Fits to semileptonic $b \to c$ decays

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Missing particle signatures and new physics at Belle II and LHCb
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Since 2012, 2014: emerging hints of LUV

- 2012: BaBar, charged current
- 2014: LHCb, neutral current

- “Who ordered that?”

  Hardly any theory discussions before the measurements

  Simplest models to fit the data do not (simply) connect to DM and hierarchy puzzle

- Forced both theory and experiment to rethink program, discard some prejudices

  New directions: model building, high-p_T searches, lepton flavor violation searches

- What would it take to convince your most skeptical colleague that the $B \to X_c \ell \bar{\nu}$ data are evidence for BSM? (Not fluctuations nor unknown systematics?)

- Huge stakes: would make the physics case for FCC (even more) obvious
  (And also pushing future upgrades of flavor experiments to the technology limits)

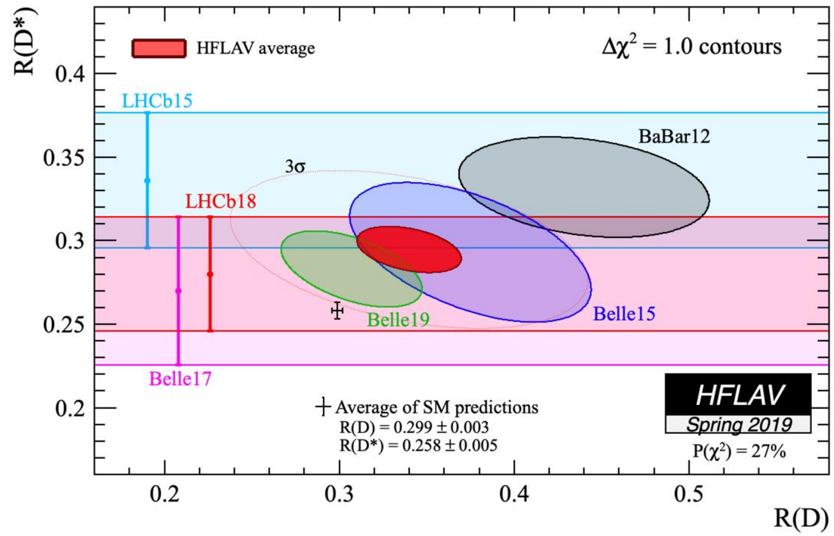
The $B \to D^{(*)}\tau\bar\nu$ decay rates

- BaBar, Belle, LHCb: $R(X) = \dfrac{\Gamma(B \to X\tau\bar\nu)}{\Gamma(B \to X(e/\mu)\bar\nu)}$

  3.1σ from SM predictions — robust due to heavy quark symmetry + lattice QCD (only D so far)

  many channels: $R(D^*)$ with $\tau \to \nu 3\pi$ [1708.08856]

  $B_c \to J/\psi\,\tau\bar\nu$ [1711.05623]



- Imply NP at fairly low scales (leptoquarks, W', etc.), likely visible at ATLAS / CMS

  Many models Fierz (mostly) to the SM operator: SM-like distributions and τ polarization

- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

  overlap with ATLAS & CMS searches for $\tilde b$, leptoquark, $H^\pm$

- Models built to fit these anomalies have impacted many ATLAS & CMS searches

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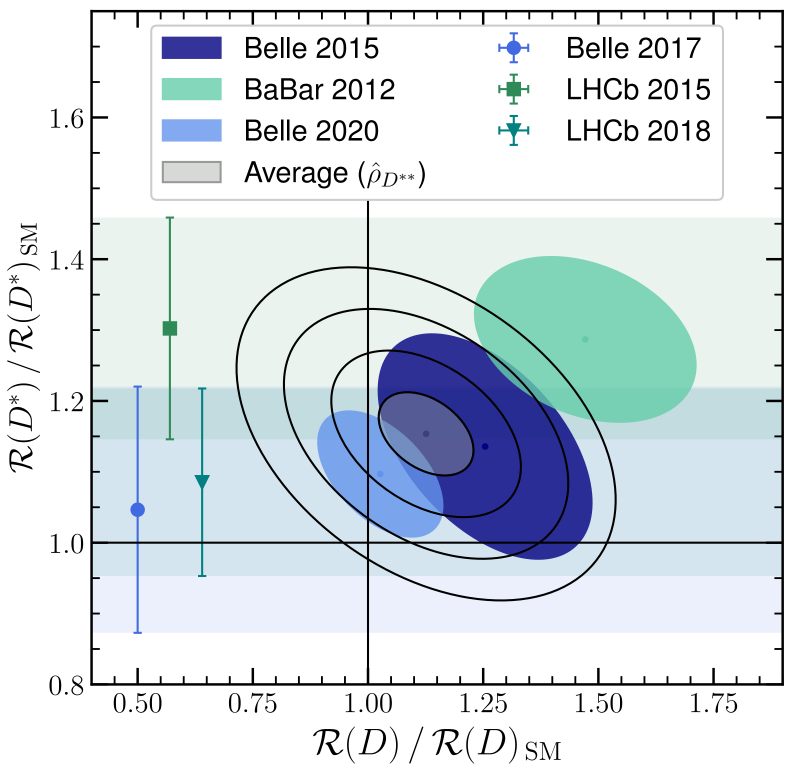
Slightly different fits are possible

- With different assumptions than HFLAV, same data averages to 3.6σ

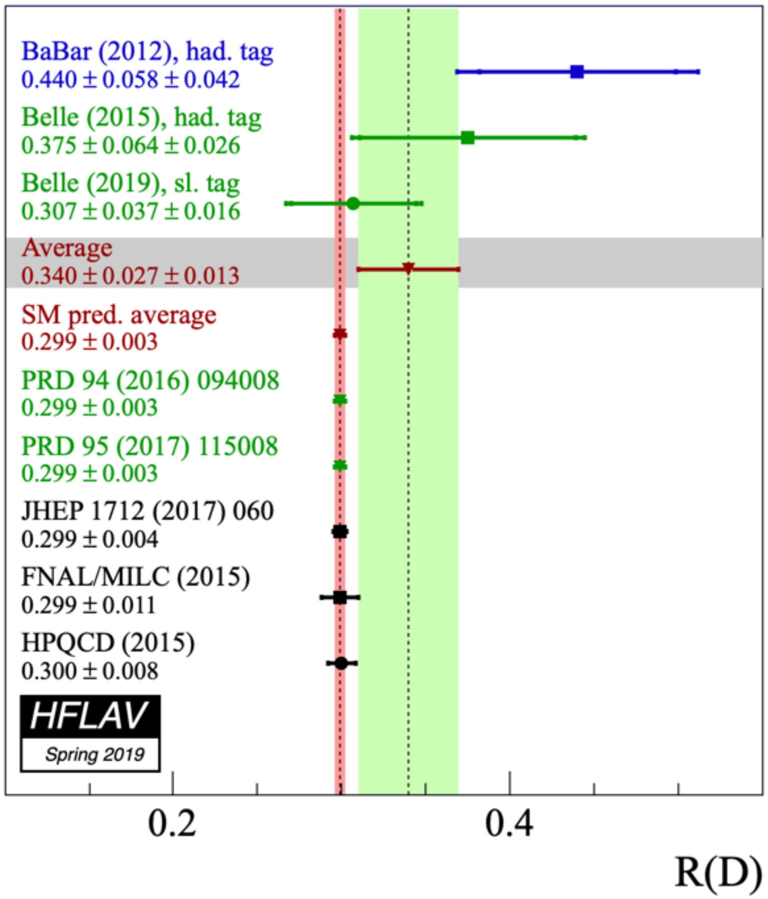
(Correlations between experiments from D^{**} feed-down backgrounds)

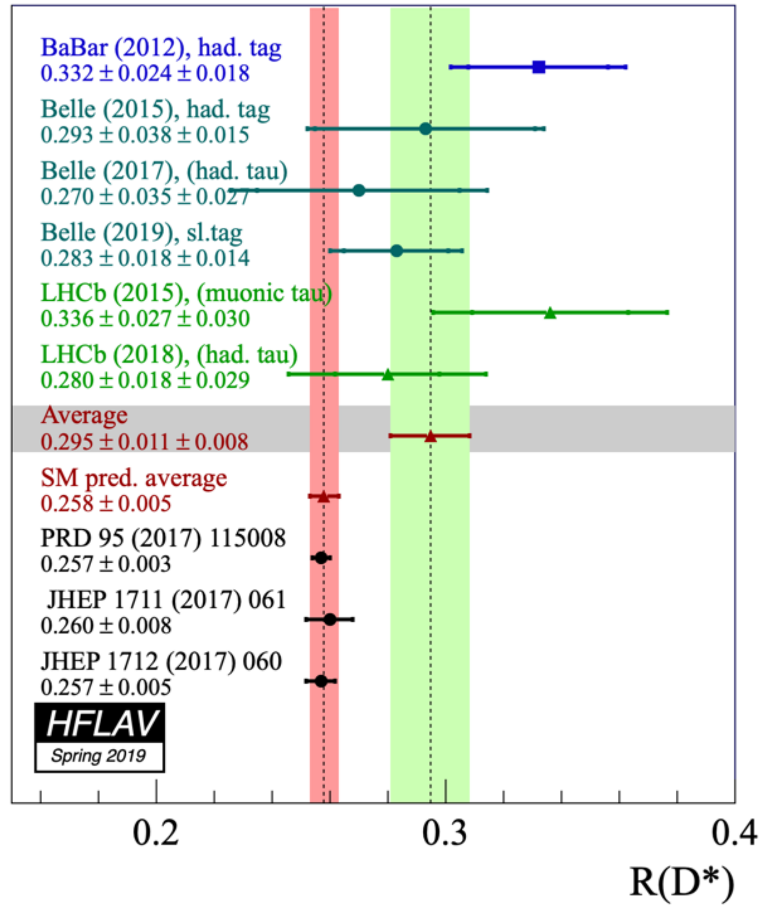


[Bernlochner, Franco Sevilla, Robinson, 2101.08326]

Another look at the data

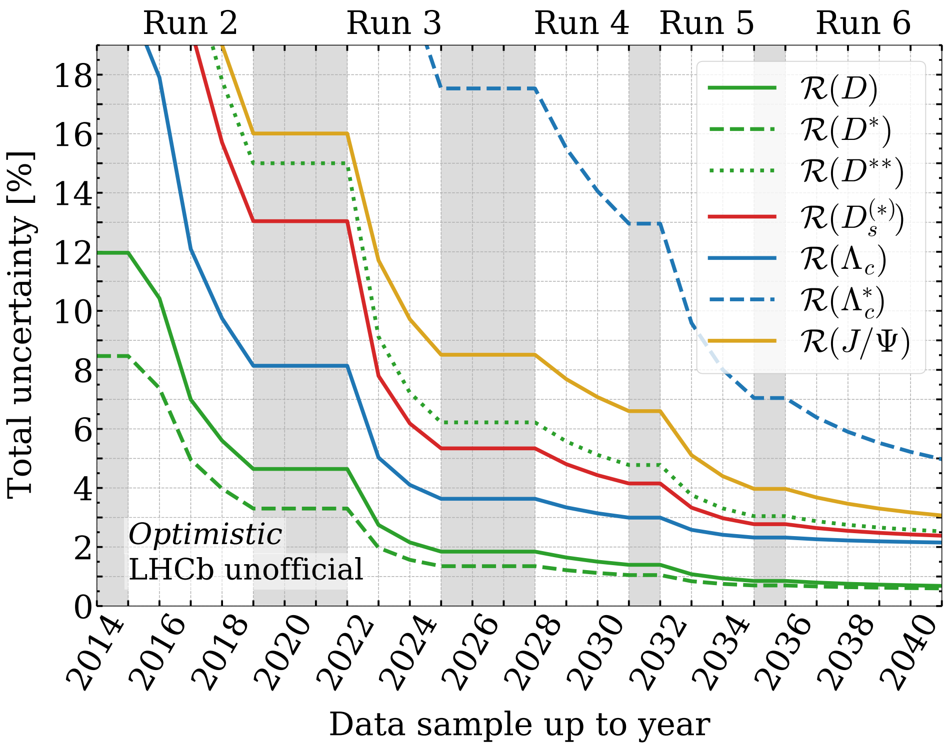
- The $R(D)$ and $R(D^*)$ measurements — all central values above SM:

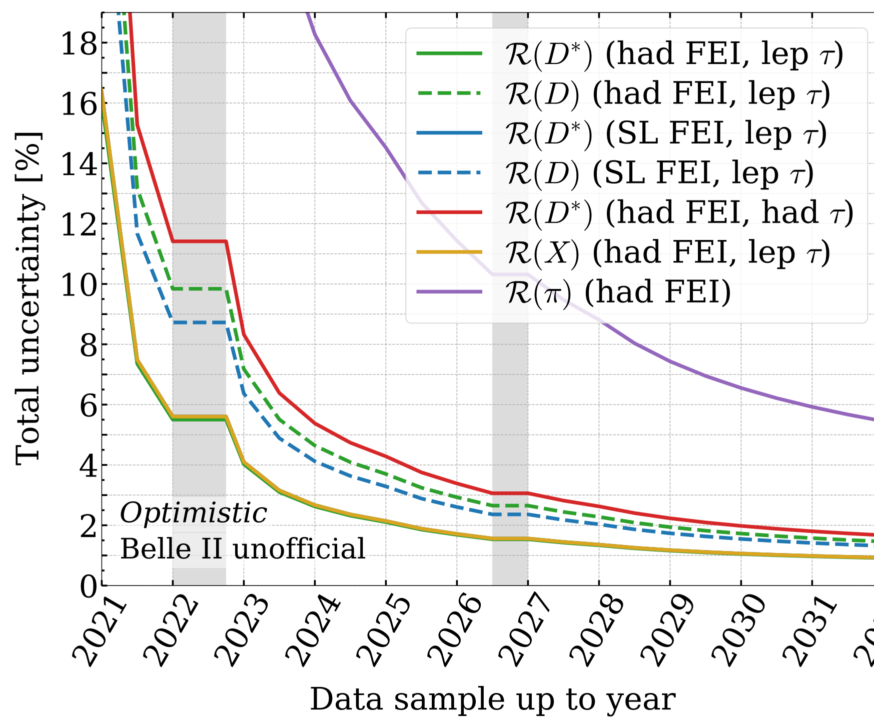




- Not decisive yet, consistent with both an emerging signal or fluctuations

Prospects





[2101.08326]

- Measurements will improve a lot! (Even if deviations from SM shrink, can establish presence of BSM)

- Competition, complementarity, cross-checks between LHCb and Belle II

Some key questions

- Can it be a theory issue? — not at the current level
- Can it be an experimental issue? — previous talks
- Can [reasonable] models fit the data? — maybe [subjective] (won't say much)

- What is the smallest deviation from SM in $R(D^{(*)})$ that can be established as NP?
  ... we know how to make progress
- Which channels are most interesting? (To establish deviation from SM / understand NP?)
  $B_{(s)} \to D_{(s)}^{(*,**)} \ell\bar{\nu}$, $\Lambda_b \to \Lambda_c^{(*)} \ell\bar{\nu}$, $B_c \to \psi\ell\bar{\nu}$, $B \to X_c\ell\bar{\nu}$, etc.
- Which calculations can be made most robust (continuum & lattice QCD)?
- What else can we learn from studying these anomalies?

$|V_{cb}|$ determinations should converge...

- $|V_{cb}|$ important to assess if there is an ε_K tension, predict $K \to \pi\nu\bar\nu$, $B \to \mu^+\mu^-$

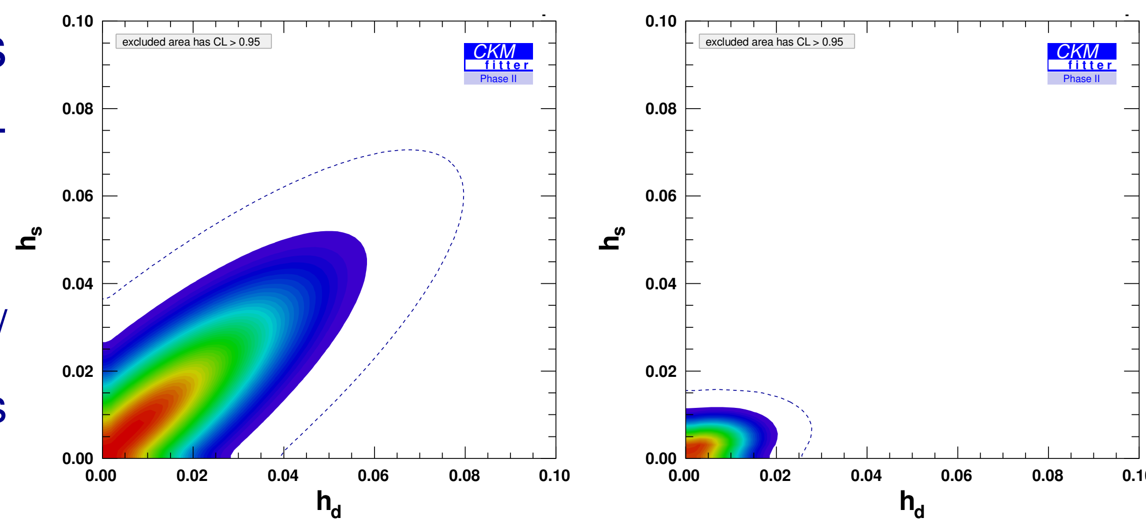
  SM predictions involve A^4, so 5% in $|V_{cb}|$ yields 20%

- The $b \to c\tau\bar\nu$ data will make $|V_{cb}|$ much better understood — are we there yet?

  To understand the τ mode thoroughly, must understand the e, μ modes better

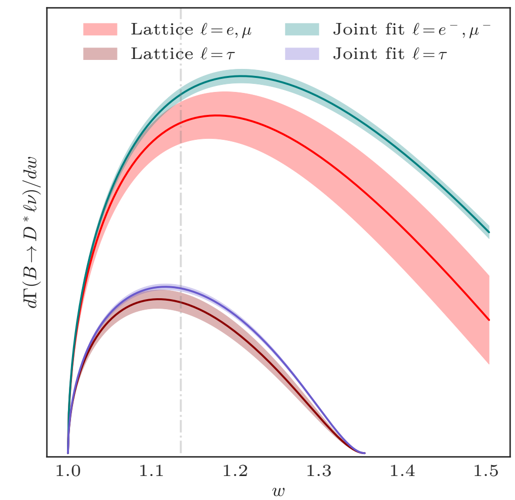
- Recently: $|V_{cb}|$ uncertainty limits future improvements in the sensitivity to NP in B and B_s mixing

  Plots: "Phase II" in late 2030-s without / with huge $|V_{cb}|$ improvements + others (unrealistic) [Charles *et al.*, 2006.04824]



$B \to D^{(*)}$: some open questions

- Won't talk about fits to unfolded vs. folded data — what I think is important is that different approaches and new ideas can be tested
- CLN is model dependent, and not self-consistent without adding more parameters ($1/m$ at zero recoil fit to data, but their slopes fixed by QCD sum rules) [1703.05330]
- Fit results (BGL, CLN) depend (more than expected?) on truncation order
  Just looking at goodness of fits is not the full story [1708.07134]
- For $B \to D^* \ell \nu$, lattice results in full q^2 range only recently
  Some tension between data and lattice $\Longrightarrow$
  They obtain: $R(D^*) = 0.266 \pm 0.014$ [FNAL & MILC, 2105.14019]
  $B_s \to D_s^* \ell \bar{\nu}$: $R(D_s^*) = 0.244 \pm 0.009$ [Harrison & Davies, 2105.11433]



- Need to address many things before $|V_{cb}|$ is "done"

$B \to D^{**}$: unsatisfactory understanding

- Large mass splitting: $m_{D_1^*} - m_{D_0^*} \sim 80\,\text{MeV}$

  (Compared to quark model, for example)

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

  [Details: Bernlochner & ZL, 1606.09300]

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

  Are these (nearly) pure $Q\bar{q}$ states?

Decay mode	Branching fraction
$B^0 \to D_2^{*-} \pi^+$	$(0.59 \pm 0.04) \times 10^{-3}$
$B^0 \to D_1^- \pi^+$	$(0.71 \pm 11) \times 10^{-3}$
$B^0 \to D_0^{*-} \pi^+$	$(0.12 \pm 0.01) \times 10^{-3}$

[Le Yaouanc, Leroy, Roudeau, 2102.11608]

- The “1/2 vs. 3/2 puzzle” remains... puzzling

- Better understand of how “inclusive $= \sum$ exclusive” works is needed

  How well can the “nonresonant” components be ultimately measured?

D_s^{**} states: some open questions

- All $4\ D_s^{**}$ states much narrower than non-strange counterparts — nice for LHCb
- $D_{s0}^*(2317)$: orbitally excited state or "molecule"?

  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 $232/\text{fb}$

  Ample motivation for Belle II to re-measure it!
- If these excited states have significant non-$Q\bar{q}$ components, then HQET-based predictions need not apply

  However, inclusive calculations (and their expected uncertainties) unaffected

Speculations on $SU(3)$ in $B_{(s)} \to D_{(s)}^{(*)} \ell \bar{\nu}$

- Considerations suggesting possibly sizable effects: [ZL @ BNL, Sep 2019 Lattice X Intensity Frontier]

  Bjorken and Voloshin sum rules relate the behavior of $B_{(s)} \to D_{(s)}^{(*)}$ ground state transition to the decays to excited states; e.g., Voloshin sum rule [PRD 46 (1992) 3062]

  "Also the sum rule shows that the slope parameter should be a growing function of the mass of the spectator quark."

$$\rho^2 = -\frac{\mathrm{d}}{\mathrm{d}w} \frac{\mathrm{d}\Gamma}{\mathrm{d}w}\bigg|_{w=1} < \frac{1}{4} + \frac{m_M - m_Q}{2(m_{M_1} - m_M)} + \dots$$

  where $m_{M_1} - m_M$ is the gap to the first excited meson state above $D_{(s)}^{(*)}$

- Expect: slope parameter increases, if larger rates to excited states (not $D_{(s)}^{(*)}$)

  if $m_{M_1} - m_M$ smaller ("gap" above $D_{(s)}^{(*)}$)

  Discovered in 2003: $m_{D_{s0}^{*\pm}} - m_{D_s^\pm} \approx 206\,\mathrm{MeV}$, but $m_{D_0^{*\pm}} - m_{D^\pm} \approx 484\,\mathrm{MeV}$

- Interesting if these arguments for larger slope hold, or compensated by something

  Recently: $\rho^2_{D_s^*} = 1.16 \pm 0.09$ [LHCb, 2003.08453] vs. HFLAV: $\rho^2_{D^*} = 1.122 \pm 0.024$ (use CLN)

  LQCD: "no significant $SU(3)$ symmetry breaking" [Harrison & Davies, 2105.11433]

$SU(3)$ and nonleptonic decays

- Compare shapes of $\mathrm{d}\Gamma/\mathrm{d}w$

- Factorization may work better in $B_s \to D_s^{(*)}\pi$ than $B \to D^{(*)}\pi$, tells us $\mathrm{d}\Gamma/\mathrm{d}w\big|_{w_{\max}}$

  Interesting for hadronic dynamics as well, to better understand: [hep-ph/0312319]

  $$|A(\bar{B}^0 \to D^+\pi^-)| = |T + E|, \quad |A(B^- \to D^0\pi^-)| = |T + C|, \quad |A(B_s \to D_s^-\pi^+)| = |T|$$

  Since $\tau_{B^0} \approx \tau_{B_s}$, we can compare directly the branching ratios:

  $[1]\ \ \mathcal{B}(B^0 \to D\pi) = (2.52 \pm 0.13) \times 10^{-3}$

  $[2]\ \ \mathcal{B}(B^0 \to D^*\pi) = (2.74 \pm 0.13) \times 10^{-3}$

  $[3]\ \ \mathcal{B}(B_s \to D_s\pi) = (3.00 \pm 0.23) \times 10^{-3}$ [LHCb, only $0.37/\mathrm{fb}$]

  $[4]\ \ \mathcal{B}(B_s \to D_s^*\pi) = (2.0 \pm 0.5) \times 10^{-3}$

  Central values: $[1] < [3]$ and $[2] > [4]$ seem puzzling, warrants more precise measurements

- Seek improvements in $B_{(s)} \to D_{(s)}^{**}\pi$ and $B_{(s)} \to D_{(s)}^{**}\ell\bar{\nu}$ rate measurements

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Baryons

(Skip most of it — unless questions)

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 $w = v \cdot v' = (m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2)/(2 m_{\Lambda_b} m_{\Lambda_c})$

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

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

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 : $\qquad m_{\Lambda_{b,c}} = m_{b,c} + \bar\Lambda_\Lambda + \ldots , \qquad \varepsilon_{b,c} = \bar\Lambda_\Lambda / (2 m_{b,c})$

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

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

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

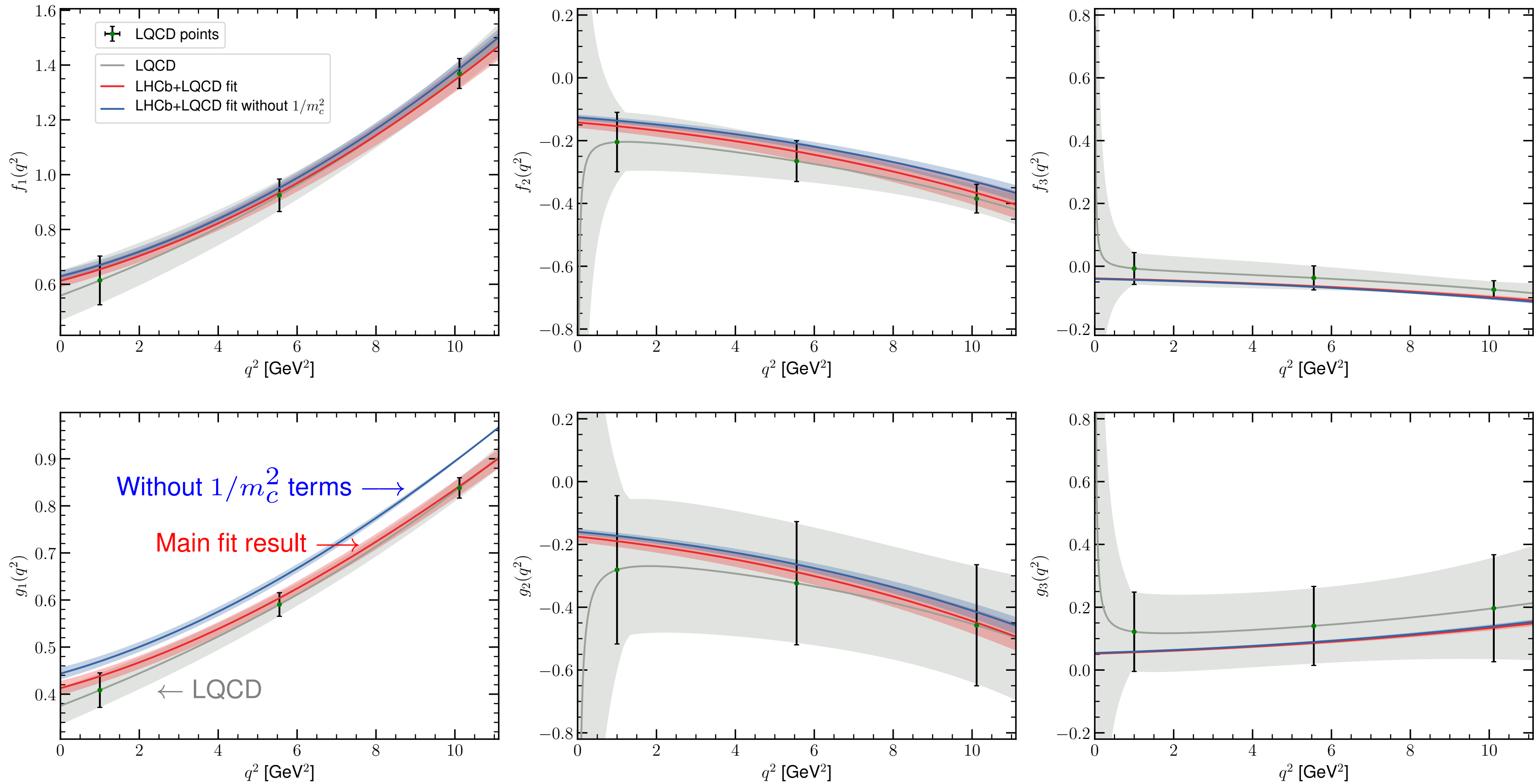
[Falk & Neubert, hep-ph/9209269]

- HQET is more constraining than in meson decays!

Fit to lattice QCD form factors and LHCb (1)

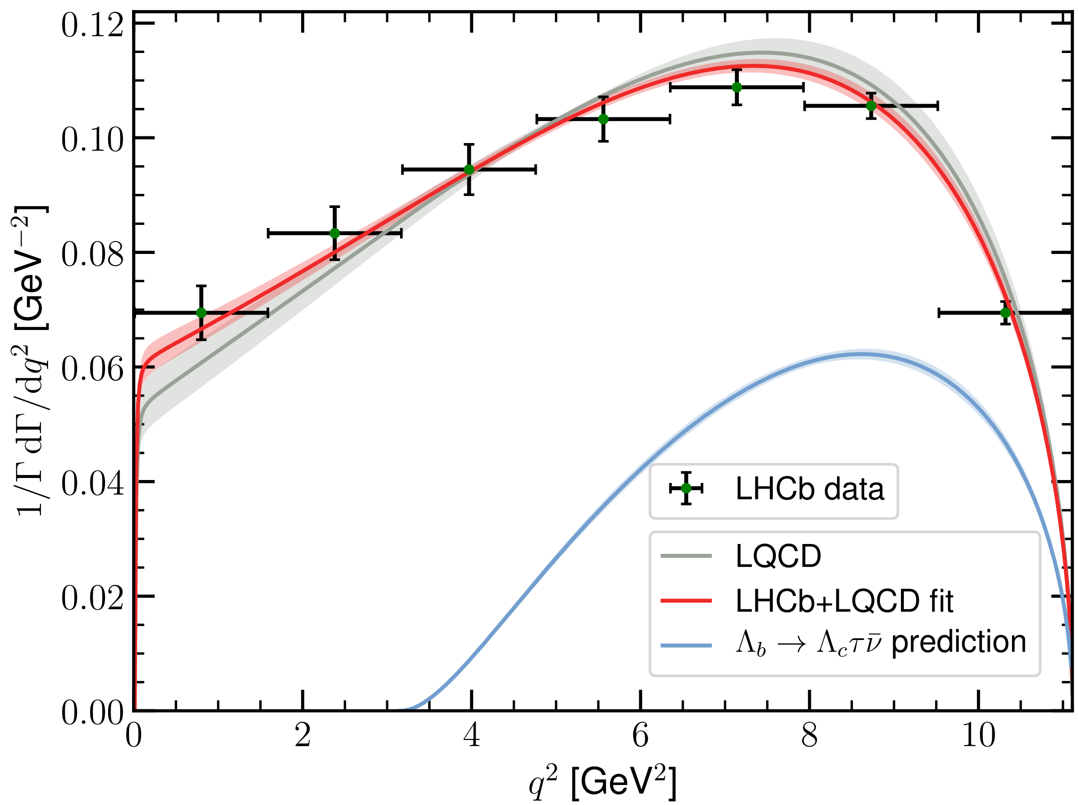
- Fit 6 form factors w/ 4 parameters: $\zeta'(1)$, $\zeta''(1)$, $\hat{b}_1$, $\hat{b}_2$

[Bernlochner, ZL, Robinson, Sutcliffe, 1808.09464, 1812.07593] [LQCD: Detmold, Lehner, Meinel, 1503.01421]



Fit to lattice QCD form factors and LHCb (2)

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



[LHCb, 1709.01920]

- 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

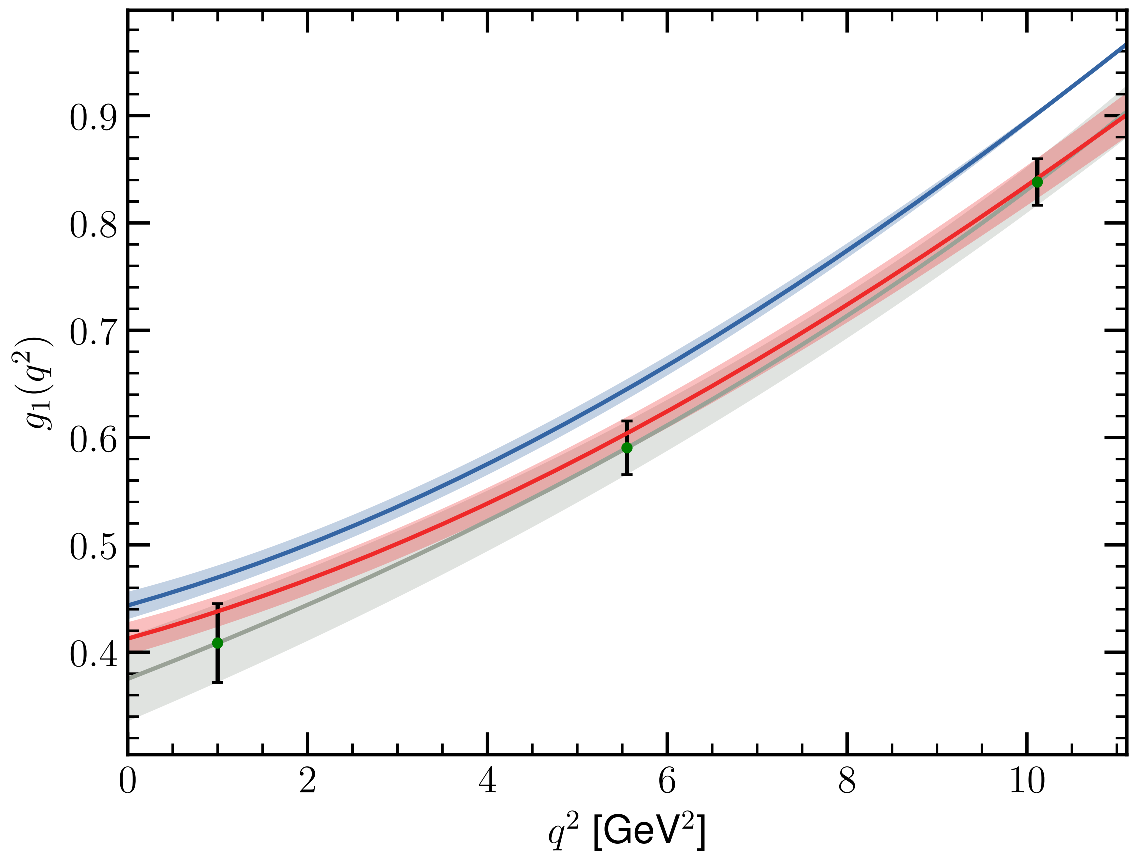
- E.g., fit results for g_1
  blue band shows fit with $\hat{b}_{1,2} = 0$

- 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 other claims)



BSM: tensor form factors — an issue?

- Parameter free predictions!

  There are 4 form factors

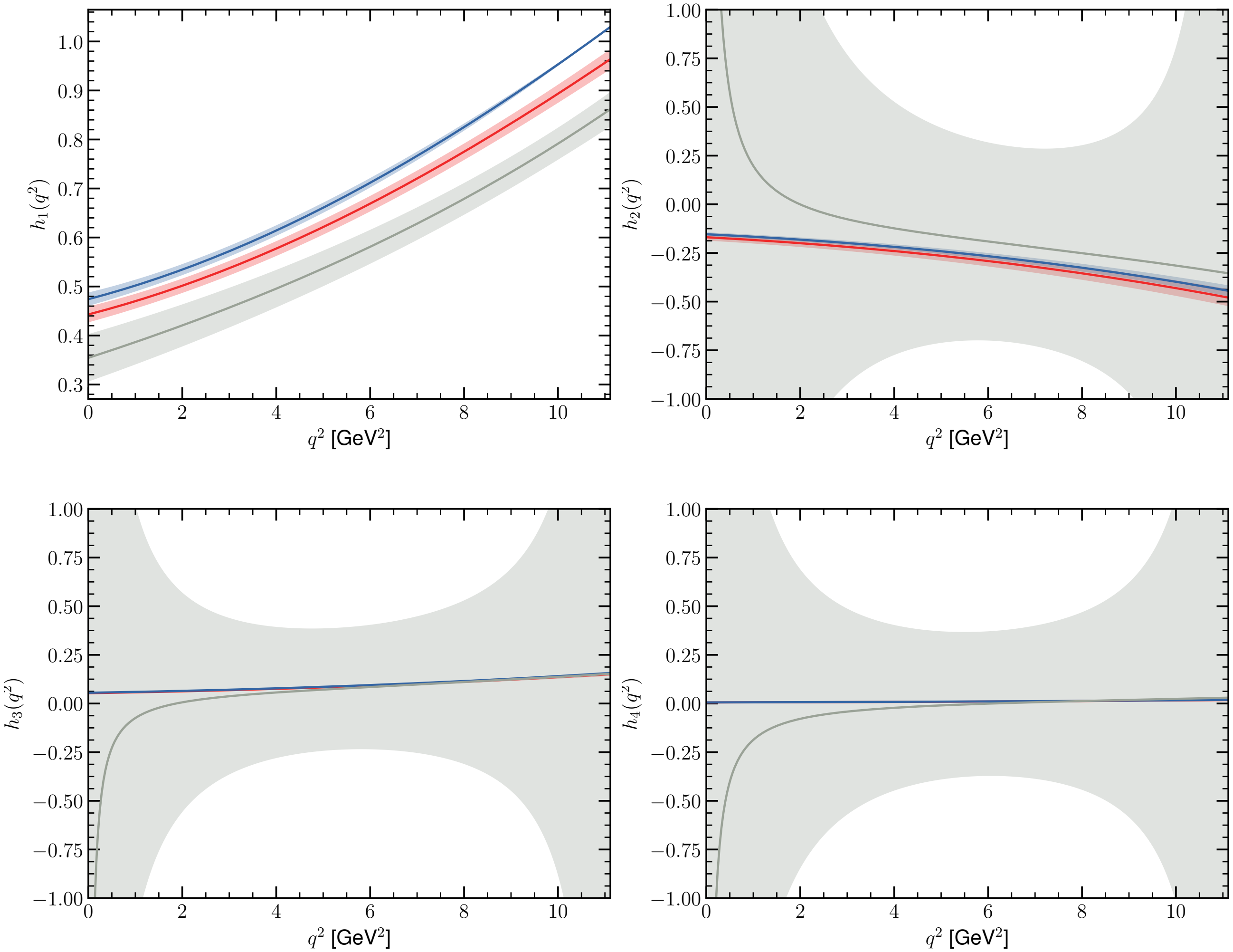
  HQET: $h_1\ (= \widetilde{h}_+) = \mathcal{O}(1)$

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

  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)

- If tensions between data and SM remain, this difference has to be sorted out

Lot more to measure in baryon decay

- What is the maximal information that the $\Lambda_b \to \Lambda_c \mu \bar{\nu}$ decay can give us?

  $\Lambda_c \to pK\pi$ complicated, $\Lambda_c \to \Lambda\pi\,(\to p\pi\pi)$ loses lots of statistics

- If Λ_c decay distributions are integrated over, but θ is measured (angle between the $\vec{p}_\mu$ and $\vec{p}_{\Lambda_c}$ in $\mu\bar{\nu}$ rest frame), then maximal info one can get:

$$\frac{\mathrm{d}^2\Gamma(\Lambda_b \to \Lambda_c \mu \bar{\nu})}{\mathrm{d}w\,\mathrm{d}\cos\theta} = \frac{3}{8}\Big[(1+\cos^2\theta)\,H_T(w) + 2\cos\theta\,H_A(w) + 2(1-\cos^2\theta)\,H_L(w)\Big]$$

(forward-backward asym.)

  Measuring the 3 terms would give more information than just $\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c \mu \bar{\nu})/\mathrm{d}q^2$

- Long term: including Λ_c decay distributions would give even more information

And the Λ_c^* states...

- Two states, $\frac{1}{2}^-: \Lambda_c^*(2595)$ and $\frac{3}{2}^-: \Lambda_c^*(2625)$ — widths 2.6 MeV and <1 MeV

  Small widths make them attractive [Long history: Leibovich & Stewart, hep-ph/9711257; Boer *et al.*, 1801.08367]

- Recently first LQCD predictions published [Meinel & Rendon, 2103.08775]

- Update of HQET-based description, both for the SM and NP [Papucci & Robinson, 2105.09330]

  Find tensions with lattice:

  – Need huge HQS breaking to fit lattice form factor results

  – Lattice form factors in tension w/ $\Gamma(\Lambda_b \to \Lambda_c^*(2595)\mu\bar{\nu})/\Gamma(\Lambda_b \to \Lambda_c^*(2625)\mu\bar{\nu}) = 0.6^{+0.4}_{-0.2}$

  [CDF, 0810.3213]

  CDF data can be accommodated in HQET framework (nominal $1/m$ terms)

- Results included in `Hammer` HAMMC Helicity Amplitude Module for Matrix Element Reweighting [Bernlochner, Duell, ZL, Papucci, Robinson, 2002.00020]

Hammer

Helicity Amplitude Module
for Matrix Element Reweighting

hammer.physics.lbl.gov — public v1.1.0 (Aug 2020), v.1.2 soon

The need for Hammer

Helicity Amplitude Module for Matrix Element Reweighting

[Bernlochner, Duell, ZL, Papucci, Robinson, 2002.00020]

- MC uncertainty is a significant component in many measurements or $R(D^{(*)})$
- Standard practice: fit HFLAV averages of $R(D^{(*)})$ with one's 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 in 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)

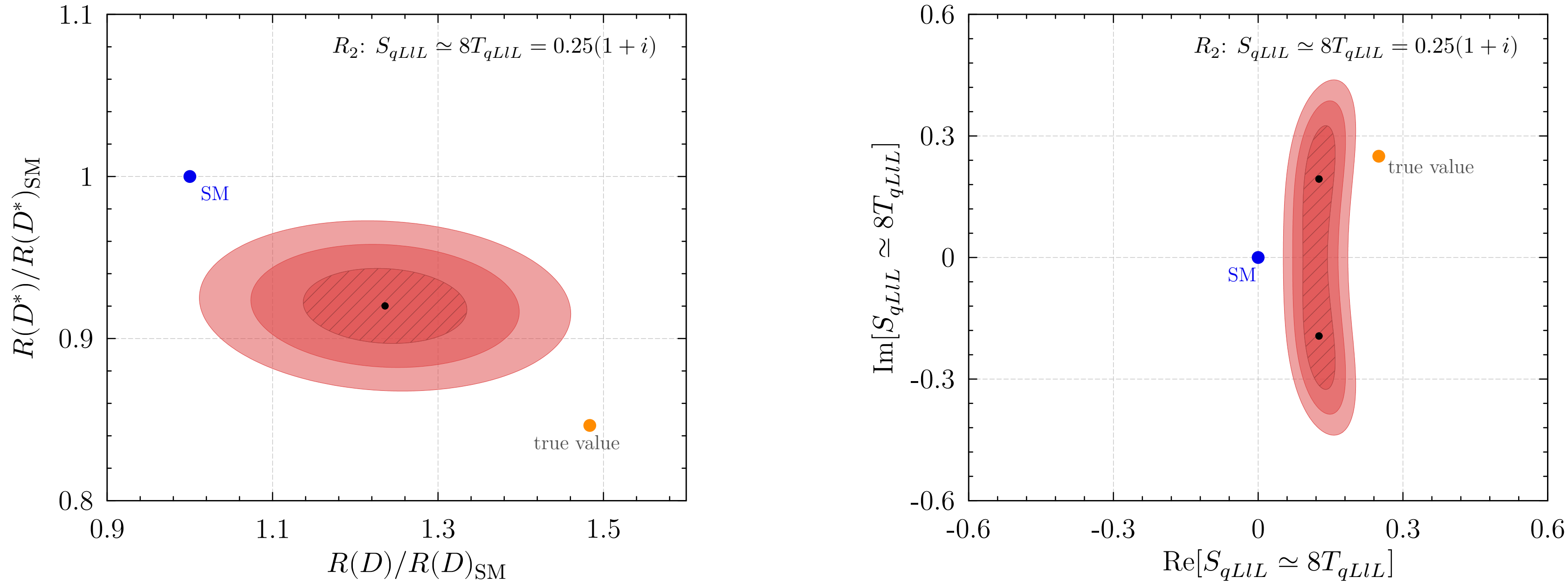
- Can do arbitrary NP couplings
- Can do arbitrary hadronic matrix elements (some form factors [not] known from first principle calc.)
- Publicly available, implemented in both Belle II and LHCb   hammer.physics.lbl.gov

Status of implementations

Process	FF parametrizations
$B \to D^{(*)}\ell\nu$	ISGW2* [16, 17], BGL* [13–15], CLN*‡ [18], BLPR‡ [19]
$B \to (D^* \to D\pi)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$B \to (D^* \to D\gamma)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡
$B \to D_0^*\ell\nu$	ISGW2*, LLSW* [20, 21], BLR‡ [22, 23]
$B \to D_1^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_1\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_2^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to (\rho \to \pi\pi)\ell\nu$	ISGW2*, BSZ‡ [24]
$B \to (\omega \to \pi\pi\pi)\ell\nu$	ISGW2*, BSZ‡
$\Lambda_b \to \Lambda_c\ell\nu$	PCR* [25], BLRS‡ [26, 27]
$\Lambda_b \to \Lambda_c^*\ell\nu$	PCR*, LSPR‡ [28, 29]
$B_c \to (J/\psi \to \ell\ell)\ell\nu$	Kiselev* [30], EFG* [31], BGL*‡ [32], ...
$B \to \pi\ell\nu$	ISGW2*, BCL*‡ [33]
$\tau \to \pi\nu$	—
$\tau \to \ell\nu\nu$	—
$\tau \to 3\pi\nu$	RCT* [34–36]
$D_1 \to (D^* \to D\pi/\gamma)\pi$	PW
$D_2^* \to (D^* \to D\pi/\gamma)\pi$	PW
$D_2^* \to D\pi$	PW
Planned for next release	
$B_{(c)} \to \ell\nu$	MSbar
$\tau \to 4\pi\nu$	RCT*
$\tau \to (\rho \to \pi\pi)\nu$	—

An illustration: the R_2 leptoquark

- An example: 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` allows experiments to directly quote bounds on BSM Wilson coeff's

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Conclusions

- Measurable NP contribution to $b \to c\ell\bar{\nu}$ would imply NP at a fairly low scale
- $B \to X_c\ell\bar{\nu}$: Need (much) more data to know how anomalies (and $|V_{cb}|$) settle

  $\Lambda_b \to \Lambda_c\ell\bar{\nu}$: HQET more predictive than in meson decays, $\Lambda^2_{\rm QCD}/m_c^2$ well behaved
- LQCD will continue to be important: lot more to calculate, some tensions

  Independent cross-checks as relevant as for continuum calculations
- `Hammer`: can bound BSM operators without full simulations (sizable past biases)
- Forced both theory and experiment to rethink program, discard some prejudices

  New directions: model building, high-p_T searches, lepton flavor violation searches
- 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 $|V_{cb}|$