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RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC

May 26, 2005

Organizers:

Satoshi Ozaki and Nicholas P. Samios

RIKEN BNL Research Center

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group currently consists of about twenty researchers, and the RBRC Experimental Group, of about fifteen researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~40 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are seventy-three proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. A 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998 and is still operational.

N. P. Samios, Director
May 2005

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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QCD SUPERCOMPUTER CENTER

Dedication of RBRC QCDOC Computer

May 26, 2005

Dedication Ceremony of RBRC QCDOC: Chair: S. Ozaki

From Left: Nicholas P. Samios, Director, RBRC; T. D. Lee, Director Emeritus, RBRC; Koji Kaya, Director, Discovery Research Institute, RIKEN; Yoshiharu Doi, Executive Director, RIKEN; Satoshi Ozaki, Special Assistant to Laboratory Director for Accelerator Projects, BNL; Ryutaro Himeno, Director, Advanced Center for Computing and Communication, RIKEN and Praveen Chaudhari, BNL Director

Agenda for
the Dedication of the RBRC QCDOC Computer

Date: Thursday, May 26, 2005
BNL Bldg 510, Large Seminar Room

Dedication of RBRC QCDOC:		**Physics Large Seminar Room**
		(Chair: S. Ozaki)
10:00 AM	Welcome Remarks	Praveen Chaudhari, BNL Director
10:30 AM	Remarks	Yoshiharu Doi, Executive Director of RIKEN
11:00 AM	Remarks	N.P. Samios, Director of RBRC
11:30 AM	**Dedication of QCDOC at the Computing Center, Bldg. 515**	
12:00 Noon to 2:00 PM		Lunch: South Room BNL Center
Symposium on RBRC QCDOC		**Physics Large Seminar Room**
		(Chair: Jeffrey Mandula)
2:00 PM	QCDOC: From Chips and Boards to Quarks and Gluons	Norman Christ, Columbia
2:30 PM	New Physics Programs on QCDOC	Taku Izubuchi, RBRC/Kanazawa U.
3:00 PM	Kaon Physics	Christopher Dawson, RBRC
3:30 PM	Break	
		(Chair: G. Bahnot)
4:00 PM	Simulating HOT Matter on COOL Computers	Frithjof Karsch, BNL
4:30 PM	QCDOC and Domain Wall Fermions: Making Lattice QCD Simpler	Robert Mawhinney, Columbia
5:00 PM	Adjourn	

Dedication of the RBRC QCDOC Computer
Welcome Remarks by Praveen Chaudhari
Director, BNL

I would like to welcome all of you to Brookhaven National Laboratory. This is a very special day for the laboratory and a very special day for the partnership between RIKEN, Columbia, IBM, and Brookhaven. I want to say a few words of reminder about the evolution of this partnership and mention a few names that played a key role and continue to do so.

It was ten years ago that the Memorandum of Understanding was signed between RIKEN and Brookhaven establishing a spin physics program at this laboratory. About two years later, the RIKEN/Brookhaven Research Center was formed, and the forerunner of the machine that we are dedicating today was proposed. This was the QCDSP computer built in a partnership between Columbia University, IBM, and Brookhaven and, of course, RIKEN was the financial driving force behind it. So this was the beginning of not only the spin physics program --- experiment and theory --- but also the beginning of a larger enterprise--- the QCD laboratory, with three legs of experiment, theory, and lattice gauge calculations.

The people who played a key role and, one in particular, who set the standard is well known to everyone: T.D. Lee. I saw his beautiful sketch of the two bulls on the entrance wall of the QCDOC room. If you imagine TD to be one then the other bull is Dr. Noyori of RIKEN. The two together make the RBRC succeed. The other person I want to recognize is Norman Christ. Without these players we would not be here today. Nick Samios has taken over from TD in running the RBRC. Nick, I hope, will follow the approach that Bruce Stillman at Cold Spring Harbor is taking and that is every time Jim Watson, who is their TD, is promoted to replace Jim, he elevates Jim to a higher designation. So Nick, you will have to find a suitable title for TD.

I believe that QCDOC represents a class of machines that people have been struggling to design for some time. For example, when I was at IBM it occurred to me that as a computer company we ought to be designing special purpose machines to solve special and important scientific problems. Computer simulation or lattice gauge calculations of QCD, as an important science problem, were proposed. So in 1982 or thereabouts, we went out and hired a man who had worked with Norman, his name is Don Weingarten. We told Don, along with some computer scientists who were present at the IBM Laboratory at Yorktown, to design and build a special purpose computer for QCD. The first of these special machines, and at that time we had what we thought was a tremendous goal, was designed to achieve 11 gigaflops. This machine, called, GF-11, was built and operated. Interestingly enough, when we started to build GF-11 our colleagues in the computer science department realized that perhaps they also ought to be building a special machine that would do something equivalent to GF-11 but in computer science, and so they came up with a machine that was designed to compete with Garry Kasparov in chess. This was the genesis of the machine called "Deep Blue."

It eventually beat Kasparov. I thought you might find the connection between QCD and chess interesting. GF11, for its time was great. However, it was evident that even more powerful machines were needed to achieve the precisions that were desired. And so the quest continued.

I believe, as you look at computational science of the future, there are two extremes of machine design to consider: one of them is a very special purpose chip like the grape chip, which does molecular dynamics very well and, I expect, a machine using the grape processor will be the first machine to break the petaflop barrier. However, the grape chip is not very flexible. It can only handle a limited set of scientific applications. The other extreme are the vector supercomputers epitomized by Cray. These can do a great variety of computing tasks and have well developed software applications. They are, however, relatively expensive, power hungry and space hungry and so it is difficult to expect the performance of these machines to go beyond 100 teraflops or thereabouts. But there is a class of problems that need, QCD being one of them, 100's of teraflops or perhaps petaflops of computer power. In order to avoid the extremes of grape or the conventional supercomputers, we need architecture that will enable us to reach the petaflop regime without restricting the number of applications unduly. Perhaps unknowingly, this is what Norman Christ and Bob Mawhinney did with their QCDOC design. I know Jim Davenport and Jim Glimm, who are here with us today, are leading an effort to try to understand what other applications can be run efficiently on QCDOC.

The other story I want to tell you is what happened to the daughter of QCDOC. Al Gara, who was a member of the team that designed QCDOC, joined IBM and he helped design a class of machines called blue gene L. These machines have been designed to have a broader application base but, of course, they can also do QCD if need be. They have already demonstrated they can achieve well over a hundred teraflops.

You can see how the quest for QCD lattice gauge calculations lead in one case to the field of chess playing machines and in another to a design suitable for commercial applications with a wider application base than grape.

I have spoken longer than I usually do or had planned to. I want to congratulate all the team members on helping put the QCDOC machine together and that includes Ed McFadden and his team. It is indeed a special day to dedicate this 10 teraflops machine. Once again, I thank all of the people who made this happen.

Dedication of the RBRC QCDOC Computer
Remarks by Yoshiharu Doi
Executive Director, RIKEN

My thanks to Dr. Chaudhari for the warm welcome and to our BNL friends for their kind hospitality.

I would like to begin with a brief message from RIKEN president, Ryoji Noyori. He has asked me to send to you his sincere regrets for not being able to be here on this special occasion, and he thanks all of you for preparing such a a well-organized and wonderful celebration. President Noyori looks forward to meeting Dr. Chaudhari and the BNL personnel when he visits here this October. He is also looking forward with pleasure to seeing the BNL facilities for himself.

It is indeed a joy to be celebrating the dedication of the QCDOC today. This machine is a forerunner of the next generation of computers and is the crystallization of the collective wisdom and knowhow of RIKEN, Columbia University, and BNL. At 10 teraflops, the QCDOC is the fastest dedicated lattice QCD calculator in the world It is most fortunate that RBRC can possess and operate such a machine. The young scientists here have the double good fortune of access to the QCDOC and the guidance of some of the leading minds in the field of lattice QCD. I look forward to seeing very satisfying reports on the results of their advanced research.

The RBRC was established in the autumn of 1997 by then-RIKEN president Akio Arima and Professor T.D. Lee in emulation of the Niels Bohr Institute which was one of the leading laboratories in the early years of quantum mechanics. Under the leadership of Professor T.D. Lee, the RBRC has come very close to achieving its ideal of providing a stimulating environment for advanced research by young scientists from such well-known institutions as Columbia University and MIT as well as the Brookhaven National Laboratory itself. This environment is, of course, even further enhanced by the RHIC, which is one of the world's most advanced relativistic heavy ion colliders.

The RBRC has achieved excellent research results and sent out many nice scientists into the world. In particular, the recently announced discovery that matter in the earliest stages of the universe may have been a liquid-like quark-gluon plasma suggests that RHIC and the new QCDOC may open up completely new possibilities in the search for the origins of the universe and matter that go well beyond anything we can imagine today. Nothing could be more appropriate in this year of 2005, which has been called the World Year of Physics in celebration of Albert Einstein's 1905 publication of his three major papers on quantum theory.

I have been told that the QCDOC has 6,144 daughter boards incorporated in each of 192 motherboards. It has a calculation speed 10 times as fast as the current QCDSP, and with excellent cost performance of less than one dollar per megaflop thanks to its extremely simple lattice QCD calculation system. It is also highly energy efficient compared to conventional super computers, consuming only five milliwatts of electricity per megaflop. Finally, the new machine is also easy to maintain.

One cannot consider the QCDOC without first taking a look at its QCDSP machine completed in 1998. Professor T.D. Lee and others worked hard to keep the QCDSP production costs down. For example, the computer chips used in the QCDSP are the same as those used in cell phones. Norman Christ of Columbia University designed the machine, and the university was most helpful in securing the required parts locally and at as low a cost as possible. As a result, as I am sure you all remember, the QCDSP was awarded the Gordon Bell Prize in 1998 for excellent price performance for a supercomputer. Since then the QCDSP has helped many young scientists in their research and sent them on their way to secure tenure at various universities. Of these young scientists, I am told, several have now returned to RBRC as RHIC Physics Fellows retaining their affiliations with their respective universities as well as with the RBRC. This time they will be working with the RBRC and helping to mentor their successors in research.

Both the QCDSP and the QCDOC were primarily a joint project of RIKEN and Columbia University, but the installation and maintenance of these computers must be credited to Ed McFadden and others of the Brookhaven Computing Facility staff. Thanks to their tireless work, there is just about no loss time with the two computers and researchers are able to get maximum performance. This is indeed something to be proud of.
Finally, a few words about the QCDOC room at the Brookhaven Computing Facility. I have only seen photographs, but I am told the BNL has set aside a very nice room for the new QCDOC. The overall tone of the room is blue, and above the entrance is the painting that everybody at the center is very familiar with, that was used for the poster celebrating the establishment of the RBRC. I look forward to seeing this room and the painting later.

Every improvement in equipment leads directly to a qualitative improvement in research. This is a truism that I have encountered repeatedly at various research facilities. I am most grateful that we are able to have this dedication in this World Year of Physics, and would like to express my sincere thanks to everyone at the RBRC and BNL who helped to make this occasion possible. I look forward to new advances in science and the continued development of the RBRC.

Finally, I would like to introduce RIKEN Directors and staffs who are participants from RIKEN Today. Dr. Kaya, he is a Director of Discovery Research Institute. Dr. Motobayashi, He is a Chief Scientist and Director of Heavy Ion Nuclear Physics Lab. Dr. Himeno, he is a Director of Advanced Center for Computing and Communication. Dr. Yanokura, he is a Director of Public Relations Office. Mr. Funada, he is a Director of DRI/FRS Promotion Division. Ms. Shimoyamada, she is a Deputy Manager of DRI/FRS Promotion Division, Mr. Komai, he is a staff of Public Relations Office.
Thank you.

Dedication of the RBRC QCDOC Computer
Remarks by Nicholas P. Samios, Director, RIKEN BNL Research Center

This is indeed an auspicious occasion--where we are here to dedicate the RIKEN BNL Research Center 10 Teraflops QCDOC Computer funded by RIKEN (The Institute of Physical and Chemical Research) of Japan and to acknowledge the efforts of many of the individuals who made this possible.

First we note the major contribution by RIKEN in the person of Dr. Kobayashi who very early on signaled his strong support of QCDOC by signing a contract with Columbia University in 2002 for the construction of QCDOC, as well as supplying R&D funds for its design. This set the stage for two identical subsequent computers, UK Edinburgh and DOE national computers. Such an initiative by RIKEN (and Columbia) had occurred previously in 1997 when a similar agreement had been signed to construct a 0.6 teraflops computer, QCDSP. Its construction, as well as a 0.4 teraflops version at Columbia, was completed in 1998, a record time and it won the Gordon Bell prize for most cost efficient computational capability in the same year.

This sequence is not an accident. The seeds were sown many years earlier at Columbia where a series of computers Kflops, Mflops, Gflops were designed and constructed to operate by physicists. This was a consequence of the vision of T.D. Lee, who understood and nurtured this advent of larger and faster computers in the pursuit of physics. As such in the early formation of RBRC he had the concept of a major computing capability at RBRC in order to study non-perturbative QCD, one of the principal physics objectives of RBRC. T.D. therefore devised the strategy that assured the success of this series of computers and also guided and encouraged the many young researchers. In addition, Professor Lee has spent considerable time and effort extolling the virtues and emphasizing the compelling need of lattice gauge calculations. He delivered this message to colleagues, and universities and elsewhere as well as important officials such as Arima, Kobayashi, Marburger, Orbach, Staffin and others.

In order to be competitive with the large industrial producers of computers--one had to find a niche--and thus emerged the concept of a low power (heat), rapid communication with nearest neighbors, parallel processor computer. QCDOC with its 12,288 individual computers each with its own memory, uses only ~ 100 kilowatts of power (compared to megawatts for most other similar computers) and a footprint of ~100 square feet of floor space instead of a football field.

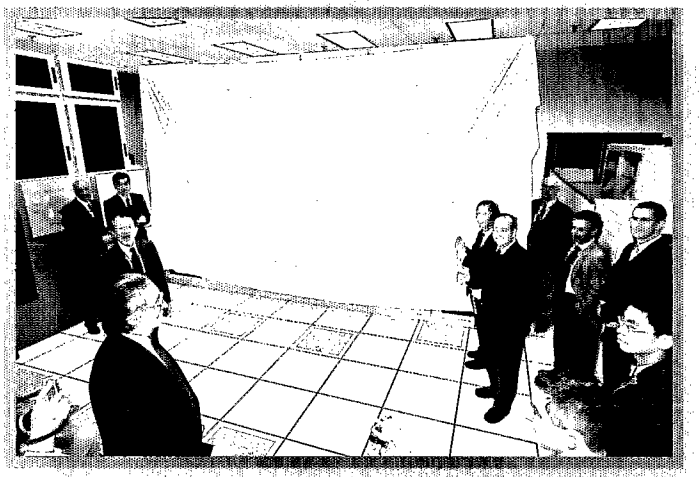
Needless to say (in spite of T.D.'s prowess) many talented individuals have contributed and dedicated themselves to the successful construction and operation of QCDOC. RBRC, Columbia, IBM, BNL and the University of Edinburgh formed this great collaboration, which solved the many problems that arose on the design, manufacture, testing, assembly and debugging of this computer. The Columbia Group has the longest track record in this business and Norman Christ certainly has been one of the

international leaders in the design and construction of fast computers, and he and Bob Mawhinney have spearheaded the whole QCDOC effort. Great strength was added by joining with IBM--a powerhouse in computing, and Al Gara has been an indispensable member of this endeavor. RBRC made major contributions via the efforts of Tilo Wettig and Shigemi Ohta and similarly the University of Edinburgh in Peter Boyle. The assembly, testing and bringing into operation of several of the QCDOC computers was the province of members of BNL's ITD group composed of Ed McFadden, Joe DePace and Ed Brosnan. As I have matured I have grown to appreciate the importance of upper management and as such would like to acknowledge the strong support of Dr. Noyori of RIKEN, Dr. Chaudhari of BNL, Bill Pulleybank of IBM, Richard Kenway of UK, and our landlord Denis Kovar of DOE.

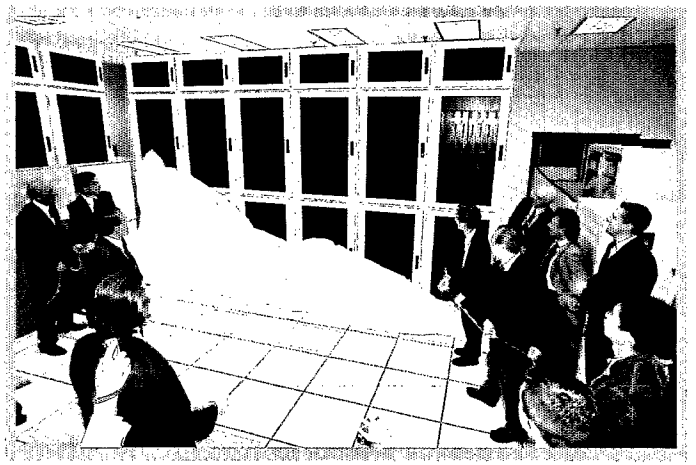
I believe that the advent of QCDOC will usher in a new era of precise calculations in lattice QCD. It will enable physicists to explore a host of exciting and important physics issues. One will now be able to explore larger lattices, smaller lattice spacing and include virtual quark pairs as well as satisfy chiral symmetry in these calculations. As such one will be able to better evaluate: hadronic masses, thermodynamic properties of a quark gluon plasma, hadronic effects associated with extractions of the parameters of the CKM matrix, CP violation in hadronic decays and nucleonic structures. Although this computer is dedicated to lattice gauge calculations, QCDOC may have more general applications and as such we are devoting 10% of its power to the investigation of other problems such as protein structures in biology and nano-materials in condensed matter physics.

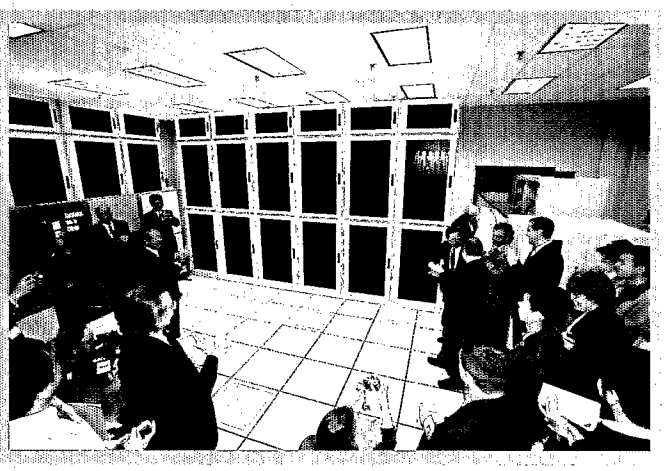
Finally, I want to note that the RBRC-QCDOC is one of three identical computing machines, the UK-Edinburgh QCDOC which was first assembled and tested at BNL--disassembled and shipped to the UK where it is in a similar operational phase as the RBRC machine. The DOE QCDOC is also being assembled at BNL and should be operational this summer.

We dedicated QCDSP in 1998 here at BNL and now we dedicate QCDOC in 2005 in the same place with many new collaborators. We have gone from 0.6 teraflops to 10 teraflops in these 7 years, a factor of 15-20, and I'm looking forward to another celebration in 5-7 years with a factor or 20-100 in computing capability and with relatively small power requirement and footprint. Hope to see many of you at that next grand occasion. In the meantime, let us proceed to dedicate the QCDOC computer.

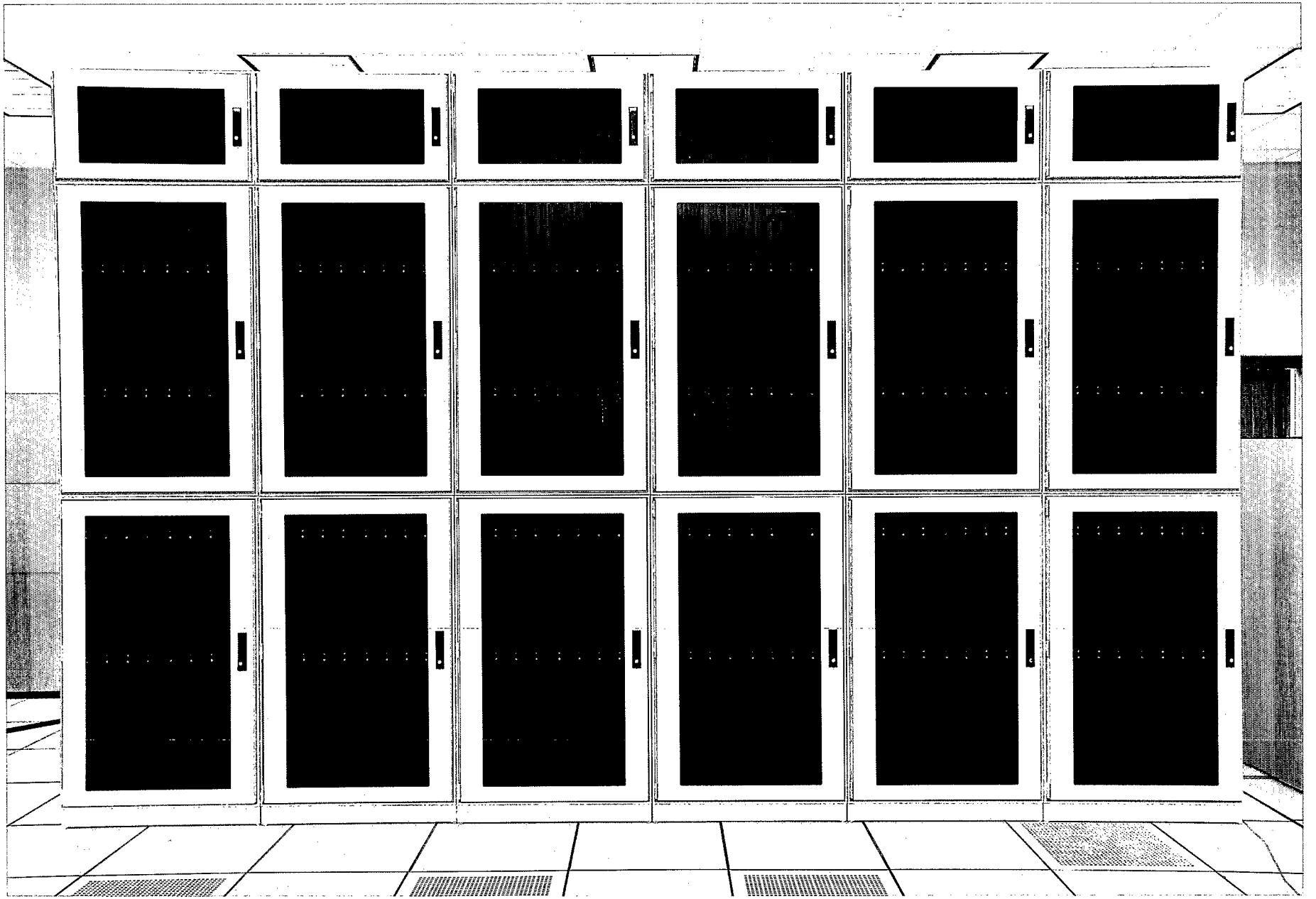


QCDOC
Supercomputer Unveiling





Back, from Left: Praveeen Chaudhari, BNL; Yoshiharu Doi, RIKEN; Norman Christ, Columbia University; Edward McFadden, BNL; T. D. Lee, Columbia University, and Koji Kaya, RIKEN; Front, from Left: Satoshi Ozaki, BNL, and Nicholas Samios, BNL/RBRC



Symposium on RBRC QCDOC

At the Symposium on RBRC QCDOC are: (from left) Norman H. Christ (Columbia University); Chris Dawson (RBRC/BNL); Frithjof Karsch (BNL); Robert D. Mawhinney (Columbia University); Jeffrey Mandula (DOE); G. Bhanot (IBM); and Taku Izubuchi (Kanazawa University/RBRC).

QCDOC: From Chips and Boards to Quarks and Gluons

Norman H. Christ, Columbia University

QCDOC: From Chips and Boards to Quarks and Gluons

RBRC QCDOC Dedication

May 26, 2005

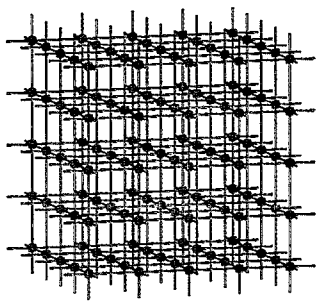
Norman H. Christ

Outline

- Overview of Lattice QCD
- QCDSP computer
- New technology: QCDOC
- Design of QCDOC
- QCDOC Construction
- Physics outlook

Overview of Lattice QCD

- Introduce a space-time lattice.
- Perform the Euclidean Feynman path integral.
  - Precise non-perturbative formulation.
  - Capable of numerical evaluation.



$$\sum_n \langle n|e^{-Ht}\mathcal{O}|n\rangle = \int d[U_\mu(n)]e^{-\mathcal{A}[U]_{\text{gauge}}}\det(D+m)\mathcal{O}[U]$$

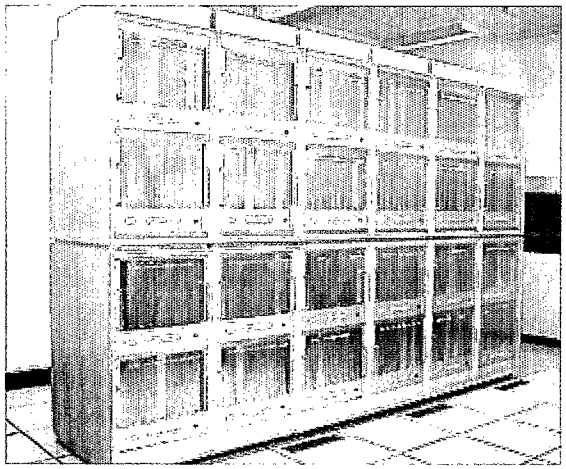
- Evaluate using Monte Carlo, importance sampling.
- Use space-time formulation directly – easily mounted on a parallel computer.

Well understood sources of error:

- Finite Volume: $Effort \sim ln(Error)$
- Quenching: $Effort \sim 100X$ [include $det(D+m)$]
- Finite MC statistics: $Effort \sim 1/(Error)^2$
- Perturbation theory $Effort \sim e^{+c/Error}$
- Quark masses too large: $Effort \sim 1/(Error)^2 + 1/(Error)^{8/n}$
- Non-zero lattice spacing: $Effort \sim 1/(Error)^{8/n}$

QCDSP Computer

- Completed in 1998
- 0.6 + 0.4 Teraflops
- QDCSP accomplishments:
  - Domain wall fermions.
    - **Theory**: Kaplan, Shamir, Narayanan/Neuberger
    - **First numerical studies**: Blum and Soni, Vranas
  - Non-perturbative renormalization.
  - Dynamical DWF simulations.

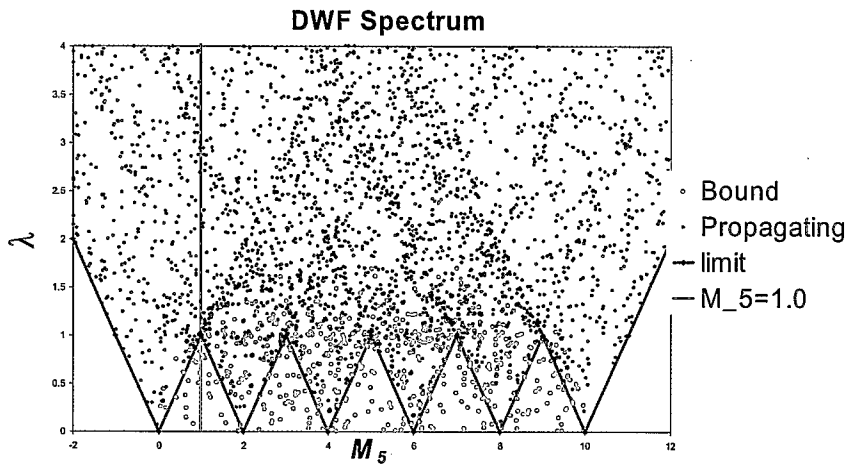


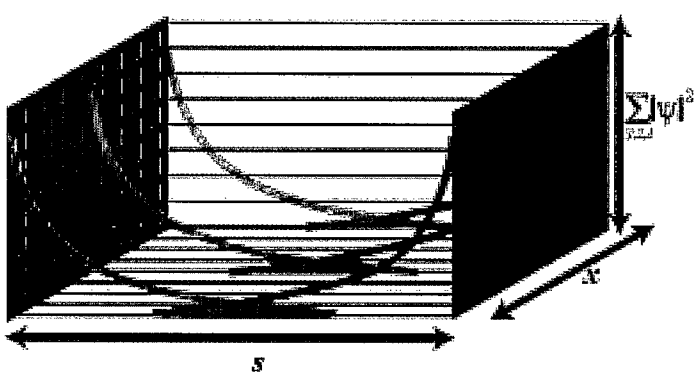
0.6 Tflops (RBRC)

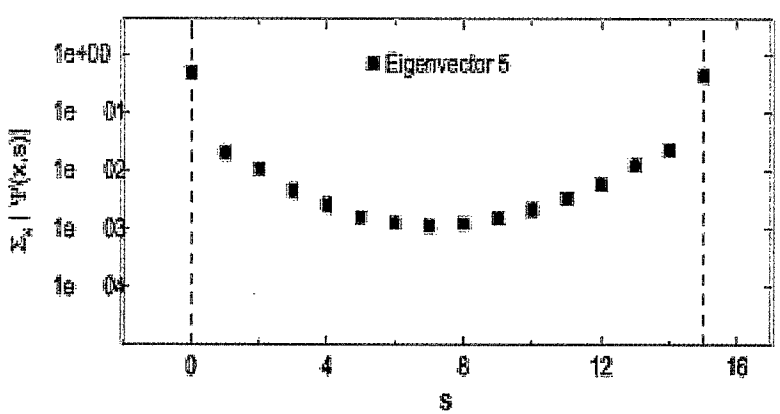
0.4 Tflops (Columbia)

Domain Wall Fermions

- 5-D theory with 4-D surface states.
- Typical 5-D extent of 16.
- "Revolution" in the lattice treatment of fermions.

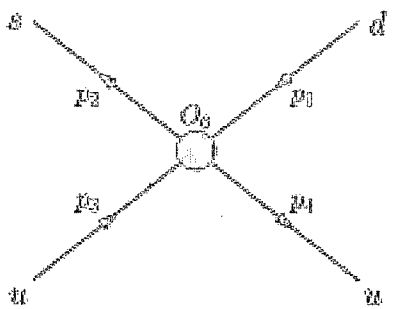






Non-Perturbative Normalization

- Many physical quantities are actually defined through perturbation theory applied at high energy:
  - Quark masses.
  - Effective, low-energy weak operators.
  - Continuum energy and momentum operators.
- Must "match" lattice operators to continuum conventions.
- Normalize lattice operators by evaluating off-shell Greens functions (RI/MOM) – closely connected to continuum conventions:
  - Nucleon structure functions
  - Kaon decay matrix elements
  - Off-shell lattice normalization



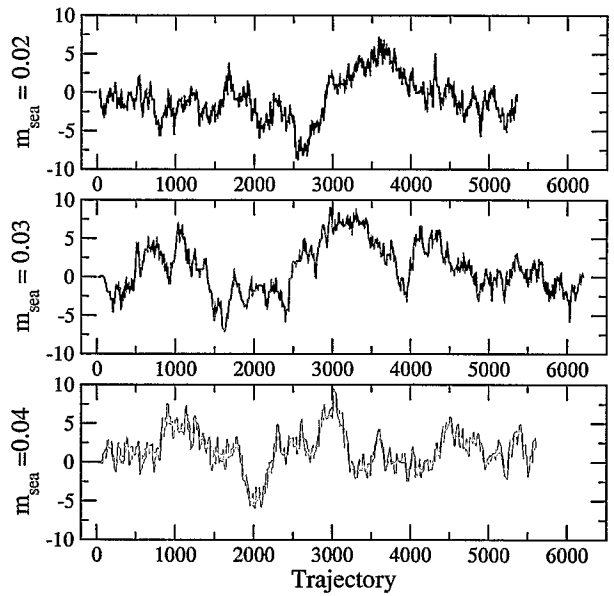
$p_i\, p_j = \mu^2(4\,\delta_{ij}-1)/3$

Simulations with Dynamical DWF

- Improved algorithms give 2-4x speed-up.
- Serious N_f=2 runs:
- 16^3 x 32, L_s=12, $1/a$=1.7 GeV
- Just at the edge of QCDSP capability

$m_{ud}/m_s = 0.5$	5361 trajectories
$m_{ud}/m_s = 0.75$	6195 trajectories
$m_{ud}/m_s = 1.0$	5605 trajectories

Evolution of topological charge



Well understood sources of error:

- Finite Volume: $Effort \sim ln(Error)$
- ~~Quenching: $Effort \sim 100X$ [include $det(D+m)$]~~
- Finite MC statistics: $Effort \sim 1/(Error)^2$
- ~~Perturbation theory $Effort \sim e^{+c/Error}$~~
- Quark masses too large: $Effort \sim 1/(Error)^2 + \cancel{1/(Error)^{8/n}}$
- Non-zero lattice spacing: $Effort \sim 1/(Error)^{8/n}\big|_{n=2}$

RBC Collaboration

- RBRC
  - Yasumichi Aoki (Wuppertal)
  - Tom Blum
  - Chris Dawson
  - Takumi Doi
  - Koichi Hashimoto (Kanazawa)
  - Taku Izubuchi (Kanazawa)
  - Yukio Nemoto
  - Jun-Ichi Noaki (Southamption)
  - Kostas Orginos (MIT)
  - Shoichi Sasaki (Tokyo)
  - Norikazu Yamada (KEK)
  - Takeshi Yamazaki
- BNL
  - Frederico Berruto
  - Michael Creutz
  - Frithjof Karsch
  - Jack Laiho (Fermilab)
  - Peter Petreczki
  - Konstantin Petrov
  - Sasa Prelovsek (Ljubljana)
  - Christian Schmidt
  - Amajit Soni
- Columbia
  - Christopher Aubin
  - Michael Cheng
  - Norman Christ
  - Saul Cohen
  - Changhoan Kim (Southampton)
  - Ludmila Levkova (Indiana)
  - Meifeng Lin
  - HueyWen Lin
  - Oleg Loktik
  - Robert Mawhinney
  - Samuel Shu
  - Azusa Yamaguchi (Glasgow)

QCDOC Motivation

- In 1999 two facts were clear:
  - We needed a lot more computer power.
  - Advancing technology offered new opportunities.
- QCD is excellent for a targeted computer architecture:
  - Regularity of lattice QCD makes parallelization easy, reduces network cost.
  - Vanishing I/O and small memory needs allow economical configuration.
  - Ferocious $1/a^8$ scaling requires
    - Small problem size per processor.
    - Large surface to volume ratio.
    - High bandwidth/low latency network.

QCDOC Collaboration

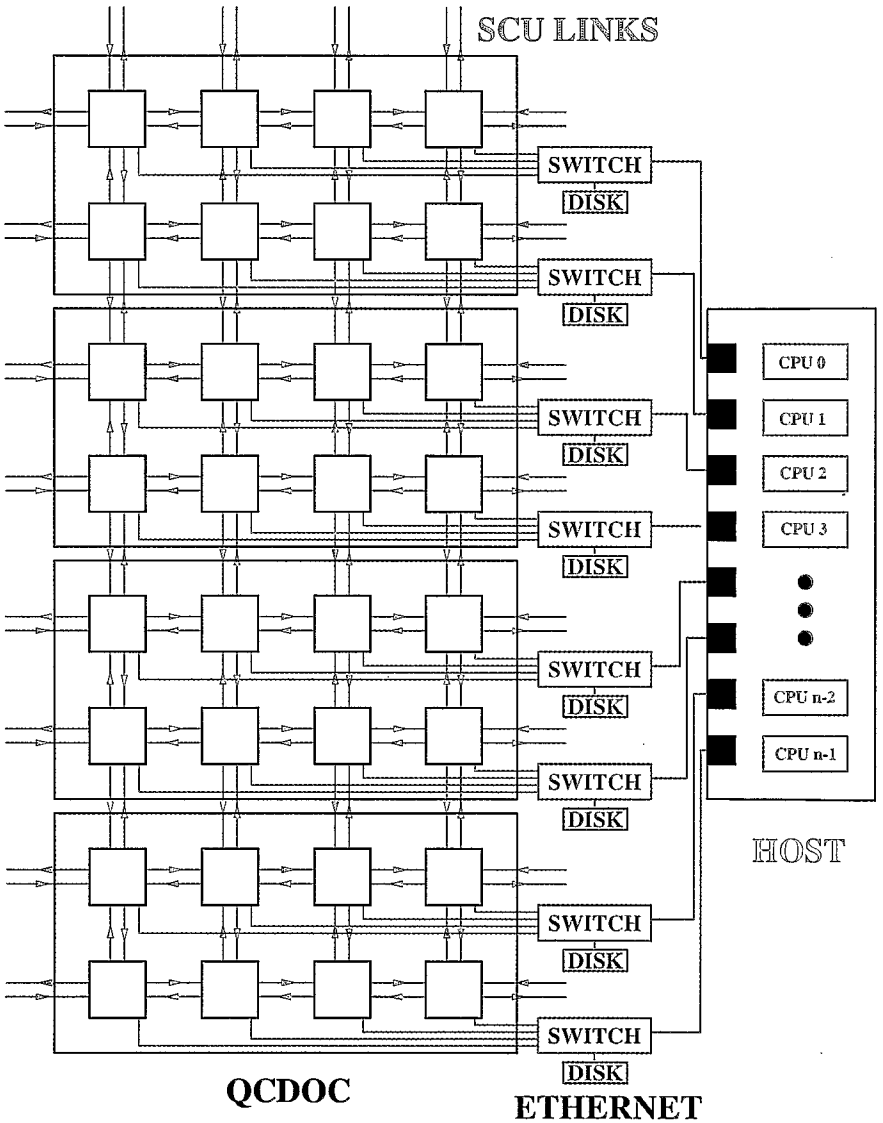
- Columbia (DOE)
  - Norman Christ
  - Saul Cohen
  - Calin Cristian
  - Zhihua Dong
  - Changhoan Kim
  - Ludmila Levkova
  - Xiaodong Liao
  - Meifeng Lin
  - Guofeng Liu
  - Robert Mawhinney
  - Shu Li
  - Azusa Yamaguchi
- BNL (SciDAC)
  - Chulwoo Jung
  - Konstantin Petrov
  - Stratos Efstathiadis
- UKQCD (PPARC)
  - Peter Boyle
  - Mike Clark
  - Balint Joo
- RBRC (RIKEN)
  - Shigemi Ohta
  - Tilo Wettig
- IBM
  - Dong Chen
  - Alan Gara
  - Design groups:
    - Yorktown Heights, NY
    - Rochester, MN
    - Raleigh, NC

QCDOC Architecture

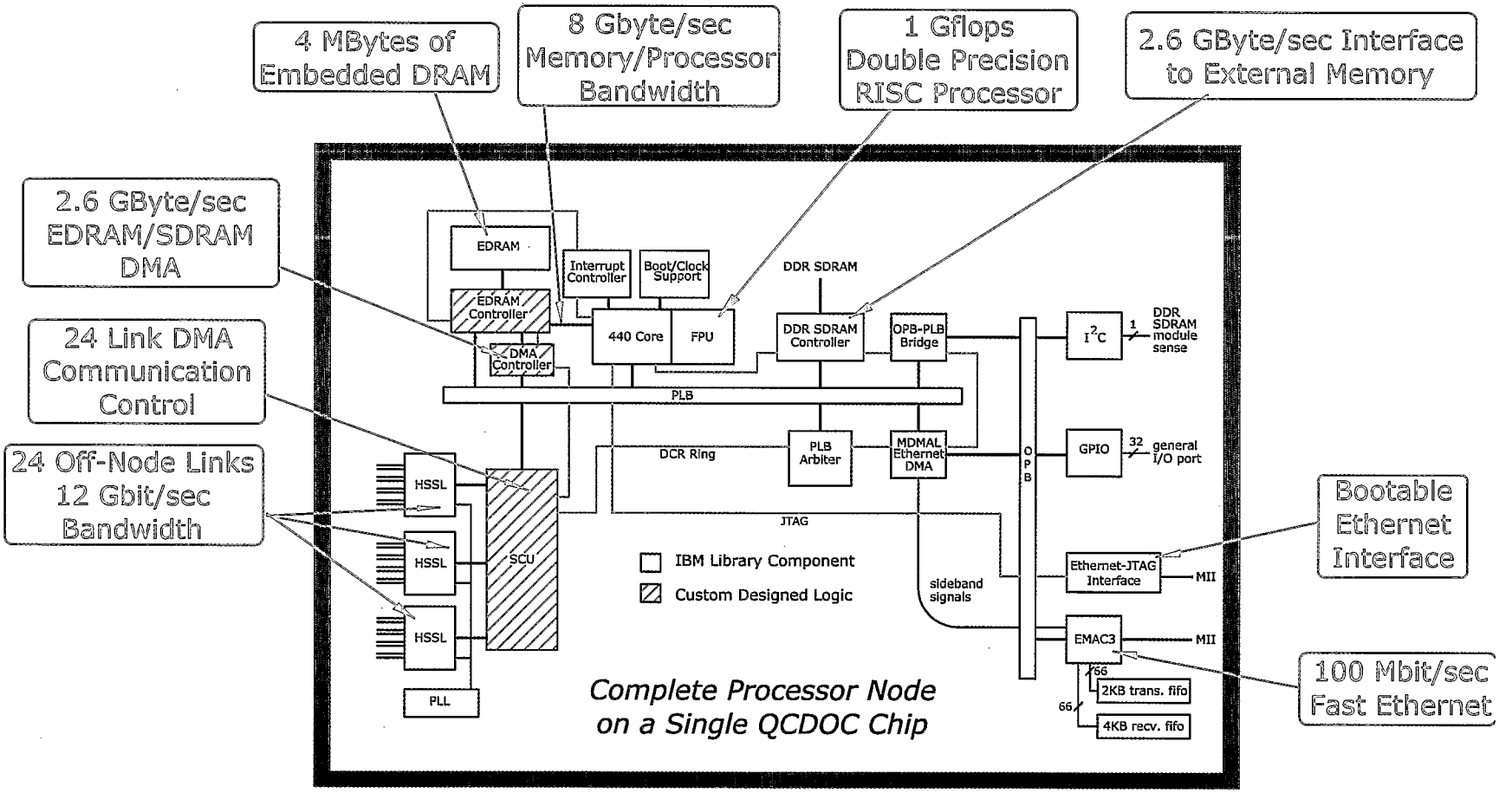
- IBM-fabricated, single-chip node.
  [50 million transistors, 5 Watt, 1.3cm x 1.3cm]
- Processor:
  - PowerPC 32-bit RISC.
  - 64-bit, 1 Gflops floating point unit.
- Memory/node: 4 Mbyte (on-chip) & <=2 Gbyte DIMM.
- Communications network:
  - 6-dim, supporting lower dimensional partitions.
  - Global sum/broadcast functionality.
  - Multiple DMA engines/minimal processor overhead.
- Ethernet connection to each node: booting, I/O, host control.
- ~7-8 Watt/node, 15 in^3 per node.

Network Architecture

- Red boxes are nodes.
- Blue boxes mother boards.
- Red lines are communications links.
- Green lines are Ethernet connections.
- Green boxes are Ethernet switches.
- Pink boxes are host CPU processors.

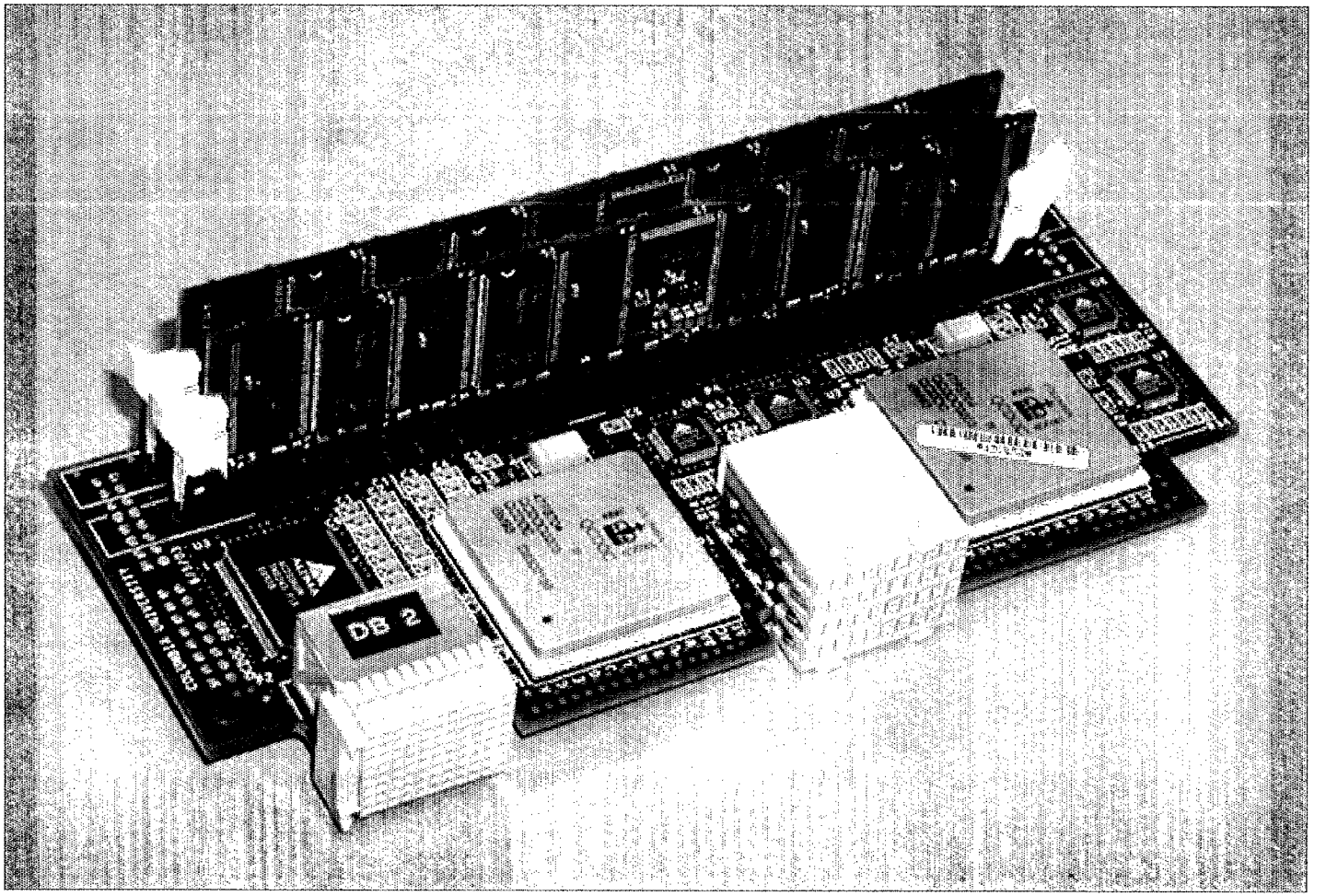


QCDOC Chip

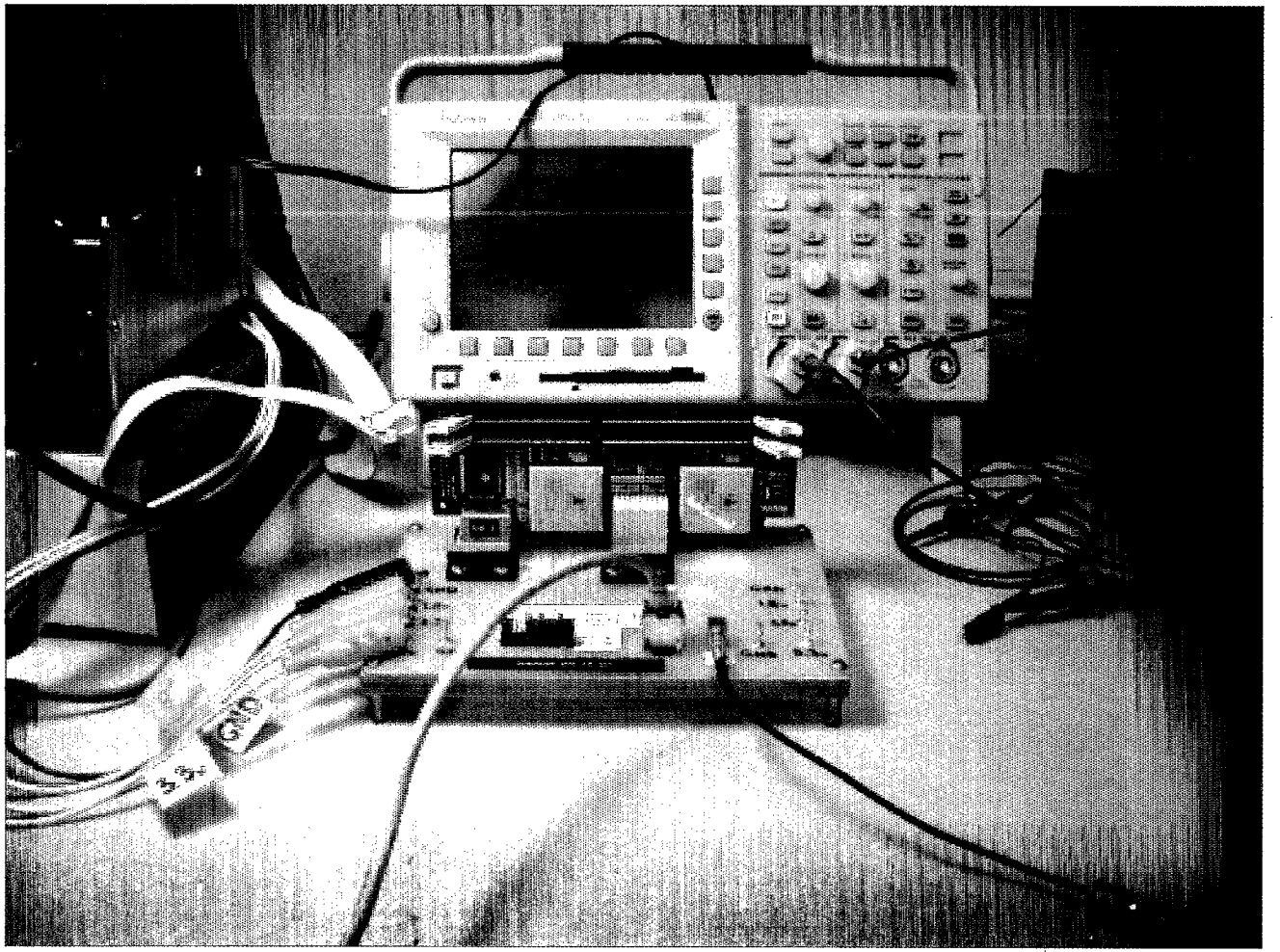


50 million transistors, 0.18 micron, 1.3 x 1.3 cm die, 5 Watt

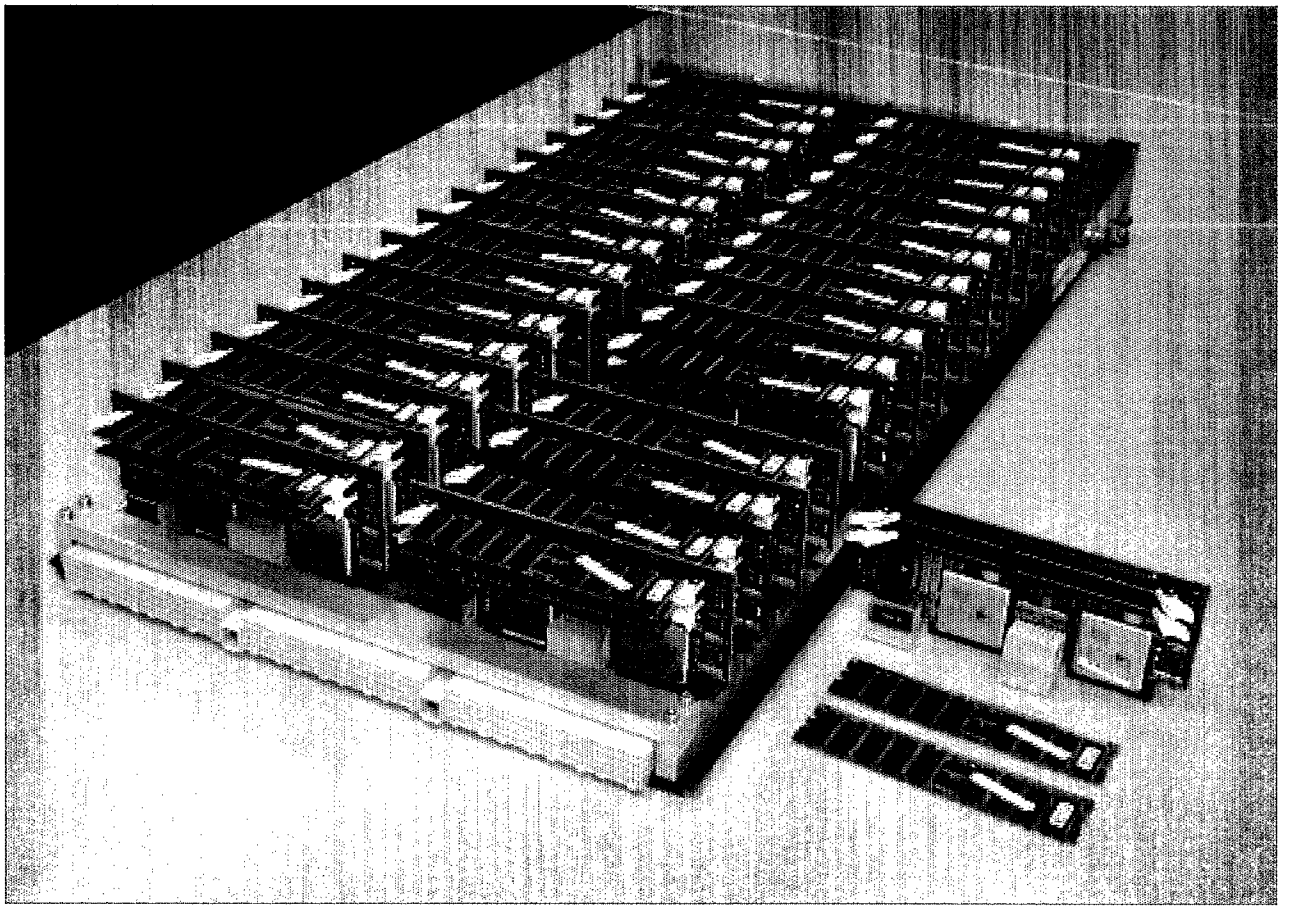
Daugher board (2 nodes)



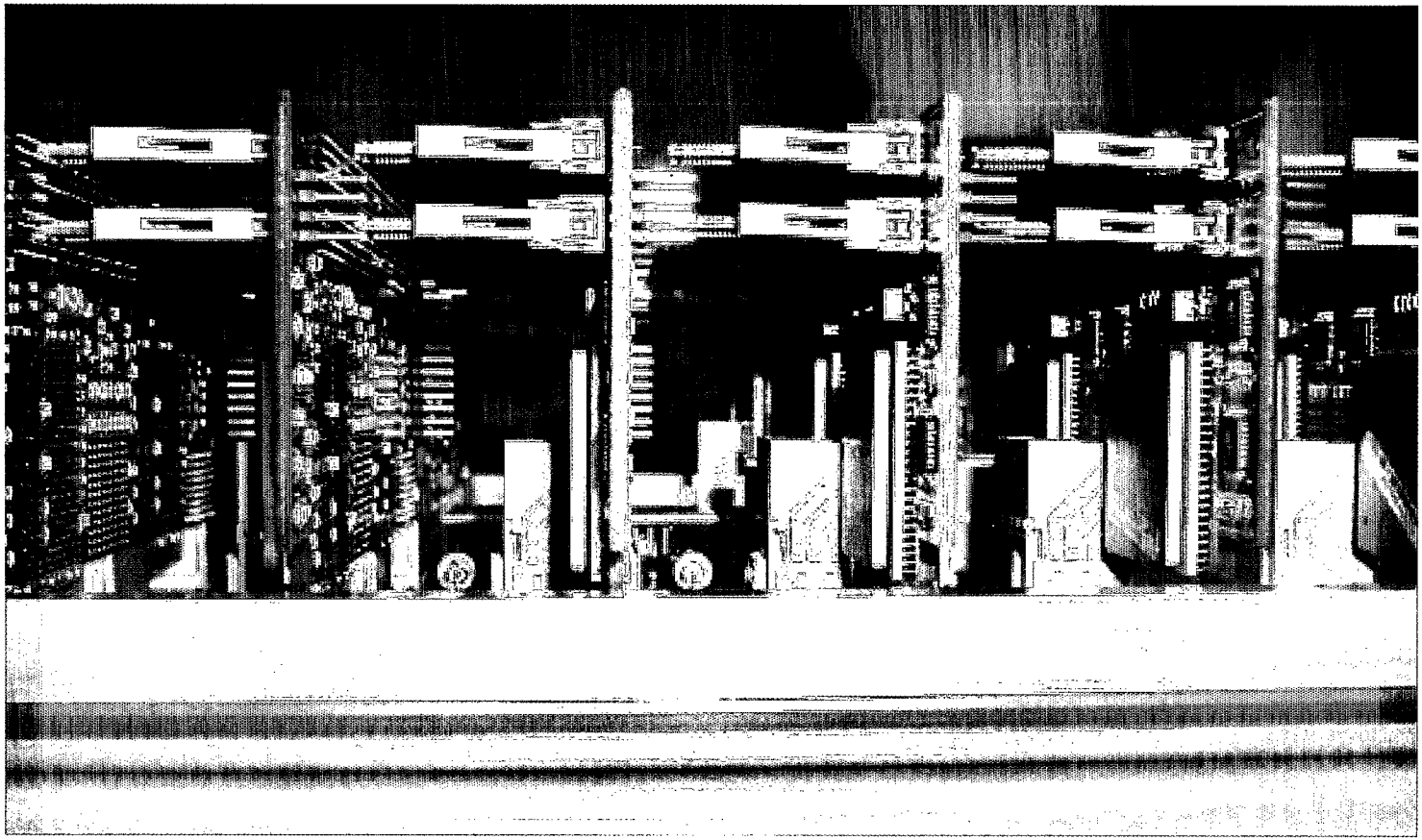
BNL – constructed test jig



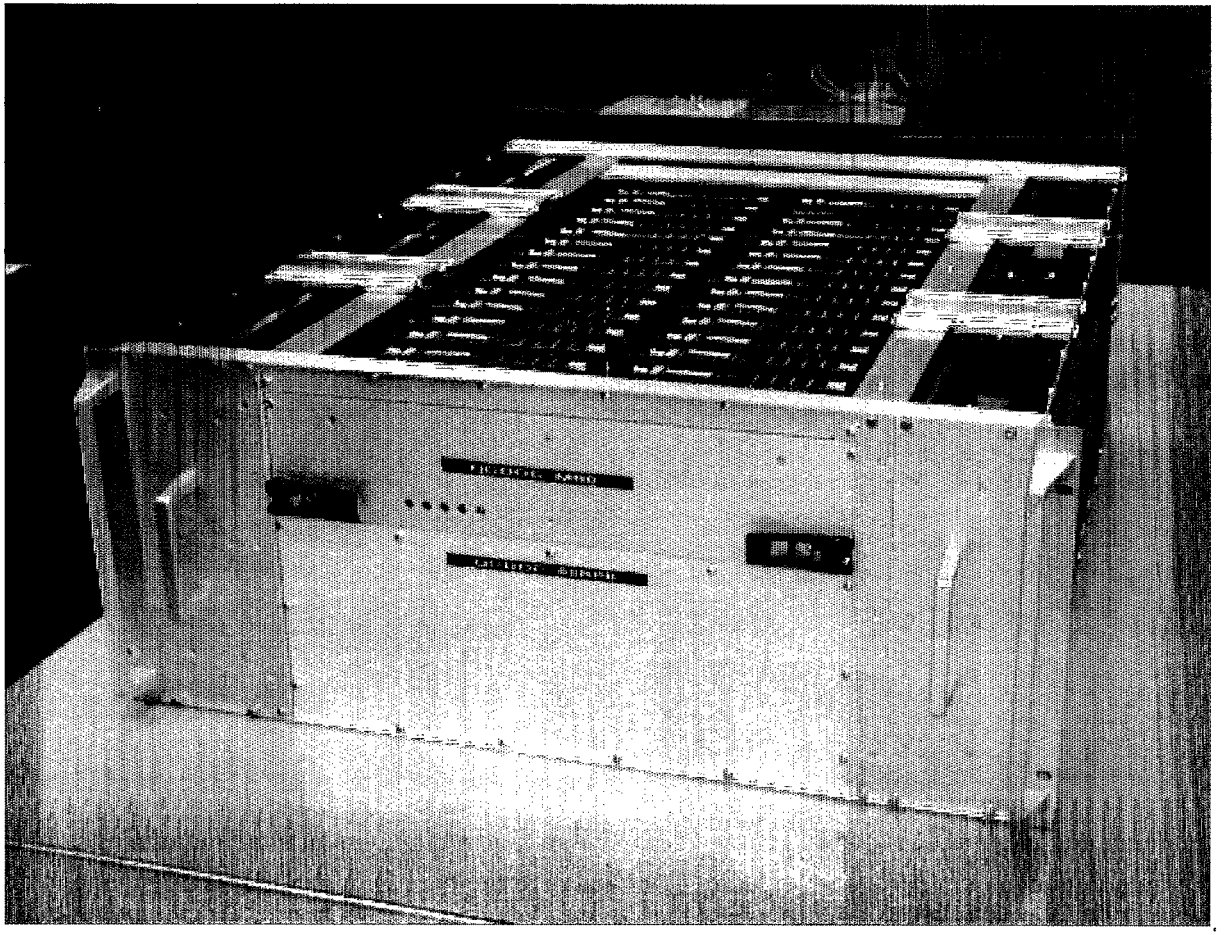
Mother board (64 nodes)



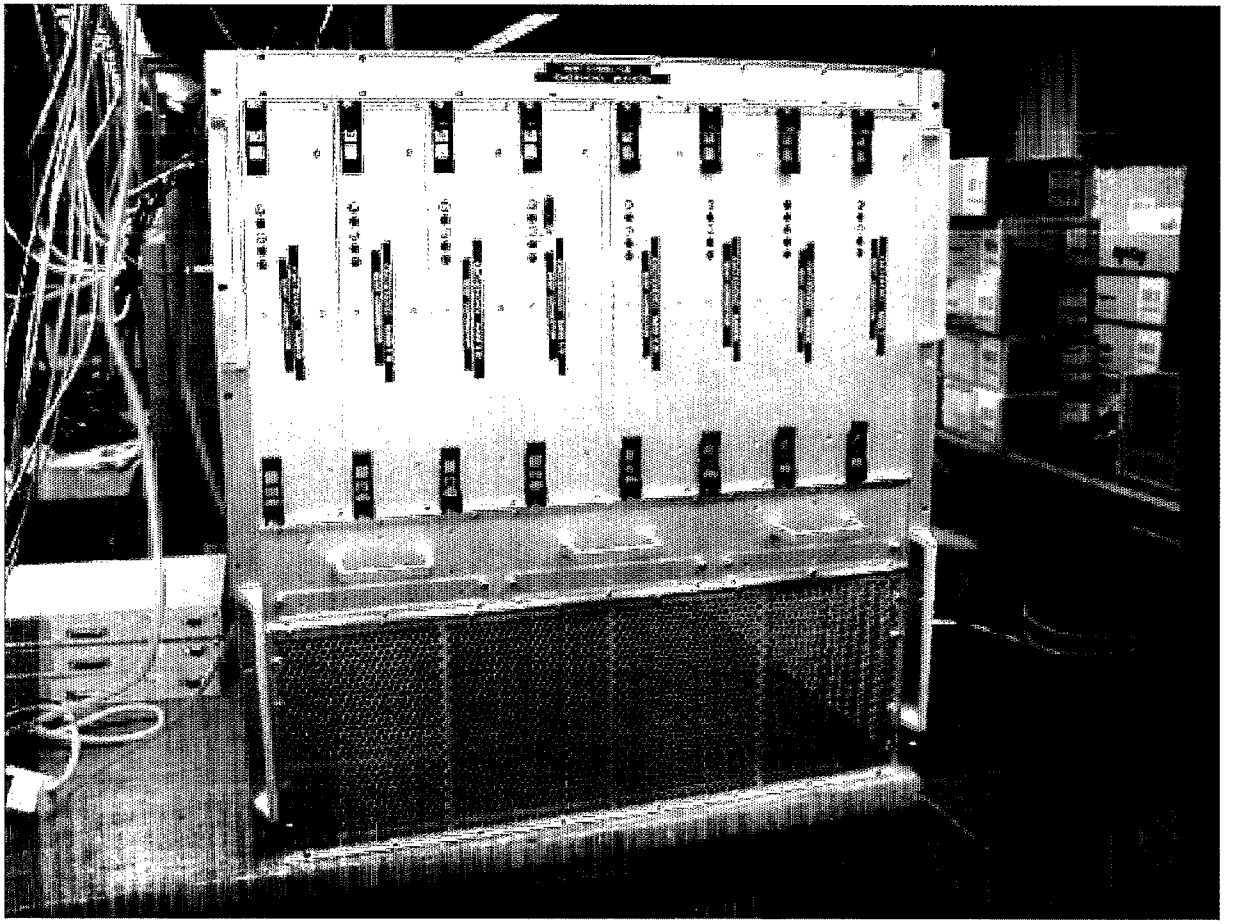
Edge view of mother board



Single mother board test jig



512-Node Machine

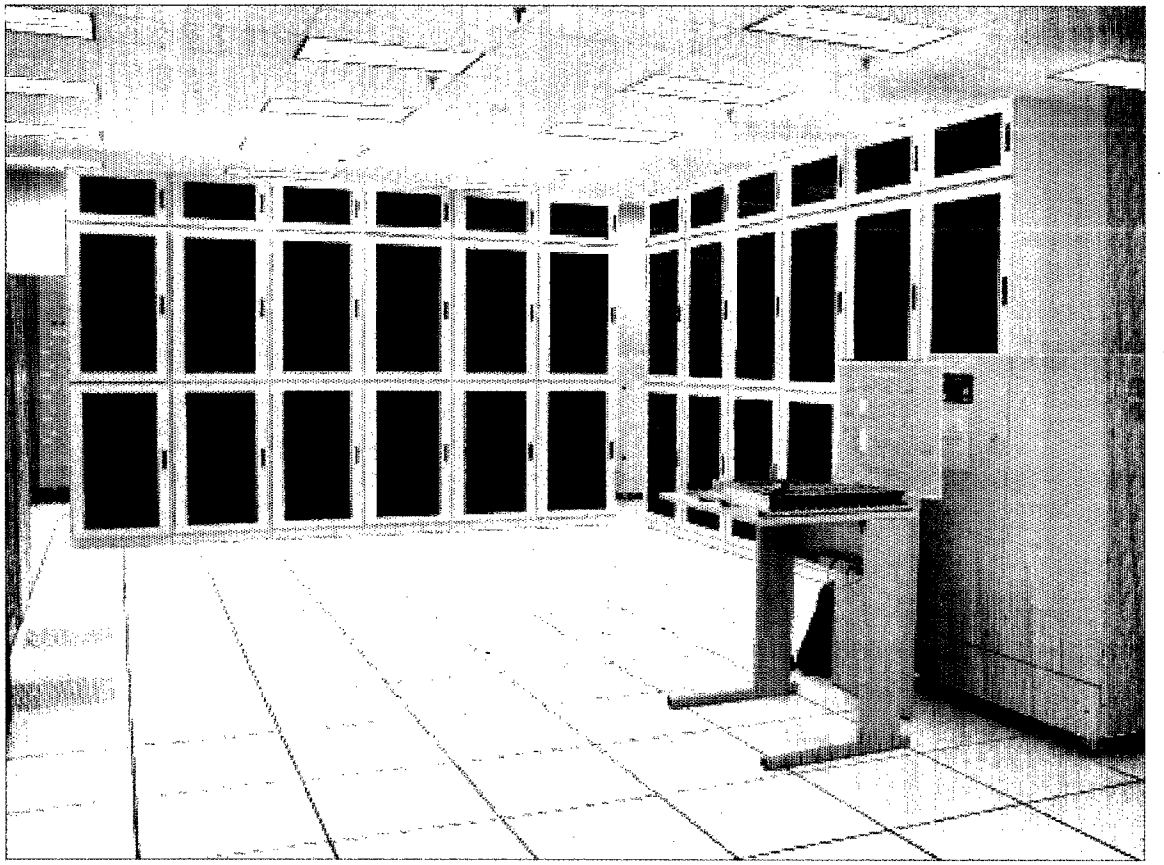


First 4 racks installed at Columbia

RBRC QCDOC Dedication May 26, 2005 (22)

UKQCD Machine (12,288 nodes/10 Tflops)

Brookhaven Installation



RBRC (right) and DOE (left) 12K-node QCDOC machines

Critical contributions from many people

- BNL staff:
  - Ed Mcfadden
  - Eric Blum
  - Ed Brosnan
  - Christopher Channing
  - Andrew Como
  - Joe Depace
  - Don Gates
  - Paul Poleski

Outlook

- New QCDOC machine offers ~20x capability.
- Large-scale dynamical DWF calculations are now possible.
- Many important new topics can be tackled:
  - Quark-gluon plasma.
  - Physical two-pion states.
  - Hyperons/electromatic effects/heavy quarks/…
- Close RBRC – UKQCD collaboration.
- We are now beginning to dream of petaflops computers with price/performance of $0.01/Mflops.

New Physics Programs on QCDOC

Taku Izubuchi, RBRC/Kanazawa University

New Physics programs on QCDOC

Taku Izubuchi

RIKEN BNL Reserch Center

Kanazawa University

for the RIKEN-BNL-Columbia collaboration,
and
Masashi Hayakawa

Symposium on RBRC QCDOC

Purpose of lattice QCD

QCD physics beyond perturbative analysis

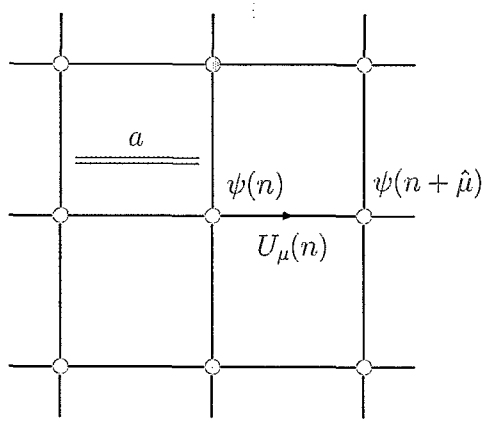
- CP violating weak matrix elements (Christ & Dawson's talk)
  uses chiral perturbation theory.
- Phase structure of QCD (Karsch's talk)
  $\mu \neq 0$ $T \neq 0$, chiral phase transitions. RHIC experiments
- Isospin breaking physics, Eectromagnetic splittings
- Hadronic contributions to muon anomalous magnetic moment
  the $g-2$ experiment
- Proton decay in beyond-standard-models
- Structure of Hadrons (Mawhinney's talk)
- η' ($U(1)_A$ problem), Nutron EDM (strong CP problem)
  chiral anomaly & topology
- ...

very exciting oppotunites to search for new physics by the first principle approach, Lattice QCD.

Lattice QCD

- Quantum Chromo Dynamics : strong coupling, needs non-perturbative calculation.

  $\Psi(x), A_\mu(x), x \in \mathcal{R}^4$: *continuous infinity*
  quantum divergences: ***needs*** *regularization* ***and*** *renormalization*



- Discretize Euclidean space-time
- lattice spacing $a \sim 0.1$ fm
  (UV cut-off $|p| \leq \pi/a$)

- $\psi(n)$: Quark field (Grassmann number)
- $U_\mu(n)$: Gluon field

- Accumulate samples of QCD vacuum, typically $\mathcal{O}(100) \sim \mathcal{O}(1,000)$ files of gluon configuration $U_\mu(n)$ on disk.

- Then measure physical observables on the vacuum ensemble.

$$\langle \mathcal{O} \rangle = \int \mathcal{D}U_\mu \ \text{Prob}[U_\mu] \times \mathcal{O}[U_\mu]$$

- A part of shorter fluctuation is taken care either perturbatively or by techniques called non-perturbative renormalization.

Taking Limits

- repeat the procedure for the three parameters,

  V : *space-time Volume*
  m_f : *mass of quarks*
  β : *coupling among quarks and gluons*

  A. Thermodynamic limit $V \to \infty$

  $\langle O \rangle |_V \sim const. \quad (V \gg V_c(m_f) \sim 1/m_{ps}^4)$,
  m_{ps} is the lightest hadron(pion) mass.

  B. Quark mass, $m_f \to m_q(phys) \sim 10$ MeV

  needs to extrapolate from $m_f > m_q(phys)$ because smaller m_f needs larger V and more computational power to solve the Dirac equation.
  chiral perturbation theory (ChPT) helps.

  C. Continuum limit, $a \to 0$ to eliminate discretization errors

  $\beta = 6/g^2 \to \infty$ à la asymptotic freedom $a\Lambda_L = \exp(-\frac{1}{2b_0 g^2}) \cdots$.
  $\langle O \rangle = O_{cont.} + c_n a^n + \cdots$.
  For DWF $n = 2$ not 1. (chiral symmetry).
  Each lattice action has different discretization error, useful for estimation of the discretization error by comparing among various lattice fermion/gauge actions.

to get the final answer.

Use of chiral symmetry on lattice

- Spontaneous breaking of chiral symmetry, $\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$.
  NG boson, $M_\pi^2 \propto m_q$. The origin of mass of constituent quark or proton.

- massless quark $q(x)$

$$S_f = \bar{q}\, \not{D} q = \bar{q}_L\, \not{D} q_L + \bar{q}_R\, \not{D} q_R$$

$$\text{symmetry:} \quad q_L \to e^{i\theta_L} q_L,\, q_R \to e^{i\theta_R} q_R$$

  Left and Right handed fermions are independently moving.

- Old lattice fermions (*e.g.* Wilson fermion, staggered fermion) break chiral and flavor symmetries: Domain Wall Fermions (DWF) has exact flavor symmetry and a good chiral symmetry (Kaplan, Furman & Shamir, Blum & Soni)

- discretization error should be small.(lattice spacing, $a > 0$)
  No local operator with dimension five preserving chiral symmetry.
  $\mathcal{O}_5 = F_{\mu\nu}\bar{q}\sigma_{\mu\nu}q, \bar{q}D^2q$
  $\mathcal{L}_{lat} = Z\mathcal{L}_{cont.} + a^2 O_6 + \cdots$ ▯
  $\mathbb{O}(a)$ error is suppressed. Results on relatively coarse lattice (large a ,smaller computational cost) is much closer to the continuum limit: $a\Lambda_{QCD} \sim 0.1$

- unphysical operator mixing is prohibited by χ-sym. (Dawson's talk)

Full QCD (including dynamical quarks)

- So far quenched approximation is widely used.

$$\det \not{D} \longrightarrow 1$$

Ignoring quark loops (sea quark loop) in QCD vacuum, and only using the external quarks (valence quarks) representing hadrons.

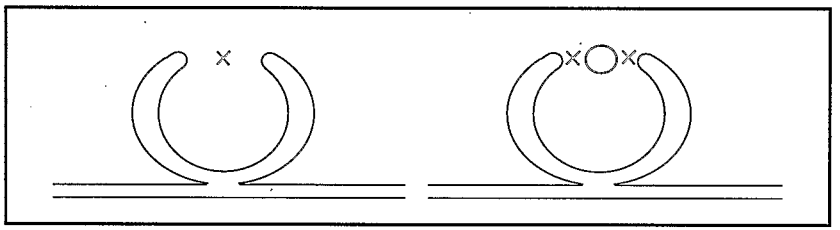
- This approximation causes the quenched pathologies.

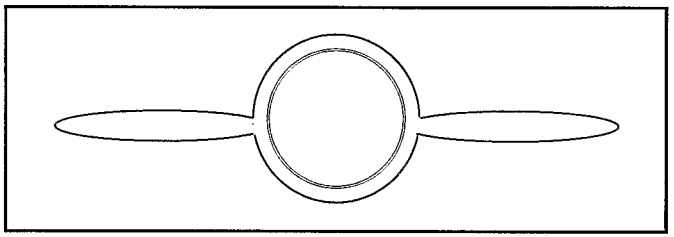
  - Lack of Unitarity.
  - quenched chiral divergences (η' loops):

    $M_\pi^2 = 2B_0 m_q \left[1 - 2\delta \ln(m_f)\right]$

    $\delta \propto m_f$ in Full QCD.
  - can't decays.

    e.g. $\rho \longrightarrow \pi\pi$:





- quark mass with less than $\sim \Lambda_{QCD}$ should play a significant role.

Unitarity violation in Non-singlet scalar meson (a_0)

- Point to point propagator of non-singlet scalar meson, $C_{a_0}(t)$, was found to be negative in quenched QCD, which is a clear signal of the unitarity violation in quenched QCD.

- In the language of mesons (ChPT),

  $$a_0 \longrightarrow \eta' + \pi \longrightarrow a_0$$

  η' has double pole in (partially) quenched QCD.

  This contribution was argued to give a negative contribution (also finite size effect), and predicted using Quenched ChPT in finite volume. (Bardeen *et. al*)

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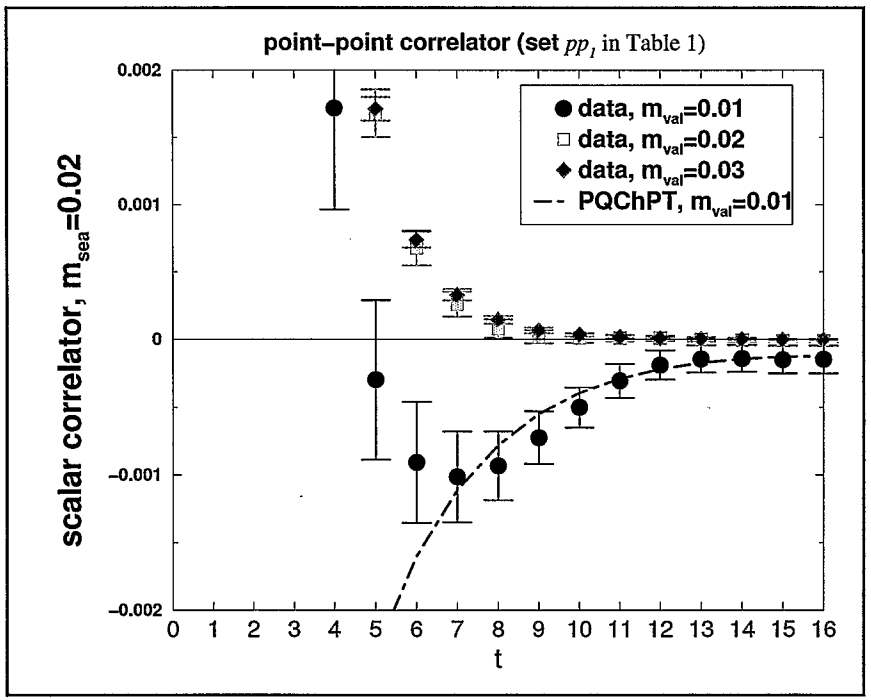
(S. Prelovsek, C. Dawson, T.I. K. Orginos, A. Soni (RBC))

- By fixing m_{sea} and changing m_{val} we found

$$C_{a_0}(t) < 0 \qquad (m_v < m_s)$$
$$C_{a_0}(t) > 0 \qquad (m_v \geq m_s)$$

- This behaviour could be understood by Partially Quenched ChPT also.

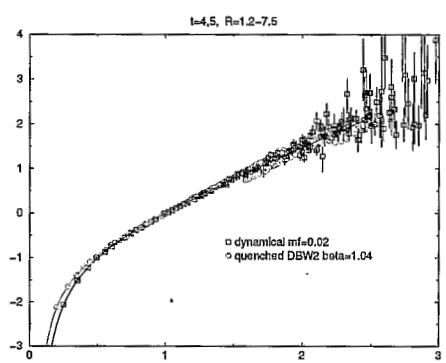


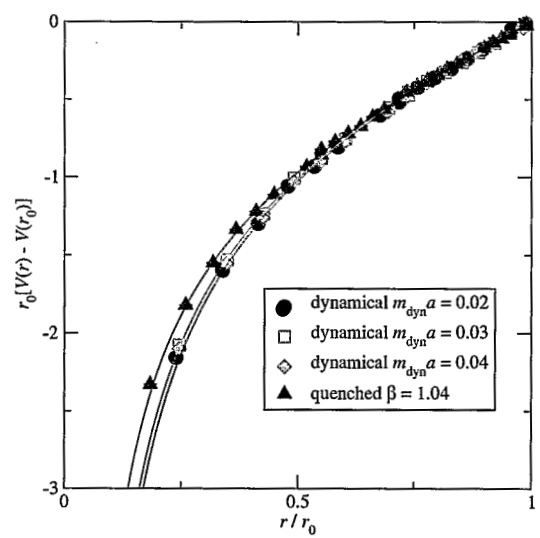
Dynamical quark effects

Quenching error (dynamical quark effect) is not a minor issue.

Other quantities very sensitive to dynamical quarks

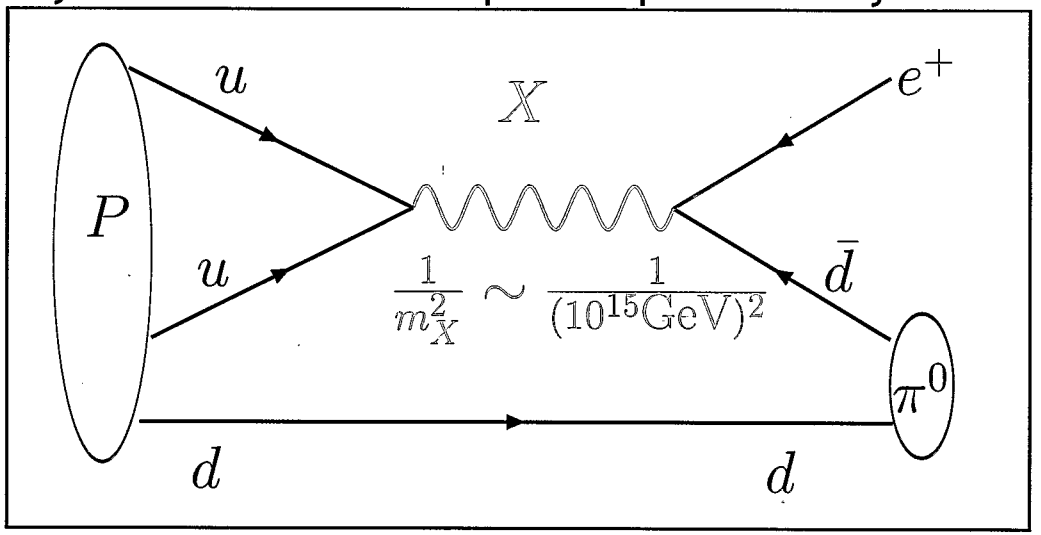
- $I = 0$ $\pi\pi$ scattering length (M. Golterman, T.I, Y. Shamir)
- Nucleon-Nucleon potential
- Static quark potential (K. Hashimoto)
  In shorter distance, $r\Lambda_{QCD} \ll 1$, coupling is weaker for $N_F = 2$:
  $\alpha_S(r; N_F = 0) < \alpha_S(r; N_F = 2)$.
  asymptotic freedom $b_0 = (33 - 2N_F)/2$





Nucleon decay matrix elements

- Beyond-Standard-Models predict proton decay



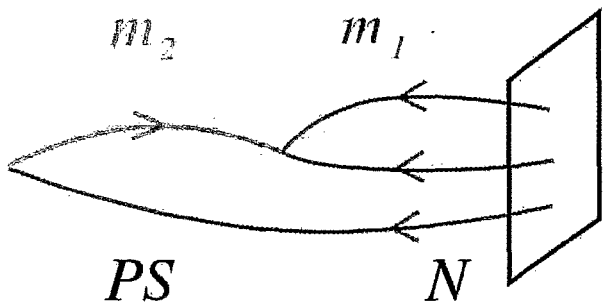
(Y. Aoki)

- One of the largest uncertainties for life time is Hadron matrix elements, a factor 10 difference among model calculations.

$$\Gamma_P \propto \left| \bar{v}_e \left\langle \pi | \epsilon_{abc} (u^{aT} C P_{R/L} d^b) P_L u^c | P \right\rangle \right|^2$$

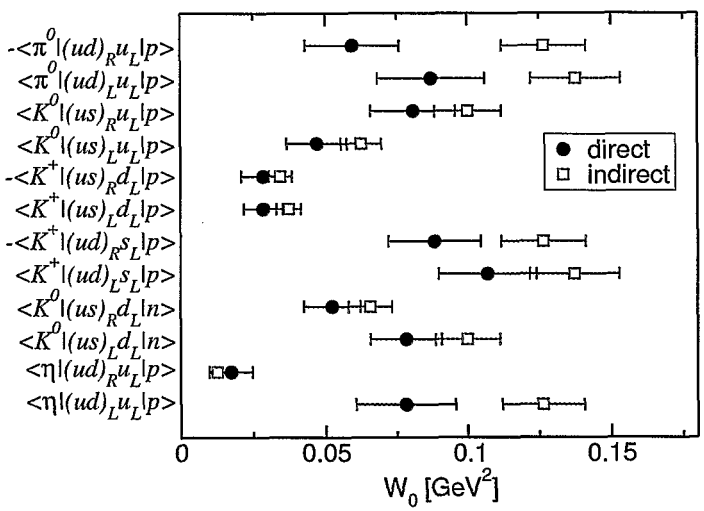
- Experimental bound on mean life time of proton:

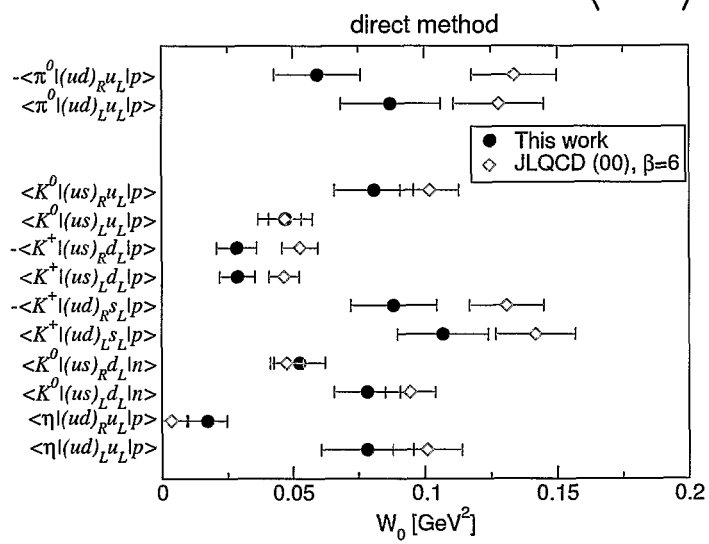
$$\tau_p > 10^{31} \sim 10^{33} \quad \text{years}$$



- Disentangles relevant piece from π's (PS) momentum dependence.
- Take a ratio to the 2pt functions

$$R_{\vec{p}} = \frac{\left\langle \pi(\vec{p})\ \mathcal{O}^{udu}_{R/L,L}(-\vec{p})\ P \right\rangle}{\left\langle \pi(\vec{p})\pi(-\vec{p}) \right\rangle \left\langle P\overline{P} \right\rangle}$$





- Non-perturbative renormalization at $\mu = 2$ GeV $\overline{\text{MS}}$ for $N_F = 0$ and 2.
- LO ChPT (Indirect) approximation gives systematically larger values for $P \to \pi$.
- Consistent results with the conservative choice in phenomenology.
- DWF scales better than Wilson fermion (JLQCD).

QCD + QED simulations

(T. Blum, M. Hayakawa, T.I., N. Yamada)

- In most of lattice QCD simulations, up and down quarks are treated to have equal mass and effects of electromagnetism (EM) is ignored (Isospin symmetry).
- More realistic first principle calculation is desirable for accurate hadron spectrum and quark mass determination.

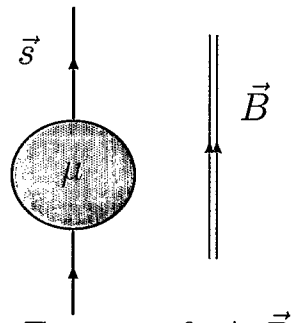
$$m_{up} \neq m_{down}, \qquad Q_{up} = 2/3e, \;\; Q_{down} = -1/3e.$$

- Hadron mass differences due to isospin breaking are measured very accurately in experiments:

$$m_{\pi^\pm} - m_{\pi^0} = 4.5936(5)\text{MeV},$$
$$m_N - m_P = 1.2933317(5)\text{MeV}$$

QCD + QED simulations

- muon anomalous magnetic moment $g_\mu - 2$ (BNL-E821) .
  g_μ gyromagnetic ratio: muon (spin 1/2)'s coupling to magnetic field



$E = -g_\mu \frac{e}{2m_\mu} \vec{s} \cdot \vec{B}$

$$a_\mu^{\text{exp}} = \frac{g_\mu - 2}{2} = 116,592,080(60) \times 10^{-11}$$

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{Had}} + a_\mu^{\text{EW}},$$

$$a_\mu^{\text{exp}} - a_\mu^{\text{th}} = (220 \pm 100) \times 10^{-11}$$

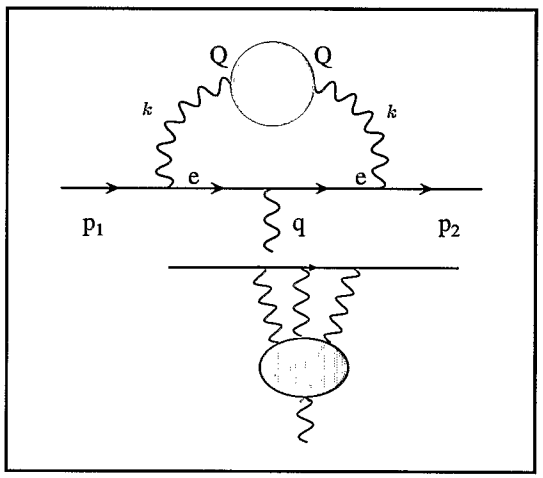
- Hadronic contributions dominates theory error.

$$a_\mu^{\text{Had}} = a_\mu^{\text{Had,LO}} + a_\mu^{\text{Had,HO}} + a_\mu^{\text{Had,LBL}}$$

$$a_\mu^{\text{had,LBL}} = 134(25) \times 10^{-11}$$

$$(\text{before} : 86(35) \times 10^{-11})$$

$$a_\mu^{\text{new}} \sim \mathcal{O}((m_\mu / M_{new})^2)$$



$a_\mu^{\text{Had,HO}}$ was explored by T. Blum in PRL 91, 2003.

EM splittings

- Axial WT identity with EM $(N_F = 2, m_u = m_d)$,

$$\mathcal{L}_{EM} = -iA_\mu(x)\bar{q}Q\gamma_\mu q(x), \quad Q = \frac{e}{3}\left(T^3 + \frac{1}{2}\right),$$

$$\partial_\mu \mathcal{A}^a_\mu(x) = 2mJ^a_5(x) - ieA_\mu(x) f_{3ab}\mathcal{A}^b_\mu$$

neutral current, $\mathcal{A}^3_\mu(x)$, is conserved: π^0 is still a NG boson.

- ChPT with EM at $\mathcal{O}(p^4, p^2e^2)$:

$$M^2_{\pi^\pm} = 2mB_0 + 2e^2\frac{C}{f_0^2} \qquad +\mathcal{O}(m^2\log m, m^2) + I_0 e^2 m\log m + K_0 e^2 m$$

$$M^2_{\pi^0} = 2mB_0 \qquad +\mathcal{O}(m^2\log m, m^2) + I_\pm e^2 m\log m + K_\pm e^2 m$$

Dashen's theorem :
The difference of squared pion mass is independent of quark mass upto $\mathcal{O}(e^2m)$,

$$\Delta M^2_\pi \equiv M^2_{\pi^\pm} - M^2_{\pi^0} = 2e^2\frac{C}{f_0^2} + (I_\pm - I_0)e^2 m\log m + (K_\pm - K_0)e^2 m$$

C is a new low energy constant. $I_\pm, I_0$ is known in terms of C.

EM splittings on lattice

- The correlator for neutral meson is calculated using the interpolation field of the third component of isospin:

$$C_{X^0}(t) = \frac{1}{2}\left[\left\langle J_X^{uu}(t) J_X^{uu\dagger}(0)\right\rangle_{conn} + \left\langle J_X^{dd}(t) J_X^{dd\dagger}(0)\right\rangle_{conn}\right]$$

- Quark mass renormalization due to EM has dependence to renormalization prescription. The counter term for quark mass due to EM:

$$\frac{3e^2}{16\pi^2} Q^2 m_q \log(\mu^2 a^2) \sim 10^{-3} m_q \quad \text{for} \quad \mu \to 2 \times \mu \quad ,$$

  thus the ambiguity of quark mass renormalization is tiny. $\sim$ 0.01 MeV for light quarks and $\sim$ 0.1 MeV for strange quark.

- Isospin breaking due to quark mass, $m_u - m_d$, is higher order effect in π, $\mathcal{O}\left((m_u - m_d)^2, (m_u - m_d)e^2\right)$.
  This is not the case for Kaons and Nucleons.

EM splittings on lattice

- In 1996, Duncan, Eichten, Thacker carried out SU(3)×U(1) simulation to do the EM splittings for the hadron spectroscopy using quenched Wilson fermion on $a^{-1} \sim 1.15$ GeV, $12^3 \times 24$ lattice.

- Using $N_F = 2$ Dynamical DWF ensemble (RBC) would have advantages such as better scaling and smaller quenching errors.

- Especially smaller systematic errors due to the the quark massless limits, $m_f \longrightarrow -m_{res}(Q_i)$, has smaller Q_i dependence than that of Wilson fermion, $K \longrightarrow K_c(Q_i)$.

- Generate Coulomb gauge fixed (quenched) non-compact U(1) gauge action with $\beta_{QED} = 1$. $U_\mu^{EM} = \exp[-iA_\mu(x)]$.

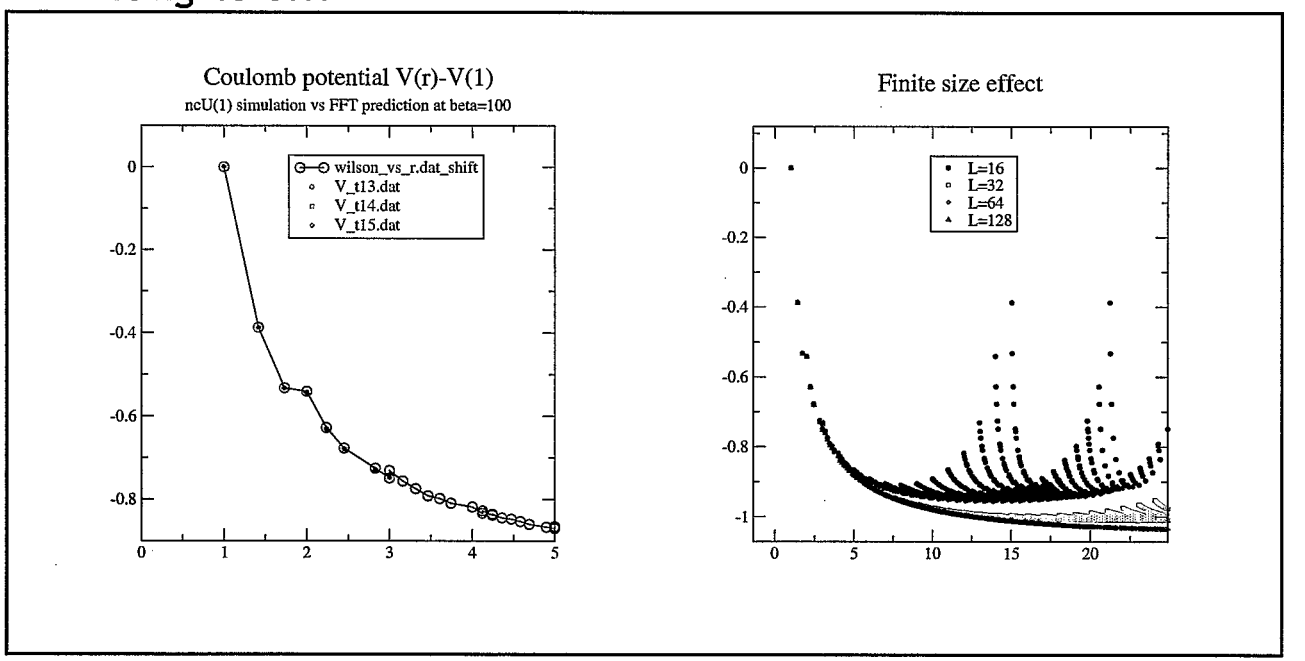
- Quark propagator, $S_{q_i}(x)$ with EM charge $Q_i = q_i e$ with Coulomb gauge fixed wall source

$$D\left[(U_\mu^{EM})^{Q_i} \times U_\mu^{SU(3)}\right] S_{q_i}(x) = b_{src}, \qquad (i = \text{up,down})$$

$$q_{\text{up}} = 2/3, q_{\text{down}} = -1/3$$

photon field on lattice

- non-compact $U(1)$ gauge generated using FFT.
- static lepton potential on $16^3 \times 32$ lattice ($\beta_{QED} = 100$, 4,000 confs) vs lattice Coulomb potential.
- L=16 has significant finite volume effect for $ra > 6 \sim 1.5r_0 \sim 0.75$ fm. We hope it's less problematic for the calculation EM splitting of hadron due to confinement. It would be worth considering for generation of U(1) on a larger lattice and cutting it off.



simulation parameters

- $N_F = 2$ Dynamical DWF configuration for QCD
- $a^{-1} = 1.691(53)$ GeV.
- degenerate quark mass at dynamical quark mass points, $m_{val} = m_{sea} = (0.02), 0.03, 0.04 \sim$ 50%, 75%, 100% of m_{strange}.
- $16^3 \times 32$ or (1.9 fm)^3.
- $Ls = 12$, $m_{res}a = 0.0013$ or a few MeV.
- EM charge: $e = 1.0, 0.6, 0.3028 = \sqrt{4\pi/137}$
- $\sim$ 94$\rightarrow$ 190 configurations for each m
- one or two QED configuration per a QCD configuration.
- All 16 mesonic connected correlators + Neutron, Proton.

Analysis methods

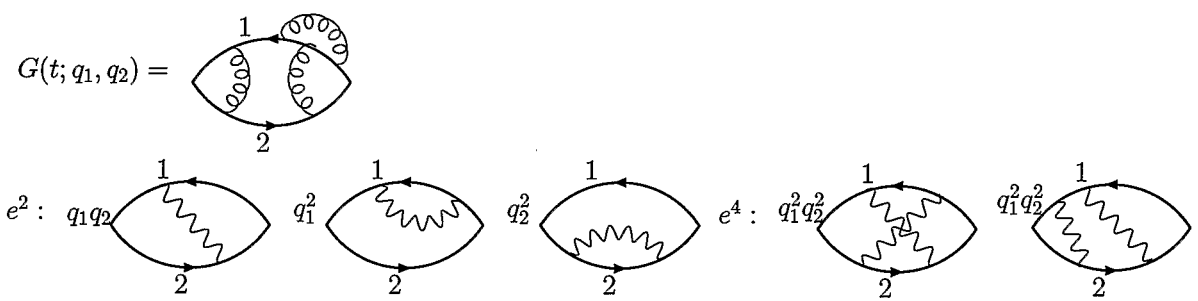
- Analysis method I :
  Fit correlator for each charge combination separately,
  then calculate the mass splittings under jackknife.

$$X = \pi, \rho, N : \Delta M_X = M_{X^\pm} - M_{X^0},$$

- Analysis method II :
  Subtract charged correlator by neutral correlator,
  and fit it by a linear function in t:

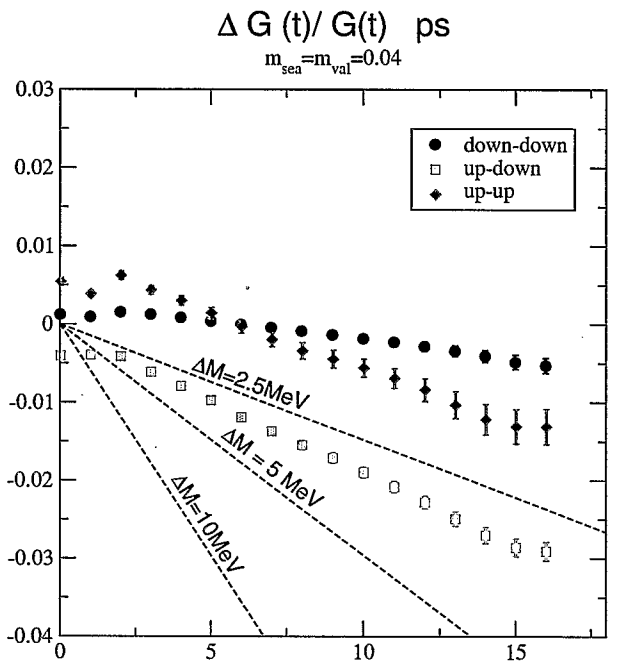
$$C_X(t) = A(e^2)e^{-M_X(e^2)t}$$

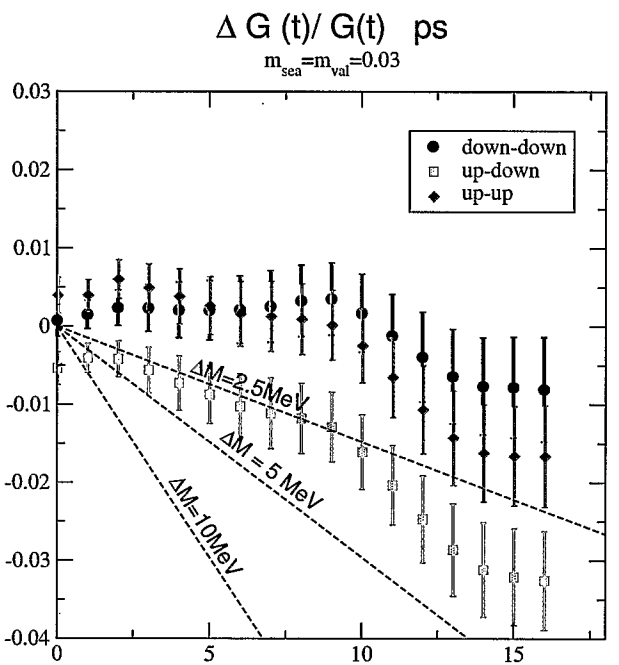
$$\frac{C_{X^\pm}(t) - C_{X^0}(t)}{C_{X^0}(t)} = \Delta M_X \times t + Const$$



results

- $G(t) = \langle J_5(0) J_5(t) \rangle$ at $m = 0.04$ and 0.03.



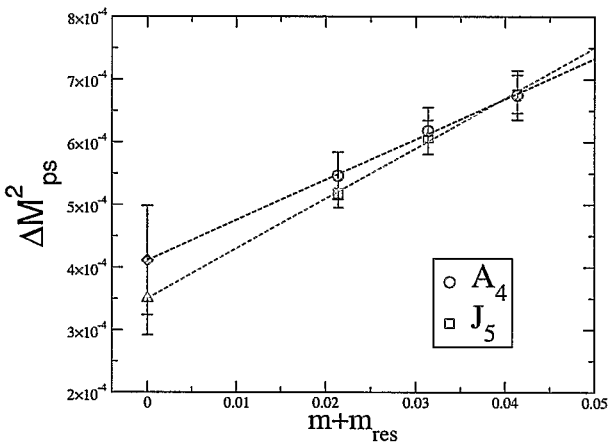


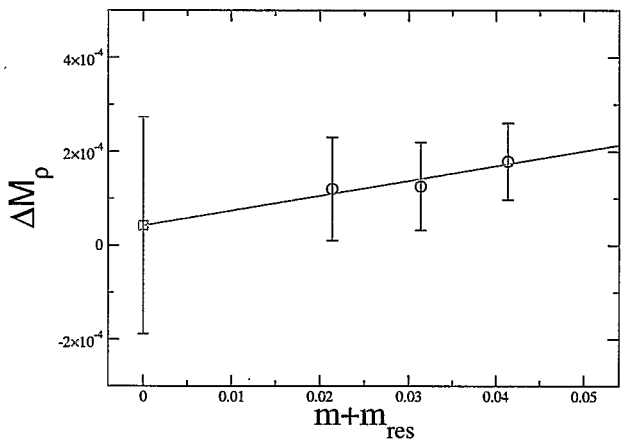
- larger e^2 doesn't help to reduce error for J_5: relative error stays almost same.
- Fluctuations due to SU(3) are comparable to that from U(1): by double the QED statistics: ΔM_π reduces by $\sim$ 4, 10, (30) % for $A_4, J_5, (N)$ resp. at $m = 0.04$.

$$\frac{\sigma_{QCD}^2 + 0.5\sigma_{QED}^2}{\sigma_{QCD}^2 + \sigma_{QED}^2} = (0.9)^2 \Longrightarrow \sigma_{QED}/\sigma_{QCD} \sim 0.85$$

ΔM_π^2

- Method I, Method II are consistent within statistical error.





- preliminary results

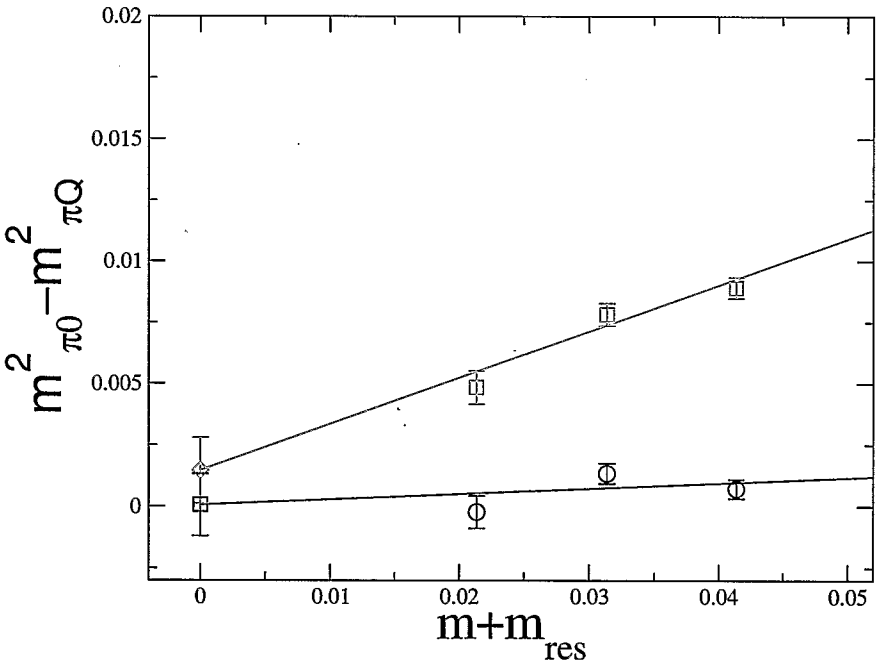
$$A_4 : \Delta M_\pi^2|_{m=m_l} = 1.20(24) \times 10^{-3}\text{GeV}^2,$$
$$J_5 : \Delta M_\pi^2|_{m=m_l} = 1.03(15) \times 10^{-3}\text{GeV}^2,$$
$$(\text{experiment} : 1.26 \times 10^{-3}\text{GeV}^2).$$

- ρ and Nucleon EM splitting is zero within statistical error.

Dashen's theorem

- $M_{\pi,Q}$: pure QCD pion ($e^2 = 0$)

$$M_{\pi^0}^2 - M_{\pi Q}^2 = I e^2 m \log m + K e^2 m$$



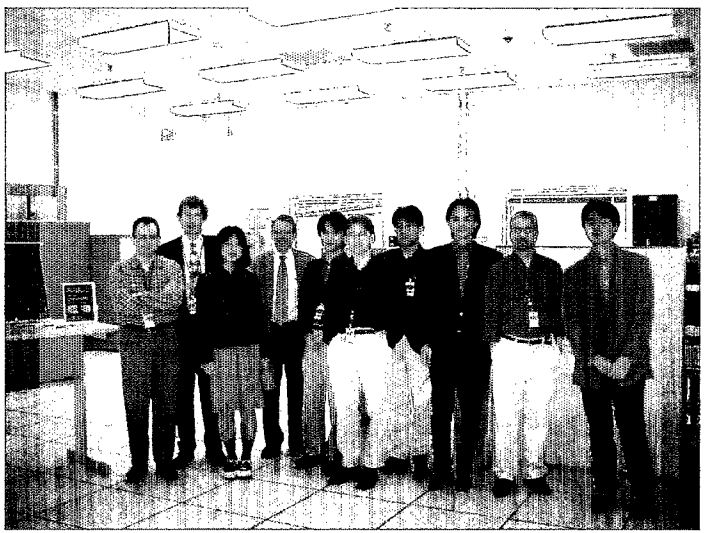
- Extraction of quark masses, $m_{up}, m_{down}, m_{strange}$, from experimental values of $m_{\pi^\pm}, m_\pi^0, m_{K^\pm}, m_{K^0}$.

conclusions

Examples of physics programs where chiral and flavor symmetry are indispensable are presented. Including dynamical strange quark effect, $N_F = 2 + 1$, will bring us closer to the final answers from Lattice QCD (also Dawson and Mawhiney's talk)

Computational hoursepower of TFLOPS speed on QCDOC will help to shoot down both systematic and statistical errors.

How and which lattice fermion formalism to implement within realistic computational costs, yet not to compromise the symmetries is a key issue. (Mawhinney's talk)



Kaon Physics

Christopher Dawson, RBRC

Kaon Physics

Chris Dawson,
RIKEN/BNL Research Center

[RBRC QCDOC dedication]

Introduction

- In this talk I will concentrate on the calculation of the kaon B-parameter, B_K , which is important in describing indirect CP - violation.
  - Definition of the Kaon B-parameter
  - Lattice QCD
  - Domain Wall Fermions
  - Calculating B_K on the lattice.
  - Results
  - Future (QCDOC)

The Neutral Kaon system

- If there was no Weak force, all forces would preserve flavour and the K^0 and $\overline{K^0}$ mesons would be stable (negative parity) particles. CP takes me between the two:

$$CP|K^0\rangle = -|\overline{K^0}\rangle$$

can arrange in CP eigenstates

$$\begin{aligned} |K_{\text{even}}\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right); CP+ \\ |K_{\text{odd}}\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}^0\rangle\right); CP- \end{aligned}$$

- CP is broken; Actually observe

$$\begin{aligned} |K_S\rangle &= \frac{|K_{\text{even}}\rangle + \overline{\epsilon}|K_{\text{odd}}\rangle}{\sqrt{1+|\overline{\epsilon}|^2}} \\ |K_L\rangle &= \frac{|K_{\text{odd}}\rangle + \overline{\epsilon}|K_{\text{even}}\rangle}{\sqrt{1+|\overline{\epsilon}|^2}} \end{aligned}$$

- $|K_S\rangle$ almost CP-even; $|K_L\rangle$ almost CP-odd

The Neutral Kaon system...

- look at decay into the (CP-even) $|\pi\pi\rangle$ state.
- If you measure $K_L \to \pi\pi$ there are two contributions
  - indirect CP-violation: due to K_{even} component (ϵ)
  - direct CP-violation: due to weak decay (ϵ')
- $\epsilon' << \epsilon$ (whole other talk),

$$\epsilon_K = \frac{A(K_L \to \pi\pi)}{A(K_S \to \pi\pi)}.$$

- Experimentally
  - $\epsilon = 2.271(17) \times 10^{-3}$
  - ϵ'/ϵ
    1. KTEV (FNAL 2001) : $20.7(2.8) \times 10^{-4}$
    2. NA48 (CERN 2001) : $15.3(2.6) \times 10^{-4}$

CKM matrix...

- All the cp-violation in the Standard model is encoded in the CKM matrix

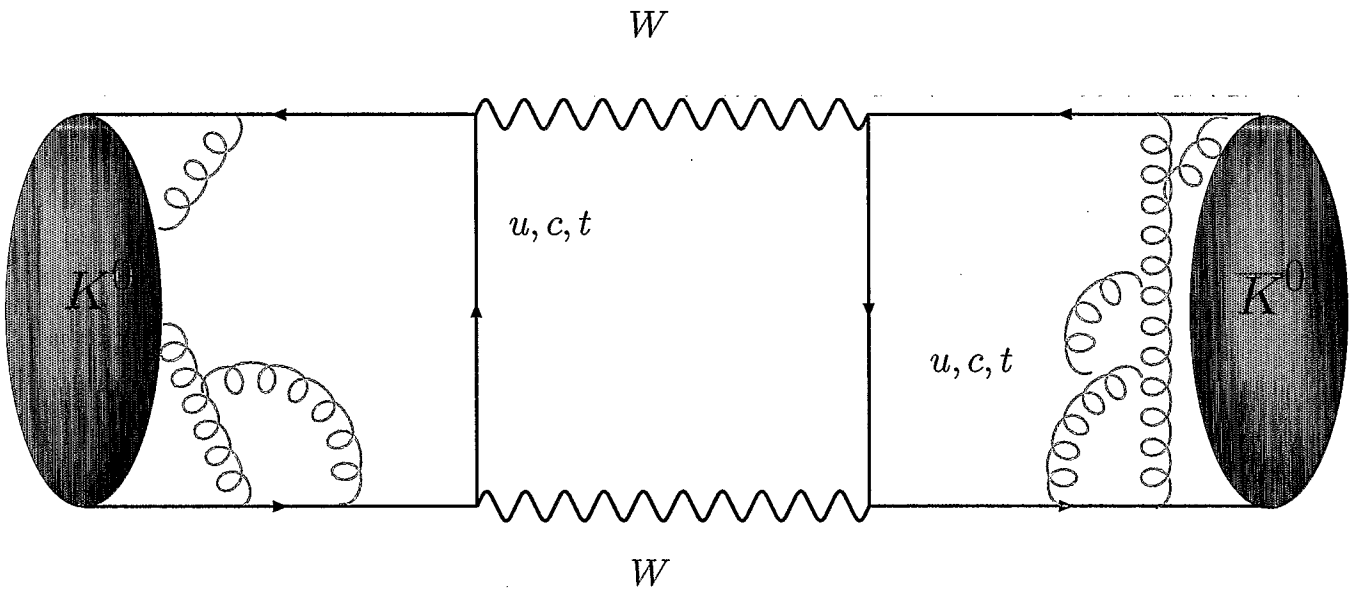
$$
\begin{aligned}
V_{CKM} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
&= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\overline{\rho}-i\overline{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2 & 1 \end{pmatrix}
\end{aligned}
$$

  - $\lambda \sim 0.23$, the Cabbibo angle.
  - All standard model CP violation enters through the parameter $\overline{\eta}$ (supressed by three factors of λ)

- The calculation i discuss later constrains the relationship between $\overline{\rho}$ and $\overline{\eta}$.

Matter-antimatter Oscillations

Diagrammatically the CP-violating mixture arises from the oscillation between K^0 and $\overline{K^0}$ mediated by:



- Weak interactions: 80GeV (perturbation theory); Strong interactions: 1GeV (need non-perturbative methods)

- Approach: use the operator product expansion and renormalisation group .

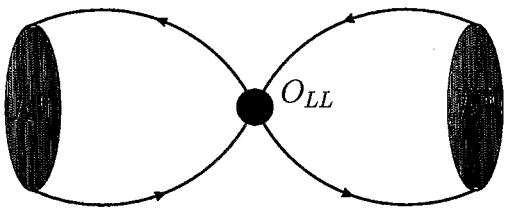
B_K...

- Weak particle much heavier than the scales at which we work:
  - Replace by effective point interaction (Higher order terms $\sim p^2/M_W^2$)
  - Continue this for all the particles which are high energy enough that perturbation theory is sensible (top, bottom, charm quarks; not up, down or strange).
  - Leave low energy excitations ($\sim$ 1GeV) to the lattice calculation

$$|\epsilon| = C_\epsilon A^2 \lambda^6 \overline{\eta} \left[-\eta_1 S(x_c) + \eta_2 S(x_t)(A^2\lambda^4(1-\overline{\rho}) + \eta_3 S(x_c, x_t) \right] \hat{B}_K$$

- need to calculate this on the lattice:

$$B_K = \frac{\langle \overline{K}^0 | O_{LL} | K^0 \rangle}{\frac{8}{3} m_K^2 f_K^2}$$



defined in some renormalisation scheme at some scale .

Lattice QCD

- Discretise QCD on a four-dimensional space-time lattice
  - Lattice QCD
- This provides:
  1. A consistent definition of QCD .
  2. A way to calculate it's predictions.

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Systematics

- Finite Volume (Want – at least – two volumes)
- Unphysical masses [The lighter the mass, the more expensive]
  - Extrapolate to physical point using effective theory for low energy QCD: Chiral Perturbation Theory .
- Finite Lattice Spacing (extrapolate from several – 3 – lattice spacings)

Fermionic Actions

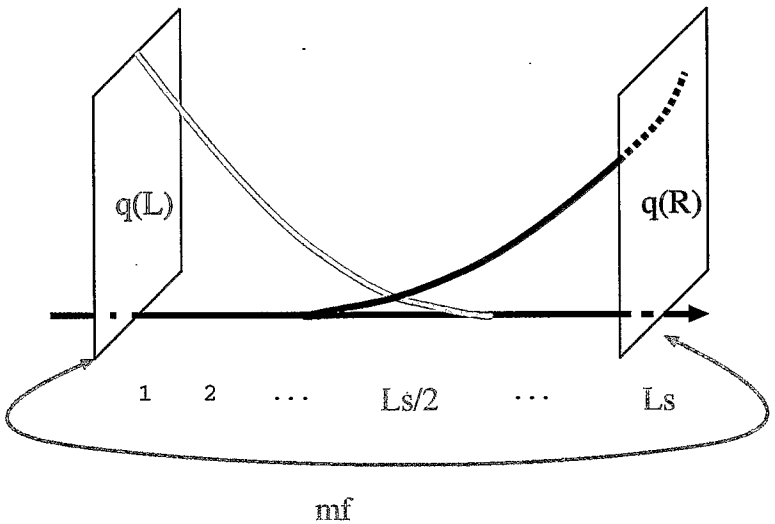
- Various ways to discretise QCD
  - all (should) be the same in continuum limit.
  - some may be much closer to continuum limit at finite lattice spacing.

Two traditional Fermionic Actions:

1. "Staggered Fermions" :
   - Cheap, extra flavours (tastes); taste mixing problem.
2. "Wilson Fermions" :
   - Exact flavour symmetry, (badly) broken chiral symmetry
     - characteristic energy scale of chiral symmetry breaking much larger than the quark masses.

Such broken symmetries require complicated operator renormalisation calculations.

Domain Wall Fermions



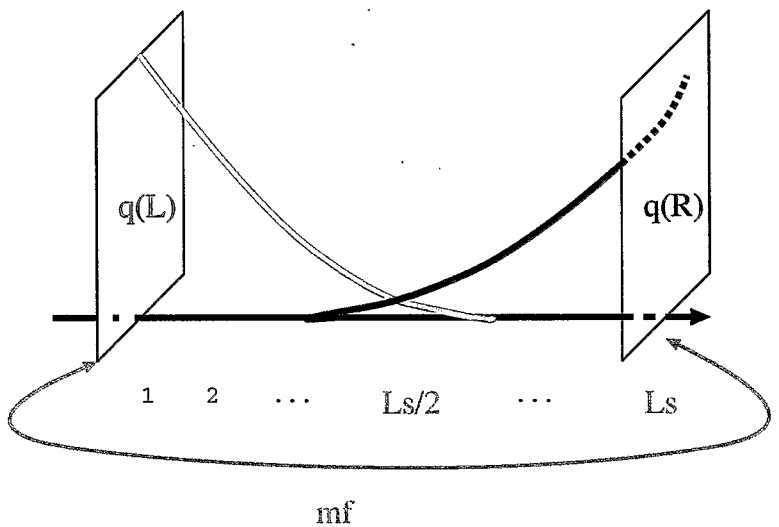
- Domain Wall Fermions preserve flavour symmetry and have greatly reduced chiral symmetry breaking.
  - at the expense of adding an extra, fifth, dimension.

- The nearest neighbour derivative in the 5th dimension distinguishes left- and right- handed fermions

$$-\gamma_\mu \frac{1}{2}\left(\nabla_\mu^+ + \nabla_\mu^-\right) + \frac{1}{2}\nabla_\mu^- \nabla_\mu^+ + M_5 \qquad \text{4d piece}$$

$$+P_L \partial_5^+ - P_R \partial_5^- \qquad \text{5d piece}$$

Domain Wall Fermions



- Define 4d quark fields on the wall

$$q_x = P_L \Psi_{x,0} + P_R \Psi_{x,L_s-1}$$

- Couple the two walls with a mass term

$$m_f \bar{q} q$$

- For finite L_s chiral symmetry is broken, leading to an additive shift of the mass

$$m_f \to m_f + m_{\text{res}}$$

plus other problems i'll explain later

- $m_{res} \to 0$ as $L_s \to \infty$; The cost in computer time $\propto L_s$
  - Can get small m_{res} (few MeV) for reasonable L_s ($O(10)$)

Operator Mixing and B_K

- If you have exact chiral and flavour symmetry at finite lattice spacing, then their is only one operator that contributes to B_K . It if of the form:

$$O_{LL} = \overline{s}_L \gamma_\mu d_L \; \overline{s}_L \gamma_\mu d_L$$

- If chiral symmetry is broken <u>four</u> other operators may mix.

$$\langle \overline{K^0} | O_{LL} | K^0 \rangle = Z_{11} \langle \overline{K^0} | O_{LL} | K^0 \rangle_{\text{latt}} + \sum_{i \geq 2} z_{1i} \langle \overline{K^0} | O_{\text{MIX,i}} | K^0 \rangle_{\text{latt}}$$

  In principle I have to calculate these five seperate quantities and then take just the right combination so that all chiral symmetry breaking effects cancel.

- If flavour symmetry is broken (Staggered fermions) many other operators may mix
  - actually under better control than the Wilson situation.

B_K ...

- First order chiral perturbation theory predicts that

$$\langle \overline{K}^0 | O_{LL} | K^0 \rangle \propto M_k^2$$

and, unfortunately, that

$$\langle \overline{K}^0 | O_{\text{THE REST}} | K^0 \rangle \propto 1$$

so... as the chiral limit is approached the wrong chirality operators will dominate .

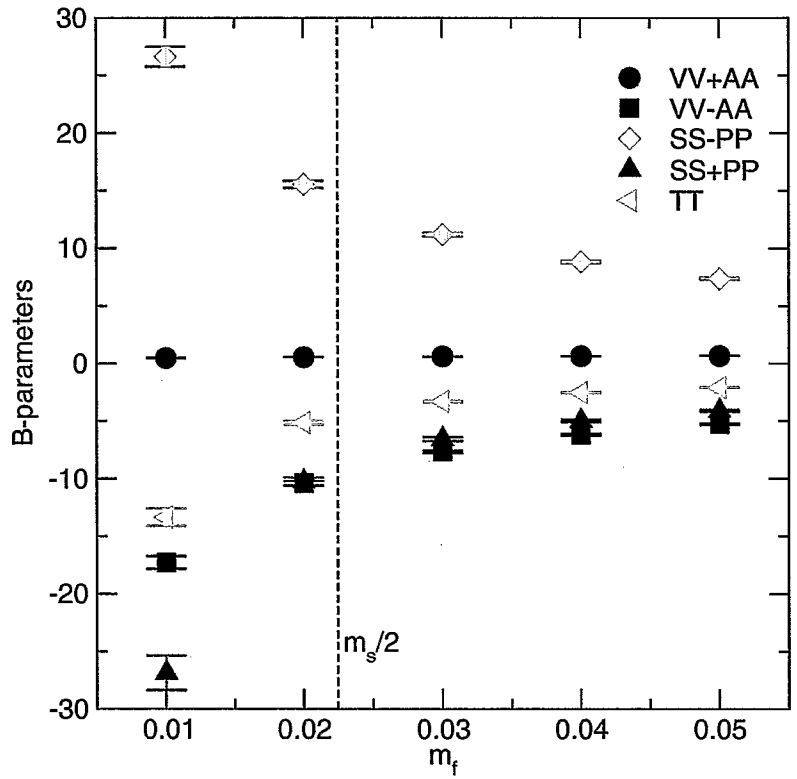
- We will always work at relatively large values of the kaon mass, but still it is important to understand the expected size the c_i coefficients.

Quenched Results for B-parameters

Not the most sensible quantity ever, but can calculate "B-parameters" for these other operators.

- up to ≈ 50 times larger than the operator we are interested in.

This kind of mixing problem also occurs in the $\Delta I = 1/2$ calculation.

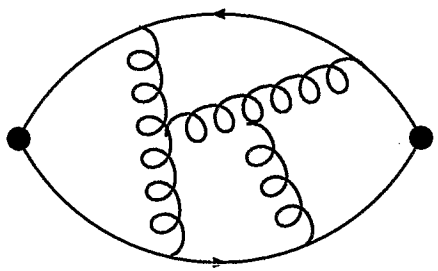


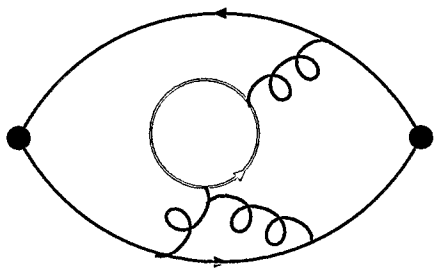
DWF allows us to simply ignore this mixing problem.

Quenched Approximation

Until recently most lattice calculation were performed in the Valence or Quenched approximation:

- Quarks propagate in background gauge field.
- In perturbative language:

include : 

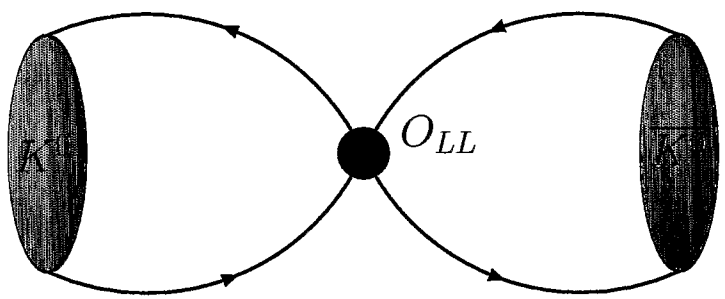
neglect : 

$O(100)$ times less computationally demanding than real QCD.

- This is an uncontrolled approximation: the only way we know how to do better, is not to do it at all.
- good place to check out control of other systematics.

Quenched Details

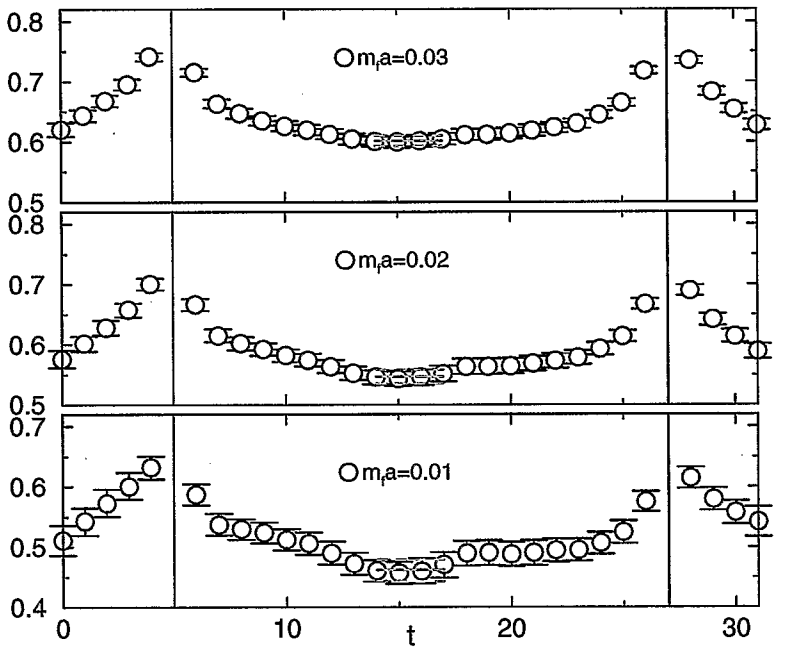
- I'm going to show some RBC results in the quenched aproximation from two different lattice spacings..
  - $a^{-1} = 2$ GeV ($L_s = 16$) and 3 GeV ($L_s = 10$)
  - $\sim 1.5\text{fm}^3 \times 3\text{fm}$ box
  - degenerate masses



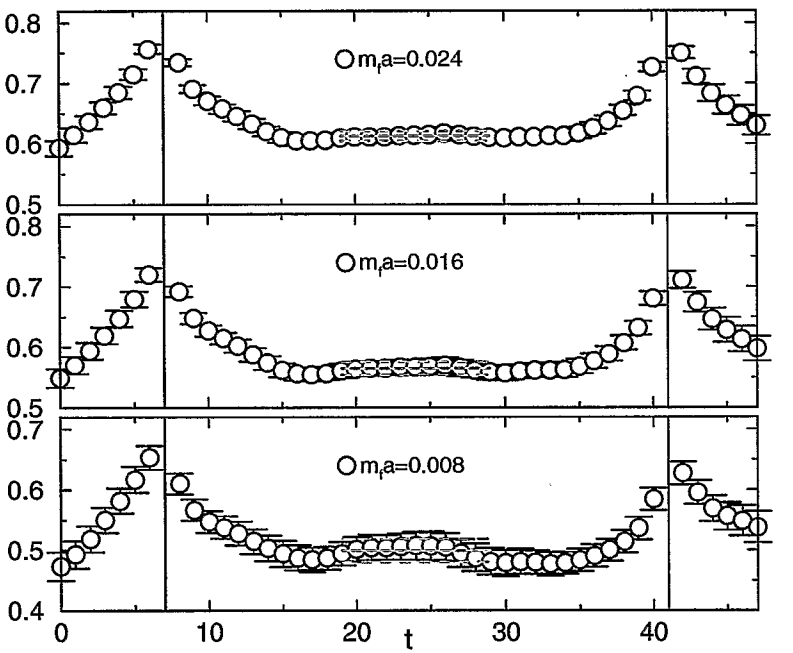
- Put operator with quantum numbers for Kaon at timeslices 4 and 28 (2 GeV)
- Move effective Weak vertex over all timeslices
  - Plateau should appear for large seperation.

Bare B_K plateaus

$a^{-1} = 3\text{GeV}$



$a^{-1} = 3\text{GeV}$

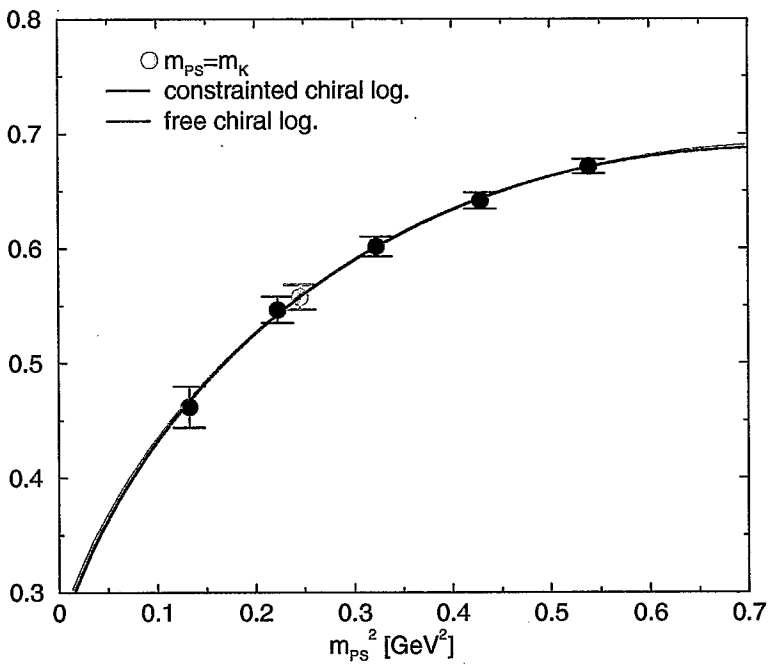


Chiral fits, extracting B_K

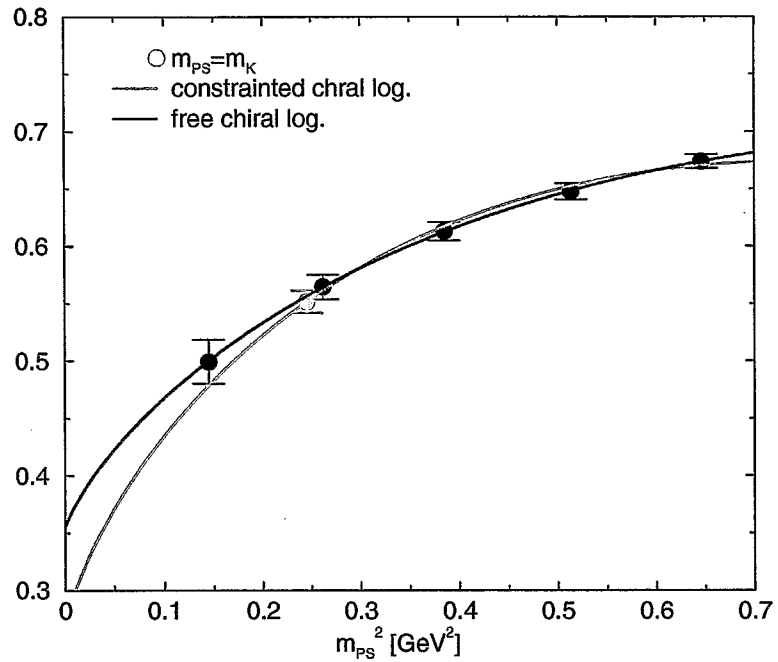
Predicted NLO ChiPT :

$$B_K = b_0 \left(1 - \frac{6}{(4\pi f)^2} M_K^2 \ln \left[\frac{M_K^2}{(4\pi f)^2} \right] \right) + b_1 M_K^2$$

DWF(RBC) $a^{-1} = 2\text{GeV}$



DWF(RBC) $a^{-1} = 3\text{GeV}$



Non-perturbative Renormalisation

- The relation between the observed ϵ_k and B_K:

$$|\epsilon| = C_\epsilon A^2 \lambda^6 \overline{\eta} \left[-\eta_1 S(x_c) + \eta_2 S(x_t)(A^2\lambda^4(1-\overline{\rho}) + \eta_3 S(x_c, x_t) \right] \hat{B}_K$$

  is calculated using perturbation theory, applying normalisation conditions on off-shell greens functions.

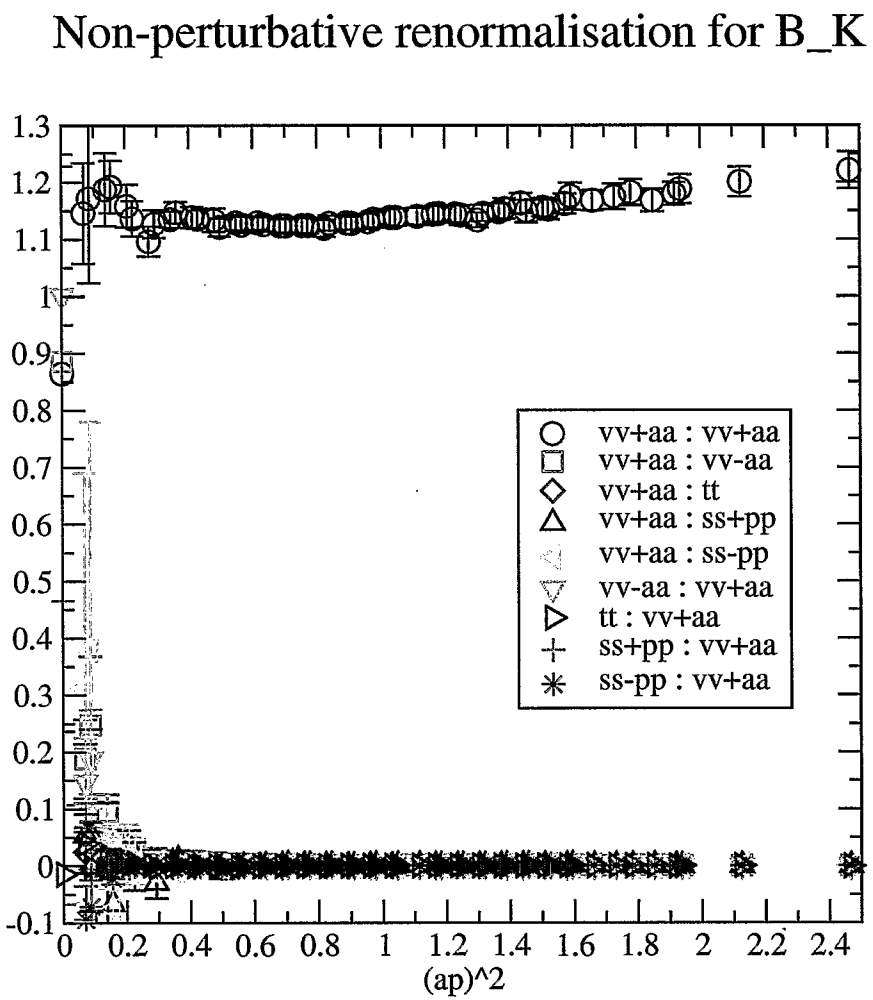
- Need to use same conditions. Either:

  1. Use lattice perturbation theory (tedious; badly convergent)
  2. Apply thse conditions directly on the lattice data

- The second option is one the RBC has found to be particularly successful for various projects (B_K , ϵ'/ϵ , quark masses...)

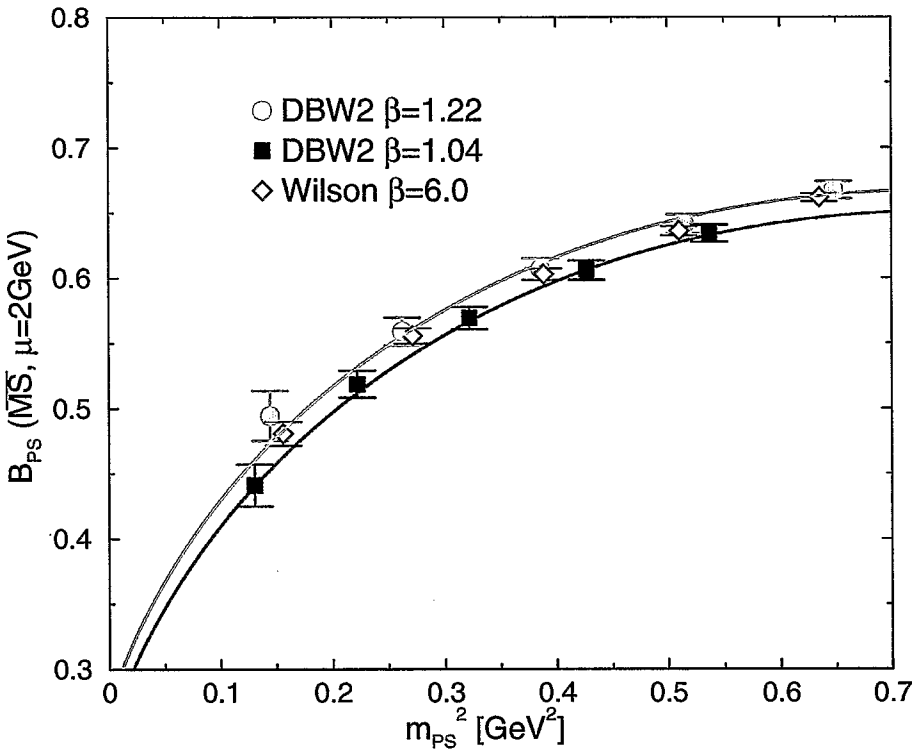
- Can also use the method to calculate the size of the mixings with wrong chirality operators.

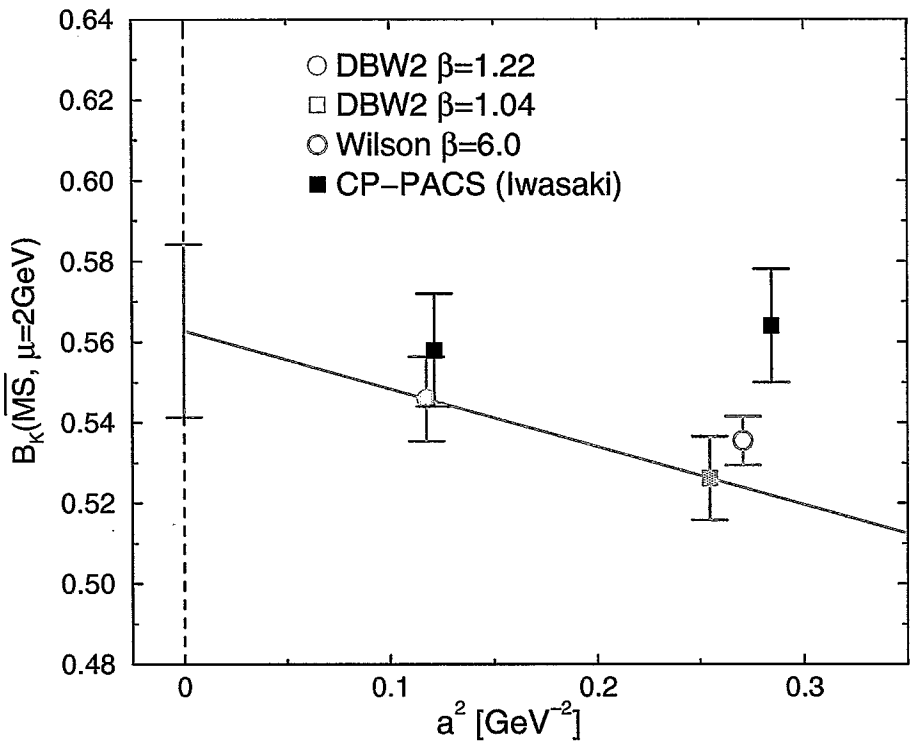
NPR: results


Non-perturbative renormalisation for B_K
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
(ap)^2
vv+aa : vv+aa
vv+aa : vv-aa
vv+aa : tt
vv+aa : ss+pp
vv+aa : ss-pp
vv-aa : vv+aa
tt : vv+aa
ss+pp : vv+aa
ss-pp : vv+aa

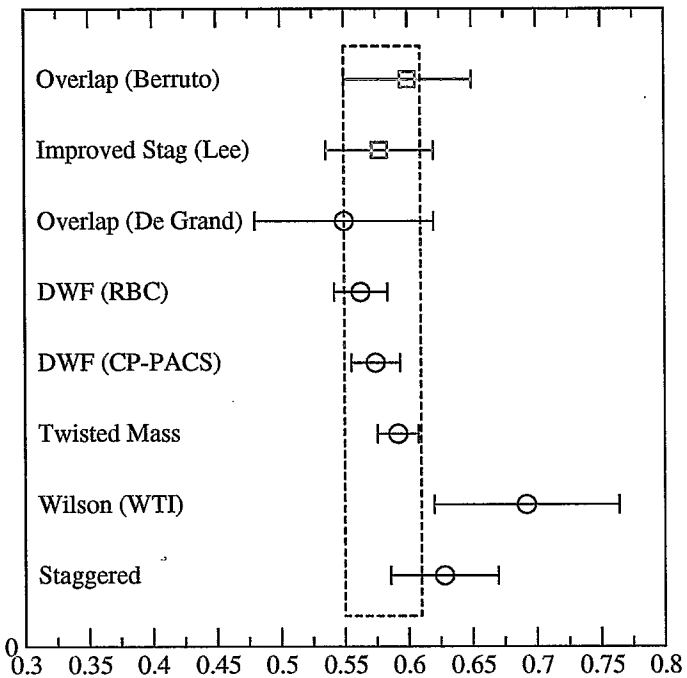
Quenched continuum limit of B_K

- Continuum limit consistent with CP-PACs Iwasaki/DWF calculation using perturbative renormalization





Quenched Summary (CKM 2005)



$$B_K^{NDR}(2\text{GeV}) = 0.58(3)$$

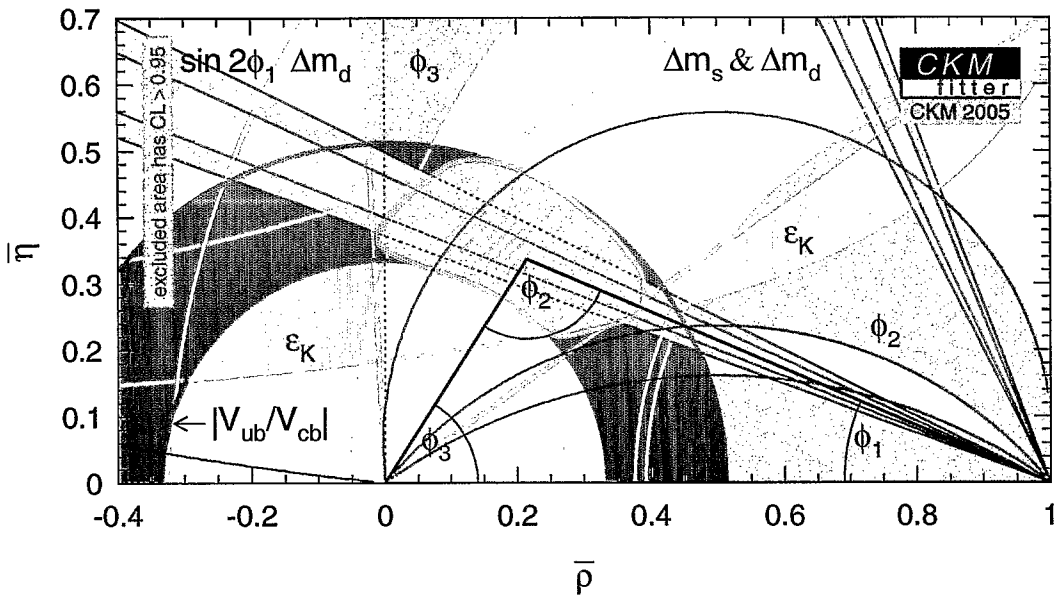
c.f.

$$B_K^{NDR}(2\text{GeV}) = 0.58(4)$$

Shoji Hashimoto (ICHEP 2004)

- Seems to be a good agreement between several different methods in the quenched approximation.
- Systematic error due to quenching is put in as a (educated) guess of 10-15%.

Unitarity Triangle



- This is a plot put together by the CKMfitter collaboration using the CKM2005 value for B_K

- The value is consistent with other measurements and the Standard Model , but is not very constraining on the allowed region.

- The main reason for this is the large error-bar; this is dominated by the ambiguity due to the Quenched Approximation

Dynamical QCD

- Vital to move beyond the quenched approximation.

- For the past two years we have been using the QCDSP supercomputer to perform the first large-scale calculations using two dynamical flavours of domain wall quarks.
  - three different masses: 0.02, 0.03 and 0.04 ($m_s/2 \rightarrow m_s$).
  - $a^{-1} \sim 1.7$GeV
  - on lattices of size $16^3 \times 32$ ($\sim (2\text{fm})^3 \times 4\text{fm}$)
  - a fifth dimension of 12
  - with a collection of over 5000 HMC trajectories for each mass
    - 94 configurations for each dynamical mass

Dynamical QCD...

- Note:
  - this is the "less quenched" approximation.
    - dynamical u and d; quenched s quark.
  - single volume, single lattice spacing, heavy masses
  - Stepping stone to $2+1$ flavour dynamical DWF on QCDOC
    - Already started: see Bob Mawhinney's talk.

- Calculated many things on these configurations. Here i'll just talk about B_K . Same approach as in quenched study described earlier. In addition:
  - Extrapolate in dynamical mass.
  - Included non-degenerate quark masses ($m_s \neq m_d$).

Degenerate fit

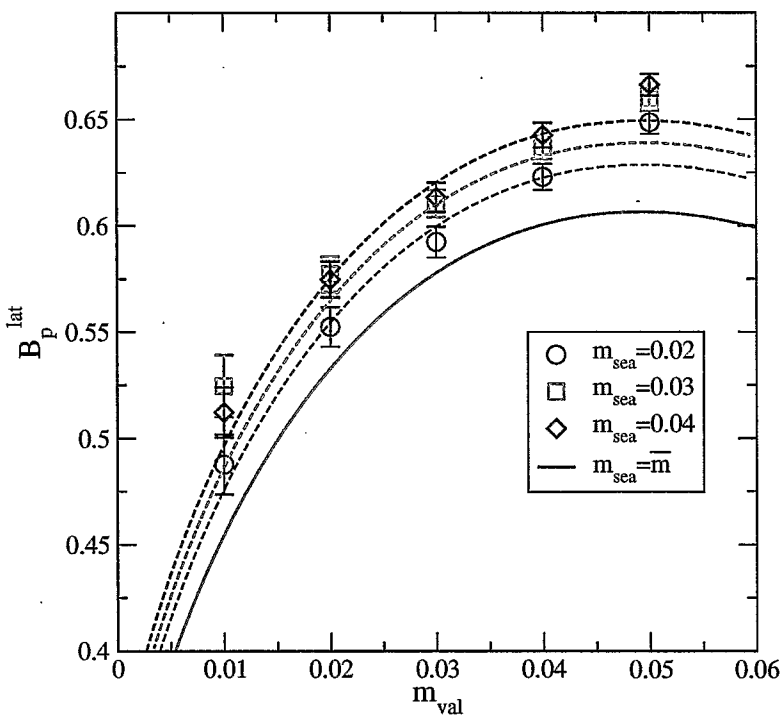
In quenched work ChiPT was used to interpolate; here we use it to extrapolate.

- relying much more on the convergence of ChiPT (known to be bad for other quantities at these masses)

m_{sea} dependence not well resolved between $m_{sea} = 0.03,\ 0.04$.

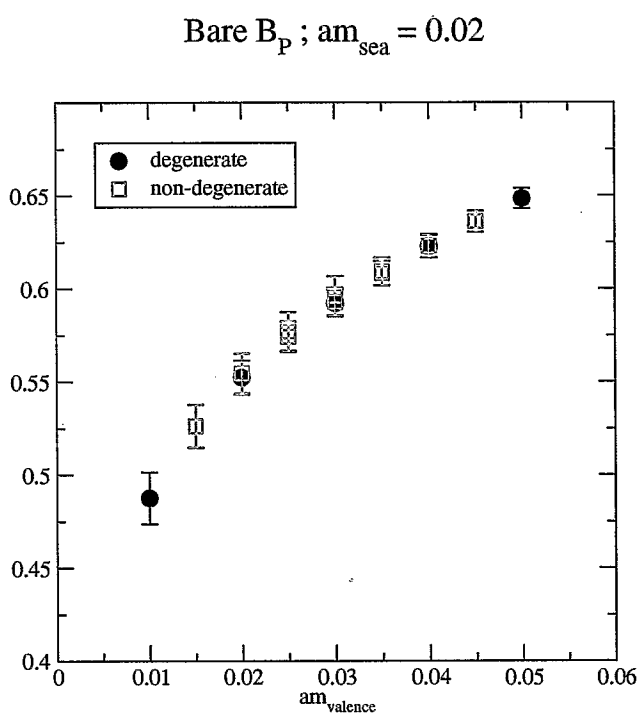
$m_{sea} = 0.02$ is clearly lower: relevant ChiPT coefficient $\sim 2\sigma$

lighest/heaviest valence points aren't fit well



Non-degenerate effects

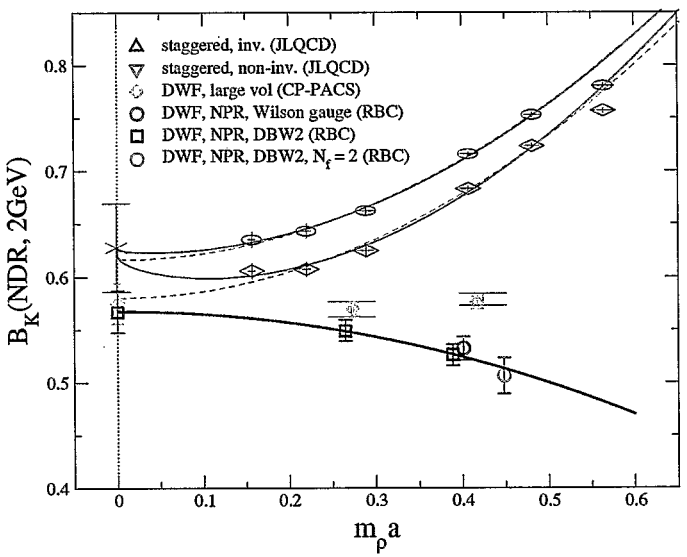
- Degenerate and non-degenerate valence quark results (plotted as $m_{val} = (m_1 + m_2)/2$)



Effects clearly small.

Fit to non-degenerate ChiPT gives a – statistically – well resolved $\sim 3\%$ lower than the degenerate number.

Dynamical B_K



- "Suggestive" graph with the quenched and dynamical DWF results on, with the a^2 extrapolation on it.
  - Not a very sensible thing to plot

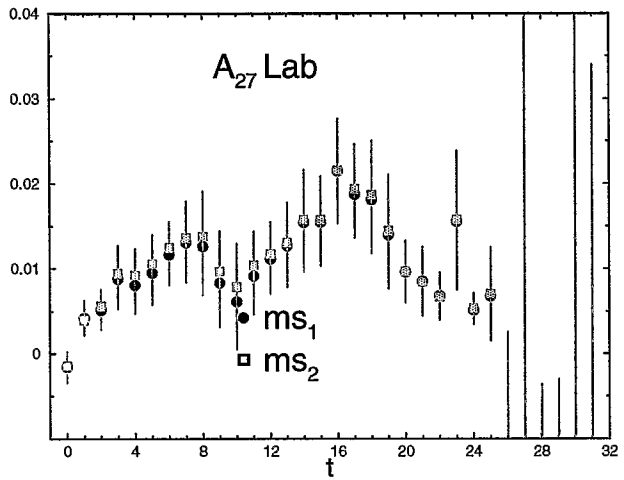
- Our dynamical result is only 3% lower than the quenched results closest in lattice spacing.

- need : smaller masses, two lattice spacings, larger volumes...
  - QCDOC

Direct CP-violation

- The RBC also has a history of interest of calculating ϵ'/ϵ ($K \to \pi\pi$)

- previous calculation:
  - quenched approximation
  - actually measure $K \to \pi$



- As well as moving to full QCD, we (Yamasaki/Christ/Kim) are testing out theoretical techinique for calculating $K \to \pi\pi$ on the lattice

- Plot is test calculation of amplitude $\langle\pi\pi|O|K\rangle$ performed on a QCDOC motherboard.

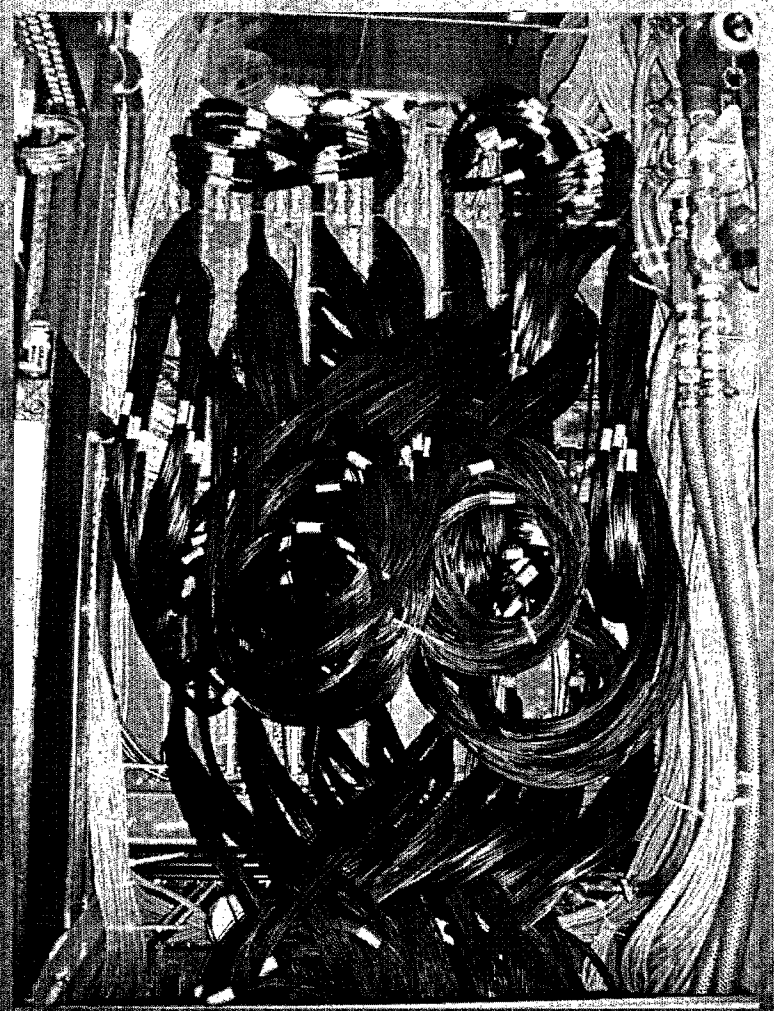
Difference in Computing Power

- This is a picture of the first QCDOC machine, taken a few days before it was shipped off to Edinburgh in November.

Simulating HOT Matter on COOL Computers

Frithjof Karsch, BNL

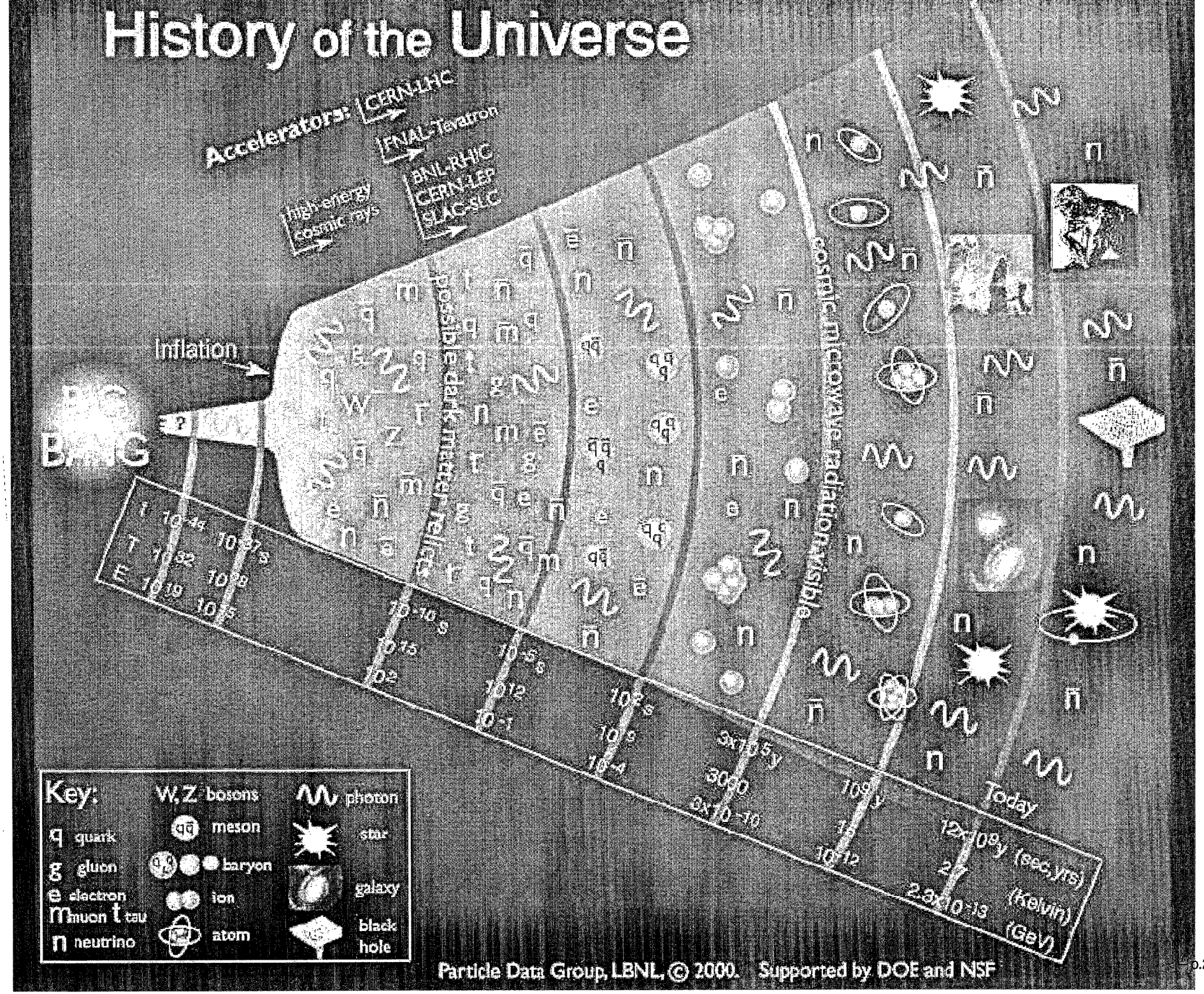
Simulating HOT Matter on COOL Computers



F. Karsch, QCDOC dedication, May 26, 2005

Studying matter at 10^{12} Kelvin

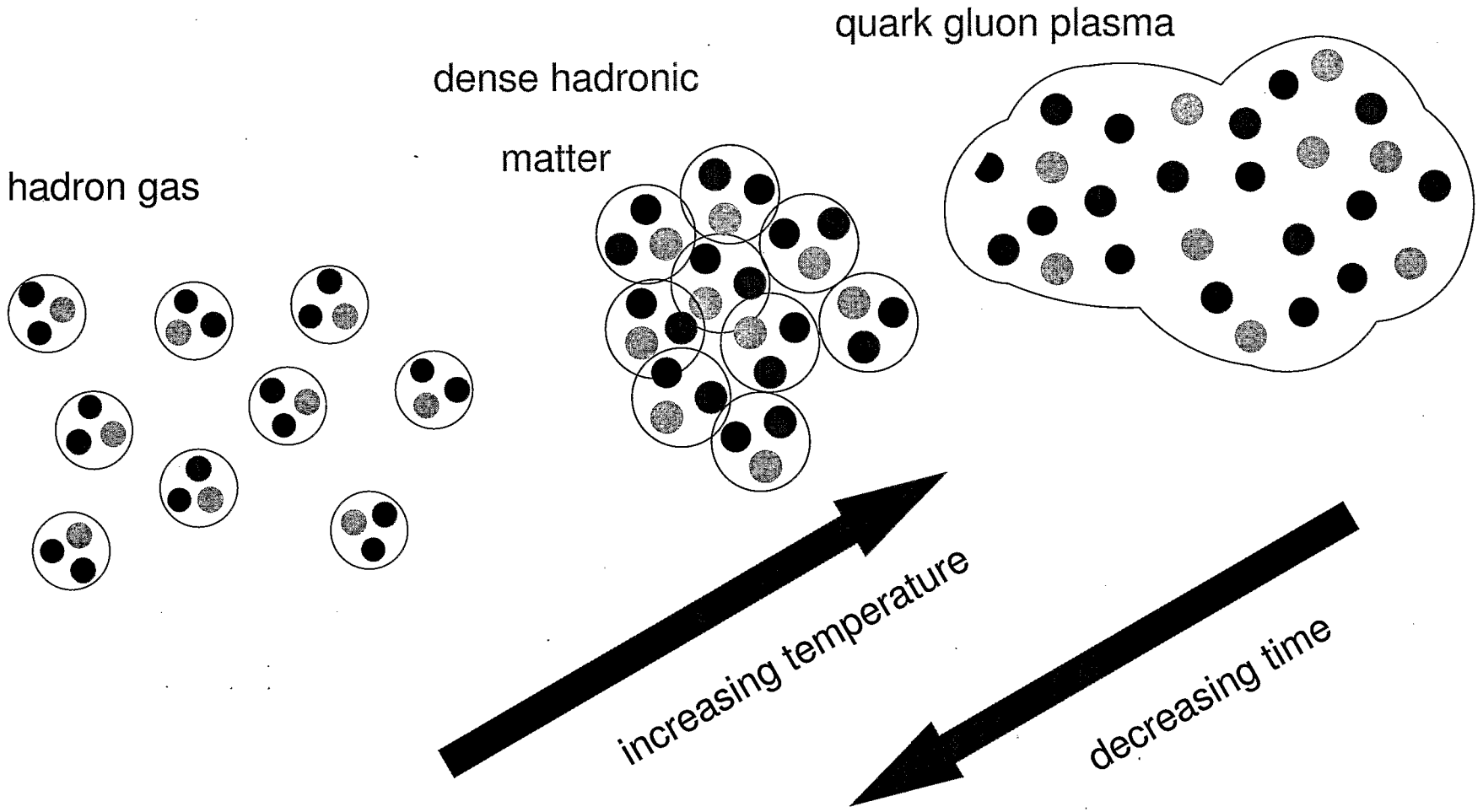
at a speed of 10^{12} Flops/sec


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Phase Transition from a Hadron Gas to the Quark-Gluon Plasma

temperatures in the early universe after 10^{-5} sec: $\sim 10^{12}$ K

density of neutron stars: $\sim$ (3-10)-times nuclear matter density



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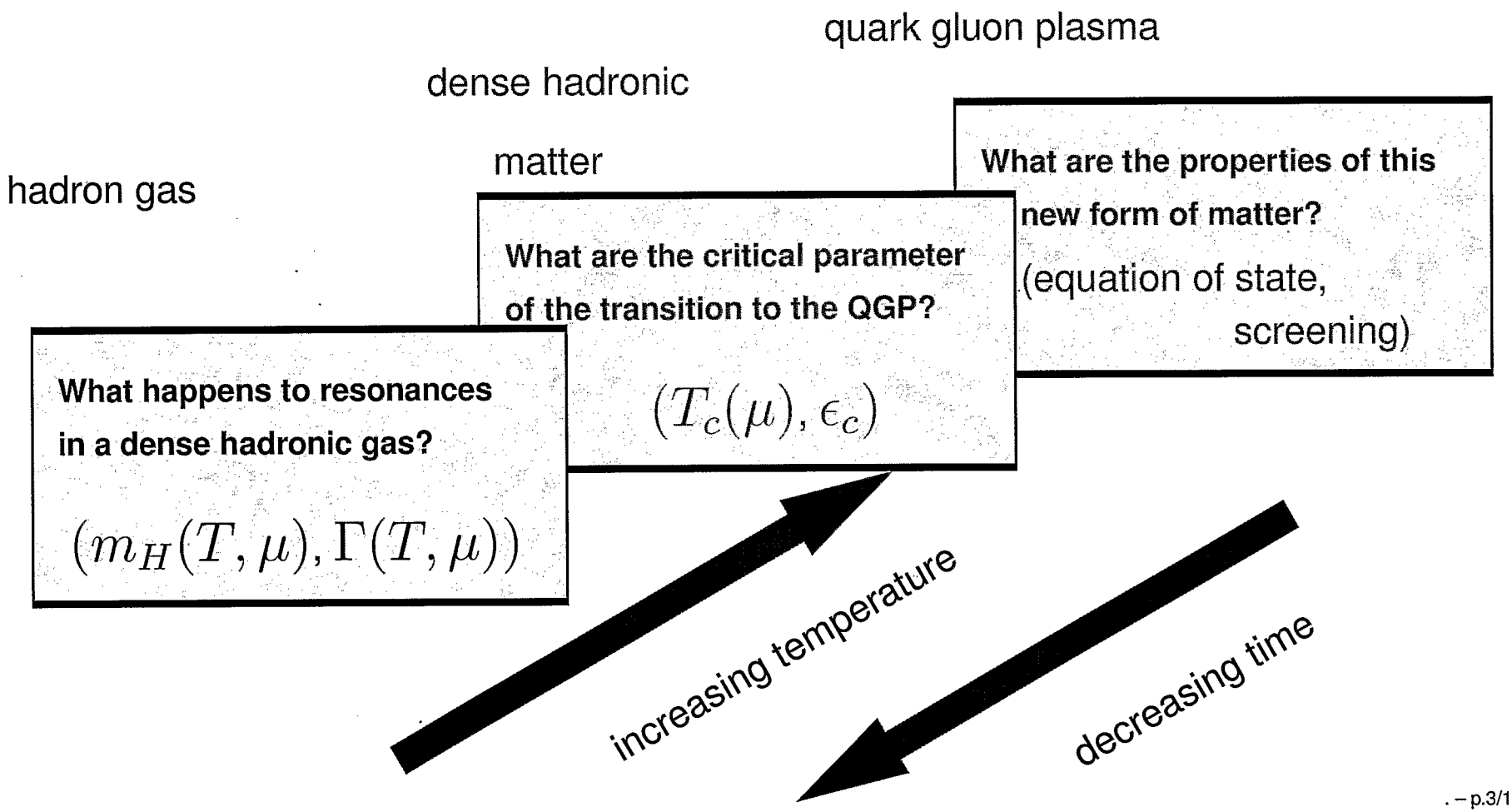
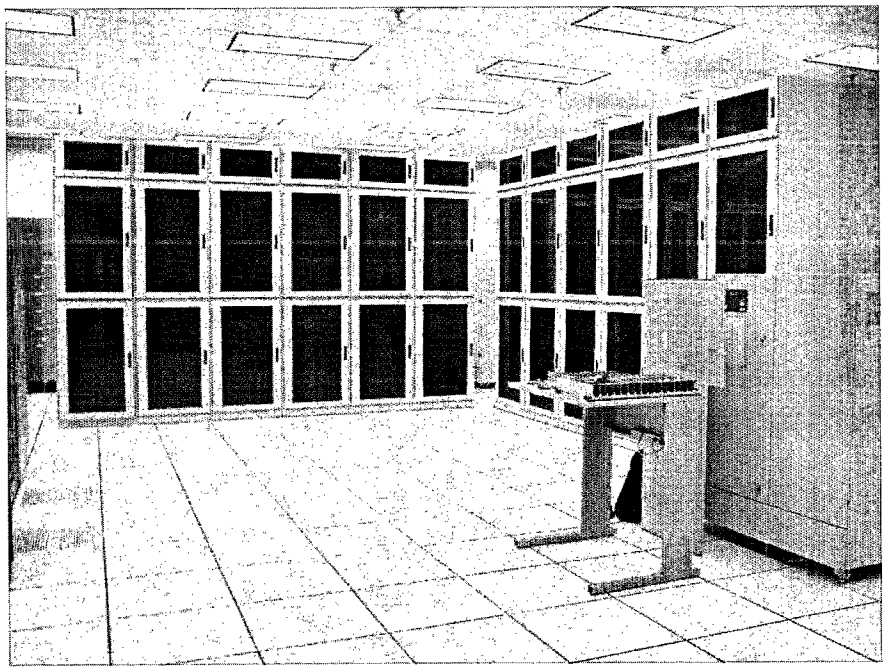
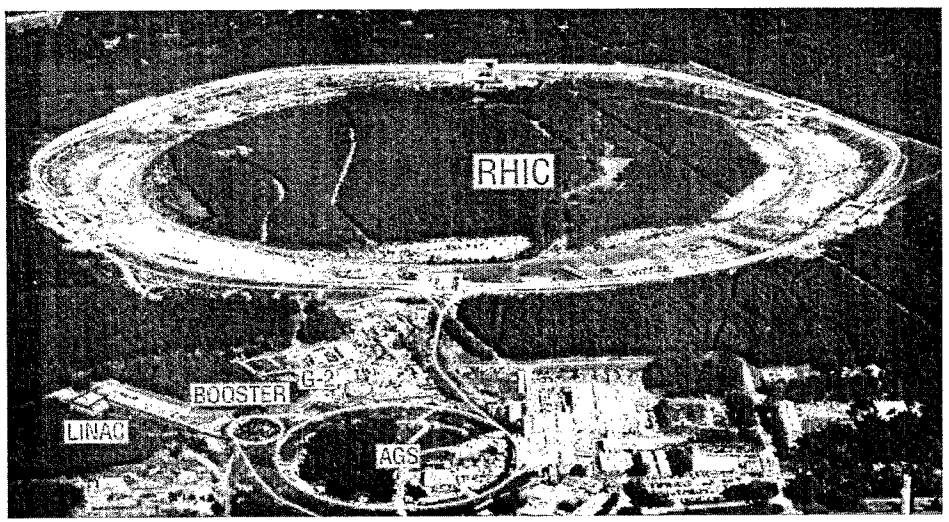


Lattice Gauge Theory and Heavy Ion Collisions

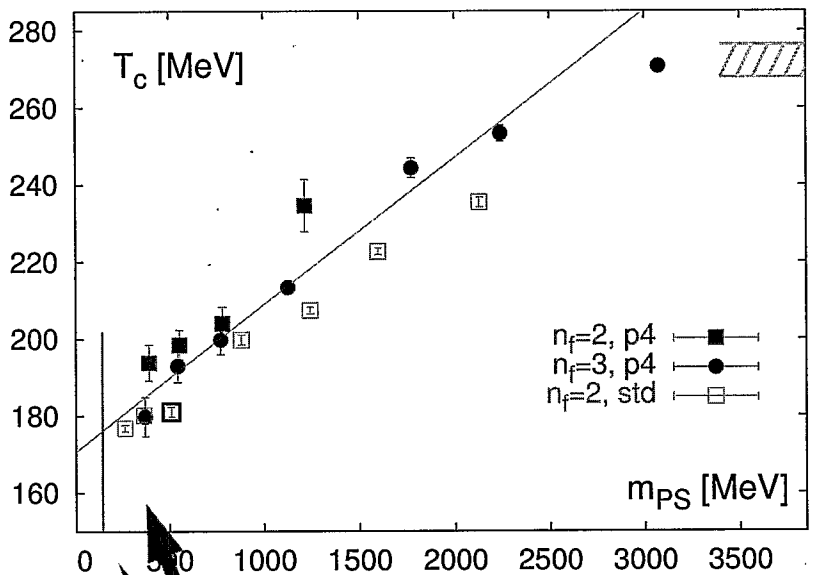


Collision of Au-Au and other ions in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven Nat. Lab. (BNL)

Lattice Simulations of Finite Temperature QCD on QCDOC at the RIKEN-BNL Research Center (RBRC)

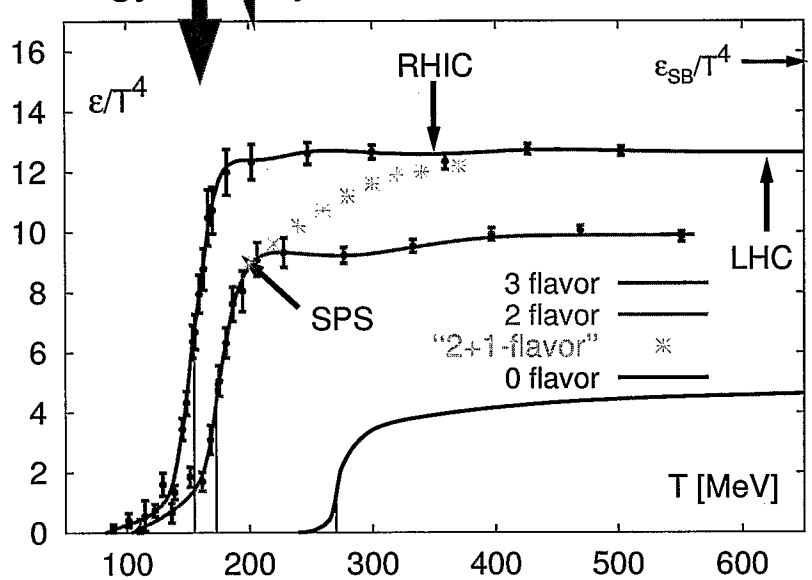


State-of-the-art: Critical temperature & equation of state



$$\epsilon_c \simeq (6 \pm 2)\, T_c^4$$
$$\simeq (0.3 - 1.3)\, GeV/fm^3$$

energy density for 0, 2 and 3-flavor QCD



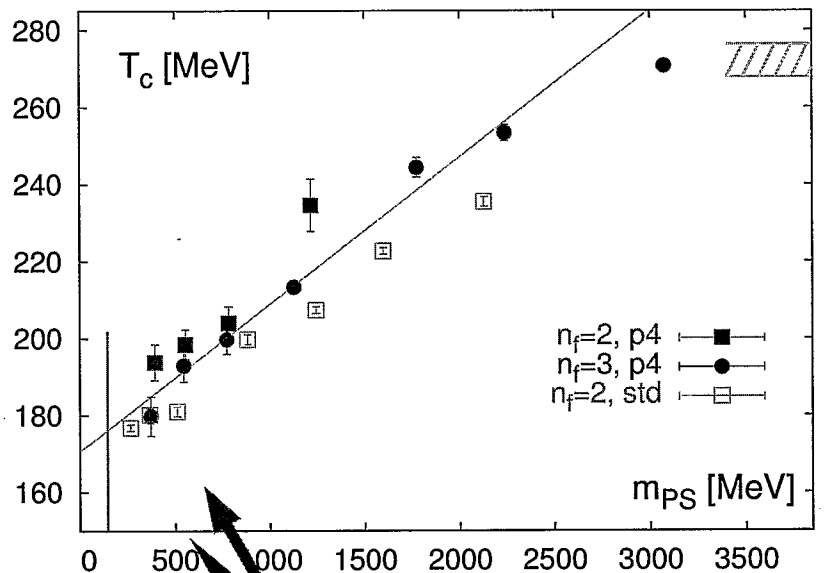
$$T_c = (173 \pm 8 \pm sys)\, MeV$$

FK, E. Laermann, A. Peikert,
Nucl. Phys. B605 (2001) 579

$$T_c = 167(13)\, [177(11)]\, MeV$$

MILC, hep-lat/0405029

State-of-the-art: Critical temperature & equation of state



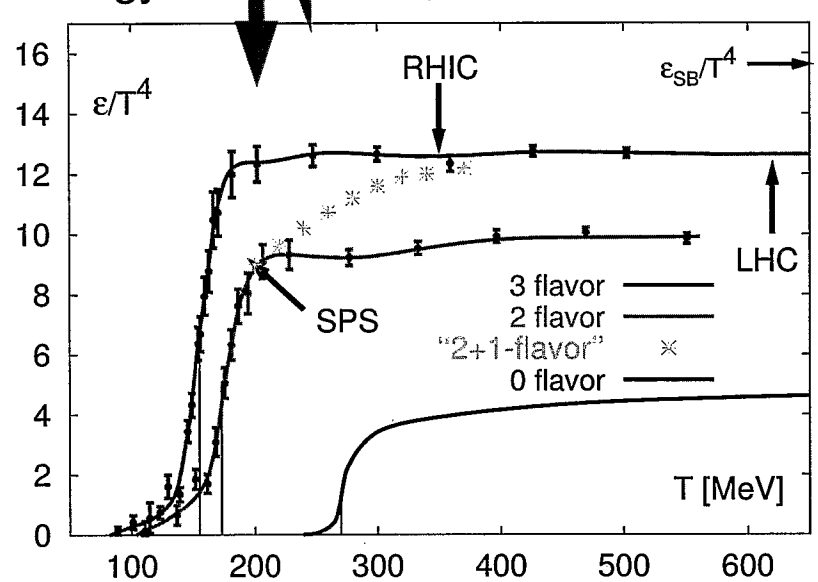
T_c

- $m_{PS} \gtrsim 300\ MeV$ (chiral limit??)
- $a \simeq 0.2\ fm$ (continuum limit??)
- improved staggered fermions,
  $\Rightarrow$ flavor symmetry breaking
  (need even better fermion actions)

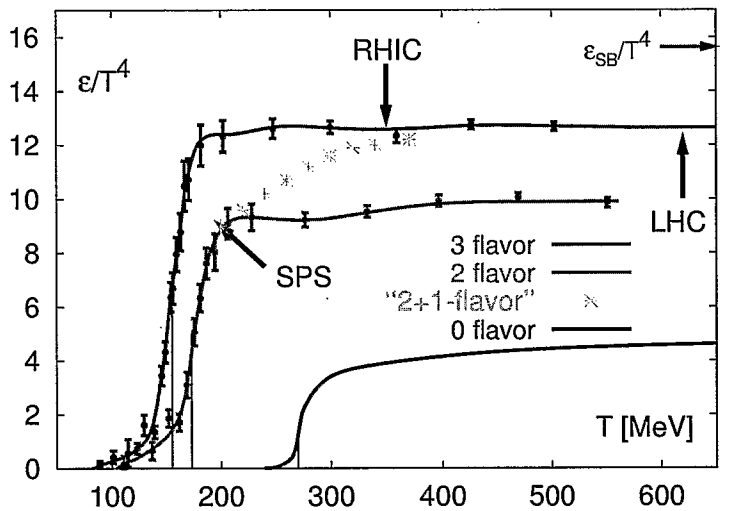
ϵ_c

- $m_{PS} \simeq 770\ MeV$ (!!!)
- $V \simeq (4\ \text{fm})^3$ (thermodynamic limit)

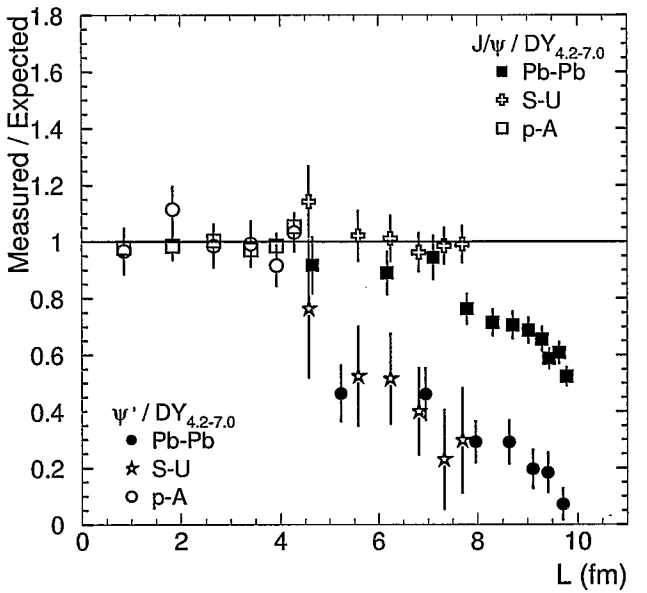
energy density for 0, 2 and 3-flavor QCD



Equation of State



state-of-the-art EoS (LGT)



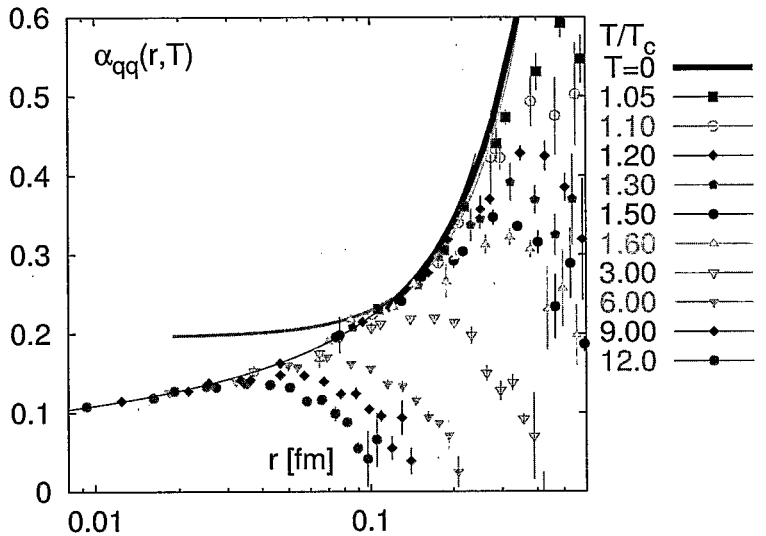
charmonium yield (SPS)

- ϵ/T^4 for $m_\pi \simeq$ 700 MeV; T_c for $m_\pi \gtrsim$ 300 MeV
- $\boldsymbol{T_c = (173 \pm 8 \pm sys)}$ MeV $\boldsymbol{\epsilon_c = (0.3 - 1.3)}$GeV/fm^3

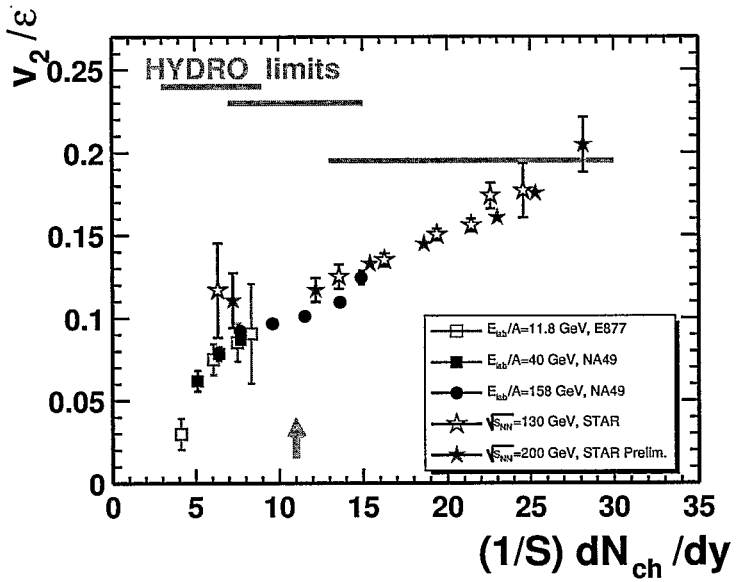
- from absorption length (L) to energy density (ϵ) using Bjorken formula
- from energy density to T/T_c using lattice results

Does the charmonium suppression at SPS turn into charmonium enhancement at RHIC ?

Strongly coupled QCD



running coupling at finite-T (LGT)



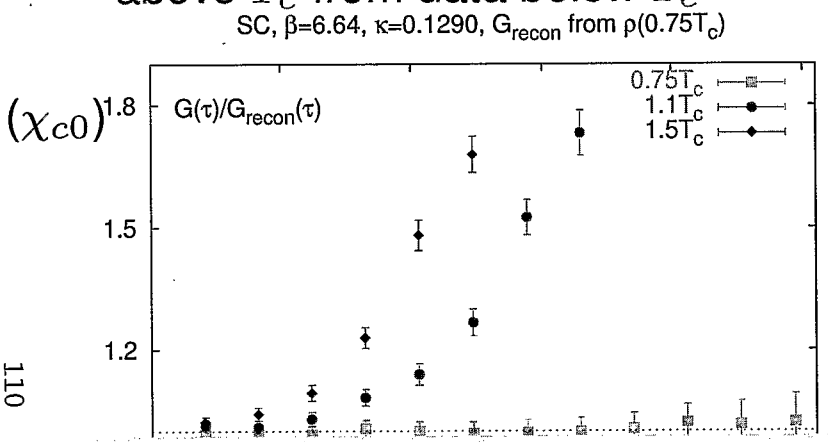
elliptic flow (RHIC)

- T-dependence of $\bar{q}q$ interaction at short and medium distance reflects asymptotic freedom as well as remnants of confinement
- large elliptic flow suggest the creation of an almost ideal fluid in a heavy ion collision at RHIC

Is there evidence for colored bound states or density correlations that could give support to the sQCD scenario suggesting a fluid phase generated at RHIC ?

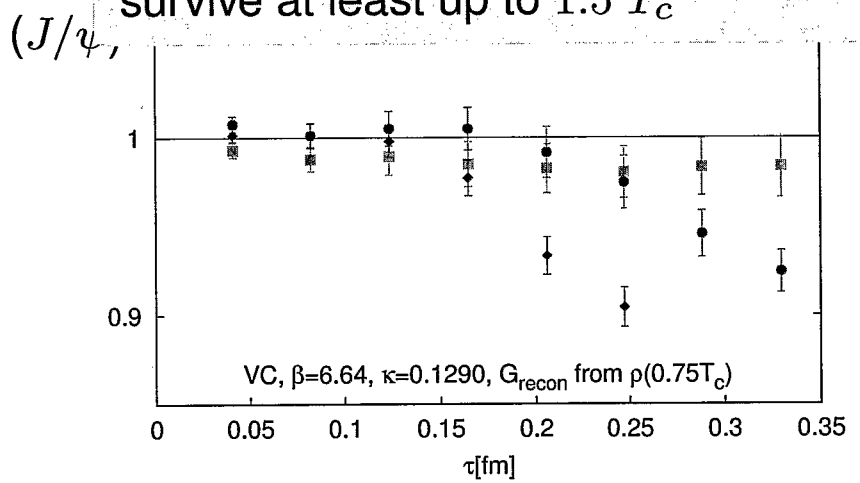
Heavy quark spectral functions and correlation functions

reconstructed correlation functions above T_c from data below T_c

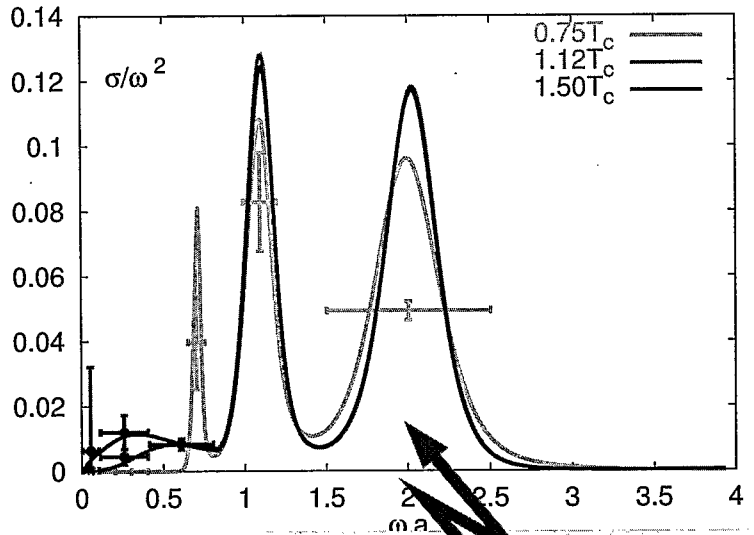


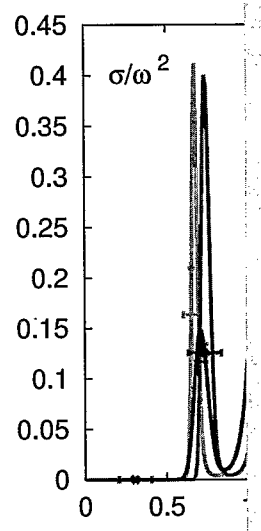
orbital excitations (χ_c) disappear at T_c;

charmonium S-states (J/ψ and η_c) survive at least up to $1.5\ T_c$



reconstructed spectral functions using the Maximum Entropy Method



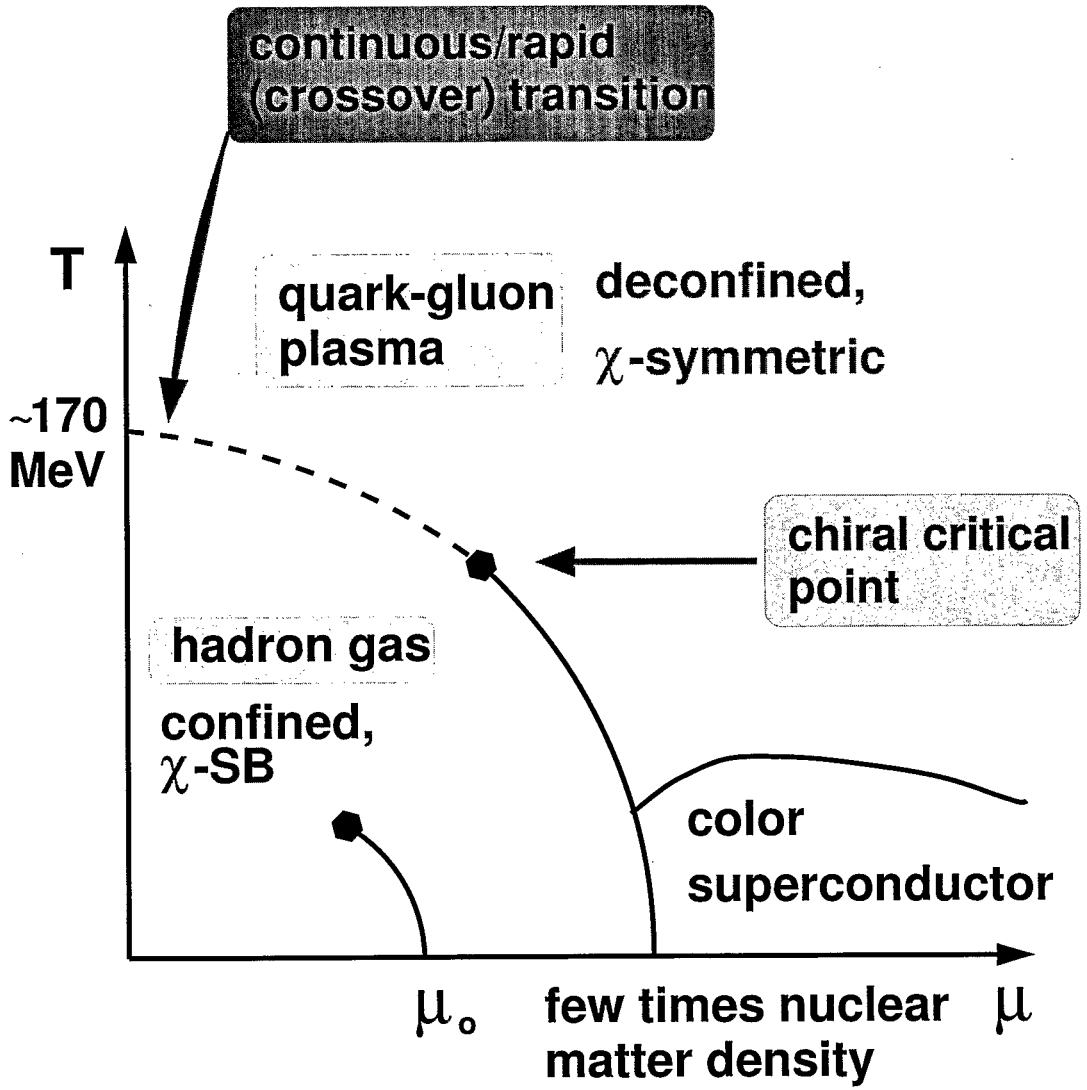


need to get better control over ultra-violet cut-off effects (Wilson-doublers)

use better fermion actions
- overlap fermions
- domain wall fermions
- (truncated) perfect actions...

Critical behavior in hot and dense matter: QCD phase diagram + Statistical Physics

K. Rajagopal and F. Wilczek, The condensed matter physics of QCD, hep-ph/0011333



continuous transition for small chemical potential and small quark masses at

$$T_c \simeq 170\, MeV$$
$$\epsilon_c \simeq 0.7\, GeV/fm^3$$

2nd order phase transition; Ising universality class

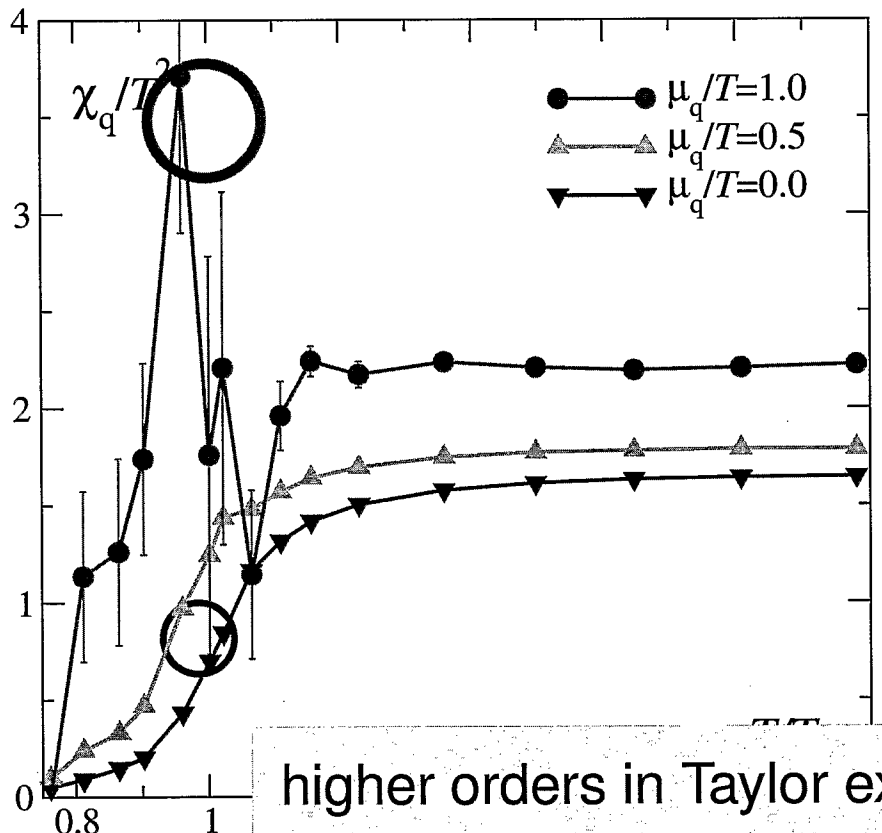
$T_c(\mu)$ under investigation

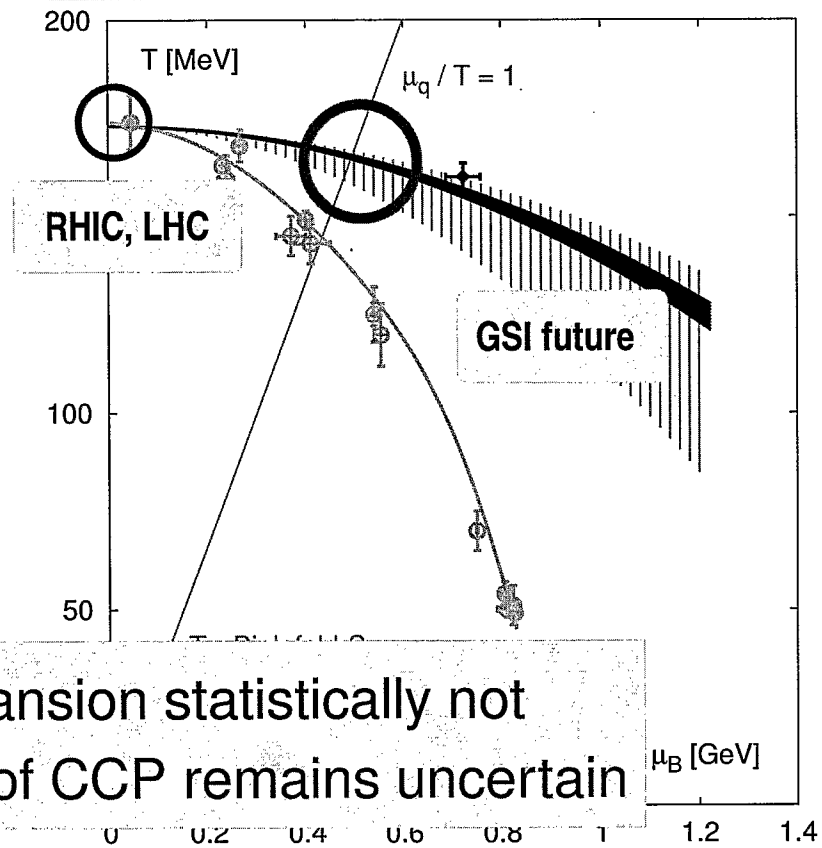
Fluctuations of the baryon number density ($\mu > 0$)

baryon number density fluctuations:
(Bielefeld-Swansea, PRD68 (2003) 014507)
up to $\mathcal{O}\left((\mu_q/T)^4\right)$

$$\frac{\chi_q}{T^3} = \left(\frac{\mathrm{d}^2}{\mathrm{d}(\mu/T)^2}\frac{p}{T^4}\right)_{T\ \mathrm{fixed}}$$

$$= \frac{9\,T}{V}\left(\langle N_B^2\rangle - \langle N_B\rangle^2\right)$$





higher orders in Taylor expansion statistically not yet under control: location of CCP remains uncertain

Next generation thermodynamics calculations

- Thermodynamics of pure gauge theory has been "solved" on (1-10)GFlops computers (1996)
- Thermodynamics of QCD with "still too heavy" quarks has been studied on (10-100) GFlops computers
- Analysis of "continuum and thermodynamic limit" of QCD thermodynamics with light quarks, requires computers with ~10 TFlops peak speed.

(LatFor proposal 2003, US white paper 2004)

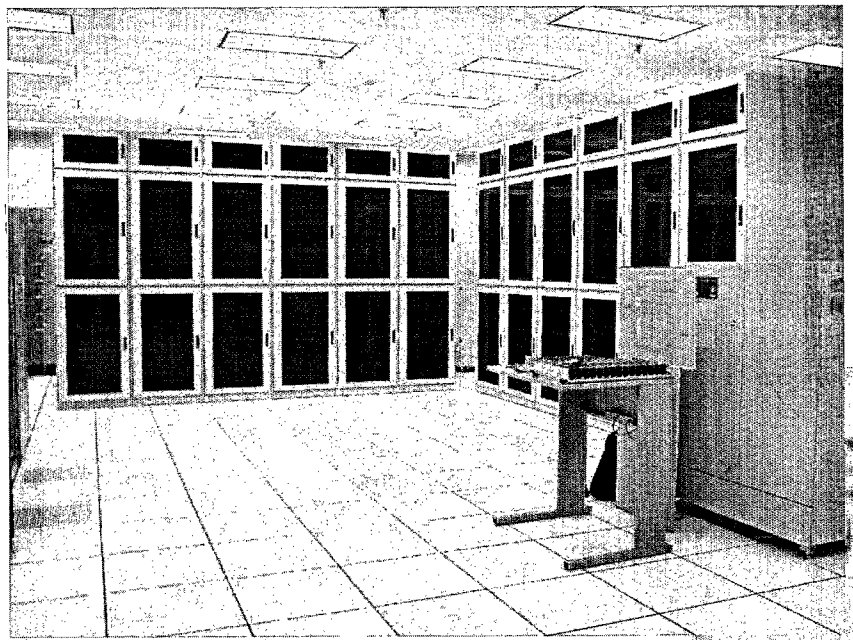
... on Teraflops computers

- T_c, EoS ($\mu = 0$ and $\mu > 0$) with light dynamical quarks:
  (2+1)-flavor QCD, close to physical m_π/m_K ratio;
  exploring the continuum limit: $a \simeq (0.1 - 0.2)$ fm
  analyzing the thermodynamic limit: $V \simeq 500$ fm^3

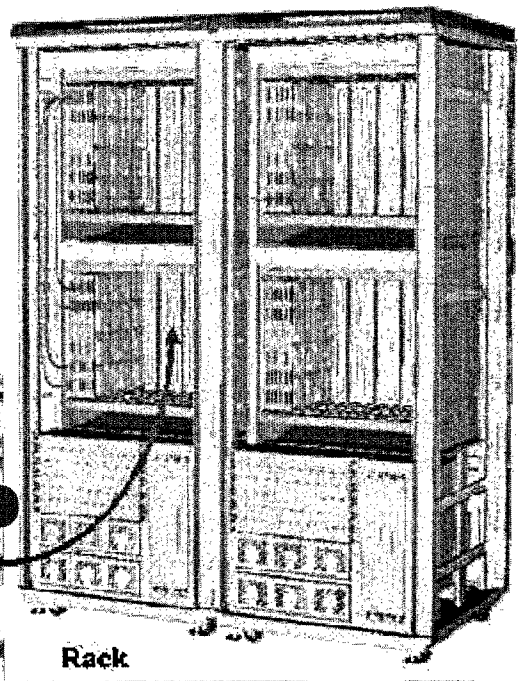
$\Rightarrow$ lattice sizes up to $32^3 \times 8$; CPU-time: $\sim$ 5 TFlops-years

Thermodynamics on QCDOC and apeNEXT

US – QCDOC – RBRC



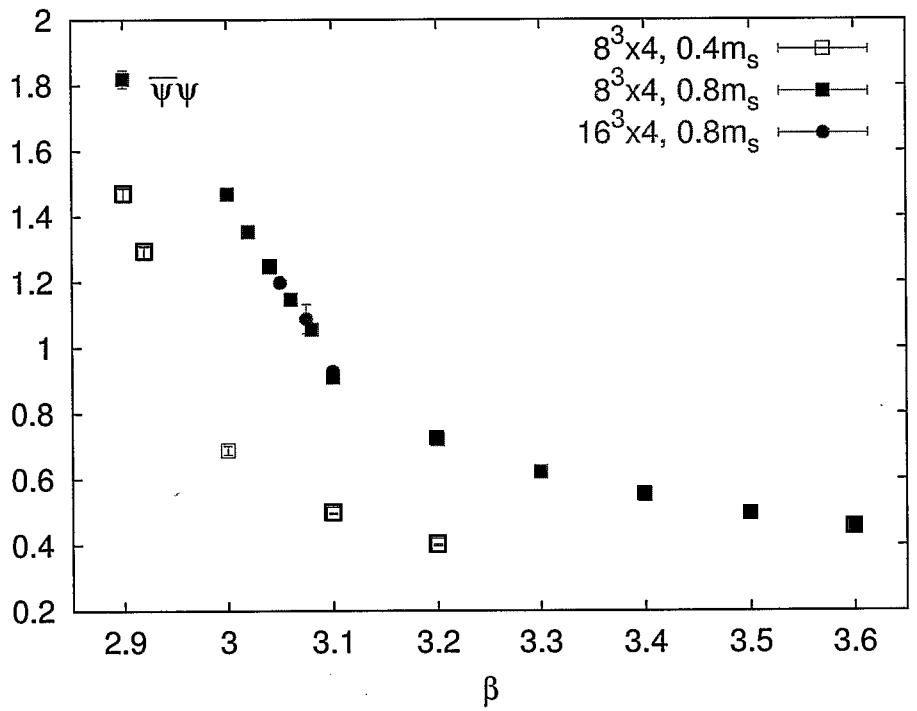
BI – apeNEXT

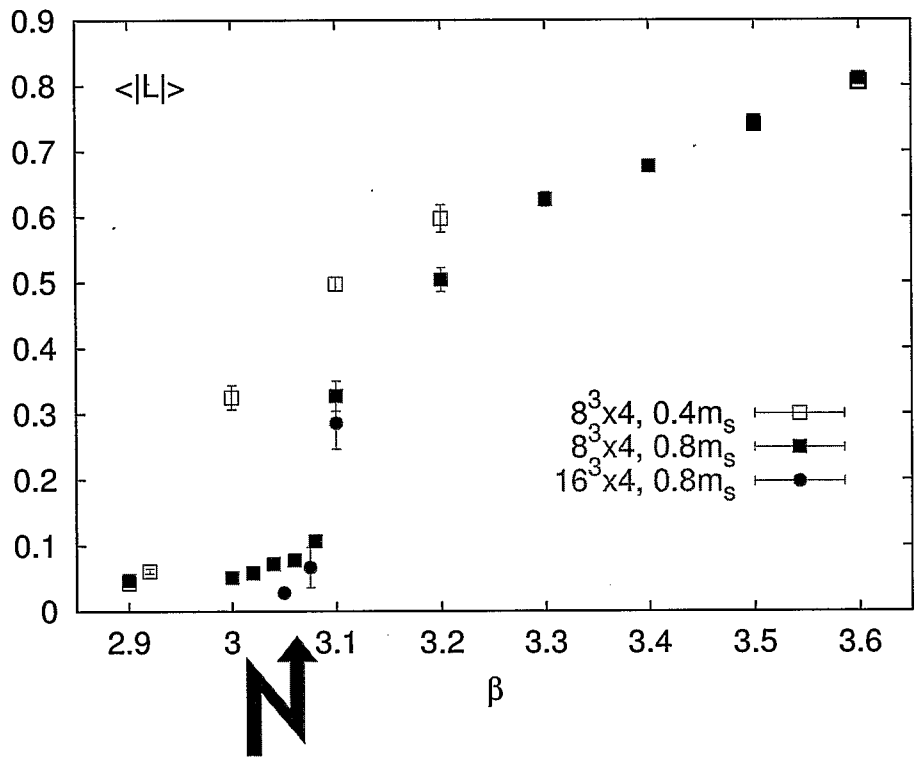


$\sim$ 6 TFlops for QCD-Thermodynamics
$\sim$ 50 times more CPU-time than for previous studies of the EoS

Thermodynamics on QCDOC

First results, May 26, 2005:...towards a determination of T_c





We see a phase transition!!!

QCDOC and Domain Wall Fermions: Making Lattice QCD Simpler?

Robert D. Mawhinney, Columbia University

QCDOC and Domain Wall Fermions: Making Lattice QCD Simpler?

Robert D. Mawhinney
Columbia University
RBC Collaboration

Dedication of the RBRC QCDOC Computer
Brookhaven National Laboratory
May 26, 2005

1. Making lattice QCD closer to the continuum case
2. Exact QCD algorithms
3. Choosing actions and parameters
4. Physics to do

RBRC-BNL-CU (RBC) Collaboration, May 2005

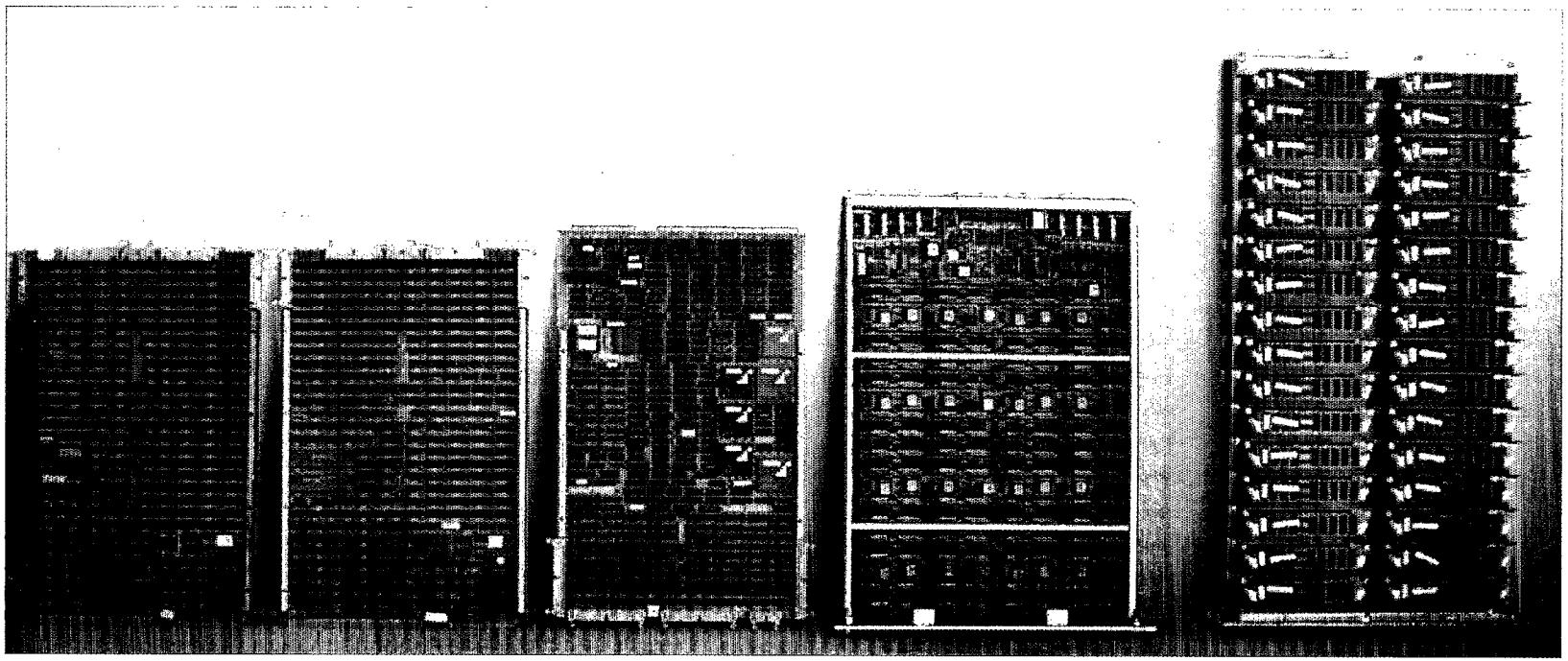
RBRC	BNL	Columbia
Blum, Tom (U Conn)	Creutz, Mike	Aubin, Christopher
Dawson, Chris	Jung, Chulwoo	Cheng, Michael
Doi, Takumi	Karsch, Frithjof	Christ, Norman
Hashimoto, Koichi	Petreczky, Peter	Cohen, Saul
Izubuchi, Taku (Kanazawa)	Petrov, Konstantin	Li, Sam
Kaneko, Takashi	Schmidt, Christian	Lin, Meifeng
Ohta, Shigemi (KEK)	Soni, Amarjit	Lin, HueyWen
Sasaki, Shoichi (KEK)		Loktik, Oleg
Yamazaki, Takeshi		Mawhinney, Robert

Recent Previous Members

Aoki, Yasumichi	Laiho, Jack	Clark, Michael
Nemoto, Yukio		Kim, Changhoan
Noaki, Jun-Ichi		Levkova, Ludmila
Orginos, Kostas		Yamaguchi, Azusa
Yamada, Norikazu		

Motherboards from Columbia University Computers

16-node	**64-node**	**256-node**	**QCDSP**	**QCDOC**
16 Mflops	16 Mflops	64 Mflops	3.2 Gflops	64 Gflops
1985	1987	1989	1998	2004
2-d mesh	2-d mesh	2-d mesh	4-d mesh	6-d mesh



QCD Description is Simple

- Jeopardy meets QCD, ala Wilczek
  - Category: numbers
  - Answer: 2 and 3
  - Question: What are the values for the 2 dimensionless numbers that determine most of low-energy QCD physics?
- QCD is an SU(3) gauge theory with 2 almost-massless quarks
- A complete description requires
  - 6 quark masses
  - A specification of the coupling constant at some scale
  - The value for the vacuum angle in QCD, θ
- Lorentz invariance and gauge invariance fix everything
- QCD has $SU_L(N_f) \otimes SU_R(N_f)$ symmetry broken only by quark masses.

QCD Near the Chiral Limit

- QCD chiral Lagrangian, $\mathcal{L}^{(2)}_{\rm QCD}$, with $\Sigma \equiv \exp\left[2i\phi^a t^a/f\right]$ and mass matrix M is:

$$\mathcal{L}^{(2)}_{\rm QCD} = \frac{f^2}{8}\mathrm{Tr}\left(\partial_\mu\Sigma\partial^\mu\Sigma^\dagger\right) + v\,\mathrm{Tr}\left[M\Sigma + (M\Sigma)^\dagger\right]$$

  where $M = \mathrm{diag}(m_u, m_d, m_s)$

- Chiral limit well described by a low-energy effective field theory.

Lattice QCD Description is More Complicated

Continuum	Lattice
Gauge invariance	Gauge invariance
Lorentz invariance	Hypercube invariance
N_f quarks	Generally more than N_f quarks
Chiral symmetry broken by quark masses	Chiral symmetry broken by quark masses and lattice effects
θ observed small	Numerical simulations with non-zero θ not currently possible
Renormalization of operators simplified by full symmetry and mass-independent schemes	Breaking symmetries makes renormalization of operators difficult to virtually impossible

Improved Fermion Actions

	$SU_V(N_f)$	$SU_A(N_f)$	$U_V(1)$	$U_A(1)$
Wilson clover	$\surd$	$\times$ $\mathcal{O}(a^2)$	$\surd$	$\times$ $\mathcal{O}(a^2)$
ASQTAD staggered	$\times$ $\mathcal{O}(a^2)$ discrete subgroup	$\times$ $\mathcal{O}(a^2)$ $U(1)$ subgroup	$\surd$	$\times$ $\mathcal{O}(a^2)$
	($4N_f$ flavors on lattice from fermion doubling)			
domain wall	$\surd$	$\surd$ $\mathcal{O}\left(ae^{-\alpha L_s}\right)$	$\surd$	$\times$ $\mathcal{O}\left(ae^{-\alpha L_s}\right)$
	(for modes bound to 4-d walls)			

- Wilson clover fermions markedly improves chiral symmetry.
- ASQTAD staggered fermions have much smaller $\mathcal{O}(a^2)$ flavor breaking.
- DWF also gives off-shell improvement.

Domain Wall Fermion Operator

- Introduce extra dimension, labeled by s

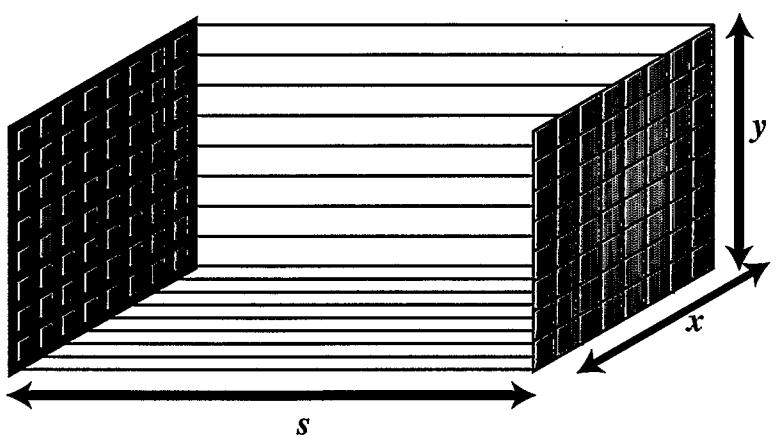
$$D_{x,s;x',s'} = \delta_{s,s'} D^{\parallel}_{x,x'} + \delta_{x,x'} D^{\perp}_{s,s'}$$

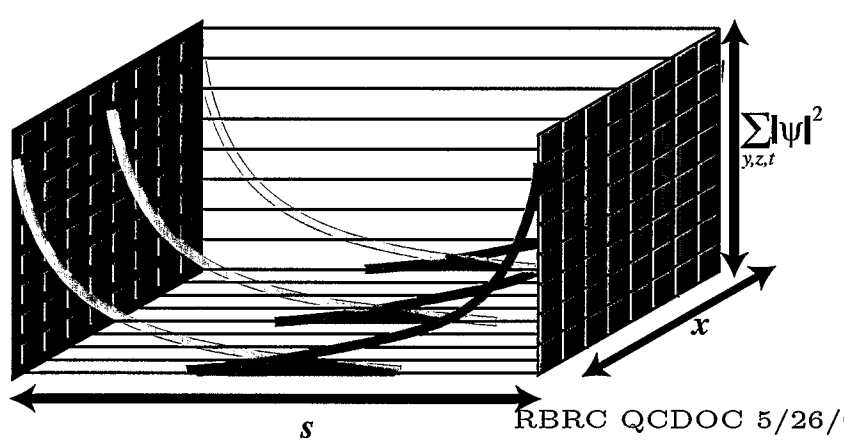
- $D^{\parallel}_{x,x'}$ is a Wilson Dirac operator with an opposite sign for the mass term.

$$D^{\parallel}_{x,x'} = \frac{1}{2}\sum_{\mu=1}^{4}\left[(1-\gamma_\mu)U_{x,\mu}\delta_{x+\hat{\mu},x'} + (1+\gamma_\mu)U^{\dagger}_{x',\mu}\delta_{x-\hat{\mu},x'}\right] + (M_5 - 4)\delta_{x,x'}$$

- $D^{\perp}_{s,s'}$ couples points in fifth dimension, distinguishing left and right handed fermions

$$\frac{1}{2}\left[(1-\gamma_5)\delta_{s+1,s'}+(1+\gamma_5)\delta_{s-1,s'}-2\delta_{s,s'}\right]-\frac{m_f}{2}\left[(1-\gamma_5)\delta_{s,L_s-1}\delta_{0,s'}+(1+\gamma_5)\delta_{s,0}\delta_{L_s-1,s'}\right]$$





Residual Chiral Symmetry Breaking for DWF

- Consider introducing in action a $SU(N_f)$ matrix Ω through term at $l \equiv L_s/2$

$$-\sum_x \left\{ \overline{\Psi}_{x,l-1} P_L \left(\Omega^\dagger - 1\right) \Psi_{x,l} + \overline{\Psi}_{x,l} P_R \left(\Omega - 1\right) \Psi_{x,l-1} \right\} \qquad \Omega \to U_R \, \Omega \, U_L^\dagger$$

- Conventional DWF recovered by $\Omega \to 1$
- QCD chiral Lagrangian $\mathcal{L}^{(2)}_{\rm QCD}$, with $\Sigma \equiv \exp\left[2i\phi^a t^a/f\right]$ and mass matrix M is:

$$\frac{f^2}{8} \mathrm{Tr}\left(\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right) + v \, \mathrm{Tr}\left[M\Sigma + (M\Sigma)^\dagger\right] + v' \, \mathrm{Tr}\left[\Omega\Sigma + (\Omega\Sigma)^\dagger\right] + v'' \, \mathrm{Tr}\left[\Omega M^\dagger + \Omega^\dagger M\right]$$

- For modes bound to walls of fifth dimension, Ω enters Green's functions as

$$\Omega e^{-\alpha L_s} \quad \Rightarrow \quad v', v'' \sim e^{-\alpha L_s}$$

- Chiral condensate from differentiating w.r.t. mass, m_π^2 from expanding Σ

$$-\langle \overline{q} q \rangle (m_f = 0, L_s) \sim v + v'' \qquad v = \frac{f^2 m_{\pi^+}^2}{4(m_u + m_d + 2m_{\rm res})} \qquad m_{\rm res} \equiv v'/v$$

Chiral Perturbation Theory Comparisons

- The chiral Lagrangian at the next order contains new low-energy constants for continuum QCD, denoted by L_i for $i = 1$ to 10.
- For m_π^2, 2 terms are needed

$$(2L_6 - L_4) \qquad\qquad (2L_8 - L_5)$$

- For DWF, at finite lattice spacing, the same terms are needed, although now one has $L_i(a) = L_i + \mathcal{O}(a^2)$.
- For DWF, to fit partially quenched data for $m_{\rm PS}^2$ and $f_{\rm PS}$ to NLO one needs 6 parameters and the known value for $m_{\rm res}$.
- For ASQTAD staggered, one needs 10 parameters. The additional 4 parameters come from lattice terms which break symmetries.
- Fewer parameters for DWF should give better control over the chiral limit.

Lattice QCD Algorithms

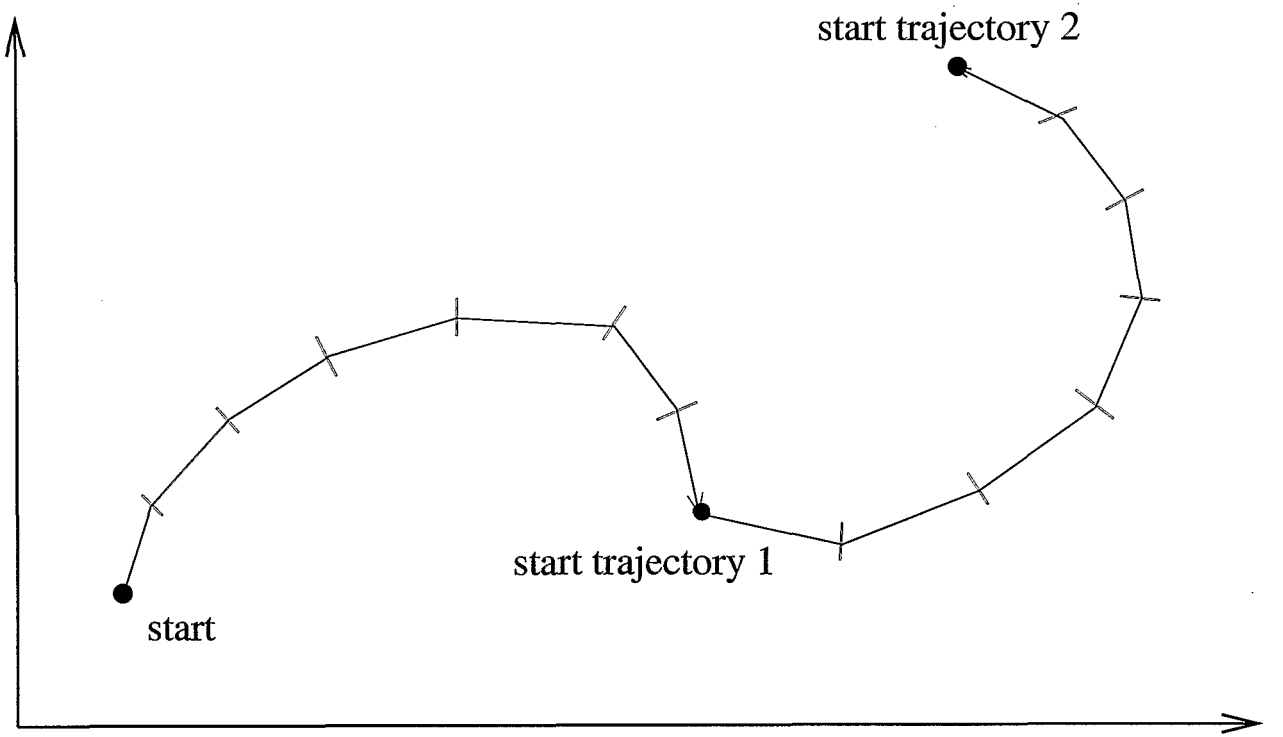
- Fermion determinant represented by "pseudo fermion" fields

$$
\begin{aligned}
Z &= \int [dU]\,[d\psi]\,[d\bar{\psi}]\,\exp\left\{-\beta S_g + \bar{\psi}(\not{D}+m)\psi\right\} = \int [dU]\,\det(\not{D}+m)\exp\left\{-\beta S_g\right\} \\
&= \int [dU]\,[d\phi^*][d\phi]\exp\left\{-\beta S_g + \phi^*(\not{D}+m)^{-1}\phi\right\} \\
&= \int [dU]\,[d\Pi]\,[d\phi^*][d\phi]\exp\left\{-\Pi^2 - \beta S_g + \phi^*(\not{D}+m)^{-1}\phi\right\} \\
&= \int [dU]\,[d\Pi]\,[d\phi^*][d\phi]\exp\left\{-\Pi^2 - \beta S_g + \phi^*[(\not{D}+m)(\not{D}^\dagger+m)]^{-1/2}\phi\right\}
\end{aligned}
$$

- Since $\det(\not{D}+m)$ is positive definite, it equals $\det[(\not{D}+m)(\not{D}^\dagger+m)]^{-1/2}$.
- All eigenvalues of $(\not{D}+m)(\not{D}^\dagger+m)$ are positive, which yields a positive definite probability weight for a single quark flavor.
- The Rational Hybrid Monte Carlo algorithm of Clark and Kennedy (UKQCD) is an exact algorithm that utilizes the square root.
- Therefore, 2+1 flavor DWF QCD can be simulated with an exact algorithm.

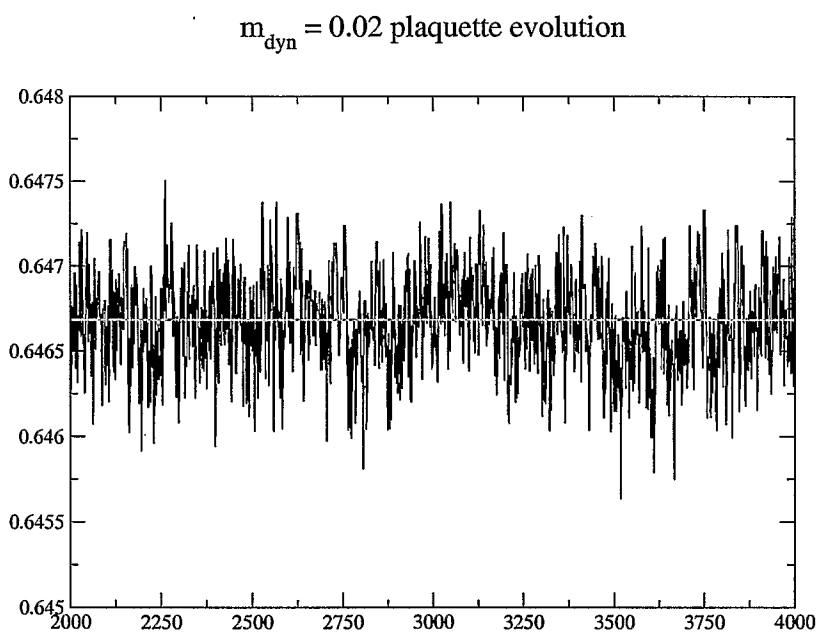
Moving Through the Phase Space of QCD

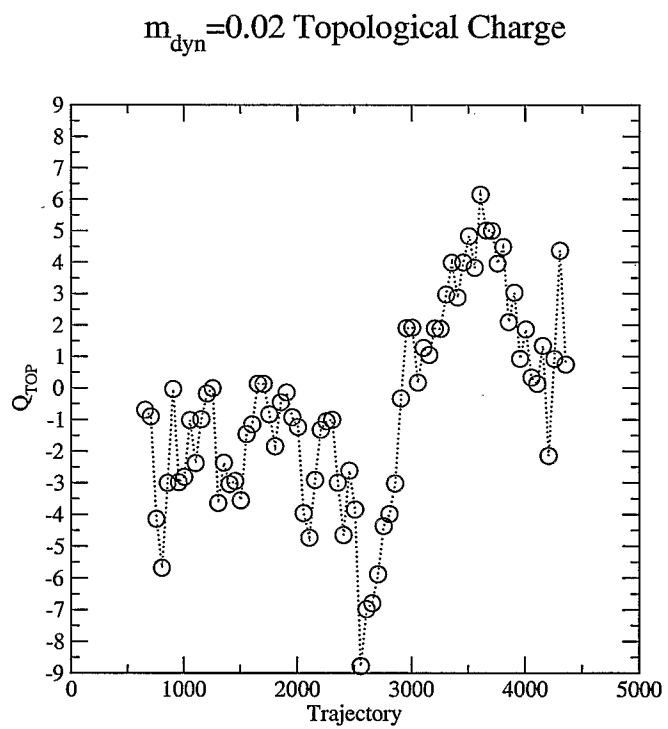
- RHMC implemented in CPS software for QCDOC
- Motion through phase space occurs in small steps
- What is efficiency for decorrelating gluon configurations?



Evolution of $N_f = 2$ Lattices with $m_{\text{dyn}} \approx m_{\text{strange}}/2$

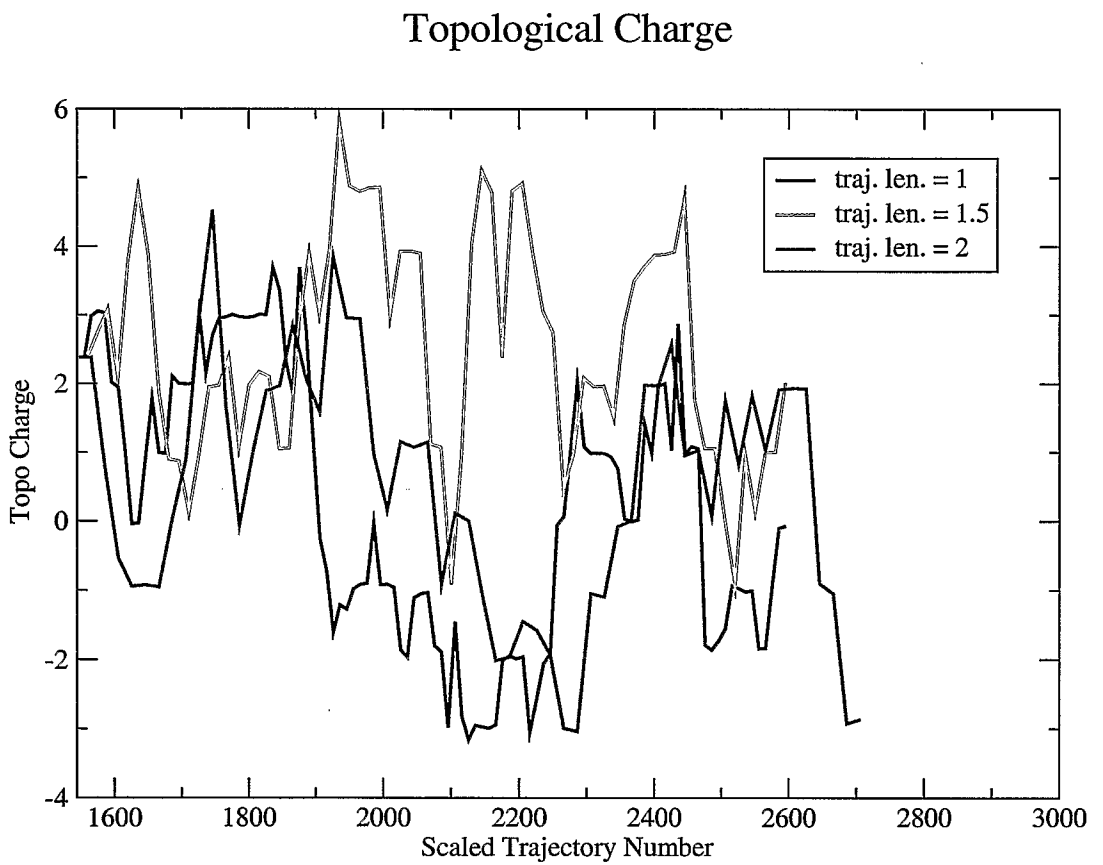
- Long autocorrelation times can yield underestimation of errors
- Topological fluctuations correctly weighted for DWF, if evolutions are long enough to sample phase space.





Evolution of $N_f = 3$ Lattices with $m_{\text{dyn}} \approx m_{\text{strange}}$

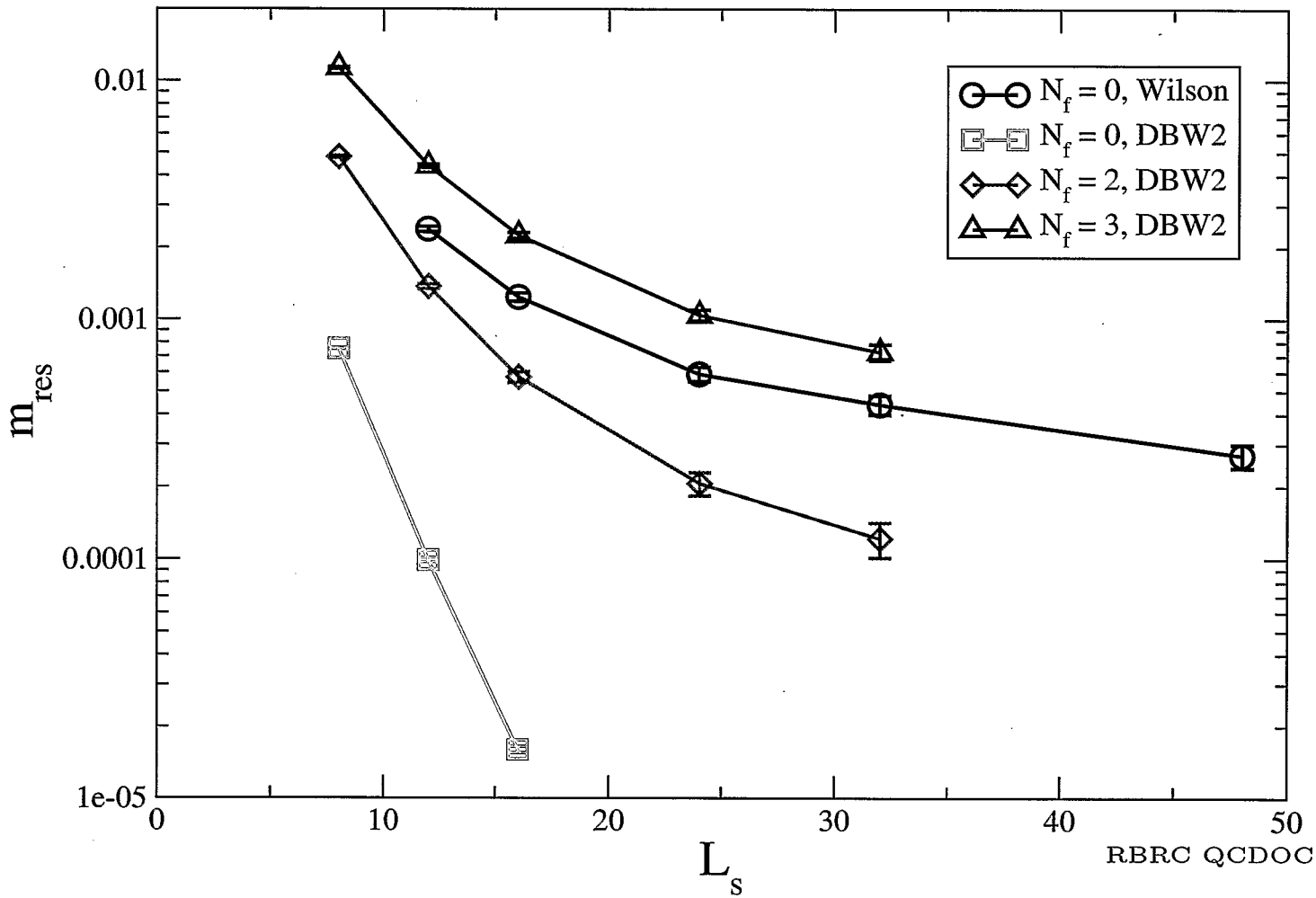
- Check correlation time versus length of trajectory with RHMC.
- 10 days of running on 3, 1024 node QCDOC racks (Meifeng Lin).



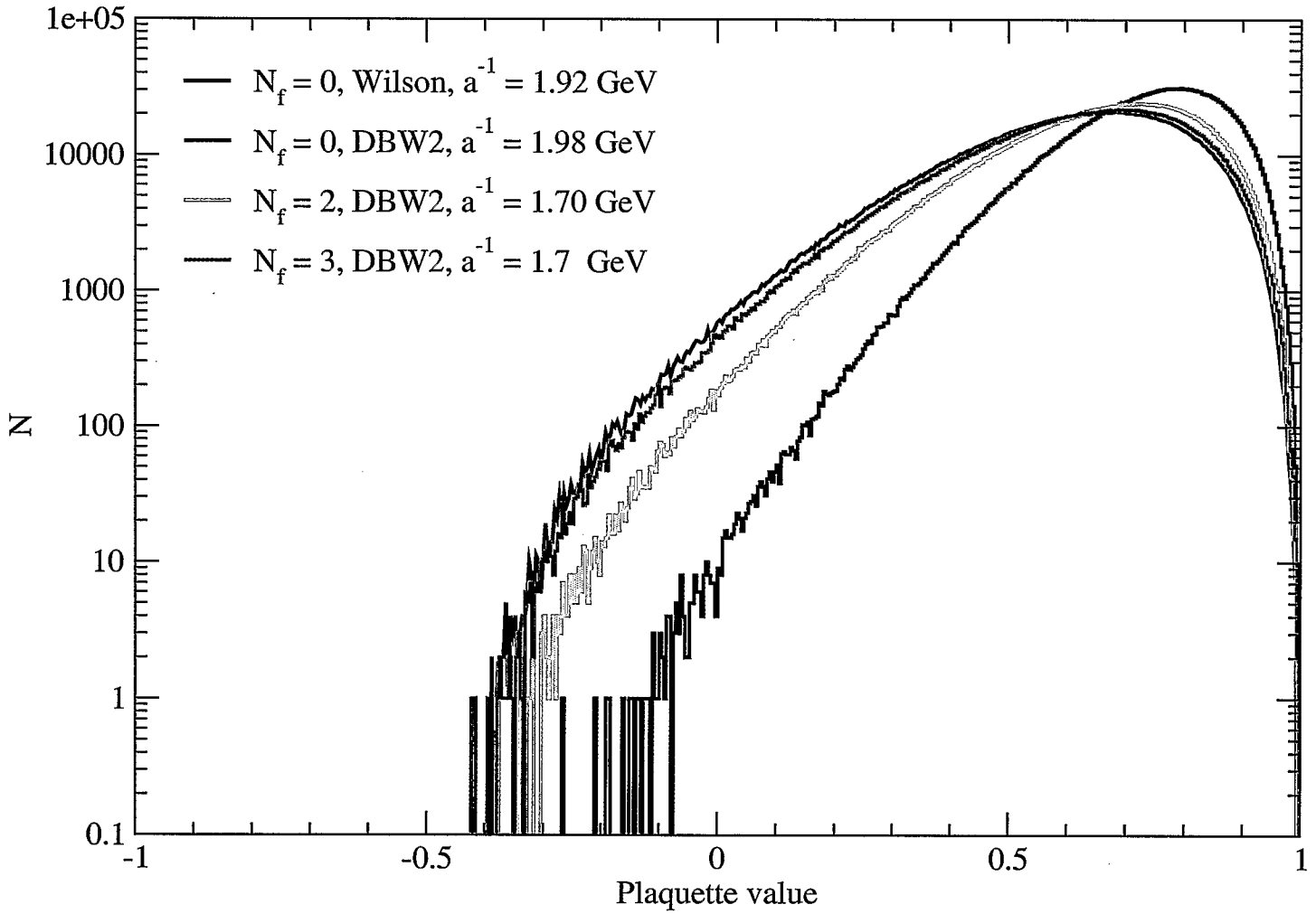
m_{res} versus L_s for $N_f = 0, 2$ and 3

Compare gauge actions composed of plaquette and rectangle terms.

$$S_g = (\beta/3)\left\{(1-8c_1)\sum \mathrm{Re}(\mathrm{Tr}U_P) + c_1 \sum \mathrm{Re}(\mathrm{Tr}U_R)\right\}$$

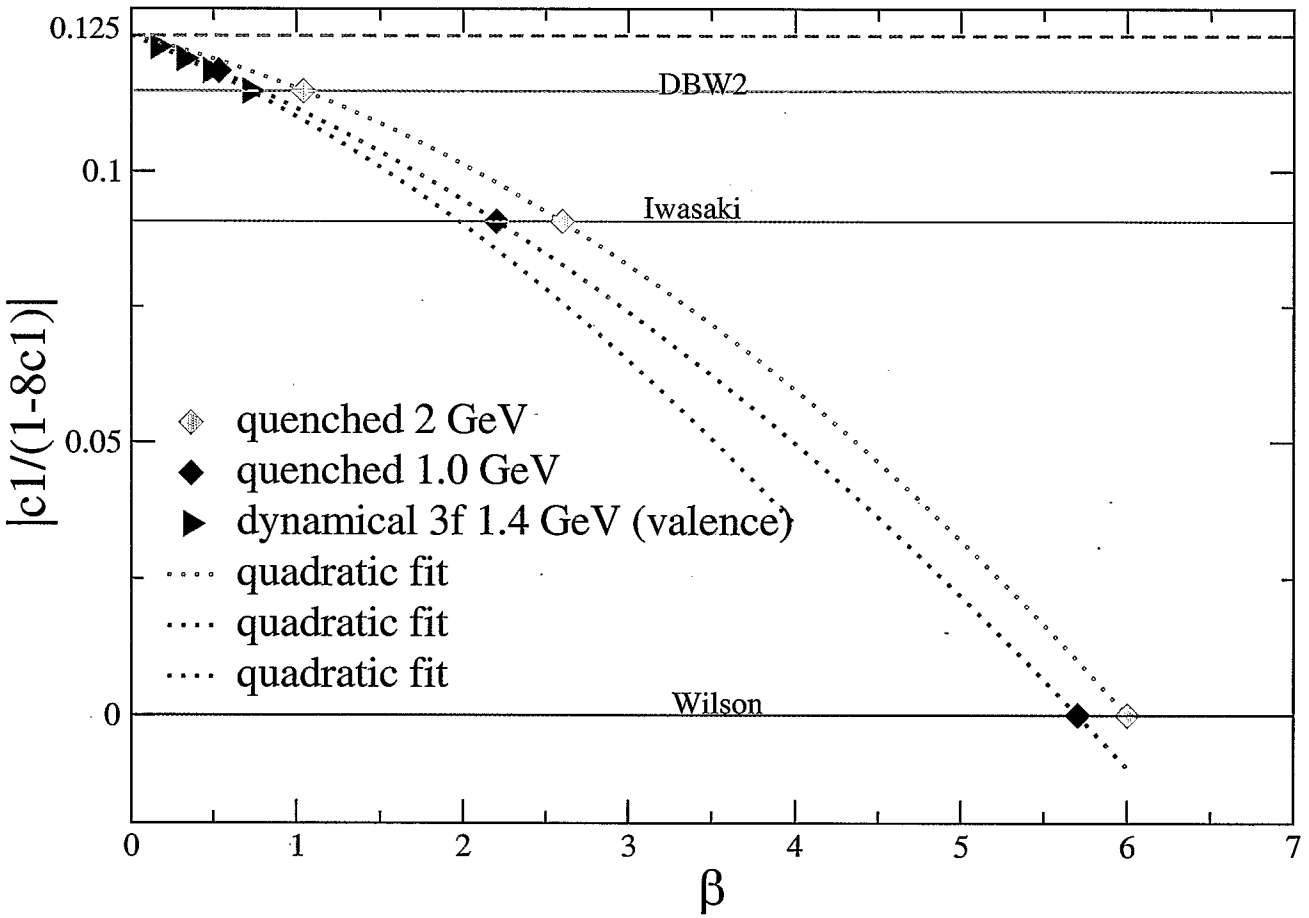


Plaquette Distributions at $a^{-1} \approx 2$ GeV

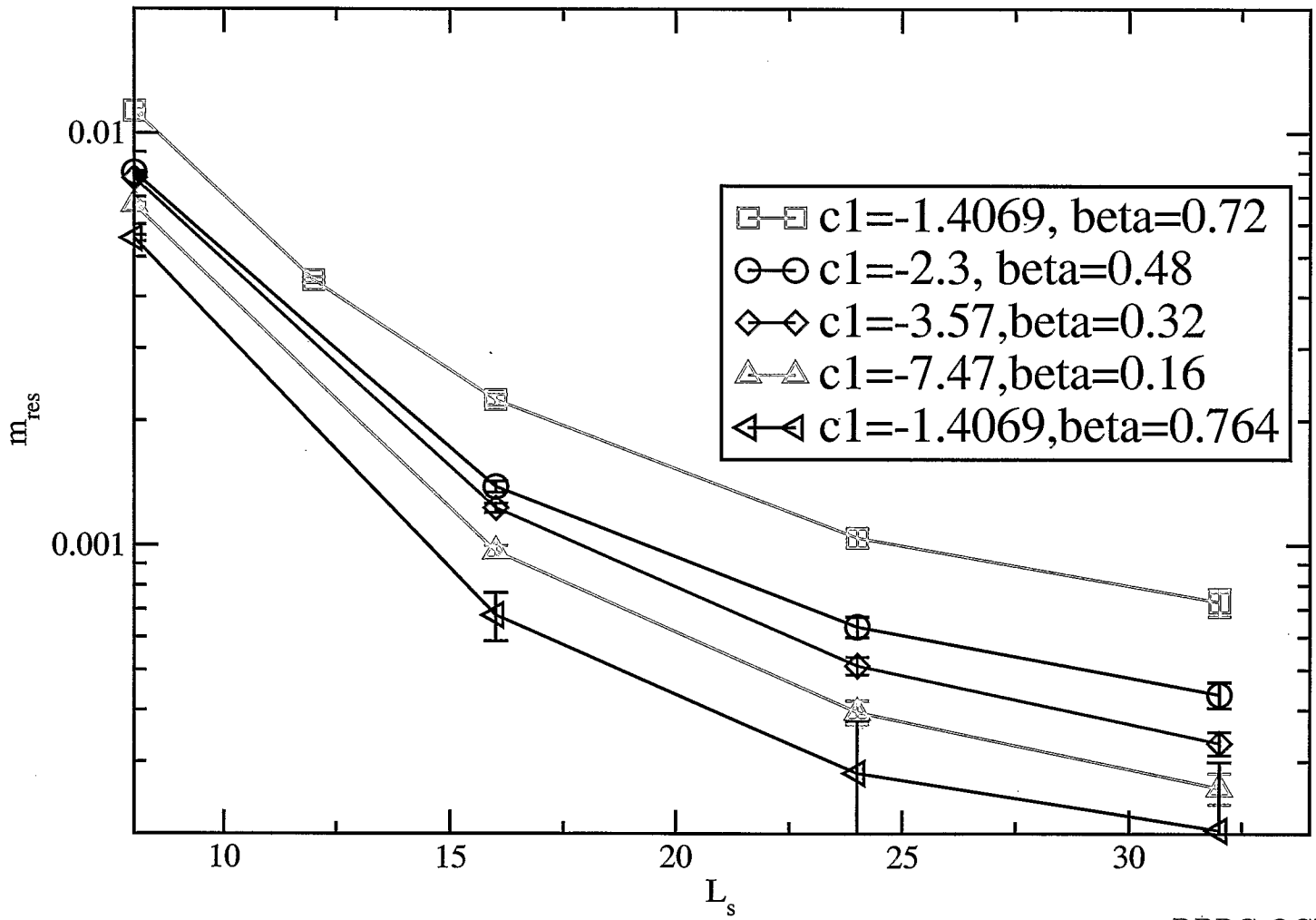


Full QCD with Plaquette plus Rectangle Actions

- Find lines with constant lattice spacing, a.
- Compare residual mass at fixed a.



m_{res} for Plaquette plus Rectangle Actions



UKQCD Collaborators on DWF Calculations, May 2005

UKQCD

Antonio, D. J.
Bowler, K. C.
Boyle, P. A.
Clark, M. A.
Joo, B.
Kennedy, A. D.
Kenway, R. D.
Maynard, C. M.
Tweedie, R. J.
Yamaguchi, A.

Physics Program -Two Primary Calculations

- 2+1 flavor $T = 0$ DWF using Rational HMC (RHMC) (≈ 0.6 of QCDOC)
  - Rectangle tests on $16^3 \times 32 \times 12$ - completed with $L_s = 8$
    - ≈ 1 month, done mostly during bring-up. 2 months
    - Can $m_{\rm res}$ be small for $a^{-1} \approx 1.3$ GeV? Yes.
  - If so, run with $16^3 \times 64 \times 16$, $a^{-1} \approx 1.3$ GeV. 2.5 fermi physical volume.
  - Follow with $24^3 \times 64 \times 16$ with $a^{-1} \approx 1.8$ GeV. 2.6 fm box. Ready to start
  - 10,000 trajectories on $24^3 \times 64 \times 16$ $m_u = m_d \approx m_s/5$ takes 1/2 year on 10k nodes. (2× uncertainty)
  - Studies above done with UKQCD collaboration. Are collaborating on lattice generation and physics.
- 2+1 flavor thermo - staggered (P4 or ASQTAD). (≈ 0.3 of QCDOC)
  - P4 has better approach to Stefan-Boltzman limit (Heller, Karsch).
  - Zero temperature scaling study of P4 needed.
  - Do state of art determination of T_c with P4.
  - Continue to investigate thermodynamics with DWF.

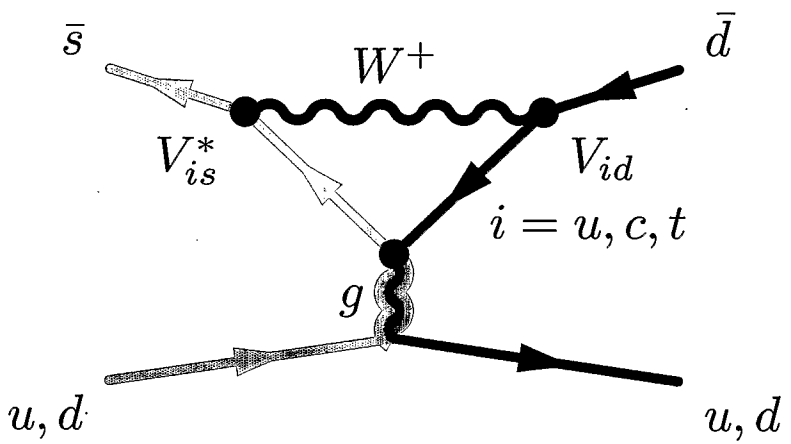
CP Violation in the Standard Model

Imaginary part for $K \to \pi\pi$ amplitudes comes from Cabbibo-Kobayashi-Maskawa (CKM) matrix, which relates quark electroweak eigenstates and quark mass eigenstates

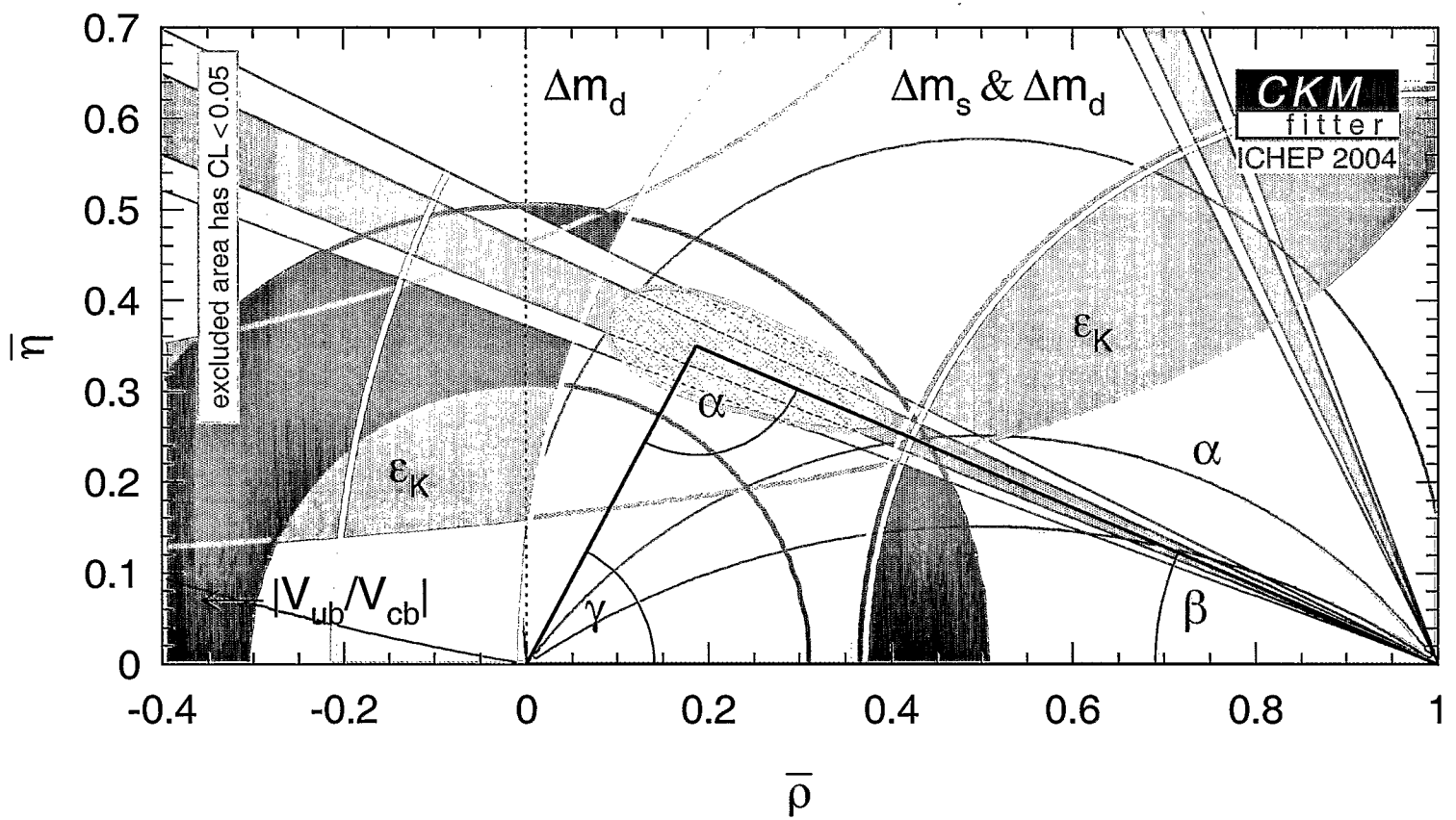
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{us} is essentially $\sin\theta_C$, where θ_C is the Cabbibo angle.

V_{ub} and V_{td} are complex. V_{td} effects $K \to \pi\pi$ through "penguin" diagrams.



Unitarity Triangle



CP Violation in the Kaon System

- Two amplitudes determine ϵ and ϵ'

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon + \epsilon' \qquad \eta_{00} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

- SM: $\overline{K}^0 - K^0$ mixing via $Q^{(\Delta S=2)} = (\bar{s}_\alpha d_\alpha)_{V-A}\,(\bar{s}_\beta d_\beta)_{V-A}$ defines B_K as;

$$\langle \overline{K}^0 | Q^{(\Delta S=2)}(\mu) | K^0 | \rangle \equiv \frac{8}{3} B_K(\mu) f_K^2 m_K^2$$

- RGI parameter $\hat{B}_K \equiv B_K(\mu)\left[\alpha_s^{(3)}(\mu)\right]^{-2/9}\left[1 + \frac{\alpha_s^{(3)}(\mu)}{4\pi} J_3\right]$ relates SM and ϵ

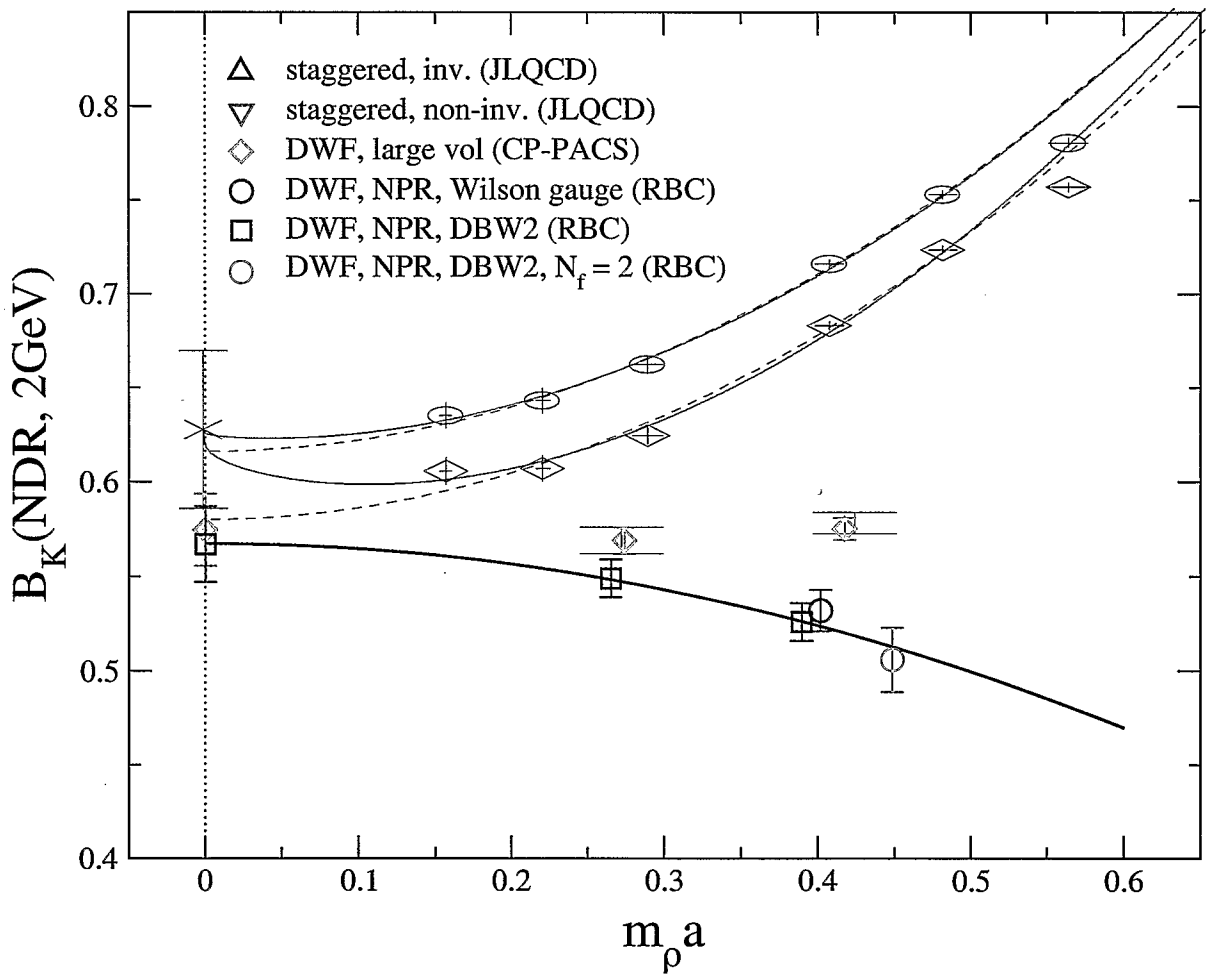
$$\epsilon = \hat{B}_K \,\mathrm{Im}\lambda_t \frac{G_F^2 f_K^2 m_K M_W^2}{12\sqrt{2}\pi^2 \Delta M_K} \left\{\mathrm{Re}\lambda_c \left[\eta_1 S_0(x_c) - \eta_3 S_0(x_c, x_t)\right] - \mathrm{Re}\lambda_t\, \eta_2 S_0(x_t)\right\} \exp(i\pi/4)$$

- Defining $A(K^0 \to \pi\pi(I)) \equiv A_I e^{(i\delta_I)}$, $P_2 \equiv \mathrm{Im}A_2/\mathrm{ReA}_2$, $P_0 \equiv \mathrm{Im}A_0/\mathrm{ReA}_0$:

$$\epsilon' = \frac{i e^{i(\delta_2 - \delta_0)}}{\sqrt{2}} \left(\frac{\mathrm{Re}\, A_2}{\mathrm{Re}\, A_0}\right)\left(\frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_2} - \frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0}\right) \qquad w \equiv \frac{\mathrm{Re}\, A_0}{\mathrm{Re}\, A_2} \approx 22$$

The Kaon B Parameter, $B_K^{\overline{\rm MS}}(\mu = 2\ {\rm GeV})$

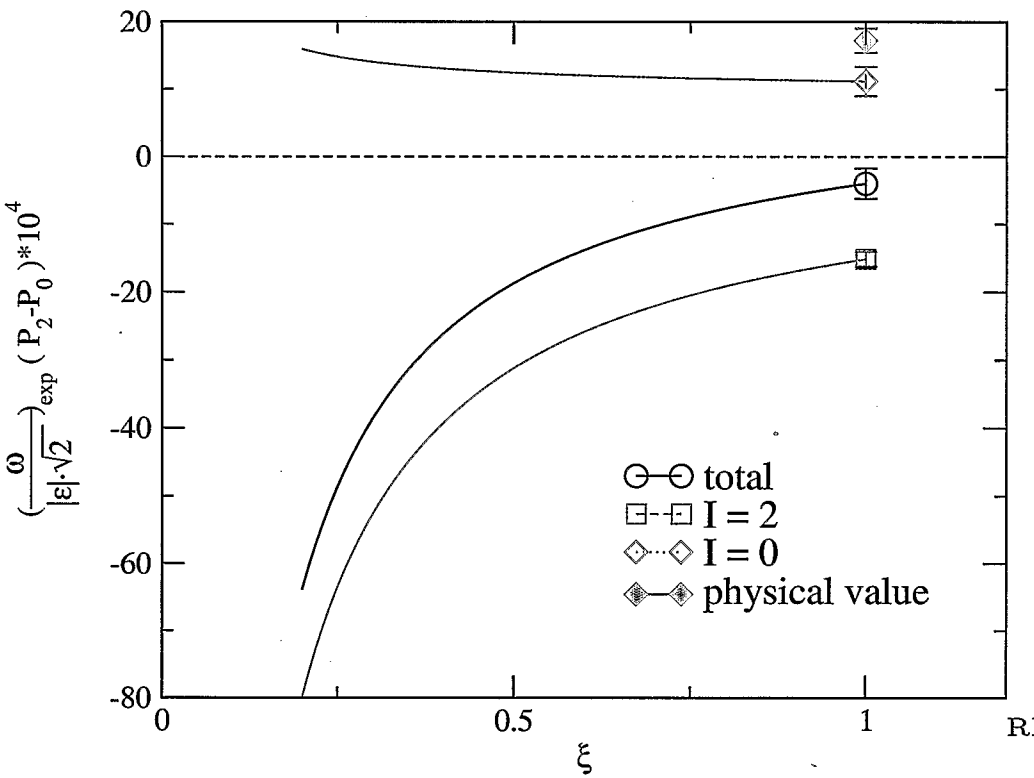
	quenched $a \to 0$			dyn. $a^{-1} = 1.7$ GeV
PDG	JLQCD (stag)	CP-PACS (DWF)	RBC (DWF)	RBC (2f DWF)
0.65 ± 0.15	0.628 ± 0.042	0.575 ± 0.019	0.570 ± 0.020	0.492 ± 0.018



ϵ'/ϵ from Quenched QCD and χPT

- Dominant contribution: Q_2 to Re A_2 and Re A_0, Q_6 to Im A_0, Q_8 to Im A_2.
- Contributions depend on renormalization scale GeV
- Schematic formula for ϵ'/ϵ

$$\mathrm{Re}(\epsilon'/\epsilon) \approx \left(\frac{\omega}{\sqrt{2}|\epsilon|}\right)_{\exp} \left\{ \left[\frac{\alpha_W \alpha_8}{\alpha_W \alpha_8 + \alpha_2 m_{K^0}^2 \xi}\right]^{(3/2)} - \left[\frac{\alpha_W \alpha_8 + \alpha_S \alpha_6 m_{K^0}^2 \xi}{\alpha_W \alpha_8 + \alpha_2 m_{K^0}^2 \xi}\right]^{(1/2)} \right\}$$



Estimating NLO ϵ'/ϵ from Quenched QCD and χPT

- Calculation determines all $K \to \pi\pi$ amplitudes to lowest order.
- ϵ'/ϵ not determined to consistent order in χPT
- Need NLO for $\Delta I = 3/2$. For physically relevant strange quark masses have:

$$\mathrm{Re}(\epsilon'/\epsilon) \approx \left(\frac{\omega}{\sqrt{2}|\epsilon|}\right)_{\mathrm{exp}} \left\{ \left[\frac{\alpha_{\mathrm{W}}\alpha_8(1 + c^{(8,8)}m_q + \mathrm{logs})}{\alpha_2 m_{K^0}^2 \xi(1 + c^{(27,1)}m_q + \mathrm{logs})}\right]^{(3/2)} - \left[\frac{\alpha_{\mathrm{S}}\alpha_6}{\alpha_2}\right]^{(1/2)} \right\}$$

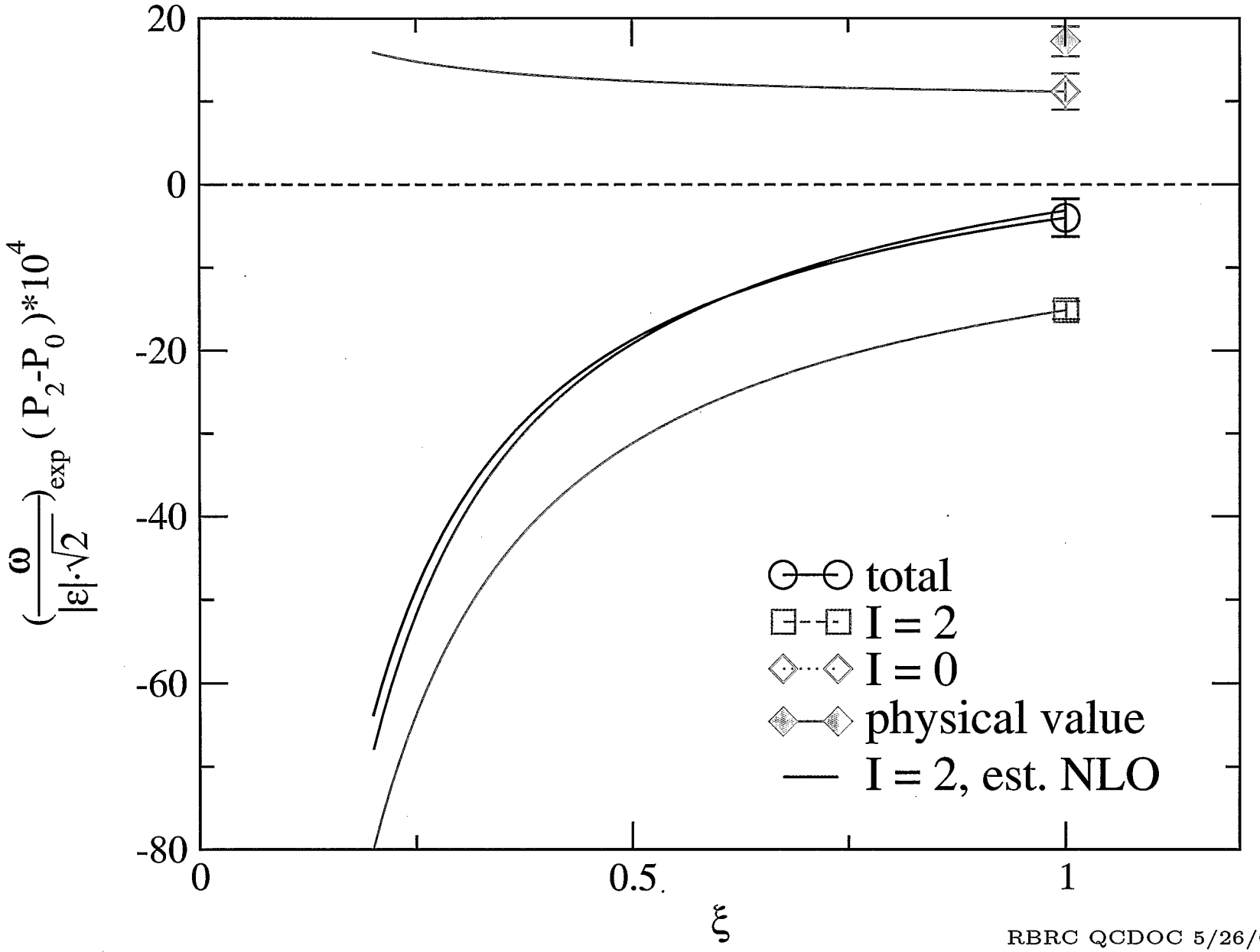
- For $K \to \pi$ matrix elements, log and m_q^2 corrections at m_{strange} to $Q_2^{(3/2)}$ similar to leading m_q term. Barring unexpected cancellation, $c^{(27,1)}m_q$ should be a considerable positive contribution to ϵ'/ϵ.

$$\mathrm{Re}(\epsilon'/\epsilon) \approx \left(\frac{\omega}{\sqrt{2}|\epsilon|}\right)_{\mathrm{exp}} \left\{ \left[\frac{\alpha_{\mathrm{W}}\alpha_8}{\alpha_2 m_{K^0}^2}\left(1 - \mathcal{O}(c^{(27,1)}m_q)\right)\right]^{(3/2)} - \left[\frac{\alpha_{\mathrm{S}}\alpha_6}{\alpha_2}\right]^{(1/2)} \right\}$$

- Putting in values from quenched simulation gives

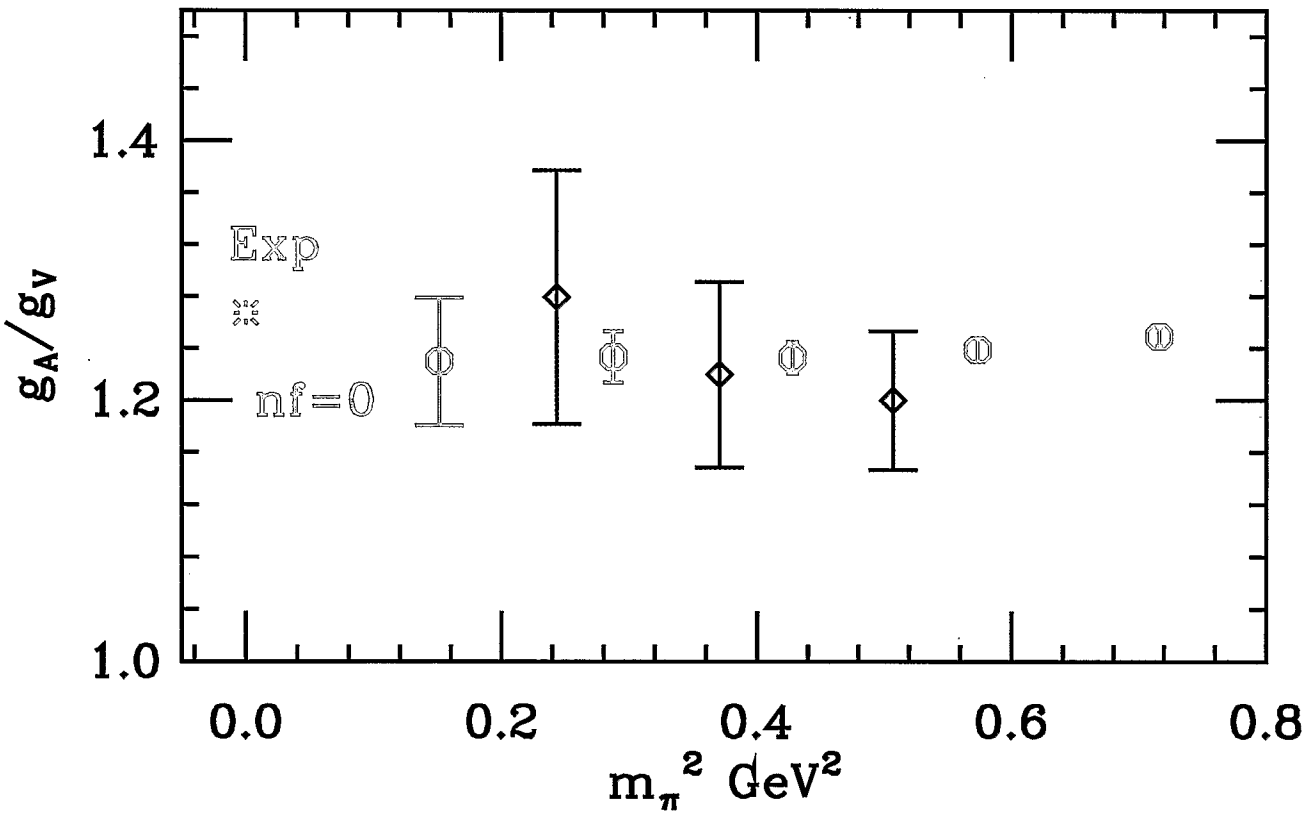
$$\mathrm{Re}(\epsilon'/\epsilon) \approx -13 \times 10^{-4}(1 - \mathcal{O}(0.95)) - (-14 \times 10^{-4})$$

Graph of Estimated NLO ϵ'/ϵ from Quenched QCD and χPT



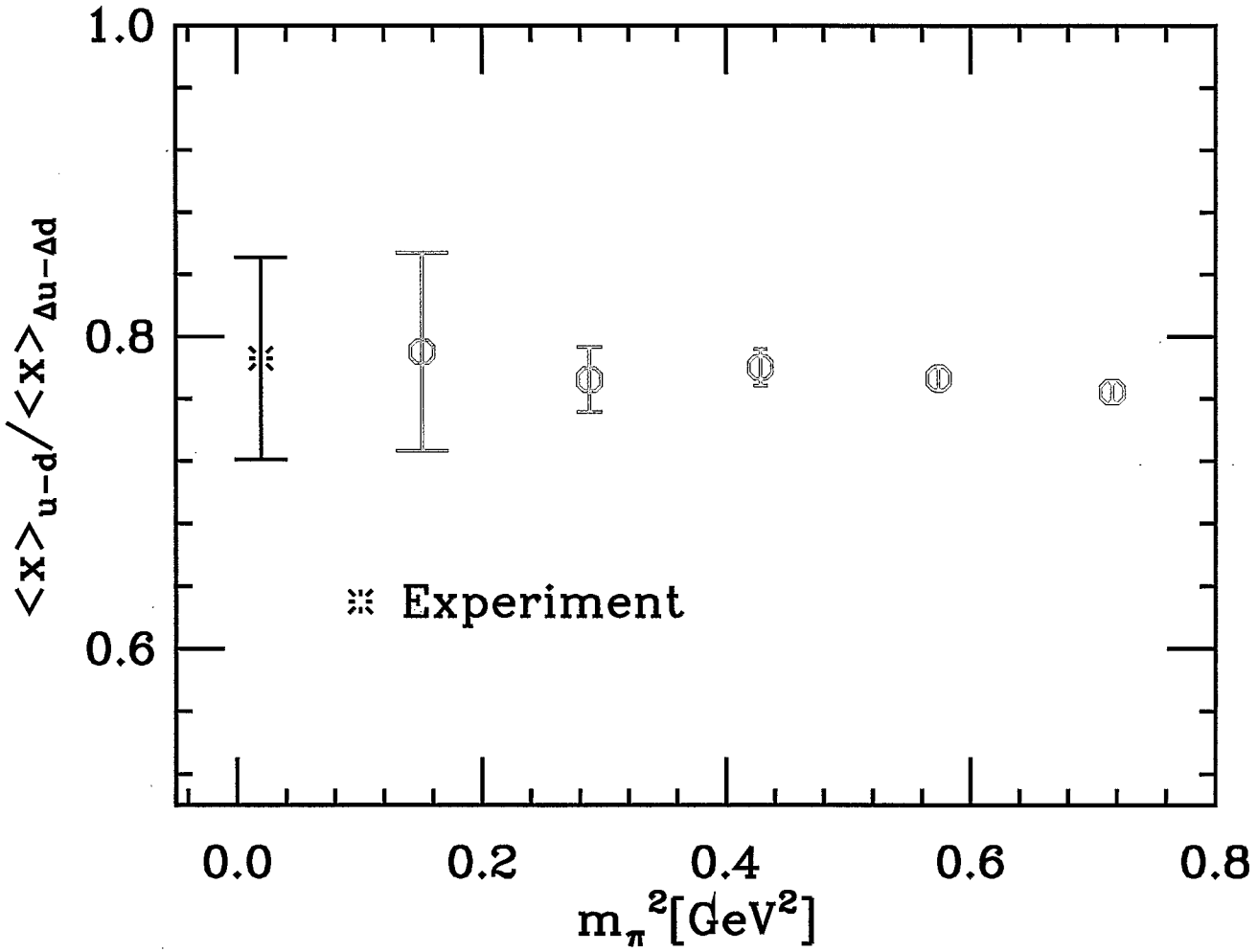
Nucleon g_A

- Quenched and full QCD simulations of g_A
- Larger volumes for dynamical calculations useful.



Quenched Nucleon Structure Functions

- Ratio of flavor non-singlet momentum fraction to the helicity distribution
- Chiral limit appears less mass dependent for ratio



IBM BlueGene/L

3-dimensional mesh architecture, similar to QCDSP and QCDOC

65,000 node, 360 TFlops installation at Livermore in early 2005

Al Gara is primary architect.

Conclusions and Outlook

- QCDOC provides powerful resource for Lattice QCD.
- 2 and 3 flavor dynamical DWF simulations on QCDSP show DWF working.
- 2+1 flavor DWF lattices allow calculations of weak matrix elements, nucleon properties and heavy quark physics.
- For B_K, no open theoretical issues. Precision requires careful control of systematics and good statistics.
- Lattices generated in next 6 months provide platform for nucleon, heavy quark, and kaon physics.
- Thermodynamics with improved staggered quarks now.
- Some QCDOC time for new ideas!

PRESS RELEASES

The Bulletin

BROOKHAVEN NATIONAL LABORATORY

Vol. 59 - No. 20 June 10, 2005

A Passion for Synchrotron Science

News from the 2005 NSLS Annual Users' Meeting

Fierce enthusiasm for the science performed at the NSLS and increasing hope that NSLS-II will become a reality was the message of the speakers at the main session of the 2005 National Synchrotron Light Source (NSLS) Annual Users' Meeting, held on Tuesday, May 24.

The incoming chair of the NSLS Users' Executive Committee (UEC), Peter Stephens of Stony Brook University, welcomed the nearly 400 attendees and then opened the stage to BNL Director Praveen Chaudhari, who gave a brief "BNL Update" talk and praised many users for their work to support NSLS-II.

"The struggle to get NSLS-II is just beginning," Chaudhari said. "But once the machine is built, you'll have the best machine in the world."

Roger Stoutenburgh 0429203

Speakers at the meeting included: (from left) Praveen Chaudhari, BNL; Patricia Dehmer, DOE; and Steven Dierker, BNL.

Chaudhari then introduced Patricia Dehmer, head of the Office of Basic Energy Sciences within the DOE Office of Science. Dehmer, who plays an important role in efforts to move NSLS-II forward, discussed the status of the proposed facility.

"NSLS-II will undoubtedly be the world's finest synchrotron; it will be a stunning facility," she said. She added that she and Office of Science Director Raymond Orbach will soon present the Laboratory's NSLS-II proposal to Deputy Secretary of Energy Clay Sell for his approval.

"This Laboratory has a wonderful history of constructing and operating major user facilities," she concluded. "NSLS-II will take that tradition and move it into the future."

NSLS Chairman Steven Dierker then gave an update

(continued on page 2)

Roger Stoutenburgh 0429203

The NSLS Users' Executive Committee (UEC) Chair, Peter Stephens (left) of Stony Brook University, presents the 2005 UEC Community Service Award to Tony Lenhard, NSLS Department.

RIKEN-BNL Research Center Dedicates New Supercomputer for Physics Research

Roger Stoutenburgh 0479203

In front of the new supercomputer, QCDOC, are: (from left) Praveen Chaudhari, BNL, Yoshiharu Doi, RIKEN, Norman Christ, Columbia University, Edward McFadden, BNL; T.D. Lee, Columbia University; and Koji Kaya, RIKEN; (front, from left) Satoshi Ozaki, BNL, and Nicholas Samios, BNL/RIKEN BNL Research Center.

Roger Stoutenburgh 0479203

At the May 26 dedication of the RIKEN BNL Research Center (RBRC) superconductor held in the BNL Physics Department are: (from left) Nicholas Samios, BNL/RBRC; T.D. Lee, Columbia University; Koji Kaya, RIKEN; Yoshiharu Doi, RIKEN; Satoshi Ozaki, BNL; Ryutaro Himeno, RIKEN; and Praveen Chaudhari, BNL.

A new supercomputer — the RIKEN BNL Research Center (RBRC) supercomputer — was unveiled at a dedication ceremony on May 26 at BNL attended by physicists from around the world. Called QCDOC for quantum chromodynamics on a chip, it was designed and built by BNL, Columbia University, IBM, RBRC, and the University of Edinburgh. The computer has 10 teraflops of peak computing power, which makes it capable of performing 10 trillion arithmetic calculations per second, with sustained speeds of five teraflops. The $5-million computer took three years to design and build and is funded by RIKEN — The Institute of Physical & Chemical Research — in Japan, with infrastructure support from DOE's Office of Science.

Satoshi Ozaki, Special Assistant to the Laboratory Director for Accelerator Projects, and chair of the event, opened the dedication ceremony, welcoming the audience of about 100 people to the "very happy occasion."

Laboratory Director Praveen Chaudhari, in his welcoming remarks, gave a brief history of the evolution of the RIKEN-BNL partnership and discussed the capabilities of QCDOC, a "special purpose" computer.

Addressing the audience, Nicholas Samios, RBRC Director, said that QCDOC is about 15 times more powerful than the previous supercomputer installed at BNL in 1998 and called QCDSP for quantum chromodynamics on digital signal processors.

"We have gone from 0.6 teraflops to 10 teraflops in seven years. I'm looking forward to another celebration in five years to dedicate a computer with a factor of 20 to 100 increase in computing capability with relatively small power requirements and small footprints," he said.

Samios and Yoshihari Doi, Executive Director of RIKEN, with RBRC's first Director, Nobel Prize winner Tsung-Dao Lee of Columbia University, all look forward to a new era of precise calculations that might, according to Doi, "open up completely new possibilities in search for the origin of the universe."

QCDOC will be used for physics research for 90 percent of its operating time. With the help of the computer, physicists hope to determine the properties of a state of matter currently under intense study at BNL's premiere accelerator, the Relativistic Heavy Ion Collider. During the remaining 10 percent of operating time, researchers will use the supercomputer to pursue scientific projects in a variety of fields, including biology and materials science.

Among those attending the dedication ceremony was Edward McFadden, Manager of the Brookhaven Scientific Computing Facility in the Information Technology Division (ITD). ITD built QCDOC, tested it, and will maintain it. Besides acknowl

(continued on page 2)

QCDOC in Action

Taking up only 100 square feet of floor space compared to a football field or more for some commercial supercomputers, QCDOC is installed at BNL in the RIKEN-BNL Research Center, a physics research center formed by RIKEN and BNL in 1997. QCDOC achieves its ultra-fast speed by harnessing the power of 12,288 individual computers, each with its own memory and an extremely fast interprocessor communication network. Each processor is constructed on a single silicon chip, so the supercomputer is essentially 12,288 interconnected chips. This simple design leads to a low power requirement of about 100 kilowatts compared to the many megawatts typical of most commercial supercomputers.

One of the major discoveries emerging from the Relativistic Heavy Ion Collider is the creation of a form of hot, dense (10 to 30 times denser than a nucleon)

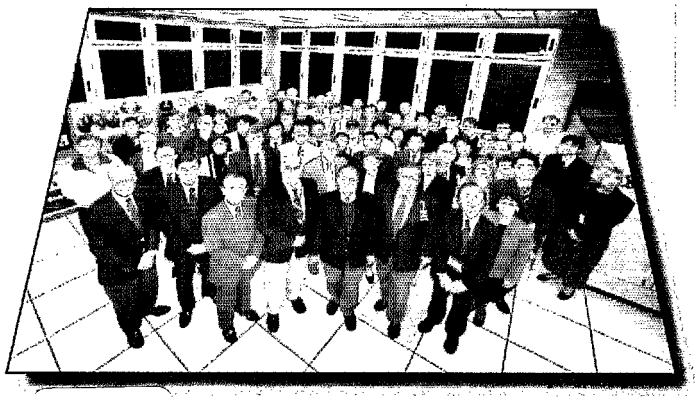
(continued on page 2)

2005 RHIC & AGS Annual Users' Meeting

June 20-24

The Relativistic Heavy Ion Collider (RHIC) & Alternating Gradient Synchrotron (AGS) Annual Users' Meeting will include three days of topical workshops followed by two days of plenary sessions on Thursday, June 23, and Friday, June 24. The plenary program will include the latest results from RHIC, AGS, and the NASA Space Radiation Laboratory; reports from Washington, elections, awards, an open forum meeting, thesis awards, a poster session with a prize for the best student/post-doc poster, and a banquet. Workshops are scheduled for Monday through Wednesday. An end-of-run party will follow the plenary session on Friday afternoon at 4 p.m. in Building 510 courtyard. □

For more information, with a complete list of workshops, go to www.bnl.gov/rhic_ags/users_meeting/



Calendar
of Laboratory Events

- *The BERA Sales Office is located in Berkner Hall and is open weekdays from 9 a.m. to 3 p.m. For more information on BERA events, contact Andrea Dohler, Ext. 3367; or Chris Carter, Ext. 2873.*
- *Additional information for Hospitality Committee events can be found at the Recreation Bldg. and at the laundry, both located in the apartment area.*
- *Contact names are provided for most events for more information.*
- *Calendar events flagged with an asterisk (*) have an accompanying story in this week's Bulletin.*

EACH WEEK

Weekdays: Free English for Speakers of Other Languages Classes
Beginner, Intermediate, and Advanced classes. Various times. All are welcome. Learn English, make friends. See www.bnl.gov/esol/schedule.html for schedule. Jen Lynch, Ext. 4894.

Mondays: BNL Gospel Choir
5:15-7 p.m. Berkner Hall. All faiths are welcome. www.bnl.gov/bera/activities/choir/.

Mondays & Wednesdays: Pilates
Mon., Noon-1 p.m. in the Rec. Hall; Wed., 5:30-6:30 p.m. in the Rec. Hall. Christine Carter, Ext. 5090.

Mon., Tues., & Thurs.: Kickboxing
$5 per class. Mon., noon-1 p.m. in the gym; Tues., 5:15-6:15 p.m. in the gym; Thurs., noon-1 p.m. in the gym; Thurs., 5:15-6:15 p.m. in Brookhaven Ctr. North Room. Registration is required. Christine Carter, Ext. 5090.

Mon., Wed., & Fri.: Tai Chi
Noon-1 p.m., Brookhaven Center North Room. Adam Rusek, Ext. 5830 or rusek@bnl.gov.

Tuesdays: Welcome Coffee
10-11:30 a.m., Rec. Hall. First Tuesday of every month is special for Lab newcomers and leaving guests. Cindy Ottemann, 849-2646.

Tuesdays: BNL Music Club
Noon, North Room, Brookhaven Center. Come hear live music. Joe Vignola, Ext. 3846.

Tuesdays: Jiu Jitsu Club
6:30-7:30 p.m. in the gym. All levels, ages 6 and above. $10 per class. Tom, Ext. 4556.

Tuesdays: Toastmasters
1st and 3rd Tuesday of each month, 5:30 p.m., Bldg. 463, room 160. Guests, visitors always welcome. www.bnl.gov/bem/activities/toastmasters/default.htm.

Tuesdays & Thursdays: Aerobics
5:15-6:30 p.m., $5 per class or $40 for ten classes. Rec. Hall. Pat Flood, Ext 7886.

Tuesdays & Thursdays: Aqua Aerobics
5:15-6:15 p.m. Eight-week session. $20 to attend once a week; $40 to attend twice a week. Ext. 2873 for more information.

Tuesdays & Thursdays: Jazzercise
Noon-1 p.m., Rec. Hall. Preregistration is required. Christine Carter, Ext. 5090.

Tues., Thurs., Fri.: Upton Nursery School
8:30-11:30 a.m. Rec. Hall. Two- and three-day program avail. 727-8082 or Ext. 5060, for information.

Tues., Wed. & Thurs: Rec Hall Activities
5:30-9:30 p.m. General activities, large-screen TV, ping pong, chess, games, and socializing. Christine Carter, Ext. 5090.

Wednesdays: On-Site Play Group
10 a.m.-noon. Rec. Hall. An infant/toddler drop-in event. Parents meet while children play. Kati Petreczky, 821-4131.

Wednesdays: Weight Watchers
Noon-1 p.m. Michael Thorn, Ext. 8612.

Wednesdays: Yoga
Noon-1 p.m., Brookhaven Center. Free. Ila Campbell, Ext. 2206, ila@bnl.gov.

Wednesdays: Open Chess Night
5-8 p.m., Rec. Hall. Christine Carter, Ext. 5090.

Wednesdays: Dance Lessons
5:15-8 p.m. Brookhaven Cntr., North Room. BNL Ballroom Dance Club hosts lessons, beginner to adv. John Millener, Ext. 3853.

Thursdays: Reiki Healing Class
Noon-1 p.m., Bldg. 211 Conference Rm. Nicole Bernhole, Ext. 2027.

Fridays: Family Swim Night
5-8 p.m. at the BNL Pool. $5 per family.

Fridays: BNL Social & Cultural Club
6-9 p.m., North Ballroom, Brookhaven Ctr., dance lessons, 9-11:30 p.m. general dancing. Rudy Alforque, Ext. 4733, rudy@bnl.gov.

THIS WEEKEND

Friday, 6/10

Lunch Talk: Yard Work Using Tools
Noon-1 p.m. Berkner Hall, Room D. Safety at Home talk on yard work using tools. All are welcome.

NEXT WEEK

Monday, 6/13

Lunch Talk: Swimming Pool Safety
Noon-1 p.m. Berkner Hall, Room D. Safety at Home talk on swimming pool safety. All are welcome.

Tuesday, 6/14

Verizon Wireless Demo
11 a.m.-2 p.m., Berkner Hall. Representatives from Verizon Wireless will present BNLers with special rates and a 15 percent BNL employee discount on wireless products and services. Edwin, 516-459-2635.

2005 NSLS Annual Users' Meeting *(cont'd.)*

on activities at the NSLS during the past year. He pointed out that the NSLS continues to thrive, even as third-generation synchrotrons have been built in the U.S.

During the remainder of the main session, participants heard several scientific talks. Henk Schenk of the University of Amsterdam discussed "The Structure of Cocoa Butter and the Quality of Chocolate." Schenk was followed by a safety presentation delivered by Stephens and Bob Casey, the NSLS Associate Chair for Environment, Safety, Health, and Quality. John Rehr of the University of Washington spoke about the theory involved in interpreting x-ray data.

Benjamin Chu from Stony Brook University described the polymer experiments he performs with his group at beam line X27C. Steve Almo from the Albert Einstein College of Medicine discussed "Structural Genomics in the 3rd Millenium." Finally, NSLS scientist Peter Abbamonte presented his work on antiferromagnetism, a state of magnetism that may be involved in superconductivity.

That evening, many meeting participants attended the banquet in Berkner Hall, where the 2005 UEC Community Service Award was presented to Tony Lenhard.

On the other two days of the meeting, May 23 and 25, several scientific workshops were held at locations across BNL, and a poster session was held in Berkner Hall on the evening of May 23. — Laura Mgrdichian

Roger Stoutenburgh

The winners of the 2005 National Synchrotron Light Source (NSLS) Annual Users' Meeting poster session are: (from left) Tejas Telivala of Stony Brook University (SBU), "Effect of Metal Ions on the Secondary Structure of Amyloid Beta in Alzheimer's Disease;" Ashtosh Ganjoo of Lehigh University, "Observation of Photo-Induced Atomistic Changes in Chalcogenide Glasses by in-situ EXAFS;" Angelo Dragone of BNL's Instrumentation Division, "The Peak Detector Derandomizing ASIC for Multichannel Energy &Timing Measurements: Characterization & Further Developments;" Holger Fleckenstein of SBU, "Scanning Transmission X-ray Microscope with Three Axes Laser Interferometer;" Meghan Ruppel of SBU, "Chemical Makeup of Microdamaged Bone Differs from Undamaged Bone;" and Brandon Chapman of BNL's NSLS, "Synchrotron X-Ray Studies of Organic-Based Devices: Molecular Transistors & Liquid Crystal Displays."

DOE, NYS Help Small Business
Series of Free Workshops, Counseling Offered

The DOE Small Business Development Center, which is located in Building 179 at BNL, in cooperation with the New York State Small Business Development Center at Stony Brook University, is sponsoring a series of free workshops to be held at noon on every second Wednesday starting from June 29 (with a break around the end of September) at the BNL cafeteria in Berkner Hall. All are welcome to attend, but pre-registration is preferred. To register, call 632-9070 or e-mail agarbarino@ notes.cc.suny sb.edu. Through these same contacts, you can arrange one-on-one counselling on Wednesday mornings at the DOE Office in Bldg. 179. Dates and workshop titles are listed below.

- 6/29 Marketing Magic
- 7/13 E-Commerce
- 7/27 Import, Export
- 8/10 Patents, Trademarks
- 8/24 Accounting Magic
- 9/14 Venture Capital
- 9/28 Legal Matters

To Develop Future Researchers, Host a Summer Student

Members of the Lab scientific community are asked to consider becoming a mentor for a High School Science Research Student. The six-week high-school program begins on July 6. The program allows talented high school juniors and seniors to participate in a full-day research program at no cost to the sponsoring department. Applications are available for review at the Science Education Center, Bldg. 438. Contact Mel Morris, Ext. 5963 or mmorris@bnl.gov.

Scharff-Goldhaber Prize Ceremony, 6/15

Brookhaven Women in Science (BWIS) invites the Lab community and faculty members and graduate students of the Department of Physics, Stony Brook University, to the award ceremony of the 2005 Gertrude Scharff-Goldhaber Prize on Wednesday, June 15, at 3 p.m., in the Large Seminar Room of the Physics Department, Bldg. 510. BNL Distinguished Scientist Maurice Goldhaber will present the award to Ann Sickles, an SBU graduate student, who will present a short seminar on her research. Refreshments will follow the presentation.

Science Camp for BNL Children, Grades 4-6

BNLers are invited to register their children or grandchildren in BNL's Summer Science Exploration camp, a free offering from the Lab's Science Museum. The three-day camp will be held Tuesday- Thursday, August 9-11, 8:30-11:30 a.m., for students entering grades 4 - 6. This year's focus will include a BNL environmental field activity, understanding energy and building/testing rubber band cars, and exploring the Museum's interactive exhibits. Children must attend all three days, and their parents are also welcome. To register or for more information, call Ext. 4495.

New Supercomputer Dedicated *(cont'd.)*

From left: Minoru Yanokura, RIKEN, Koji Kaya, RIKEN; Hideto En'yo, RBRC/RIKEN; Praveen Chaudhari, BNL; and Nicholas Samios, BNL

Norman Christ, Columbia University (CU), Jeffrey Mandula, DOE, and T.D. Lee, CU

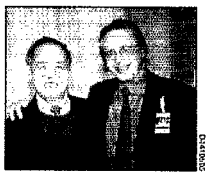
Michael Holland, DOE, and Gulshan Rai, DOE

Praveen Chaudhari and Nicholas Samios

Thomas Blum, University of Connecticut/RBRC, and Robert Jaffe, Massachusetts Institute of Technology

Pictures on this page are by Roger Stoutenburgh.

Doris Rueger and Rae Greenburg, Physics Department


T.D. Lee and Nicholas Samios

edging the outstanding efforts of this staff at ITD, McFadden also wished to give credit to Plant Engineering and many of the trades at BNL. He said, "There were many important contributions from support personnel in making the QCDOC project a success, such as the preparation of the physical facility, the engineering design, assembly of hardware, container construction, and international shipping."

Good Things Come in Threes

The RIKEN-BNL QCDOC is one of three similar computers that have been built by the same team of collaborators. Funded by the Particle Physics & Astronomy Research Council in the United Kingdom, the second computer, now completed and beginning operation, is located at the University of Edinburgh, Scotland. The third, which is funded by DOE's Office of Science, will also be located at BNL and used by a community of U.S. scientists for calculations in quantum chromodynamics. Now undergoing testing, the third QCDOC is due to be ready for operations in the summer 2005. Working on related and sometimes different problems using these three supercomputers, researchers hope to make significant contributions in physics and other scientific fields.

— Diane Greenberg

QCDOC In Action *(cont'd.)*

matter whose properties are consistent with those of a strongly coupled plasma of subatomic quarks and gluons — the "quark-gluon plasma" that existed a few microseconds after the birth of the universe.

Related to this effort, the supercomputer will be used for calculations in quantum chromodynamics — the physics theory that describes the interactions of subatomic quarks and gluons. In particular, physicists hope to understand the reason for the existence of six types of quarks that have widely varied masses. With this powerful computer, they can disentangle quarks from their interactions with gluons to gain important data about both particles' properties.

During the remaining 10 percent of operating time, researchers will use the supercomputer to pursue scientific projects in a variety of fields, including biology and materials science. — DG

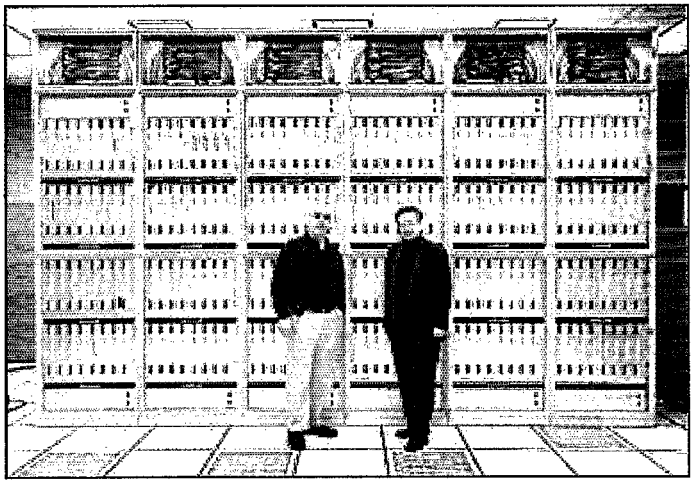
BROOKHAVEN NATIONAL LABORATORY

Contact: Diane Greenberg, (631) 344-2347 or Mona S. Rowe, (631) 344-5056

RIKEN BNL Research Center Dedicates New Supercomputer for Physics Research

May 26, 2005

UPTON, NY - A new computer — the RIKEN BNL Research Center supercomputer -- was unveiled today at a dedication ceremony at the U.S. Department of Energy's Brookhaven National Laboratory attended by physicists from around the world. It is called QCDOC for quantum chromodynamics on a chip, and it was designed and built by Brookhaven Lab, Columbia University, IBM, RIKEN -- The Institute of Physical and Chemical Research in Japan, and the University of Edinburgh. The computer has 10 teraflops of peak computing power, which makes it capable of performing 10 trillion arithmetic calculations per second, with sustained speeds of five teraflops. The $5-million computer took three years to build and is funded by RIKEN, with infrastructure support from DOE's Office of Science.



Edward McFadden (left, BNL Informtaion Technology Division) and Nicholas Samios (Physics Department) in front of the QCDOC supercomputer.

Taking up only 100 square feet of floor space, the supercomputer is installed at Brookhaven Lab in the RIKEN BNL Research Center, a physics research center formed by RIKEN and Brookhaven Lab in 1997. QCDOC achieves its ultra-fast speed by harnessing the power of 12,288 individual computers, each with its own memory and an extremely fast interprocessor communication network. Each processor is constructed on a single silicon chip, so the supercomputer is essentially 12,288 interconnected chips. This simple design leads to a low power requirement of about 100 kilowatts compared to the many megawatts typical of most commercial supercomputers.

QCDOC will be used for physics research for 90 percent of its operating time. With the help of the computer, physicists hope to determine the properties of a state of matter currently under intense study at Brookhaven's premiere accelerator, the Relativistic Heavy Ion Collider (RHIC). One of the major discoveries emerging from RHIC is the creation of a form of hot, dense (10 to 30 times denser than a nucleon) matter whose properties are consistent with those of a strongly coupled plasma of subatomic quarks and gluons – the so-called quark-gluon plasma that existed a few microseconds after the birth of the universe.

Related to this effort, the supercomputer will be used for calculations in quantum chromodynamics – the physics theory that describes the interactions of subatomic quarks and gluons. In particular, physicists hope to understand the reason for the existence of six types of quarks that have widely varied masses. With this powerful computer, they can disentangle quarks from their interactions with gluons to gain important data about both particles' properties.

During the remaining 10 percent of operating time, researchers will use the supercomputer to pursue scientific projects in a variety of fields, including biology and materials science.

The RIKEN BNL QCDOC is one of three similar computers that have been built by the same team of collaborators. Funded by the Particle

Physics and Astronomy Research Council in the United Kingdom, the second computer, now completed and beginning operation, is located at the University of Edinburgh, Scotland. The third, which is funded by DOE's Office of Science, will be located at Brookhaven Lab and used by a community of U.S. scientists for calculations in quantum chromodynamics. Now undergoing testing, the third QCDOC is due to be ready for operations in the summer of 2005. Working on related and sometimes different problems using these three supercomputers, researchers hope to make significant contributions in physics and other scientific fields.

Particle Physics and Astronomy Research Council QCDOC page

Number: 05-58

One of ten national laboratories overseen and primarily funded by the Office of Science of the U.S. Department of Energy (DOE), Brookhaven National Laboratory conducts research in the physical, biomedical, and environmental sciences, as well as in energy technologies and national security. Brookhaven Lab also builds and operates major scientific facilities available to university, industry and government researchers. Brookhaven is operated and managed for DOE's Office of Science by Brookhaven Science Associates, a limited-liability company founded by Stony Brook University, the largest academic user of Laboratory facilities, and Battelle, a nonprofit, applied science and technology organization.

Solving the Mysteries of Quarks

Particle Physicists are embarking on a new attempt to solve the mysteries of quarks with the completion of the three most powerful supercomputers ever applied to this problem, including one at the University of Edinburgh for use by the UKQCD collaboration of scientists from seven British Universities.

Quarks are the fundamental particles that make up 99.9% of ordinary matter; yet it is impossible to examine a single quark in the laboratory. Consequently, some of the basic properties of quarks are not known, such as their precise masses or why they exist in six different types. Quarks are bound together by the Strong Force, which is weak when the quarks are close, but increases steadily as you try to separate them, making it impossible to isolate a single quark. Instead, the theory describing the Strong Force, called Quantum Chromodynamics (QCD), has to be simulated on huge computers.

The Edinburgh computer is the first of three similar machines and has been operating since January. The second computer is being inaugurated today at the RIKEN Brookhaven Research Center in Brookhaven National Laboratory in the USA. The third is part of the U.S. Department of Energy Program in High Energy and Nuclear Physics, and is also installed at Brookhaven where it is currently undergoing testing.

The computers are built with processing chips designed for the purpose, known as QCD-on-a-chip, or QCDOC for short. A little slower than the microprocessor in your laptop, the QCDOC chip was designed to consume a tenth of the electrical power, so that tens of thousands of them could be put into a single machine. The computers were designed and built jointly by Columbia University (USA), the University of Edinburgh, the RIKEN Brookhaven Research Center (USA) and IBM.

Each QCDOC machine operates at a speed of 10 Teraflops, or 10 trillion (i.e. million million) floating point operations per second. By comparison, a regular desktop computer operates at a few Gigaflops (a thousand million floating point operations per second), whilst IBM's BlueGene, a close relative of QCDOC and the fastest computer in the world, operates at over 100 Teraflops. Edinburgh's machine and part of the QCDOC development costs were funded through a Joint Infrastructure Award of £6.6million administered by the Particle Physics and Astronomy Research Council, who also fund the UK scientists in this field.

Professor Richard Kenway, who led UK participation in the QCDOC Project, said "After five years building this machine, it's exhilarating to be able to compute in days things which take everybody else months. Now we are about to run QCDOC for months to do the most realistic QCD simulation yet. It's like standing on the shore of a new continent after a long voyage, we've chosen our path of exploration, but we don't know what we're going to find."

Notes for Editors

The Mysteries of Quarks

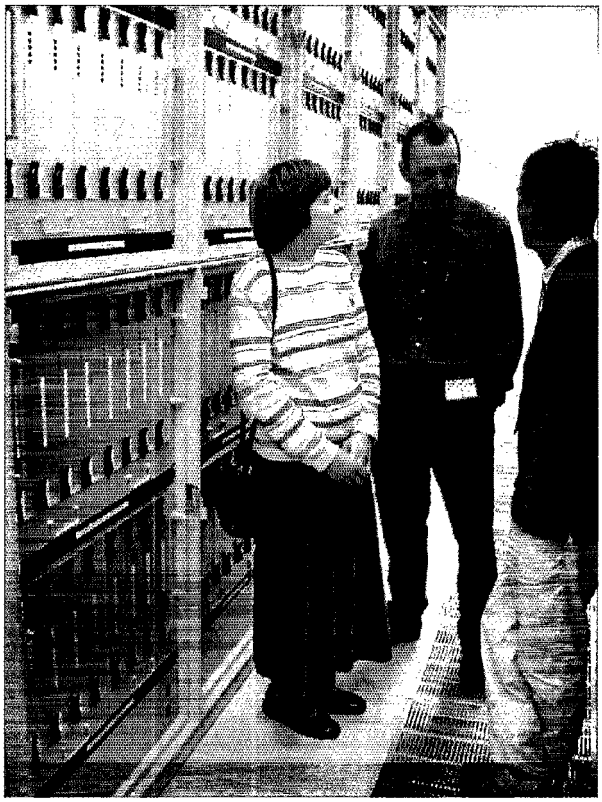
- Quarks never appear singly, but always as bound states of two or more, called hadrons, such as the protons and neutrons that make up the atomic nucleus. Thus, Nature hides its fundamental particles and we would like to understand better how the Strong Force achieves this.

- Only the mass of the top quark is accurately known, because QCD effects are small for such a heavy particle. To determine the masses of the lighter quarks accurately (called up, down, strange, charm and bottom), QCD effects have to be computed. These masses are needed for detailed understanding of many phenomena and should eventually be predicted by the much sought after Theory of Everything.
- There are six types of quark and this seems to be related to the small difference between matter and antimatter, called CP violation, that may help to explain why our Universe is dominated by matter (and hence why we can exist at all). QCD simulations are needed to discover whether our current theories can explain this, or there is some new physics at work.
- The Theory of Everything is very likely to permit protons to decay. If so, the proton lifetime must be enormous, since no decay has yet been observed. Experimental lower bounds on the lifetime, together with QCD simulations, place restrictions on what the Theory of Everything can be and have already ruled out some candidates.
- At enormously high temperatures and densities, such as may be found in neutron stars, everyday matter made of bound quarks may melt into a new type of matter. This change of phase, which is being searched for at Brookhaven National Laboratory by colliding gold and lead nuclei at high energies, is accessible to QCD simulations. What happens may tell us about what is going on inside some of the most exotic objects in the Universe.

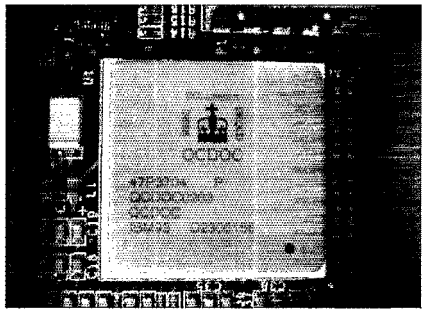
The UKQCD Collaboration

UKQCD is a collaboration of particle physicists from the Universities of Edinburgh, Southampton, Swansea, Liverpool, Glasgow, Oxford and Cambridge. It was formed in 1989 and has exploited a series of novel architecture computers for QCD simulations, becoming one of the leading projects in this field world wide. QCDOC gives UKQCD for the first time the fastest computer in the world available for QCD simulations.

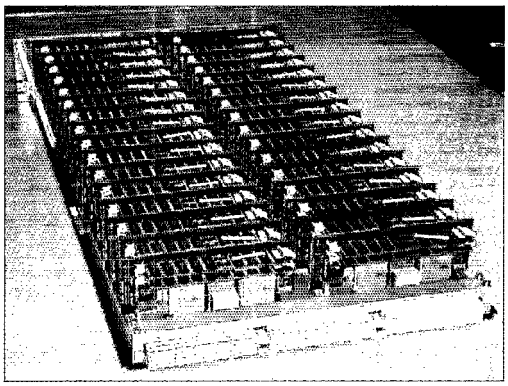
The QCDOC Computer



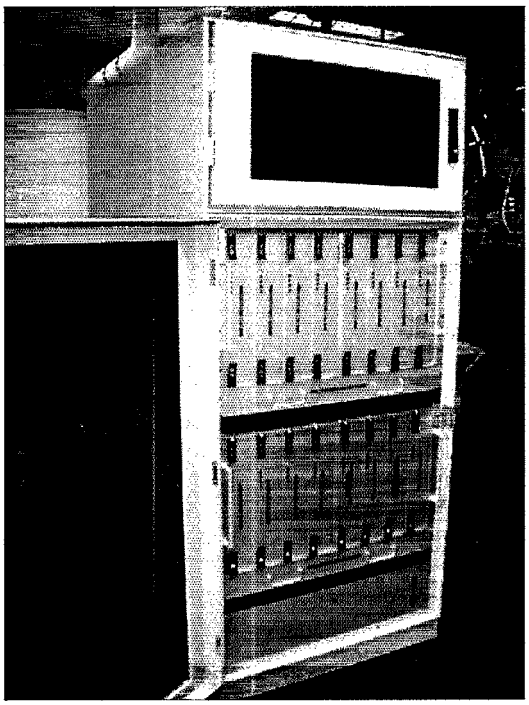
Professors Christine Davies and Richard Kenway, and Technician Andrew Main with the 12,288 processor QCDOC machine at Edinburgh in November 2004



The QCDOC chip integrates 50 million transistors on a 1.3cm × 1.3cm die and consumes approximately 5 Watts at a clock speed of 400 MHz.



A fully populated mother board containing 32 daughter boards each with 2 QCDOC chips.



A water-cooled QCDOC rack containing 16 mother boards with 1024 QCDOC chips. The upper compartment holds Ethernet switches.

Contacts

University of Edinburgh: Professor Richard Kenway, 0131 650 5245
University of Glasgow: Professor Christine Davies, 0141 330 4710
University of Liverpool: Professor Alan Irving, 0151 794 3782
University of Oxford: Dr Mike Teper, 01865 273 972
University of Cambridge: Professor Ron Horgan, 01223 337 839
University of Southampton: Professor Chris Sachrajda, 023 8059 2105
University of Wales Swansea: Dr Chris Allton, 01792 295 738

本件の取り扱いについては、下記の解禁時間以降でお願い申し上げます。
新聞　　：日本時間 平成１７年５月２７日付け朝刊
テレビ・ラジオ・インターネット：日本時間 平成１７年５月２６日午後１１時

RIKEN

平成１７年５月２６日
独立行政法人理化学研究所

１０ TFlops 級の格子 QCD 数値計算用並列計算機の完成
― 量子色力学(QCD)の新領域の開拓に向けて ―

独立行政法人理化学研究所（野依良治理事長）は米国・コロンビア大学及び、米国・ブルックヘブン国立研究所(BNL)との共同で開発を進めてきた10 TFlops 級の格子 QCD 数値計算用並列計算機 QCDOC を完成させ本格稼動を開始しました。この新しい計算機は用途を物理学理論計算に特化することで高性能であるとともに高いコストパフォーマンスを実現しています。システム全体のピーク性能では、理論上毎秒約１０兆回の割合で浮動小数点計算が可能（１０TFlops：テラフロップス）であり、通常運用においてもピーク性能の約半分を維持するという高効率を記録しています。

この計算機 QCDOC によって陽子や中性子(核子)を構成するクォークとグルーオンの力学、「量子色力学(QCD)」※1の理論計算を、例えば核子質量において、実験値との誤差がこれまでの５－１０％程度からより高い精度（数％レベルの誤差）で行うことが可能になります。今後、この新しい計算機を利用しての第一原理計算による精密な素粒子標準理論の検証を通して、標準模型を超える新しい物理の発見の可能性が期待されています。更に、現在 BNL で稼働中の衝突型加速器 RHIC の生み出す実験データに対する理論的解釈が進み、核子や中間子の構造やクォーク・グルーオン・プラズマ(QGP)※2状態に対する理解が飛躍的に高まる事となるでしょう。

なお完成記念披露式典は理研が運営する理研 BNL 研究センター(N. P. Samios センター長)は BNL の協賛のもと、BNL の主催にて２００５年５月２６日午前１０時(米国東部時間)より米国ニューヨーク州ロングアイランド、アプトンに所在する BNL 内において開催予定です。

１．背　景

理研 BNL 研究センター（RBRC）は 1997 年にノーベル物理学受賞者である T. D. Lee（李政道）コロンビア大学教授をセンター長(現センター長は前 BNL 所長の N. P. Samios)に迎え、当時は特殊法人であった理化学研究所と米国ブルックヘブン国立研究所（BNL）の共同研究協定を基にして設立されました。

このような計算ノードを６４個搭載したマザーボードを単位とし、システム全体で１９２のマザーボードからなる、最大理論ピーク性能で毎秒約１０兆回の浮動小数点計算が可能（１０ TFlops：テラフロップス）な並列計算機です。

３．今後の展開

このような高速専用計算機を得ることで、従来の高速計算機では、その性能によって制限されてきた量子色力学による第一原理計算の、より精密で、より高度な展開が可能となります。具体的には、前機種であるQCDSPを用いて行われてきた、質量が軽いアップとダウンの二種類のクォークの自由度のみ考慮されていた格子QCD数値計算から、アップやダウンよりやや重いクォーク、ストレンジの自由度まで含む格子QCD数値計算へとさらに現実の自然界に近い理論計算が可能になり、カイラル対称性に支配されるハドロン物理学諸過程（スピン物理学を含む）の理論的解明を目指すことになります。

ここで得られる理論計算上の進歩は、核子や中間子などのハドロンの構造を精密に計算することに繋がり、また、カラー閉じ込めを開放した系であるクォーク・グルーオン・プラズマの性質を理解する為にも重要です。現在BNLで稼働中の衝突型加速器RHICはこれらの物理に対する新しい実験データを続々と生み出しつつあります。今回の新しい１０Tflops級の計算機QCDOCを駆使した理論研究が、実験結果の精密な解釈を可能とします。

また、比較的質量の軽いハドロンの質量や崩壊定数、あるいは弱い相互作用に伴うハドロン遷移振幅などを精密に計算し、実験値と比較することによって、素粒子標準理論を検証していくことになります。

（問い合わせ先）
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補足説明

※１　量子色力学(QCD)

自然界を司る４つの力の一つ「強い力」の第一原理は、陽子や中間子の構成要素であるクォークとグルーオンを自由度として記述される量子色力学(Quantum Chromo Dynamics)として知られています。この「強い力」は、クォーク同士の距離が長い程強くなり、短い程弱くなるという、重力や電磁気力とは全く正反対の性質を持っています。この性質は「漸近的自由性」と呼ばれ、1973年にD. J. Gross, H. D Politzer, F. Wilczekにより発見され、その後の実験により検証されました。３氏はこの業績により、2004年にノーベル物理学賞を受賞しました。

※２　クォーク・グルーオン・プラズマ

核子や中間子などのハドロンを構成しているクォークやグルーオンは非常に強く結び合っていて決して外に取り出すことができません。これは「カラーの閉じ込め」と言われる現象です。しかし、核子同士が重なりあうくらいに物質の密度を非常に高くしたり、温度を高くするとこの結びつきが弱くなり、ハドロンの内部に閉じ込められていたクォークやグルーオンが解放されることが量子色力学からの理論的予言です。このような新しい物質状態は、普通の原子から電子が離れるときにできるプラズマ状態に似ていると想像されるため、「クォーク・グルーオン・プラズマ」と呼ばれています。

※３　格子QCD

連続４次元時空を有限な格子間隔に正則化する、格子正則化法に基づいた計算技術を量子色力学に応用したもの。

※４　ドメインウォールフェルミオン法

フェルミ粒子に対する新しい格子正則化法で、我々の４次元時空を５次元空間の断面（ドメインウォール）として捉えて定式化する方法。この新しいドメインウォール正則化法によって、従来の方法では難しかった、質量のないフェルミ粒子がもつべきカイラル対称性を有限な格子間隔（格子場上）においても厳密に保つことができる。

※５　カイラル対称性

質量のないフェルミ粒子が持つ基本的対称性の一つ。QCDにおいては、核子や π 中間子を構成するアップとダウンの二つの軽いクォークの質量が数MeV程度とハドロン物理の典型的なスケール（数百MeV）に比べて非常に小さいことに起因して、近似的にこの対称性を有する。ハドロン物理における多くの物理現象はこのカイラル対称性に支配されている。

開発経緯

[1998] QCDSP 完成
[2000-2002] Collaboration Agreement in the Development of QCDSP2 between RIKEN and Columbia University in the City of New York 締結
[2002-2005] Agreement for the Development of QCDOC between RIKEN and Columbia University in the City of New York 締結
[2005, Jan] テスト運用開始

システム構成

マザーボード	192枚
ドーターボード	6,144枚 （1マザーボードにつき32ボード）
ノード（CPU）	12,288個 （1ドーターボードにつき2ノード）

共同開発者

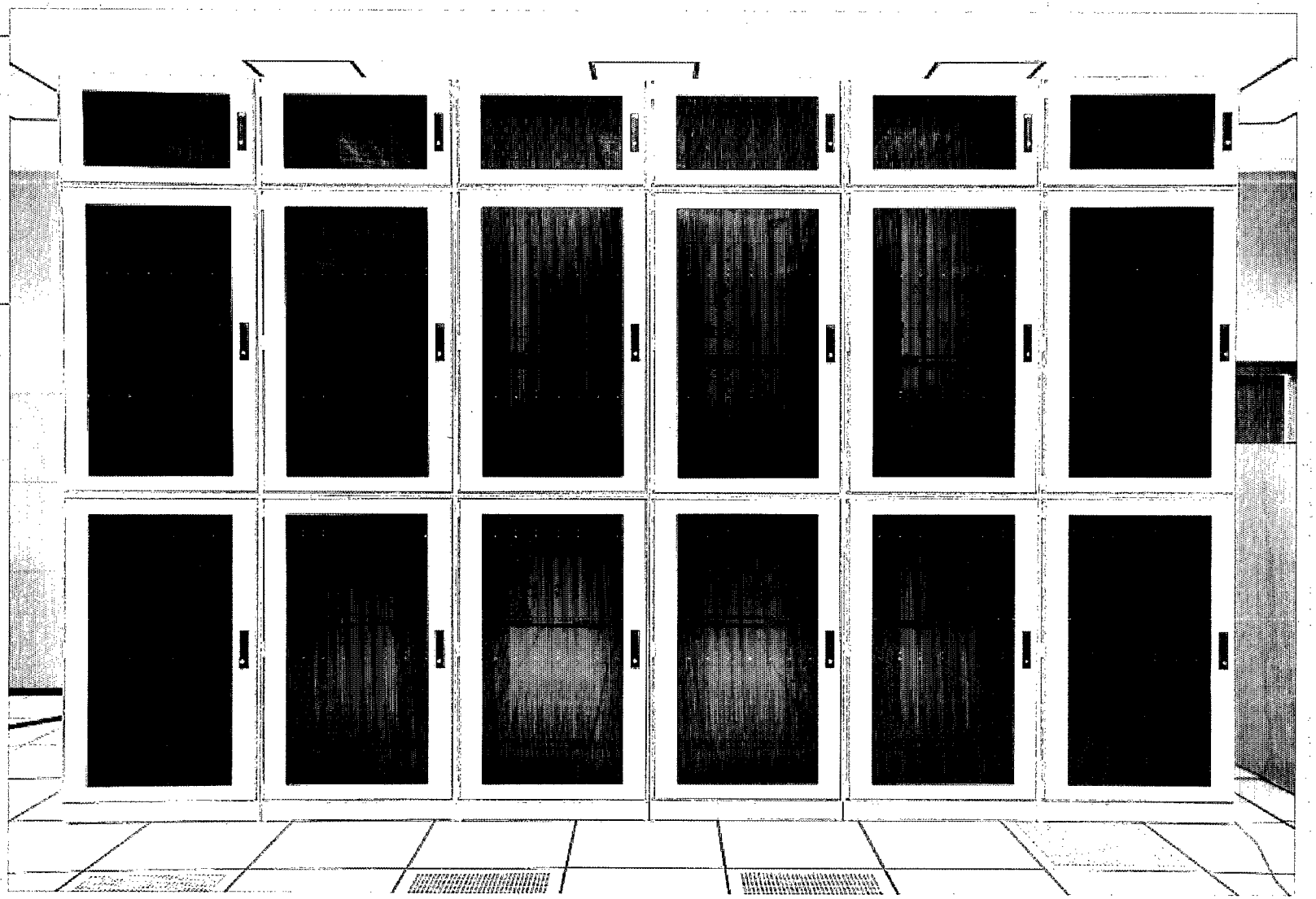
○米国コロンビア大学(DOE)
○英国エジンバラ大学（UKQCD）
※UKQCD-6大学からなる英国立共同体
○IBM

総経費(US$)

理研投資額(システム)	5,000,000
BNL（DOE）投資額(インフラ)	516,000

OCDOC

Supplement Photo1



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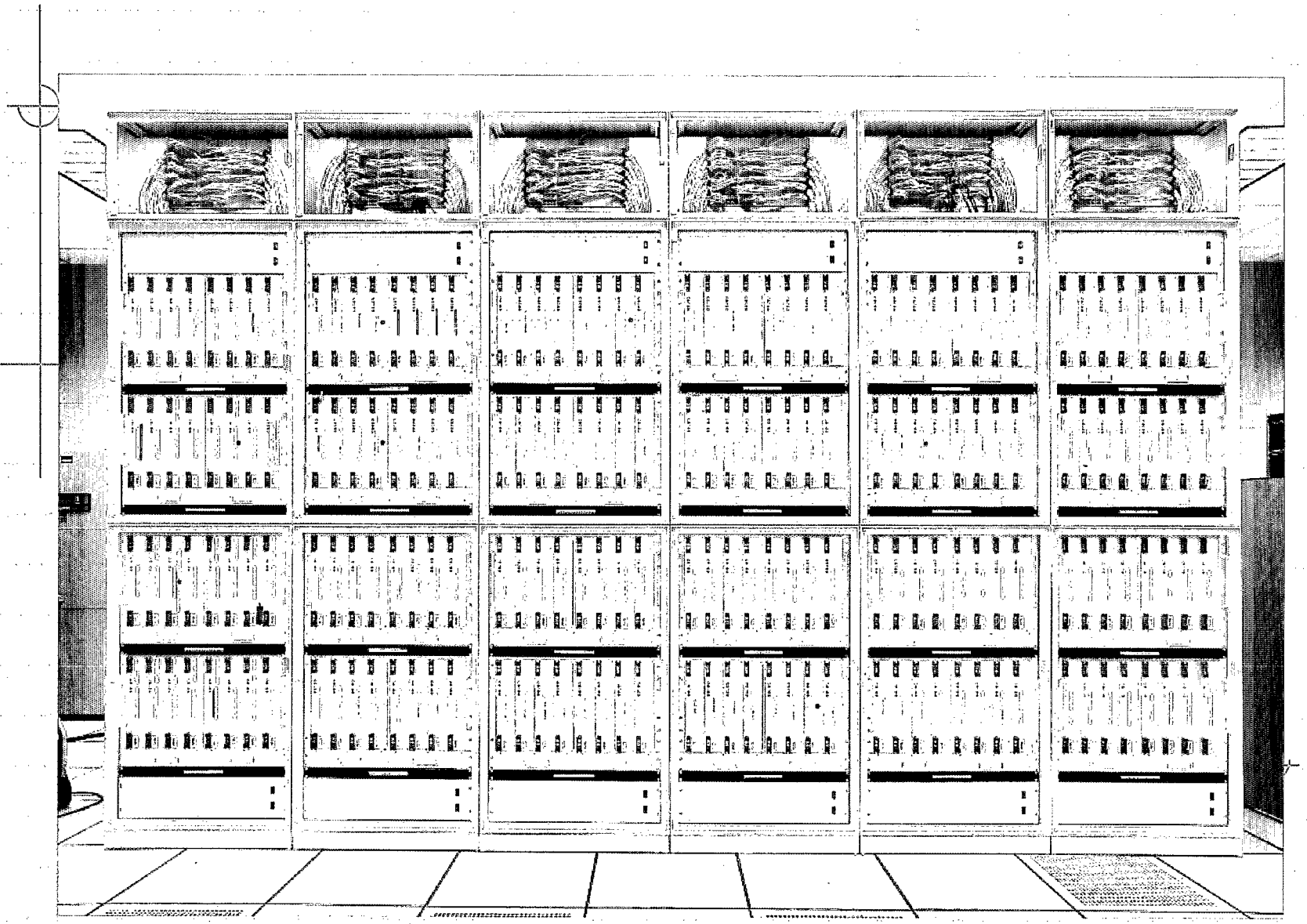
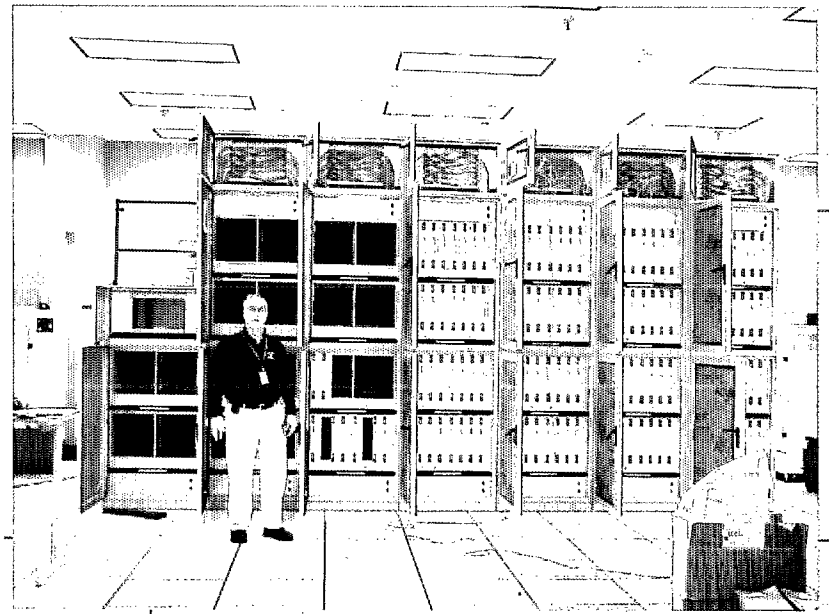
Supplement Photo2

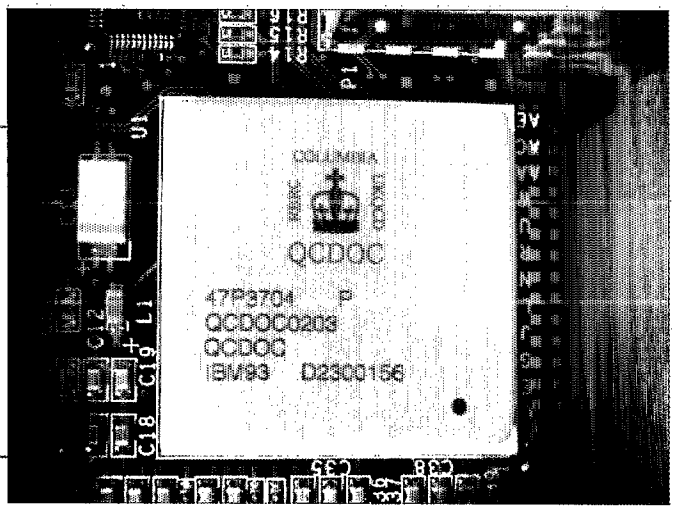


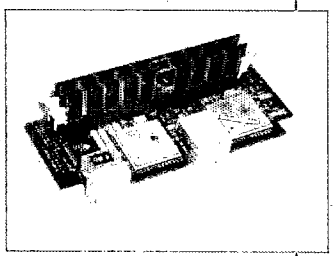
Supplement Photo3

QCDOC組み立て中

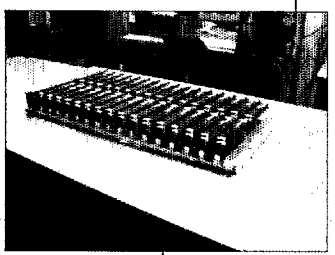


PowerPC embedded core

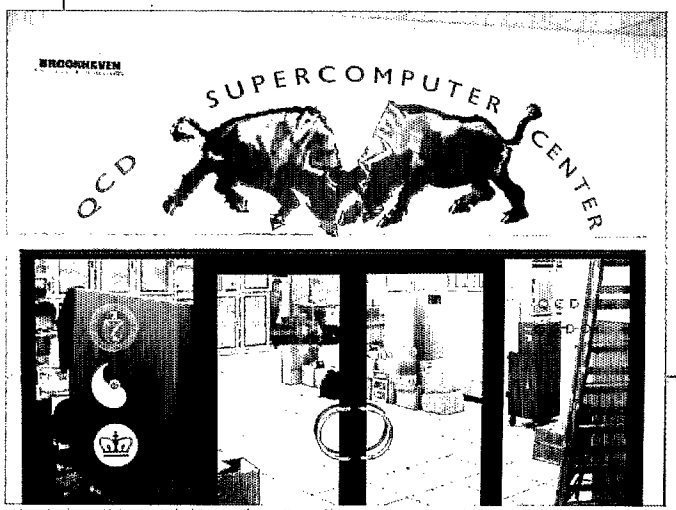




QCDOCドーターボード

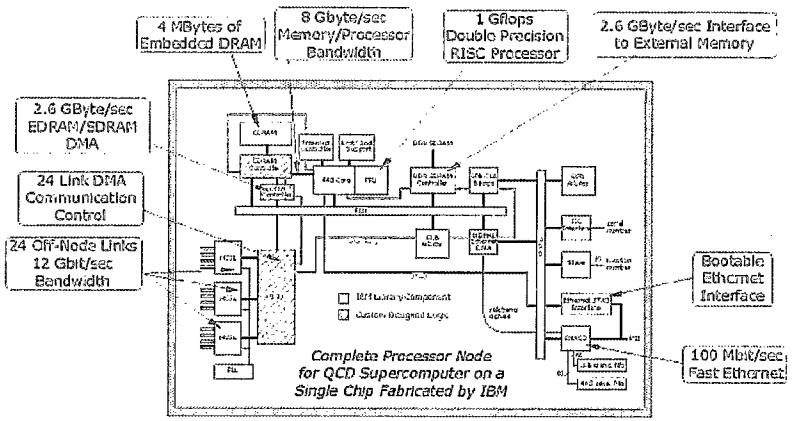


QCDOCマザーボード



QCDOC概念設計

QCDOC ASIC DESIGN



Mission-critical, custom logic (hatched) for high-performance memory access and fast, low-latency off-node communications is combined with standards-based, highly integrated commercial library components.

Brookhaven Computing Facility (BCF)内に設けられたQCDマシン専用の部屋。入り口のデザインはRBRC名誉センター長T.D. Lee氏によるもの

RBRC(理研BNL研究センター／RIKEN BNL Research Center

Fact Sheet

1995	「ブルックヘブン国立研究所と理化学研究所との相対論的重イオン衝突施設(RHIC)におけるスピン物理プログラムに関する共同研究覚書」締結 PHENIX建設開始
1997	理研BNL研究センター設立(センター長T. D. Lee) 「QCD並列計算機の整備に関する理化学研究所とコロンビア大学との研究協力同意書」締結
1998	QCDSP完成 QCDSPがGordon Bell 賞受賞
1999	RHIC 完成(BNL) RHICフィジックスフェロー制度開始
2000	RHIC金イオン同士の衝突に成功(BNL) 「QCDSP2の開発に関する理化学研究所とコロンビア大学との研究協力同意書」締結
2001	和光実験データ解析センター完成 偏極陽子ビームの加速・衝突に世界で初めて成功
2002	「QCDOCの開発に関する理化学研究所とコロンビア大学との研究協力同意書」締結 「ブルックヘブン国立研究所と理化学研究所との相対論的重イオン衝突施設(RHIC)におけるスピン物理プログラムに関する共同研究覚書」更新
2003	スピンローテーター電磁石を用いた縦偏極陽子衝突を開始 センター長にN. P. Samiosが就任
2004	AGSスネーク電磁石の導入により偏極陽子の偏極度45%を達成
2005	**QCDOC完成**

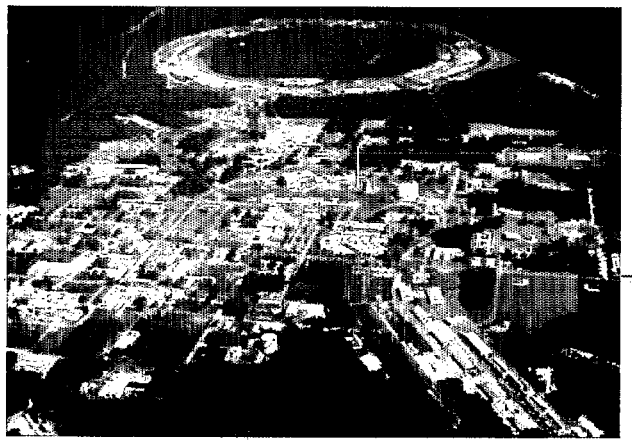
センター長: N. P. Samios
副センター長: 延與秀人
(理化学研究所主任研究員)

理論研究グループ Group Leader: Larry McLerran Deputy G.L.: Anthony J. Baltz	27(12)
実験研究グループ Group Leader: H. En'yo Deputy G.L.: Gerald Bunce	30(23)

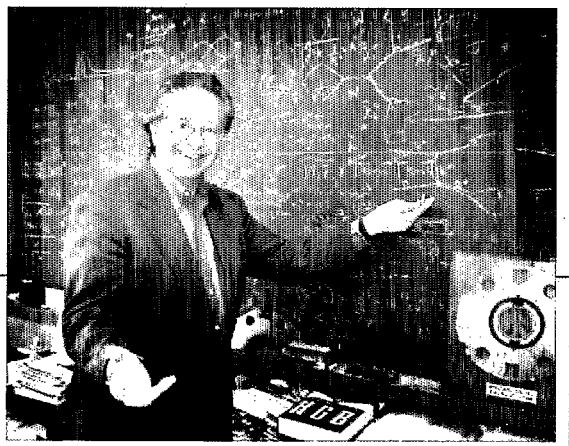
( )内は日本人研究者の内数:非常勤含む

	2003	2004
RBRC 現地運営予算	3.37M	3.34M

単位:米国ドル

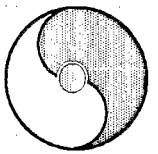


ブルックヘブン国立研究所
(米国ニューヨーク州アプトン)



理研BNL研究センターセンター長
N. P. サミオス(前BNL所長)

名誉センター長／理化学研究所顧問:
T.D.Lee



理研BNL研究センターのロゴは、T.D.Lee名誉センター長がデザインしました。

中央の赤い丸は日本を表し、赤青白の3色でアメリカの国旗をもイメージしています。

青と白の模様は、老子の思想による「太極(タイチー)」を意味し、宇宙の万物が持つ2元性(例えば陰と陽)を表しています。ここでは、青と白のタイチーにより第3の新しいもの(赤い丸)が創り出され、さらにこれら3つのものが三位一体となって無限に新しい物を創り出していくという精神が表されていて、RBRCの目標である新しい物理を次々に創出するということに通じています。

Completing a Supercomputer

Joe DePace (below), Information Technology Division (ITD), installs the final components in a supercomputer, one of three built by the division and designed by collaborators from Columbia University, IBM, the University of Edinburgh, the RIKEN BNL Research Center, and ITD. The huge computers will perform the numerical calculations of quantum chromodynamics (QCD), the physics theory that describes the interactions of quarks and gluons, the basic building blocks of matter. The computers, known as QCDOC for QCD On a Chip, were specially designed to provide cost-effective, massively parallel computing capability. Together, the three supercomputers have 36,864 processors (compared to one processor in a typical PC) and 30 teraflops of computing power, which makes them capable of performing 30 billion arithmetic operations per second.

Last Modified: April 8, 2005

One of ten national laboratories overseen and primarily funded by the Office of Science of the U.S. Department of Energy (DOE), Brookhaven National Laboratory conducts research in the physical, biomedical, and environmental sciences, as well as in energy technologies and national security. Brookhaven Lab also builds and operates major scientific facilities available to university, industry and government researchers. Brookhaven is operated and managed for DOE's Office of Science by Brookhaven Science Associates, a limited-liability company founded by Stony Brook University, the largest academic user of Laboratory facilities, and Battelle, a nonprofit, applied science and technology organization.

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Supercomputer could hold universe's secrets

By Jennett Meriden Russell

A compact, super-intelligent computer designed to solve the mysteries of the universe. While it might seem like the stuff of science fiction, scientists at the U.S. Department of Energy's Brookhaven National Laboratory unveiled a new "supercomputer" at their Upton facility last Thursday, May 26, which is designed to do just that.

Dubbed QCDOC for Quantum Chromodynamics On a Chip, the computer is designed to explore complex mathematical equations associated with quantum chromodynamics (QCD), the theory of the so-called strong interactions that bind ultra-tiny building blocks of the universe together.

Physicists from around the world attended the dedication ceremony of the new RIKEN-BNL Research Center supercomputer. RIKEN is the Institute of Physical and Chemical Research in Japan, which has been collaborating with BNL on physical and chemical research since 1997. RIKEN financed the $5-million computer, which took three years to build, and employed the computer skills of RIKEN, BNL, Columbia University, IBM, and the University of Edinburgh technicians to create.

In search of the origin of matter and the universe itself, quantum physicists have taken us deeper and deeper inside atoms, which were once thought to be the smallest particles in the universe. First to come into view was the atomic nucleus, and then the individual protons and neutrons that constitute the nucleus.

At least for three decades, nucleons (protons and neutrons) were considered to be the smallest elements in the universe, but then, peering into them, scientists detected shadows of yet another layer of matter that lurks inside. Unable—so far—to crack open a nucleon and bring out one of these shadowy objects for observation and measurement, physicists can only guess what the mysterious substance is made of.

Dubbed "quarks," scientists believe that two types of quarks—one named "up" and the other "down"—make up the proton and the neutron. An unseen power called the "chromo force," represented by particles dubbed "gluons," holds quarks together. So it is the quarks and gluons that physicists currently believe may lie at the bottom of all known matter.

BNL and RIKEN physicists hope that the supercomputer will help them understand what the mysterious chromo force is. But, since the fundamental properties of QCD cannot be directly tested, scientists can use the computer to create a virtual laboratory to explore the theories of quantum chromodynamics. RBRC Director Dr. Nicholas P. Samios said the supercomputer would work in conjunction with BNL's premiere accelerator Relativistic Heavy Ion Collider (RHIC).

With the help of the computer, RBRC physicists hope to determine the properties of a state of matter currently under intense study at Brookhaven. One of the major discoveries emerging from work with the collider is the creation of a form of hot, dense (10 to 30 times denser than a nucleon) matter with properties that are consistent with those of a strongly coupled plasma of subatomic quarks and gluons—the so-called quark-gluon plasma that existed a few microseconds after the birth of the universe.

"We're trying to understand what happened about 10 microseconds after the Big Bang," Dr. Samios said. "As these computers become more and more powerful, we're able to make more and more precise calculations, where the theoretical predictions are comparable to the hypothetical."

Taking up only 100 square feet of floor space, the supercomputer achieves its ultra-fast speed by harnessing the power of 12,288 individual

THE PRESS of Manorville and The Moriches

Brookhaven National Laboratory scientists, from left to right, Dr. Nicholas P. Samios, Dr. Yoshiharu Doi, Robert Mawhinney, and Norman Chris helped to unveil a new supercomputer at the lab in Upton on Thursday, May 26. JENNETT MERIDEN RUSSELL

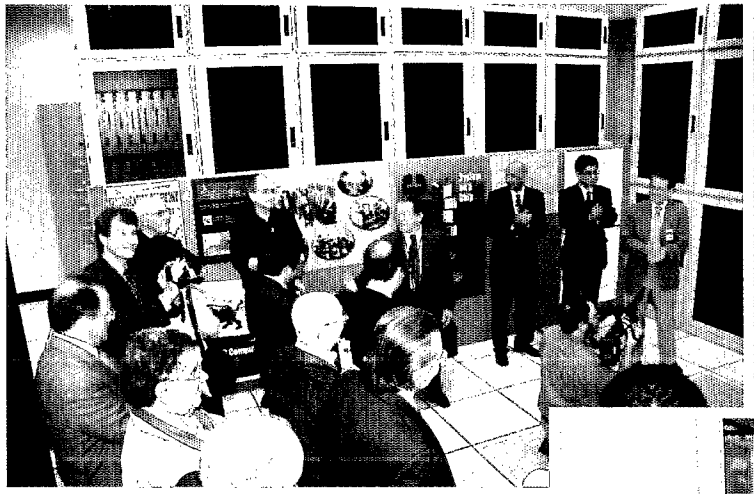
computers, each with its own memory and an extremely fast inter-processor communication network.

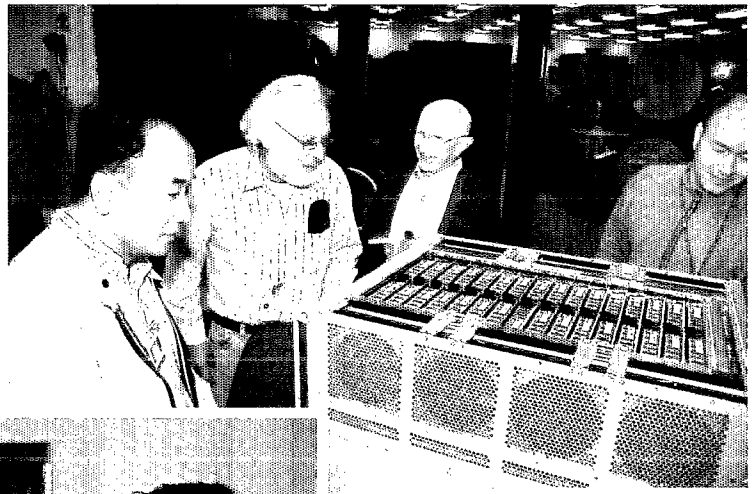
Edward McFadden, manager of the Brookhaven Scientific Computing Facility, said each processor is constructed on a single silicon chip, so the supercomputer is essentially 12,288 interconnected chips. "A computer with this much memory would have been the size of a football field years ago," he said.

This simple design leads to a low power requirement of about 100 kilowatts, compared to the many megawatts typical of most commercial supercomputers.

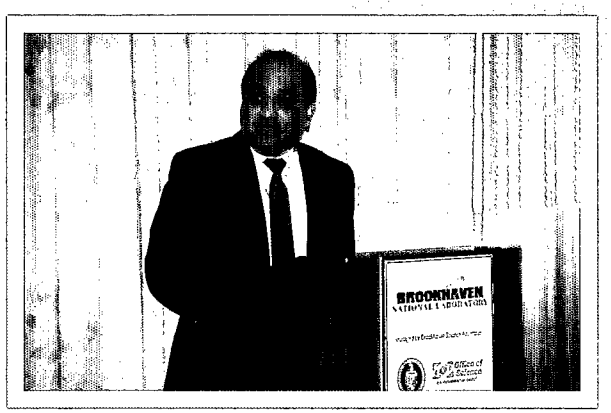
RIKEN Executive Director Dr. Yoshiharu Doi said the supercomputer has been designed to provide a highly cost-effective computer capable of focusing significant computing resources on relatively small but extremely demanding problems. Dr. Doi said the computer has 10 teraflops of computing power, which makes it capable of performing 10 trillion arithmetic calculations per second. To give some perspective of how powerful the QCDOC is, the average home personal computer manages only one ten thousandth of a teraflop.

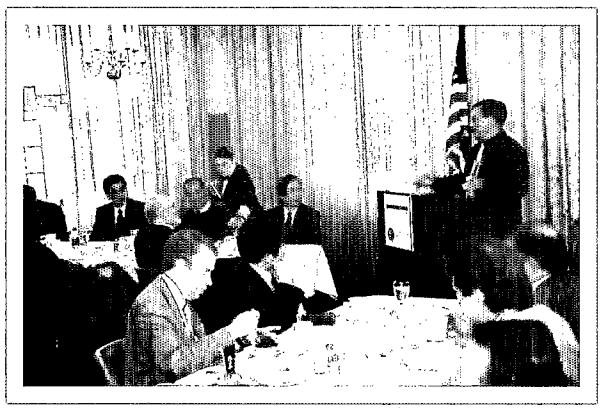
PHOTOGRAPHS



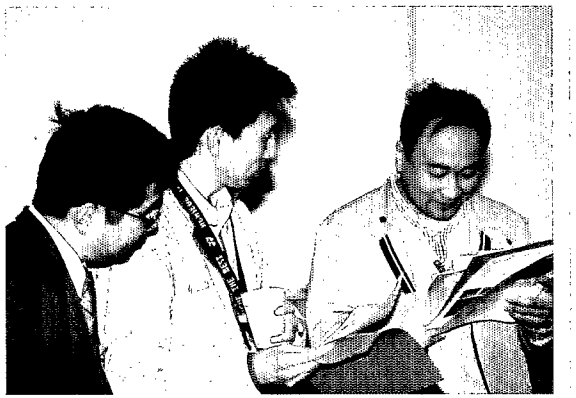


Computer Center





Dedication Luncheon —
Brookhaven Center



Symposium

Additional RIKEN BNL Research Center Proceedings:

Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005

Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005

Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005

Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005

Volume 69 – Review Committee – BNL-73546-2004

Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004

Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-

Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004

Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004

Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004

Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004

Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004

Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004

Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004

Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004

Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004

Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004

Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003

Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003

Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003

Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003

Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003

Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003

Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003

Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679

Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003

Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003

Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678

Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035

Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003

Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672

Volume 42 – Baryon Dynamics at RHIC – BNL-52669

Volume 41 – Hadron Structure from Lattice QCD – BNL-52674

Additional RIKEN BNL Research Center Proceedings:

Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634

Additional RIKEN BNL Research Center Proceedings:

Volume 7 – RHIC Spin Physics – BNL-65615

Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234

Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105

Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics –BNL-64912

Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724

Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723

Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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RIKEN BNL RESEARCH CENTER

RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC

May 26, 2005

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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Speakers:

P. Chaudhari	N. H. Christ	C. Dawson	Y. Doi
F. Karsch	T. Izubuchi	R. D. Mawhinney	N. P. Samios

Session Chairs: G. Bhanot, J. Mandula, S. Ozaki
Organizers: S. Ozaki and N. P. Samios