# $\Lambda_b \to \Lambda_c \ell \bar{\nu}$ and tests of HQS

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**Implications of LHCb measurements and future prospects**
**CERN, Oct 17–19, 2018**

[Details: F. Bernlochner, ZL, D. Robinson, W. Sutcliffe, arXiv:1808.09464, arXiv:1810.?????]

# Ancient knowledge: baryons simpler than mesons

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

VOLUME 75, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 1995

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

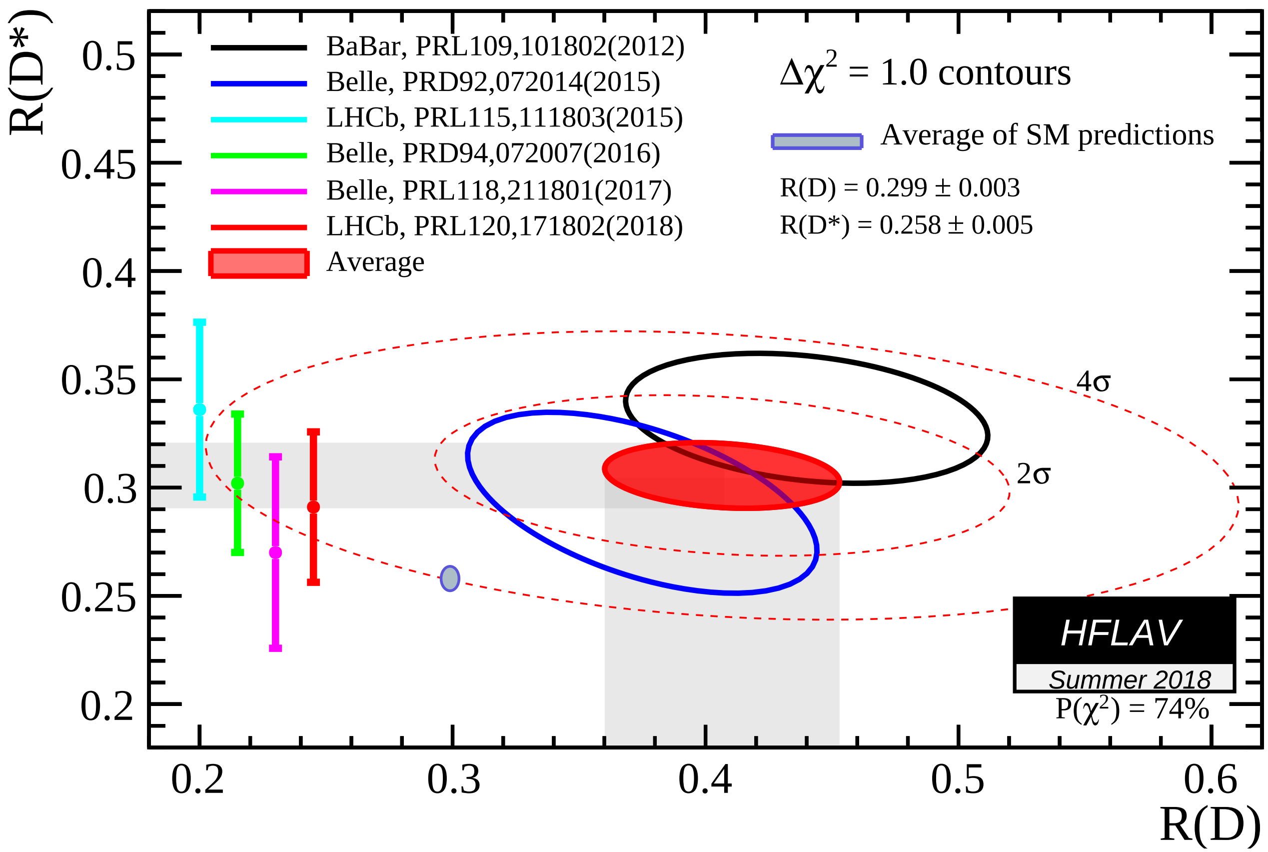
G. Crawford,[1] C. M. Daubenmier,[1] R. Fulton,[1] D. Fujino,[1] K. K. Gan,[1] K. Honscheid,[1] H. Kagan,[1] R. Kass,[1] J. Lee,[1]

[CLEO]

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

# $R(D)$ and $R(D^*)$

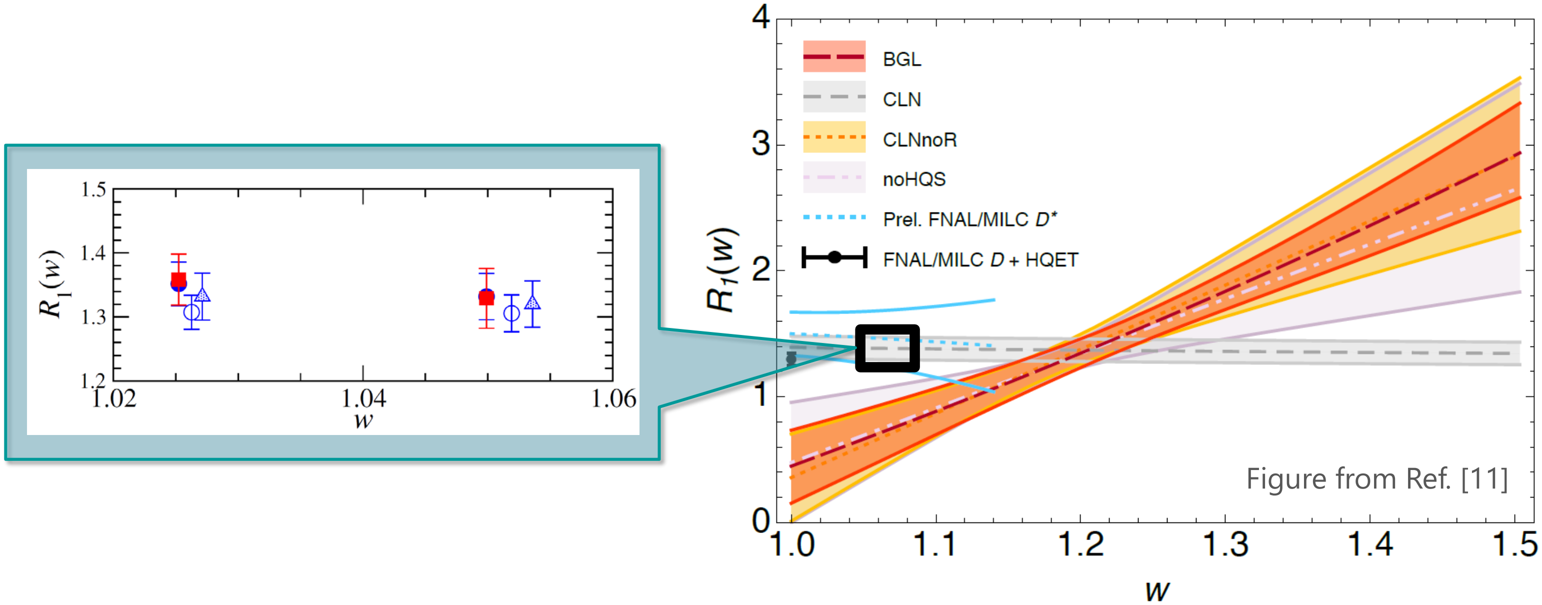
- BaBar, Belle, LHCb: enhanced $\tau$ rates, $R(D^{(*)}) = \dfrac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}l\bar{\nu})}$ $\quad (l = e, \mu)$



# Is $|V_{cb}|$ settled...?

- Besides FNAL, JLQCD is also calculating the $B \to D^{(*)}$ form factors

  Independent formulations: staggered vs. Mobius domain-wall actions

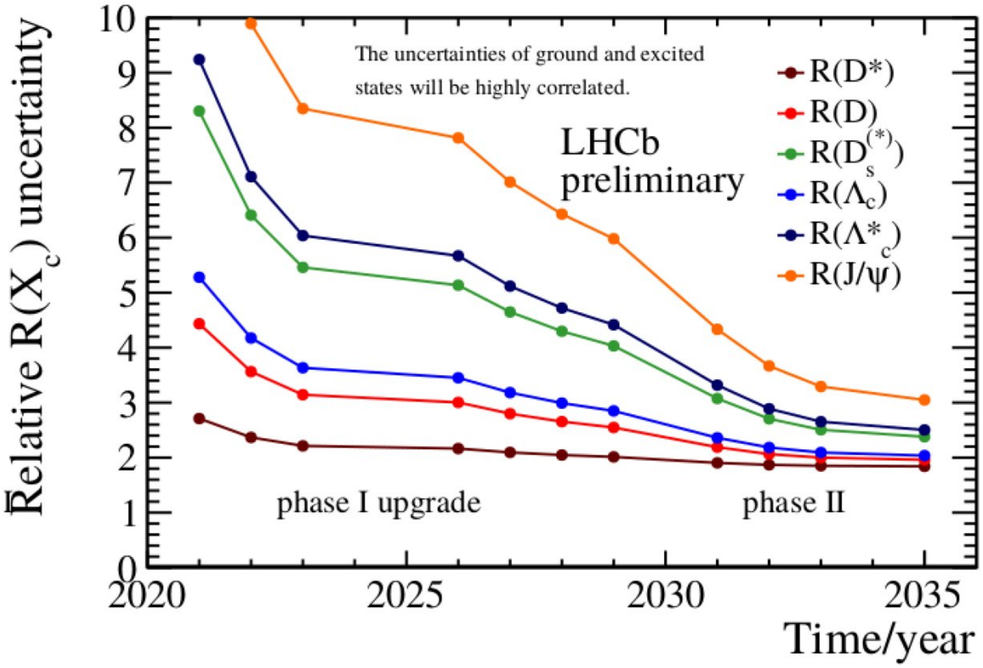



Therefore, this issue is still open. These parametrizations should be eventually replaced by a lattice-based parametrization.

[T. Kaneko, JLQCD poster at Lattice 2018]

# Exciting future

- LHCb and Belle II: increase $pp \to b\bar{b}$ and $e^+e^- \to B\overline{B}$ data sets by factor $\sim 50$
- 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

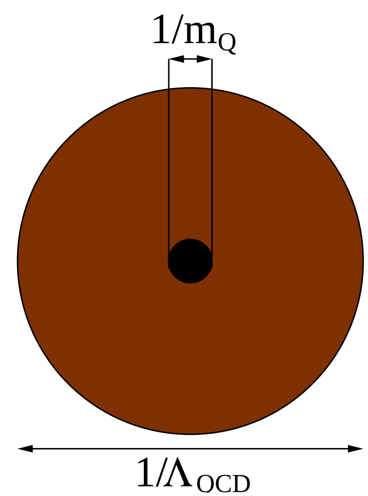
$$\boldsymbol{\Lambda_b \to \Lambda_c \ell \bar{\nu}}$$

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] — what can we learn?

# 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 $v^\mu$ [Isgur & Wise]

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

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

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

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

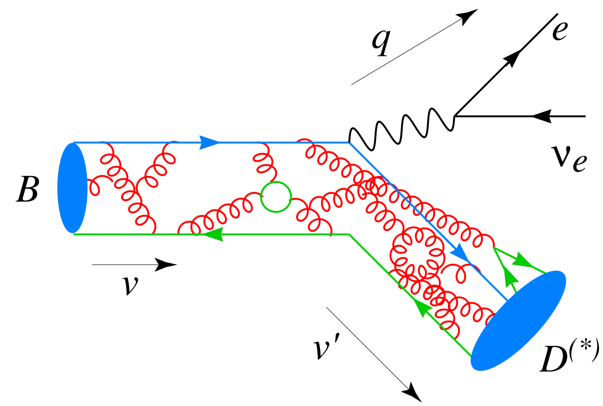
- In the $m_{b,c} \gg \Lambda_{\rm QCD}$ limit, configuration of brown muck only depends on the four-velocity of the heavy quark, but not on its mass and spin

- 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 $\zeta(1) = 1$]

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

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

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

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

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

- 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 $\mathcal{O}(\Lambda_{\mathrm{QCD}}^2/m_c^2)$

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# 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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- Our fit has only $4$ parameters: $\{\zeta',\ \zeta'',\ \hat{b}_1,\ \hat{b}_2\}$

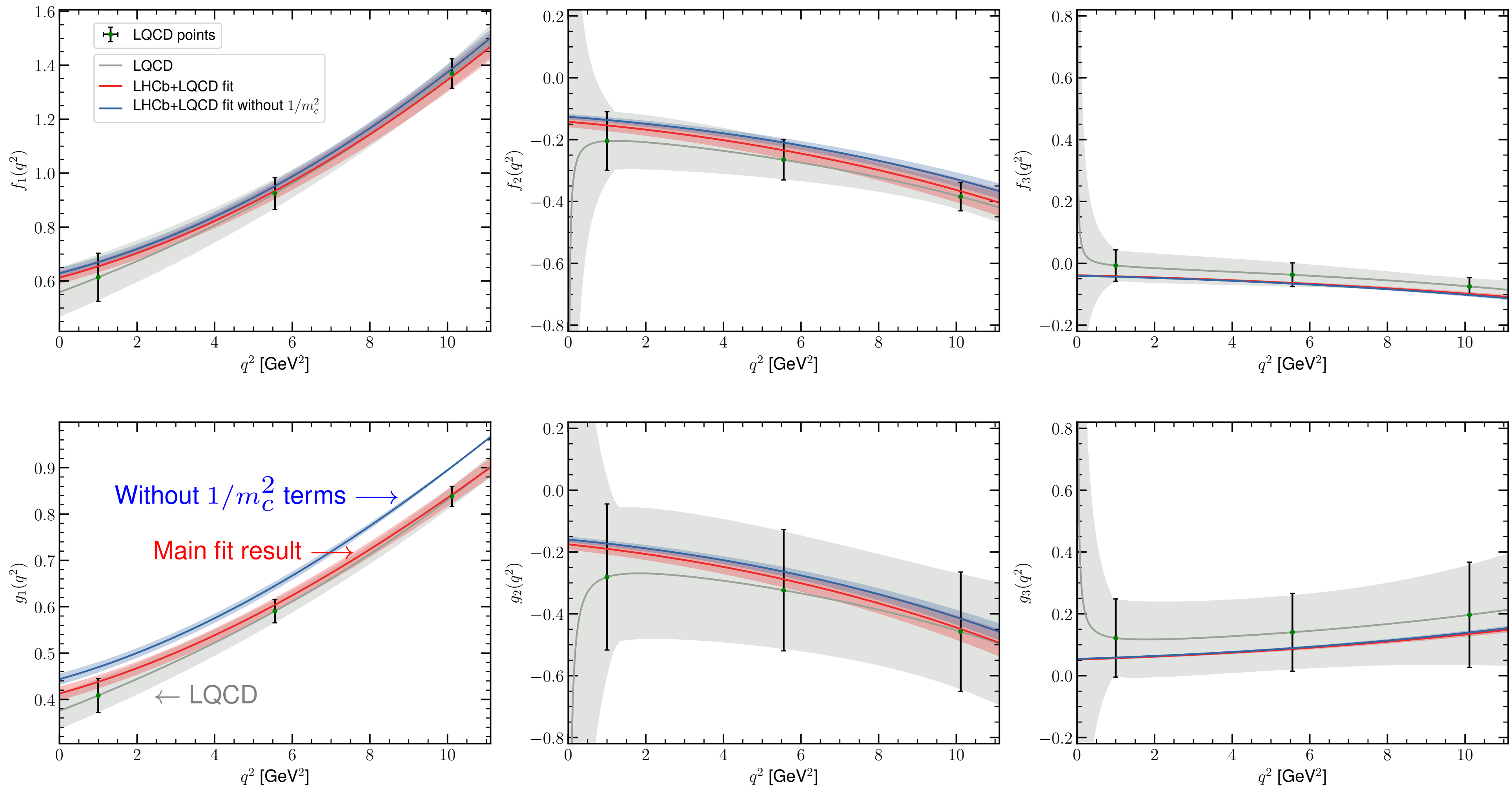
  $\zeta(w) = 1 + (w-1)\,\zeta' + \frac{1}{2}(w-1)^2\,\zeta'' + \dots \qquad b_{1,2}(w) = \zeta(w)\,\big(\hat{b}_{1,2} + \dots\big)$

  (Expanding to quadratic order in $w-1$ or in conformal parameter, $z$, makes no difference)

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

# 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]

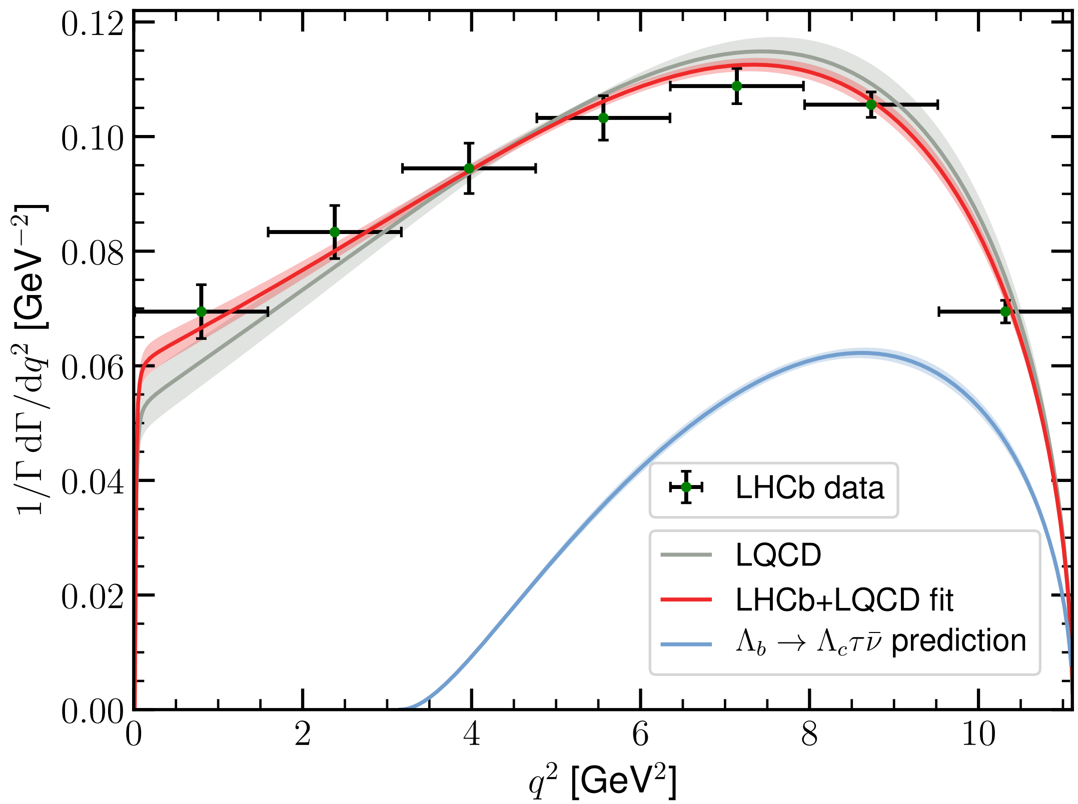


# Fit to lattice QCD form factors and LHCb (2)

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

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

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




We do not follow: "In order to determine the shape of the Isgur-Wise function $\xi_B(w)$, we use the square root of $dN_{\rm corr}/dw$ ... evaluated at the midpoint in the seven unfolded $w$ bins." [1709.01920]



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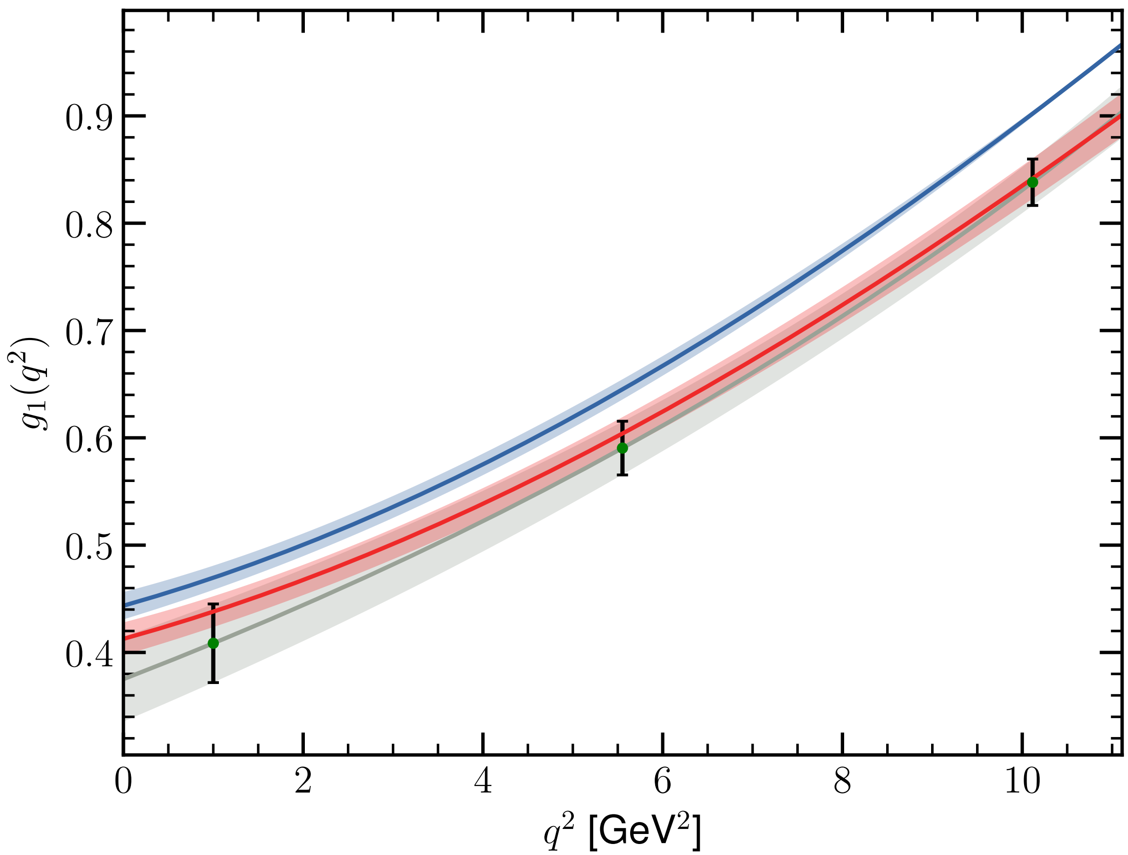
# The fit requires the $1/m_c^2$ terms

- 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: $\hat{b}_1 = -3\bar{\Lambda}_\Lambda^2 \simeq -2\,\mathrm{GeV}^2$

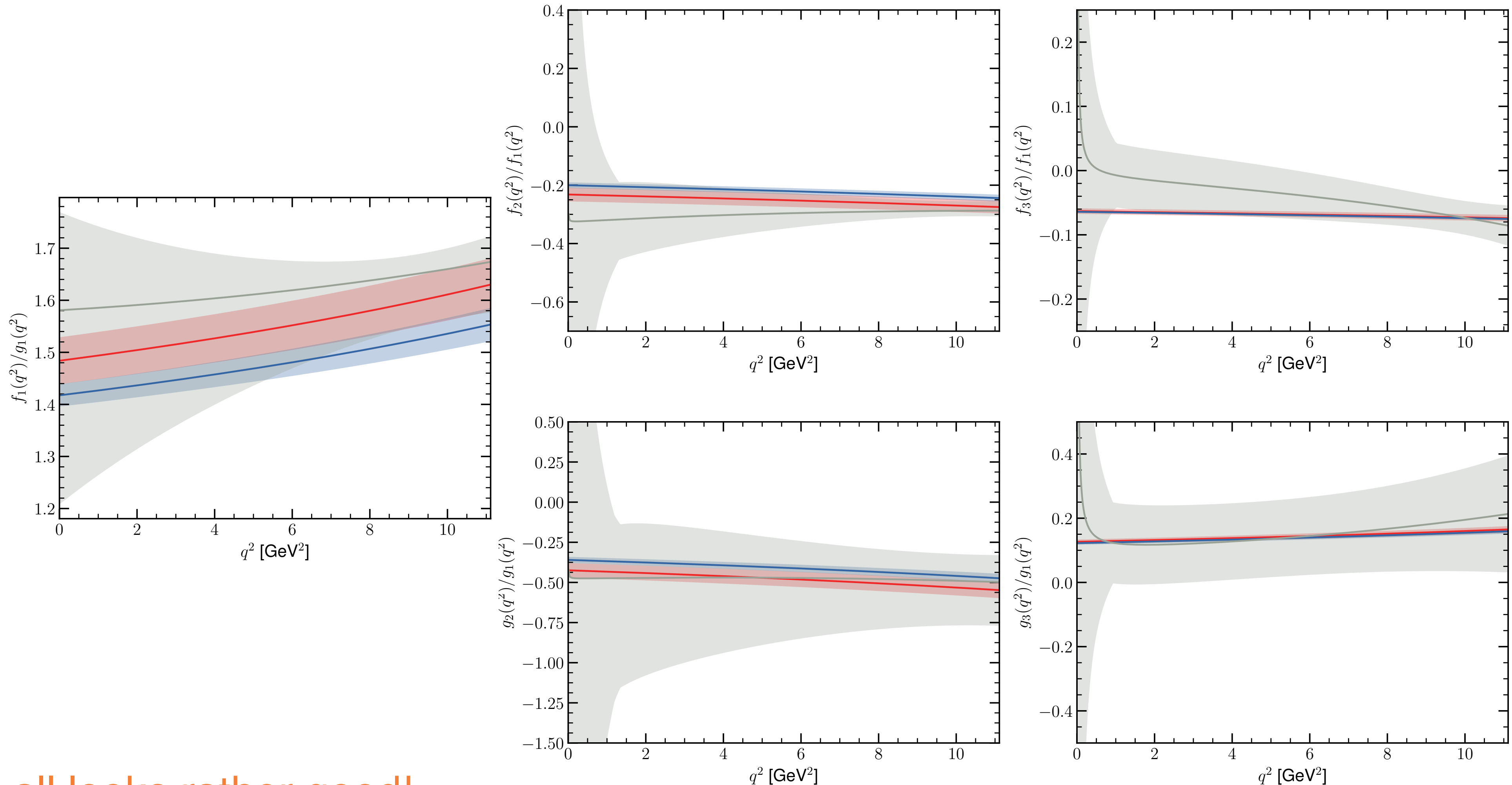
  [Falk & Neubert, hep-ph/9209269]

- 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

- There are $4$ form factors

  **We get parameter free predictions!**

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

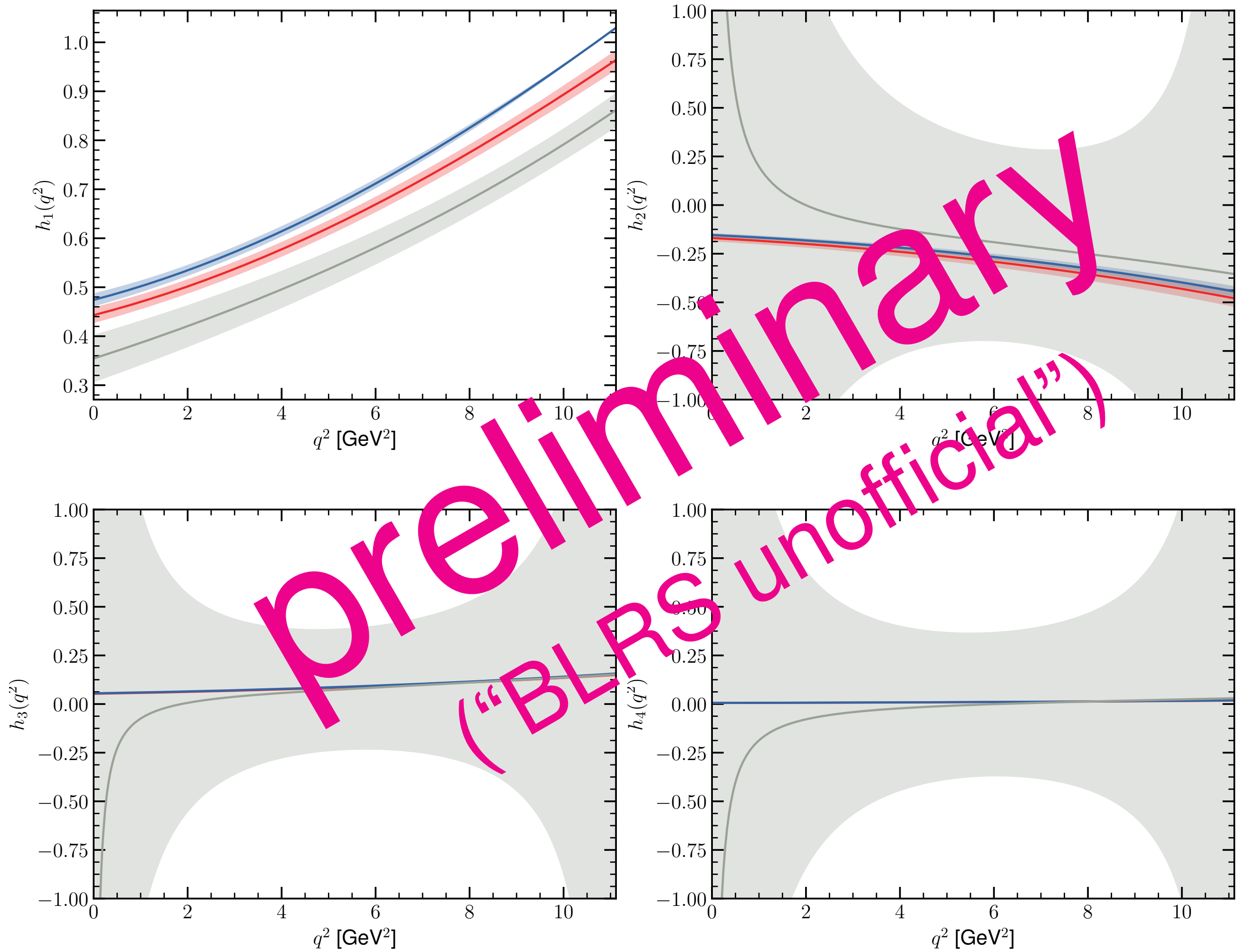
  $$h_{2,3,4} = \mathcal{O}(\alpha_s, \varepsilon_{c,b})$$

  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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# More to measure...!

- 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, $\Lambda_c \to \Lambda\pi\ (\to p\pi\pi)$ looses lots of statistics

- If $\Lambda_c$ decay distributions are integrated over, but $\theta$ 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 $\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c \mu \bar{\nu})/\mathrm{d}q^2$

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

# Conclusions

- Measurable NP contribution to $b \to c\ell\bar{\nu}$ would imply NP at a fairly low scale
- $\Lambda_b \to \Lambda_c \ell\bar{\nu}$ will provide important cross checks, ultimate uncertainty near $R(D^{(*)})$
- HQET is a model independent framework; improvable w/ more $\Lambda_b \to \Lambda_c \mu\bar{\nu}$ data
- First clear evidence for $\Lambda_{\rm QCD}/m_c^2$ term in an exclusive decay (independent of $|V_{cb}|$)
- The expansion in $\Lambda_{\rm QCD}/m_c^2$ appears well behaved
- Looking forward to LHCb results, try to measure besides $q^2$ the lepton angle $\theta$

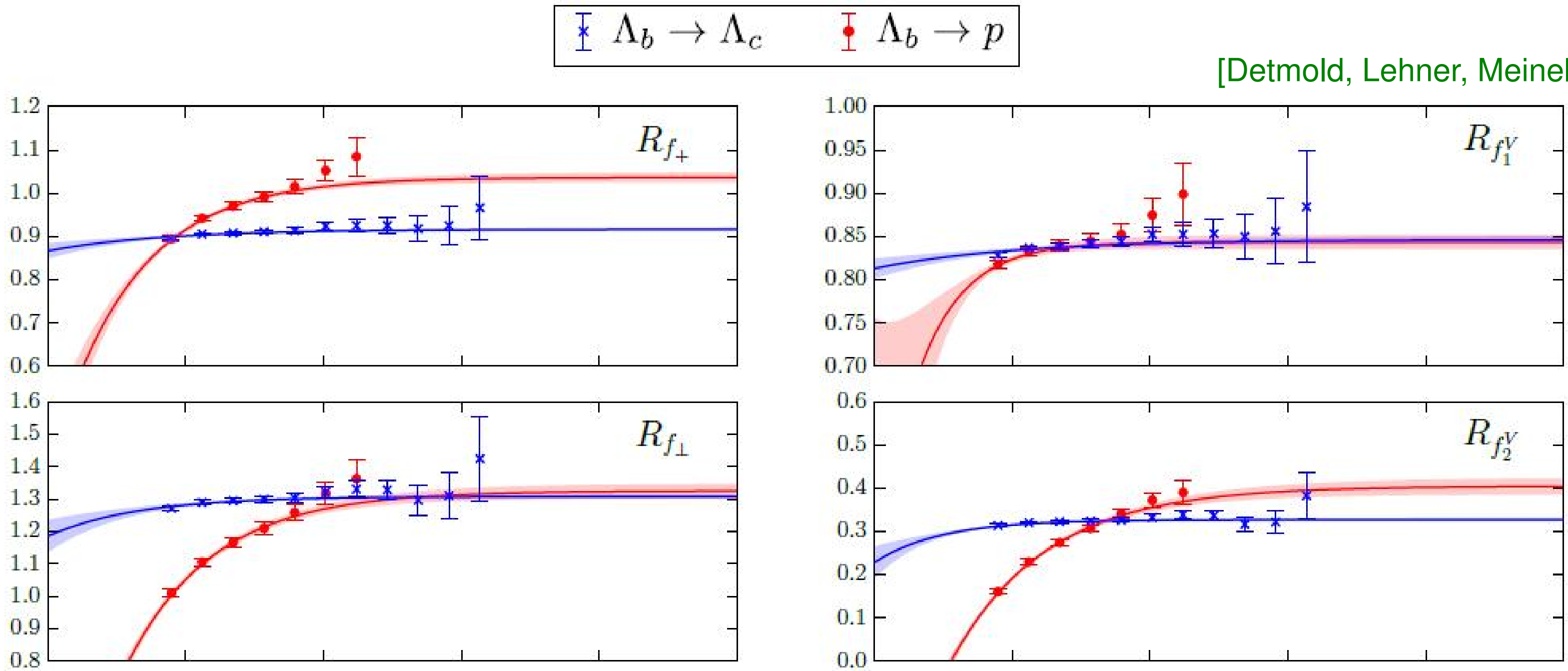
(Even if $R(D^{(*)})$ central values change, plenty of room for significant deviations from SM)


# Extra slides

# 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]



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# 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:

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

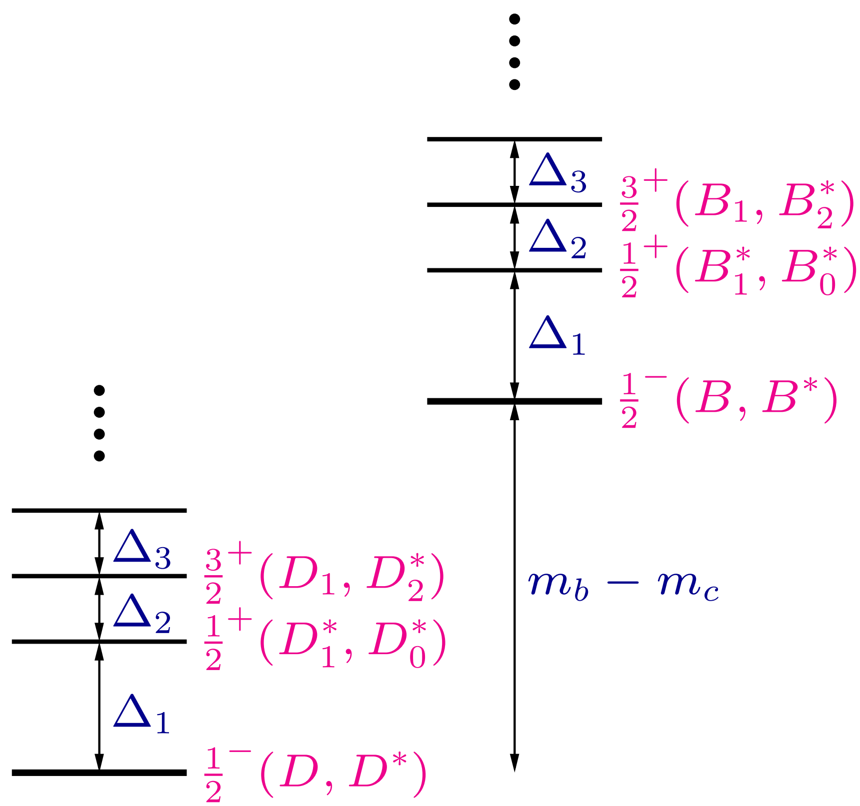
$\Rightarrow \Delta_i = \mathcal{O}(\Lambda_{\rm QCD})$ — same in $B$ and $D$ sector

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

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

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

ratio $\sim m_c/m_b$



# Importance of many cross-checks

- Consistent treatment of signals and main backgrounds, both mediated by $b \to c\ell\bar{\nu}$ decay, are important if disagreement with the SM prevails

  Important to study several hadronic channels, leptonic and hadronic $\tau$ decays

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- Use $B \to D^{(*)} l\bar{\nu}$ to refine $B \to D^{(*)}\tau\bar{\nu}$, lattice independent, improvable
  Understanding $|V_{cb}|$ determinations [Bernlochner, ZL, Papucci, Robinson, 1703.05330, 1708.07134]

- $B \to D^{**}\ell\bar{\nu}$ and $R(D^{**})$ [Bernlochner, ZL, 1606.09300; Bernlochner, ZL, Robinson, 1711.03110]

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- Rest of this talk: $\Lambda_b \to \Lambda_c\ell\bar{\nu}$ and $R(\Lambda_c)$ [Bernlochner, ZL, Robinson, Sutcliffe, 1808.09464, 1810.?????]

  Idea (simple): combine LHCb measurement of $\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c\mu\bar{\nu})/\mathrm{d}q^2$ shape [1709.01920] with the LQCD calculation of (axial-)vector form factors [1503.01421] — what can we learn?

- Will make its way into `Hammer` HAMMER MC (Helicity Amplitude Module for Matrix Element Reweighting) [Bernlochner, Duell, ZL, Papucci, Robinson, soon]

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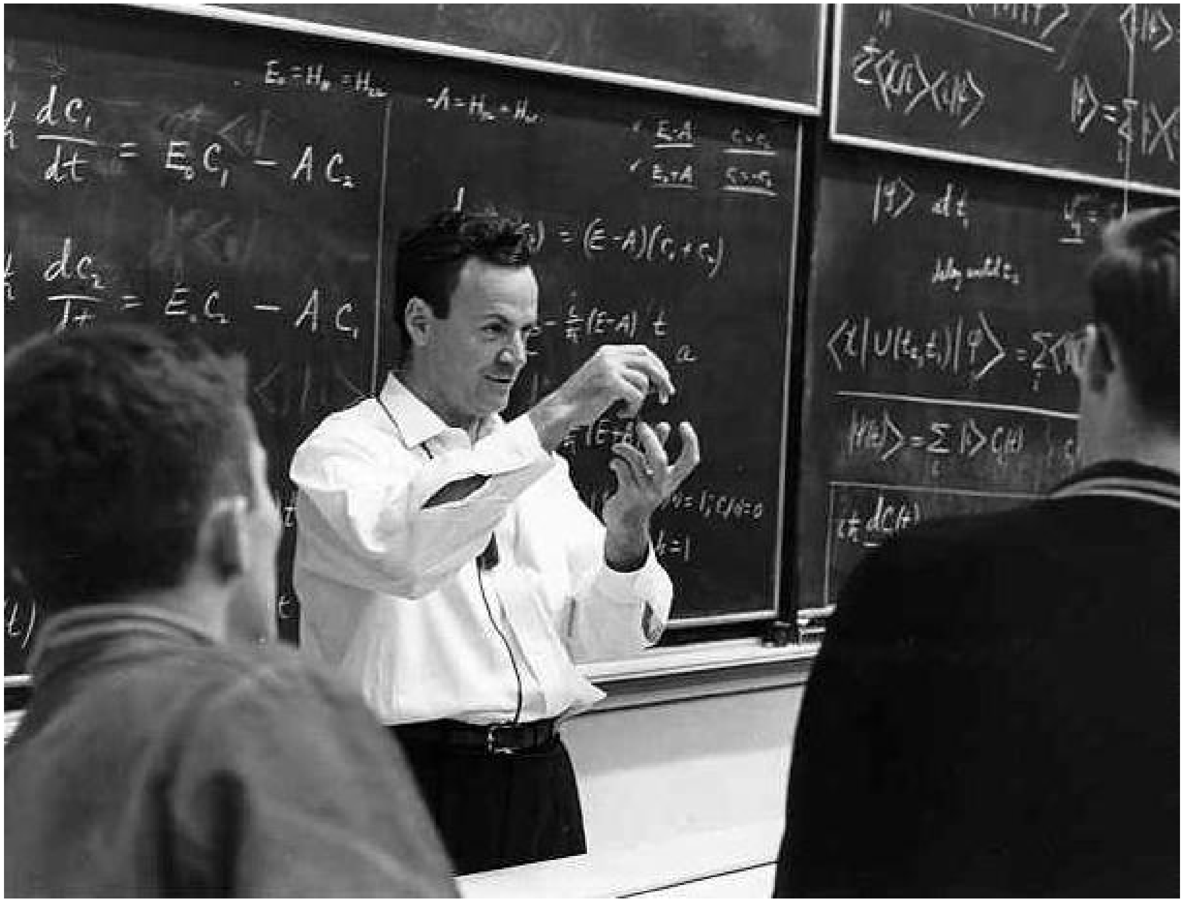
# Ultimately, data will tell



"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]