

$B \rightarrow D^* \ell \nu$ from LQCD and its impact in $|V_{cb}|$ and $R(D^*)$

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February 16th, 2023

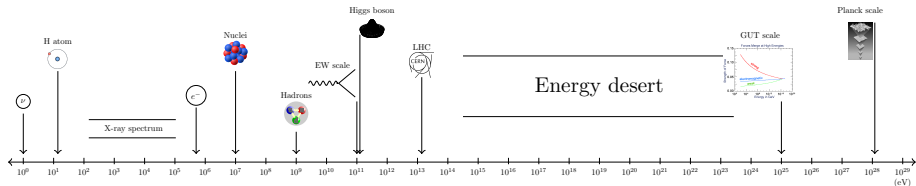


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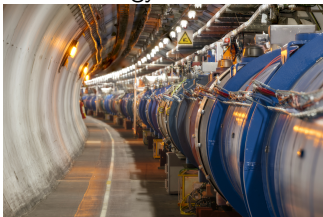
Motivation: Searches for new physics

- 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

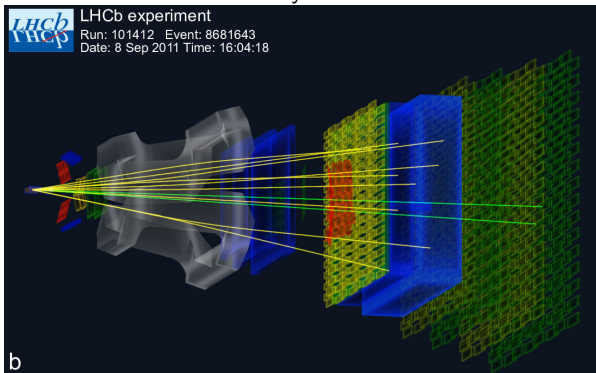
Energy frontier



Cosmology frontier



Intensity frontier



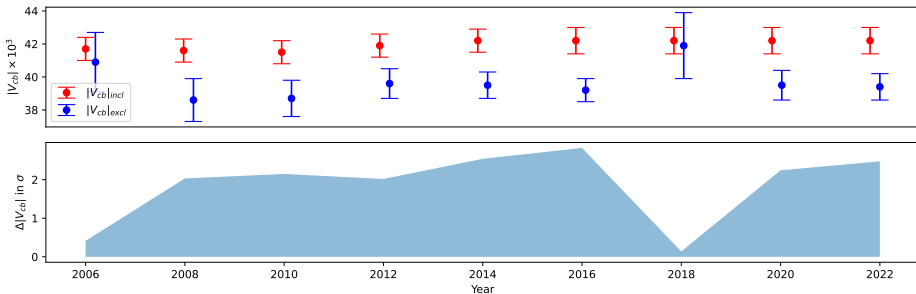
- High expectations with the LHC
- Intensity frontier becoming increasingly important

Motivation: New physics in the flavor sector of the SM

The CKM matrix

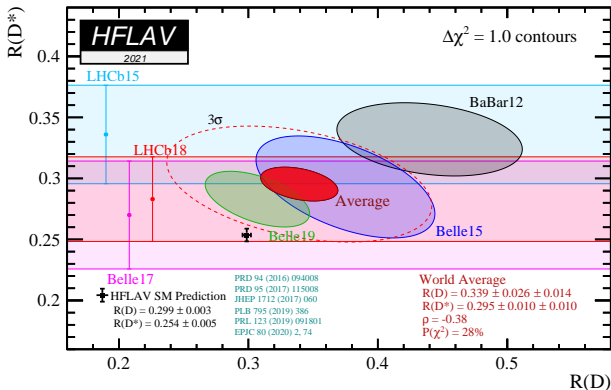
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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



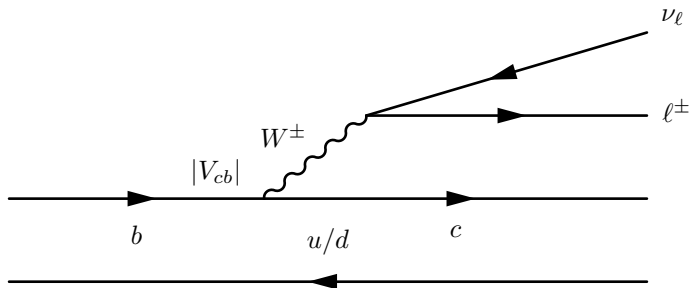
Motivation: Tensions in lepton universality ratios

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



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

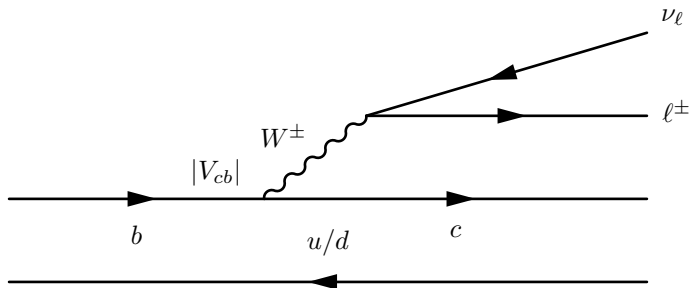
Semileptonic B decays on the lattice: Exclusive $|V_{cb}|$



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

- 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 decays on the lattice: Universality ratios



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

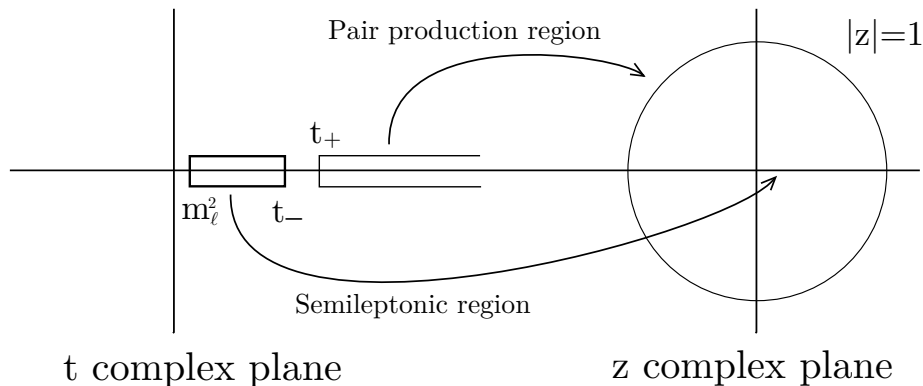
- The universality ratio depends only on the form factors
- It is possible to extract $R(D^*)$ without experimental data!

Semileptonic B decays on the lattice: Parametrizations

Most parametrizations perform an expansion in the z parameter

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

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



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

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

- 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 successors 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: Parametrizations

- Dispersive approach

Bourrely et al. *Nucl.Phys.B* 189 (1981) 157, Lellouch *Nucl.Phys.B* 479 (1996) 353

Di Carlo et al. *Phys.Rev.D* 104 (2021) 054502

- Express unitarity bounds as a norm, define an inner product

$$\langle \phi f | \phi f \rangle = \frac{1}{2\pi i} \int_{|z|=1} \frac{dz}{z} \left| \phi(z, q_0^2) f(z) \right|^2 \leq \chi(q_0^2), \quad \langle g | h \rangle \equiv \frac{1}{2\pi i} \int_{|z|=1} \frac{dz}{z} \bar{g}(z) h(z)$$

- Use Cauchy integral theorem to test unitarity in synthetic data at

$$z = z_{t_1}, z_{t_2} \dots$$

$$g_t(z) \equiv \frac{1}{1 - \bar{z}_t z}$$

$$\langle g_t | \phi f \rangle = \phi(z_t, q_0^2) f(z_t)$$

$$\det \mathcal{M} = \begin{vmatrix} \langle \phi f | \phi f \rangle & \langle \phi f | g_{t_1} \rangle & \langle \phi f | g_{t_2} \rangle & \dots \\ \langle g_{t_1} | \phi f \rangle & \langle g_{t_1} | g_{t_1} \rangle & \langle g_{t_1} | g_{t_2} \rangle & \dots \\ \langle g_{t_2} | \phi f \rangle & \langle g_{t_2} | g_{t_1} \rangle & \langle g_{t_2} | g_{t_2} \rangle & \dots \\ \vdots & \vdots & \vdots & \ddots \end{vmatrix} \geq 0$$

Matrix \mathcal{M} positive semidefinite

Semileptonic B decays on the lattice: Formalism

- Form factors

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

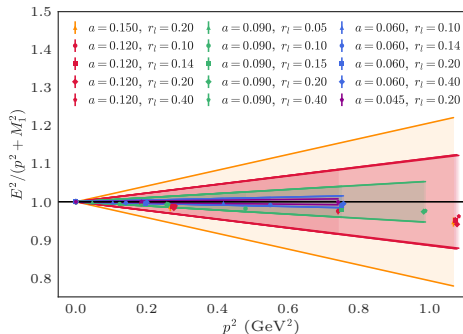
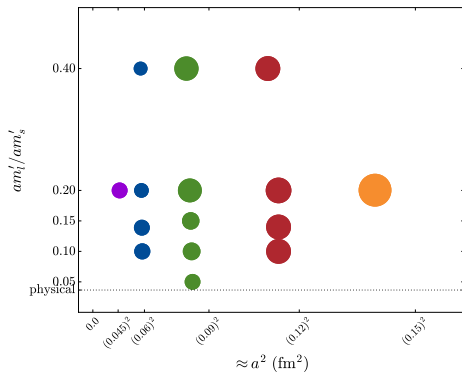
$$\frac{\langle D^*(p_{D^*}, \epsilon^\nu) | \mathcal{A}^\mu | \bar{B}(p_B) \rangle}{2\sqrt{m_B m_{D^*}}} =$$

$$\frac{i}{2} \epsilon^{\nu*} [g^{\mu\nu} (1+w) \mathbf{h}_{A_1}(w) - v_B^\nu (v_B^\mu \mathbf{h}_{A_2}(w) + v_{D^*}^\mu \mathbf{h}_{A_3}(w))]$$

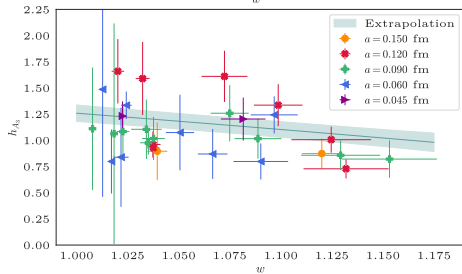
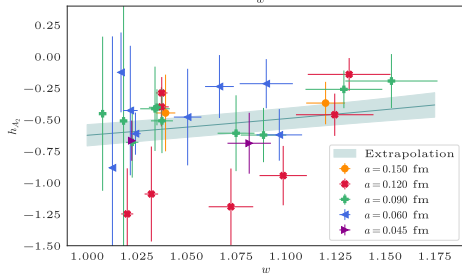
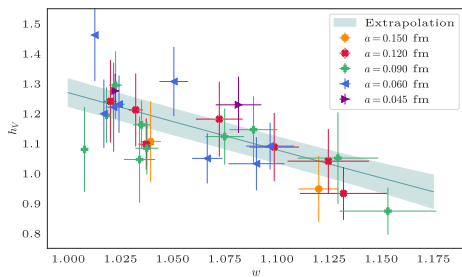
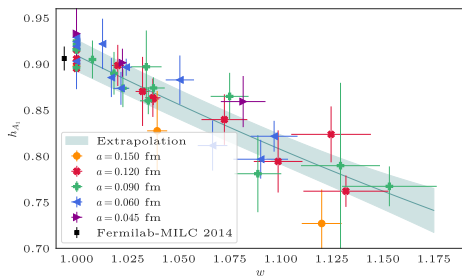
- \mathcal{V} and \mathcal{A} are the vector/axial currents in the continuum
- The h_X enter in the definition of the decay amplitudes
- We can calculate h_X directly from the lattice

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

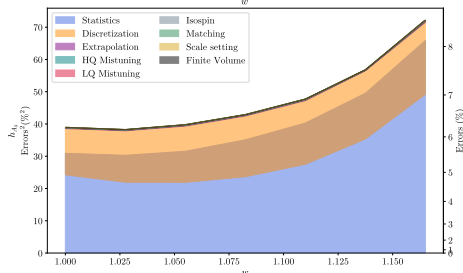
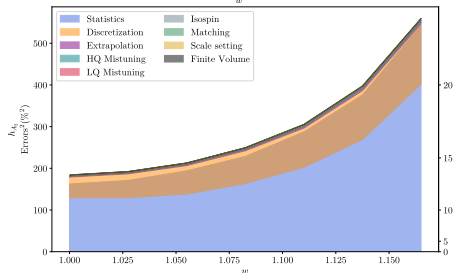
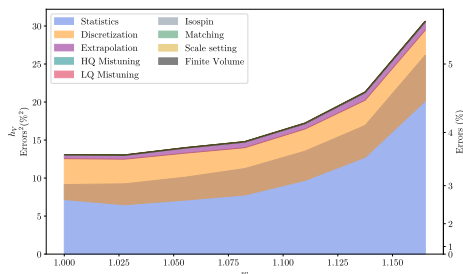
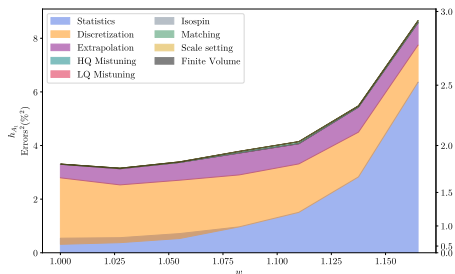


Semileptonic B decays on the lattice: Fermilab/MILC



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

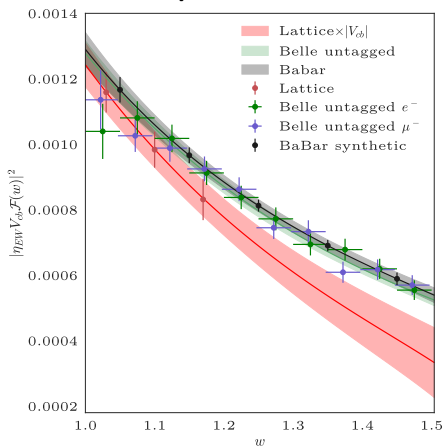
Semileptonic B decays on the lattice: Fermilab/MILC



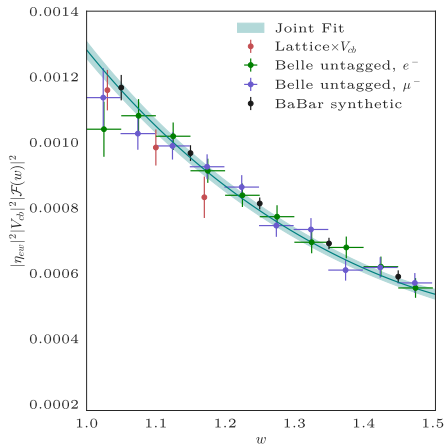
Largest systematic errors come from discretization

Semileptonic B decays on the lattice: Fermilab/MILC

Separate fits



Joint fit



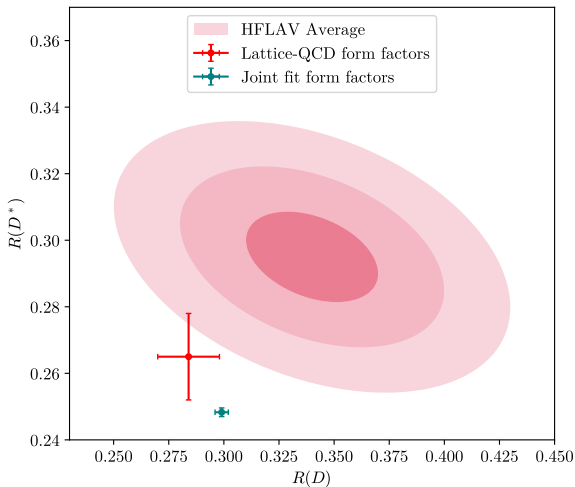
Fit	Lattice	Exp	Lat + Belle	Lat + BaBar	Lat + Exp
χ^2/dof	0.63/1	104/76	111/79	8.50/4	126/84

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

Semileptonic B decays on the lattice: Fermilab/MILC

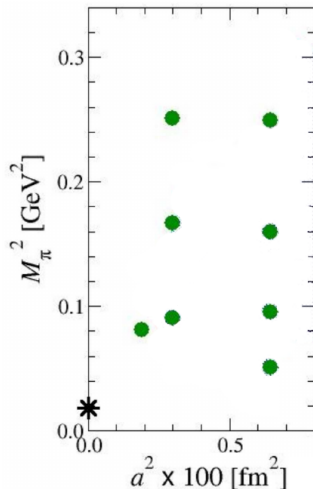
$$R(D^*)_{\text{Lat}} = 0.265(13) \quad R(D^*)_{\text{Lat+Exp}} = 0.2483(13)$$

Phys.Rev.D92 (2015), 034506; Phys.Rev.D100 (2019), 052007; Phys.Rev.D103 (2021), 079901; Phys.Rev.Lett. 123 (2019), 091801

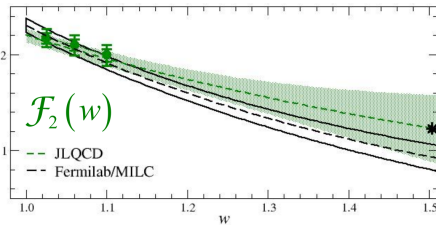
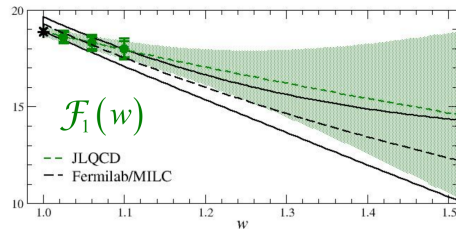
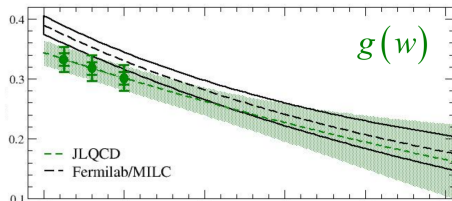
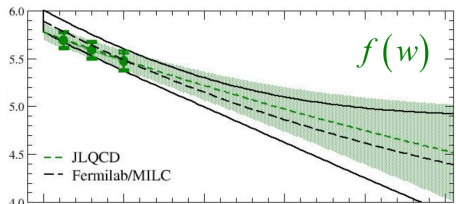


Semileptonic B decays on the lattice: JLQCD

- Using 8 $N_f = 2 + 1$ ensembles of sea DW quarks
- The heavy quarks use the same DW action
 - Simulations at unphysical b masses
 - Requires extrapolation
 - Easier and more precise renormalization
- m_π is as small as 230 MeV
 - Stable D^*

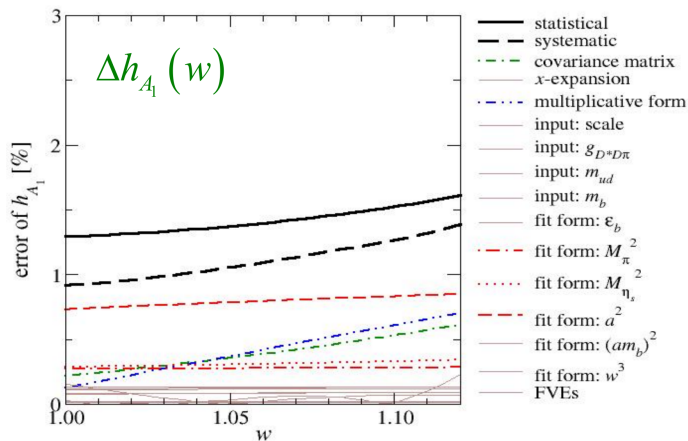


Semileptonic B decays on the lattice: JLQCD



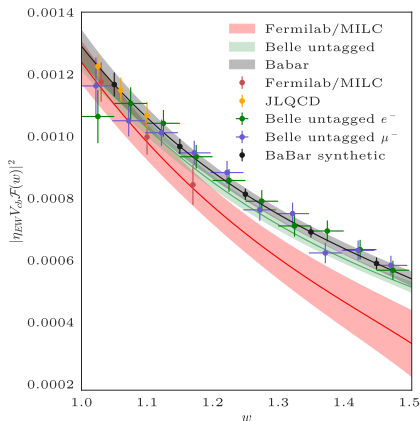
- Milder slope than Fermilab/MILC, but reasonable agreement

Semileptonic B decays on the lattice: JLQCD



- Discretization errors dominate the systematic contributions
- Statistical errors are the largest contribution in most ff

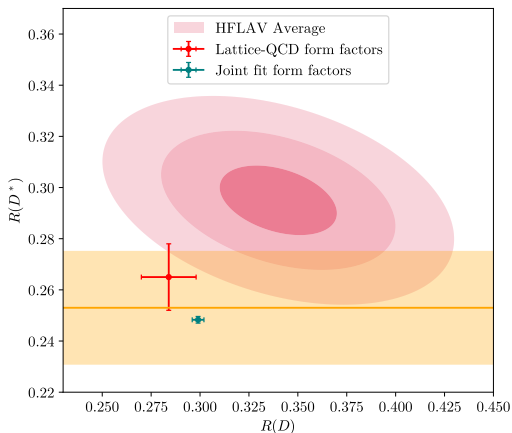
Semileptonic B decays on the lattice: JLQCD



$$|V_{cb}|^{\text{JLQCD}} = 39.85(95) \times 10^{-3}$$

$$|V_{cb}|^{\text{FerMILC}} = 38.60(86) \times 10^{-3}$$

- Fit to Belle dataset, no Coulomb factor
- Combined fit $\chi^2/\text{dof} = 0.94$

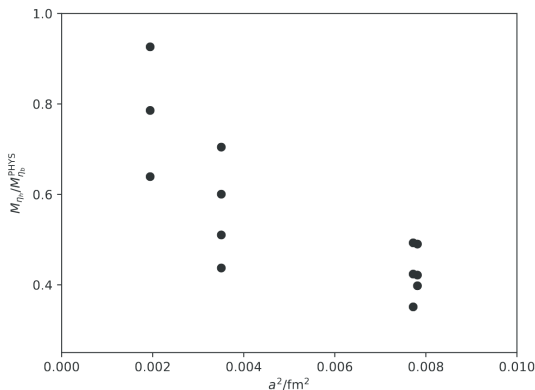


$$R(D^*)^{\text{JLQCD}} = 0.253(22)$$

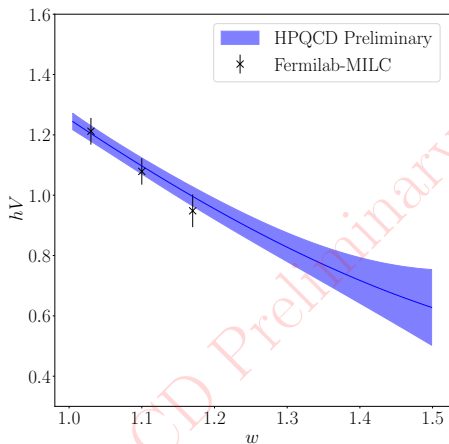
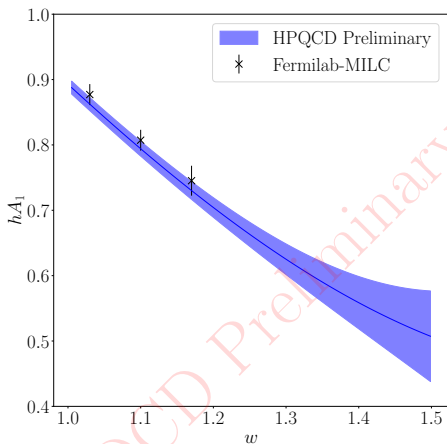
$$R(D^*)^{\text{FerMILC}} = 0.265(13)$$

Semileptonic B decays on the lattice: HPQCD

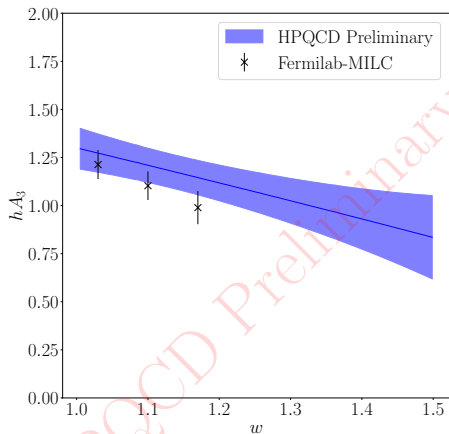
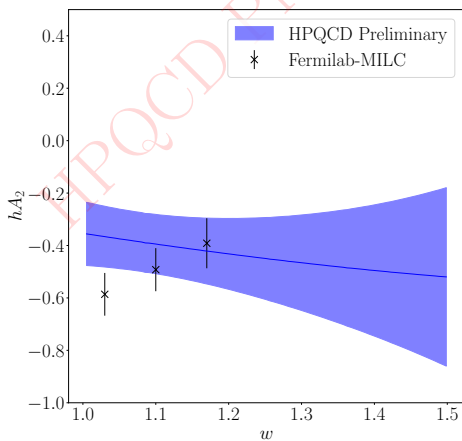
- Using 4 $N_f = 2 + 1 + 1$ MILC ensembles of sea HISQ quarks
- The b quark uses the HISQ action and unphysical masses
- m_π ranges from 330 MeV to 129 MeV



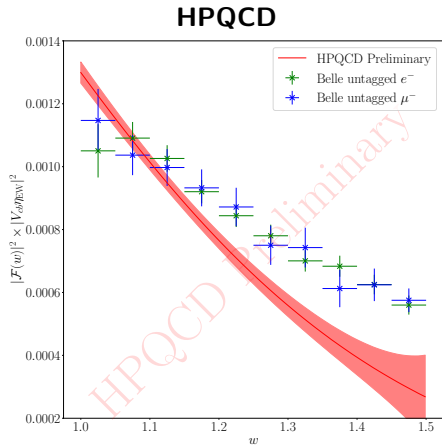
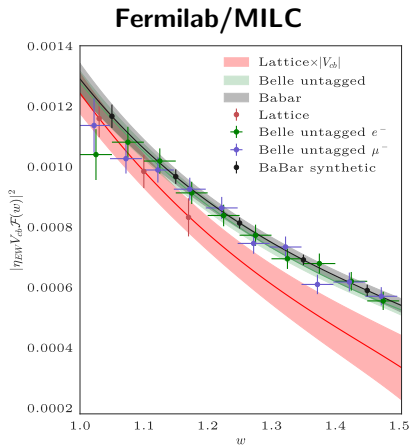
Semileptonic B decays on the lattice: HPQCD



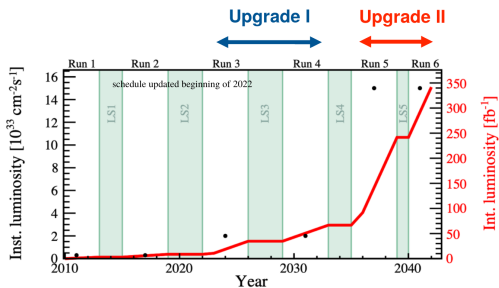
Semileptonic B decays on the lattice: HPQCD



Semileptonic B decays on the lattice: HPQCD



Semileptonic B decays on the lattice: Experimental data



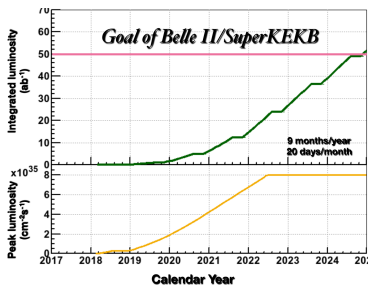
- Belle II IL 424 fb^{-1}
 - Target 50 ab^{-1}
 - Results at 190 fb^{-1}

ICHEP 2022

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

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

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



Summary

- Exciting times in flavor physics
 - Good progress, both in theoretical and experimental fronts
- Current results are not conclusive:
 - $|V_{cb}|$ agrees with previous determinations and the inclusive-exclusive tension remains unsolved
 - Results show $R(D^*)$ very close to **phenomenological expectations**, still in tension with experiment
- As we reduce our errors, new problems arise
 - Stability of the D^* meson
 - QED effects (Coulomb factor and beyond)
- Expect interesting results from the flavor sector in the next years

THANK YOU

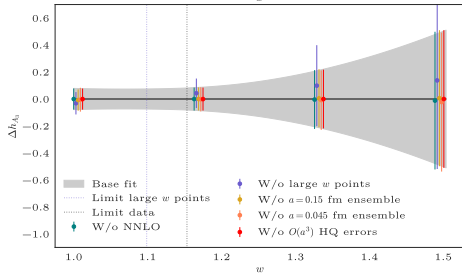
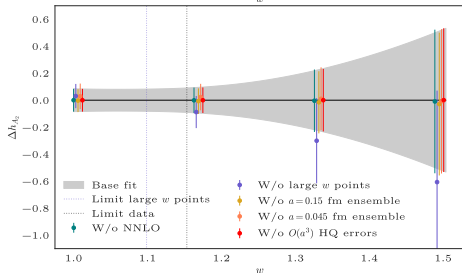
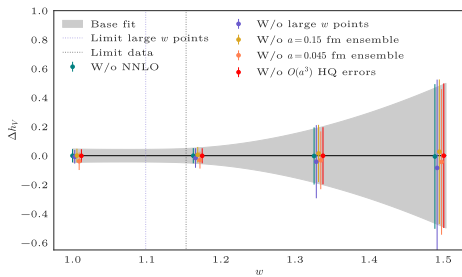
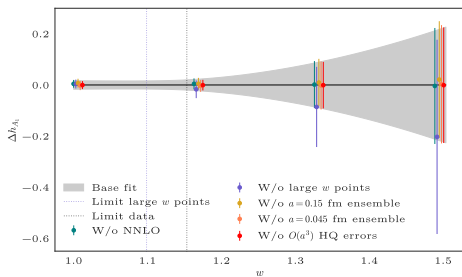
BACKUP SLIDES

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: Fermilab/MILC



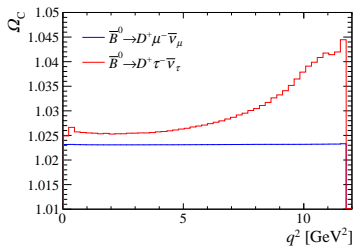
For all fits $\chi^2/\text{dof} \lesssim 1$

Semileptonic B decays on the lattice: QED effects

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

D. Atwood, W. Marciano, Phys.Rev.D41 (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.C79 (2019), 744