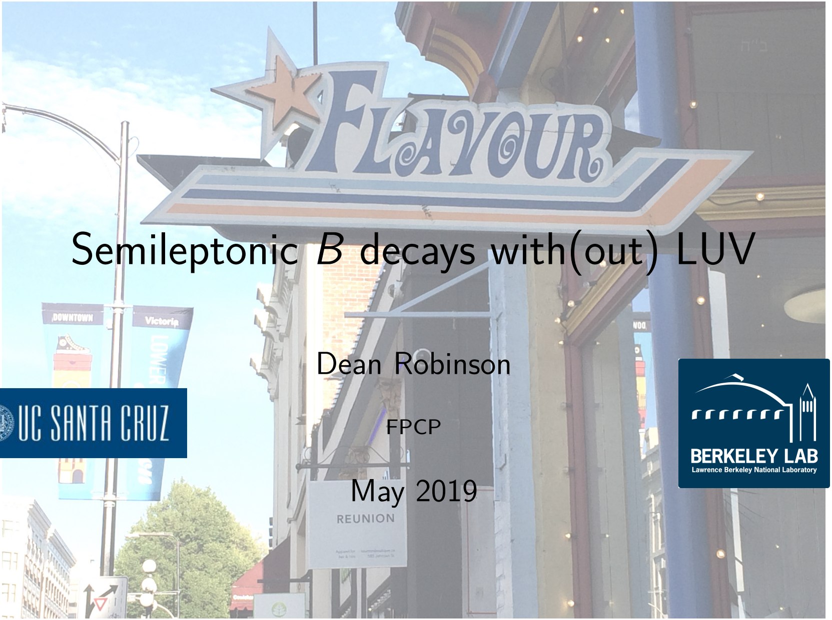


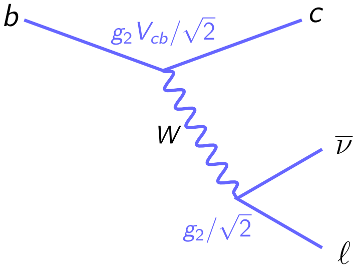
Semileptonic B decays with(out) LUV

Dean Robinson

FPCP

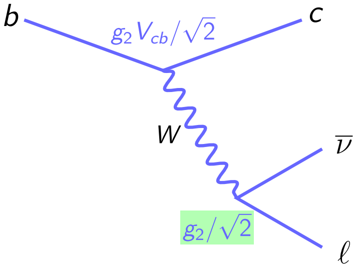
May 2019

Semileptonic Decays: $b \to c\ell\nu$



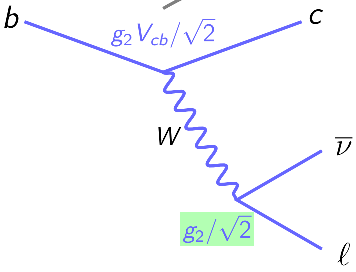
- Tree-level W exchange (in the SM)
- Approx. 25% of all B decays: huge statistics!

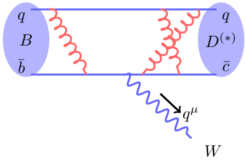
Semileptonic Decays: $b \to c\ell\nu$



- Tree-level W exchange (in the SM)
- Approx. 25% of all B decays: huge statistics!
- Theoretically clean:

Probe of lepton flavor universality
($\ell = e$, μ, τ) up to masses: PS
and FF effects





NB: Hadronic decays:

$B \to D^{(*)}$ (spin 0, 1)

$\Lambda_b \to \Lambda_c$ (spin 1/2)

...

- Tree-level W exchange (in the SM)
- Approx. 25% of all B decays: huge statistics!
- Theoretically clean:

Probe of lepton flavor universality ($\ell = e, \mu, \tau$) up to masses: PS and FF effects

Measurement of $|V_{cb}|$ inclusively (OPE)

Hadronic matrix elements $\Longrightarrow$ measure $|V_{cb}|$ in exclusive modes

Two Anomalies/Puzzles

1. Inclusive $B \to X_c l\nu$ versus exclusive $B \to D^* l\nu$ $(l = e,\, \mu)$

$$|V_{cb}|_{X_c} \simeq (42.2 \pm 0.8) \times 10^{-3}$$
$$|V_{cb}|_{D^*} \simeq (38.7 \pm 0.7) \times 10^{-3}$$

   A 3σ tension?!?

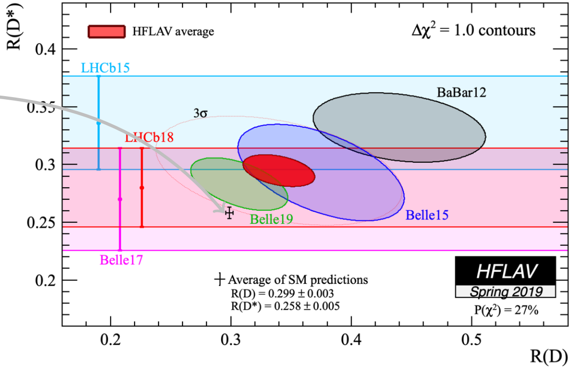
2. Can factor out $|V_{cb}|$, and measure the ratios

$$R(D^{(*)}) \equiv \frac{\Gamma[B \to D^{(*)}\tau\nu_\tau]}{\Gamma[B \to D^{(*)} l\nu]}\,, \qquad l = e,\, \mu\,.$$

$R(D^{(*)})$ anomaly

Persistent signals lepton flavor universality violation for 7+ years

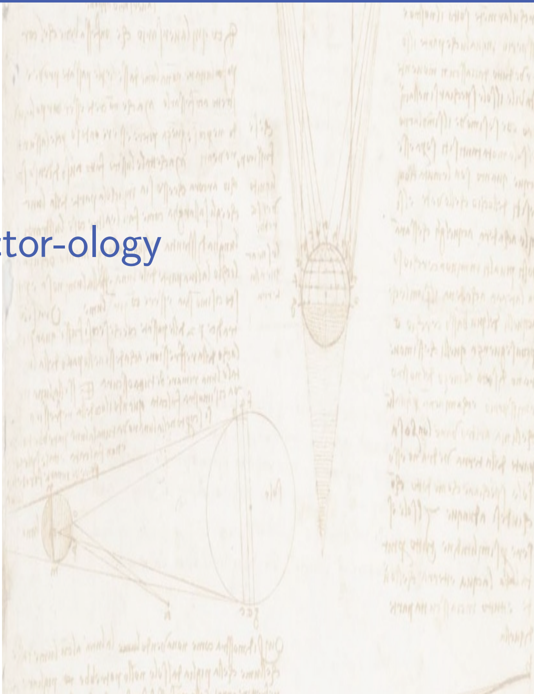
SM prediction



$\sim$ 20-30% tension at $\sim$ 3.1σ level with SM predictions
(was 4σ < March)

Also mild anomaly in $B_c \to J/\psi\tau\nu$, and (possibly) in $B \to X_c\tau\nu$. More measurements are coming ($R(D)$ from LHCb)

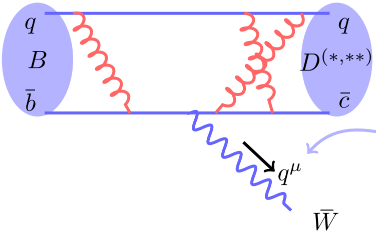
$\rightarrow |V_{cb}|$ & Form Factor-ology



$R(D^{(*)})$ & NP

Puzzle: Hadronic Matrix Elements

For exclusive processes: Main theory uncertainty is mapping partons $\to$ hadrons:



$$w = v \cdot v' = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$

$$w = 1 \Rightarrow \text{'zero recoil'}$$

$V - A$

- $|V_{cb}|$: Need SM predictions for $\langle D^{(*)} | \bar{c}\,\Gamma\, b | \bar{B} \rangle$
- $R(D^{(*)})$: Some SM matrix elements couple $\sim m_\tau$. Suppressed in e, μ.
- $R(D^{(*)})$: Also need NP predictions for $\langle D^{(*)} | \bar{c}\,\Gamma\, b | \bar{B} \rangle$ for any NP current

$V \pm A$, S, P or T

FF parametrizations

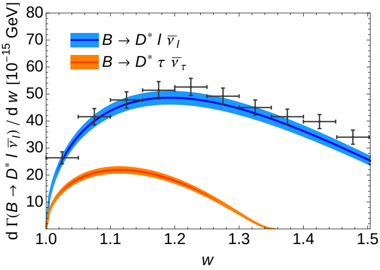
Schematically, for $B \to D^* l\nu$:

$$\langle D^* | \bar{c}\Gamma^\mu b | \bar{B} \rangle \sim FF_\varepsilon(q^2)\,\varepsilon^\mu + FF_B(q^2)\,p_B^\mu + FF_{D^*}(q^2)\,p_{D^*}^\mu\,,$$

$$\frac{d\Gamma[B \to D^* l\nu]}{dw} \sim |V_{cb}|^2 \sqrt{w^2-1} \times \mathcal{F}(w)^2\,,$$

Phase space $\to 0$ as $w \to 1$

Comb. of FFs. $\mathcal{F}(1)$ computed by lattice



- Obtain $|V_{cb}|\mathcal{F}(1)$ by fitting $d\Gamma/dw$ and extrapolating to $w = 1$
- $\mathcal{F}(1)$ from lattice $\implies |V_{cb}|$
- Extrapolation into low stats region highly sensitive to FF fit!

Also: NP predictions!

'Standard' Approach hep-ph/9712417 [Caprini, Lellouch, and Neubert]

CLN: Dispersion + analyticity + HQET

- HQET:

$$FF \sim 1(0) + \Lambda_{\mathrm{QCD}}/m_{c,b} + \alpha_s + \ldots$$

- Makes use of QCD sum rule predictions: model dependence
- FF ratios, $\mathcal{F}^2 \sim \mathrm{quadratic}(R_1, R_2)$

$$R_i(w) = R_i(1) + \mathrm{fixed}(w-1) + \mathrm{fixed}(w-1)^2 + \ldots$$

Not implemented self-consistently at NLO in HQET

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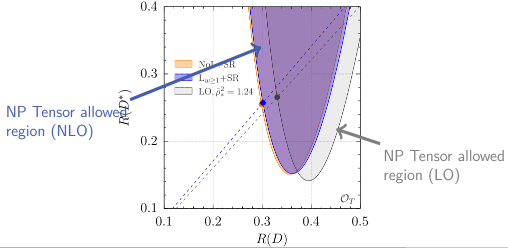
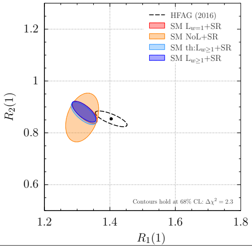
$$R_i(w) = R_i(1) + \text{fixed}(w-1) + \text{fixed}(w-1)^2 + \ldots$$

Not implemented self-consistently at NLO in HQET

- Self-consistent SM + NP treatment in new adaptation w/o QCDSR

1703.05330 [Bernlochner, Ligeti, Papucci, DR] 'BLPR'



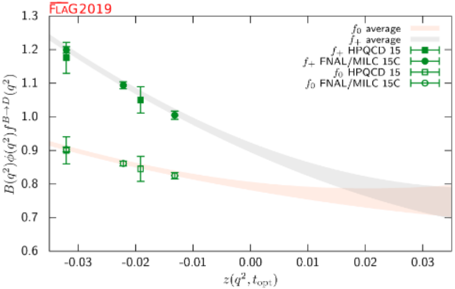


Lattice

Ultimate: Lattice QCD calculation of all NP matrix elements Fermilab/MILC & HPQCD

Current status: 1902.08191 [FLAG 2019]

$B \to D$:



$w > 1$ results not yet available for D^* SM see Alejandro's talk

$$\mathcal{F}(1) = 0.904(12)$$

BGL [Boyd, Grinstein, and Lebed]

Uses only dispersion relations and analyticity hep-ph/9508211

- Form factors

$$FF(w) \sim \sum a_n z^n, \qquad z = z(w)$$

- unitarity bound $\sum |a_n|^2 < 1$
- For SM $m_\ell = 0$, 3 FFs, g, f and $\mathcal{F}_1$

$$\{a_n^g,\, a_n^f,\, a_n^{\mathcal{F}_1}\} \longleftrightarrow \{a_n,\, b_n,\, c_n\}\,.$$

- No QCDSR; more ‘model-independent’
- No HQET
- Drawback: Can't use for NP analyses or $R(D^{(*)})$ predictions

$|V_{cb}|$ extractions

2017: BGL + Belle unfolded data 1702.01521 yields higher $|V_{cb}|$

$|V_{cb}|_{\text{CLN}} = (38.2 \pm 1.5) \times 10^{-3}\,,$	1702.01521 [Belle]
$|V_{cb}|_{\text{BGL}_{332}} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}\,,$	1703.06124, 1707.09509 [Bigi, Gambino, Schacht]
$|V_{cb}|_{\text{BGL}_{222}} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}\,,$	1703.08170 [Grinstein, Kobach]

How many BGL ‘abc’ parameters do you need to describe the data?

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How many BGL 'abc' parameters do you need to describe the data?

- Nested hypothesis test: a test of an N-parameter fit hypothesis versus $N+1$.
- Set threshold for accept/reject via $\Delta\chi^2 = \chi^2_N - \chi^2_{N+1} < 1$ (1-dof χ^2)
- For Belle 2017 tagged dataset: '$n_a n_b n_c$' = '222' (6 parameters) appears optimal 1902.09553

New $|V_{cb}|$ from Belle untagged dataset:

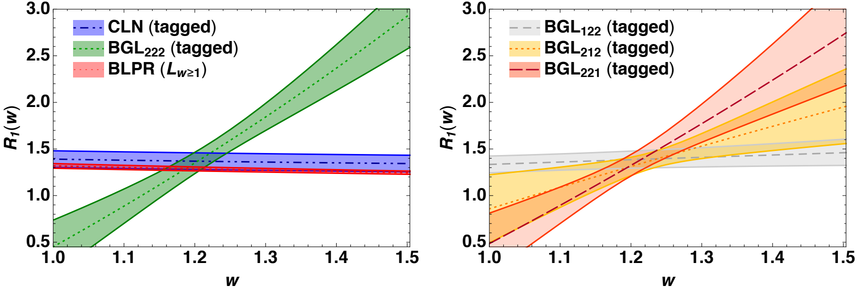
$$|V_{cb}|_{\text{BGL}_{122}} = (38.4 \pm 0.7) \times 10^{-3}$$ 1809.03290 [Belle]

Tensions

But: The BGL best fits that lift $|V_{cb}|$ lead to HQET tensions

1708.07134, 1902.09553

- Expect FF ratio $R_{1,2}(w) \sim 1$
- Large deviations for BGL fits



1902.09553

SM $R(D^{(*)})$ predictions

Coll.	Approach	$R(D)$	$R(D^*)$	corr.
1607.00299 [FLAG]	Lattice	0.300 ± 0.008	–	–
1606.08030 [Bigi, Gambino]	Lattice + Belle/BaBar	0.299 ± 0.003	—	—
1203.2654 [Fajfer, Kamenik, Nisandzic]	Cont.+ Belle	—	0.252 ± 0.003	—
1703.05330 [Bernlochner, Ligeti, Papucci, & DR]	Lattice + Belle + HQET NLO	0.299 ± 0.003	0.257 ± 0.003	0.44
1707.09509 [Bigi, Gambino, Schacht]	BGL + BLPR + $1/m_c^2$ error estimate	—	0.260 ± 0.008	—
1707.09977 [Jaiswal, Nandi, Patra]	BGL/HQET + $1/m_c^2$ parameter	0.299 ± 0.004	0.257 ± 0.005	~ 0.1
HFLAV	Arithmetic average	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.258 \pm 0.005}$	–

Main question: Are $1/m_c^2$ expected to be enhanced?

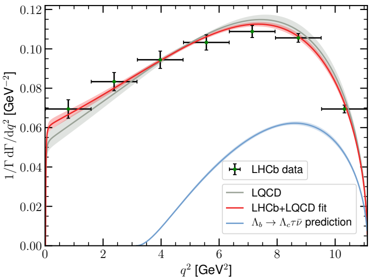
$1/m_c^2$ and $R(\Lambda_c)$

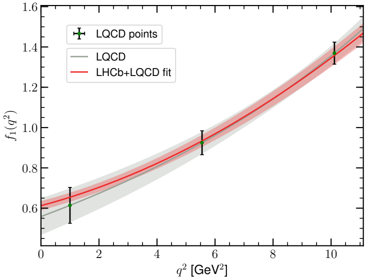
- Look at $\Lambda_b(= bdu) \to \Lambda_c \ell \nu$ baryon decay (LHCb)
- Exceptionally theoretically clean in HQET.

  The brown muck is in spin-0 state: $\frac{1}{2}^+_c \otimes 0^+ = \frac{1}{2}^+$

  HQ expansion has only 2 IW functions at NNLO!

- Fit to LHCb data ($l = \mu$) plus lattice for first extraction of $1/m_c^2$ terms from exclusive data 1808.09464, 1812.07593 [Bernlochner, Ligeti, DR Sutcliffe]





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	LHCb + LQCD	Lattice	Model-dep hep-ph/9209269
$\widehat{b}_1/4m_c^2$	-0.066 ± 0.023		$\mathcal{O}(20\%)$
$\widehat{b}_2/4m_c^2$	-0.056 ± 0.056		
$R(\Lambda_c)$	0.3237 ± 0.0036	0.3328 ± 0.0098	

- SM $1/m_c^2$ terms non-zero at $\sim 3\sigma$!
- Size is consistent with well-behaved HQ expansion $(0.2^2 \sim 0.04)$

$R(D^{(*)})$: What NP Models are interesting

A brief overview of what is, and is not, a compelling model to choose for $R(D^{(*)})$ explanations

or

What you need to know to build $R(D^{(*)})$ models

There is a huge literature on this; comprehensive citations requires a dedicated review!

General 4-Fermi basis

At dimension-6

$$\mathcal{O}_6 \sim \frac{C}{\Lambda^2}\left(\bar{c}\Gamma b\right)\left(\bar{\tau}\Gamma'\nu\right) \qquad C \in \mathbb{C}(\Rightarrow \text{CPV})$$

Wilson coefficients:

LH (RH) $\nu_{L(R)}$

Vector: $C^V_{LL(LR)}$, $C^V_{RL(RR)}$,

Scalar: $C^S_{LL(LR)}$, $C^S_{RL(RR)}$,

Tensor: $C^T_{LL(RR)}$,

Simplified models:

EW scalars	C^S
W'	C^V
Scalar/Vector LQ	C^V, $C^{S\pm T}$

Normalized against SM: $\Lambda \sim 870\,\text{GeV}$. For 20–30% enhancement, expect TeV scale NP

- No* NP in $B \to D^{(*)} l\nu$: $|V_{cb}|$ constraints.
- Simplified models mediators: EW charged scalars, W''s or leptoquarks ($\widetilde{R}_2$, S_1, U_1, ...) see Marta's talk

Immediate Dangers

Simplified models for $R(D^{(*)})$ explanations should be electroweak consistent in the UV.

- Since $\nu_L \in L_L$, all simplified model mediators are $SU(3)_c$ and/or $SU(2)_L$ charged. Strong collider constraints from $pp \to \tau\tau$ or $\tau +$ MET modes
  1609.07138, 1606.00524, 1705.00929

- If $c \in Q_L$, can have dangerous strange processes, e.g. $b \to s\nu\nu$ or B_s–$\overline{B}_s$

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  1609.07138, 1606.00524, 1705.00929

- If $c \in Q_L$, can have dangerous strange processes, e.g. $b \to s\nu\nu$ or B_s–$\overline{B}_s$

- One loophole: Consider contributions from RH sterile ν
  1804.04135 [Asadi, Buckley, Shih] 1804.04642 [Greljo, DR, Shakya, Zupan], 1807.04753, 1807.10745

  $B \quad \to \quad$ charm hadron $\quad + \quad \tau \quad + \quad$ missing energy

  - Can make mediator that is EW sterile, colorless
  - Relax $b \to s$ problems
  - But: $pp \to \tau\nu$ can still be dangerous!

$B_c \to \tau\nu$ bounds

$B_c \to \tau\nu$ is necessarily modified by $b \to c\tau\nu$ enhancements!
1605.09308, 1611.06676

$$\Gamma[B_c \to \tau\nu] = \Gamma_{\mathrm{SM}}\left[1 + C_{RL}^V + \frac{m_{B_c}^2}{m_\tau(m_b - m_c)}\left(C_{LL}^S - c_{RL}^S\right)\right]^2$$

- Scalar operators lift chiral suppression. Enhancement: $\sim m_{B_c}/m_\tau \sim 3.5$

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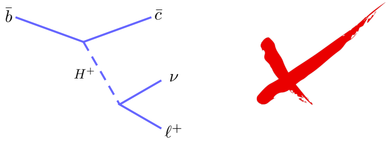
1605.09308, 1611.06676

$$\Gamma[B_c \to \tau\nu] = \Gamma_{\text{SM}}\left[1 + C^V_{RL} + \frac{m^2_{B_c}}{m_\tau(m_b - m_c)}\big(C^S_{LL} - c^S_{RL}\big)\right]^2$$

- Scalar operators lift chiral suppression. Enhancement: $\sim m_{B_c}/m_\tau \sim 3.5$
- $B_c \to \tau\nu$ is not measured, but the B_c lifetime *is* and hadronic BRs are *estimated* in OPE. Sets requirement

$$\text{Br}[B_c \to \tau\nu] \lesssim 10\text{–}40\% \quad \text{1904.10432} \quad \text{or} \quad \Gamma/\Gamma_{\text{SM}} \lesssim 5\text{–}20$$

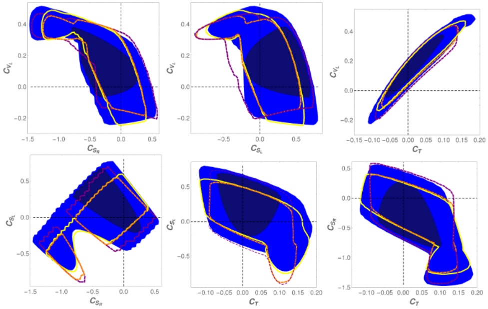
- Dangerous for single scalar current models



NP Status

Latest (post-Moriond) global fits to $R(D^{(*)})$, plus $F_L(D^*)$, P_τ

1904.09311, 1904.10432, see Marta's and Jacky's talks



1904.09311

- W' models face tensions from $pp \to \tau\tau/\nu$ and flavor
- Leptoquark C_V and $C_{S\pm T}$ type models may be viable, though restricted by collider bounds (single or pair production + bc, $b\tau$, $c\tau$ final states) or b–s bounds (If there is a quark doublet involved)
- Pure C_S (Φ, $\widetilde{R}_2$) leptoquark models face B_c lifetime tensions

But: MC Template Dependence

To measure $R(D^{(*)})$, expts perform a simultaneous BG+signal MC template float

What happens if you change the model-template?

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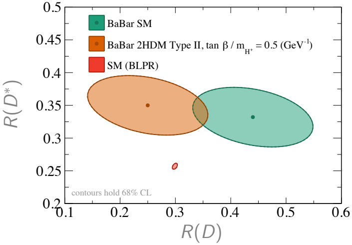
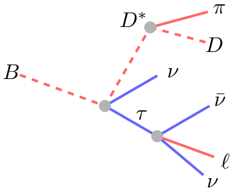
Eg BaBar SM $\rightarrow$ 2HDM Type II Courtesy F Bernlochner





Fitting to expt measurements tells you confidence to reject SM, not accept NP!

NP needs to be included a priori (a "forward-folded" analysis)

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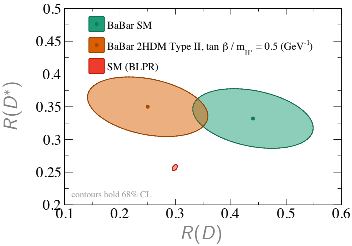
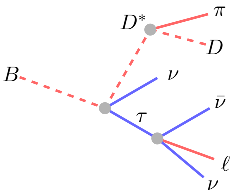




Efficient MC reweighting for self-consistent direct expt WC fits!

`Hammer`: Implementing/ed in LHCb and Belle II analysis frameworks

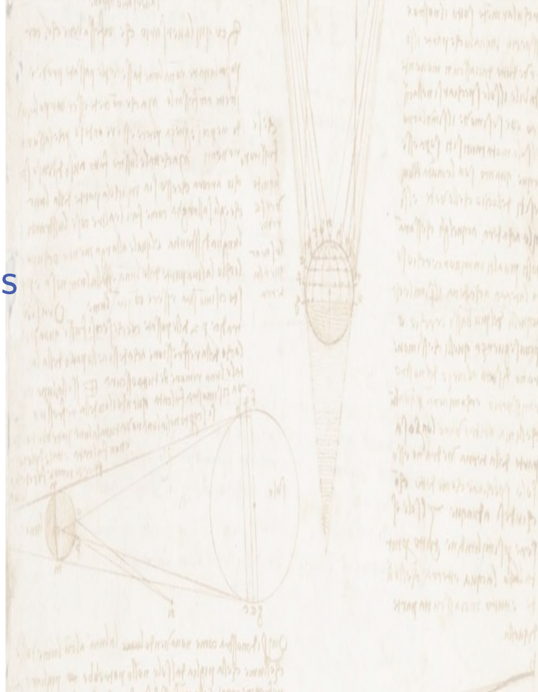
Stopgap for analyses: Check expected variation in the diff. information. E.g. p_ℓ, m^2_{miss}, E_D, opening angles etc

Outlook

- More data is needed to settle $|V_{cb}|$ measurements and FF params. At least some new evidence that HQET expansion is well-behaved for baryons
- Self-consistent FF parametrization implementations available for NP predictions
- Prolific NP analyses with multiple constraints from collider and flavor data; possibly viable leptoquark models
- Template dependence will be resolved with direct Wilson Coefficient fits by expts (`Hammer`)

Thanks!

→Extras and Details



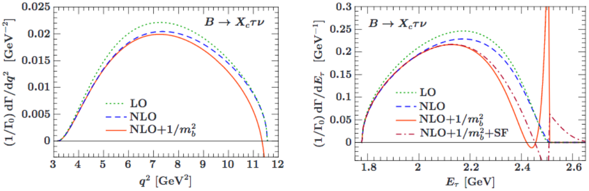
Inclusive $B \to X_c \ell \nu$

- X_c can be a multibody state with arbitrary invariant mass.
- In $m_b \to \infty$ limit, the inclusive hadronic decay $\Leftrightarrow$ free quark decay
- More generally, rate calculable via an OPE

$$\sum_{X_c} \langle B|J^\dagger|X_c\rangle\langle X_c|J|B\rangle \sim \langle B|T[J^\dagger J]|B\rangle$$

- Incorporates radiative α_s and non-perturbative $1/m_b$ corrections .

OPE predictions up to and including $\Lambda^2_{\mathrm{QCD}}/m_b^2$ have been computed see e.g. 1406.7013 [Ligeti Tackmann]



Branching Ratios

Predictions for $R(X_c)$ incl. two-loop QCD 1506.08896 [Freytsis, Ligeti Ruderman]

$$R(X_c) = 0.223 \pm 0.004\,.$$

Another way to see the anomaly: Current inclusive BR HFLAV

$$\text{Br}[B \to X_c e\nu] = (10.65 \pm 0.16)\%\,,$$
$$\implies \text{Br}[B \to X_c \tau\nu] = (2.38 \pm 0.05)\%$$

But the direct sum

$$\text{Br}[B \to D\tau\nu] + \text{Br}[B \to D^*\tau\nu] + \text{Br}[B \to D^{**}\tau\nu]_{\text{pred}} \simeq 3\%!$$

Directly measuring $\text{Br}[B \to X\tau\nu]$ at Belle II (and/or with BaBar data) would be interesting! [There is a Belle thesis result $R(X_c) = 0.298 \pm 0.012 \pm 0.018$]

Form Factor Basis (HQ)

Form factors encode matrix element structure in terms of momenta, polarizations, as allowed by Poincaré symmetry + parity.

(NB: $v = p_B/m_B$, $v' = p_{D^{(*)}}/m_{D^{(*)}}$)

$\bar{B} \to D$

$$\begin{aligned}
\langle D | \bar{c}\, b | \bar{B} \rangle &= \sqrt{m_B m_D}\, h_S\, (w+1)\,,\\
\langle D | \bar{c}\gamma^5 b | \bar{B} \rangle &= \langle D | \bar{c}\gamma^\mu\gamma^5 b | \bar{B} \rangle = 0\,,\\
\langle D | \bar{c}\gamma^\mu b | \bar{B} \rangle &= \sqrt{m_B m_D}\, \big[h_+(v+v')^\mu + h_-(v-v')^\mu\big],\\
\langle D | \bar{c}\sigma^{\mu\nu} b | \bar{B} \rangle &= i\sqrt{m_B m_D}\, \big[h_T\, (v'^\mu v^\nu - v'^\nu v^\mu)\big],
\end{aligned}$$

$\bar{B} \to D^*$

$$\begin{aligned}
\langle D^* | \bar{c} b | \bar{B} \rangle &= 0\,,\\
\langle D^* | \bar{c}\gamma^5 b | \bar{B} \rangle &= -\sqrt{m_B m_{D^*}}\, h_P\, (\epsilon^* \cdot v)\,,\\
\langle D^* | \bar{c}\gamma^\mu b | \bar{B} \rangle &= i\sqrt{m_B m_{D^*}}\, h_V\, \varepsilon^{\mu\nu\alpha\beta}\, \epsilon^*_\nu v'_\alpha v_\beta\,,\\
\langle D^* | \bar{c}\gamma^\mu\gamma^5 b | \bar{B} \rangle &= \sqrt{m_B m_{D^*}}\, \big[h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^*\cdot v)v^\mu - h_{A_3}(\epsilon^*\cdot v)v'^\mu\big]\,,\\
\langle D^* | \bar{c}\sigma^{\mu\nu} b | \bar{B} \rangle &= -\sqrt{m_B m_{D^*}}\, \varepsilon^{\mu\nu\alpha\beta}\big[h_{T_1}\epsilon^*_\alpha(v+v')_\beta + h_{T_2}\epsilon^*_\alpha(v-v')_\beta\\
&\quad + h_{T_3}(\epsilon^*\cdot v)v_\alpha v'_\beta\big]\,.
\end{aligned}$$

Form factors $h_{\Gamma_i} = h_{\Gamma_i}(w)$ or $h_{\Gamma_i}(q^2)$: for $B \to D^{(*)} l\nu$ $w - 1 \lesssim 0.6$

Truncation dependence

Nested hypothesis test: a test of an N-parameter fit hypothesis versus $N+1$.

- Define a space of BGL models
- Set threshold for accept/reject via $\Delta\chi^2 = \chi^2_N - \chi^2_{N+1} < 1$ (1-dof χ^2)

n_c \ n_a	1	2	3	1	2	3	1	2	3
1	33.2 38.6 ± 1.0	31.6 38.6 ± 1.0	31.2 38.6 ± 1.0	33.0 39.0 ± 1.5	29.1 40.7 ± 1.6	28.9 40.7 ± 1.6	30.4 40.7 ± 1.7	29.1 40.6 ± 1.8	28.9 40.6 ± 1.8
2	32.9 38.8 ± 1.1	31.3 38.7 ± 1.1	31.1 38.8 ± 1.0	32.7 39.5 ± 1.7	**27.7** $\mathbf{41.7 \pm 1.8}$	27.7 41.6 ± 1.8	29.2 41.8 ± 2.0	27.7 41.8 ± 2.0	27.7 41.7 ± 2.0
3	31.7 39.0 ± 1.1	31.3 38.6 ± 1.2	31.0 38.6 ± 1.1	29.1 41.9 ± 2.0	27.7 41.8 ± 2.0	27.6 41.7 ± 2.0	29.2 41.8 ± 2.0	27.6 41.7 ± 1.9	23.2 41.4 ± 2.0
		$n_b = 1$			$n_b = 2$			$n_b = 3$	

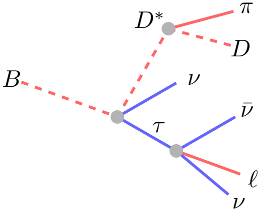
- For Belle 2017 tagged dataset: '$n_a n_b n_c$' = '222' (6 parameters) appears optimal 1902.09553
- The preferred 5 parameter fit is '221' ($a^g_{0,1}$, $a^f_{0,1}$, $a^{\mathcal{F}_1}_1$)

MC Template Dependence

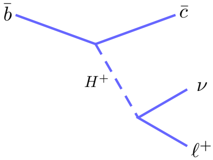
To measure $R(D^{(*)})$/observables, expts perform a simultaneous BG+signal MC template float

Huge amount of MC just for SM study
What happens if you change the model-template?

- The D^* and τ decay: interference effects
  [$\mathcal{O}(m_\tau/m_B)$ for SM, but $\mathcal{O}(1)$ with NP!]
- Phase space cuts
  $\Rightarrow$ Total acceptances change!
- τ frame not* reconstructible
- Downfeed BGs from orbitally excited $D^{**} \to D^{(*)}X$ states
  [very sensitive to (the same) NP! 1711.03110]

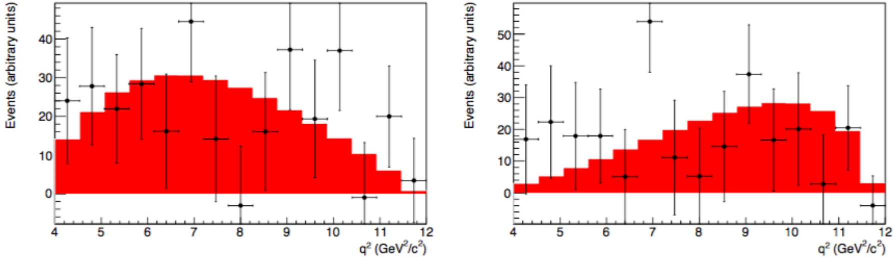


Signal Model Dependence



Extracted Belle spectra for SM → 2HDM Type II

[Belle 1507.03233]

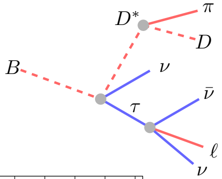


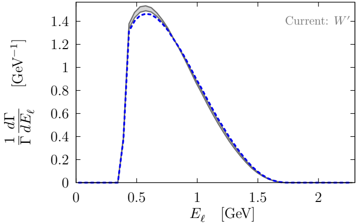
SM: $R(D) = 0.375 \pm 0.064 \pm 0.026$

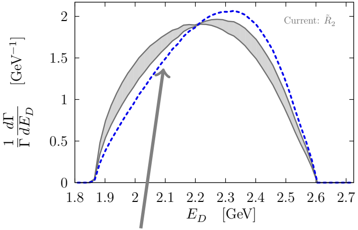
2HDM $R(D) = 0.329 \pm 0.060 \pm 0.022$ [Belle 1507.03233]

Stopgap

Check expected variation in the differential information of fit from SM. E.g. p_ℓ, m^2_{miss}, E_D, opening angles etc







SM disjoint from 2σ fit region: Possibly unreliable conclusions!