B 反常和重夸克物理

B Anomalies and Heavy Quark Physics

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粒子物理与原子核物理研究所

References

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...

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    - The only source of quark flavor change in the SM
- Many testable relations, sensitive to possible deviations from the SM

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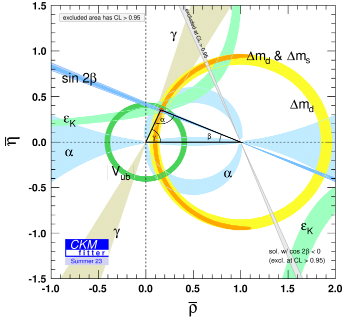

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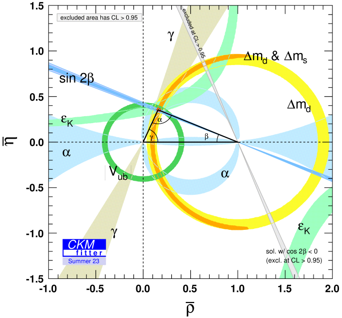

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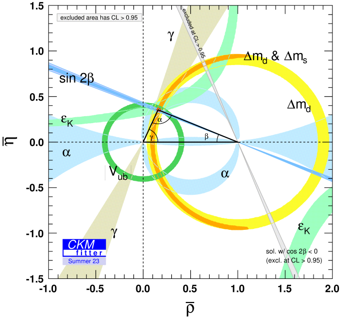

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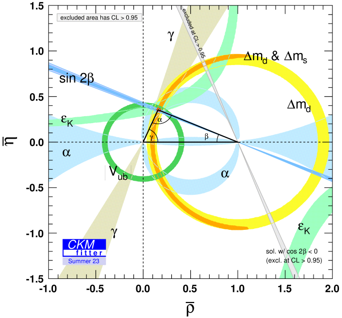

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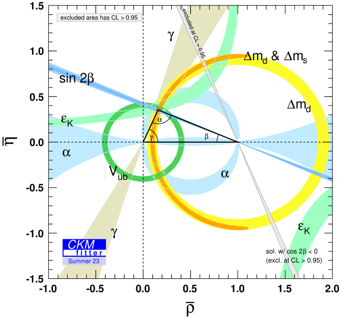

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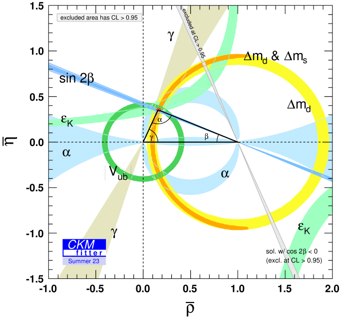

- Tree-level (mainly V_{ub} & γ) vs. loop-dominated measurements
- In loop (FCNC) processes *NP/SM* $\sim 20\%$ is still allowed
  (mixing , $B \to X\ell^+\ell^-, X\gamma, etc.$)

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

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

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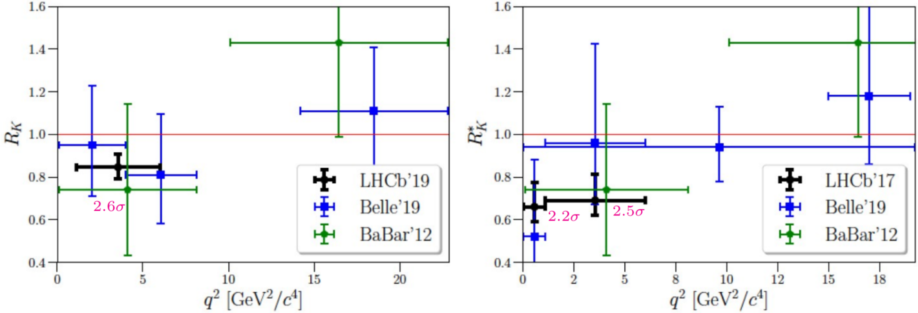

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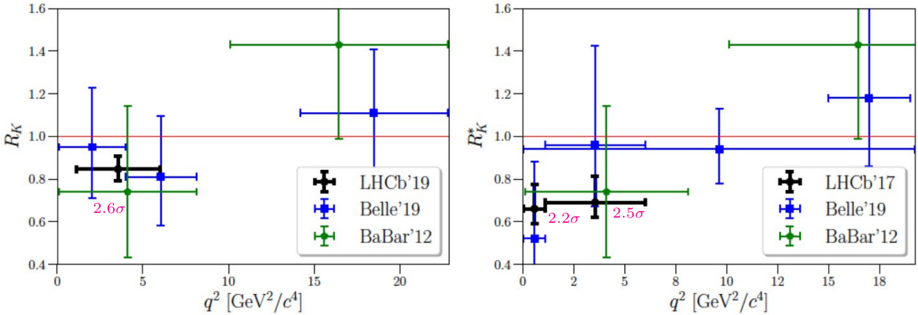

- Theorists' fits quote $3-5\sigma$ (sometimes including P_5' and/or $B_s \to \phi\mu^+\mu^-$)

$R(D)$ and $R(D^*)$ – 3σ tension with SM

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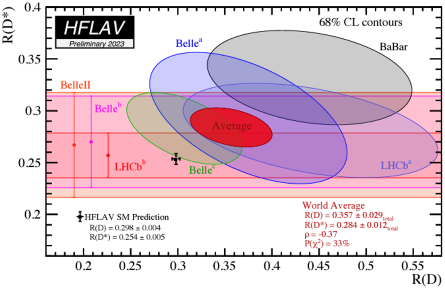

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Tension with SM at the level of **3.34 σ.**

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[NEW!]
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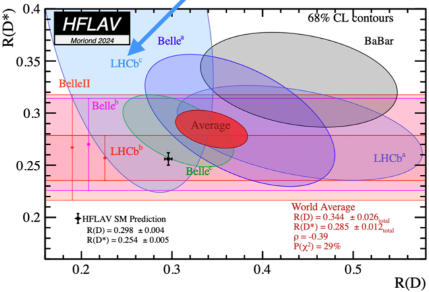

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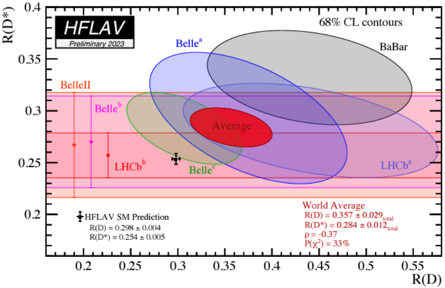

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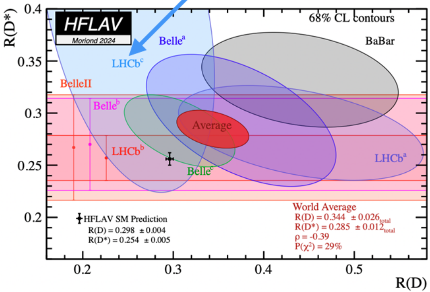

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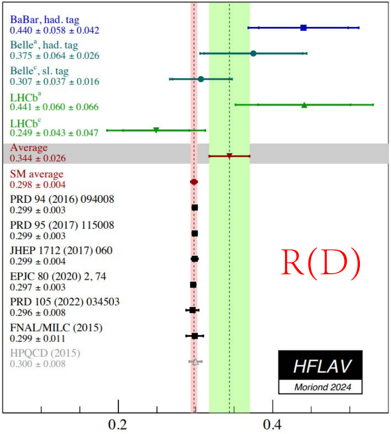

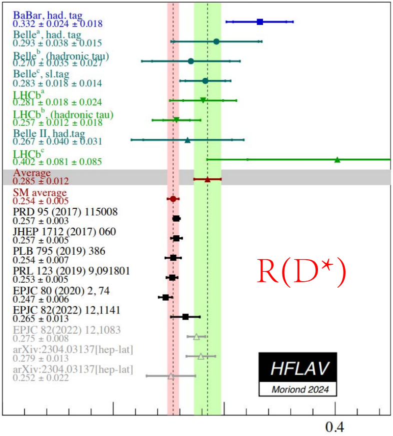

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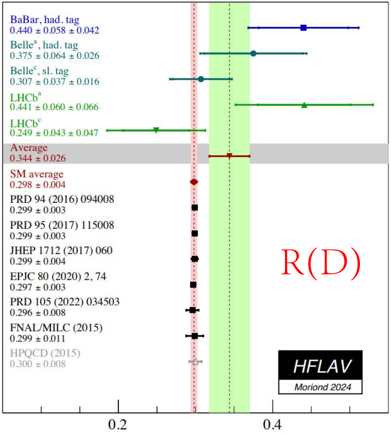

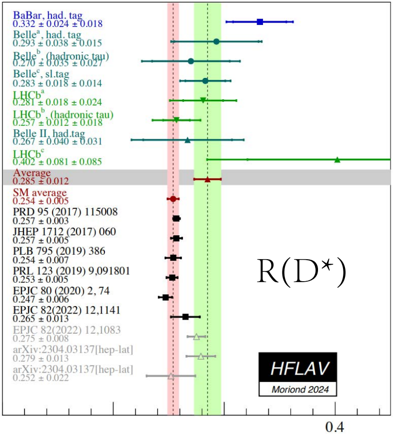

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- Results from BaBar, Belle, LHCb are consistent
- Often when measurements disagreed in the past, averages were still meaningful
- Enhancement is also seen in similar ratio in $B_c \to J/\psi \ell \bar{\nu}$
- If Nature were as most theorist imagined,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

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- Which calculations can be made most robust?
- What else can we learn from studying these anomalies?

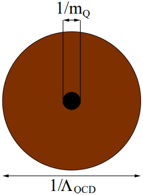
Heavy quark symmetry

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

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

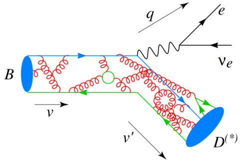
- In the $m_{b,c} \gg \Lambda_{\text{QCD}}$ limit, configuration of brown muck only depends on the four-velocity of the heavy quark, but not on its mass and spin
- On a time scale $\ll \Lambda_{\text{QCD}}^{-1}$ weak current changes $b \to c$
  i.e.: $\vec{p}_b \to \vec{p}_c$ and possibly $\vec{s}_Q$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

  In $m_{b,c} \gg \Lambda_{\text{QCD}}$ 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

$$\langle D|\,\bar{c}\gamma^\mu b\,|\overline{B}\rangle = f_+(q^2)(p_B+p_D)^\mu + \left[f_0(q^2) - f_+(q^2)\right]\frac{m_B^2 - m_D^2}{q^2}\,q^\mu$$

$$\langle D^*|\,\bar{c}\gamma^\mu b\,|\overline{B}\rangle = -ig(q^2)\,\epsilon^{\mu\nu\rho\sigma}\,\varepsilon_\nu^*\,(p_B+p_{D^*})_\rho\,q_\sigma$$

$$\langle D^*|\,\bar{c}\gamma^\mu\gamma^5 b\,|\overline{B}\rangle = \varepsilon^{*\mu} f(q^2) + a_+(q^2)\,(\varepsilon^*\cdot p_B)\,(p_B+p_{D^*})^\mu + a_-(q^2)\,(\varepsilon^*\cdot p_B)\,q^\mu$$

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 $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ $+\ldots$

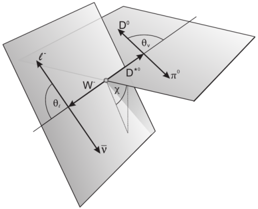
- Constrain all 4 functions from $B \to D^{(*)}\,l\bar{\nu}$ $\Rightarrow$ $\mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2\,,\ \alpha_s^2)$ uncertainties

[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

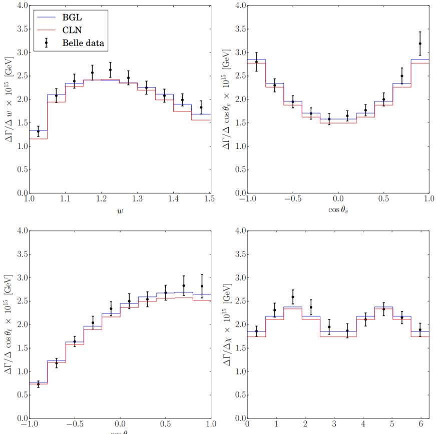
- Belle published the unfolded $B \to D^* l \bar{\nu}$ distributions [1702.01521]



- Can perform different fits to data
- Need input on the fitted shape:

  BGL: Boyd, Grinstein, Lebed, '95–97

  CLN: Caprini, Lellouch, Neubert, '97



[Grinstein & Kobach, 1703.08170]

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 ± 0.046	0.306 ± 0.015	-20%
Lattice [FLAG]	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

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

($\bar\Lambda_\Lambda \sim 0.8\,\text{GeV}$ 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 $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$

[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 $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$ [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]

- 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 negligible difference)

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

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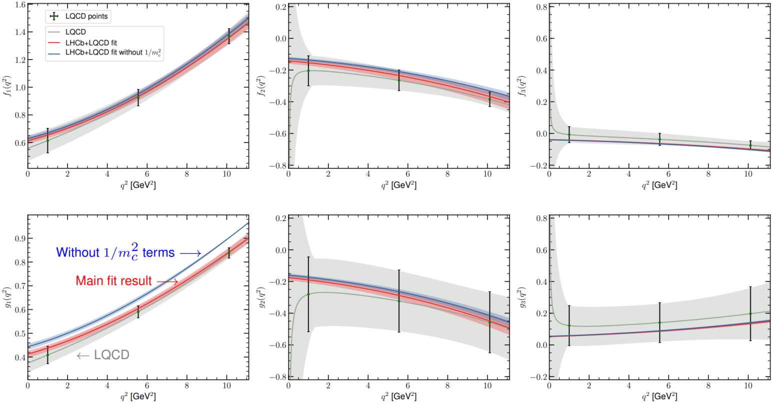
Fit to lattice QCD form factors and LHCb(1)

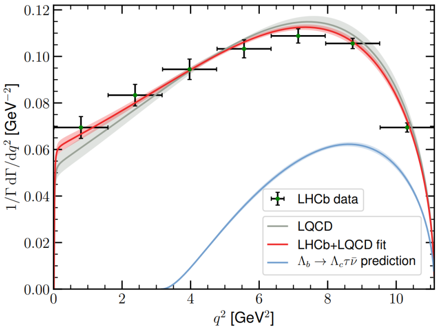
- Fit 6 form factors w/ 4 parameters: $\zeta'(1)$, $\zeta''(1)$, $\hat{b}_1$, $\hat{b}_2$ [LQCD: Detmold, Lehner, Meinel, 1503.01421]



Fit to lattice QCD form factors and LHCb(2)

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

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

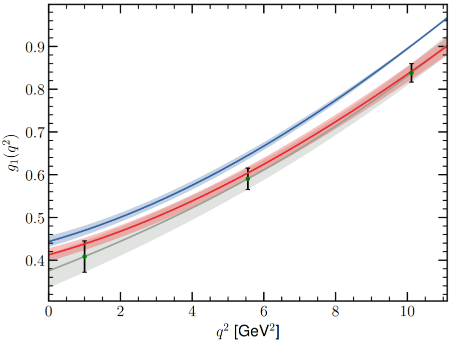


The fit requires the $1/m_c^2$ terms

- E.g., fit results for g_1
  blue band shows fit with $\hat{b}_{1,2} = 0$
- Find: $\hat{b}_1 = -(0.46 \pm 0.15)\,\mathrm{GeV}^2$
  ... of the expected magnitude

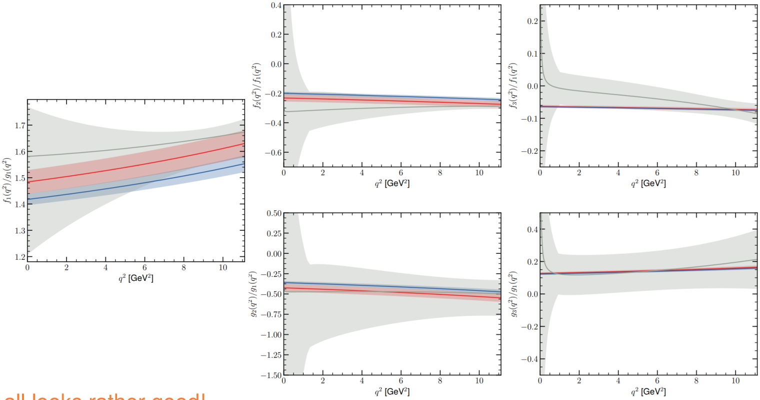
  Well below the model-dependent estimate: $\hat{b}_1 = -3\bar{\Lambda}_\Lambda^2 \simeq -2\,\mathrm{GeV}^2$

  [Falk & Neubert, hep-ph/9209269]
- Expansion in $\Lambda_{\mathrm{QCD}}/m_c$
  appears well behaved
  (contrary to some 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!

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

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

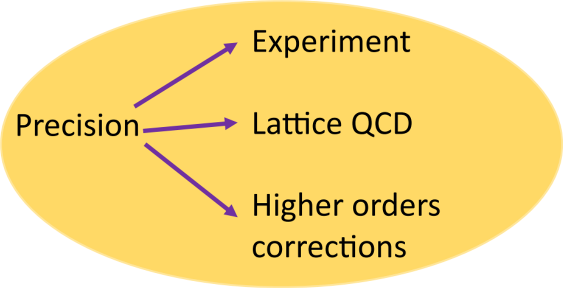
  Measuring the 3 terms would give more information than just $\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c \mu \bar{\nu})/\mathrm{d}q^2$

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

Conclusions and Outlook

- $\Lambda_b \to \Lambda_c \ell \bar{\nu}$: HQET more predictive than in meson decays, Λ^2_{QCD}/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, discard some prejudices
- Measurements and SM predictions will both improve a lot in future



Thanks!