Semileptonic B-decays with a vector final state

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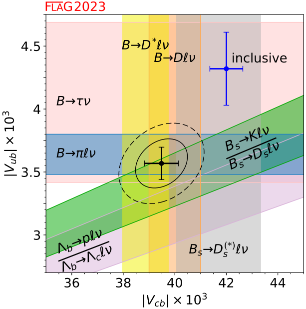
Zoom@MIT

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.



FNAL-MILC allHISQ-b program 2403.03959

- 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 our work 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
  - Update on results w/ pseudoscalar final state
- Progress with vector final states
- Summary

FNAL-MILC allhisq working group

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Jack Laiho
Jim Simone
Alejandro Vaquero

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*.

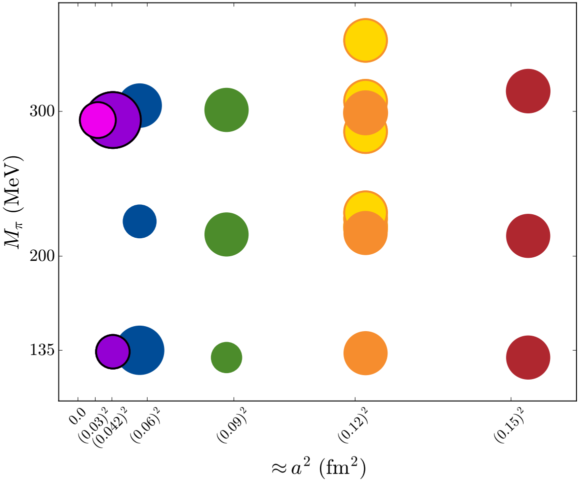
See Lattice 2023 proceeding for more details. 2403.03959

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.

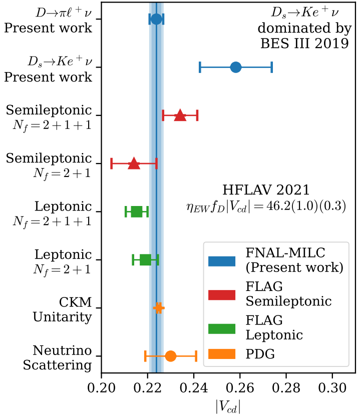
MILC ensemble parameters

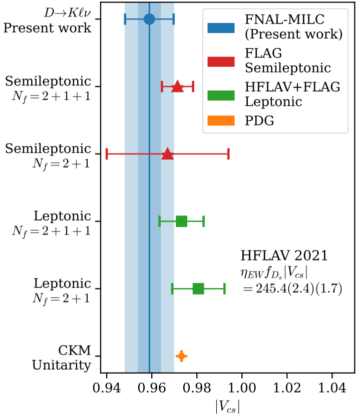
1712.09262



allHISQ b updates

Updates on allHISQ: D decays 2212.12648





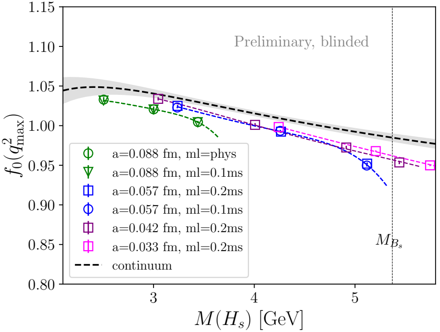
allHISQ b

- 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 $a^2 \to 0, m_h \to m_b$.

$B_s \to D_s$ - a simple $f_0(q^2_{\mathrm{max}})$ fit

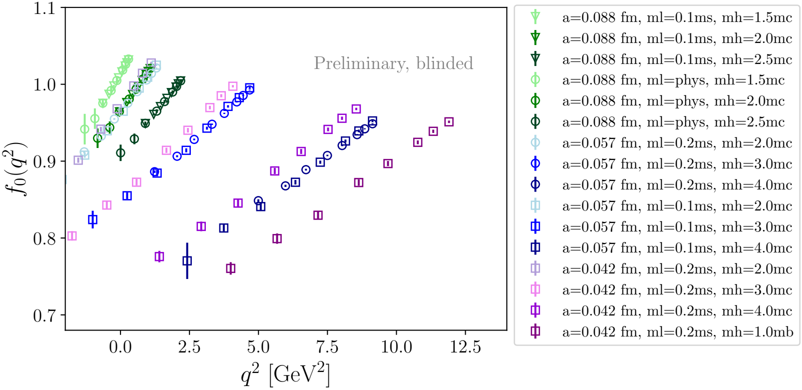
Basic fit parameterizing M_H dependence and heavy quark discretization.

$$f_0(q^2_{\mathrm{max}})[M_H, am_h] = \sum_{ij} c_{ij} \left(\frac{1}{M_H}\right)^i \left(am_h\right)^{2j}$$



Good precision obtained ($\sim 0.5\%$) at M_{B_s}.

$B_s \to D_s$: $f_0(q^2)$



- Good precision out to `p` $=$ `400`
- Rightmost points on figure have $m_h = m_b$

Chiral/cont. extrapolations

Build from chiral forms used in D analysis.

$$f_{0,\|,\perp}(E) = \frac{c_0}{E+\Delta}(1 + \cdots + c_H \chi_{H_s} + \cdots)$$

$$\Delta = \frac{M_{D^*}^2 - M_{D_s}^2 - M_K^2}{2M_{D_s}}, \qquad \chi_{H_s} = \frac{\Lambda_{\mathrm{HQET}}}{M_{H_s}} - \frac{\Lambda_{\mathrm{HQET}}}{M_{D_s}^{\mathrm{PDG}}}$$

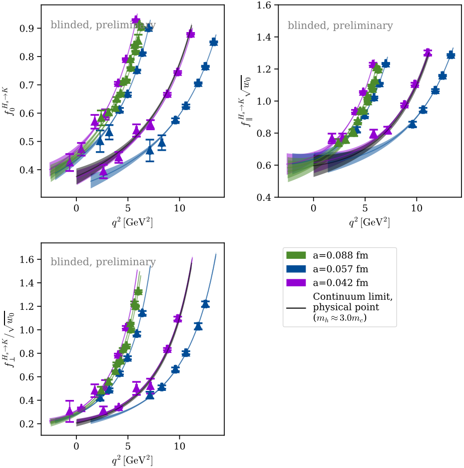
Generalize to incorparate HQET expansion:

$$c_0 \to c_0 + c_1 \frac{\Lambda_{\mathrm{HQET}}}{M_{H_s}} + \cdots, \quad \Delta \to \frac{M_{D^*}^2 - M_{D_s}^2 - M_K^2}{2M_{H_s}} \text{ (1st order)}$$

$$\chi_{H_s} = \frac{\Lambda_{\mathrm{HQET}}}{M_{H_s}} - \frac{\Lambda_{\mathrm{HQET}}}{M_{H_s}^{\text{``phys''}}}$$

$H_s \to K$

Here building off D_s chiral analysis, working out towards B_s.



- Data at 2–3m_c, 3 lattice spacings, 3 $m_{l,\text{sea}}$ values
- Note 0.057 fm has $m_h \approx 2.2, 3.3 m_c$
- Reasonable $\chi^2/\text{dof} = 0.92, 1.79, 0.75$ for $f_0, f_\parallel, f_\perp$

Tensor current renormalization

Started computing tensor Z-factors for (one-link) tensor currents. (Also relevant for $P \to V$ tensor currents.)

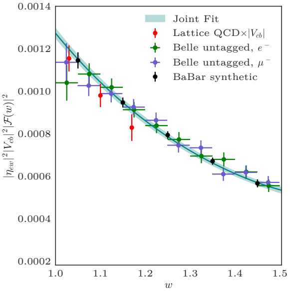
- Use tensor decay constant $f_{J/\psi}^{T,\mathrm{SMOM}}(\mu)$ as fiducial.
- $Z_{\mathrm{SMOM}}^{\gamma_\mu\gamma_\nu\otimes\gamma_\mu\gamma_\nu}(\mu)$ (local tensor) determined in 2008.02024.
- $Z_T' = Z_T\sqrt{\frac{a_0 E_0'}{a_0' E_0}}$, where a_0, E_0 are ground state amplitude/energy of the J/ψ from local and one-link tensor operators.

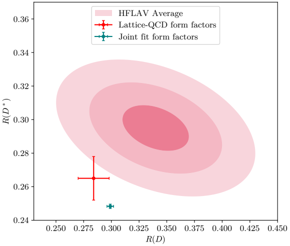
Analysis by Abhishek Samlodia (Syracuse)

$P \to V$ updates

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

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

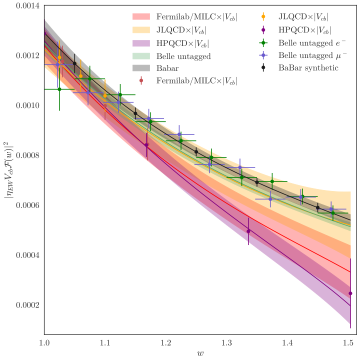


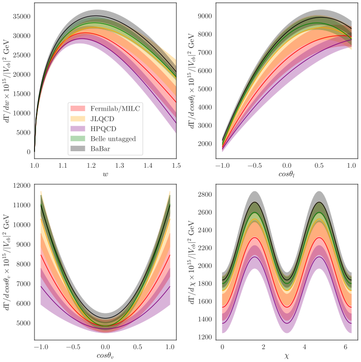


Figs. courtesy A. Vaquero

- FNAL-HISQ analysis in progress (Vaquero).

$B \to D^*$ comparisons



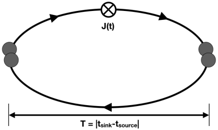


Figs. courtesy A. Vaquero

Lattice refs:	$\lvert V_{cb}\rvert \times 10^3$
• JLQCD 2306.05657	39.19(90)
• HPQCD 2304.03137	39.31(54)(51)
• FNAL/MILC 2105.14019	38.40(78)

Extending allhisq to vector final states

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



Decay	$\mathcal{O}_{H_{(s)}}$	$\mathcal{O}_{H'}$	$\mathcal{O}_J$	Matrix element
$P \to P$	$\gamma_5 \otimes \gamma_5$	$\gamma_5 \otimes \gamma_5$	$\gamma_i \otimes 1$	$\langle H' \vert V_i \vert H_{(s)} \rangle$
$P \to P$	$\gamma_0\gamma_5 \otimes \gamma_0\gamma_5$	$\gamma_5 \otimes \gamma_5$	$\gamma_0 \otimes \gamma_0$	$\langle H' \vert V_4 \vert H_{(s)} \rangle$
$P \to V$	$\gamma_0\gamma_5 \otimes \gamma_1\gamma_3$	$\gamma_1 \otimes \gamma_1$	$\gamma_3 \otimes \gamma_3$	$\langle H' \vert V_3 \vert H_{(s)} \rangle$
$P \to V$	$\gamma_5 \otimes \gamma_5$	$\gamma_1 \otimes 1$	$\gamma_5 \otimes \gamma_5$	$\langle H' \vert A_0 \vert H_{(s)} \rangle$
$P \to V$	$\gamma_5 \otimes \gamma_5$	$\gamma_3 \otimes \gamma_3$	$\gamma_3\gamma_5 \otimes \gamma_3\gamma_5$	$\langle H' \vert A_1 \vert H_{(s)} \rangle$
$P \to V$	$\gamma_5 \otimes \gamma_5$	$\gamma_1 \otimes \gamma_1$	$\gamma_1\gamma_5 \otimes \gamma_1\gamma_5$	$\langle H' \vert A_2 \vert H_{(s)} \rangle$

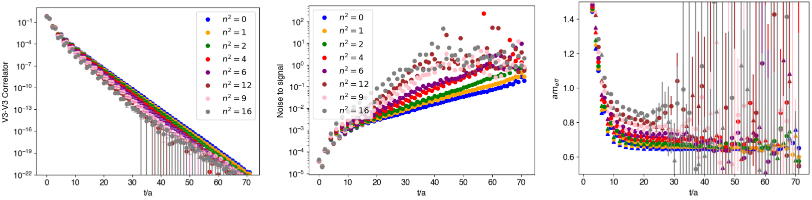
Normalize vector (axial vector) current using PCVC (PCAC).

Current year running update

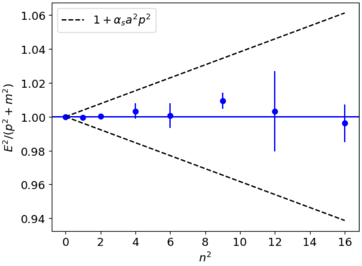
- 2023 allocation cycle: Awarded 3.8M Sky-core-hours on `lq`.
  ~ 300 confs on 0.06fm-0.2m_s ensemble.
- April 18: 103% used (+1M Sky-core-hour jeopardy boost).
  Over 400 confs/data generated.
- Preliminary analysis on 326 confs.
  Expect to achieve 500 confs/data by end of allocation cycle.
- Tested run scripts on `lq2_gpu`. Ready for production here.

For next year's proposed running, we would like to extend data to 0.09fm-0.1m_s (`lq1_cpu`), and 0.09fm-0.2m_s (`lq2_gpu`) $\rightarrow$ First look at discretization and sea-quark mass effects.

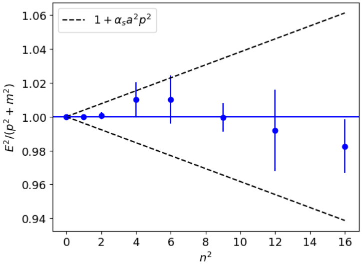
Look at the $D^*_{(s)}$



D_s^*



D^*



Figures courtesy of Akhil Chauhan (UIUC)

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.
- Extending these calculations to vector final states, to obtain $B_{(s)} \to D^*_{(s)}$ form factors over the full kinematic range.

Thank you!

Normalization of axial vector currents

$$\partial_\mu A_\mu^{\rm cons} = (m_h + m_l) P$$

Applied to zero-momentum two-point correlators,

$$Z_{A^0} M'_H \langle 0 | A^0 | H' \rangle = (m_h + m_l) \langle 0 | P | H \rangle \,,$$

Here A^0 has spin-taste $\gamma^5\gamma^0 \otimes \gamma^5\gamma^0$, P has spin-taste $\gamma_5 \otimes \gamma_5$. We use that $Z_{A^0} = Z_{A^i}$ up to polynomial discretization effects.

$P \to V$ tensor insertions

- Three correlators needed to extract three tensor form factors T_1, T_2, T_3.
- One-link current insertions can be used with same initial/final state interpolating operators to obtain vector and axial-vector form factors.

Decay	$\mathcal{O}_{H_{(s)}}$	$\mathcal{O}_{H'}$	$\mathcal{O}_J$	Matrix element
$P \to V$	$\gamma_0\gamma_5 \otimes \gamma_1\gamma_3$	$\gamma_3 \otimes \gamma_3$	$\gamma_1\gamma_2 \otimes \gamma_1$	$\langle H' \vert T1, T2 \vert H_{(s)} \rangle$
$P \to V$	$\gamma_0\gamma_5 \otimes \gamma_1\gamma_3$	$\gamma_1 \otimes \gamma_1$	$\gamma_2\gamma_3 \otimes \gamma_3$	$\langle H' \vert T_1, T_2, T_3 \vert H_{(s)} \rangle$
$P \to V$	$\gamma_5 \otimes \gamma_5$	$\gamma_3 \otimes \gamma_3$	$\gamma_0\gamma_1 \otimes \gamma_3\gamma_5$	$\langle H' \vert T_1, T_2 \vert H_{(s)} \rangle$