Semi-leptonic decays on the lattice

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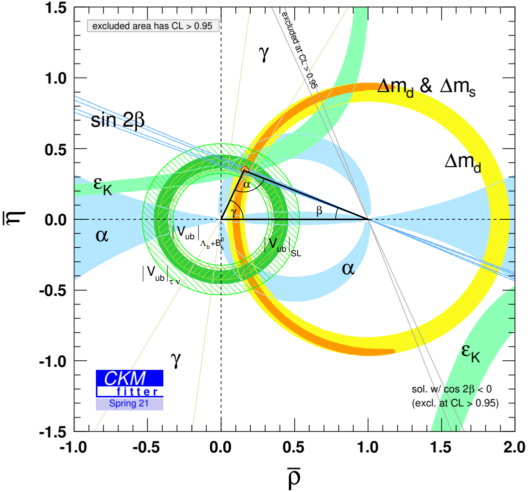
Heavy Flavours – Quo vadis?
Ardbeg, Islay, Scotland · Juni 22, 2023

Motivation: CKM unitarity triangle

- Combine several determinations to perform an over-constrained fit
- Use tree-level determinations of $|V_{ub}|$ and $|V_{cb}|$
  - → Commonly used $B \to \pi\ell\nu$ and $B \to D^{(*)}\ell\nu$
  - → Long standing $2-3\sigma$ discrepancy between exclusive ($B \to \pi\ell\nu$) and inclusive ($B \to X_u\ell\nu$)
  - → $B \to \tau\nu$ has larger error



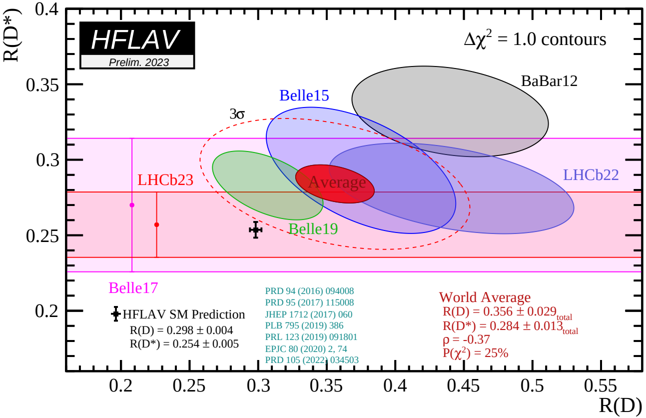
[http://ckmfitter.in2p3.fr]

Tension in $R_D^{(*)}$

- Testing universality of lepton flavors

$$R^{\tau/\mu}_{D^{(*)}} \equiv \frac{BF(B\to D^{(*)}\tau\nu_\tau)}{BF(B\to D^{(*)}\mu\nu_\mu)}$$

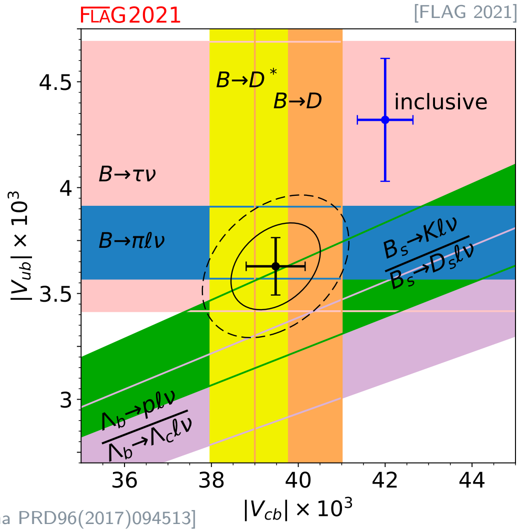
[HFLAV]



$|V_{ub}|$ and $|V_{cb}|$

- Leptonic decays $B^+_{(c)} \to \ell^+ \nu_\ell$ experimentally difficult
  - → Only $B^+ \to \tau^+ \nu_\tau$ measured (large error)
- Semileptonic decays preferred
  - → Exclusive e.g. $B \to \pi \ell \nu$
  - → Inclusive e.g. $B \to X_u \ell \nu$
  - → B, B_s, Λ_b initial state
- Longstanding tension between exclusive and inclusive determinations
  - → Novel ideas for inclusive lattice calculations

    [Hashimoto PTEP(2017)053B03] [Hansen, Meyer, Robaina PRD96(2017)094513]
    [Bailas et al. PTEP(2020)043B07] [Gambino, Hashimoto PRL 125(2020)032001]
    [Barone et al. arXiv:2305.14092]. . .



[FLAG 2021]

Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 0.97370(14) & 0.2245(8) & 0.00382(24) \\ 0.221(4) & 0.987(11) & 0.041(14) \\ 0.0080(3) & 0.0388(11) & 1.013(30) \end{bmatrix}$$

[PDG, Workman et al. PTEP (2022) 083C01]

$$\frac{|\delta V_{CKM}|}{|V_{CKM}|} = \begin{bmatrix} 0.014 & 0.35 & 6.3 \\ 1.8 & 1.1 & 3.4 \\ 3.8 & 2.8 & 3.0 \end{bmatrix} \%$$

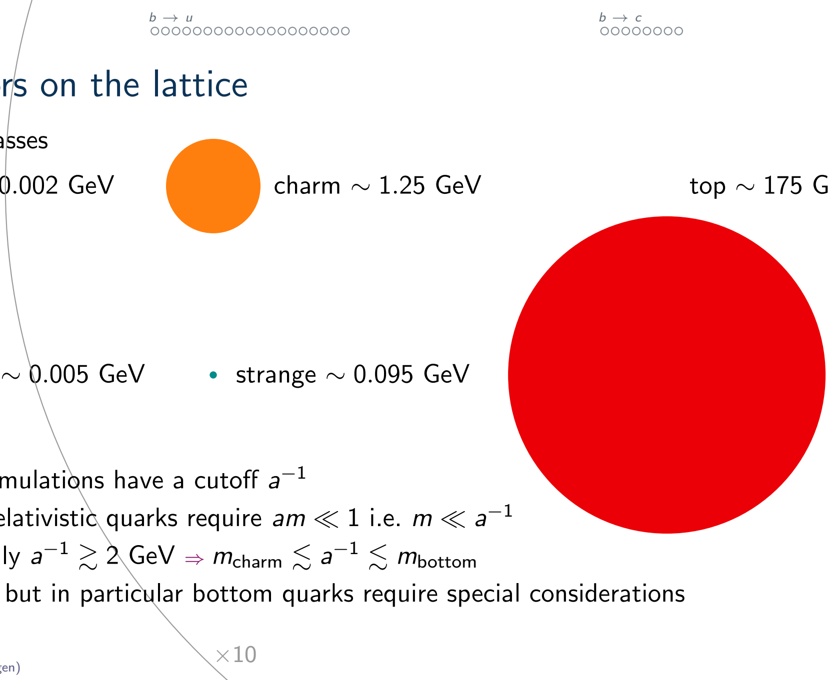
- Heavy sector less well explored compared to light sector
- Large experimental efforts: LHCb, Belle II, BESIII, . . .

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \leftsquigarrow \begin{bmatrix} \pi \to \ell\nu & K \to \ell\nu & B \to \pi\ell\nu \\ & K \to \pi\ell\nu & B_s \to K\ell\nu \\ & & \\ D \to \ell\nu & D_s \to \ell\nu & B_{(s)} \to D_{(s)}\ell\nu \\ D \to \pi\ell\nu & D \to K\ell\nu & B_{(s)} \to D^*{}_{(s)}\ell\nu \\ & & \\ B_d \leftrightarrow \overline{B}_d & B_s \leftrightarrow \overline{B}_s & \end{bmatrix}$$

- Typical nonperturbative LQCD calculations to extract CKM matrix elements
- Why is the uncertainty for $|V_{ub}|$ and $|V_{cb}|$ so large?

Heavy flavors on the lattice

- Quark masses



up ~ 0.002 GeV

charm ~ 1.25 GeV

top ~ 175 GeV

down ~ 0.005 GeV

strange ~ 0.095 GeV

bottom ~ 4.2 GeV

- Lattice simulations have a cutoff a^{-1}
  - → Fully relativistic quarks require $am \ll 1$ i.e. $m \ll a^{-1}$
  - → Typically $a^{-1} \gtrsim 2$ GeV $\Rightarrow m_{\text{charm}} \lesssim a^{-1} \lesssim m_{\text{bottom}}$
  - → Charm but in particular bottom quarks require special considerations

Simulating heavy flavors

- Traditionally: simulate charm and bottom using effective actions
  - → Heavy quark effective Theory (HQET), Non-Relativistic QCD, Relativistic Heavy Quark (RHQ, Fermilab, Tsukuba)
  - → Allows to simulate charm and bottom quarks on coarser lattices
  - → Additional systematic uncertainties, partly perturbative renormalization, . . .
  - → Few percent total errors

- State-of-the-art: fully relativistic simulations at $a^{-1} > 2$ GeV
  - → Heavy Highly Improved Staggered Quarks (HISQ), Heavy Domain-Wall Fermions (DWF), . . .
  - → Same action for light (up/down/strange) as for heavy (charm/bottom) quarks
    - ⇝ Simulate heavier than charm and extrapolate
  - → Fully nonperturbative renormalization straight-forward, reduced systematic uncertainties
  - → Sub-percent precision feasible ⇝ QED effects become relevant

Overview

- Semileptonic $b \to u$ decays (hadronic pseudoscalar final states)

$B \to \pi \ell \nu$ and $B_s \to K \ell \nu$

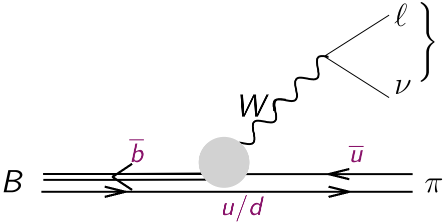
- Semileptonic $b \to c$ decays (hadronic vector final states)

$B \to D^* \ell \nu$

- Summary

$b \to u$
(hadronic pseudoscalar final states)

Exclusive semi-leptonic decays: $B \to \pi\ell\nu$



$$q^2 = M_B^2 + M_\pi^2 - 2M_B E_\pi$$

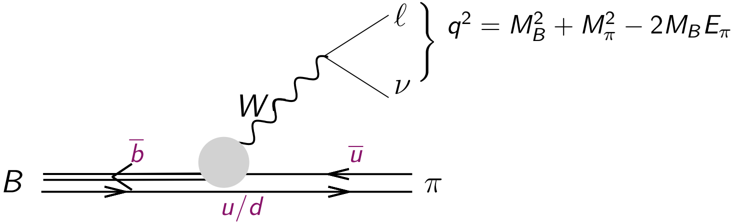
- Conventionally parametrized placing the B meson at rest

$$\underbrace{\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2}}_{\text{experiment}} = \underbrace{\frac{G_F^2|V_{ub}|^2}{24\pi^3}}_{\text{CKM}} \underbrace{\frac{(q^2-m_\ell^2)^2\sqrt{E_\pi^2-M_\pi^2}}{q^4M_B^2}}_{\text{known}}$$

$$\times\left[\left(1+\frac{m_\ell^2}{2q^2}\right)M_B^2(E_\pi^2-M_\pi^2)|f_+(q^2)|^2+\frac{3m_\ell^2}{8q^2}(M_B^2-M_\pi^2)^2|f_0(q^2)|^2\right]$$

nonperturbative input

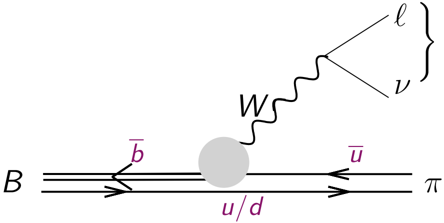
Exclusive semi-leptonic decays: $B \to \pi\ell\nu$



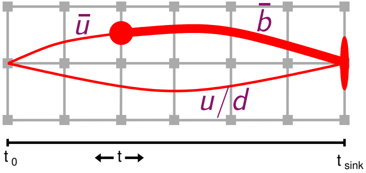
$$q^2 = M_B^2 + M_\pi^2 - 2M_B E_\pi$$

- Nonperturbative input
  - → Parametrizes interactions due to the (nonperturbative) strong force
  - → Use operator product expansion (OPE) to identify short distance contributions
  - → Calculate the flavor changing currents as point-like operators using lattice QCD

Exclusive semi-leptonic decays: $B \to \pi\ell\nu$



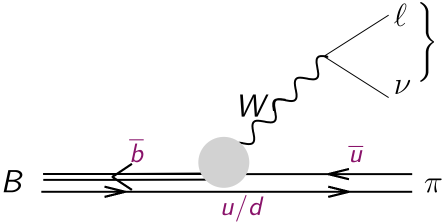
$$q^2 = M_B^2 + M_\pi^2 - 2M_B E_\pi$$



- Calculate hadronic matrix element for the flavor changing vector current V^μ in terms of the form factors $f_+(q^2)$ and $f_0(q^2)$

$$\langle\pi|V^\mu|B\rangle = f_+(q^2)\left(p_B^\mu + p_\pi^\mu - \frac{M_B^2-M_\pi^2}{q^2}q^\mu\right) + f_0(q^2)\frac{M_B^2-M_\pi^2}{q^2}q^\mu$$

Exclusive semi-leptonic decays: $B \to \pi\ell\nu$



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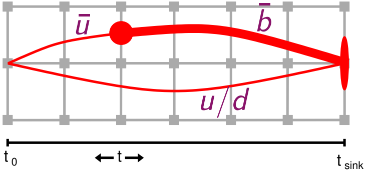


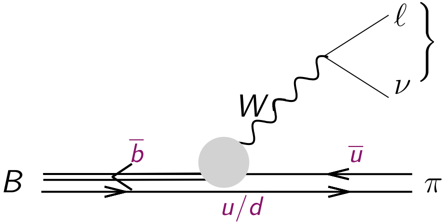
- Calculate hadronic matrix element for the flavor changing vector current V^μ in terms of the form factors $f_+(q^2)$ and $f_0(q^2)$
- On the lattice $f_\perp$ and $f_\parallel$ are directly proportional to 3-point functions

$$f_\parallel(E_P) = \langle P|V^0|B_{(s)}\rangle/\sqrt{2M_{B_{(s)}}} \quad \text{and} \quad f_\perp(E_P)p_P^i = \langle P|V^i|B_{(s)}\rangle/\sqrt{2M_{B_{(s)}}}$$

$$f_0(q^2) = \frac{\sqrt{2M_{B_{(s)}}}}{M^2_{B_{(s)}} - M_P^2}\left[(M_{B_{(s)}} - E_P)f_\parallel(E_P) + (E_P^2 - M_P^2)f_\perp(E_P)\right]$$

$$f_+(q^2) = \frac{1}{\sqrt{2M_{B_{(s)}}}}\left[f_\parallel(E_P) + (M_{B_{(s)}} - E_P)f_\perp(E_P)\right]$$

Exclusive semi-leptonic decays: $B \to \pi\ell\nu$



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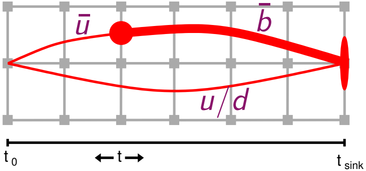

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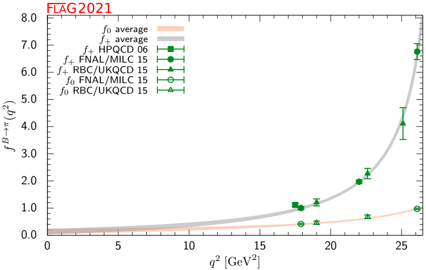
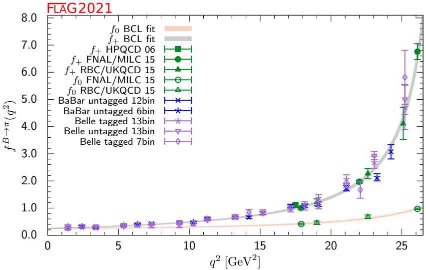
- Alternatively, express form factors in terms of f_1 and f_2 with $v^\mu = p_B^\mu/M_B$ motivated by HQET

$$f_1(v\cdot p_\pi) + f_2(v\cdot p_\pi) = f_\parallel(E_\pi)/\sqrt{2} \quad \text{and} \quad f_2(v\cdot p_\pi) = f_\perp(E_\pi)\cdot\left(v\cdot p_\pi/\sqrt{2}\right)$$

FLAG average [FLAG 2021]





- FLAG average: Fermilab/MILC [Bailey et al. PRD92(2015)014024], RBC/UKQCD [Flynn et al. PRD 91 (2015) 074510]
  → Shown in addition HPQCD [Dalgic et al. PRD73(2006)074502][PRD75(2007)119906]
- Used effective actions only allowed determinations of form factors at large q^2
- Combined fit with experimental data gives $|V_{ub}^{\text{excl}}|$
  [BaBar PRD 83 (2011) 032007][PRD 86 (2012) 092004] [Belle PRD 83 (2011) 071101][PRD 88 (2013) 032005]
- Shape of lattice data largely consistent with experimental data

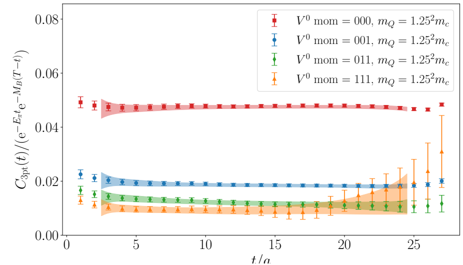
JLQCD 2022: $B \to \pi \ell \nu$

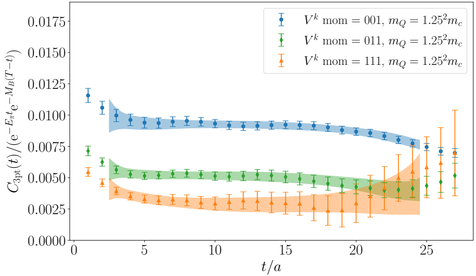
[Colquhoun et al. PRD 106 (2022) 054502]

- Unitary setup
  - → MDWF light/strange and heavy quarks with $am_c \leq am_Q \leq 2.44 \cdot am_c$
  - → Additional extrapolation in the heavy quark mass to reach m_b
  - → Fully nonperturbative renormalization

- $a \approx 0.044$ fm, 0.055 fm, 0.080 fm
- $M_\pi \gtrsim 230$ MeV

- Comparable stat. and sys. errors
  - → Total errors: $f_+ \sim 10\%$, $f_0 \sim 6\%$

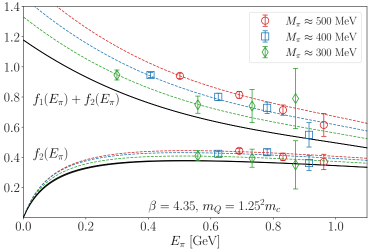


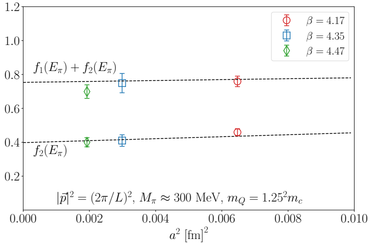


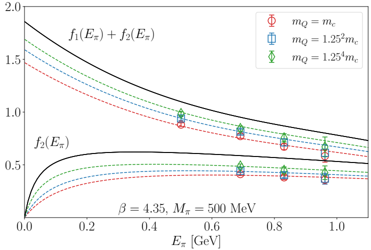
- $a \approx 0.080$ fm, $am_{u/d} = 0.007$, $am_Q = 0.68808$

JLQCD 2022: combined chiral, heavy-quark, continuum limit

[Colquhoun et al. PRD 106 (2022) 054502]



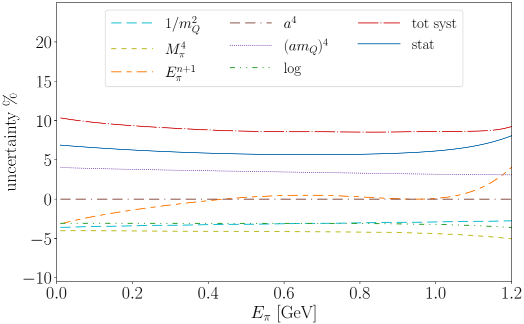




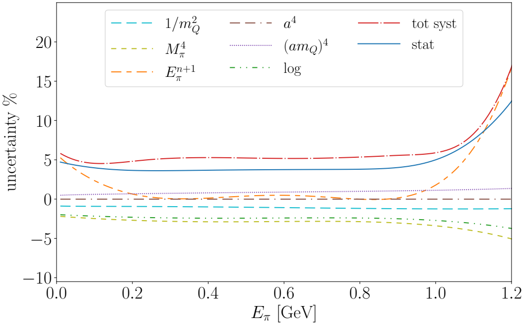
- Extrapolate in M_π
- Extrapolate in a^2
- Extrapolate in m_Q

- Extrapolation over the simulated range of "high q^2"
- Extract "synthetic" data points for z-expansion from continuum-physical quark mass limit

JLQCD 2022: error budget [Colquhoun et al. PRD 106 (2022) 054502]



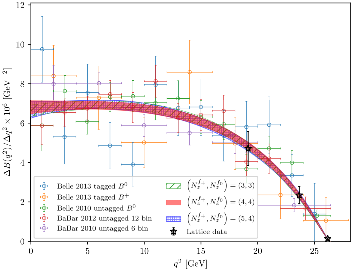
- Systematic uncertainties for f_+

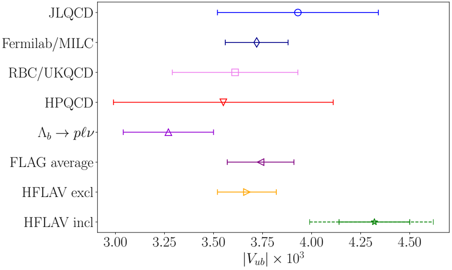


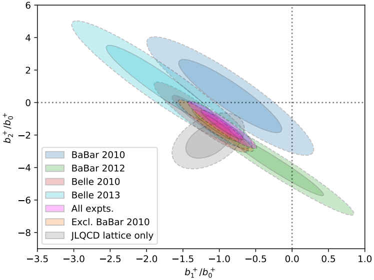
- Systematic uncertainties for f_0

JLQCD 2022: $|V_{ub}|$ and comparisons

[Colquhoun et al. PRD 106 (2022) 054502]







- Joint fit to determine $|V_{ub}|$
  $\Rightarrow |V_{ub}| = (3.93 \pm 0.41) \cdot 10^{-3}$
- Updates from other collaborations expected relatively soon
- Shape parameters of BCL z-fit
  $\rightarrow$ Tension with BaBar 2010
  $\rightarrow$ Looking forward to new data from Belle II

What are the challenges calculating $B \to \pi\ell\nu$?

- Ratio of $m_{\text{bottom}}/m_{\text{up}}$ is worst
  $\Rightarrow$ Signal-to-noise issue

- B meson are heavy (5279 MeV), pions are light (138 MeV)
  $\to$ Decay releases lots of energy $\rightsquigarrow$ large range in q^2 to be covered
  $\to$ Requires simulations of pions with very high momenta (noisy)

- Experimentally clean environment of B factories (strongly) preferred

- Alternative B decay modes have their own theoretical/experimental challenges e.g. $B \to \rho(\to \pi\pi)\ell\nu$ on the lattice

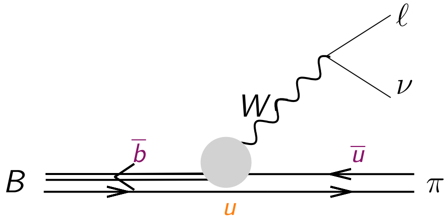
Alternative: $B_s \to K\ell\nu$ or $\Lambda_b \to p\ell\nu$

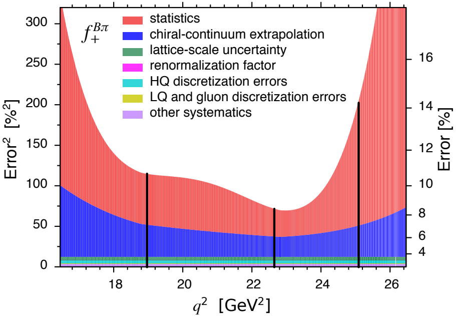
- Experimentally not ideal for B factories
  → Running at $\Upsilon(5s)$ is less efficient in creating $B_s\bar{B}_s$ pairs

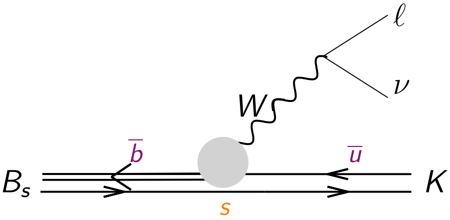
- Abundantly created in pp collisions at the LHC ⇝ LHCb
  → Normalization not straight forward at LHCb, better to consider (double-)ratios
  → Determine $|V_{cb}|/|V_{ub}|$ from $B_s \to D_s\ell\nu / B_s \to K\ell\nu$
  or $\Lambda_b \to \Lambda_c\ell\nu / \Lambda \to p\ell\nu$ [Detmold, Lehner, Meinel, PRD92 (2015) 034503]

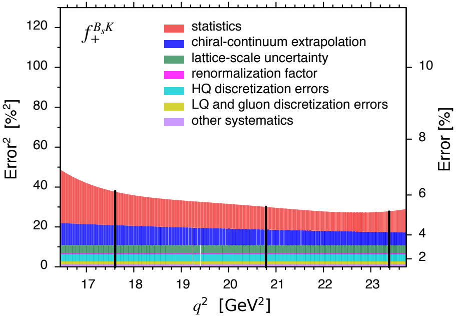
- Compare:
  $M_B \ = 5279$ MeV : $M_\pi = 138$ MeV ~ 38, q^2 range $\sim [m_\ell^2, 27]$ GeV^2
  $M_{B_s} = 5367$ MeV : $M_K = 494$ MeV ~ 11, q^2 range $\sim [m_\ell^2, 24]$ GeV^2
  ⇝ cheaper and more precise to compute with LQCD

Comparison $B \to \pi\ell\nu$ vs. $B_s \to K\ell\nu$ [Flynn et al. PRD 91 (2015) 074510]

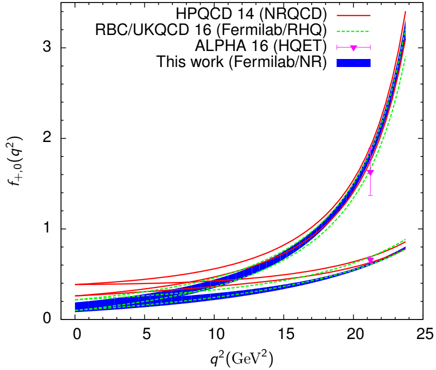


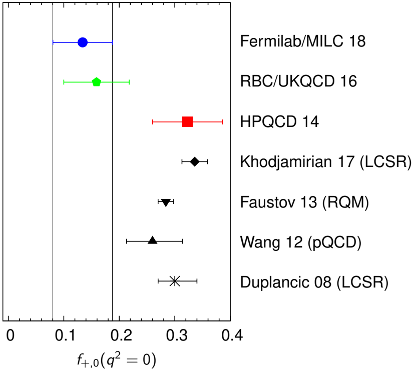






$B_s \to K\ell\nu$ tensions (< 2023)





- HPQCD, RBC-UKQCD, ALPHA, Fermilab/MILC

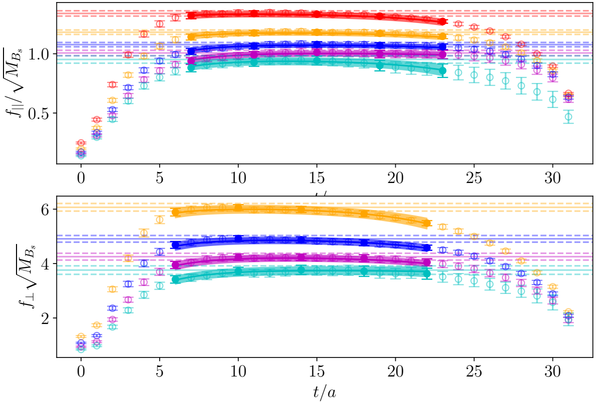
  [Bouchard et al. PRD90(2014)054506] [Flynn et al. PRD91(2015)074510] [Bahr et al. PLB757(2016)473] [Bazavov et al. PRD100(2019)034501]
- Lattice form factors differ at $q^2 = 0$

RBC/UKQCD 2023: Update $B_s \to K\ell\nu$ [Flynn et at. PRD 107 (2023) 114512]

$\rightsquigarrow$ J.Tobias Tsang, Andreas Jüttner, Jonathan Flynn, Ryan Hill, Amarjit Soni, OW

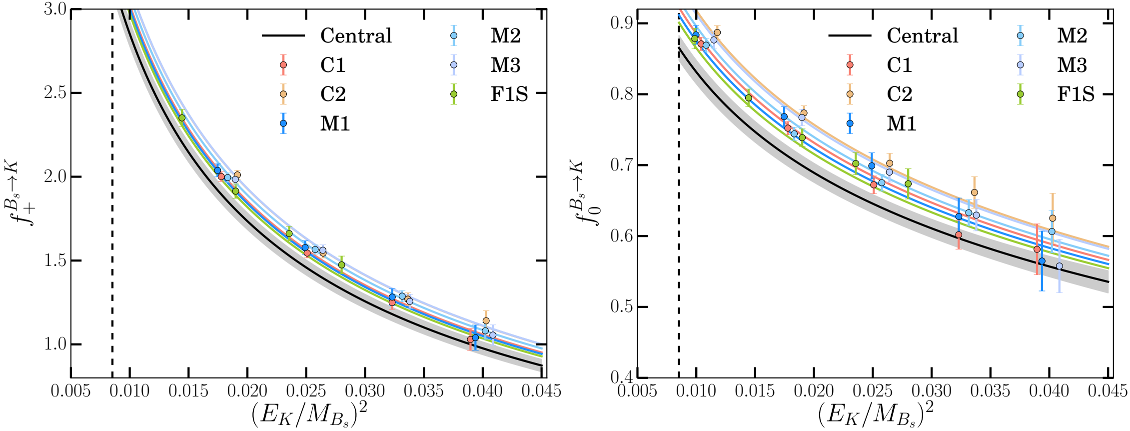
- Effective RHQ action for b quarks
  - → SDWF light/strange
  - → Nonperturbatively tuned RHQ parameters
  - → Directly simulating physical b quarks
  - → Mostly nonperturbative renormalization

- $a \approx 0.11$ fm, 0.08, 0.07 fm
- $M_\pi \gtrsim 250$ MeV



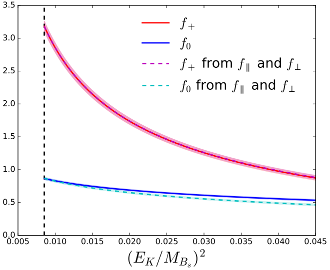
- $a \approx 0.07$ fm, $M_\pi = 250$ GeV

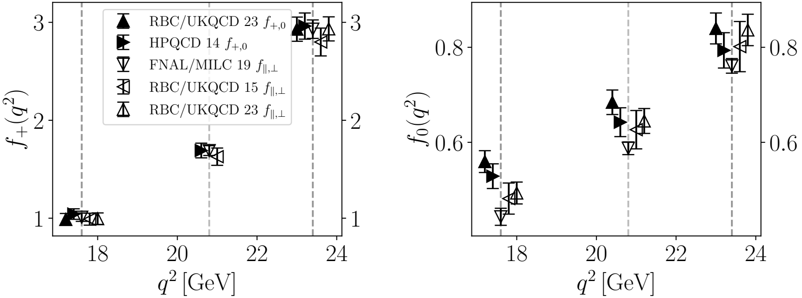
RBC/UKQCD 2023: Chiral-continuum extrapolation [Flynn et at. PRD 107 (2023) 114512]



- Chiral-continuum fit in terms of f_+ and f_0 over simulated range in q^2

RBC/UKQCD 2023: f_+ and f_0 vs. $f_\parallel$ and $f_\perp$ [Flynn et at. PRD 107 (2023) 114512]

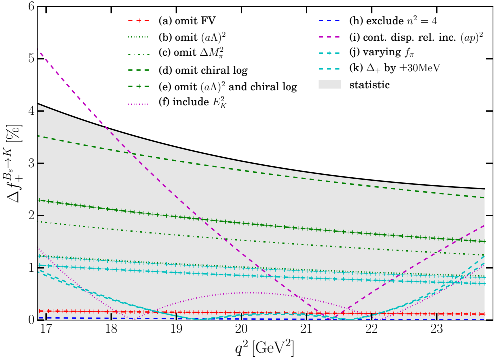




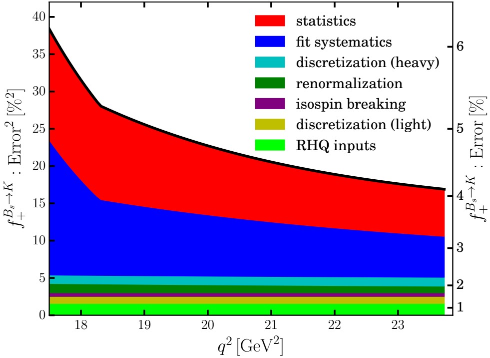
- Chiral-continuum fit in terms of f_+ and f_0 vs. fitting $f_\parallel$ and $f_\perp$ and then constructing f_+ and f_0

- Comparing literature results for $B_s \to K\ell\nu$
- No resolved effect for f_+ but shift for f_0

RBC/UKQCD 2023: Error budget [Flynn et at. PRD 107 (2023) 114512]

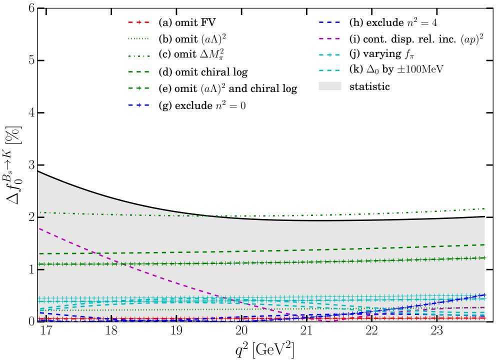


- Systematic of chiral-continuum fit f_+

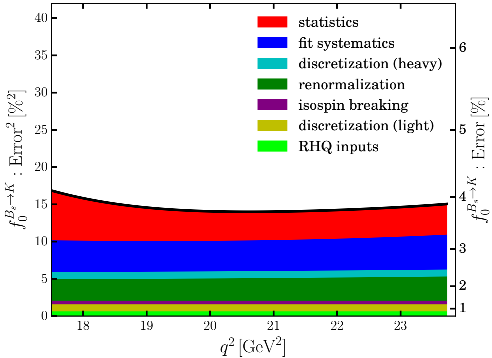


- Total error budget f_+

RBC/UKQCD 2023: Error budget [Flynn et at. PRD 107 (2023) 114512]



- Systematic of chiral-continuum fit f_0



- Total error budget f_0

Kinematical z-expansion (BGL) [Boyd, Grinstein, Lebed, PRL 74 (1995) 4603]

- Map complex q^2 plane with cut $q^2 > t_*$ onto the unit disk in z

$$z(q^2, t_*, t_0) = \frac{\sqrt{t_* - q^2} - \sqrt{t_* - t_0}}{\sqrt{t_* - q^2} + \sqrt{t_* - t_0}}$$

with

$$t_* = (M_B + M_\pi)^2 \qquad \text{(two-particle production threshold)}$$

$$t_\pm = (M_{B_s} \pm M_K)^2 \qquad \text{(with } t_- = q^2_{max}\text{)}$$

$$t_0 \equiv t_{\rm opt} = t_* - \sqrt{t_*(t_* - t_-)} \qquad \text{(symmetrize range of } z\text{)}$$

- BGL express form factors $f_X = f_+$, f_0 as

$$f_X(q^2) = \frac{1}{B_X(q^2)\phi_X(q^2, t_0)} \sum_{n\geq 0} a_{X,n}(t_0) z^n$$

- With outer function $\phi_X(q^2, t_0)$ and Blaschke factors $B_X(q^2)$
- Account for cut differing from pair-production threshold [Gubernari, van Dyk, Virto JHEP02 (2021) 088] [Gubernari, van Dyk, Reboud, Virto JHEP09 (2022) 133]

Kinematical z-expansion [Flynn et at. PRD 107 (2023) 114512] [Flynn, Jüttner, Tsang arXiv:2303.11285]

$\rightsquigarrow$ Andreas Jüttner, J.Tobias Tsang, Jonathan Flynn

- Terms in the z expansion are limited:
  - → Number of synthetic data points plus kinematic constraint: $K_+ + K_0 - 1 < N_+ + N_0$

- Truncation errors (e.g. large variations in $f_+(q^2 = 0)$ and $f_0(q^2 = 0)$) when
  - → Varying q^2 values of synthetic points
  - → Varying t_0 in z-transformation

- Avoid frequentist fit introducing systematic error
  - → Perform Bayesian fit aiming to fit full z expansion (no truncation)
  - → Use unitarity constraint to control higher-order coefficients

Bayesian inference for form factors [Flynn, Jüttner, Tsang arXiv:2303.11285]

- Compute z expansion coefficients as expectation values: $\langle g(a)\rangle = N \int da\, g(a)\pi(a|f, C_f)\pi_a$
- Probability for parameters given model and data

$$\pi(a|f, C_f) \propto \exp\left\{-\frac{1}{2}\chi^2(a, f)\right\} \qquad \chi^2(a, f) = (f - Za)^T C_f^{-1}(f - Za)$$

and prior knowledge from unitarity constraint $\pi_a \propto \theta(1 - |a_+|_\alpha^2)\theta(1 - |a_0|_\alpha^2)$

- Perform Monte Carlo integration using multivariate distribution a

  but drop samples incompatible with unitarity

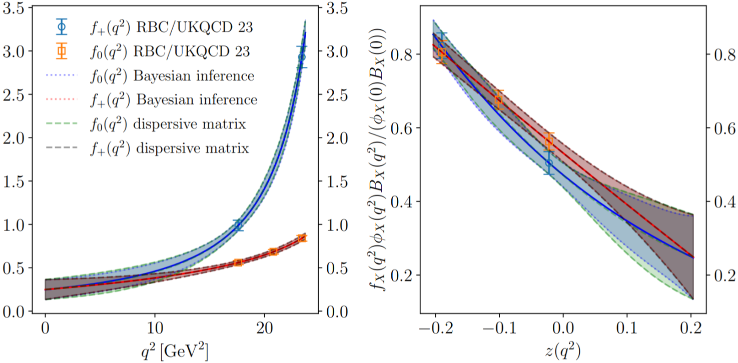
- To increase probability modify expression and correct with an accept-reject step

$$\pi(a|f_p, C_{f_p})\pi_a(a_p|M) \propto \theta(a)\exp\left\{-\frac{1}{2}\left(f_p - Za\right)^T C_{f_p}^{-1}\left(f_p - Za\right) - \frac{1}{2}a^T\frac{M}{\sigma^2}a\right\}$$

with $\quad p \le \dfrac{\exp\left\{-1/\sigma^2\right\}}{\exp\left\{-a^T\frac{M}{2\sigma^2}a\right\}}$

RBC/UKQCD 2023: z-expansion

[Flynn et at. PRD 107 (2023) 114512] [Flynn, Jüttner, Tsang arXiv:2303.11285]



	$q^2 = 0$
Duplancic, Melic	$0.30(^{+4}_{-3})$
Khodjamirian, Rusov	0.336(23)
Faustov, Galkin	0.284(14)
Wang, Xiao	$0.26(^{+4}_{-3})(2)$
RBC/UKQCD 23	0.25(11)
Fermilab/MILC 18	0.13(5)
HPQCD 14	0.32(6)

- Consistent with result of dispersive matrix method by Martinelli, Simula, Vitorio et al.

$b \to c$
(hadronic vector final states)

Determining $|V_{cb}|^{\mathrm{excl}}$

- Heavy-to-heavy transition $\rightsquigarrow$ HQET relations

- Available channels
  - → $B \to D\ell\nu$
  - → $B_s \to D_s\ell\nu$
  - → $B \to D^*\ell\nu$
  - → $B_s \to D_s^*\ell\nu$

pseudoscalar final states

vector final states

- D^* and D_s^* suitable for using the narrow width approximation
  - → Treat as QCD-stable particle

Exclusive semi-leptonic decays: $B_{(s)} \to D^*_{(s)}\ell\nu$

$$\begin{aligned}
\langle D^*_{(s)}(k,\varepsilon_\nu)|\mathcal{V}^\mu|B_{(s)}(p)\rangle =& V(q^2)\frac{2i\varepsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma}{M_{B_{(s)}}+M_{D^*_{(s)}}}\\
\langle D^*_{(s)}(k,\varepsilon_\nu)|\mathcal{A}^\mu|B_{(s)}(p)\rangle =& A_0(q^2)\frac{2M_{D^*_{(s)}}\varepsilon^*\cdot q}{q^2}q^\mu\\
&+A_1(q^2)(M_{B_{(s)}}+M_{D^*_{(s)}})\left[\varepsilon^{*\mu}-\frac{\varepsilon^*\cdot q}{q^2}q^\mu\right]\\
&-A_2(q^2)\frac{\varepsilon^*\cdot q}{M_{B_{(s)}}+M_{D^*_{(s)}}}\left[k^\mu+p^\mu-\frac{M^2_{B_{(s)}}-M^2_{D^*_{(s)}}}{q^2}q^\mu\right]
\end{aligned}$$

- Determine the four form factors $V(q^2)$, $A_0(q^2)$, $A_1(q^2)$, $A_2(q^2)$ or in HQE convention $h_V(w)$, $h_{A_0}(w)$, $h_{A_1}(w)$, $h_{A_2}(w)$
- Narrow-width approximation i.e. $D^*_{(s)}$ is treated as a QCD-stable particle

First lattice calculations over the full q^2 range

- $B \to D^*\ell\nu$
  - → 2021 Fermilab/MILC [Bazavov et al. EPJC 82(2022)1141]
  - → 2023 HPQCD [Harrison, Davies, arXiv:2304.03137]
  - → 2023 JLQCD [Y. Aoki et al. arXiv:2306.05657]
  - → Preliminary LANL/SWME [Jang et al. PoS Lattice2019 (2020) 056]

- $B_s \to D_s^*\ell\nu$
  - → 2022 HPQCD [Harrison, Davies PRD105(2022).094506][arXiv:2304.03137]

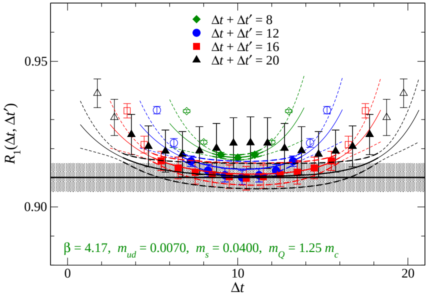
- Some tension in the shape of the form factors
  - → Further scrutiny required

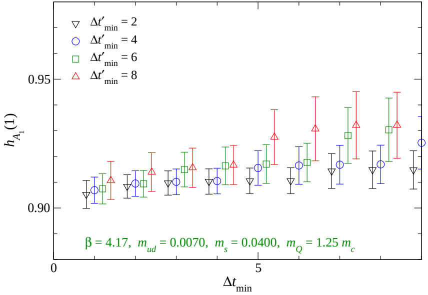
JLQCD 2023: $B \to D^* \ell \nu$ [Y. Aoki et al. arXiv:2306.05657]

- Unitary setup
  - → MDWF light/strange and heavy quarks with $am_c \leq am_Q \leq 2.44 \cdot am_c$
  - → Additional extrapolation in the heavy quark mass to reach m_b
  - → Fully nonperturbative renormalization

- $a \approx 0.044$ fm, 0.055 fm, 0.080 fm
- $M_\pi \gtrsim 230$ MeV

- Carefully checking for excited state contamination using multiple source sink separations (e.g. for h_{A_1})

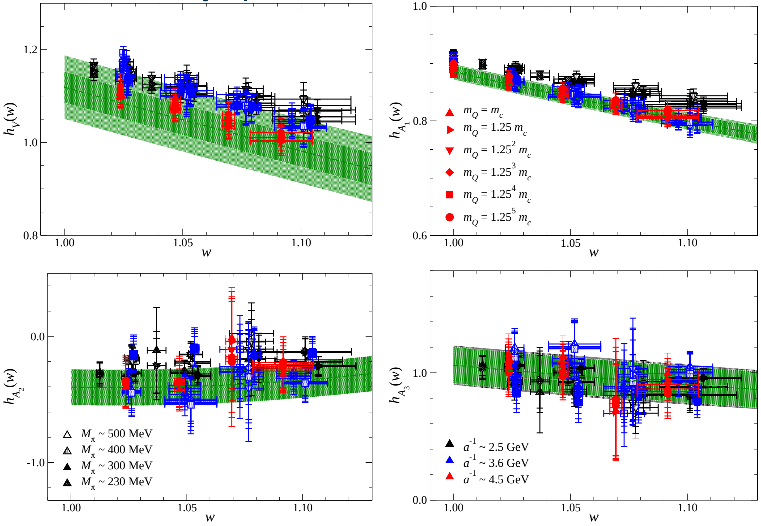




JLQCD 2023: combined chiral, heavy-quark, continuum limit

[Y. Aoki et al. arXiv:2306.05657]

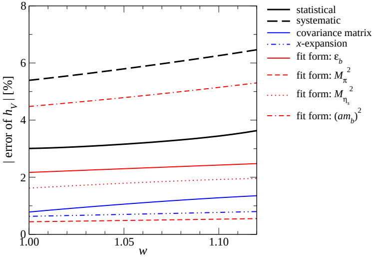
- h_V: sys. error dominates
- h_{A1} stat. and sys. error similar
- $h_{A2,A3}$ stat. error dominates
  - ⇝ Different setup with moving B meson would help

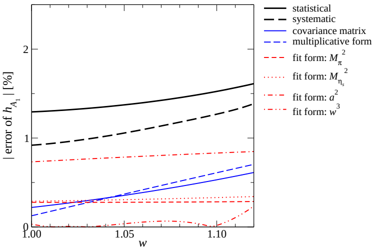


- Extrapolation over simulated range of q^2
- Predictions consistent with HQET-based parametrization

JLQCD 2023: error budget [Y. Aoki et al. arXiv:2306.05657]

- h_V: sys. error dominates
- h_{A1} stat. and sys. error similar
- $h_{A2,A3}$ stat. error dominates
  ⇝ Different setup with moving B meson would help





- Extrapolation over simulated range of q^2
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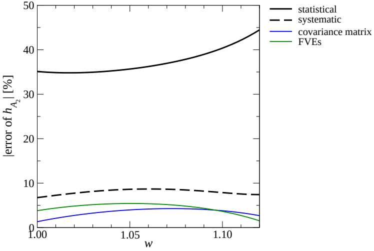
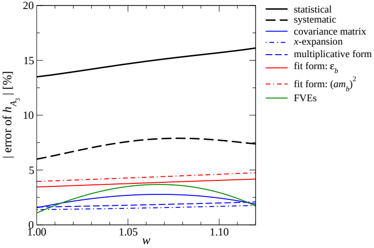
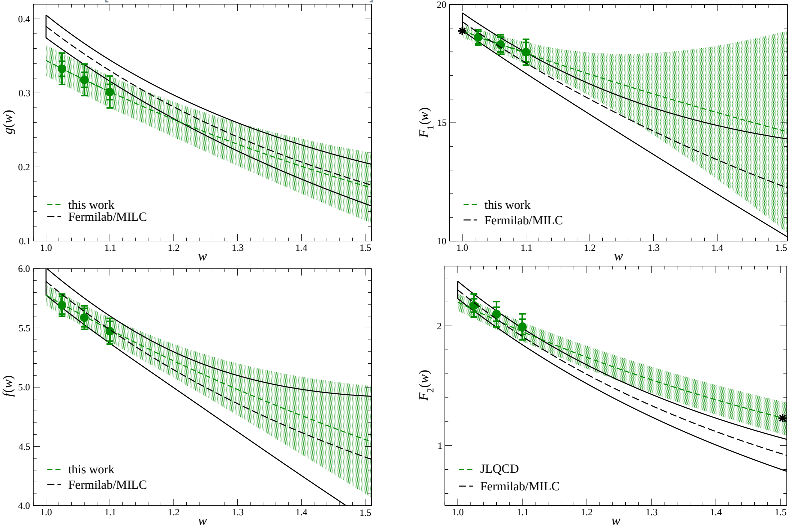




JLQCD 2023: comparison [Y. Aoki et al. arXiv:2306.05657]

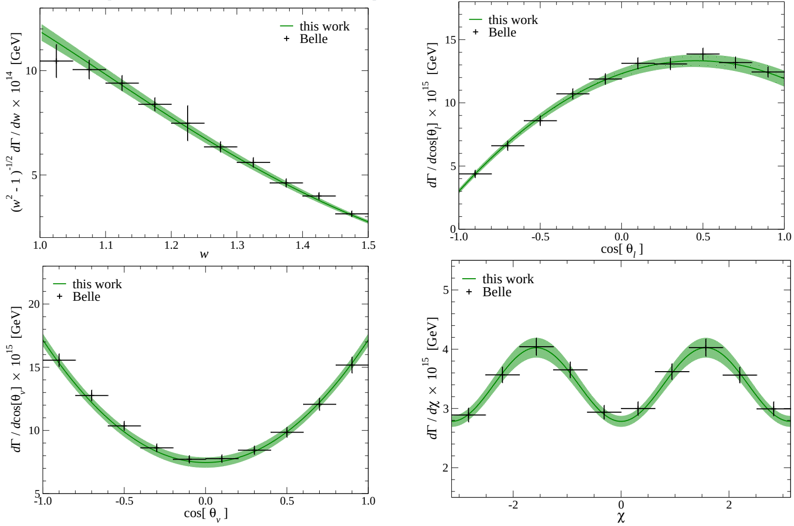
- Convert h_V, h_{A1}, h_{A2}, h_{A3} to relativistic convention g, f, $\mathcal{F}_1$, $\mathcal{F}_2$
- Synthetic data points in 2σ agreement with Fermilab/MILC
- Slopes/shapes differ



JLQCD 2023: comparison [Y. Aoki et al. arXiv:2306.05657]

- Convert h_V, h_{A1}, h_{A2}, h_{A3} to relativistic convention g, f, $\mathcal{F}_1$, $\mathcal{F}_2$
- Good agreement with Belle 2019 data

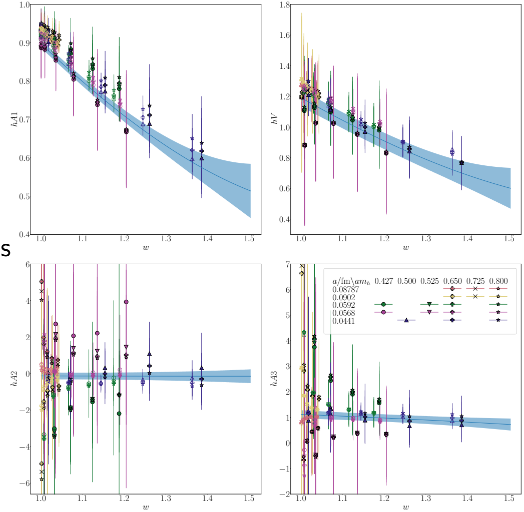
  [Belle PRD 100 (2019) 052007]



HPQCD 2023: $B_{(s)} \to D^*_{(s)}\ell\nu$ [Harrison, Davies, arXiv:2304.03137]

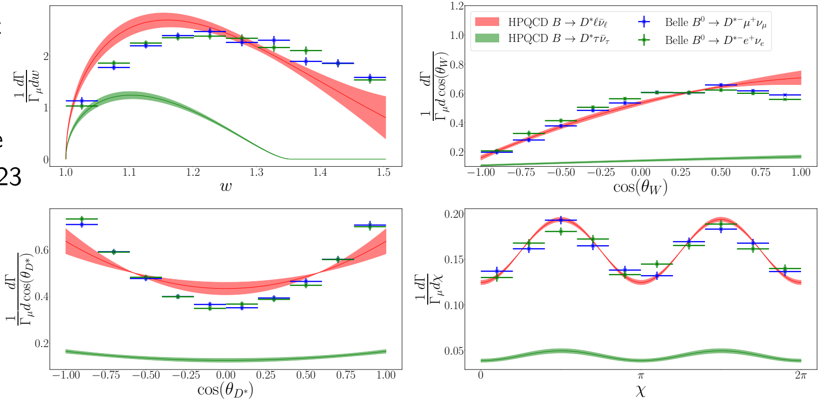
- All-HISQ setup
  - → Updating [Harrison, Davies PRD105(2022).094506]
  - → Fully non-perturbative renormalization
  - → Simulate heavier-than-charm → close-to-bottom
  - → Directly cover most of the allowed q^2 range at the finest lattice spacing
  - ⇝ Parametrize pole mass for different charm masses in a combined chiral, heavy quark, continuum, kinematical extra-/interpolation
  - → Also analyzing tensor BSM operators

- h_V, h_{A1}, h_{A2}, h_{A3} for $B \to D^*\ell\nu$



HPQCD 2023: $B_{(s)} \to D^*_{(s)}\ell\nu$ [Harrison, Davies, arXiv:2304.03137]

- Shape largely consistent with Fermilab/MILC 21
- Some tension with Belle 2019 data and JLQCD 23



Summary

- Heavy flavors are challenging
  - → Require to accommodate another scale on the lattice
  - → Simulations with physical light quarks are even more challenging
  - → Semi-leptonic decay processes cover a large range q^2
  - → Leptonic decays experimentally difficult

- Puzzles in heavy flavor physics
  - → Tension between $|V_{ub}|^{\mathrm{excl}}$ vs. $|V_{ub}|^{\mathrm{incl}}$ and $|V_{cb}|^{\mathrm{excl}}$ vs. $|V_{cb}|^{\mathrm{incl}}$
  - → Shape comparisons of form factors