The $\mathcal{R}(D^{(*)})$ Anomaly and New Physics

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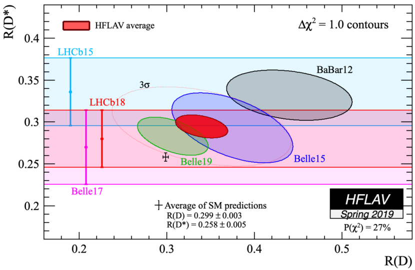
The $\mathcal{R}(D^{(*)})$ Anomaly

Test of lepton flavour universality in semi-leptonic B decays

$$\mathcal{R}(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$

➢ tension between SM prediction and data for almost 10 years!



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb (so far $\mathcal{R}(D^*)$ only) in good agreement with each other
- LHCb found $\mathcal{R}(J/\psi)$ to be larger than expected in SM

➢ **3.1σ anomaly** HFLAV (2019)

Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale described model-independently[1] by

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = 2\sqrt{2}G_F V_{cb}\Big[(1 + C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\Big]$$

with the vector, scalar and tensor operators

$$\begin{aligned}
O_V^L &= (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \\
O_S^R &= (\bar{c} P_R b)\,(\bar{\tau} P_L \nu_\tau) \\
O_S^L &= (\bar{c} P_L b)\,(\bar{\tau} P_L \nu_\tau) \\
O_T &= (\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)
\end{aligned}$$

Note: $(\bar{c}\gamma^\mu P_R b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$ not generated at dimension-six level in the $SU(2)_L \times U(1)_Y$-invariant theory

[1] assuming heavy/no ν_R and NP only in τ channel

Additional Observables

- **ratio of baryonic decay rates**

$$\mathcal{R}(\Lambda_c) = \frac{\text{BR}(\Lambda_b \to \Lambda_c \tau \nu)}{\text{BR}(\Lambda_b \to \Lambda_c \ell \nu)} \qquad (\ell = e, \mu)$$

- **longitudinal D^* polarisation**

$$F_L(D^*) = \frac{\Gamma(B \to D^*_L \tau \nu)}{\Gamma(B \to D^* \tau \nu)}$$

$$\text{Belle}: \ 0.60 \pm 0.08 \pm 0.035$$
$$\text{SM}: \ 0.46 \pm 0.04$$

- **τ polarisation asymmetries**

$$P_\tau(D^{(*)}) = \frac{\Gamma(B \to D^{(*)} \tau^{\lambda=+1/2} \nu) - \Gamma(B \to D^{(*)} \tau^{\lambda=-1/2} \nu)}{\Gamma(B \to D^{(*)} \tau \nu)}$$

- **BR($B_c \to \tau\nu$)** – particularly sensitive to scalar contributions

A Closer Look at $B_c \to \tau\nu$

- no direct experimental bound on BR$(B_c \to \tau\nu)$
- constraints advocated in the literature

Akeroyd, Chen (2017)

➢ **searches for $B_{u,c} \to \tau\nu$ at LEP1:** BR$(B_c \to \tau\nu) < 10\%$

caveats of theory interpretation

- relies crucially on ratio of $b \to B_c$ vs. $b \to B_u$ fragmentation functions
- Tevatron and LHC determinations of f_c/f_u not applicable to LEP (hadron collisions vs. Z peak observables)
- indeed NRQCD yields smaller f_c value — Zheng et al. (2017), (2019)

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Alonso, Grinstein, Martin Camalich (2016)

➢ **measured total B_c lifetime:** BR$(B_c \to \tau\nu) < 30\%$

caveats of τ_{B_c} theory prediction — Beneke, Buchalla (1996)

- large m_c dependence (LO QCD calculation, $1.4\,\text{GeV} < m_c < 1.6\,\text{GeV}$)
- based on heavy quark expansion and non-rel. QCD, but B_c decays dominantly through charm decay

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Our critical assessment (2018/2019)

- more refined studies needed
- conservative (agnostic) bound: **BR$(B_c \to \tau\nu) \lesssim 60\%$**

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018), (2019)

Recent News on the B_c Lifetime

- **updated SM prediction using OPE** Aebischer, Grinstein (2021-I)
  large uncertainties and significant scheme dependence

$$\Gamma_{B_c}^{\overline{\text{MS}}} = (1.51 \pm 0.38|^{\mu} \pm 0.08|^{\text{n.p.}} \pm \ldots)\,\text{ps}^{-1}$$
$$\Gamma_{B_c}^{\text{meson}} = (1.70 \pm 0.24|^{\mu} \pm 0.20|^{\text{n.p.}} \pm \ldots)\,\text{ps}^{-1}$$
$$\Gamma_{B_c}^{\text{Upsilon}} = (2.40 \pm 0.19|^{\mu} \pm 0.21|^{\text{n.p.}} \pm \ldots)\,\text{ps}^{-1}$$

  ➢ no clear-cut conclusion on size of NP effects in Γ_{B_c} possible

- **determination from B, D decay rates** Aebischer, Grinstein (2021-II)
  based on quark-hadron duality

$$\Gamma_{B_c} \sim (3.0 \pm 0.5)\,\text{ps}^{-1}$$

  ➢ significantly larger than $\Gamma_{B_c}^{\text{exp}} = 1.961(35)\,\text{ps}^{-1}$

  ➢ underestimated uncertainties? failure of quark-hadron duality?

  ➢ would require *destructive* NP interference

Possible Single-Particle Explanations

New Physics fit scenarios

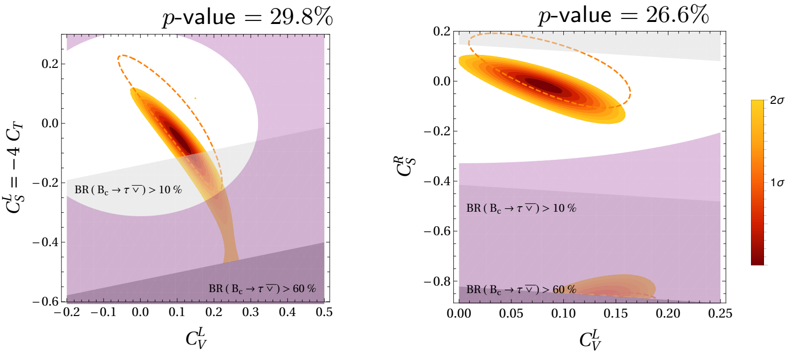
MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)

C_V^L	vector $\mathrm{SU}(2)_L$-triplet W'
$(C_V^L,\, C_S^L = -4C_T)$	$\mathrm{SU}(2)_L$-singlet scalar leptoquark (LQ)
$(C_V^L,\, C_S^R)$	$\mathrm{SU}(2)_L$-singlet vector LQ
$(C_S^R,\, C_S^L)$	charged Higgs
$(\mathrm{Re}[C_S^L = 4C_T],$ $\mathrm{Im}[C_S^L = 4C_T])$	scalar $\mathrm{SU}(2)_L$-doublet LQ with CP-violating couplings

see also Aebischer et al (2019); Murgui et al (2019); Shi et al (2019)...

Two-Dimensional Fit Results (I)

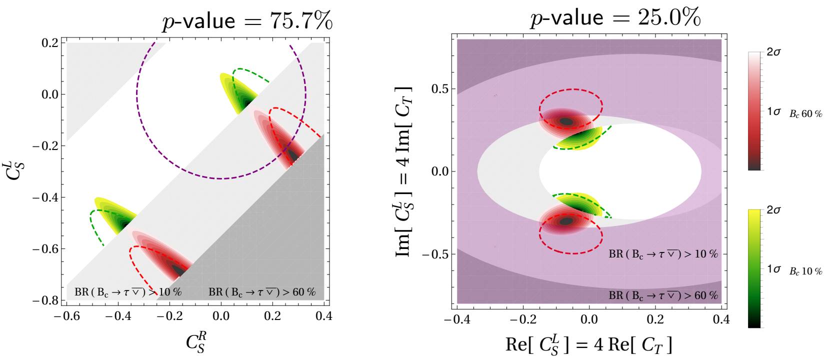
MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)



- good fit for both $(C_V^L,\, C_S^L = -4C_T)$ and $(C_V^L,\, C_S^R)$
- consistent with only $C_V^L \neq 0$ (W' scenario; challenged by EWP tests)
- small impact of BR$(B_c \to \tau\nu)$ and LHC mono-τ constraints

Two-Dimensional Fit Results (II)

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)

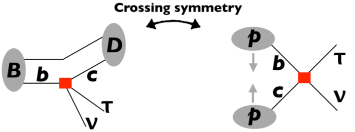


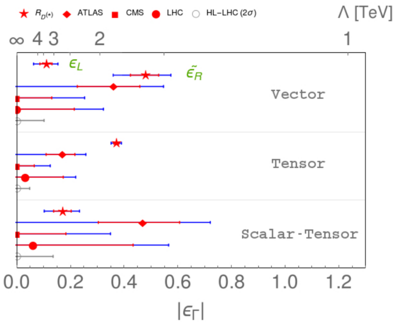
- very good fit for (C_S^R, C_S^L), but implies large BR$(B_c \to \tau\nu)$
- decent fit for $(C_S^L = 4C_T)$, unless BR$(B_c \to \tau\nu) < 10\%$ is imposed
- soon to be probed by LHC searches with τ's

LHC Mono-τ Searches

Greljo, Martin Camalich, Ruiz-Alvarez (2018)

- crossing symmetry relates $b \to c\tau\nu$ to $pp \to X\tau\nu$
- high-p_T tails constrain EFT operators (as opposed to resonance searches)





➢ **LHC has become competitive in testing the $b \to c\tau\nu$ anomaly**

- pure tensor (two LQs) and RH neutrino solutions disfavoured
- HL-LHC will probe *all* possible NP explanations of anomaly

The $\mathcal{R}(\Lambda_c)$ Sum Rule

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018), (2019)

Approximate sum rule relating $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}^{\rm SM}(D^*)}$$

- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\rm SM}(\Lambda_c) = 0.33 \pm 0.01$
- consistent with expectation from heavy-quark symmetry

Model-independent prediction[2] from current $\mathcal{R}(D^{(*)})$ data:

$$\mathcal{R}(\Lambda_c) = 0.38 \pm 0.01_{\mathcal{R}(D^{(*)})} \pm 0.01_{\text{form factors}}$$

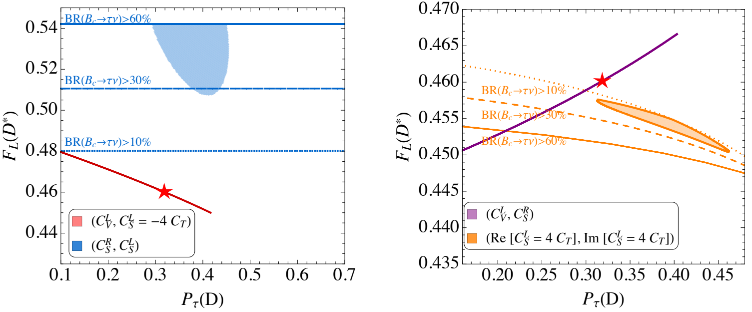
➢ **experimental consistency check of $\mathcal{R}(D^{(*)})$ anomaly**

[2] even in the presence of light ν_R

Correlations between Polarization Observables (I)

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić(2019)

Disentangling between different NP scenarios



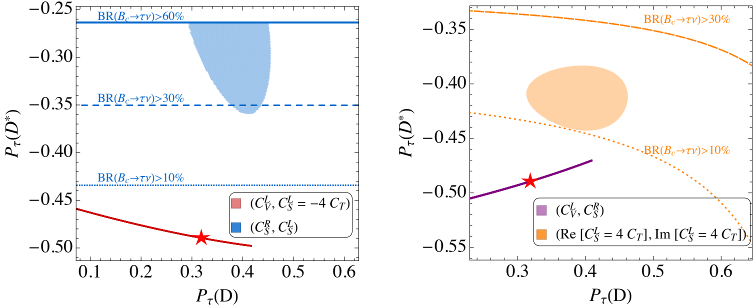
- different pattern of effects in polarization observables
- only (C_S^R, C_S^L) scenario can enhance $F_L(D^*)$ into 1σ exp. region

$$F_L(D^*)_{\text{Belle}} = 0.60 \pm 0.08 \pm 0.035$$

Correlations between Polarization Observables (II)

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić(2019)

Disentangling between different NP scenarios



- remaining ambiguity can be resolved by inclusion of $P_\tau(D^*)$

➢ **more precise measurements and form-factor predictions needed!**

for full $B \to D^* \tau \nu$ angular analysis, see Becirevic et al. (2019)

Complementary Constraints

Implied by $SU(2)_L$ symmetry (dep. on operator structure)

- large impact on $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \tau^+\tau^-$, $B \to K\tau^+\tau^-$

  Crivellin, Müller, Ota (2017)

- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$ Aloni et al. (2017)

Complementary probes in high-p_T searches

- stringent limits from direct searches for W'/Z' and leptoquarks
- strong constraints from mono-τ and $\tau^+\tau^-$ searches at LHC

  Faroughy, Greljo, Kamenik (2016); Altmannshofer, Dev, Soni (2017)
  Greljo, Martin Camalich, Ruiz-Alvarez (2018)

➢ **full NP resolution of $\mathcal{R}(D^{(*)})$ anomaly challenging**

Summary

$\mathcal{R}(D^{(*)})$ anomaly approaching its 10th birthday

- anomaly persists at 3σ level, central values shifted towards SM
- experimental consistency check by sum rule prediction
  $\mathcal{R}(\Lambda_c) = 0.38 \pm 0.01$
- possible NP origins – new tree-level contributions
  - W' gauge boson
  - charged Higgs
  - scalar or vector leptoquark
- model-discriminating complementary constraints
  - polarization observables
  - $SU(2)_L$-related decays
  - high-p_T LHC data

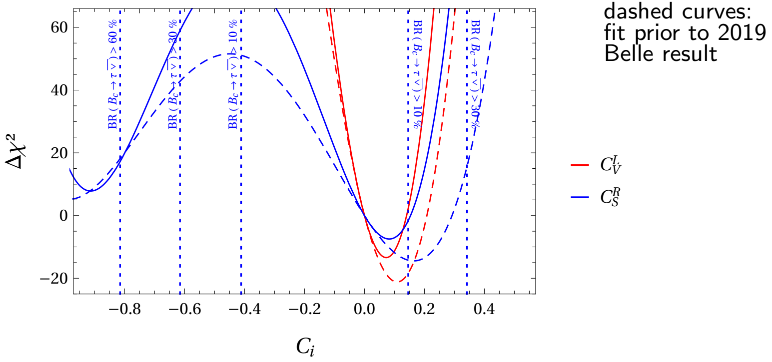
➢ **challenging for many concrete NP models**

Backup slides

Few Technical Remarks on our Fit

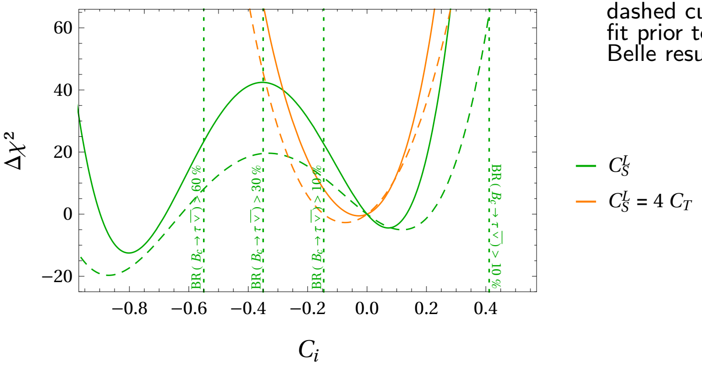
- assume NP only in τ channel – e and μ channels are SM like
- no light right-handed neutrinos
- fit includes $\mathcal{R}(D)$, $\mathcal{R}(D^*)$, $P_\tau(D^*)$, $F_L(D^*)$
- fit uses central values of form factors
  - $B \to D$ vector and scalar form factors from FLAG Working Group
  - $B \to D^*$: V, A_1, A_2 fit results from HFLAV
    A_0 from Bernlochner et al (2017)
  - tensor form factors from Bernlochner et al (2017)
  - full set of baryonic $\Lambda_b \to \Lambda_c$ form factors from Detmold et al. (2015); Datta et al. (2017)
- values of Wilson coefficients correspond to scale $\mu = 1\,\text{TeV}$

One-Dimensional Fit Results



- best fit for $C_V^L \sim 0.07$
- noticeable improvement also for $C_S^R \sim 0.09$

One-Dimensional Fit Results



dashed curves: fit prior to 2019 Belle result

- best fit for $C_V^L \sim 0.07$
- noticeable improvement also for $C_S^R \sim 0.09$
- large impact of BR$(B_c \to \tau\nu)$ on C_S^L scenario
- no relevant improvement for $C_S^L = 4C_T$ with real Wilson coefficients

Correlations between Polarization Observables (III)

$P_\tau(D^*)$ vs. $F_L(D^\star)$