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

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LHCb and Belle II Opportunities for Model Builders
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The $\mathcal{R}(D^{(*)})$ Anomaly

Test of lepton flavour universality in semi-leptonic $B$ decays

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

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

- **ratio of baryonic decay rates**
  \[ R(\Lambda_c) = \frac{\text{BR}(\Lambda_b \to \Lambda_c \tau \nu)}{\text{BR}(\Lambda_b \to \Lambda_c \ell \nu)} \quad (\ell = e, \mu) \]

- **longitudinal $D^*$ polarisation**
  \[ F_{L}(D^*) = \frac{\Gamma(B \to D^*_L \tau \nu)}{\Gamma(B \to D^* \tau \nu)} \quad \text{Belle} : 0.60 \pm 0.08 \pm 0.035 \]
  \[ \text{SM} : 0.46 \pm 0.04 \]

- **$\tau$ 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 $B_c \rightarrow \tau \nu$

Constraints on $\text{BR}(B_c \rightarrow \tau \nu)$ advocated in the literature:

- measured total $B_c$ lifetime $\geq \text{BR}(B_c \rightarrow \tau \nu) < 30\%$
  
  **Alonso, Grinstein, Martin Camalich (2016)**

  *caveats of $\tau_{B_c}$ theory prediction*  
  
  - 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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Critical assessment: more refined studies needed

Our conservative bound: $\text{BR}(B_c \rightarrow \tau \nu) < 60\%$
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- searches for $B_{u,c} \rightarrow \tau \nu$ at LEP1 $\geq \text{BR}(B_c \rightarrow \tau \nu) < 10$
  
  Akeroyd, Chen (2017)

Caveats of theory interpretation:

- relies crucially on ratio of $b \rightarrow B_c$ vs. $b \rightarrow B_u$ 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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Effective Hamiltonian

New Physics above $B$ meson scale described model-independently by

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

with the vector, scalar and tensor operators

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

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 $\tau$ channel – $e$ and $\mu$ channels are SM like
- no light right-handed neutrinos
- fit includes $R(D)$, $R(D^*)$, $P_\tau(D^*)$, $F_L(D^*)$
- 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 $\mu = 1$ TeV
One-Dimensional Scenarios

**single particle scenarios**

- **$C^L_V$**
  - 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)

- **$C^R_S$**
  - charged Higgs (2HDM-II at large $\tan \beta$)
  - SU(2)$_L$-doublet vector LQ

- **$C^L_S$**
  - charged Higgs with generic flavor structure

- **$C^L_S = 4C_T$**
  - scalar SU(2)$_L$-doublet (relation at NP scale, modified by RG effects)
One-Dimensional Fit Results

- best fit for $C^L_V \sim 0.11$
- small impact of $F_L(D^*)$ measurement (solid vs. dashed)
- large impact of $\text{BR}(B_c \rightarrow \tau \nu)$ on scalar scenarios
Two-Dimensional Scenarios

single particle scenarios

\((C_L^L, C_S^L = -4C_T)\)

SU\((2)_L\)-singlet scalar LQ

\((C_L^L, C_R^S)\)

SU\((2)_L\)-singlet vector LQ

\((C_R^S, C_L^S)\)

charged Higgs

\((\text{Re}[C_S^L = 4C_T], \text{Im}[C_S^L = 4C_T])\)

scalar SU\((2)_L\)-doublet LQ with CP-violating couplings
Two-Dimensional Fit Results (I)

- good fit for both \((C^L_V, C^L_S = -4C_T)\) and \((C^L_V, C^R_S)\)
- small impact of \(\text{BR}(B_c \rightarrow \tau \nu)\) constraint
very good fit for \( (C^R_S, C^L_S) \), but only allowed for \( \text{BR}(B_c \rightarrow \tau\nu) < 60\% \)

- good fit for \( (C^L_S = 4C_T) \), unless \( \text{BR}(B_c \rightarrow \tau\nu) < 10\% \) 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:

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

- 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 $P_\tau(D^*)$

\[ P_\tau(D) \text{ and } P_\tau(D^*) \]

- $\text{BR}(B_s \to \tau\nu) > 60\%$
- $\text{BR}(B_s \to \tau\nu) > 30\%$
- $\text{BR}(B_s \to \tau\nu) > 10\%$

- $(C^L_v, C^L_S) = -4 C_T$
- $(C^R_S, C^L_S)$
- $(\text{Re } [C^L_S = 4 C_T], \text{Im } [C^L_S = 4 C_T])$
Correlations between Polarization Observables (II)

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

![Graph showing correlations between $P_\tau(D)$ and $F_L(D^*)$ with different branching ratios and polarization observables.](image)

- $BR(B_c \rightarrow \tau \nu) > 60\%$
- $BR(B_c \rightarrow \tau \nu) > 30\%$
- $BR(B_c \rightarrow \tau \nu) > 10\%$

Legend:
- $C_V^l, C_S^l = -4 C_T$
- $C_S^R, C_S^l$
- $\text{Re} [C_S^l = 4 C_T], \text{Im} [C_S^l = 4 C_T]$
Correlations between Polarization Observables (III)

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

![Graph showing correlations between $P_{\tau}(D^*)$ and $F_L(D^*)$.](image)

- $(C_T^V, C_S^V = -4 C_T)$
- $(C_S^R, C_T^L)$
- $(\text{Re}[C_S^T = 4 C_T], \text{Im}[C_S^T = 4 C_T])$

New Physics in $b \rightarrow c\tau\nu$
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