Heavy to heavy semileptonic decays in LQCD: current status

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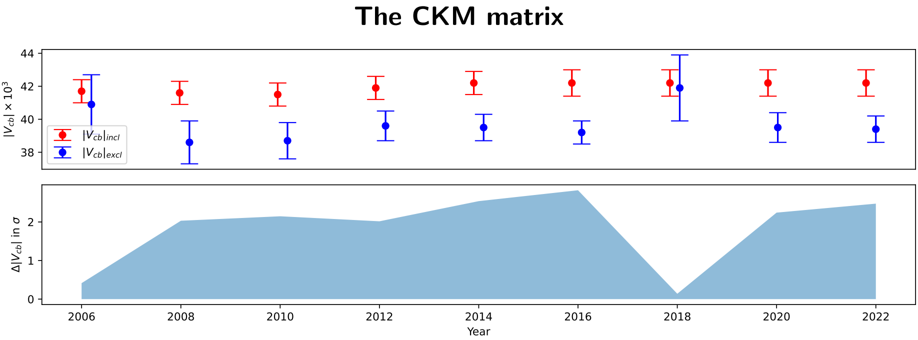
23^{rd} September 2024

Motivation: Tensions in $|V_{cb}|$ inclusive vs exclusive



- Current values (PDG 2024):

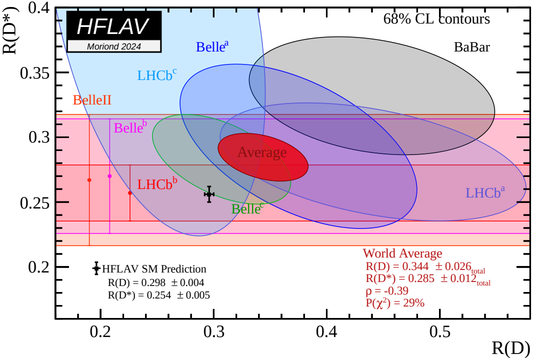
$$|V_{cb}|_{\text{excl}} \times 10^{-3} = 39.8(6)$$

$$|V_{cb}|_{\text{incl}} \times 10^{-3} = 42.2(5)$$

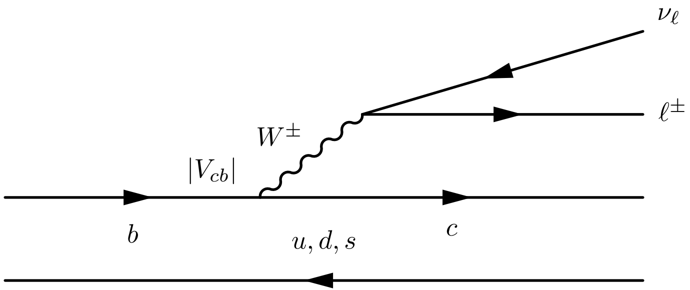
- The 3σ difference between these two values shows that we have not improved much

Motivation: Tensions in LFU ratios

$$R\left(D_{(s)}^{(*)}\right) = \frac{\mathcal{B}\left(B_{(s)} \to D_{(s)}^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(B_{(s)} \to D_{(s)}^{(*)}\ell\nu_\ell\right)}$$



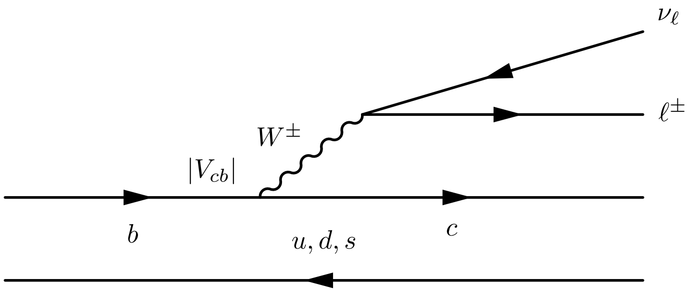
- Current $\approx 2.8\sigma$ combined tension with the SM (HFLAV)
  - Tension in $R(D) \approx 1.5\sigma$ Tension in $R(D^*) \approx 2.8\sigma$



$$\underbrace{\frac{d\Gamma}{dw}\left(B_{(s)} \to D^{(*)}_{(s)}\ell\bar{\nu}_\ell\right)}_{\text{Experiment}} = \underbrace{K_{B_{(s)}\to D^{(*)}_{(s)}}(w, m_\ell)}_{\text{Known factors}} \underbrace{|\mathcal{F}(w)|^2}_{\text{Theory}} \times |V_{cb}|^2\,, \qquad w = v_{D^{(*)}_{(s)}} \cdot v_{B_{(s)}}$$

- The amplitude $\mathcal{F}$ must be calculated in LQCD
  - Data more precise at w close to 1
- $K_{B_{(s)}\to D^{(*)}_{(s)}}(w, m_\ell) \propto (w^2 - 1)^{\frac{3}{2},\frac{1}{2}}$ requires extrapolation of experimental data

Semileptonic B decays on the lattice: Universality ratios



$$R(D_{(s)}^{(*)}) = \frac{\int_1^{w_{\mathrm{Max},\tau}} dw\, K_{B_{(s)}\to D_{(s)}^{(*)}}(w, m_\tau)\, |\mathcal{F}(w)|^2 \times \cancel{|V_{cb}|^2}}{\int_1^{w_{\mathrm{Max}}} dw\, K_{B_{(s)}\to D_{(s)}^{(*)}}(w, 0)\, |\mathcal{F}(w)|^2 \times \cancel{|V_{cb}|^2}}$$

- The universality ratio depends only on the form factors
- It is possible to extract $R(D_{(s)}^{(*)})$ without experimental data!

Semileptonic B decays on the lattice: Heavy quarks

- For heavy quarks $(m_Q > \Lambda_{QCD})$, discretization errors grow as $\sim \alpha_s^k (am_Q)^n$
- Mainly two ways to address this problem
  - Effective actions (FermiLab, NRQCD...)
  - Treat the bottom as a light quark
    - Use unphysical values for m_b and extrapolate

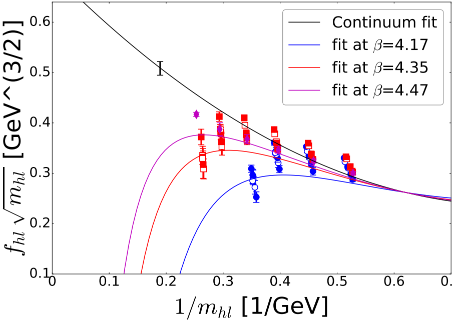
Different quark actions have different discretization errors when applied to heavy quarks

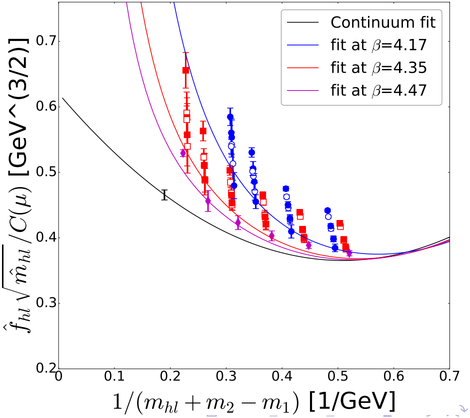
Semileptonic B decays on the lattice: Heavy quarks

- Domain-Wall fermions from JLQCD
- Errors **start** at $O(a^2 m_Q^2)$
- Data beyond $am_Q \approx 0.65$ features **large** discretization systematics
- Large correction in the extrapolation

PoS LATTICE2016 (2016) 118

$a \approx 0.044 - 0.080$ fm, $M_\pi \approx 230 - 500$ MeV, $am_Q \lesssim 0.86$, $m_Q \lesssim 3.0$ GeV

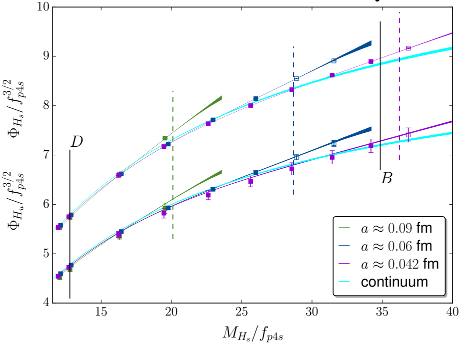




Semileptonic B decays on the lattice: Heavy quarks

- HISQ fermions from Fermilab/MILC Phys.Rev.D 98 (2018) 7, 074512; Phys.Rev.D 107 (2023) 9, 094516
- From HPQCD Phys.Rev.D 75 (2007) 054502; Phys.Rev.D 87 (2013) 3, 034017
- Errors **start** at $O(\alpha_s v a^2 m_Q^2)$, one order of magnitude smaller than $O(a^2 m_Q^2)$
- Reasonable correction, even at large am_Q, without ap issues
- HISQ corrects at all orders, theoretical limit with fine tuning $am_Q = \pi/2$

$$a \approx 0.042 - 0.088 \text{ fm}, \; M_\pi \approx 135 \text{ MeV}, \; am_Q \lesssim 1.3, \; m_Q \sim m_b$$



Some statistical errors are missing

Review of lattice results

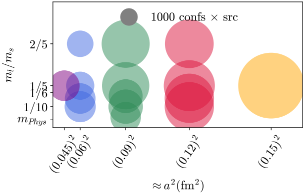
- Latest calculations and tensions (mainly $B \to D^* \ell \nu$)
- Calculations in progress
  - HPQCD $B_c \to J/\psi \ell \nu$
  - RBQCD/UKQCD $B_s \to D_s^* \ell \nu$
  - Fermilab/MILC $B_{(s)} \to D_{(s)}^* \ell \nu$
  - JLQCD $B \to D \ell \nu$
- Not covered $\rightarrow$ Inclusive determinations from LQCD

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

Review of lattice results: $B \to D^*\ell\nu$

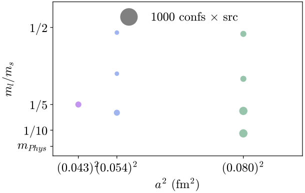
Fermilab/MILC

- ASQTAD + Fermilab



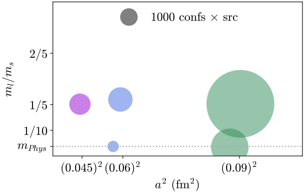
JLQCD

- DW + DW

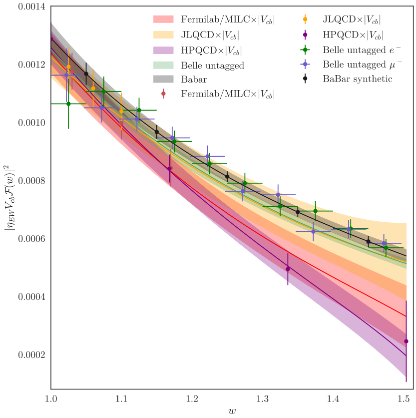


HPQCD

- HISQ + HISQ



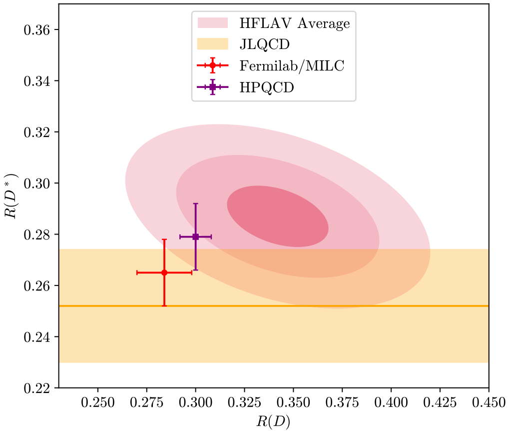
Review of lattice results: $B \to D^* \ell \nu$



$$|V_{cb}|^{\mathrm{FM}} = 38.40(78) \times 10^{-3}$$

$$|V_{cb}|^{\mathrm{JLQCD}} = 39.19(90) \times 10^{-3}$$

$$|V_{cb}|^{\mathrm{HPQCD}} = 39.31(74) \times 10^{-3}$$



$$R(D^*)^{\mathrm{FM}} = 0.265(13)$$

$$R(D^*)^{\mathrm{JLQCD}} = 0.252(22)$$

$$R(D^*)^{\mathrm{HPQCD}} = 0.279(13)$$

Review of lattice results: D'Agostini bias

- V_{cb} value well below the latest inclusive one (everything $\times 10^3$)

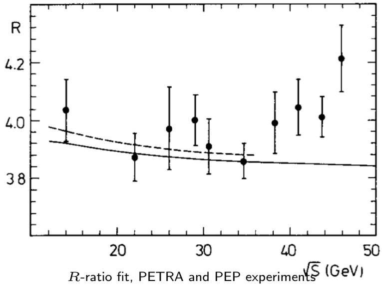
$$|V_{cb}|^{\text{FM}}_{\text{excl}} = 38.40(78) < |V_{cb}|^{BCG}_{\text{incl}} = 42.16(51)$$

Eur.Phys.J.C**82** (2022), 1141; Phys.Lett.B**822** (2021), 136679; JHEP10(2022)068

- Could this be a consequence of D'Agostini effect? Nucl.Instrum.Meth.A**346** (1994), 306
  - Correlated data
  - Overall normalization factor ($|V_{cb}|$)

$$\hat{V}_{cb} = \frac{\bar{V}_{cb}}{1 + \chi^2_{\text{Exp}}\sigma^2_{V_{cb}}},$$

$$\chi^2 = \chi^2_{\text{LQCD}} + \chi^2_{\text{Exp}}$$



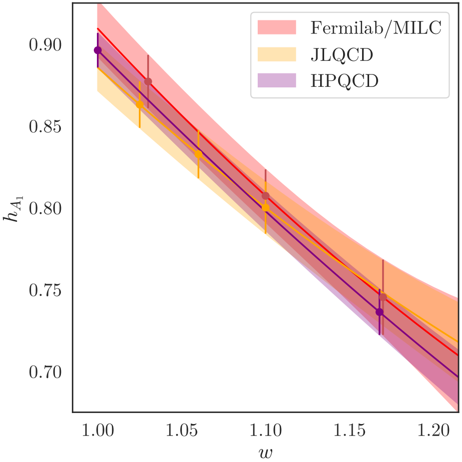
R-ratio fit, PETRA and PEP experiments

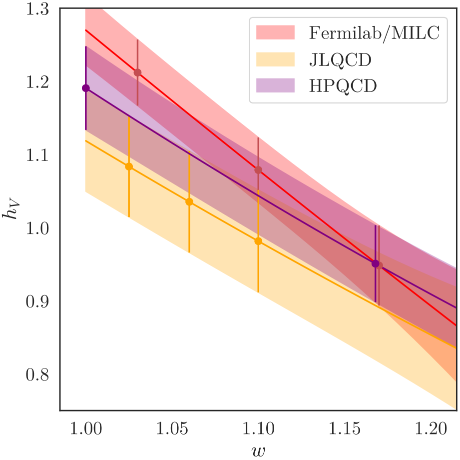
- Compare fits **Belle + all LQCD** with **Belle fits + LQCD** $\mathcal{F}(w = 1)$

$$|V_{cb}|^{\text{FM}}_{\text{All}} = 38.60(86), \qquad |V_{cb}|^{\text{FM}}_{\mathcal{F}(1)} = 38.17(78)$$

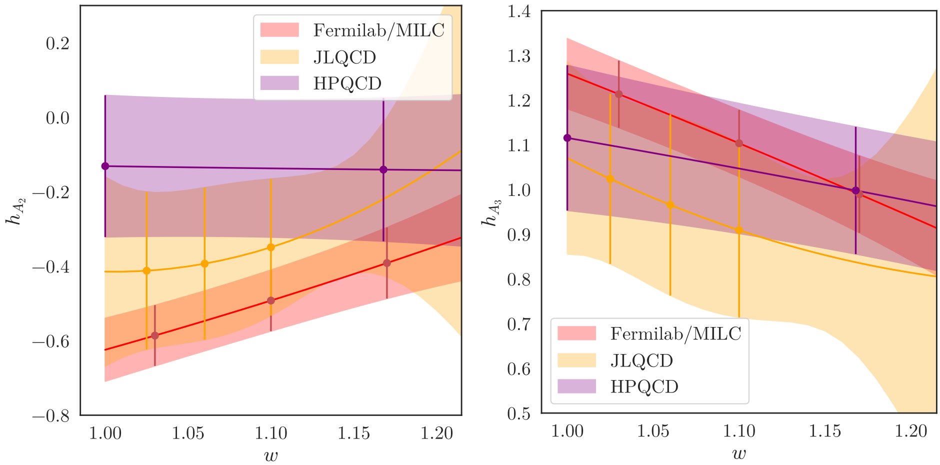
We do not see any **D'Agostini bias** in our calculation

Review of lattice results: Comparison of HQET form factors

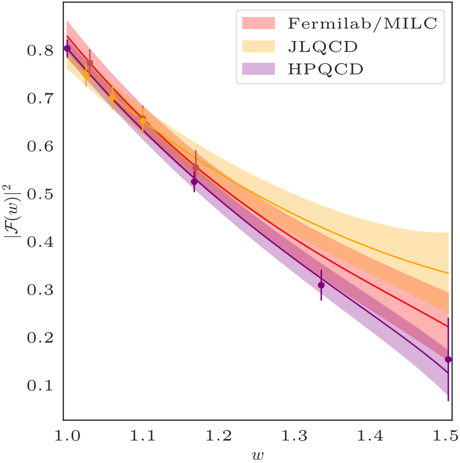




Review of lattice results: Comparison of HQET form factors



Review of lattice results: Comparison of decay amplitudes



- Maximum difference $\begin{cases} \text{Fermilab/MILC – JLQCD} & 1.02\sigma \\ \text{Fermilab/MILC – HPQCD} & 1.14\sigma \\ \text{JLQCD – HPQCD} & 2.20\sigma \end{cases}$

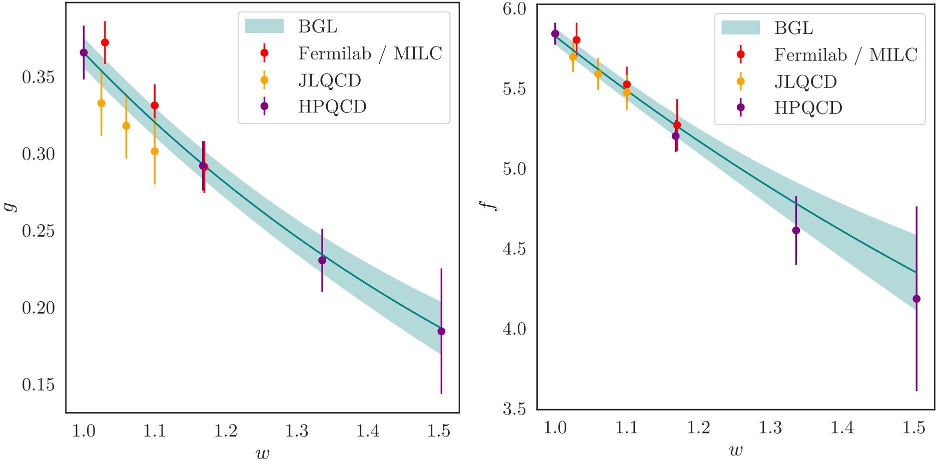
Review of lattice results: Combined fits

- Combined fits with priors 0(1)
- Kinematic constraint imposed with priors
- BGL fit 2222

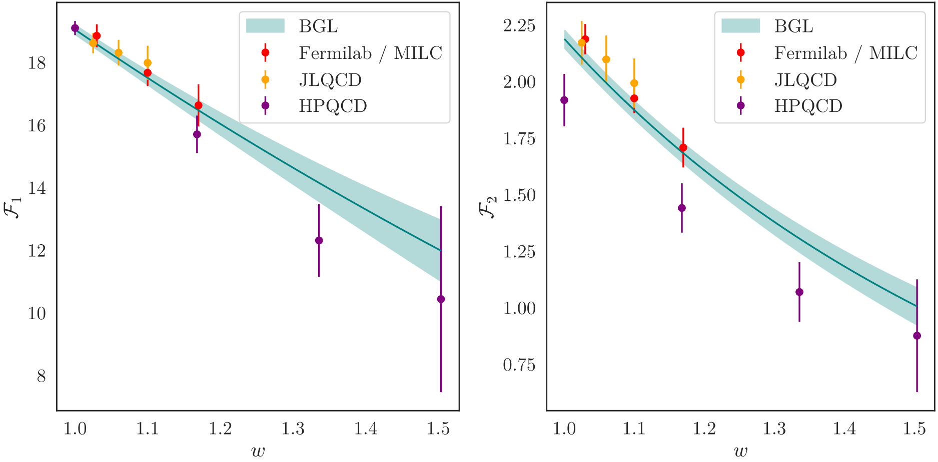
	w Constraint		w/o Constraint	
	p	$R_2(1)$	p	$R_2(1)$
MILC	0.51	1.20(12)	0.43	1.27(13)
JLQCD	0.52	0.98(19)	0.25	0.97(19)
HPQCD	0.77	1.39(16)	0.65	1.39(16)
MILC+JLQCD	0.40	1.118(97)	0.36	1.16(11)
MILC+HPQCD	0.44	1.262(93)	0.37	1.262(93)
JLQCD+HPQCD	0.73	1.18(12)	0.67	1.18(12)
All	0.56	1.193(83)	0.50	1.193(83)

- p-value of Belle untagged + BaBar BGL fit 223 is ≈ 0.04
- Combined $R(D^*) = 0.2667(57)$

Review of lattice results: Combined fits



Review of lattice results: Combined fits

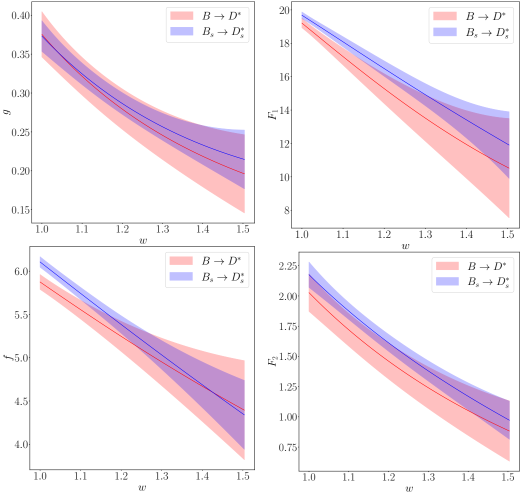


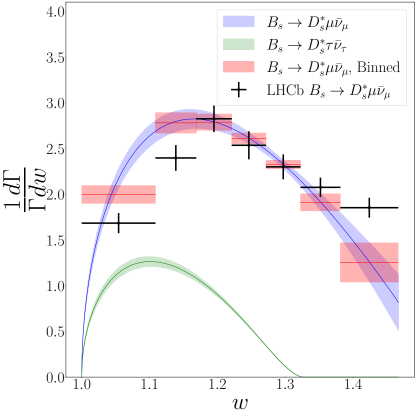
Review of lattice results

$$B_s \to D_s^* \ell \nu$$

Review of lattice results: $B_s \to D_s^* \ell\nu$

- HPQCD with the same setup as $B \to D^* \ell\nu$

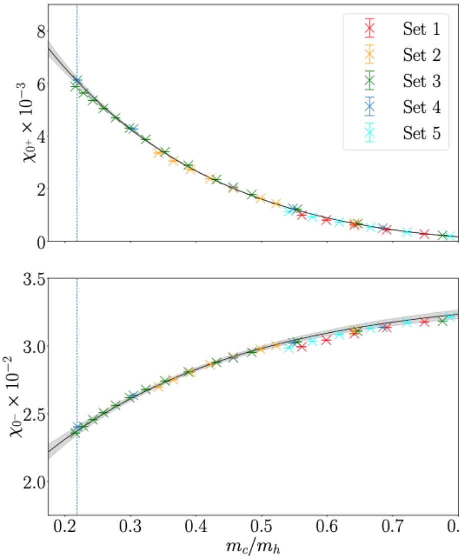




$R(D_s^*) = 0.266(9)$

$$B_c \to J/\psi \ell \nu$$

Review of lattice projects: $B_c \to J\psi\ell\nu$



- HPQCD with similar setup to $B_{(s)} \to D^*_{(s)}\ell\nu$
- Update of the 2020 calculation
  Phys.Rev.D**102** (2020), 094518
- Plan to include an extra 0.03 fm ensemble
- Chiral-continuum extrapolation includes a z expansion
- Susceptibilities computed using LQCD Phys.Rev.D**104** (2021), 094512; Phys.Rev.D**110** (2024), 054506
    - Large reduction in errors
    - Large shifts wrt the previous calculation (!!) (**Preliminary**)

$$R(J/\psi) = 0.2582(38) \to 0.2674(31)$$

$$F_L = 0.4416(92) \to 0.4510(88)$$

Review of lattice projects

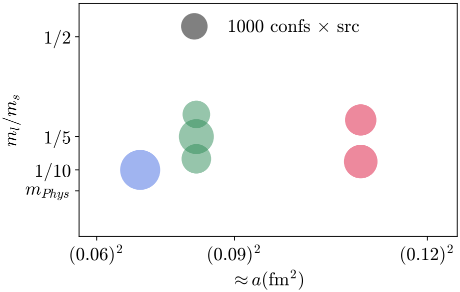
$$B_s \to D_s^* \ell \nu$$

Review of lattice projects: $B_{(s)} \to D^*_{(s)}\ell\nu$

- Different group RBC/UKQCD
- Using 6 $N_f = 2 + 1$ ensembles of sea DW quarks
- The bottom quark use an effective action
  - Good crosscheck against JLQCD
  - Potentially large systematics due to a mismath between b and c actions

    Phys.Rev.D87 (2018), 054502

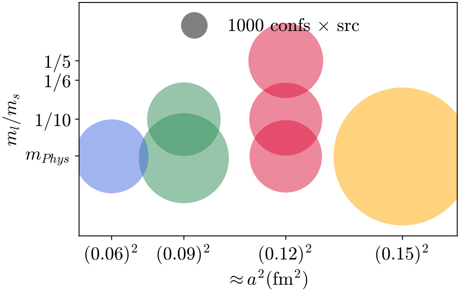
- m_π in the range $270 - 433$ MeV



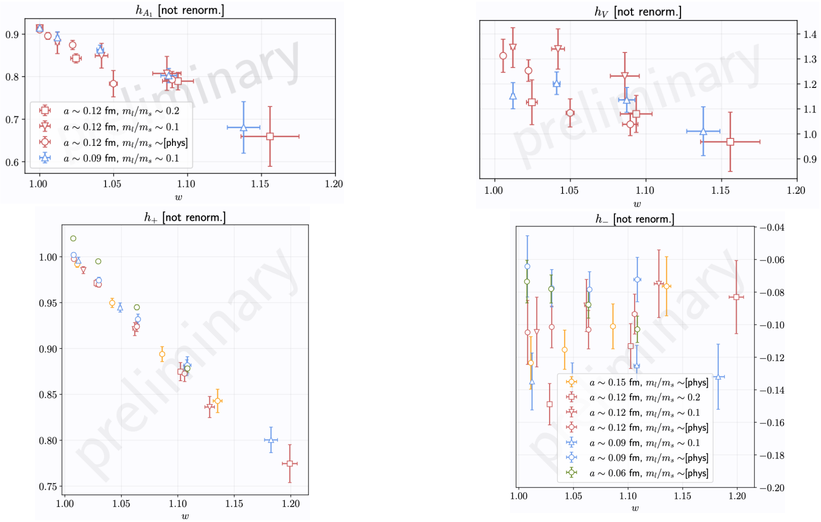
Review of lattice projects

$$B_{(s)} \to D_{(s)}^{(*)} \ell \nu$$

- Fermilab/MILC calculation
- Using 7 $N_f = 2+1+1$ ensembles of sea HISQ quarks
- The heavy quarks use the Fermilab effective action
  - Correlated with a $B \to L\ell\nu$ analysis using the same data
  - Four channels in a single correlated analysis

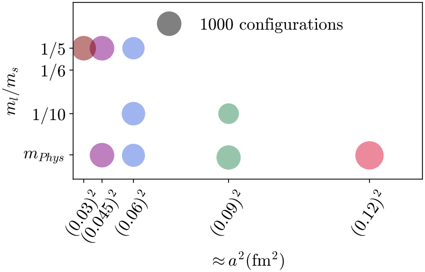


Review of lattice projects: $B_{(s)} \to D^{(*)}_{(s)} \ell \nu$

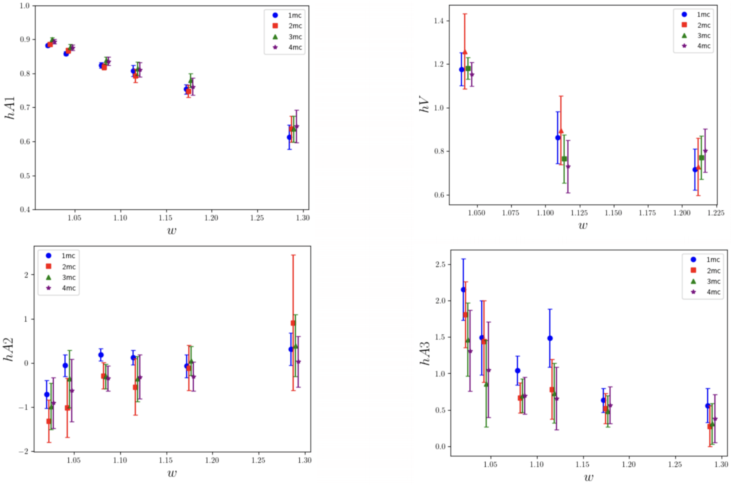


Review of lattice projects: $B_{(s)} \to D_{(s)}^{(*)} \ell \nu$

- Fermilab/MILC calculation
- Planning to use 9 $N_f = 2+1+1$ ensembles of sea HISQ quarks
- The heavy quarks use the HISQ action
  - Physical bottom mass reachable with the finest ensembles
- m_π physical in several ensembles



Review of lattice projects: $B_{(s)} \to D_{(s)}^{(*)} \ell \nu$



Preliminary results $B_s \to D_s^* \ell \nu$, statistics 24×426
Single ensemble $a = 0.06$ fm and $m_l / m_s = \frac{1}{5}$ at different values of am_b

Thank you for your time