

# The Fermilab Lattice Gauge Theory Project

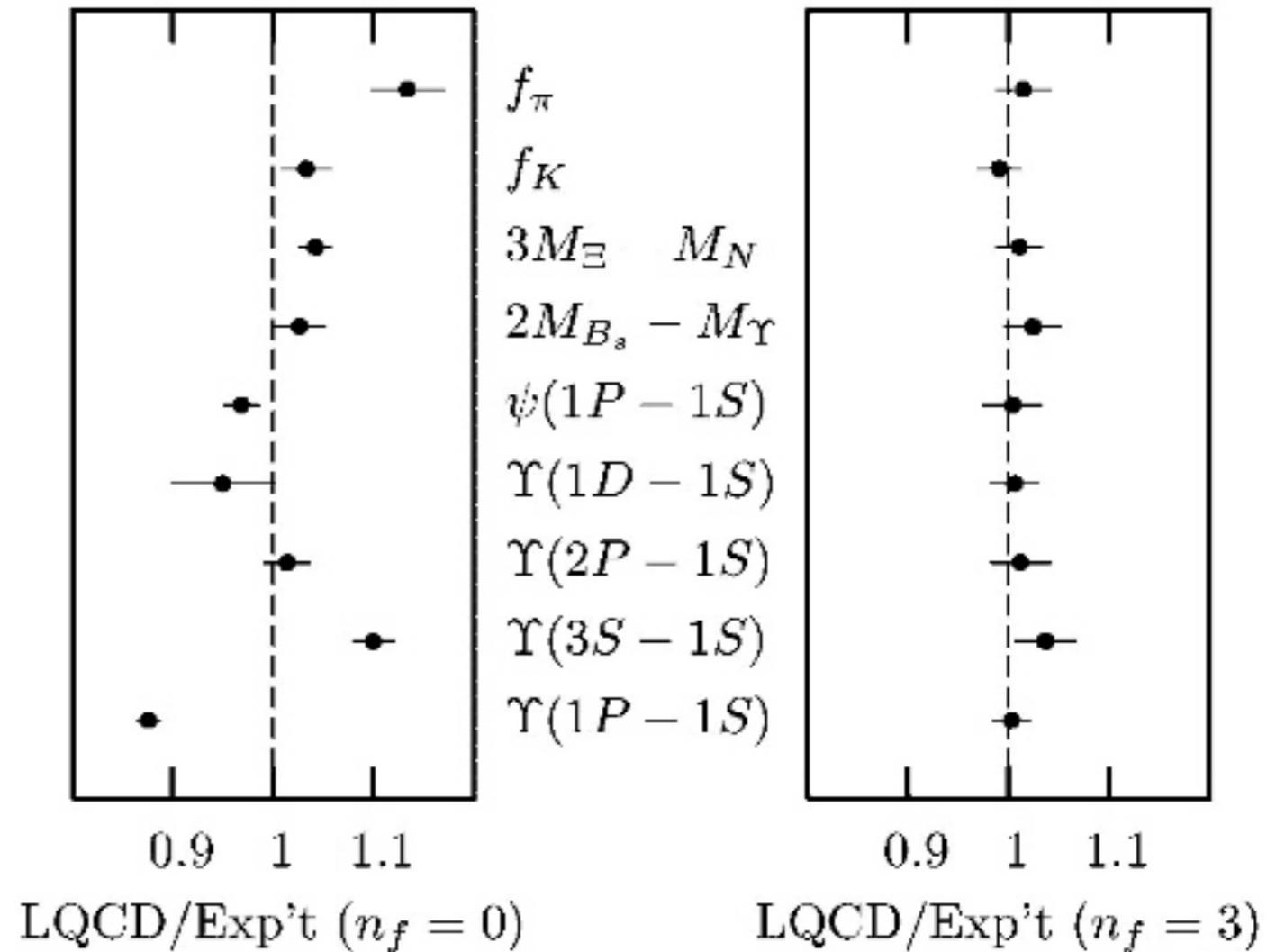
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Additional material at:  
<http://lqcd.fnal.gov>.

URA Annual Review  
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Recent big progress with unquenched improved staggered fermions.

Several groups compared their simplest calculations. 10% disagreement quenched → few per cent agreement unquenched.



C.T.H. Davies *et al.*, **Phys.Rev.Lett.**92:022001,2004, hep-lat/0304004.

What about slightly more complicated quantities?  
Do other light quark methods agree?



# The progress has been reported in nice articles in Physics Today and Nature.

news and views

## Lattice window on strong force

Ian Shipsey

A long-awaited breakthrough has been made in lattice quantum chromodynamics — a means of calculating the effect of the strong force between sub-atomic particles that could, ultimately, unveil new physics.

The fundamental particles called quarks exist in atom-like bound states, such as are held

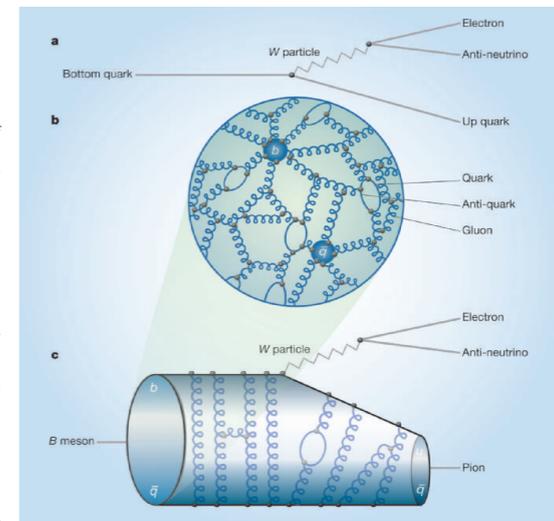


Figure 1 Bottom's up. a. An idealized representation of the decay of a free bottom quark into an up quark. In the standard model of particle physics, the process occurs through the weak force, mediated by a W particle, and also produces an electron and an anti-neutrino. b. In the real world, however, there is no such thing as a free quark. Instead, a bottom quark exists in a bound state with other quarks — such as in a B meson, bound by the exchange of gluons to an anti-quark. Gluons and quark pairs are constantly emitted then reabsorbed; only a fraction of this 'sea' of particles is shown here. c. So the realistic picture of the decay of a bottom quark is complex. The B meson — a bottom quark and anti-quark pair — becomes a pion (an up quark and an anti-quark), but the route is obscured by the mass of gluons and quarks (of which, again, only a fraction are shown). Calculating the details of the process is fiendishly complicated. But new advances in lattice quantum chromodynamics mean that precise theoretical correction factors can be worked out, and the problem effectively reduced to the simple process shown in a.

would be no matter in the Universe today. So how did that asymmetry arise? If heavy particles that existed in the early Universe decayed preferentially into matter over antimatter, that could have created the matter excess. In the standard model, two types of quark, bottom and strange, do decay asymmetrically. But this effect alone is far too small to account for the asymmetry. However, there are many theories that predict the existence of other, massive particles that could readily produce the asymmetry. And

nature.com/nature

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### High-Precision Lattice QCD Confronts Experiment

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(Dated: 31 March 2003)

We argue that high-precision lattice QCD is now possible, for the first time, with improved staggered quark discretization. We compare a wide variety of lattice QCD calculations with experiment, and find agreement to within statistical and systematic errors. We also present a new determination of  $\alpha_{\text{MS}}^{(5)}(M_Z)$ ; we obtain 0.121(1) of this breakthrough for phenomenology and, in particular, for heavy quarkonium.

PACS numbers: 11.15.Ha, 12.38.Aw, 12.38.Gc

For almost thirty years precise numerical studies of nonperturbative QCD, formulated on a space-time lattice, have been stymied by our inability to include the effects of realistic quark vacuum polarization. In this paper we present detailed evidence of a breakthrough that may now permit a wide variety of nonperturbative QCD calculations including, for example, high-precision B and D meson decay constants, mixing amplitudes, and semi-leptonic form factors—all quantities of great importance in current experimental work on heavy-quark physics. The breakthrough comes from a new discretization for light quarks: Symanzik-improved staggered quarks [1, 2, 3, 4, 5, 6, 7, 8].

Quark vacuum polarization is by far the most expensive ingredient in a QCD simulation. It is particularly difficult to simulate with small quark masses, such as u and d masses. Consequently, most lattice QCD (LQCD) simulations in the past have either omitted quark vacuum polarization ("quenched QCD"), or they have included effects for only u and d quarks, with masses 10–20 times larger than the correct values. This results in uncon-

trolled systematic errors. Symanzik-improved staggered quarks are the most accurate and efficient available, and are possible on a wide variety of exact chiral symmetry lattices. In this paper we compare our results with existing controlled systematics, and find agreement to within statistical and systematic errors.

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## Lattice Quantum Chromodynamics Comes of Age

Quantum chromodynamics is the elegant but notoriously intractable theory of the strong interactions. Recent advances in numerical computer simulation are beginning to reveal, in impressive detail, what the theory predicts.

Carleton DeTar and Steven Gottlieb

The strength of the strong interaction is characterized by the fine-structure constant  $\alpha_s \approx 0.1187(08)$ . Because  $\alpha_s$  is so small, quantum chromodynamics (QCD), the theory of interacting quarks and gluons, can be solved to very good approximation with the traditional technology of perturbation theory. By contrast, quantum chromodynamics (QCD), the generally accepted theory of strongly interacting quarks and gluons, has proven to be remarkably resistant to that approach. But in recent years, advances in computer technology and algorithms have brought the objective, numerical simulation of QCD to a level of credibility that will have a significant impact on scientific discovery.

### Lattice QCD

In formulation, QCD and QED are strikingly similar. Both are gauge-invariant quantum field theories. The key difference is that photons in QED are neutral, so they don't interact directly with each other. The gluons in the QCD analog of the photon mediate the strong force between quarks. For quite unlike photons, gluons do carry color charge, the analog of electric charge. So gluons interact directly with each other as well as with quarks (see the article by Frank Wilczek in *Physics Today*, August 2000, page 49).

That seemingly innocent change has dramatic consequences for phenomenology. It is the root of QCD's daunting complexity: Gluons, positrons, and photons can be separated and isolated at macroscopic distances. Quarks, antiquarks, and gluons cannot. This confinement, called color confinement, means that all the elementary particles (the hadrons) composed of quarks, antiquarks, and gluons come in particular color-neutral combinations. Locally speaking, this means that they come either in quark-antiquark pairs (the mesons) or in triplets of quarks (the baryons). Several recently discovered "pentaquark" candidates appear to combine a quark triplet with a quark-antiquark pair (see page 19 of this issue).

Why only color-neutral combinations? In QCD, quarks can have three colors. Conventionally they are labeled red, blue, and green, but of course they have nothing to do with green. Antiquarks have the corresponding anticolors. Triplets of quarks containing equal portions of the three

colors are color neutral.

By the way, because one of the three valence quarks in a proton, before being used for the color of the proton, has a spin of  $1/2$  or  $3/2$  and, you'd think, enough work to create a new quark-antiquark pair, they promptly appear, choose new partners, and you find a meson in one hand

and a proton or neutron in the other. No isolated quarks! At distances on the order of magnitude smaller than  $1 \text{ fm}$  or, equivalently, of interaction energies or momenta on the order of the multi-GeV range, the nonperturbative QCD analog of the fine-structure constant is effectively zero. In this limited regime, perturbation theory works, and semi-empirical methods succeed. But for the larger distances and softer interactions, where confinement is the dominating process, a successful theory and we must resort to computational numerical simulation.

In 1971, Kenneth Wilson at Cornell University formulated a version of QCD on a discrete spacetime lattice (see the left panel of figure 1 and, with pen and paper, used it to provide a plausible, but nonrigorous, argument for color confinement. Wilson argued that, in a compact spacetime lattice, the potential energy of separation of a quark and an antiquark must rise linearly with distance. In 1979 at Brookhaven National Laboratory, Michael Creutz, Luciano Montesi, and Claude Rabby demonstrated the feasibility of the first meaningful numerical simulations with Wilson's formulation on a Cornell Univ. Cray T3E computer. Shortly thereafter, Creutz obtained numerical results for the confinement potential that supported Wilson's conclusion. That success launched a new branch of computational physics, called lattice gauge theory or lattice QCD. The right panel of figure 1 shows a modern lattice-QCD result for the quark-antiquark potential.

### High-precision calculations

For two decades after Creutz's pioneering 1979 calculations, advances in algorithms and computing power brought steady gains in precision and consistency. Just only in the past four years have powerful algorithmic and hardware improvements pushed us into the age of high-precision lattice QCD—at least for some key hadronic quantities.

By the standards of the strong interaction, "high precision" means 1 or 2%. The impact of two new periodic updates to the strong interaction, determining key features of the weak interactions of hadrons. In summary, the Creutz-Montesi-Rabby (CMR) parameters—requires correcting measured weak decay rates for strong interaction effects, see box 1. The uncertainties in our knowledge of such fundamental parameters limits the precision with which the standard model of elementary particles can be tested and probed for new realms of physics.

The most important theoretical advance in recent

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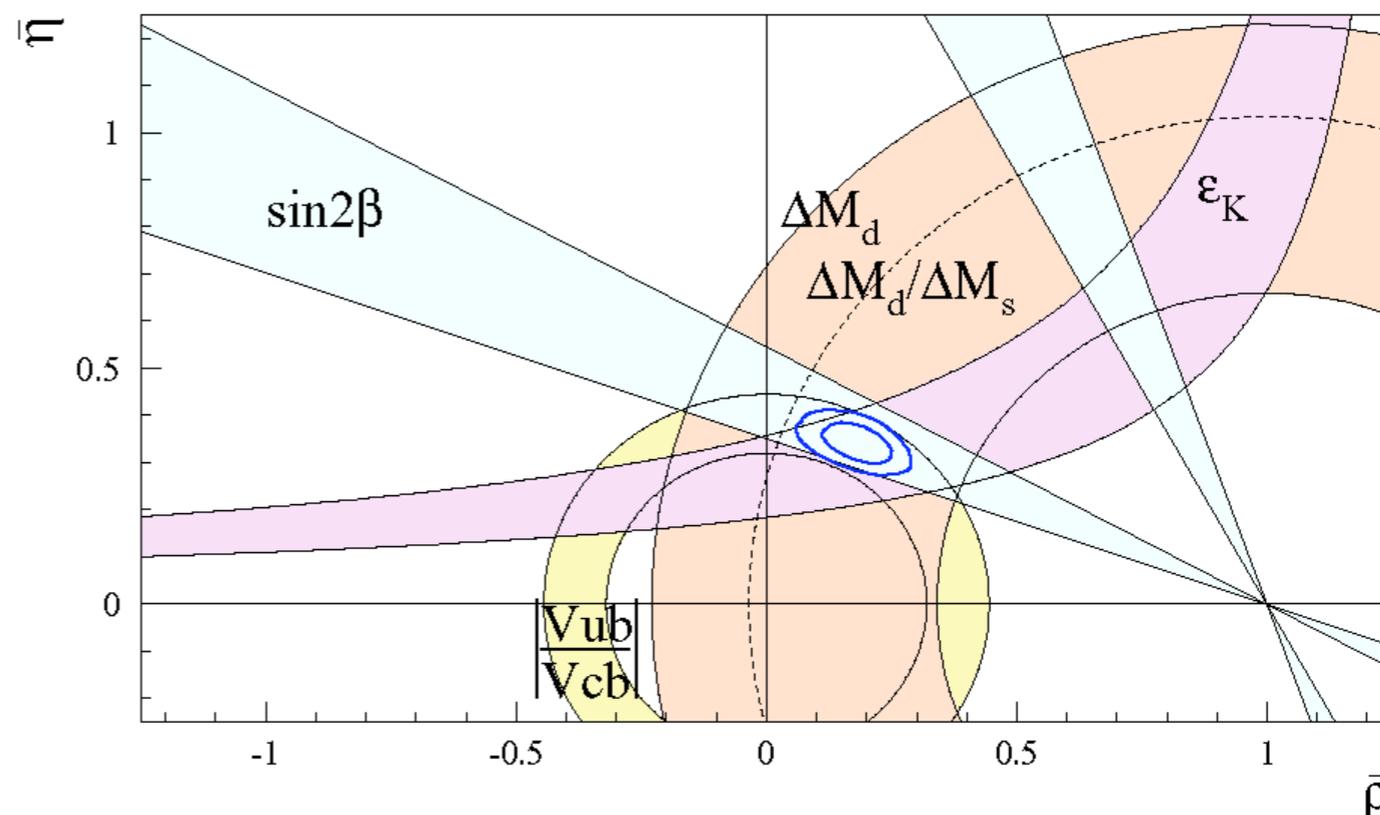
arXiv:hep-lat/0304004 v1 7 Apr 2003

These are examples of “golden quantities of lattice QCD”: single stable-hadron processes.

Many of the most important deliverables of lattice QCD are in this class and a special focus of our group’s work:

$B \bar{B}$ ,  $B_s \bar{B}_s$  mixing,

$B$ ,  $D$  leptonic and semileptonic decay.



M. Ciuchini [hep-ph/0307195](https://arxiv.org/abs/hep-ph/0307195).

# Example of current work : $D \rightarrow \pi l \nu$ .

Cleo-c will measure

$f_D / D \rightarrow \pi l \nu$  and

$f_{D_s} / D \rightarrow K l \nu$  to 2%. Interesting and rare

CKM independent test of lattice heavy-light methods.

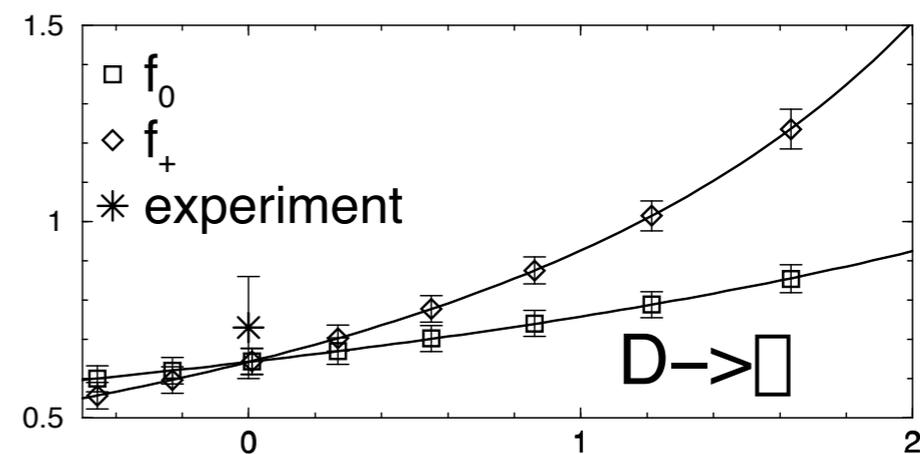
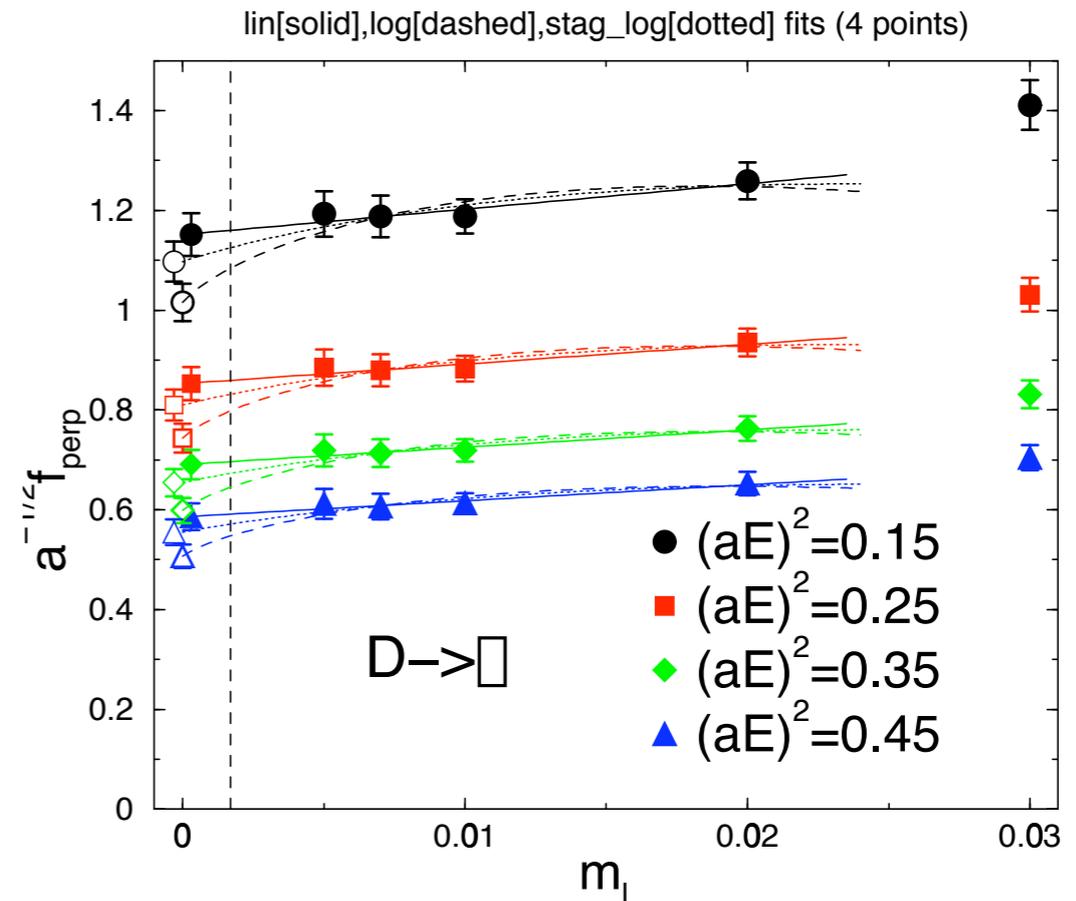
One-loop perturbative calculations (in progress) will leave 8-10% perturbative uncertainties.

Goal: make all other uncertainty significantly smaller than this.

$$f_+^{DK} = 0.75$$

$$f_+^{D\pi} = 0.63$$

(Preliminary!)



M. Okamoto et al., at Lattice 2003, hep-lat/0309107.

Fermilab lattice cluster effort is led by Don Holmgren.

The clusters are currently housed in the New Muon Lab.



The 176 node Pentium 4 cluster.  
~100 GFlops.





2000: 80 node Pentium III  
700 MHz duals, Myrinet.



2002: 48 node Pentium 4  
2 GHz duals, Myrinet.

2002: 128 node Pentium 4  
2.4 GHz duals, Myrinet.

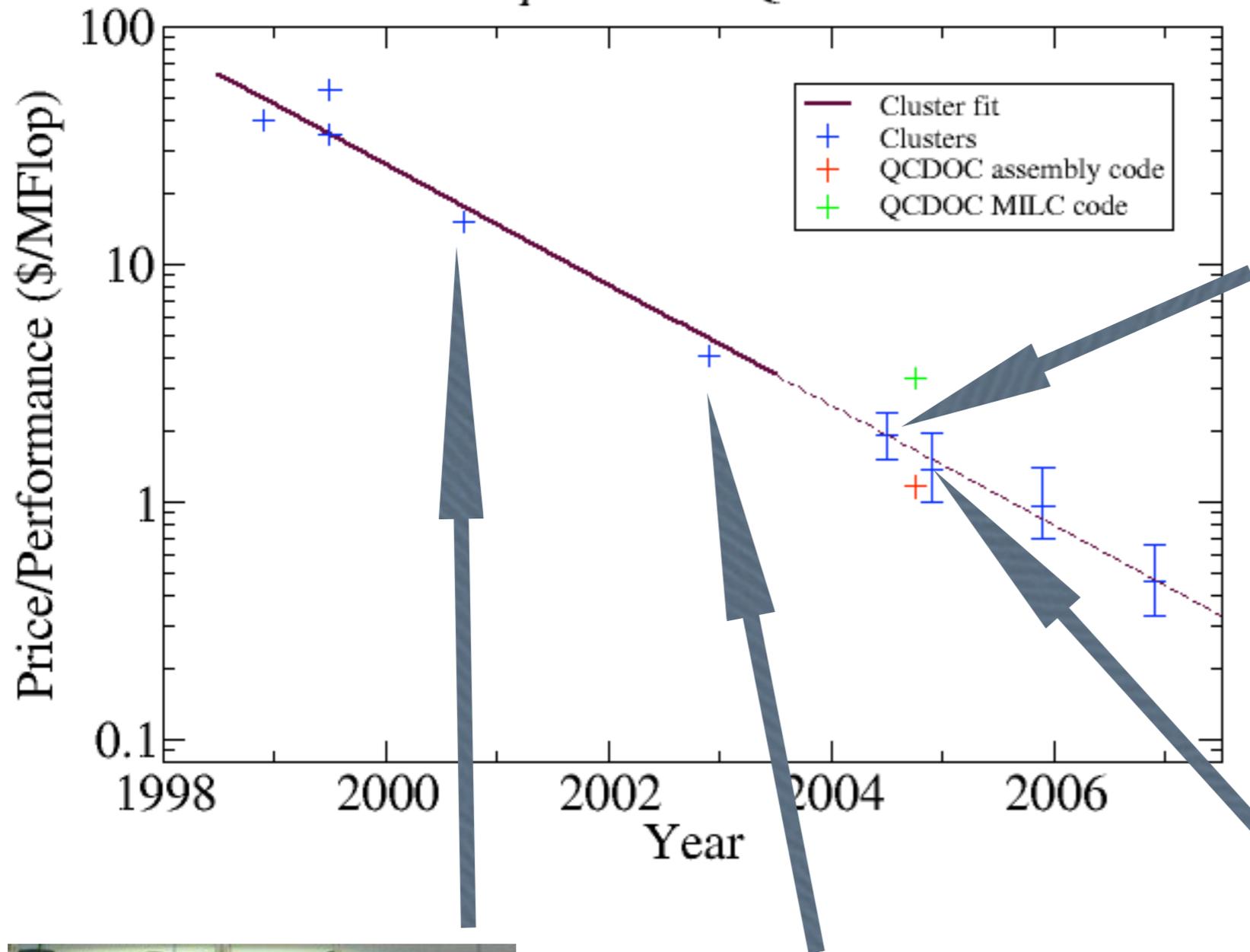
2004 plan: 256 node 3.2 GHz, Infiniband? 350 GF.

2005: 512 node 4 GHz, Infiniband? \$1M. 1 TF.

2006: 1024 node 5 GHz, Infiniband? \$1.5M. 3 TF.

# Cluster Performance Trends

## "Asqtad" Lattice QCD Code



128 P<sub>4</sub> singles,  
reuse Myrinet switch.  
Incremental cost:  
\$<sub>I</sub>/MF.

256 node, P<sub>4</sub> singles?  
Infiniband switch.



US “Lattice QCD Executive Committee” (Sugar, chair, Brower, Christ, Creutz, Mackenzie, Negele, Rebbi, Sharpe, Watson) reports to DoE on plans and needs of US lattice QCD.

At February, 2004 HEPAP meeting, Bob Sugar, in a well-received talk, reported the “absolute minimum support required for health of field”.

Our answer: \$3M/year.

In FY04/05, 5 TF QCDOC + 1 TF cluster.

DoE-HEP response: \$2M/yr.

Discussions are ensuing.

