$\overline{B} \to D^{(*)}$ form factors — theory perspective

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Challenges in semileptonic b decays
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Overview

- heavy-quark expansion very effective since both quark flavours b & c are heavy [Isgur,Wise '89]
  - simultaneous expansion in α_s up to NLO and $\Lambda_{\text{had}}/m_{b,c}$ up to 2nd power [Falk,Neubert hep-ph/9209268 & hep-ph/9209269]
  - heavy-quark spin symmetry yields relations between form factors across different currents and processes
  - relates BSM-only (tensor) form factors to form-factors for SM predictions [Bernlochner et al. 1703.05330]

dimensionless variable w useful for discussion

- parametrizes recoil energy of the $D^{(*)}$ in the $\overline{B}$ rest frame
- zero recoil: $w = 1$, "max" recoil: $w \simeq 1.5$

Frameworks to parametrize form factors

1. BGL: dispersive or unitarity bounds [Okubo '71; Boyd et al. '97]
   - relates form factors to inclusive hadron cross section
   - convenient choices of form factors and basis functions renders bound "diagonal"

$$f(w) = \frac{p_f(w)}{B_f(w)\phi_f(w)} \sum_k a_k^{(f)} z(w)^k$$

2. HQE: heavy-quark expansion [Isgur/Wise '90; Falk/Neubert '92; ...]
   - heavy-quark spin symmetry reduces number of independent functions and enlarges number of processes governed by the same functions (Isgur-Wise functions)
     - to $1/m_c^2$: 10 independent IW functions
     - $\overline{B} \to D^{(*)}$: 10 form factors
   - able to constrain IW function [Bordone et al. '19]
3. CLN: HQE and bounds together [Caprini et al. '97]
   - uses HQE to $1/m_Q$, only for w dependence of ratios of form factors
   - more predictive than BGL due to fewer parameters
   - less flexible, impacts V_{cb} extraction [Bigi/Gambino '17]

- precise lattice QCD results for $\overline{B}_{(s)} \to D_{(s)}$ [FNAL/MILC 1503.07237; HPQCD 1505.03925]
  - cover large parts of phase space
  - small and systematically improvable uncertainties
- light-cone sum rules provide all form factors at negative q^2 [Faller et al. '08] [Gubernari et al. '18]
  - large uncertainties, difficult to estimate systematic unc.
- sum rules provide IW and derivatives at max recoil [Neubert/Nir/Ligeti '93 – '94]
  - large uncertainties, difficult to estimate systematic unc.
- consistent picture of these theory inputs to NLO in α_s & $1/m^2$ [Bordone et al. 1908.09398 & 1912.09335]

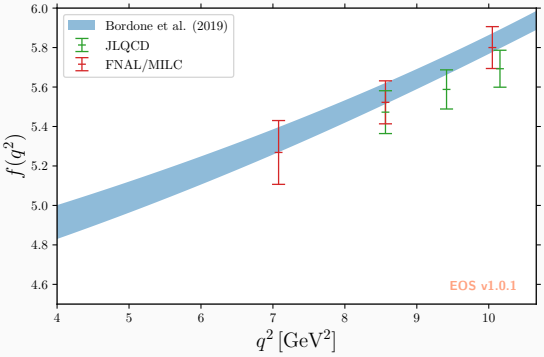
New and upcoming theory inputs

- first lattice QCD results for $\overline{B}_{(s)} \to D^*_{(s)}$ form factor at non-zero recoil

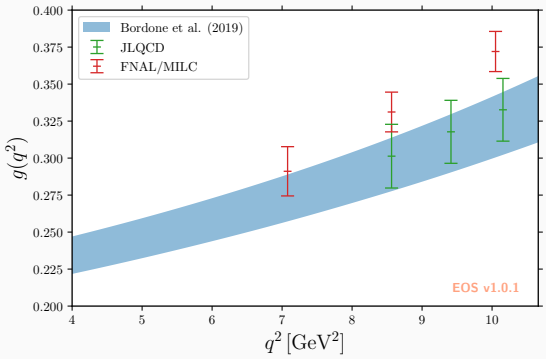
  [HPQCD 2105.11433; FNAL/MILC 2105.14019]

  - more than $A_1/h_{A_1}/f$!
  - all four $V-A$ form factors available, in machine readable form
  - data available in full (HPQCD) or substantial parts of (FNAL/MILC) phase space

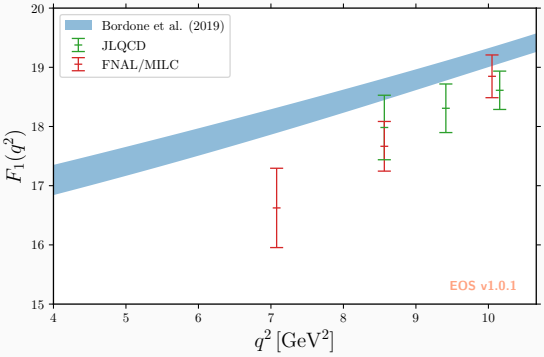
- upcoming lattice QCD result for $\overline{B} \to D^*$ from factors at non-zero recoil [JLQCD, to appear]
  - access to substantial parts of phase space



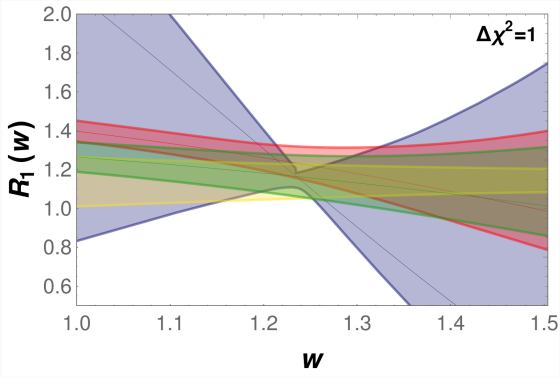
- lattice QCD analyses agree well with each other!
  - if at all, small difference in slope
- lattice QCD analyses agree well with HQE fit!



- lattice QCD analyses agree less well with each other than for f
  - clear difference in value and slope!
- preliminary JLQCD points better with HQE (and with Belle, not shown) than FNAL/MILC points

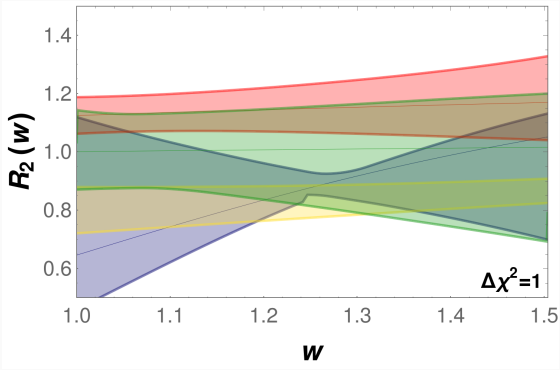


- lattice QCD analyses agree in value
  - stark difference in slope!
- preliminary JLQCD points better with HQE (and with Belle, not shown) than FNAL/MILC points



plots and numerics by Martin Jung

- BGL fit (blue) to Belle data in agreement with HQE fit (yellow) to theory
- BGL fit (green) to JLQCD in good agreement with both BGL fit and HQE fit
- BGL fit (red) to FNAL/MILC in tension with Belle and Belle + JLQCD fits
  - Belle only: increases χ^2 by ~ 17 for 8 d.o.f.; $\sim 2.2\sigma$
  - Belle+JLQCD: increases χ^2 by ~ 23 for 8 d.o.f.; $\sim 3\sigma$



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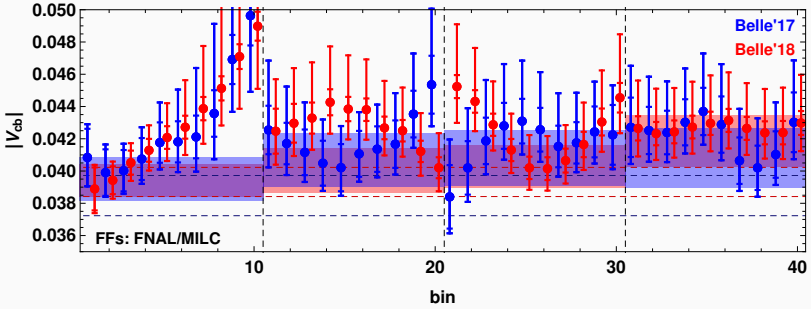

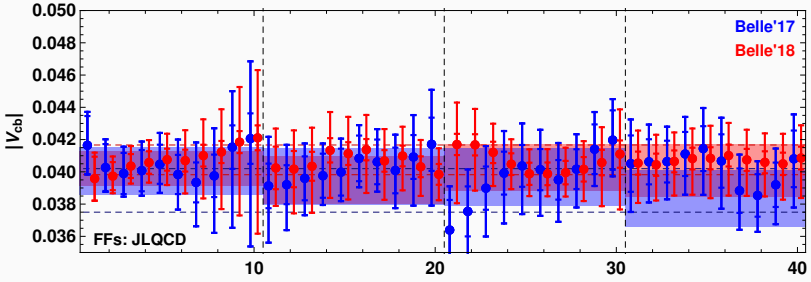

- w shape disagreement

Plots and numerics by Martin Jung

What's Next?

- global HQE form factor fits need updating, due to new theory inputs
  - how to combine FNAL/MILC and JLQCD data?
  - need to carefully check compatibility of either with $\overline{B} \to D$ lattice QCD inputs
- global (exclusive) V_{cb} fit needed, should include new LHCb measurements
  - $\overline{B}_s \to D_s^* \ell \nu$ shape contains valueable information
- Belle II in excellent position to contribute in near future
- a lot of interesting work left for all of us

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