Lattice determinations of $B \to D^* \ell \nu$ form factors

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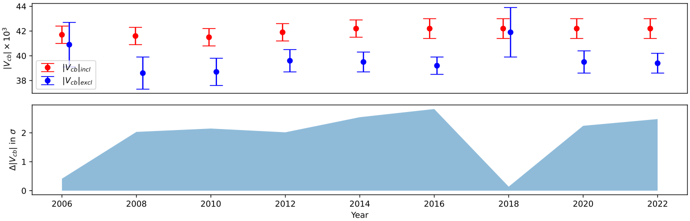
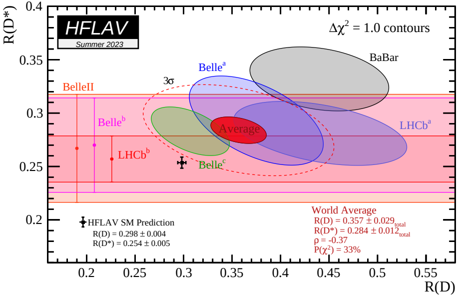
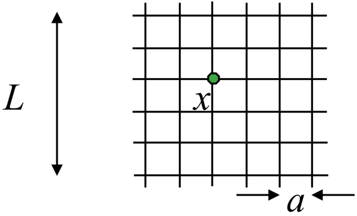
Motivation: $|V_{cb}|$ and $R(D^*)$





Semileptonic B decays on the lattice: Introduction to Lattice QCD

$$\mathcal{L}_{QCD} = \sum_f \bar{\psi}_f \left(\gamma^\mu D_\mu + m_f\right) \psi_f + \frac{1}{4}\mathrm{tr} F_{\mu\nu} F^{\mu\nu}$$



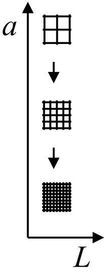
- Discretize space-time in a computer
  - Finite lattice spacing a
  - Finite spatial volume L
  - Finite time extent T

- Perform simulations in an unphysical setup and approach the physical limit
  - Enlarge the volume and reduce a
  - Quark masses $\Longrightarrow$ Pion masses (hadrons are matched)
  - Number of sea quarks $n_f = 2+1, \quad 2+1+1, \quad 1+1+1+1\ldots$

Semileptonic B decays on the lattice: Introduction to Lattice QCD

The systematic error analysis is based on **EFT** descriptions of QCD
The EFT description:

- provides functional form for different extrapolations (or interpolations)
- can be used to construct improved actions
- can estimate the size of the systematic errors



In order to keep the systematic errors under control we must repeat the calculation for several lattice spacings, volumes, light quark masses... and use the EFT to extrapolate to the physical theory

Semileptonic B 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 decays on the lattice: Formalism

- Form factors

$$\frac{\langle D^*(p_{D^*},\epsilon^\nu)|\,\mathcal{V}^\mu\,\left|\bar{B}(p_B)\right\rangle}{2\sqrt{m_B\,m_{D^*}}} = \frac{1}{2}\epsilon^{\nu*}\varepsilon^{\mu\nu}_{\ \ \rho\sigma}v_B^\rho v_{D^*}^\sigma \boldsymbol{h_V}(w)$$

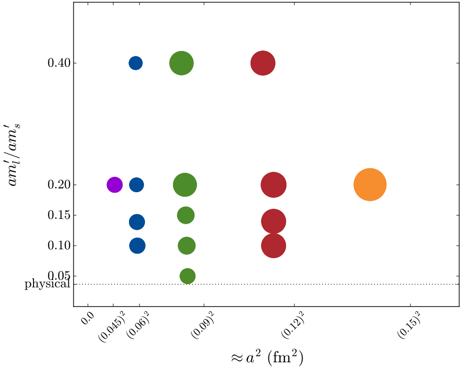
$$\frac{\langle D^*(p_{D^*},\epsilon^\nu)|\,\mathcal{A}^\mu\,\left|\bar{B}(p_B)\right\rangle}{2\sqrt{m_B\,m_{D^*}}} =$$

$$\frac{i}{2}\epsilon^{\nu*}\left[g^{\mu\nu}\left(1+w\right)\boldsymbol{h_{A_1}}(w) - v_B^\nu\left(v_B^\mu \boldsymbol{h_{A_2}}(w) + v_{D^*}^\mu \boldsymbol{h_{A_3}}(w)\right)\right]$$

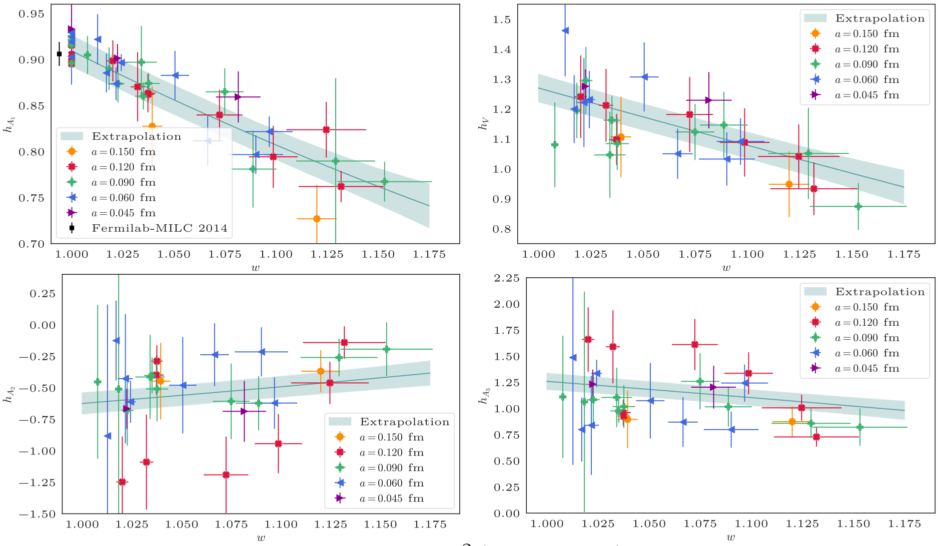
- $\mathcal{V}$ and $\mathcal{A}$ are the vector/axial currents in the continuum
- The h_X enter in the definition of the decay amplitudes
- We can calculate h_X directly from the lattice

Semileptonic B decays on the lattice: Fermilab/MILC

- Using 15 $N_f = 2 + 1$ MILC ensembles of sea asqtad quarks
- The heavy quarks are treated using the Fermilab action
- Lightest $m_\pi \approx 180$ MeV

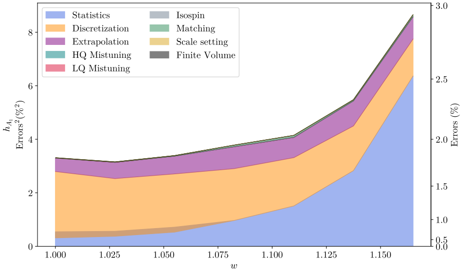


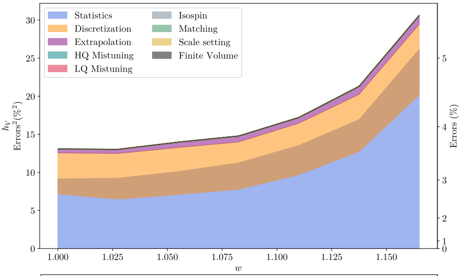
Semileptonic B decays on the lattice: Fermilab/MILC

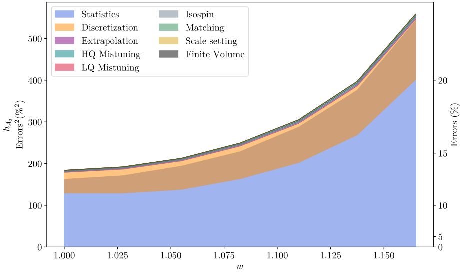


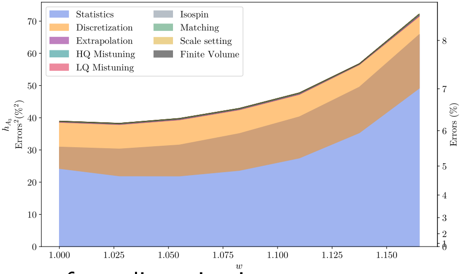
Combined fit $\chi^2/\mathrm{dof} = 85.2/95$

Semileptonic B decays on the lattice: Fermilab/MILC





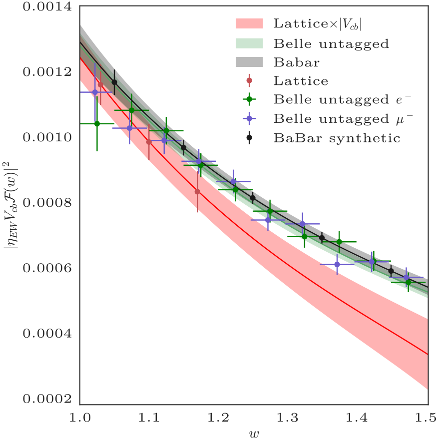




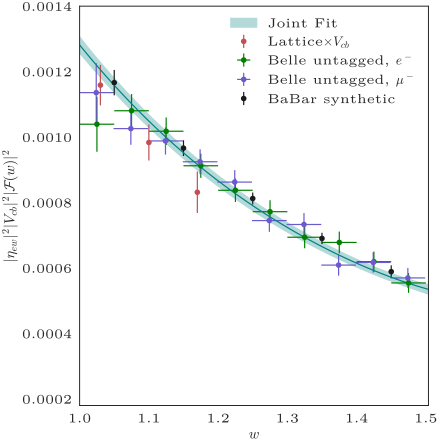
Largest systematic errors come from discretization

Semileptonic B decays on the lattice: Fermilab/MILC

Separate fits



Joint fit



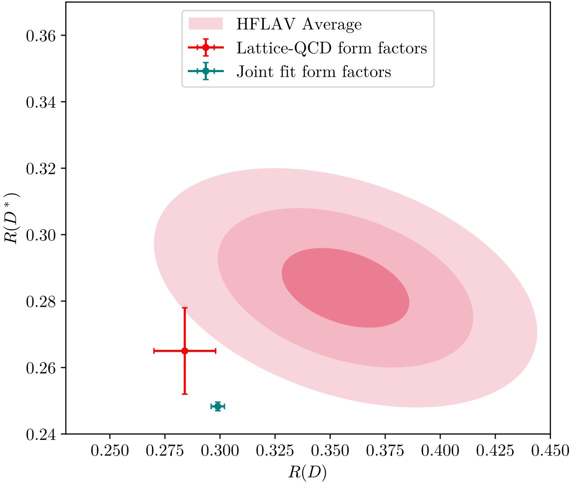
Fit	Lattice	Exp	Lat + Belle	Lat + BaBar	Lat + Exp
χ^2/dof	$0.63/1$	$104/76$	$111/79$	$8.50/4$	$126/84$

Unblinded, final result $|V_{cb}| = 38.40(78) \times 10^{-3}$

Semileptonic B decays on the lattice: Fermilab/MILC

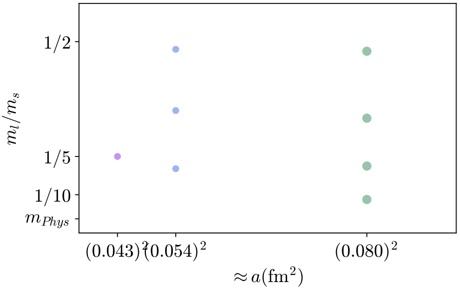
$$R(D^*)_{\mathbf{Lat}} = 0.265(13) \quad R(D^*)_{\mathbf{Lat+Exp}} = 0.2483(13)$$

Phys.Rev.D**92** (2015), 034506; Phys.Rev.D**100** (2019), 052007; Phys.Rev.D**103** (2021), 079901; Phys.Rev.Lett. **123** (2019), 091801

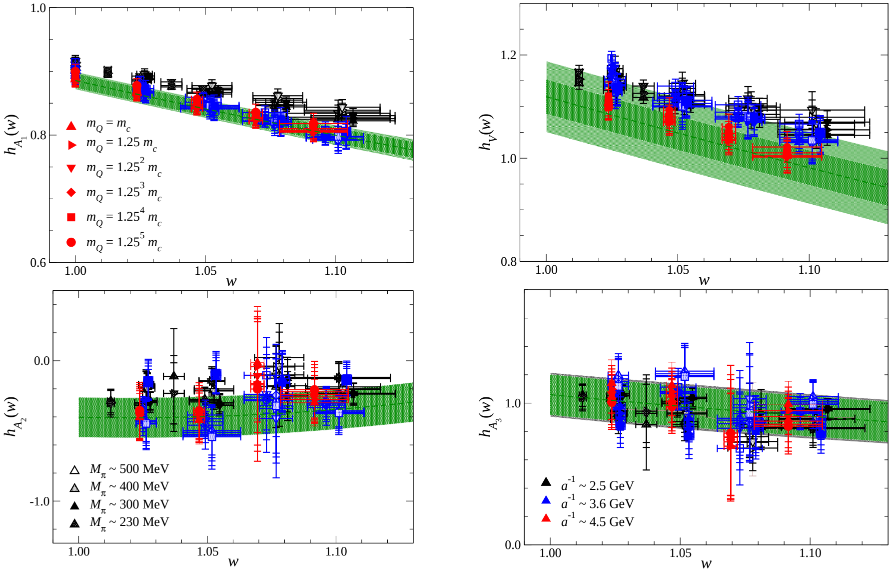


Semileptonic B decays on the lattice: JLQCD

- Using 8 $N_f = 2 + 1$ ensembles of sea DW quarks
- The heavy quarks use the same DW action
  - Simulations at unphysical b masses $m_b \lesssim 0.7a$
  - Requires extrapolation
  - Easier and more precise renormalization
- m_π in the range $230 - 500$ MeV
  - Stable D^*

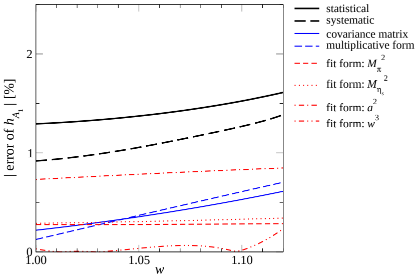


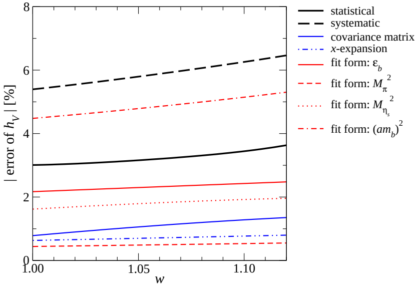
Semileptonic B decays on the lattice: JLQCD

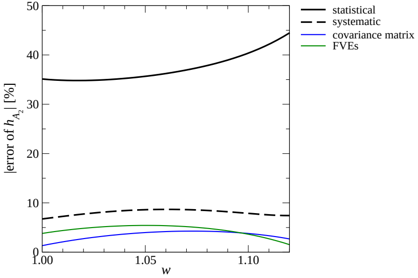


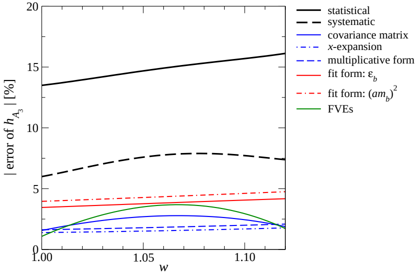
Several fits with $\chi^2/\mathrm{dof} \lesssim 0.2$

Semileptonic B decays on the lattice: JLQCD



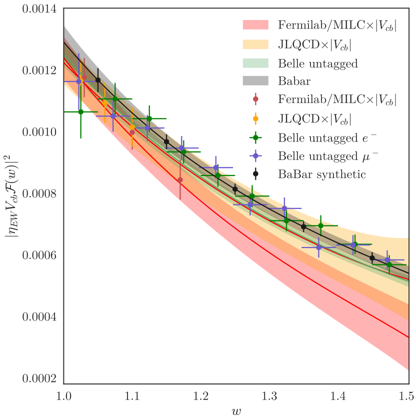


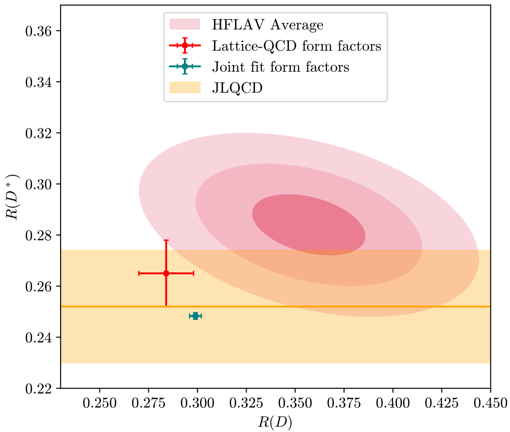




Discretization errors dominate the systematic contributions

Semileptonic B decays on the lattice: JLQCD





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

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

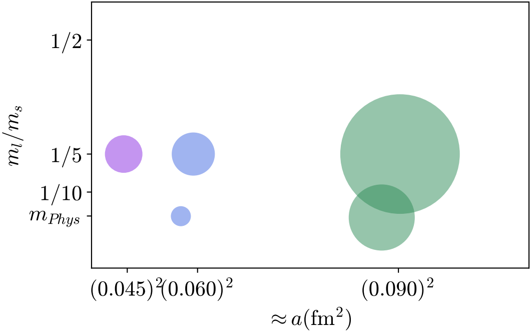
$$R(D^*)^{\mathrm{JLQCD}} = 0.252(22)$$

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

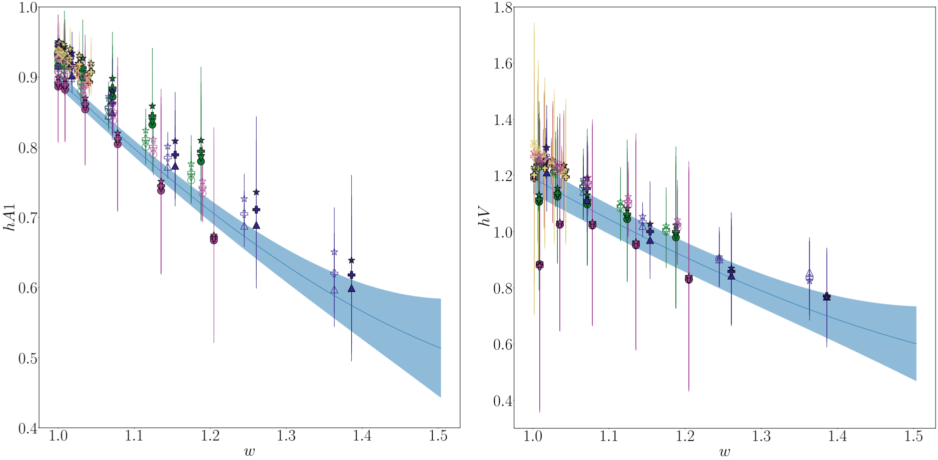
- Fit to Belle dataset including the Coulomb factor
- Combined fit $\chi^2/\mathrm{dof} \sim 0.90$

Semileptonic B decays on the lattice: HPQCD

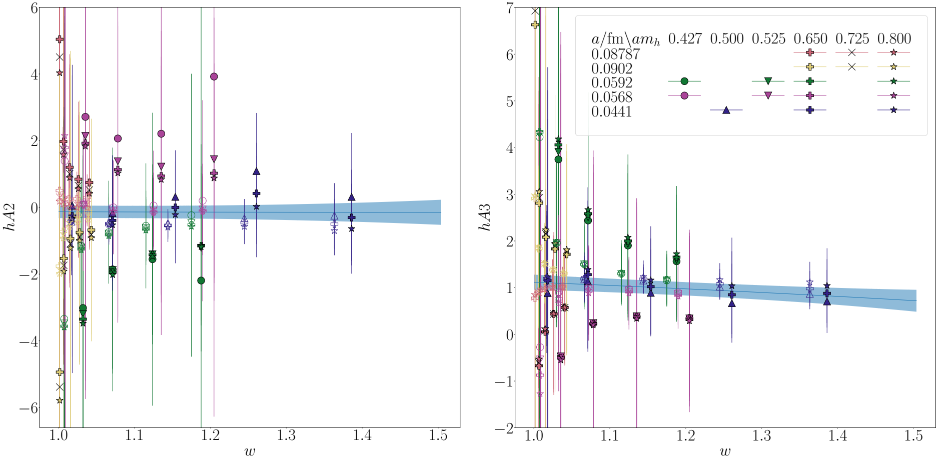
- Using 5 $N_f = 2 + 1 + 1$ MILC ensembles of sea HISQ quarks
- The b quark uses the HISQ action and unphysical masses
- m_π ranges from 330 MeV to 129 MeV



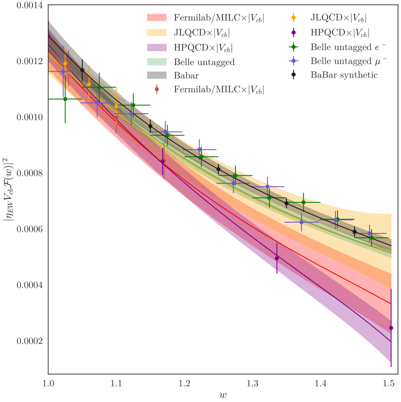
Semileptonic B decays on the lattice: HPQCD

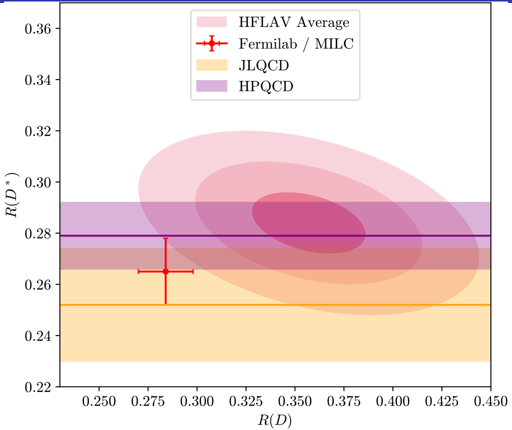


Semileptonic B decays on the lattice: HPQCD



Semileptonic B decays on the lattice: HPQCD





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

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

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

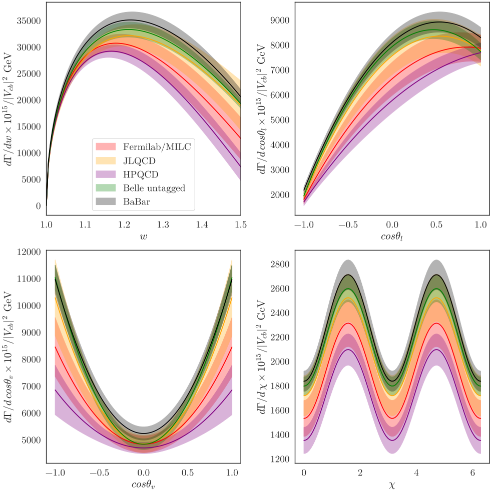
$$R(D^*)^{\rm HPQCD} = 0.279(13)$$

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

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

- Fit to Belle dataset WITH the Coulomb factor

Semileptonic B decays on the lattice: HPQCD



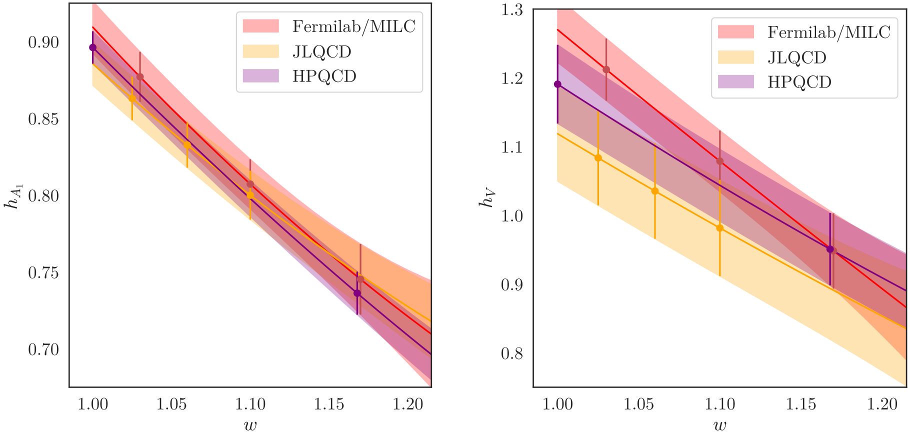
- From total decay rate $|V_{cb}| = 44.2(1.8) \times 10^{-3}$

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

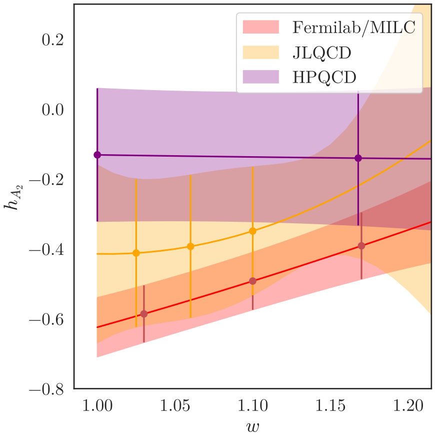
	w Constraint		w/o Constraint	
	p	$R_2(1)$	p	$R_2(1)$
MILC	0.51	1.20(12)	0.43	1.27(13)
JLQCD	0.52	0.98(19)	0.25	0.97(19)
HPQCD	0.77	1.39(16)	0.65	1.39(16)
MILC+JLQCD	0.40	1.118(97)	0.36	1.16(11)
MILC+HPQCD	0.44	1.262(93)	0.37	1.262(93)
JLQCD+HPQCD	0.73	1.18(12)	0.67	1.18(12)
All	0.56	1.193(83)	0.50	1.193(83)

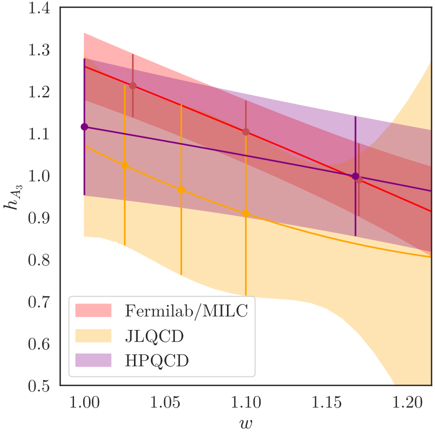
- p-value of Belle untagged + BaBar BGL fit 2232 is ≈ 0.04
- Combined $R(D^*) = 0.2667(57)$

Semileptonic B decays on the lattice: Comparison of HQET form factors

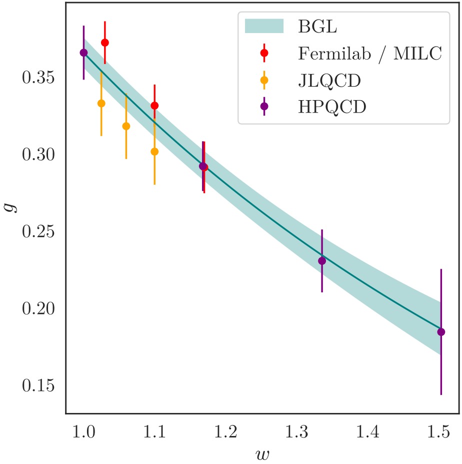


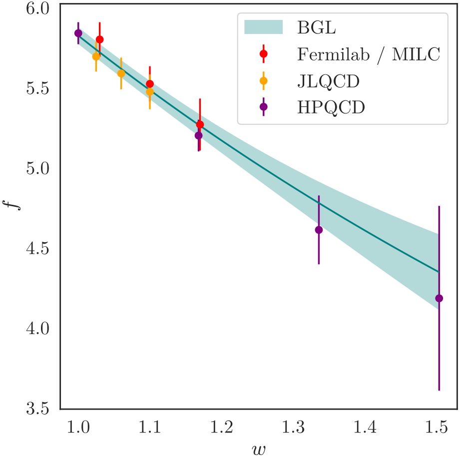
Semileptonic B decays on the lattice: Comparison of HQET form factors



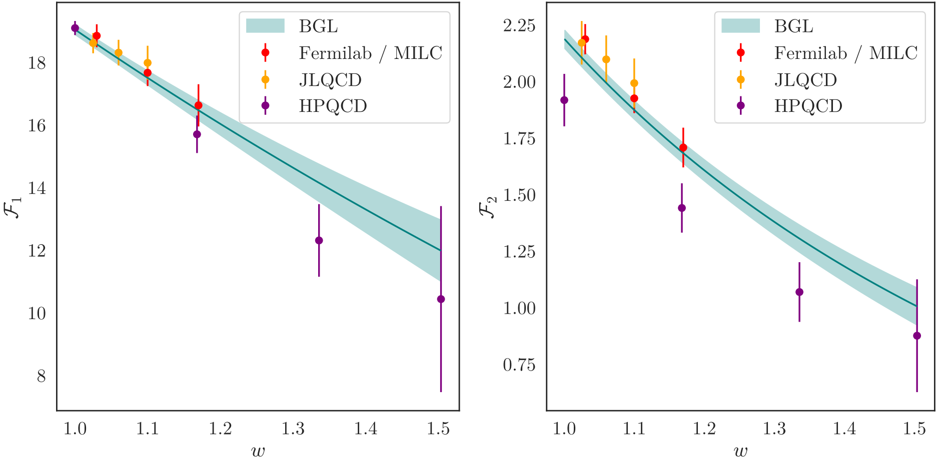


Semileptonic B decays on the lattice: Combined fits

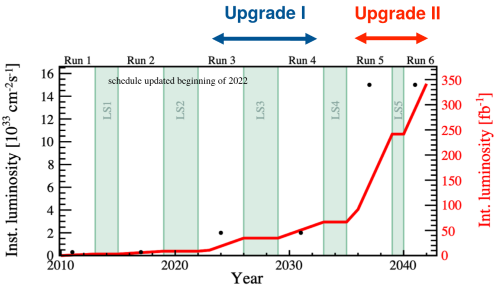




Semileptonic B decays on the lattice: Combined fits



Semileptonic B decays on the lattice: Experimental data



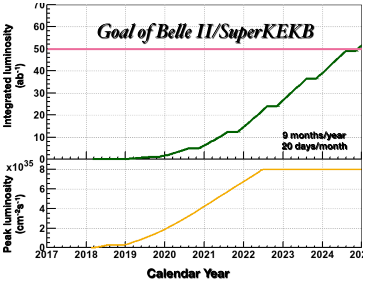
- Belle II IL 424 fb^{-1}
  - Target 50 ab^{-1}
  - Results at 190 fb^{-1}

ICHEP 2022

$$|V_{cb}|^{\mathrm{Untag}}_{B\to D\ell\nu} = 38.28 \pm 1.16$$

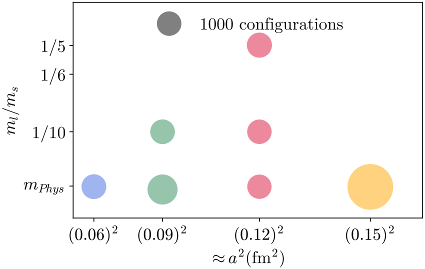
$$|V_{cb}|^{\mathrm{Tag}}_{B\to D^*\ell\nu} = 37.9 \pm 2.9$$

$$\eta_{\mathrm{EW}} = 1.0066 \pm 0.0050$$



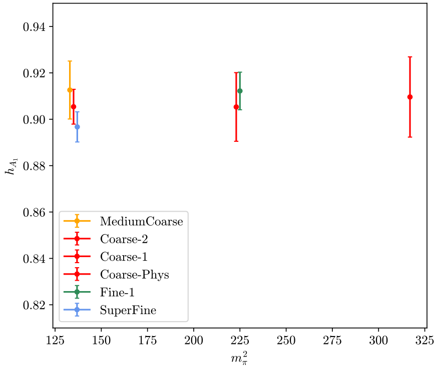
Semileptonic B decays on the lattice: New Fermilab / MILC analysis

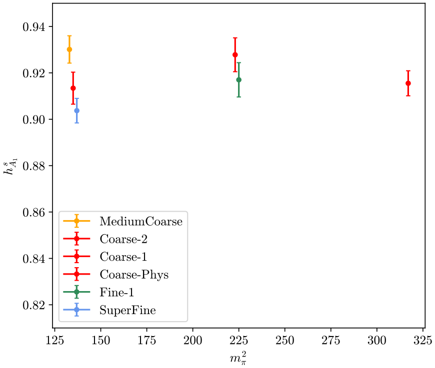
- Using 7 $N_f = 2 + 1 + 1$ MILC ensembles of sea HISQ quarks
- The heavy quarks are treated using the Fermilab action
- Half the ensembles feature a physical pion mass
- Analysis of $B_{(s)} \to D^*_{(s)} \ell\nu$ channels, and $B \to \pi/K$



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

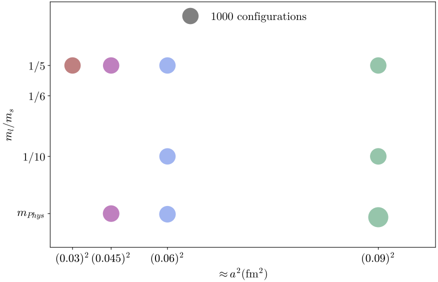
- Current status: Analyzing ratio fits to extract form factors





Semileptonic B 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 $\mathrm{remains\ unsolved}$
  - Results show $R(D^*)$ very close to **phenomenological expectations**, still in tension with experiment
- 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

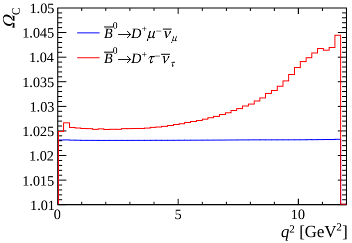
BACKUP SLIDES

Semileptonic B decays on the lattice: QED effects

- Most important correction: Coulomb factor $(1 + \alpha\pi) = 1.023$

  D. Atwood, W. Marciano, Phys.Rev.D**41** (1990), 1736

  - **Not** included in PHOTOS
  - Applies to decays with a charged D^*
  - Experiments should distinguish between both decays
  - Structure-dependent corrections $\approx (1 + \alpha/\pi)$
- Velocity-dependent correction, but $\approx$ constant for light leptons
- Current consensus (Barolo) is to include it as much as possible



S. Cali, S. Klaver, M. Rotondo, B. Sciascia, Eur.Phys.J.C**79** (2019), 744