Implications of new physics in \( b \to c \tau \nu \) for polarisation observables and \( \Lambda_b \to \Lambda_c \tau \nu \)

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Precision era in high-energy physics
Portorož, 17 Apr 2019
I’ll present an update of

Impact of polarisation observables and $B_c \to \tau \nu$ on new physics explanations of the $b \to c \tau \nu$ anomaly


1. $b \to c \tau \nu$ and new physics
2. Polarisation observables
3. Magic relation for $\mathcal{R}(\Lambda_c)$
4. Summary
$b \rightarrow c\tau\nu$

$$\mathcal{R}(D^{(*)}) \equiv \frac{\text{BR}(B \rightarrow D^{(*)}\tau\nu)}{\text{BR}(B \rightarrow D^{(*)}\ell\nu)}$$

measured above SM expectation by $3.1\sigma$
New BELLE measurements:

\[
\mathcal{R}(D)_{\text{Belle}} = 0.307 \pm 0.037_{\text{stat}} \pm 0.016_{\text{syst}}
\]

\[
\mathcal{R}(D^*)_{\text{Belle}} = 0.283 \pm 0.018_{\text{stat}} \pm 0.014_{\text{syst}}
\]

New world average:

\[
\mathcal{R}(D) = 0.334 \pm 0.031
\]

\[
\mathcal{R}(D^*) = 0.297 \pm 0.015
\]

deviates from SM by 3.1\sigma:

\[
\mathcal{R}_{\text{SM}}(D) = 0.299 \pm 0.003
\]

\[
\mathcal{R}_{\text{SM}}(D^*) = 0.258 \pm 0.005
\]
\[ \frac{\mathcal{R}(D)}{\mathcal{R}(D)_{SM}} = 1.12 \pm 0.10_{\text{stat}} \pm 0.08_{\text{syst}}, \quad 1.1\sigma \]

\[ \frac{\mathcal{R}(D^*)}{\mathcal{R}(D^*)_{SM}} = 1.15 \pm 0.06_{\text{stat}} \pm 0.027_{\text{syst}}, \quad 2.6\sigma \]

Which new physics could compete with a SM tree–level decay?
Two-Higgs-doublet models (2HDM) predict a charged Higgs boson:


Two independent $H^+$ couplings to quarks: $b_L - c_R$ and $b_R - c_L$

This is not the type-I or type-II 2HDM.
The charged-Higgs explanation is under pressure from $B_c \to \tau \bar{\nu}$: From the measured lifetime we know the total decay width $\Gamma_{\text{tot}}(B_c)$. Since

$$\text{BR}(B_c \to \tau \bar{\nu}) \equiv \frac{\Gamma(B_c \to \tau \bar{\nu})}{\Gamma_{\text{tot}}(B_c)},$$

we have

$$\Gamma(B_c \to \tau \bar{\nu}) = \Gamma_{\text{tot}}(B_c) \text{BR}(B_c \to \tau \bar{\nu}).$$

Now $\Gamma(B_c \to \tau \bar{\nu})$ involves the same combination of charged-Higgs couplings as $\Gamma(B \to D^* \tau \nu)$, and the $\mathcal{R}(D^*)$ data are compatible only with an excessive enhancement of $\text{BR}(B_c \to \tau \bar{\nu})$ over $\text{BR}(B_c \to \tau \bar{\nu})_{\text{SM}} = 0.02$. Alonso, Grinstein, Martin Camalich 2015

$\rightarrow$ more on this later
Leptoquarks

Theorists’ current darlings: **leptoquarks**

Leptoquarks . . .

- . . . are bosons with **spin 0** or **spin 1**,  
- . . . couple quark to lepton,  
- . . . must be **colour (anti-)triplets** (like the (anti-)quarks),  
- . . . must carry **weak hypercharge** and **electric charge** \( Q \),  
- . . . are either **singlets, doublets** or **triplets** of **weak-isospin SU(2)**.

Examples:

- **spin 0 SU(2) singlet**  
  \[ Q = \frac{1}{3} \]

- **spin 1 SU(2) singlet**  
  \[ Q = \frac{2}{3} \]
Whatever it is (charged Higgs or leptoquark of any kind), it must be charged and therefore very heavy.
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One can describe all possible new physics effects by effective four-fermion interactions.

Need these four-fermion operators:

\[
O^L_V = \bar{c}_L \gamma^\mu b_L \bar{\tau}_L \gamma_\mu \nu_{\tau L},
\]

\[
O^R_S = \bar{c}_L b_R \bar{\tau}_R \nu_{\tau L},
\]

\[
O^L_S = \bar{c}_R b_L \bar{\tau}_R \nu_{\tau L},
\]

\[
O_T = \bar{c}_R \sigma^{\mu \nu} b_L \bar{\tau}_R \sigma_{\mu \nu} \nu_{\tau L}.
\]

The corresponding coefficients \( C^L_V, C^R_S, C_T \) can be fitted to data.
The coefficients are suppressed by $\frac{M_{W}^{2}}{M_{\text{new}}^{2}}$, where $M_{\text{new}}$ is the mass of the charged Higgs boson or leptoquark. The SM suppression factor $|V_{cb}| \approx 0.04$ is absent, so $M_{\text{new}} \sim 1.5 \text{ TeV}$ could explain $\mathcal{R}(D^{(*)})$.

Note:
The operator $\bar{c}_{R}\gamma^{\mu}b_{R} \bar{\tau}_{L}\gamma_{\mu}\nu_{\tau L}$ has the same coefficient as $\bar{c}_{R}\gamma^{\mu}b_{R} \bar{\ell}_{L}\gamma_{\mu}\nu_{\ell L}$, $\ell = e, \mu$ at order $\frac{M_{W}^{2}}{M_{\text{new}}^{2}}$. Lepton flavour universality violation is only possible at order $\frac{M_{W}^{4}}{M_{\text{new}}^{4}}$. 

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Two-dimensional scenarios

coefficients

real $C_V^L$, $C_S^L = -4C_T$

real $C_S^R$, $C_S^L$

real $C_V^L$, $C_S^R$

Re[$C_S^L = 4C_T$], Im[$C_S^L = 4C_T$]
Apart from $\mathcal{R}(D(\ast))$ we use the $\tau$ polarisation asymmetry in $B \to D^*\tau \nu$:

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

where $\lambda$ denotes the $\tau$ helicity.

$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16} \quad \text{Belle 2016}$$

At present $P_\tau(D^*)$ is not constraining new-physics scenarios.
New: longitudinal $D^*$ polarisation fraction in $B \rightarrow D^*\tau\nu$

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

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.035 \quad \text{Belle 2018}$$

While consistent with

$$F_{L,SM}(D^*) = 0.46 \pm 0.04$$

at 1.5$\sigma$, the measurement of $F_L(D^*)$ already helps to favour some new-physics scenarios over others.
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From our fit results we predict $F_L(D^*), P_{\tau}(D^*), P_{\tau}(D)$ and

$$R(\Lambda_c) \equiv \frac{BR(\Lambda_b \to \Lambda_c\tau\nu_\tau)}{BR(\Lambda_b \to \Lambda_c\ell\nu_\ell)}.$$
$B_c \rightarrow \tau \nu$

$\text{BR}(B_c \rightarrow \tau \nu)$ severely affects the charged Higgs scenario. From the non-observation of $Z \rightarrow b\bar{b}[\rightarrow B_c \rightarrow \tau \nu]$ at LEP 1 an upper bound $\text{BR}(B_c \rightarrow \tau \nu) < 10\%$ has been inferred. Akeroyd, Chen 2017
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This bound estimates the ratio $f_c/f_u$ of the $b \rightarrow B_c$ and $b \rightarrow B_u$ fragmentation probability from $pp$ and $p\bar{p}$ data, especially from

$$R \equiv \frac{f_c}{f_u} \frac{\text{BR}(B_c^- \rightarrow J/\psi\pi^-)}{\text{BR}(B^- \rightarrow J/\psi K^-)}.$$

$$R = (4.8 \pm 0.5 \pm 0.6) \cdot 10^{-3} \quad \text{with } p_T > 15 \text{ GeV, CMS 2014}$$

$$R = (6.83 \pm 0.18 \pm 0.09) \cdot 10^{-3} \quad \text{with } 0 < p_T < 20 \text{ GeV, LHCb 2014}$$

$p_T$ dependence indicates process-dependent effects:

$B_c$ production is not the same as $b \rightarrow B_c$ fragmentation.
\( B_c \rightarrow \tau \nu \)

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We perform our analyses for three cases, assuming \( \text{BR}(B_c \rightarrow \tau \nu) < 10\% \), \( \text{BR}(B_c \rightarrow \tau \nu) < 30\% \), or \( \text{BR}(B_c \rightarrow \tau \nu) < 60\% \).
Compare leptoquark $S_1$ scenario (feeding $C^L_V, C_S = -4C_T$) and charged-Higgs scenario (feeding $C^{L,R}_S$) with $\text{BR}(B_c \rightarrow \tau\nu) < 10\%$, $\text{BR}(B_c \rightarrow \tau\nu) < 30\%$, or $\text{BR}(B_c \rightarrow \tau\nu) < 60\%$:

<table>
<thead>
<tr>
<th>2D hyp.</th>
<th>best-fit</th>
<th>$p$-value (%)</th>
<th>pull_{SM}</th>
<th>$\mathcal{R}(D)$</th>
<th>$\mathcal{R}(D^*)$</th>
<th>$F_L(D^*)$</th>
<th>$P_\tau(D^*)$</th>
<th>$P_\tau(D)$</th>
<th>$\mathcal{R}(\Lambda_c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(C^L_V, C^L_S = -4C_T)$</td>
<td>(0.11, -0.05)</td>
<td>31.5</td>
<td>3.3</td>
<td>0.327</td>
<td>-0.2 $\sigma$</td>
<td>0.300</td>
<td>-0.2 $\sigma$</td>
<td>0.47</td>
<td>-1.5 $\sigma$</td>
</tr>
<tr>
<td>$(C^R_S, C^L_S)_{60%}$</td>
<td>(0.30, -0.26)</td>
<td>77.4</td>
<td>3.5</td>
<td>0.333</td>
<td>0.0 $\sigma$</td>
<td>0.299</td>
<td>0.0 $\sigma$</td>
<td>0.54</td>
<td>-0.7 $\sigma$</td>
</tr>
<tr>
<td>$(C^R_S, C^L_S)_{30%}$</td>
<td>(0.20, -0.15)</td>
<td>29.9</td>
<td>3.3</td>
<td>0.348</td>
<td>+0.4 $\sigma$</td>
<td>0.280</td>
<td>-1.2 $\sigma$</td>
<td>0.51</td>
<td>-1.0 $\sigma$</td>
</tr>
<tr>
<td>$(C^R_S, C^L_S)_{10%}$</td>
<td>(0.11, -0.04)</td>
<td>3.2</td>
<td>2.6</td>
<td>0.360</td>
<td>+0.8 $\sigma$</td>
<td>0.263</td>
<td>-2.2 $\sigma$</td>
<td>0.48</td>
<td>-1.4 $\sigma$</td>
</tr>
</tbody>
</table>

- $S_2$ scenario in good shape, with SM-like $F_L(D^*)$.
- Charged-Higgs scenario still alive.
- $F_L(D^*) > F_{L_{\text{SM}}}(D^*)$ favours charged-Higgs over other scenarios.

If a charged Higgs is behind $\mathcal{R}(D^{(*)})$, then either $\text{BR}(B_c \rightarrow \tau\nu) \gtrsim 30\%$ or $\mathcal{R}(D^*)$ will come down in future measurements.
Compare scenarios with leptoquarks $U_1$ (feeding $C^L_V, C^R_S$) and $S_2$ (feeding $C^L_S = 4C_T$):

<table>
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<th>$F_L(D^*)$</th>
<th>$P_\tau(D^*)$</th>
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<th>$\mathcal{R}(\Lambda_c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(C^L_V, C^R_S)$</td>
<td>$(0.08, -0.02)$</td>
<td>25.9</td>
<td>3.2</td>
<td>0.337 $\pm 0.1 \sigma$</td>
<td>0.296 $-0.1 \sigma$</td>
<td>0.46 $-1.6 \sigma$</td>
<td>$-0.50$</td>
<td>$-0.2 \sigma$</td>
<td>0.29</td>
</tr>
<tr>
<td>$(\text{Re}[C^L_S = 4C_T], \text{Im}[C^L_S = 4C_T])</td>
<td>_{60,30%}$</td>
<td>$(-0.07, \pm 0.30)$</td>
<td>25.0</td>
<td>3.2</td>
<td>0.333</td>
<td>0.297</td>
<td>0.45 $-1.7 \sigma$</td>
<td>$-0.41$</td>
<td>$-0.1 \sigma$</td>
</tr>
<tr>
<td>$(\text{Re}[C^L_S = 4C_T], \text{Im}[C^L_S = 4C_T])</td>
<td>_{10%}$</td>
<td>$(-0.03, \pm 0.23)$</td>
<td>7.1</td>
<td>2.9</td>
<td>0.326 $-0.2 \sigma$</td>
<td>0.276 $-1.4 \sigma$</td>
<td>0.46 $-1.6 \sigma$</td>
<td>$-0.44$</td>
<td>$-0.1 \sigma$</td>
</tr>
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</table>

- $F_L(D^*)$ SM-like in both scenarios.
- $U_1$ scenario in good shape, can also explain the $b \to \mu^+\mu^-$ anomalies $R_K^{(*)}, P_5^\prime$
  - Buttazzo, Greljo, Isidori, Marzocca 2017
  - Calibbi, Crivellin, Li 2017
- For the $S_2$ scenario it is essential to permit complex coefficients to get a good fit.

- The $S_2$ scenario will also be under pressure, if future bounds on $\text{BR}(B_c \to \tau\nu)$ approach 10% while $\mathcal{R}(D^{(*)})$ stays high.
- The $S_2$ scenario is further already meaningfully probed by high-$p_T$ data from ATLAS and CMS.
  - Greljo, Martin Camalich, Ruiz-Álvarez, 2018
Polarisation observables

Future more precise measurements can distinguish the scenarios:

The plotted regions correspond to the $1\sigma$ ranges of the coefficients.

Red: leptoquark $S_1$
Blue: charged Higgs
Violet: leptoquark $U_1$
Orange: leptoquark $S_2$
A simultaneous explanation of $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$ data with scalar leptoquarks needs two leptoquarks to suppress excessive contributions to $b \to s\bar{\nu}\nu$.

Here $\Phi_1 = S_1$ and $\Phi_3$ is an SU(2) triplet.
What about

$$R(\Lambda_c) \equiv \frac{\text{BR}(\Lambda_b \rightarrow \Lambda_c \tau \nu_\tau)}{\text{BR}(\Lambda_b \rightarrow \Lambda_c \ell \nu_\ell)}$$

In all scenarios with good $p$-values we essentially predict the same value for $R(\Lambda_c)$. 
Inspecting the analytic expressions we find a sum rule:

\[
\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{SM}(\Lambda_c)} = 0.262 \frac{\mathcal{R}(D)}{\mathcal{R}_{SM}(D)} + 0.738 \frac{\mathcal{R}(D^*)}{\mathcal{R}_{SM}(D^*)} + x.
\]

The remainder \( x \) is a function of the new-physics coefficients \( C_V^L, C_S^L, C_T \) and stays small, \(|x| \leq 0.05\), when \( C_V^L, C_S^L, C_T \) are varied within the ranges allowed by the measured values of \( \mathcal{R}(D^{(*)}) \).
Magic relation

Inspecting the analytic expressions we find a sum rule:

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

The remainder $x$ is a function of the new-physics coefficients $C_V^L, C_S^{L,R}, C_T$ and stays small, $|x| \leq 0.05$, when $C_V^L, C_S^{L,R}, C_T$ are varied within the ranges allowed by the measured values of $\mathcal{R}(D^*)$.

Thus current data entail

$$\mathcal{R}(\Lambda_c) = \mathcal{R}_{SM}(\Lambda_c) (1.14 \pm 0.06) = 0.38 \pm 0.02_{\text{exp}} \pm 0.02_{\text{th}}$$

in any model of new physics!
Suppose you will measure $R(\Lambda_c)$ by $3\sigma$ below the SM value of $R_{SM}(\Lambda_c) = 0.33 \pm 0.01$.
This will actually weaken the case of new physics and point to inconsistent measurements!

If you instead find $R(\Lambda_c)$ complying with our prediction of $R(\Lambda_c) = 0.38 \pm 0.02 \pm 0.02$ you give support to the new-physics interpretation of $R(D^*)$.  

All possible new-physics (without light right-handed neutrinos) in all possible observables of $b \rightarrow c\tau\nu$ decays can be parametrised in terms of the four complex coefficients $C_L^V, C_L^S, C_R^S, C_T$.

The charged-Higgs scenario (with non-zero $C_L^S$) is not ruled out yet. (But collider data put this scenario under pressure.)

Scalar leptoquark $S_1$ and vector leptoquark $U_1$ exchange give good fits as well.

The leptoquark $S_2$ scenario works with complex coefficient only and is cornered by high-$p_T$ searches.

Polarisation measurements can discriminate between different scenarios.

$\mathcal{R}(\Lambda_c)$ is an important redundant measurement to validate the $\mathcal{R}(D^{(*)})$ anomaly. In any model of new physics one has $\mathcal{R}(\Lambda_c) = 0.38 \pm 0.02 \pm 0.02$. 