B Anomalies: Still HQETing

Zoltan Ligeti

Caltech, HEP Seminar

November 5, 2018

- Introduction
- The data
- Mesons
- Baryons
- Outlook

Details: Bernlochner, ZL, Robinson, Sutcliffe, arXiv:1808.09464 to appear in PRL; 1811.?????

Bernlochner, ZL, Papucci, Robinson, 1703.05330

Disclaimers.... first 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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- I could have (almost) given this talk as a postoc here... (no one would have cared)

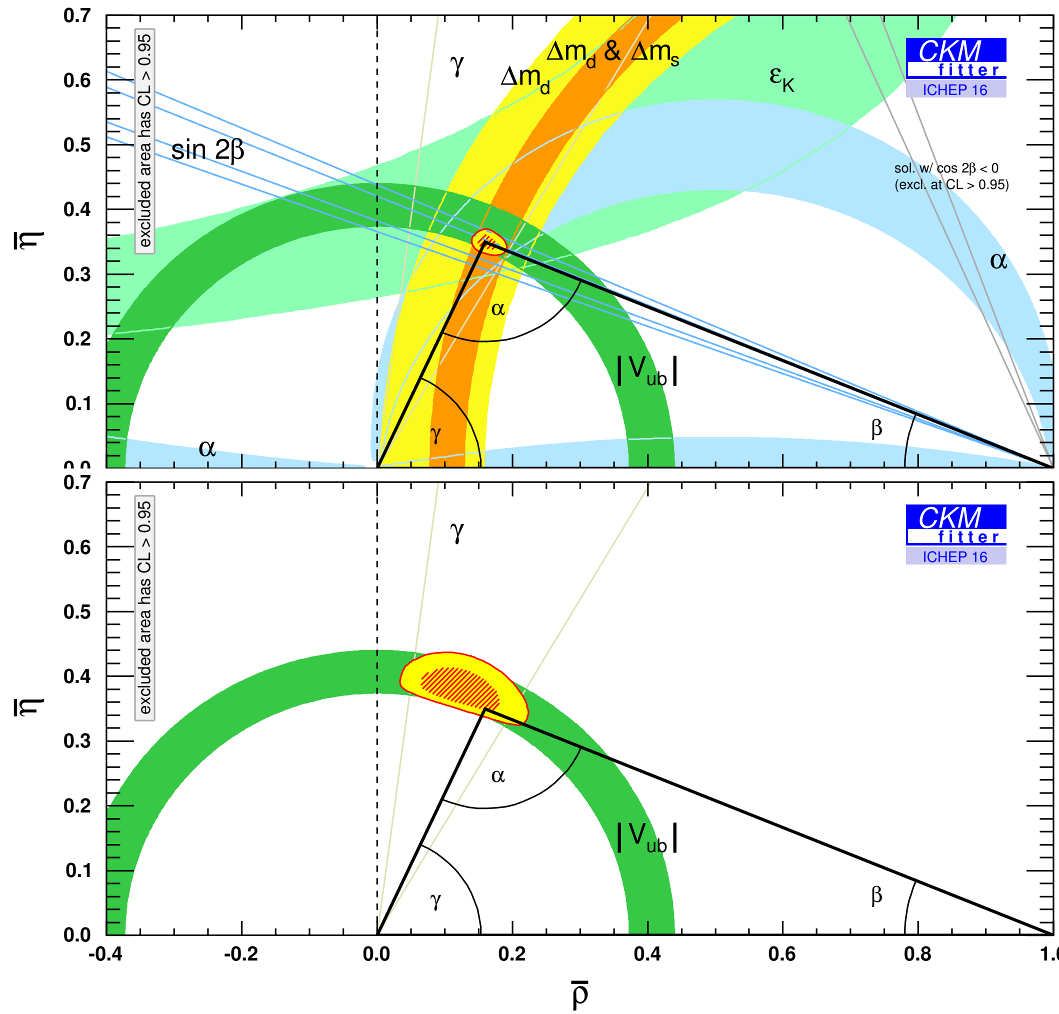
CKM fit: plenty of room for new physics

- 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

- Related to Yukawa couplings, scalar sector, maybe connected to hierarchy puzzle
  Only know that Higgs field is responsible for (bulk of) the heaviest fermion masses

- Important cosmological implications (Baryogenesis)

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

  Establishing any of the flavour anomalies would set upper bound on NP scale

- Experiment: expect huge improvements, many new measurements

- Theory: Progress and new directions both in SM calculations and model building

Some intriguing tensions with SM

- Could become clear evidence for NP

  1) R_K and R_{K^*} $\sim 20\%$ correction to SM loop diagram $(B \to X\mu^+\mu^-)/(B \to Xe^+e^-)$

  2) $R(D)$ and $R(D^*)$ $\sim 20\%$ correction to SM tree diagram $(B \to X\tau\bar{\nu})/(B \to X(e,\mu)\bar{\nu})$

  ---

  3) P_5' angular distribution (in $B \to K^*\mu^+\mu^-$)

  4) $B_s \to \phi\mu^+\mu^-$ rate

- Theoretically cleanest: 1) and 2) — both relate to lepton non-universality

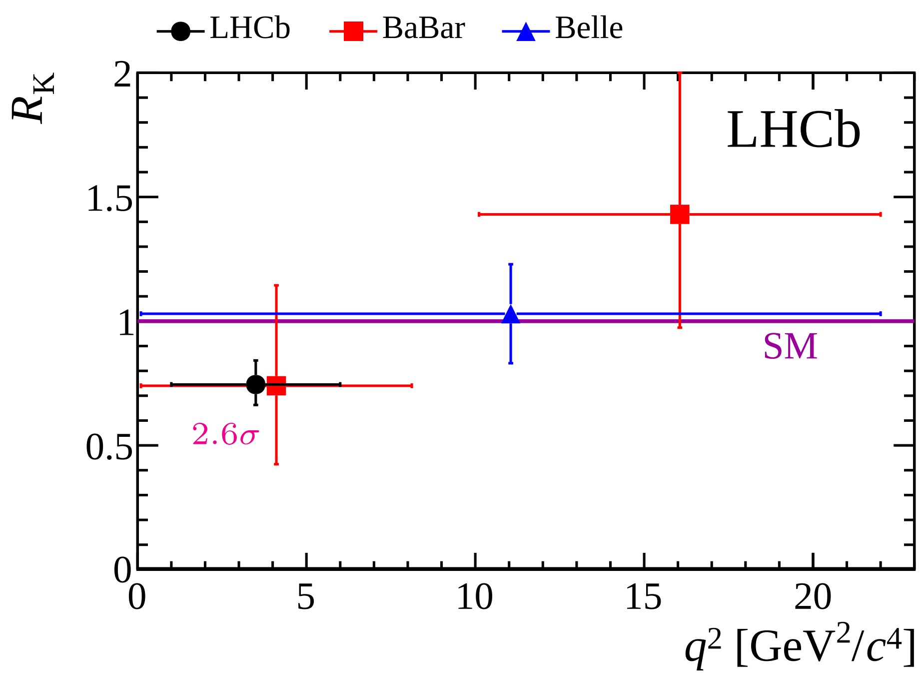
  Can fit 1), 3), 4) simultaneously: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2\,, \quad C_{9,\mu} = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu)$

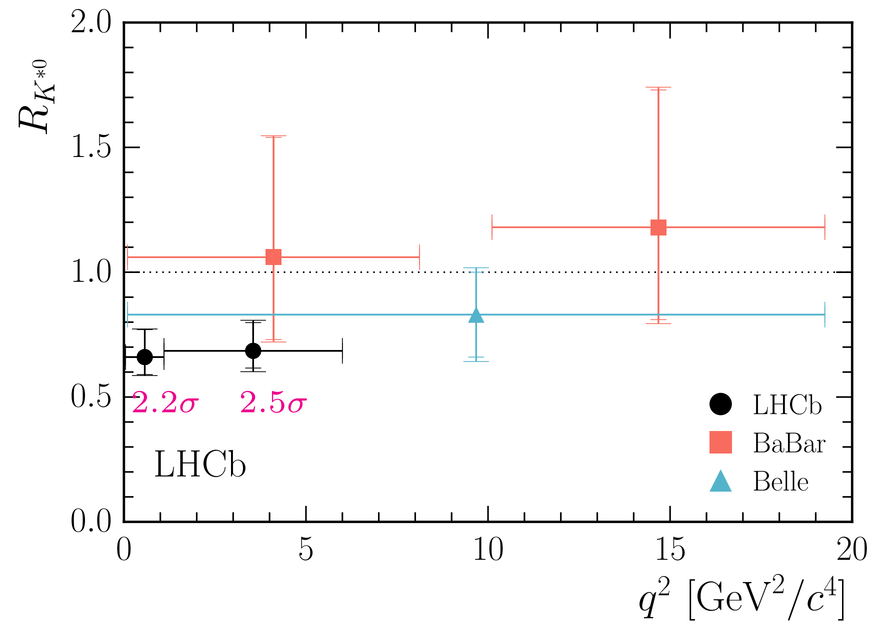
- Focus on $R(D^{(*)})$, b/c theory can be improved a lot, independent of current data

- What are smallest deviations from SM, which can be unambiguously established?

R_K and R_{K^*}: theoretically cleanest

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ both ratios over 2.5σ from lepton universality





- Theorists' fits quote $4-5\sigma$ (sometimes including P_5' and/or $B_s \to \phi\mu^+\mu^-$)

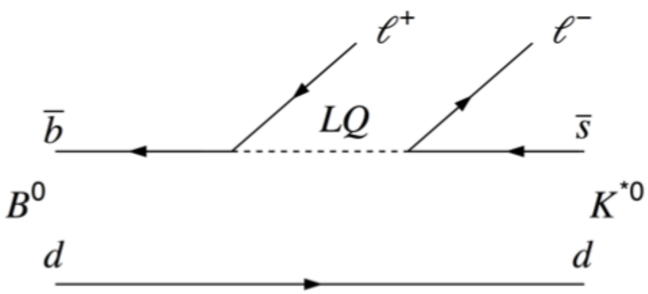
- Modifying one Wilson coefficient in $\mathcal{H}_{\rm eff}$ gives good fit: $\delta\, C_{9,\mu} \sim -1$

E.g., leptoquarks & flavor structures

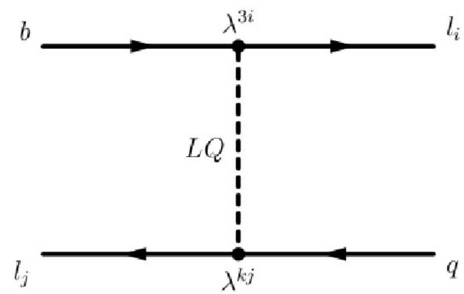
- Leptoquarks are some of the most often discussed models for $R_{K^{(*)}}$ and $R(D^{(*)})$

  A-priori no reason for the leptoquark couplings to be (approx.) flavor conserving

  Need this to explain $b \to s\ell^+\ell^-$ data



  Need to worry about all $b \to q\ell_1^+\ell_2^-$ couplings



$$\lambda = \begin{pmatrix} \lambda_{de} & \lambda_{d\mu} & \lambda_{d\tau} \\ \lambda_{se} & \lambda_{s\mu} & \lambda_{s\tau} \\ \lambda_{be} & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix}$$

- R_K implies: $0.7 \lesssim \mathrm{Re}(\lambda_{se}\lambda_{be}^* - \lambda_{s\mu}\lambda_{b\mu}^*)\,\dfrac{(24\,\mathrm{TeV})^2}{M^2} \lesssim 1.5$

- Search for LFV in $B \to K^{(*)}\mu^\pm e^\mp$, $B \to K^{(*)}\mu^\pm\tau^\mp$, etc.,

  similarly in D and K decays, and LFV in purely leptonic processes

[E.g.: de Medeiros Varzielas, Hiller, 1503.01084; Freytsis, ZL, Ruderman, 1506.08896; many more]

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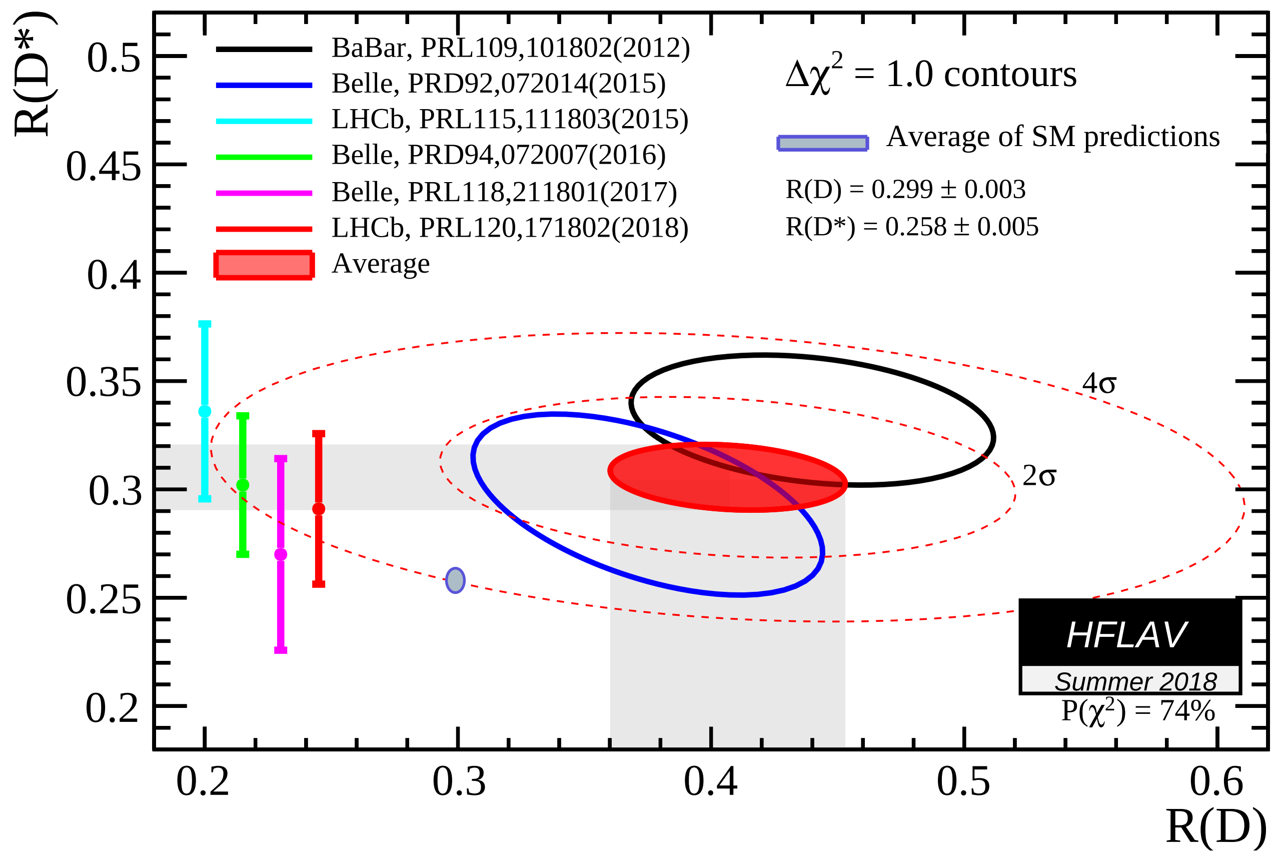
The $b \to c\tau\bar{\nu}$ data

$R(D)$ and $R(D^*)$ — $4\,\sigma$ tension with SM

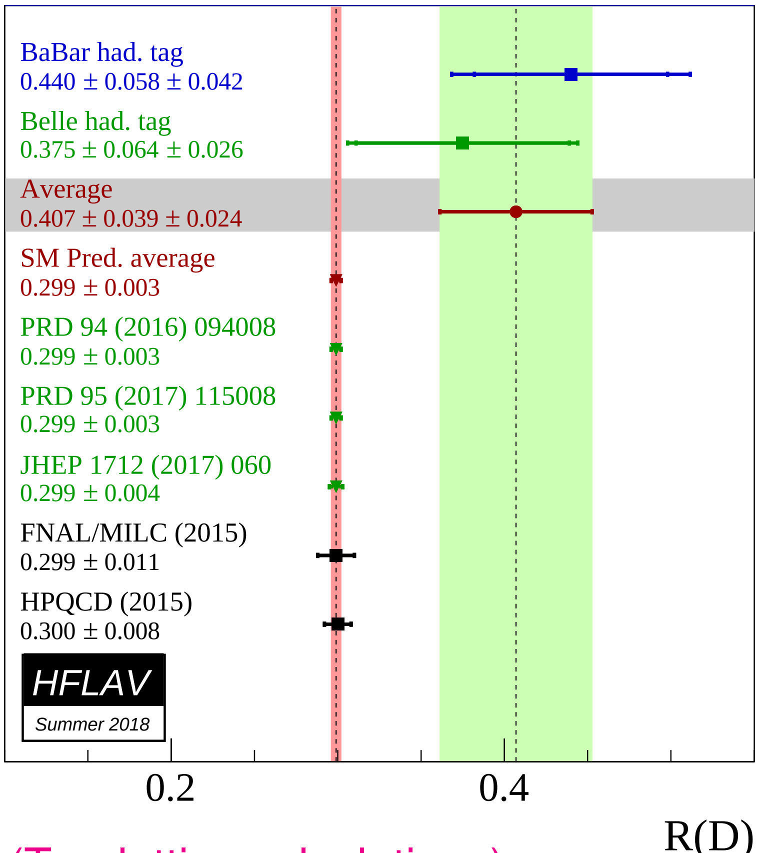
- BaBar, Belle, LHCb: enhanced τ rates, $R(D^{(*)}) = \dfrac{\Gamma(B \to D^{(*)}\tau\bar\nu)}{\Gamma(B \to D^{(*)}l\bar\nu)} \qquad (l = e, \mu)$

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

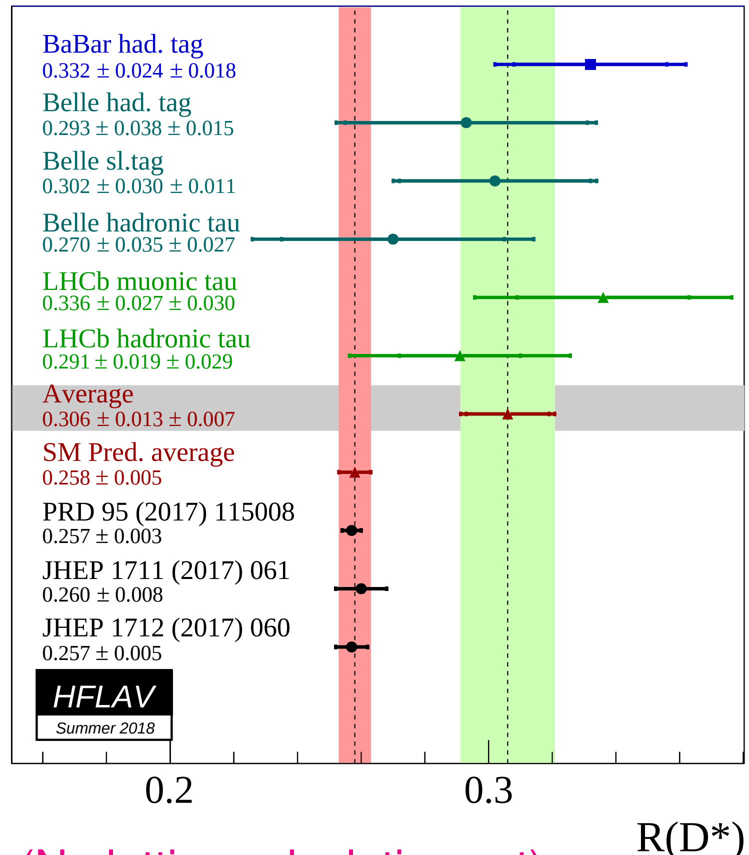


Another look at the data

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



(Two lattice calculations)



(No lattice calculation yet)

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

Not discussed 1981 – 2012 ?

CLNS 51/505
CLEO 81/05
JULY 1981

CLEO

CORNELL HARVARD ROCHESTER RUTGERS SYRACUSE VANDERBILT

WHAT CAN WE HOPE TO LEARN
FROM B MESON DECAY?

Proceedings of a
CLEO Collaboration Workshop

Fig. 3. A Program to Understand B Decay

1. Search for exotic B decays.
   If found, explore details;
   -otherwise-

   $\Rightarrow$ dark sector searches? violating symmetries?

2. Search for flavor changing neutral currents.
   If found, measure $(b \to dZ^o)/(b \to sZ^o)$;
   -otherwise-

   $\Rightarrow$ big part of the program

3. Measure semileptonic decay branching ratio.

   $\Rightarrow$ big part of the program

4. Measure ratio $(b \to uW^-)/(b \to cW^-)$.

   $\Rightarrow$ $|V_{ub}/V_{cb}|$: essential to constrain NP

$\Rightarrow$ 5. Measure $e\nu:\mu\nu:\tau\nu$ ratio in semileptonic decay.

   $\Rightarrow$ Prophecy of $R(D^{(*)})$?

- - - - - - - - - -

Non-b-Decay Features of B Decay

6. Look for lifetime difference between $B^\pm$ and B^o.

   $\Rightarrow$ Seems less important now

7. Look for B^o-$\bar{B}^o$ mixing.

   $\Rightarrow$ Was the first item accomplished

[8. CP violation?]

   $\Rightarrow$ Became a central focus of the field

[Ed Thorndike's overview; Mark discussed Higgs in B decay]

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Reasons (not) to take the tension seriously

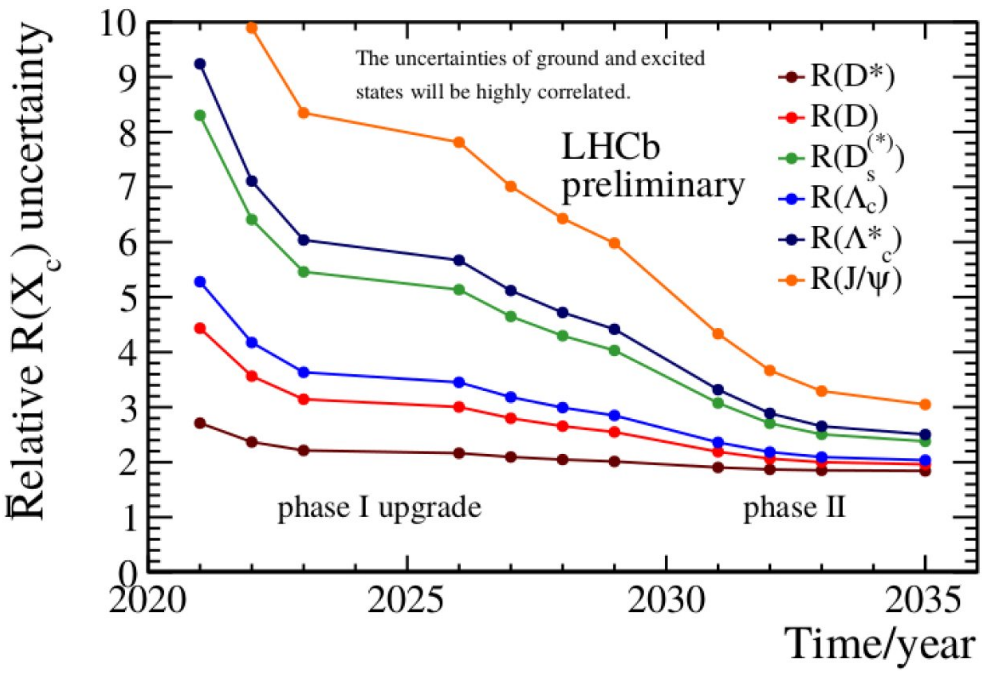
- Measurements with τ leptons are difficult
- Need a large tree-level contribution, SM suppression only by m_τ

  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

Exciting future

- LHCb: $R_{K^{(*)}}$ sensitivity with Run 1–2 data $> 5\sigma$ for current central values
- LHCb and Belle II: increase $pp \to b\bar{b}$ and $e^+e^- \to B\overline{B}$ data sets by factor ~ 50
- LHCb:



Belle II (50/ab, at SM level):

$\delta R(D) \sim 0.005\ (2\%)$

$\delta R(D^*) \sim 0.010\ (3\%)$

Measurements will improve a lot!

(Even if central values change, plenty of room for establishing deviations from SM)

- Competition, complementarity, cross-checks between LHCb and Belle II
- Focus on the 3 modes that are expected to be most precise in the long trem

Other players: CMS ?

- CMS collected $\sim 10^{10}$ B decays this year with new trigger [CMS @ LHCC, May 2018]

B - parking

CMS is attempting to collect a **large dataset enriched in B physics**. One specific and one general use cases:

- Allow CMS to measure R_K and R_{K^*} in a competitive way
- Prepare a O(10 B) sample of unbiased B hadron decays
  - Trigger on "the other B"
- How: on average, we need to increase our parking rate from 500Hz to 2kHz
  - This collects ~10B of Bs
- This is new: after a lot of internal discussions, green light on May 10th

Trigger Strategy:

- Muon trigger at L1 (as inclusive as possible)
- Minimal cleanup at HLT
- Requirement on impact parameter, to enhance b-quark content

Usage:

- Offline, look for the other b
- Measure ratios: Trigger efficiency will cancel out

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}$$

How?
When?
Where?

Some key questions — now and in the future

- Can it be a theory issue? — not at the current level
- Can it be an experimental issue? — someone else's job
- Can [reasonable] models fit the data? — yes [subjective] (won't say much)

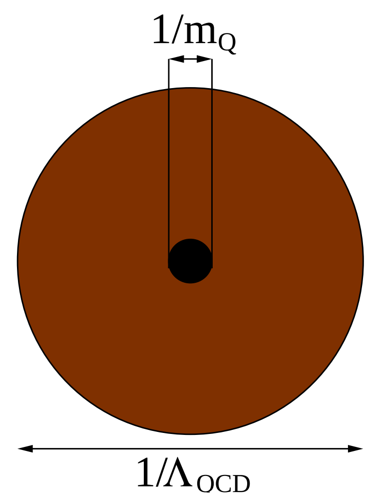
- What is the smallest deviation from SM in $R(D^{(*)})$ that can be established as NP?
  ... we know how to make progress
- Which channels are most interesting? (To establish deviation from SM / understand NP?)
  $B_{(s)} \to D_{(s)}^{(*,**)} \ell\bar{\nu}$, $\Lambda_b \to \Lambda_c^{(*)} \ell\bar{\nu}$,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

SM predictions — mesons

Heavy quark symmetry 101

- $Q\,\overline{Q}$: positronium-type bound state, perturbative in the $m_Q \gg \Lambda_{\rm QCD}$ limit
- $Q\,\bar{q}$: 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 $\to 0$]

Spectroscopy of heavy-light mesons

- In $m_Q \gg \Lambda_{\rm QCD}$ limit, spin of the heavy quark is a good quantum number, and 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:

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

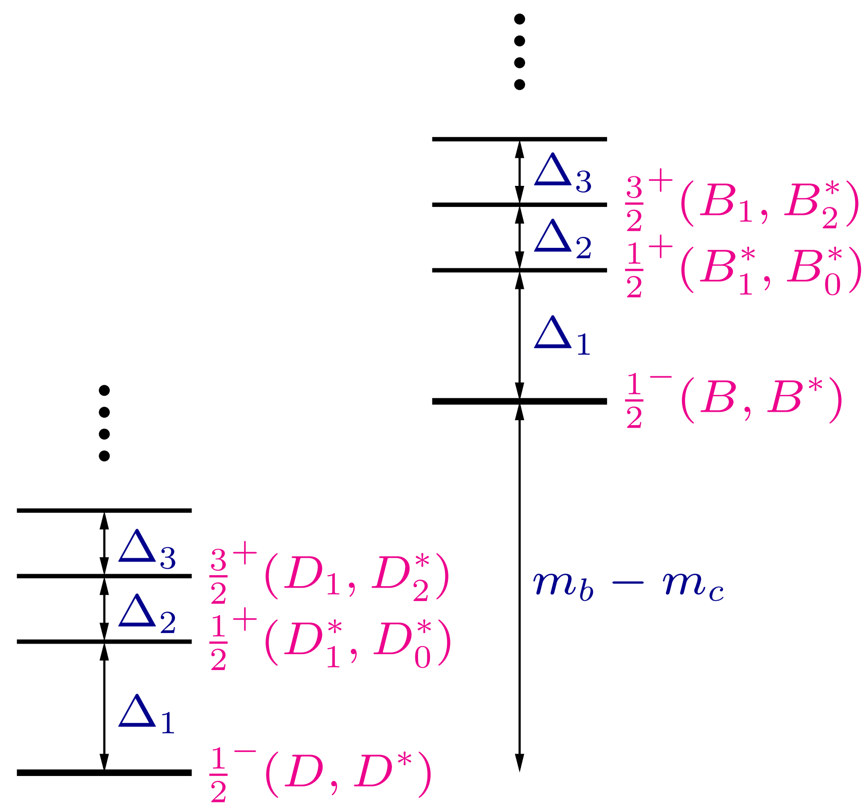
$\Rightarrow \Delta_i = \mathcal{O}(\Lambda_{\rm QCD})$ — same in B and D sector

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

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

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

ratio $\sim m_c/m_b$



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

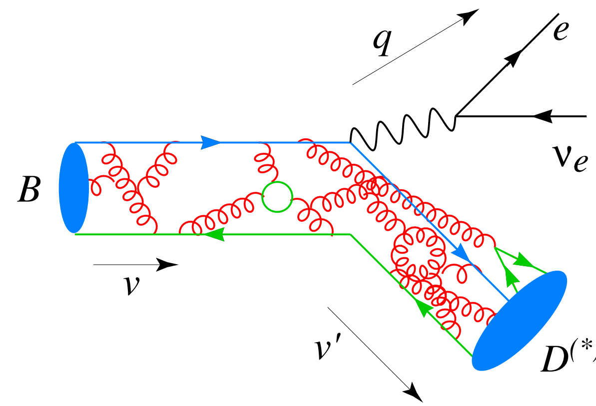
- In the $m_{b,c} \gg \Lambda_{\rm QCD}$ limit, configuration of brown muck only depends on the four-velocity of the heavy quark, but not on its mass and spin
- On a time scale $\ll \Lambda_{\rm QCD}^{-1}$ weak current changes $b \to c$
  i.e.: $\vec{p}_b \to \vec{p}_c$ and possibly $\vec{s}_Q$ flips

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

  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 $\zeta(1) = 1$]

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

- "Idea": fit 4 functions with 4 observables...
- Lorentz invariance: 6 functions of q^2, only 4 measurable with e, μ 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 $f_0 - f_+$ 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 $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$

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

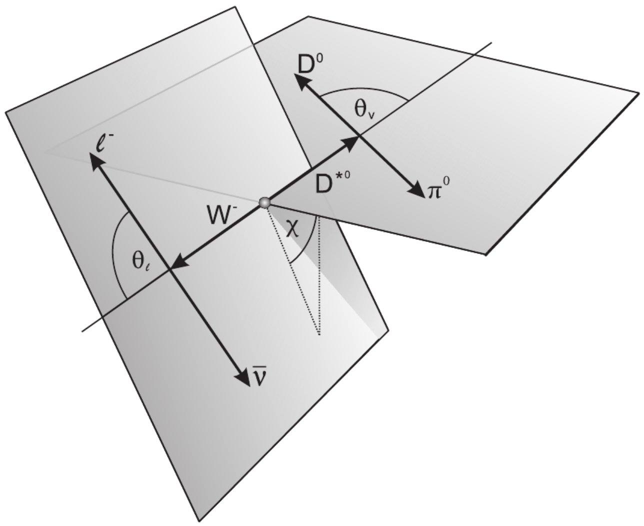
[Bernlochner, ZL, Papucci, Robinson, 1703.05330]

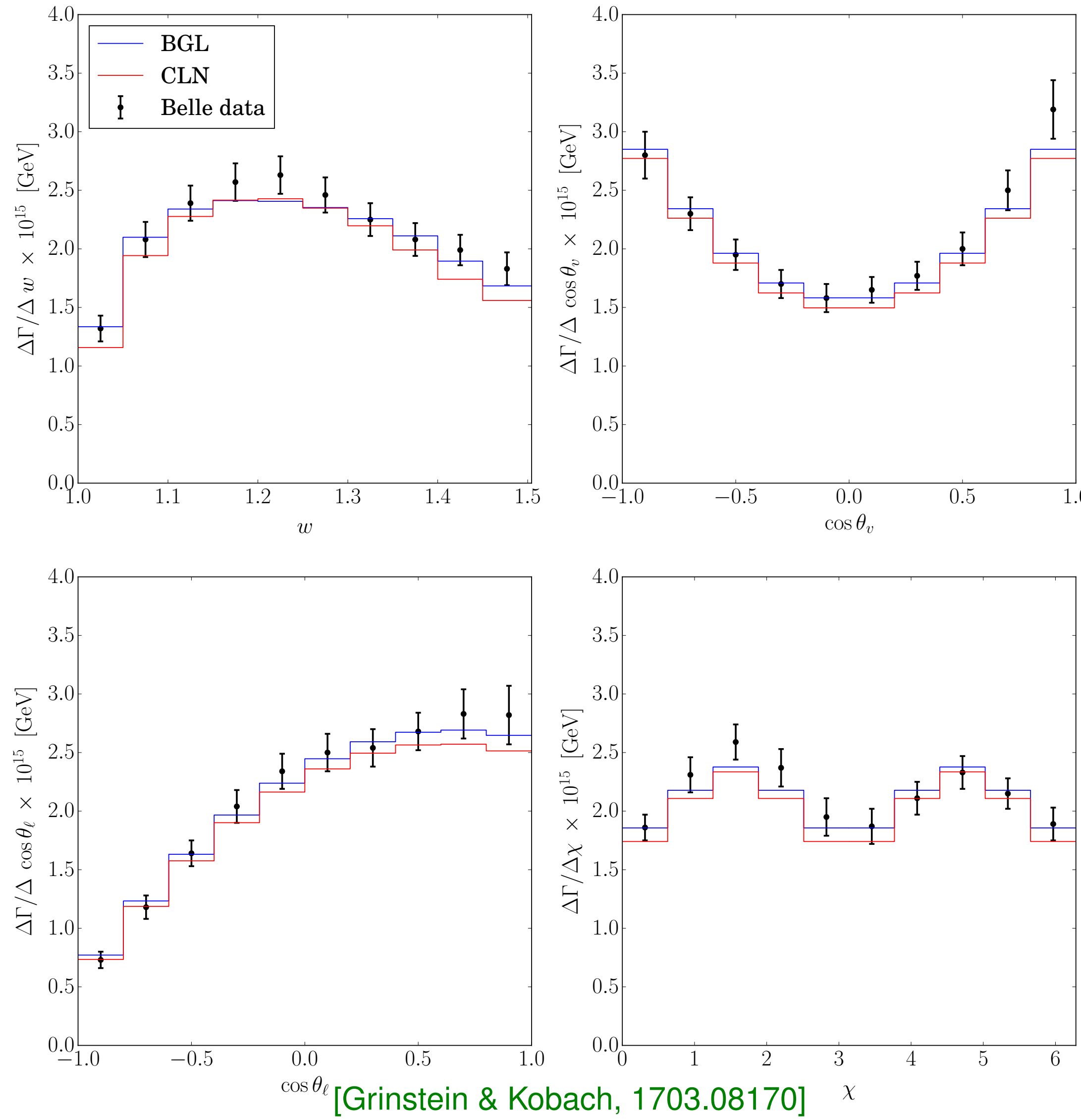
- Observables: $B \to Dl\bar\nu:\ \mathrm{d}\Gamma/\mathrm{d}w$ (Only Belle published fully corrected distributions)

  $B \to D^* l\bar\nu:\ \mathrm{d}\Gamma/\mathrm{d}w$ and $R_{1,2}(w)$ form factor ratios

Available for the first time in 2017

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





[Grinstein & Kobach, 1703.08170]

- Can perform different fits to data

- Need input on the fitted shape:

  BGL: Boyd, Grinstein, Lebed, ’95–97

  CLN: Caprini, Lellouch, Neubert, ’97

Explored 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	+	+	+	+	—

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

Same parameters determine $R_{1,2}(1) - 1$ (fit) and $R^{(n)}_{1,2}(1)$ (rely on QCDSR)

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

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

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

Reference (Scenario)	$R(D)$	$R(D^*)$	Correlation
Data [HFLAV]	0.407 ± 0.046	0.306 ± 0.015	-20%
Lattice [HFLAV]	0.300 ± 0.008	—	—
Fajfer et al. '12	—	0.252 ± 0.003	—
Bernlochner *et al.* '17 ($\mathrm{L}_{w\geq1}$)	0.298 ± 0.003	0.261 ± 0.004	19%
Bernlochner *et al.* '17 ($\mathrm{L}_{w\geq1}$+SR)	0.299 ± 0.003	0.257 ± 0.003	44%
Bigi, Gambino '16	0.299 ± 0.003	—	—
Bigi, Gambino, Schacht '17	—	0.260 ± 0.008	—
Jaiswal, Nandi, Patra '17 (case-3)	0.302 ± 0.003	0.262 ± 0.006	14%
Jaiswal, Nandi, Patra '17 (case-2)	0.302 ± 0.003	0.257 ± 0.005	13%

- HFLAV SM expectation neglects correlations present in any theoretical framework

  (Light-cone QCD SR & HQET QCD SR inputs are model dependent)

- None of these are "ultimate" results — can be improved in coming years

SM predictions — baryons

No $R(\Lambda_c)$ measurement yet — maybe soon?

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 to appear in PRL; 1811.?????]

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

($\bar\Lambda_\Lambda \sim 0.8\,\text{GeV}$ 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 $\mathcal{O}(\Lambda_{\text{QCD}}/m_{b,c})$ subleading Isgur-Wise function, only 2 at $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$
- Can do more using HQET than for meson decays

In $B \to D^{(*)} \ell \bar\nu$ decay, there are 6 sub-subleading Isgur-Wise functions at $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$

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

---

- 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 no difference)

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

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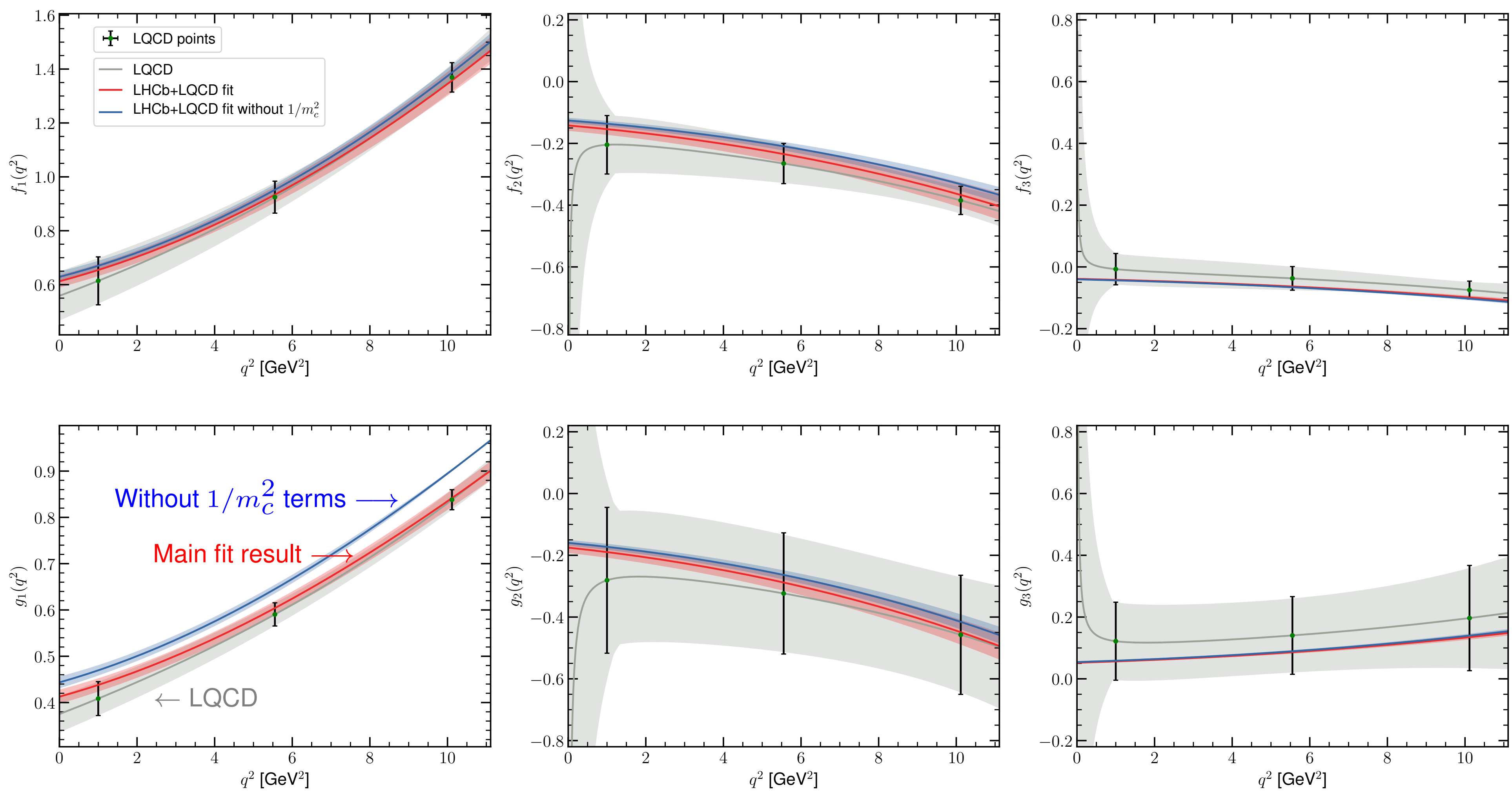
Fit to lattice QCD form factors and LHCb (1)

- 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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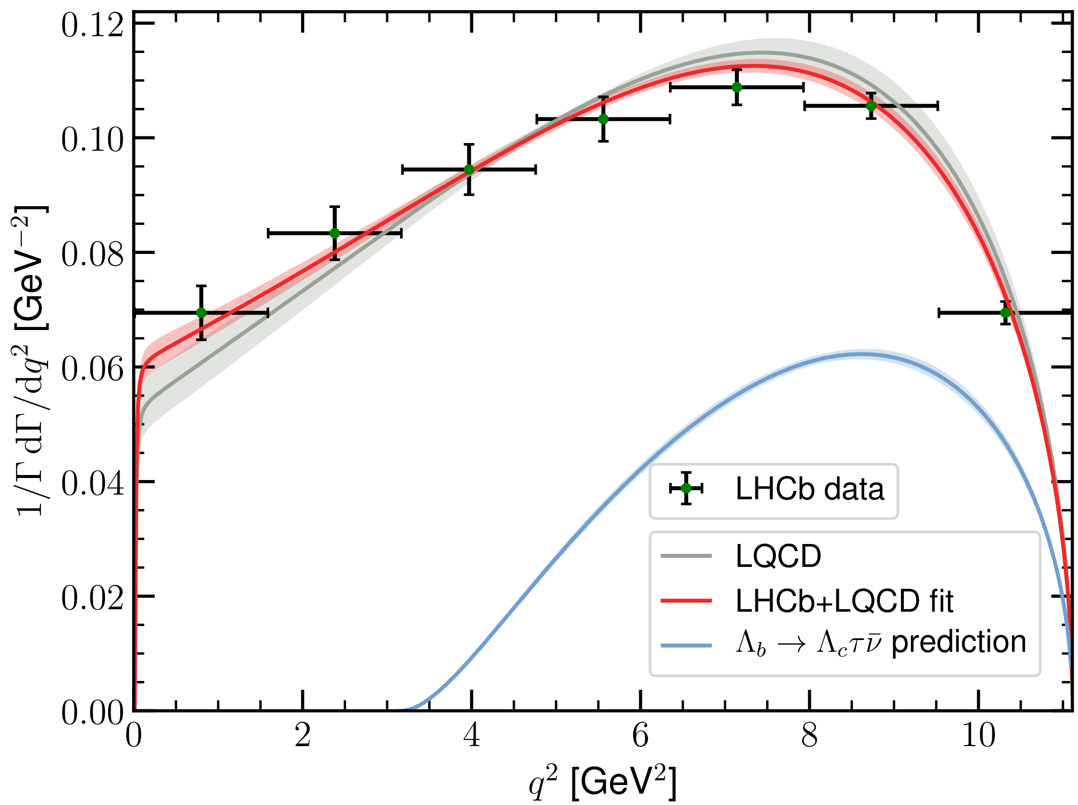
Fit to lattice QCD form factors and LHCb (2)

- 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 $R(\Lambda_c)$

- Our results will make their way into Hammer MC (Helicity Amplitude Module for Matrix Element Reweighting) [Bernlochner, Duell, ZL, Papucci, Robinson, soon]

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

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

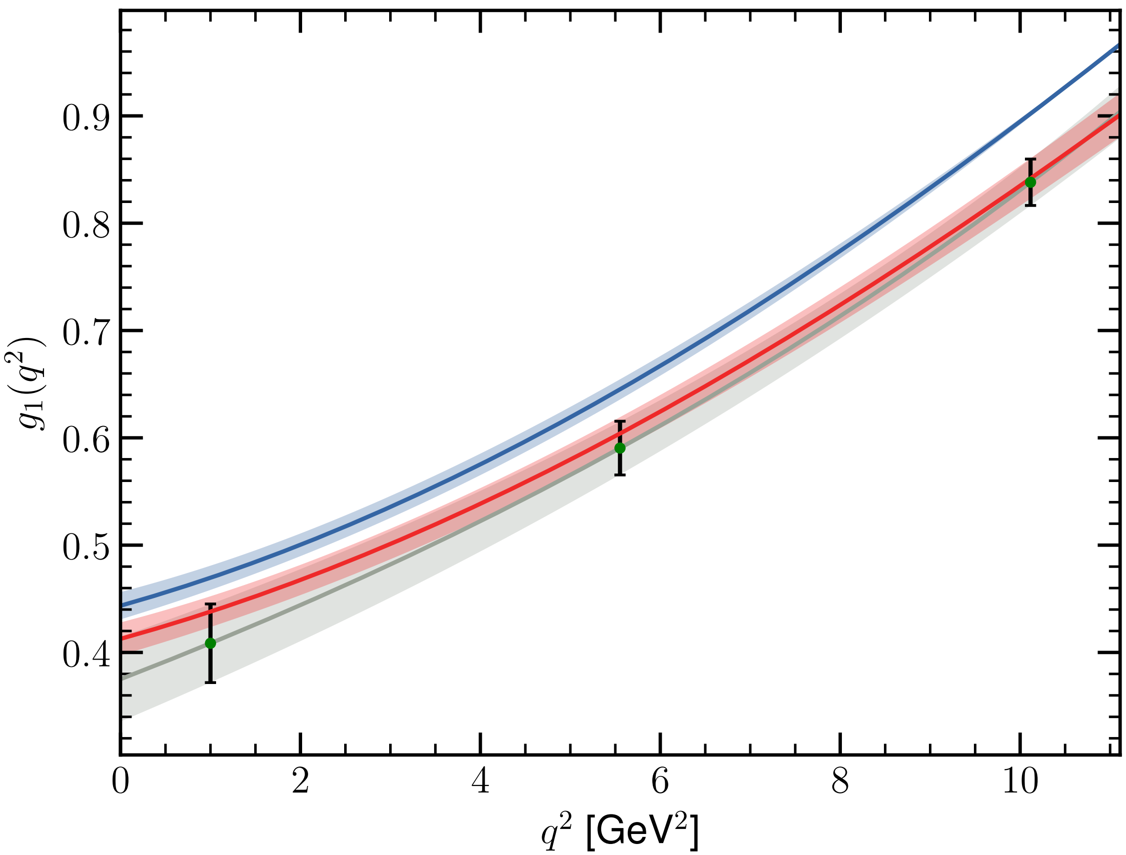
- Find: $\hat{b}_1 = -(0.46 \pm 0.15)\,\mathrm{GeV}^2$
  ... of the expected magnitude

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

  [Falk & Neubert, hep-ph/9209269]

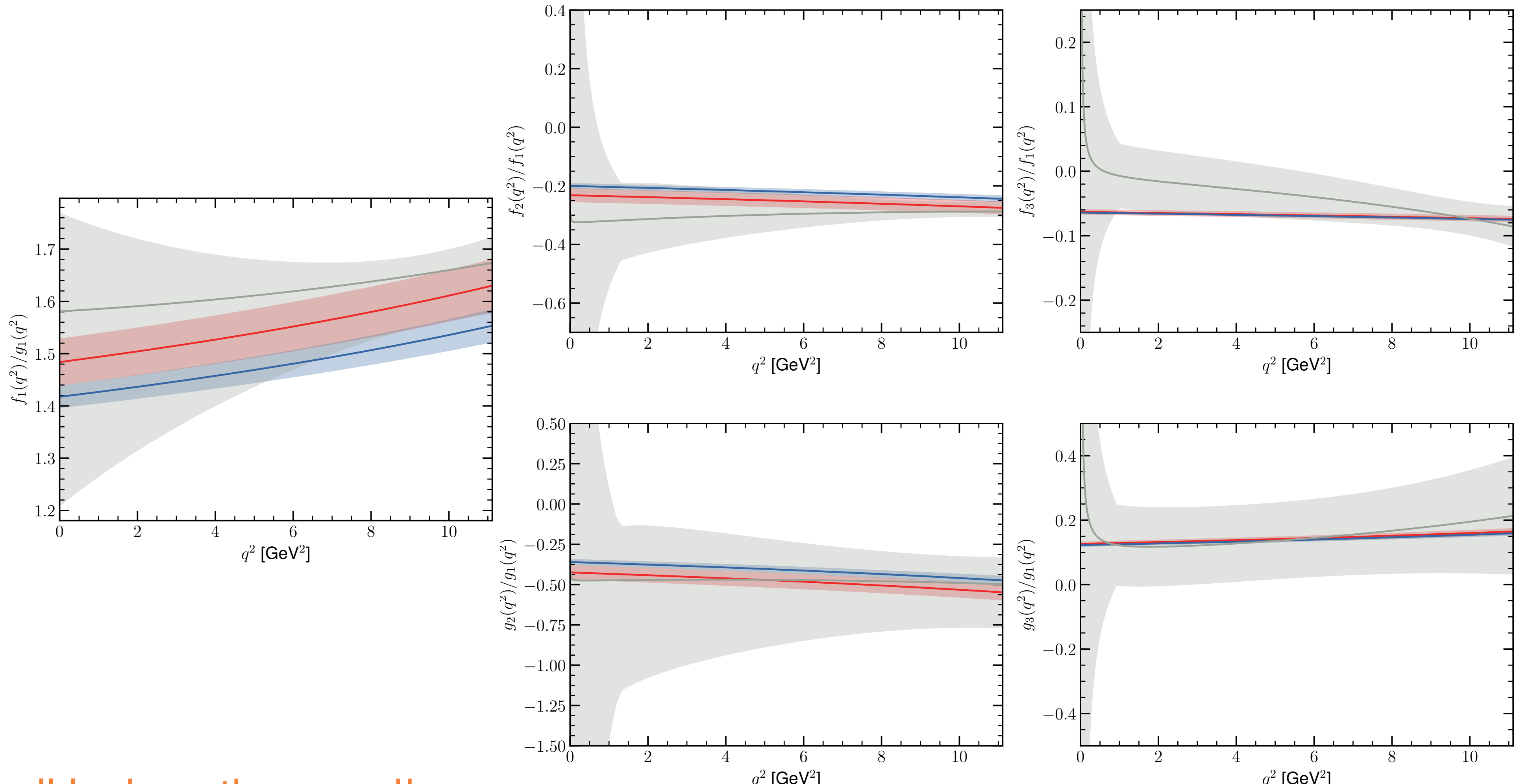
- Expansion in $\Lambda_{\mathrm{QCD}}/m_c$
  appears well behaved

  (contrary to some claims in literature)



The 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 — problems?

- There are 4 form factors

We get parameter free predictions!

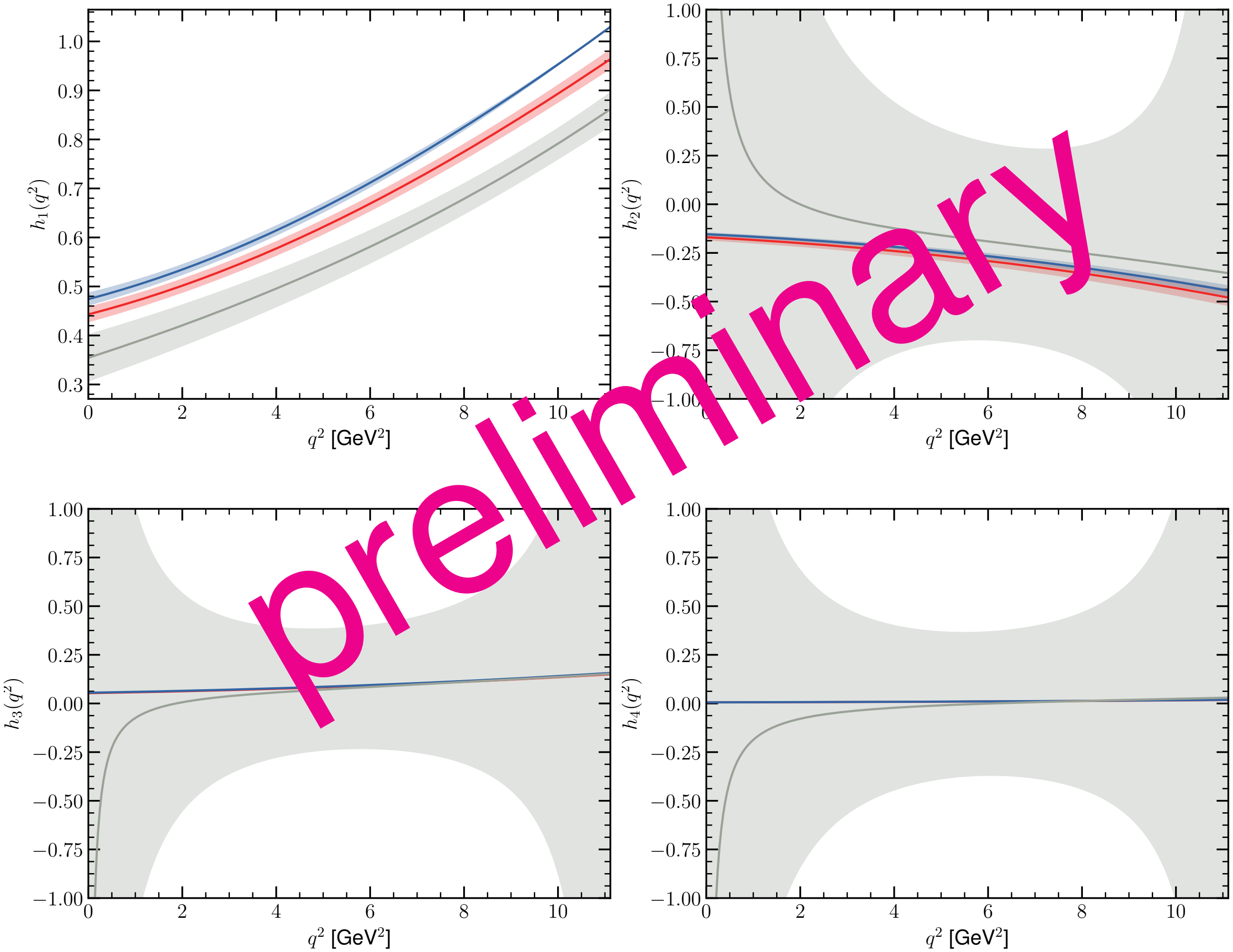
HQET: $h_1\,(=\widetilde{h}_+) = \mathcal{O}(1)$

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

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, double checking possible issues for the leading term

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Spinoffs, byproducts, etc.

Has $|V_{cb}|$ been settled?

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

- 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

- Inclusive / exclusive tension resolved? Fits to Belle $B \to D^* l\bar\nu$ data (all good χ^2):

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

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

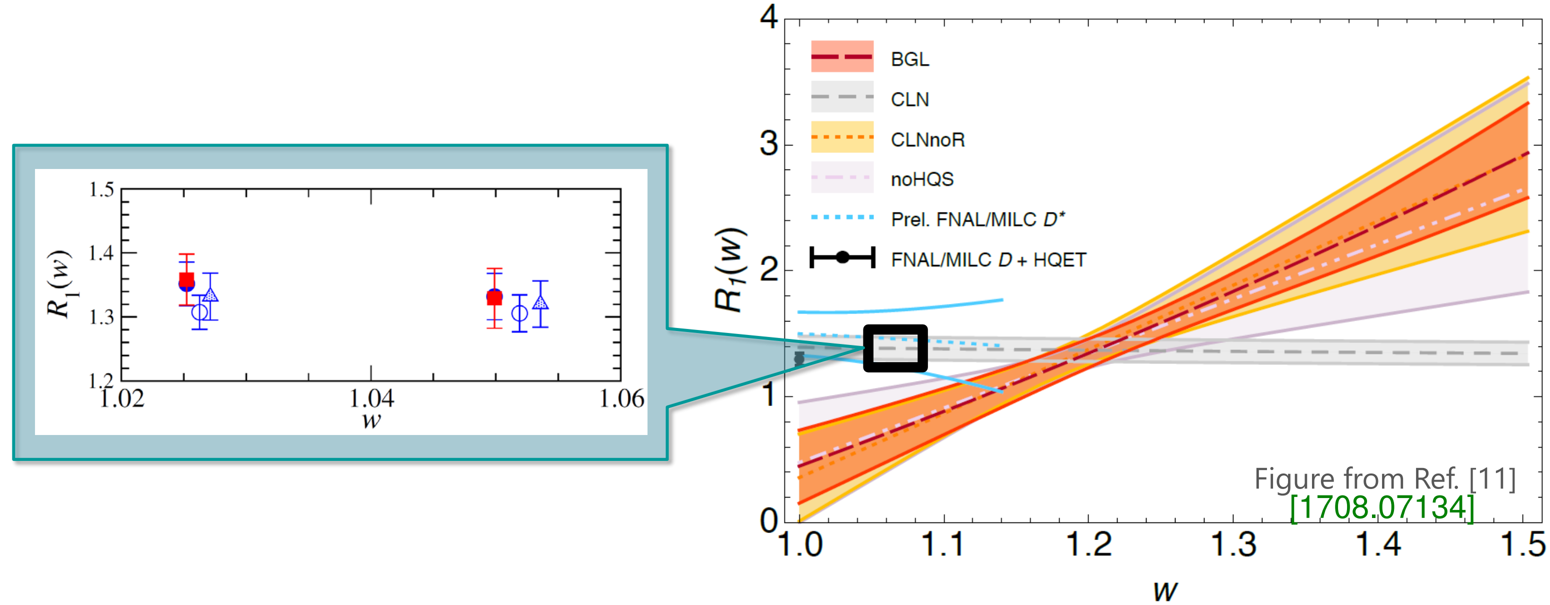
  Belle, 1702.01521, $|V_{cb}|_{\rm CLN} = (38.2 \pm 1.5) \times 10^{-3}$

- Besides BGL, CLN, we considered 2 other frameworks to "interpolate" [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	$a_0,\ a_1$	$\left\{ R_1(1),\ R_2(1) \right.$	$\left\{ \begin{matrix} R_1(1),\ R_1'(1) \\ R_2(1),\ R_2'(1) \end{matrix} \right.$	$\left\{ \begin{matrix} R_1(1),\ R_1'(1) \\ R_2(1),\ R_2'(1) \end{matrix} \right.$
$\mathcal{F}$	$c_1,\ c_2$			

Understanding $|V_{cb}|$

- Besides FNAL, JLQCD is also calculating the $B \to D^* \ell \bar{\nu}$ form factors
  Independent formulations: staggered vs. Mobius domain-wall actions



Therefore, this issue is still open. These parametrizations should be eventually replaced by a lattice-based parametrization.

[T. Kaneko, JLQCD poster at Lattice 2018, 1811.00794 today]

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

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Importance of lepton flavor violation searches

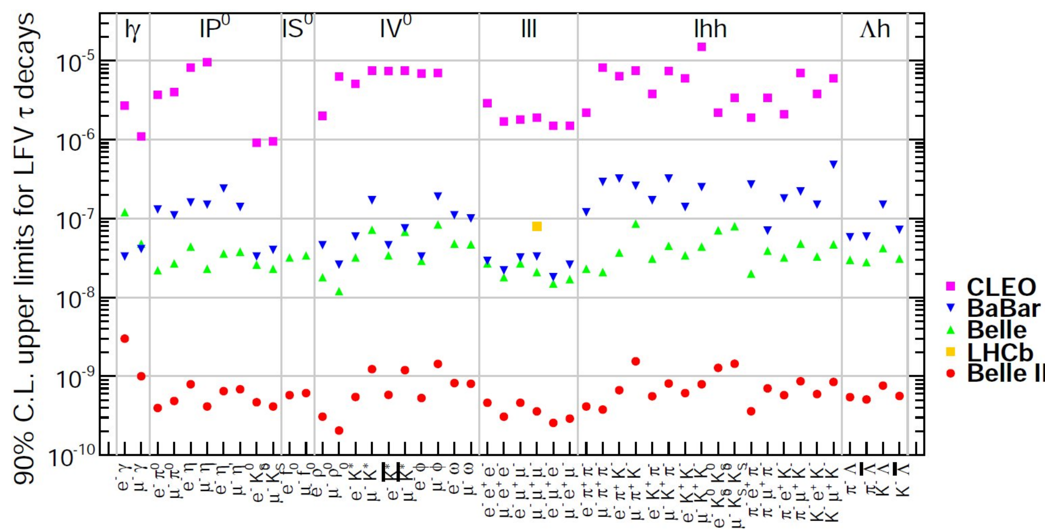
- Quark sector: If TeV-scale NP couples to quarks, some mechanism is needed to align couplings with SM Yukawas in order not to generate too large FCNCs

- Lepton sector: New lepton non-universal interaction would in general yield lepton flavor violation (LFV) at some level

- Many LFV searches became more interesting, not previously of high profile:
  E.g.: $B \to K^{(*)} e^{\pm}\mu^{\mp}$, $B \to K^{(*)} e^{\pm}\tau^{\mp}$, $B \to K^{(*)} \mu^{\pm}\tau^{\mp}$, also in D & K decay

  $\mu \to e\gamma,\ \mu \to eee,\ \mu + N \to e + N^{(\prime)}$,

  τ decays: $\tau \to \mu\gamma,\ \mu\mu\mu,\ eee,\ \mu\mu e$, etc.
  Belle II: improve 2 orders of magnitude



- Any discovery $\Rightarrow$ broad program to map out the detailed structure

ATLAS & CMS: extend high p_T searches

- In some sense unusual & unexpected models: mediator masses, couplings, generation (non-)universality patterns differ from NP signals expected years ago

- Even just extending prior searches can be interesting
  (allowed regions of masses & couplings in strange models can be ... strange)
  - Extend $\tilde{t}$ and $\tilde{b}$ searches to higher production cross section
  - Search for $t \to b\tau\bar{\nu}$, $c\tau^+\tau^-$ nonresonant decays
  - Search for states on-shell in t-channel, but not in s-channel
  - Search for $t\tau$ resonances

  ... Could be an entire talk

Conclusions

- Measurable NP contribution to $b \to c\ell\bar{\nu}$ would imply NP at a fairly low scale

  Viable BSM models (leptoquarks? no clear connection to DM & hirearchy puzzle)

- HQET predictions systematically improvable with more e, μ data

- The $\Lambda_{\mathrm{QCD}}/m_c$ terms are important, no evidence for bad behavior of expansion

- Measurements will improve in the next decade by nearly an order of magnitude

  (Even if central values change, plenty of room for significant deviations from SM)

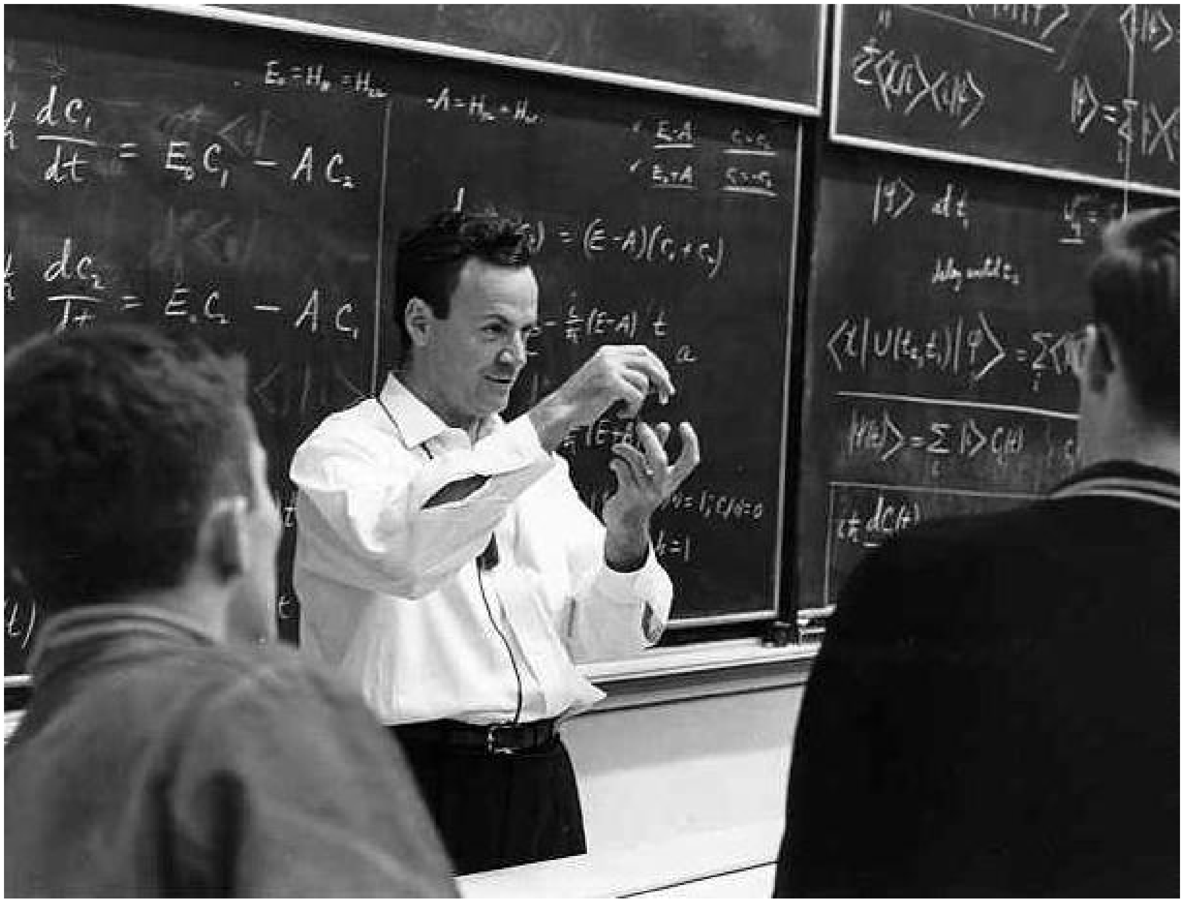
- New directions: model building, high-p_T searches, lepton flavor violation searches

- Best case: discover new physics

  Worst case: better SM tests, better CKM determination, better NP sensitivity

- We will find out: more data + improved predictions

Ultimately, data will tell



"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

Extra slides

Aside: the P_5' anomaly in $B \to K^* \mu^+ \mu^-$

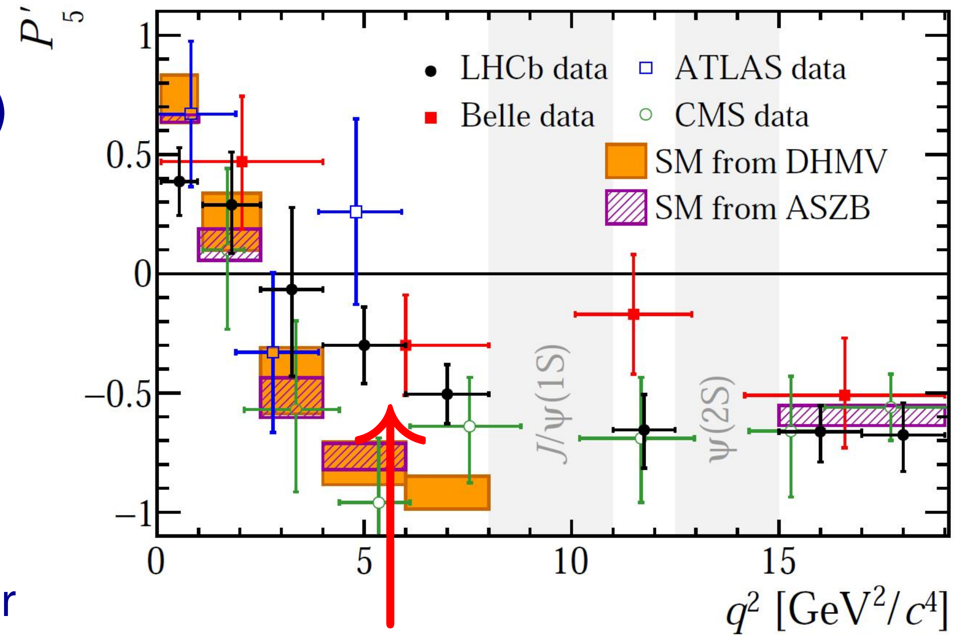
- "Optimized observables" [1202.4266 + long history]
  (some assumptions about what's optimal)

  Global fits: best solution: NP reduces C_9

  [Altmannshofer, Straub; Descotes-Genon, Matias, Virto; Jager, Martin Camalich; Bobet, Hiller, van Dyk; many more]

  Difficult for lattice QCD, large recoil

  What is the calculation which detremines how far below the J/ψ this comparison can be trusted?



NP, fluctuation, SM theory?

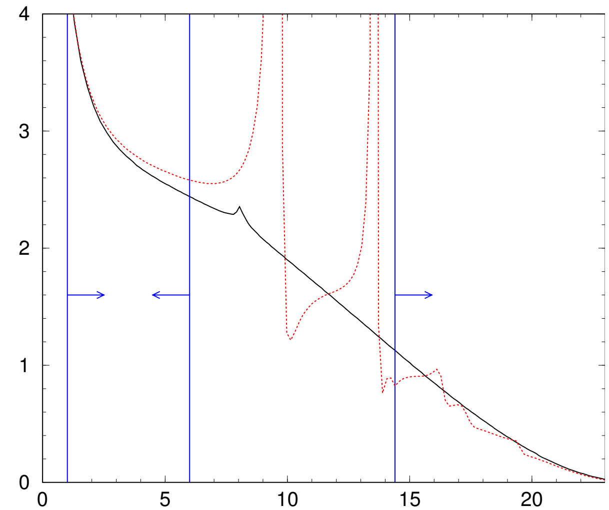
- Tests: other observables, q^2 dependence, B_s and Λ_b decays, other final states

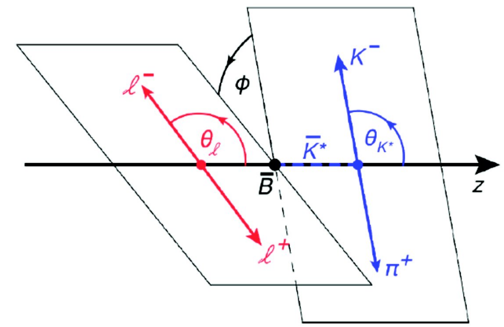
- Connected to many other processes: Is the $c\bar{c}$ loop tractable perturbatively at small q^2? Can one calculate form factors (ratios) reliably at small q^2?
  Impacts: semileptonic & nonleptonic, interpreting CP viol., etc.

Hadronic physics starts to enter

- Rate determined (mostly) by:

$$
\begin{aligned}
O_7 &= \overline{m}_b\, \bar{s}\sigma_{\mu\nu} e F^{\mu\nu} P_R b \\
O_9 &= e^2 (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \\
O_{10} &= e^2 (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)
\end{aligned}
$$





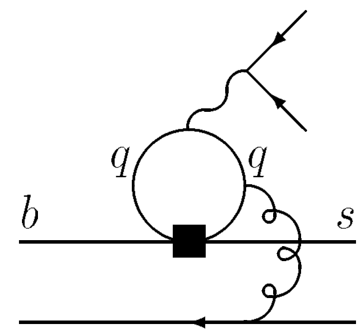
- Most often debated: validity of perturbative methods for:

$$\mathcal{B}(B \to \psi X_s) \sim 4 \times 10^{-3}$$

$$\downarrow$$

$$\mathcal{B}(\psi \to \ell^+\ell^-) \sim 6 \times 10^{-2}$$ their product: $\sim 2 \times 10^{-4}$

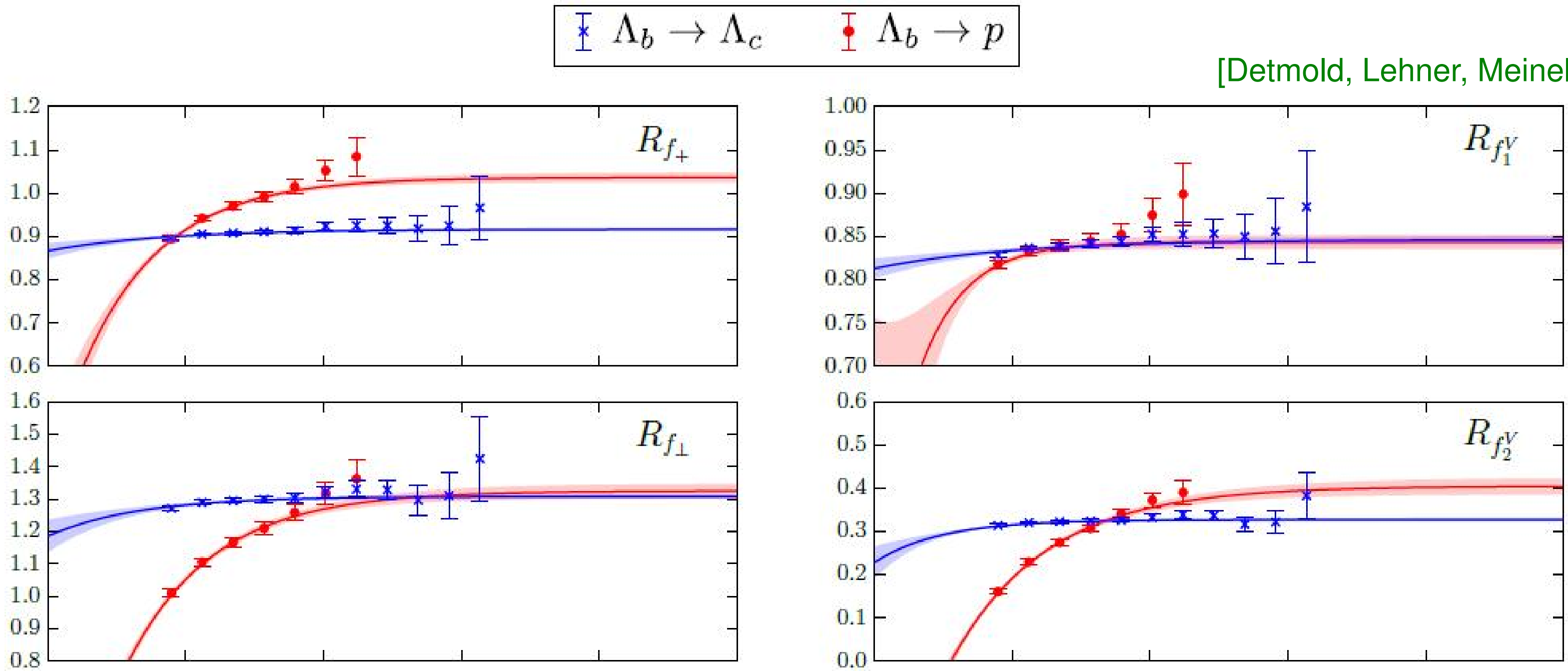
Much bigger than the short distance contribution...



- Not clear why so different than $e^+e^- \to$ hadrons

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]