Lattice QCD and Beyond

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Overview of work done (and being done) with:

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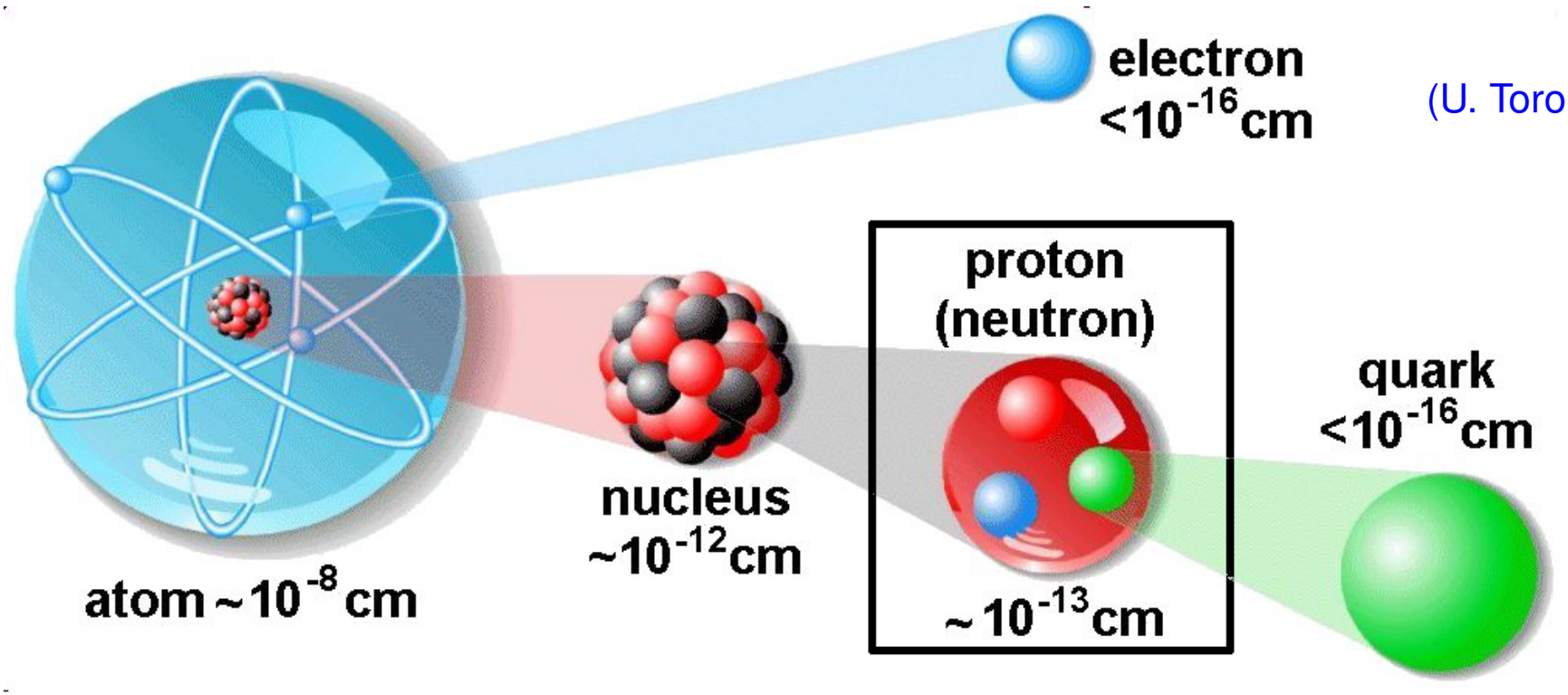
T. Appelquist, M. Buchoff, G. Fleming, F.-J. Jiang, J. Kiskis, M. Lin, E. Neil, P. Vranas

Setting the scene

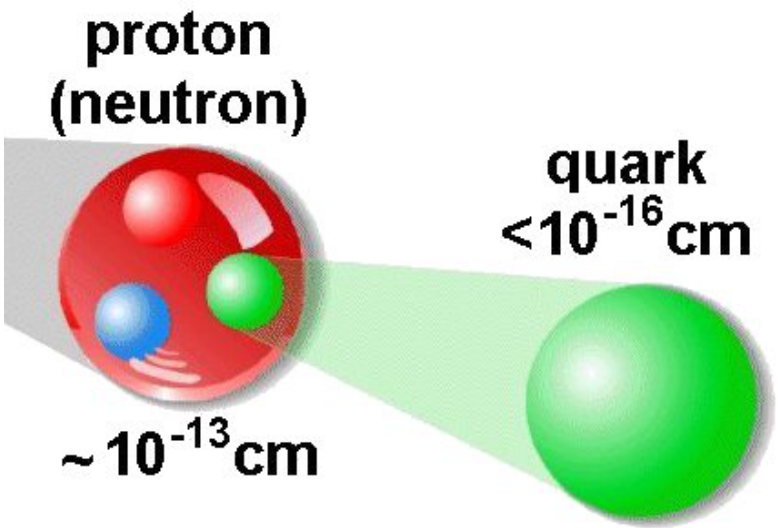


Quantum chromodynamics (QCD)

Fundamental theory of the strong nuclear force
describing quarks confined into composite particles by gluon fields

What's in a proton?

$$\frac{\text{Mass of proton}}{\text{Mass of three quarks}} \approx 100 \Rightarrow \text{ three-quark picture is too simple!}$$

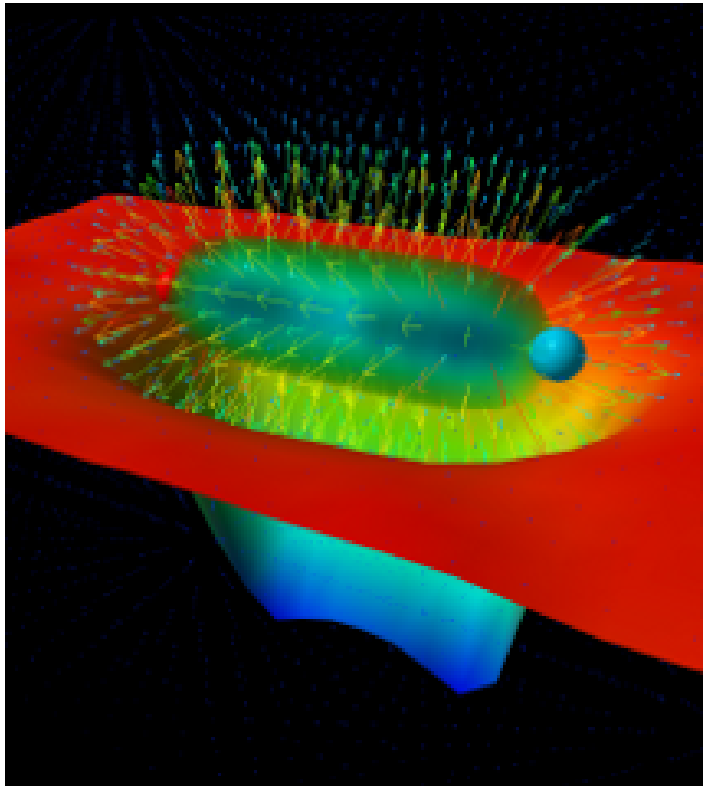


Why is the internal structure of composite particles so complicated?

It's a **strong** interaction!

Separating two quarks generates
a gluon flux tube acting like a string

With $\sim$ 1 fm separation
the string tension is $\sim$ **10 tons**



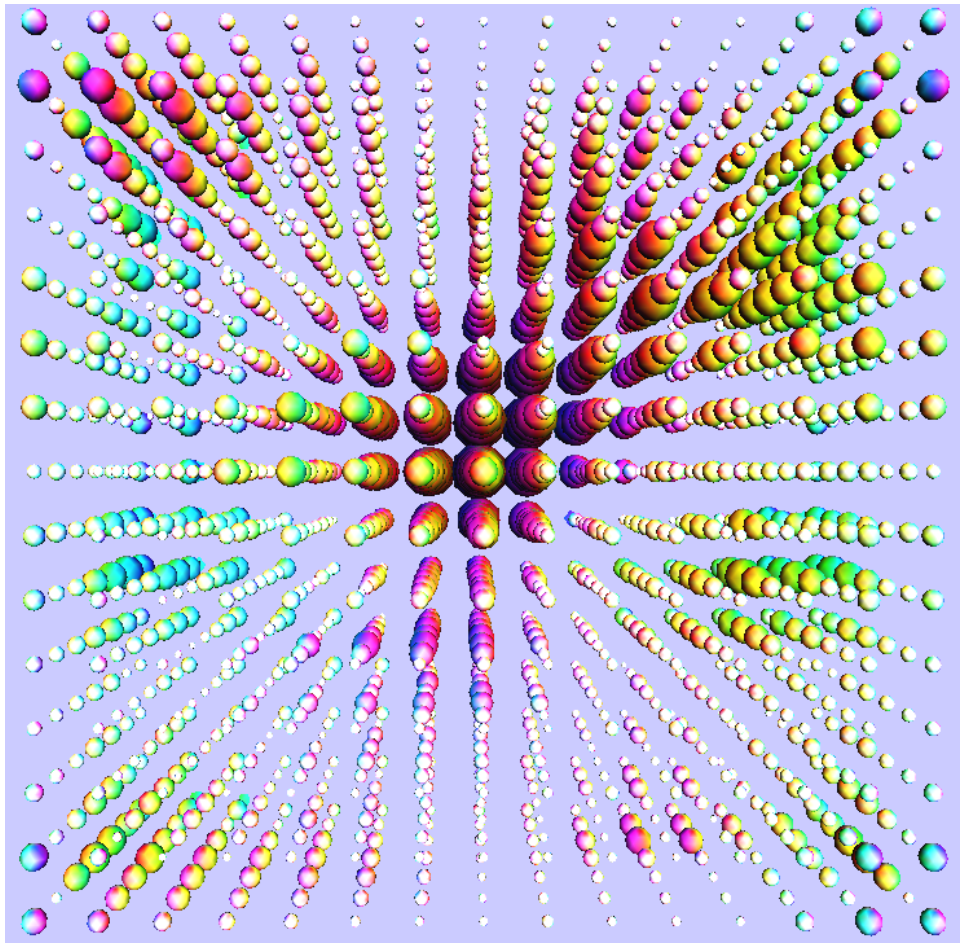
(Derek Leinweber)

Implications

- Strong interaction energy appears as mass via $E = mc^2$
- Standard techniques (perturbation theory) inapplicable

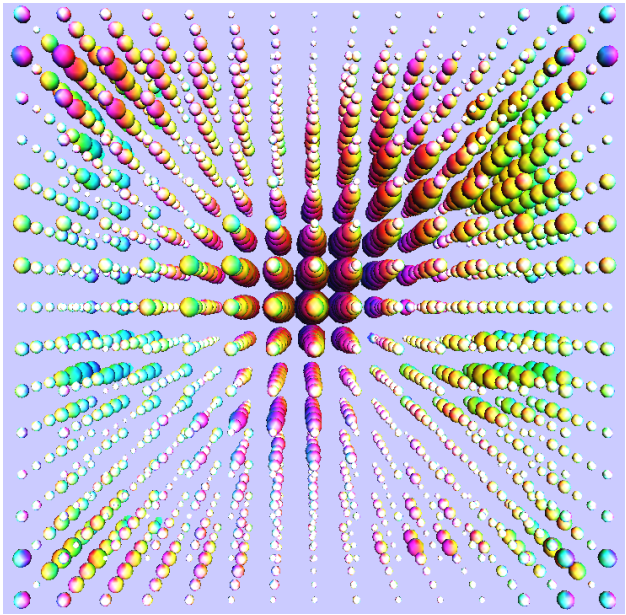
Non-perturbative QCD on a space-time lattice

To perform non-perturbative calculations,
define the theory on a space-time lattice (Kenneth Wilson, 1974)



(Claudio Rebbi)

Lattice QCD



Numerically evaluate observables from the defining functional integral

$$\langle \mathcal{O} \rangle = \frac{\int \mathcal{D}U \;\; \mathcal{O}(U) \;\; e^{-S(U)}}{\int \mathcal{D}U \;\; e^{-S(U)}}$$

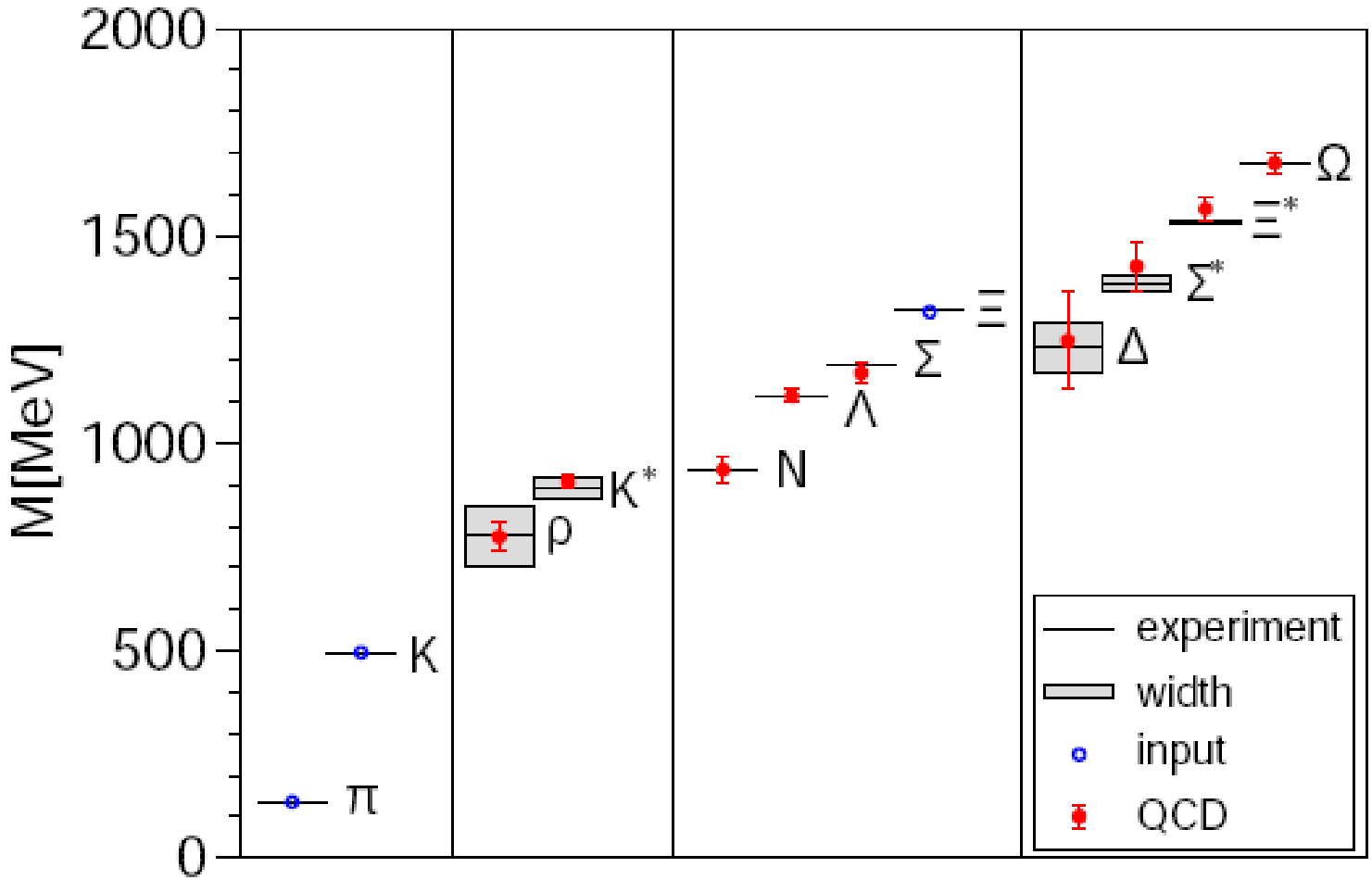
U: four-dimensional field configurations
S: action giving probability distribution e^{-S}

Typical algorithm: **hybrid Monte Carlo**

1. Generate random "momenta" with Gaussian distribution $e^{-p^2/2}$
2. Molecular dynamics evolution through fictitious MD "time" to produce new four-dimensional field configuration
3. Use MD discretization errors in Metropolis accept/reject step

Recent advances in the state of the art

Hardware and software advances improve standard lattice calculations and open up new frontiers for exploration



(BMW Collaboration)

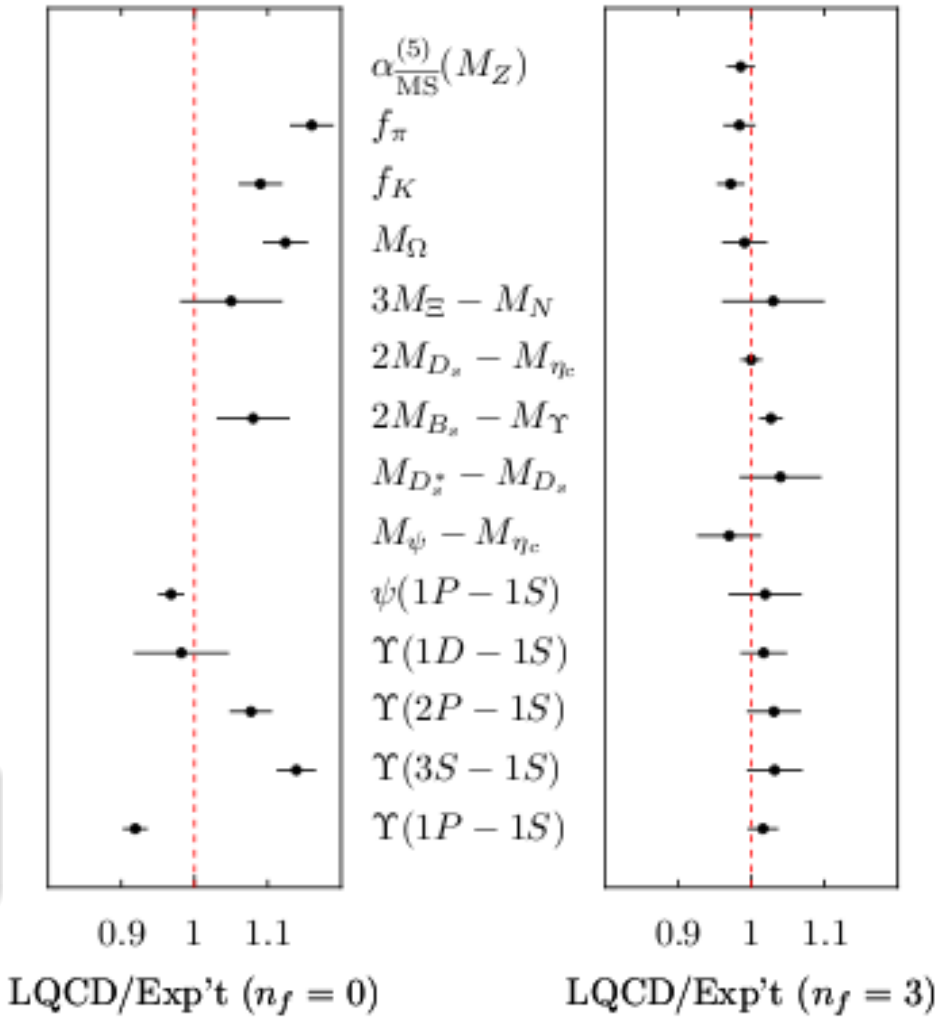
Example: effects of virtual quark pairs

Accounting for virtual quark pairs requires repeatedly inverting large sparse matrices

$$\sum_y [D(U)]_{x,y}\ \psi_y = \eta_x$$

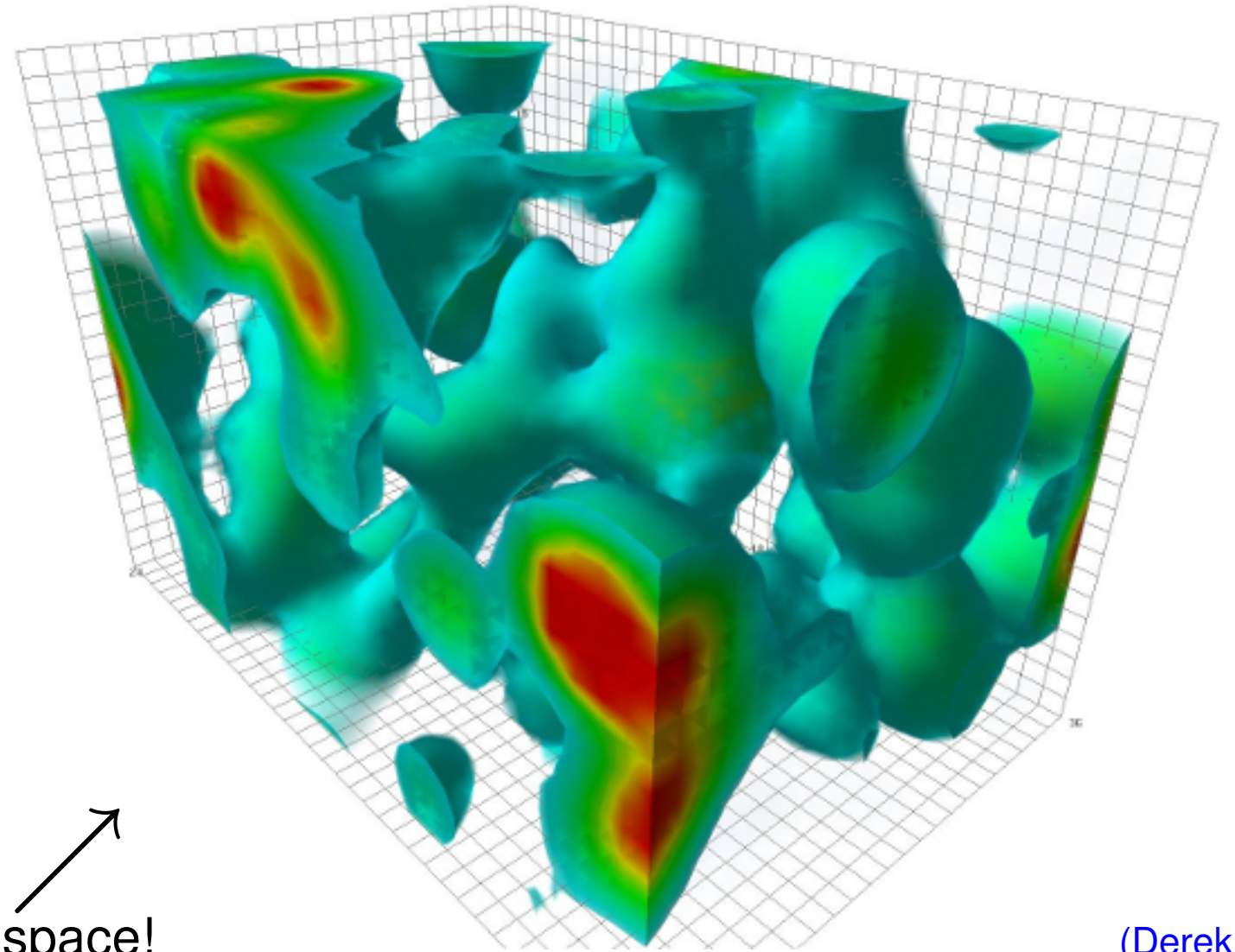
$D(U) \sim$ 100M $\times$ 100M matrix

Computationally expensive but crucial to success



(HPQCD, UKQCD, MILC and FNAL collaborations compiled by Peter Lepage)

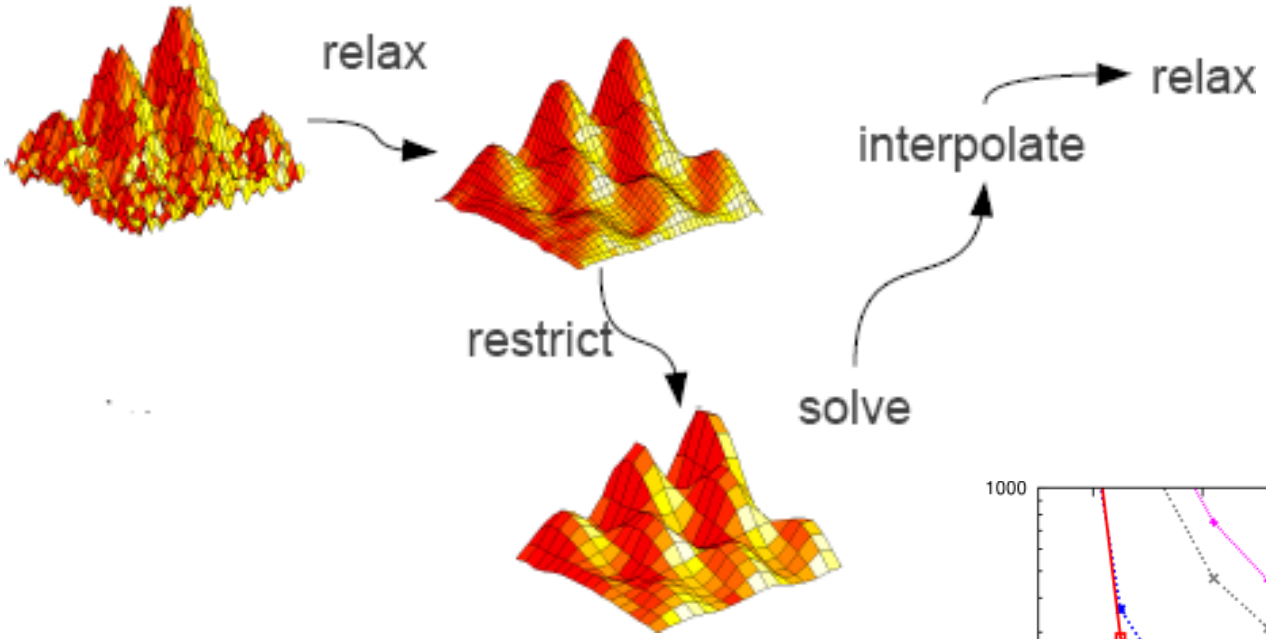
Dynamically generated multi-scale structure. . .



"Empty" space!

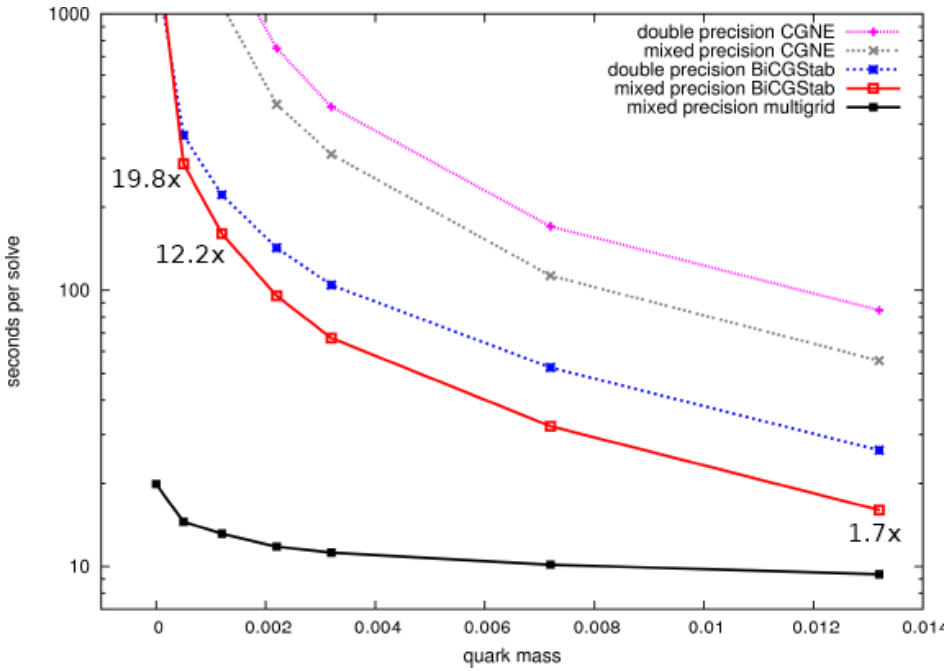
(Derek Leinweber)

. . . motivates multigrid algorithms



Use coarser grid(s)
to accelerate convergence

$\rightsquigarrow$

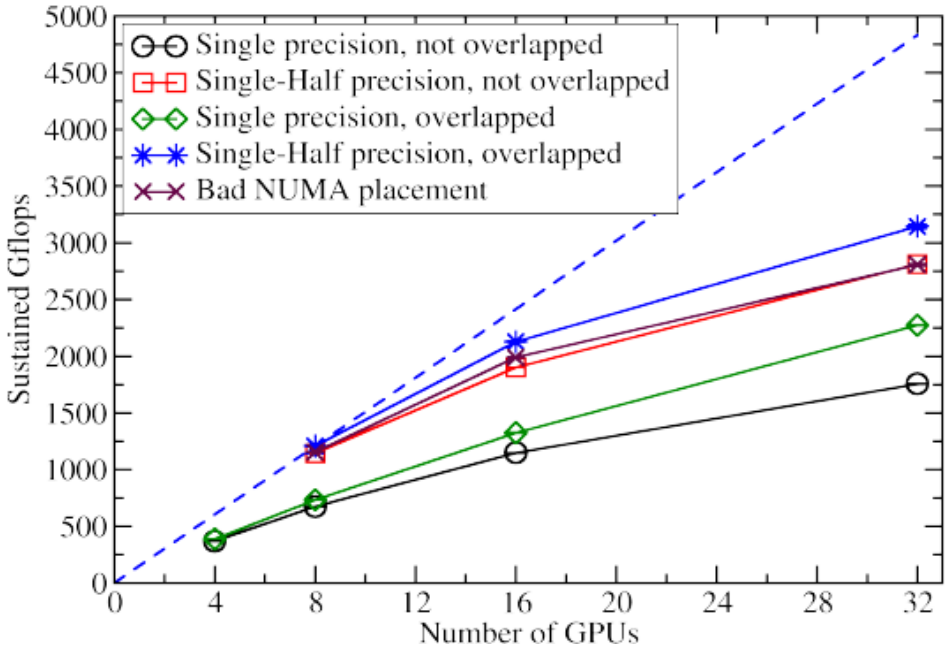


(Rob Falgout, James Osborn)

QCD on GPUs

Great strides in applying GPU computing to lattice QCD

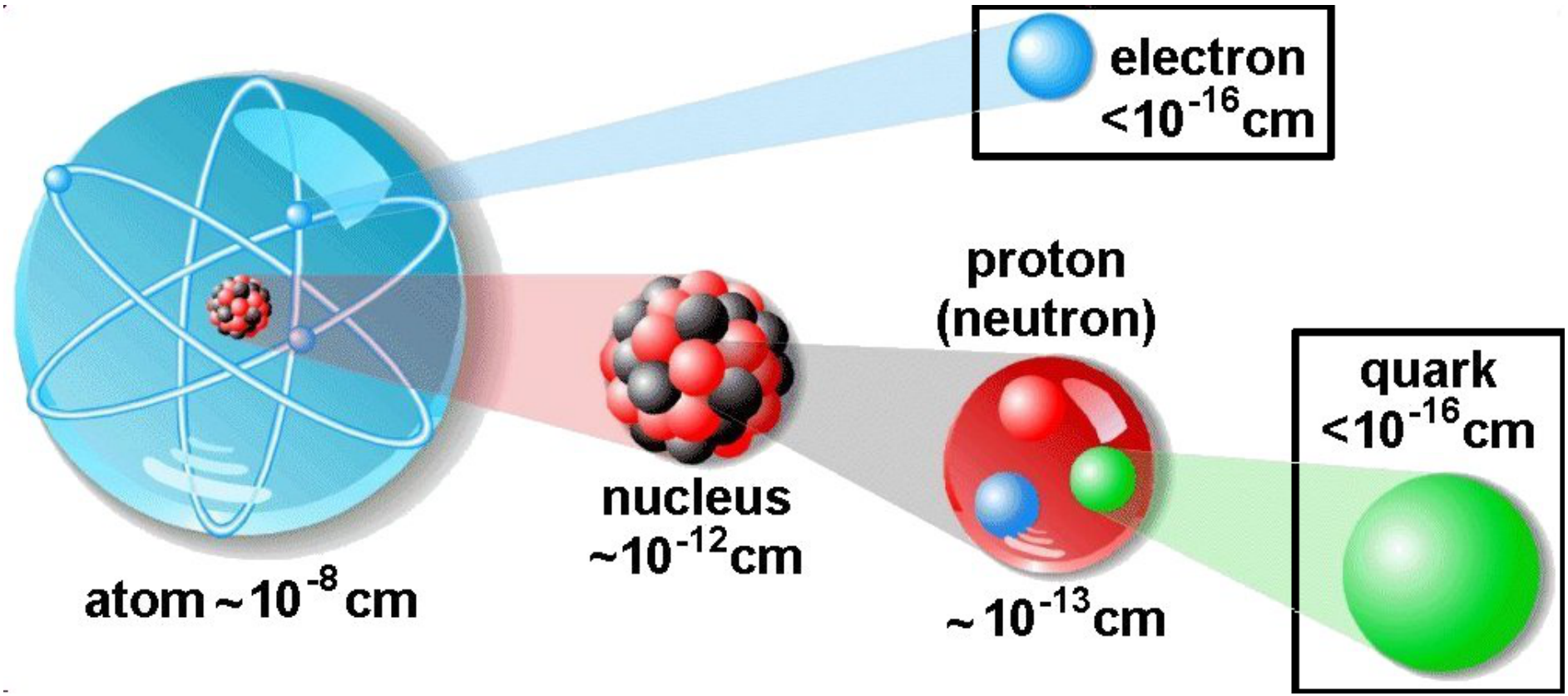
(discussed earlier this year by Ron Babich)



Current frontier is scaling to many GPUs

May be a taste of things to come in high-performance computing

Going beyond QCD on the lattice

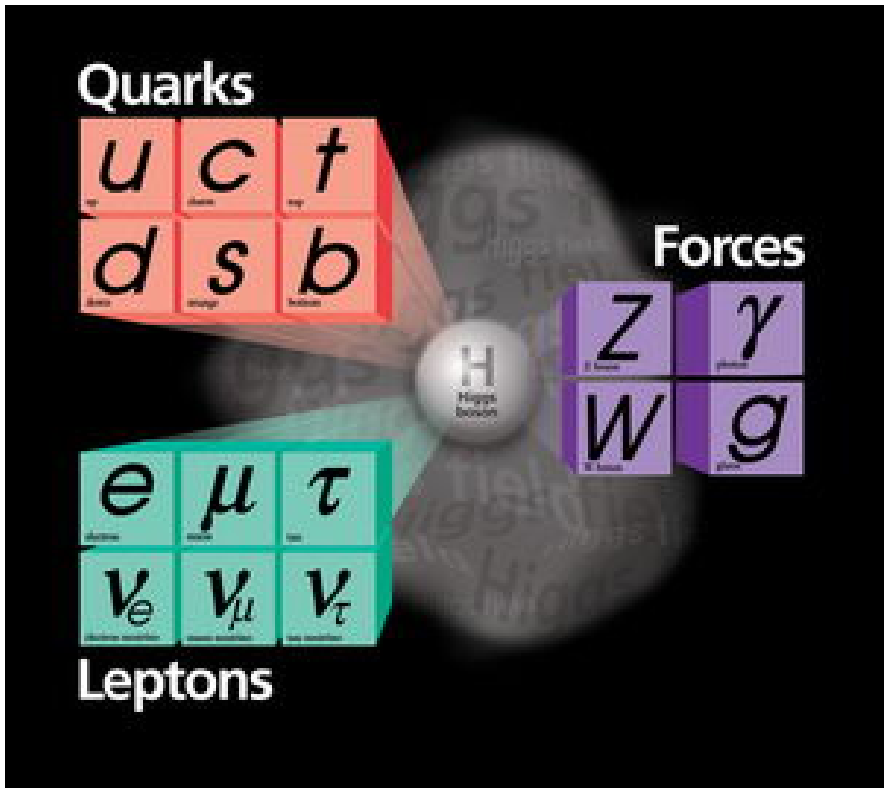


What explains the masses of *elementary* (non-composite) particles?

Elementary particle masses

Symmetries of nature appear to require *massless* elementary particles

The **Higgs mechanism** hides these symmetries



(Fermilab)

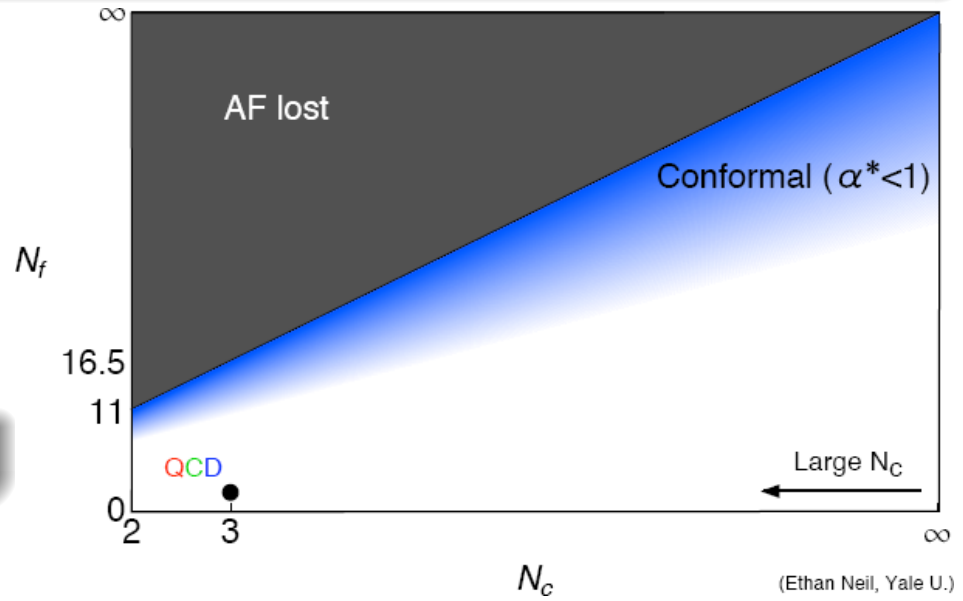
The nature of the Higgs mechanism remains unknown!

Technicolor

Proposal: The Higgs mechanism involves new strong dynamics
(Steven Weinberg 1976/1979, Leonard Susskind 1979)

Experiments indicate that technicolor dynamics must be *different* than QCD

Strong dynamics $\Rightarrow$ lattice



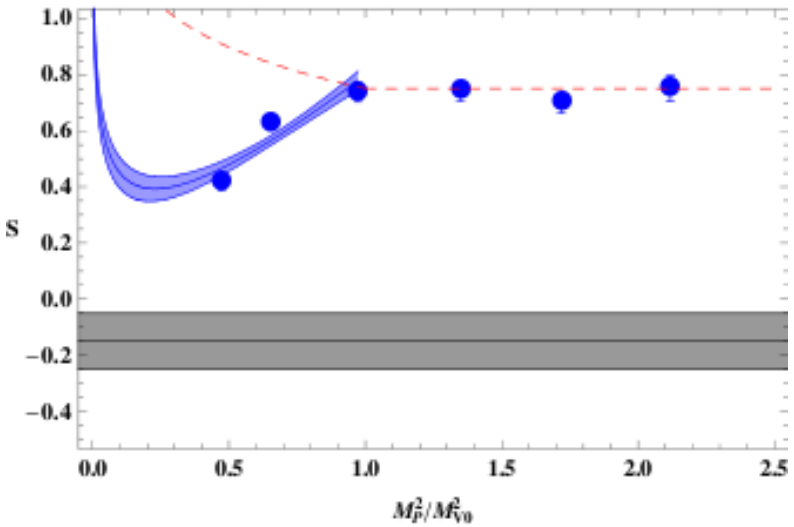
Challenges

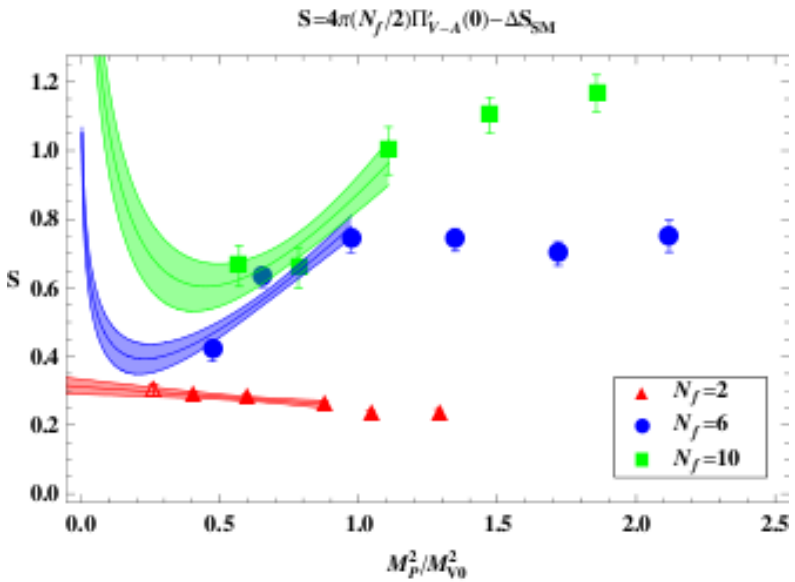
- Most attractive models involve
  very large (orders of magnitude) separation of scales
- We don't know the answer!

Recent result: S parameter

S parametrizes information about the Higgs mechanism

- Experimentally, $S \approx -0.15 \pm 0.10$ (black band)
- In QCD-like theories, S is large and positive (red dotted line)
- We find deviations from QCD-like behavior





Thank you!

Acknowledgements

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Elsewhere

Tom Appelquist, Mike Buchoff, George Fleming, Fu-Jiun Jiang, Joe Kiskis, Meifeng Lin, Ethan Neil, Pavlos Vranas

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