Observables and EFT aspects of B-anomalies

J. Martin Camalich

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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)

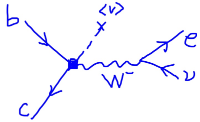
$$\mathcal{L}_{\rm eff}^{\ell} = -\frac{G_F V_{cb}}{\sqrt{2}}\big[(1+\epsilon_L^{\ell})\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{c}\gamma^\mu(1-\gamma_5)b + \epsilon_R^{\ell}\,\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\,\bar{c}\gamma^\mu(1+\gamma_5)b$$

$$+\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{c}[\epsilon_S^{\ell}-\epsilon_P^{\ell}\gamma_5]b + \epsilon_T^{\ell}\,\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b\big] + \text{h.c.},$$

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

- Matching to high-energy Lagrangian – SMEFT
  - Symmetry relations for ϵ_Γ
    - In charged-currents ϵ_R^{ℓ}:

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

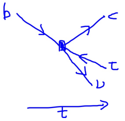


☛ RHC is lepton universal: $\epsilon_R^{\ell} \equiv \epsilon_R + \mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4}) \Rightarrow$ **Cannot explain LUR $R_{D^{(*)}}$!**

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

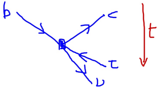
The constraint of the B_c-lifetime

- $B \to D^* \tau\nu$ 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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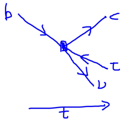

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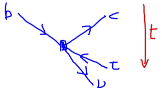
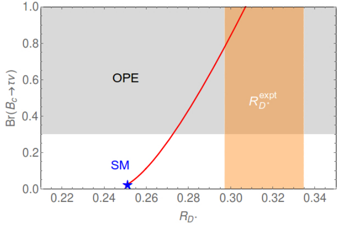


$$\frac{\mathrm{Br}(B_c^- \to \tau \bar{\nu}_\tau)}{\mathrm{Br}(B_c^- \to \tau \bar{\nu}_\tau)^{\mathrm{SM}}} = \left| 1 + \epsilon_L + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} \epsilon_P \right|^2$$



Alonso, Grinstein&JMC, arXiv: 1611.06676

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

- A complementary bound BR$(B_c \to \tau\nu) \lesssim 10\%$ can be obtained from **LEP data**!

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 3rd 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 $C_{\tau\tau}^{(1)} \simeq C_{\tau\tau}^{(3)}$

Tensor and scalar operators

- **Tensor $\epsilon_T = 0.38$**
  - Mixing in $H^3\psi^2$ operators that **modify Yukawas** Jenkins *et al.*, arXiv: 1310.4838
  - **EW+QED corrections:** Large mixing tensor into scalars

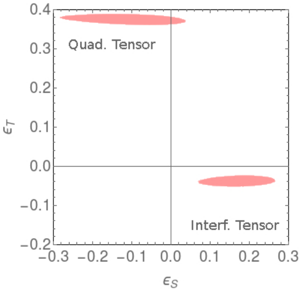
$$\begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w^{(3)}_{\ell equ} \end{pmatrix}_{(\mu=m_Z)} = \begin{pmatrix} 1.19 & 0. & 0. \\ 0. & 1.20 & \boxed{-0.185} \\ 0. & -0.00381 & 0.959 \end{pmatrix} \begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w^{(3)}_{\ell equ} \end{pmatrix}_{(\mu=1\ \mathrm{TeV})}$$

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** (1,1/3) produces $\epsilon_T = -\frac{\epsilon_{S_L}}{4}$
  - ★ $\epsilon_P \sim 0.2$ produces BR$(B_c \to \tau\nu) \sim 6\%$

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

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

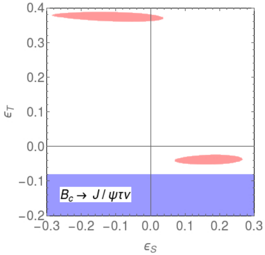
- Comparison with SM **NOW** is subtle because of **model dependence**

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

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

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



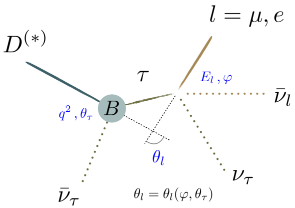
- For the LH solution one predicts

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

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

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

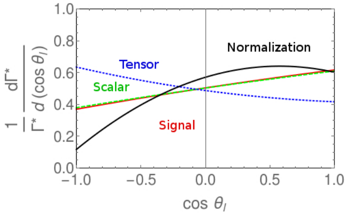
Alonso, Kobach, JMC, PRD94(2016)no.9,094021; Alonso, JMC, Westhoff, PRD95(2017)no.9,093006



- **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: P_L

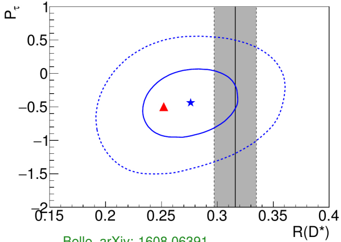
$$\frac{dP_L}{dq^2} = \frac{d\Gamma_{B,+}/dq^2 - d\Gamma_{B,-}/dq^2}{d\Gamma_B/dq^2}$$

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

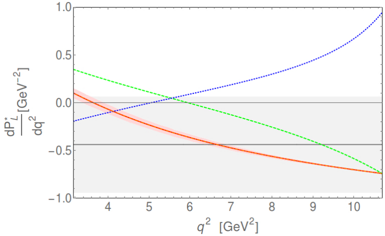
$$\frac{d^2\Gamma_4}{dq^2 dE_\pi} = \frac{\mathcal{B}[\tau_\pi]}{|\vec{p}_\tau|}\frac{d\Gamma_B}{dq^2}\left[1 + \xi(E_\pi, q^2)\frac{dP_L}{dq^2}\right], \quad \xi(E_\pi, q^2) = \frac{1}{\beta_\tau}\left(2\frac{E_\pi}{E_\tau} - 1\right)$$

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

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



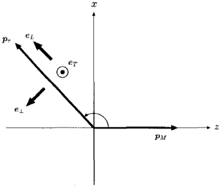
Belle, arXiv: 1608.06391



$\tau^- \to \pi^- \nu_\tau$ as a τ polarimeter: $P_\perp$ (and A_{FB}^τ!)

Alonso, JMC & Westhoff, arXiv:1702.02773

- Decay rate into a τ polarized along a given direction $\hat{s}$



Tanaka Z. Phys. C 67, 321

$$d\Gamma_B(\hat{s}) = d\Gamma + \tfrac{1}{2} d\Gamma \left(dP_L\, \hat{z}' + dP_\perp\, \hat{x}' + dP_T\, \hat{y}' \right) \cdot \hat{s}$$

- dP_L measured by Belle
- dP_T (T-odd): Not accessible without τ **direction**
- $dP_\perp$ **accessible from the pionic** ***FB*** **asymmetry!**

- $P_\perp$ probes **interference between τ polarization states**

$$d\Gamma dP_\perp = \frac{(2\pi)^4\, d\Phi_3}{2 m_B} 2\mathrm{Re}\left[\mathcal{M}_{B+} \mathcal{M}_{B-}^\dagger\right]$$

$$\frac{d^2 A_{FB}^d}{dq^2 dE_d} = \mathcal{B}[\tau_d] \left[f_{FB}^d(E_d, q^2) \frac{dA_\tau}{dq^2} + f_\perp^d(E_d, q^2) \frac{dP_\perp}{dq^2} \right]$$

$$f_{FB}^\pi = -\frac{\left(2E_\pi E_\tau - m_\tau^2\right)(E_\tau - |\vec{p}_\tau| - 2E_\pi)}{2|\vec{p}_\tau|^3 E_\pi} \qquad f_\perp^\pi = -\frac{4E_\pi^2 - 4E_\pi E_\tau + m_\tau^2}{\pi E_\pi |\vec{p}_\tau|^3 m_\tau}$$

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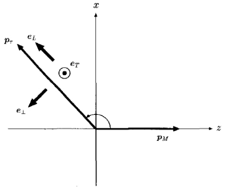

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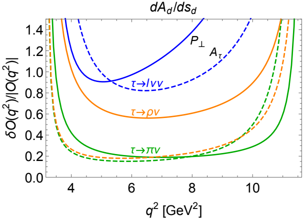
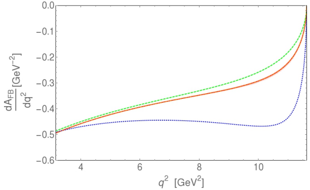
- dP_L measured by Belle
- dP_T (T-odd): Not accessible without τ **direction**
- $dP_\perp$ **accessible from the pionic *FB* asymmetry!**

- Prospects at Belle (II)

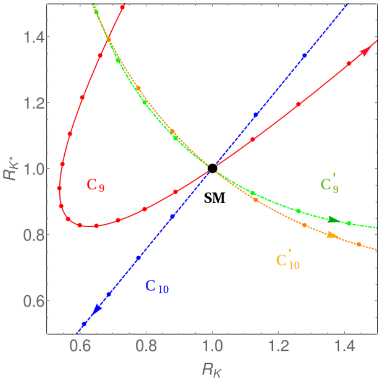


- Sensitivity to NP



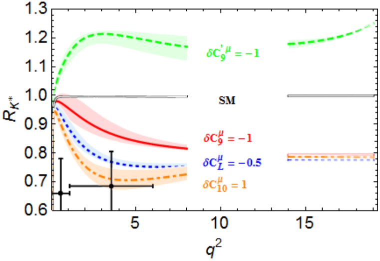
Lepton-universality violation in $b \to s\ell\ell$ decays

- **New physics in muons**



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

- Nodes indicate steps of $\Delta C^\mu = +0.5$
  - **Primed operators** $C'_{9,10}$**:** Monotonically decreasing dependence $R_{K^*}(R_K)$!
- New physics in electrons$\sim$ mirror image of above (see D'Amico *et al.* 1704.05438)



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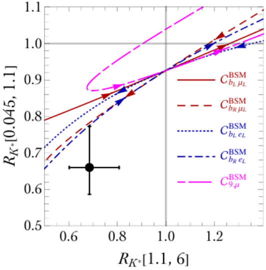


D'Amico *et al.* 1704.05438

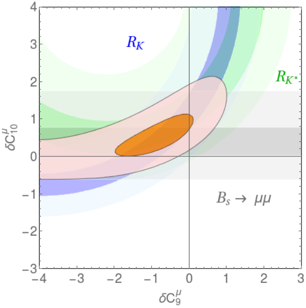
Obs.	Expt.	SM	$\delta C_L^{\mu} = -0.5$	$\delta C_9^{\mu} = -1$	$\delta C_{10}^{\mu} = 1$	$\delta C_9'^{\mu} = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1] GeV^2	0.66 ± 0.12	$0.920^{+0.007}_{-0.006}$	$0.88^{+0.01}_{-0.02}$	$0.91^{+0.01}_{-0.02}$	$0.862^{+0.016}_{-0.011}$	$0.98^{+0.03}_{-0.03}$
R_{K^*} [1.1, 6] GeV^2	0.685 ± 0.120	$0.996^{+0.002}_{-0.002}$	$0.78^{+0.02}_{-0.01}$	$0.87^{+0.04}_{-0.03}$	$0.73^{+0.03}_{-0.04}$	$1.20^{+0.02}_{-0.03}$
R_{K^*} [15, 19] GeV^2	–	$0.998^{+0.001}_{-0.001}$	$0.776^{+0.002}_{-0.002}$	$0.793^{+0.001}_{-0.001}$	$0.787^{+0.004}_{-0.004}$	$1.204^{+0.007}_{-0.008}$

Very clean null-tests of the SM!

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

Fits with clean observables only

- **Assume NP is μ-specific**



Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	1σ range	3σ range
δC_9^{μ}	-1.64	5.65	0.130	3.87	[-2.31, -1.12]	[<-4, -0.31]
δC_{10}^{μ}	0.91	4.98	0.173	3.96	[0.66, 1.18]	[0.20, 1.85]
δC_L^{μ}	-0.61	3.36	0.339	4.16	[-0.78, -0.46]	[-1.14, -0.16]
Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^{\mu}, \delta C_{10}^{\mu})$	(-0.76, 0.54)	3.31	0.191	3.76	$C_9^{\mu} \in$ [-1.50, -0.16]	$C_{10}^{\mu} \in$ [0.18, 0.92]

- **Deviation of the SM**: p-value of 3.7×10^{-4} (3.6σ)
- Best fit suggests a leptonic left-handed scenario δC_L^{μ}

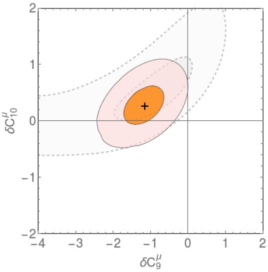
Global fits

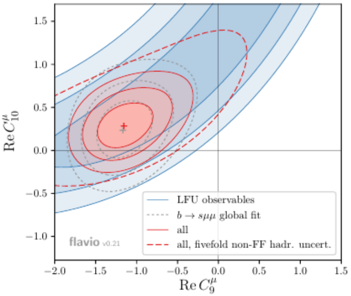
- **Include 70-100 observables**

Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	1σ range	3σ range
δC_9^μ	-1.37	61.98 [64 dof]	0.548	4.37	[-1.70, -1.03]	[-2.41, -0.41]
δC_{10}^μ	0.60	71.72 [64 dof]	0.237	3.06	[0.40, 0.82]	[-0.01, 1.28]
δC_L^μ	-0.59	63.62 [64 dof]	0.490	4.18	[-0.74, -0.44]	[-1.05, -0.16]
Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(-1.15, 0.28)	60.33 [63 dof]	0.572	4.17	$C_9^\mu \in$ [-1.54, -0.81]	$C_{10}^\mu \in$ [0.06, 0.50]

- C_9 in global fits is subject to hadronic uncertainties!

  - Results in the $(\delta C_9^\mu,\ \delta C_{10}^\mu)$ plane





Altmannshofer *et al.* arXiv:1704.05435

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

- Go to the angular analysis of $B \to K^* \ell\ell$...

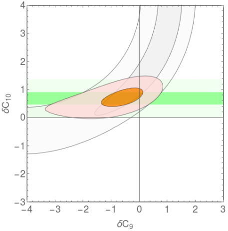
$$I_6^{(\ell)} = N C_{10}^{\ell} q^2 \beta_\ell^2(q^2) |\vec{k}| \left(\mathrm{Re}[H_{V-}^{(\ell)}(q^2)] V_-(q^2) + \mathrm{Re}[H_{V+}^{(\ell)}(q^2) \frac{H_{A+}^{(\ell)}(q^2)}{C_{10}^{\ell}}] \right)$$

  - The $H_{V,A+}$ amplitudes are suppressed unles we have primed operators!

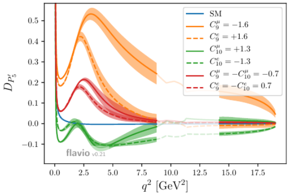
$$R_6[a,b] \approx \frac{C_{10}^{\mu}}{C_{10}^{e}} \times \frac{\int_a^b |\vec{k}| q^2 \beta_\mu^2 \, \mathrm{Re}[H_{V-}^{(\mu)}(q^2)] V_-(q^2)}{\int_a^b |\vec{k}| q^2 \, \mathrm{Re}[H_{V-}^{(e)}(q^2)] V_-(q^2)}$$

R_6 is an optimal C_{10} LUV analyser!

- Prospects for R_6 with a 5% precision



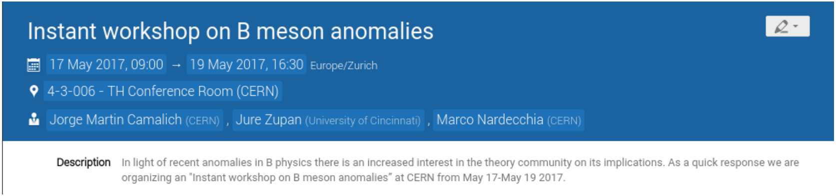
- $D_{P'_5} = P_5'^{\mu} - P_5'^{e}$



Altmannshofer *et al.* arXiv:1704.05435

Conclusions

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



- **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!

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

- 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

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

  - 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

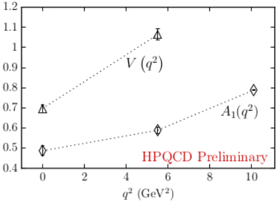
Searches for $B_c \to \tau\nu$ at LEP

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

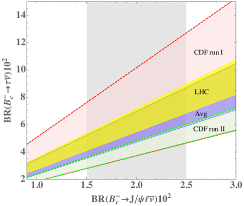
	pQCD	WSL [9]	EFG [7]	ISK [6]	HNV [5]	DV [4]
$V^{B_c \to J/\Psi}$	0.42	0.74	0.49	0.83	0.61	0.91
$A_0^{B_c \to J/\Psi}$	0.59	0.53	0.40	0.57	0.45	0.58
$A_1^{B_c \to J/\Psi}$	0.46	0.50	0.50	0.56	0.49	0.63
$A_2^{B_c \to J/\Psi}$	0.64	0.44	0.73	0.54	0.56	0.74

Wang, Fang&Xiao, arXiv: 1212.5903

- **Ongoing efforts in LQCD!**
  - **Preliminary** results to select models
  - Constrains BR($B_c \to \tau\nu$) $< 10\%$



HPQCD Collaboration, PoS LATTICE2016 (2016) 281



Akeroyd&Chen, 1708.04072