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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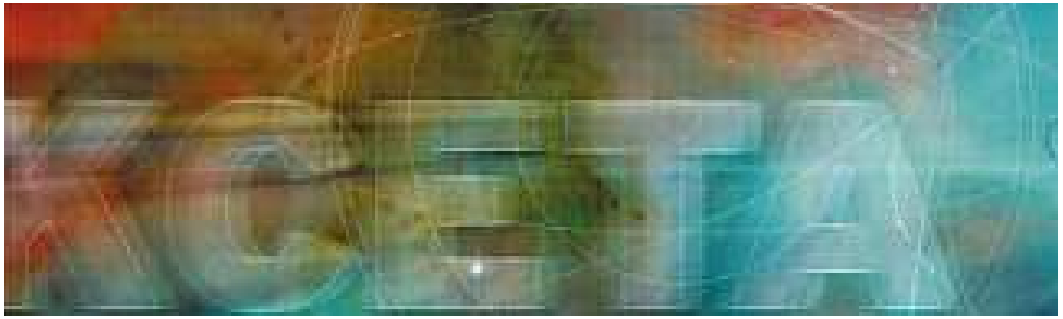
TRR 257: Particle Physics after the Higgs Discovery



Precision era in high-energy physics
Portorož, 17 Apr 2019

Contents

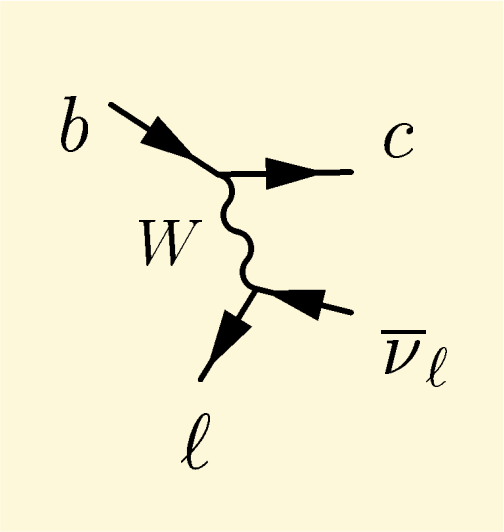
I'll present an update of

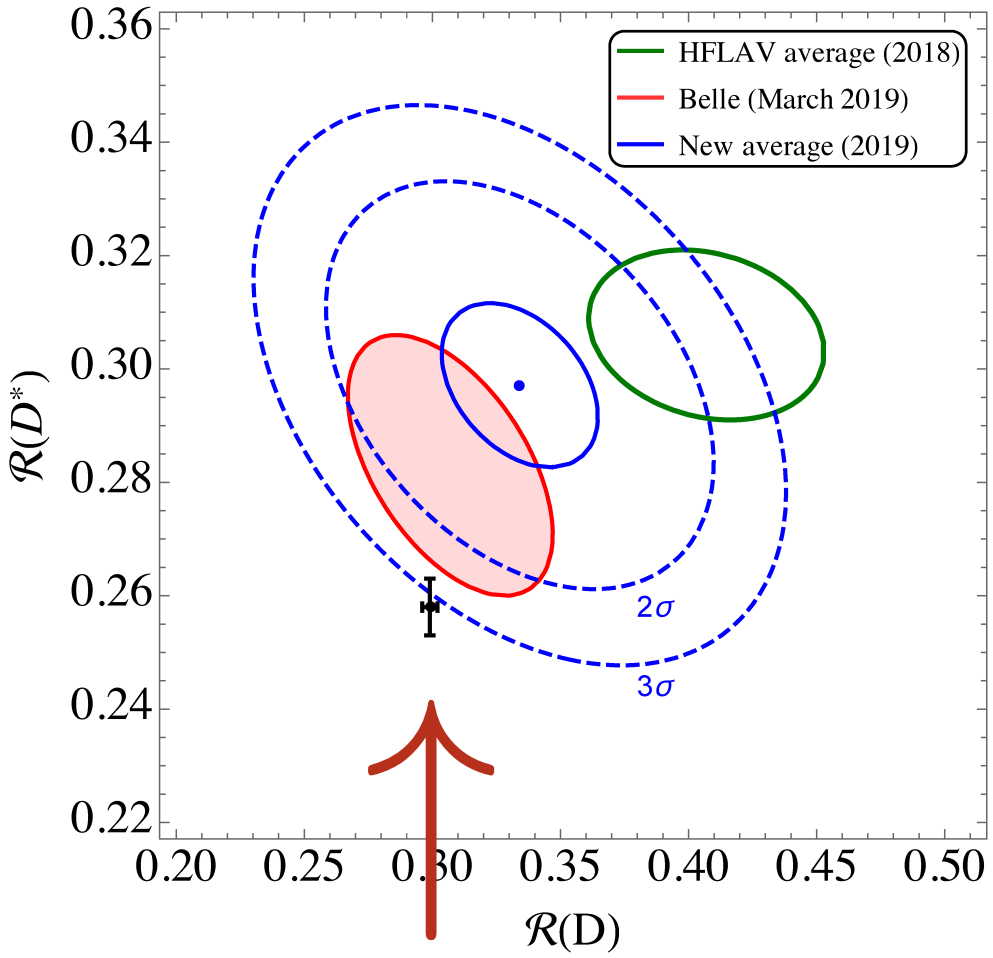
Impact of polarisation observables and $B_c \to \tau\nu$ on new physics explanations of the $b \to c\tau\nu$ anomaly

by M. Blanke, A. Crivellin, S. de Boer, M. Moscati, U.N., I. Nišandžić, and T. Kitahara, Phys. Rev. D 99, 075006 [arXiv:1811.09603].

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

measured above SM expectation by 3.1σ





SM values

New BELLE measurements:

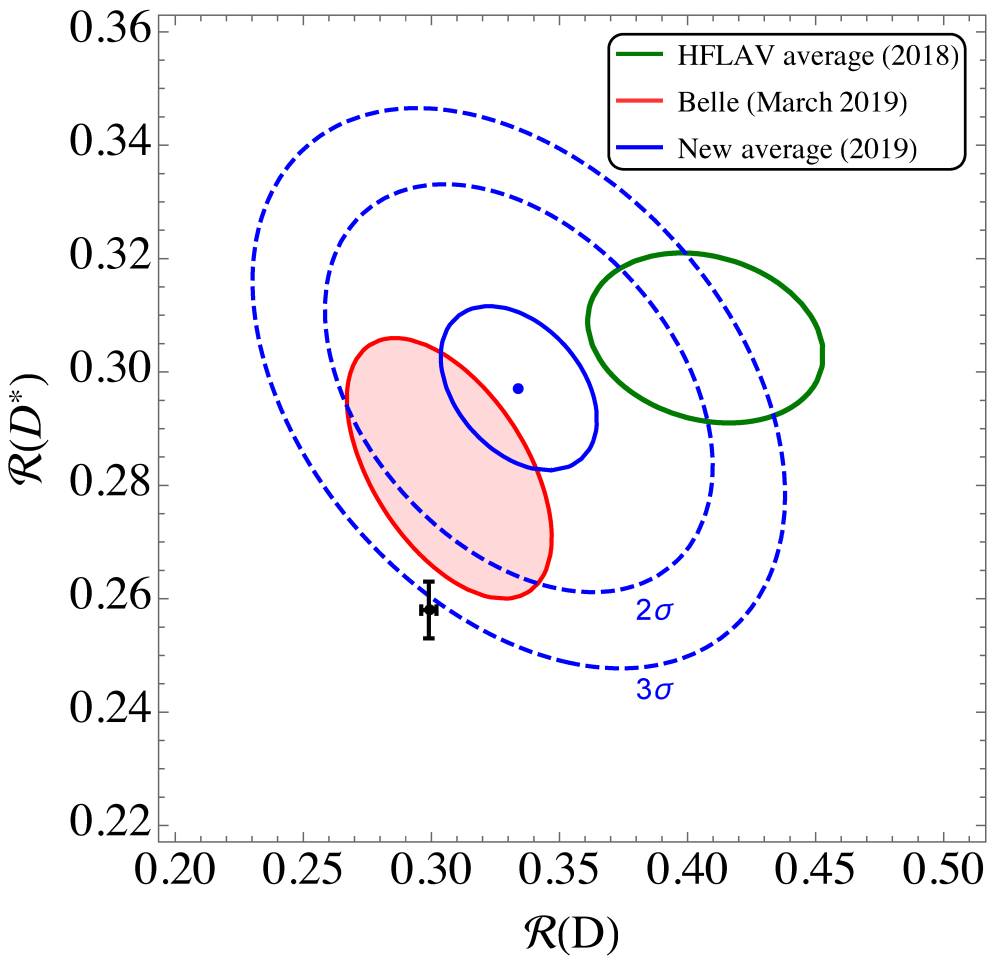
$$\mathcal{R}(D)_{\text{Belle}} = 0.307 \pm 0.037_{\text{stat}} \pm 0.016_{\text{syst}}$$
$$\mathcal{R}(D^*)_{\text{Belle}} = 0.283 \pm 0.018_{\text{stat}} \pm 0.014_{\text{syst}}$$

New world average:

$$\mathcal{R}(D) = 0.334 \pm 0.031$$
$$\mathcal{R}(D^*) = 0.297 \pm 0.015$$

deviates from SM by 3.1σ:

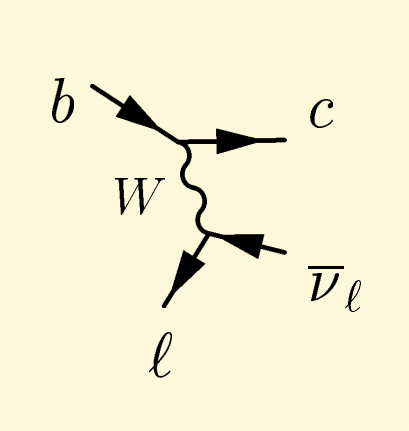
$$\mathcal{R}_{\text{SM}}(D) = 0.299 \pm 0.003$$
$$\mathcal{R}_{\text{SM}}(D^*) = 0.258 \pm 0.005$$



$$\frac{\mathcal{R}(D)}{\mathcal{R}(D)_{\rm SM}} = 1.12 \pm 0.10_{\rm stat} \pm 0.08_{\rm syst}, \qquad 1.1\sigma$$

$$\frac{\mathcal{R}(D^*)}{\mathcal{R}(D^*)_{\rm SM}} = 1.15 \pm 0.06_{\rm stat} \pm 0.027_{\rm syst}, \qquad 2.6\sigma$$

Which new physics could compete with a SM tree–level decay?



Charged Higgs

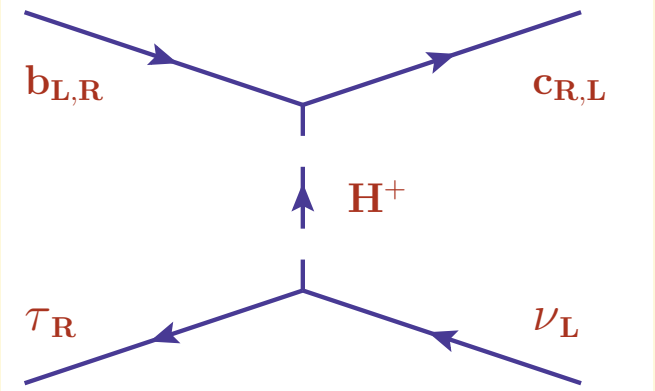
Two-Higgs-doublet models (2HDM) predict a charged Higgs boson:

B. Grzadkowski and W. S. Hou, *Searching for $B \to D\tau\bar{\nu}_\tau$ at the 10-percent level,* Phys. Lett. B **283** (1992) 427.
K. Kiers and A. Soni, *Improving constraints on $\tan\beta/m_H$ using $B \to D\tau\bar{\nu}_\tau$,* Phys. Rev. D **56** (1997) 5786.
U.N., S. Trine and S. Westhoff, *Charged-Higgs effects in a new $B \to D\tau\nu$ differential decay distribution,* Phys. Rev. D **78** (2008) 015006.

Two independent H^+ couplings to quarks:

$$b_L - c_R \text{ and } b_R - c_L$$

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 $\Gamma_{\rm tot}(B_c)$.
Since

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

we have

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

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 $\mathrm{BR}(B_c \to \tau\bar{\nu})$ over $\mathrm{BR}(B_c \to \tau\bar{\nu})_{\rm SM} = 0.02$. Alonso, Grinstein, Martin Camalich 2015

$\to$ more on this later

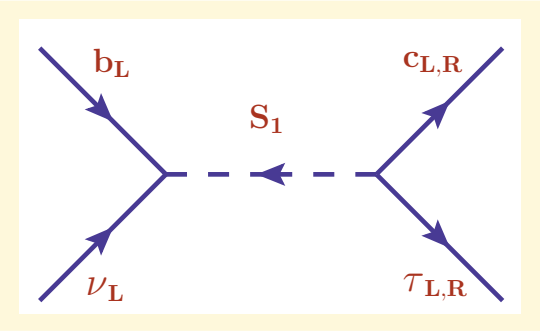
Leptoquarks

Theorists' current darlings: leptoquarks

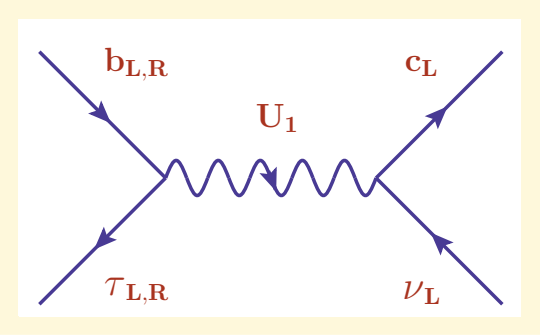
Leptoquarks...

- ...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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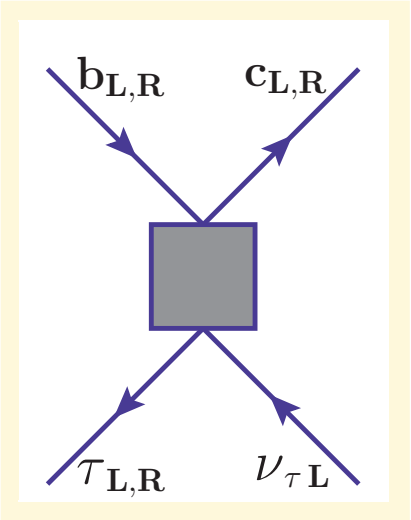
One can describe all possible new physics effects by effective four-fermion interactions.

Need these four-fermion operators:

$$
\begin{aligned}
O_V^L &= \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_{\tau L} \,, \\
O_S^R &= \bar{c}_L b_R \, \bar{\tau}_R \nu_{\tau L} \,, \\
O_S^L &= \bar{c}_R b_L \, \bar{\tau}_R \nu_{\tau L} \,, \\
O_T &= \bar{c}_R \sigma^{\mu\nu} b_L \, \bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L} \,.
\end{aligned}
$$

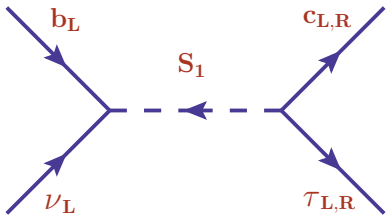
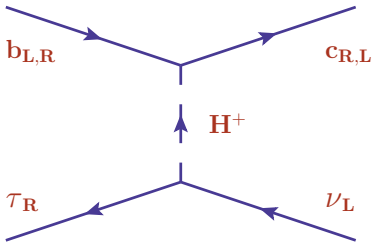
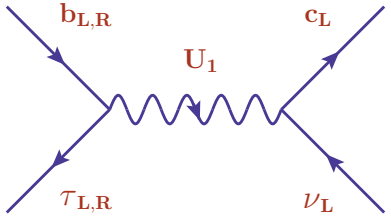
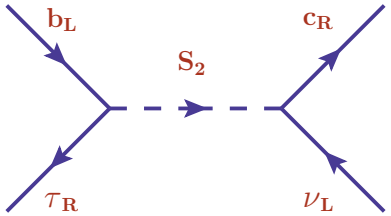


The corresponding coefficients $C_V^L, C_S^{R,L}, C_T$ can be fitted to data.

The coefficients are suppressed by $\frac{M_W^2}{M_{\rm new}^2}$, where $M_{\rm new}$ is the mass of the charged Higgs boson or leptoquark. The SM suppression factor $|V_{cb}| \approx 0.04$ is absent, so $M_{\rm new} \sim 1.5\,\text{TeV}$ 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 $\frac{M_W^2}{M_{\rm new}^2}$. Lepton flavour universality violation is only possible at order $\frac{M_W^4}{M_{\rm new}^4}$!

Two-dimensional scenarios

coefficients	motivated by
real C_V^L, $C_S^L = -4C_T$	
real C_S^R, C_S^L	
real C_V^L, C_S^R	
$\mathrm{Re}[C_S^L = 4C_T]$, $\mathrm{Im}[C_S^L = 4C_T]$	

Observables

Apart from $\mathcal{R}(D^{(*)})$ we use the τ 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 λ denotes the τ helicity.

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

At present $P_\tau(D^*)$ is not constraining new-physics scenarios.

New: longitudinal D^* polarisation fraction in $B \to D^* \tau \nu$

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

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.035$$ Belle 2018

While consistent with

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

at 1.5σ, 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

$$\mathcal{R}(\Lambda_c) \equiv \frac{\mathrm{BR}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathrm{BR}(\Lambda_b \to \Lambda_c \ell \nu_\ell)}.$$

$B_c \to \tau\nu$

$\mathrm{BR}(B_c \to \tau\nu)$ severely affects the charged Higgs scenario.
From the non-observation of $Z \to b\bar{b}[\to B_c \to \tau\nu]$ at LEP 1 an upper bound $\mathrm{BR}(B_c \to \tau\nu) < 10\%$ has been inferred. Akeroyd, Chen 2017

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This bound estimates the ratio f_c/f_u of the $b \to B_c$ and $b \to B_u$ fragmentation probability from pp and $p\bar{p}$ data, especially from

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

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

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

p_T dependence indicates process-dependent effects:
B_c production is not the same as $b \to B_c$ fragmentation.

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We perform our analyses for three cases, assuming
$\mathrm{BR}(B_c \to \tau\nu) < 10\%$, $\mathrm{BR}(B_c \to \tau\nu) < 30\%$, or $\mathrm{BR}(B_c \to \tau\nu) < 60\%$.

Compare leptoquark S_1 scenario (feeding $C_V^L, C_S = -4C_T$) and charged-Higgs scenario (feeding $C_S^{L,R}$) with $\mathrm{BR}(B_c \to \tau\nu) < 10\%$, $\mathrm{BR}(B_c \to \tau\nu) < 30\%$, or $\mathrm{BR}(B_c \to \tau\nu) < 60\%$:

2D hyp.	best-fit	p-value (%)	$\mathrm{pull}_{\mathrm{SM}}$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
$(C_V^L, C_S^L = -4C_T)$	$(0.11, -0.05)$	31.5	3.3	0.327 $-0.2\,\sigma$	0.300 $+0.2\,\sigma$	0.47 $-1.5\,\sigma$	-0.48 $-0.2\,\sigma$	0.21	0.38
$(C_S^R, C_S^L)\|_{60\%}$	$(0.30, -0.26)$ $(-0.15, -0.70)$	77.4	3.5	0.333 $0.0\,\sigma$	0.299 $+0.1\,\sigma$	0.54 $-0.7\,\sigma$	-0.27 $+0.2\,\sigma$	0.38	0.38
$(C_S^R, C_S^L)\|_{30\%}$	$(0.20, -0.15)$ $(-0.26, -0.61)$	29.9	3.3	0.348 $+0.4\,\sigma$	0.280 $-1.2\,\sigma$	0.51 $-1.0\,\sigma$	-0.35 $0.0\,\sigma$	0.41	0.37
$(C_S^R, C_S^L)\|_{10\%}$	$(0.11, -0.04)$ $(-0.37, -0.51)$	3.2	2.6	0.360 $+0.8\,\sigma$	0.263 $-2.2\,\sigma$	0.48 $-1.4\,\sigma$	-0.44 $-0.1\,\sigma$	0.43	0.36

- S_2 scenario in good shape, with SM-like $F_L(D^*)$.
- Charged-Higgs scenario still alive.
- $F_L(D^*) > F_{L\,\mathrm{SM}}(D^*)$ favours charged-Higgs over other scenarios.
- If a charged Higgs is behind $\mathcal{R}(D^{(*)})$, then either $\mathrm{BR}(B_c \to \tau\nu) \gtrsim 30\%$ or $\mathcal{R}(D^*)$ will come down in future measurements.

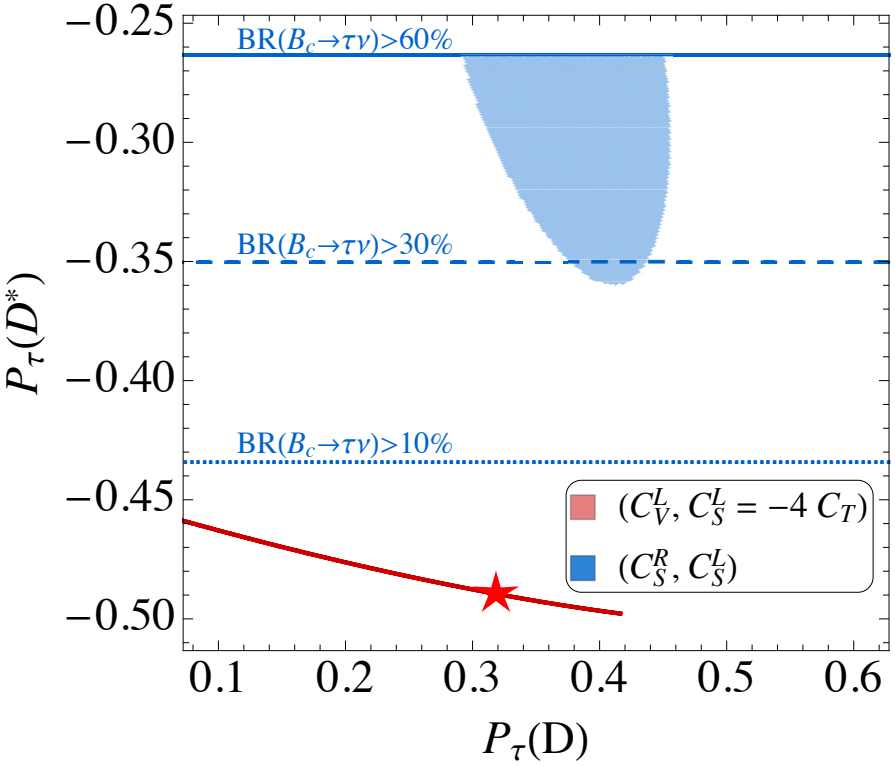
Compare scenarios with leptoquarks U_1 (feeding C_V^L, C_S^R) and S_2 (feeding $C_S^L = 4C_T$):

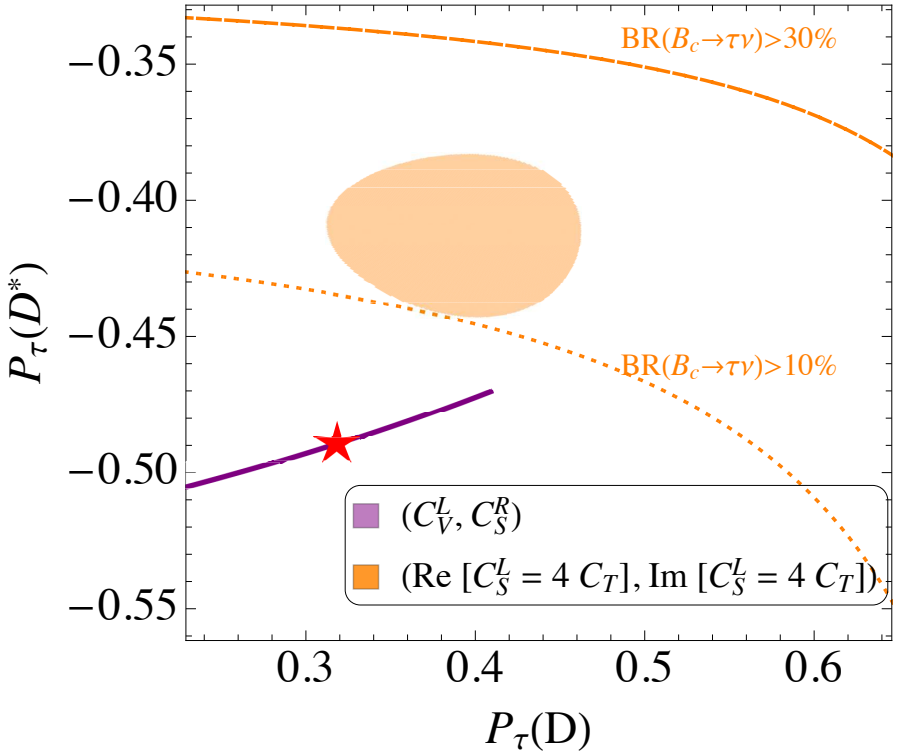
2D hyp.	best-fit	p-value (%)	pull_{SM}	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
(C_V^L, C_S^R)	$(0.08, -0.02)$	25.9	3.2	0.337 $+0.1\,\sigma$	0.296 $-0.1\,\sigma$	0.46 $-1.6\,\sigma$	-0.50 $-0.2\,\sigma$	0.29	0.38
$(\text{Re}[C_S^L = 4C_T], \text{Im}[C_S^L = 4C_T])\|_{60,30\%}$	$(-0.07, \pm 0.30)$	25.0	3.2	0.333 $0.0\,\sigma$	0.297 $0.0\,\sigma$	0.45 $-1.7\,\sigma$	-0.41 $-0.1\,\sigma$	0.40	0.38
$(\text{Re}[C_S^L = 4C_T], \text{Im}[C_S^L = 4C_T])\|_{10\%}$	$(-0.03, \pm 0.23)$	7.1	2.9	0.326 $-0.2\,\sigma$	0.276 $-1.4\,\sigma$	0.46 $-1.6\,\sigma$	-0.44 $-0.1\,\sigma$	0.38	0.36

- $F_L(D^*)$ SM-like in both scenarios.
- U_1 scenario in good shape, can also explain the $b \to \mu^+\mu^-$ anomalies $R_K^{(*)}, P_5'$
  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:





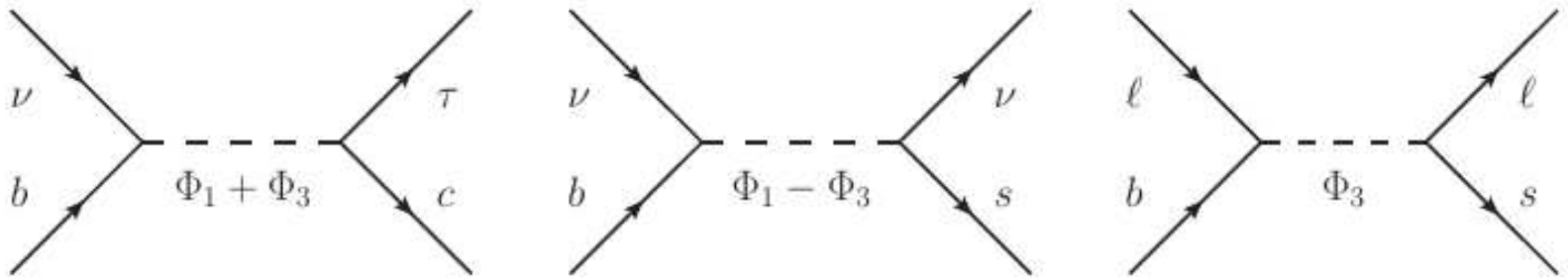
Red: leptoquark S_1
Blue: charged Higgs

Violet: leptoquark U_1
Orange: leptoquark S_2

The plotted regions correspond to the 1σ ranges of the coefficients.

Scalar leptoquarks

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 $b \to s\bar{\nu}\nu$.



Crivellin, Müller, Ota 2017

Here $\Phi_1 = S_1$ and Φ_3 is an SU(2) triplet.

What about

$$\mathcal{R}(\Lambda_c) \equiv \frac{\mathrm{BR}(\Lambda_b \to \Lambda_c \tau \nu_\tau)}{\mathrm{BR}(\Lambda_b \to \Lambda_c \ell \nu_\ell)}?$$

In all scenarios with good p-values we essentially predict the same value for $\mathcal{R}(\Lambda_c)$.

Magic relation

Inspecting the analytic expressions we find a sum rule:

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

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 $\mathcal{R}(D^{(*)})$.

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Thus current data entail

$$\begin{aligned}\mathcal{R}(\Lambda_c) =& \mathcal{R}_{\rm SM}(\Lambda_c)\,(1.14 \pm 0.06)\\ =& 0.38 \pm 0.02_{\rm exp} \pm 0.02_{\rm th}\end{aligned}$$

in any model of new physics!

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

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

Summary

- All possible new-physics (without light right-handed neutrinos) in all possible observables of $b \to c\tau\nu$ decays can be parametrised in terms of the four complex coefficients C_V^L, C_S^L, C_S^R, C_T.
- The charged-Higgs scenario (with non-zero $C_S^{L,R}$) 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 $\mathcal{R}(\Lambda_c) = 0.38 \pm 0.02 \pm 0.02$.