B_c meson lifetime

and the shape of New Physics in $B \to D^{(*)}\tau\nu$

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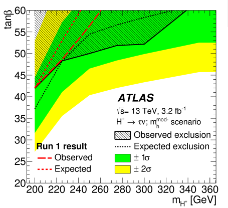
Miniworkshop on $B \to D^{(*)}\tau\nu$ and related topics
Nagoya, Japan

Introduction



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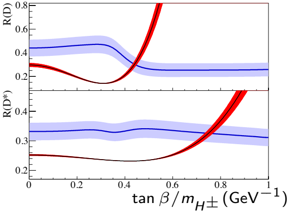

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- Famously 2HDM model does not explain τ anomalies
- Right ingredients:
  - charged "current"
  - LUV (lepton universality violation)
- Fails on combined fit, as function of $\tan\beta/m_{H^\pm}$
- Specific to 2HDM? Need to re-do analysis for each NP model?

No: Use EFT to characterize any model with heavy mediators

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F V_{cb}}{\sqrt{2}} \Bigg[\Big(1 + \epsilon_L\Big) \bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_L b + \epsilon_R \bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_R b$$

$$+ \epsilon_T \,\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau \cdot \bar{c}\sigma^{\mu\nu} P_L b + \epsilon_{S_L} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_L b + \epsilon_{S_R} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_R b \Bigg] + \text{h.c.}$$

2HDM: $\epsilon_L = \epsilon_R = \epsilon_T = 0$

$$\epsilon_{S_L} = \frac{m_\tau m_c}{m^2_{H^\pm}} \xi_{S_L}, \quad \epsilon_{S_R} = \frac{m_\tau m_b}{m^2_{H^\pm}} \xi_{S_R}$$

	type I	type II	lep-specific	flipped
ξ_{S_L}	$-\cot^2\beta$	1	1	$-\cot^2\beta$
ξ_{S_R}	$\cot^2\beta$	$\tan^2\beta$	-1	-1

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Could have plotted against ϵ_{S_R}!

Objective

The purpose of this work
is to constrain $\mathcal{L}_{\text{eff}}$
(the shape of New Physics)
by means unrelated to $B \to D^{(*)}\tau\nu$

1. Introduction
2. SM-EFT
3. B_c lifetime
4. Interplay with $B \to D^{(*)}\ell\nu$ observables
5. One line conclusion

SM-EFT

- SM-EFT: Effective Field Theory of SM
- Assume SM field content: all new particles have masses above $\Lambda \gg m_t$
- Supplement SM with operators of dimension ≥ 5
- Find contributions to $\mathcal{L}_{\text{eff}}$ at low energies (integrate out heavy (SM) fields)

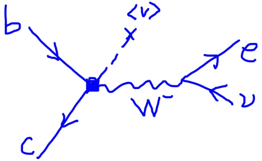
4-fermion operators:

$$Q^{(1)}_{lequ} = (\bar{\ell} e_R)(\bar{q}_L u_R) + \text{h.c.} \qquad Q^{(3)}_{lequ} = (\bar{\ell}\sigma_{\mu\nu} e_R)(\bar{q}_L \sigma^{\mu\nu} u_R) + \text{h.c.}$$

$$Q^{(3)}_{\ell q} = (\bar{q}\vec{\tau}\gamma^\mu q_L)\cdot(\bar{\ell}\vec{\tau}\gamma_\mu \ell_L) \qquad Q_{\ell edq} = (\bar{\ell}_L e_R)(\bar{d}_R q) + \text{h.c.}$$

None give $\mathcal{L}_{\text{eff}} = -\frac{4 G_F V_{cb}}{\sqrt{2}}\left[\cdots + \epsilon_R \bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_R b + \cdots\right]$

Only $Q_{HHud} = i\tilde{H}^\dagger D_\mu H\, \bar{u}\gamma^\mu d_R$ contributes to ϵ_R:



Respects Lepton Universality; discard:

$$\mathcal{L}_{\rm eff} = -\frac{4G_F V_{cb}}{\sqrt{2}}\Bigg[\Big(1+\epsilon_L\Big)\bar{\tau}\gamma_\mu P_L\nu_\tau\cdot\bar{c}\gamma^\mu P_L b + \epsilon_R\bar{\tau}\gamma_\mu P_L\nu_\tau\cdot\bar{c}\gamma^\mu P_R b$$

$$+\,\epsilon_T\,\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau\cdot\bar{c}\sigma^{\mu\nu}P_L b + \epsilon_{S_L}\bar{\tau}P_L\nu_\tau\cdot\bar{c}P_L b + \epsilon_{S_R}\bar{\tau}P_L\nu_\tau\cdot\bar{c}P_R b\Bigg] + \text{h.c.}$$

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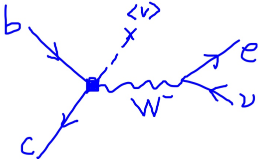

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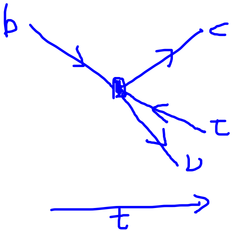
B_c lifetime

For $B \to D^{(*)}\tau\nu$



B_c lifetime

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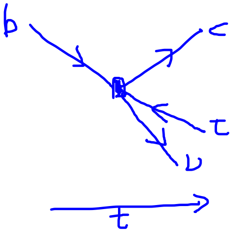
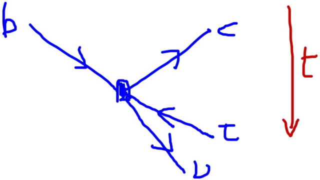


For $B_c \to \tau\nu$



- Bounds from B_c decays are independent of observed anomaly
- Branching fraction

$$\mathrm{Br}(B_c \to \tau\bar{\nu}_\tau) = \tau_{B_c^-} \frac{m_{B_c} m_\tau^2 f_{B_c}^2 G_F^2 |V_{cb}|^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left|1 + \epsilon_L + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}\epsilon_P\right|^2$$

depends on pseudoscalar coupling $\epsilon_P = \epsilon_{S_R} - \epsilon_{S_L}$ and ϵ_L through

$$\epsilon_L + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}\epsilon_P \simeq \epsilon_L + 4\epsilon_P$$

Below use $\epsilon_L = 0$; to restore ϵ_L in bounds: $\epsilon_P \to \epsilon_P + \frac{1}{4}\epsilon_L$

- $R_{D^*}^{\mathrm{expt}} = 0.316$, need $\epsilon_P = 1.48 \Rightarrow \mathrm{Br}(B_c \to \tau\bar{\nu}_\tau) \approx 104\%$.
- Measurement of $\mathrm{Br}(B_c^- \to \tau\bar{\nu}_\tau)$: sensitive probe. [Du et al, PLB414 (1997) 130]

Problem is

B_c^+ DECAY MODES × $B(\bar{b} \to B_c)$

B_c^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)		Confidence level
	The following quantities are not pure branching ratios; rather the fraction $\Gamma_i/\Gamma \times B(\bar{b} \to B_c)$.			
Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	$(5.2\ ^{+2.4}_{-2.1}\ ) \times 10^{-5}$		
Γ_2	$J/\psi(1S)\mu^+\nu_\mu$			
Γ_3	$J/\psi(1S)\pi^+$	seen		
Γ_4	$J/\psi(1S)K^+$	seen		
Γ_5	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen		
Γ_6	$J/\psi(1S)a_1(1260)$	< 1.2	$\times 10^{-3}$	90%
Γ_7	$J/\psi(1S)K^+K^-\pi^+$	seen		
Γ_8	$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen		
Γ_9	$\psi(2S)\pi^+$	seen		
Γ_{10}	$J/\psi(1S)D_s^+$	seen		
Γ_{11}	$J/\psi(1S)D_s^{*+}$	seen		
Γ_{12}	$J/\psi(1S)p\bar{p}\pi^+$	seen		
Γ_{13}	$D^*(2010)^+\bar{D}^0$	< 6.2	$\times 10^{-3}$	90%
Γ_{14}	D^+K^{*0}	< 0.20	$\times 10^{-6}$	90%
Γ_{15}	$D^+\bar{K}^{*0}$	< 0.16	$\times 10^{-6}$	90%
Γ_{16}	$D_s^+K^{*0}$	< 0.28	$\times 10^{-6}$	90%
Γ_{17}	$D_s^+\bar{K}^{*0}$	< 0.4	$\times 10^{-6}$	90%
Γ_{18}	$D_s^+\phi$	< 0.32	$\times 10^{-6}$	90%
Γ_{19}	K^+K^0	< 4.6	$\times 10^{-7}$	90%
Γ_{20}	$B_s^0\pi^+$ / $B(\bar{b} \to B_s)$	$(2.37^{+0.37}_{-0.35}) \times 10^{-3}$		

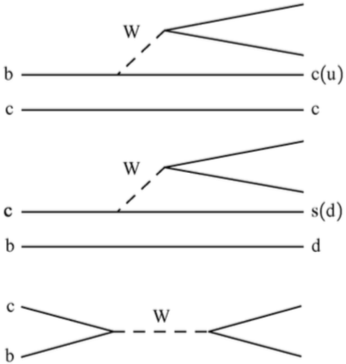
- Measurement of $\mathrm{Br}(B_c^- \to \tau\bar{\nu}_\tau)$ may be sensitive probe in future?
- NEW strategy: **lifetime**
  - Very high precision (1.5%): $\tau_{B_c} = 0.507(8) \times 10^{-12}$ s
  - Relatively well understood
  - Overview of result using NR-OPE: [Beneke&Buchala, PRD53,4991]
    - $\tau_{B_c}^{\rm OPE} = 0.52^{+0.18}_{-0.12}$ ps; take $\tau_{B_c}^{\rm OPE} < 0.70$ ps
    - OPE is inclusive; but only Weak Annihilation (WA) gives $B_c \to \tau\nu$.
    - $\Gamma_{\rm WA}^{\rm OPE} \leq 3\%$

$$\Gamma^{\rm exp} = 0.97\Gamma^{\rm OPE} + \Gamma_{\rm WA}^{\rm OPE} > 0.97\Gamma^{\rm OPE} + \Gamma(B_c \to \tau\nu)$$
$$> 0.97\Gamma^{\rm OPE}_{\rm min} + \Gamma(B_c \to \tau\nu)$$

    - $\Rightarrow \mathrm{Br}(B_c \to \tau\nu) < 30\%$
  - *Note* Strategy does nothing for ϵ_L:
    - with $R_D^{(*)}/R_{D,\rm SM}^{(*)} = 1.3 = (1+\epsilon_L)^2$ gives small effect $\mathrm{Br}(B_c \to \tau\nu) = 2.7\%$ (and $\Gamma_{\rm WA} < 4\%$)
    - even for perfect theory and including tau from spectator diagrams get effect below experimental uncertainty: $\Delta\tau_{B_c}/\tau_{B_c} = 1.2\%$

Lusignoli/Massetti, Z.Phys.C51,549(1991)
Gershtein et al, P.Uspekhi 38,1,(1995)
Bigi, PLB 371, 105(1996)
Beneke/Buchala, PRD 53,4991(1996)
Change et al, PRD 64, 014003(2001)
Kiselev, NPB 585, 353(2000)
Gouz et al, Phys Atm Nucl 67, 1559(2004)

Theory of B_c lifetime
0-th order, free quark decay



Simple:

$$\Gamma = \Gamma(b \to X) + \Gamma(c \to X) + \Gamma(ann)$$

with

$$\Gamma(b \to X) = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3} \times 9$$

$$\Gamma(c \to X) = \frac{G_F^2 |V_{cs}|^2 m_c^5}{192\pi^3} \times 5$$

and $\Gamma(ann)$ as in $\mathrm{Br}(\tau\nu)$
(with a factor of $3|V_{cs}|^2$ for $\bar{c}s$)

1st order, phase space correction:
large effect on $c \to s$ because $m_B/m_{B_c} \sim 0.8$

Effect of phase space in pictures:

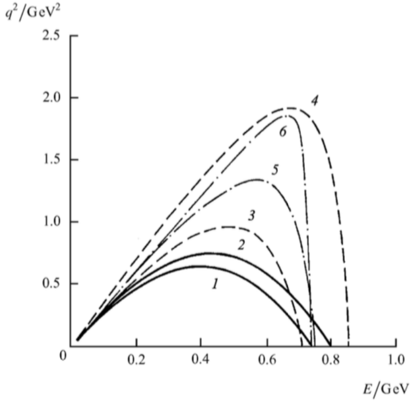


Figure 3. The Dalitz diagrams for the semileptonic decays: (1) $B_c \to B_s^* l\nu$, (2) $B_c \to B_s l\nu$, (3) $D \to K^* l\nu$, (4) $D \to K l\nu$, (5) $c \to s l\nu$ ($m_c = 1.7$ GeV, $m_s = 0.55$ GeV), (6) $c \to s l\nu$ ($m_c = 1.5$ GeV, $m_s = 0.15$ GeV); E is the lepton energy, q^2 is the square of the lepton pair mass.

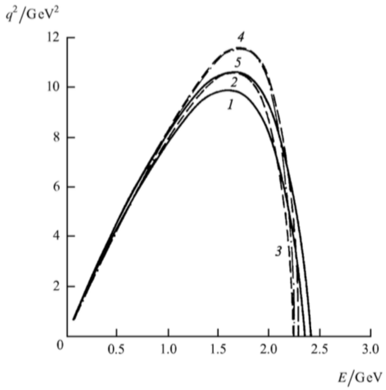


Figure 4. Dalitz diagrams for the semileptonic decays: (1) $B_c \to \psi l\nu$, (2) $B_c \to \eta_c l\nu$, (3) $B \to D l\nu$, (4) $B \to D^* l\nu$, (5) $b \to c l\nu$; E is the lepton energy, q^2 is the square of the lepton pair mass.

This simple minded approach gives widths (10^{-6}eV) and Br's

Decay mode	Free quarks	B_c^+	BR	Decay mode	Free quarks	B_c^+	BR
$\bar{b} \to \bar{c} + e^+\nu_e$	62	62	4.7	$c \to s + e^+ + \nu_e$	124	74	5.6
$\bar{b} \to \bar{c} + \mu^+\nu_\mu$	62	62	4.7	$c \to s + \mu^+ + \nu_\mu$	124	74	5.6
$\bar{b} \to \bar{c} + \tau^+\nu_\tau$	14	14	1.0	$c \to s + u + \bar{d}$	675	405	30.5
$\bar{b} \to \bar{c} + \bar{d} + u$	248	248	18.7	$c \to s + u + \bar{s}$	33	20	1.5
$\bar{b} \to \bar{c} + \bar{s} + u$	13	13	1.0	$c \to d + e^+\nu$	7	4	0.3
$\bar{b} \to \bar{c} + \bar{s} + c$	87	87	6.5	$c \to d + \mu^+ + \nu_\mu$	7	4	0.3
$\bar{b} \to \bar{c} + \bar{d} + c$	5	5	0.4	$c \to d + u + \bar{d}$	39	23	1.7
$B_c^+ \to \tau^+ + \nu_\tau$	—	63	4.7	$B_c^+ \to c + \bar{s}$	—	162	12.2
$B_c^+ \to c + \bar{d}$	—	8	0.6	$B_c^+ \to \text{all}$	—	1328	100

Note: $10^6/1328\text{eV}^{-1} = 0.496\text{ps}$

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3rd order: OPE in NRQFT, basically same result, but systematic

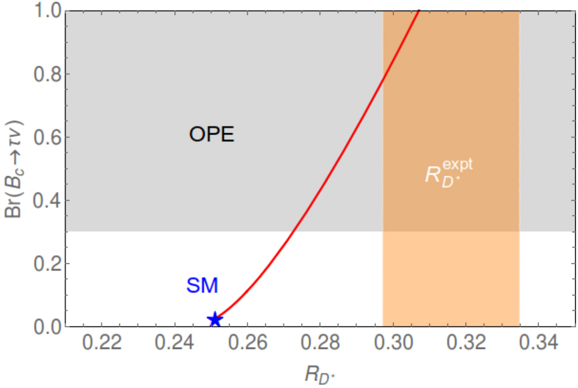
$$\Gamma_{B_c} = \frac{1}{2m_{B_c}} \langle B_c | \text{Im}\, i \int d^4x T \mathcal{H}_{\text{eff}}(x) \mathcal{H}_{\text{eff}}(0) | B_c \rangle$$

followed by OPE expansion

- Not fully proven, but works pretty well for Γ_B, Γ_Λ
- Matrix Elements fairly accurate from potential model
- Largest uncertainty: quark masses (huge room for improvement)

Mode	Partial rate (ps^{-1})
$\bar{b} \to \bar{c} u \bar{d}$	0.310
$\bar{b} \to \bar{c} c \bar{s}$	0.137
$\bar{b} \to \bar{c} e \nu$	0.075
$\bar{b} \to \bar{c} \tau \nu$	0.018
$\Sigma \bar{b} \to \bar{c}$	0.615
$c \to s u \bar{d}$	0.905
$c \to s e \nu$	0.162
$\Sigma c \to s$	1.229
WA:$\bar{b}c \to c\bar{s}$	0.138
WA:$\bar{b}c \to \tau\nu$	0.056
PI	−0.124
Total	1.914

Taking care of errors (using $\mathrm{Br}(B_c \to \tau\nu) < 30\%$ as above)



Correlation between R_{D*} and $\mathrm{Br}(B_c \to \tau\nu)$ for a pseudoscalar NP interaction (red line). The shaded areas are the 1σ-band corresponding to the measurement of R_{D*} (vertical orange) and to the bound on the NP contribution to the lifetime of the B_c assuming that the SM accounts for the 70% of it (gray horizontal).

Interplay with $B \to D^{(*)}\ell\nu$ observables

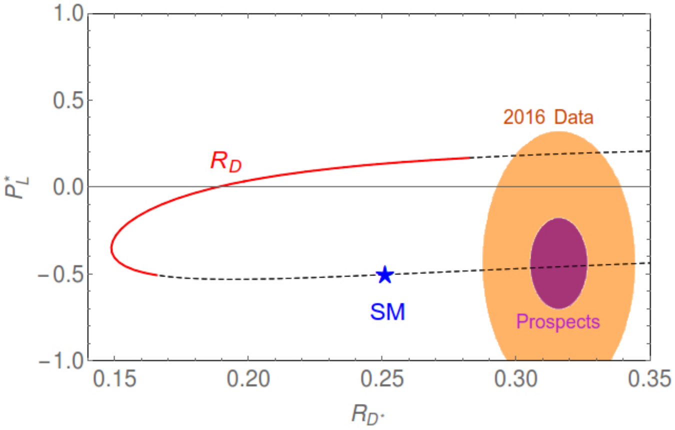
- Only choices left for $R_{D^{(*)}}$: ϵ_L and ϵ_T
  ($\epsilon_S \neq 0$ with $\epsilon_P = 0$ probably requires fine tuning in SM-EFT)
- $\epsilon_L \approx 0.13$ is a universal enhancement of all $b \to c\tau\nu$: no change in shapes of distributions
- ϵ_T (and ϵ_S) modifies also shapes.
- Fitting ϵ_T to R_D and R_{D^*},

$$\epsilon_T = 0.377(12), \quad \chi^2 = 1.49 \qquad (vs\ \epsilon_L = 0.13(3), \quad \chi^2 = 0.013)$$

- Shape, e.g.,

$$dP_L^{(*)} = \frac{d\Gamma_+ - d\Gamma_-}{d\Gamma_+ + d\Gamma_-} \quad \lambda_\tau = \pm \text{ is } \tau\text{-helicity}$$

- $P_L^{*,\mathrm{expt}} = -0.44(47)^{+0.20}_{-0.17}$ [Belle, 1608.06391]
- Fit above: $P_L^* = 0.190(10)$ ($P_L^{*,\mathrm{SM}} = -0.504(24)$)
- New fit, ϵ_T unchanged, but $\chi^2 = 3$



The (black) dashed line represents the parametric ϵ_T-dependence of R_{D^*} and P_L^*. The overlaid (red) solid line corresponds to values of ϵ_T for which R_D is consistent with the experimental measurement at 1σ. The shaded areas are the 1σ-bands corresponding to current data set (orange) and *naïve* experimental prospects discussed in the main text (purple).

Conclusion

If I were a model builder
and wanted to explain τ anomalies
I would build a model with

$$\epsilon_R = \epsilon_{S_R} = \epsilon_{S_L} = \epsilon_T = 0$$

and

$$\epsilon_L = 0.13$$