Progress and Prospects

In Lattice Gauge Theory

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for

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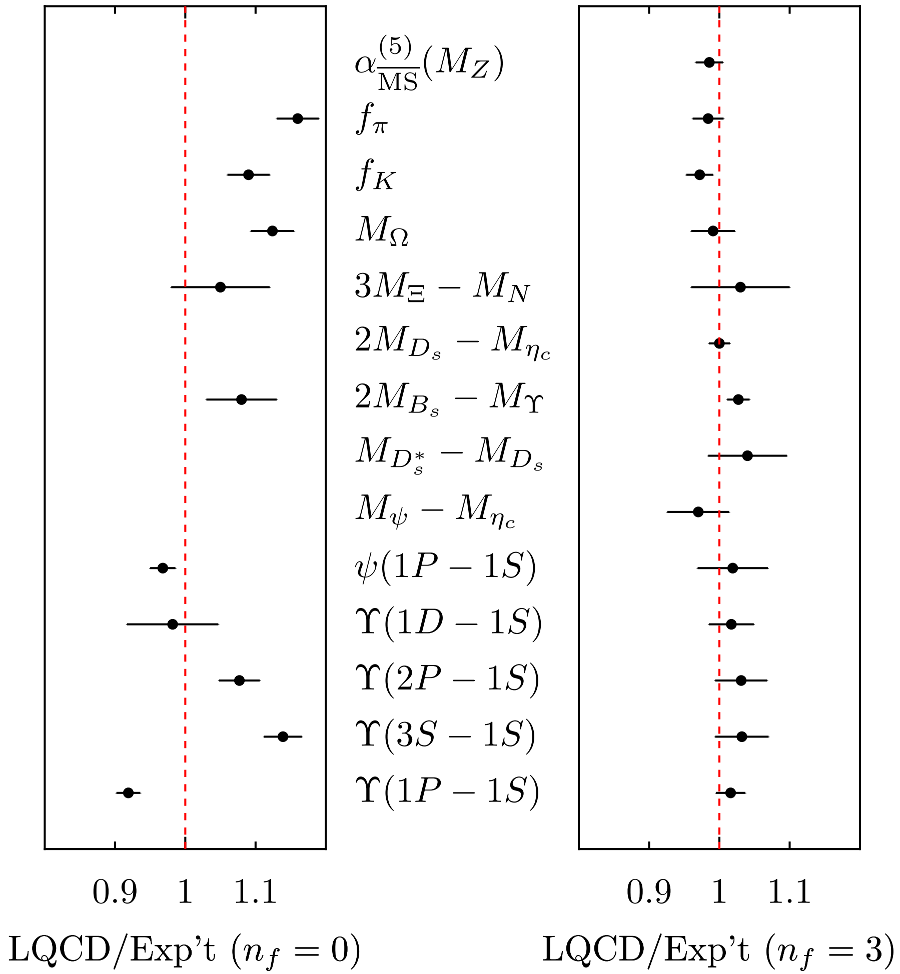
Background

- In February, 2004 I made a presentation to HEPAP outlining the plans of the U.S. lattice gauge theory community to acquire dedicated computers for the study of QCD.
- HEPAP's judgment that lattice QCD calculations could play a valuable role in high energy physics was instrumental in the DOE's decision to fund dedicated hardware.
- A great deal of progress has been made in lattice QCD over the last several years, in no small part because of the availability of dedicated hardware.

Status of Lattice QCD Calculations

- Lattice QCD calculations have reached the point where some quantities have been calculated to an accuracy that equals or exceeds that of the corresponding experiments, providing checks of our methods.
- A limited number of predictions have been made, which were later confirmed by experiment.
- New algorithms, new formulations of QCD on the lattice, software developed under the DOE's SciDAC program, and rapid increases in computing power will enable accurate determination of a wide range of important quantities in coming years.

Some Comparisons with Experiment

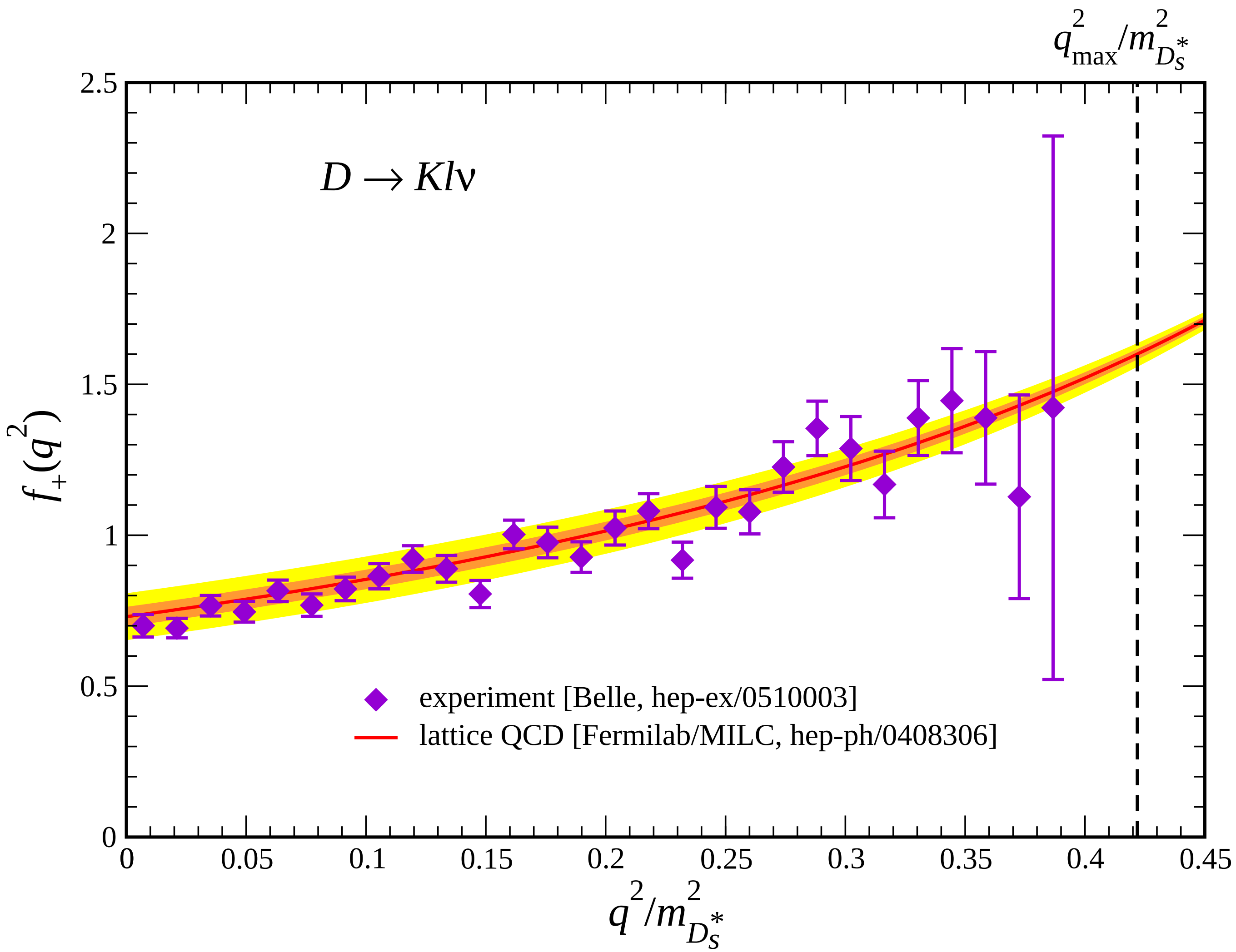


The ratio of various quantities calculated on the lattice to their experimental values in the quenched approximation (left panel) and in full QCD with up, down and strange sea quarks (right panel).

Predictions Verified by Experiment

Quantity	Lattice QCD	Experiment
$\mathbf{f_D}$	$\mathbf{201 \pm 3 \pm 17}$ MeV	$\mathbf{223 \pm 17 \pm 3}$ MeV
$\mathbf{f_{D_s}/f_D}$	$\mathbf{1.21 \pm 0.01 \pm 0.04}$	$\mathbf{1.27 \pm 0.12 \pm 0.03}$
$\mathbf{m_{Bc}}$	$\mathbf{6304 \pm 22}$ MeV	$\mathbf{6286 \pm 5}$ MeV
$\mathbf{f_B}$	$\mathbf{216 \pm 22}$ MeV	$\mathbf{229 \pm 36 \pm 34}$ MeV

Semileptonic Form Factor of the D Meson



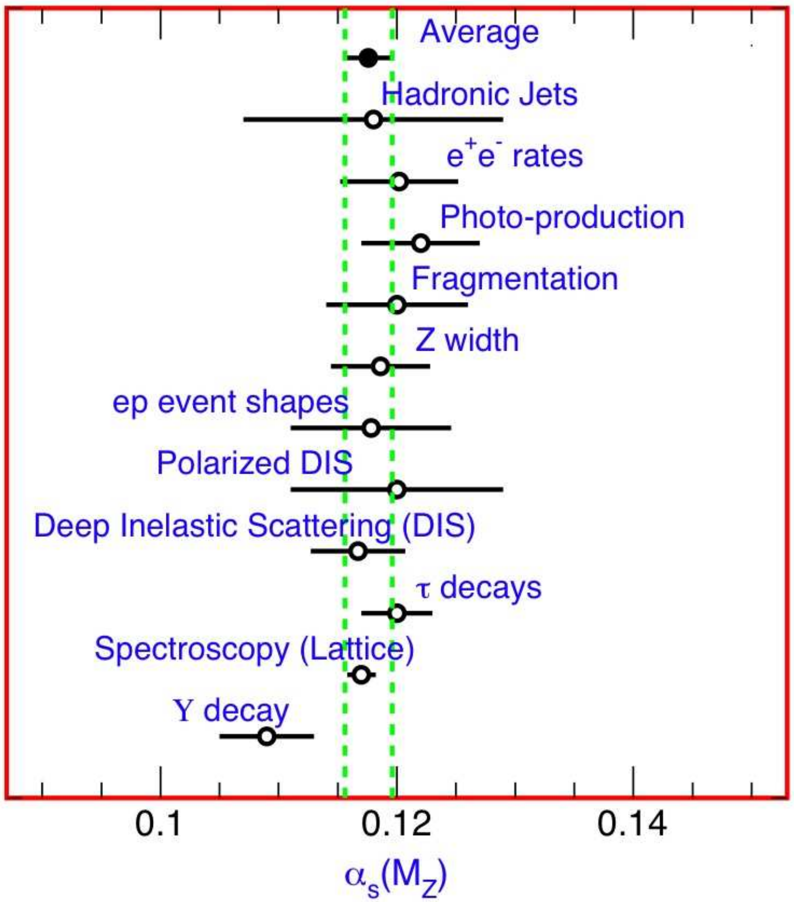
Prediction of the semileptonic form factor for the decay $\mathbf{D}^+ \to \mathbf{Kl}\nu$ by the Fermilab Lattice and MILC Collaborations.

Areas of Focus

- The determination of fundamental parameters of the Standard Model, and precision tests of the Standard Model.
- Theories for Physics Beyond the Standard Model.
- QCD at nonzero temperature and density.
- The spectrum, internal structure, and interactions of hadrons.

Fundamental Parameters

Strong Coupling Constant



Lattice value: $\alpha_{\mathbf{s}}(\mathbf{m_Z}) = \mathbf{0.1170 \pm 0.0012}$ (HPQCD Collaboration).

World average of perturbative QCD determinations: $\alpha_{\mathbf{s}}(\mathbf{m_Z}) = \mathbf{0.1185 \pm 0.0015}$ (PDG).

Quark Masses

- Quark masses $\mathbf{m_u}$, $\mathbf{m_d}$, $\mathbf{m_s}$, $\mathbf{m_c}$, and $\mathbf{m_b}$.
  - Provide input to beyond the Standard Model physics.
  - Have been calculated to an accuracy of 6% to 10%, and errors are expected to be reduced to the one percent level in the next few years.
- Some recent results (MILC Collaboration):

$$\mathbf{m_s = 88(0)(3)(4)}\ \text{MeV}$$

$$\mathbf{\hat{m} = \frac{1}{2}(m_u + m_d) = 3.2(0)(1)(2)}\ \text{MeV}$$

$$\mathbf{m_s/\hat{m} = 27.2(1)(3)(0)}$$

Errors are (statistical)(systematic)(perturbative).

- The conventional quark model value of $\mathbf{m_s = 150}$ MeV is clearly not tenable.

Weak Interaction Matrix Elements

- Lattice determinations of weak interaction matrix elements can lead to accurate determinations of CKM matrix elements, precise tests of the Standard Model, and constraints on the nature of new physics that are complementary to the direct searches of the LHC.
- We have only recently obtained full control of all sources of systematic errors for some matrix elements, while such control is still to be obtained for others. As work progresses, the magnitude of our systematic errors decrease, and the reliability of our estimates of these errors increases.
- The work to date provides confidence that we can calculate weak matrix elements accurately, but the era of precision testing of the CKM paradigm by lattice calculations is just beginning.

Determination of CKM Matrix Elements

Quantity	CKM element	present expt. error	present lattice error	2009 lattice error	2014 lattice error	error from non-lattice method
f_K/f_π	V_{us}	0.3%	0.9%	0.5 %	0.3%	–
$f_{K\pi}(0)$	V_{us}	0.4%	0.5%	0.3%	0.2%	1% (ChPT)
$D \to \pi\ell\nu$	V_{cd}	3%	11%	6%	4%	–
$D \to K\ell\nu$	V_{cs}	1%	11%	5%	2%	5% (ν scatt.)
$B \to D^*\ell\nu$	V_{cb}	1.8%	2.4%	1.6%	0.8%	$< 2\%$ (Incl. $b \to c$)
$B \to \pi\ell\nu$	V_{ub}	3.2%	14%	10%	4%	10% (Incl. $b \to u$)

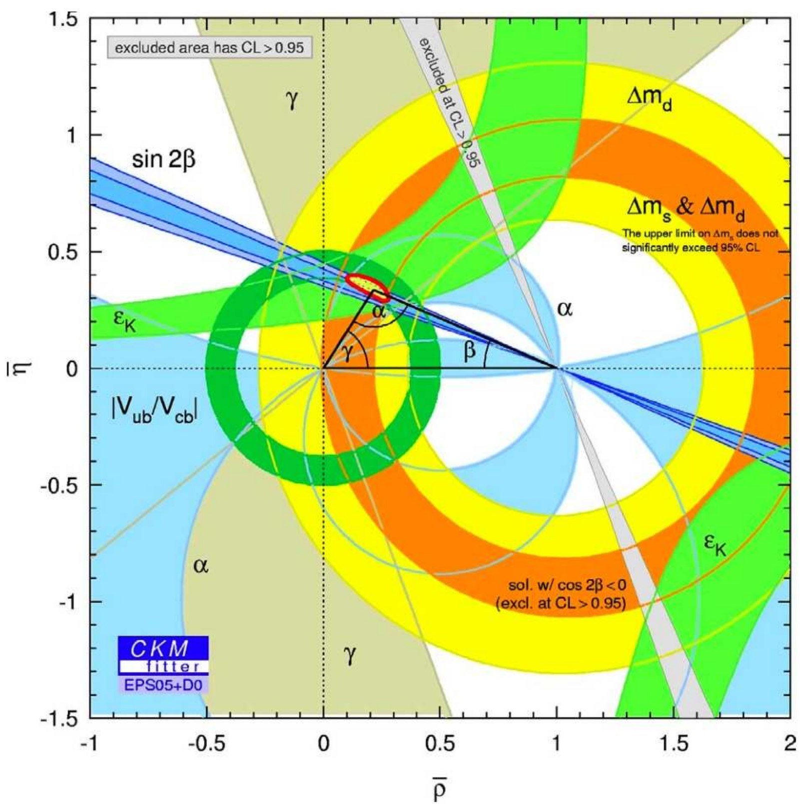
Present status and future prospects for lattice calculations which directly determine elements of the CKM matrix. All errors are quoted for the CKM elements themselves. Estimates are from the contributions of Juettner, Laiho, Lüth, Shipsey, and van de Water to the recent workshop Lattice QCD Meets Experiment. The last column, if present, shows the present error attainable on the CKM element using competing, non-lattice approaches.

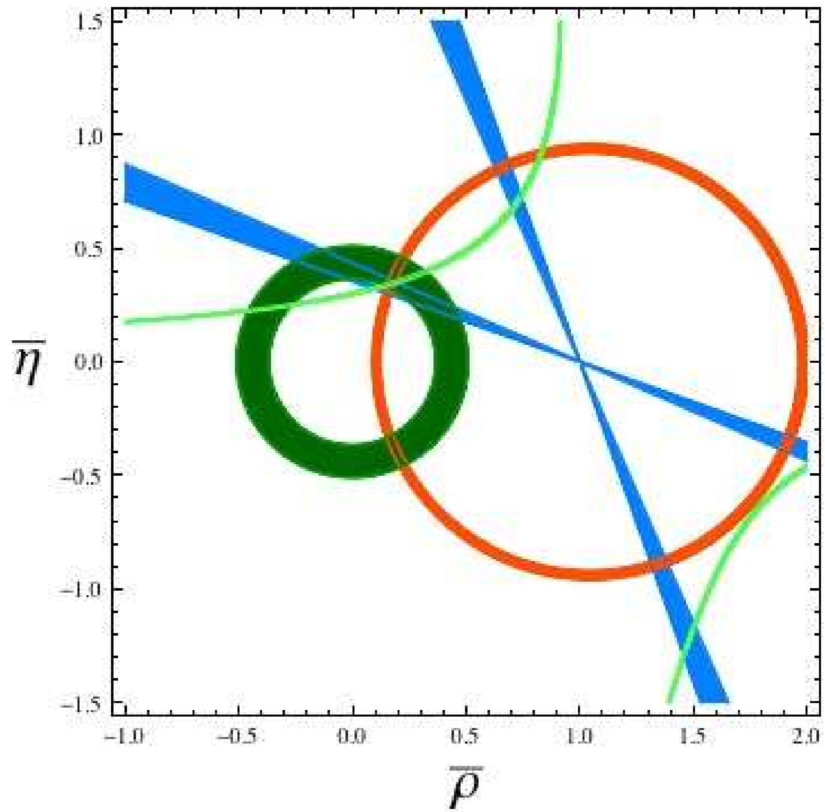
Meson Mixing

Hadronic Matrix Element	UT results current	Lattice results current	Lattice errors 2009	Lattice errors 2014
$\widehat{B}_K$	0.78 ± 0.09	0.77 ± 0.05	± 0.025	± 0.01
$f_{B_s}\sqrt{\widehat{B}_{B_s}}$	261 ± 6 MeV	282 ± 21 MeV	± 10 MeV	± 5 MeV
ξ	1.25 ± 0.06	1.23 ± 0.06	± 0.02	± 0.01

Status of and prospects for lattice calculations of meson mixing matrix elements which play a key role in the determination of CKM matrix elements. The column labeled UT are the "predictions" for the matrix elements from unitarity triangle fits assuming that the Standard Model is correct. The prospective improvement of the lattice calculations will allow a test of the Standard Model at the 1% level.

Impact on $\rho - \eta$ Bounds





The left panel shows the constraints on the $\rho - \eta$ plane with today's experimental and theoretical errors, the right panel the constraints with today's experimental and future theoretical errors.

International Standing

“In the area of weak-matrix elements and fundamental parameters, the committee found that the USQCD is leading the world competition, making a very efficient use of computational resources which are not superior to, but more or less competitive with, those in the rest of the world (without LQCD this would not be the case).”

The 2007 LQCD Computing Project Review Report

Lattice Gauge Theory for Physics Beyond the Standard Model

Status of BSM Calculations

- Experiments at the LHC are likely to focus interest on strongly coupled field theories that go beyond the Standard Model.
- Methods for studying such theories are not as well established as those for QCD, but exploratory studies are in progress.
- The parameter space to be studied is likely to be much larger than for the Standard Model, but the accuracy required will initially be much less stringent.

Roles for Lattice Gauge Theory in BSM Physics

- If the Higgs is discovered at the LHC without other new particles, then lattice studies of the Higgs–Top system, could shed new light on the structure of the Standard Model, and the energy scale at which new physics is to be expected.
- If supersymmetry is discovered at the LHC, then lattice calculations could determine the SUSY breaking mechanism and the particle spectrum, thereby helping to distinguish among competing supersymmetric models.
- If new strong dynamics for electroweak symmetry breaking is discovered at the LHC, then lattice studies can help to distinguish among the wide range of gauge theories that have been proposed for this scenario.
- Exploratory work is in progress in each of these areas.

USQCD Infrastructure Projects

USQCD Goals

- The USQCD Collaboration consists of nearly all of the high energy and nuclear physicists in the United States involved in the numerical study of Lattice QCD. Membership is open to all physicists based in the United States.
- USQCD was formed nine years ago with the goal of developing the computational infrastructure needed for the study of Lattice QCD and other strongly coupled lattice field theories of interest in high energy and nuclear physics.
- USQCD software is publicly available, and its hardware is open to all of its members on a peer reviewed basis.
- We build infrastructure as a community, but do science in groups or as individuals.

USQCD Software

- SciDAC I grant (2001 – 2006)
  - Development of the QCD API which enables lattice gauge theorists to write highly efficient, portable code.
  - Development of prototype clusters optimized for lattice QCD (1.65 teraflop/s sustained now in operation).
- SciDAC II grant (2006 – 2011)
  - Optimization of the QCD API for BlueGene, Cray and clusters base on multi-core processors.
  - Physics toolbox containing sharable codes.
- SciDAC software is widely used in the US and abroad.

USQCD Hardware Projects

- Construction of the QCDOC (2004 – 2005)
  - Computer specially designed for lattice gauge theory by a group of physicists centered at Columbia University.
  - Sustains 4.2 teraflop/s.
  - In the direct design line of the IBM BlueGene computers.
- LQCD Computing Project (2006 – 2009)
  - Clusters which sustain 6.2 teraflop/s are in production use at FNAL and TJNAF.
  - A cluster estimated to sustain 6.2 teraflop/s is planned for installation at FNAL in 2008–2009.

LQCD II Proposal

- USQCD has proposed a new hardware project for the period 2010 – 2014.
- In order to meet our scientific goals during this period a mixture of access to the DOE's Leadership Class computers and acquisition of dedicated hardware is needed, with roughly equal numbers of cycles coming from each class of machine.
- The plan calls for sustaining over 200 teraflop/s on each class of computer by its final year.
- The panel that recently reviewed our proposal expressed strong support during the exit interview.