EFT analysis of *B*-decay anomalies

J. Martin Camalich

ZPW2018 - Flavours: light, heavy and dark

January 16th 2018

Lepton-universality violation in $b \to c\tau\nu$ decays

EFT of new-physics in $b \to c\tau\nu$

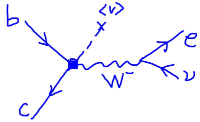
- Low-energy effective Lagrangian (no RH ν)

$$\mathcal{L}_{\rm eff}^{\ell}=-\frac{G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^{\ell})\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{c}\gamma^\mu(1-\gamma_5)b+\epsilon_R^{\ell}\;\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\;\bar{c}\gamma^\mu(1+\gamma_5)b$$
$$+\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{c}[\epsilon_S^{\ell}-\epsilon_P^{\ell}\gamma_5]b+\epsilon_T^{\ell}\;\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b]+\text{h.c.},$$

Wilson coefficients: ϵ_Γ decouple as $\sim v^2/\Lambda_{\rm NP}^2$

- Matching to high-energy Lagrangian – SMEFT Cirigliano, Gonzalez-Alonso & Jenkins '10
  - Symmetry relations for ϵ_Γ
    - In charged-currents ϵ_R^{ℓ}:

$$\mathcal{O}_{Hud}=\frac{i}{\Lambda_{\rm NP}^2}\left(\tilde{H}^\dagger D_\mu H\right)\left(\bar{u}_R\gamma^\mu d_R\right)$$

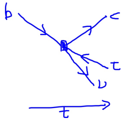


☛ RHC is lepton universal: $\epsilon_R^{\ell}\equiv\epsilon_R+\mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4})\Rightarrow$ **Cannot explain LUR $R_{D^{(*)}}$!**

Down to **4** operators to explain R_{D^*}: ϵ_L, ϵ_S, ϵ_P, ϵ_T

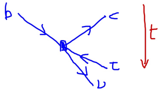
The constraint of the B_c-lifetime

- $B \to D^* \tau \nu$ receives a contribution from ϵ_P



$$\epsilon_P \; \langle D^*(k,\epsilon)|\bar{c}\gamma_5 b|\bar{B}(p)\rangle = -\frac{2\epsilon_P \; m_{D^*}}{m_b+m_c} A_0(q^2)\epsilon^* \cdot q$$

- $B_c \to \tau\nu$ **also** receives a **helicity-enhanced** contribution from ϵ_P!



$$\frac{\mathrm{Br}(B_c^- \to \tau\bar{\nu}_\tau)}{\mathrm{Br}(B_c^- \to \tau\bar{\nu}_\tau)^{\mathrm{SM}}} = \left|1 + \epsilon_L + \frac{m_{B_c}^2}{m_\tau(m_b+m_c)}\epsilon_P\right|^2$$

- Use the lifetime of B_c
  - Very high experimental precision (1.5%):

$$\tau_{B_c} = 0.507(8) \text{ ps}$$

  - **QCD**: "Most of the B_c lifetime comes from $\bar{c} \to \bar{s}$ ($\sim$ 65%) and $b \to c$ ($\sim$ 30%)"

Bigi PLB371 (1996) 105, Beneke *et al.* PRD53(1996)4991,. . .

$$\tau_{B_c}^{\mathrm{OPE}} = 0.52^{+0.18}_{-0.12} \text{ ps}$$

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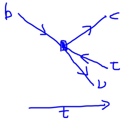

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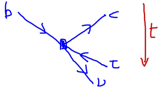

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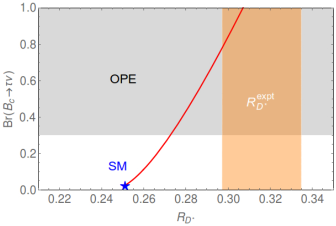


τ_{B_c} makes **implausible ANY**
"scalar solution"
(e.g. 2HDM) to the R_{D^*} anomaly!

Alonso, Grinstein&JMC, arXiv: 1611.06676

(see also Xin-Qiang Li *et al.*, JHEP 1608 (2016) 054)

Searches for $B_c \to \tau\nu$ at LEP

- $\mathrm{BR}(B_c \to \tau\nu)$ measured in a e^+e^- collider at the Z pole Akeroyd&Chen, 1708.04072
  - Searches of $B^- \to \tau^-\nu$ above $B_c\,\bar{B}_c$ threshold really measure

    Mangano&Slabospitsky, PLB410(1997)299

$$\overbrace{\mathrm{BR}_{\rm eff}}^{\rm LEP} = \overbrace{\mathrm{BR}(B \to \tau\nu)}^{\rm Belle\ \&\ BaBar} + \overbrace{\frac{f_c}{f_u}}^{\rm TH.input}\ \mathrm{BR}(B_c \to \tau\nu)$$

  - B_c contribution suppressed by $f_c/f_u \sim 10^{-3}$-10^{-2} but enhanced by $\frac{|V_{cb}|^2}{|V_{ub}|^2}\frac{f_{B_c}^2}{f_B^2} \sim$ **700**

- f_c/f_u: Fraction of hadronization into B_c over B
  - Traded by experimental data and **computable TH. input**

$$R_\ell = \frac{f_c}{f_u}\frac{\mathrm{BR}(B_c \to J/\psi\mu\nu)}{B \to J/\psi K}$$

  - R_ℓ measured by **CDF** and reconstructed from **LHCb** data

Searches for $B_c \to \tau\nu$ at LEP

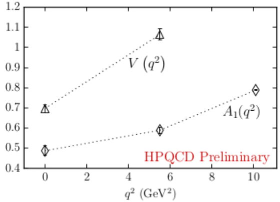
- **Model calculations** predict BR($B_c \to J/\psi\mu\nu$) $\in 1 - 7\%$!

	pQCD	WSL[9]	EFG[7]	ISK[6]	HNV[5]	DV[4]
$V^{B_c\to J/\Psi}$	0.42	0.74	0.49	0.83	0.61	0.91
$A_0^{B_c\to J/\Psi}$	0.59	0.53	0.40	0.57	0.45	0.58
$A_1^{B_c\to J/\Psi}$	0.46	0.50	0.50	0.56	0.49	0.63
$A_2^{B_c\to J/\Psi}$	0.64	0.44	0.73	0.54	0.56	0.74

Wang, Fang&Xiao, arXiv: 1212.5903

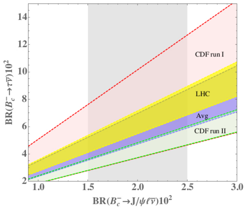
- **Ongoing efforts in LQCD!**

  - **Preliminary** results to select models



HPQCD Collaboration, PoS LATTICE2016 (2016) 281

  - Constrains BR($B_c \to \tau\nu$) $< 10\%$



Akeroyd&Chen, 1708.04072

New-physics solutions and challenges: The left-handed operator

- Left-handed $\epsilon_L = 0.13$: *Universal* enhancement of the $b \to c\tau\nu$ rates by 30%

  SMEFT operators: $Q_{\ell q}^{(1)} = \frac{1}{\Lambda^2}(\bar{Q}_L \gamma^\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$, $\qquad Q_{\ell q}^{(3)} = \frac{1}{\Lambda^2}(\bar{Q}_L \gamma^\mu \vec{\tau} Q_L)\cdot(\bar{L}_L \gamma_\mu \vec{\tau} L_L)$

  - **Warning ☠ Radiative LUV contributions in τ and Z decays!**

    Ferruglio *et al.* PRL118 (2017), 011801

  - **Problem with 3^{rd} generation:** Non-trivial flavor str. Buttazzo *et al.* arXiv:1706.07808
  - **Model dependence:** EFT only gives log parts (mixing)

- It can also solve $b \to s\ell\ell$ anomaly! Bhattacharya et al. '14, Alonso, JMC & Grinstein. '15, ...
  - **Lepton flavor structure:**
    - ★ Large enhancements $\tilde{C}_{\tau\tau} \gg \tilde{C}_{\mu\mu}$ ruled out by $B \to K^{(*)}\nu\nu$ unless $C_{\tau\tau}^{(1)} \simeq C_{\tau\tau}^{(3)}$
    - ★ **Vector Leptoquark** U_1^μ $(\bar{3},1,2/3)$ produces this! Alonso, JMC & Grinstein. '15, Barbieri *et al.* '15, ...

Tensor and scalar operators

- Mixing in $H^3\psi^2$ operators that **modify Yukawas** Jenkins *et al.*, arXiv: 1310.4838

- Tensor $\epsilon_T = 0.38$
  - **EW+QED corrections:** Large mixing tensor into scalars

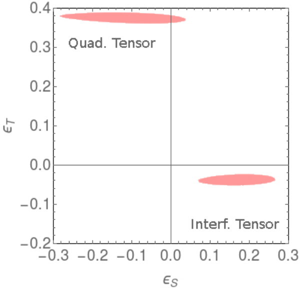
$$\begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w^{(3)}_{\ell equ} \end{pmatrix}_{(\mu = m_Z)} = \begin{pmatrix} 1.19 & 0. & 0. \\ 0. & 1.20 & \boxed{-0.185} \\ 0. & -0.00381 & 0.959 \end{pmatrix} \begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w^{(3)}_{\ell equ} \end{pmatrix}_{(\mu = 1\ \mathrm{TeV})}$$

Gonzalez-Alonso, JMC & Mimouni arXiv: 1706.00410

  - **No explicit models** that give *only* tensor operators

- Tensor & Scalar

- Fit to current values of $R_{D(*)}$



- **New solution:** ϵ_T interferes constructively in R_{D^*}
  - ★ **Best Fit:** $\epsilon_S = 0.17$, $\epsilon_T = -0.04$
  - ★ **Scalar Leptoquark** S_1 $(\bar{3},1,1/3)$ produces

$$\epsilon_T(M) = -\frac{\epsilon_{S_L}(M)}{4}$$

  - ★ $\epsilon_P \sim 0.2$ produces BR$(B_c \to \tau\nu) \sim 6\%$

Adding new channels: $B_c \to J/\psi\tau\nu$

$$R_{J/\psi}^{\text{LHCb}} = 0.71 \pm 0.17 \pm 0.18$$

Greg's talk yesterday

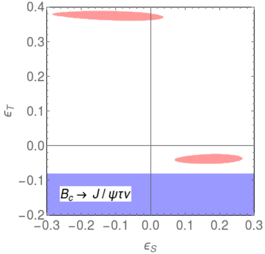
- Comparison with SM **NOW** is subtle because of **model dependence**

Mode	This paper	[8, 30]	[11]	[15]	[16]	[31]	[32]
$B_c^- \to J/\psi\ell\nu$	$6.7^{+2.1+1.0+0.9}_{-1.2-0.4-0.6}$	1.9	2.37	1.5	1.49	1.20	2.07
$B_c^- \to J/\psi\tau\nu$	$0.52^{+0.16+0.08+0.08}_{-0.09-0.03-0.05}$	0.48	0.65	0.4	0.37	0.34	0.49

Qiao&Zhu, 1208.5916

$$R_{J/\psi}^{\text{SM}^*} \sim 0.24 - 0.29$$

- Goes in the *right* direction of NP but effect is **large**



- For the LH solution one predicts

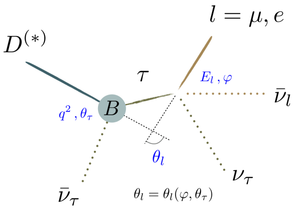
$$R_{J/\psi}^{\text{LH}^*} \sim 0.35 - 0.4$$

(see also Watanabe, arXiv: 1709.08644)

- Besides more data, **LQCD input urgently needed!**

Adding new observables: Kinematic distributions ($\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$)

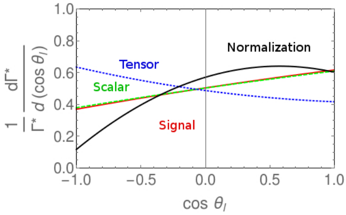
Alonso, Kobach, JMC, PRD94(2016)no.9,094021; Alonso, JMC, Westhoff, PRD95(2017)no.9,093006



- **Integrate analytically the τ and ν's angular phase-space:**

$$\frac{d^3\Gamma_5}{dq^2\, dE_\ell\, d(\cos\theta_\ell)} = \mathcal{B}[\tau_\ell]\ \mathcal{N}\ \left[I_0(q^2, E_\ell) + I_1(q^2, E_\ell)\cos\theta_\ell + I_2(q^2, E_\ell)\cos\theta_\ell^2\right]$$

- Angular distribution help discriminate signal, **normalization**, NP



$\tau^- \to \pi^- \nu_\tau$ as a τ polarimeter

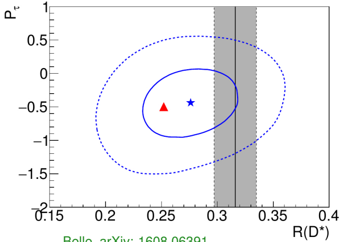
$$\frac{dP_L}{dq^2} = \frac{d\Gamma_{B,+}/dq^2 - d\Gamma_{B,-}/dq^2}{d\Gamma_B/dq^2}$$

Slope in E_π of $d\Gamma_4$ $\Rightarrow$ **Longitudinal Polarization**

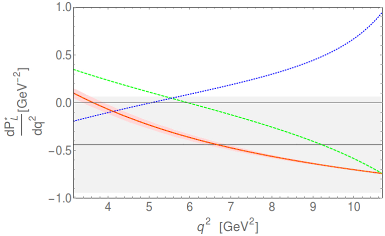
$$\frac{d^2\Gamma_4}{dq^2 dE_\pi} = \frac{\mathcal{B}[\tau_\pi]}{|\vec{p}_\tau|}\frac{d\Gamma_B}{dq^2}\left[1 + \xi(E_\pi, q^2)\frac{dP_L}{dq^2}\right], \quad \xi(E_\pi, q^2) = \frac{1}{\beta_\tau}\left(2\frac{E_\pi}{E_\tau} - 1\right)$$

M. Davier *et al.* PLB306, 411 (1993), Tanaka&Watanabe, PRD82, 034027 (2010)

- Applied to the BD^* channel by *Belle*

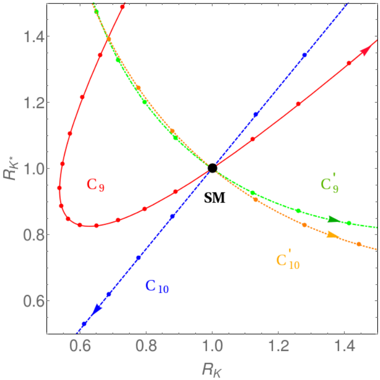


Belle, arXiv: 1608.06391



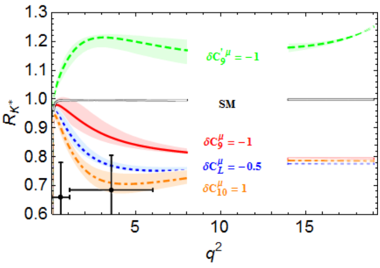
Lepton-universality violation in $b \to s\ell\ell$ decays

- **New physics in muons**
  - No $b \to s\ell\ell$ **tensor operators** in the SMEFT
  - **Scalar operators** severely constrained by $B_s \to \mu\mu$ Alonso, Grinstein, JMC, PRL113 (2014) 241802

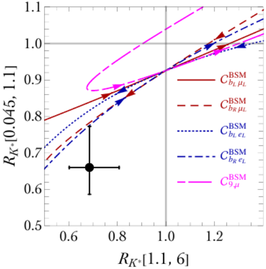


Geng, Grinstein, Jäger, JMC, Ren, Shi, arXiv: 1704.05446

- Nodes indicate steps of $\Delta C^{\mu} = +0.5$
  - **Primed operators** $C'_{9,10}$**:** Monotonically decreasing dependence $R_{K^*}(R_K)$!



Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi, arXiv: 1704.05446



D'Amico *et al.* 1704.05438

Very clean null-tests of the SM!

Discussion Diego Guadagnoli this morning!

- **Warning ☠:** Value at ultralow-q^2 is difficult to accommodate with UV physics

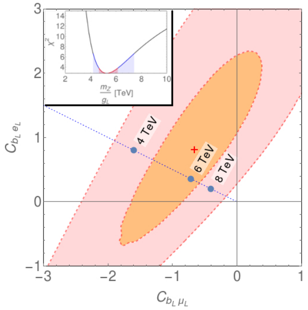
Top-down approach: Fits for UV completions

- **Gauged flavor symmetries** Altmannshofer *et al.* arXiv:1403.1269, Alonso *et al.* arXiv:1704.08158,...
  - **Gauge** $SU(3)_L \times SU(3)_R$ Cline&JMC arXiv:1706.08510
    - ★ Dynamically generate Flavor and UV consistent (no Landau poles)
    - ★ *Baroque* field content for gauge anomalies/SSB-structure, and *ad-hoc* flavor structure

- Couplings to the leptons

$$V_l^L T^8 V_l^{L\dagger} \cong \frac{1}{2\sqrt{3}} \begin{pmatrix} 1 & \epsilon_1 & \epsilon_2 \\ \epsilon_1^* & -2 & \epsilon_3 \\ \epsilon_2^* & \epsilon_3^* & 1 \end{pmatrix}$$

Coupling to both electrons and muons!



- Couplings to electrons opens up much more stringent phenomenology!

Precision probes of lepton nonuniversal $C^{\ell}_{9,10}$

Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi, arXiv: 1704.05446

- **Can we pin down specific contributions to electrons/muons?**
- Go to the angular analysis of $B \to K^* \ell\ell$...

$$I_6^{(\ell)} = N C_{10}^{\ell} q^2 \beta_\ell^2(q^2) |\vec{k}| \left(\mathrm{Re}[H_{V-}^{(\ell)}(q^2)] V_-(q^2) + \mathrm{Re}[H_{V+}^{(\ell)}(q^2) \frac{H_{A+}^{(\ell)}(q^2)}{C_{10}^{\ell}}] \right)$$

  - The $H_{V,A+}$ amplitudes are suppressed at low q^2!
  - Photon-pole enhancement of $H_{V-}^{(\ell)}(q^2)$ at low q^2!

$$R_6[a,b] \approx \frac{C_{10}^{\mu}}{C_{10}^{e}} \times \frac{\int_a^b |\vec{k}| q^2 \beta_\mu^2 \, \mathrm{Re}[H_{V-}^{(\mu)}(q^2)] V_-(q^2)}{\int_a^b |\vec{k}| q^2 \, \mathrm{Re}[H_{V-}^{(e)}(q^2)] V_-(q^2)}$$

R_6 is an optimal C_{10} LUV analyser!

- **Combine this with $B_s \to \mu\mu$ to separate $C_{10}^{e,\mu}$!**

Conclusions

- **Interesting times ahead!**
- "Instant" workshop at CERN last May

Instant workshop on B meson anomalies

17 May 2017, 09:00 → 19 May 2017, 16:30 Europe/Zurich

4-3-006 - TH Conference Room (CERN)

Jorge Martin Camalich (CERN) , Jure Zupan (University of Cincinnati) , Marco Nardecchia (CERN)

Description In light of recent anomalies in B physics there is an increased interest in the theory community on its implications. As a quick response we are organizing an "Instant workshop on B meson anomalies" at CERN from May 17-May 19 2017.

- **Check recordings @** https://indico.cern.ch/event/633880/

CERN-TH Institute programmed for the next year

"From flavor anomalies to direct discovery of New Physics"

Oct. 22nd to Nov. 2nd 2018 (tentative)

THANKS!