Lattice determinations of $B_{(s)} \to D^*_{(s)} \ell\nu$ form factors

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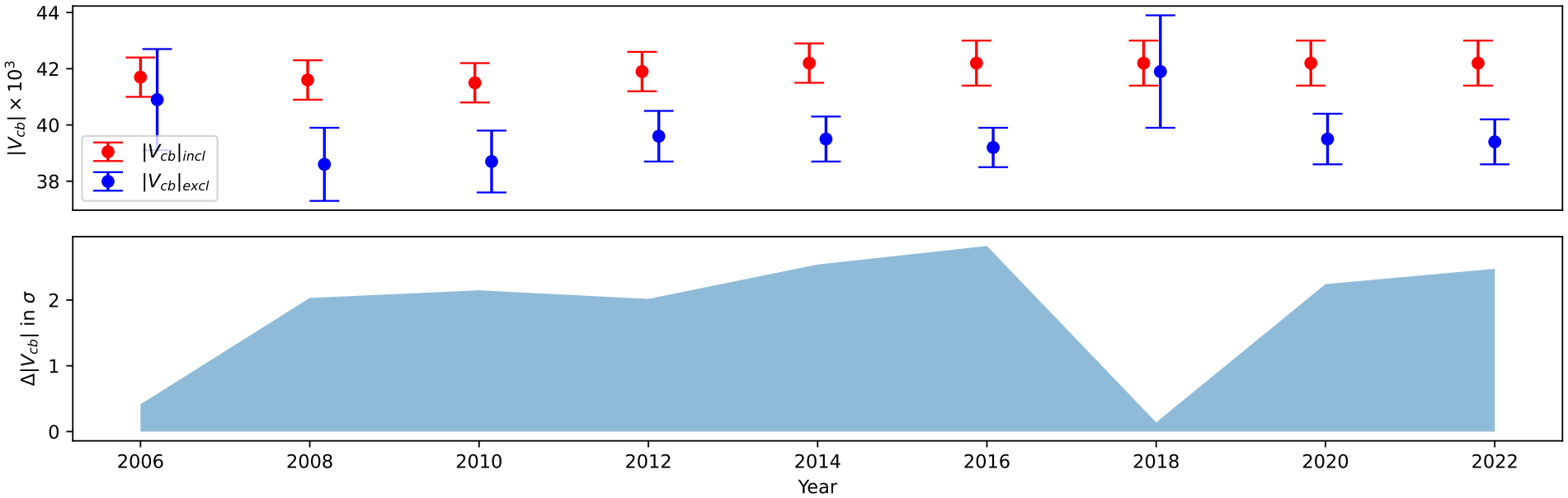
AGENCIA ESTATAL DE INVESTIGACIÓN

Motivation: New physics in the flavor sector of the SM

The CKM matrix

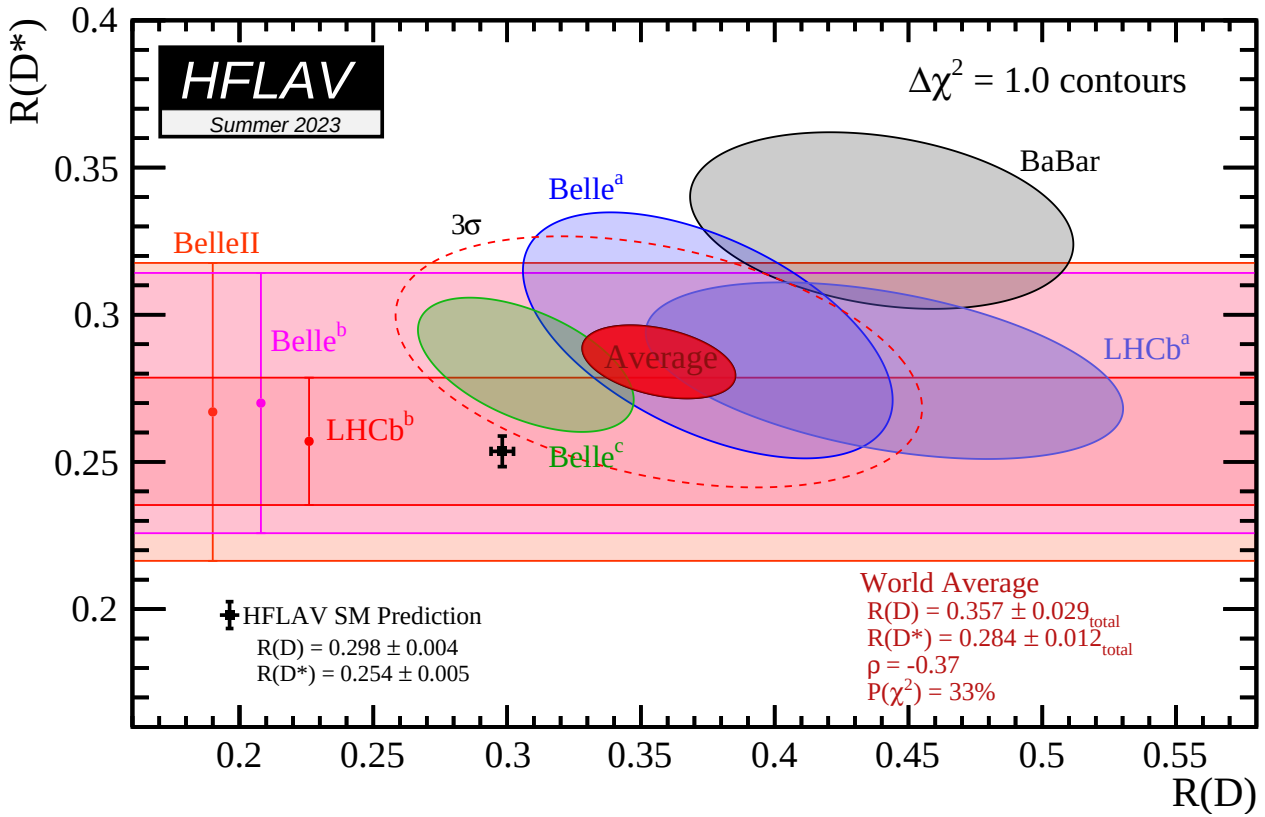
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & \boldsymbol{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Matrix must be unitary (preserve the norm)
- Tensions have been there for a long time
- Evolution of the tensions according to PDG



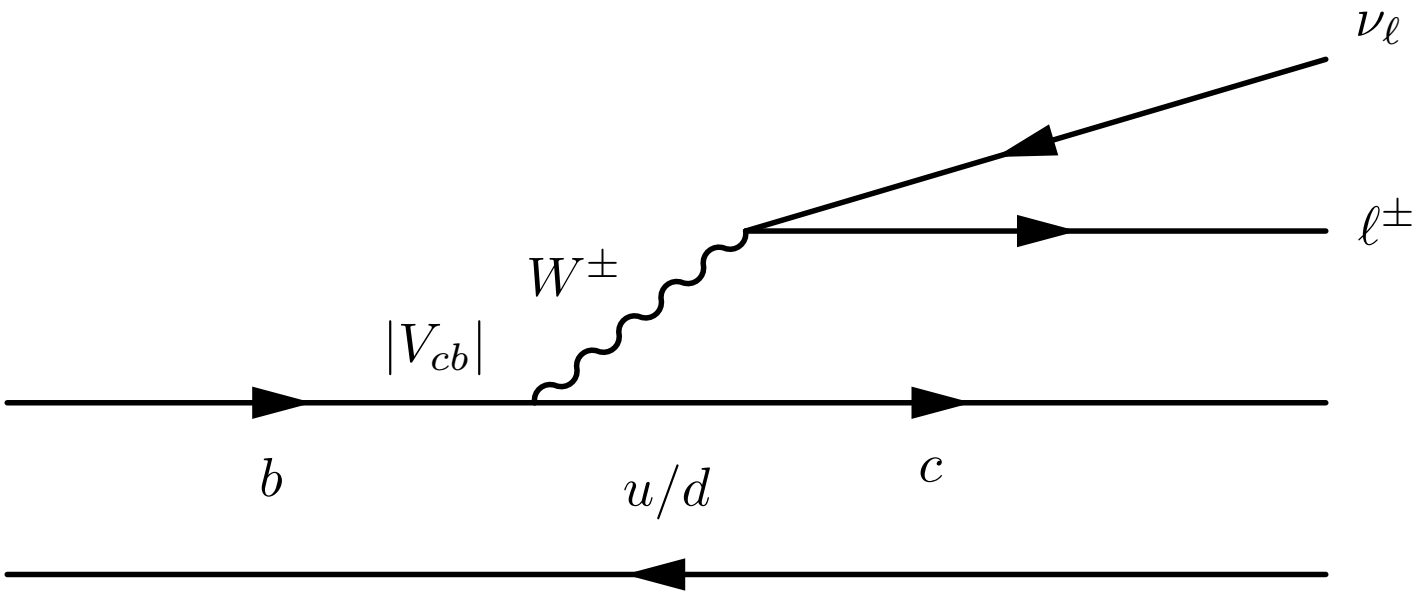
Motivation: Tensions in lepton universality ratios

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



- Current $\approx 3.3\sigma$ tension with the SM (HFLAV)

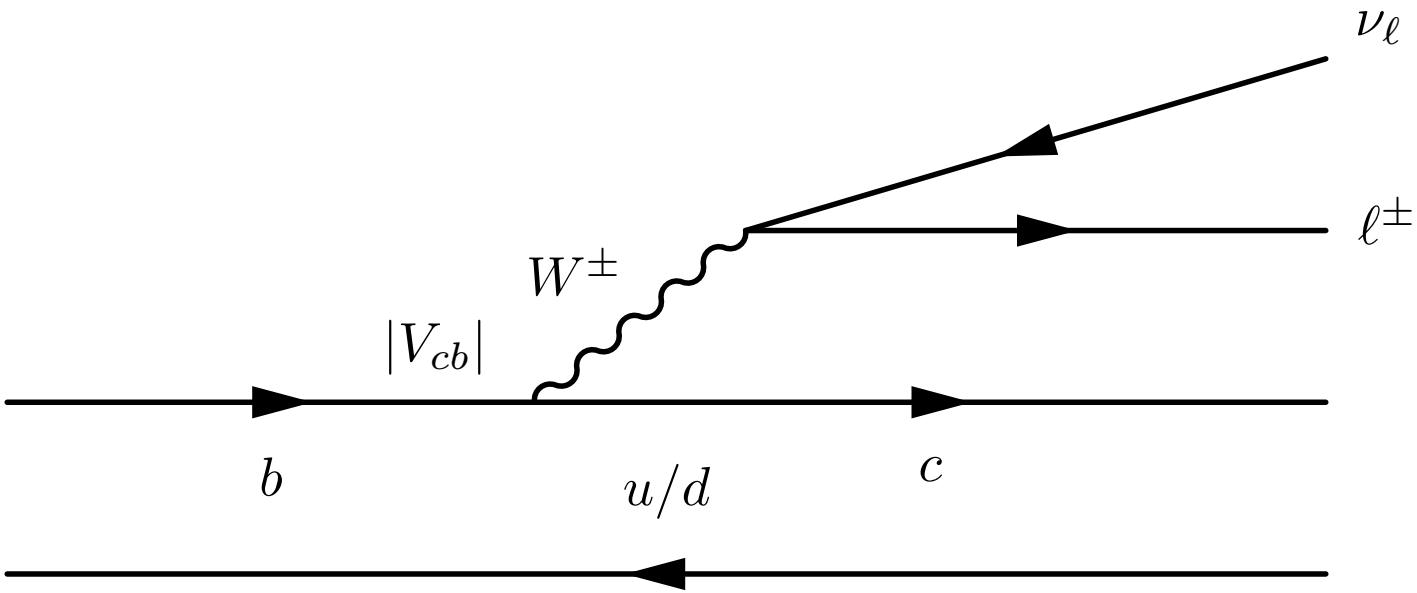
Semileptonic $B_{(s)}$ decays on the lattice: Exclusive $|V_{cb}|$



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

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

Semileptonic $B_{(s)}$ decays on the lattice: Universality ratios



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

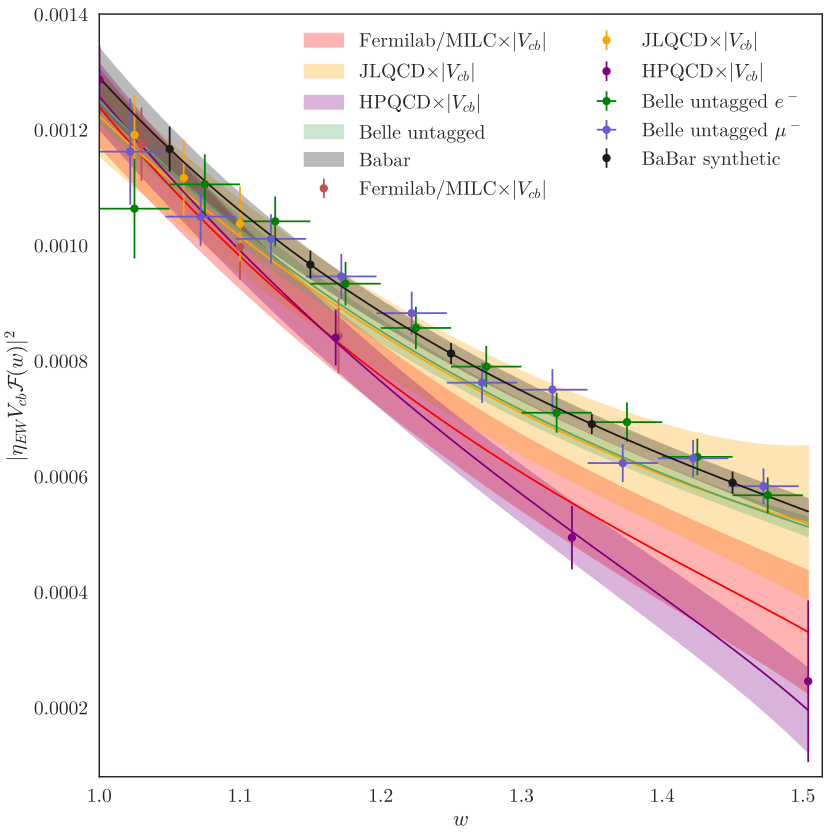
- The universality ratio depends only on the form factors
- It is possible to extract $R(D^*)$ without experimental data!

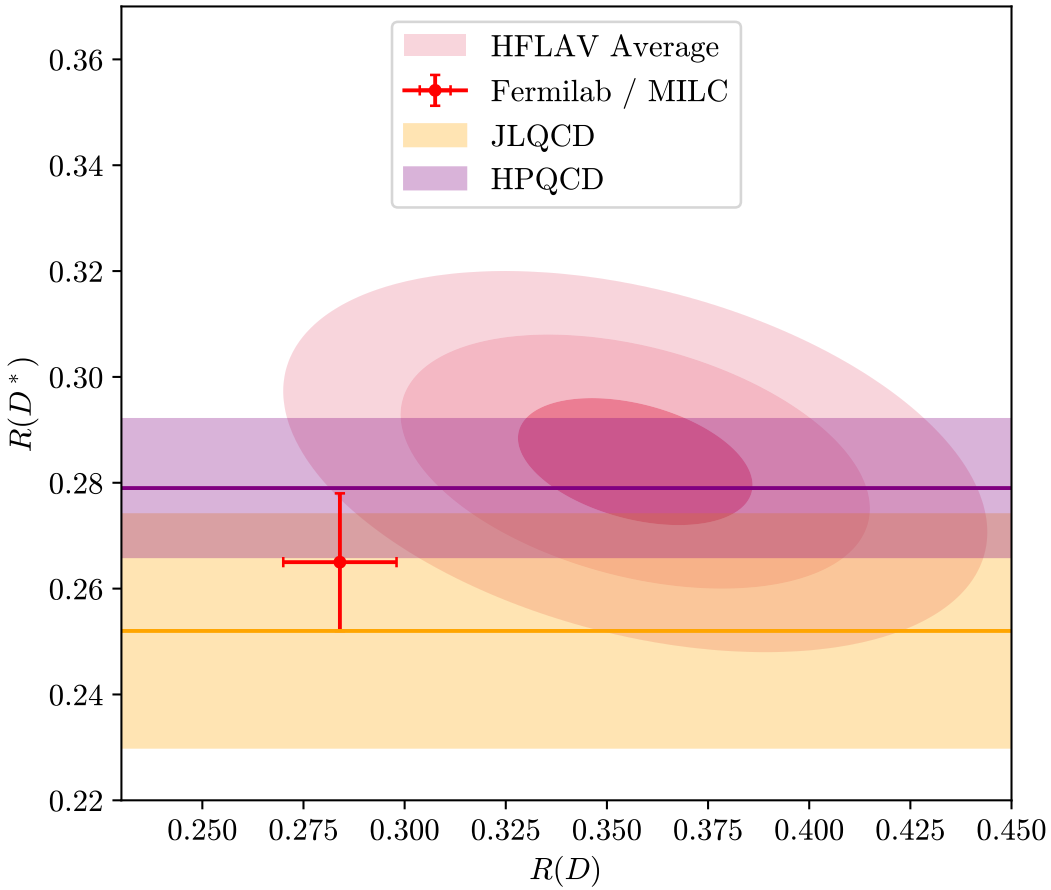
Semileptonic $B_{(s)}$ decays on the lattice: Heavy quarks

- Heavy quark treatment in Lattice QCD
  - For light quarks ($m_l \lesssim \Lambda_{QCD}$), leading discretization errors $\sim \alpha_s^k (a\Lambda_{QCD})^n$
  - For heavy quarks ($m_Q > \Lambda_{QCD}$), discretization errors grow as $\sim \alpha_s^k (am_Q)^n$
- Need special actions to describe the bottom quark, difficult renormalization
  - Relativistic HQ actions (f.i. FermiLab)
  - Non-Relativistic QCD (NRQCD)
- If the action is improved enough, one can treat the bottom as a light quark
  - Highly improved action AND small lattice spacing
  - Use unphysical values for m_b and extrapolate

The discretization errors needn't disappear **as long as we keep them under control**

Semileptonic $B_{(s)}$ decays on the lattice: HPQCD





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

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

$$|V_{cb}|^{\mathrm{FerMILC}} = 38.17(85) \times 10^{-3}$$

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

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

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

- Fit to Belle untagged dataset WITH the Coulomb factor

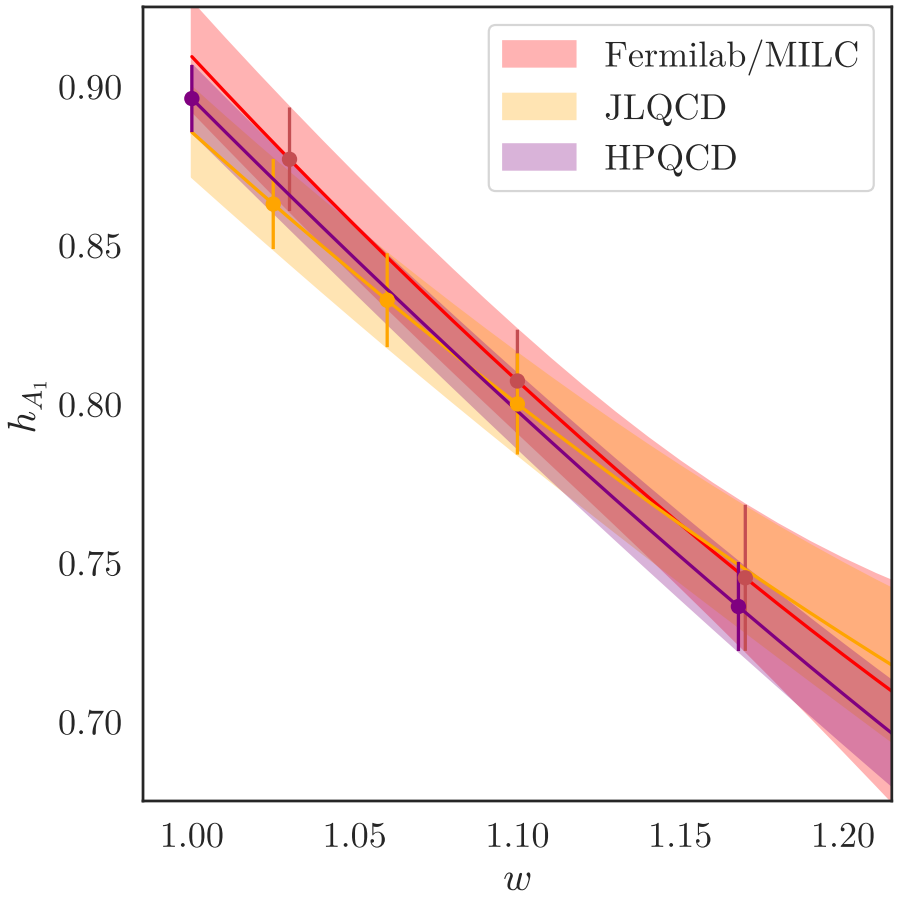
Semileptonic $B_{(s)}$ decays on the lattice: Combined fits

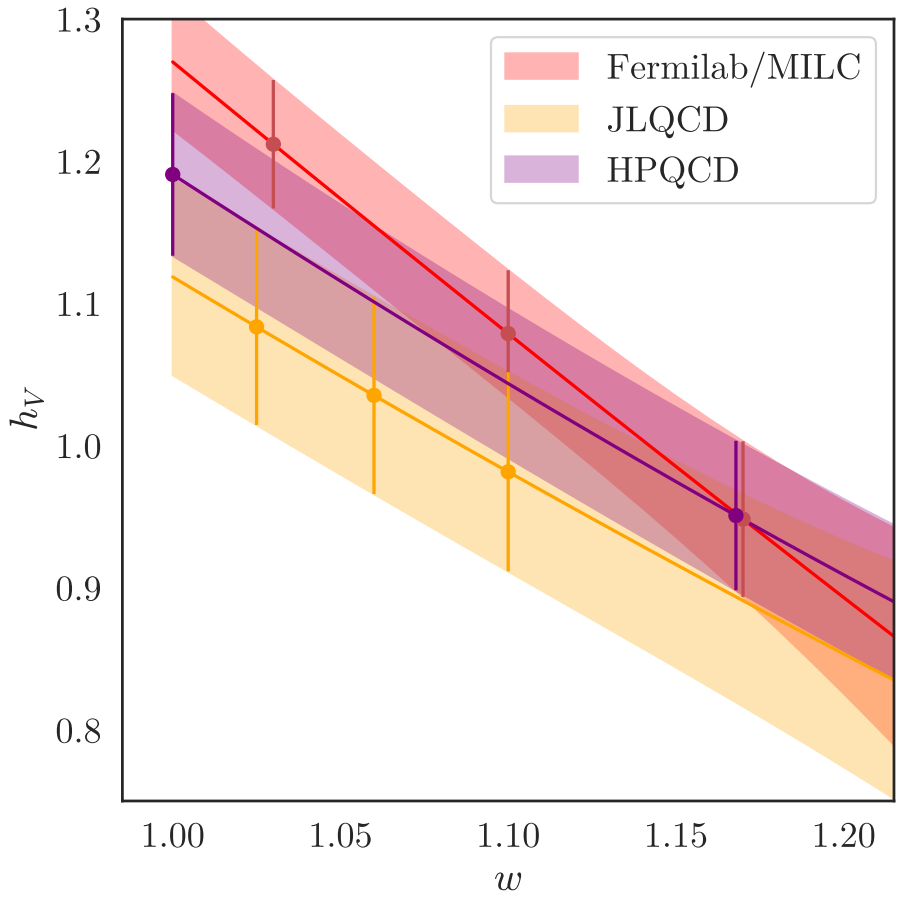
- Combined fits with priors 0(1)
- Kinematic constraint imposed with priors
- BGL fit 2222

	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 2232 is ≈ 0.04
- Combined $R(D^*) = 0.2667(57)$

Semileptonic $B_{(s)}$ decays on the lattice: Comparison of HQET form factors





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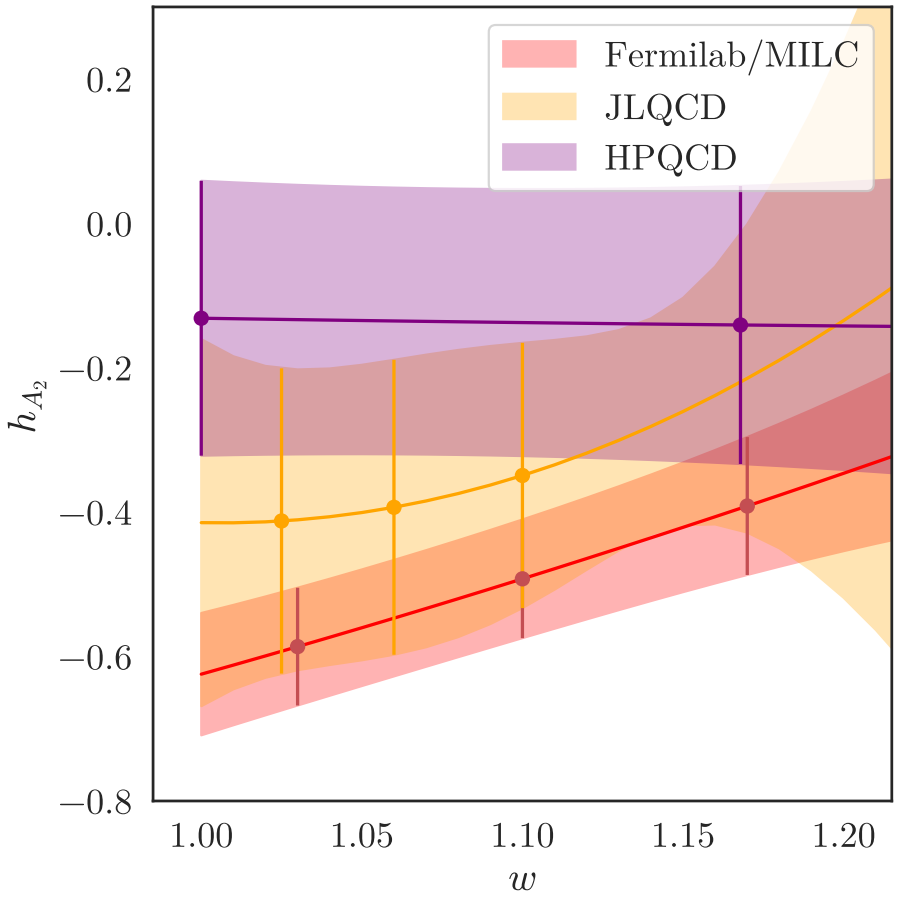
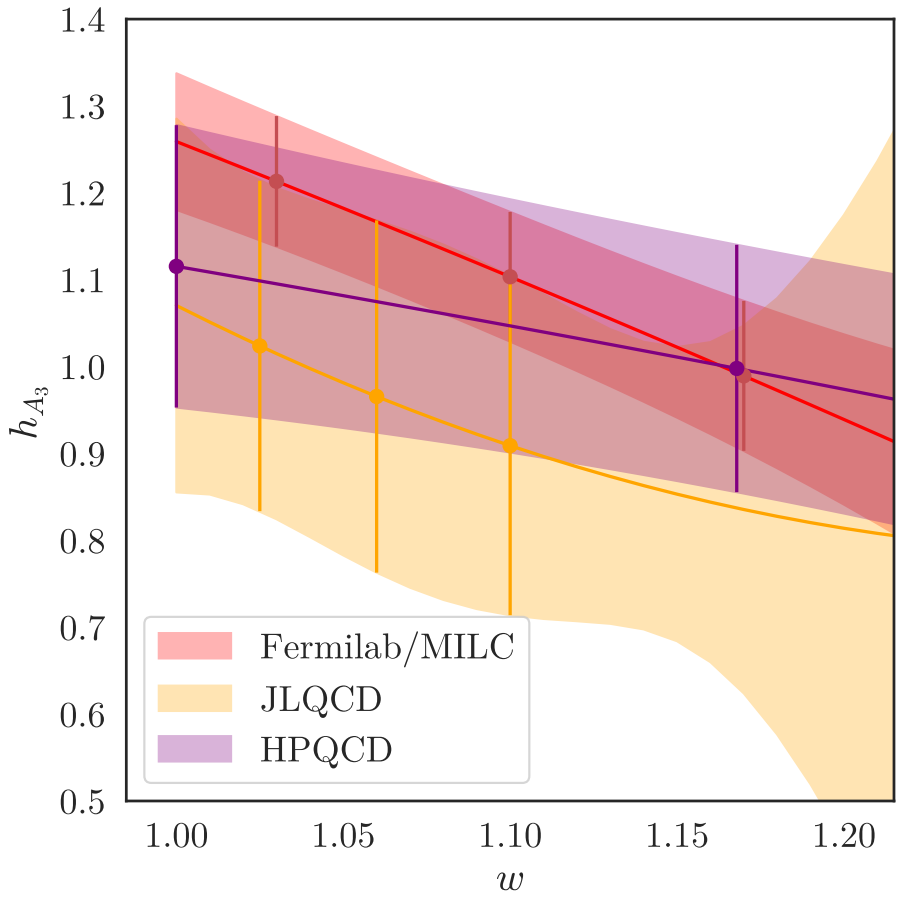
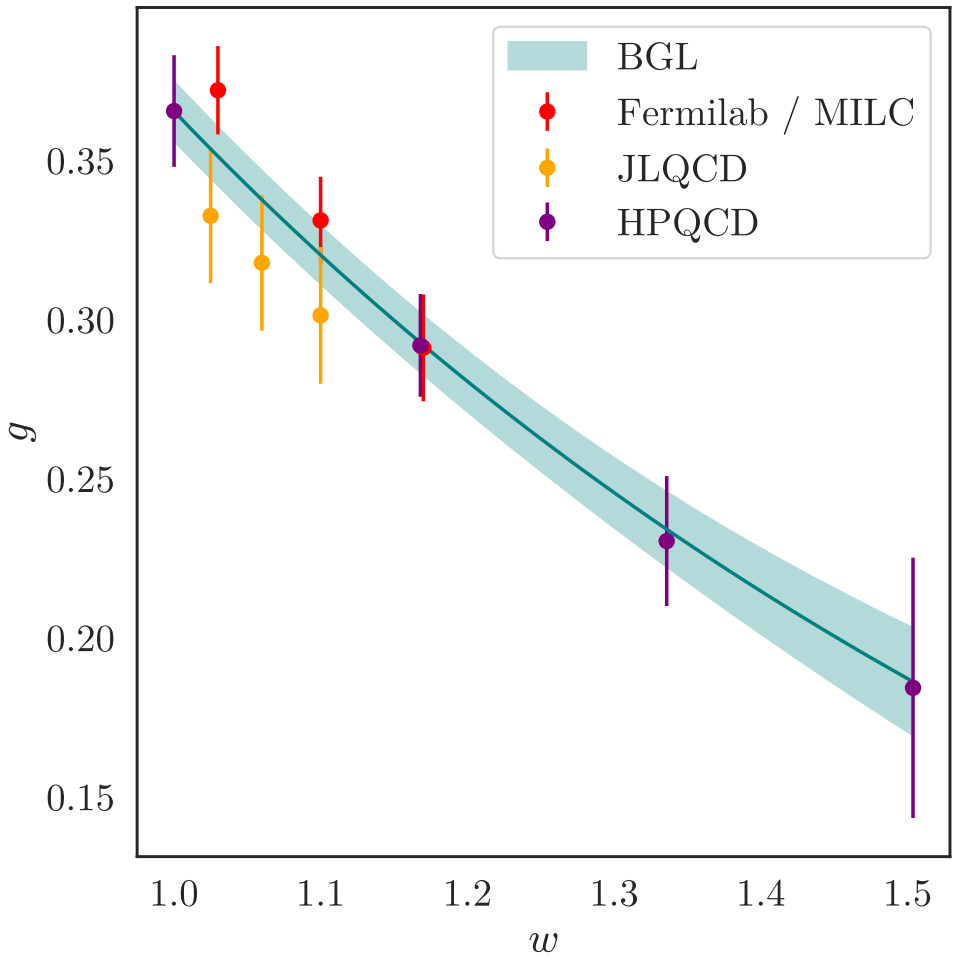
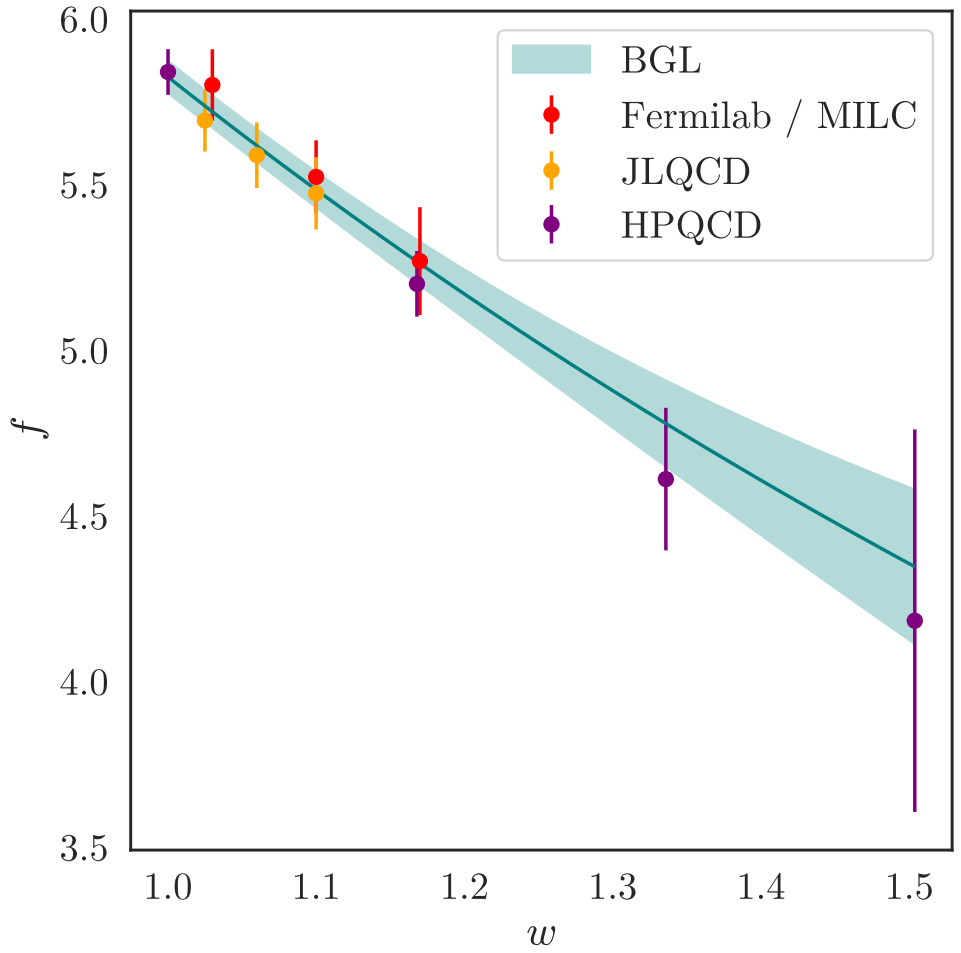




Semileptonic $B_{(s)}$ decays on the lattice: Combined fits





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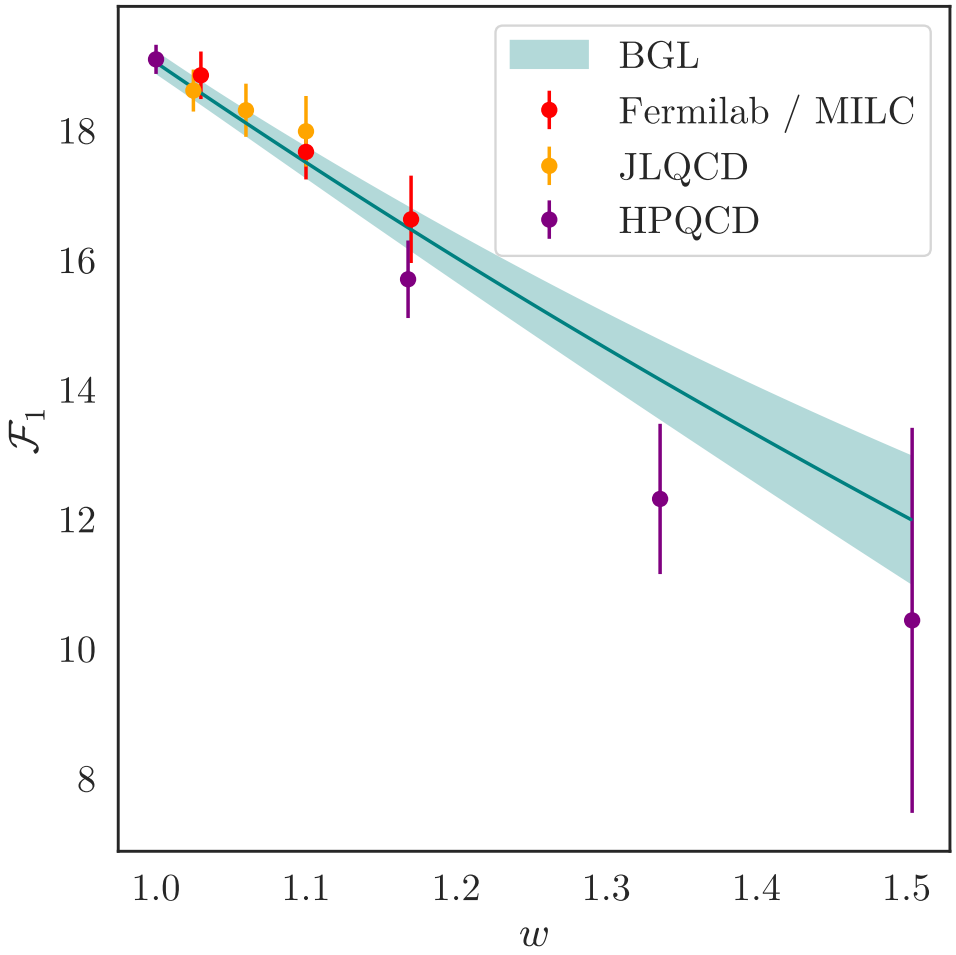
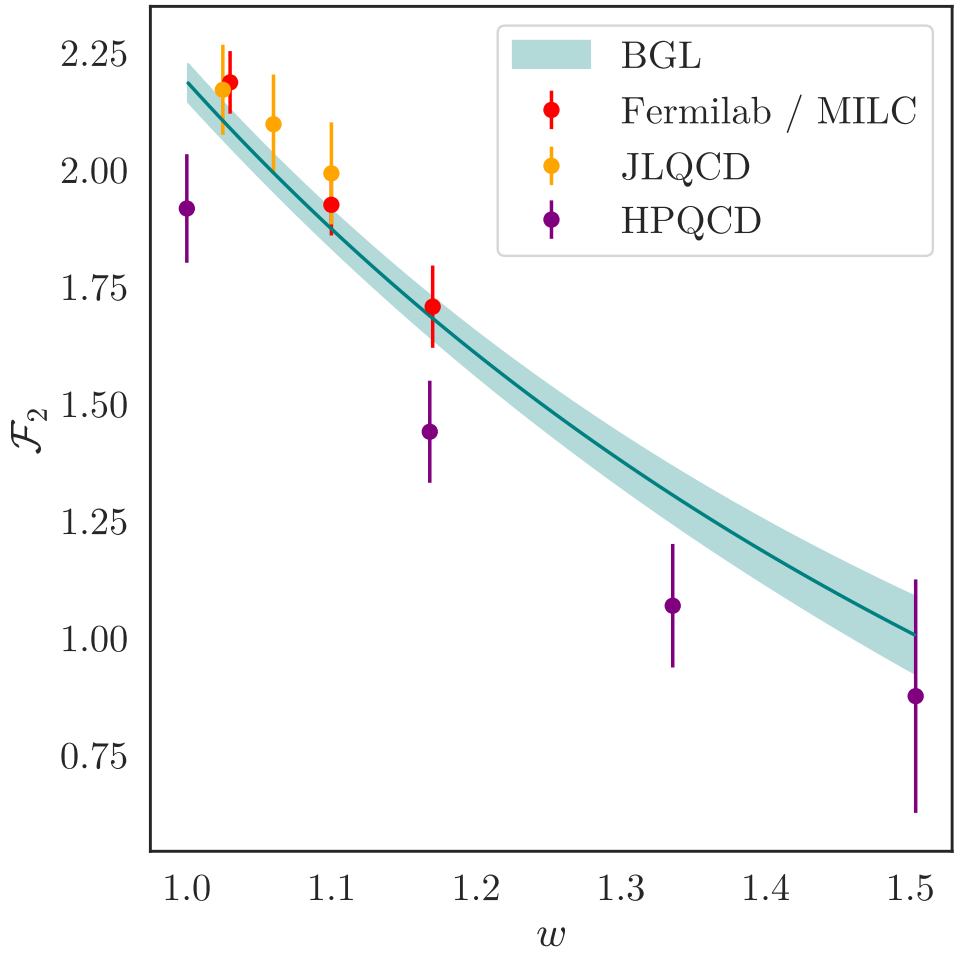
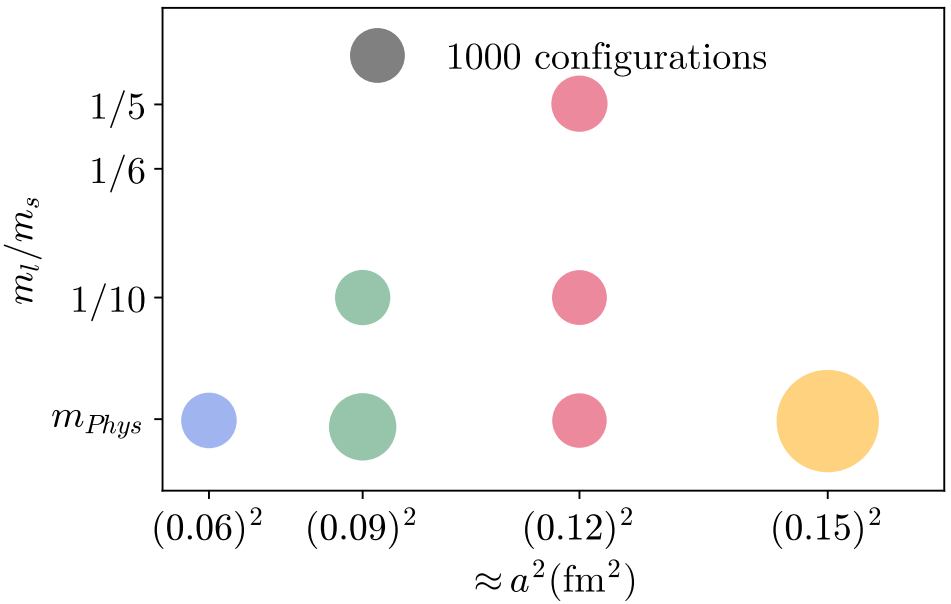




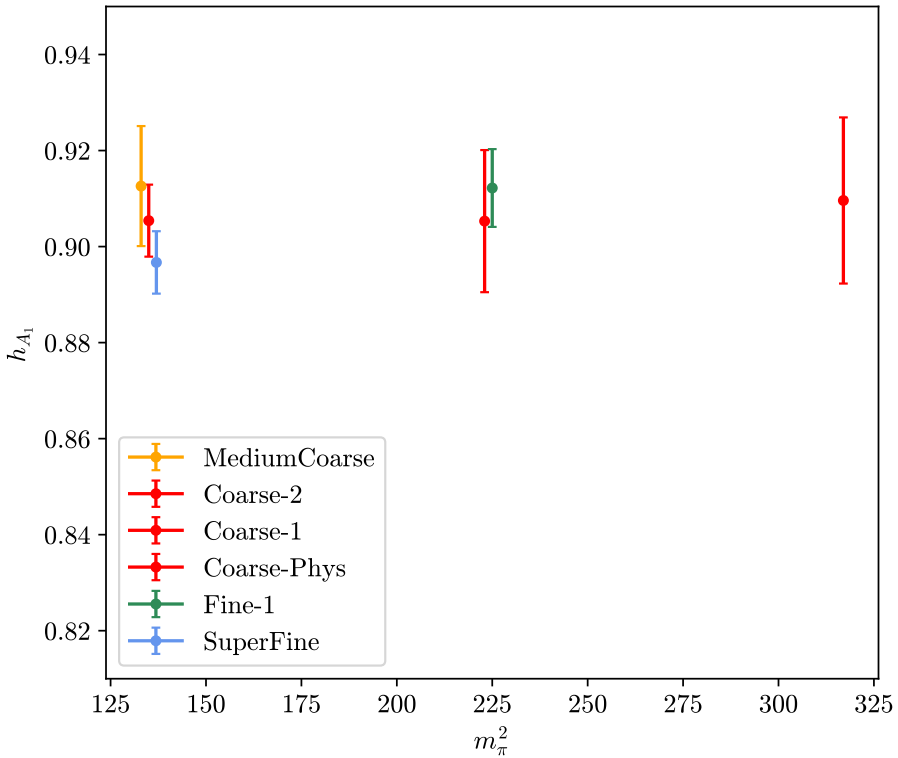
Semileptonic $B_{(s)}$ decays on the lattice: New Fermilab / MILC analysis

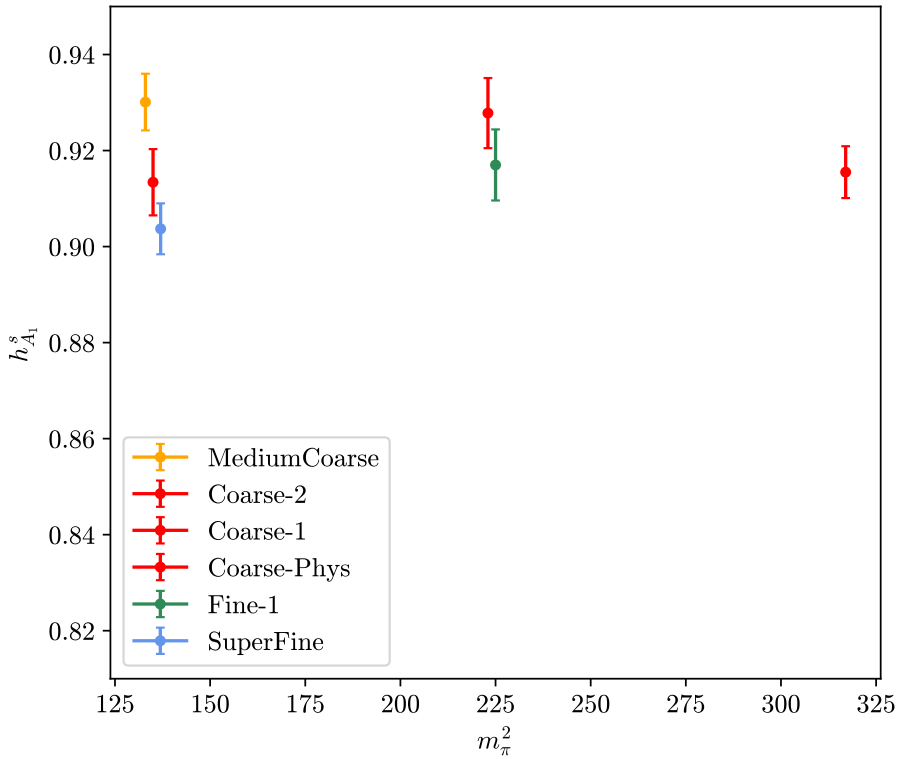
- Using 7 $N_f = 2 + 1 + 1$ MILC ensembles of sea HISQ quarks
- The heavy quarks are treated using the Fermilab action
- Half the ensembles feature a physical pion mass
- Analysis of $B_{(s)} \to D^*_{(s)} \ell\nu$ channels, and $B \to \pi/K$



Semileptonic $B_{(s)}$ decays on the lattice: New Fermilab / MILC analysis

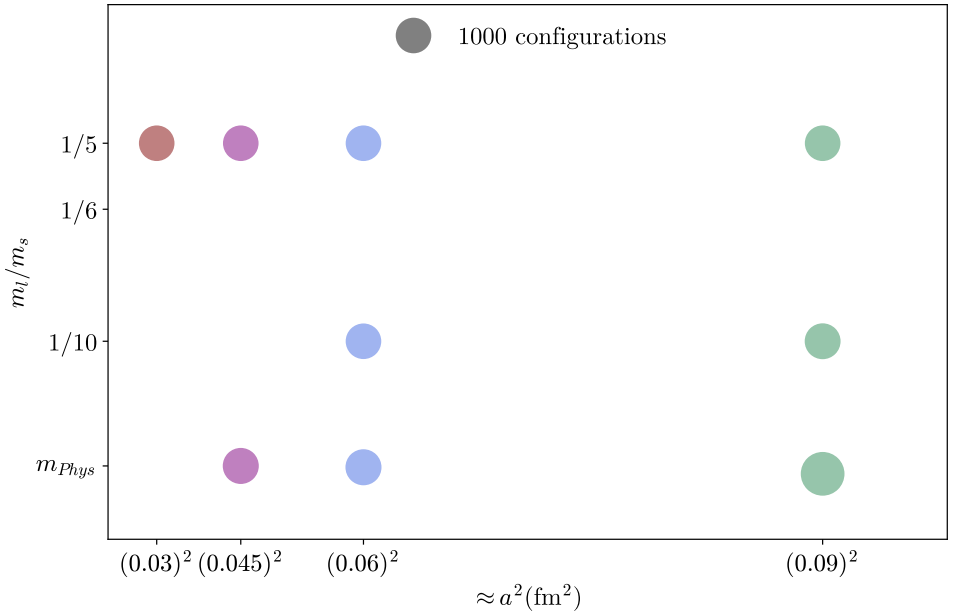
- Current status: Analyzing ratio fits to extract form factors





Semileptonic $B_{(s)}$ decays on the lattice: New Fermilab / MILC analysis

- Using 9 $N_f = 2 + 1 + 1$ MILC ensembles of sea HISQ quarks
- The heavy quarks are treated using the HISQ action at unphysical m_b
- Many ensembles at physical pion masses
- **Extremely fine ensembles** $a \approx 0.042$ fm, 0.03 fm
- Combined analysis $\rightarrow$ information on heavy quark discretization errors



Summary

- Major progress in LQCD calculations of $B_{(s)} \to D^*_{(s)}\ell\nu$ form factors
  - In a three year span we got three new calculations
  - Although the three calculations show some differences, they combine nicely in a joint fit

Use the data

- Current results are not conclusive:
  - $|V_{cb}|$ agrees with previous determinations and the inclusive-exclusive tension remains unsolved
  - Results in $R(D^*)$ are not precise enough
- The LQCD community is determined to improve these results and find better agreements among different collaborations' results
  - The Fermilab / MILC collaboration is preparing **two** new calculations of the $B_{(s)} \to D^*_{(s)}\ell\nu$ form factors
    - Emphasis in heavy quark discretization errors
    - Possibility of correlating these analyses with $B \to D_{(s)}\ell\nu$ analyses, for a correlated $R(D)$ vs $R(D^*)$ plot
    - Possibility of correlating these analyses with $B \to \pi/K$ for a V_{ub} vs V_{cb} correlated plot
- Expect interesting results from these channels in the following years

THANK YOU