$B \to D^{**} \ell \bar{\nu}$ and the extraction of $|V_{cb}|$ and searches for NP

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Challenges in semileptonic B decays

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Outline / main points

- $B \to D^{**}\ell\bar{\nu}$: SM and $R(D^{**})$ [Bernlochner, ZL, 1606.09300]
- $B \to D^{**}\ell\bar{\nu}$: arbitrary NP, importance of $\Lambda_{\rm QCD}/m_{c,b}$ [Bernlochner, ZL, Robinson, arXiv:1711.03110]
- Developing `Hammer` HAMMC (Helicity Amplitude Module for Matrix Element Reweighting) [Bernlochner, Duell, ZL, Papucci, Robinson, soon]

- Refine $R(D^{(*)})$ in SM, fits for $|V_{cb}|$ [Bernlochner, ZL, Papucci, Robinson, 1703.05330, 1708.07134]

Notation: $\ell = e, \mu, \tau$ and $l = e, \mu$

Spectroscopy of heavy-light mesons

- In $m_Q \gg \Lambda_{\text{QCD}}$ limit, spin of the heavy quark is a good quantum number
  $\Rightarrow$ so is the spin of the light d.o.f., since $\vec{J} = \vec{s}_Q + \vec{s}_l$ and

$$\left.\begin{array}{r} \text{angular momentum conservation: } [\vec{J}, \mathcal{H}] = 0 \\ \text{heavy quark symmetry: } [\vec{s}_Q, \mathcal{H}] = 0 \end{array}\right\} \Rightarrow [\vec{s}_l, \mathcal{H}] = 0$$

- For a given s_l, two degenerate states:

$$J_\pm = s_l \pm \tfrac{1}{2}$$

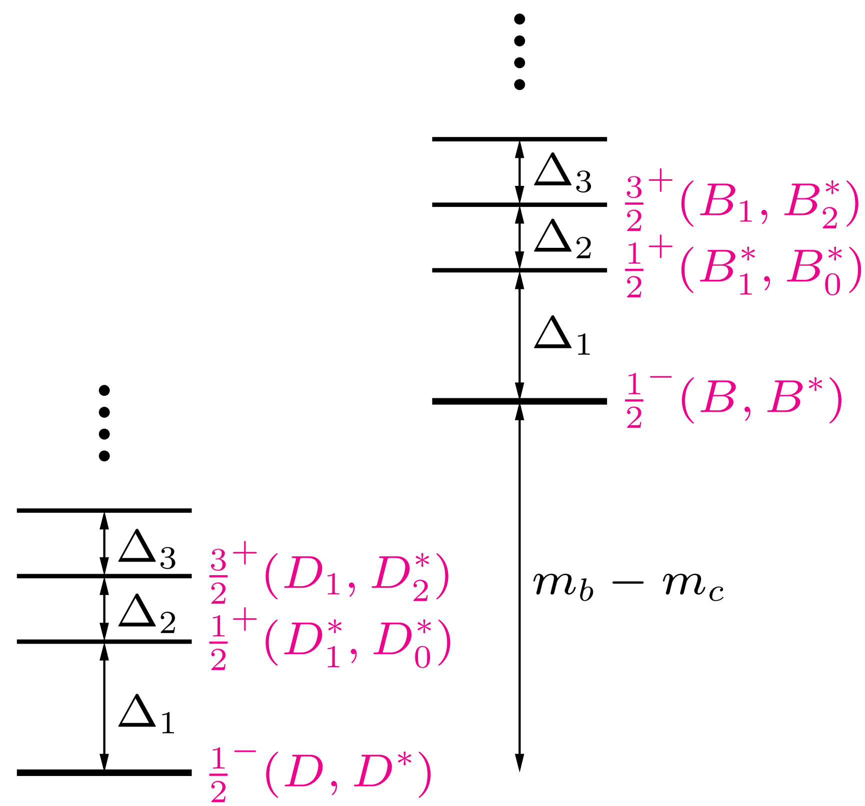
$\Rightarrow \Delta_i = \mathcal{O}(\Lambda_{\text{QCD}})$ — same in B and D sector

Doublets are split by order $\Lambda_{\text{QCD}}^2/m_Q$, e.g.:

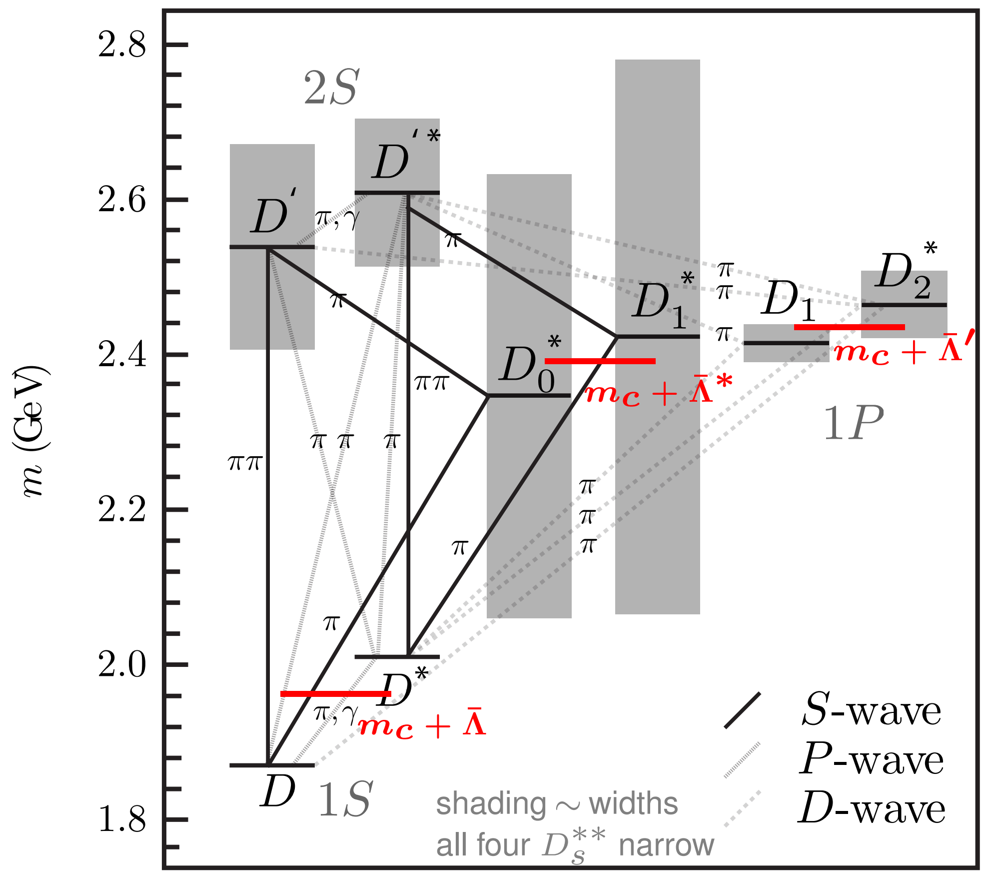
$m_{D^*} - m_D \sim 140\,\text{MeV}$

$m_{B^*} - m_B \sim 45\,\text{MeV}$

ratio $\sim m_c/m_b$



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



Why bother...?

- $B \to D^{**}\,\tau\bar\nu$: rates to narrow D_1, D_2^* measurable soon?

  In $B_s \to D_s^{**}\ell\bar\nu$ case, all 4 D_s^{**} states are narrow $\Rightarrow$ LHCb?

- Large(st) syst. uncertainty in $R(D^{(*)})$
- May matter for tensions between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ determinations
- Complementary sensitivity to NP
- Complementary experimentally
- Decay rates not too small

	$R(D)$ [%]	$R(D^*)$ [%]	Correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
Fake D yield	0.5	0.3	0.13
Fake ℓ yield	0.5	0.6	-0.66
D_s yield	0.1	0.1	-0.85
Rest yield	0.1	0.0	-0.70
Efficiency ratio f^{D^+}	2.5	0.7	-0.98
Efficiency ratio f^{D^0}	1.8	0.4	0.86
Efficiency ratio $f_{\rm eff}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\rm eff}^{D^{*0}}$	0.7	1.1	0.94
CF double ratio g^+	2.2	2.0	-1.00
CF double ratio g^0	1.7	1.0	-1.00
Efficiency ratio $f_{\rm wc}$	0.0	0.0	0.84
$M^2_{\rm miss}$ shape	0.6	1.0	0.00
$o'_{\rm NB}$ shape	3.2	0.8	0.00
Lepton PID efficiency	0.5	0.5	1.00
Total	7.1	5.2	-0.32

[Belle, 1507.03233]

Consequences of HQET

- Schematic form of $B \to D^{(*,**)}\ell\bar{\nu}$ rates: $[\varepsilon^n \sim (\Lambda_{\rm QCD}/m_Q)^n]$

$$\frac{d\Gamma_{D^*}}{dw} \sim \sqrt{w^2-1}\,\Big[\big(1_{\rm (HQS)} + 0_{\rm (Luke)}\,\varepsilon + \varepsilon^2 + \ldots\big) + (w-1)\,(1+\varepsilon+\ldots) + \ldots\Big]$$

$$\frac{d\Gamma_{D,\,D_0^*}}{dw} \sim (w^2-1)^{3/2}$$

for $V - A$ current and $m_\ell = 0$, but in general:

$\sqrt{w^2-1}$ terms for D (D_0^*) have the same structure as D^* above (D_1, D_1^* below)

$$\frac{d\Gamma_{D_1,\,D_1^*}}{dw} \sim \sqrt{w^2-1}\,\Big[\big(0_{\rm (HQS)} + 0_{\rm (HQS)}\,\varepsilon + \varepsilon^2 + \ldots\big) + (w-1)\,(1+\varepsilon+\ldots) + \ldots\Big]$$

$$\frac{d\Gamma_{D_2^*}}{dw} \sim (w^2-1)^{3/2}$$

for all terms $\Rightarrow$ no HQS constraints

- For $B \to D^{**}\ell\bar{\nu}$, the $\mathcal{O}(\Lambda_{\rm QCD}/m_Q)$ corrections can be very important, due to suppression at $w = 1$ in heavy quark limit

- $\sqrt{w-1}\,\varepsilon^2$ terms for D^{**} determined by hadron masses and leading Isgur-Wise fn

[Leibovich, ZL, Stewart, Wise, hep-ph/9703213, hep-ph/9705467]

Some model independent results

- At $w = 1$, the $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ matrix element is determined by hadron masses and the leading order Isgur-Wise function [Leibovich, ZL, Stewart, Wise, hep-ph/9703213, hep-ph/9705467]

  Kinematic range: $1 \le w \lesssim 1.3$ and in the τ case $1 \le w \lesssim 1.2$

  Meson masses: $$m_{H_\pm} = m_Q + \bar\Lambda^H - \frac{\lambda_1^H}{2m_Q} \pm \frac{n_\mp\,\lambda_2^H}{2m_Q} + \ldots \qquad n_\pm = 2J_\pm + 1$$

  For example:
  $$\frac{\langle D_1(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_{D_1}\,m_B}} = f_{V_1}\epsilon^{*\mu} + (f_{V_2}v^\mu + f_{V_3}v'^\mu)(\epsilon^*\cdot v)$$
  $$\sqrt{6}\,f_{V_1}(w) = (1-w^2)\,\tau(w) - 4\,\frac{\bar\Lambda' - \bar\Lambda}{m_c}\,\tau(w) + \mathcal{O}\left(\frac{w-1}{m_{c,b}}\right) + \ldots$$

- These “known” $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ terms can be numerically very significant

- SM and $m_\ell \neq 0$ [Bernlochner, ZL, 1606.09300]

  fully generally [Bernlochner, ZL, Robinson, arXiv:1711.03110]

Some surprises (for me)

- Mass splitting: $m_{D_1^*} - m_{D_0^*} \sim m_{D^*} - m_D$?

  Poor consistency of $m_{D_0^*}$ measurements

Parameter	$\bar\Lambda$	$\bar\Lambda'$	$\bar\Lambda^*$
Value [GeV]	0.40	0.80	0.76

Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (MeV)
D_0^*	$\frac{1}{2}^+$	0^+	2349	236
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
D_1	$\frac{3}{2}^+$	1^+	2421	31
D_2^*	$\frac{3}{2}^+$	2^+	2461	47

- $\mathcal{B}(B \to D_0^*\pi)$ puzzling: $\ll D_1\pi$ and $D_2^*\pi$

  breakdown of factorization?

  Small fraction of BaBar & Belle data $+$ LHCb

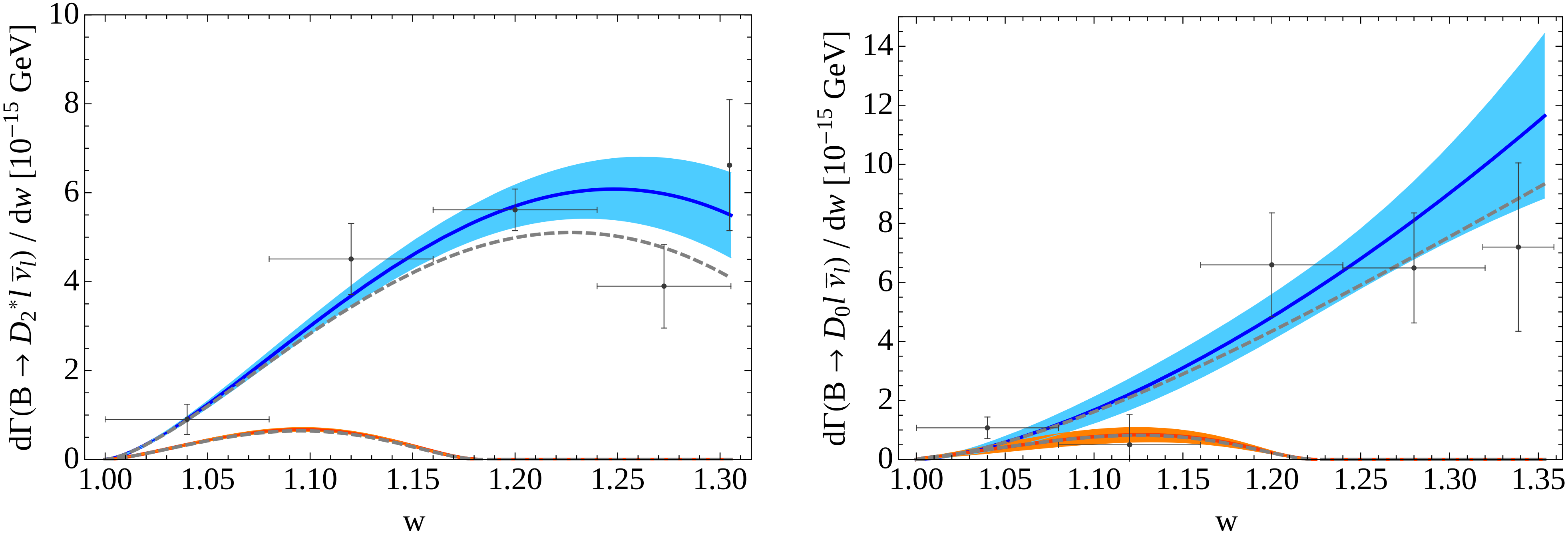
Decay mode	Branching fraction
$B^0 \to D_2^{*-}\pi^+$	$(0.59 \pm 0.13) \times 10^{-3}$
$B^0 \to D_1^-\pi^+$	$(0.75 \pm 0.16) \times 10^{-3}$
$B^0 \to D_0^{*-}\pi^+$	$(0.12 \pm 0.02) \times 10^{-3}$

- $D_{s0}^*(2317)$: orbitally excited state or "molecule"? Nice for LHCb, $\Gamma_{D_{s0}^*} < 4$ MeV

  If D_{s0}^* is excited $c\bar s$ state, predict $\mathcal{B}(D_{s0}^* \to D_s^*\gamma)/\mathcal{B}(D_{s0}^* \to D_s\pi)$ above CLEO bound, < 0.059 [Mehen & Springer, hep-ph/0407181; Colangelo & De Fazio, hep-ph/0305140; Godfrey, hep-ph/0305122]

  CLEO used 13.5/fb, the Belle bound < 0.18 used $87/\text{fb}$, the BaBar bound < 0.16 used $232/\text{fb}$

Turning the crank: spectra

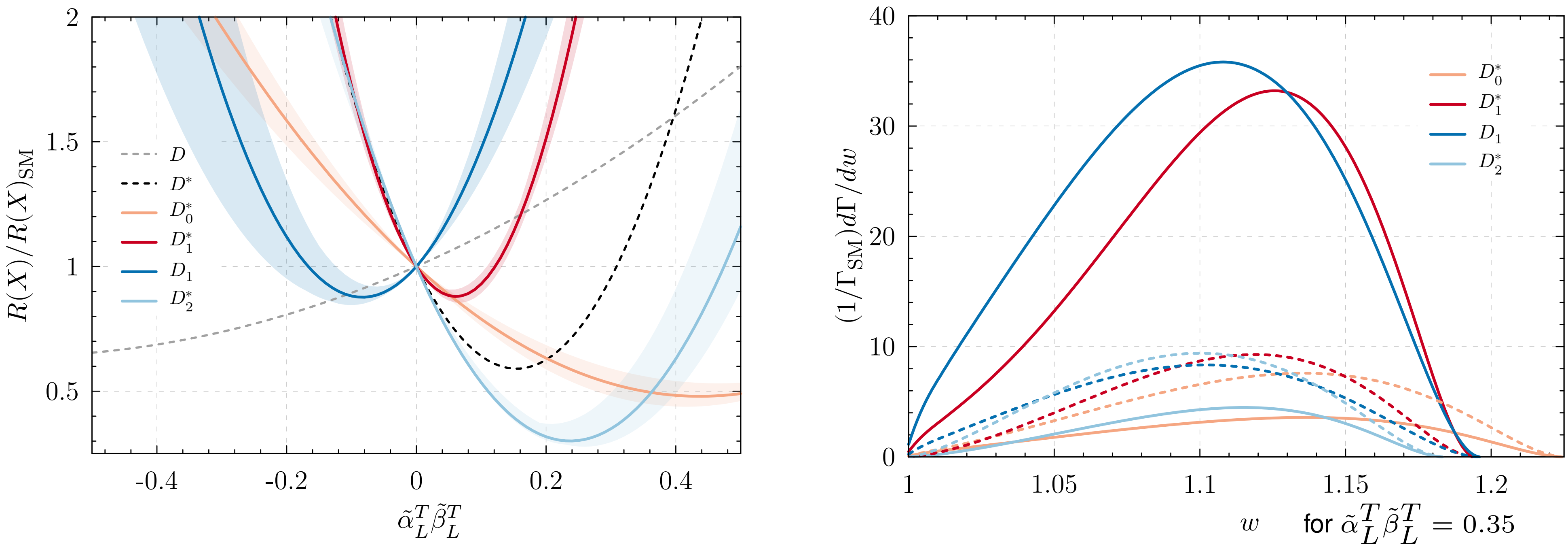


Rates for e, μ vs. τ [Belle, 0711.3252; fit Bernlochner, ZL, 1606.09300]

- Large suppression of $\Gamma(B \to D_2^* l\nu)/\Gamma(B \to D_1 l\nu)$ compared to heavy quark limit
- Study all uncertainties, including effects neglected in LLSW
- As in $B \to D^{(*)}\ell\bar{\nu}$, HQS relates form factors $\propto q_\mu$ to those measurable for $m_l = 0$

$R(D^{**})$: complementary sensitivities

- Consider tensor operator, which can fit $R(D^{(*)})$ [Bernlochner, ZL, Robinson, arXiv:1711.03110]



Different patterns from $R(D^{(*)})$, where $\tilde{\alpha}_L^T \tilde{\beta}_L^T = 0.35$ gives good fit

- Large variation of predictions — explore influence of all possible BSM operators

- $B_s \to D_s^{**}$: same formalism, $SU(3)$ relations, info on NP & QCD structure of D_s^{**}

The Hammer tool

HAMMER: Helicity Amplitude Module for Matrix Element Reweighting

[Bernlochner, Duell, ZL, Papucci, Robinson]

COMING SOON

- Fully differential distributions of detected particles, incl. D & τ decay interference

  Include arbitrary NP interaction and $m_\ell \neq 0$, for all 6 decays: $B \to \{D, D^*, D^{**}\}\, \ell\bar{\nu}$

  – Efficiently reweight fully simulated samples (detector simulation only once)

  – Makes it feasible and fast to explore and run fits in all NP model space

- Weight matrix: For a given MC sample, calculate a reweight tensor which determines event weights for any NP (C_n) and any form factor parametrization (F_m)

$$F_i^\dagger\, C_j^\dagger\, \mathcal{W}_{ijkl}\, C_k\, F_l$$

  Rapidly calculate differential distributions for any NP & form factors (contractions)

- Ongoing discussion with LHCb and Belle II members — publicly available soon

Few slides on $B \to D^{(*)}\ell\bar{\nu}$

$B \to D^{(*)}\ell\bar\nu$ and HQET

- Only Lorentz invariance: 6 functions of q^2, only 4 measurable with $e,\ \mu$ final states

$$\begin{aligned}
\langle D|\,\bar c\gamma^\mu b\,|\overline{B}\rangle &= f_+(q^2)(p_B+p_D)^\mu + \Big[f_0(q^2)-f_+(q^2)\Big]\frac{m_B^2-m_D^2}{q^2}\,q^\mu \\
\langle D^*|\,\bar c\gamma^\mu b\,|\overline{B}\rangle &= -ig(q^2)\,\epsilon^{\mu\nu\rho\sigma}\,\varepsilon^*_\nu\,(p_B+p_{D^*})_\rho\,q_\sigma \\
\langle D^*|\,\bar c\gamma^\mu\gamma^5 b\,|\overline{B}\rangle &= \varepsilon^{*\mu} f(q^2) + a_+(q^2)\,(\varepsilon^*\cdot p_B)\,(p_B+p_{D^*})^\mu + a_-(q^2)\,(\varepsilon^*\cdot p_B)\,q^\mu
\end{aligned}$$

  The a_- and $f_0 - f_+$, involving $q^\mu = p_B^\mu - p_{D^{(*)}}^\mu$, do not contribute for $m_l = 0$

- HQET: 1 Isgur-Wise function in $m_{c,b} \gg \Lambda_{\rm QCD}$ limit $+3$ more at $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$

- Constrain all 4 functions from $B \to D, D^*\, l\bar\nu\ \Rightarrow\ \mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2\,,\ \alpha_s^2)$ uncertainties

[Bernlochner, ZL, Papucci, Robinson, 1703.05330]

- Experimental inputs: $B \to Dl\bar\nu:\ {\rm d}\Gamma/{\rm d}w$ (Only Belle published fully corrected distributions)
  $B \to D^*l\bar\nu:\ {\rm d}\Gamma/{\rm d}w + R_{1,2}(w)$ form factor ratios

We considered 7 fit scenarios

- Our fits:

Fit	QCDSR	Lattice QCD $\mathcal{F}(1)$	Lattice QCD $f_{+,0}(1)$	Lattice QCD $f_{+,0}(w>1)$	Belle Data
$L_{w=1}$	—	+	+	—	+
$L_{w=1}$+SR	+	+	+	—	+
NoL	—	—	—	—	+
NoL+SR	+	—	—	—	+
$L_{w\geq 1}$	—	+	+	+	+
$L_{w\geq 1}$+SR	+	+	+	+	+
th:$L_{w\geq 1}$+SR	+	+	+	+	—

- Exp papers based on CLN: $R_{1,2}(w) = \underbrace{R_{1,2}(1)}_{\text{fit}} + \underbrace{R'_{1,2}(1)}_{\text{fixed}}(w-1) + \underbrace{R''_{1,2}(1)}_{\text{fixed}}(w-1)^2/2$

In HQET: $R_{1,2}(1) = 1 + \mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b}\,,\alpha_s)$ $\qquad R^{(n)}_{1,2}(1) = 0 + \mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b}\,,\alpha_s)$

$\Lambda_{\text{QCD}}/m_{c,b}$ terms depend on the same model dependent calculations

Sometimes calculations using QCD sum rule predictions for $\Lambda_{\text{QCD}}/m_{c,b}$ corrections are called the HQET predictions

Our SM predictions for $R(D)$ and $R(D^*)$

- Small variations: heavy quark symmetry & phase space leave little wiggle room

Scenario	$R(D)$	$R(D^*)$	Correlation
$L_{w=1}$	0.292 ± 0.005	0.255 ± 0.005	41%
$L_{w=1}$+SR	0.291 ± 0.005	0.255 ± 0.003	57%
NoL	0.273 ± 0.016	0.250 ± 0.006	49%
NoL+SR	0.295 ± 0.007	0.255 ± 0.004	43%
$L_{w\geq1}$	$\mathbf{0.298 \pm 0.003}$	$\mathbf{0.261 \pm 0.004}$	19%
$L_{w\geq1}$+SR	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.257 \pm 0.003}$	44%
th:$L_{w\geq1}$+SR	0.306 ± 0.005	0.256 ± 0.004	33%
Data [HFAG]	0.403 ± 0.047	0.310 ± 0.017	-23%
Fajfer et al. '12	—	$\mathbf{0.252 \pm 0.003}$	—
Lattice [FLAG]	0.300 ± 0.008	—	—
Bigi, Gambino '16	0.299 ± 0.003	—	—
Bigi, Gambino, Schacht '17	—	0.260 ± 0.008	—

- Our prediction for $R(D^*)$ higher than Fajfer et al., shown by HFAG (+ correlations)

Inclusive / exclusive $|V_{cb}|$ resolved?

- Two other fits (few days later), only to the Belle $B \to D^* l \bar{\nu}$ data:

  Bigi, Gambino, Schacht, 1703.06124, $|V_{cb}|_{\rm BGL} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$

  Grinstein & Kobach, 1703.08170, $|V_{cb}|_{\rm BGL} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$

  Belle, 1702.01521, $|V_{cb}|_{\rm CLN} = (38.2 \pm 1.5) \times 10^{-3}$

- Claim (more-or-less) that tension between inclusive / exclusive $|V_{cb}|$ is resolved

- Fitting the same data: if correlation near 100%, huge inconsistency!

- PDG 2016: The values obtained from inclusive and exclusive determinations are only marginally consistent with each other:

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \quad \text{(inclusive)} \qquad (1)$$

$$|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3} \quad \text{(exclusive)}; \qquad (2)$$

- $|V_{cb}|$ important for interpreting ϵ_K, $K \to \pi \nu \bar{\nu}$, $B_s \to \mu^+ \mu^-$, etc.

Fits and correlations

- Besides BGL, CLN, we consider 2 more theory frameworks to explore differences

form factors	BGL	CLN	CLNnoR	noHQS
axial $\propto \epsilon_\mu^*$	$b_0,\ b_1$	$h_{A_1}(1),\ \rho^2_{D*}$	$h_{A_1}(1),\ \rho^2_{D*}$	$h_{A_1}(1),\ \rho^2_{D*},\ c_{D*}$
vector	$a_0,\ a_1$	$R_1(1),\ R_2(1)$ (vector and $\mathcal{F}$)	$R_1(1),\ R_1'(1)$	$R_1(1),\ R_1'(1)$
$\mathcal{F}$	$c_1,\ c_2$		$R_2(1),\ R_2'(1)$	$R_2(1),\ R_2'(1)$

CLN $\simeq$ BGL $+$ heavy quark symmetry $+$ QCD sum rules for $\Lambda_{\rm QCD}/m_{c,b}$ terms

- Correlations: determined from replicas of unfolded distributions, using published covariance

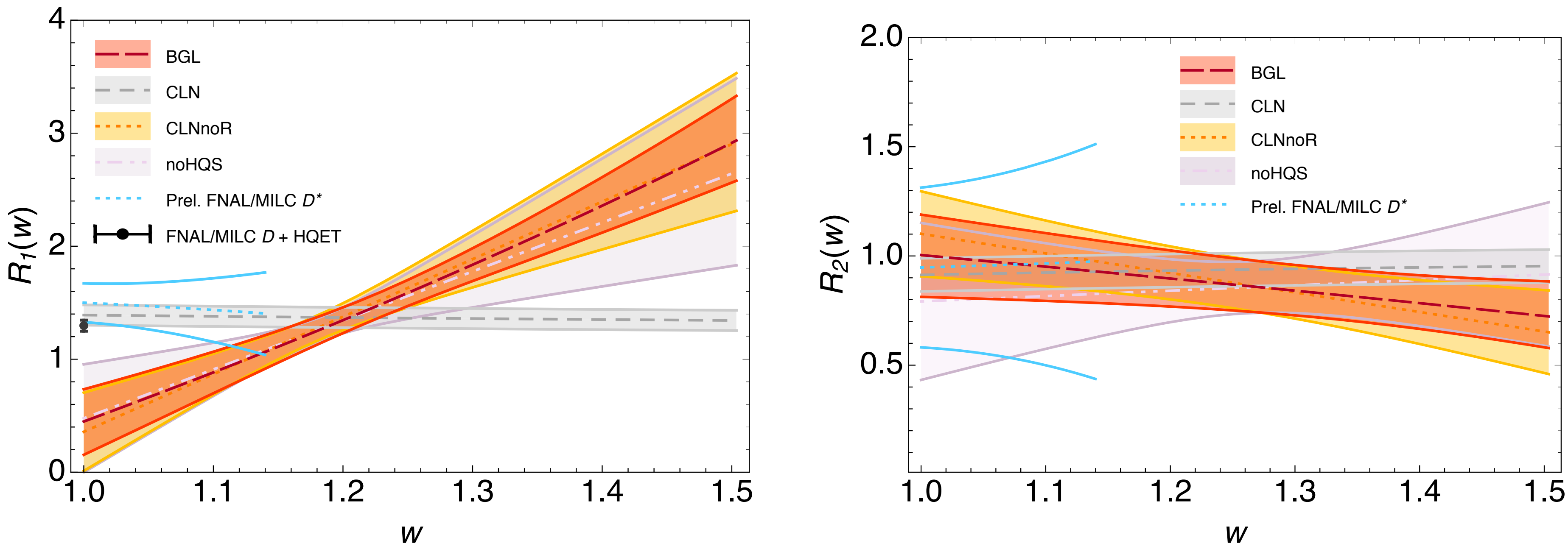
	$\lvert V_{cb}\rvert_{\rm CLN}$	$\lvert V_{cb}\rvert_{\rm CLNnoR}$	$\lvert V_{cb}\rvert_{\rm noHQS}$	$\lvert V_{cb}\rvert_{\rm BGL}$
$\lvert V_{cb}\rvert_{\rm CLN}$	1.	0.75	0.69	0.76
$\lvert V_{cb}\rvert_{\rm CLNnoR}$		1.	0.95	0.97
$\lvert V_{cb}\rvert_{\rm noHQS}$			1.	0.97
$\lvert V_{cb}\rvert_{\rm BGL}$				1.

- Values well below 1 in first row reduce the tension between the fits below 3σ

[$\sigma^2 = \sigma_1^2 + \sigma_2^2 - 2$(corr)$\sigma_1\sigma_2$]

Open questions remain...

- Larger values of $|V_{cb}| \longleftrightarrow R_1$ far from heavy quark symmetry



This would be a spectacular breakdown of heavy quark symmetry

Tension w/ prelim. lattice QCD results for R_1 — same calculation determines $F(1)$

- If you don't trust lattice $R_1 \Rightarrow$ cannot trust lattice $F(1)$ and $|V_{cb}|$
- If any issues with the data $\Rightarrow$ cannot trust $|V_{cb}|$

Conclusions

- Measurable NP contribution to $b \to c\ell\bar\nu$ would imply NP at a fairly low scale
- Better understanding of $B \to D^{**}\ell\bar\nu$ are important for $R(D^{(*)})$, $|V_{cb}|$, $|V_{ub}|$
- Model independent framework; systematically improved w/ more $B \to D^{**}l\bar\nu$ data
- The $\Lambda_{\rm QCD}/m_{c,b}$ terms are crucial — at higher orders, power counting should work
- Measurements will improve a lot; competition of LHCb & Belle II will be crucial

  (Even if central values change, plenty of room for significant deviations from SM)
- We shall find out: more data $+$ improved theory

Extra slides

On theory uncertainties

- No clearly right way how to assign theory uncertainties (maybe except LQCD stat.)
- [strong interaction] model independent

  $\equiv$ theor. uncertainty suppressed by small parameters

  ... so theorists argue about $\mathcal{O}(1)\times$(small numbers) instead of $\mathcal{O}(1)$ effects

  Well defined starting point is crucial to claim a deviation from SM
- Most progress have come from expanding in $\Lambda_{\rm QCD}/m_Q$ and $\alpha_s(m_Q)$
  - Estimating higher orders in α_s by scale variation is not fail-safe
  - Can get unlucky (e.g., in some cases $\Lambda_{\rm QCD}/m_c$ expansion might not work well)

  Need experimental guidance: $f_\pi \sim 140\,{\rm MeV}$, $m_\rho \sim 770\,{\rm MeV}$, $m_K^2/m_s \sim 2\,{\rm GeV}$
- Consequently: pdf interpretation of theory uncertainties are fraught with peril