Semileptonic B-decays with a vector final state

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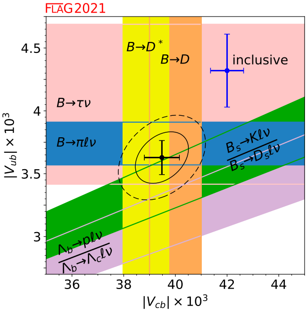
04.22.22
USQCD All Hands Meeting
Zoom@MIT

Intro & Motivation

- Semileptonic decays are a rich source of information for determining CKM matrix elements.
- Lattice data a critical source of input for testing the CKM paradigm.



- With new experimental and theoretical data on the horizon, these are interesting times!

FNAL-MILC allHISQ-b program 2111.05184

- Overall aim: Precision ($\sim 1\%$) determination of a range of $B_{(s)}$ (and $D_{(s)}$) semileptonic form factors, of direct relevance for current and upcoming experimental programs.

- Here we discuss extending this program to decays with vector final states (specifically the processes $B_{(s)} \to D^*_{(s)}$).

- Support/enhance physics of $B \to D^*$ with FNAL heavy quarks on asqtad (and hisq) sea. 2105.14019

Outline

- Intro & Motivation
- FNAL/MILC all-HISQ semileptonic decays
  - Calculation framework
  - Preliminary results w/ pseudoscalar final state
- Including vector final states
- Summary

FNAL-MILC allhisq working group

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Heavy quarks

Treatment of c and especially b quarks challenging in lattice simulation due to lattice artifacts which grow as $(am_h)^n$

- May use an effective theory framework to handle the b quark.
  - Fermilab method, RHQ, OK, NRQCD
  - Pros: Solves problem w/ am_h artifacts.
  - Cons: Requires matching, can still have ap artifacts.

- Also possible to use relativistic fermion provided a is sufficiently small $am_c \ll 1$, $am_b < 1$.
  - Use improved actions e.g. $\mathcal{O}(a^2) \to \mathcal{O}(\alpha_s a^2)$
  - Pros: Absolutely normalised current, straightforward continuum extrap.
  - Cons: Numerically expensive, extrapolate $m_h \to m_b$.

allhisq simulations

- Here we simulate *all* quarks with the HISQ action.
- Unified treatment for wide range of $B_{(s)}$ (and $D_{(s)}$) to pseudoscalar transitions
  - $B_{(s)} \to D_{(s)}$
  - $B_{(s)} \to K$
  - $B \to \pi$
- Ensembles with (HISQ) sea quarks down to physical at each lattice spacing.
- Enables correlated studies of ff *ratios*.

See our 2021 Lattice proceeding for more details! 2111.05184

MILC ensembles [1004.0342, 1212.4768]

- HISQ fermion action.
  - Discretization errors begin at $\mathcal{O}(\alpha_s a^2)$.
  - Designed for simulating heavy quarks (m_c and higher at current lattice spacings).

- Symanzik-improved gauge action, takes into account $\mathcal{O}(N_f \alpha_s a^2)$ effects of HISQ quarks in sea. [0812.0503]

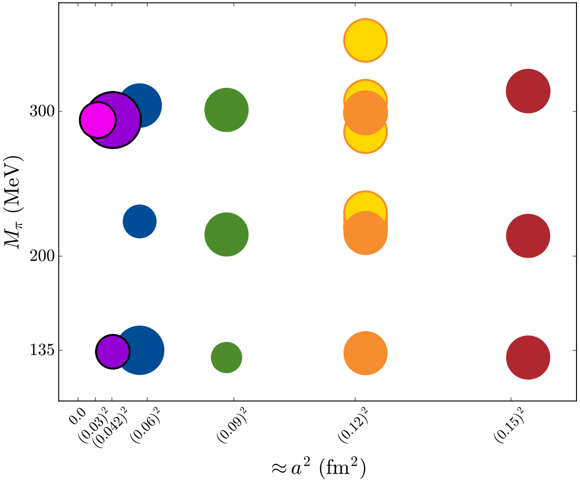
- Multiple lattice spacings down to ~ 0.042 (now 0.03) fm.

- Effects of u/d, s, and c quarks in the sea.

- Multiple light-quark input parameters down to physical pion mass.
  - Chiral fits.
  - Reduce statistical errors.

MILC ensemble parameters

1712.09262



allHISQ b

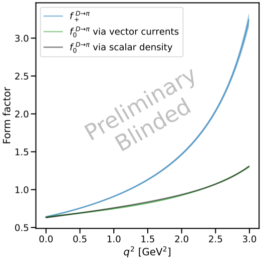
- Use a heavy valence mass h as a proxy for the b quark.

- Work at a range of m_h, with $am_c < am_h \lesssim 1$ on each ensemble. On sufficiently fine ensembles, m_h is near to m_b (e.g. m_b at $am_h \approx 0.65$ on $a = 0.03$ fm).

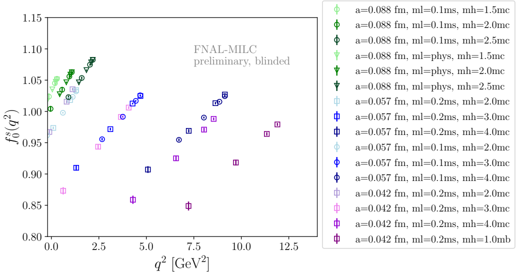
- Map out physical dependence on m_h, remove discretisation effects $\sim (am_h)^{2n}$ using information from several ensembles. Extrapolate results $a^2 \to 0, m_h \to m_b$.

Update on allHISQ $P \to P$

$D \to \pi$



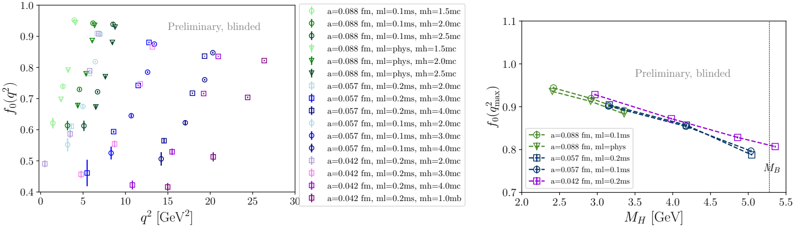
$B_s \to D_s$



- Will Jay's D-decay analysis $(D \to \pi, K\ D_s \to K)$ at an advanced stage. Percent-level targets achieved.
- For B decays, vector operator renorm. and chiral/continuum extrapolations remain.

Update on allHISQ $P \to P$

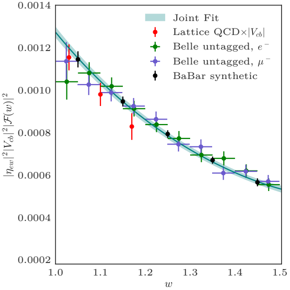
$B_s \to K$

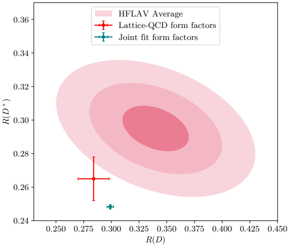


- Good statistical precision out to `p=300`.
- Tree-level disc. artifacts removed in right-hand figure.

$B \to D^*$ at non-zero recoil 2105.14019

- Pioneering FNAL-MILC calculation beyond zero-recoil using FNAL b and c quarks.



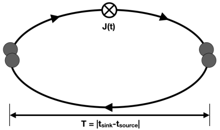


Figs. courtesy A. Vaquero

- FNAL-HISQ analysis in progress (Vaquero).
- all-HISQ approach normalizes currents exactly (Ward identities), reducing an important source of uncertainty.

Extending allHISQ to vector final states

Structurally, calculation is similar to $P \to P$ – need to modify spin-taste at source/sink/current.



	$\mathcal{O}_{H_{(s)}}$	$\mathcal{O}_{P/V}$	$\mathcal{O}_J$
f_+	$\gamma_5 \otimes \gamma_5$	$\gamma_5 \otimes \gamma_5$	$\gamma_i \otimes 1$
f_0	$\gamma_0\gamma_5 \otimes \gamma_0\gamma_5$	$\gamma_5 \otimes \gamma_5$	$\gamma_0 \otimes \gamma_0$
V	$\gamma_5 \otimes \gamma_1$	$\gamma_1 \otimes \gamma_1$	$\gamma_3 \otimes 1$
A_0	$\gamma_5 \otimes \gamma_5\gamma_1$	$\gamma_1 \otimes \gamma_1$	$\gamma_5 \otimes \gamma_5$
A_1	$\gamma_5 \otimes \gamma_5\gamma_3$	$\gamma_3 \otimes \gamma_3$	$\gamma_3\gamma_5 \otimes \gamma_5$
A_2	$\gamma_5 \otimes \gamma_5\gamma_1$	$\gamma_1 \otimes \gamma_1$	$\gamma_1\gamma_5 \otimes \gamma_5$

Normalize vector (axial vector) current using PCVC (PCAC).

Summary & Conclusion

- Semileptonic decays are crucial sources of information for fundamental physics, e.g. $|V_{ub}|$ and $|V_{cb}|$. Lattice results needed to support experimental physics programs at LHCb and Belle II.
  - Understand inclusive/exclusive discrepancies.
  - Pure SM predictions for R-ratios.
- The FNAL-MILC allHISQ-b program aims to produce high quality form factor data for a range of phenomenologically important channels.
- Propose to extend these calculations to vector final states, to obtain $B_{(s)} \to D^*_{(s)}$ form factors over the full kinematic range.

Thank you!