$B \to \pi/K$ and $B_s \to K$ decays from LQCD

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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.

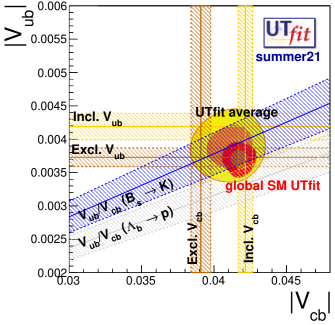


Fig. courtesy M. Bona

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

Outline

- Intro & Motivation
- Review of lattice results (cf FLAG review 2111.09849)
  - $B \to \pi$
  - $B_s \to K$
  - $B \to K$
- FNAL/MILC all-HISQ semileptonic decays
  - Calculation framework
  - Preliminary results
- Summary & Outlook

$$B \to \pi \ell \nu$$

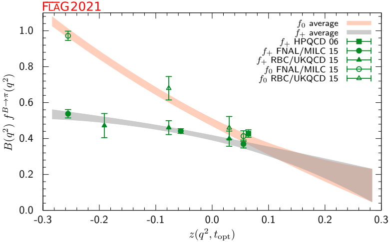
$B \to \pi\ell\nu$

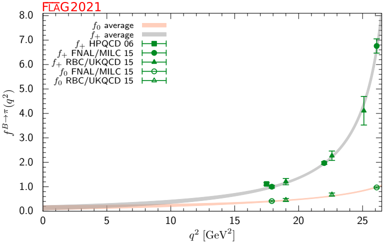
- Process gives the most precise determination of $|V_{ub}|$.
- Challenges:
  - Simulating at physical pion masses / quantifying chiral behavior
  - Large pion recoil, lattice results best near $q^2_{\rm max}$
- Particularly difficult calculation requiring significant time/resources.
- Expt'l reconstruction best at low q^2, resulting in model dependence to bridge low–high q^2.

$B \to \pi \ell \nu$ - Lattice results

Three published results quoted by FLAG, from 2015 or earlier.

- hep-lat/0601021 HPQCD, NRQCD b on $n_f = 2+1$ staggered
- 1501.05373 RBC/UKQCD, RHQ b on $n_f = 2+1$ domain wall
- 1503.07839 FNAL/MILC, Fermilab b on $n_f = 2+1$ staggered (asqtad)





$B \to \pi \ell \nu$ - In progress/proceedings

- 1912.09946 RBC/UKQCD extend to a third lattice spacing $a^{-1} \approx 2.77$ GeV w/ lightest pion mass $m_\pi \approx 234$ MeV.

- 1912.02409 JLQCD (new calculation) Moebius domain-wall three lattice spacings $a^{-1} \approx 2.4, 3.6, 4.5$ GeV, lightest $m_\pi \approx 225$ MeV. $am_h < 0.7 \to m_h \approx 2.44 m_c$

- 1912.13358 FNAL/MILC Fermilab b on staggered HISQ, successor calculation to 1503.07839 asqtad.

- 2111.05184 FNAL/MILC all-HISQ calculation (see part II)

$B \to \pi\ell\nu$ - Takeaways

- Three published calculations (2015 and earlier) from HPQCD, RBC/UKQCD, and FNAL/MILC.
- Differing treatments of b and different discretizations, overall agreement in continuum among these.
- Combining results FLAG obtains: $|V_{ub}| = 3.73(14) \times 10^{-3}$
- Several in progress calculations - new lattice spacings (RBC/UKQCD), new ensembles (FNAL/MILC), new groups (JLQCD) $\to$ expect new results in coming years.

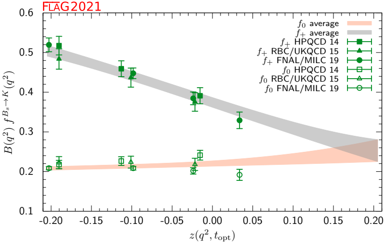
$B_s \to K \ell \nu$

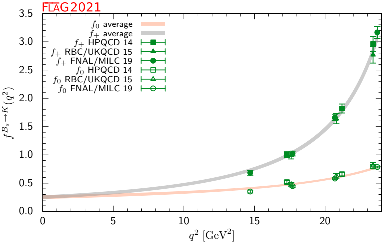
$B_s \to K\ell\nu$

- Computationally similar to $B \to \pi$ (spectator $l \to s$).
- Kaon mass easier to access $\to$ Systematics related to chiral extrapolation smaller
- $B_s \to K\mu\nu$ measured for the first time by LHCb! 2012.05143
- Normalized by $B_s \to D_s\mu\nu$, gives new constraint on $|V_{ub}|/|V_{cb}|$, competitive with constraint from baryon decay.

$B_s \to K\ell\nu$ - Lattice results

- 1501.05373 RBC/UKQCD, RHQ b on $n_f = 2 + 1$ domain wall
- 1406.2279,1808.09285 HPQCD, NRQCD b on $n_f = 2 + 1$ staggered (asqtad)
- 1901.02561 FNAL/MILC, Fermilab b on $n_f = 2 + 1$ staggered (asqtad) + ratio with $B_s \to D_s$



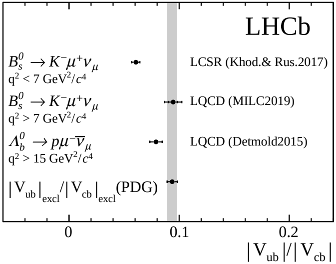


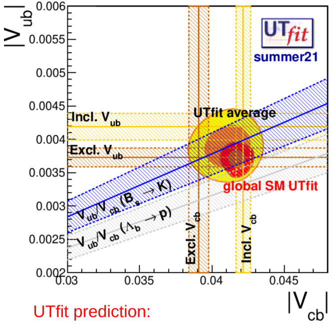
$B_s \to K\ell\nu$ - In progress/proceedings

- 1912.09946, 2012.04323 RBC/UKQCD extend to a third lattice spacing $a^{-1} \approx 2.77$ GeV w/ lightest pion mass $m_\pi \approx 234$ MeV.
- 1912.13358 FNAL/MILC Fermilab b on staggered HISQ, successor calculation to 1901.02561 asqtad.
- 2111.05184 FNAL/MILC all-HISQ calculation (see part II)

- New measurements from LHCb combined with lattice form factor predictions give new CKM constraint on $|V_{ub}|/|V_{cb}|$:

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.0946(30)_{\text{stat}}(25)_{\text{syst}}(13)_{D_s}(68)_{\text{FF}}$$





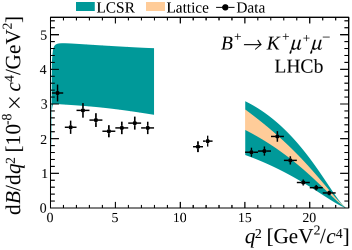
UTfit prediction:

- $B_s \to K$ at low q^2 needed from lattice!
- Total uncertainty can be reduced from the lattice side.

$B \to K\ell\ell$

$B \to K\ell\ell$

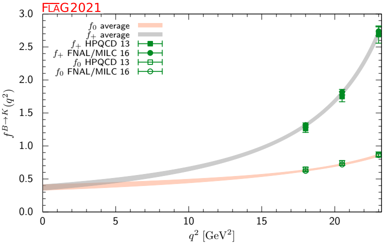
- FCNC interaction potentially sensitive to new physics.
- $b \to s$ transition forbidden at tree level – considerably more complicated effective Hamiltonian.
- Most important contributions still come from $\langle K|\mathcal{O}|B\rangle$ matrix elements, with $\mathcal{O} = V, T \to f_0(q^2),\ f_+(q^2), f_T(q^2)$

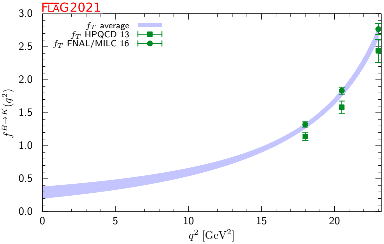


1403.8044

$B \to K$ - Lattice results

- 1306.2384,1306.0434 HPQCD, NRQCD b on $n_f = 2+1$ staggered (asqtad), HISQ valence
- 1509.06235,1510.02349 FNAL/MILC, Fermilab b on $n_f = 2+1$ staggered (asqtad)





$B \to K\ell\ell$ - In progress/proceedings

- HPQCD all-HISQ calculation Lattice 2021
  https://indico.cern.ch/event/1006302/contributions/4375436/
- 1912.13358 FNAL/MILC Fermilab b on staggered HISQ, successor calculation to 1509.06235 asqtad.
- 2111.05184 FNAL/MILC all-HISQ calculation (see part II)

$B \to K\ell\ell$ - Takeaways

- Important process sensitive to new physics.
- Lattice calculations from HPQCD (2013) and FNAL-MILC (2015), some tension in the tensor form factor.
- Additional contributions from lattice needed!

FNAL-MILC all-HISQ semileptonic decays

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*.

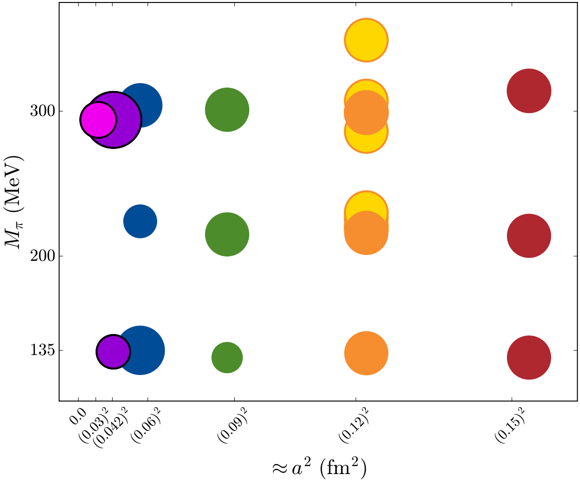
See our 2021 Lattice proceeding for more details! 2111.05184

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



all hisq b

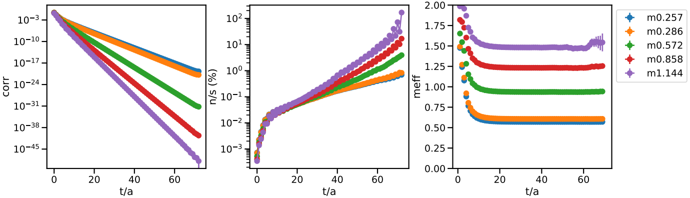
- Use a heavy valence mass h as a proxy for the b quark.
- Work at a range of m_h, with $am_c < am_h \lesssim 1$ on each ensemble. On sufficiently fine ensembles, m_h is near to m_b (e.g. m_b at $am_h \approx 0.65$ on $a = 0.03$ fm).
- Map out physical dependence on m_h, remove discretisation effects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

Preliminary results

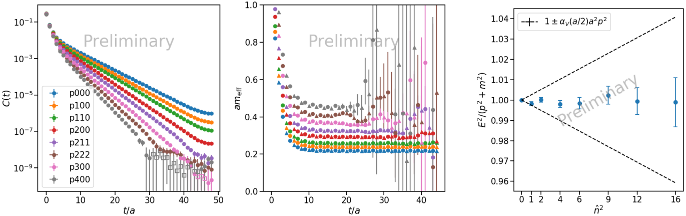
Two point functions

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

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

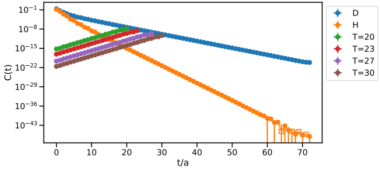


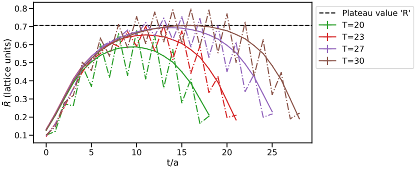
- Compute K mesons for a range of momenta:



Three point functions

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

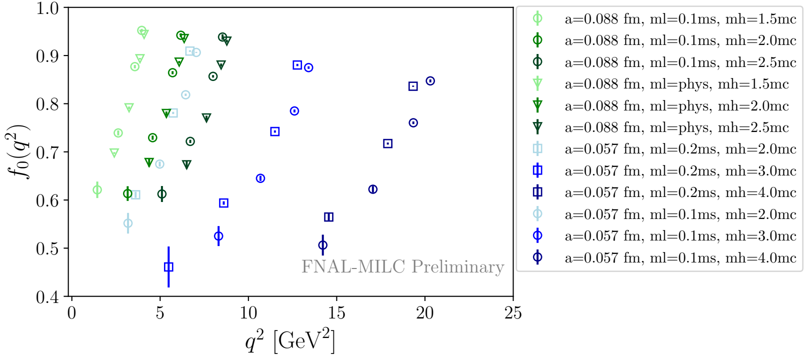




Scalar form factor extracted directly from scalar current:

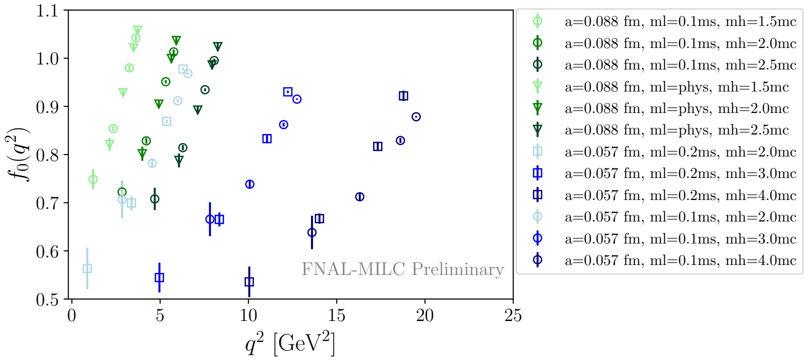
$$f_0^{(s)}(q^2) = \frac{m_b - m_{s(u)}}{M^2_{H_{(s)}} - M^2_K} \langle K|S|H_{(s)}\rangle$$

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



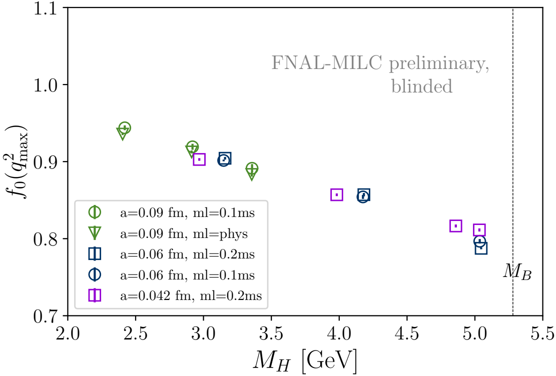
- $a = 0.088$ fm: $m_h = 1.5, 2, 2.5\, m_c$
- $a = 0.057$ fm: $m_h = 2, 2.5, 3\, m_c$
- Good precision out to `p` = `300`

$B \to K$: $f_0(q^2)$



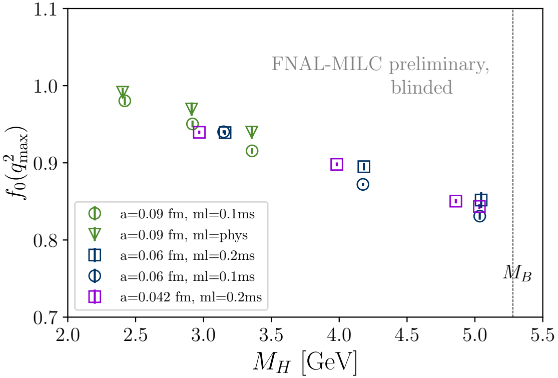
- $a = 0.088$ fm: $m_h = 1.5, 2, 2.5\, m_c$
- $a = 0.057$ fm: $m_h = 2, 2.5, 3\, m_c$
- Increasing stat error at large momentum.

$B_s \to K$ at zero-recoil



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

$B \to K$ at zero-recoil



- Good statistical control ($a = 0.042$ fm stats still limited).
- Small disc. effects even for $am \gtrsim 1$.
- Add'l structure consists of light quark, heavy quark, and lattice spacing dependences.

Summary & Outlook - I

- 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.

Summary & Outlook - II

- Reviewed lattice results for $B \to \pi/K$ and $B_s \to K$
- Each of these processes plays an important role in constraining the flavor sector.
  - $B \to \pi$: gives precision $|V_{ub}|$
  - $B_s \to K$: lattice + new LHCb result constrains $|V_{ub}|/|V_{cb}|$
  - $B \to K$: FCNC process sensitive to new physics, current tensions w/ SM predictions.
- Good quality results from lattice community, with more on the way.

Thank you!