$B \to D$ Transitions

Determination of V_{cb} from $B \to D^{(*)}\ell\nu$ using the Oktay-Kronfeld Action

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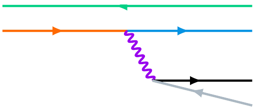
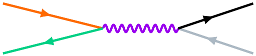
CKM Matrix and Flavor Physics

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

- CP Violation in the Standard Model
- Precision test of the SM
- Quarks in bound states
- Hadronic matrix elements from Lattice QCD
  - decay constants f, form factors $\mathcal{F}$, ...
  - $d\Gamma/d\omega \propto |V_{cb}|^2 |\mathcal{F}(\omega)|^2 \times$(known factor)





Long-Standing Puzzle of V_{cb}

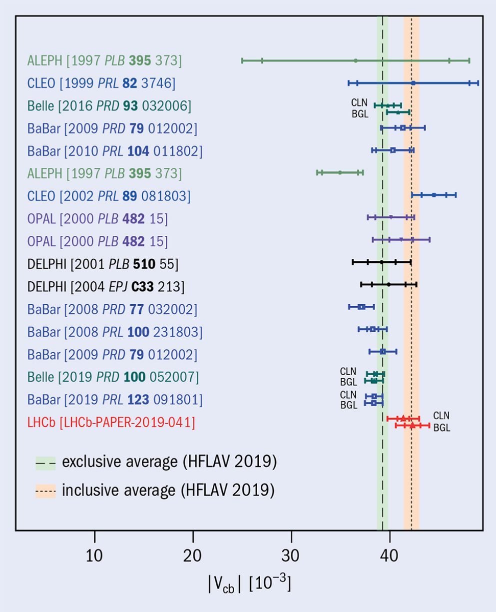


Figure: CERN Courier, Jan./Feb. 2020

- 2.8 – 3.2σ tension in $|V_{cb}^{\text{excl}} - V_{cb}^{incl}|$

- HFLAV2019
  $V_{cb} \times 10^3 = 42.19(78)$ incl. vs $39.25(56)$ excl.

- FLAG2019 [arXiv:1902.08191v3] exclusive averages
  $V_{cb}^{\text{excl}} \times 10^3 = 39.09(68)$ BGL vs $39.41(61)$ CLN

- Gambino et. al., [PLB763(2016)60]
  $V_{cb}^{\text{incl}} \times 10^3 = 42.00(65)$

- HFLAV2019 and FLAG2019 do not include recent results BaBar [2019 PRL] and LHCb [LHCb-PAPER-2019-041]

  CLN [Caprini, Lellouch, Neubert, Nucl. Phys. B 530, 153 (1998)]

  BGL [Boyd, Grinstein, Lebed, Phys. Rev. Lett. 74, 4603 (1995)]

Long-Standing Puzzle of V_{cb}

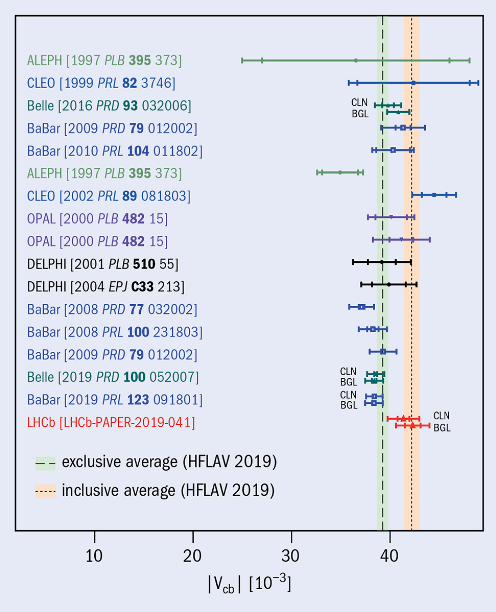
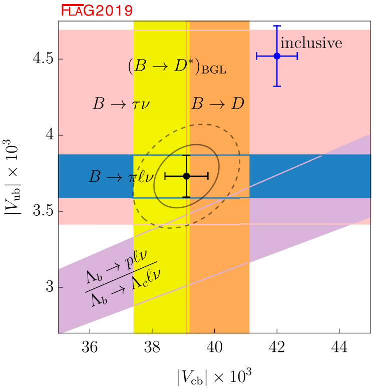
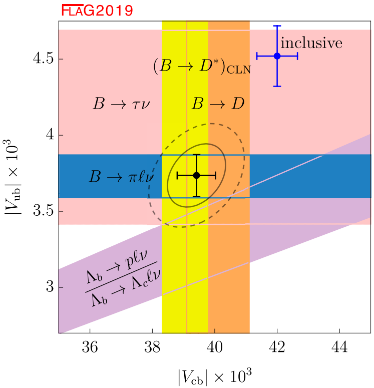


Figure: CERN Courier, Jan./Feb. 2020

- CLN and BGL are *compatible* for $B \to D^* \ell\nu$ (Belle [2019 PRD], BaBar [2019 PRL]) , $B \to D\ell\nu$ (Belle [2016 PRD]), and new LHCb results
- First $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ analysis from LHCb [LHCb-PAPER-2019-041] (PRD 101, 072004 (2020))
- Differences among $B \to D^*$, $B \to D$, and $B_s \to D_s^{(*)}$ $\Rightarrow$ form factors for *all* channels with a increased precision are interesting

V_{ub} and V_{cb}





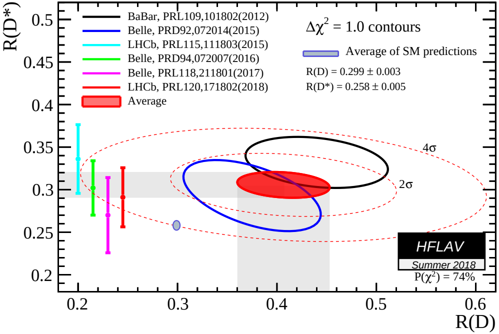
- about 3σ tension is in $|V_{ub}^{\rm excl} - V_{ub}^{\rm incl}|$
- need more lattice calculations for $B \to \pi\ell\nu$ and Λ_b decays form factors
- experimental error dominates $B \to \tau\nu$

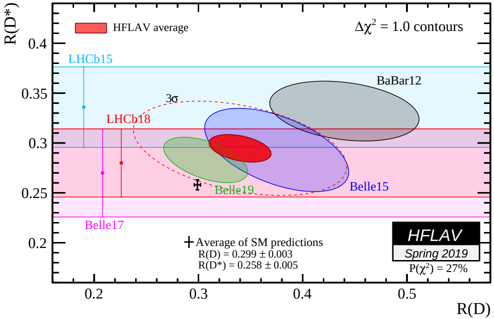
$R(D)$ and $R(D^*)$ for a test of Lepton Universality

$$R(D) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell)}, \qquad R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell)}$$

$$(\ell = e, \mu)$$

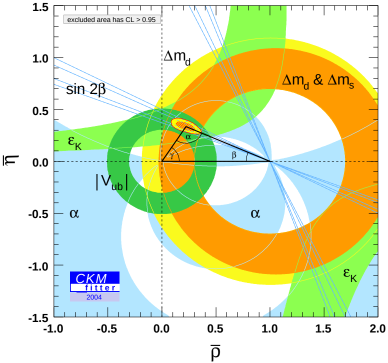
$R(D)$ and $R(D^*)$ for a test of Lepton Universality



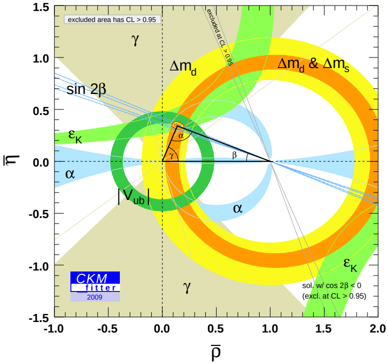


- Tension in the combined $R(D)$ and $R(D^*)$ analysis: $3.8\,\sigma \to 3.1\,\sigma$ [HFLAV19] with Belle 19 resutls @ Moriond EW 2019 [arXiv:1904.08794]
- SM prediction of $R(D)$ uses LQCD form factor calculations
- SM prediction of $R(D^*)$ uses Belle unfolded data for form factors
- $B \to D^*$ form factors from LQCD for all kinematic range is important / on-going progress [A. Vaquero et. al. (FNAL/MILC) arXiv:1912.05886]
- $B \to D$ form factors from LQCD with a higher precision is desirable

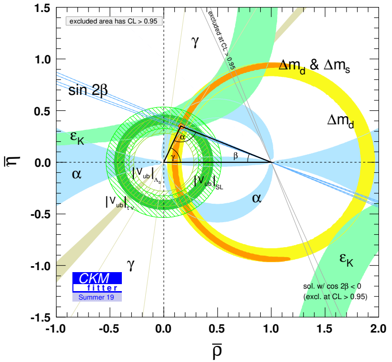
Impact on Unitarity Triangle Analysis



2004



2009



2019

- As B experiments improved, the measurements of angles (α, β, γ) and the mass differences $(\Delta m_{d,s})$ became more precise
- The parabolic band ε_K still has a largest uncertainty in the global unitarity triangle fit
- The leading contribution to $\varepsilon_K \propto c_\varepsilon \hat{B}_K |V_{cb}|^4$

  $\rightarrow$ lattice form factors / exclusive V_{cb} with $\sim 1\%$ error

Collaborators
LANL/SWME

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- (SNU) Jon A. Bailey, Benjamin J. Choi, Seungyeob Jwa, Sunkyu Lee, Weonjong Lee
- (KIAS) Jaehoon Leem

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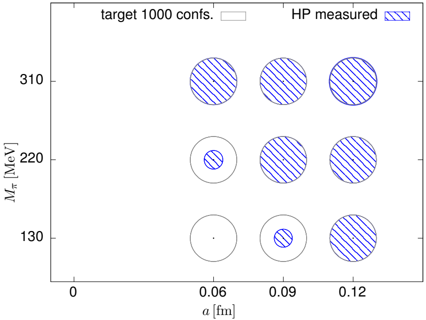
We thanks to MILC collaboration for making their HISQ ensembles publicly available

Lattice Setup

- Valence c, b: Oktay-Kronfeld action [PRD 78, 014504 (2008)]
  improved up to $\mathcal{O}(\lambda^3)$, $\lambda \sim \Lambda_{QCD}/m_{b,c}$, significantly reduces the heavy quark discretization error (dominant error)
- Valence d, s: HISQ, unitary points
- MILC HISQ ensemble [Bazavov et. al., PRD 87, 054505 (2013)]
  $N_f = 2+1+1$ dynamical quarks, improves continuum/chiral extrapolation (second largest error)
- 3 lattice spacings and 3 pion masses
  $M_\pi \approx 130, 220, 310\,\mathrm{MeV}$ ($m_l/m_s \approx 1/27, 1/10, 1/5$)
  m_s and m_c are physical mass

statistics

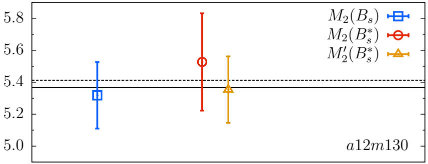


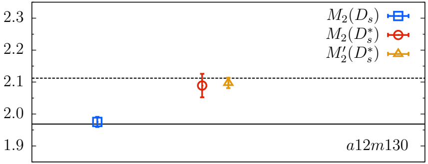
- anticipate to finish $a09m130$ meas. by using USQCD allocation
- $a06m220$ meas. started at KISTI

- Coherent sequential sources: 1 sequential inversion for $N_{src} = 3$
- Gaussian smeared quark source and sink operators improve statistics and systematics, e.g., excited-state contamination in $B, D^{(*)}$

Quark Mass Tuning

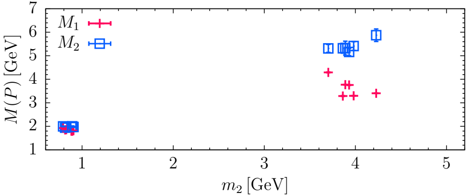
- heavy quarks are tuned with physical B_s, D_s

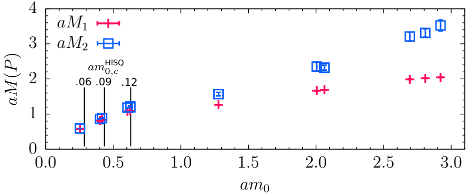




(solid) PS, (dashed) V meson physical masses

$$M_2'(V) = M_2(P) + M_1(V) - M_1(P)$$



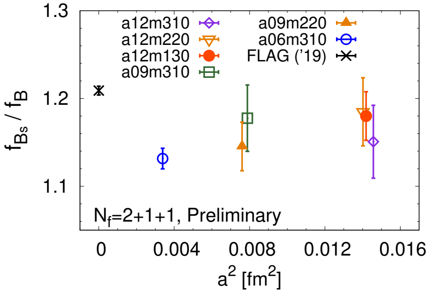


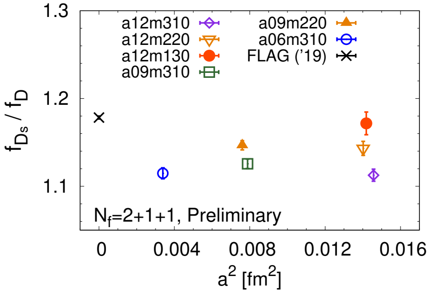
- meson [quark] kinetic mass M_2 [m_2] is interpreted as phyiscal mass
- $am_0 > 1$ can be directly simulated ($am_{0,b} \approx 1.3, 2.0, 2.8$ for $a = 0.06, 0.09, 0.12\,\mathrm{fm}$)
- κ_{crit} is nonperturbatively tuned [J. A. Bailey et. al., EPJ Web Conf. 175, 13012 (2018)]

Decay Constants

$$\langle 0|A^\mu|P(k)\rangle = ik^\mu f_P \,, \text{where } A^\mu = Z_A\bar{\Psi}_h\gamma^\mu\gamma_5\psi_l \,, \Psi_h = \sum_i d_i\mathcal{R}_i\psi_h$$

- Improved heavy quark field Ψ_h with rotation operators $\mathcal{R}_i$ for the current
- Perturbative matching for the coefficients d_i up to $\mathcal{O}(\lambda^3)$
  [J. A. Bailey, YJ, Sunkyu Lee, WL, Jaehoon Leem, arXiv:2001.05590]
- Preliminary results implement up to $\mathcal{O}(\lambda^2)$ current improvement [S. Park et. al., arXiv:2002.04755]





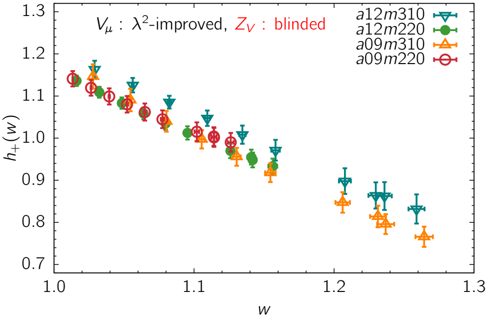
- lattice spacing dependence is mild in f_{D_s}/f_D, less clear in f_{B_s}/f_B
- $a12m130$ results are consistent with FLAG2019 (499 confs $\to$ 1000 confs.)
- noteworthy error reduction in f_{B_s}/f_B at $a = 0.06\,\mathrm{fm}$

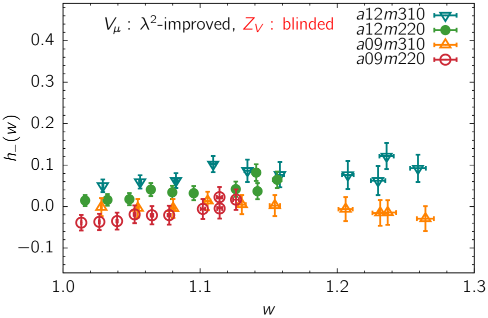
$B \to D\ell\nu$ Form Factors

$$\frac{\langle D(M_D, \mathbf{p}')|V_\mu|B(M_B, \mathbf{0})\rangle}{\sqrt{M_D}\sqrt{M_B}} = h_+(\omega)(v+v')_\mu + h_-(\omega)(v-v')_\mu$$

$$v = p/M_B = (1, \mathbf{0}), v' = p'/M_D = (E_D/M_D, \mathbf{p}'/M_D), \omega = v \cdot v' = E_D/M_D$$

- Preliminary results with $\mathcal{O}(\lambda^2)$ improved current V_μ [Y.-C. Jang et. al., arXiv:2003.09206]

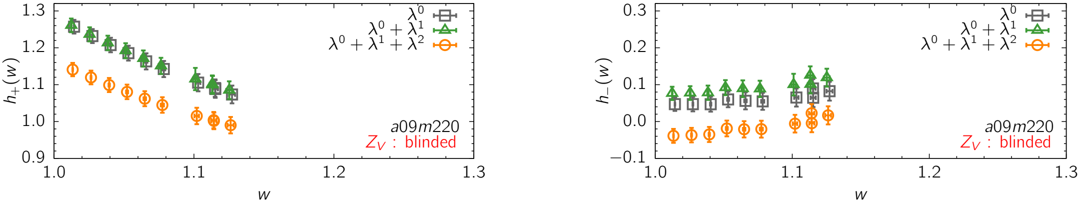




- Renormalization (matching) factor beside the tree-level $Z_V^{\text{tree}} = \exp((am_{1c} + am_{1b})/2)$ is expected to be small yet unknown
- nonperturbative calculation [RI-(s)MOM] is underway

$B \to D\ell\nu$ Form Factors

- Comparison of different current improvement orders (preliminary) [Y.-C. Jang et. al., arXiv:2003.09206]

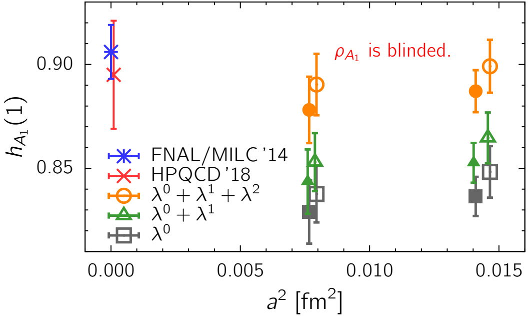


- $\mathcal{O}(\lambda^2)$ improved current is crucial
- other ensembles show similar shifts in $h_\pm(\omega)$ by $\mathcal{O}(\lambda^1)$ and $\mathcal{O}(\lambda^2)$ improvements

$h_{A_1}(\omega=1)$: $B \to D^*\ell\nu$ Form Factor at zero-reocil $\omega = 1$

$$\rho^2 \frac{\langle B|A^{bc}|D^*\rangle\langle D^*|A^{cb}|B\rangle}{\langle B|V^{bb}|B\rangle\langle D^*|V^{cc}|D^*\rangle} = |h_{A_1}(1)|^2\,, \quad \rho^2 = \frac{Z_A^{bc} Z_A^{cb}}{Z_V^{bb} Z_V^{cc}}\,,$$

- 4 matrix elements need for the double ratio are separately extracted from 3-pt correlators
- Preliminary results up to $\mathcal{O}(\lambda^2)$ improved currents A_μ, V_μ [Y.-C. Jang et. al., arXiv:2003.09206]



- The matching factor ρ_{A_1} is expected to be close to 1, yet blinded
- Current improvement is crucial
- Improved action and current operator are expected to give a mild dependence in a

Summary & Outlook

- Current improvement at $\mathcal{O}(\lambda^2)$ is crucial for the form factors, and the preliminary results are close to the continuum limit
- $\mathcal{O}(\lambda^3)$ current improvement is being implemented.
- Renormalization (matching) factor calculation is underway

- Improved action and current operator are expected to give a mild dependence in a.
- Analyzing more ensembles at physical pion mass or finer lattice spacing ($a = 0.06\,\mathrm{fm}$) will give us a better handle for chiral continuum extrapolation

- Statistics will be increased ($\times 8$) with truncated solver method with a bias correction

- $B \to D^* \ell \nu$ nonzero recoil data will be analyzed soon

- More excitements will come with updates from Belle II and LHCb + LQCD efforts

Thank you for your attention