B-meson semileptonic decays with highly improved staggered quarks

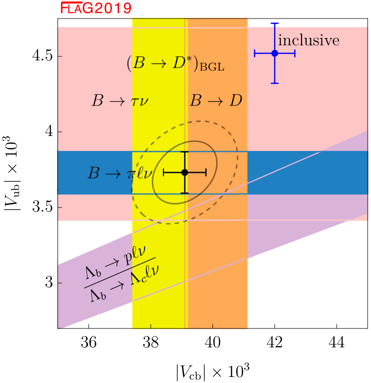
Andrew Lytle
University of Illinois @ Urbana-Champaign

07.29.21
Lattice 2021
Zoom/Gather@MIT

Motivation

- Semileptonic decays are a rich source of information for determining CKM matrix elements.
- Relatively simple decay processes – measured in accelerator experiments, require theoretical input from lattice QCD to extract fundamental parameters.
- Desire precise measurements of $|V_{xb}|$ from multiple decay processes to test the consistency of the Standard Model.

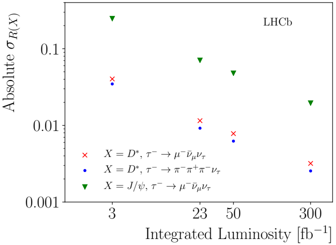
Stress-testing the CKM paradigm



- Inclusive/exclusive discrepancies for $|V_{ub}|$ and $|V_{cb}|$
- Also discrepancies from SM expectations in $R(D, D^*, J/\psi, K^*, ...)$
- $\to$ Want high accuracy SM predictions for sl decays

Experimental outlook - V_{cb} and V_{ub}

- Belle II
  - $\delta V_{cb} \approx 2\% \to 1.4\%$ by ~ 2025.
  - $\delta V_{ub} \approx 2\% \to 1.2\%$ by ~ 2025.
- Increasing precision of measured R-ratios:



- New channels LHCb 2020:

$$V_{cb} = 42.3(8)_{\text{stat}}(9)_{\text{syst}}(12)_{\text{ext}} \times 10^{-3} \quad \text{LHCb } B_s \to D_s^{(*)}$$

$$V_{cb} = 38.3(3)_{\text{stat}}(7)_{\text{syst}}(6)_{\text{lqcd}} \times 10^{-3} \quad \text{Belle total } B \to D^*$$

Outline

1. Intro & Motivation.
2. Computational framework.
3. Status and preliminary results.
   - Two-point and three-point correlators.
   - $B_{(s)} \to D_{(s)}\ f_0$.
4. Summary & Outlook.

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.

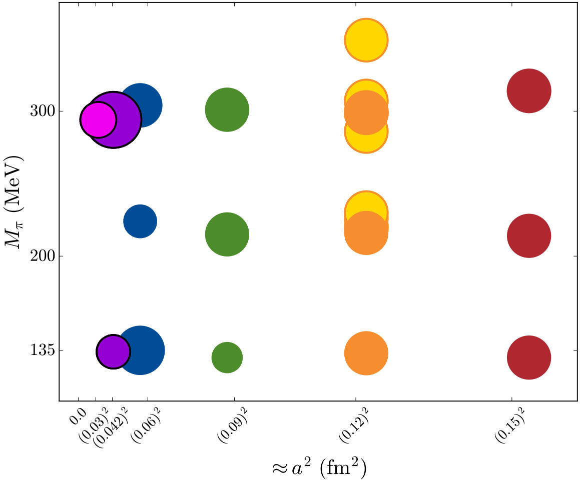
See Will Jay's talk on $D_{(s)} \to$ light transitions in this session!

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



all hisq b

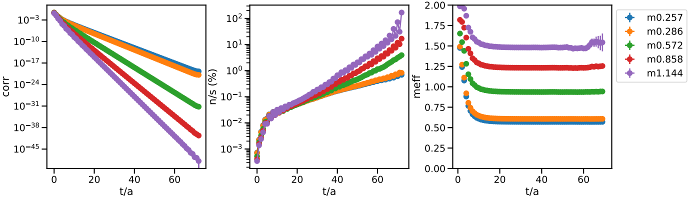
- Use a heavy valence mass h as a proxy for the b quark.
- Work at a range of m_h, with $am_c < am_h \lesssim 1$ on each ensemble. On sufficiently fine ensembles, m_h is near to m_b (e.g. m_b at $am_h \approx 0.65$ on $a = 0.03$ fm).
- Map out physical dependence on m_h, remove discretisation effects $\sim (am_h)^{2n}$ using information from several ensembles. Extrapolate results $a^2 \to 0, m_h \to m_b$.

Preliminary results

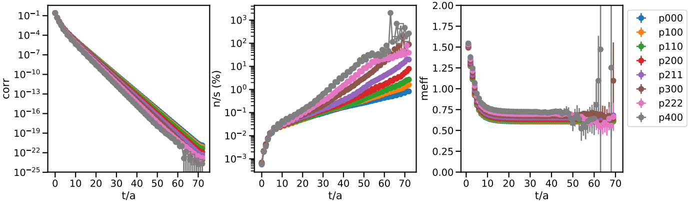
Two point functions

Consider $B_{(s)} \to D_{(s)}$ decays for $a = 0.06$ fm, $m_l/m_s = 0.1$.

- Compute $H_{(s)}$ mesons at a range of am_h values:

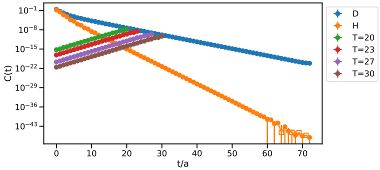


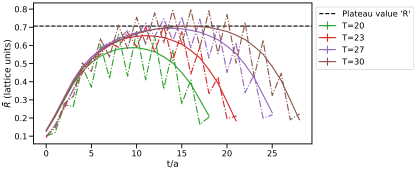
- $D_{(s)}$ mesons for a range of momenta:



Three point functions

- Generate three-point functions for scalar, vector, and tensor current insertions, $\langle D_{(s)}(T)\, J(t)\, H^{\dagger}_{(s)}(0)\rangle$.
- Fit simultaneously with two-point functions to extract the matrix elements of interest $\rightarrow \langle D_{(s)}|J|H_{(s)}\rangle$

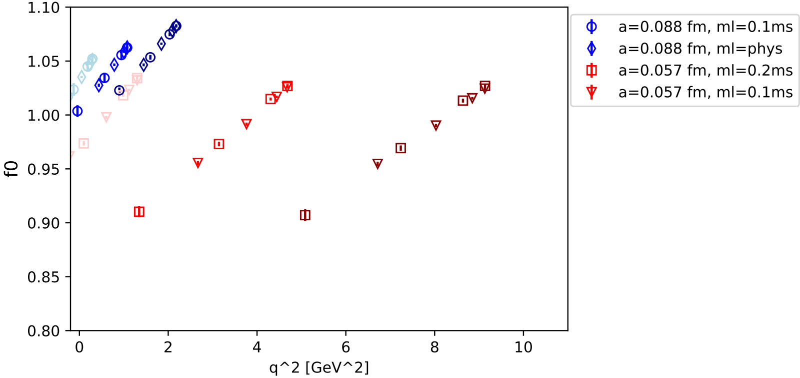




Scalar form factor extracted directly from scalar current:

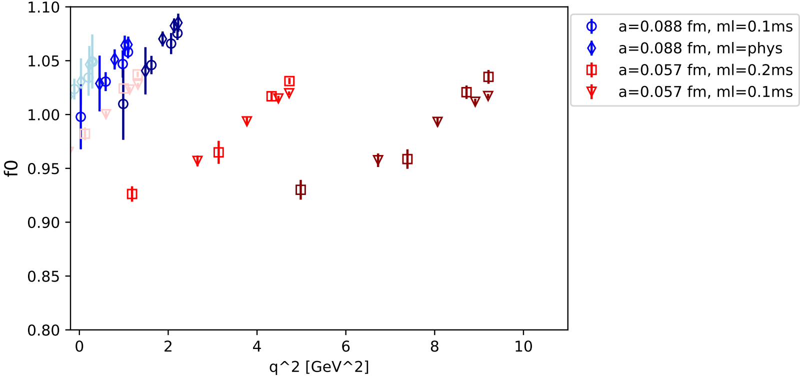
$$f_0^{(s)}(q^2) = \frac{m_b - m_c}{M^2_{H_{(s)}} - M^2_{D_{(s)}}} \langle D_{(s)}|S|H_{(s)}\rangle$$

$f_0^s(q^2)$



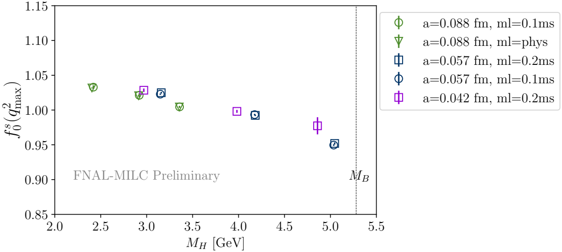
- $a = 0.088$ fm: $m_h = 1.5, 2, 2.5\, m_c$
- $a = 0.057$ fm: $m_h = 2, 2.5, 3\, m_c$
- Excellent precision out to $\texttt{p} = 300$

$f_0(q^2)$



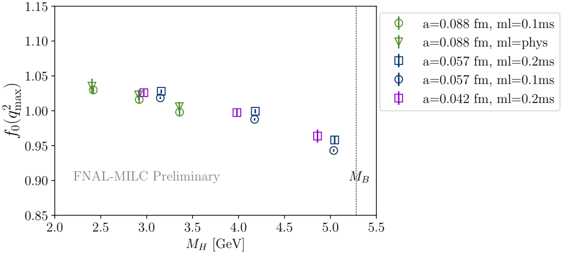
- Increasing stat error at large momentum.
- Light-quark mass dependence apparent for $B \to D$.

$B_s \to D_s$ at zero-recoil



- Good statistical control ($a = 0.042$ fm stats still limited).
- Small disc. effects even for $am \gtrsim 1$.

$B \to D$ at zero-recoil



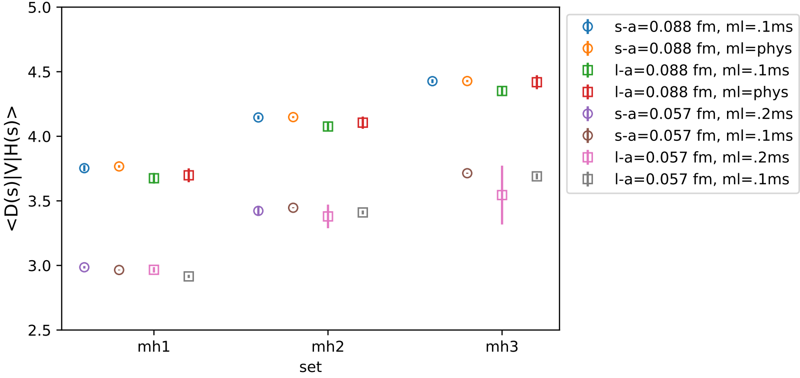
- Good statistical control ($a = 0.042$ fm stats still limited).
- Small disc. effects even for $am \gtrsim 1$.

Summary & Outlook

- Unified treatment for range of semileptonic decays.
- HISQ action used for *all* quarks.
- Good statistical precision (percent-level or less) achieved.
- Small discretization effects.
- Will permit *interpolation* in both m_l and m_h.

Thank you!

Vector operator



- Stable fit results from `V4-V4` correlators at zero recoil.