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Institute for Theoretical Particle Physics

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

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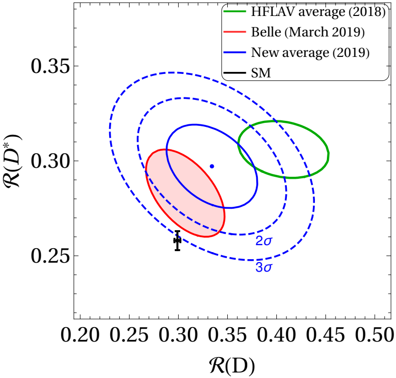
Motivation: the $R_{D^{(*)}}$ anomalies

Test of lepton flavour universality in $b \to c\ell\nu$

$$R_{D^{(*)}} = \frac{\mathcal{BR}(B \to D^{(*)}\tau\nu)}{\mathcal{BR}(B \to D^{(*)}\ell\nu)}$$

- theoretically clean, since hadronic uncertainties largely cancel in ratio
- measured by BaBar, LHCb, Belle $\to$2019: Semileptonic tagging [arXiv:1904.08794]
- 3.1σ tension between experimental average and SM theory prediction
- $R_{\mu/e}$ agrees with SM $\Rightarrow$ disagreement in τ-channel



Parametrisation of new physics

New physics lies above the scale m_B, so we can parametrise it in terms of four-fermion interactions

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2} G_F V_{cb} [(1 + C_V^L)(\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + \\ + C_S^R (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) + C_S^L (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau) \\ + C_T (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)]$$

- no light ν_R
- NP in τ only

Procedure: perform a fit of the Wilson coefficients

- including all available data on the vertex $(\bar{c}\Gamma b)(\bar{\tau}\Gamma\nu_\tau)$
- restricting to single-particle scenarios

One particle scenarios

$(C_V^L, C_S^L = -4C_T)$ Scalar Leptoquark S_1, $SU(2)$ singlet

(C_S^R, C_S^L) Charged Higgs

(C_V^L, C_S^R) Vector Leptoquark U_1, $SU(2)$ singlet

$C_S^L = 4C_T$ Scalar Leptoquark S_2, $SU(2)$ doublet

$(\bar{c}\Gamma b)\,(\bar{\tau}\Gamma\nu_\tau)$ – Fit

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Observables available for the fit

- $\mathcal{R}_D$
- $\mathcal{R}_{D^*}$
- τ polarisation in $B \to D^*$:
  $P_\tau(D^*) = \frac{\Gamma(\tau^{\lambda=+1/2})-\Gamma(\tau^{\lambda=-1/2})}{\Gamma(\tau^{\lambda=+1/2})+\Gamma(\tau^{\lambda=-1/2})}$
- D^* polarisation:$F_L(D^*) = \frac{\Gamma(D^*_L)}{\Gamma(D^*)}$

Predicted observables

- $P_\tau(D) = \frac{\Gamma(\tau^{\lambda=+1/2})-\Gamma(\tau^{\lambda=-1/2})}{\Gamma(\tau^{\lambda=+1/2})+\Gamma(\tau^{\lambda=-1/2})}$
- $\mathcal{R}(\Lambda_c) = \frac{\mathrm{BR}(\Lambda_b\to\Lambda_c\tau\nu)}{\mathrm{BR}(\Lambda_b\to\Lambda_c\ell\nu)}$

B_c

$\mathrm{BR}(B_c \to \tau\nu)$ not measured. We perform the fit requiring

- $\mathrm{BR}(B_c \to \tau\nu) < 10\%$ [Akeroyd, Chen (2017)]
- $\mathrm{BR}(B_c \to \tau\nu) < 30\%$ [Alonso, Grinstein, Martin Camalich (2016)]
- $\mathrm{BR}(B_c \to \tau\nu) < 60\%$ [Conservative limit]

Fit results

Mediator	p-value (%)	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
Charged Higgs$_{60\%}$	77.4	0.333 $0.0\,\sigma$	0.299 $+0.1\,\sigma$	0.54 $-0.7\,\sigma$	-0.27 $+0.2\,\sigma$	0.38	0.38
Charged Higgs$_{30\%}$	29.9	0.348 $+0.4\,\sigma$	0.280 $-1.2\,\sigma$	0.51 $-1.0\,\sigma$	-0.35 $0.0\,\sigma$	0.41	0.37
Charged Higgs$_{10\%}$	3.2	0.360 $+0.8\,\sigma$	0.263 $-2.2\,\sigma$	0.48 $-1.4\,\sigma$	-0.44 $-0.1\,\sigma$	0.43	0.36
Scalar LQ $S_{2;60,30\%}$	25.0	0.333 $0.0\,\sigma$	0.297 $0.0\,\sigma$	0.45 $-1.7\,\sigma$	-0.41 $-0.1\,\sigma$	0.40	0.38
Scalar LQ $S_{2;10\%}$	7.1	0.326 $-0.2\,\sigma$	0.276 $-1.4\,\sigma$	0.46 $-1.6\,\sigma$	-0.44 $-0.1\,\sigma$	0.38	0.36

Correlation: BR($B_c \to \tau\nu$) and $\mathcal{R}(D^{(*)})$

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If the charged Higgs or the scalar LQ S_2 are responsible for the anomaly, we expect BR($B_c \to \tau\nu$) $> 10\%$

Mediator	p-value (%)	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
Charged Higgs$_{60\%}$	77.4	0.333 $0.0\,\sigma$	0.299 $+0.1\,\sigma$	0.54 $-0.7\,\sigma$	-0.27 $+0.2\,\sigma$	0.38	0.38
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Impact of $F_L(D^*)$

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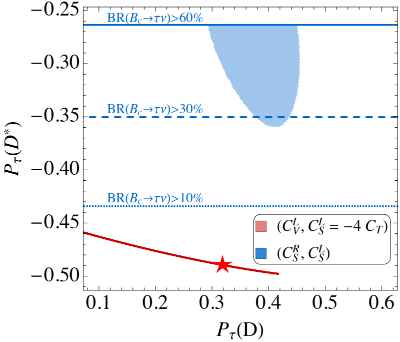
The current value of $F_L(D^*)$ favors the charged Higgs scenario

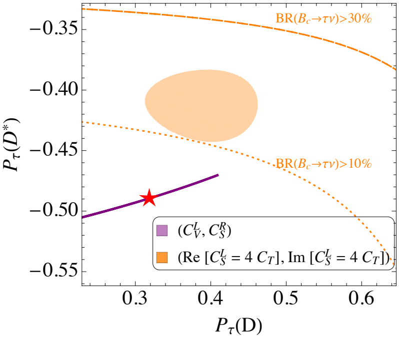
$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.035 \qquad \text{[Belle, 2018]}$$

Mediator	p-value (%)	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
Scalar LQ S_1	31.5	0.327 $-0.2\,\sigma$	0.300 $+0.2\,\sigma$	0.47 $-1.5\,\sigma$	-0.48 $-0.2\,\sigma$	0.21	0.38
Charged $\text{Higgs}_{60\%}$	77.4	0.333 $0.0\,\sigma$	0.299 $+0.1\,\sigma$	0.54 $-0.7\,\sigma$	-0.27 $+0.2\,\sigma$	0.38	0.38
Vector LQ U_1	25.9	0.337 $+0.1\,\sigma$	0.296 $-0.1\,\sigma$	0.46 $-1.6\,\sigma$	-0.50 $-0.2\,\sigma$	0.29	0.38
Scalar LQ $S_{2;60,30\%}$	25.0	0.333 $0.0\,\sigma$	0.297 $0.0\,\sigma$	0.45 $-1.7\,\sigma$	-0.41 $-0.1\,\sigma$	0.40	0.38

Polarisation observables

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





Scalar LQ S_1
Charged Higgs
⋆ Standard Model

Vector LQ U_1
Scalar LQ S_2
⋆ Standard Model

Polarisation observables

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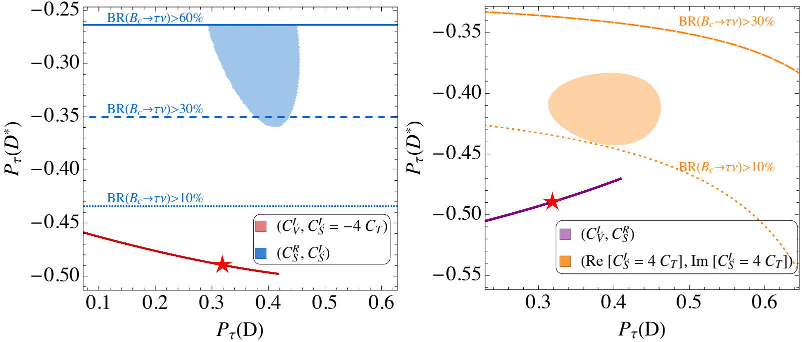
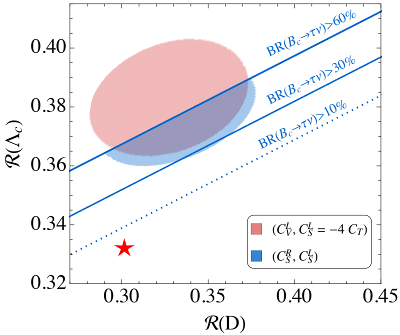
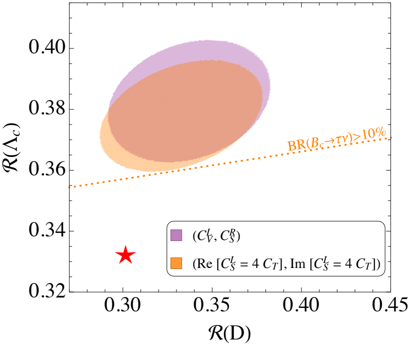
Correlation between $P_\tau(D^*)$ and $P_\tau(D)$



Polarisation observables distinguish new physics scenarios

Correlation between $\mathcal{R}(\Lambda_c)$ and $\mathcal{R}(D^{(*)})$





Scalar LQ S_1
Charged Higgs
⋆ Standard Model

Vector LQ U_1
Scalar LQ S_2
⋆ Standard Model

Correlation between $\mathcal{R}(\Lambda_c)$ and $\mathcal{R}(D^{(*)})$

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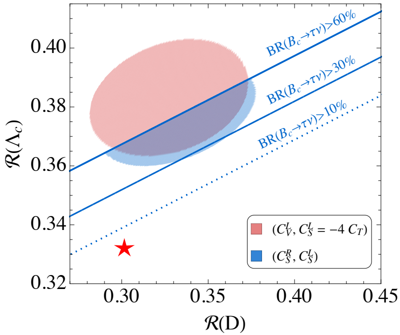

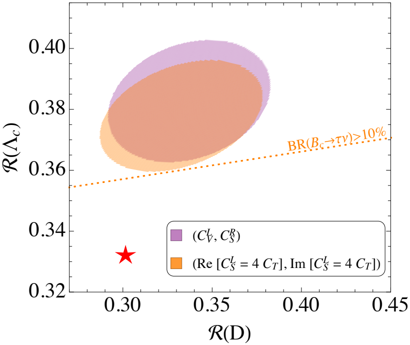

Fitting the current $\mathcal{R}(D^{(*)})$ central values always implies an increase of $\mathcal{R}(\Lambda_c)$

$\mathcal{R}(\Lambda_c)$ sum rule

The numerical expressions for $\mathcal{R}(\Lambda_c)$ and $\mathcal{R}(D^{(*)})$ lead to the sum rule

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

- $x \sim \mathcal{O}(0.1(\frac{\Lambda_{\rm EW}}{\Lambda_{\rm NP}})^2)$
- heavy quark limit: $\mathcal{R}(\Lambda_c), \mathcal{R}(D^{(*)})$ correspond to the (same) branching ratios at the quark level

Standard Model

$\mathcal{R}_{\rm SM}(\Lambda_c) = 0.33 \pm 0.01$

[Detmold, Lehner, Meinel 2015]

$\mathcal{R}_{\rm SM}(\Lambda_c) = 0.324 \pm 0.004$

[Bernlochner, Ligeti, Robinson, Sutcliffe 2018]

New Physics

$\mathcal{R}_{\rm NP}(\Lambda_c) = 0.38 \pm 0.02 \pm 0.01$

$\mathcal{R}(\Lambda_c)$ will serve as cross-check of the $\mathcal{R}(D^{(*)})$ measurements

Summary

- Update of the $b \to c\tau\nu$ fit, including $F_L(D^*)$ and new Belle data
- Analysis of correlations between observables:
  - $\mathrm{BR}(B_c \to \tau\nu)$ and $\mathcal{R}(D^{(*)})$: charged Higgs and scalar Leptoquark S_2 predict $\mathrm{BR}(B_c \to \tau\nu) > 10\%$
  - polarisation observables crucial in distinguishing new physics scenarios
  - $\mathcal{R}(\Lambda_c)$ will serve as cross-check of $\mathcal{R}(D^{(*)})$