# $B$ Anomalies: Still HQETing

**Zoltan Ligeti**

HEP Theory Seminar

November 2, 2020

- Introduction
- The data
- Mesons
- Baryons
- Outlook

Details: Bernlochner, ZL, Papucci, Robinson, 1703.05330 [PRD], 1708.07134 [PRD]
Bernlochner, ZL, Robinson, Sutcliffe, arXiv:1808.09464 [PRL]; 1812.07593 [PRD]
Bernlochner, Duell ZL, Papucci, Robinson, 2002.00020, & more...

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

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

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

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- “Who ordered that?”

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

This talk: mostly about SM, motivated by a hint for BSM

(Much bigger literature on BSM scenarios)

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

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

# Introduction

# What is flavor physics?

- Interactions that distinguish the $3$ generations — SM simple, BSM maybe complicated

  SM: neither strong nor EM, only couplings of $W^\pm$ (diagonalizing Higgs couplings)

- Flavor parameters: quark & lepton masses, $m_i$ $(12)$

  quark & lepton mixing, $V_{ij}$, $U_{ij}$ $(10$, or $8?)$

  Majority of the parameters of the SM (extended for $m_{\nu_i} \neq 0$) (only $6$ other)

- Quark mixing: $(u,\, c,\, t)\, W^\pm (d,\, s,\, b)$ couplings — 4 param's, $\eta \neq 0$ $CP$ violation

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \ldots$$

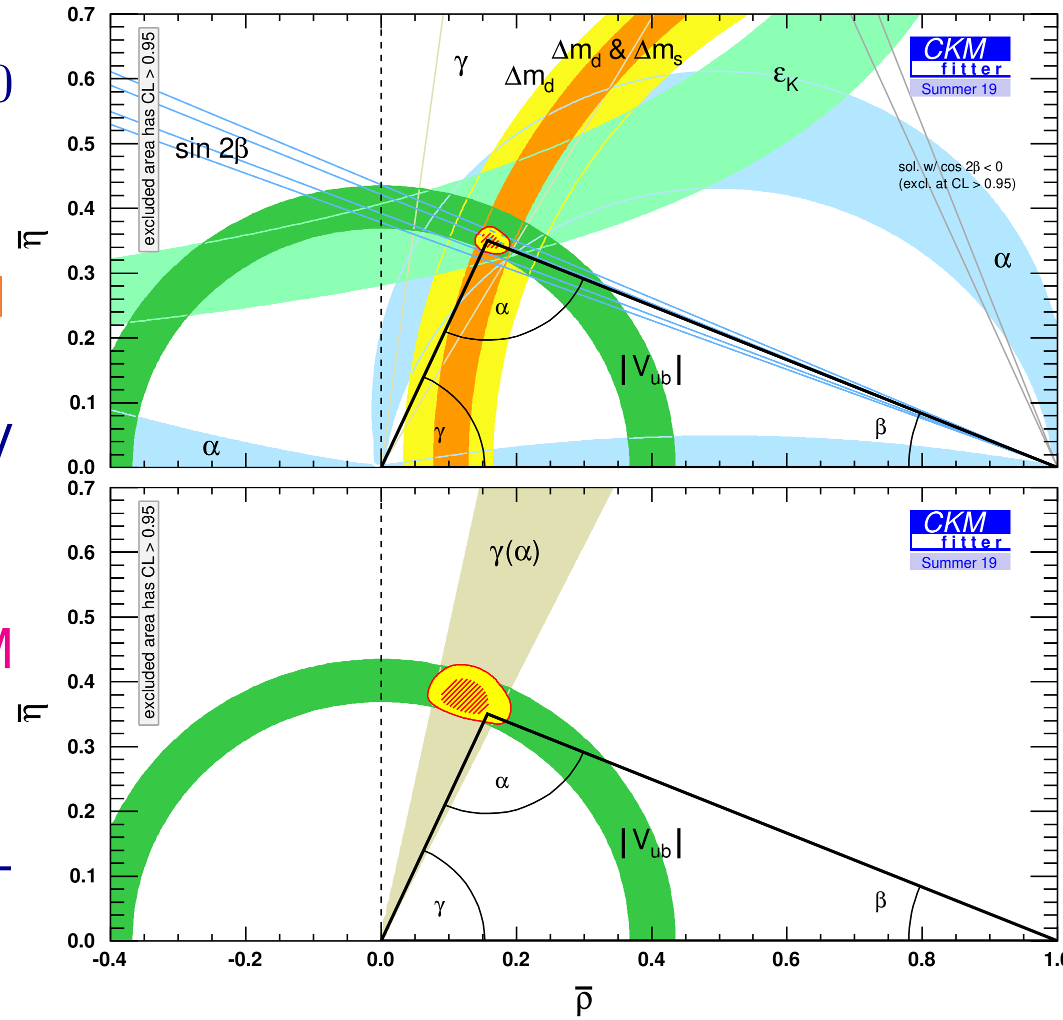
  Cabibbo-Kobayashi-Maskawa (CKM) matrix (unitary)

  The only source of quark flavor change in the SM

- Many testable relations, sensitive to possible deviations from the SM

# CKM fit: plenty of room for new physics

- Unitarity: $V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$
  $(\rho, \eta)$ plane, compare data
- 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 $V_{ub}$ & $\gamma$) vs. loop-dominated measurements




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

# Many open questions about flavor

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

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

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

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

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

  We only know that Higgs is responsible for (bulk of) the heaviest fermion masses

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

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

- Experiment: expect big improvements (LHC & Belle II), many new measurements

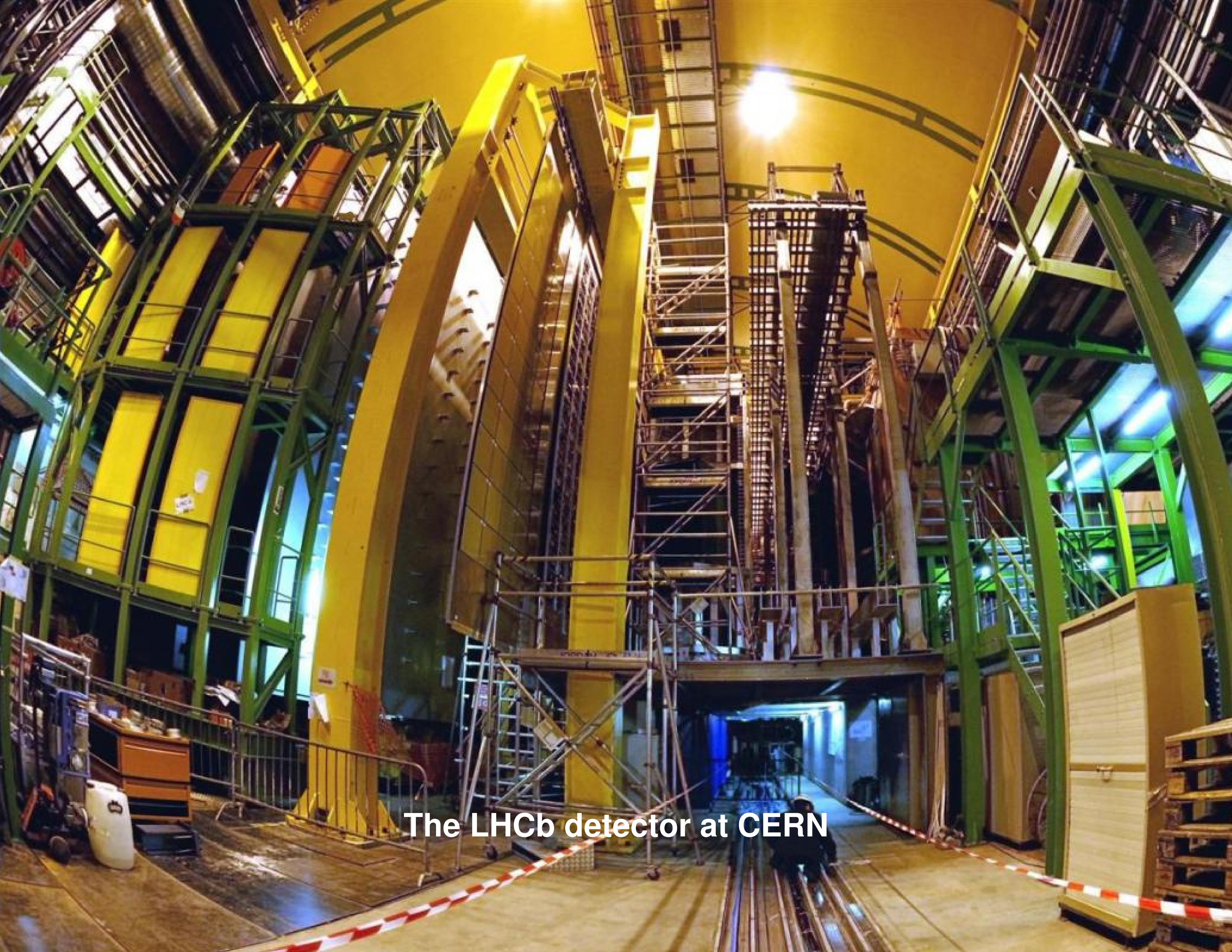
- Theory: progress and new directions both in SM calculations and model building

# CERN — LHC plans

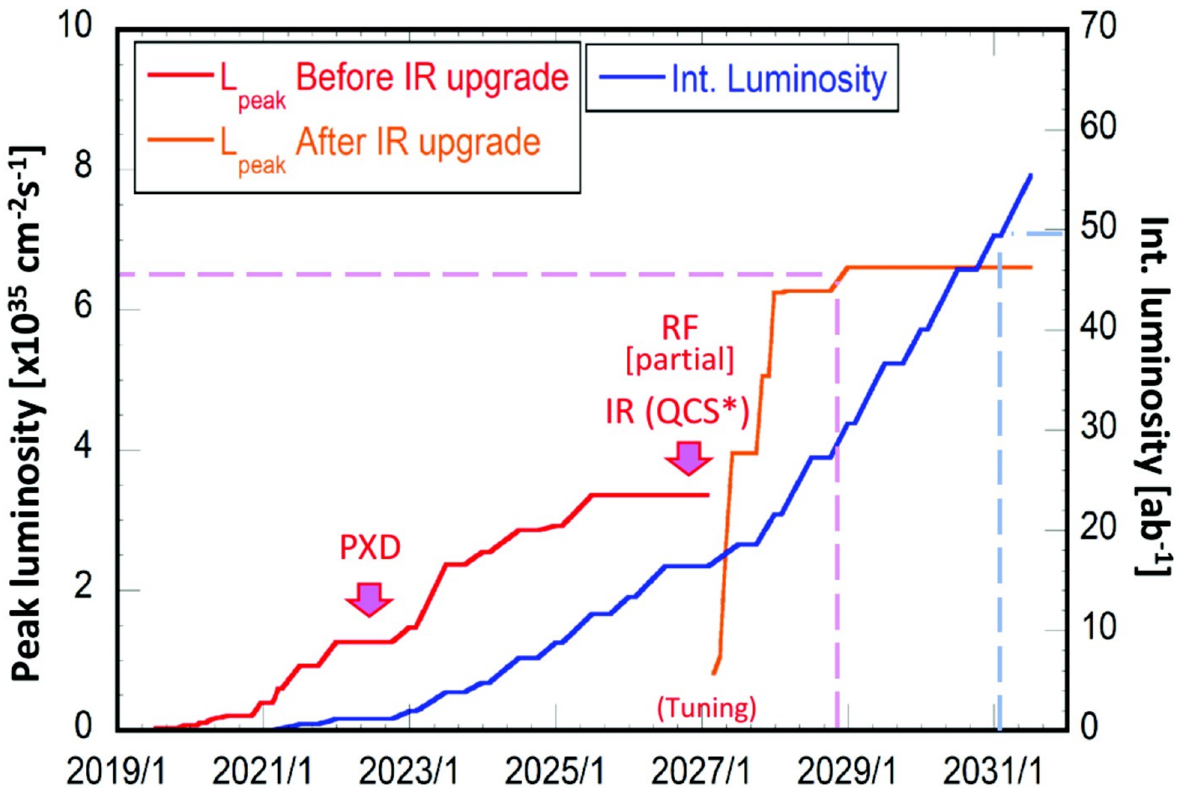
| | LHC era | | | HL-LHC era | |
|---|---|---|---|---|---|
| | Run 1 (2010-12) | Run 2 (2015-18) | Run 3 (2021-24) | Run 4 (2027-30) | Run 5+ (2031+) |
| ATLAS, CMS | 25 $\text{fb}^{-1}$ | 150 $\text{fb}^{-1}$ | 300 $\text{fb}^{-1}$ | ⟶ | 3000 $\text{fb}^{-1}$ |
| LHCb | 3 $\text{fb}^{-1}$ | 9 $\text{fb}^{-1}$ | 23 $\text{fb}^{-1}$ | 50 $\text{fb}^{-1}$ | *300 $\text{fb}^{-1}$ |

* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$

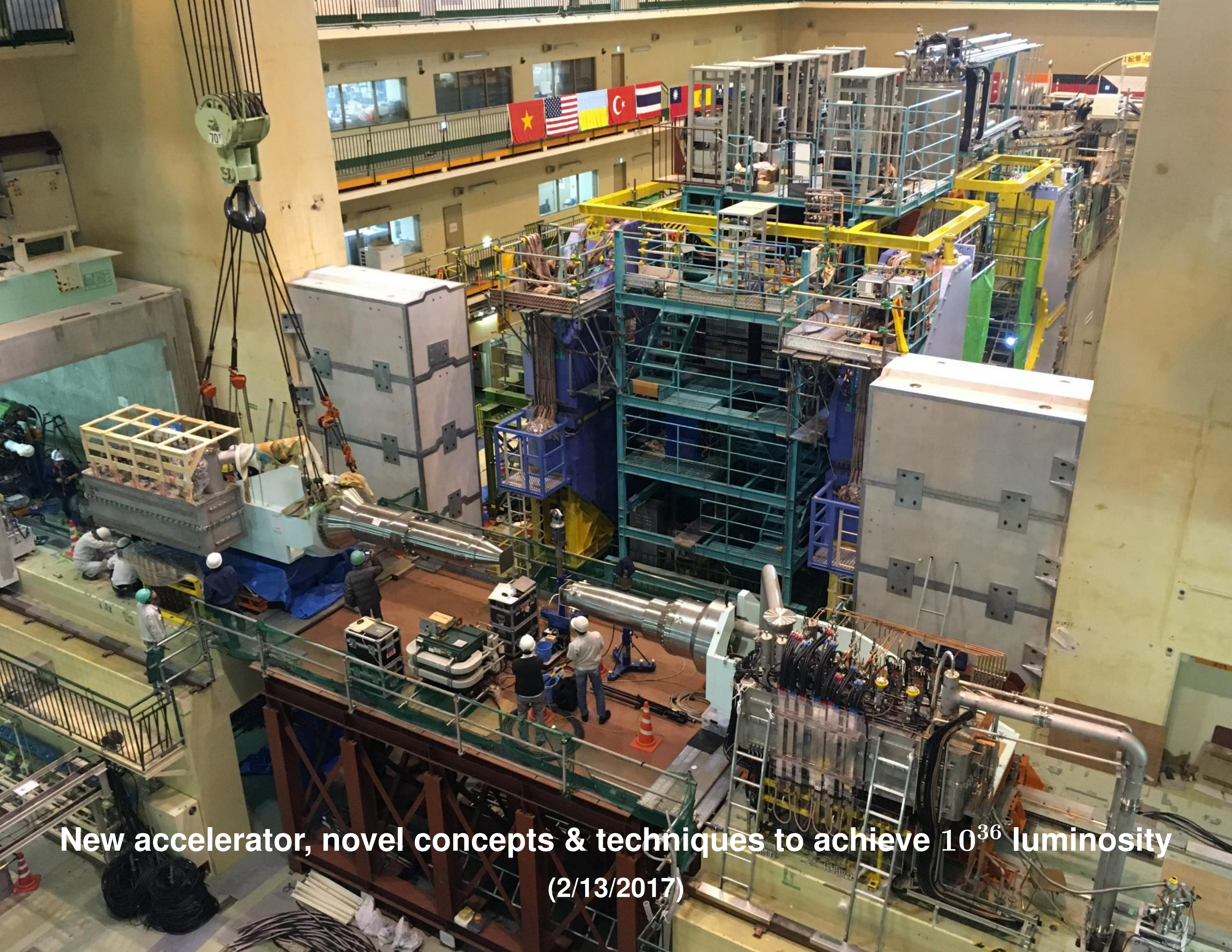
- Major LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33}/\text{cm}^2/\text{s}$)
  Major ATLAS and CMS upgrades come in LS3 for HL-LHC
- LHCb, 2017, Expression of Interest for an upgrade in LS4 to $2 \times 10^{34}/\text{cm}^2/\text{s}$
- European Particle Physics Strategy Update
  Part of the full exploitation of the LHC, but not yet funded


The LHCb detector at CERN

# Belle II — SuperKEKB in Japan




- First collisions 2018 (unfinished detector), with full detector starting spring 2019
  Goal: $50\times$ the Belle and nearly $100\times$ the BaBar data set
- Discussions started about physics case and feasibility of a factor $\sim 5$ upgrade, similar to LHCb Phase-II upgrade aiming 50/fb $\to$ 300/fb, after LHC LS4

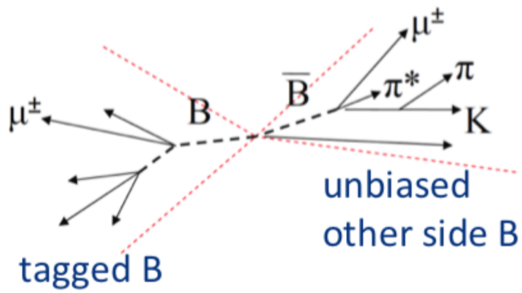


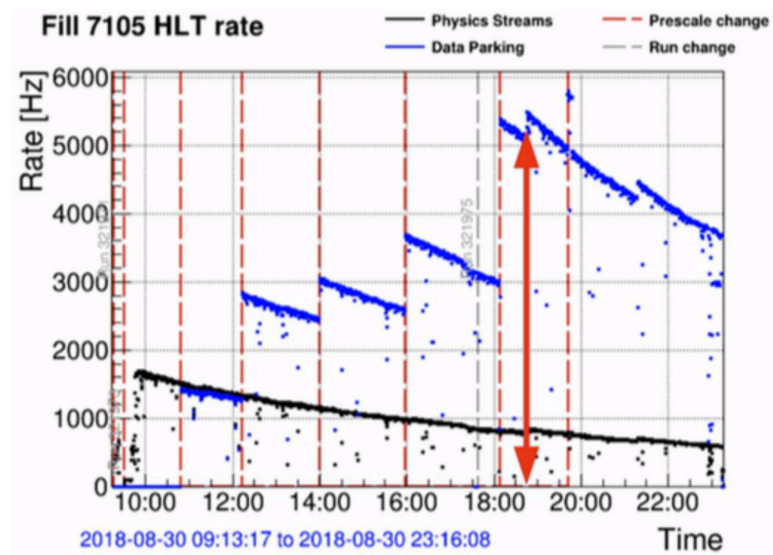
New accelerator, novel concepts & techniques to achieve $10^{36}$ luminosity

(2/13/2017)

# A surprise in 2018: CMS "$B$ parking"

- CMS collected $\sim 10^{10}$ $B$ decays; goal: check LHCb $R_{K^{(*)}}$ result [CMS @ LHCC, Nov 2018]




Effort in 2018 paid off, 12B triggered events on tape

- Up to 5.5 kHz in the second part of the fill where events are smaller

Now studying processing strategy

- 1.1B events were already fully processed in order to help development of trigger/ reconstruction

7.6 PB on tape
Avg event size is 0.64 MB
(1MB for standard events)

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# Intriguing tensions with SM

- Lepton non-universality — would be 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 $(B \to X\tau\bar{\nu})/(B \to X(e,\mu)\bar{\nu})$

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  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

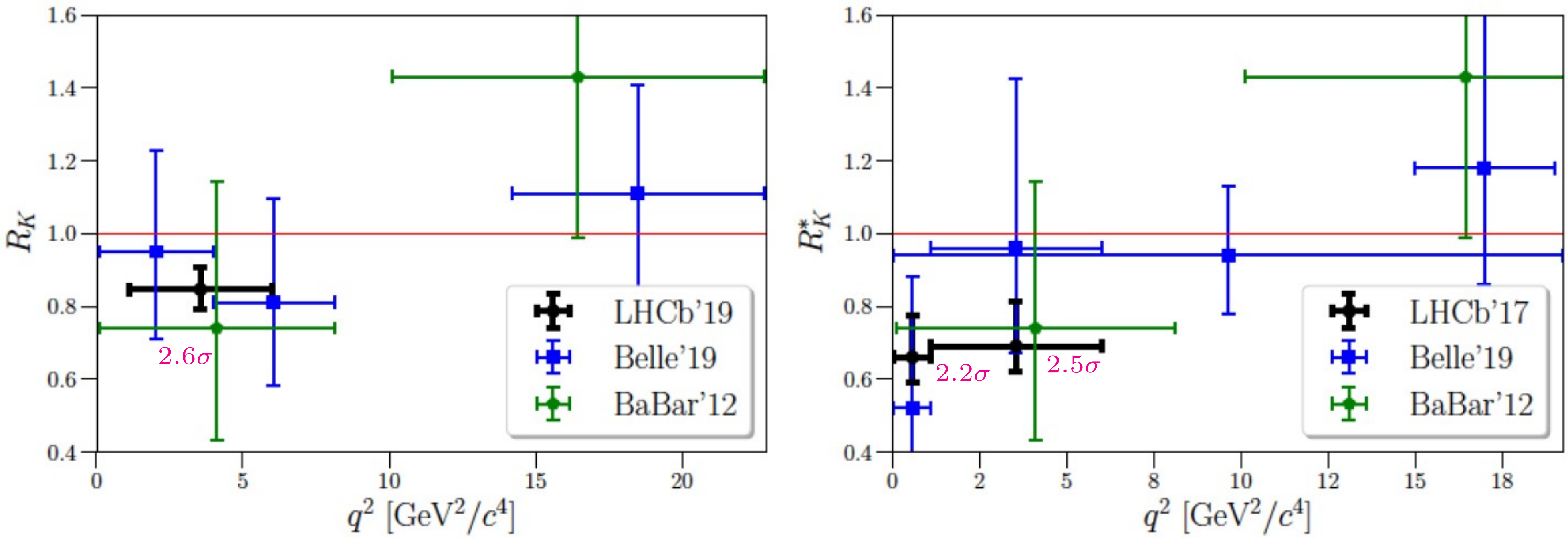
  Can fit 1), 3), 4) simultaneously: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2$, $C_{9,\mu} = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu)$

- Focus on $R(D^{(*)})$, because theory can be improved, 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 $\sim 2.5\sigma$ from lepton universality




- Theorists' fits quote $3-5\sigma$ (sometimes including $P_5'$ and/or $B_s \to \phi\mu^+\mu^-$)

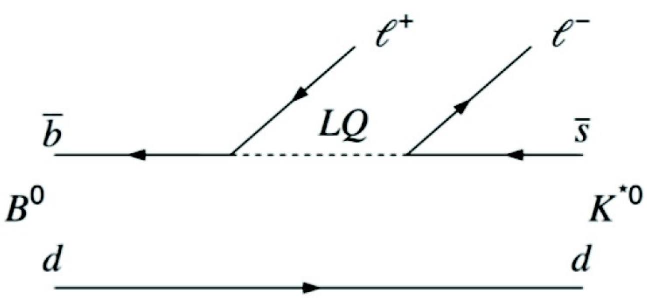
- Modifying one Wilson coefficient in $\mathcal{H}_{\text{eff}}$ (due to NP?) gives good fit: $\delta\, C_{9,\mu} \sim -1$

# E.g., leptoquarks & flavor structures

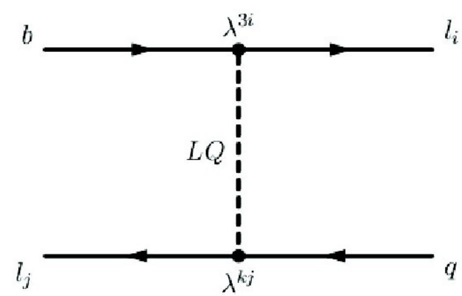
- Leptoquarks are some of the most often discussed models for $R_{K^{(*)}}$ and $R(D^{(*)})$

  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

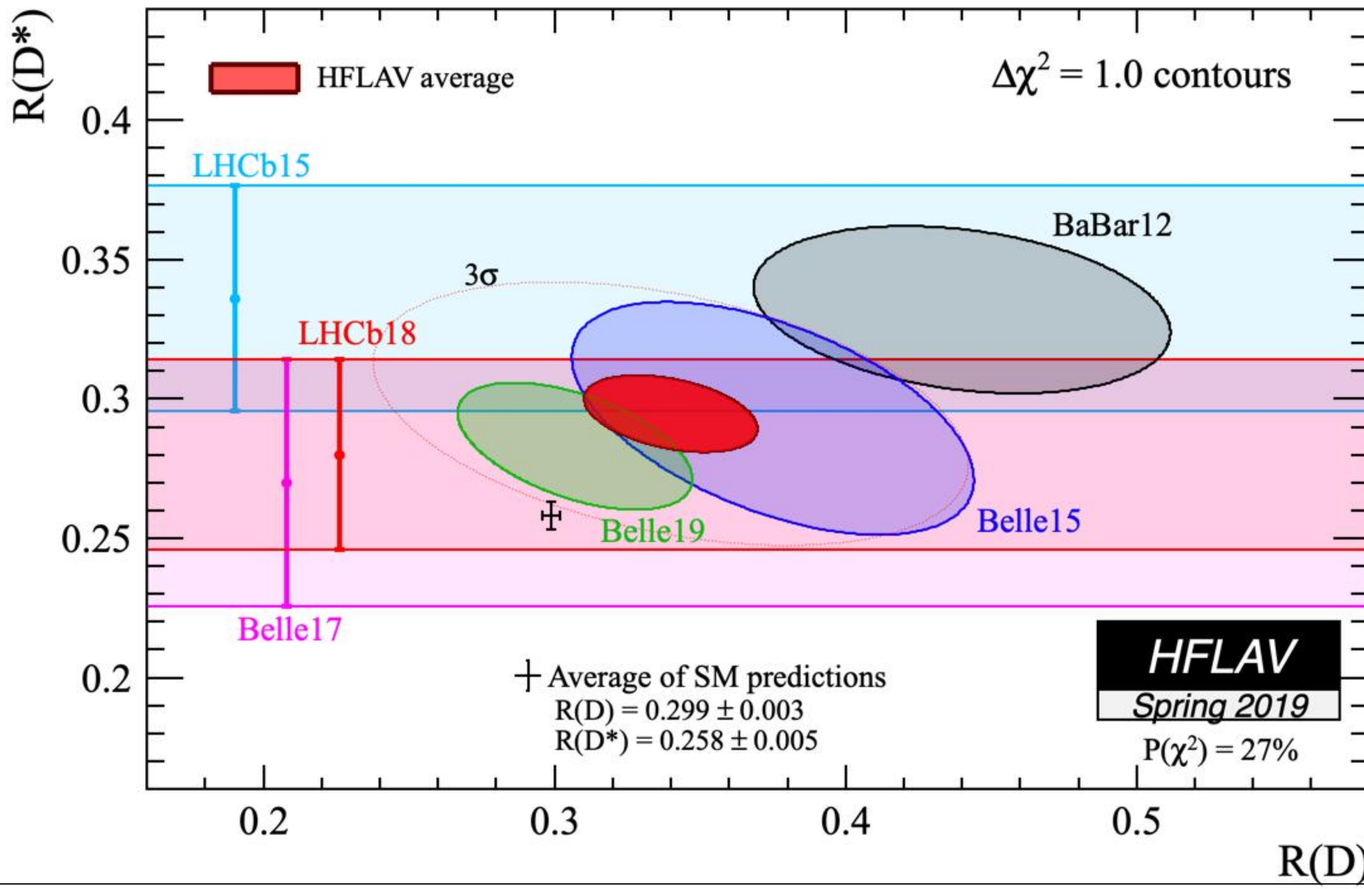
[E.g.: de Medeiros Varzielas, Hiller, 1503.01084; Freytsis, ZL, Ruderman, 1506.08896; many more]

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

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

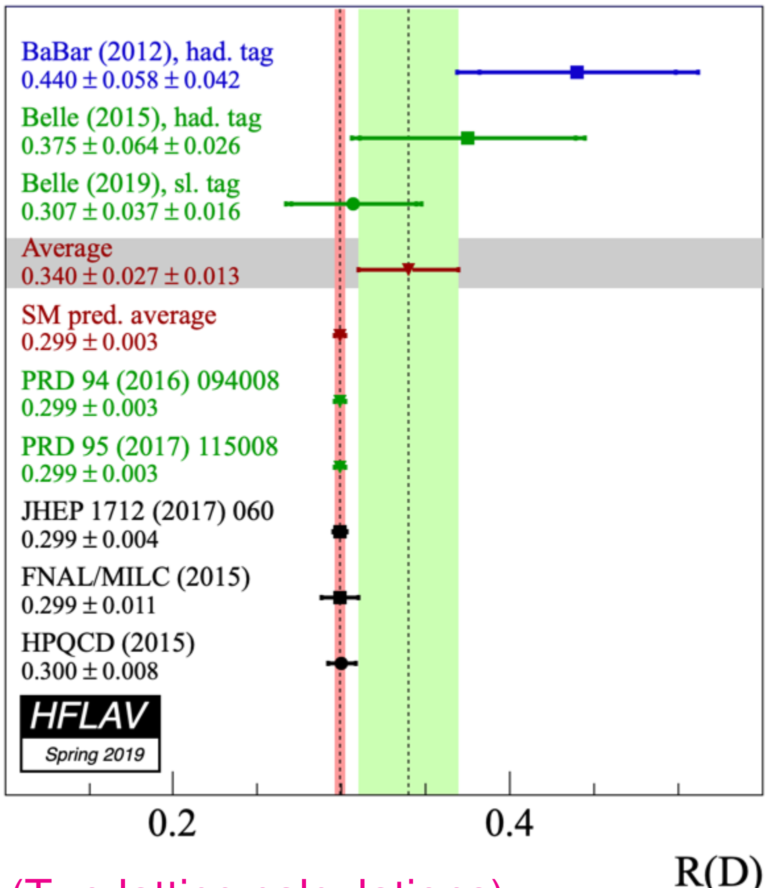
- BaBar, Belle, LHCb: enhanced $\tau$ rates, $R(D^{(*)}) = \dfrac{\Gamma(B \to D^{(*)}\tau\bar\nu)}{\Gamma(B \to D^{(*)}l\bar\nu)}$ $\quad (l = e, \mu)$

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

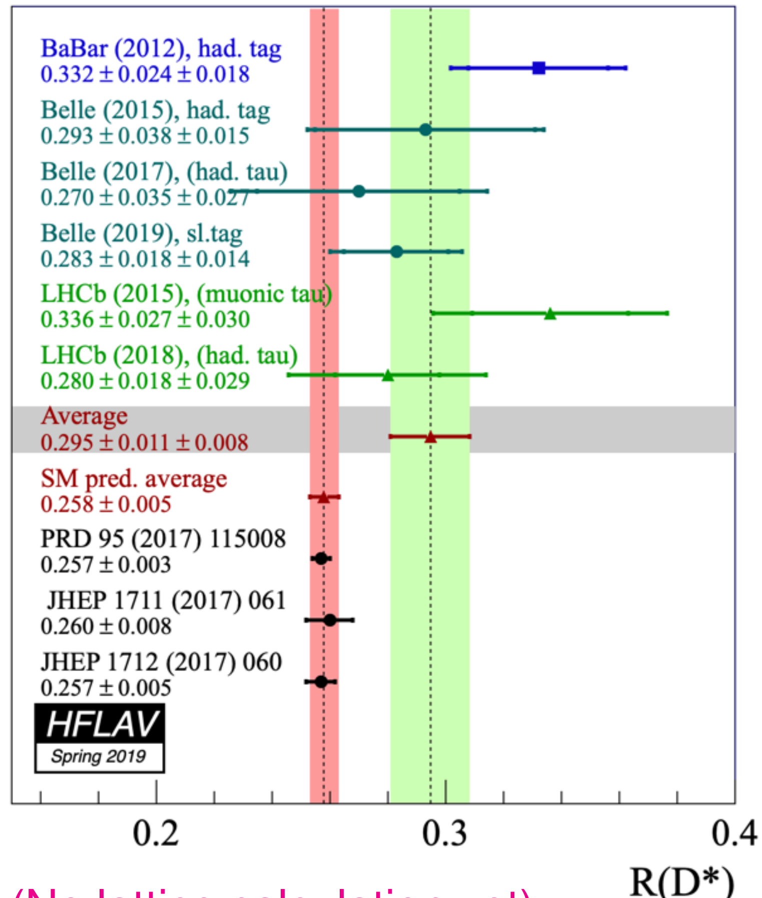


# Another look at the data

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




(Two lattice calculations)




(No lattice calculation yet)

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

# 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-$p_T$

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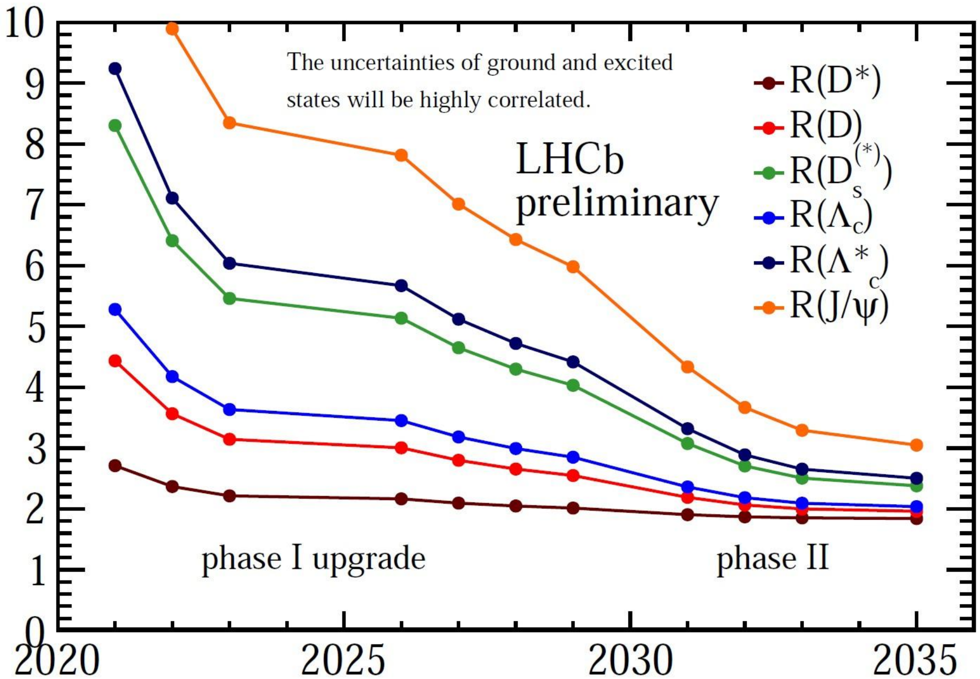
- Results from BaBar, Belle, LHCb are consistent
- Often when measurements disagreed in the past, averages were still meaningful
- Enhancement is also seen in similar ratio in $\Gamma(B_c \to J/\psi\,\ell\bar{\nu})$
- If Nature were as most theorist imagined (until $\sim 10$ years ago), then the LHC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

# Exciting future prospects

- 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 $\sim 50$
- 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
- 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 job
- Can [reasonable] models fit the data? — maybe [subjective]    (won't say much)

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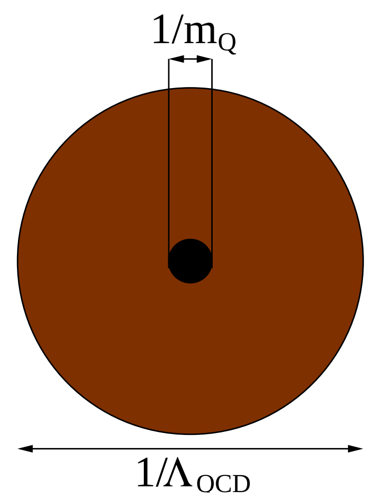
- What is the smallest deviation from SM in $R(D^{(*)})$ that can be established as NP?
  ... we know how to make progress
- Which channels are most interesting?  (To establish deviation from SM / understand NP?)
  $B_{(s)} \to D_{(s)}^{(*,**)} \ell\bar{\nu}$, $\Lambda_b \to \Lambda_c^{(*)} \ell\bar{\nu}$, $B_c \to \psi\ell\bar{\nu}$, $B \to X_c\ell\bar{\nu}$, 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 $v^\mu$ [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 $\to 0$]

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

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

- On a time scale $\ll \Lambda_{\rm QCD}^{-1}$ weak current changes $b \to c$

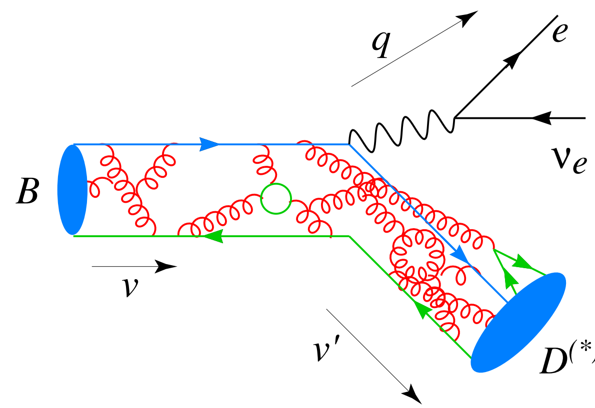
  i.e.: $\vec{p}_b \to \vec{p}_c$ and possibly $\vec{s}_Q$ flips

  In $m_{b,c} \gg \Lambda_{\rm QCD}$ limit, 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 $\zeta(1) = 1$]

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

- "Idea": fit $4$ functions with $4$ observables...
- Lorentz invariance: $6$ functions of $q^2$, only $4$ measurable with $e$, $\mu$ final states

$$\langle D|\,\bar c\gamma^\mu b\,|\overline{B}\rangle \;=\; f_+(q^2)(p_B+p_D)^\mu + \Big[f_0(q^2)-f_+(q^2)\Big]\frac{m_B^2-m_D^2}{q^2}\,q^\mu$$
$$\langle D^*|\,\bar c\gamma^\mu b\,|\overline{B}\rangle \;=\; -ig(q^2)\,\epsilon^{\mu\nu\rho\sigma}\,\varepsilon^*_\nu\,(p_B+p_{D^*})_\rho\,q_\sigma$$
$$\langle D^*|\,\bar c\gamma^\mu\gamma^5 b\,|\overline{B}\rangle \;=\; \varepsilon^{*\mu}f(q^2)+a_+(q^2)\,(\varepsilon^*\cdot p_B)\,(p_B+p_{D^*})^\mu + a_-(q^2)\,(\varepsilon^*\cdot p_B)\,q^\mu$$

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

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

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- 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

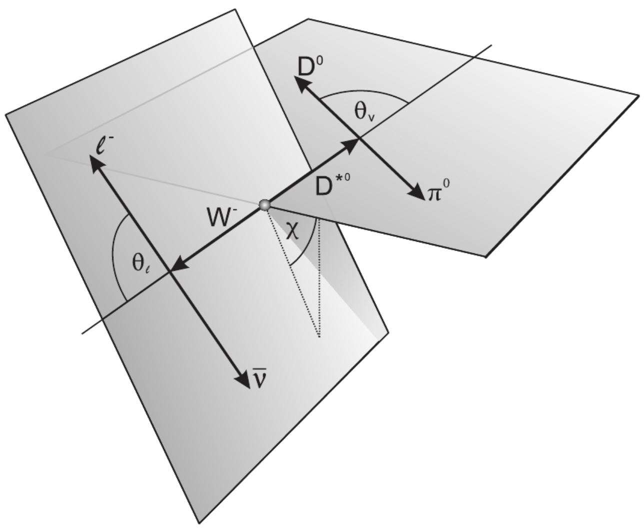
[Bernlochner, ZL, Papucci, Robinson, 1703.05330]

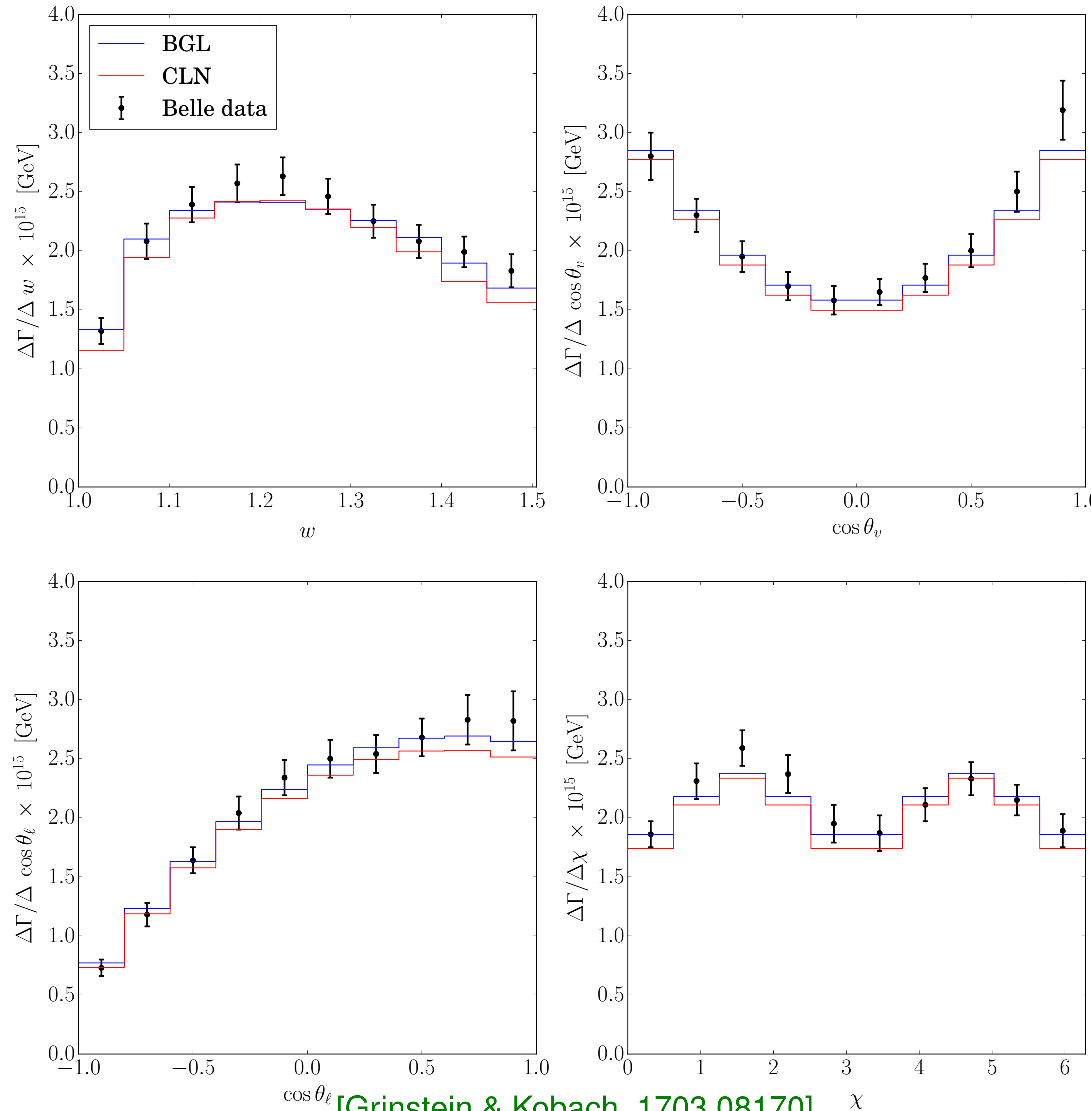
- Observables: $B\to Dl\bar\nu:\; {\rm d}\Gamma/{\rm d}w$ (Only Belle published fully corrected distributions)

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

# 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

# Did 7 fits with different assumptions

- 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

# Robust 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 [FLAG] | $0.300 \pm 0.008$ | — | — |
| 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) | $0.302 \pm 0.003$ | $0.257 \pm 0.005$ | $13\%$ |

- 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], $\Lambda$-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]

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

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

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

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

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

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

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

($\bar\Lambda_\Lambda \sim 0.8\,\mathrm{GeV}$ 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 $\mathcal{O}(\Lambda_{\rm QCD}/m_{b,c})$ 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!

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

# Fits and form factor definitions

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

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

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

  All $6$ form factors computed in LQCD $\sim$ Isgur-Wise fn $\Rightarrow$ despite good precision, limited constraints on subleading terms and their $w$ dependence [Detmold, Lehner, Meinel, 1503.01421]

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

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

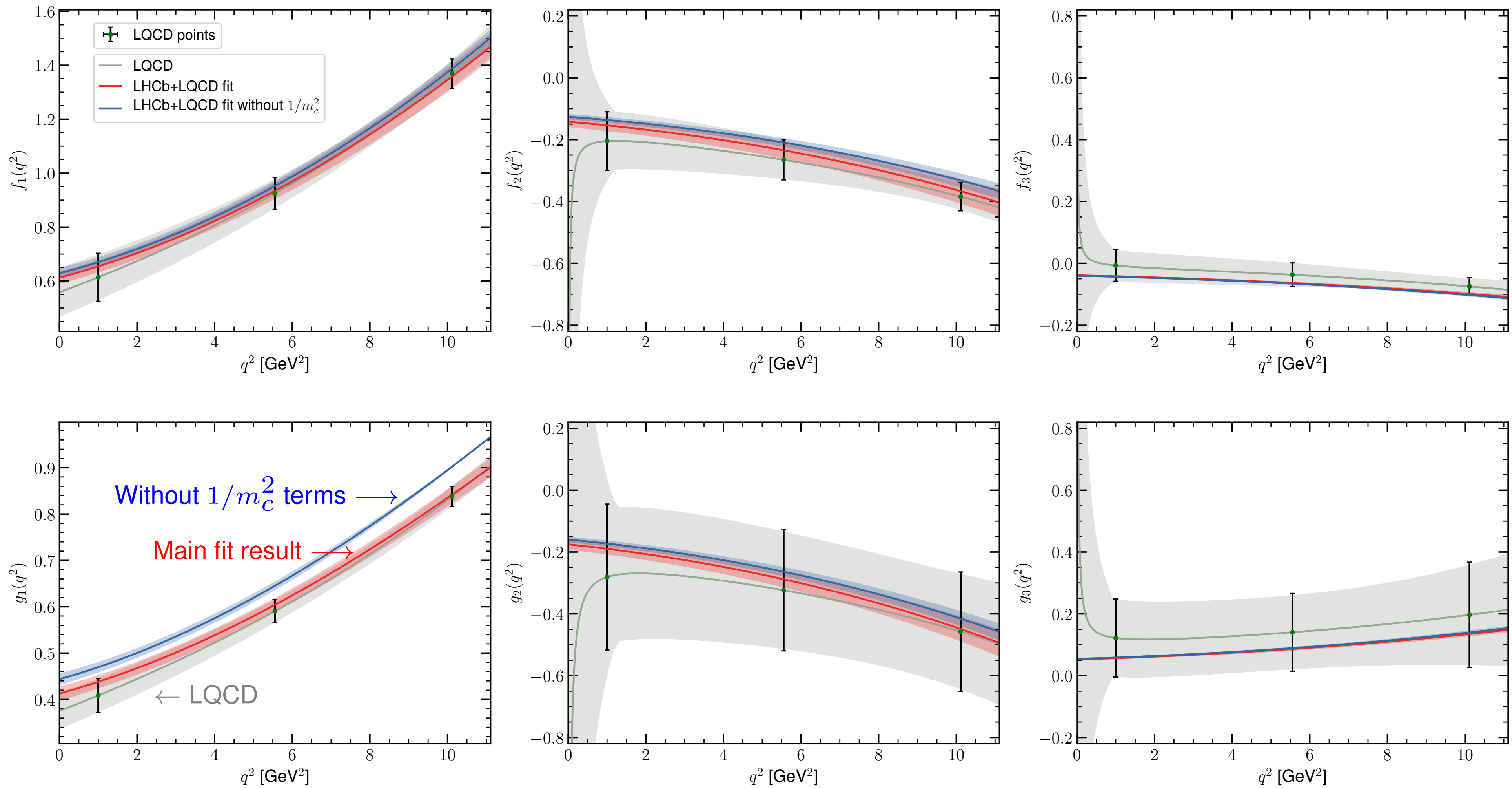
  (Expanding in $w-1$ or in conformal parameter, $z$, makes negligible difference)

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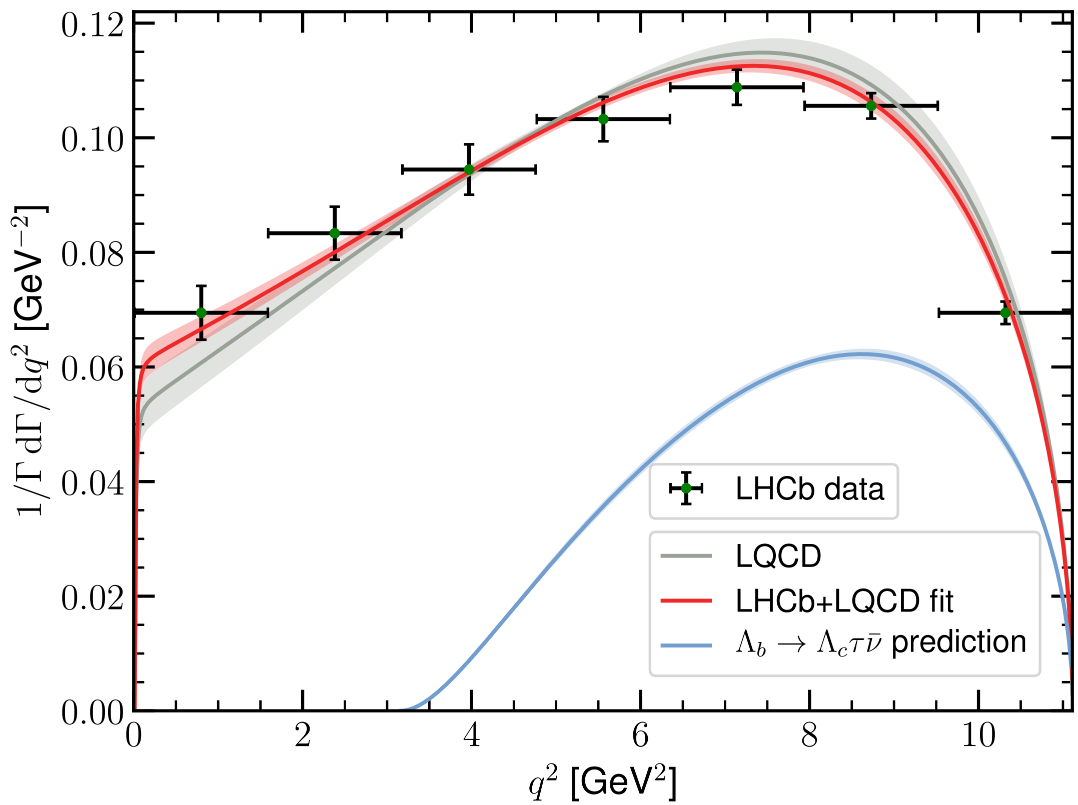
# Fit to lattice QCD form factors and LHCb (2)

- 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 $R(\Lambda_c)$



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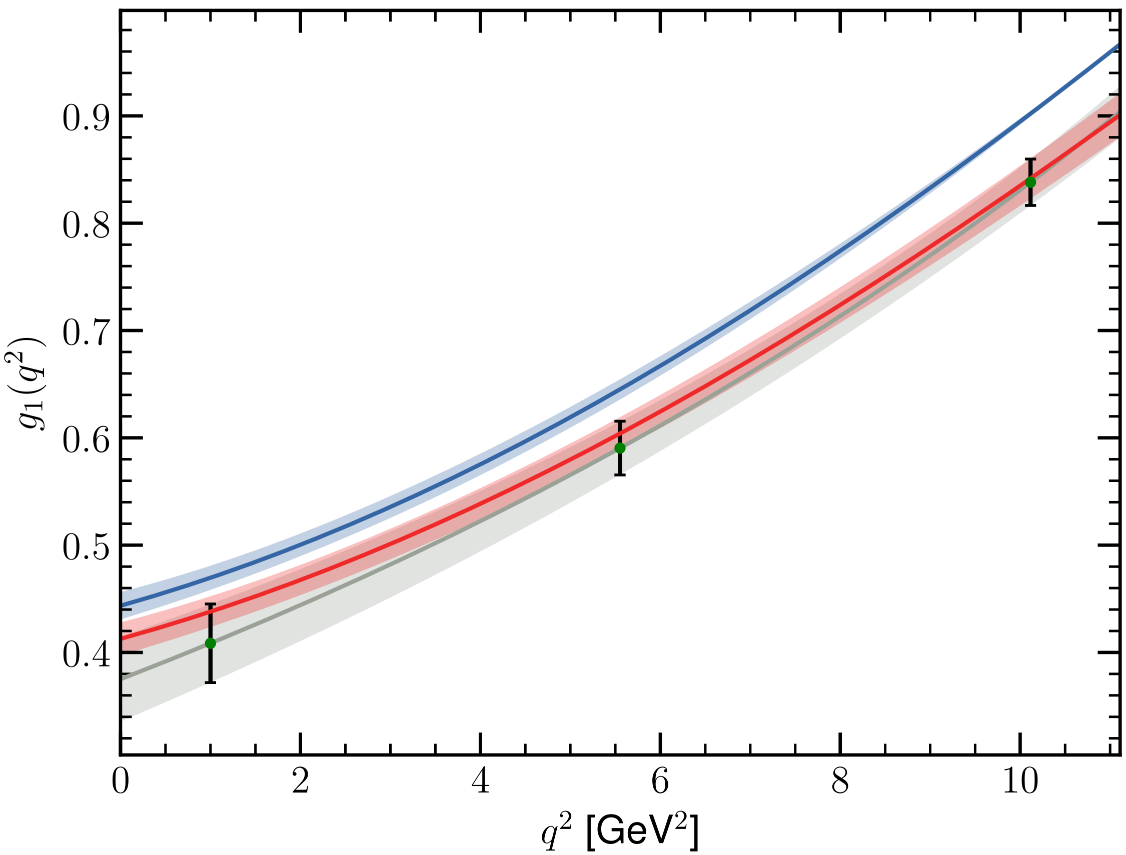
# The fit requires the $1/m_c^2$ terms

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

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

- Our results will make their way into `Hammer` [Bernlochner, Duell, ZL, Papucci, Robinson, soon]



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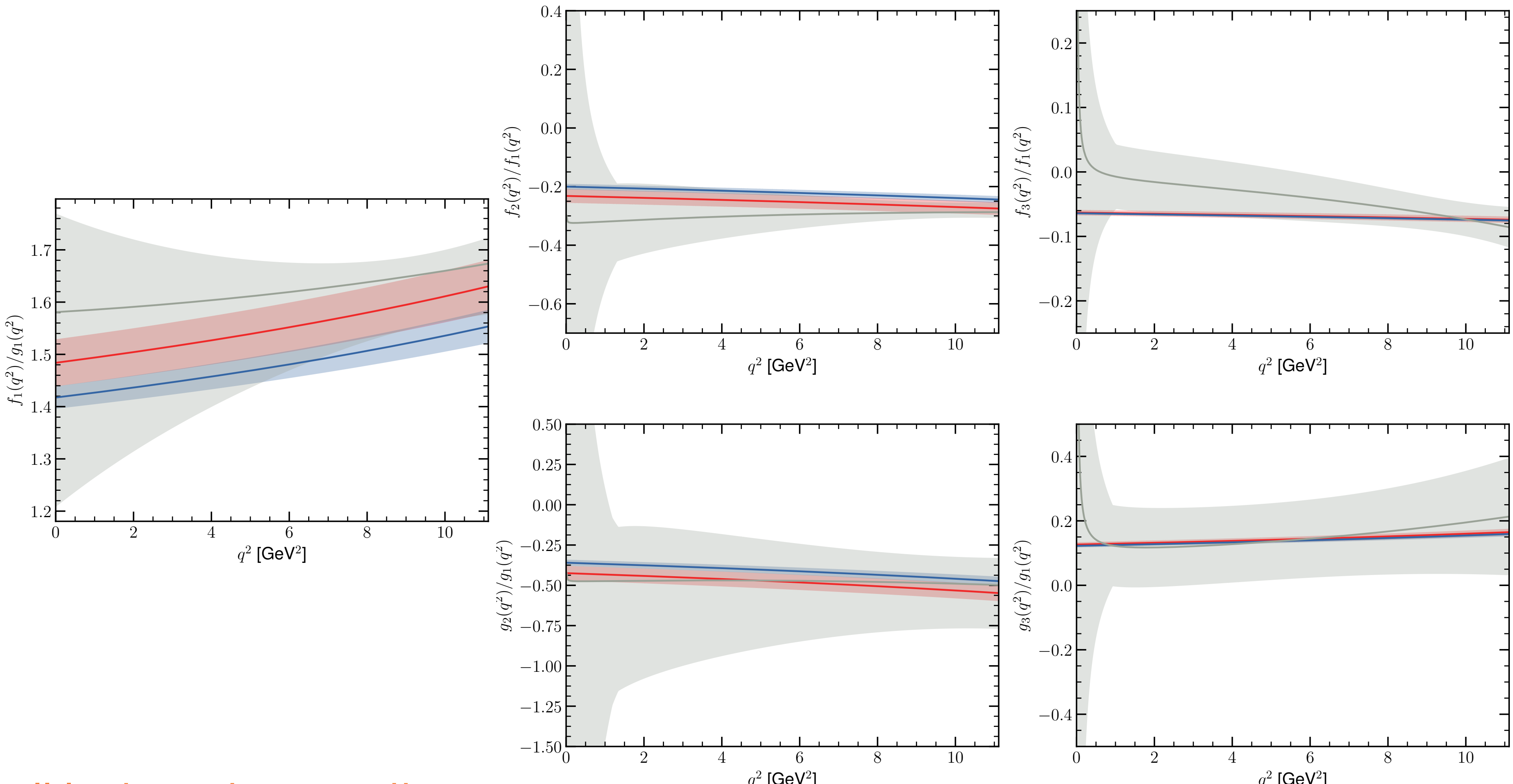
# The ratios of form factors

- $f_1(q^2)/g_1(q^2) = \mathcal{O}(1)$, 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 — issues?

- There are $4$ form factors

  **We get parameter free predictions!**

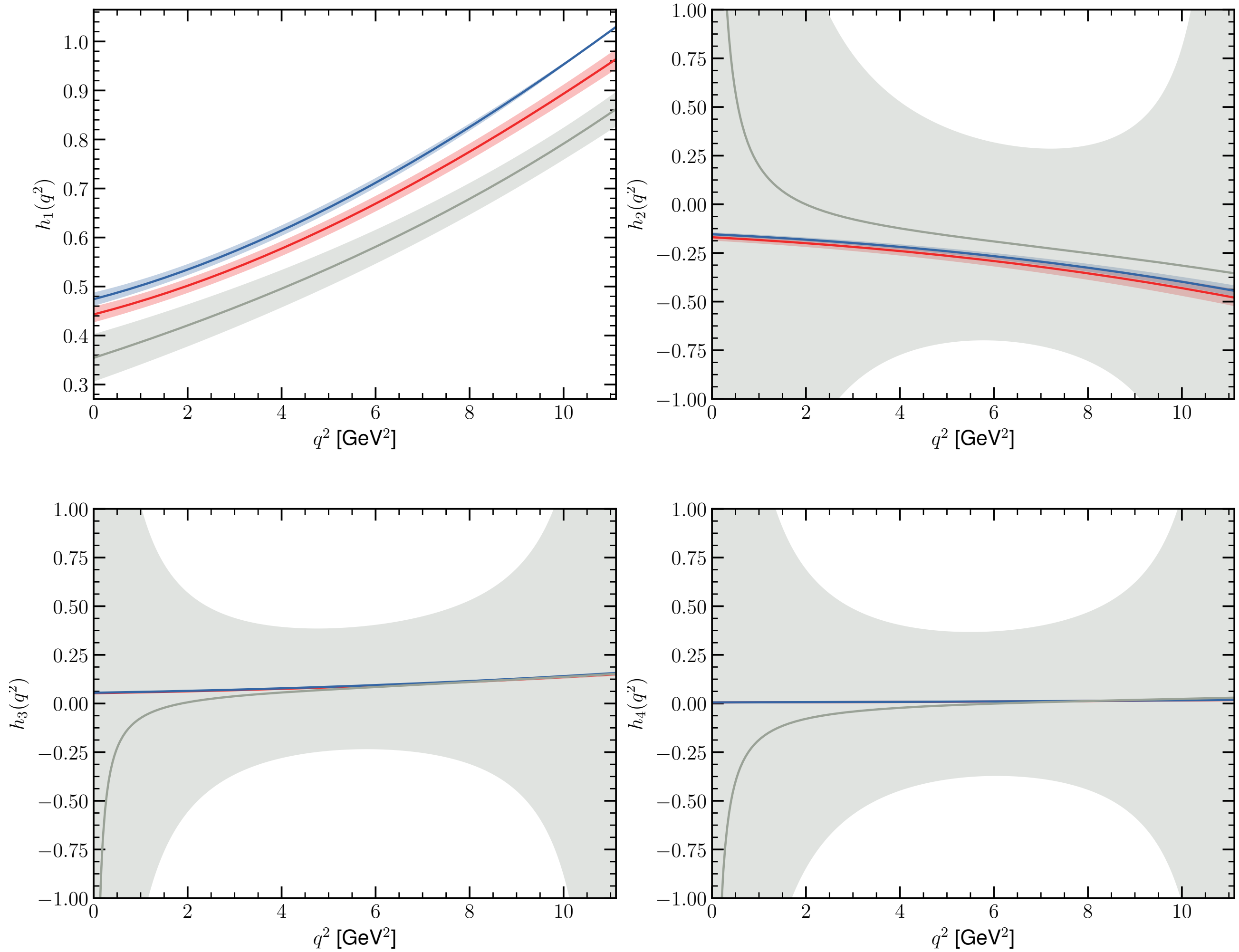
  HQET: $h_1\ (= \widetilde{h}_+) = \mathcal{O}(1)$

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

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

  [Datta, Kamali, Meinel, Rashed, 1702.02243]

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




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

- If tensions between data and SM remain, we'll have to sort out this difference

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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 $\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c \mu \bar{\nu})/\mathrm{d}q^2$

- Long term: including $\Lambda_c$ decay distributions would give even more information

# Spinoffs, byproducts, etc.

# Have $|V_{cb}|$ determinations converged?

- $|V_{cb}|$ important to assess if there is an $\varepsilon_K$ 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 $\tau$ 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, $|V_{cb}|_{\rm BGL} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$

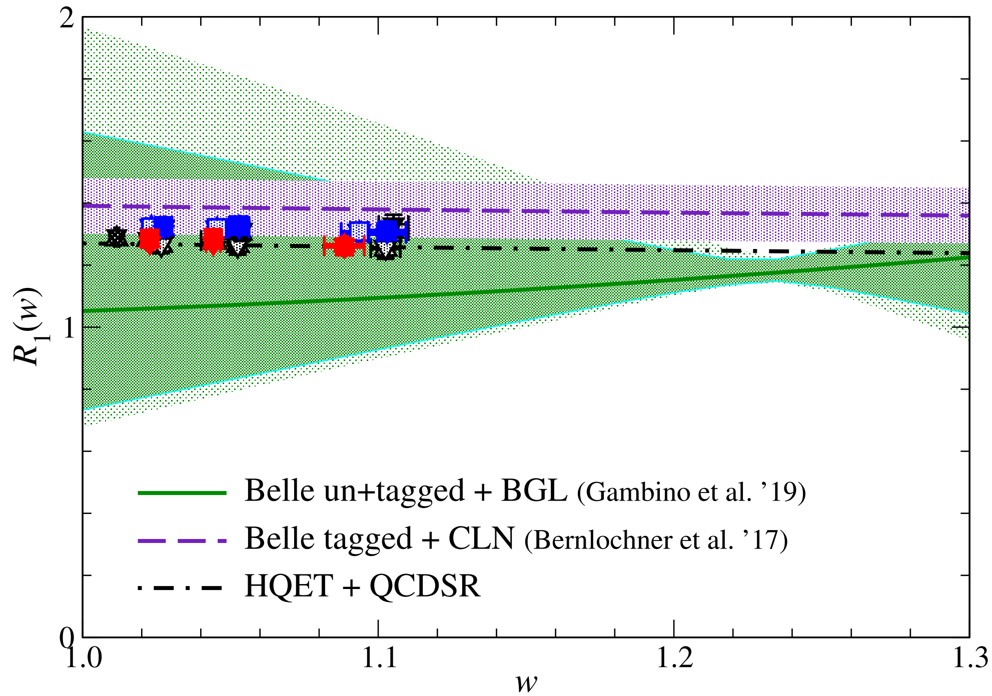
  Grinstein & Kobach, 1703.08170, $|V_{cb}|_{\rm BGL} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$

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

# Lattice QCD, preliminary results

- FNAL/MILC and JLQCD are both working on the $B \to D^* \ell \bar{\nu}$ form factors
  Independent formulations: staggered vs. Mobius domain-wall actions




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

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

# 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

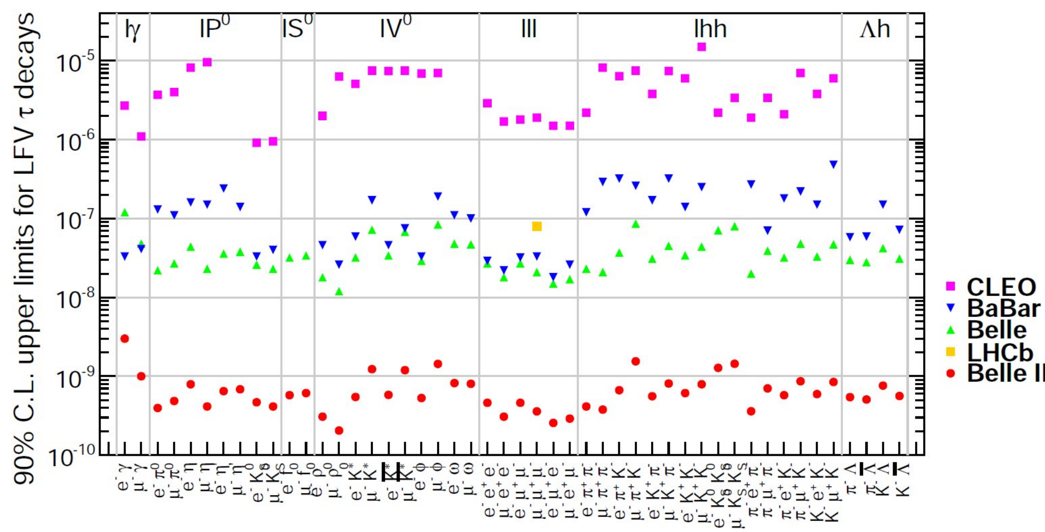
- Many LFV searches became more interesting, not previously of high profile:

  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

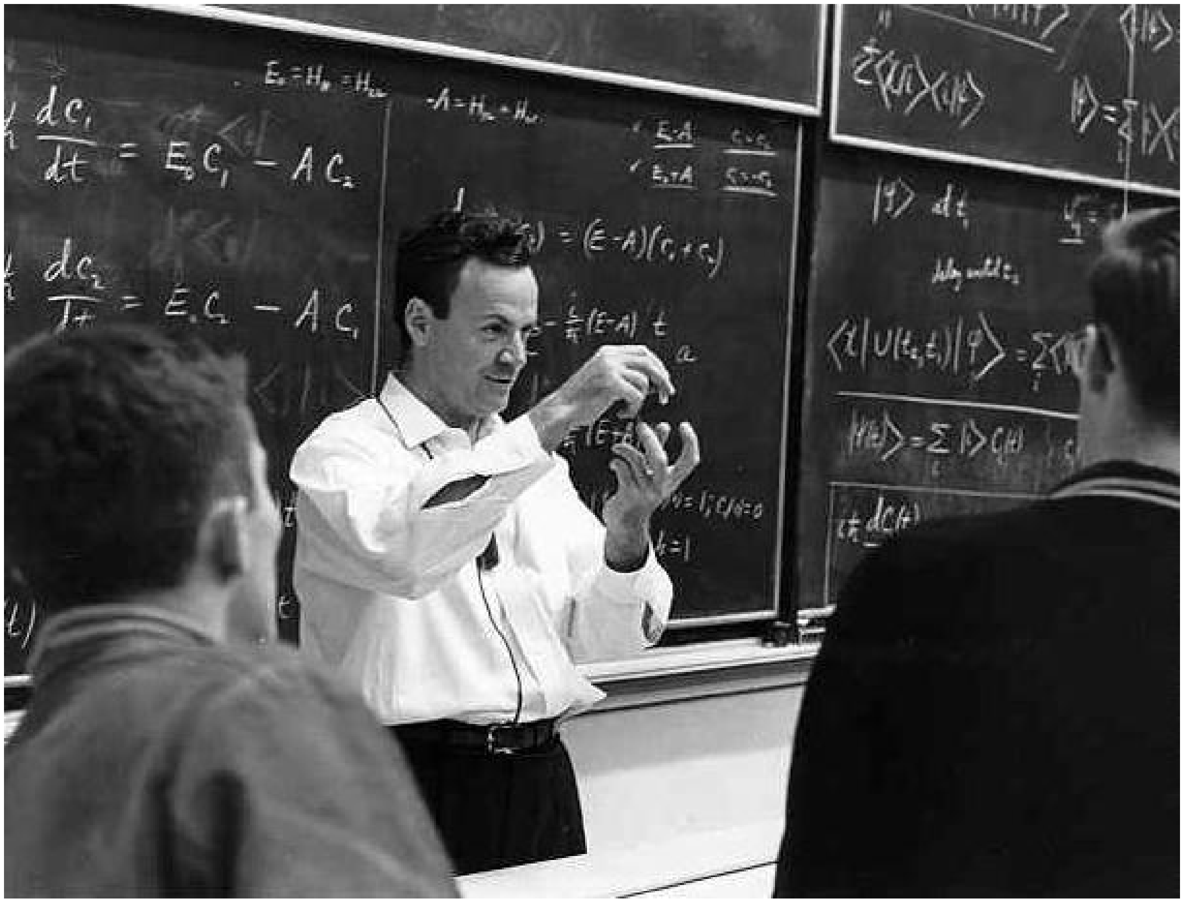
- Even just extending prior searches can be interesting
(allowed regions of masses & couplings in strange models can be ... strange)
  - Extend $\tilde{t}$ and $\tilde{b}$ searches to higher production cross section
  - Search for $t \to b\tau\bar{\nu}$, $c\tau^+\tau^-$ nonresonant decays
  - Search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

... Could be an entire talk — some of these resenctly done

# 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 & hierarchy puzzle)
- $\Lambda_b \to \Lambda_c \ell\bar\nu$: HQET more predictive than in meson decays, $\Lambda_{\rm QCD}^2/m_c^2$ terms essential
- $B \to D^*\ell\bar\nu$: Need (much) more data to know how anomalies (and $|V_{cb}|$) settle
- 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 CKM determinations, and NP sensitivity

# Ultimately, data will tell

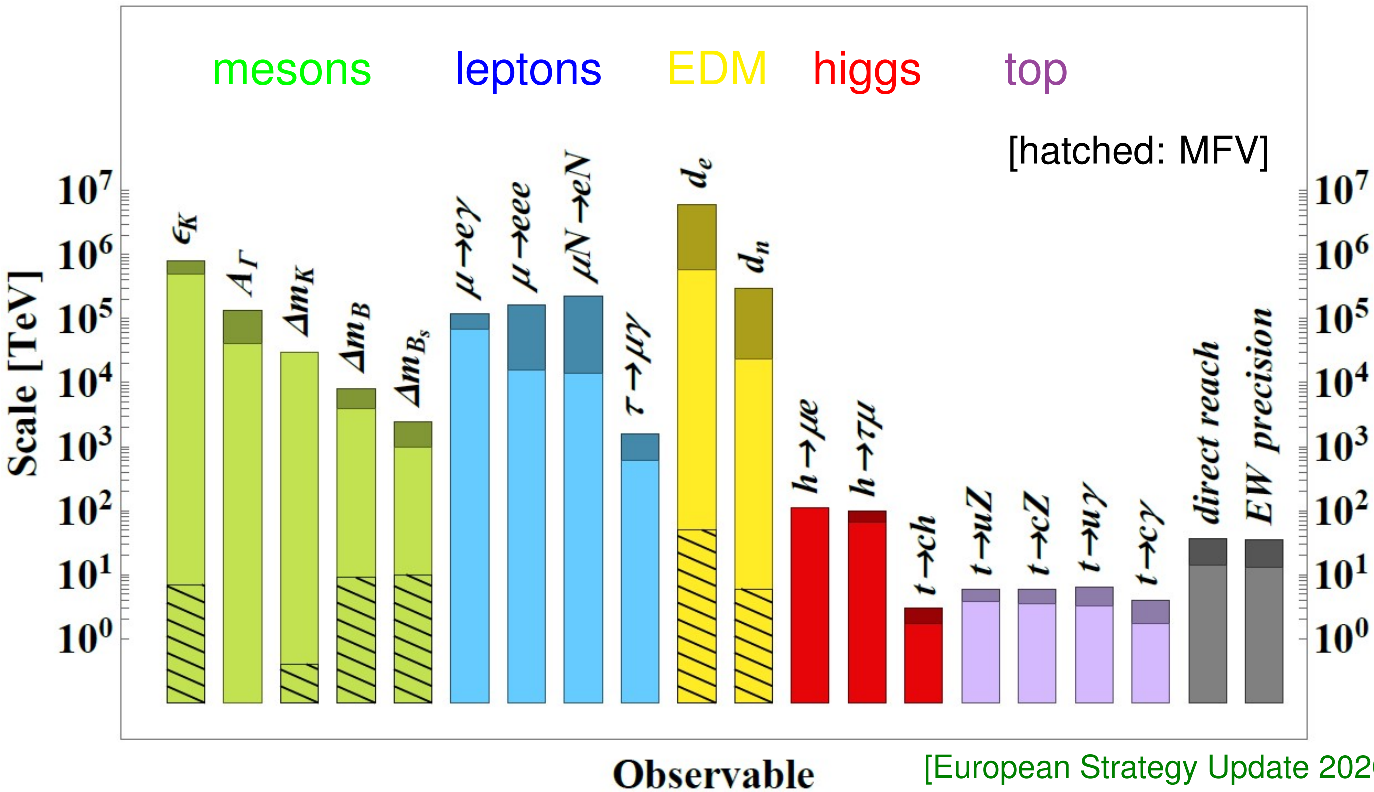


"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]


# Extra slides

# Anticipated increases in sensitivity

- Scales of dim-6 operators probed — various mechanisms devised to let TeV-scale NP obey these bounds (Pattern and orders of magnitudes matter more than precise values)




[European Strategy Update 2020, arXiv:1910.11775]

- Mu2e is probably the largest increase in mass-scale sensitivity in next 10–15 yrs

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

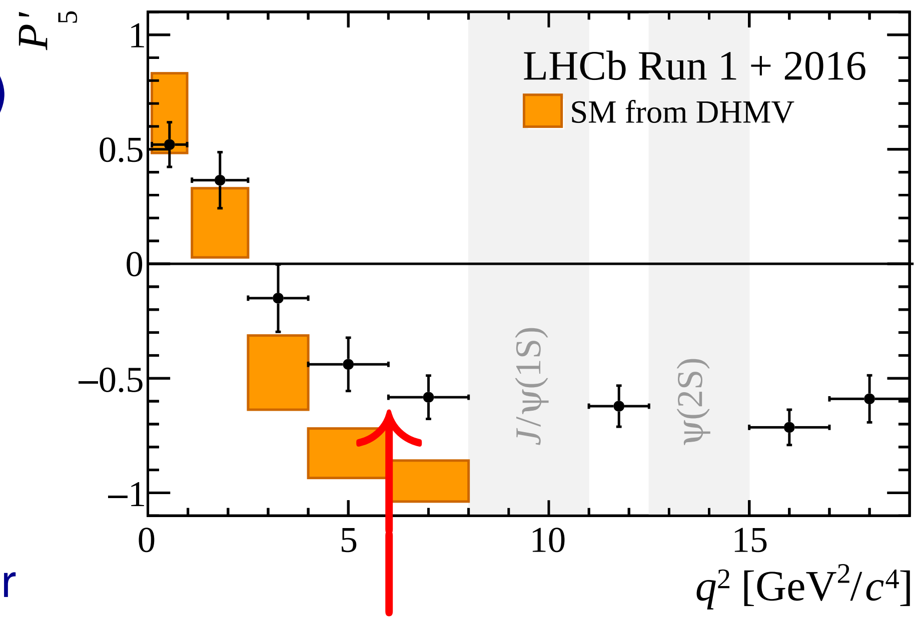
- "Optimized observables" [1202.4266 + long history]
  (some assumptions about what's optimal)

  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 $J/\psi$ this comparison can be trusted?




NP, fluctuation, SM theory? [2003.04831]

- Tests: other observables, $q^2$ dependence, $B_s$ and $\Lambda_b$ 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.



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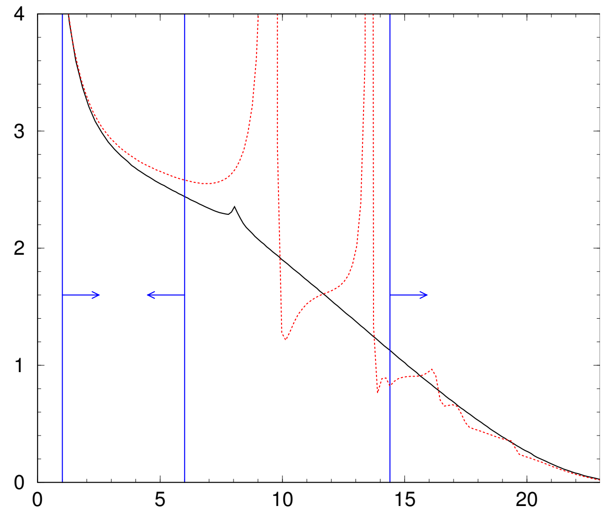
# Hadronic physics starts to enter

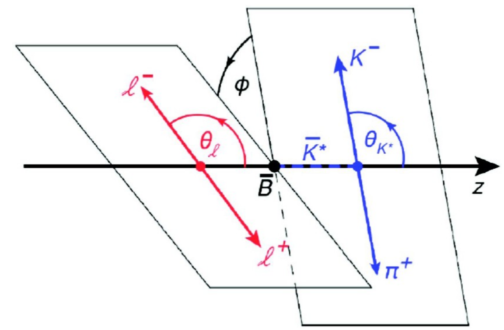
- Rate determined (mostly) by:

$$O_7 = \overline{m}_b\, \bar{s}\sigma_{\mu\nu} e F^{\mu\nu} P_R b$$

$$O_9 = e^2(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10} = e^2(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



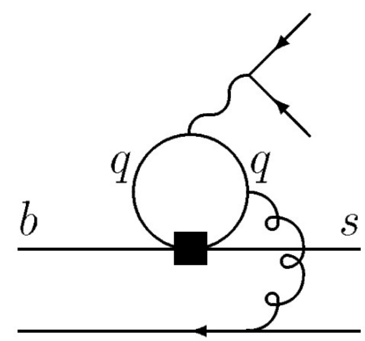




- Most often debated: validity of perturbative methods for:

$$\mathcal{B}(B \to \psi X_s) \sim 4 \times 10^{-3}$$
$$\downarrow$$
$$\mathcal{B}(\psi \to \ell^+\ell^-) \sim 6 \times 10^{-2}$$

their product: $\sim 2 \times 10^{-4}$

Much bigger than the short distance contribution...




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



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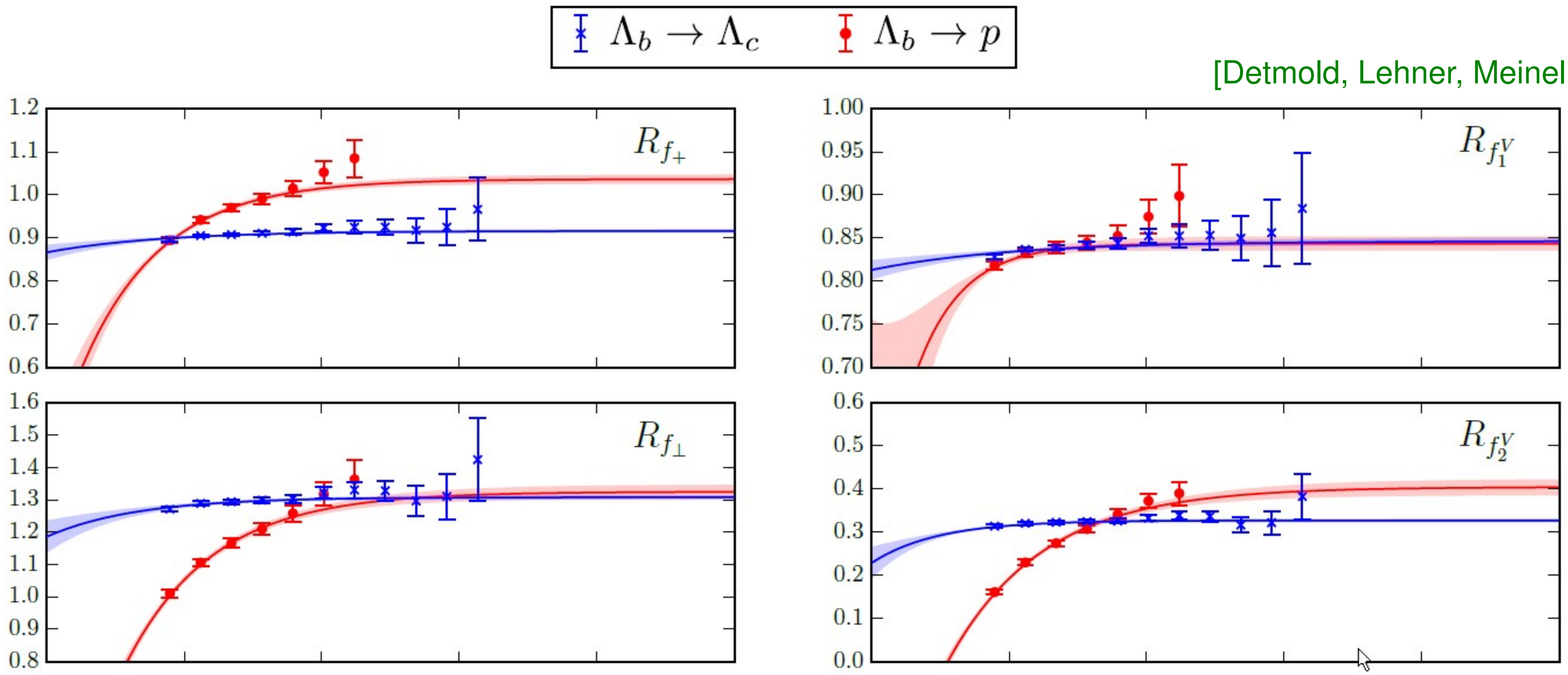
# Lattice QCD details

- 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]

# Hammer

Helicity Amplitude Module
for Matrix Element Reweighting

hammer.physics.lbl.gov — you can download and use v1.1.0, Aug 2020

# The need for Hammer

Helicity Amplitude Module for Matrix Element Reweighting

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

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

  All measurements use numerous cuts, acceptances depend on distributions of $D^{(*)}\tau\bar{\nu}$ and their decay products in many variables — the SM is assumed for these, to make the measurements
- Reported CL of (dis)agreement with SM is correct, but cannot determine CL of accepting a certain NP model, nor what NP parameters give the best fit to data
- Prohibitively expensive computationally to redo the MC for general NP

  One operator in SM, while $5$ (or $10$ with $\nu_R$) in general

# What Hammer does

- Fully differential distributions of detected particles, incl. $D^*$ & $\tau$ 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.)

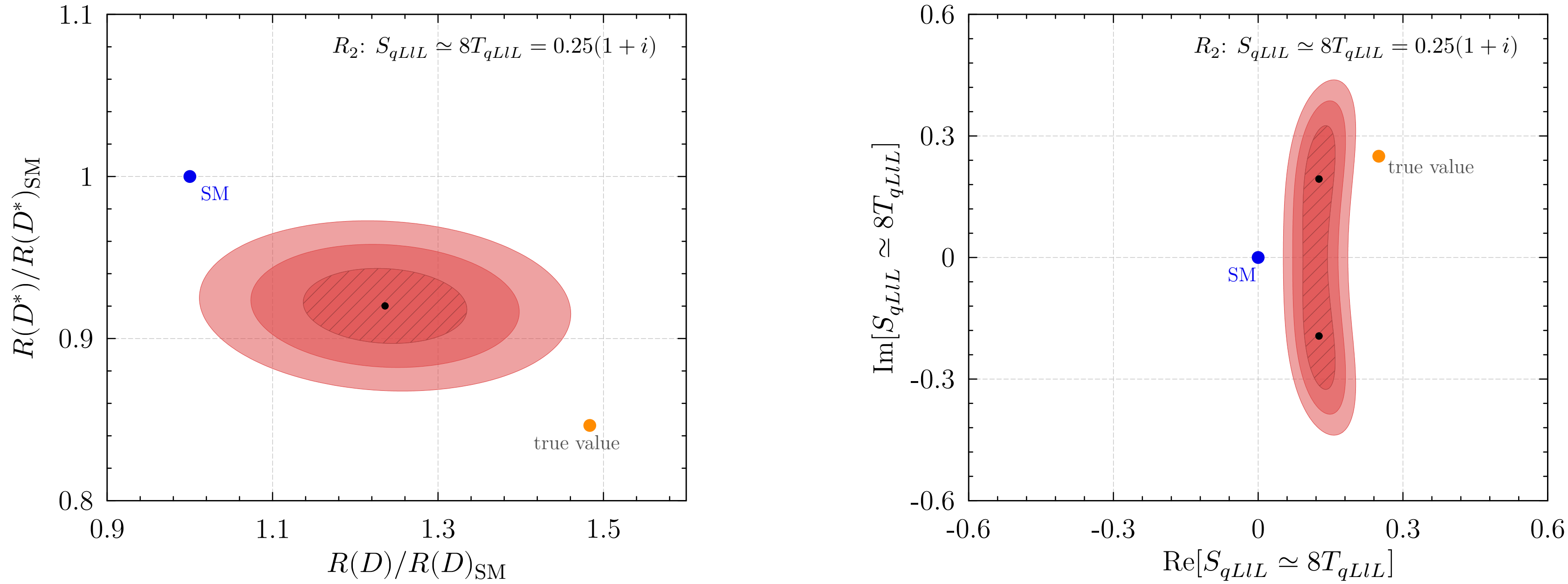
- Publicly available, implementations in experiments in progress hammer.physics.lbl.gov

# Current status

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

# An illustration: the $R_2$ leptoquark

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




- Recovered parameters, from fitting toy (Asimov) data, are several $\sigma$ from "truth"

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

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