Planned whitepaper:

Opportunities for lattice QCD in quark and lepton flavor physics

Christoph Lehner, Stefan Meinel, *et al.*

USQCD All Hands Meeting, Fermilab, April 2018

Current strategy for the white paper

- Focus on explaining why the physics is exciting and timely.
- Focus on future opportunities for lattice QCD. No exhaustive review of past results (only a few highlights).
- Do not write about computational requirements; leave this for the hardware proposal.

Discussion needed!

Draft outline for the white paper

I. EXECUTIVE SUMMARY

II. INTRODUCTION

- Motivation for searching for new physics in the flavor sector. Sensitivity to a wide range of BSM scenarios beyond the reach of direct searches.
- Track record & connection to experiments. U.S. leadership & experience. Involvement in theory initiatives. Work hand-in-hand with experimentalists to pursue the most promising leads.
- The precision goals for several quantities as set out in the previous whitepaper were achieved or exceeded.
- In this white paper we will outline future opportunities that could be exploited using our experience and expertise in precision flavor-physics calculations.

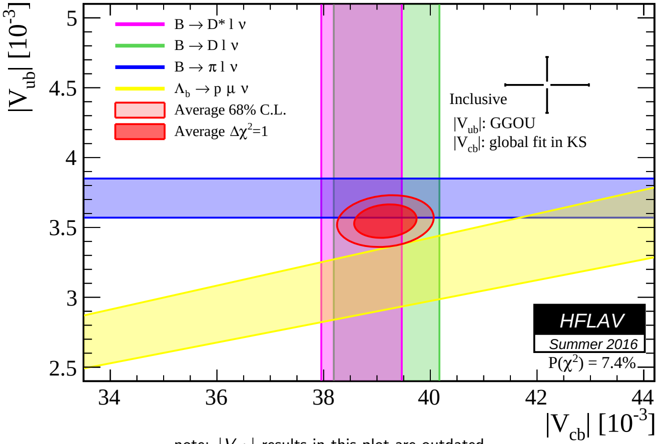
III. QUARK FLAVOR PHYSICS

IV. LEPTON FLAVOR PHYSICS

III. QUARK FLAVOR PHYSICS

Charged-current b decays

Exclusive-inclusive discrepancy in $|V_{qb}|$ as of 2016:



note: $|V_{cb}|$ results in this plot are outdated

Charged-current b decays

- $|V_{cb}|$ from $B \to D^{(*)}\ell\bar{\nu}$: $\lesssim 1\%$ experimental uncertainty expected from Belle II.
  [P. Urquijo, talk at "Challenges in semileptonic B decays," MITP, April 2018]

- Need precise form factors for $B \to D$ and $B \to D^*$ at nonzero recoil.

- Important issue: EM corrections.
  Recent work on leptonic decays: D. Giusti *et al.*, arXiv:1711.06537/PRL 2018

- Precise $|V_{cb}|$ is critical for the Standard-Model prediction of ε_K.

Charged-current b decays

$|V_{ub}|$ from $B \to \pi \ell \bar{\nu}$

$\mathcal{L}$	Year	Experiment	Theory[1]	Total
BaBar+Belle, $\approx 1\ \text{ab}^{-1}$	2016	2.5%	3.3%	4.1%
Belle II, $5\ \text{ab}^{-1}$	2020	1.2%	?	?
Belle II, $50\ \text{ab}^{-1}$	2024	0.9%	?	?

[1] BCL fit to Exp., Lattice QCD, LCSR

[A. Schwarz, Talk at HL LHC Workshop, Fermilab, April 2018]

$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\bar{\nu}$, $\Lambda_b \to \Lambda_c\mu\bar{\nu}$

$\mathcal{L}$	Year	Experiment	Lattice QCD	Total
LHCb, $2\ \text{fb}^{-1}$	2015	4.8%	4.9%	6.8%
LHCb, $8\ \text{fb}^{-1}$	2019	?	?	3.4%
LHCb, $50\ \text{fb}^{-1}$	2030	?	?	2.1%

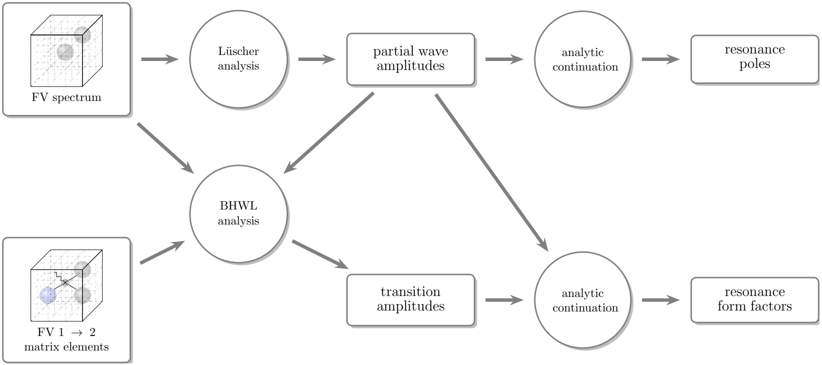
"we assume modest improvement to the uncertainty arising from lattice QCD"

[J. Albrecht *et al.*, arXiv:1709.10308]

Other $b \to u$ decay modes that need better (or first) form factor calculations:

- $B_s \to K\ell\bar{\nu}$ (LHCb)
- $B \to \pi\pi\ell\bar{\nu}$ (Belle II), in particular ρ contribution. Helps constrain right-handed currents.

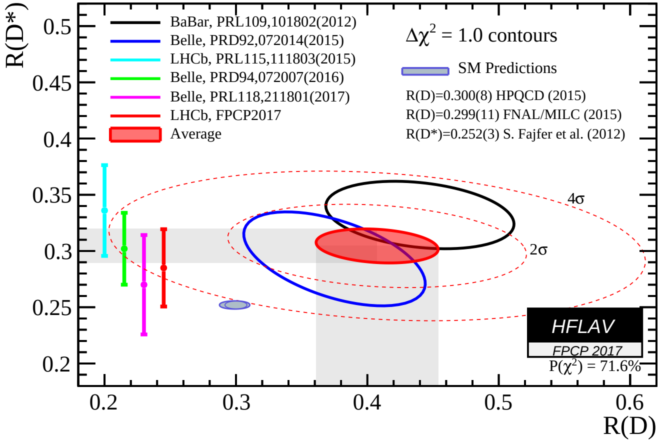
Formalism for $1 \to 2$ transition matrix elements ($B \to \pi\pi\ell\bar{\nu}$ etc.)



[R. Briceño, M. Hansen, A. Walker-Loud, arXiv:1406.5965/PRD 2015]

Charged-current b decays

$$R(D^{(*)}) = \Gamma(B \to D^{(*)}\tau\bar{\nu})/\Gamma(B \to D^{(*)}\ell\bar{\nu})$$



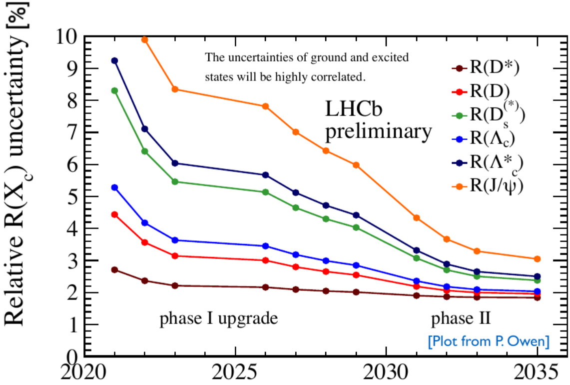
$\approx 4\sigma$ tension

Note: $R(D^*)$ SM prediction uses experimental data plus HQET; uncertainties are currently underestimated. Need LQCD FFs at nonzero recoil (underway).

Charged-current b decays

Belle II will focus on $R(D^{(*)})$.

LHCb will also measure analogous ratios for other species of hadrons:



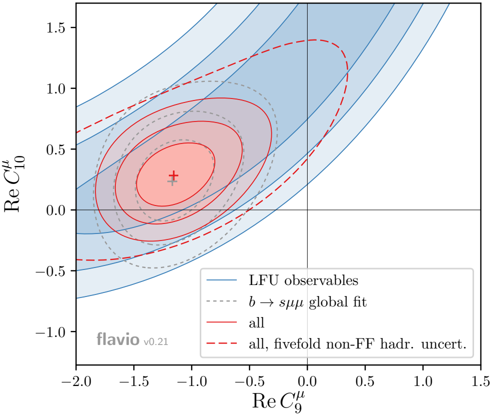
[G. Cohan, Talk at 2017 LHCb Implications Workshop]

Considering decays with hadrons of different spin allows to disentangle different BSM operators.

Form factors are needed from lattice QCD for all of these!

Neutral-current b decays

Fit of C_9^μ and C_{10}^μ (NP contributions for muons only) to mesonic $b \to s\ell^+\ell^-$ decay rates, angular distributions, and $R_{K^{(*)}} = \Gamma(B \to K^{(*)}\mu^+\mu^-)/\Gamma(B \to K^{(*)}e^+e^-)$



$\approx 4\sigma$ tension

[W. Altmannshofer, P. Stangl, D. M. Straub, arXiv:1704.05435/PRD 2017]

Simultaneous BSM explanations of $b \to s\mu^+\mu^-$ and $b \to c\tau\bar{\nu}$ anomalies are possible, e.g. $(3, 1, 2/3)$ vector leptoquark.
See, for example, D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, arXiv:1706.07808/JHEP 2017.

Neutral-current b decays

- $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ is the decay mode with the highest statistics, and also provides many angular observables. With 50 fb^{-1}, LHCb will reach $\sim 1.5\%$ precision for the branching fractions at both low and high q^2. [J. Albrecht *et al.*, arXiv:1709.10308]

- Even the μ/e ratios $R_{K^{(*)}}$ become strongly dependent on hadronic physics in the presence of lepton-flavor-universality-violating new physics.

- Form factors are needed from LQCD for:
  $B \to K$, $B \to K^*$, $B_s \to \phi$, $\Lambda_b \to \Lambda^{(*)}$, ...

- Proper treatment of K^* requires $B \to K\pi$ matrix elements using Briceño-Hansen-Walker-Loud formalism [arXiv:1406.5965/PRD 2015]

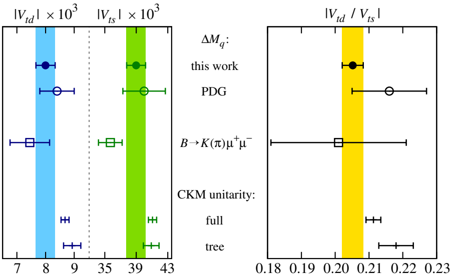
- $B \to K^{(*)}\bar{\nu}\nu$ does not have the problem with photon-mediated charm long-distance contributions. Belle II expected precision (assuming SM rate): 10%. May be significantly enhanced in BSM models.

Neutral $B_{(s)}$ meson mixing

BSM physics contributing to $b \to s\ell^+\ell^-$ decays may also affect B_s mixing.

The complete set of dimension-6 operators was computed by FNAL/MILC.

[A. Bazavov *et al.*, arXiv:1602.03560/PRD 2016]



$\sim 2\sigma$ "tension" with CKM unitarity.

- $\Delta M_{(s)}$: Theory uncertainty (from lattice QCD) is much larger than experimental uncertainty.
- $\Delta\Gamma_s$: Theory uncertainty is also much larger than experimental uncertainty. Dominated by matrix elements of dim-7 operators. First lattice calculation underway [M. Wingate, Lattice 2017; C. Davies *et al.*, arXiv:1712.09934].

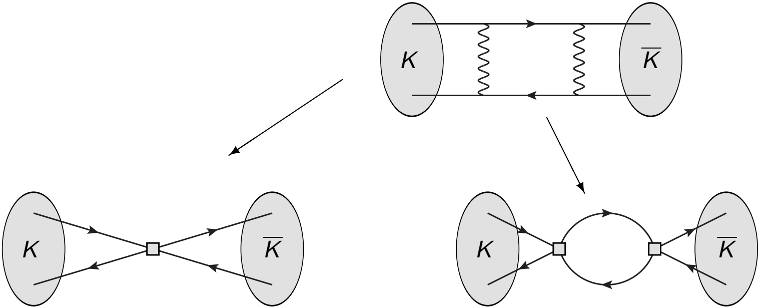
Neutral D meson mixing

Long-distance-dominated, but the short-distance matrix elements are still useful to constrain physics beyond the SM.

[A. Bazavov *et al.*, arXiv:1706.04622/PRD 2018]

Lattice calculation of long-distance contributions?

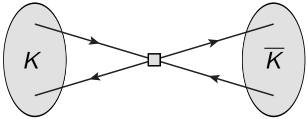
Neutral kaon mixing

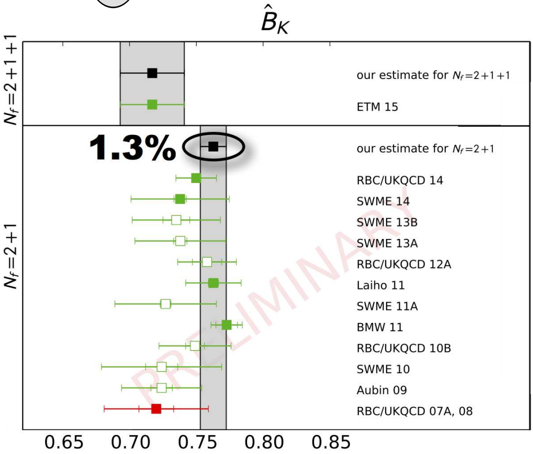


- Established lattice methodology, see next slide

- "Long-distance contribution" under active research
- Estimated to yield $\approx 5\%$ correction
- Non-local (bi-local) methodology has broad impact

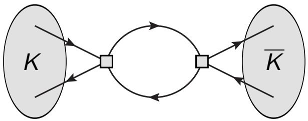
Neutral kaon mixing



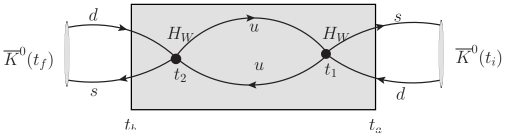


[FLAG preliminary 2015 summary as shown by Van De Water at EPS 2015]

Neutral kaon mixing



Long-distance methodology [N. Christ, 2011]



$$\mathcal{A} = \frac{1}{2}\sum_{t_1,t_2=t_a}^{t_b} \langle 0|T\{\overline{K}^0(t_f)H_W(t_2)H_W(t_1)\overline{K}^0(t_i)\}|0\rangle$$

Inserting a complete set of states, $T = t_b - t_a + 1 \Rightarrow$ 2nd order PT expression is accessible

$$\mathcal{A} = N_K^2 e^{-M_K(t_f-t_i)} \underline{\sum_n \frac{\langle\overline{K}^0|H_W|n\rangle\langle n|H_W|K^0\rangle}{m_K-E_n}} \left(-T + \frac{e^{(M_K-E_n)T}-1}{M_K-E_n}\right)$$

Challenges:

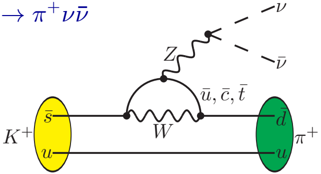
- Finite-volume effects
- Exponentially growing contributions
- Short-distance subtraction (more next)

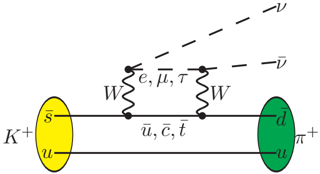
Applications:

- ΔM_K
- ε_K (B_K)
- rare K decays

Rare kaon decays, using new long-distance methodology

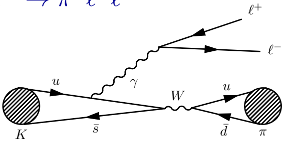
$K^+ \to \pi^+ \nu \bar{\nu}$





NA62 at CERN aims at $O(10\%)$ measurement of $\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu})$.

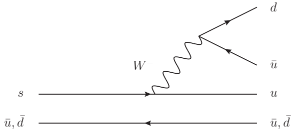
$K^+ \to \pi^+ \ell^+ \ell^-$



Well known from experiments, e.g. $\mathrm{Br}(K^+ \to \pi^+ e^+ e^-) = 3.00(9) \times 10^{-7}$ [PDG]

Long-distance dominated.

$K \to \pi\pi$



$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}.$$

$$\mathrm{Re}(\epsilon'/\epsilon) \approx \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{\pm}}\right|^2\right) = 16.6(2.3) \times 10^{-4} \quad \text{(experiment)}$$

measure of direct CPV

measure of indirect CPV

RBC/UKQCD 2015 SM prediction: $\varepsilon'/\varepsilon = 1.4(5.2)(4.4) \times 10^{-4}$

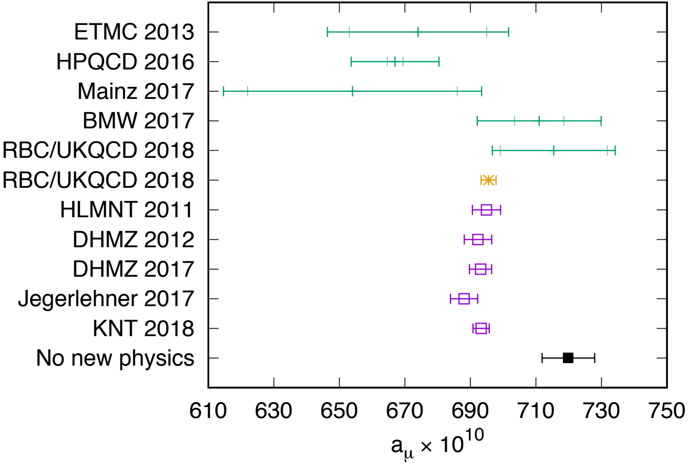
2σ "tension" with exp.

[Z. Bai *et al.*, arXiv:1505.07863/PRL 2015]

IV. (CHARGED-) LEPTON FLAVOR PHYSICS

Muon $g-2$

Using Glasgow consensus for HLbL, status of $(g-2)_\mu$ tension:



$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 27.4 \underbrace{(2.7)}_{\mathrm{HVP}} \underbrace{(2.6)}_{\mathrm{HLbL}} \underbrace{(0.1)}_{\mathrm{other}} \underbrace{(6.3)}_{\mathrm{EXP}} \times 10^{-10} \qquad 3.7\sigma$$

[T. Blum *et al.*, arXiv:1801.07224]

Muon $g-2$

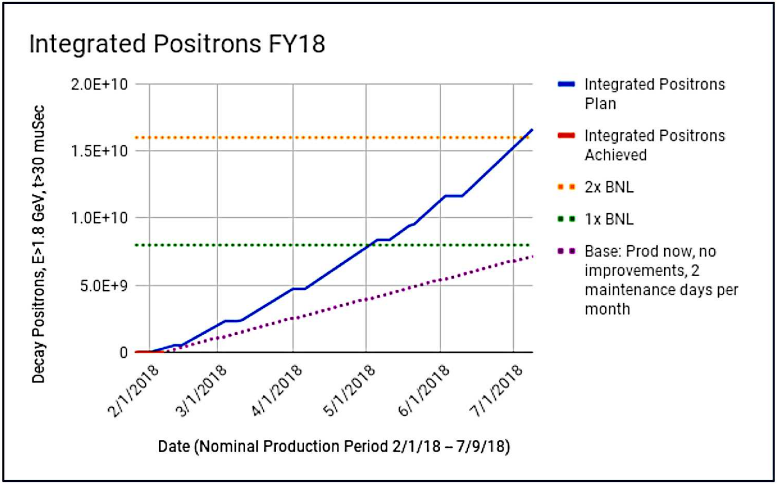
Cautionary remark:

Right now all precise HVP determinations shown on previous slide use local χ^2 inflation for experimental tension between BaBar and KLOE input data. Tension between those two data sets corresponds to a global shift of approximately 10×10^{-10} or about $3\times$ the current uncertainty.

Lattice calculations are urgently needed to check the numbers! This will be part of the $g-2$ theory initiative.

Muon $g - 2$

Fermilab E989 - Run plan



Anticipate experimental update with 1x–2x BNL statistics in spring 2019 (see also g-2 theory initiative effort)

Muon $g-2$

HLbL ongoing efforts

- a_μ^{HLbL} in finite-volume QCD and QED:
  - T. Blum *et al.*, arXiv:1510.07100/PRD 2016: Connected diagram with $m_\pi = 171$ MeV; $a_\mu^{\text{HLbL}} = 13.21(68) \times 10^{-10}$
  - T. Blum *et al.*, 1610.04603/PRL 2017: Connected and leading disconnected diagram with $m_\pi = 139$ MeV; $a_\mu^{\text{HLbL}} = 5.35(1.35) \times 10^{-10}$ (potentially large finite-volume systematics)

  Strategy: extrapolate away $1/L^n$ ($n \geq 2$) errors. Can we use effective theory to remove leading terms?

- a_μ^{HLbL} in finite-volume QCD and infinite-volume QED:
  - Method proposed and successfully tested against the lepton-loop analytic result:

    J. Green *et al.*, arXiv:1510.08384/Lattice2015, N. Asmussen *et al.*, arXiv:1609.08454/Lattice2016
  - Similar method plus subtraction scheme to reduce systematic errors; successfully tested against lepton-loop analytic result:

    T. Blum *et al.*, arXiv:1705.01067/PRD 2017

  Strategy: FV errors exponentially suppressed but still may be significant, effect on noise?

Muon $g - 2$

Further thoughts:

- JPARC ultra cold muon experiment likely will have at least BNL-level uncertainties in a few years

- Gabrielse electron g-2 experiment may soon be updated; currently hadronic uncertainties are 1/10 of experimental uncertainties

White paper: Current assignments

- Tom Blum: $K \to \pi\pi$ and muon $g - 2$
- Norman Christ: ΔM_K, long-distance contributions to ε_K, rare kaon decays
- Jack Laiho: "simple," precision observables in B and D physics, such as decay constants and $1 \to 1$ form factors (including $B_{(s)}$ mixing?)
- Ethan Neil: D meson mixing
- Stefan Meinel: Λ_b decays, $B \to \pi\pi\ell\bar{\nu}$, $B \to K\pi\ell\ell$
- Steve Sharpe: $K \to \pi\pi\pi$, nonleptonic D decays
- QED corrections to leptonic and semileptonic decays?
- Inclusive semileptonic B decays?

Questions

Reminder: current strategy:

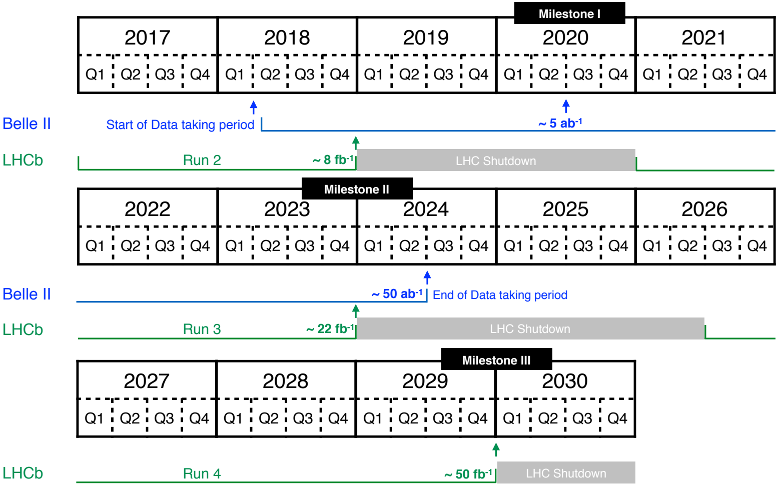
- Focus on explaining why the physics is exciting and timely.
- Focus on future opportunities for lattice QCD. No exhaustive review of past results (only a few highlights).
- Do not write about computational requirements; leave this for the hardware proposal.

What do you think about this?

Other questions:

- What topics are missing?
- Should we discuss the plans for generating new gauge field configurations?
- Should the different white papers have a similar structure?

EXTRA SLIDES



[J. Albrecht *et al.*, arXiv:1709.10308]