

A lattice QCD perspective on weak decays of b and c quarks.

Snowmass 2022 whitepaper

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Whitepaper info

“A lattice QCD perspective on weak decays of b and c quarks”

- Currently 33 authors from 7 countries
(11 authors from US institutions)
- Project initiated by Oliver Witzel
- Co-editors: Oliver Witzel & ATL,
Significant input from members of the lattice community
- Handed over to RP frontier conveners
- Currently making final editing rounds, arXiv 2205.xxxx

Understanding B anomalies

- Ratios testing lepton flavor universality for tree-level decays such as $B \rightarrow D^{(*)}\ell\nu$
- Tests of lepton flavor universality for rare, loop-level decays such as $B \rightarrow K^{(*)}\ell^+\ell^-$
- Differences in certain q^2 bins/ranges for rare decay differential branching fractions e.g. $B \rightarrow K^*\ell^+\ell^-$, $B_s \rightarrow \phi\ell^+\ell^-$ and corresponding derived angular observables like P_5'
- Some tension in the branching fraction for the rare leptonic decay $B_s \rightarrow \mu^+\mu^-$
- Tension between exclusive and inclusive determinations of CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$

Heavy flavor physics

The current era of experiments (LHC, Belle II, BES III, ...) providing huge amount of new information.

- Increasing precision
- New channels
- More granular measurements

Lattice techniques give us systematically improvable tools to understand hadron physics.

- Determine CKM matrix elements
- SM predictions for R -ratios
- Differential quantities

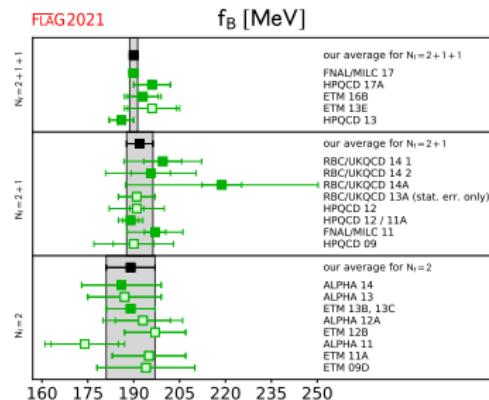
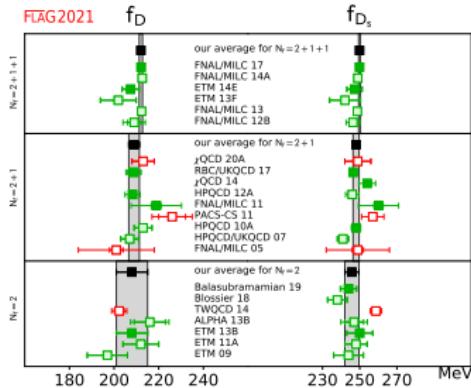
Outline

- Introduction
- Prospects and Challenges
 - ▶ Leptonic decays
 - ▶ Semileptonic decays
 - ▶ Meson mixing and lifetimes
 - ▶ b and c quark masses
 - ▶ Radiative decays
 - ▶ Inclusive decays
- Computational Resources

Leptonic decays - I

- Relatively straightforward to compute, with meson 2-point functions.
- Allow extraction of CKM matrix elements via leptonic decay measurements.
 - ▶ $f_D \rightarrow |V_{cd}| = 0.2173(47)_{\text{exp}}(28)_{\text{em}}(7)_{\text{latt}}$
 - ▶ $f_{D_s} \rightarrow |V_{cs}|$ (sl decays now competitive)
 - ▶ $f_B \rightarrow |V_{ub}|$
- $f_{B_{(s)}}$ used for SM prediction of rare processes $B_{(s)} \rightarrow \mu^+ \mu^-$
- In all cases lattice QCD uncertainties well below experimental uncertainties

Leptonic decays - II



- Sub-percent precision obtained, results from different collaborations in good agreement.
- To improve substantially requires including QED and strong-isospin breaking
- Substantial progress including QED corrections to these processes (cf radiative decays)

$$B_{(s)} \rightarrow \mu^+ \mu^- \text{ and } B \rightarrow \ell \nu$$

$$B_{(s)} \rightarrow \mu^+ \mu^-$$

- Highly suppressed FCNC process can give important constraints on new physics
- $\mathcal{B}(B_s \rightarrow \mu\mu)_{\text{SM}} = 3.64(4)_{f_{B_s}}(8)_{\text{CKM}}(7)_{\text{other}} \times 10^{-9}$
 $\mathcal{B}(B_s \rightarrow \mu\mu)_{\text{exp}} = 2.69(37) \times 10^{-9}$ ATLAS-CONF-2020-049
- $\mathcal{B}(B^0 \rightarrow \mu\mu)_{\text{SM}} = 1.00(1)_{f_B}(2)_{\text{CKM}}(2)_{\text{other}} \times 10^{-10}$
 $\mathcal{B}(B^0 \rightarrow \mu\mu)_{\text{exp}} < 1.6 \times 10^{-10}$

B leptonic decays

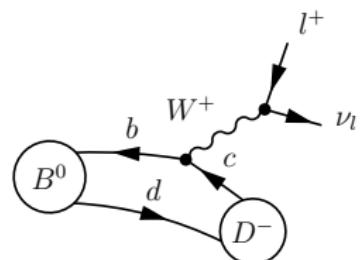
- $B \rightarrow \tau\nu$ may reach 3-5% precision at Belle II
- $B \rightarrow \mu\nu$ may reach $\sim 7\%$ precision at Belle II 1808.10567

Semileptonic decays - I

SL Decay processes critical inputs for heavy flavor studies.

Lattice predictions needed for:

- Extracting CKM matrix elements from expt'l measurements
- Pure SM predictions of R-ratios
- SM predictions $\frac{d\Gamma}{dq^2}$, etc.



Lattice calculations based on 2- & 3-point correlators give matrix elements $\rightarrow f_i(q^2)$

Semileptonic decays - II

Tree level decays:

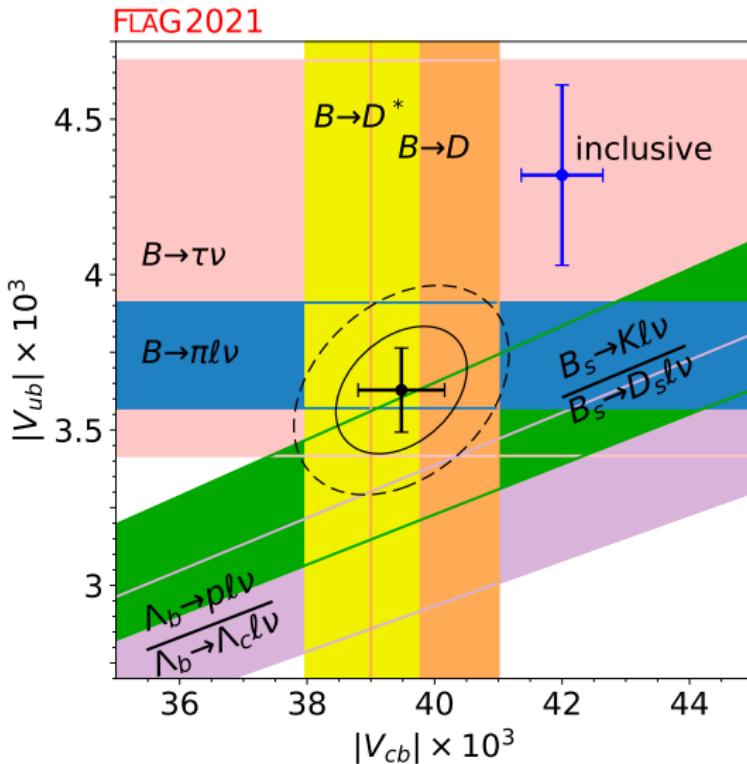
- $B \rightarrow D^{(*)} : \rightarrow |V_{cb}|$
- $B \rightarrow \pi : \rightarrow |V_{ub}|$
- $D \rightarrow K : \rightarrow |V_{cs}|$
- Baryon decays: $\rightarrow |V_{ub}|/|V_{cb}|$

Many different processes and results, can only highlight a few illustrative developments!

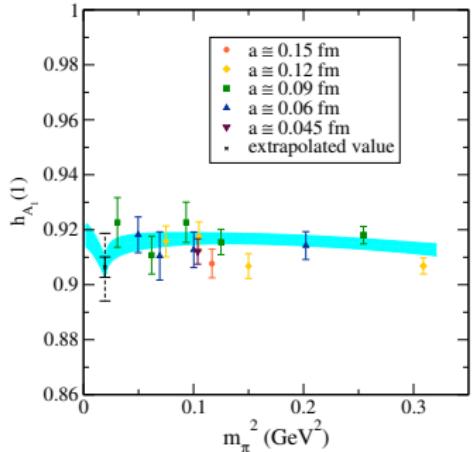
Loop level decays:

- Lattice form factors important for $B \rightarrow K\ell^+\ell^-$
- $B \rightarrow K^*\ell^+\ell^-$ requires recent theory developments in handling resonances/multi-hadron final states.

Semileptonic decays - III



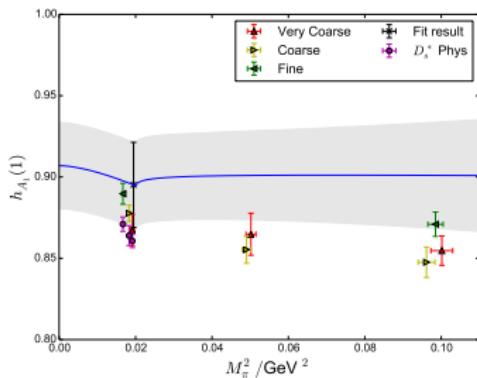
$B \rightarrow D^*$ at zero recoil from LQCD



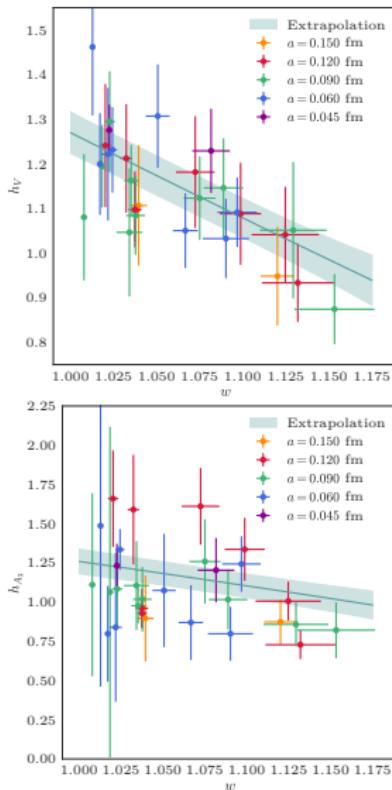
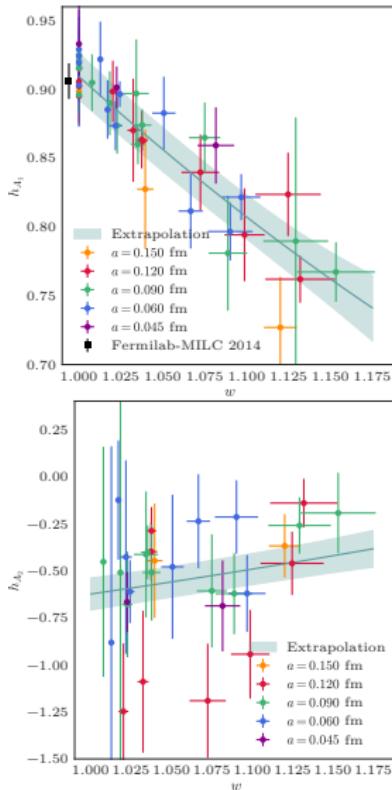
FNAL/MILC 1403.0635

- $n_f = 2 + 1$ MILC asqtad ensembles
- Clover b with Fermilab interpretation
- $h_{A_1}(1) = 0.906(4)(12)$

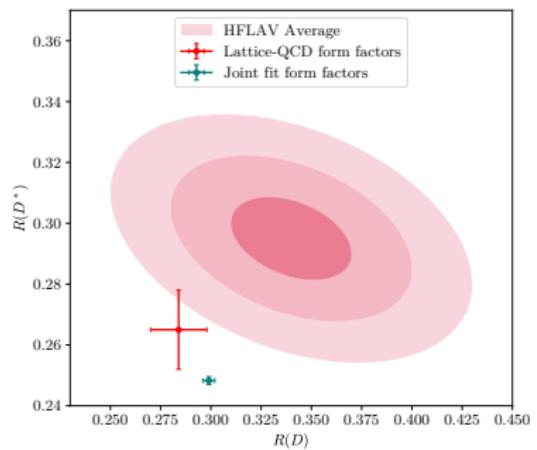
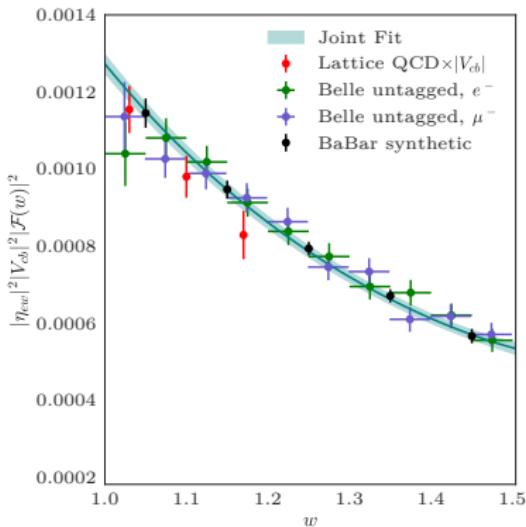
HPQCD 1711.11013



- $n_f = 2 + 1 + 1$ MILC HISQ ensembles
- NRQCD b quark
- $h_{A_1}(1) = 0.895(10)(24)$
- $h_{A_1}^s(1) = 0.883(12)(28)$



Figs. courtesy A. Vaquero



Figs. courtesy A. Vaquero

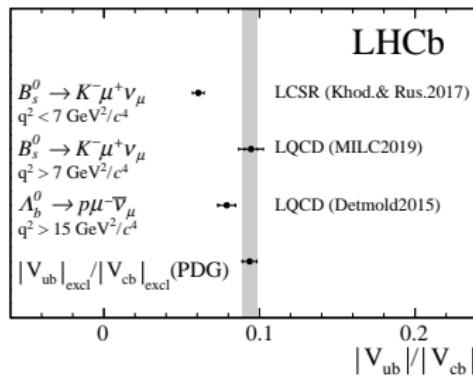
New set of measurements based on LHC Run 1 data.

- CLN: $|V_{cb}| = 41.4(6)_{\text{stat}}(9)_{\text{syst}}(12)_{\text{ext}} \times 10^{-3}$
- BGL: $|V_{cb}| = 42.3(8)_{\text{stat}}(9)_{\text{syst}}(12)_{\text{ext}} \times 10^{-3}$
- In this analysis, LQCD inputs improve statistical precision by 20% and 50% for CLN and BGL, respectively.

See also talk by Mirco Dorigo @LHCb2020

indico.cern.ch/event/856696/contributions/3742179/

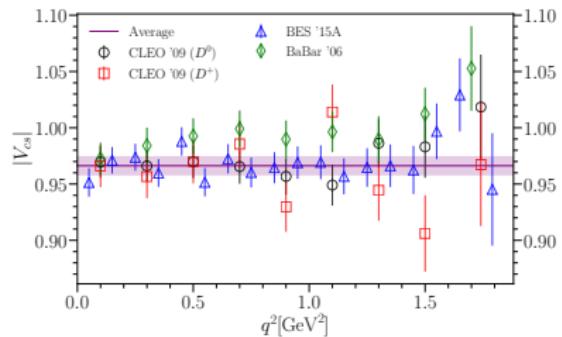
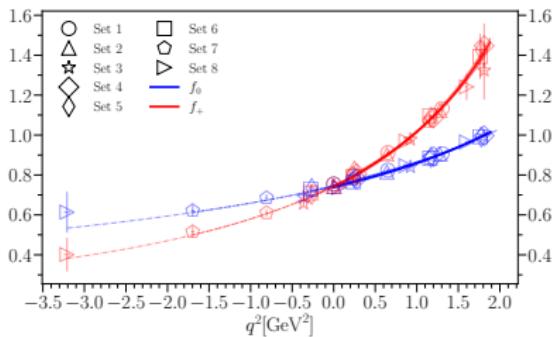
New CKM constraints from LHCb. Based on baryon decays
1504.01568, and first msm't of $B_s \rightarrow K \mu \nu$ 2012.05143.



Extractions use lattice form factor calculations of baryon decays ($\Lambda_b \rightarrow \Lambda_c$ and $\Lambda_b \rightarrow p$ 1503.01421) and $B_s \rightarrow K$ and $B_s \rightarrow D_s$ form factors, respectively.

$|V_{cs}|$ from $D \rightarrow K$

New result from HPQCD 2104.09883. See also ETMC calculations 1706.03017, 1706.03657, 1803.04807.



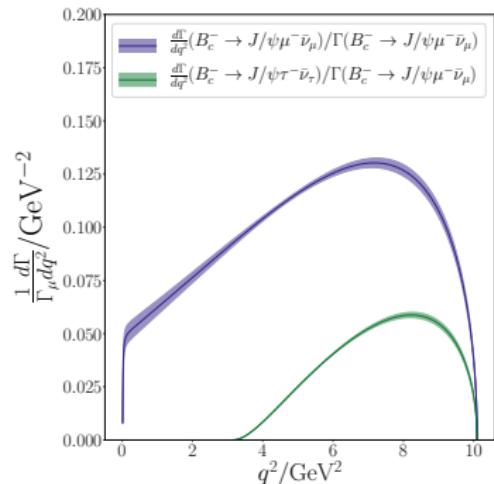
$$|V_{cs}| = 0.9663(53)_{\text{latt}}(39)_{\text{exp}}(19)_{\eta_{\text{EW}}}(40)_{\text{EM}}$$

Semileptonic determination of $|V_{cs}|$ now has smaller errors than leptonic determinations.

$R(B_c \rightarrow J/\psi)$

First lattice calculation of $B_c \rightarrow J/\psi$ 2007.06956
(All form factors across q^2 range)

- LHCb 1711.05623
 $R(J/\psi) = 0.71(17)\text{stat}(18)\text{syst}$
- w/in 2σ of theory range [0.25, 0.28]
- LQCD result: 0.2582(38)

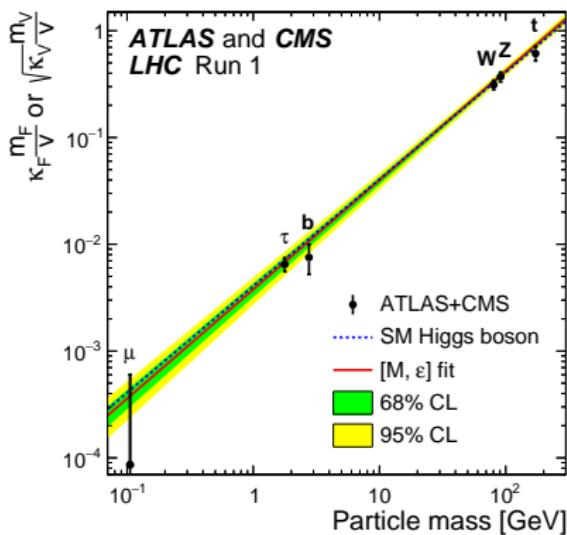


Semileptonic decays - Summary

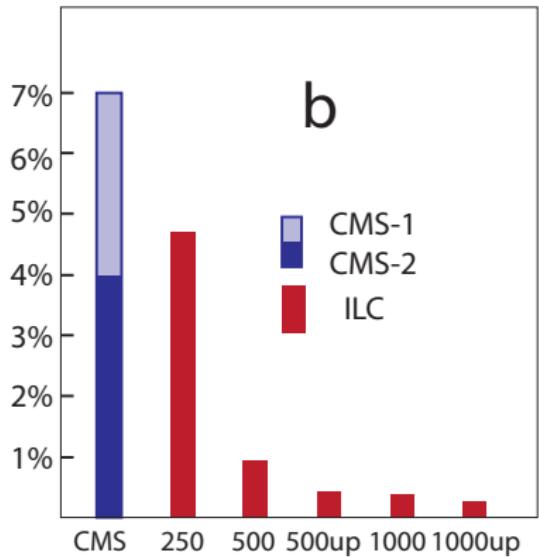
- Thus far, successful collaboration with experiment in the LHC era
 - ▶ Theory predictions for new channels
 - ▶ Improved kinematic range
 - ▶ Improved precision
- Lattice errors roughly commensurate with experimental errors. In the next 5 years or so, these should continue to improve and lattice error may become sub-dominant.
- To go beyond this requires adding EM and strong isospin breaking effects.

Quark masses - I

[1606.02266]



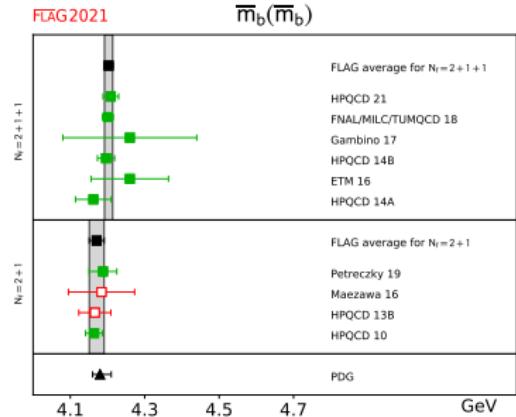
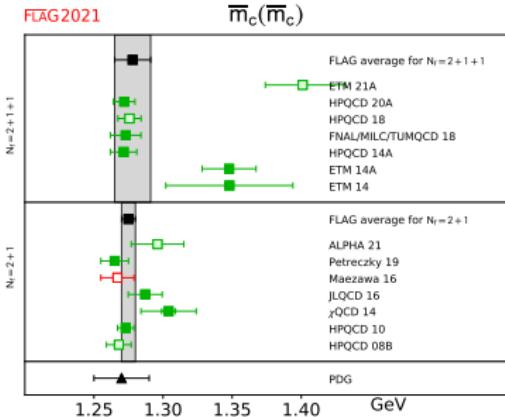
[1312.4974]



HL-LHC estimates $\sim 3\% h b\bar{b}$, evidence for charm CMS:2022cju

Est'd final ILC precision in $h b\bar{b}$ ($h c\bar{c}$) coupling: ~ 0.3 (0.7%).

Quark masses - II



- A variety of different methods, with different systematics, being used. See 2110.15090 for a recent review.
- FLAG averages 2111.09849 $N_f = 2 + 1 + 1$
 $m_b(m_b) = 4.203(11)$ GeV $m_c(3 \text{ GeV}) = 0.988(11)$

Quark masses - III

- Since CHARM 2015 - Highlights
 - ▶ Many new results: 13 since 2015, 4 since FLAG19.
 m_c : $6 \rightarrow 13$, $n_f = 3$: $5 \rightarrow 9$
 m_b : $4 \rightarrow 9$, $n_f = 4$: $5 \rightarrow 13$
 - ▶ From more collaborations → differing discretizations/lattice artifacts under control.
 - ▶ New techniques with different sources of systematic uncertainty.
- QED corrections are small ($\lesssim 0.2\%$ for charm).
- Precision continues to improve.
- Complementary techniques - good agreement at sub-percent level.

Radiative decays

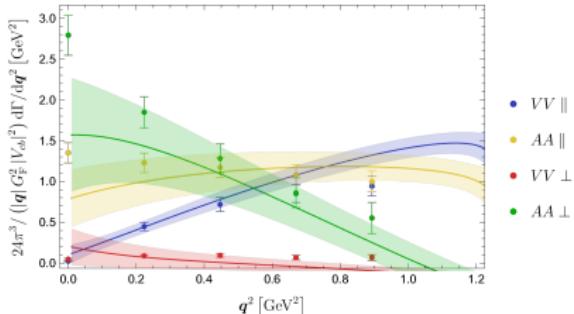
Progress including QED effects to hadronic processes,
e.g. $P \rightarrow \ell\nu_\ell[\gamma]$

- Determination of CKM elements at $\mathcal{O}(\alpha_{\text{em}})$ requires real photon amplitudes 1502.00257, 1904.08731
- For example, $|V_{cd}|$ and $|V_{cs}|$ from leptonic $D_{(s)}$ decays can be improved. Recent work: 2006.05358, 2110.13196
- Radiative decays lift helicity suppression.
 $\mathcal{B}(B_s \rightarrow \mu^+ \mu^- \gamma) / \mathcal{B}(B_s \rightarrow e^+ e^- \gamma)$ test LFU. 1708.02649
- Probes of internal hadron structure, e.g. λ_B from $B \rightarrow \ell\nu\gamma$

Inclusive decays from the lattice

- Long-standing tensions between inclusive and exclusive determinations of $|V_{ub}|$ and $|V_{cb}|$.
- Theoretically difficult problem: Extracting Minkowski-space spectral densities from finite-volume Euclidean correlation functions.

Several ideas put forth in recent years to overcome this hurdle.
New results comparing lattice data with OPE: 2203.11762



Computational resources

- Treating b quarks relativistically requires $am_b \lesssim 1$.
- Improved actions can help here (e.g. $a^2 \rightarrow \alpha_s a^2$)
- $M_\pi L = 7$ and $a = 0.04$ fm ($a^{-1} \approx 5$ GeV) \rightarrow $256^3 \times 512$ lattice size
- Decreasing a results in critical slowing down: new algorithmic advances and ideas needed

Post-exascale resources needed: See “Lattice QCD and the Computational Frontier” 2204.00039

Summary - I

- Lattice calculations provide a wealth of information for heavy flavor studies
- Allow CKM studies from a wide variety of exclusive processes
- Reliable SM predictions can help unravel the nature of B anomalies (R-ratios, differential info).
- Leptonic decays, lattice errors below expt'l uncertainties – EM corrections can further reduce errors.
- Semileptonic decays – many processes. Here uncertainties roughly commensurate between theory/expt. EM corrections may also be calculated.

Summary - II

- Quark masses sub-percent for m_c and m_b .
- Innovative directions using Euclidean QFT to expand what can be calculated.
 - ▶ Radiative decays and corrections
 - ▶ Decays to resonances and multi-hadron final states
 - ▶ Inclusive rates
- Computational perspective: Heavy quarks introduce an additional scale: $am_b \ll 1$, $m_\pi L \gg 1 \rightarrow L/a \gg m_b/m_\pi$. Post-exascale resources needed (hardware+software)

Thank you!

