Searching for new physics in B semileptonic decays using lattice QCD

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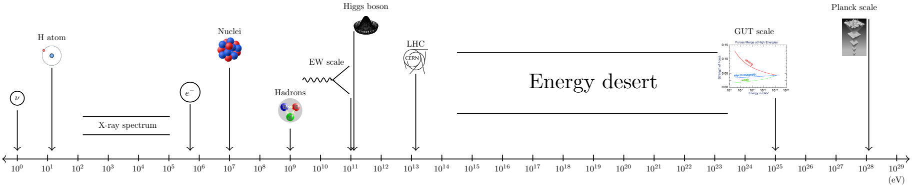
The motivation

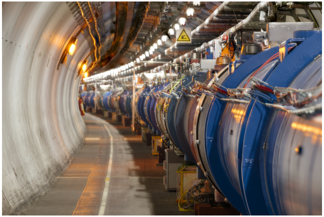
Motivation: Searches for new physics

- The Standard Model (SM) describes phenomena in a wide range of scales
- Yet, we expect it to fail at some point
  - Hierarchy problem, too many parameters, absence of gravity, dark matter/energy, neutrino mixing...
  - SM regarded as an Effective Field Theory (EFT)
- New physics searches more important than ever



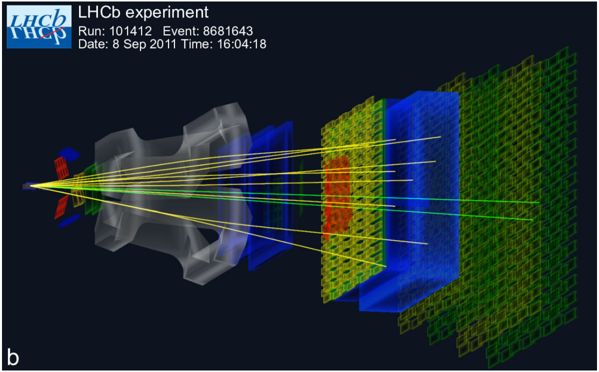
Motivation: Searches for new physics

Energy frontier



Cosmology frontier

Intensity frontier



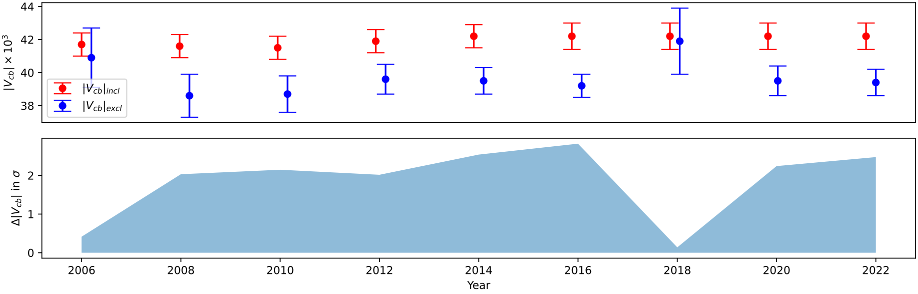
- High expectations with the LHC
- Intensity frontier becoming increasingly important

Motivation: New physics in the flavor sector of the SM

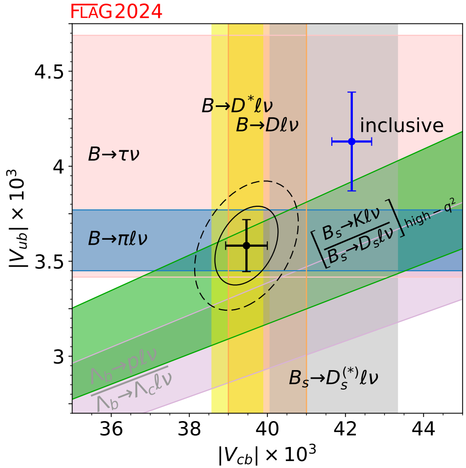
The CKM matrix

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

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



Motivation: CKM matrix elements

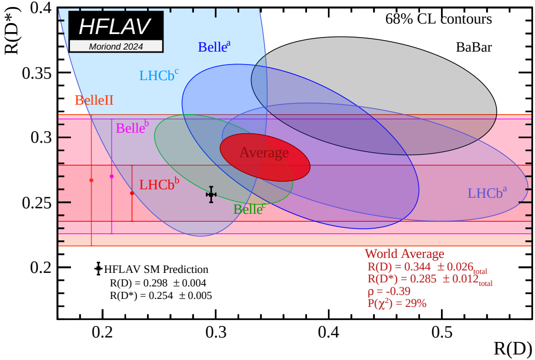


Strong arguments disfavoring new physics

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

Motivation: Tensions in LFU ratios

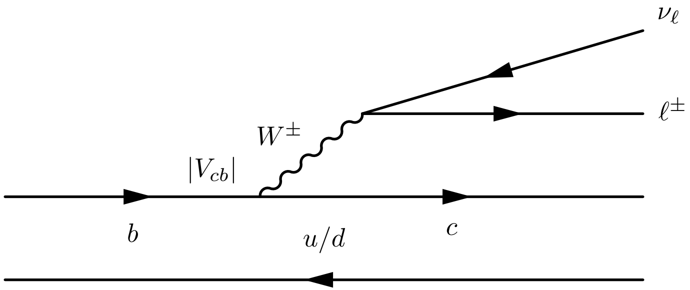
$$R\left(D^{(*)}\right)=\frac{\mathcal{B}\left(B\to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(B\to D^{(*)}\ell\nu_\ell\right)}$$



- Current $\approx 3.3\sigma$ combined tension with the SM (HFLAV)
  - Tension in $R(D) \approx 1.6\sigma$ Tension in $R(D^*) \approx 2.5\sigma$

The theory

Semileptonic B decays on the lattice: Exclusive $|V_{cb}|$



- Decay described in the SM by 4 form factors: $g, f, \mathcal{F}_1, \mathcal{F}_2 \quad \Longrightarrow \quad \mathcal{F}$

$$\underbrace{\frac{d\Gamma}{dw}\left(\bar{B} \to D^* \ell \bar{\nu}_\ell\right)}_{\text{Experiment}} = \underbrace{K_1(w, m_\ell \approx 0)}_{\text{Known factors}} \underbrace{|\mathcal{F}(w)|^2}_{\text{Theory}} |V_{cb}|^2 , \quad w = v_{D^*} \cdot v_B$$

- The amplitude $\mathcal{F}$ must be calculated in QCD, which is non-perturbative
  - HQET provides $\mathcal{F}(1)$, but $K_1(w, m_\ell \approx 0) \propto (w^2 - 1)^{\frac{1}{2}} \to$ no data @ $w = 1$
  - LQCD can calculate the form factors away from $w = 1$

Semileptonic B decays on the lattice: Universality ratios

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

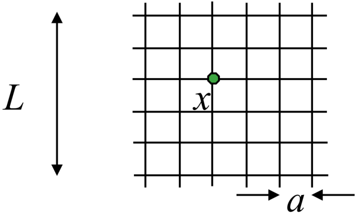
- The amplitudes $\mathcal{F}$,$\mathcal{F}_2$ must be calculated in the theory
- Since $K_2(w,0)=0$, $\mathcal{F}_2$ only contributes significantly with the τ
- Knowing these amplitudes, one can extract $|V_{cb}|$ from experiment
  - It is possible to extract $R(D^*)$ without experimental data!

$$R(D^*) = \frac{\int_1^{w_{\mathrm{Max},\tau}} dw\, \left[K_1(w,m_\tau)\,|\mathcal{F}(w)|^2 + K_2(w,m_\tau)\,|\mathcal{F}_2(w)|^2\right] \times \cancel{|V_{cb}|^2}}{\int_1^{w_{\mathrm{Max}}} dw\, \left[K_1(w,0)\,|\mathcal{F}(w)|^2\right] \times \cancel{|V_{cb}|^2}}$$

- $|V_{cb}|$ cancels out

Semileptonic B decays on the lattice: Introduction to Lattice QCD

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



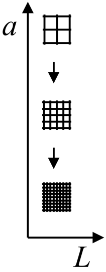
- Discretize space-time in a computer
  - Finite lattice spacing a
  - Finite spatial volume L
  - Finite time extent T

- 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



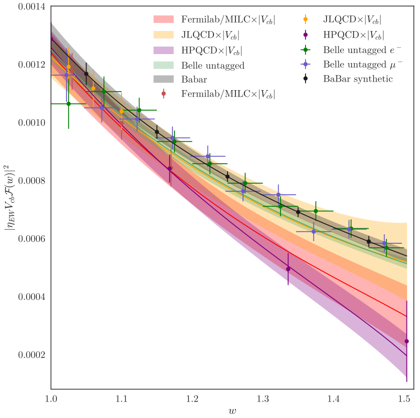
In order to keep the systematic errors under control we must repeat the calculation for several lattice spacings, volumes, light quark masses... and use the EFT to extrapolate to the physical theory

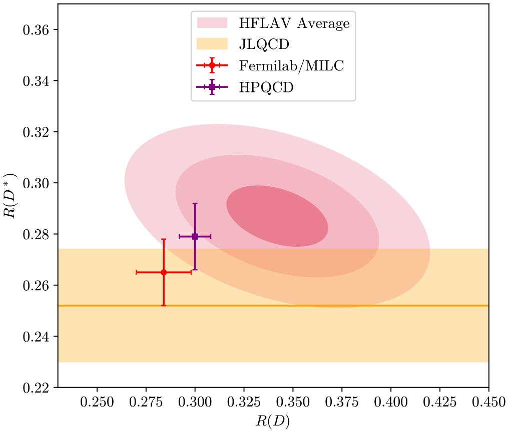
Semileptonic B decays on the lattice: Heavy quarks

- Heavy quark treatment in Lattice QCD
  - For heavy quarks $(m_Q > \Lambda_{QCD})$, discretization errors typically grow as $\sim a^2 m_Q^2$
  - Two treatments
    - EFTs: Physical heavy masses, but requires matching and renormalization
    - Same action as the light quarks: Unphysical heavy masses, requires extrapolation
  - Not all actions perform equally well
    - Typical action $\sim a^2 m_Q^2$ VS HISQ action $\sim \alpha_s a^2 m_Q^2$

The mess

The mess: Lattice results





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

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

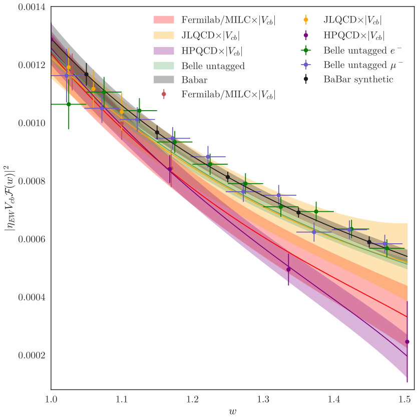
$$|V_{cb}|^{\text{HPQCD}} = 39.31(74) \times 10^{-3}$$

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

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

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

The mess: Lattice results



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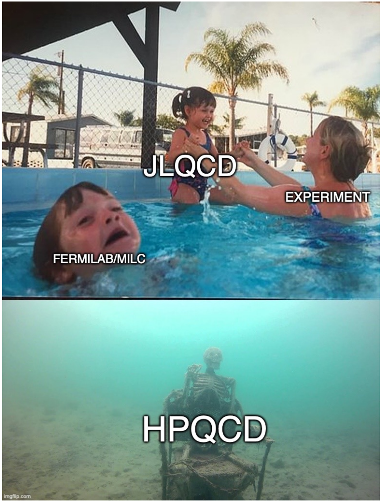

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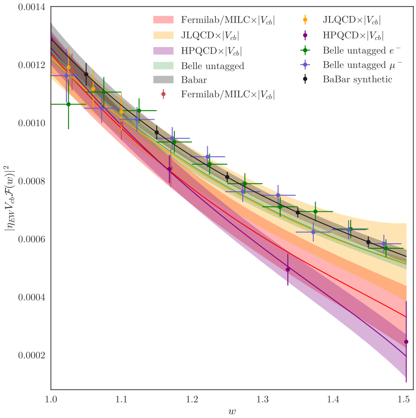

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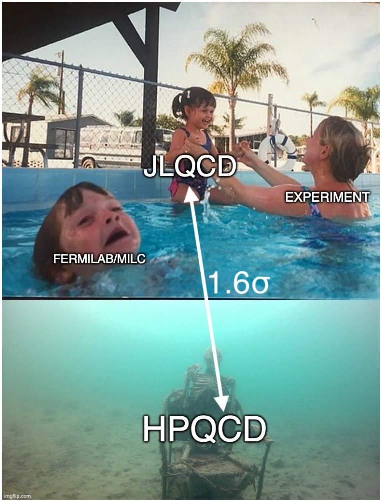
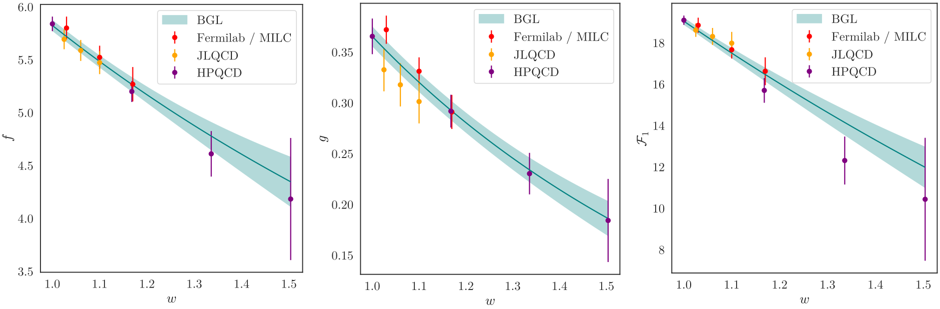


The mess: Combined lattice fits

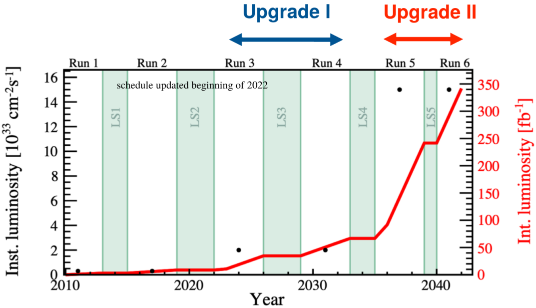
- Combined fits with priors 0(1)
- p-value of Belle untagged + BaBar fit is ≈ 0.04
- Combined $R(D^*) = 0.2667(57)$

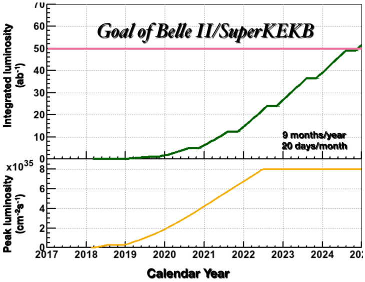
	p
MILC+JLQCD	0.40
MILC+HPQCD	0.44
JLQCD+HPQCD	0.73
All	0.56



The mess: Experimental data

$$\text{Total Events} = \int dt \; \text{Luminosity} \times \text{Cross Section}$$





- LHCb integrated luminosity (IL) $\approx 7\ \mathrm{fb}^{-1}$
  - Target 300-350 fb^{-1}
  - Cross-section $\approx 10^5$ larger than in Belle, but spread around many particles
- Belle II IL $\approx 360\ \mathrm{fb}^{-1}$
  - Target $50\ \ \mathrm{ab}^{-1} = 50000\ \ \mathrm{fb}^{-1}$
  - Belle I $711\ \mathrm{fb}^{-1}$ $(\times 70!!)$

Conclusions

- Great progress in LQCD calculations of $B \to D^* \ell\nu$ form factors
- Good agreement between different LQCD results
  - Not so good between LQCD and experiment

- New calculations are needed to clarify the situation

Thank you for your attention

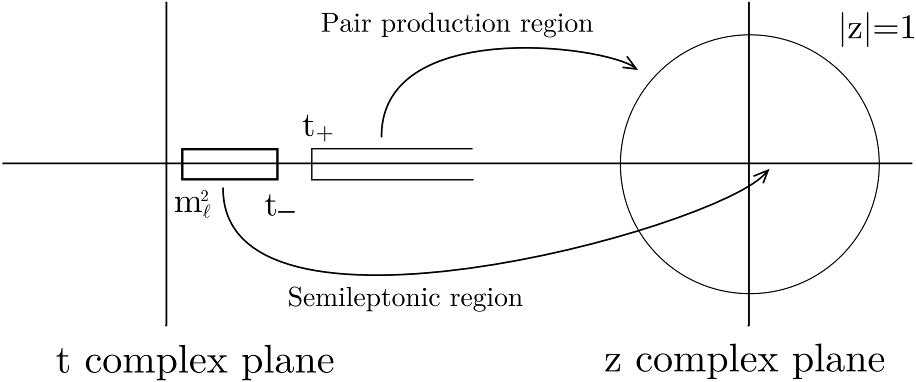
BACKUP SLIDES

Semileptonic B decays on the lattice: Parametrizations

Most parametrizations perform an expansion in the z parameter

$$\frac{1+z}{1-z} = \sqrt{\frac{t_+ - t}{t_+ - t_-}}, \qquad z = \frac{\sqrt{w+1} - \sqrt{2N}}{\sqrt{w+1} + \sqrt{2N}}$$

with $t_\pm = (m_B \pm m_{D^*})^2\,, \quad t = (p_B - p_{D^*})^2\,, \quad w = v_B \cdot v_{D^*}$



Semileptonic B decays on the lattice: Parametrizations

- Boyd-Grinstein-Lebed (BGL)

Phys. Rev. Lett. 74 (1995) 4603-4606

Phys.Rev. D56 (1997) 6895-6911

Nucl.Phys. B461 (1996) 493-511

$$f_X(w) = \frac{1}{B_{f_X}(z)\phi_{f_X}(z)} \sum_{n=0}^{\infty} a_n z^n$$

  - B_{f_X} Blaschke factors, includes contributions from the poles
  - ϕ_{f_X} is called outer function and must be computed for each form factor
  - Weak unitarity constraints $\sum_n |a_n|^2 \leq 1$

- Caprini-Lellouch-Neubert (CLN)

Nucl. Phys. B530 (1998) 153-181

$$F(w) \propto 1 - \rho^2 z + c z^2 - d z^3, \quad \text{with } c = f_c(\rho),\, d = f_d(\rho)$$

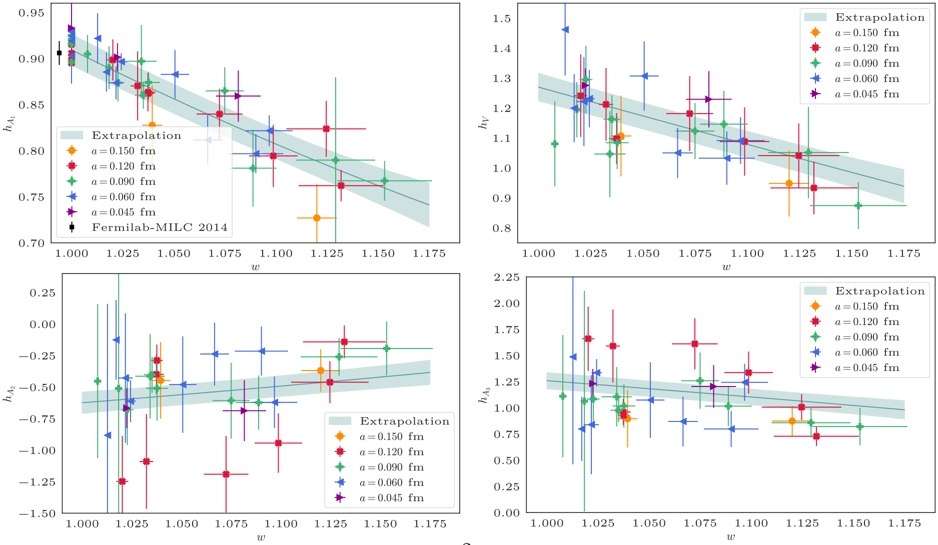
  - Relies strongly on HQET, spin symmetry and (old) inputs
  - Tightly constrains $F(w)$: four independent parameters, one relevant at $w = 1$

- Current consensus: abandon CLN
  - Spiritual sucessors of CLN

Bernlochner et al. Phys.Rev.D 95 (2017) 115008, Phys.Rev.D 97 (2018) 059902

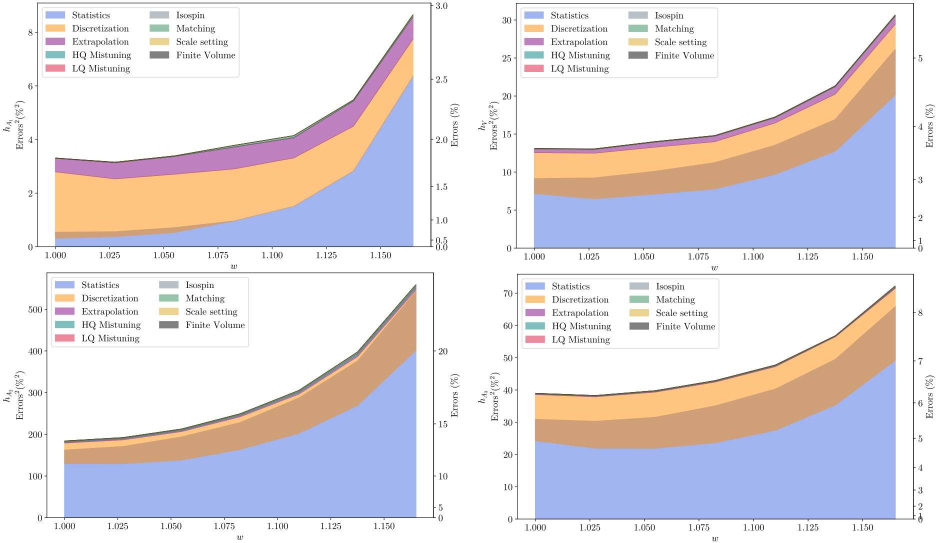
Bordone, Gubernari, Jung, Straub, Van Dyk... Eur.Phys.J.C 80 (2020) 74, Eur.Phys.J.C 80 (2020) 347, JHEP 01 (2019) 009

Semileptonic B decays on the lattice: Chiral-continuum extrapolation



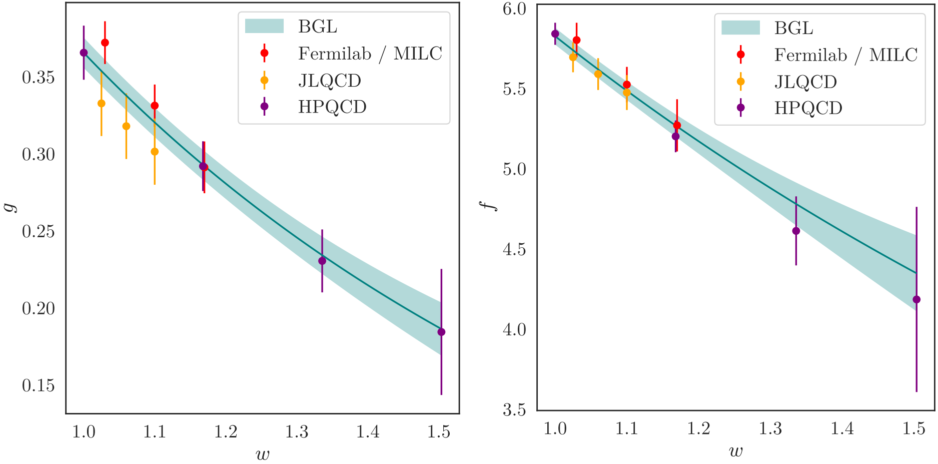
Combined fit $\chi^2/\text{dof} = 85.2/95$

$B \to D^*\ell\nu$: Chiral-continuum extrapolation



Largest systematic errors come from discretization

The mess: Combined lattice fits



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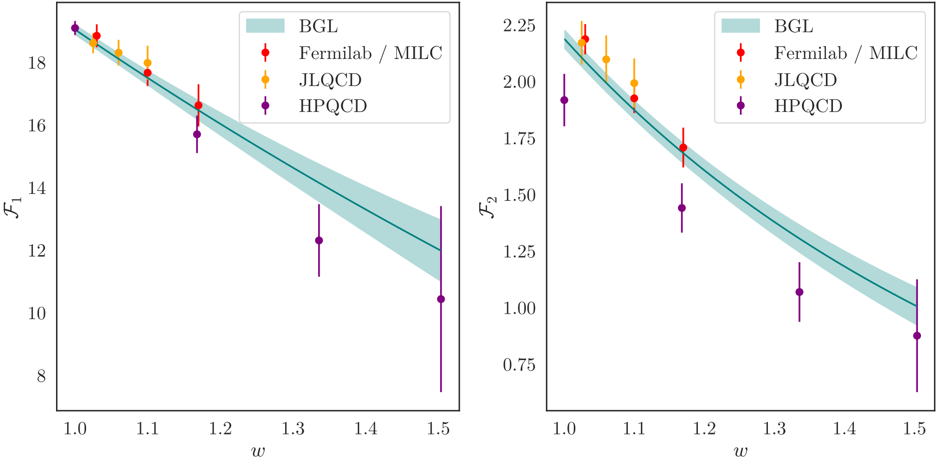
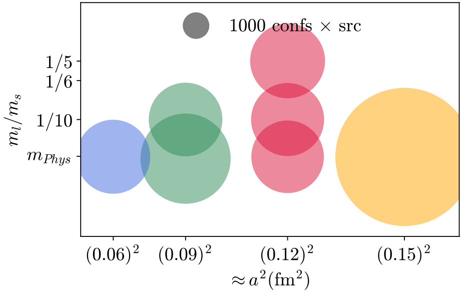


Future projects: HISQ + Fermilab

- 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 $B_{(s)} \to D^{(*)}_{(s)}\ell\nu$ in a single correlated analysis



Future projects: HISQ^2

- 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