

# $B$ meson semileptonic decays from Lattice QCD

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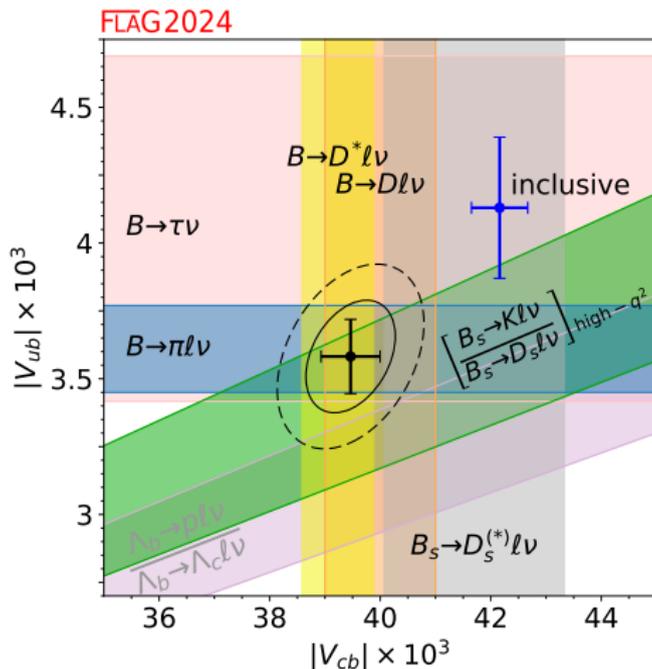
Fermilab Lattice and MILC collaborations

Universidad de Zaragoza

March 16<sup>th</sup>, 2026

# The motivation

# Motivation: CKM matrix elements

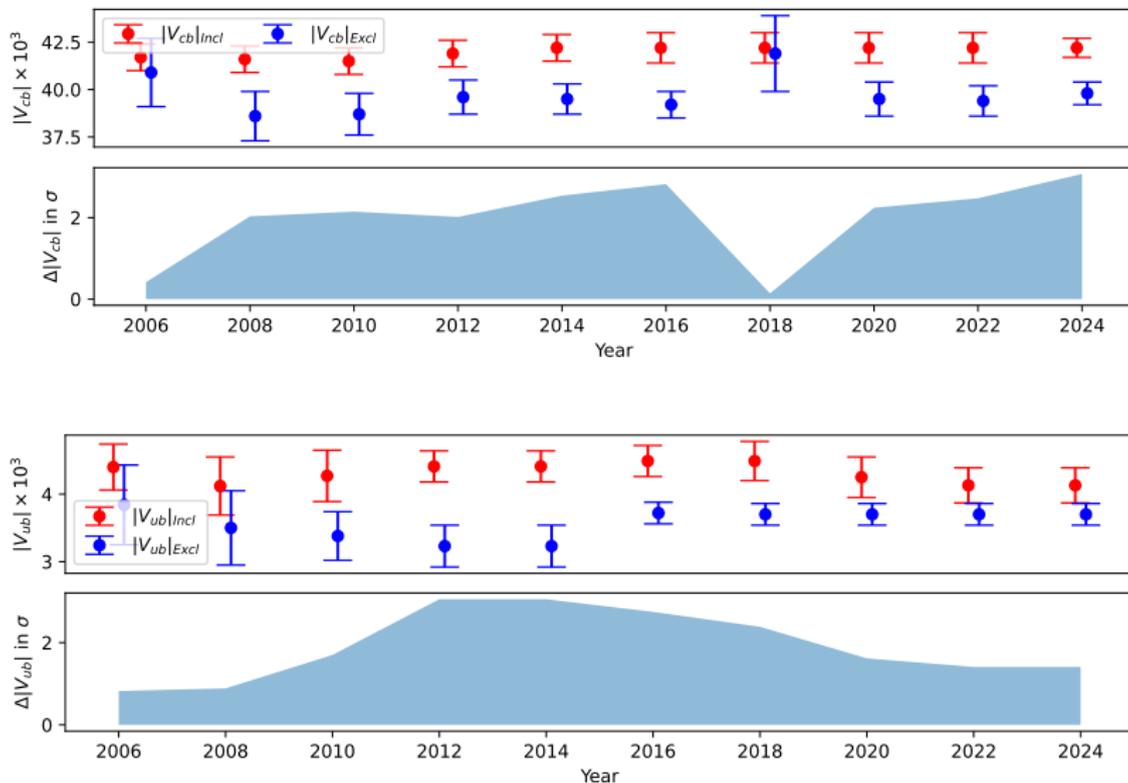


FLAG Review 2024, Phys.Rev.D 113, 014508 (2026)

Strong arguments disfavoring new physics

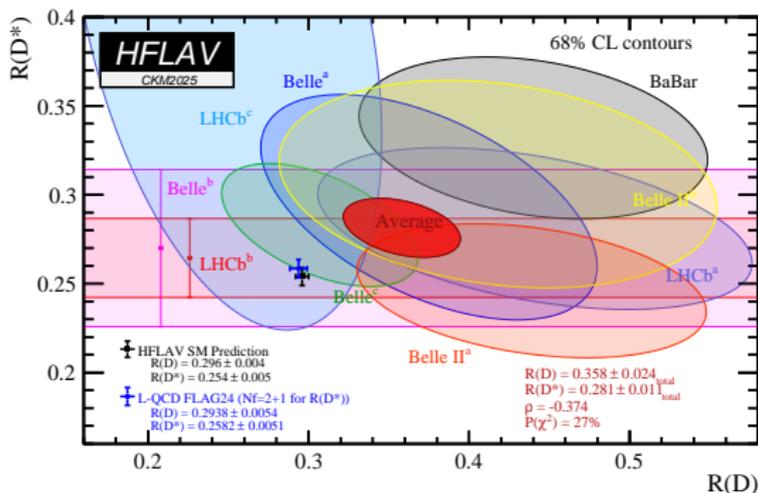
Phys. Rev. Lett. 114, 011802 (2015)

# Motivation: CKM matrix elements



# Motivation: Tensions in LFU ratios

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu_\ell)}$$

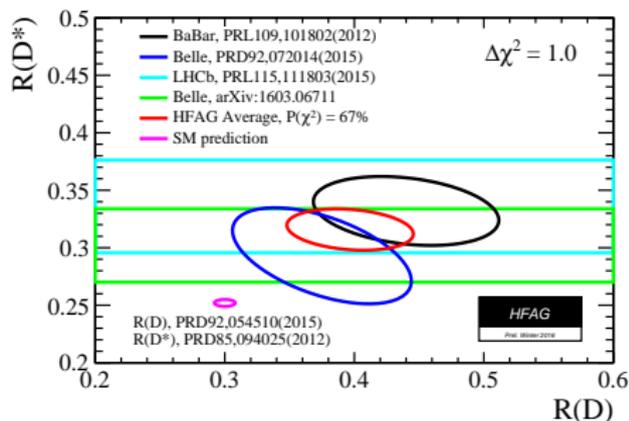
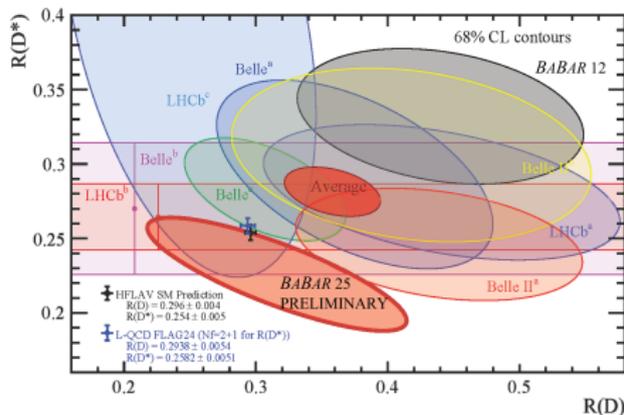


HFLAV update in CKM 2025

- Current  $\approx 3.5\sigma$  combined tension exp VS LQCD (HFLAV)
  - Tension in  $R(D) \approx 2.6\sigma$     Tension in  $R(D^*) \approx 1.9\sigma$

# Motivation: Tensions in LFU ratios

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu_\ell)}$$

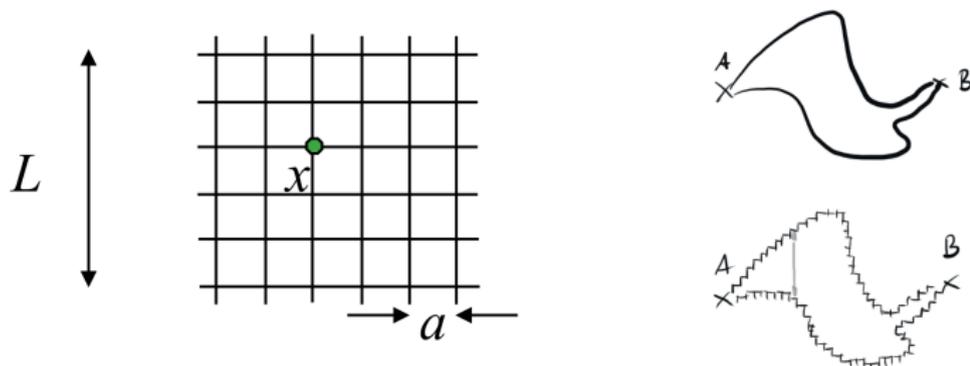


D. Hitlin (BaBar) @ VFSB 2025

HFAG 2016

Would  $R(D) - R(D^*)$  be so interesting  
 if we had BaBar 2025 result from the start?

# Semileptonic $B$ decays on the lattice: Introduction to Lattice QCD

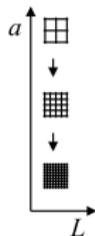


- Discretize spacetime + Finite volume = Finite number of dof
  - Unphysical setup: finite lattice spacing  $a$ , volume, quark masses  $m_q \dots$
- Literally perform the path integral
  - Each configuration is a path in the path integral
  - Only the relevant paths are explored  $\rightarrow$  **importance sampling**

# Semileptonic $B$ decays on the lattice: Introduction to Lattice QCD

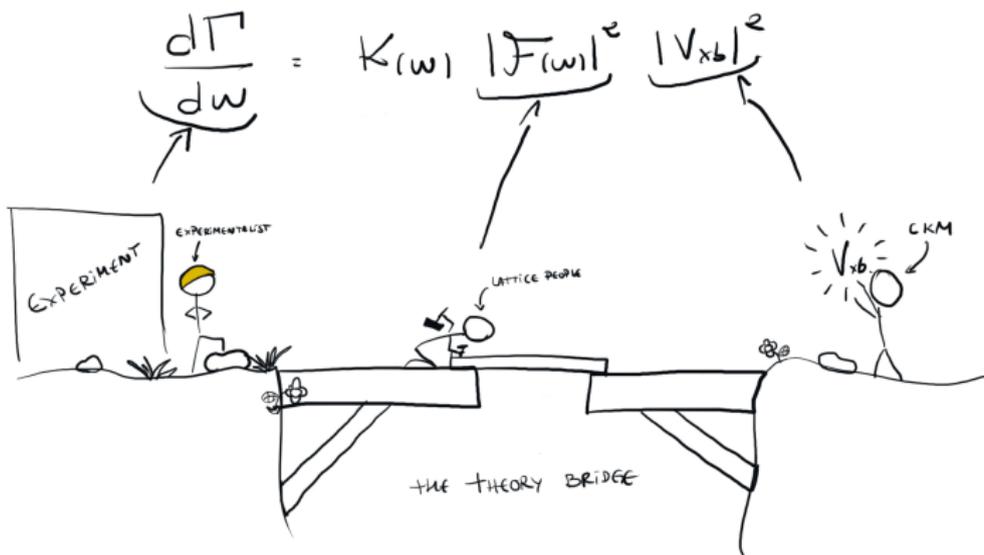
Systematic error analysis  $\rightarrow$  **EFT** descriptions of QCD

- provides ansätze for extrapolations
- can estimate the size of the systematic errors
- is systematically improvable
  
- Lattice spacing  $a =$  UV regulator  $\rightarrow$  HQ errors  $O(a^2 m_Q^2)$
- **Describe the  $b$  with an EFT**
  - Physical  $b$  mass
  - Requires matching, renormalization errors up to  $\approx 10\%$
- **The  $b$  uses the light quark action**
  - Easy setup, no matching, non-perturbative renormalization
  - unphysical  $b$  masses, must extrapolate to physical  $b$  mass



# The theory

# Semileptonic $B$ decays on the lattice: Exclusive $|V_{cb}|$ and LFU ratios



# Semileptonic $B$ decays on the lattice: Exclusive $|V_{cb}|$ and LFU ratios

- If the lepton mass is not negligible, a second term contributes

$$\underbrace{\frac{d\Gamma}{dw} \left( \bar{B} \rightarrow D_{(s)}^* \ell \nu \right)}_{\text{Experiment}} = \underbrace{[K_1(w, m_\ell)]}_{\text{Known factors}} \underbrace{|\mathcal{A}(w)|^2}_{\text{Theory}} + \underbrace{K_2(w, m_\ell)}_{\text{Known factors}} \underbrace{|\mathcal{A}_2(w)|^2}_{\text{Theory}} \times |V_{cb}|^2$$

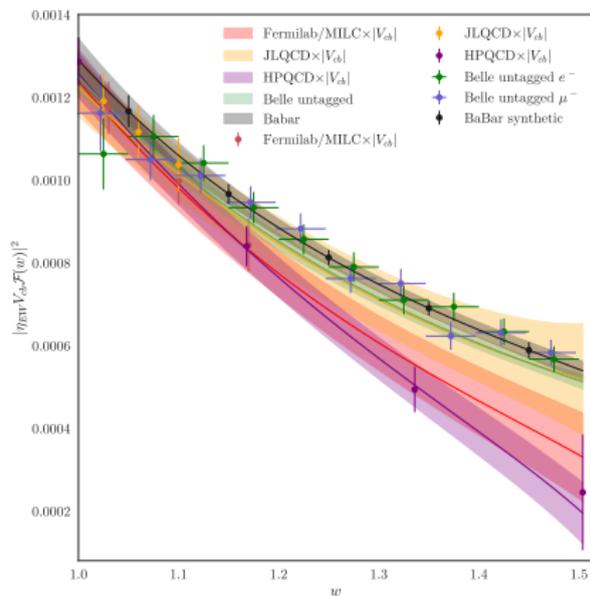
- $K_2(w, 0) = 0$  so  $\mathcal{A}_2$  contributions relevant with  $\ell = \tau$ 
  - It is possible to extract  $R(D_{(s)}^*)$  without experimental data!

$$R(D_{(s)}^*) = \frac{\int_1^{w_{\text{Max}, \ell}} dw [K_1(w, m_\ell) |\mathcal{A}(w)|^2 + K_2(w, m_\ell) |\mathcal{A}_2(w)|^2] \times \cancel{|V_{cb}|^2}}{\int_1^{w_{\text{Max}}} dw [K_1(w, 0) |\mathcal{A}(w)|^2] \times \cancel{|V_{cb}|^2}}$$

- $|V_{cb}|$  cancels out

# The mess

# The mess: Lattice results



- $|V_{cb}|$  agrees in all calculations

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

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

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

- Good combined LQCD fits

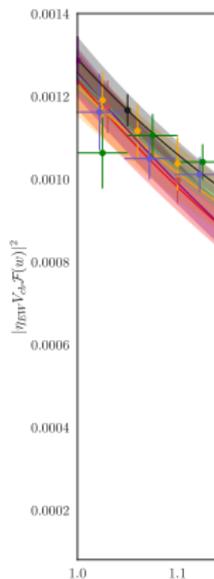
$$\text{BGL 2222 fit} \rightarrow p \sim 0.4 - 0.7$$

**No tension between different LQCD calculations**

- Not so good combined experimental fits

$$\text{BGL 223 BaBar} + \text{Belle fit} \rightarrow p \sim 0.04$$

BaBar: Phys. Rev. Lett. 123, 091801 (2019); Belle: Phys. Rev. D100, 052007 (2019)



Tensions  
between LQCD  
calculations

ns  
 $10^{-3}$   
 $\times 10^{-3}$   
 $\times 10^{-3}$

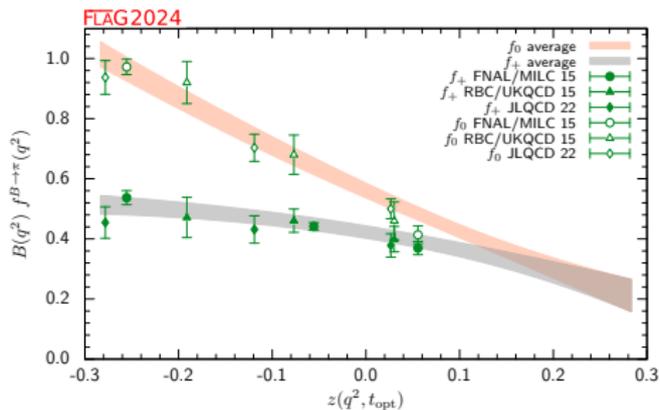
4 – 0.7

Tensions  
between  
different  
experiments

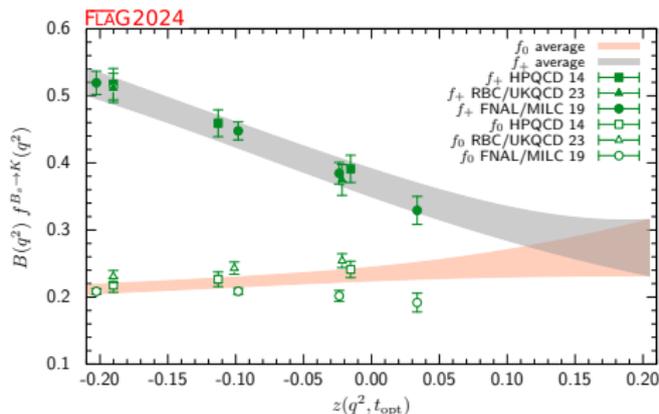
different LQCD  
experimental fits  
 $\rightarrow p \sim 0.04$

D100, 052007 (2019)

# The mess: $B$ to light



$$\chi^2/\text{dof} = 3.63$$



$$\chi^2/\text{dof} = 3.82$$

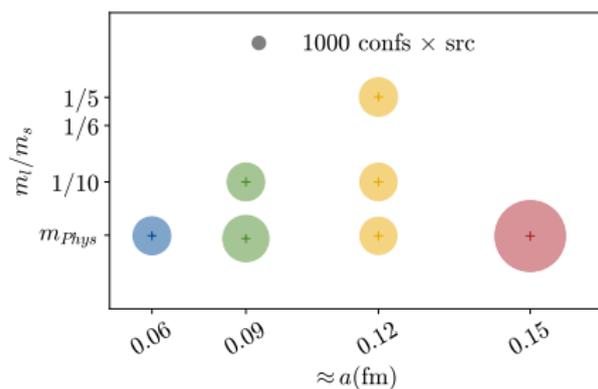
FLAG Review 2024 arXiv:2411.04268

Tensions among different lattice results

# The future

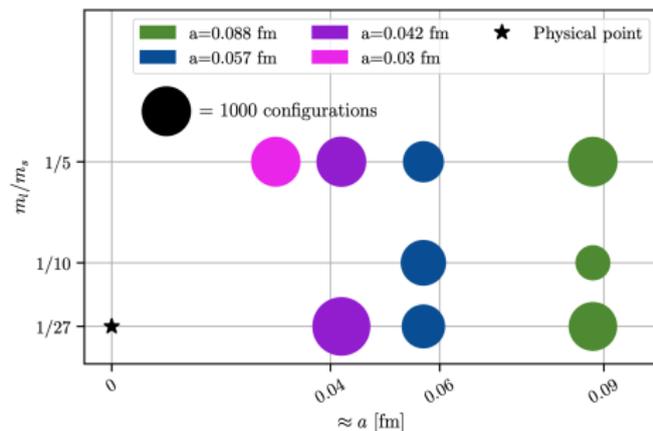
## HISQ+Fermilab

- 7  $N_f = 2 + 1 + 1$  HISQ ensembles
- $c, b$  Fermilab action
- 4 ensembles with physical  $m_\pi$
- Smallest  $a \approx 0.06$  fm
- mNP renormalization (matching)



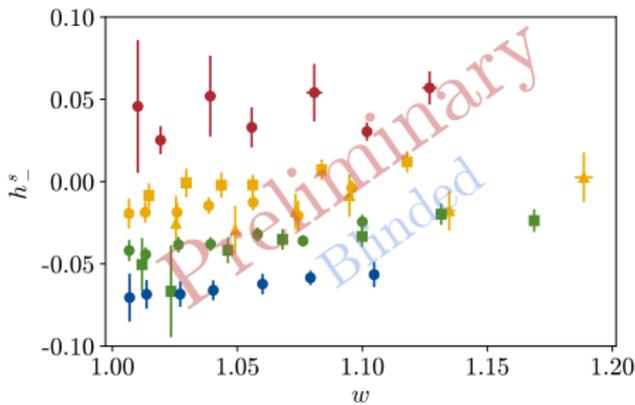
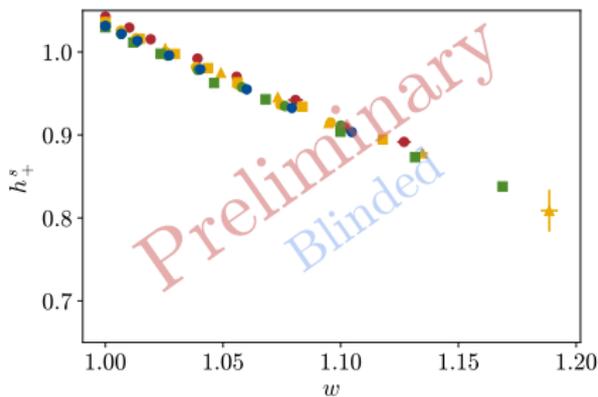
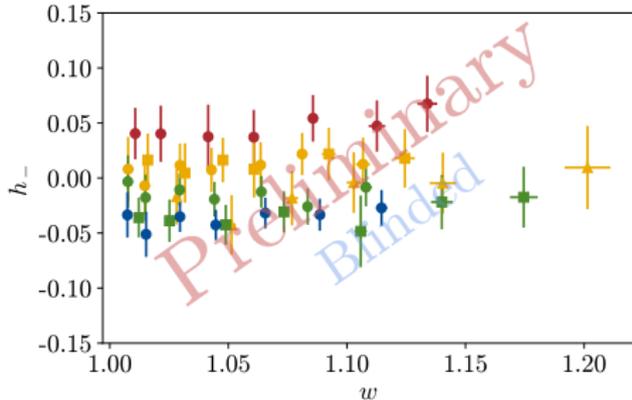
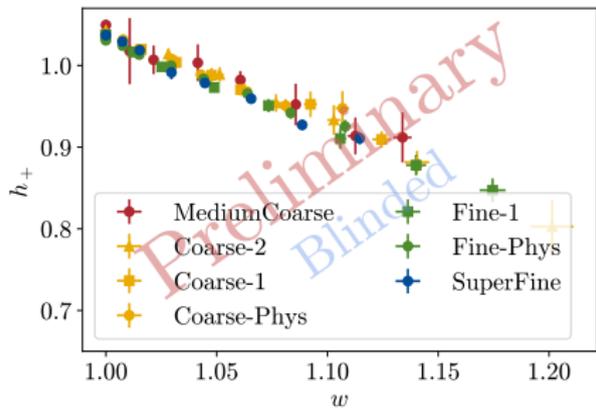
## All HISQ

- 9  $N_f = 2 + 1 + 1$  HISQ ensembles
- HISQ heavy quarks
- 3 ensembles with physical  $m_\pi$
- Smallest  $a \approx 0.03$  fm
- Full NP renormalization



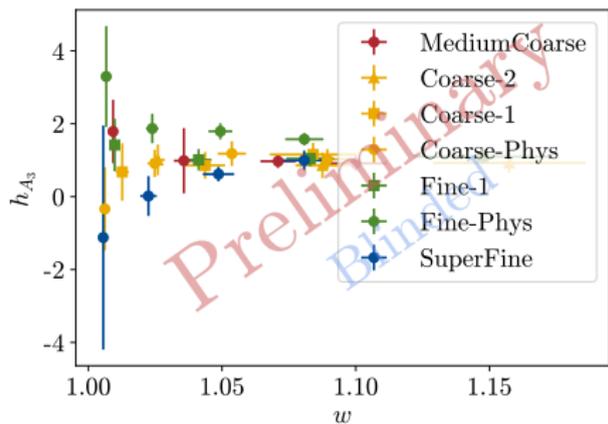
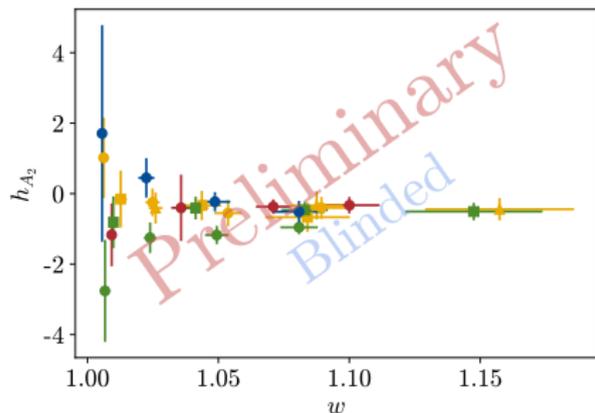
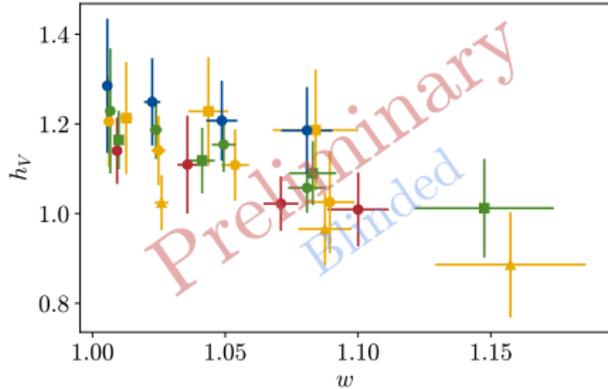
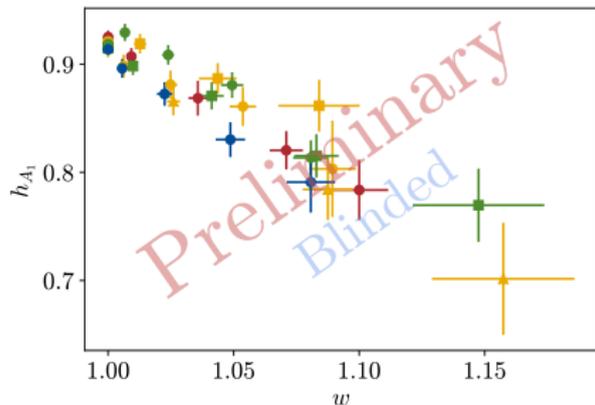
# Status HISQ+Fermilab

# Status $B_{(s)} \rightarrow D_{(s)}\ell\nu$

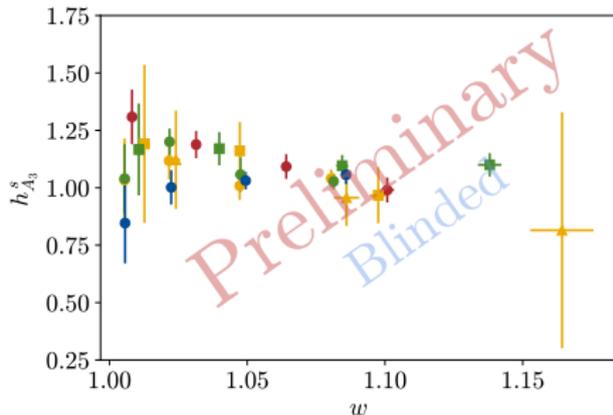
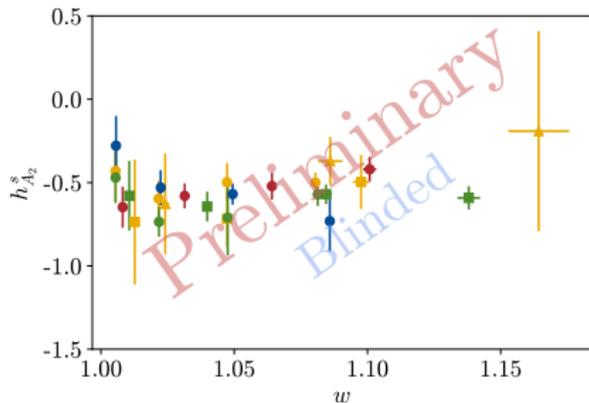
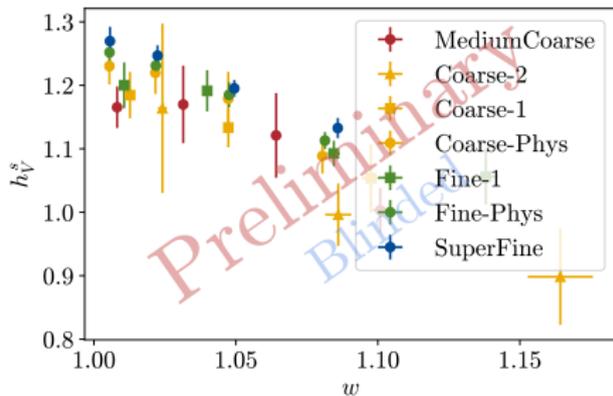
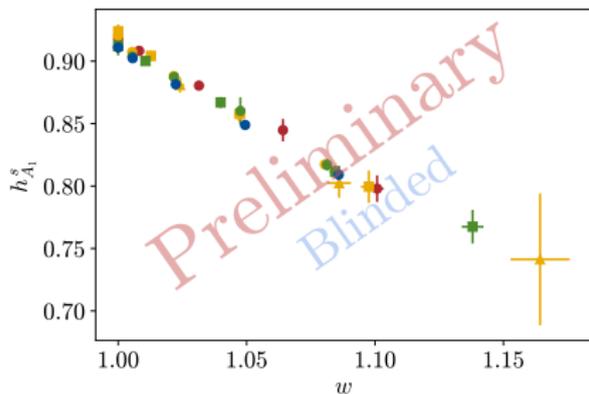


Preliminary and blinded, no systematic

# Status $B \rightarrow D^* \ell \nu$ HISQ+Fermilab

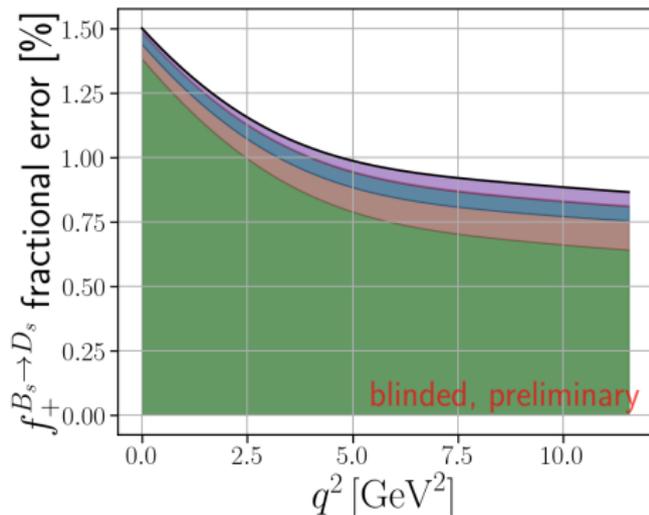
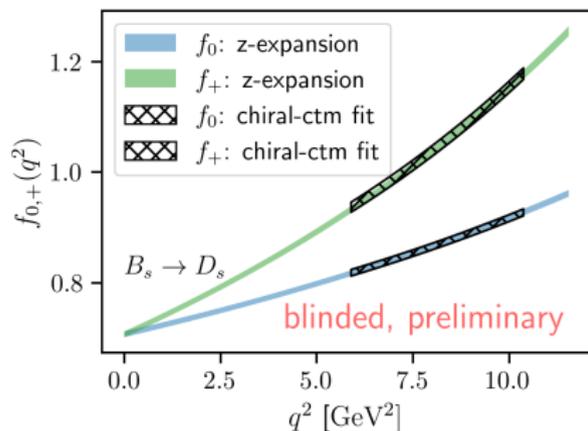


# Status $B_s \rightarrow D_s^* \ell \nu$ HISQ+Fermilab



# Status all HISQ

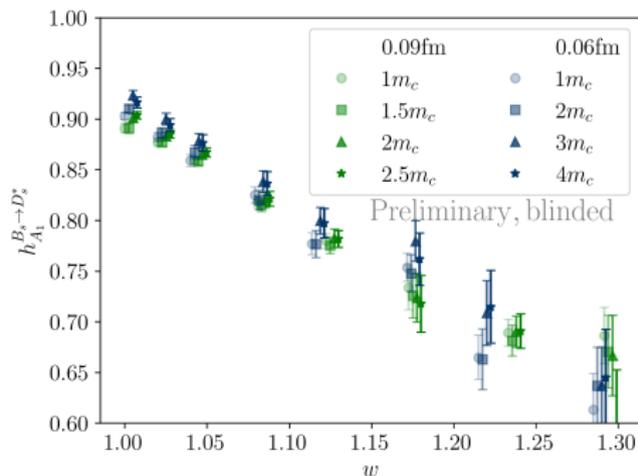
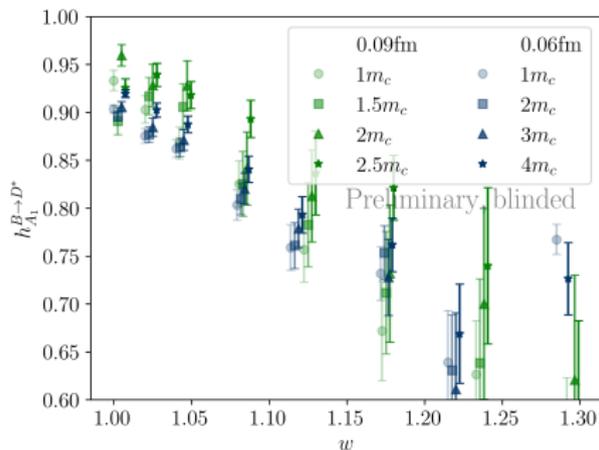
# Status $B_s \rightarrow D_s \ell \nu$ all HISQ



- $B \rightarrow D \ell \nu$  also in advanced state

**Blinded, preliminary results**

# Status $B_{(s)} \rightarrow D_{(s)}^* \ell \nu$ all HISQ



- Still generating data, work in progress

**Blinded, very preliminary results**

- Current situation: must improve LQCD results
  - **Heavy to heavy** Good agreement between LQCD calculations, large errors
  - **Heavy to light** No good agreement between LQCD calculations

**Must reduce errors and converge on a single result**

- **Urgent:** Experimentalist are improving their datasets (Belle 2, LHCb)
  - One of the largest errors in  $|V_{cb}|$  comes from LQCD
- **Our roadmap can improve existing lattice results**
  - Expect a sizable reduction in the errors with this new analysis
    - Similar statistical errors, better systematics
  - Also ongoing  $B_{(s)} \rightarrow D_{(s)}^* \ell \nu$  with all HISQ
    - Physical bottom mass reachable with the finest ensembles
    - Common ensembles between analyses to better address HQ systematics

# Thank you for your attention

## Backup Slides

# 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  $am_Q = \pi/2$  (typical action  $am_Q \lesssim 0.6$ )

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

