USQCD

Searching for Physics Beyond the Standard Model with Strongly Coupled Field Theories

Project Director: Paul B. Mackenzie, Fermilab

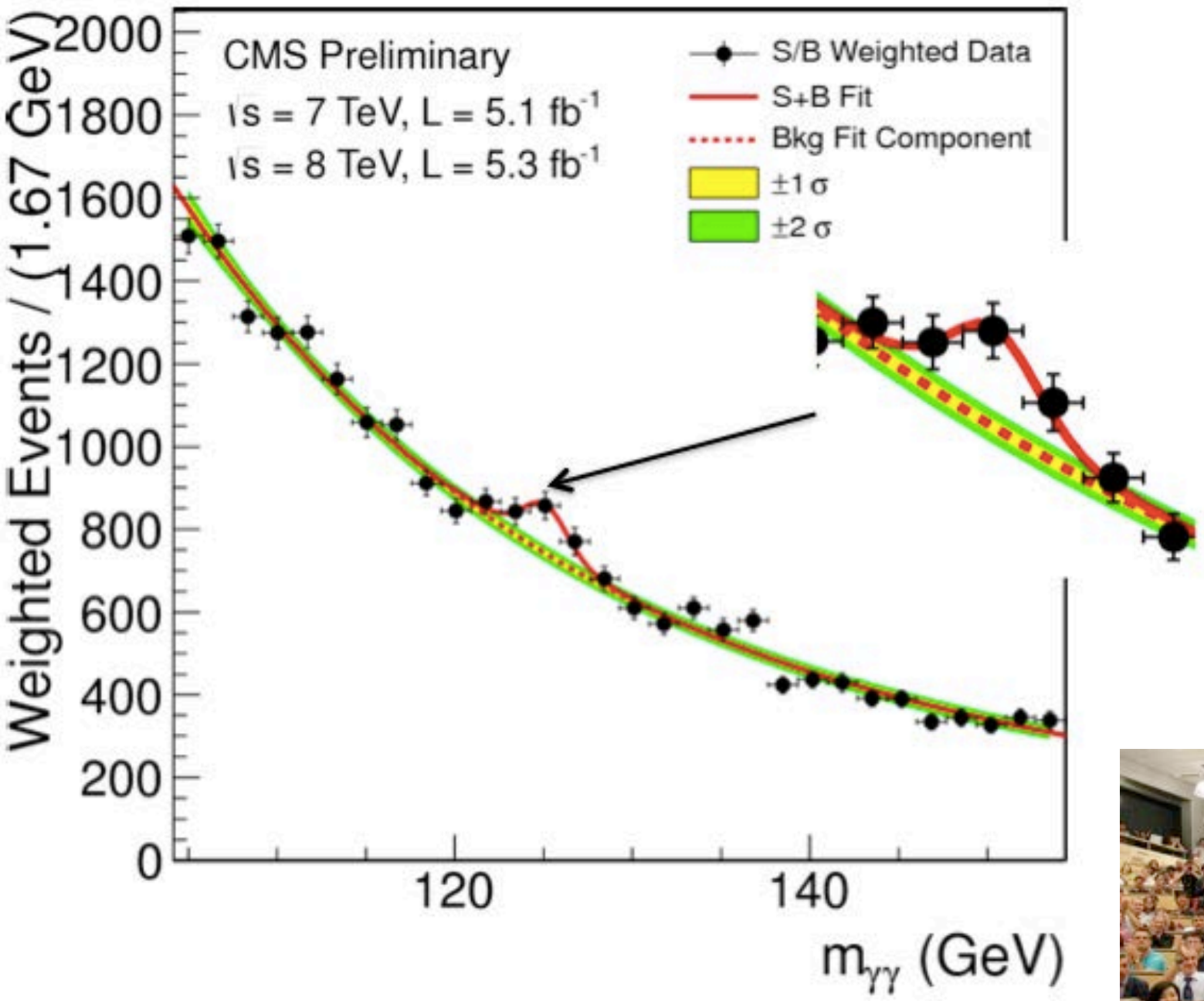
Project Co-director for Science: Stephen Sharpe, University of Washington

Project Co-Director for Computation: Richard Brower, Boston University

Participating Institutions and Principal Investigators:
Argonne National Laboratory, James Osborn
Boston University, Richard Brower
Brookhaven National Laboratory, Frithjof Karsch
Columbia University, Norman Christ
Fermi National Accelerator Laboratory, Paul Mackenzie
Lawrence Livermore National Laboratory, Pavlos Vranas
Syracuse University, Simon Catterall
University of Arizona, Doug Toussaint
University of California, Santa Barbara, Robert Sugar
University of California, San Diego, Julius Kuti
University of Utah, Carleton DeTar
University of Washington, Stephen Sharpe

SciDAC-3 PI Meeting
Rockville
Sept. 10-12, 2012

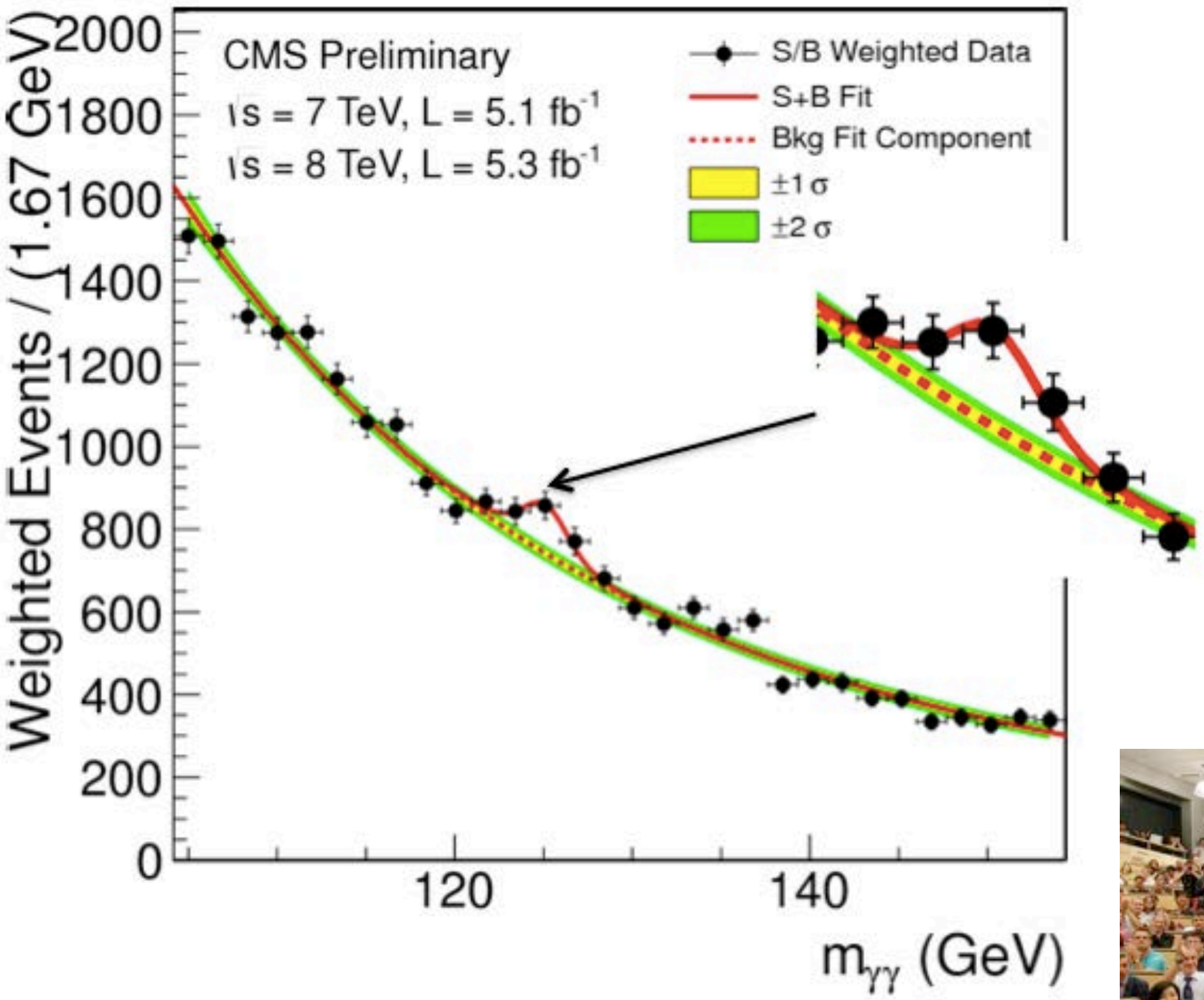
A new particle



The discovery of new particle was announced at CERN in July.

Is it the "Higgs"?

A new particle



The discovery of new particle was announced at CERN in July.

Is it the "Higgs"?

Many particle physicists hope it's something more interesting!

The Standard Model

- Three forces (strong, weak, and electromagnetic), with coupling strengths:

$$\alpha_{\rm s},\ \alpha_{\rm w},\ \alpha_{\rm em}$$

- Six quark and six lepton masses

$$m_u,\ m_d,\ m_c,\ m_s,\ m_t,\ m_b$$
$$m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3}$$

- Mixings among the quarks, the Cabibbo-Kobayashi-Maskawa matrix (2008 Nobel Prize), and (as of the last few years) among the leptons:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad \begin{pmatrix} V_{e\nu_1} & V_{e\nu_2} & V_{e\nu_3} \\ V_{\mu\nu_1} & V_{\mu\nu_2} & V_{\mu\nu_3} \\ V_{\tau\nu_1} & V_{\tau\nu_2} & V_{\tau\nu_3} \end{pmatrix}$$

Where do these parameters come from?
Can we predict them with a more fundamental theory?

The Standard Model

- Three forces (strong, weak, and electromagnetic), with coupling strengths:

$$\alpha_{\rm s},\ \alpha_{\rm w},\ \alpha_{\rm em}$$

Domain of lattice QCD

- Six quark and six lepton masses

$$m_u,\ m_d,\ m_c,\ m_s,\ m_t,\ m_b$$

$$m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3}$$

- Mixings among the quarks, the Cabibbo-Kobayashi-Maskawa matrix (2008 Nobel Prize), and (as of the last few years) among the leptons:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad \begin{pmatrix} V_{e\nu_1} & V_{e\nu_2} & V_{e\nu_3} \\ V_{\mu\nu_1} & V_{\mu\nu_2} & V_{\mu\nu_3} \\ V_{\tau\nu_1} & V_{\tau\nu_2} & V_{\tau\nu_3} \end{pmatrix}$$

Where do these parameters come from?
Can we predict them with a more fundamental theory?

The Standard Model is *maddeningly* successful. It accounts for every particle physics experiment performed so far, sometimes to great precision (one part in a billion for the electron anomalous magnetic moment).

Why maddeningly? It contains obvious gaps and puzzles!

- A mathematically consistent theory cannot be constructed from the currently observed particles.
  - The mathematically simplest solution is the addition of a single new particle, the ‘’Higgs” boson. Such a possibility leaves many questions about the standard model unanswered, so most speculations involve new physics that is much more complicated.
- Why is there more than one generation of quark?
- What is the relation between the three forces?
- How can gravity be incorporated?
- No explanation for dark matter.
- ...

The search for a more fundamental theory underlying the Standard Model is the central task of particle physics today.

The Standard Model is *maddeningly* successful. It accounts for every particle physics experiment performed so far, sometimes to great precision (one part in a billion for the electron anomalous magnetic moment).

Why maddeningly? It contains obvious gaps and puzzles!

- A mathematically consistent theory cannot be constructed from the currently observed particles.

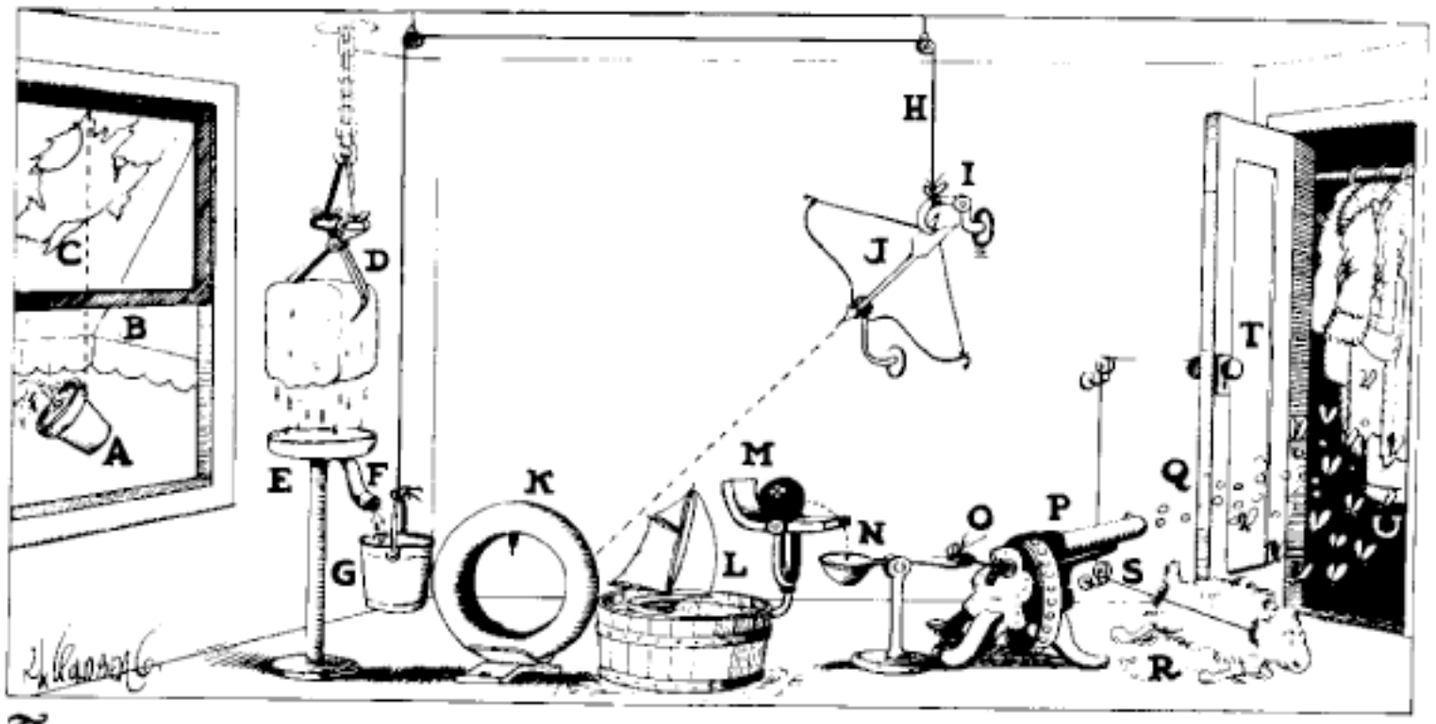
  May not be true anymore.

  - The mathematically simplest solution is the addition of a single new particle, the ''Higgs" boson. Such a possibility leaves many questions about the standard model unanswered, so most speculations involve new physics that is much more complicated.
- Why is there more than one generation of quark?
- What is the relation between the three forces?
- How can gravity be incorporated?
- No explanation for dark matter.
- ...

The search for a more fundamental theory underlying the Standard Model is the central task of particle physics today.

The standard model is a Rube Goldberg device.

"Complex gadgets that perform simple tasks in indirect, convoluted ways" - Wikipedia



THE PROFESSOR EMERGES FROM THE GOOFY BOOTH WITH A DEVICE FOR THE EXTERMINATION OF MOTHS.
START SINGING. LADY UPSTAIRS, WHEN SUFFICIENTLY ANNOYED, THROWS FLOWER POT (A) THROUGH AWNING (B). HOLE (C) ALLOWS SUN TO COME THROUGH AND MELT CAKE OF ICE (D). WATER DRIPS INTO PAN (E) RUNNING THROUGH PIPE (F) INTO PAIL (G). WEIGHT OF PAIL CAUSES CORD (H) TO RELEASE HOOK (I) AND ALLOW ARROW (J) TO SHOOT INTO TIRE (K). ESCAPING AIR BLOWS AGAINST TOY SAILBOAT (L) DRIVING IT AGAINST LEVER (M) AND CAUSING BALL TO ROLL INTO SPOON (N) AND PULL STRING (O) WHICH SETS OFF MACHINE GUN (P) DISCHARGING CAMPHOR BALLS (Q). REPORT OF GUN FRIGHTENS LAMB (R) WHICH RUNS AND PULLS CORD (S), OPENING CLOSET DOOR (T). AS MOTHS (U) FLY OUT TO EAT WOOL FROM LAMB'S BACK THEY ARE KILLED BY THE BARRAGE OF MOTH BALLS.
IF ANY OF THE MOTHS ESCAPE AND THERE IS DANGER OF THEIR RETURNING, YOU CAN FOOL THEM BY MOVING.

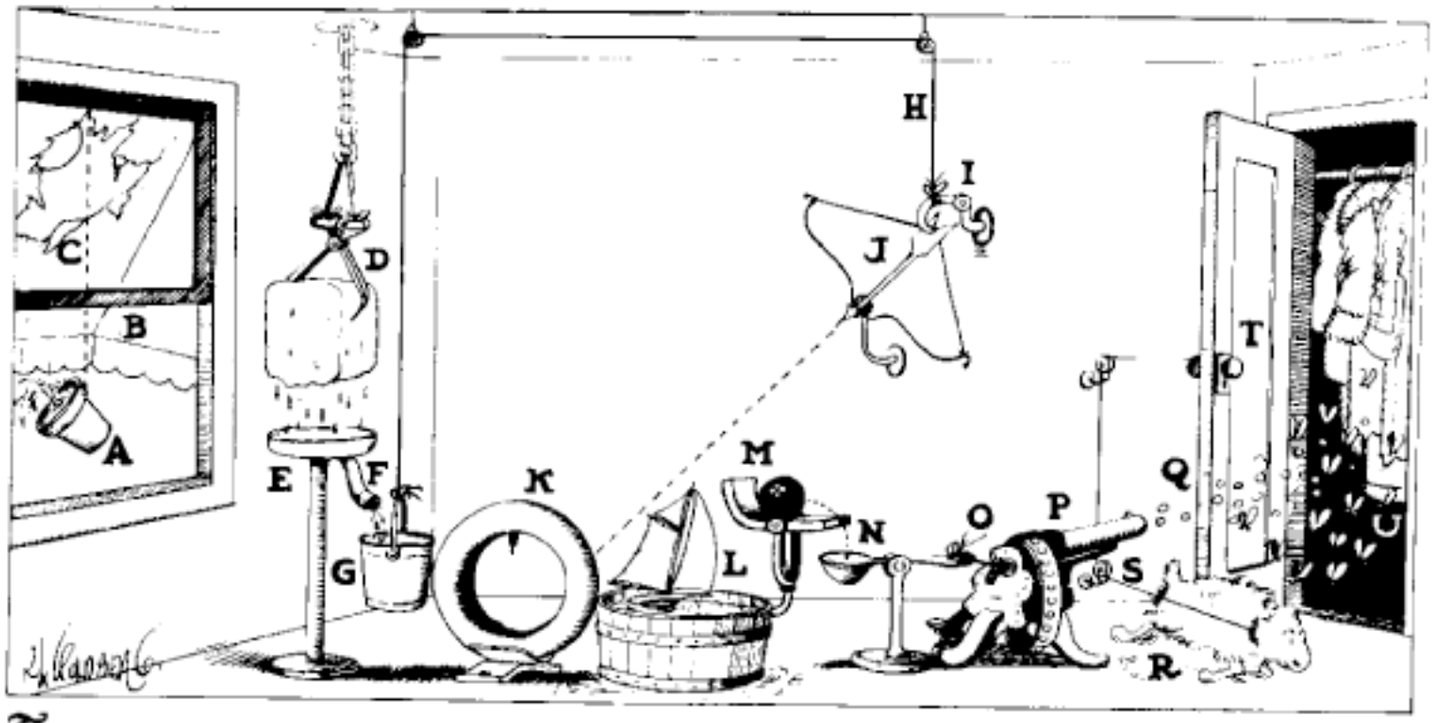
Unfortunately:

1) It describes experiment perfectly.
2) Nothing simpler has been found.

The search for a more fundamental theory underlying the Standard Model is the central task of particle physics today.

The standard model is a Rube Goldberg device.

"Complex gadgets that perform simple tasks in indirect, convoluted ways" - Wikipedia



THE PROFESSOR EMERGES FROM THE GOOFY BOOTH WITH A DEVICE FOR THE EXTERMINATION OF MOTHS.
START SINGING, LADY UPSTAIRS, WHEN SUFFICIENTLY ANNOYED, THROWS FLOWER POT (A) THROUGH AWNING (B). HOLE (C) ALLOWS SUN TO COME THROUGH AND MELT CAKE OF ICE (D). WATER DRIPS INTO PAN (E) RUNNING THROUGH PIPE (F) INTO PAIL (G). WEIGHT OF PAIL CAUSES CORD (H) TO RELEASE HOOK (I) AND ALLOW ARROW (J) TO SHOOT INTO TIRE (K). ESCAPING AIR BLOWS AGAINST TOY SAILBOAT (L) DRIVING IT AGAINST LEVER (M) AND CAUSING BALL TO ROLL INTO SPOON (N) AND PULL STRING (O) WHICH SETS OFF MACHINE GUN (P) DISCHARGING CAMPHOR BALLS (Q). REPORT OF GUN FRIGHTENS LAMB (R) WHICH RUNS AND PULLS CORD (S), OPENING CLOSET DOOR (T). AS MOTHS (U) FLY OUT TO EAT WOOL FROM LAMB'S BACK THEY ARE KILLED BY THE BARRAGE OF MOTH BALLS.
IF ANY OF THE MOTHS ESCAPE AND THERE IS DANGER OF THEIR RETURNING, YOU CAN FOOL THEM BY MOVING.

very well.

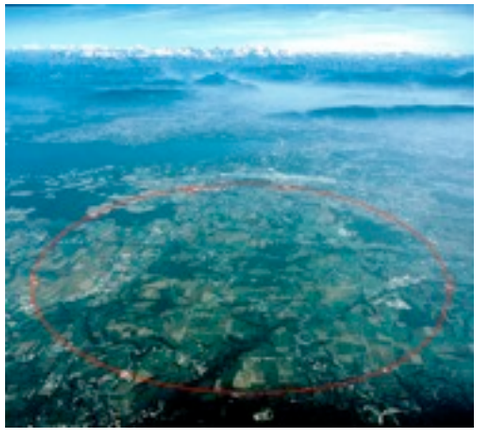
Unfortunately:

1) It describes experiment perfectly.
2) Nothing simpler has been found.

The search for a more fundamental theory underlying the Standard Model is the central task of particle physics today.

To understand what physics lies “Beyond the Standard Model”, two complementary approaches:

- The Energy Frontier: direct search for new particles and forces.
  - The LHC at CERN collides protons at the highest possible energies to push the search for direct evidences of new physics to the highest possible energies.



- The Intensity Frontier: search for small, indirect effects of new physics in interactions of known particles.
  - Heavy flavor factories at CERN, KEK, Fermilab, and elsewhere are pouring (or will pour) out huge amounts of high precision data to pin down the CKM matrix elements.

Lattice gauge theory in the SciDAC-1, -2 eras

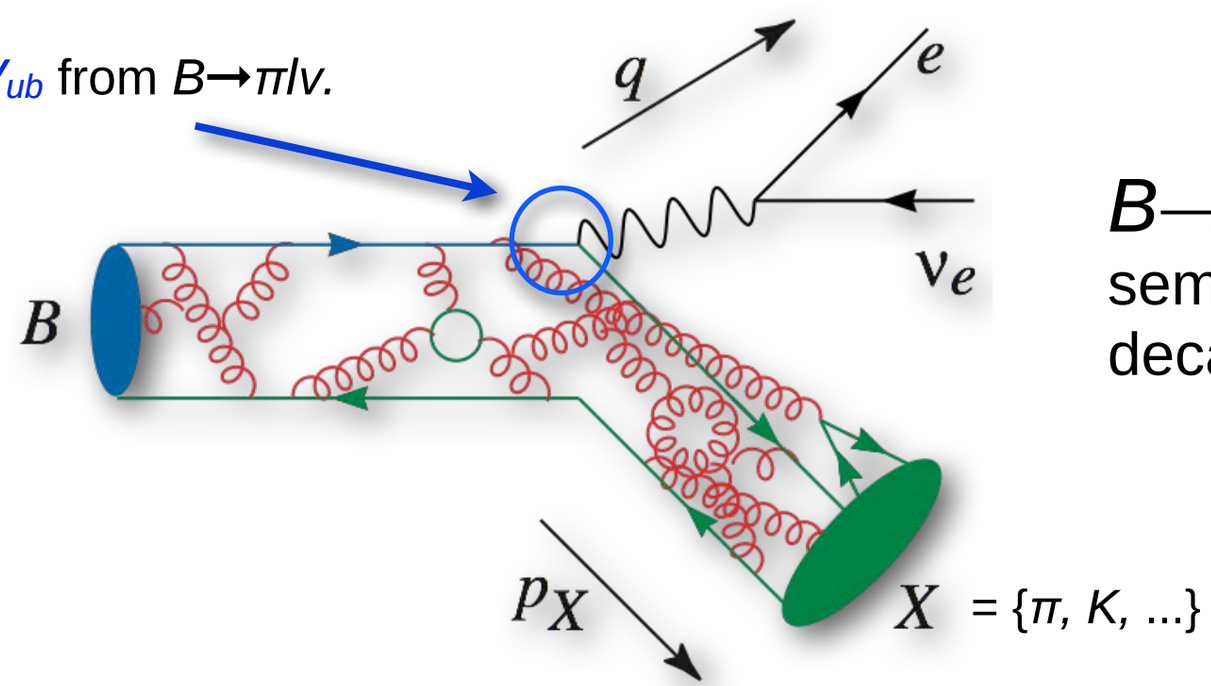
The theory of the strong interactions is quantum chromodynamics (QCD), the theory of quarks and gluons. Quarks and gluons cannot be directly observed because the forces of QCD are strongly interacting.

Quarks are permanently confined inside hadrons, even though they behave as almost free particles at asymptotically high energies.

"Asymptotic freedom", Gross, Politzer, and Wilczek, Nobel Prize, 2004.

Determine V_{ub} from $B \to \pi l \nu$.

Lattice QCD is used to determine the properties of quarks and gluons from the observed properties of hadrons.

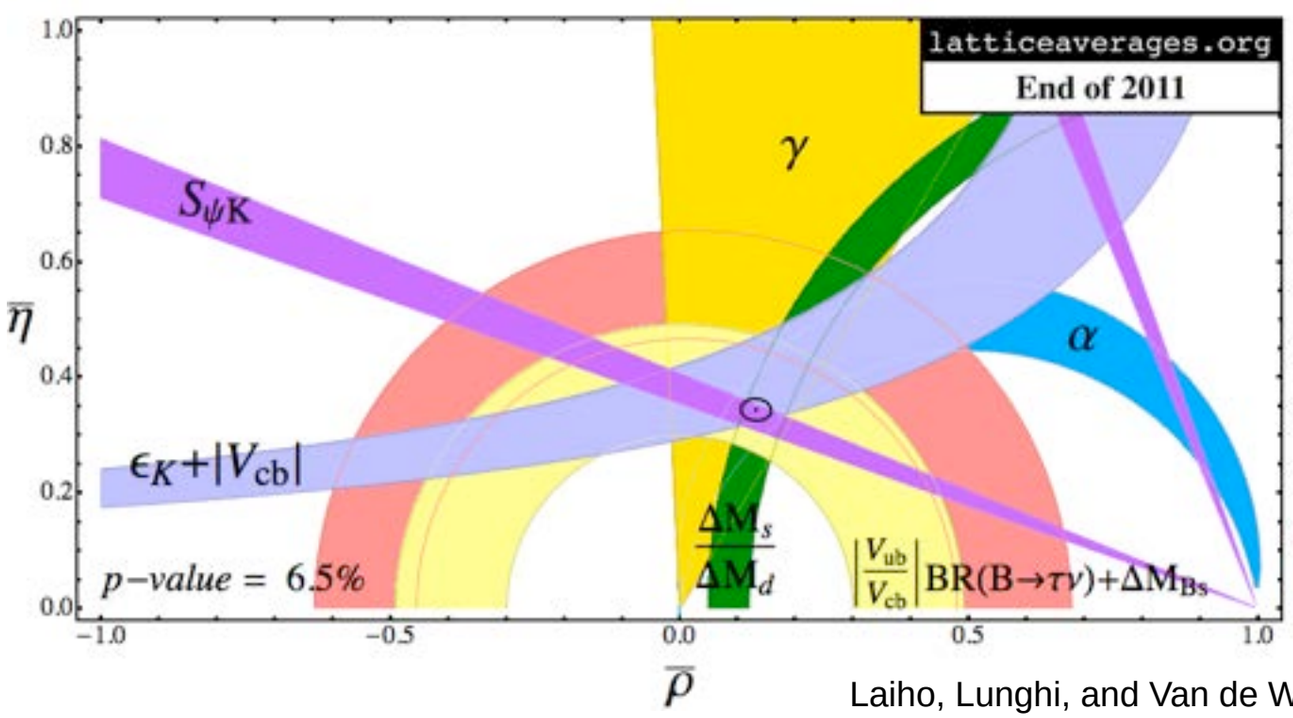


$B \to \pi l \nu$ semileptonic decay

A crucial goal in Intensity Frontier physics is the determination of the CKM matrix elements.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \overset{\text{in SM}}{\Longrightarrow} V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

In the standard model, the quark mixing matrix is (special) unitary, and determined by four parameters, but new, beyond-the-standard-model interactions could make the nine matrix elements independent.



Laiho, Lunghi, and Van de Water, http:www.latticeaverages.org.

Determinations of ρ and η are inconsistent at the ~2.5 σ level.
Is it a hint of new physics, or mis-estimated uncertainties from experiment or theory?

Some of the experimental inputs are accurate to 0.5%. New physics could be hidden in existing data, obscured by blurry lattice calculations. Comparably accurate lattice calculations are urgently needed.

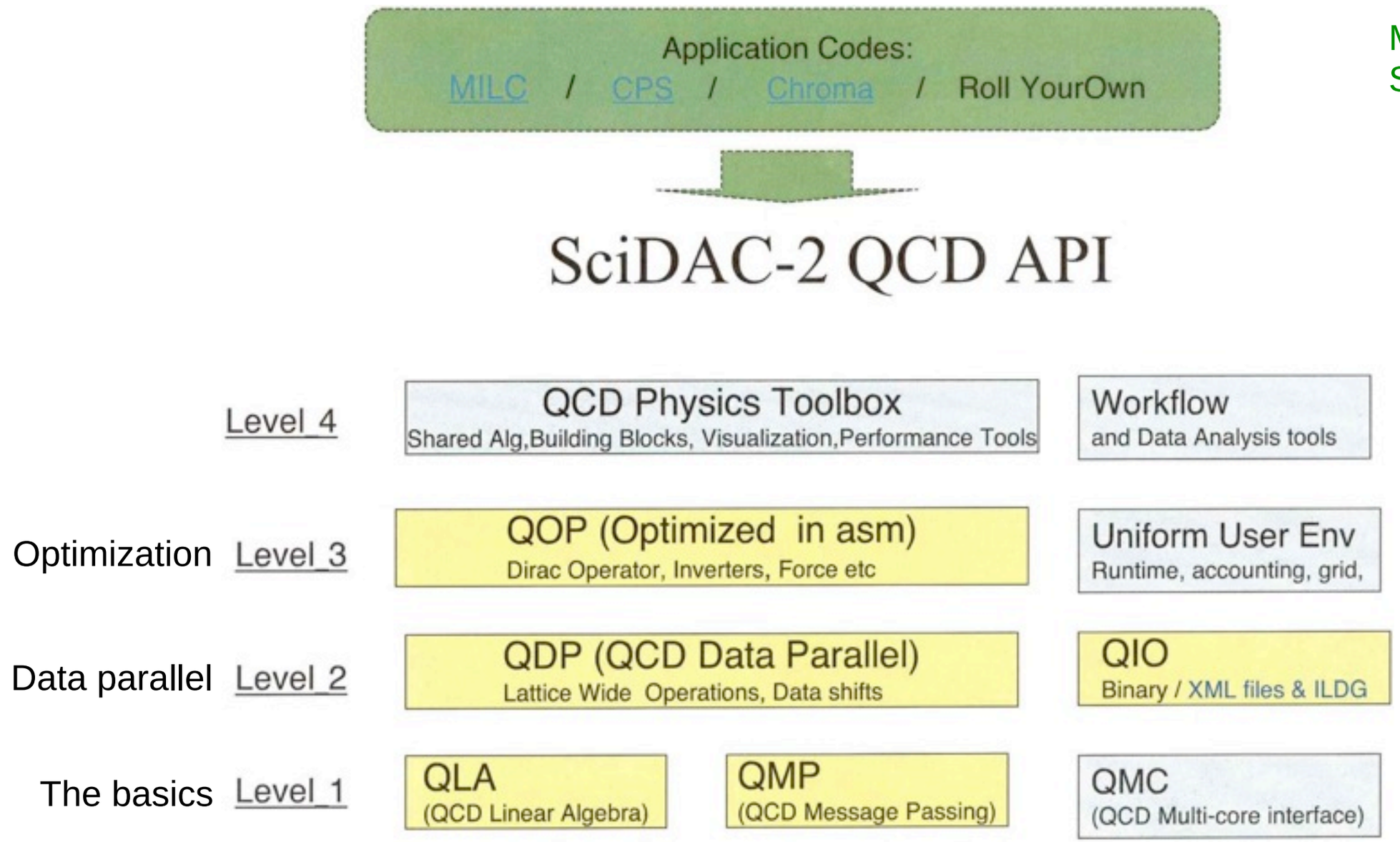
USQCD

- The US lattice gauge theory community consists of ~150 people, in both high energy and nuclear physics.
  - About a dozen or so competing physics collaborations.
- Almost all of them have combined into the USQCD Collaboration for the purpose of organizing the hardware and software infrastructure needed for lattice calculations.
- Software program managed by the software committee, Rich Brower, chair.
  - 20-25 participants. Weekly conference calls.
  - Includes SciDAC postdocs and computer scientists, people on other grants, industrial collaborators, and professors on their regular salaries.

SciDAC software

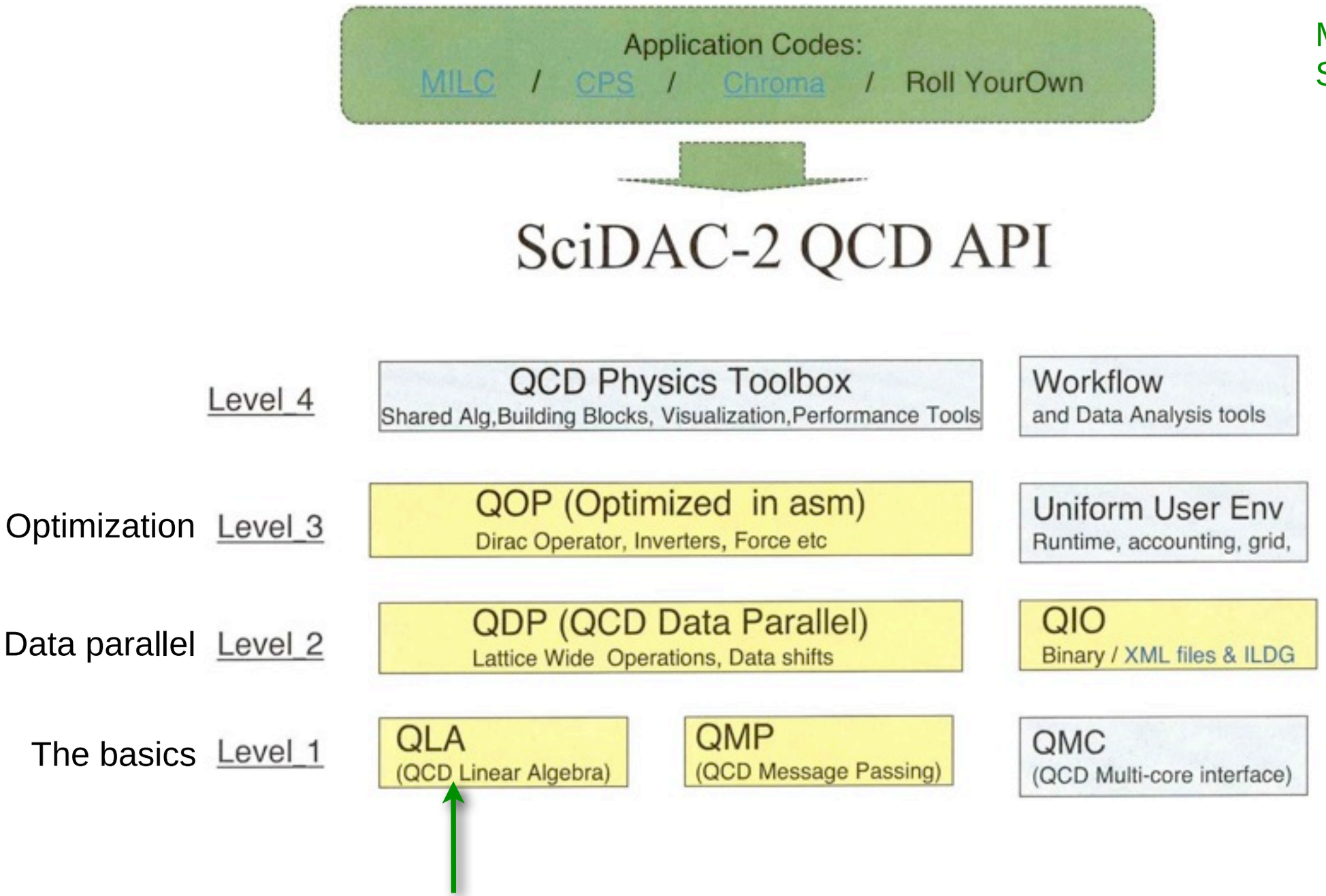
- Essential to our physics program
  - for using hardware resources efficiently, both our INCITE resources and our LQCD-ext capacity hardware at Fermilab and JLab,
  - for integrating new methodological developments.
- SciDAC-1 and -2 achievements include
  - community libraries for QCD programming, called the QCD API,
  - optimized high-level QCD codes and software packages,
  - porting to new platforms,
  - work with SciDAC centers and institutes and with computer scientists and applied mathematicians.

The QCD-API



Main structure was in SciDAC-1.

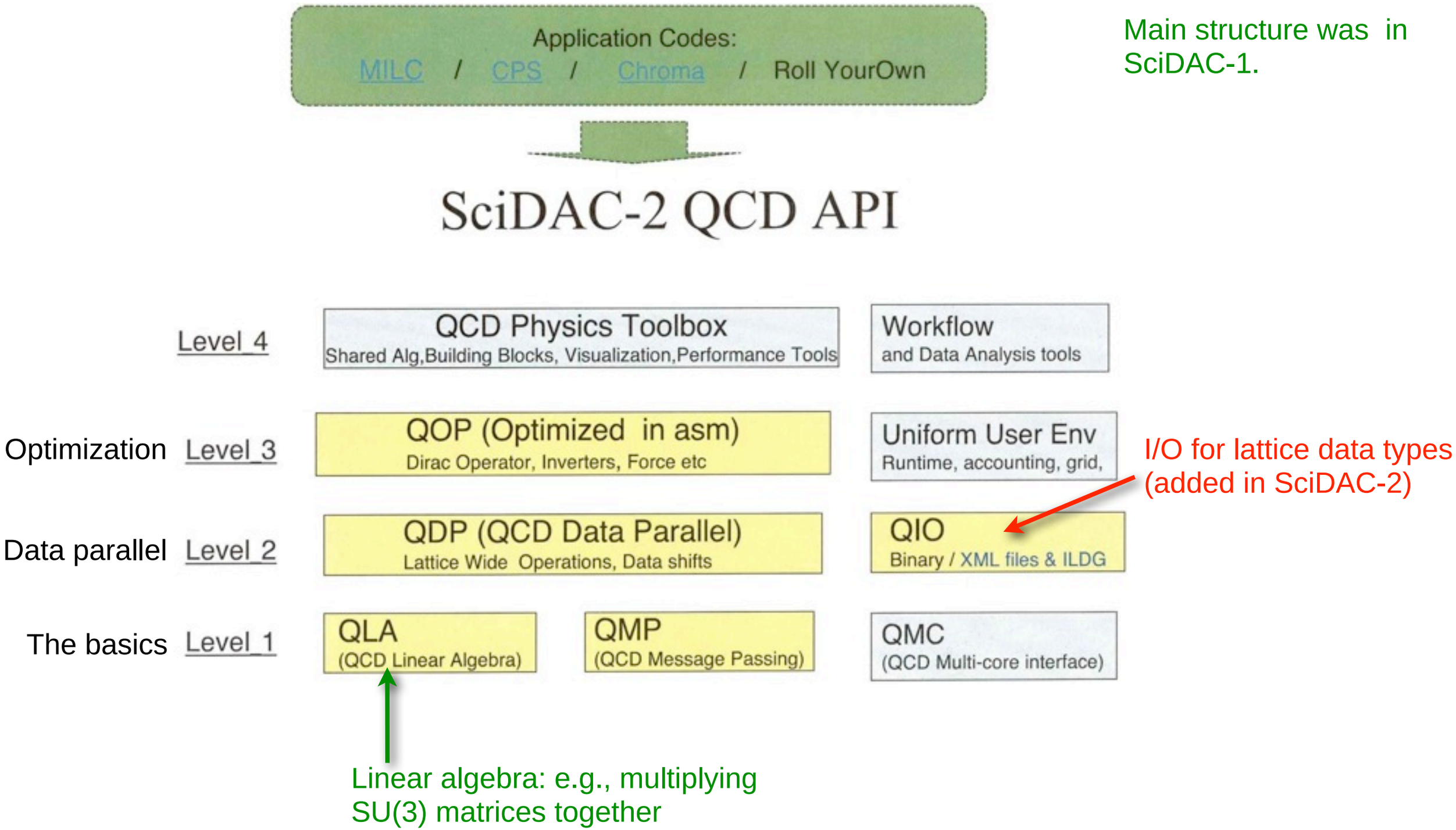
The QCD-API



Main structure was in SciDAC-1.

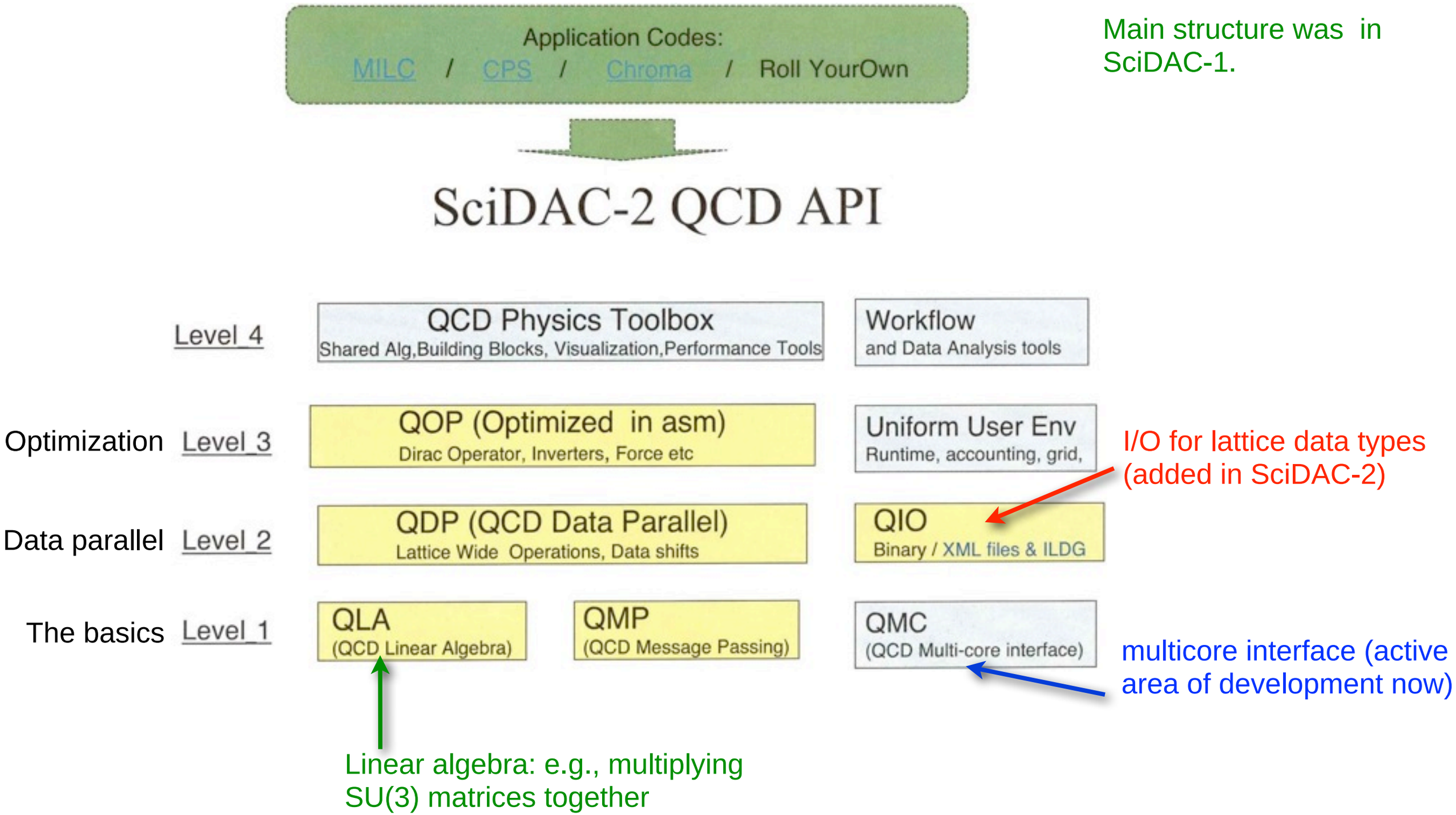
Linear algebra: e.g., multiplying SU(3) matrices together

The QCD-API



Main structure was in SciDAC-1.

The QCD-API



Main structure was in SciDAC-1.

Software challenges in the SciDAC-3 era

- Intensity frontier
  - Existing QCD libraries and codes need to be extended and optimized for new architectures.
  - Improved methods and algorithms need to be developed and implemented.
- Energy frontier
  - Libraries and community codes of the QCD-API need to be adapted for new strongly interacting theories which may be demanded by experiment.
  - Renewed investigation of uncertainty analysis may be required.

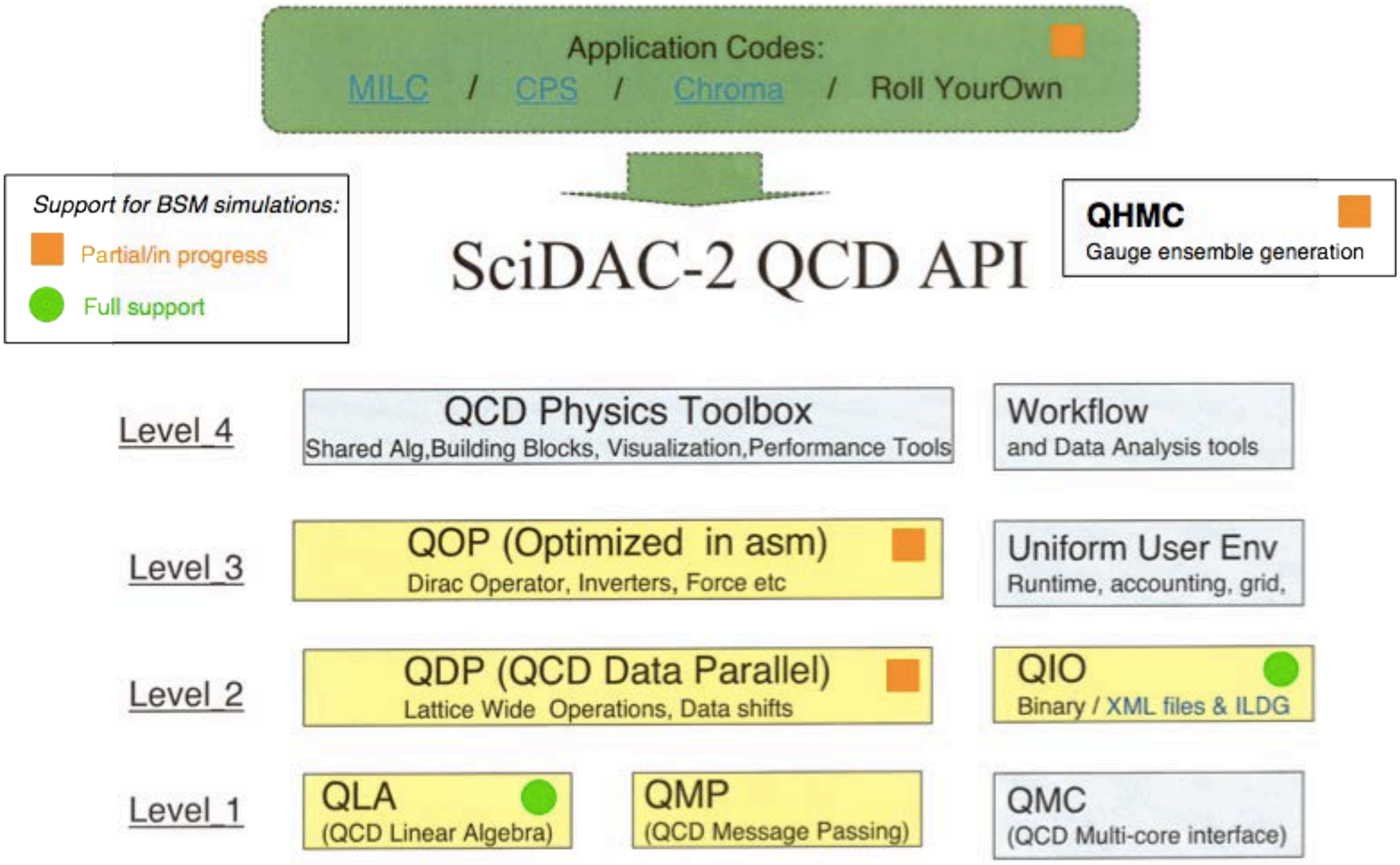
Energy Frontier software challenges

Speculations have ranged in many directions for new physics to explain various puzzling features of the standard model.

- Technicolor, top-color:
  - The role played by the Higgs in the standard model is played by composite particles produced by a new strong interactions. (Ethan Neil poster.)
- Supersymmetry:
  - A new symmetry of nature associates with every observed particle a partner with higher mass.
- Extra dimensions:
  - Space has more than four dimensions; the extra dimensions are compact with radii of sub-atomic scale.
- ...

These new interactions generically involve new strongly interacting sectors, including new forces with gauge groups other than the SU(3) of QCD and matter with charges different from the complex 3-vectors of QCD.

This requires generalizing the USQCD libraries in SciDAC-3 beyond the data types of QCD (SU(3) matrices and 3-vectors). (Ethan Neil poster.)



New strongly coupled theories may strain or break the uncertainty analysis that is well established for QCD.

Lattice gauge theories start from the fundamental equations. No model uncertainty.

- In QCD, uncertainties arise from
  - statistics
  - finite volume
  - discretization
  - extrapolation to physical quark mass (in early calculations)

Known coefficients

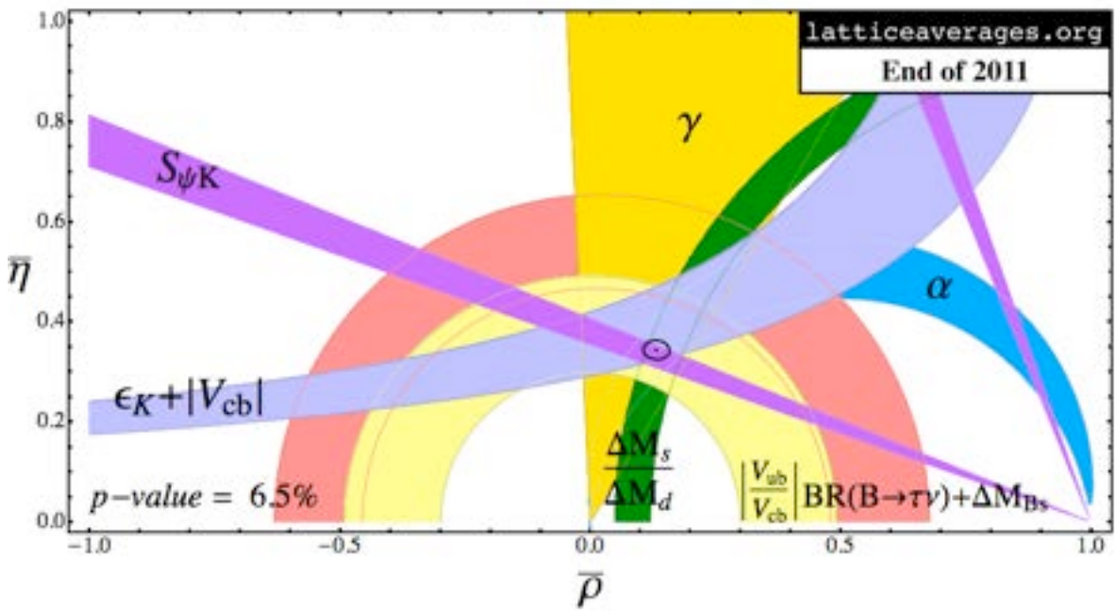
Asymptotic forms are convergent series with known functional forms

Coefficients that can be estimated within ranges from physical arguments.

⇒ Use Bayes' formula

In QCD, this is well understood and solid.
In new theories, these theories may converge poorly or not at all, and we have no experimental experience with the physics we are describing.

Intensity Frontier software challenges



The quest to improve the search for beyond-the-standard-model effects in the quark sector by an order of magnitude requires lattice QCD calculations an order of magnitude more precise.

SciDAC-3 goal is to push QCD to faster algorithms and bigger computers.

Operationally, lattice QCD computations consist of

1) Sampling a representative set of gauge configurations with Monte Carlo methods,

   E.g., the Metropolis method, the hybrid Monte Carlo algorithm, ...
   Consists of one long Markov chain.

2) Calculating the propagation of quarks through the gauge configurations,

   Solve the Dirac equation (a sparse matrix equation) on each configuration with relaxation methods, e.g., biconjugate gradient algorithm, etc.

3) Constructing hadron correlation functions from the quark propagators.

Better algorithms

- In the last 30 years, the development of better methods has contributed even more to lattice calculations than the factor of a billion raw machine speedup from the VAX 11/780 to the Blue Gene/Q.
  - Algorithms for generating gauge configurations have sped up by factors of 10-100 in the past ten years.
- Highest priority is improving the quark solvers, a sparse-matrix problem.
  - Very promising multi-grid methods have emerged.
  - Working with collaborators in the FASTMath Institute and the NVIDIA emerging applications group.
    - FASTMath colleagues will provide a framework for fast turn-around exploration and testing of novel algorithmic ideas; we will interface lattice QCD kernels with the FASTMath HYPRE applied mathematics effort.
    - With NVIDIA, we will adapt these methods for many-core architectures.

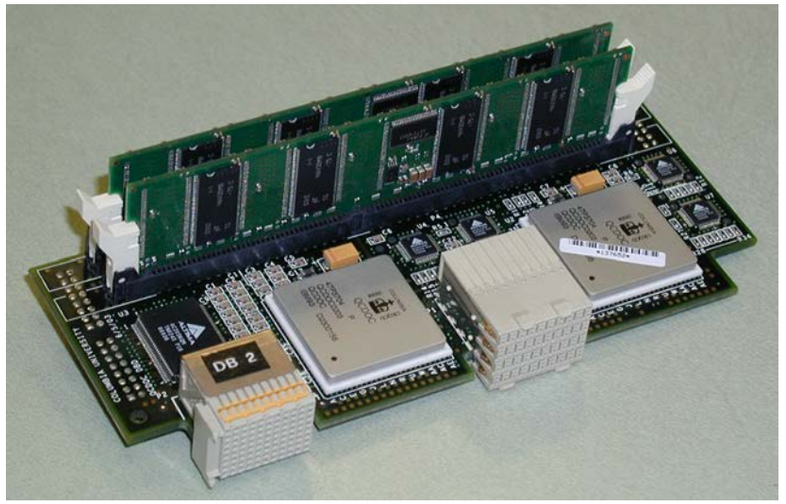
Bigger machines

Lattice gauge theorists have been involved with the development of supercomputing from the beginning; our ability to program the largest current machines is enhanced by close relationships with vendors.

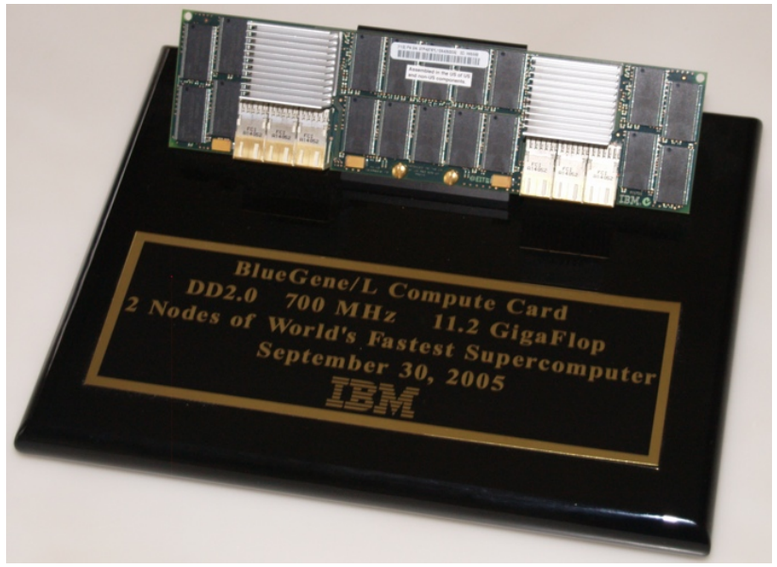
- Ken Wilson, inventor of lattice gauge theory, was an early proponent of supercomputing.
  - In the 70s, he was programming array processors in assembly language to attack critical phenomena problems for which he won the Nobel Prize.
  - In the 80s, he pushed for establishment of the NSF supercomputing centers.
- After the introduction of Monte Carlo methods to lattice QCD in the early 80s, lattice gauge theorists worked to design machines aimed at lattice QCD
  - in academic efforts at Caltech (Cosmic Cube), Columbia, IBM (GF11, not a commercial project), Fermilab, ...
  - as part of the Thinking Machines project.

The QCDSP, the QCDOC, and the Blue Gene/L

- The Columbia group, led by Norman Christ, won the Gordon Bell prize for price/performance in 1998 for the QCDSP, a machine purpose-built for lattice QCD.
- It was succeeded by the QCDOC.
- A team led by Al Gara that had been part of these projects went to IBM and designed the closely related (and commercial product!) BG/L, which won the Gordon Bell prize for performance in 2005.
  - The system-on-a-chip design, tightly coupled standard processor and FP unit, torus network, and style of mechanical design (small easily replaced node cards) were modeled on the Columbia machines.

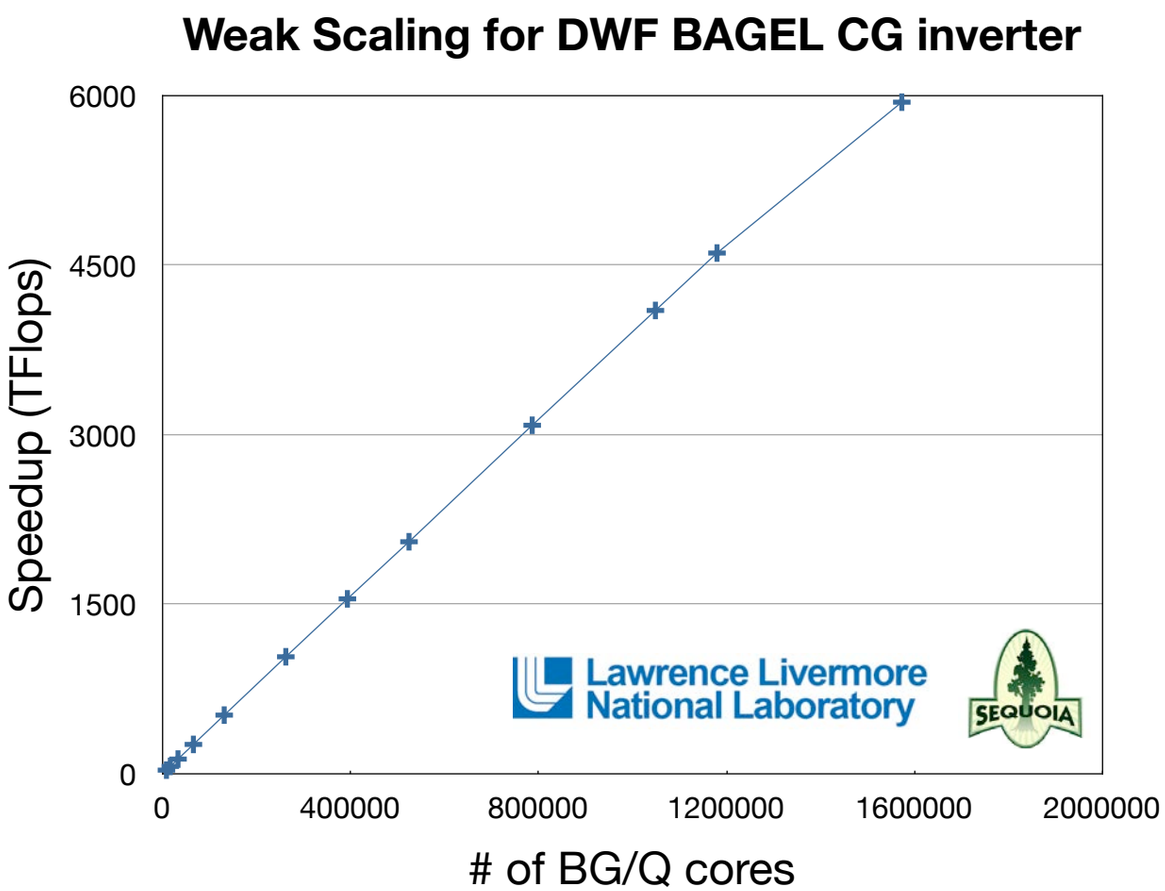


QCDOC compute card.



BG/L compute card.

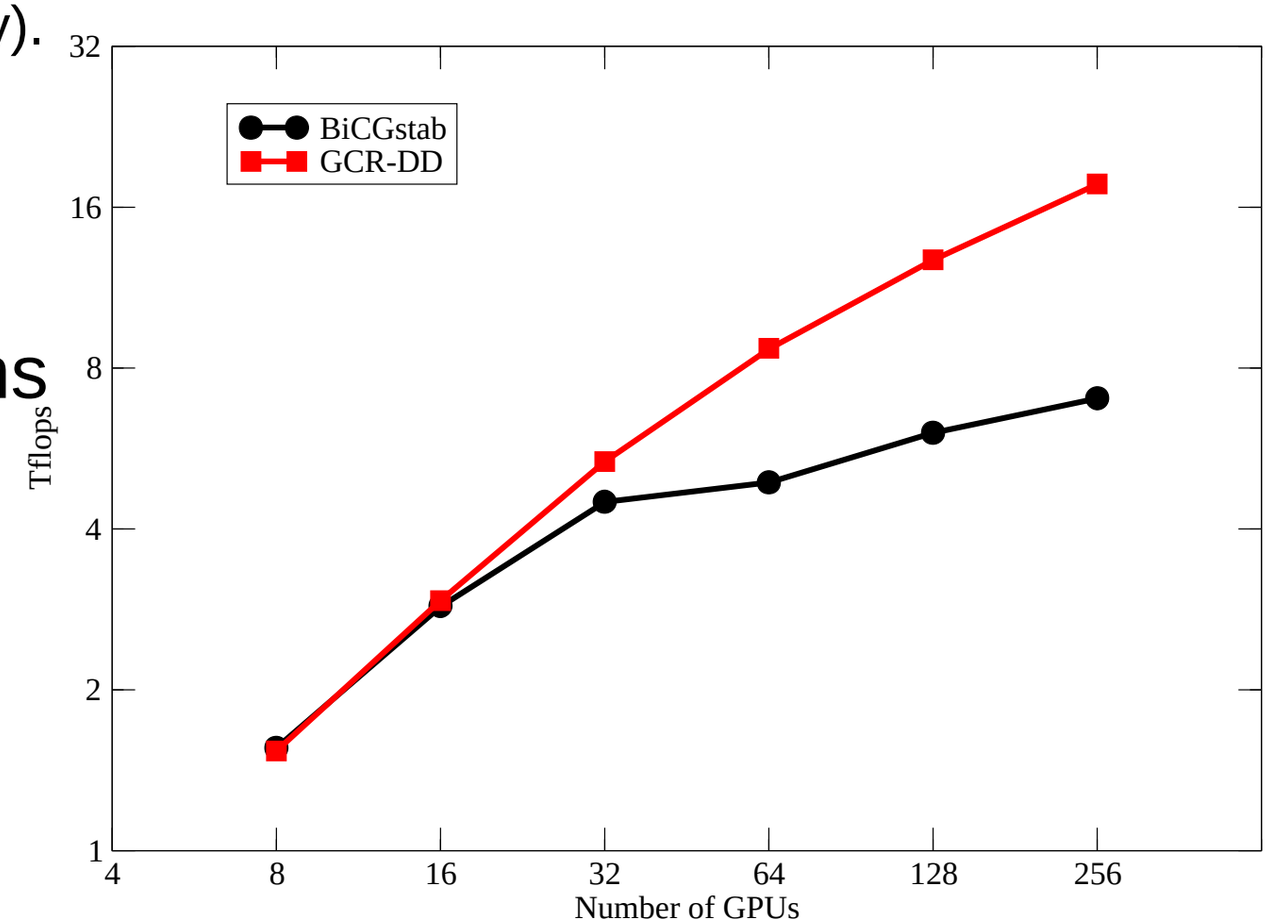
The BG/Q



- The Columbia group participated in the design of the BG/Q. Under contract with IBM, they designed and implemented:
  - The interface between the processor core and the level-2 cache, and
  - The look-ahead algorithms used to prefetch data from level-2 cache and main memory, anticipating misses in the level-1 cache.
- Almost perfect weak scaling, 6 PF sustained, achieved on 96 racks of Sequoia (Columbia UK collaborator Peter Boyle).
- Our SciDAC-3 effort is working to port our libraries and codes. (Heechang Na poster.)

GPUs

- Break some of the software model in the QCD-API.
  - How much of the QCD-API can be ported?
- NVIDIA has hired two of USQCD's top GPU experts.
  - They work with academic collaborators to attain best performance,
  - Mike Clark, former BU postdoc, evaluates potential future architectures in terms of QCD (cache sizes, memory bandwidths, network bandwidth, latency sensitivity).
- Strong scaling for GPUs improved with communications minimizing algorithms
  - Schwarz domain decomposition,
  - mixed precision solvers.



Outlook: Lattice gauge theory in the '10s

- There are 1,000s of potentially interesting strongly coupled beyond-the-standard-model theories.
  - It will be impossible to investigate them all carefully using the computers of the 2010s. Each is at least as difficult as QCD.
  - Experimental guidance will be required to guide the investigations.
- The experimental precisions obtained in quark mixing experiments require lattice QCD calculations accurate to a few tenths of a percent.
  - An order of magnitude more accurate than we've achieved so far.
    - It's not clear how to achieve this, even with the computers of 2020.
- A vast wilderness of new lattice calculations is still waiting for us.