Fun with Λ_b, V_{cb}, and `Hammer`

Zoltan Ligeti

New Physics on the Low-Energy Precision Frontier

CERN, Jan. 20 – Feb. 7, 2020

February 4, 2020

- Introduction
- HQET predictions for $\Lambda_b \to \Lambda_c \ell \bar{\nu}$
- `Hammer`
- BGL fits to $B \to D^* \ell \bar{\nu}$ and $|V_{cb}|$
- Outlook

Details: Bernlochner, ZL, Robinson, Sutcliffe, 1808.09464 [PRL]; 1812.07593 [PRD]
Bernlochner, ZL, Robinson, 1902.09553 [PRD] $+$ works in progress
Bernlochner, Duell, ZL, Papucci, Robinson, arXiv:2002.00020

B Anomalies: Still HQETing

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Disclaimers.... starting with the title...

- Plagiarizing David Politzer, “Still QCDing” (1979 lectures)

Abstract: “ ... The exposition is purposefully informal, in the hope that anyone familiar with Feynman diagrams might profit from a single, casual reading. However, the text is sprinkled with sufficiently many outrageous claims, slanderous libels, and inadequate references that a serious student or even a practicing expert will find much upon which to chew.”

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- “Who ordered that?”

If you try it, you may like it...

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- "Who ordered that?"

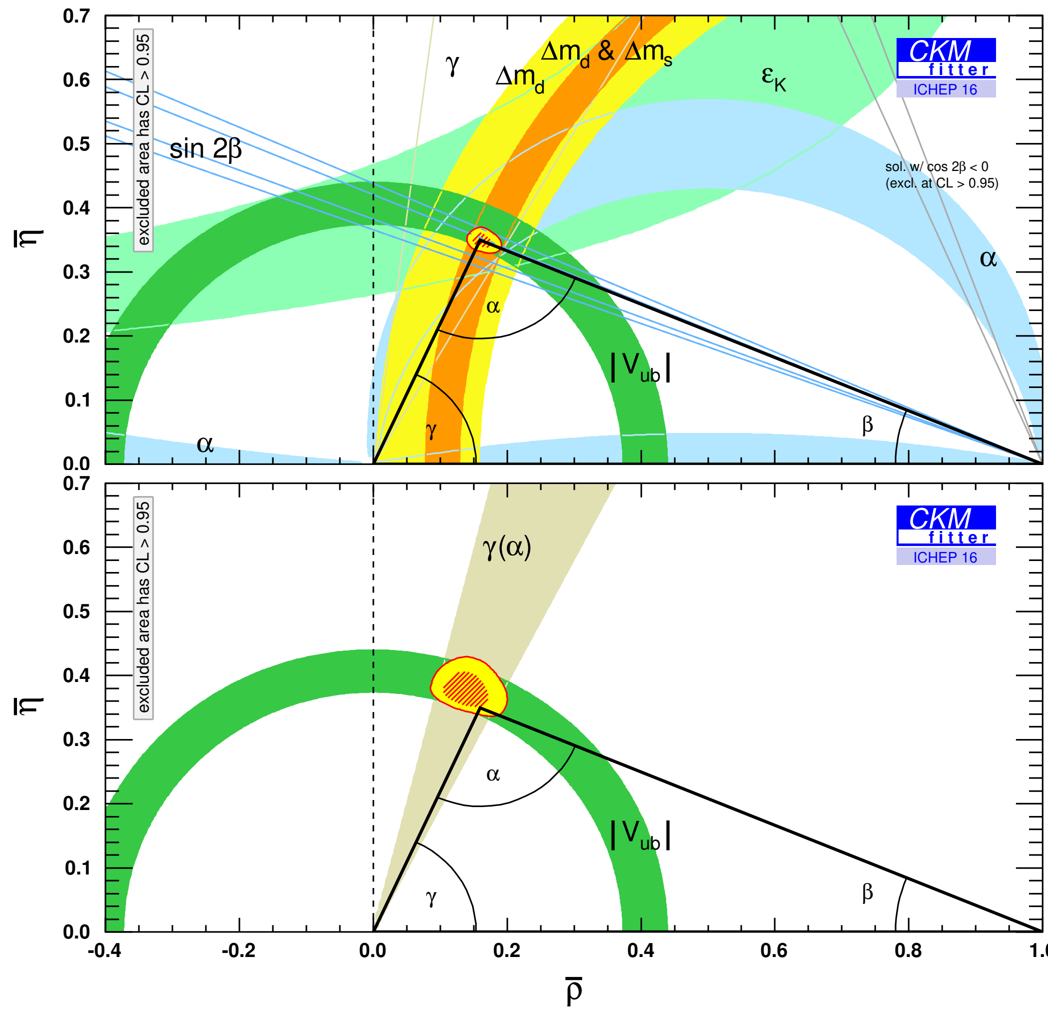
  If you try it, you may like it...

- Much of this could have been done in the 1990s... (no one would have cared)

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

CKM fit: plenty of room for new physics

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency are often overstated
- Much larger allowed region if the SM is not assumed
- Tree-level (mainly V_{ub} & γ) vs. loop-dominated measurements



- In loop (FCNC) processes NP / SM $\sim 20\%$ is still allowed (mixing, $B \to X\ell^+\ell^-$, $X\gamma$, etc.)

Many open questions about flavor

- Theoretical prejudices about new physics did not work as expected before LHC

  After Higgs discovery, no more guarantees, situation may resemble around 1900

  (Michelson 1894: “... it seems probable that most of the grand underlying principles have been firmly established ...”)

- Flavor structure and CP violation are major pending questions — baryogenesis

- Related to Yukawa couplings, scalar sector, maybe connected to hierarchy puzzle

  Know little about Higgs — responsible for (bulk of) heaviest fermion masses

- Sensitive to new physics at high scales, beyond LHC reach

  Establishing any of the flavor anomalies $\Rightarrow$ upper bound on NP scale

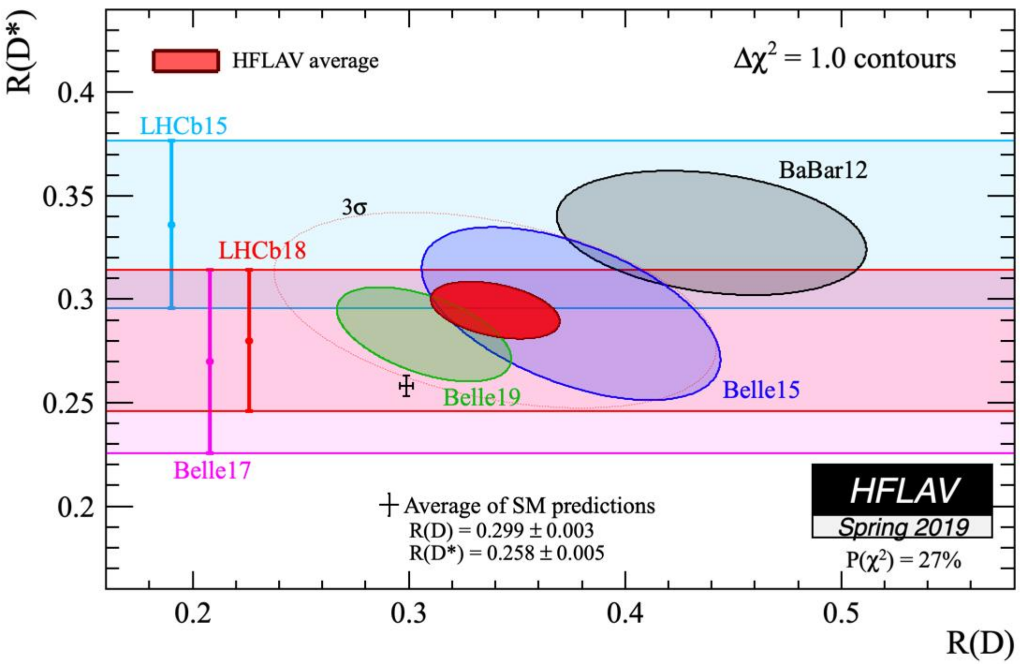
- Experiment: Huge improvements will occur (LHCb and Belle II)

- Theory: How small deviations from the SM can be unambiguously established?

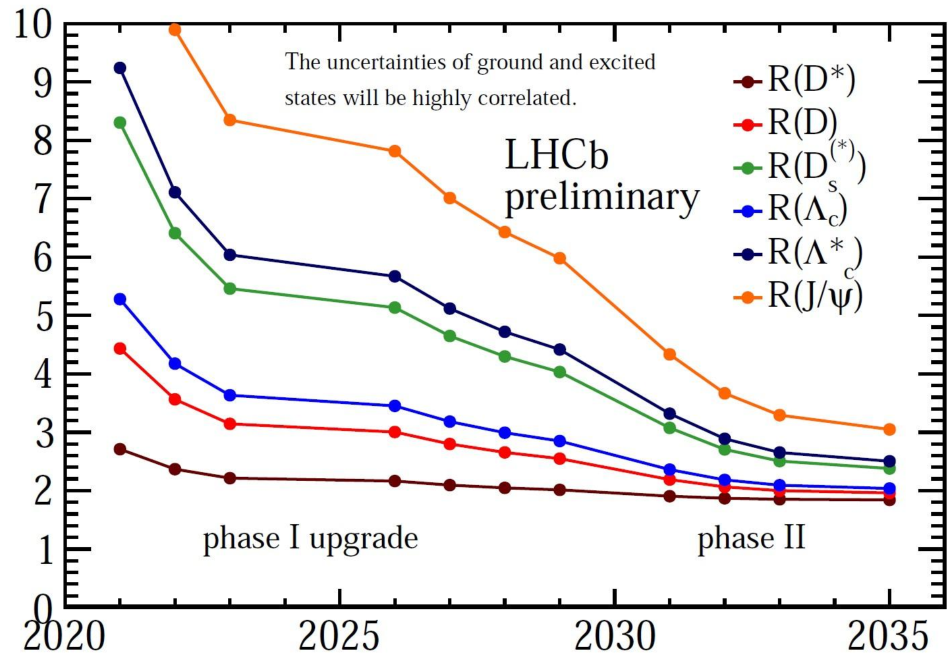
$R(D)$ and $R(D^*)$ — $3\,\sigma$ tension with SM

- BaBar, Belle, LHCb: enhanced τ rates, $R(D^{(*)}) = \dfrac{\Gamma(B \to D^{(*)}\tau\bar\nu)}{\Gamma(B \to D^{(*)}l\bar\nu)} \qquad (l = e, \mu)$

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



Future:



Belle II: $\delta R(D^{(*)}) \sim 2(3)\%$ (50/ab, in SM)

- Big improvements: even if central values change, plenty of room to establish NP

  $B \to D^{(*)}$ and $\Lambda_b \to \Lambda_c$ are expected to be the most precise; no $R(\Lambda_c)$ measurement yet

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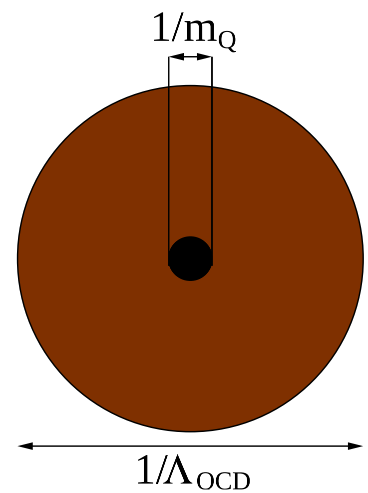
$$\Lambda_b \to \Lambda_c \ell \bar{\nu}$$

Heavy quark symmetry 101

- Model independent (QCD), used both in some continuum & LQCD methods
- $Q\overline{Q}$: positronium-type bound state, perturbative in the $m_Q \gg \Lambda_{\rm QCD}$ limit
- $Q\,\overline{q}$: wave function of the light degrees of freedom
  ("brown muck") insensitive to spin and flavor of Q

  (A B meson is a lot more complicated than just a $b\bar{q}$ pair)



In the $m_Q \gg \Lambda_{\rm QCD}$ limit, the heavy quark acts as a static color source with fixed four-velocity v^μ [Isgur & Wise]

$SU(2n)$ heavy quark spin-flavor symmetry at fixed v^μ [Georgi]

- Similar to atomic physics: $(m_e \ll m_N)$

1. Flavor symmetry $\sim$ isotopes have similar chemistry [Ψ_e independent of m_N]
2. Spin symmetry $\sim$ hyperfine levels almost degenerate [$\vec{s}_e - \vec{s}_N$ interaction $\to 0$]

Basics of $B \to D^{(*)}\ell\bar\nu$ or $\Lambda_b \to \Lambda_c\ell\bar\nu$

- In the $m_{b,c} \gg \Lambda_{\rm QCD}$ limit, configuration of brown muck only depends on the four-velocity of the heavy quark, but not on its mass and spin

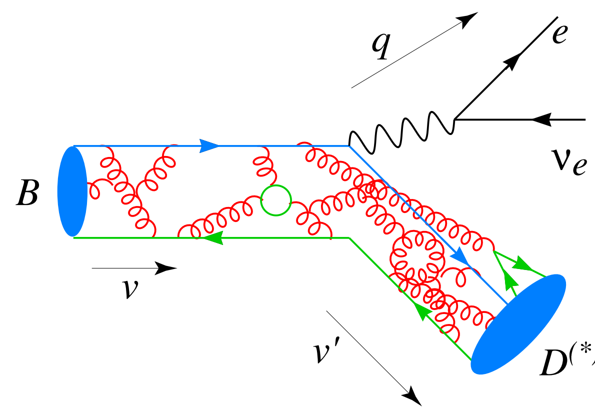
- On a time scale $\ll \Lambda_{\rm QCD}^{-1}$ weak current changes $b \to c$
  i.e.: $\vec p_b \to \vec p_c$ and possibly $\vec s_Q$ flips

  In $m_{b,c} \gg \Lambda_{\rm QCD}$ limit, only $v_b \to v_c$ affects brown muck

  Form factors independent of Dirac structure of weak current $\Rightarrow$ all form factors related to a single function of $w = v \cdot v'$, the Isgur-Wise function, $\xi(w)$

  $\Uparrow$

  Contains all nonperturbative low-energy hadronic physics



- $\xi(1) = 1$, because at "zero recoil" configuration of brown muck not changed at all

- Same holds for $\Lambda_b \to \Lambda_c\ell\bar\nu$, different Isgur-Wise fn, $\xi \to \zeta$ [also satisfies $\zeta(1) = 1$]

Ancient knowledge: baryons simpler than mesons

- Used to be well known — forgotten by experimentalists as well as theorists...

VOLUME 75, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 1995

Form Factor Ratio Measurement in $\Lambda_c^+ \to \Lambda e^+ \nu_e$

G. Crawford,[1] C. M. Daubenmier,[1] R. Fulton,[1] D. Fujino,[1] K. K. Gan,[1] K. Honscheid,[1] H. Kagan,[1] R. Kass,[1] J. Lee,[1]

[CLEO]

element $|V_{cs}|$ is known from unitarity [1]. Within heavy quark effective theory (HQET) [2], Λ-type baryons are more straightforward to treat than mesons as they consist of a heavy quark and a spin and isospin zero light diquark.

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Combine LHCb measurement of $\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c \mu \bar{\nu})/\mathrm{d}q^2$ shape [1709.01920] with LQCD results for (axial-)vector form factors [1503.01421]

[Bernlochner, ZL, Robinson, Sutcliffe, 1808.09464; 1812.07593]

Intro to $\Lambda_b \to \Lambda_c \ell \bar\nu$

- Ground state baryons are simpler than mesons: brown muck in (iso)spin-0 state
- SM: 6 form factors, functions of $w = v \cdot v' = (m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2)/(2m_{\Lambda_b} m_{\Lambda_c})$

$$\langle \Lambda_c(p', s') | \bar c \gamma_\nu b | \Lambda_b(p, s)\rangle = \bar u_c(v', s') \Big[f_1 \gamma_\mu + f_2 v_\mu + f_3 v'_\mu \Big] u_b(v, s)$$

$$\langle \Lambda_c(p', s') | \bar c \gamma_\nu \gamma_5 b | \Lambda_b(p, s)\rangle = \bar u_c(v', s') \Big[g_1 \gamma_\mu + g_2 v_\mu + g_3 v'_\mu \Big] \gamma_5\, u_b(v, s)$$

Heavy quark limit: $f_1 = g_1 = \zeta(w)$ Isgur-Wise fn, and $f_{2,3} = g_{2,3} = 0$ $\quad [\zeta(1) = 1]$

- Include α_s , $\varepsilon_{b,c}$, $\alpha_s \varepsilon_{b,c}$, ε_c^2 : $\quad m_{\Lambda_{b,c}} = m_{b,c} + \bar\Lambda_\Lambda + \dots , \quad \varepsilon_{b,c} = \bar\Lambda_\Lambda / (2m_{b,c})$

($\bar\Lambda_\Lambda \sim 0.8\,\mathrm{GeV}$ larger than $\bar\Lambda$ for mesons, enters via eq. of motion $\Rightarrow$ expect worse expansion?)

$$f_1 = \zeta(w) \bigg\{ 1 + \frac{\alpha_s}{\pi} C_{V_1} + \varepsilon_c + \varepsilon_b + \frac{\alpha_s}{\pi} \Big[C_{V_1} + 2(w-1) C'_{V_1} \Big] (\varepsilon_c + \varepsilon_b) + \frac{\hat b_1 - \hat b_2}{4m_c^2} + \dots \bigg\}$$

- No $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_{b,c})$ subleading Isgur-Wise function, only 2 at $\mathcal{O}(\Lambda_{\mathrm{QCD}}^2/m_c^2)$

[Falk & Neubert, hep-ph/9209269]

- HQET is more constraining in baryon than in meson decay!

$B \to D^{(*)} \ell \bar\nu$: 6 Isgur-Wise fn-s at $\mathcal{O}(1/m_c^2)$ [Can constrain w/ LCSR: Bordone, Jung, van Dyk, 1908.09398]

Fits and form factor definitions

- Standard HQET form factor definitions: $\{f_1,\, g_1\} = \zeta(w)\, \big[1 + \mathcal{O}(\alpha_s, \varepsilon_{c,b})\big]$
$\{f_{2,3},\, g_{2,3}\} = \zeta(w)\, \big[0 + \mathcal{O}(\alpha_s, \varepsilon_{c,b})\big]$

  Form factor basis in LQCD calculation: $\{f_{0,+,\perp},\, g_{0,+,\perp}\} = \zeta(w)\, \big[1 + \mathcal{O}(\alpha_s, \varepsilon_{c,b})\big]$

  LQCD results published as fits to 11 or 17 BCL parameters, including correlations

  All 6 form factors computed in LQCD $\sim$ Isgur-Wise fn $\Rightarrow$ despite good precision, limited constraints on subleading terms and their w dependence

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- Only 4 parameters (and m_b^{1S}): $\{\zeta',\, \zeta'',\, \hat{b}_1,\, \hat{b}_2\}$

  $\zeta(w) = 1 + (w-1)\,\zeta' + \frac{1}{2}(w-1)^2\,\zeta'' + \dots \qquad b_{1,2}(w) = \zeta(w)\,\big(\hat{b}_{1,2} + \dots\big)$

  (Expanding in $w-1$ or in conformal parameter, z, makes negligible difference)

- Current LHCb and LQCD data do not yet allow constraining ζ''' and/or $\hat{b}'_{1,2}$

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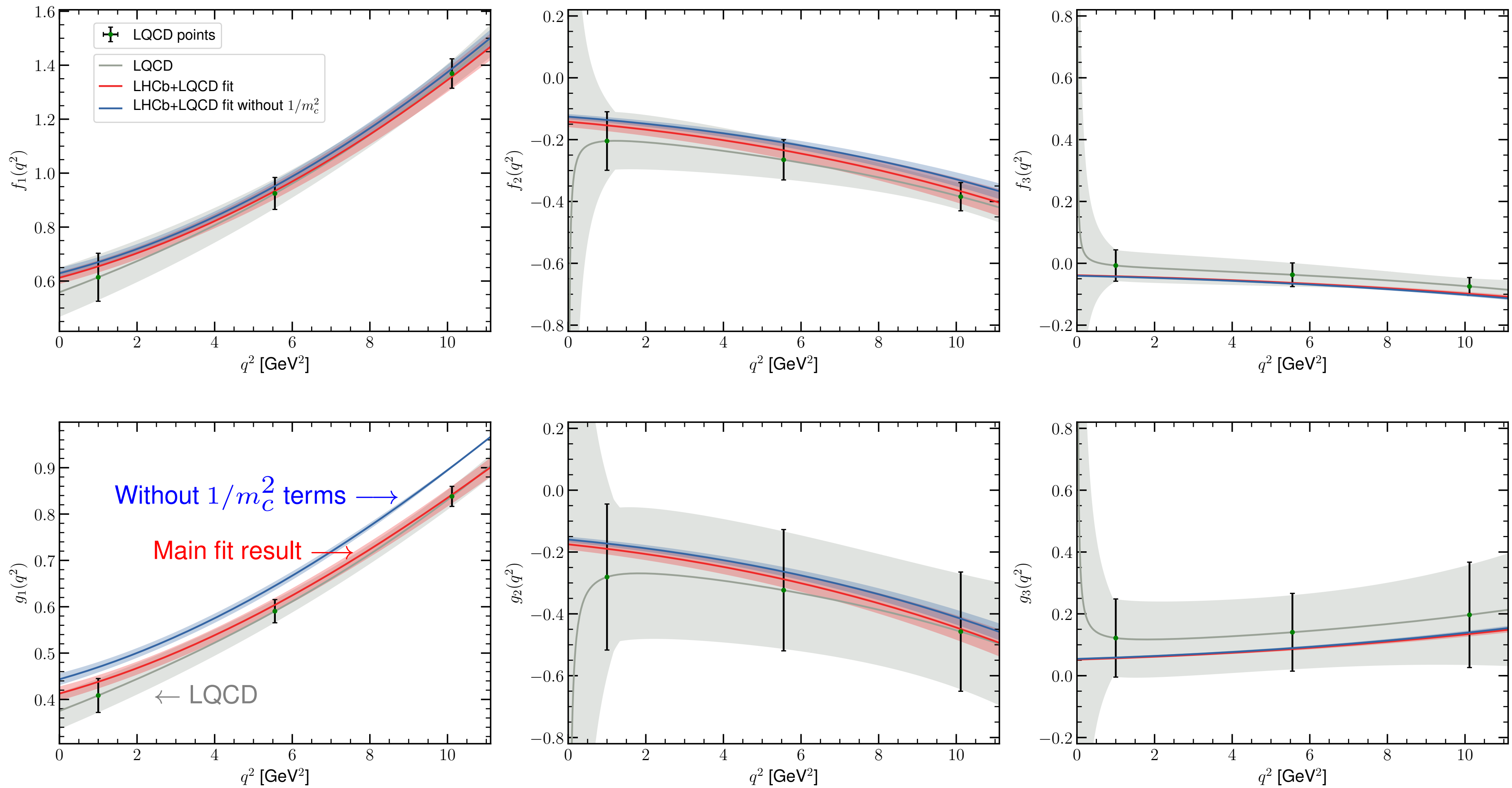
Fit to lattice QCD form factors and LHCb (1)

- Fit 6 form factors w/ 4 parameters: $\zeta'(1)$, $\zeta''(1)$, $\hat{b}_1$, $\hat{b}_2$ [LQCD: Detmold, Lehner, Meinel, 1503.01421]



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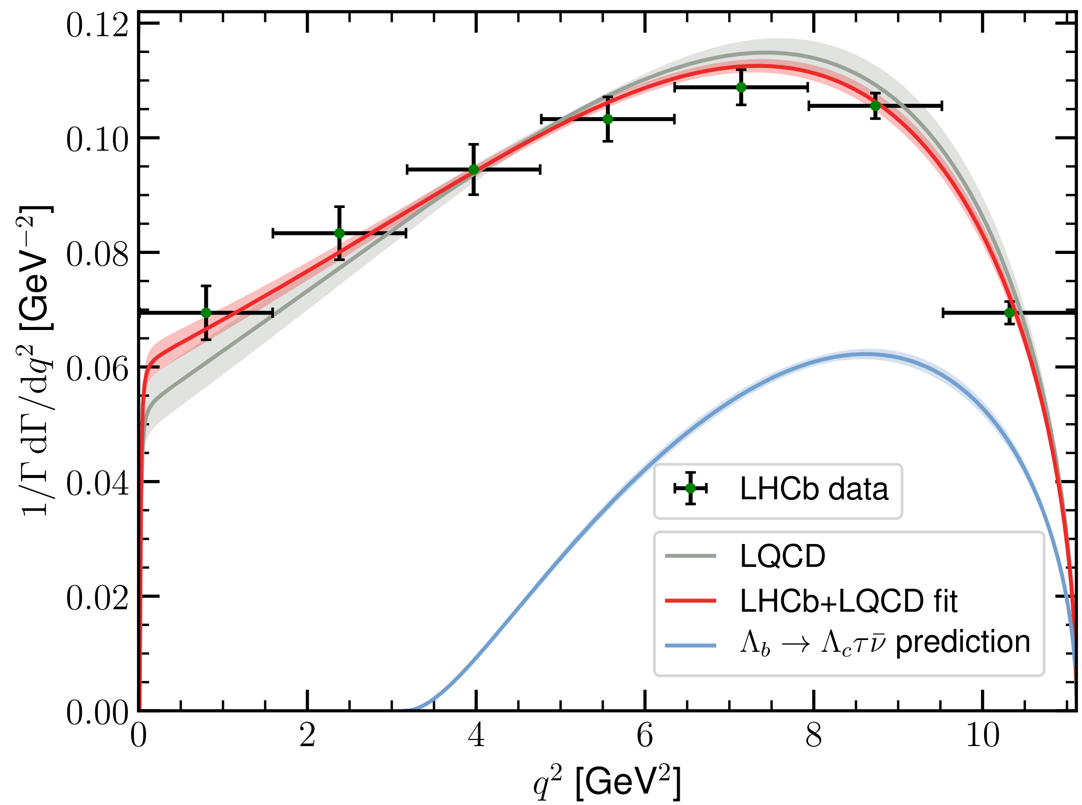
Fit to lattice QCD form factors and LHCb (2)

- Our fit, compared to the LQCD fit to LHCb:



- Obtain: $R(\Lambda_c) = 0.324 \pm 0.004$

  A factor of ~ 3 more precise than LQCD prediction — data constrains combinations of form factors relevant for predicting $R(\Lambda_c)$

The fit requires the $1/m_c^2$ terms

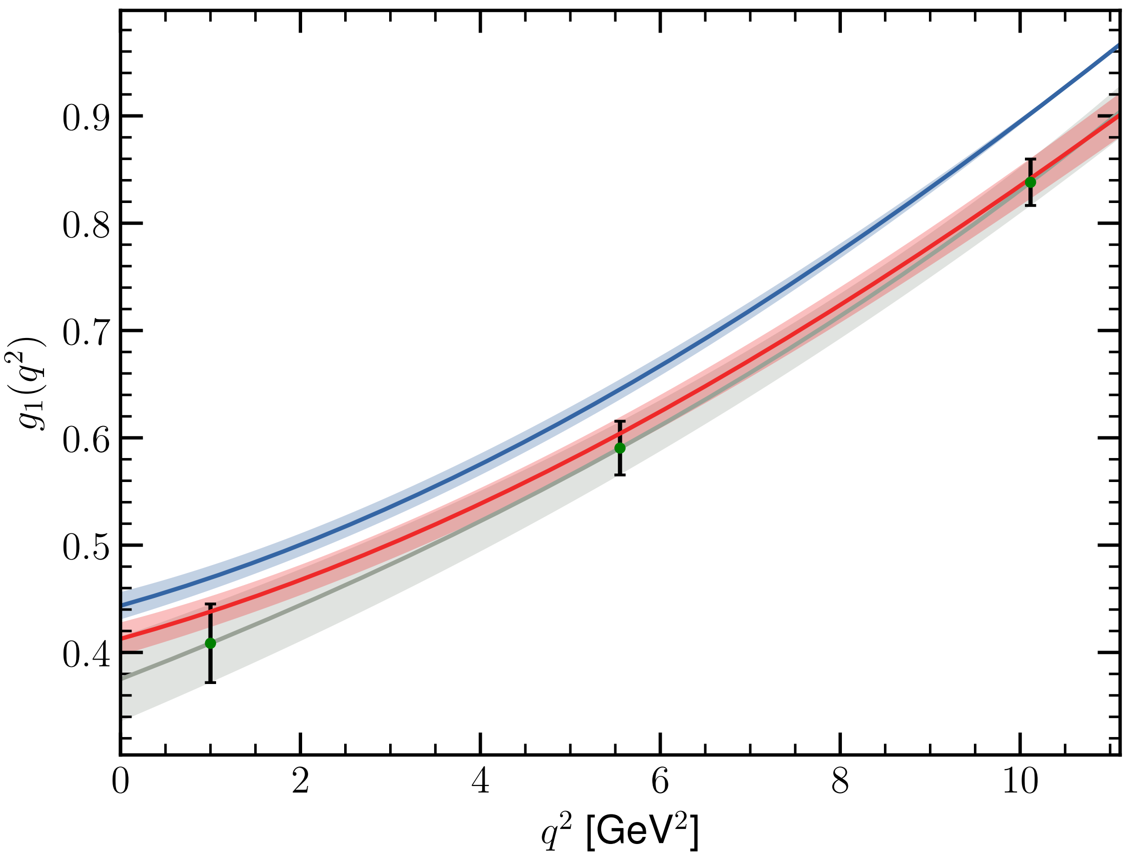
- E.g., fit results for g_1
  blue band shows fit with $\hat{b}_{1,2} = 0$

- Find: $\hat{b}_1 = -(0.46 \pm 0.15)\,\mathrm{GeV}^2$
  ... of the expected magnitude

  Well below the model-dependent estimate: $\hat{b}_1 = -3\bar{\Lambda}_\Lambda^2 \simeq -2\,\mathrm{GeV}^2$

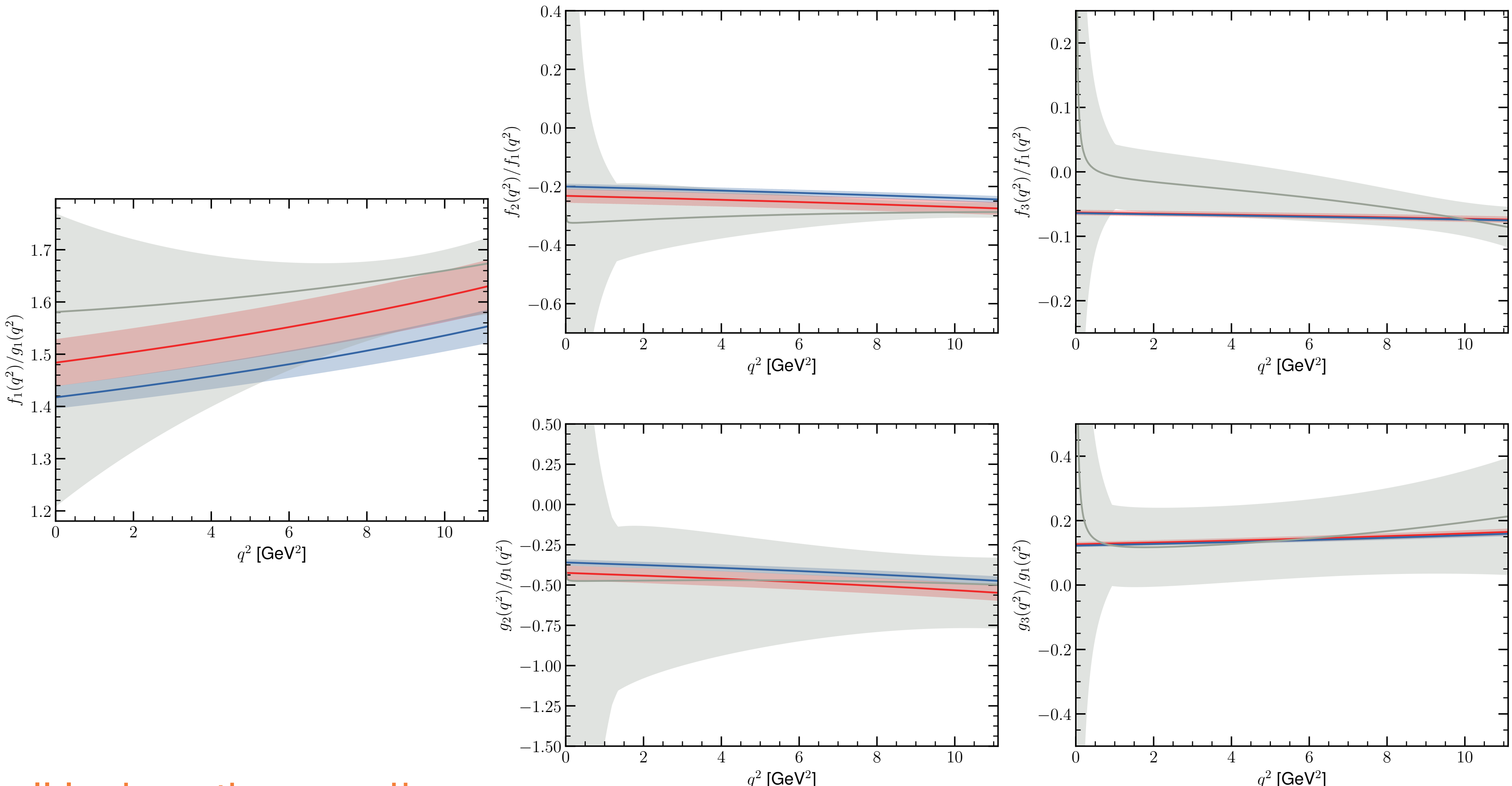
  [Falk & Neubert, hep-ph/9209269]

- Expansion in $\Lambda_{\mathrm{QCD}}/m_c$
  appears well behaved
  (contrary to some claims in literature)



Ratios of form factors

- $f_1(q^2)/g_1(q^2) = \mathcal{O}(1)$, whereas $\{f_{2,3}(q^2)/f_1(q^2),\ g_{2,3}(q^2)/g_1(q^2)\} = \mathcal{O}(\alpha_s, \varepsilon_{c,b})$



- It all looks rather good!

BSM: tensor form factors — issues?

- There are 4 form factors

  We get parameter free predictions!

  HQET: $h_1\,(=\widetilde{h}_+) = \mathcal{O}(1)$

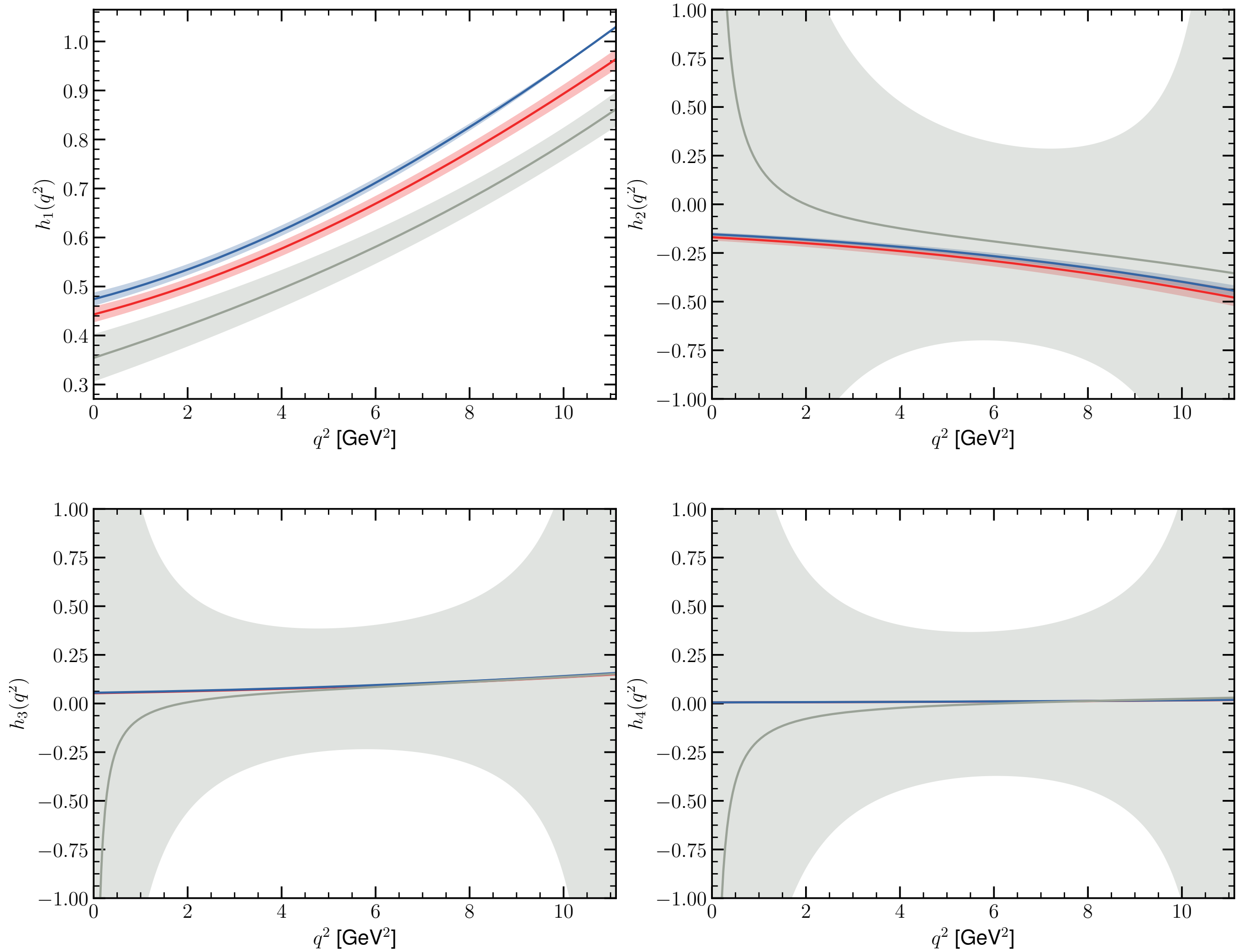
  $$h_{2,3,4} = \mathcal{O}(\alpha_s, \varepsilon_{c,b})$$

  LQCD basis: all 4 form factors calculated are $\mathcal{O}(1)$

  [Datta, Kamali, Meinel, Rashed, 1702.02243]

  Compare at $\mu = \sqrt{m_b m_c}$

- Heavy quark symmetry breaking terms consistent (weakly constrained by LQCD)



Hammer

HAMMER

Helicity Amplitude Module
for Matrix Element Reweighting

The need for Hammer

Helicity Amplitude Module for Matrix Element Reweighting

[Bernlochner, Duell, ZL, Papucci, Robinson, arXiv:2002:00020]

- MC uncertainty is a significant component in many measurements or $R(D^{(*)})$
- Standard practice: fit HFLAV averages of $R(D^{(*)})$ with your favorite NP model
- If NP was indeed present, $R(D^{(*)})$ measurements would be different

  All measurements use numerous cuts, acceptances depend on distributions of $D^{(*)}\tau\bar{\nu}$ and their decay products in many variables — the SM is assumed for these, to make the measurements

- Reported CL of (dis)agreement with SM is correct, but cannot determine CL of accepting a certain NP model, nor what NP parameters give the best fit to data
- Prohibitively expensive computationally to redo the MC for general NP

  One operator in SM, while 5 (or 10 with ν_R) in general

What Hammer does

- Fully differential distributions of detected particles, incl. D^* & τ decay interference
  Include arbitrary NP interaction and $m_\ell \neq 0$, for all 6 mesons: $B \to \{D, D^*, D^{**}\}\, \ell\bar\nu$
  - Efficiently reweight fully simulated samples (detector simulation only once)
  - Makes it feasible and fast to explore and run fits in all NP parameter 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)

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

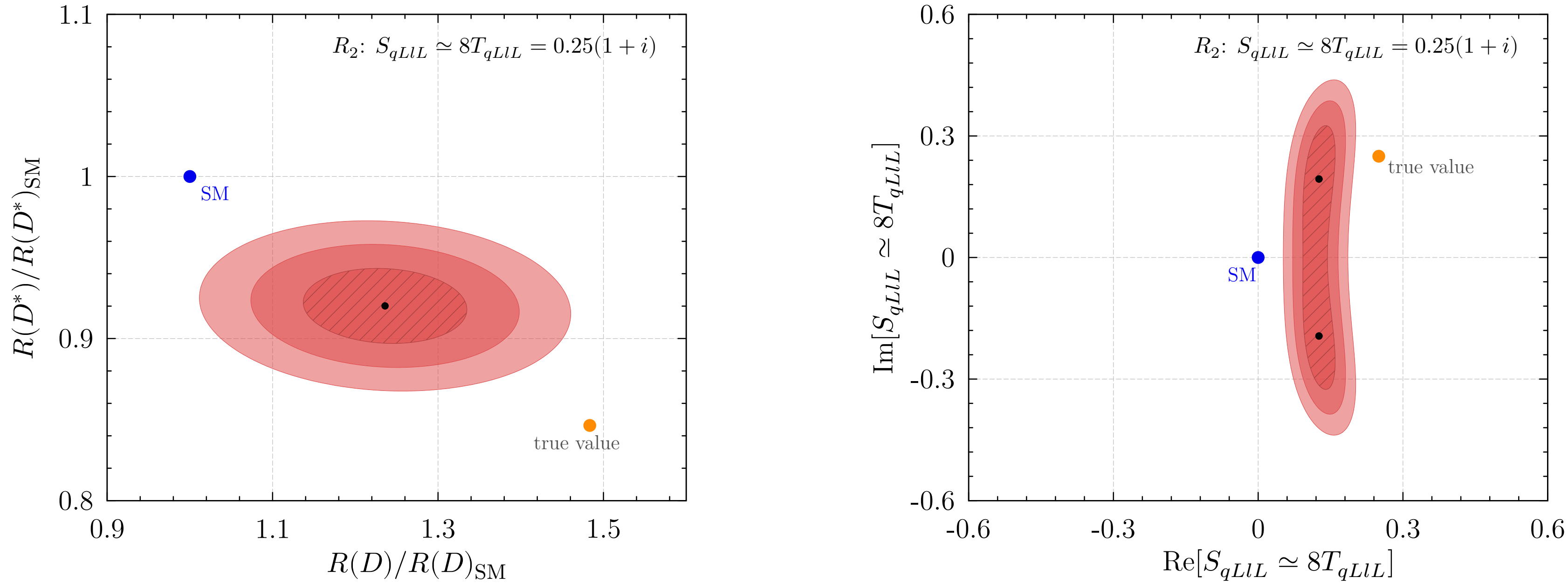
  Rapidly calculate differential distributions for any NP & form factors (contractions)
- Can do arbitrary NP couplings
- Can do arbitrary hadronic matrix elements (some form factors [not] known from first principle calc.)
- Will be publicly available, implementations in experiments in progress

Current status

Process	Form factor parametrizations
$B \to D^{(*)}\ell\nu$	ISGW2* [34, 35], BGL* [36–38], CLN*‡ [39], BLPR‡ [16]
$B \to (D^* \to D\pi)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$B \to (D^* \to D\gamma)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$\tau \to \pi\nu$	—
$\tau \to \ell\nu\nu$	—
$\tau \to 3\pi\nu$	RCT* [40–42]
$B \to D_0^*\ell\nu$	ISGW2*, LLSW* [43, 44], BLR‡ [45, 46]
$B \to D_1^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_1\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_2^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$\Lambda_b \to \Lambda_c\ell\nu$	PCR* [47], BLRS‡ [48, 49]
Planned for next release	
$B_{(c)} \to \ell\nu$	MSbar
$B \to (\rho \to \pi\pi)\ell\nu$	BCL*, BSZ
$B \to (\omega \to \pi\pi\pi)\ell\nu$	BCL*, BSZ
$B_c \to (J/\psi \to \ell\ell)\ell\nu$	
$\Lambda_b \to \Lambda_c^*\ell\nu$	PCR*, BLRS
$\tau \to 4\pi\nu$	RCT*
$\tau \to (\rho \to \pi\pi)\nu$	—

An illustration: the R_2 leptoquark

- As an illustration, consider the R_2 leptoquark model ($S_{qLlL} \sim 8\, T_{qLlL}$)



- Recovered parameters, from fitting toy (Asimov) data, are several σ from "truth"

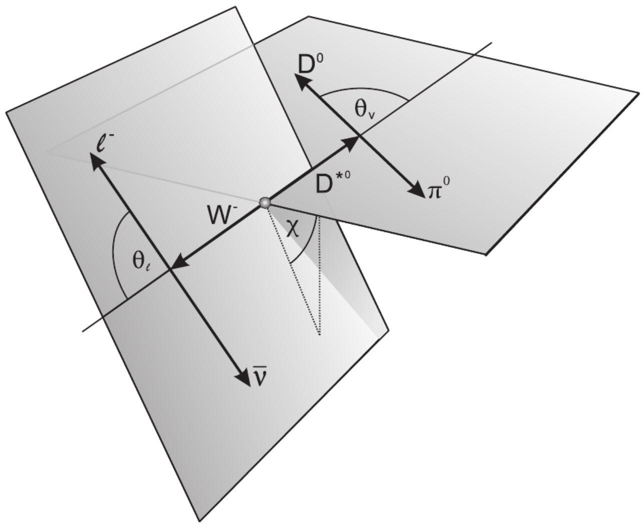
  Sizable bias in measured $R(D^{(*)})$ values, due to SM template built into the measurements

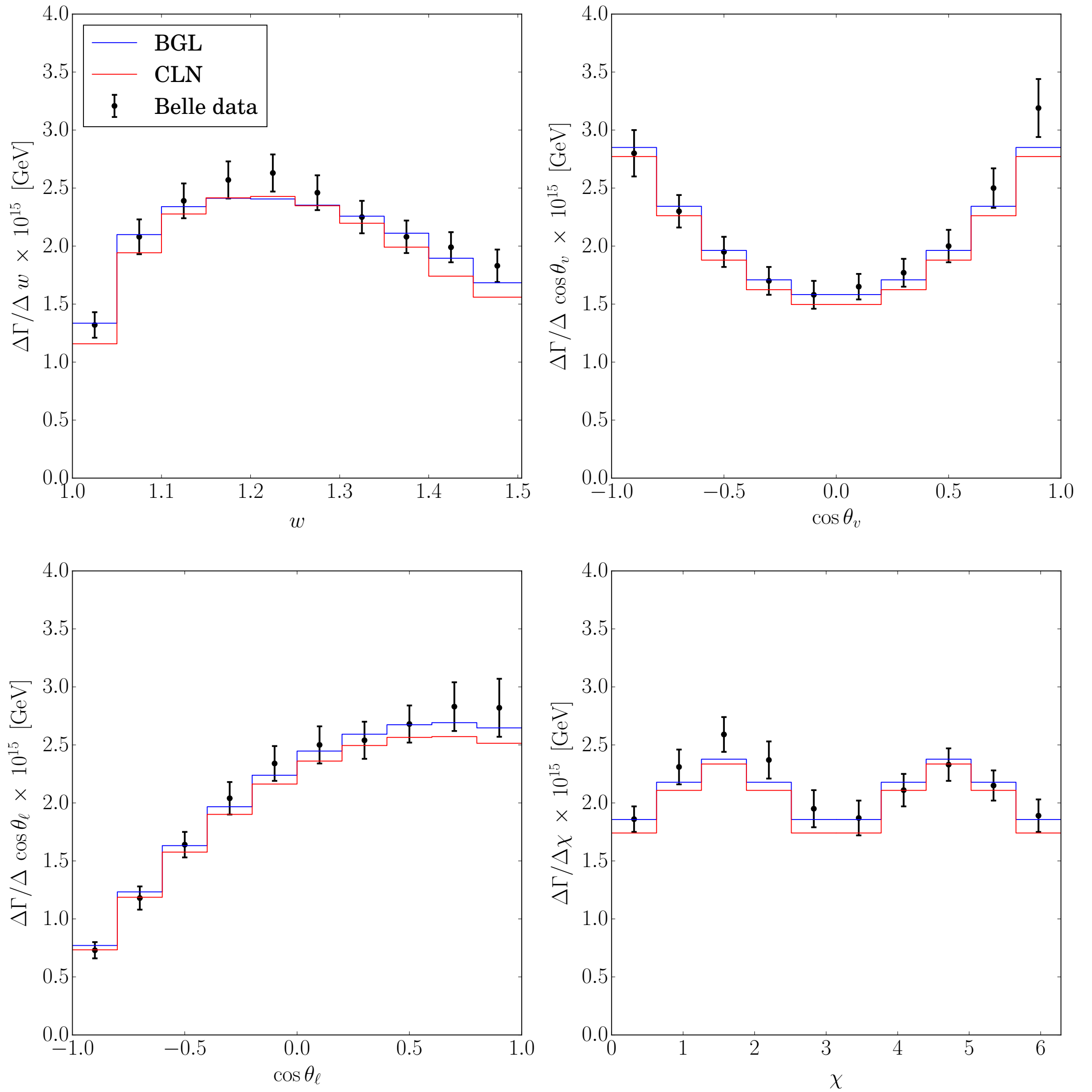
- `Hammer` will allow experiments to directly quote bounds on BSM Wilson coeff's

$|V_{cb}|$ and $B \to D^* \ell \bar{\nu}$

Available for the first time in 2017

- Belle published unfolded $B \to D^* l \bar{\nu}$ distributions [1702.01521]





[plots: Grinstein & Kobach, 1703.08170, also Bigi, Gambino, Schacht, 1703.06124]

- **We can all perform fits to data**

- Need input on the fitted shape:

  BGL: Boyd, Grinstein, Lebed, '95–97

  CLN: Caprini, Lellouch, Neubert, '97

Some subsequent developments

- $|V_{cb}|$ essential for: ϵ_K, $K \to \pi\nu\bar{\nu}$, $B_{(s)} \to \mu^+\mu^-$, $B_{(s)}$ mixing bounds, etc.
- The $R(D^{(*)})$ puzzle will necessarily make $|V_{cb}|$ much better understood
  To understand the τ mode precisely, must understand e & μ really well
- Field revitalized: unfolded $B \to D^* l\bar{\nu}$ measurement (tagged) [Belle, 1702.01521]

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

  Bigi, Gambino, Schacht, 1703.06124, $|V_{cb}|_{\rm BGL_{332}} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$

  Grinstein & Kobach, 1703.08170, $|V_{cb}|_{\rm BGL_{222}} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$

  Claim (more-or-less) that tension between inclusive / exclusive $|V_{cb}|$ is resolved
- Sept. 2018: another $B \to D^* l\bar{\nu}$ measurement (untagged) [Belle, 1809.03290v3]

$$|V_{cb}|_{\rm CLN} = (38.4 \pm 0.9) \times 10^{-3}$$

$$|V_{cb}|_{\rm BGL_{122}} = (38.3 \pm 1.0) \times 10^{-3}$$

BGL_{ijk} denote BGL fits with different number of fit parameters — details below

$B \to D^{(*)}\ell\bar\nu$ and heavy quark symmetry

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

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

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

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

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

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

- $|V_{cb}|$ extracted from measuring $\mathrm{d}\Gamma(B\to D^*\ell\bar\nu)/\mathrm{d}w$ at $w=1$ (maximal q^2)

  rate $\propto$ (Isgur-Wise fn.)$^2 \times \big[1+\mathcal{O}\big(\alpha_s,\, \Lambda_{\rm QCD}^2/m_{c,b}^2\big)\big]$

- Lattice QCD is most precise at $w=1$ — also related to heavy quark symmetry

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Making the most of heavy quark symmetry

- "Idea": fit 4 functions (1 leading-order $+$ 3 subleading Isgur-Wise functions) from
  $B \to D^{(*)}\, l\bar\nu \;\Rightarrow\; \mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2\,,\ \alpha_s^2)$ uncertainties

  [Bernlochner, ZL, Papucci, Robinson, 1703.05330]

- 4 observables: in $B \to D l\bar\nu$: $\mathrm{d}\Gamma/\mathrm{d}w$ (Only Belle published fully corrected distributions)
  in $B \to D^* l\bar\nu$: $\mathrm{d}\Gamma/\mathrm{d}w$
  $R_{1,2}(w)$ form factor ratios

  – Systematically improvable with more data

  – $\mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2)$ uncertainties can be constrained comparing w/ lattice form fact.

- Considered many fit scenarios, with/without LQCD and/or QCD sum rule inputs
  $\Rightarrow$ results for $|V_{cb}|$ and $R(D^{(*)})$

Boyd-Grinstein-Lebed constraints on shapes

- Based on analyticity and unitarity constraints on form factors; Taylor expansions

$$\frac{1}{P_i(z)\phi_i(z)} \sum a_n^i z^n \qquad\qquad i = g,\, f,\, \mathcal{F}_1 \text{ (lin. comb.)}$$

  $z(w)$ is a conformal parameter, maps physical region $1 < w < 1.5$ to $0 < z < 0.056$

  $P_i(z)\,,\ \phi_i(z)$ are known functions

  c_0 is fixed by b_0

  Some papers use notation: $\{a_n,\, b_n,\, c_n\} \longleftrightarrow \{a_n^g,\, a_n^f,\, a_n^{\mathcal{F}_1}\}$

- Does not use constraints from heavy quark symmetry, but can be added

- Denote by BGL_{ijk} a BGL fit with parameters: $\{a_{0,\dots,i-1},\ b_{0,\dots,j-1},\ c_{1,\dots,k}\}$

  Used in recent fits: $N = i + j + k = 5,\, 6,\, 8$

- Must truncate expansions at some order — what is the optimal choice?

The CLN fits used 1997–2017

- CLN added QCD SR to BGL: $R_{1,2}(w) = \underbrace{R_{1,2}(1)}_{\text{fit}} + \underbrace{R'_{1,2}(1)}_{\text{fixed}}\,(w-1) + \underbrace{R''_{1,2}(1)}_{\text{fixed}}\,(w-1)^2/2$

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

The $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ terms are determined by 3 subleading Isgur-Wise functions

- Inconsistent fits: same param's determine $R_{1,2}(1) - 1$ (fit) and $R^{(1,2)}_{1,2}(1)$ (QCDSR)

Sometimes calculations using QCD sum rules are called the HQET predictions

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- Devised fits to "interpolate" between BGL and CLN [Bernlochner, ZL, Robinson, Papucci, 1708.07134]

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	$a_0,\ a_1$	$\{\ R_1(1)$	$\{\ R_1(1),\ R'_1(1)$	$\{\ R_1(1),\ R'_1(1)$
axial $(\mathcal{F}_1)$	$c_1,\ c_2$	$R_2(1)$	$R_2(1),\ R'_2(1)$	$R_2(1),\ R'_2(1)$

Relaxing constraints on $R'_{1,2}(1)$, fit results similar to BGL

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The BGL_{122} fit in the 1809 Belle analysis

- A constraint, $a_1 = 0$, used to reduce the number of BGL parameters to 5

[Belle, 1809.03290]

- Problematic, significance of $|a_1| \neq 0$ is nearly 3σ in BGL_{222} fit (to unfolded data)

Param	Value $\times\ 10^2$	Correlation					
		$\tilde{a}_0$	$\tilde{a}_1$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$	$\tilde{c}_2$
$\tilde{a}_0$	0.0379 ± 0.0249	1.000	-0.952	-0.249	0.417	0.137	-0.054
$\tilde{a}_1$	2.6954 ± 0.9320		1.000	0.383	-0.543	-0.268	0.165
$\tilde{b}_0$	0.0550 ± 0.0023			1.000	-0.793	-0.648	0.461
$\tilde{b}_1$	-0.2040 ± 0.1064				1.000	0.542	-0.333
$\tilde{c}_1$	-0.0433 ± 0.0264					1.000	-0.953
$\tilde{c}_2$	0.5350 ± 0.4606						1.000

- Explore relation between the 6- and 5-parameter BGL fits, based on unfolded data

  Three simplest ways to truncate 6 BGL parameters to 5: remove a_1, b_1, or c_2

Compare 5-parameter BGL fits with BGL_{222}

- Explore differences based on unfolded (tagged) 1702.01521 measurement

form factors	BGL_{222}	BGL_{122}	BGL_{212}	BGL_{221}
vector	$a_0,\ a_1$	a_0	$a_0,\ a_1$	$a_0,\ a_1$
axial $\propto \epsilon_\mu^*$	$b_0,\ b_1$	$b_0,\ b_1$	b_0	$b_0,\ b_1$
axial $(\mathcal{F}_1)$	$c_1,\ c_2$	$c_1,\ c_2$	$c_1,\ c_2$	c_1

- The χ^2 goes up most in the BGL_{122} fit, as $|a_1| \neq 0$ was the most significant

	BGL_{222}	BGL_{122}	BGL_{212}	BGL_{221}
χ^2 / ndf	$27.7/34$	$32.7/35$	$31.3/35$	$29.1/35$
$\lvert V_{cb}\rvert \times 10^3$	41.7 ± 1.8	39.5 ± 1.7	38.7 ± 1.1	40.7 ± 1.6

- Based on this data, $|V_{cb}|$ from BGL_{122} is ~ 0.002 below $|V_{cb}|$ from BGL_{222}

  Would the same occur for 1809 Belle measurement, yielding $|V_{cb}| \sim 0.040$?

- BGL_{122} fit param's based on the two Belle measurements only consistent at $\sim 2\sigma$

Nested hypothesis tests

- Optimal BGL fit parameter choice, given available data? (upper: χ^2, lower: $|V_{cb}| \times 10^3$)

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
		$n_b = 1$			$n_b = 2$			$n_b = 3$	

– Fit w/ 1 param added / removed: $\mathrm{BGL}_{(n_a \pm 1) n_b n_c}$, $\mathrm{BGL}_{n_a (n_b \pm 1) n_c}$, $\mathrm{BGL}_{n_a n_b (n_c \pm 1)}$

– Accept descendant (parent) if $\Delta\chi^2$ is above (below) a boundary, say, $\Delta\chi^2 = 1$

– Repeat until "stationary" fit is found, preferred over its parents and descendants

– If multiple stationary fits, choose smallest N, then smallest χ^2 (333 is an overfit!)

Start from small N, to avoid overfitting e.g.: $\begin{cases} 111 \to 211 \to 221 \to 222 \\ 121 \to 131 \to 231 \to 232 \to 222 \end{cases}$

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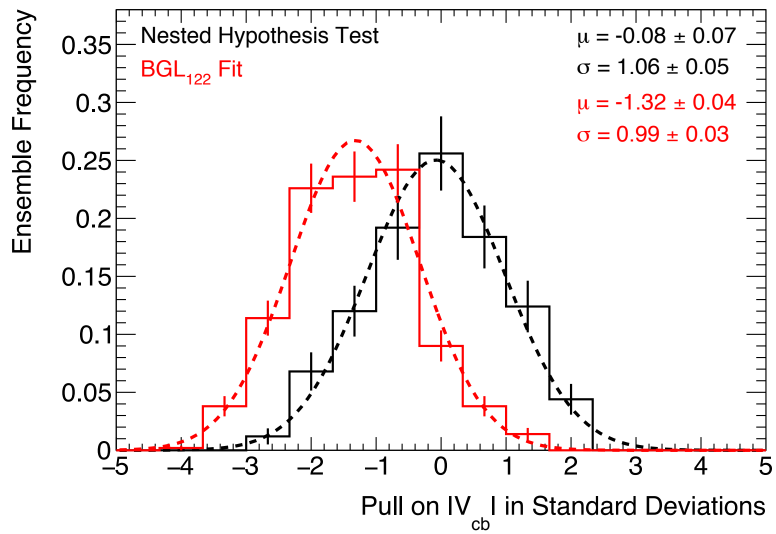
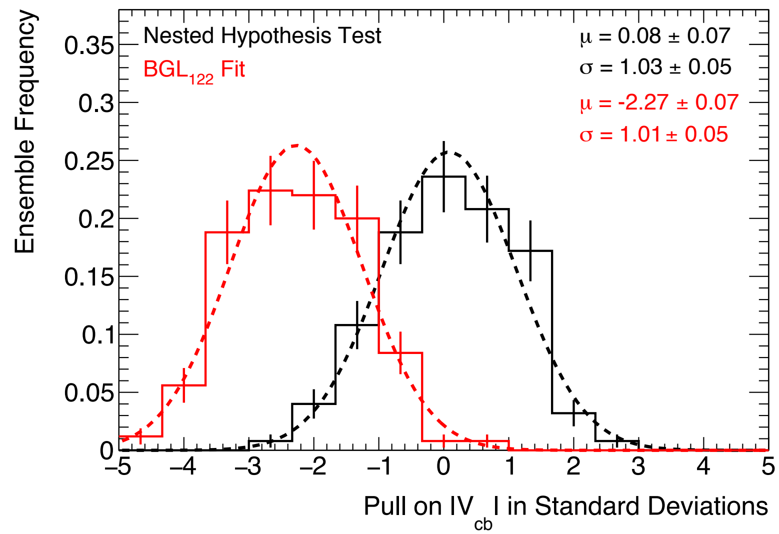
Toy studies: show $|V_{cb}|$ is unbiased

- Set $\{\tilde{a}_{0,1},\, \tilde{b}_{0,1},\, \tilde{c}_{1,2}\} = \mathrm{BGL}_{222}$ fit result, and $\{\tilde{a}_2,\, \tilde{b}_2,\, \tilde{c}_3\} = (1$ or $10) \times \{\tilde{a}_1,\, \tilde{b}_1,\, \tilde{c}_2\}$

  Generate MC data using experimental covariance, fit each set w/ our prescription





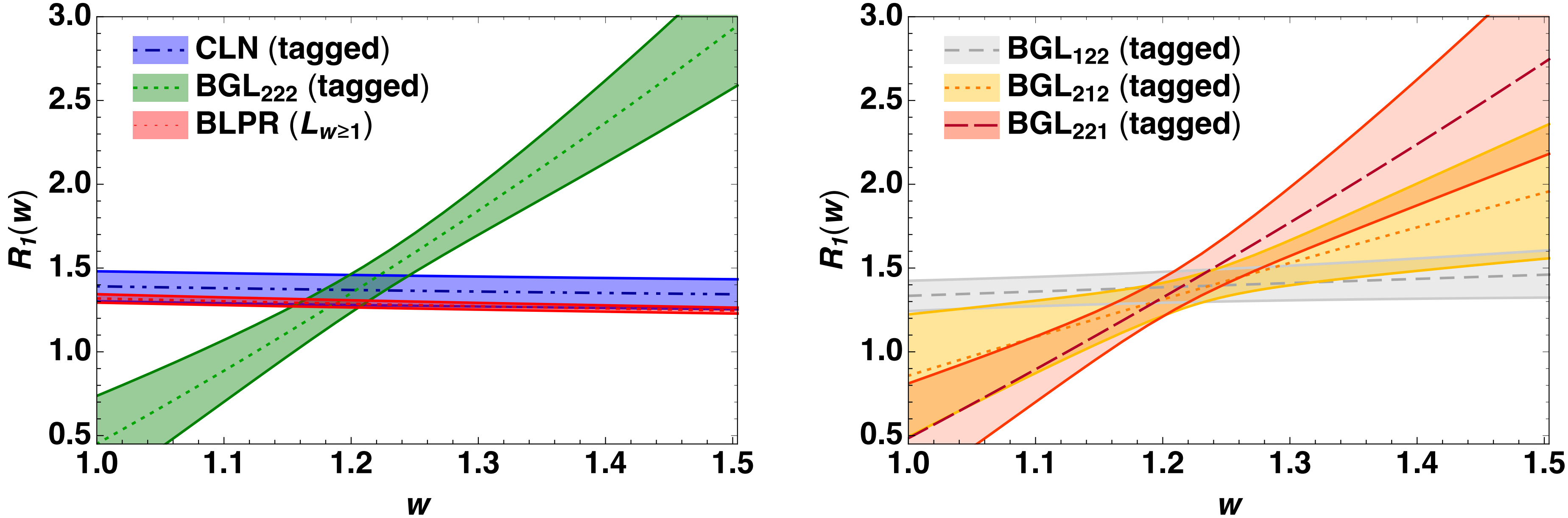
- Frequency of the selected hypotheses, with two scenarios for higher order terms:

	BGL_{122}	BGL_{212}	BGL_{221}	BGL_{222}	BGL_{223}	BGL_{232}	BGL_{322}	BGL_{233}	BGL_{323}	BGL_{332}	BGL_{333}
'1-times'	6%	0%	37%	27%	6%	6%	11%	0%	2%	4%	0.4%
'10-times'	0%	0%	8%	38%	14%	8%	16%	3%	4%	8%	1%

BGL fits with higher $|V_{cb}|$ in tension with HQET

- Compare 6 fits for $R_1(w)$: higher $|V_{cb}| \leftrightarrow R_1(w)$ far from HQET

  Expect: $R_{1,2}(w) = 1 +$ corrections   [$R_2(w)$ has a less clear pull]



- The BGL_{222}, BGL_{212}, and BGL_{221} fits are in tension with heavy quark symmetry

  (The BGL_{122} fits give a “flatter” $R_1(w)$, at least partly due to setting $a_1 = 0$)

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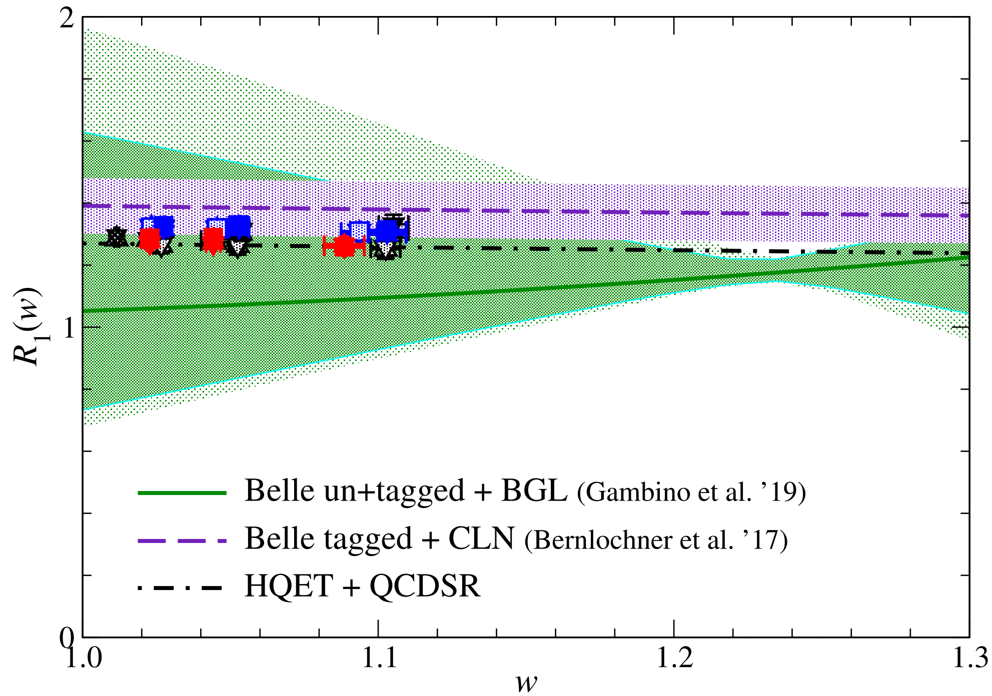
Lattice QCD, preliminary results

- FNAL/MILC and JLQCD are both working on the $B \to D^* \ell \bar{\nu}$ form factors

  Independent formulations: staggered vs. Mobius domain-wall actions



[Kaneko *et al.*, JLQCD, 1912.11770; similar work by Fermilab/MILC, 1912.05886]

- No qualitative difference between LQCD calculation at $w = 1$, or slightly above

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Final comments

Conclusions

- Measurable NP contribution to $b \to c\ell\bar{\nu}$ would imply NP at a fairly low scale
- $\Lambda_b \to \Lambda_c \ell\bar{\nu}$: HQET more predictive than in meson decays
  The $\Lambda_{\rm QCD}/m_c$ terms are important, and no evidence for bad behavior
- `Hammer`: Allow experiments to quote measurements directly on BSM operators
  Sizable biases in several past analyses
- $B \to D^*\ell\bar{\nu}$: Need even more data to know how $|V_{cb}|$ story settles
  BGL – CLN fits: nested hypothesis test determine optimal number of fit param's
- Measurements and SM predictions will both improve a lot (continuum + lattice)
  (Even if central values change, plenty of room for significant deviations from SM)
- Best case: new physics, new directions
  Worst case: better SM tests, better CKM determinations and NP sensitivity

Extra slides

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
$\mathsf{L}_{w=1}$	0.292 ± 0.005	0.255 ± 0.005	41%
$\mathsf{L}_{w=1}$+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%
$\mathbf{L}_{w\geq1}$	$\mathbf{0.298 \pm 0.003}$	$\mathbf{0.261 \pm 0.004}$	19%
$\mathbf{L}_{w\geq1}$+SR	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.257 \pm 0.003}$	44%
th:$\mathsf{L}_{w\geq1}$+SR	0.306 ± 0.005	0.256 ± 0.004	33%
Data [HFLAV]	0.340 ± 0.030	0.295 ± 0.014	-38%
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	—
Jaiswal, Nandi, Patra '17	0.302 ± 0.003	0.257 ± 0.005	13%
SM [HFLAV]	0.299 ± 0.003	0.258 ± 0.005	—

Reasons (not) to take the tension seriously

- Measurements with τ leptons are difficult
- Need a large tree-level contribution, SM suppression only by m_τ

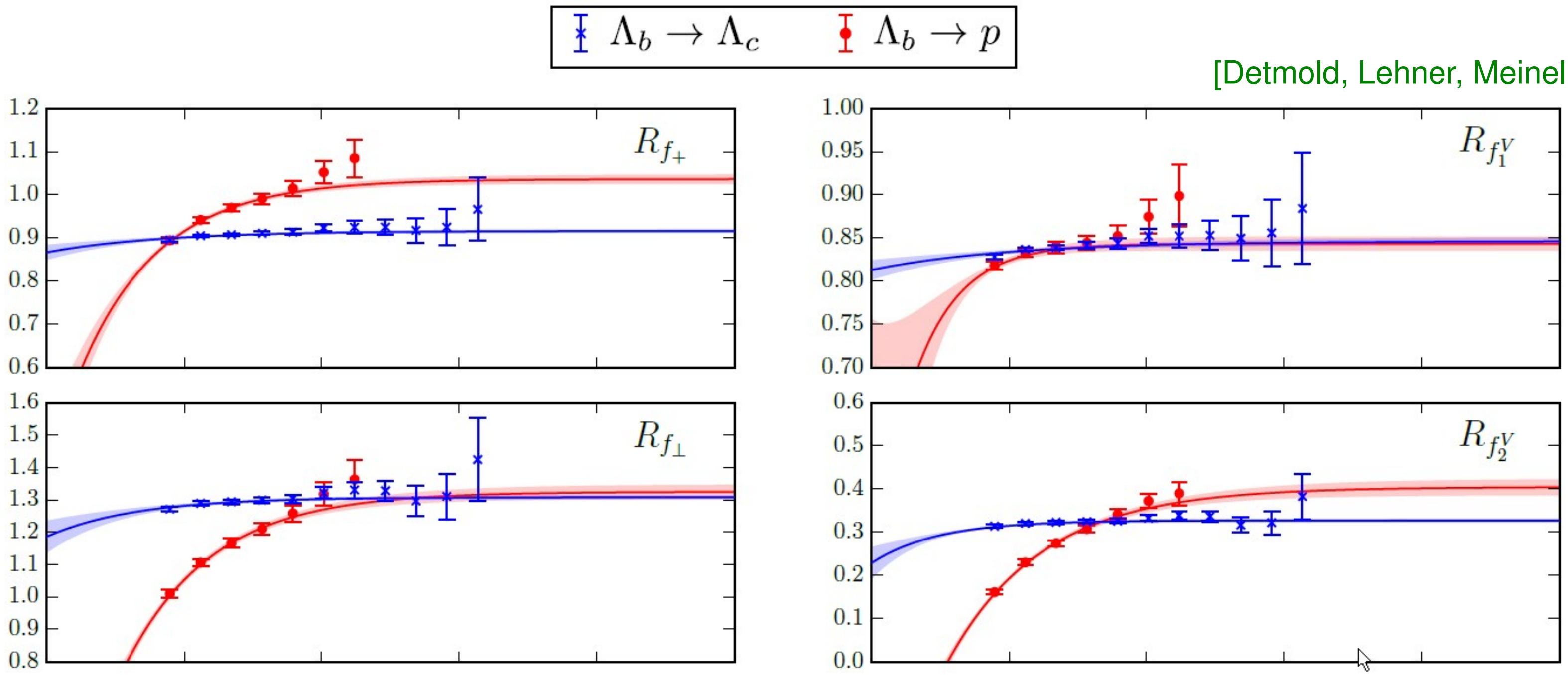
  NP was expected to show up in FCNCs — need fairly light NP to fit the data
- Strong constraints on concrete models from flavor physics, as well as high-p_T

- Results from BaBar, Belle, LHCb are consistent
- Often when measurements disagreed in the past, averages were still meaningful
- Enhancement is also seen in similar ratio in $\Gamma(B_c \to J/\psi\, \ell\bar\nu)$
- If Nature were as most theorist imagined (until ~ 10 years ago), then the LHC (Tevatron, LEP, DM searches) should have discovered new physics already

Lattice QCD details

- Baryons have been thought to be harder than mesons on lattice (more stat noise)

[Detmold, Lehner, Meinel, 1503.01421]



Horizontal axis: source-sink separation

- Is plateau reached before signal dies? Fit with multi-exp?
  Is ground state extraction robust?

[See: Hashimoto, Lattice 2018 plenary]