Flavor anomalies in $b \to c\tau\nu$ transitions

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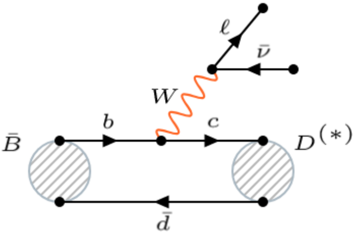
$b \to c\ell\bar{\nu}$ transitions



- Tree-level W-mediated transitions (within SM) with relatively large $BR \sim 1\text{-}2\%$
- Theoretical uncertainties from form factors (FF) - under control
- Original motivation: τ-modes sensitive to charged Higgs contributions within a Two-Higgs-Doublet-Model (2HDM)
- Could also be affected by other new intermediate heavy particles (such as a W'-boson or a leptoquark)
- Anticipation of precise measurements by collaborations Belle II and LHCb

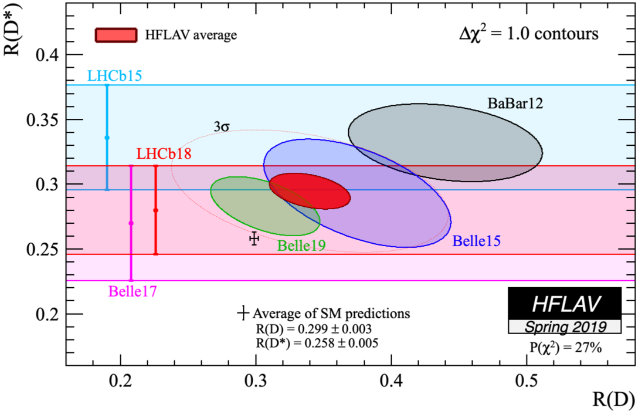
Motivation: $\mathcal{R}(D)$, $\mathcal{R}(D^*)$

- Theory predictions for individual modes (e, μ, τ) involve FF uncertainties and the parametric uncertainty from V_{cb}
- Introduce the ratios to cancel (significantly reduce) V_{cb} (FF uncertainties)

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

- Probe of beyond the Standard Model (BSM) sources of lepton flavor universality violation
- Measured values deviate from the SM expectations

Summary of current theoretical/experimental status



New result by Belle 2019 (in green)

- New global average HFLAV

$$\mathcal{R}(D) = 0.340 \pm 0.027 \pm 0.013, \quad \mathcal{R}(D^*) = 0.295 \pm 0.011 \pm 0.008\,,$$
$$\rho = -0.38\,.$$

- Compared to the SM values (HFLAV 2018 average)

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

- Including all observables $\mathcal{R}(D^{(*)}), F_L(D^*), P_\tau(D^*)$ we find current discrepancy w.r.t SM at level of $\sim 3.3\sigma$

Effective description

- An interesting deviation from the SM
- New physics modifying these ratios needs to compete with tree-level exchange of W-boson (Scale Λ_{NP} up to $\mathcal{O}(1\,\text{TeV})$)
- Heavy (charged) mediators integrated out ($\Lambda_{\text{NP}} \gg m_b$). Effective description:

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

with dimension-6 four-fermion operators:

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$

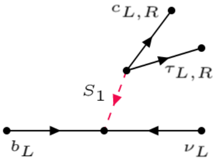
$$O_S^R = (\bar{c} P_R b)\,(\bar{\tau} P_L \nu_\tau)$$

$$O_S^L = (\bar{c} P_L b)\,(\bar{\tau} P_L \nu_\tau)$$

$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

- We do not consider $(\bar{c}\gamma^\mu P_R b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$ - does not appear in dimension-six SM-invariant eff. theory

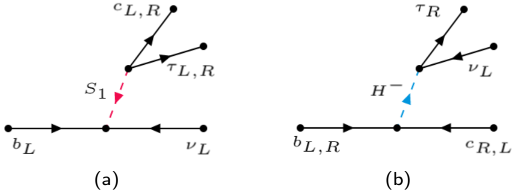
- We consider combinations of Wilson coefficients that could result from exchange of a single heavy intermediate state:



(a)

(a) real (C_V^L, $C_S^L = -4C_T$) - scalar leptoquark $S_1(3, 1, -1/3)$

- In this talk focus on two-parameter scenarios. Consider combinations of Wilson coefficients that result from exchange of a single heavy intermediate state:



(a) real (C_V^L, $C_S^L = -4C_T$) - scalar leptoquark $S_1(3,1,-1/3)$
(b) real (C_S^R, C_S^L) - charged Higgs

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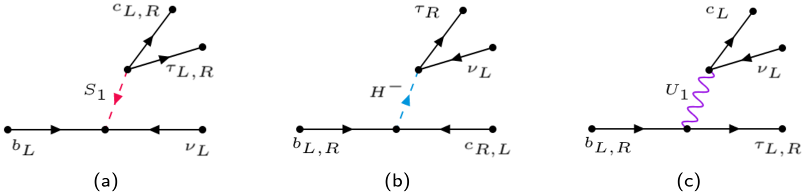

(a) real (C_V^L, $C_S^L = -4C_T$) - scalar leptoquark $S_1(3,1,-1/3)$
(b) real (C_S^R, C_S^L) - charged Higgs
(c) real (C_V^L, C_S^R) - vector leptoquark $U_1(3,1,2/3)$

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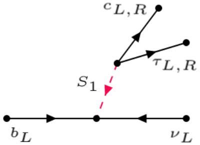

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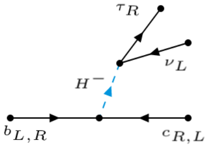

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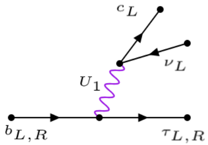
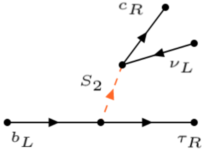


(c)



(d)

(a) real (C_V^L, $C_S^L = -4C_T$) - scalar leptoquark $S_1(3, 1, -1/3)$
(b) real (C_S^R, C_S^L) - charged Higgs
(c) real (C_V^L, C_S^R) - vector leptoquark $U_1(3, 1, 2/3)$
(d) $\mathrm{Re}[C_S^L = 4C_T], \mathrm{Im}[C_S^L = 4C_T]$ - scalar leptoquark $S_2(3, 2, 7/6)$

Observables

Perform fits for the Wilson coefficients of the four scenarios using the measured observables as inputs

- In addition to $\mathcal{R}(D^{(*)})$ we use τ-polarization asymmetry in $B \to D^* \tau \nu$

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

with λ denoting τ-helicity

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

Presently does not constrain NP scenarios.

New: Longitudinal D^*-polarization fractions in $B \to D^* \tau \nu$

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

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

consistent with SM value:

$$F_L(D^*)_{\mathsf{SM}} = 0.46 \pm 0.04$$

at 1.5σ, but nonetheless helps to favor some of the NP scenarios over others

Use the results of the fits to predict the yet unmeasured baryonic ratio:

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

and τ-polarization in $B \to D \tau \nu$.

$B_c \to \tau\nu$

- Charged Higgs explanation under pressure from B_c-lifetime that constraints yet unmeasured $BR(B_c \to \tau\nu)$
- $B_c \to \tau\nu$ is affected by the same pseudoscalar Wilson coefficient $C_S^R - C_S^L$ that enters $\mathcal{R}(D^*)$
- Total width $\Gamma_{\text{tot}}(B_c)$ known from measured lifetime and $\Gamma(B_c \to \tau\nu) = \Gamma_{\text{tot}} \times BR(B_c \to \tau\nu)$
- Within a charged Higgs scenario, $\mathcal{R}(D^*)$ data compatible only with excessive enhancement of $BR(B_c \to \tau\nu)$ over its SM-value Alonso, Grinstein, Martin Camalich (2015)

- An upper bound $BR(B_c \to \tau\nu) < 10\%$ inferred from non-observation of $Z \to b\bar{b}[B_c \to \tau\nu]$ at LEP   Akeroyd, Chen 2017

- The extraction of that bound used the estimate of the ratio f_c/f_u of $b \to B_c$ and $b \to B_u$ hadronization probabilities from pp-data using:

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

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

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

- Fragmentation functions depends on kinematics. Besides, pp-collisions produce B_c through mechanisms that have no counterpart in Z-decays.
- The extraction of 30%-bound by Alonso, Grinstein, Martin Camalich (2015) using the theoretical predictions of $\Gamma(B_c)$ from Beneke, Buchalla (1996)
- The latter results are very sensitive to the value of charm quark mass. The B_c-bound is not settled.
- We chose three hard constraints in our analysis: $BR(B_c \to \tau\nu) < 10\%$, $BR(B_c \to \tau\nu) < 30\%$, $BR(B_c \to \tau\nu) < 60\%$

Fits

- Concerning one-dimensional fit scenarios motivated by a single particle mediators, only C_V^L gives good fit
- Including the new result, best fit point $C_V^L \sim 0.07$ ($p_{val} \sim 40\%$), with $F_L(D^*) = F_{L,SM}(D^*)$
- Impact of the choice of the limit of $BR(B_c \to \tau\nu)$ on these scenarios is limited. Only C_S^R, that does not give good fit anyway, is slightly affected

2D fits

Compare the two scenarios $C_V^L, C_S^L = -4C_T$ (from leptoquark S_1) and $C_S^{L,R}$ (from charged Higgs)

2D hyp.	best-fit	p-value percent	pull$_{\text{SM}}$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
$(C_V^L, C_S^L = -4C_T)$	$(0.10, -0.04)$	**29.8**	3.6	0.333 $-0.2\ \sigma$	0.297 $+0.2\,\sigma$	**0.47** $-1.5\ \sigma$	-0.48 $-0.2\ \sigma$	0.25	0.38
$(C_S^R, C_S^L)\vert_{60\%}$	$(0.29, -0.25)$ $(-0.16, -0.69)$	**75.7**	3.9	0.338 $+0.1\,\sigma$	0.297 $+0.2\ \sigma$	**0.54** $-0.7\ \sigma$	-0.27 $+0.2\,\sigma$	0.39	0.38
$(C_S^R, C_S^L)\vert_{30\%}$	$(0.21, -0.15)$ $(-0.26, -0.61)$	30.9	3.6	0.353 $+0.4\,\sigma$	0.280 $-1.1\ \sigma$	0.51 $-1.0\ \sigma$	-0.35 $0.0\,\sigma$	0.42	0.37
$(C_S^R, C_S^L)\vert_{10\%}$	$(0.11, -0.04)$ $(-0.37, -0.51)$	2.6	2.9	0.366 $+0.9\,\sigma$	**0.263** $-2.3\ \sigma$	0.48 $-1.4\ \sigma$	-0.44 $-0.1\,\sigma$	0.44	0.36

- S_1 performs well, with F_L and the predicted value of $P_\tau(D^*)$ SM-like
- F_L favors charged-Higgs solution
- If this scenario is true then either $\mathcal{R}(D^*)$ will go down towards its SM value or $BR(B_c \to \tau\nu) \gtrsim 30\%$

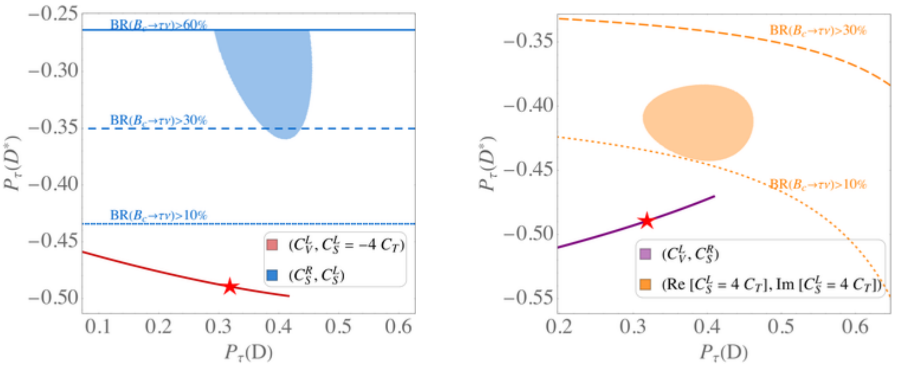
2D fits continued

Compare the two scenarios C_V^L, C_S^R (from leptoquark U_1) and $C_S^L = 4C_T$ complex from leptoquark S_2:

2D hyp.	best-fit	p-value percent	pull$_{\text{SM}}$	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$F_L(D^*)$	$P_\tau(D^*)$	$P_\tau(D)$	$\mathcal{R}(\Lambda_c)$
(C_V^L, C_S^R)	$(0.08, -0.01)$	**26.6**	3.6	0.343 $+0.1\,\sigma$	0.294 $-0.1\ \sigma$	**0.46** $-1.6\ \sigma$	-0.49 $-0.2\ \sigma$	0.31	0.38
$(\text{Re}[C_S^L = 4C_T], \text{Im}[C_S^L = 4C_T])\vert_{60,30\%}$	$(-0.06, \pm 0.31)$	**25.0**	3.6	0.339 $0.0\ \sigma$	0.295 $0.0\ \sigma$	**0.45** $-1.7\,\sigma$	-0.41 $-0.1\,\sigma$	0.41	0.38
$(\text{Re}[C_S^L = 4C_T], \text{Im}[C_S^L = 4C_T])\vert_{10\%}$	$(-0.03, \pm 0.24)$	**5.9**	3.2	0.330 $-0.3\ \sigma$	0.275 $-1.4\ \sigma$	**0.46** $-1.6\ \sigma$	-0.45 $-0.1\ \sigma$	0.38	0.36

- Collider constraints on $b \to c\tau\nu$ operators from high p_T tails in monotau searches Greljo, Martin Camalich, Ruiz-Álvarez 2018
- The constraints cut out a slice of the 2σ region for the scenario $C_S^L = 4C_T$ complex

Use the results of the fits to predict correlations between observables for different scenarios, e.g.

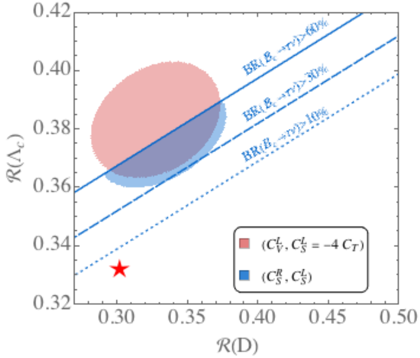


(a) (b)

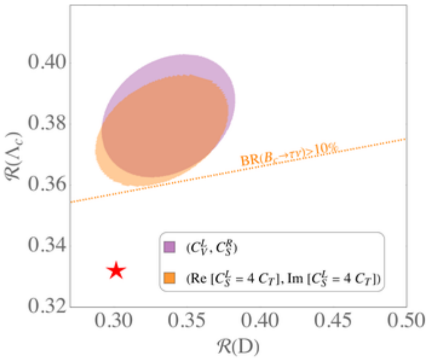
(a) leptoquark S_1
charged Higgs

(b) leptoquark U_1
leptoquark S_2

Regions on the plots from 1σ ranges of the Wilson coefficients



(a)



(b)

(a) leptoquark S_1
charged Higgs

(b) leptoquark U_1
leptoquark S_2

'Magic relation'

- In fact, in all scenarios with good p-values the $\mathcal{R}(\Lambda_c)$ has essentially the same value
- Inspecting the formulas for the observables in terms of Wilson coefficients 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 function of Wilson coefficients C_i^j - stays small $|x| < 0.05$ for C_i^j in their 1σ ranges
For the current data (including new Belle result):

$$\begin{aligned}\mathcal{R}(\Lambda_c) &= \mathcal{R}(\Lambda_c)_{\mathsf{SM}}(1.14 \pm 0.06)\\ &= 0.38 \pm 0.01_{\mathsf{exp}} \pm 0.01_{\mathsf{th}}\end{aligned}$$

in any model of NP

- All possible new physics in all possible observables of $b \to c\tau\nu$ decays can be parametrized in terms of four complex coefficients C_V^L, C_S^R, C_S^L, C_T
- Charged-Higgs scenario (with non-zero $C_S^{L,R}$) is not ruled out yet
- Scalar leptoquark S_1 and vector LQ U_1 provide good fits
- Measurements of polarization observables could differentiate between scenarios.
- $\mathcal{R}(\Lambda_c)$ is important 'redundant' observable whose measurement could provide a crosscheck of the anomaly

Backup slide