Scientific & Computational Challenges at the Intensity Frontier

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Based on 2013 white paper

LATTICE QCD AT THE INTENSITY FRONTIER

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Paul Mackenzie, Stephen Sharpe, Robert Sugar and Ruth Van de Water

(USQCD Collaboration)

SUMMARY

Lattice QCD calculations now play an essential role in the search for new physics at the intensity frontier. They provide accurate results for many of the hadronic matrix elements needed to realize the potential of present experiments probing the physics of flavor. The methodology has been validated by comparison with a broad array of measured quantities, several of which had not been well measured in experiment when the first good lattice calculation became available. In the US, this effort has been supported in an essential way by hardware and software support provided to the USQCD Collaboration.

This document has laid out an ambitious five year vision for future LQCD calculations, explaining how they can provide essential and timely information for upcoming experiments at the intensity frontier, by undertaking calculations of new, more computationally challenging, quantities. In addition, steady improvements in lattice results for matrix elements which are already well calculated will ensure that existing experimental results are fully utilized in the search for new physics. Our plans rely on continuing hardware and software support at similar levels to those of the last decade.

www.usqcd.org/documents/13flavor.pdf

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Input from experimentalists and phenomenologists

We gratefully acknowledge suggestions and comments from Marina Artuso, Brendan Casey, Tim Gershon, Enrico Lunghi, Bob Tschirhart and Jure Zupan.

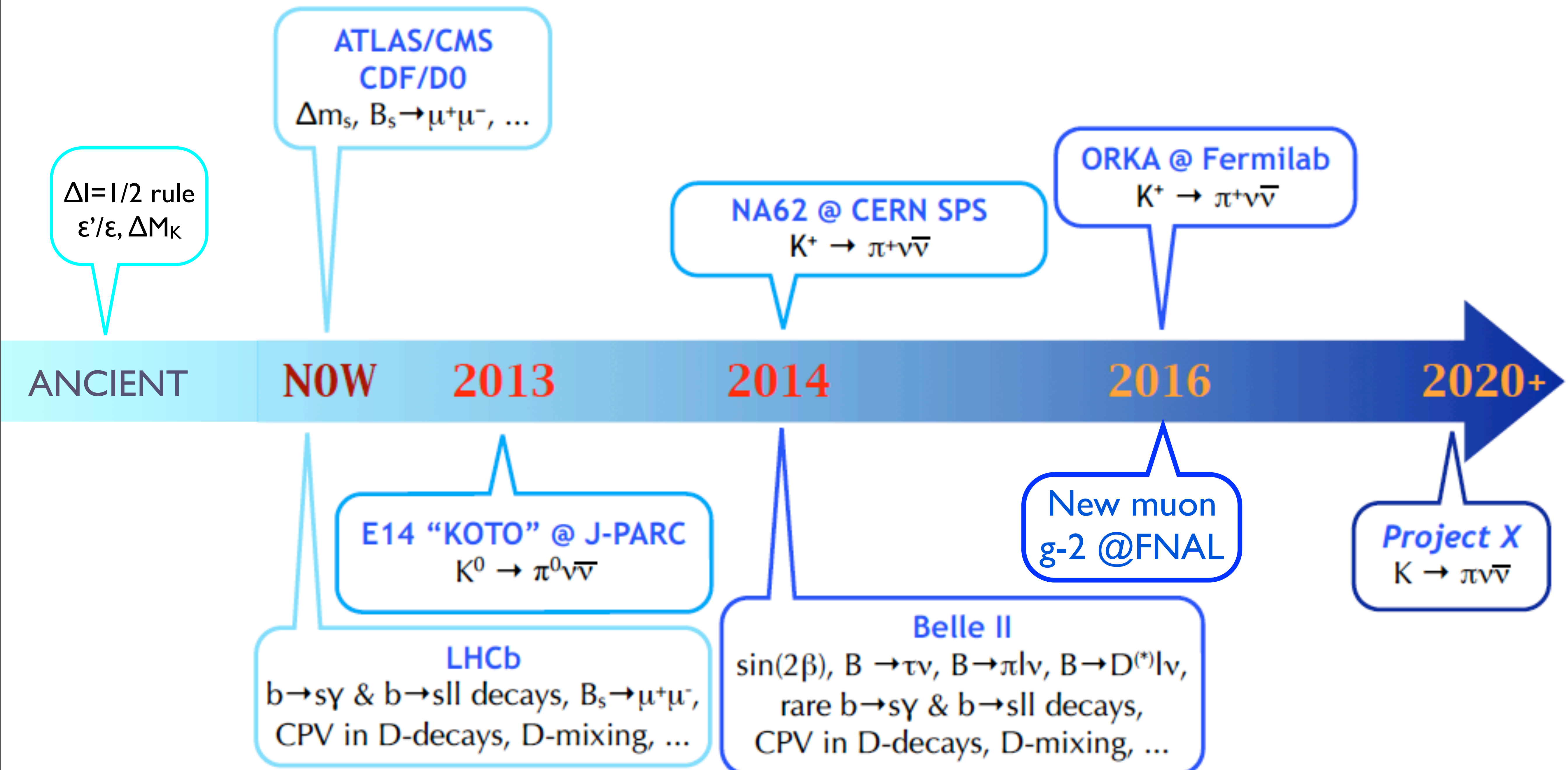
Outline

- Overall aims
- Present status
- 5-year plan
  - Doing standard (& closely related) calculations better
  - Calculating new quantities---methods pretty well known
  - Dreaming about new frontiers
- Draft computational plans

Aims

- Determine electroweak (& dark matter) matrix elements sufficiently accurately that searches for new physics in CKM fits, in rare decays, in extremely precise measurements (g-2, dipole moments, ...), and in dark matter experiments are limited by experimental rather than theory errors
- Prioritize our efforts so as to provide timely results for ongoing and planned experiments
- Determine fundamental parameters of standard model with every increasing accuracy (quark masses and Λ_{QCD})
- As precision improves, continue to cross-check methods with comparisons of spectrum with experiment & comparisons of different discretizations

Experimental vista (partial & optimistic)



Adapted from Ruth Van de Water

Present status

- Last 5 years have been a tremendous success!
- Large ensembles with N_f=2+1 for several fermion discretizations have allowed control of all errors
- In 2007, only fully controlled result was for f_K/f_π (error ~1%)
- In 2013, nearly 20 matrix elements are fully controlled with small errors
  - Decay constants: f_π, f_K, f_D, f_{Ds}, f_B, f_{Bs}
  - Form factors: $K\to\pi$, $D\to K$, $D\to\pi$, $B\to D$, $B\to D^*$, $B_s\to D_s$ & $B\to\pi$
  - Mixing matrix elements: B_K, B_B, B_{Bs}

Present status for "standard qties"

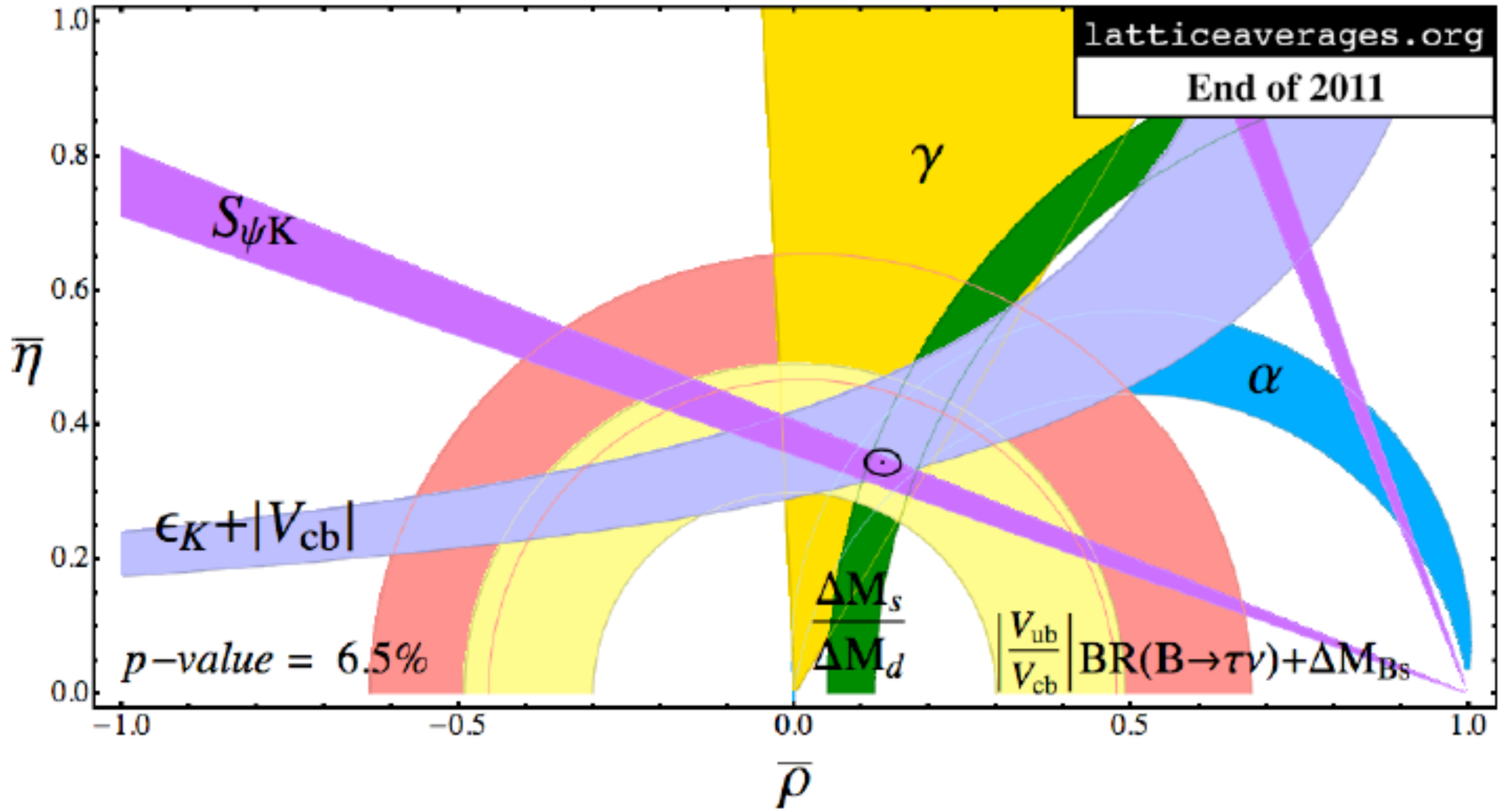
2013 white paper (already partly out of date!)

Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error
f_K/f_π	$\|V_{us}\|$	0.2%	0.5%	0.5%
$f_+^{K\pi}(0)$	$\|V_{us}\|$	0.2%	–	0.5%
f_D	$\|V_{cd}\|$	4.3%	5%	2%
f_{D_s}	$\|V_{cs}\|$	2.1%	5%	2%
$D \to \pi\ell\nu$	$\|V_{cd}\|$	2.6%	–	4.4%
$D \to K\ell\nu$	$\|V_{cs}\|$	1.1%	–	2.5%
$B \to D^*\ell\nu$	$\|V_{cb}\|$	1.3%	–	1.8%
$B \to \pi\ell\nu$	$\|V_{ub}\|$	4.1%	–	8.7%
f_B	$\|V_{ub}\|$	9%	–	2.5%
ξ	$\|V_{ts}/V_{td}\|$	0.4%	2-4%	4%
ΔM_s	$\|V_{ts}V_{tb}\|^2$	0.24%	7–12%	11%
B_K	$\mathrm{Im}(V_{td}^2)$	0.5%	3.5–6%	1.3%

- Forecasts met or exceeded
- Lattice error subdominant for some quantities (though experiments will improve)
- Substantial need for further improvement (particularly in B sector)

Forecasts assumed
10-50 TFlop-yrs
which is roughly correct

Lattice plays key role in CKM fit



Tension in fit motivates further work to reduce lattice errors

Future plan 1: improve standard q'ties

- Steadily improve calculations of standard matrix elements, in particular using:
  - Physical light-quark masses
  - Isospin breaking & EM effects (quenched?)
  - Charmed sea
  - Finer lattice spacings & improved actions (heavy quarks)
  - Improved statistical errors
  - Improved methods of normalizing operators (e.g. SMOM)

Forecasts

2013 white paper

Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error	2014 lattice error	2018 lattice error
f_K/f_π	$\lvert V_{us}\rvert$	0.2%	0.5%	0.5%	0.3%	0.15%
$f_+^{K\pi}(0)$	$\lvert V_{us}\rvert$	0.2%	–	0.5%	0.35%	0.2%
f_D	$\lvert V_{cd}\rvert$	4.3%	5%	2%	1%	$< 1\%$
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USQCD expects ~100 TFlop-yrs for all intensity frontier in 2013

Assuming ~1 PFlop-yrs

Forecasts

2013 white paper

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Very substantial progress possible
However, for subpercent accuracy, isospin breaking and EM effects enter, so forecasting not so straightforward

Forecasts

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Improved determination of V_{cb} key for reducing errors in CKM fit (ε_K) & for SM predictions for rare K decays (e.g. $K\to\pi\nu\nu$)

Forecasts

2013 white paper

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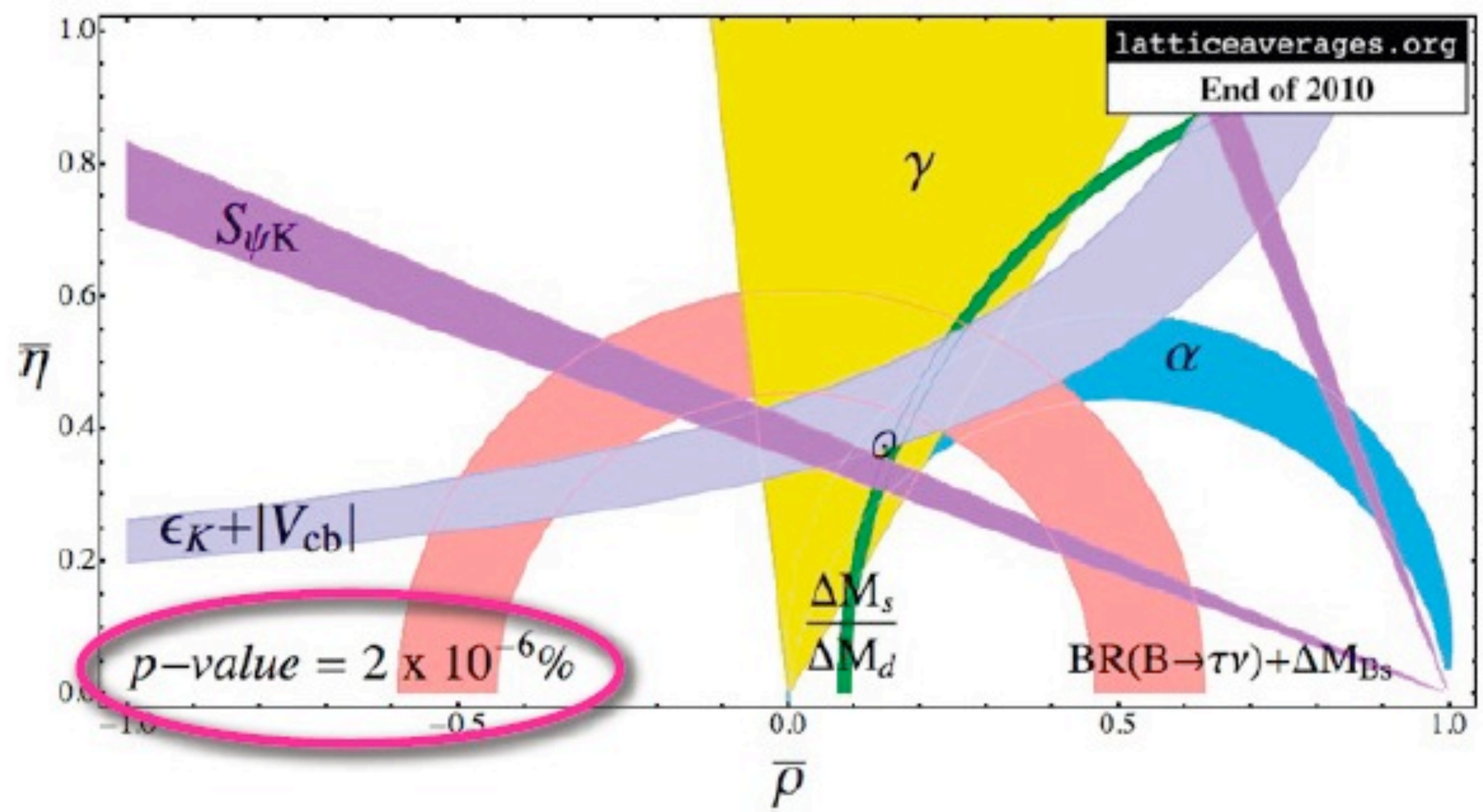
Improved determination of V_{ub} tightens CKM constraint & may help solve disagreement with inclusive (HQET) determination

Future CKM?

- Currently the constraints from ε_K, $\Delta M_s/\Delta M_d$, and $|V_{ub}/V_{cb}|$ are **limited by uncertainties in the lattice QCD calculations** of $|V_{cb}|_{excl.}$, ξ, and $|V_{ub}|_{excl.}$, respectively
- To illustrate the potential impact of future lattice calculations, reduce the lattice uncertainties to 1% with central values fixed, but keep experimental uncertainties fixed



- *Lattice QCD is poised to play a key role in discovering new physics in the flavor sector!*

[Van de Water, 2012]

Expanding our portfolio

Quantities that are straightforward to calculate

- Contributions of BSM physics to K, D & B-meson mixing
- $B \to K\, l^+ l^-$, $\Lambda_b \to \Lambda\, l^+ l^-$ and related form factors
- Nucleon beta-decay BSM form factors
- Nucleon EDM matrix elements (from SM and BSM theories)
- Nucleon-decay matrix elements (any takers?)
- Neutron-antineutron mixing
- Dark-matter-related nucleon matrix elements
- ...

Can achieve few-10% accuracy on few year timescale, which is commensurate with experimental program, and significantly enhances search for BSM physics

Plan 2: extend to new quantities

- Greater resources, plus new methods, allow significant expansion of reach of lattice calculations. Calculations at various stages of development.
  - $K \to \pi\pi$ decays: understand $\Delta I=1/2$ rule & predict ε'
    - Challenges: 2-particle states & disconnected diagrams. Pilot study completed.
    - I=0 channel requires special-purpose configurations (G-parity BC)
  - Muonic g-2: lattice calculation crucial for experimental success
    - Major challenge is "light-by-light" contribution requiring novel methods. Pilot study completed.
  - Long-distance part of ΔM_K (2nd order weak process)
    - Theory developed, pilot study completed.
  - Rare kaon decays involving 2nd order weak processes ($K \to \pi\nu\nu$, $K \to \pi l^+ l^-$)
    - Lattice can test model assumptions (e.g. pQCD controlled at m_c), and provide motivation for extending experimental program (to ee or $\mu\mu$ final states)
    - On the drawing board, but should be doable.

Plan 3: R&D

- Very challenging calculations where method not known
  - $D \to \pi\pi$, KK decays. Evidence for CP-violation puts us in the same situation as we've been in with ε' for decades: can we reliably predict the SM contribution?
    - Challenge is final states above elastic threshold (4π, 6π, etc.). Some progress with 3π case.
  - D-Dbar mixing (measured but not useful yet to constrain BSM physics)
    - Challenge: 2nd order weak process with inelastic intermediate states.
  - Non-leptonic B decays, e.g. $B \to D\pi$. Analysis of huge amount of data relies on factorization, which has significant corrections. No lattice method at present.
    - Any ideas?

Computational plans: DWF

Ensembles included in draft LQCD3 proposal

All quark masses physical; $m_\pi L \gtrsim 6$

No.	N_f	a(fm)	$N_s \times N_t$	Time units	TF years (configs.)	TF years (meas.)
#1	2+1	0.110	$48^3 \times 96$	2,500	90	60
#2	2+1	0.086	$64^3 \times 128$	2,500	95	70
#3	2+1+G	0.144	$32^3 \times 64$	4,000	90	50
#4	1+1+1+QED	0.110	$48^3 \times 96$	2,500	130	90
#5	1+1+1+QED	0.086	$64^3 \times 128$	2,500	145	100
#6	2+1	0.057	$96^3 \times 192$	1,800	320	220
#7	2+1+1	0.057	$96^3 \times 192$	1,800	320	220
#8	2+1+1	0.043	$128^3 \times 256$	1,400	1,050	750
Total DWF intensity frontier resource estimate						3,800

Computational plans: HISQ

Ensembles included in draft LQCD3 proposal

All quark masses physical; $m_\pi L \gtrsim 6$

N_f	a (fm)	m_u/m_d	$N_s^3 \times N_t$	Configuration generation (TF years)	Pseudoscalar measurements (TF years)
2+1+1	0.060	1.00	$96^3 \times 192$	14	24
2+1+1	0.045	1.00	$128^3 \times 256$	72	100
2+1+1	0.030	1.00	$192^3 \times 384$	650	760
1+1+1+1+QED	0.060	0.44	$96^3 \times 192$	32	56
1+1+1+1+QED	0.045	0.44	$128^3 \times 256$	170	240
Total HISQ intensity frontier resource estimate					2,118

Dynamical b-quark attainable?

Summary & Questions

- Balance of steady improvements & new calculations
  - Will inclusion of EM effects be straightforward?
  - Need to understand impact of dynamical charm on B_K, ε', etc.
- We need to monitor progress carefully on those quantities most time-sensitive for experiments, e.g. g-2
  - Are there any ways we could stimulate further efforts?
- Are the suggested ensembles the best choice?
  - Should we use a very fine lattice for b-quarks with u & d not at their physical values?