# Perspectives on $b \to c\tau\bar{\nu}$

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**Workshop on high-energy implications of flavor anomalies**

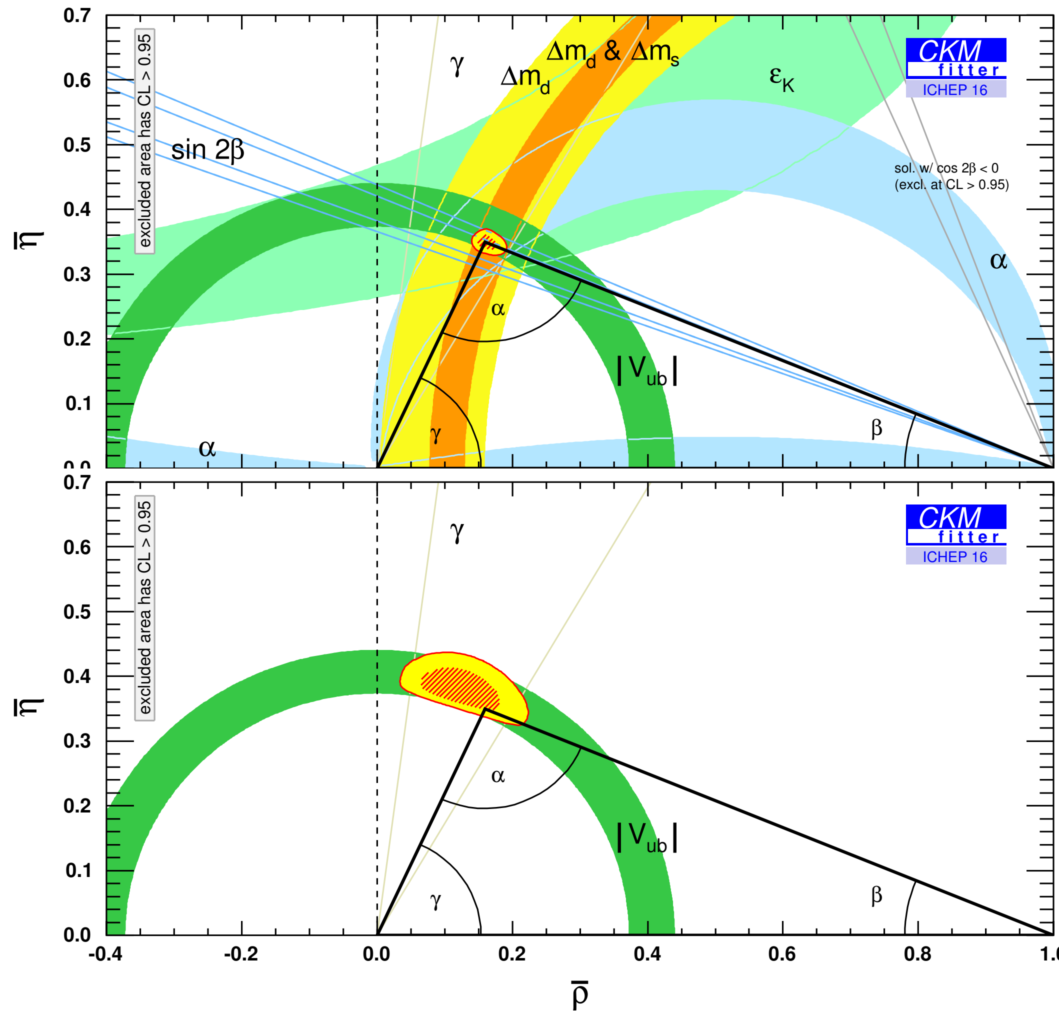
**CERN, Oct 22–24, 2018**

# Many open questions about flavor

- Flavor structure and $CP$ violation are major pending questions
- Related to Yukawa couplings, scalar sector, maybe connected to hierarchy puzzle
  Know only 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

# CKM fit: plenty of room for new physics

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




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

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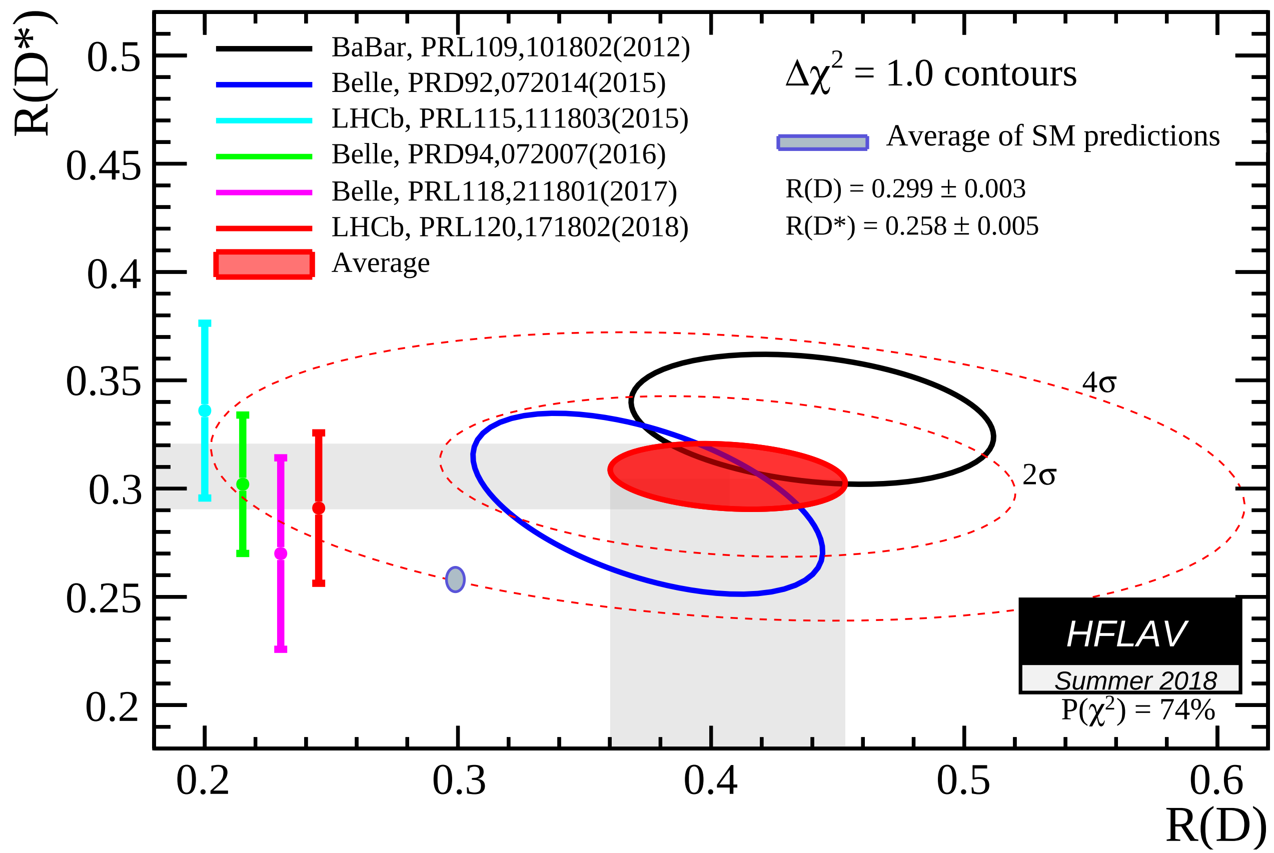
# $R(D)$ and $R(D^*)$ — $4\,\sigma$ tension with SM

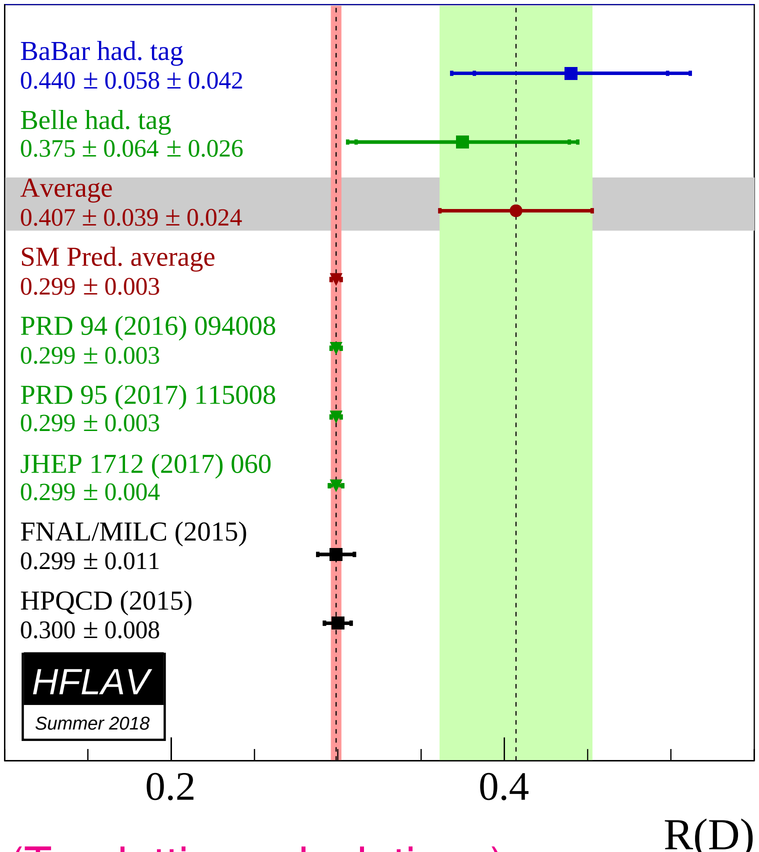
- BaBar, Belle, LHCb: enhanced $\tau$ rates, $R(D^{(*)}) = \dfrac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}l\bar{\nu})}$ $\quad (l = e, \mu)$

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

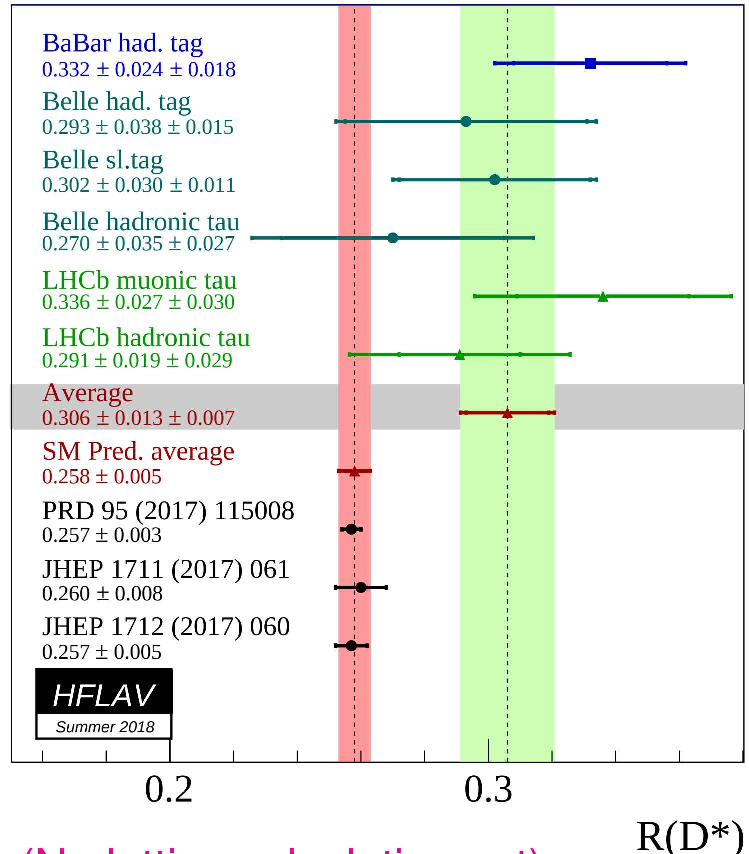


# Another look at the data

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




(Two lattice calculations)




(No lattice calculation yet)

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

# Roadmap: 1981

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 $(b \to dZ^0)/(b \to sZ^0)$;

   -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 $R(D^{(*)})$ ?

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Non-b-Decay Features of B Decay

6. Look for lifetime difference between $B^\pm$ and $B^0$.

   $\Rightarrow$ Seems less important now

7. Look for $B^0$-$\bar{B}^0$ mixing.

   $\Rightarrow$ Was the first item accomplished

[8. CP violation?]

   $\Rightarrow$ Became a central focus of the field

# Reasons not to take the tension seriously

- Measurements with $\tau$ leptons are difficult
- Need a large tree-level contribution, SM suppression only by $m_\tau$

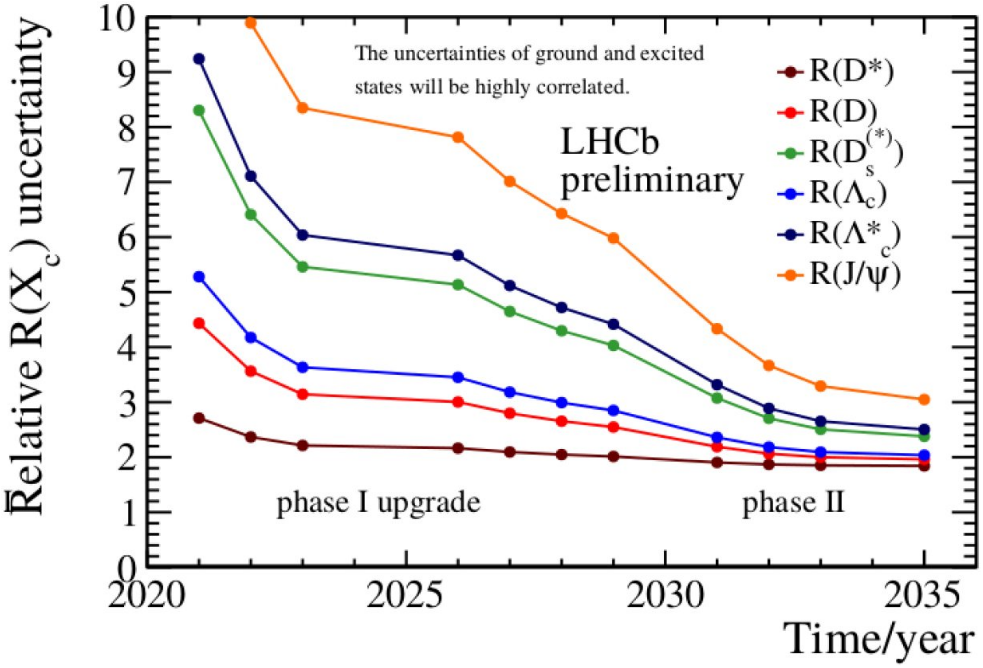
  NP was expected to show up in FCNCs — need fairly light NP to fit the data
- Strong constraints on concrete models from flavor physics, as well as high-$p_T$

# Reasons to take the tension seriously

- Results from BaBar, Belle, LHCb are consistent
- Often when measurements disagreed in the past, averages were still meaningful
- If Nature were as most theorist imagined (until $\sim 10$ years ago), then the LHC (Tevatron, LEP, DM searches) should have discovered new physics already

# 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
- I'll focus on the $3$ modes that are expected to be most precise in the long trem

# 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 task
- Can [reasonable] models fit the data? — yes [depends on your definition]

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- What is the smallest deviation from SM in $R(D^{(*)})$ that can be established as NP?
  TBD: 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 (both continuum and LQCD)?
- What else can we learn from studying these anomalies?

# What is (not) in this talk...

- I will not talk much about model building

  Excellent summaries last week at Implications of LHCb measurements and future prospects by Monika Blanke and Toni Pich + several talks at this workshop

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- I am (currently) most interested in:

  What is the smallest deviation from SM, that can be unambiguously established?

  What are the best observables / distributions to utilize huge increases in data?

- Importance of many cross-checks
  - Measure several hadronic channels, both leptonic and hadronic $\tau$ decays
  - Consistent treatment of signals and main backgrounds, also due to $b \to c\ell\bar{\nu}$

    (Partly theory, $B \to D^{**}\ell\bar{\nu}$, etc.)

# SM predictions — mesons

# Aside: theory uncertainties

- No clearly right way how to assign theory uncertainties (maybe except LQCD stat.)

- [strong interaction] model independent

  $\equiv$ theor. uncertainty suppressed by small parameters

  ... so theorists argue about $\mathcal{O}(1)\times$(small numbers) instead of $\mathcal{O}(1)$ effects

  Well defined starting point is crucial to claim a deviation from SM

- Most progress have come from expanding in $\Lambda_{\rm QCD}/m_Q$ and $\alpha_s(m_Q)$

  – Estimating higher orders in $\alpha_s$ by scale variation is not fail-safe

  – Can get unlucky (e.g., in some cases $\Lambda_{\rm QCD}/m_c$ expansion might not work well)

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

- Consequently: pdf interpretation of theory uncertainties are fraught with peril

# $B \to D^{(*)}\ell\bar{\nu}$ 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 $b \to c$

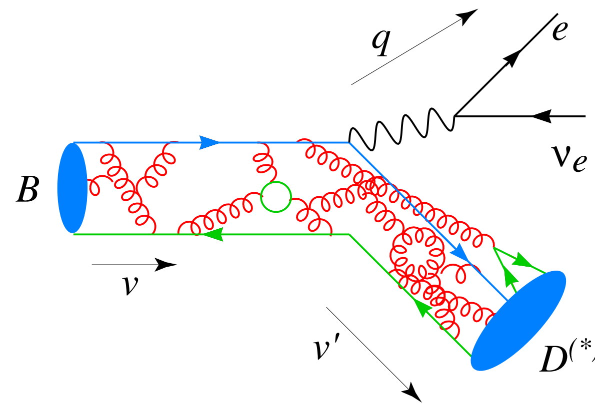
  i.e.: $\vec{p}_b \to \vec{p}_c$ and possibly $\vec{s}_Q$ flips

  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

- Only Lorentz invariance: $6$ functions of $q^2$, only $4$ measurable with $e$, $\mu$ 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 $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$

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

[Bernlochner, ZL, Papucci, Robinson, 1703.05330]

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

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

# Explored 7 fit scenarios

- Our fits:

| Fit | QCDSR | Lattice QCD $\mathcal{F}(1)$ | $f_{+,0}(1)$ | $f_{+,0}(w>1)$ | 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: $R_{1,2}(1) = 1 + \mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b}\,,\alpha_s)$ $\quad R^{(n)}_{1,2}(1) = 0 + \mathcal{O}(\Lambda_{\text{QCD}}/m_{c,b}\,,\alpha_s)$

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 $\Lambda_{\text{QCD}}/m_{c,b}$ 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] | $0.407 \pm 0.046$ | $0.306 \pm 0.015$ | $-20\%$ |
| Lattice [HFLAV] | $0.300 \pm 0.008$ | — | — |
| Fajfer et al. ’12 | — | $0.252 \pm 0.003$ | — |
| Bernlochner *et al.* ’17 ($L_{w\geq1}$) | $0.298 \pm 0.003$ | $0.261 \pm 0.004$ | $19\%$ |
| Bernlochner *et al.* ’17 ($L_{w\geq1}$+SR) | $0.299 \pm 0.003$ | $0.257 \pm 0.003$ | $44\%$ |
| Bigi, Gambino ’16 | $0.299 \pm 0.003$ | — | — |
| Bigi, Gambino, Schacht ’17 | — | $0.260 \pm 0.008$ | — |
| Jaiswal, Nandi, Patra ’17 (case-3) | $0.302 \pm 0.003$ | $0.262 \pm 0.006$ | $14\%$ |
| Jaiswal, Nandi, Patra ’17 (case-2) | $0.302 \pm 0.003$ | $0.257 \pm 0.005$ | $13\%$ |

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

  HFLAV SM expectation neglects correlations present in any theoretical framework

- 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 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.

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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] — what can we learn?

[Bernlochner, ZL, Robinson, Sutcliffe, 1808.09464 to appear in PRL; 1810.?????]



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

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

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

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

- 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

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- Only $4$ parameters (and $m_b^{1S}$): $\{\zeta',\, \zeta'',\, \hat b_1,\, \hat b_2\}$

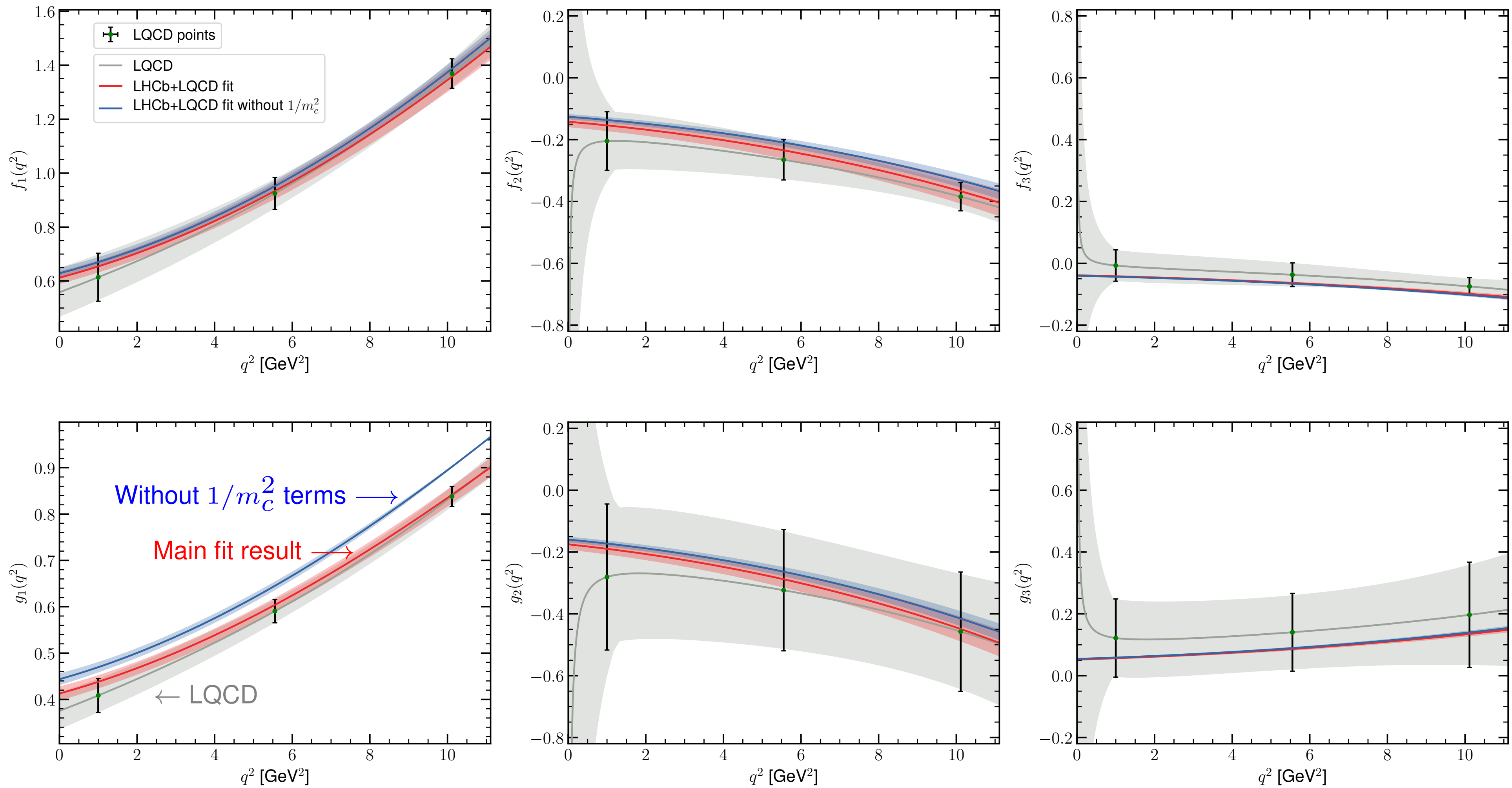
  $\zeta(w) = 1 + (w-1)\,\zeta' + \frac{1}{2}(w-1)^2\,\zeta'' + \dots \qquad b_{1,2}(w) = \zeta(w)\,\big(\hat b_{1,2} + \dots\big)$

  (Expanding 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]



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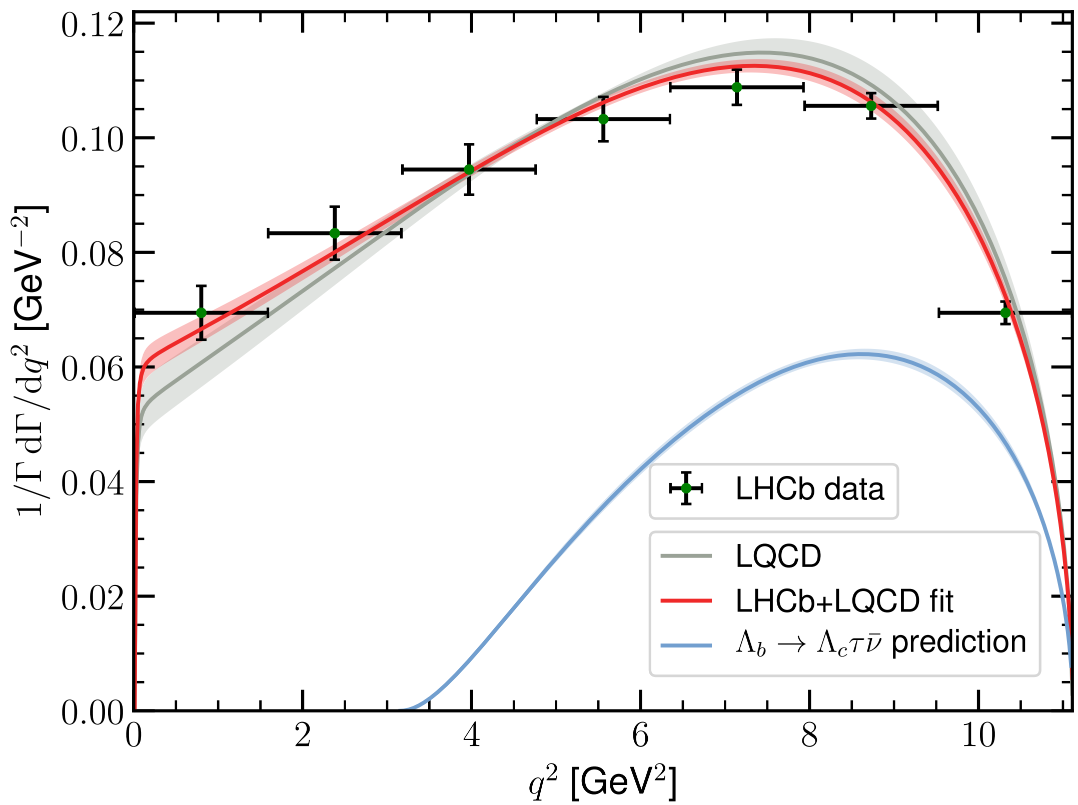
# Fit to lattice QCD form factors and LHCb (2)

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




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

  A factor of $\sim 3$ 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 [Bernlochner, Duell, ZL, Papucci, Robinson, soon]

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

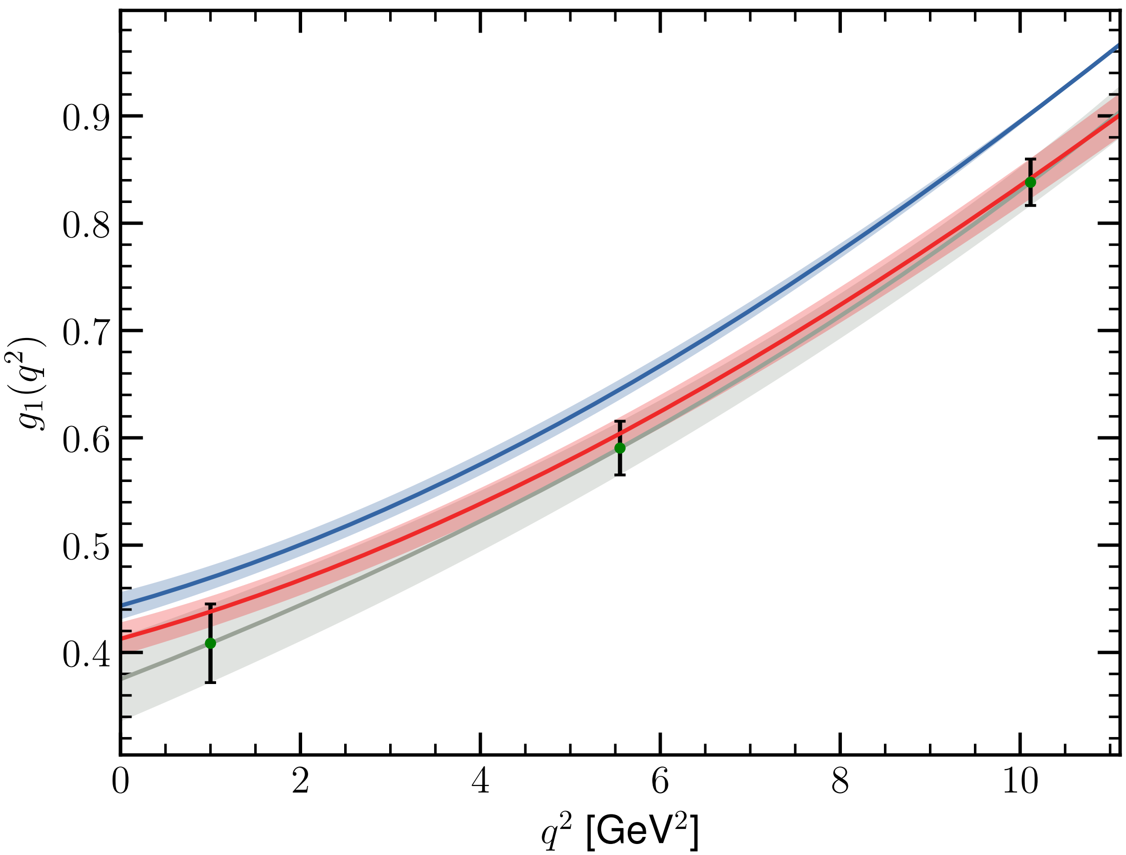
- E.g., fit results for $g_1$
  blue band shows fit with $\hat{b}_{1,2} = 0$

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

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

  [Falk & Neubert, hep-ph/9209269]

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



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# Spinoffs, byproducts, etc.

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

- $|V_{cb}|$ important to assess if there is an $\varepsilon_K$ problem, 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 $\tau$ mode thoroughly, must understand the $e, \mu$ modes better
- Inclusive / exclusive tension resolved? Fits to Belle $B \to D^* l\bar\nu$ data (all good $\chi^2$):

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

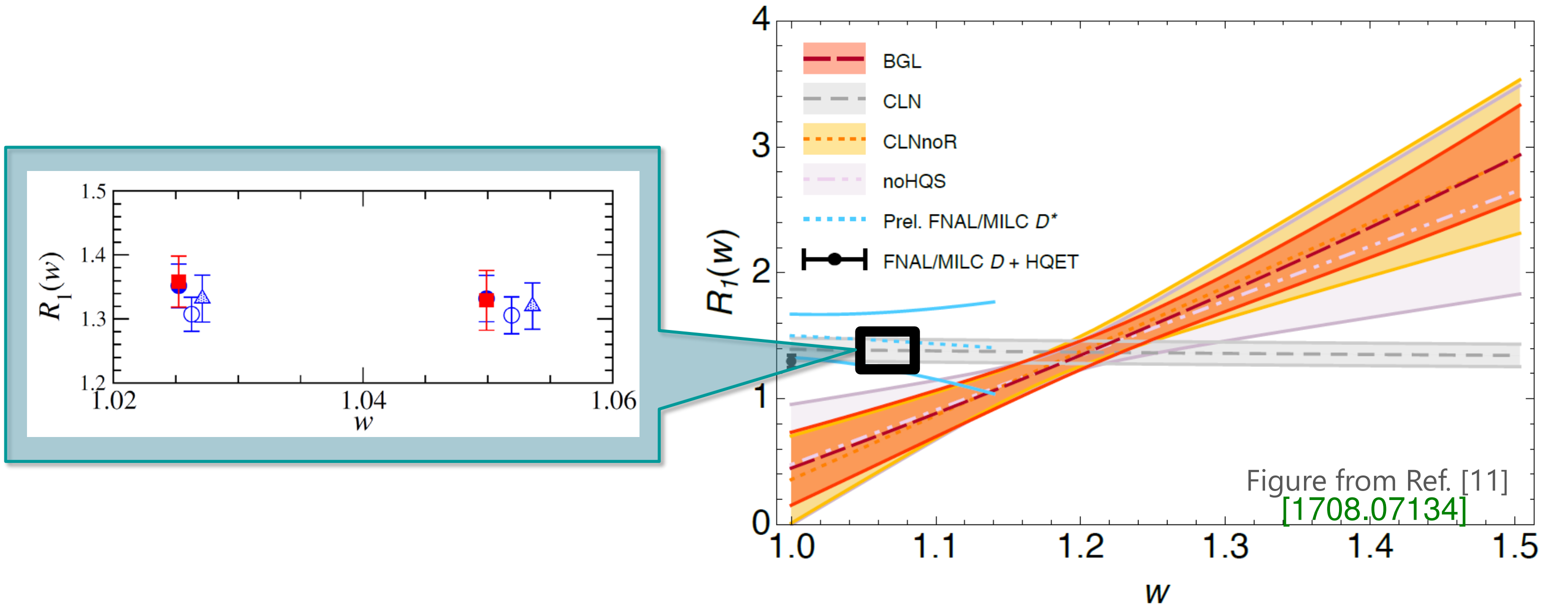
  Grinstein & Kobach, 1703.08170, $|V_{cb}|_{\rm BGL} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$

  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 | $a_0,\ a_1$ | $R_1(1),\ R_2(1)$ | $R_1(1),\ R_1'(1)$ | $R_1(1),\ R_1'(1)$ |
| $\mathcal{F}$ | $c_1,\ c_2$ | | $R_2(1),\ R_2'(1)$ | $R_2(1),\ R_2'(1)$ |

# 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]

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

# 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

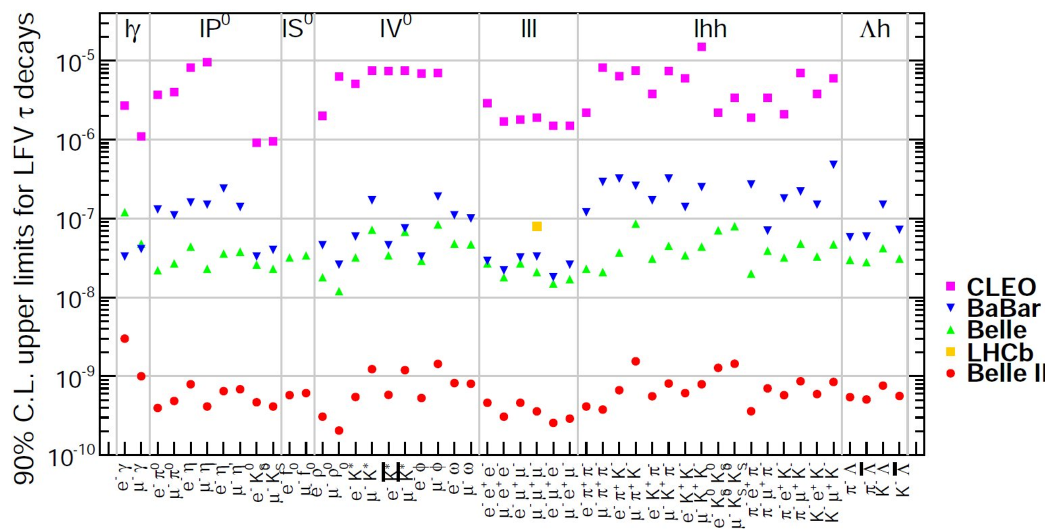
- Lepton sector: New lepton non-universal interaction would in general yield lepton flavor violation (LFV) at some level

- 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

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

  $\tau$ 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 existing 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

... Discussed in more detail in other talks

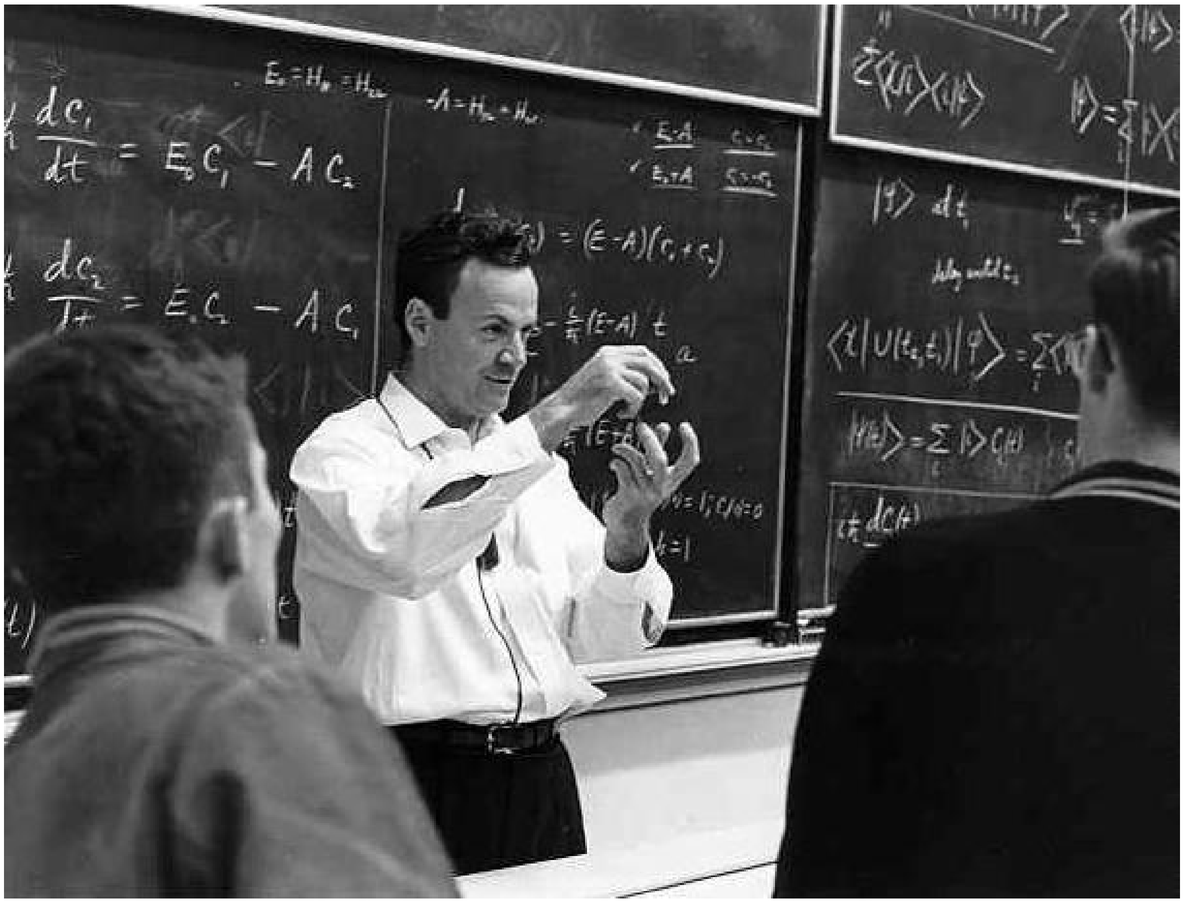
# Conclusions

- Measurable NP contribution to $b \to c\ell\bar{\nu}$ would imply NP at a fairly low scale
- HQET is a model independent framework, improvable with more $e, \mu$ data
- The $\Lambda_{\rm QCD}/m_c$ 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



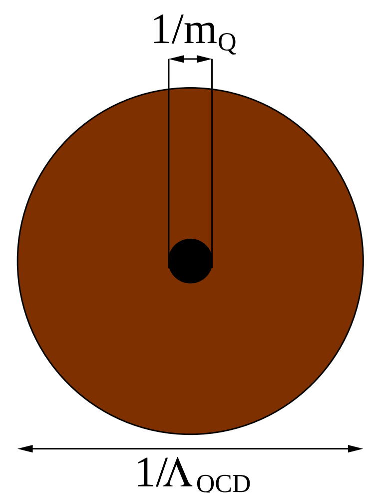
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]


**Extra slides**

# 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]

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

1. Flavor symmetry $\sim$ isotopes have similar chemistry [$\Psi_e$ 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.:

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

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

ratio $\sim m_c/m_b$