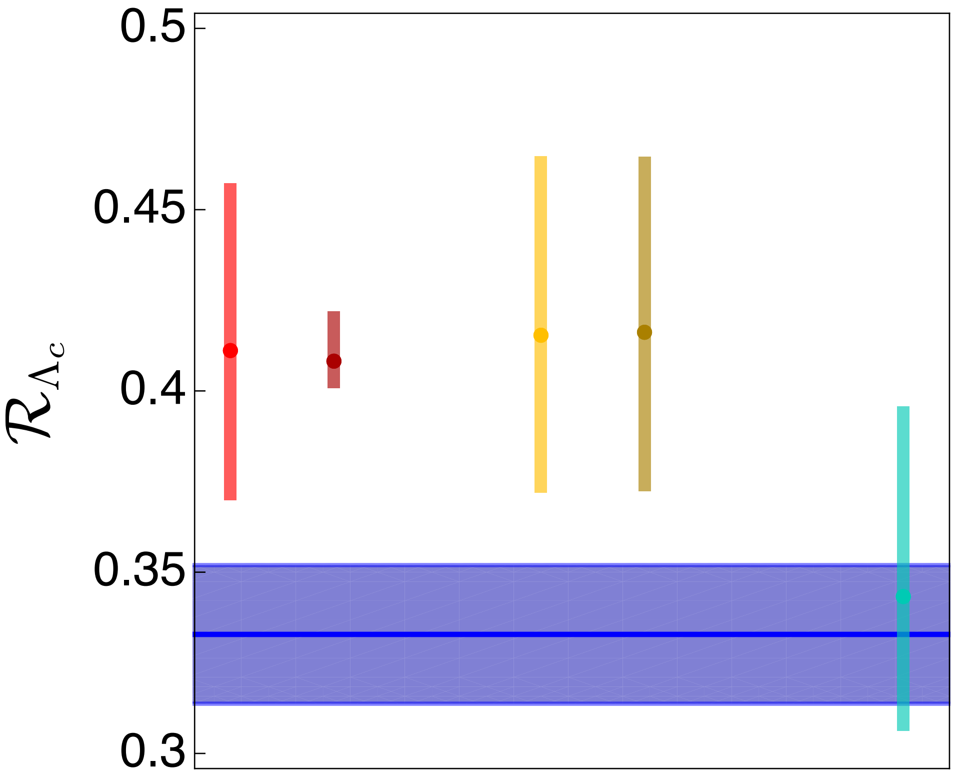




$$\mathcal{R}_{J/\Psi} = \frac{\mathcal{B}(B_c \to J/\Psi \tau \bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\Psi \ell \bar{\nu}_\ell)}$$

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

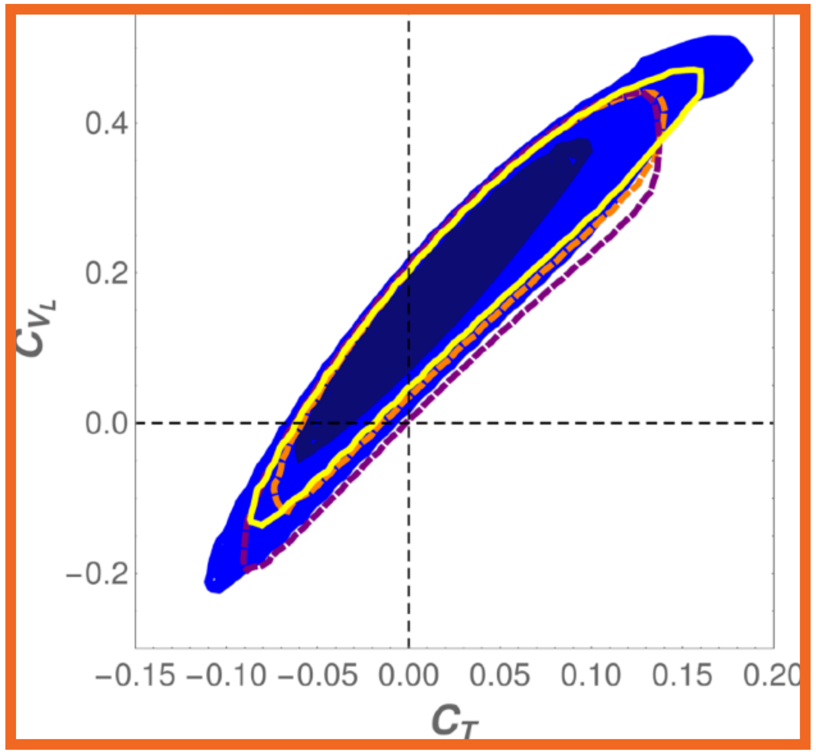




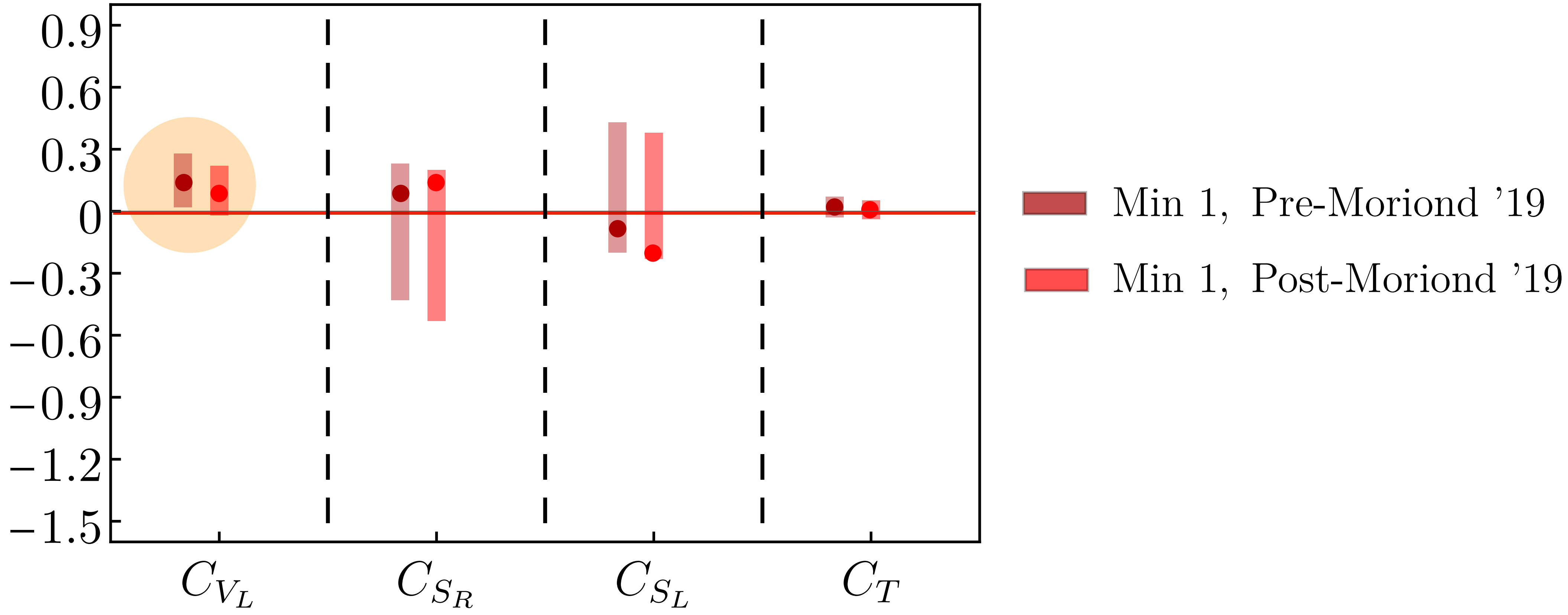
# Global Fit: Results

- SM: $\chi^2_{SM} = 65.5\,/\,57$ d.o.f.
- New Physics:

$$\boxed{\chi^2_{min1b} = 37.4\,/\,54 \text{ d.o.f.}}$$



10%



# What is going on?

- Theory assumptions:
  - ⇨ EFT
  - ⇨ New physics only in the third generation
  - ⇨ $C_{V_R}$ flavour universal
  - ⇨ CP conserving W.C.
- Experimental measurements

An unidentified or underestimated systematic uncertainty...

# What is going on?

- Theory assumptions:
  - ⇨ EFT
  - ⇨ New physics only in the third generation of leptons
  - ⇨ $C_{V_R}$ flavour universal
  - ⇨ CP conserving W.C.

No significant improvement of $\chi^2$
by promoting the W.C. to be complex

- Experimental measurements

An unidentified or underestimated systematic uncertainty...

# What is going on?

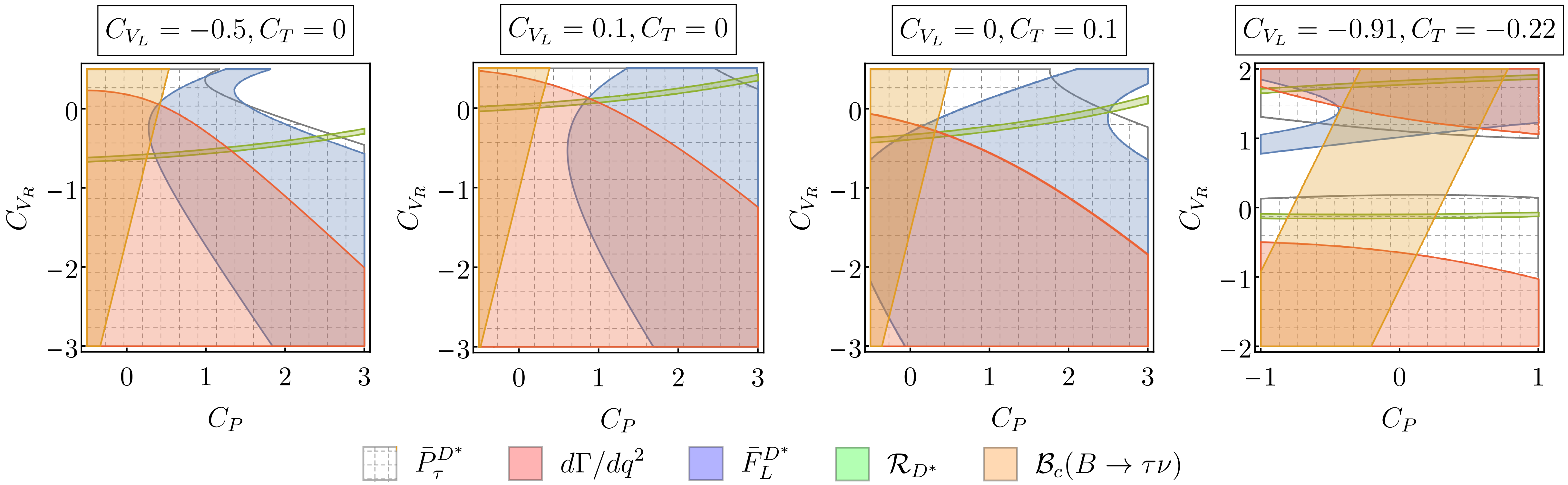
- Theory assumptions:
  - EFT
  - New physics only in the third generation of leptons
  - ~~$C_{V_R}$ flavour universal~~
  - CP conserving W.C.

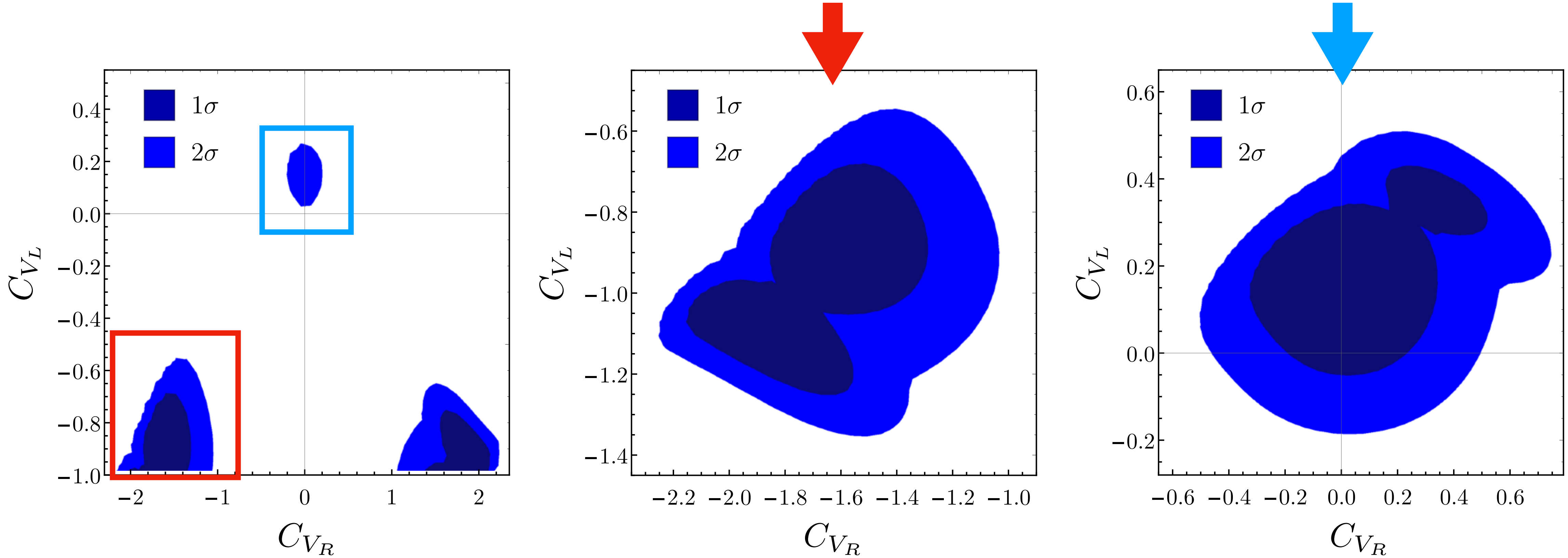
EW breaking is non-linear?

- Experimental measurements

An unidentified or underestimated systematic uncertainty...

# Global fit + $C_{V_R}$





# What is going on?

- Theory assumptions:

  - ⇨ ~~EFT~~    New light d.o.f.

  - ⇨ New physics only in the third generation of leptons

  - ⇨ $C_{V_R}$ flavour universal

  - ⇨ CP conserving W.C.

- Experimental measurements

  An unidentified or underestimated systematic uncertainty...

# What is going on?

- Theory assumptions:
  - EFT    New light d.o.f.

    [C. Bobeth et al., a month ago]
  - New physics only in the third generation of leptons    **??**
  - $C_{V_R}$ flavour universal
  - CP conserving W.C.
- Experimental measurements

  An unidentified or underestimated systematic uncertainty...

# What is going on?

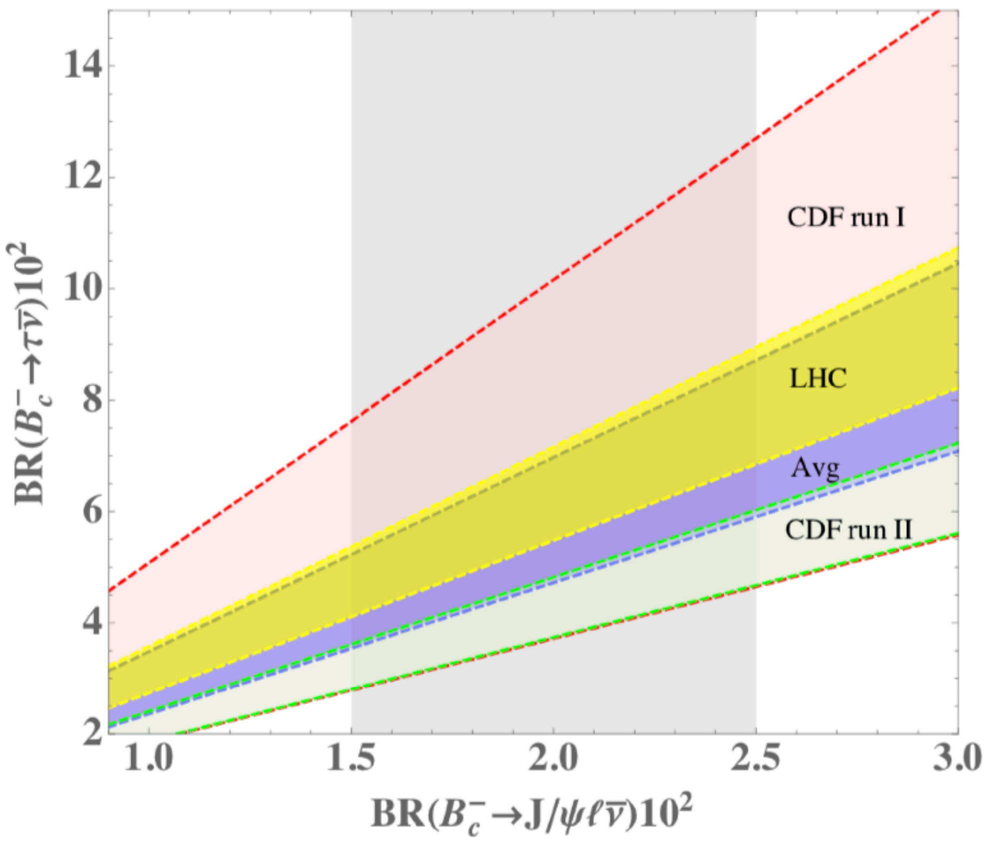
- Theory assumptions:
  - ⇨ EFT New light d.o.f.
  - ⇨ New physics only in the third generation of leptons
  - ⇨ $C_{V_R}$ flavour universal
  - ⇨ CP conserving W.C.
- Experimental measurements

An unidentified or underestimated systematic uncertainty...

# Bounds on Br($B_c \to \tau\bar{\nu}$)

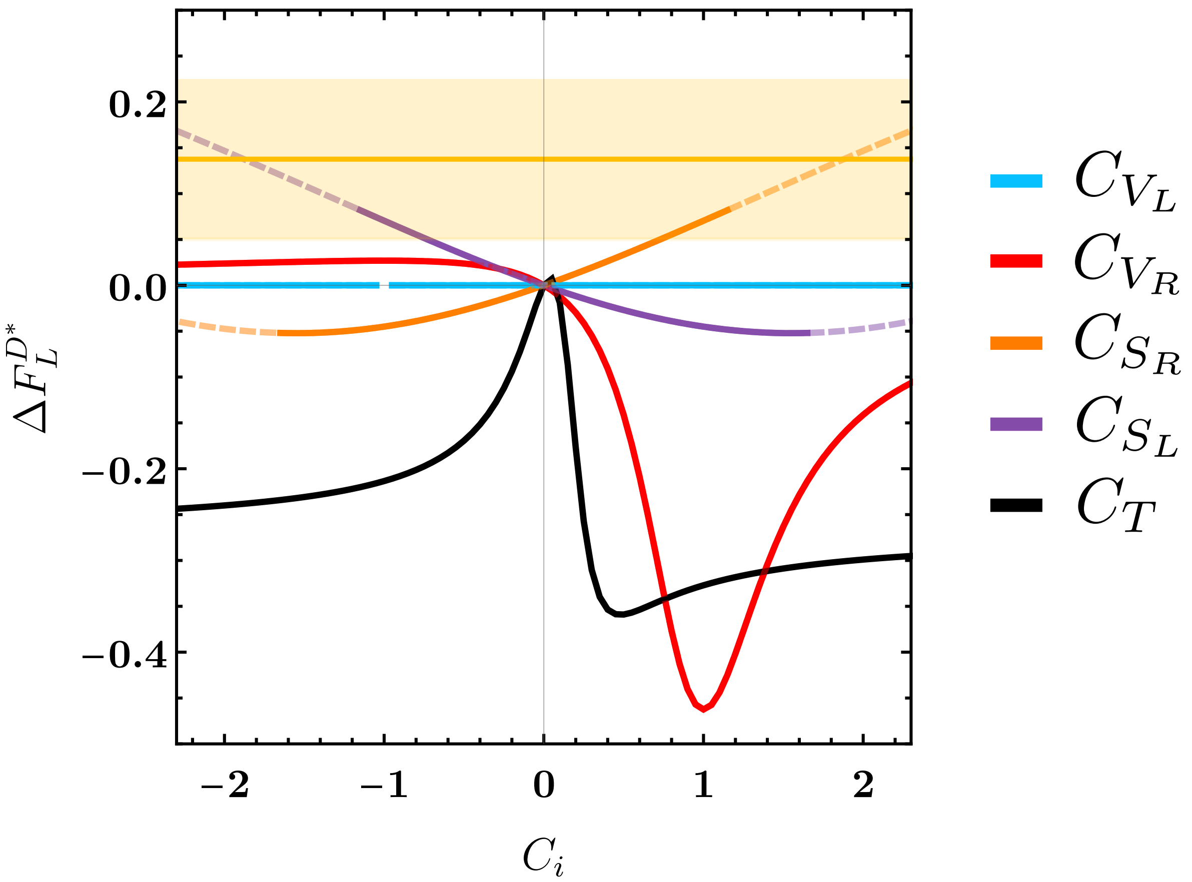
Resurrection of the scalar candidates **?**

$\mathcal{B}(B_c \to \tau\bar{\nu}) < 10\%$



[Akeroyd et al., 2017]

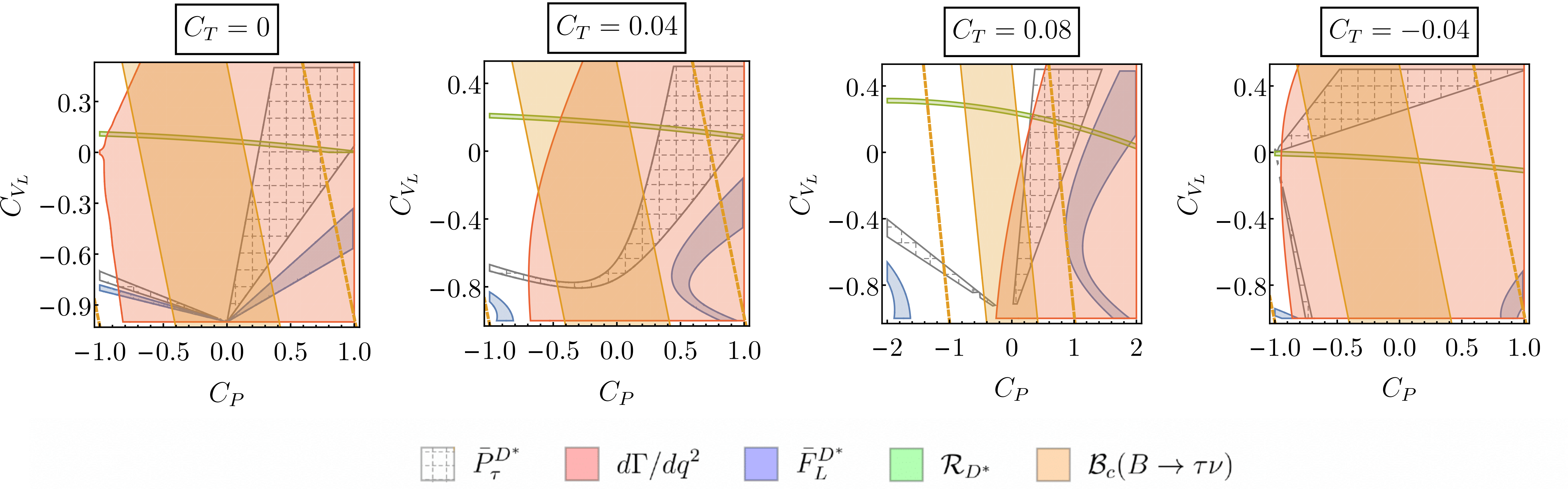
$\mathcal{B}(B_c \to \tau\bar{\nu}) < 60\%$



See discussion in [M. Blanke et al., 2019]

# Implications of new measurements?

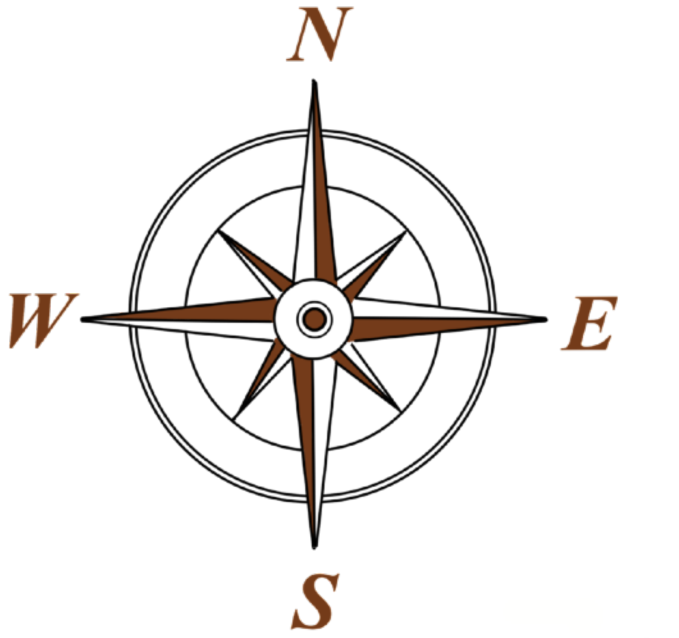
[Speculating...]



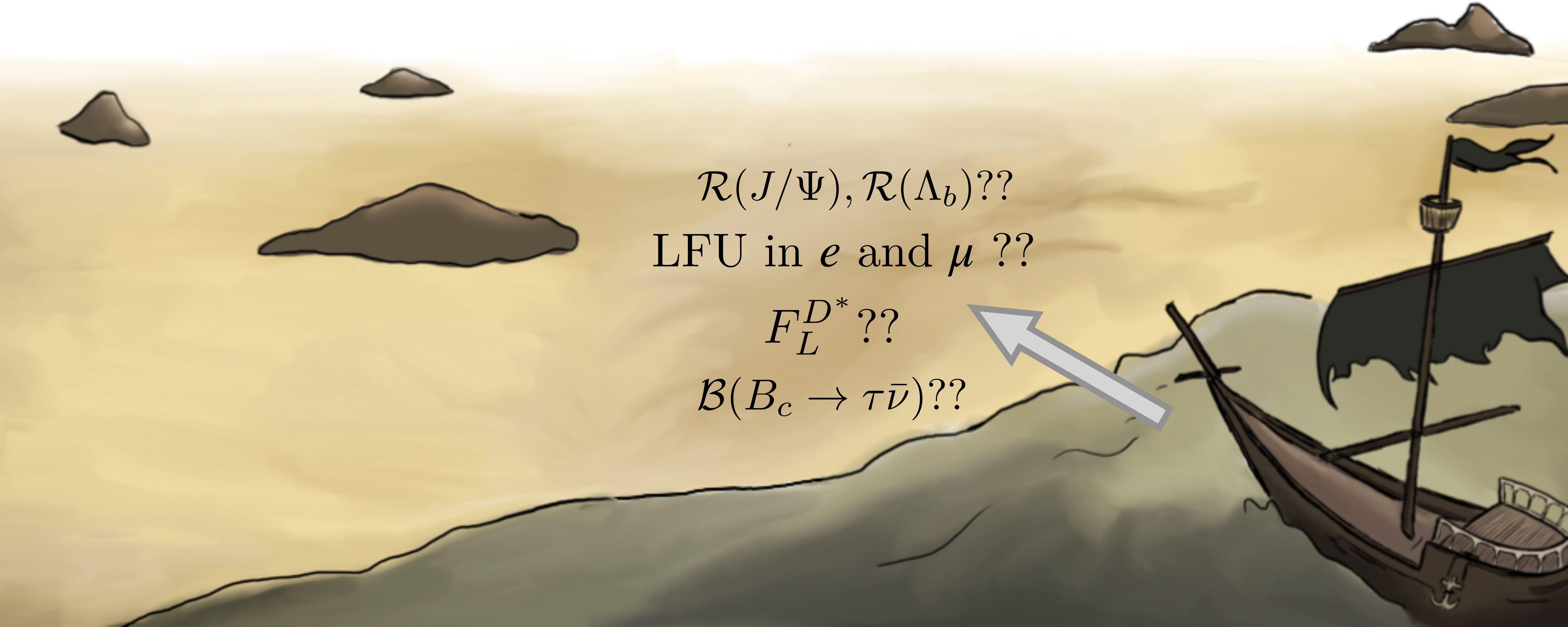
| Belle-II | 5 ab$^{-1}$ | 50 ab$^{-1}$ |
|---|---|---|
| $\mathcal{R}_{D^*}$ | $(\pm 3.0 \pm 2.5)\%$ | $(\pm 1.0 \pm 2.0)\%$ |
| $\bar{P}_\tau^{D^*}$ | $\pm 0.18 \pm 0.08$ | $\pm 0.06 \pm 0.04$ |

My guess: $F_L^{D^*} \sim 15\%$ ⇨ 5%

# The EFT approach journey



??$_?$



$\mathcal{R}(J/\Psi), \mathcal{R}(\Lambda_b)$??

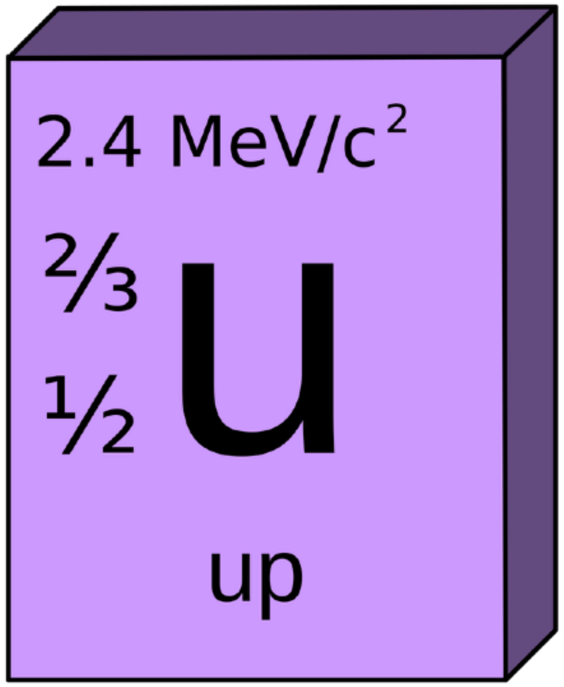
LFU in $e$ and $\mu$ ??

$F_L^{D^*}$??

$\mathcal{B}(B_c \to \tau\bar{\nu})$??

Thank you!

BACK



# SLIDES

# Global Fit: Goodness of the fit

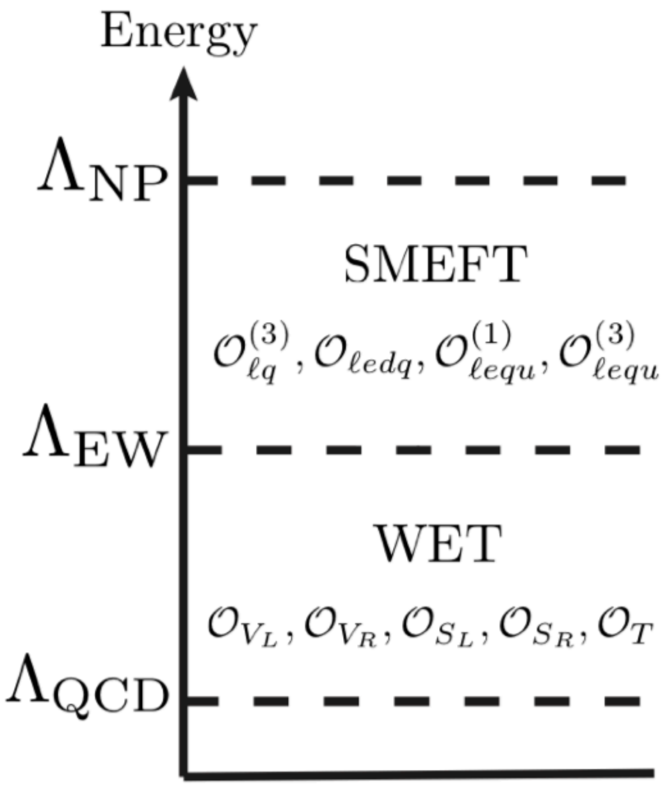
- P-value

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

- Pull [# of standard deviations]

$$\mathrm{Pull}_{\rm SM} \equiv \mathrm{prob}(\Delta\chi^2_i, \Delta n_i)[\sigma] = \sqrt{2}\mathrm{Erf}^{-1}[\mathrm{CDF}(\Delta\chi^2_i, \Delta n_i)]$$

# Global Fit: New Physics interpretations

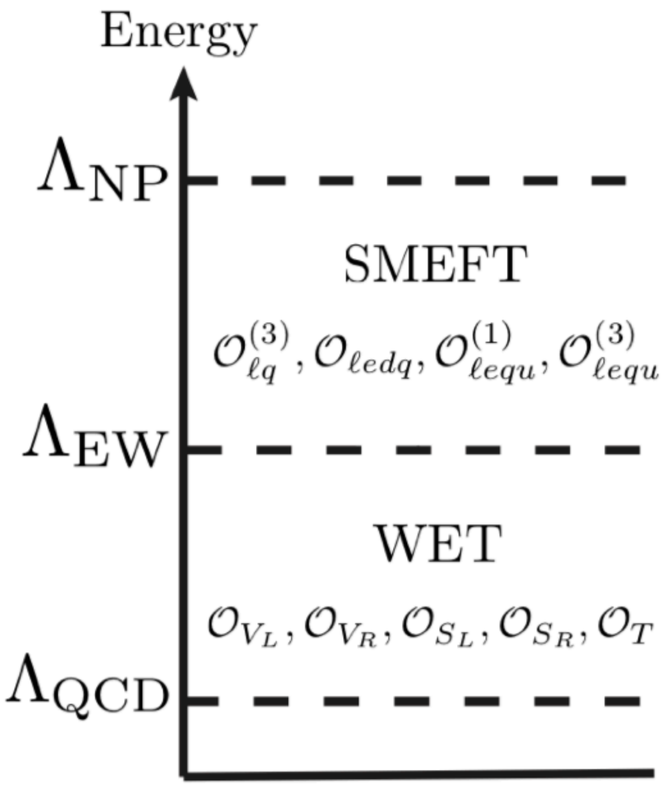


| Spin | Q.N. | Nature | Allowed couplings | SMEFT | WET |
|---|---|---|---|---|---|
| 0 | $S_1 \sim (\bar{3}, 1, 1/3)$ | LQ | $\overline{q_L^c}\ell_L, \overline{d_R}u_R^c, \overline{u_R^c}e_R$ | $\tilde{C}_{V_L}, \tilde{C}_{S_L}, \tilde{C}_T$ | $C_{V_L}, C_{S_L}, C_T$ |
| 0 | $S_3 \sim (\bar{3}, 3, 1/3)$ | 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 | $\overline{\ell_L}\gamma_\mu\ell_L, \overline{q_L}\gamma_\mu q_L$ | $\tilde{C}_{V_L}$ | $C_{V_L}$ |

- Effect of the running between WET and SMEFT W.C ($\Lambda = 1$ TeV)

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

# Global Fit: New Physics interpretations



| 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 | $\overline{\ell_L}\gamma_\mu\ell_L, \overline{q_L}\gamma_\mu q_L$ | $\tilde{C}_{V_L}$ | $C_{V_L}$ |

- Global minimum:

$$C_{V_L} = 0.09^{+0.13}_{-0.11}, \quad C_{S_R} = 0.14^{+0.06}_{-0.67}, \quad C_{S_L} = -0.20^{+0.58}_{-0.03}, \quad C_T = 0.007^{+0.046}_{-0.044}$$

- New gauge mediator: $W' \sim$ (1,3,0)

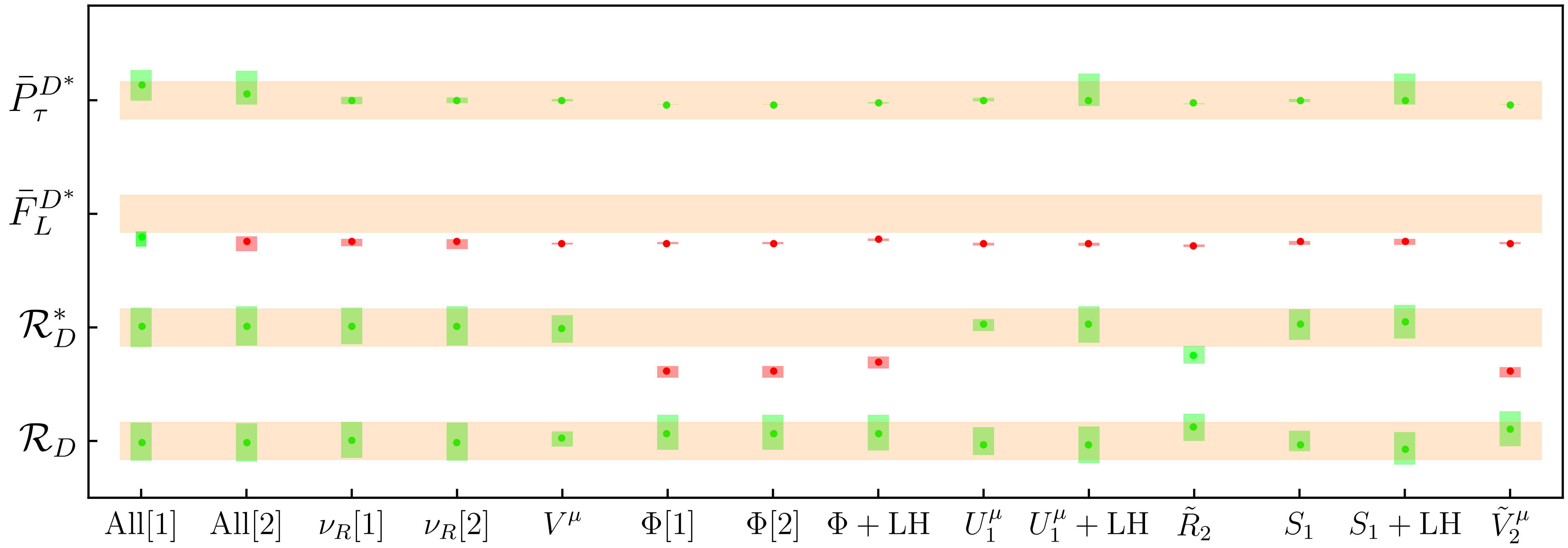
$$\mathcal{L}_{\rm eff} \supset -\frac{\tilde{g}_{\ell\nu_\ell}\tilde{g}_{du}^\dagger}{M_{W'}^2}(\bar{\ell}_L\gamma_\mu\nu_{\ell L})(\bar{u}_L\gamma^\mu d_L) \qquad \Rightarrow M_{W'} = 0.22 \text{ TeV}$$

**Ruled out**

(sequential W')

# Global fit + $\nu_R$

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



- Motivated scenarios:

$C_{LL}^V +$ All RH

All

All RH

$\nu_R$

$\Phi \sim (1, 2, 1/2)$

$S_1 \sim (\bar{3}, 1, 1/3)$

$\tilde{R}_2 \sim (3, 2, 1/6)$

SCALAR

$U_1^\mu \sim (3, 1, 2/3)$

$U_3^\mu \sim (3, 3, 2/3)$

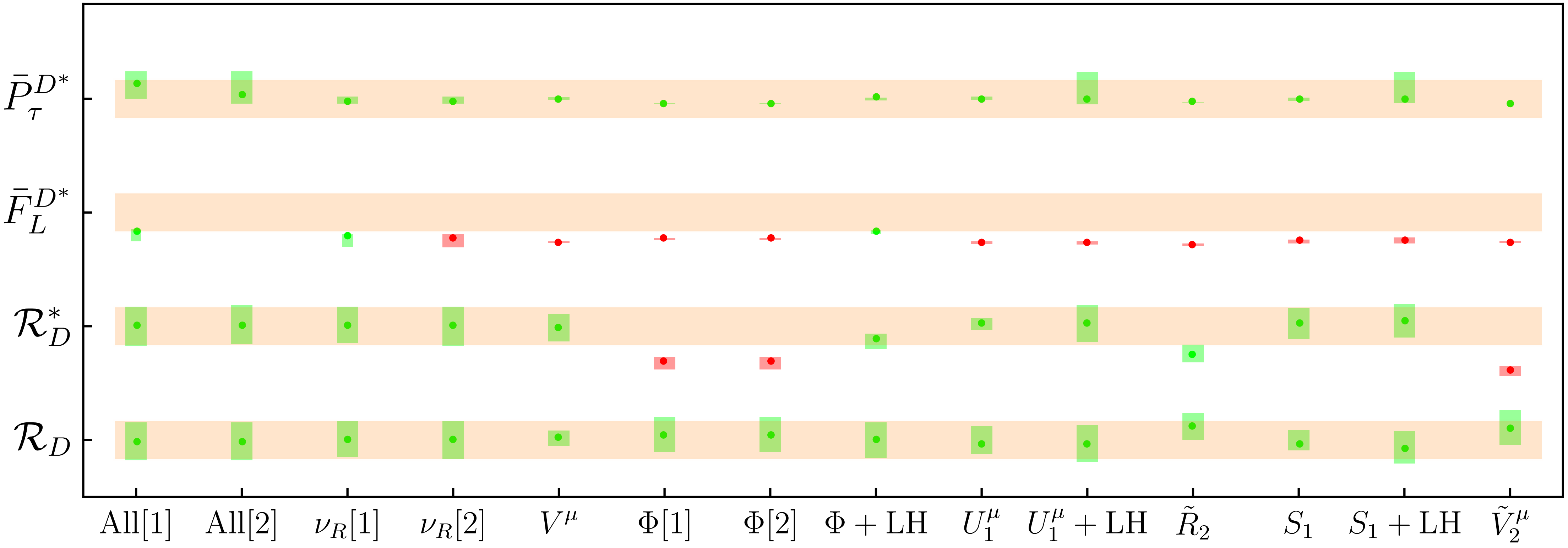
$\tilde{V}_2^\mu \sim (\bar{3}, 2, -1/6)$

$V^\mu \sim (1, 1, -1)$

VECTOR

# Global fit + $\nu_R$

$\mathcal{B}(B_c \to \tau\nu) \leq 30\%$



- Motivated scenarios:

$C_{LL}^V +$ All RH

**All**

All RH

$\nu_R$

$\Phi \sim (1, 2, 1/2)$

$S_1 \sim (\bar{3}, 1, 1/3)$

$\tilde{R}_2 \sim (3, 2, 1/6)$

**SCALAR**

$U_1^\mu \sim (3, 1, 2/3)$

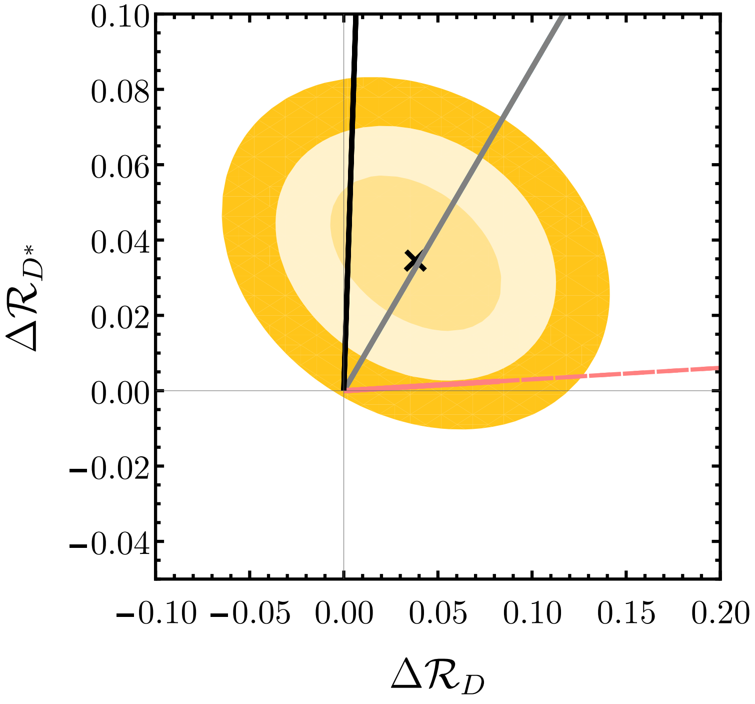
$U_3^\mu \sim (3, 3, 2/3)$

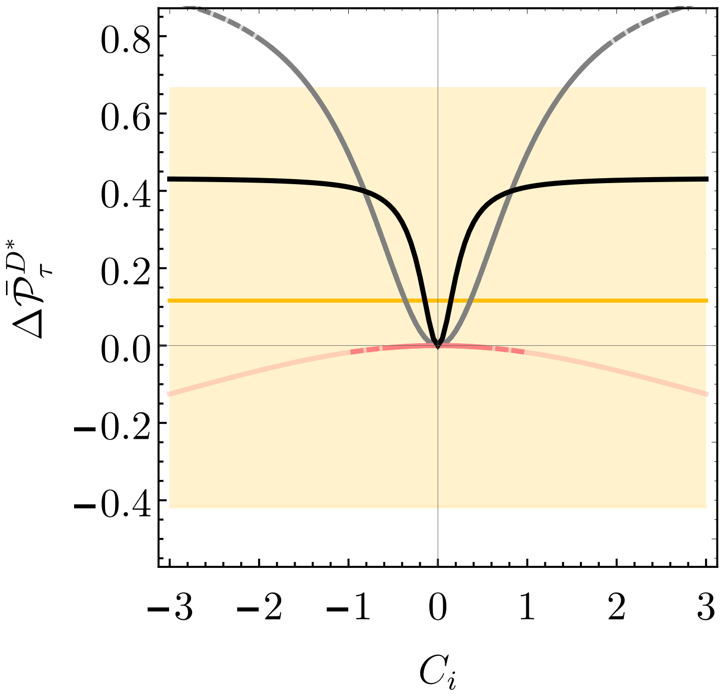
$\tilde{V}_2^\mu \sim (\bar{3}, 2, -1/6)$

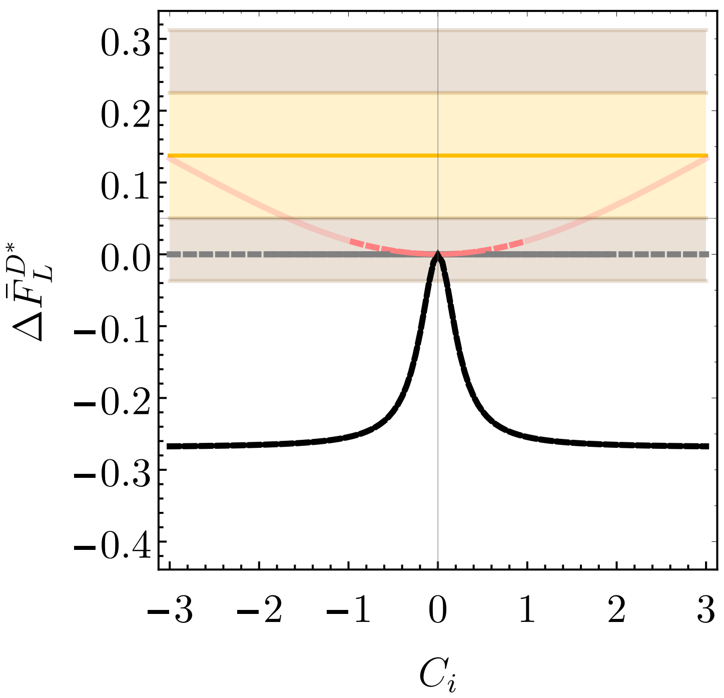
$V^\mu \sim (1, 1, -1)$

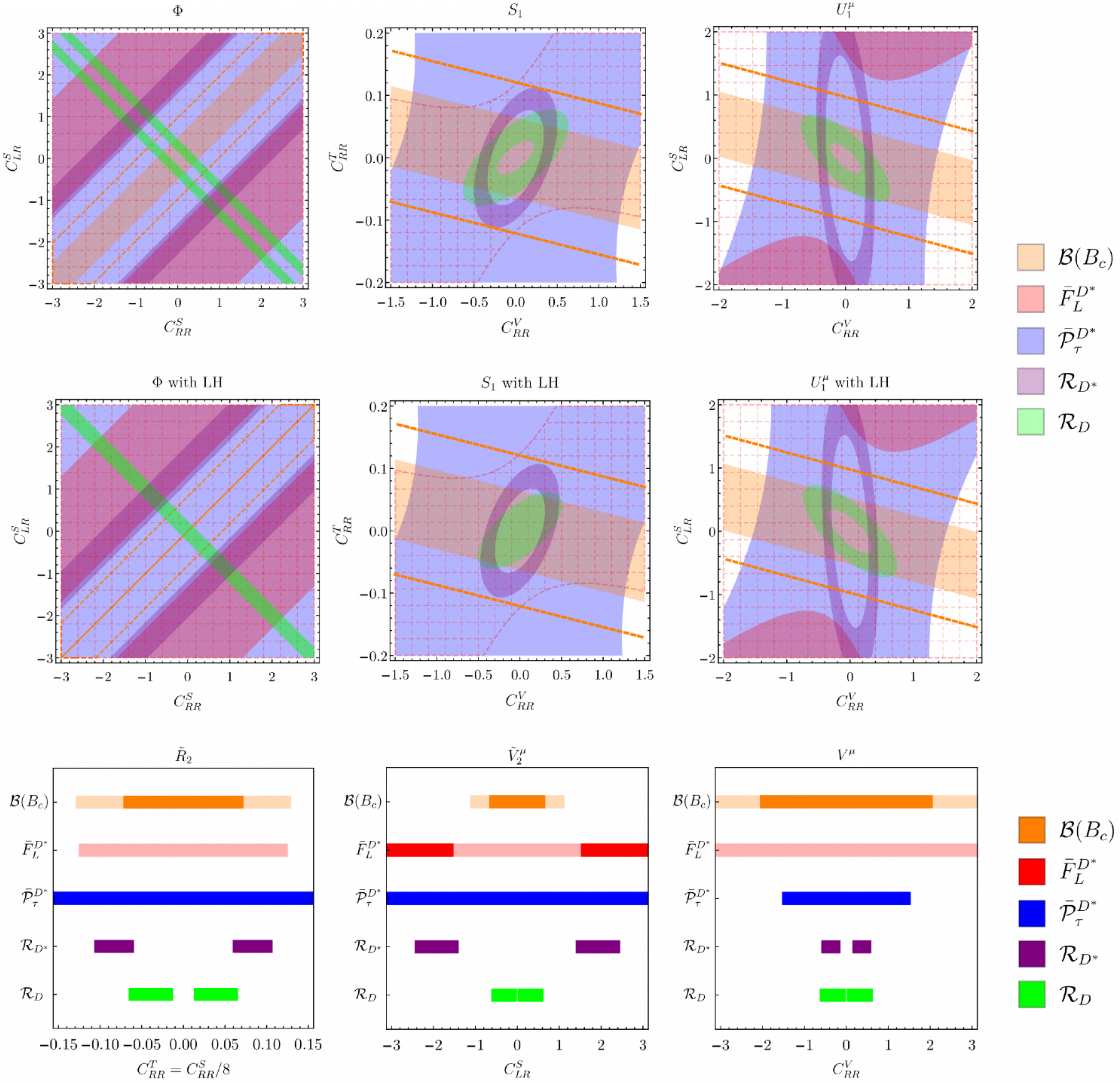
**VECTOR**

# Global fit + $\nu_R$



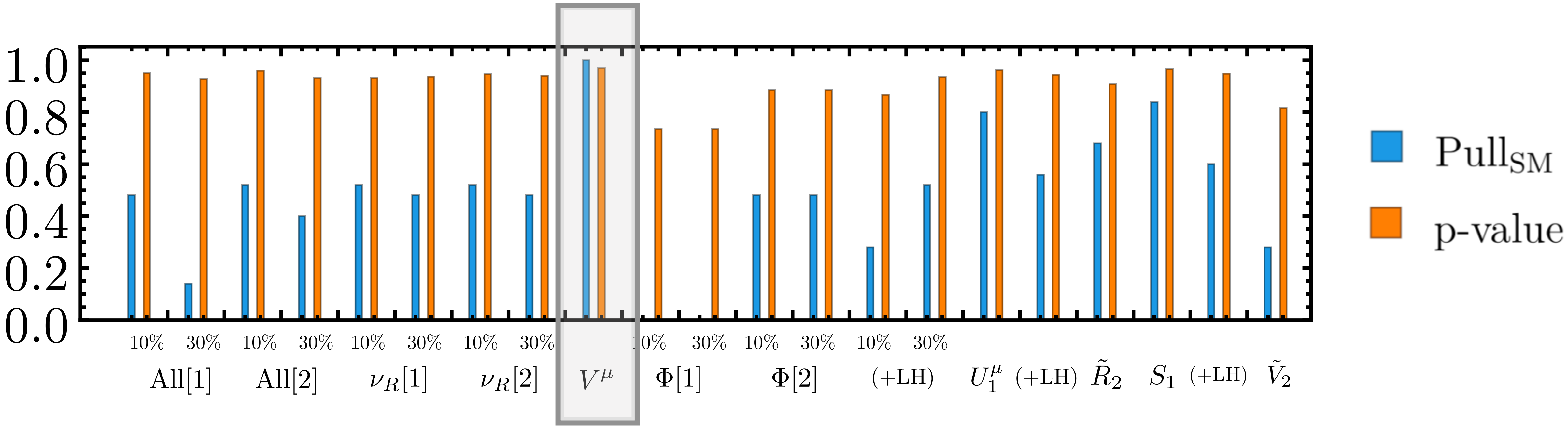





$\Phi$
$S_1$
$U_1^\mu$
$C_{LR}^S$
$C_{RR}^S$
$C_{RR}^T$
$C_{RR}^V$
$\Phi$ with LH
$S_1$ with LH
$U_1^\mu$ with LH
$\tilde{R}_2$
$\tilde{V}_2^\mu$
$V^\mu$
$\mathcal{B}(B_c)$
$\bar{F}_L^{D^*}$
$\bar{\mathcal{P}}_\tau^{D^*}$
$\mathcal{R}_{D^*}$
$\mathcal{R}_D$
$C_{RR}^T = C_{RR}^S/8$
$C_{LR}^S$
$C_{RR}^V$

# Global fit + $\nu_R$

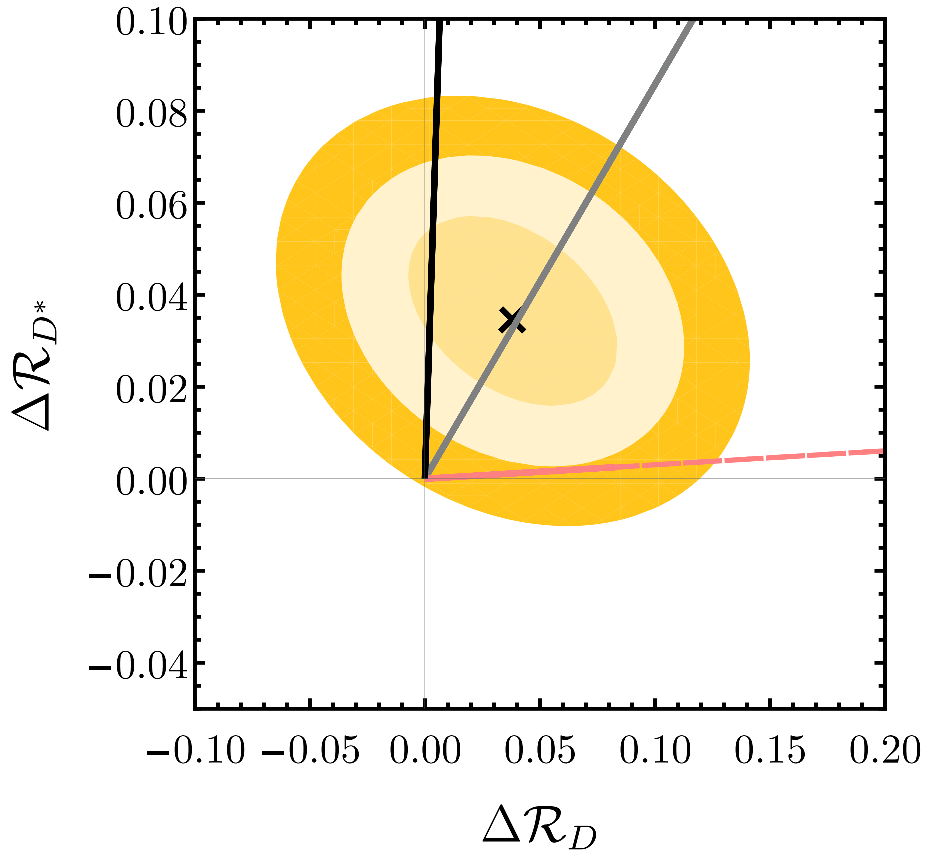
- Preferred scenarios:



$$V^\mu \sim (1,1,-1) \Rightarrow C^V_{RR}$$

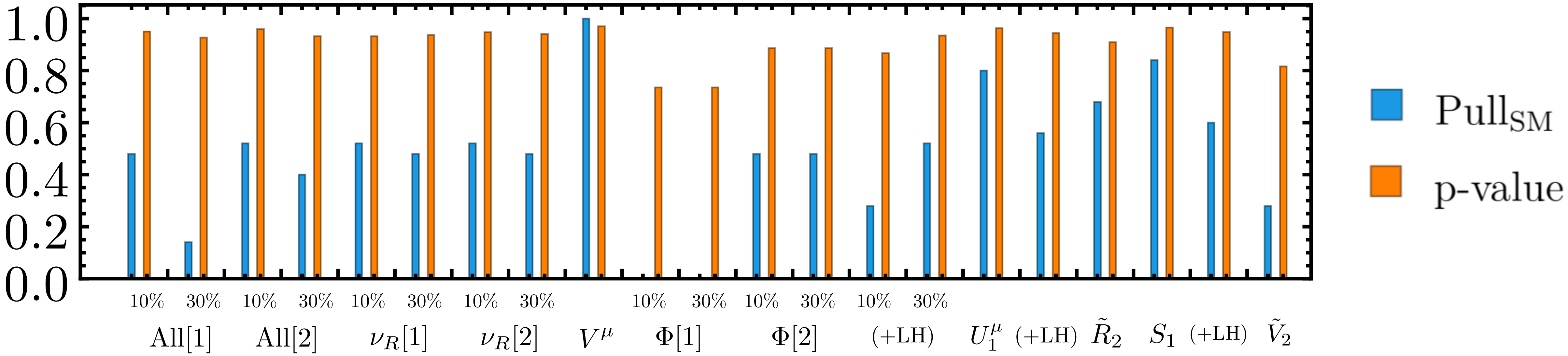
Pull: 3.7

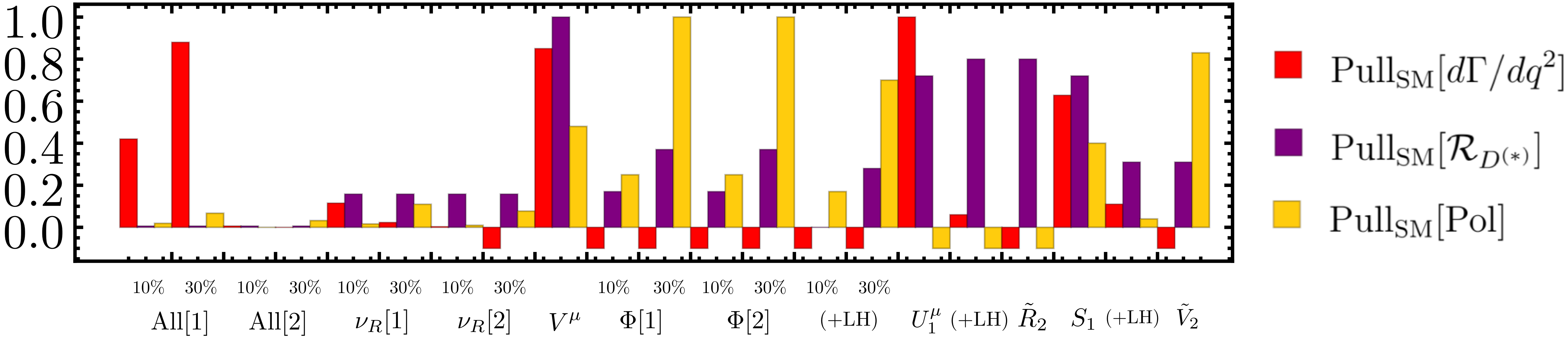
$\nu_R$ ▬ $C^V_{LR} = C^V_{RR}$ ▬ $C^S_{RR} = C^S_{LR}$ ▬ $C^T_{RR}$



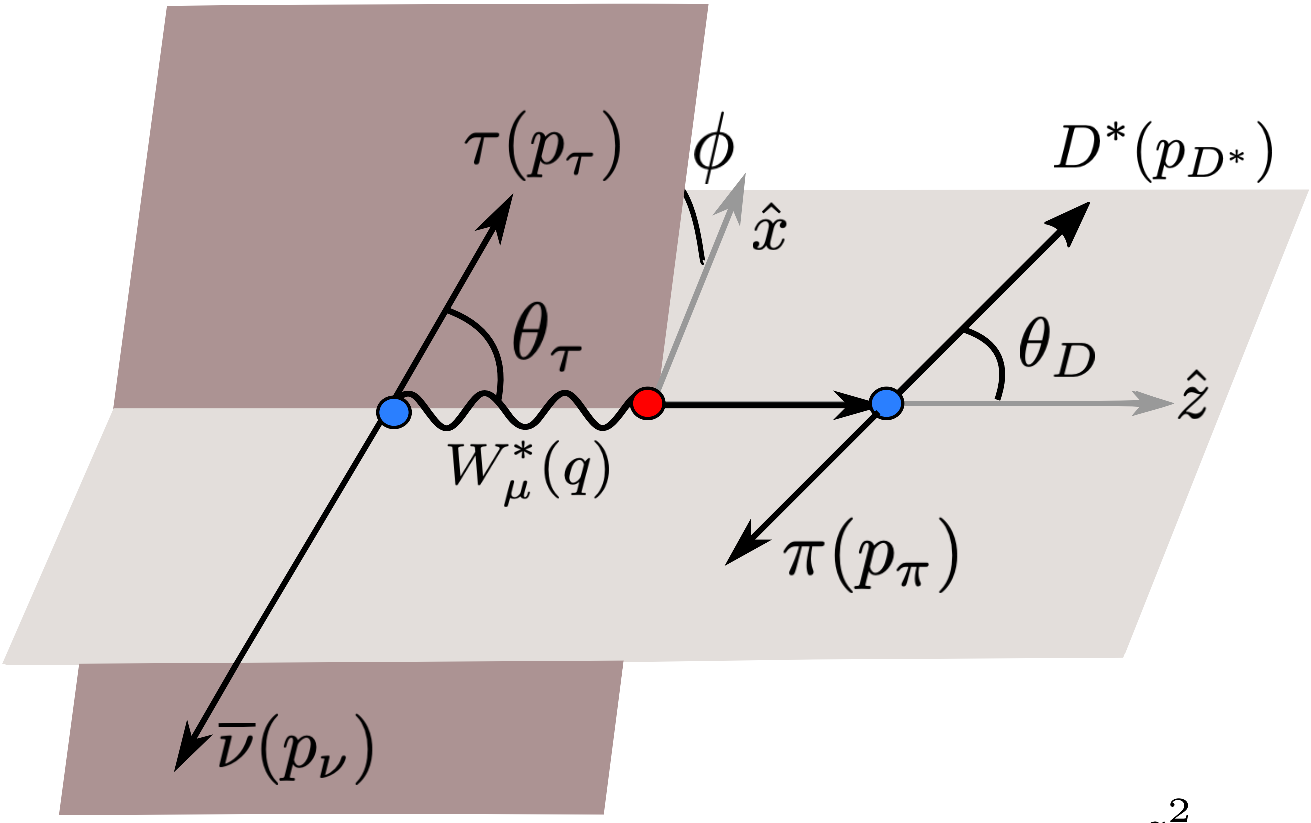
# Global fit + $\nu_R$

- Preferred scenarios:





# Angular observables (D*)



$$F_L^{D^*} = \frac{1}{\Gamma}\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \frac{d\Gamma_{\lambda_{D^*}=0}}{dq^2}$$

$$\mathcal{P}_\tau^{D^*} = \frac{1}{\Gamma}\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \left(\frac{d\Gamma_{\lambda_\tau=1/2}}{dq^2} - \frac{d\Gamma_{\lambda_\tau=-1/2}}{dq^2}\right)$$

$$\mathcal{A}_{\rm FB}^{D^*} = \frac{1}{\Gamma}\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\tau \, \frac{d^2\Gamma}{dq^2 d\cos\theta_\tau}$$