New Physics in $b \to c\tau\nu$: Impact of Polarisation Observables and $B_c \to \tau\nu$

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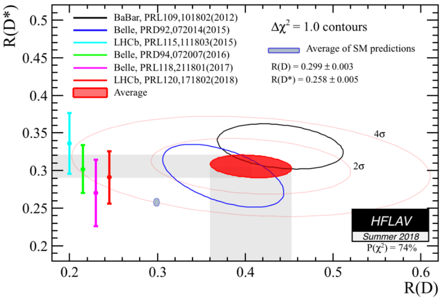
Particle Physics Phenomenology after the Higgs Discovery

LHCb and Belle II Opportunities for Model Builders
MITP – January 31, 2019

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

Test of lepton flavour universality in semi-leptonic B decays

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



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb (so far $\mathcal{R}(D^*)$ only)
- 3.8σ tension between HFLAV fit and SM value
- (qualitatively) supported by measurement of $\mathcal{R}(J/\psi)$ (LHCb)

Related Observables

- **ratio of baryonic decay rates**

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

- **longitudinal D^* polarisation**

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

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

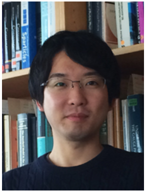
- **τ polarisation asymmetries**

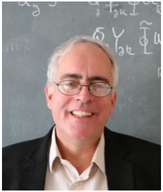
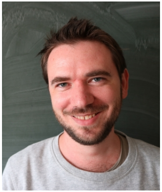
$$P_\tau(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau^{\lambda=+1/2}\nu) - \Gamma(B \to D^{(*)}\tau^{\lambda=-1/2}\nu)}{\Gamma(B \to D^{(*)}\tau\nu)}$$

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

The Crew



MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić
arXiv:1811.09603

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

Constraints on BR($B_c \to \tau\nu$) advocated in the literature:

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

  Alonso, Grinstein, Martin Camalich (2016)

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

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

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

  Akeroyd, Chen (2017)

  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)

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Critical assessment:

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

Effective Hamiltonian

New Physics above B meson scale described model-independently 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

Few Technical Remarks

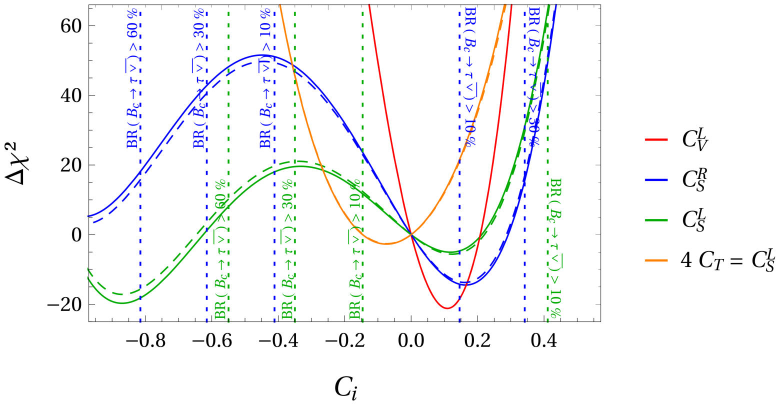
- assume NP only in τ channel – e and μ channels are SM like
- no light right-handed neutrinos
- fit includes $\mathcal{R}(D)$, $\mathcal{R}(D^*)$, $P_\tau(D^*)$, $F_L(D^*)$
- fit uses central values of form factors
  - $B \to D$ vector and scalar form factors from FLAG Working Group
  - $B \to D^*$: 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 Scenarios

single particle scenarios

C_V^L	left-handed W' boson left-handed SU$(2)_L$-singlet vector leptoquark (LQ) scalar SU$(2)_L$-triplet and/or -singlet LQ (LH couplings only)
C_S^R	charged Higgs (2HDM-II at large $\tan\beta$) SU$(2)_L$-doublet vector LQ
C_S^L	charged Higgs with generic flavor structure
$C_S^L = 4C_T$	scalar SU$(2)_L$-doublet (relation at NP scale, modified by RG effects)

One-Dimensional Fit Results

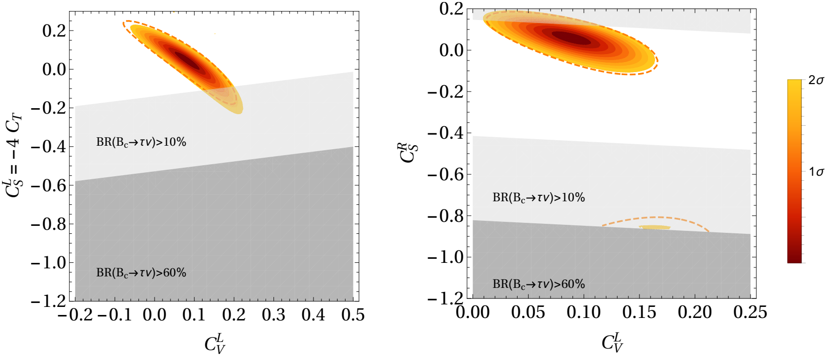


- best fit for $C_V^L \sim 0.11$
- small impact of $F_L(D^*)$ measurement (solid vs. dashed)
- large impact of BR$(B_c \to \tau\nu)$ on scalar scenarios

Two-Dimensional Scenarios

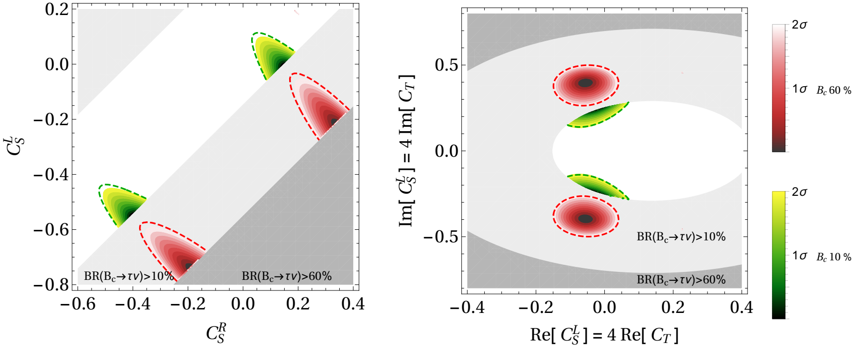
	single particle scenarios
$(C_V^L,\, C_S^L = -4C_T)$	$\mathrm{SU}(2)_L$-singlet scalar LQ
$(C_V^L,\, C_S^R)$	$\mathrm{SU}(2)_L$-singlet vector LQ
$(C_S^R,\, C_S^L)$	charged Higgs
$(\mathrm{Re}[C_S^L = 4C_T],$ $\mathrm{Im}[C_S^L = 4C_T])$	scalar $\mathrm{SU}(2)_L$-doublet LQ with CP-violating couplings

Two-Dimensional Fit Results (I)



- good fit for both $(C_V^L, C_S^L = -4C_T)$ and (C_V^L, C_S^R)
- small impact of $\mathrm{BR}(B_c \to \tau\nu)$ constraint

Two-Dimensional Fit Results (II)



- very good fit for (C_S^R, C_S^L), but only allowed for BR$(B_c \to \tau\nu) < 60\%$
- good fit for $(C_S^L = 4C_T)$, unless BR$(B_c \to \tau\nu) < 10\%$ is imposed

The $\Lambda_b \to \Lambda_c \tau\nu$ Sum Rule

From the phenomenological expressions for $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$, we derive an **approximate sum rule**:

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\text{SM}}(\Lambda_c)} \simeq 0.262 \frac{\mathcal{R}(D)}{\mathcal{R}_{\text{SM}}(D)} + 0.738 \frac{\mathcal{R}(D^*)}{\mathcal{R}^{\text{SM}}(D^*)} + \mathcal{O}(10^{-2})$$

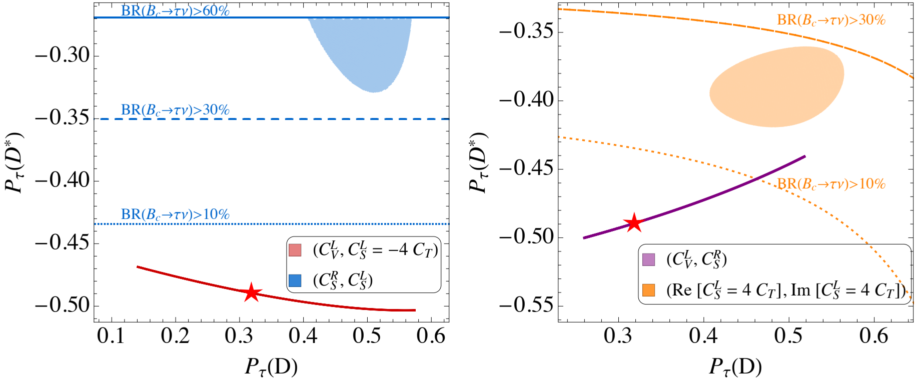
- ➢ enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\text{SM}}(\Lambda_c) = 0.33 \pm 0.01$
- ➢ model-independent prediction from current $\mathcal{R}(D^{(*)})$ data:

$$\mathcal{R}(\Lambda_c) = 0.41 \pm 0.02_{\mathcal{R}(D^{(*)})} \pm 0.01_{\text{form factors}}$$

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

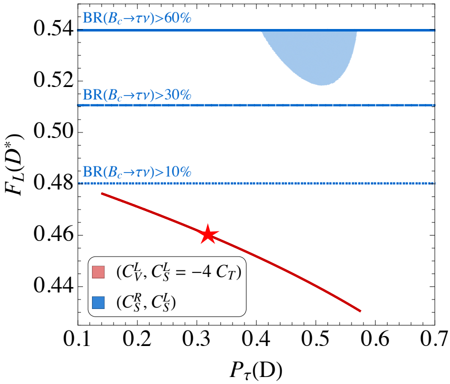
Correlations between Polarization Observables (I)

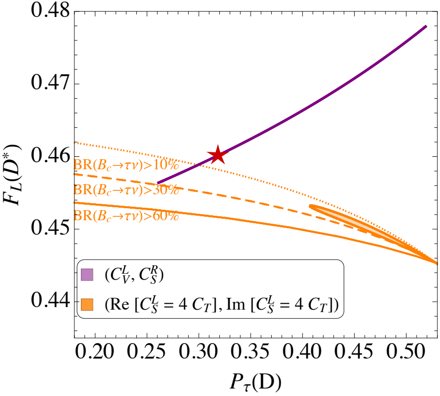
$P_\tau(D)$ and $P_\tau(D^*)$



Correlations between Polarization Observables (II)

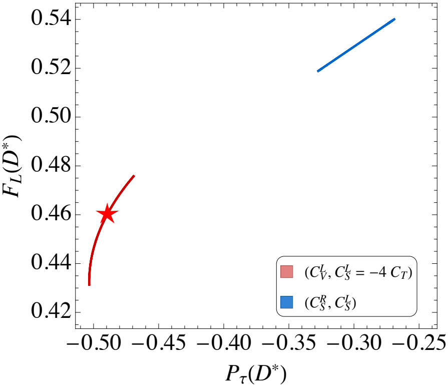
$P_\tau(D)$ and $F_L(D^*)$

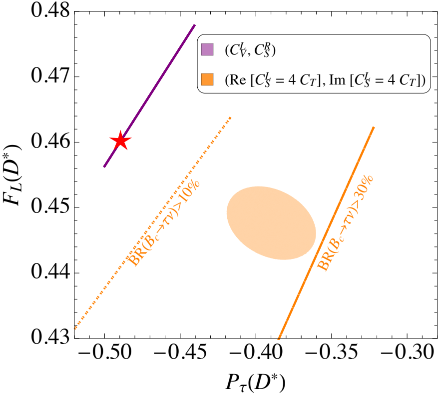




Correlations between Polarization Observables (III)

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





Summary: What's New in $b \to c\tau\nu$

- updated 1D and 2D fits, including recent $F_L(D^*)$ measurement
- critical assessment of $B_c \to \tau\nu$ constraint
- $\Lambda_b \to \Lambda_c\tau\nu$ provides experimental cross-check of $\mathcal{R}(D^{(*)})$ anomaly
- polarisation observables well suited to distinguish among different EFT scenarios ➢ requires better understanding of form factors in addition to decently precise measurements