

$B \rightarrow D^{**} \ell \bar{\nu}$: signals & backgrounds


Zoltan Ligeti

(ligeti@berkeley.edu)

Lawrence Berkeley Lab

Implications of LHCb measurements and future prospects
CERN, Nov 8–10, 2017

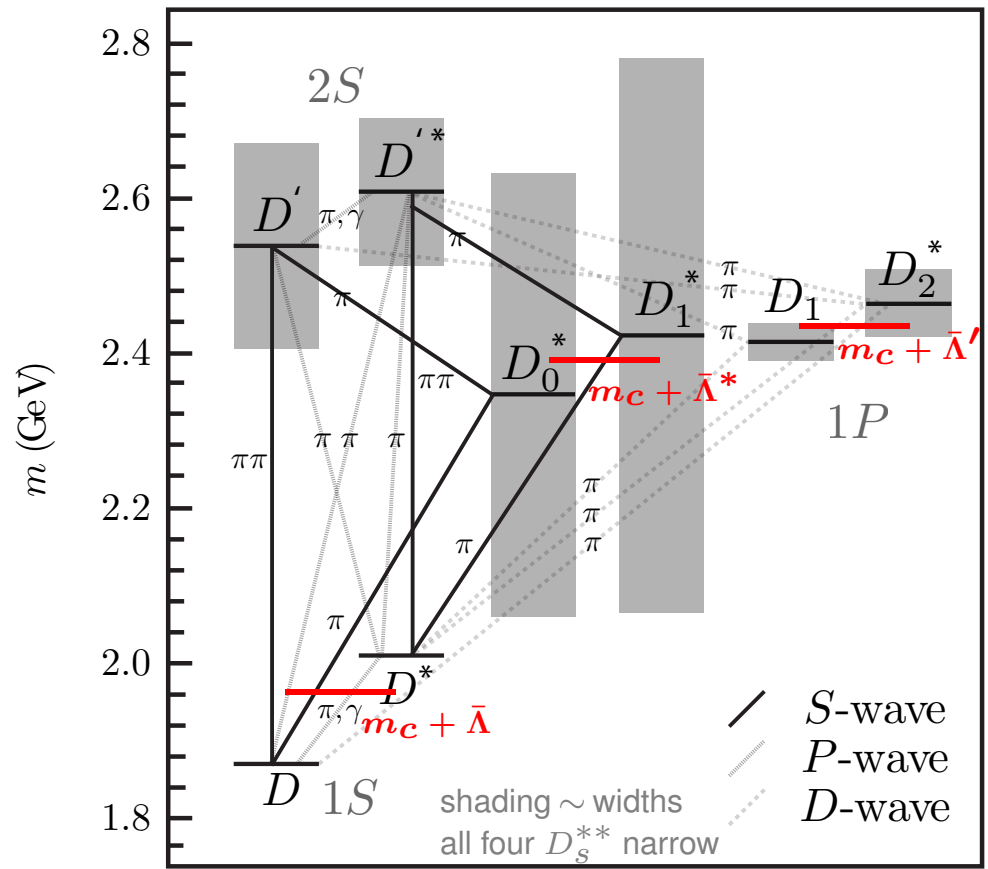
Outline / main points

- $B \rightarrow D^{**} \ell \bar{\nu}$: SM and $R(D^{**})$ [Bernlochner, ZL, 1606.09300]
 - $B \rightarrow D^{**} \ell \bar{\nu}$: arbitrary NP, importance of $\Lambda_{\text{QCD}}/m_{c,b}$ [Bernlochner, ZL, Robinson, arXiv:submit/2063791]
 - Developing Hammer  [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 $l = e, \mu$

“When you think you can finally forget a topic, it’s just about to become important”

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



Why bother...?

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

In $B_s \rightarrow D_s^{**} \ell \bar{\nu}$ 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 $f_{\text{eff}}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\text{eff}}^{D^{*0}}$	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_{wc}	0.0	0.0	0.84
M_{miss}^2 shape	0.6	1.0	0.00
o'_{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 $B \rightarrow D^{(*,**)} \ell \bar{\nu}$ rates: [$\varepsilon^n \sim (\Lambda_{\text{QCD}}/m_Q)^n$]

$$\frac{d\Gamma_{D^*}}{dw} \sim \sqrt{w^2 - 1} \left[(1 + \mathcal{O}_{(\text{Luke})} \varepsilon + \varepsilon^2 + \dots) + (w - 1) (1 + \varepsilon + \dots) + \dots \right]$$

$$\frac{d\Gamma_{D, D_0^*}}{dw} \sim (w^2 - 1)^{3/2} \text{ in the SM and for } m_\ell = 0$$

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

$$\frac{d\Gamma_{D_1, D_1^*}}{dw} \sim \sqrt{w^2 - 1} \left[(0 + 0 \varepsilon + \varepsilon^2 + \dots) + (w - 1) (1 + \varepsilon + \dots) + \dots \right]$$

$$\frac{d\Gamma_{D_2^*}}{dw} \sim (w^2 - 1)^{3/2} \text{ for all terms } \Rightarrow \text{no constraints}$$

- For $B \rightarrow D^{**} \ell \bar{\nu}$, the $\mathcal{O}(\Lambda_{\text{QCD}}/m_Q)$ corrections can be very important, due to suppression at $w = 1$ in heavy quark limit
- $(w - 1)^0 \varepsilon^2$ terms are 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 $\mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b})$ 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: $1 \leq w \lesssim 1.3$ and in the τ case $1 \leq w \lesssim 1.2$

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

For example:

$$\frac{\langle D_1(v', \epsilon) | V^{\mu} | B(v) \rangle}{\sqrt{m_{D_1} m_B}} = f_{V_1} \epsilon^{*\mu} + (f_{V_2} v^{\mu} + f_{V_3} v'^{\mu}) (\epsilon^* \cdot v)$$

$$\sqrt{6} f_{V_1}(w) = (1 - w^2) \tau(w) - 4 \frac{\bar{\Lambda}' - \bar{\Lambda}}{m_c} \tau(w) + \mathcal{O}\left(\frac{w - 1}{m_{c,b}}\right) + \dots$$

- These “known” $\mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b})$ terms are numerically comparable to leading order
- SM and $m_{\ell} \neq 0$ [Bernlochner, ZL, 1606.09300]
fully generally [Bernlochner, ZL, Robinson, arXiv:submit/2063791]

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^+	2330	270
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

- **The $B \rightarrow D_0^* \pi$ rate is very puzzling**

Only use small fraction of BaBar & Belle data

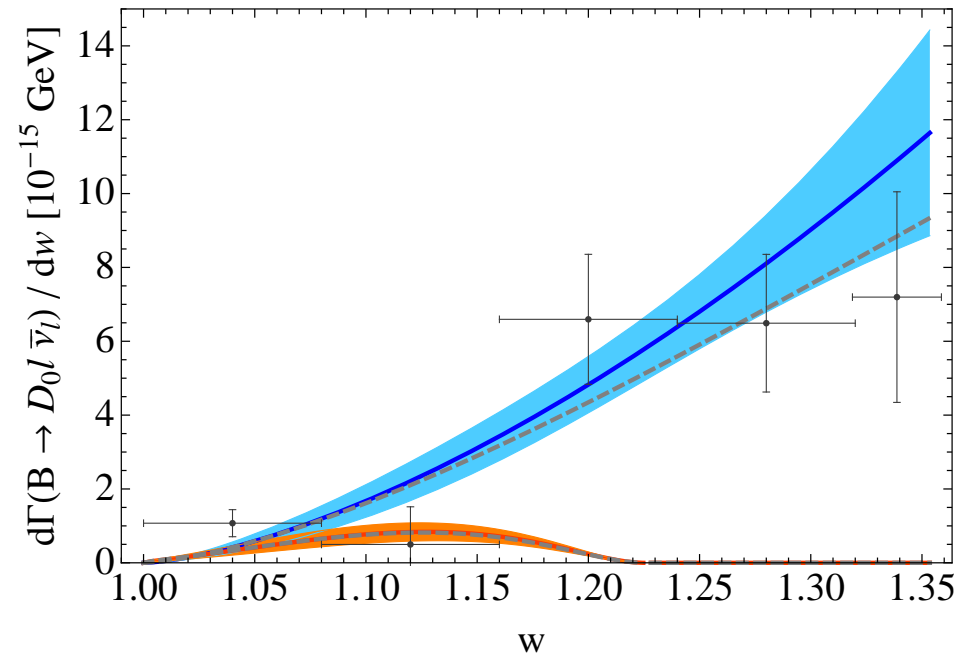
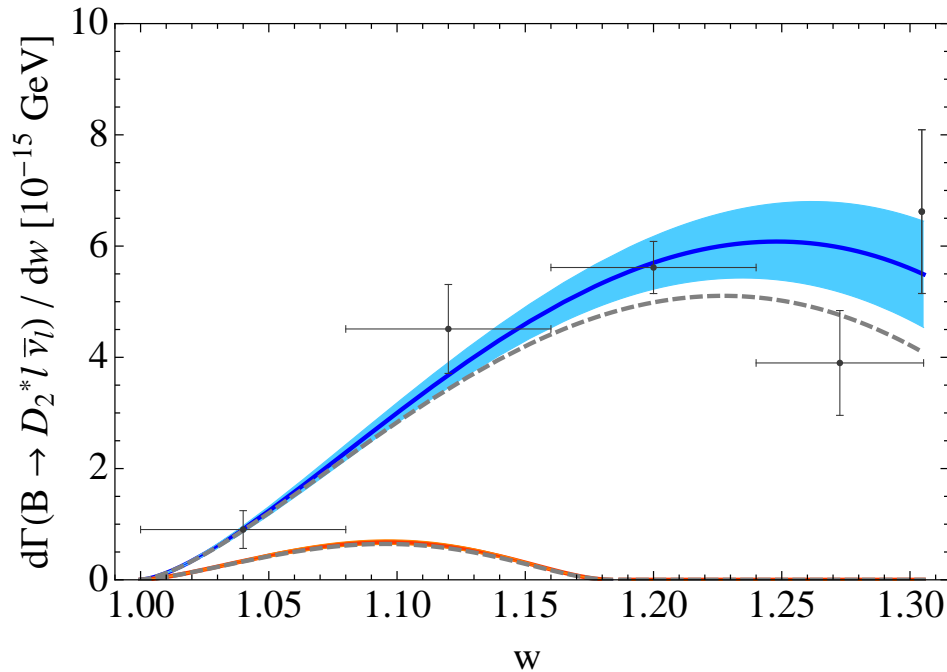
Decay mode	Branching fraction
$B^0 \rightarrow D_2^{*-} \pi^+$	$(0.59 \pm 0.13) \times 10^{-3}$
$B^0 \rightarrow D_1^- \pi^+$	$(0.75 \pm 0.16) \times 10^{-3}$
$B^0 \rightarrow D_0^{*-} \pi^+$	$(0.09 \pm 0.05) \times 10^{-3}$

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

If D_{s0}^* is excited $c\bar{s}$ state, predict $\mathcal{B}(D_{s0}^* \rightarrow D_s^* \gamma) / \mathcal{B}(D_{s0}^* \rightarrow D_s \pi)$ 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/fb, the BaBar bound < 0.16 used 232/fb

Turning the crank: spectra



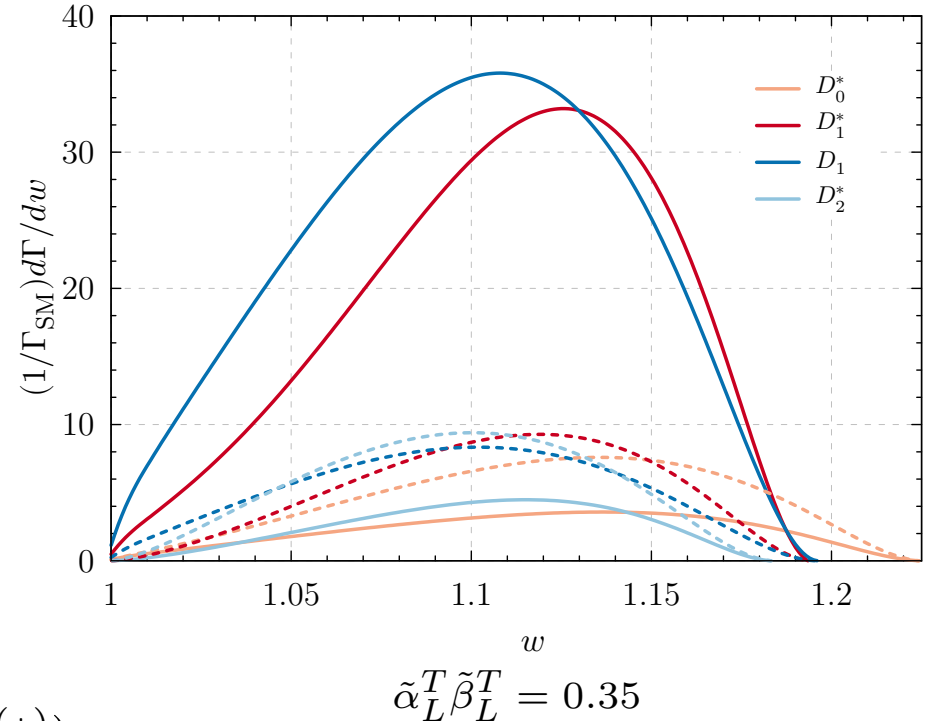
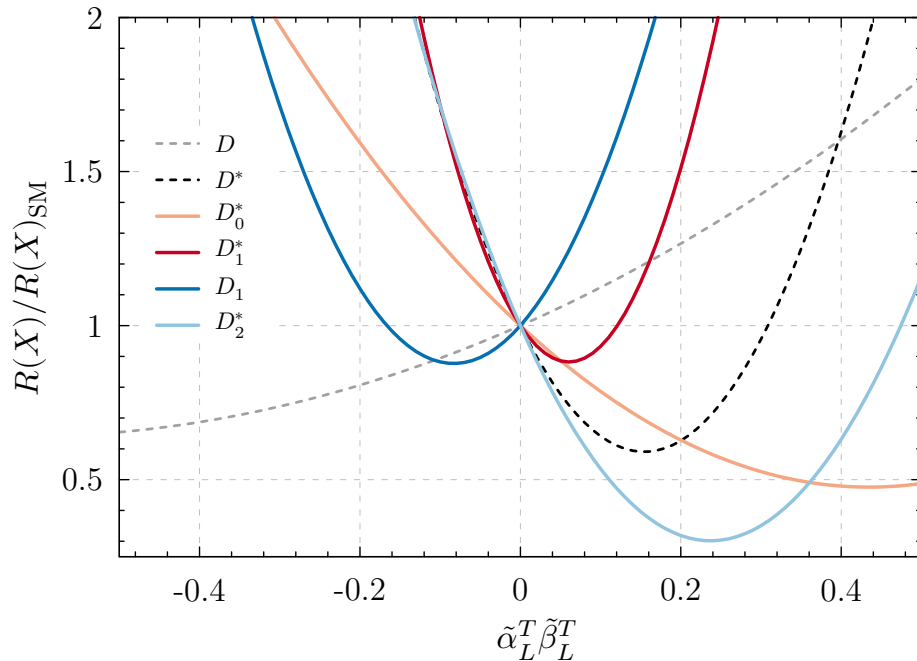
Rates for e, μ vs. τ [Belle, 0711.3252; fit Bernlochner, ZL, 1606.09300]

- Large deviation (as expected) from heavy quark limit: $\Gamma(B \rightarrow D_2^* l \nu) / \Gamma(B \rightarrow D_1 l \nu)$
- Study all uncertainties, including effects neglected in LLSW
- As in $B \rightarrow D^{(*)} l \bar{\nu}$, 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:submit/2063791]



The patterns are quite different from $R(D^{(*)})$

- Large variation of predictions — explore influence of all possible BSM operators
- $B_s \rightarrow D_s^{**}$: same formalism, $SU(3)$ relations, info on NP & QCD structure of D_s^{**}

The Hammer tool



Helicity Amplitude Module for Matrix Element Reweighting

[Bernlochner, Duell, ZL, Papucci, Robinson] — See Dean's talk at LAL next Tuesday



- Fully differential distributions of detected particles, incl. D & τ decay interference
Include arbitrary NP interaction and $m_\ell \neq 0$, for all 6 decays: $B \rightarrow \{D, D^*, D^{**}\} \ell \bar{\nu}$
 - 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 — will be publicly available

$$B \rightarrow D^{(*)} \tau \bar{\nu} \text{ and } |V_{cb}|$$

B → D^(*)ℓν̄ and HQET

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

$$\langle D | \bar{c} \gamma^\mu b | \bar{B} \rangle = f_+(q^2) (p_B + p_D)^\mu + [f_0(q^2) - f_+(q^2)] \frac{m_B^2 - m_D^2}{q^2} q^\mu$$

$$\langle D^* | \bar{c} \gamma^\mu b | \bar{B} \rangle = -ig(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\nu^* (p_B + p_{D^*})_\rho q_\sigma$$

$$\langle D^* | \bar{c} \gamma^\mu \gamma^5 b | \bar{B} \rangle = \epsilon^{*\mu} f(q^2) + a_+(q^2) (\epsilon^* \cdot p_B) (p_B + p_{D^*})^\mu + a_-(q^2) (\epsilon^* \cdot p_B) q^\mu$$

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 $m_{c,b} \gg \Lambda_{\text{QCD}}$ limit + 3 more at $\mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b})$

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

[Bernlochner, ZL, Papucci, Robinson, 1703.05330]

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

We considered 7 fit scenarios

- Our fits:

Fit	QCDSR	Lattice QCD			Belle Data
		$\mathcal{F}(1)$	$f_{+,0}(1)$	$f_{+,0}(w > 1)$	
$L_{w=1}$	—	+	+	—	+
$L_{w=1}+SR$	+	+	+	—	+
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: $R_{1,2}(1) = 1 + \mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b}, \alpha_s)$ $R_{1,2}^{(n)}(1) = 0 + \mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b}, \alpha_s)$

$\Lambda_{\text{QCD}}/m_{c,b}$ 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%
$L_{w=1} + \text{SR}$	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%
$L_{w \geq 1}$	0.298 ± 0.003	0.261 ± 0.004	19%
$L_{w \geq 1} + \text{SR}$	0.299 ± 0.003	0.257 ± 0.003	44%
th: $L_{w \geq 1} + \text{SR}$	0.306 ± 0.005	0.256 ± 0.004	33%
Data [HFAG]	0.403 ± 0.047	0.310 ± 0.017	-23%
Fajfer et al. '12	—	0.252 ± 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 $B \rightarrow D^* l \bar{\nu}$ data:

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

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

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

- 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:

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

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

- $|V_{cb}|$ important for interpreting ϵ_K , $K \rightarrow \pi \nu \bar{\nu}$, $B_s \rightarrow \mu^+ \mu^-$, 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	$h_{A_1}(1), \rho_{D^*}^2$	$h_{A_1}(1), \rho_{D^*}^2$	$h_{A_1}(1), \rho_{D^*}^2, c_{D^*}$
vector \mathcal{F}	a_0, a_1 c_1, c_2	$\left\{ R_1(1), R_2(1) \right\}$	$\left\{ R_1(1), R'_1(1) \right\}$ $\left\{ R_2(1), R'_2(1) \right\}$	$\left\{ R_1(1), R'_1(1) \right\}$ $\left\{ R_2(1), R'_2(1) \right\}$

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

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

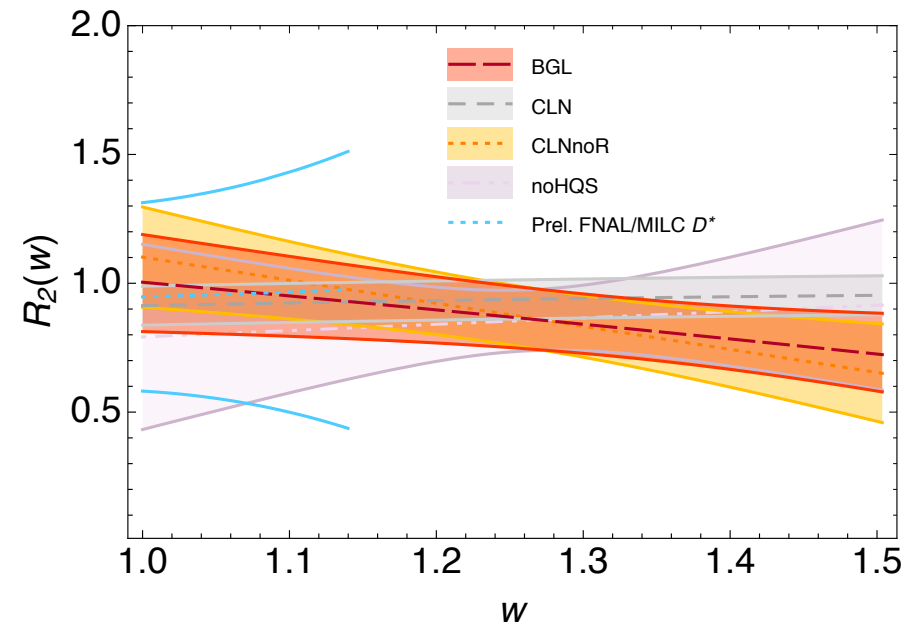
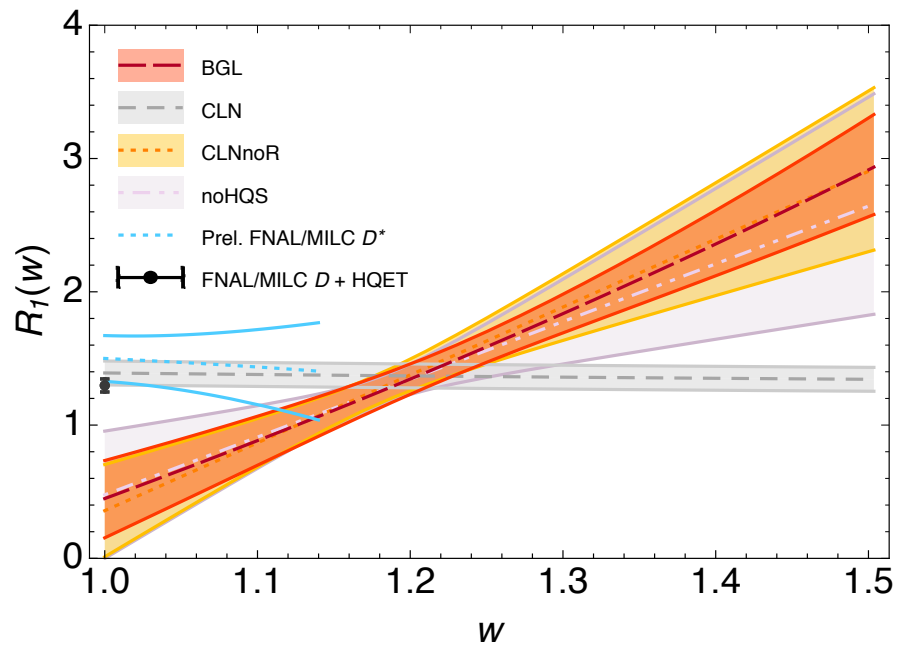
	$ V_{cb} _{\text{CLN}}$	$ V_{cb} _{\text{CLNnoR}}$	$ V_{cb} _{\text{noHQS}}$	$ V_{cb} _{\text{BGL}}$
$ V_{cb} _{\text{CLN}}$	1.	0.75	0.69	0.76
$ V_{cb} _{\text{CLNnoR}}$		1.	0.95	0.97
$ V_{cb} _{\text{noHQS}}$			1.	0.97
$ V_{cb} _{\text{BGL}}$				1.

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

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

Tensions 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 issues with lattice \Rightarrow cannot trust $|V_{cb}|$
- If issues with data \Rightarrow cannot trust $|V_{cb}|$

Conclusions

- Measurable NP contribution to $b \rightarrow c\ell\bar{\nu}$ would imply NP at a fairly low scale
- Better understanding of $B \rightarrow D^{**}\ell\bar{\nu}$ are important for $R(D^{(*)})$, $|V_{cb}|$, $|V_{ub}|$
- Model independent framework; systematically improved w/ more $B \rightarrow D^{**}\ell\bar{\nu}$ data
- The $\Lambda_{\text{QCD}}/m_{c,b}$ terms are crucial — beyond those, 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

Preliminaries

- [strong interaction] model independent
≡ theor. uncertainty suppressed by small parameters
... so theorists argue about $\mathcal{O}(1) \times (\text{small numbers})$ instead of $\mathcal{O}(1)$ effects
- Most progress have come from expanding in Λ_{QCD}/m_Q and $\alpha_s(m_Q)$

Can get unlucky (e.g., in some cases expansion in Λ_{QCD}/m_c might not work well), but well defined starting point is crucial to claim a deviation from SM

Need experimental guidance: $f_\pi \sim 140 \text{ MeV}$, $m_\rho \sim 770 \text{ MeV}$, $m_K^2/m_s \sim 2 \text{ GeV}$

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

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

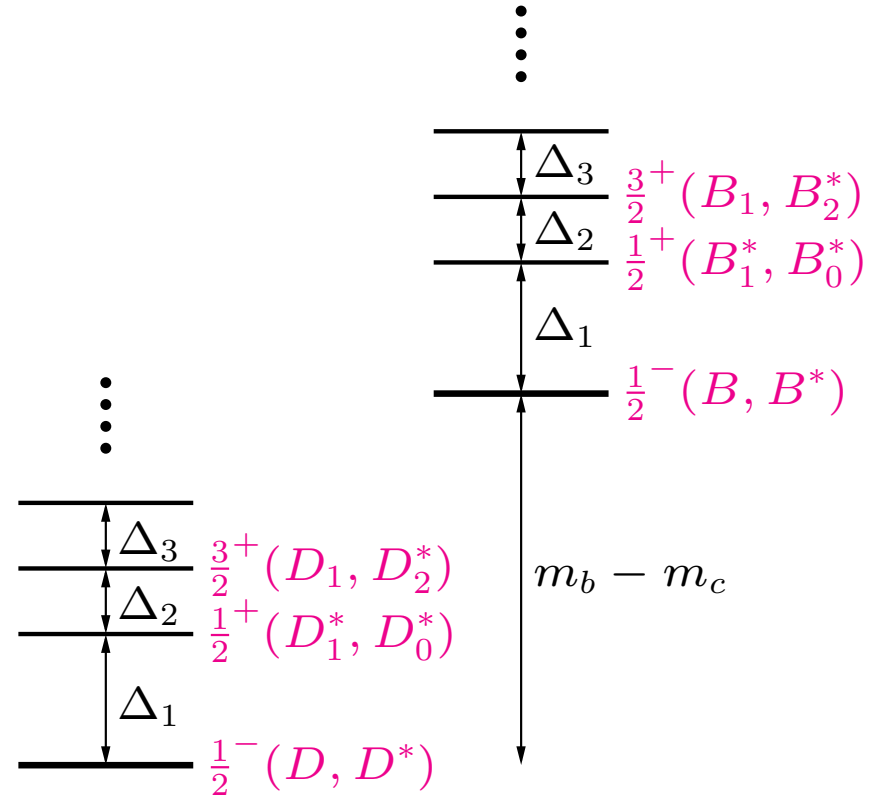
- For a given s_l , two degenerate states:

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

$\Rightarrow \Delta_i = \mathcal{O}(\Lambda_{\text{QCD}})$ — 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 $\sim m_c/m_b$



Lepton universality vs. lepton flavor violation

- Data sets will increase by nearly two orders of magnitude
- **Connection to LFV:** “any departure from lepton universality is necessarily associated with the violation of lepton flavor conservation. No known symmetry principle can protect the one in the absence of the other.” [Glashow, Guadagnoli, Lane, 1411.0565]
- Same issue as generic new physics altering FCNCs in the quark sector
- With a given leptoquark model and patterns of couplings, can make predictions:

$$\begin{aligned}
 \mathcal{B}(B \rightarrow K \mu^\pm e^\mp) &\simeq 3 \cdot 10^{-8} \kappa^2 \left(\frac{1 - R_K}{0.23} \right)^2, & \mathcal{B}(\mu \rightarrow e \gamma) &\simeq 2 \cdot 10^{-12} \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2, \\
 \mathcal{B}(B \rightarrow K e^\pm \tau^\mp) &\simeq 2 \cdot 10^{-8} \kappa^2 \left(\frac{1 - R_K}{0.23} \right)^2, & \mathcal{B}(\tau \rightarrow e \gamma) &\simeq 4 \cdot 10^{-14} \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2, \\
 \mathcal{B}(B \rightarrow K \mu^\pm \tau^\mp) &\simeq 2 \cdot 10^{-8} \left(\frac{1 - R_K}{0.23} \right)^2, & \mathcal{B}(\tau \rightarrow \mu \gamma) &\simeq 3 \cdot 10^{-14} \frac{1}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2,
 \end{aligned}$$

[de Medeiros Varzielas, Hiller, 1503.01084]