BNL-76863-2006
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 82

RHIC Physics in the Context of the Standard Model

June 18-23, 2006

Organizers:

Abhay Deshpande, Dmitri Kharzeev, Raju Venugopalan and Werner Vogelsang

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

DISCLAIMER

This work was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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-six 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
October 2005

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

CONTENTS

Preface to the Series

Introduction
A. Deshpande, D. Kharzeev, R. Venugopalan, W. Vogelsang i

Experimental Overview
M. Grosse Perdekamp 1

Perfect Fluid QGP or CGC?
T. Hirano 7

Some Topics about Color Glass Condensate
K. Itakura 13

Quarkonium Production and Propagation in Partonic Media
H. Fujii 19

Charm Production at High Parton Densities
K. Tuchin 25

Strangeness Physics at RHIC
J. Schaffner-Bielich 31

Fluctuations in Hot and Dense Matter
S. Jeon 37

Numerical Studies of Thermalization
Y. Nara 43

Electric Dipole Moment Searches in Nuclei, Atoms, and Molecules
D. Kawall 49

QCD at the High Energy/Density Frontier
D. Kharzeev 55

Experiments at RHIC: Exciting Discoveries & Future Plans
B. Jacak 61

Spin: Some Answers, Many Questions
R. Jaffe 69

RHIC Spin Experiments: Current Status and Future Prospects
N. Saito 75

Lattice QCD: Past, Present and Future
N. Christ 81

Chiral Symmetry Restoration and In-Medium Hadron Properties
D. Rischke 87

The State of the Universe
J. Huchra 93

Electroweak Physics
W. Marciano 99

Neutrino Oscillation Experiments – Present and Future
T. Kajita 105

Using AdS/CFT to Explore the Strong Coupling Regime of Gauge Theories: I
S. Gubser 111

Using AdS/CFT to Explore the Strong Coupling Regime of Gauge Theories: II
D. Son 117

QCD Thermodynamics
J.-P. Blaziot 123

Instabilities in Non-Abelian Plasmas
D. Bodeker 129

QCD Phase Diagram
M. Stephanov 135

Static/Dynamic Correlations in Hot QCD
T. Hatsuda 141

Physics of Ultrahigh Energy Cosmic Rays
A. Kusenko 147

Non-Perbative Methods in QCD at Finite μ and T
T. Schaefer 153

Light Quarks on the Lattice
S. Aoki 159

Semi-Leptonic Decays on the Lattice – from CKM to Proton Spin Problem
S. Sasaki 165

QCD Spin Physics – A Theoretical Overview
D. Boer 171

Experimental Overview
D. Fields 177

Parity-Odd Asymmetry in W-Jet Events
H. Yokoya 183

Structure Functions on the Lattice
K. Orginos 189

Electromagnetic Splittings of Hadrons and Calculations Towards $g_\mu - 2$ Light-by-Light Contribution
T. Izubuchi 195

Lattice and Effective Field Theory for Cold Fermionic Atoms
M. Wingate 201

Thermodynamics at $\mu = 0$ on the Lattice
Y. Aoki 207

Kaon Physics in the Full Domain-Wall QCD
J. Noaki 213

Light Hadron Spectrum in 2+1 Flavor QCD with Wilson Quarks
T. Ishikawa 219

List of Registered Participants 225

Agenda 227

Additional RIKEN BNL Research Center Proceeding Volumes 233

Contact Information

INTRODUCTION

Abhay Deshpande, Dima Kharzeev, Raju Venugopalan and Werner Vogelsang

The RIKEN BNL Center workshop and symposium "RHIC Physics in the Context of the Standard Model" was held at Brookhaven National Laboratory from June 19-23, 2006. Several physics workshops are organized by RBRC each year on a wide range of physics topics. This particular workshop was noteworthy because it represented the first reunion of RBRC Fellows and Research Associates since the founding of the RBRC in 1997.

The workshop was organized as mini-workshops on heavy ion physics, spin physics and lattice QCD, as well as a symposium encompassing these topics in the broader context of the standard model. The talks at the mini-workshops were all by RBRC alumni, showcasing the range and depth of the contributions in these areas. The symposium was a mix of talks by RBRC alumni and a number of senior experts on various areas of the standard model. We hope these Proceedings convey a sense of the high quality of the physics talks in both presentation and content.

In addition to the physics discussions, the workshop provided an excellent opportunity for the RBRC alumni to interact with each other and their colleagues at BNL. At an informal discussion session during the workshop, several ideas were suggested for a continuation of these reunions and for ways for the alumni to maintain their contact with RBRC. We hope some of these will come to fruition and contribute to the intellectual vitality of the Center.

Experimental Overview

Matthias Grosse Perdekamp

University of Illinois at Urbana-Champaign
1110 West Green Street
Urbana, IL 61801-3080 USA

and

RIKEN BNL Research Center
Physics Department
Brookhaven National Laboratory
Upton, NY 11973

Experimental Overview

- o **Overview**
- o **Heavy Ion Physics**
  - Experimental challenges
  - RBRC contributions
- o **Experimental Results**
  - Initial state
  - Elliptic Flow
  - Hard Probes
  - Heavy Flavor

based on input from my heavy ion colleagues at RHIC!

pp2pp

PHENIX

STAR

(I) RHIC 2001 – 2005: Discovery

Key Observations

RBRC workshop, May 2004 served as starting point for the white paper discussion: Nucl. Phys. A757, 2003

1. Jets are suppressed in central Au + Au collisions
   - Suppression is flat up to p_t ~ 10 GeV/c
   - Absence of suppression in d+Au
2. Strong elliptic flow
   - Scaling of v_2 with eccentricity shows that a high degree of collectivity builds up at a very early stage of collision – evidence for early thermalization
   - Data described by ideal hydrodynamic models → fluid description of matter applies.
3. Energy density allows for a non-hadronic state of matter
   - Energy density estimates from measurements of dN/dy are well in excess of the ~1 GeV/fm^3 lattice QCD prediction for the energy density needed to form a deconfined phase.

⇨ Strongly interacting Quark Matter

(II) Survey of sQGP Properties at RHIC

Formulate sQGP predictions and test with present and future precision data from RHIC, examples:

- R_{AA} at very high p_T
- Charm energy loss
- Baryon multiplicities in hadronization
- Chiral symmetry restoration
- Thermal radiation
- J/ψ
- Modification of jets

From Nuclear Physics and HEP to Heavy Ions → The Experimental Challenge

Central Au-Au at RHIC	Contact between final state and the physics of the fire ball ?
$\sqrt{s}$ = 38 TeV	Variable collision systems and energy
~28 TeV released in the collisions	Control measurements and their systematics
~ 7500 particles in the final state	Event Characterization
	Occupancy

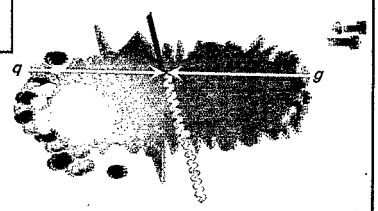
Heavy ion physics has advanced the frontiers for accelerators, experiment and theory!

RBRC Contributions, Examples

(I) hard probes in pQCD

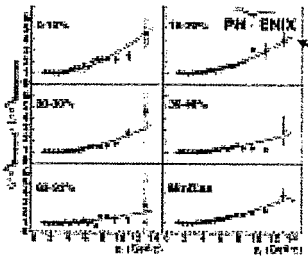
RBRC (Theory):
Werner Vogelsang

Studying the medium with high p_T probes



Direct Photons in Au-Au

PRL 94, 232301



Expectation for N_{coll} scaling of direct photons

Resummed pQCD calculations permit calibration of hard probes at RHIC in a model independent way.

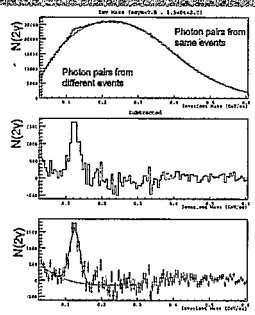
RBRC Contributions, Examples

(II) Event Mixing for neutral pion reconstruction

(Sasha Bazilevsky, Hisayuki Torii)

→ reconstruction of π^0 in central Au-Au collisions possible

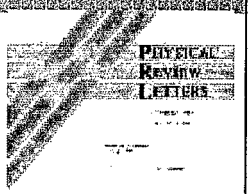
RBRC (analysis):
Hisayuki Torii, Sasha Bazilevsky

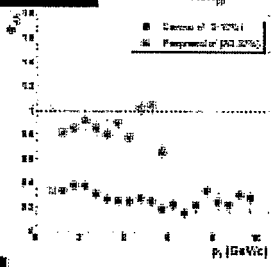


Au-Au vs = 130 GeV: High p_T Suppression

PHENIX

$$R_{AA} = \frac{Yield_{AuAu}/\langle N_{binary}\rangle_{AuAu}}{Yield_{pp}}$$





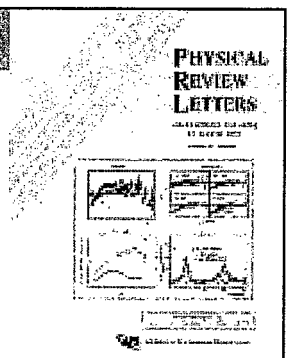
Examples

(III) Event selection

(Yuji Goto, Kensuke Okada, Hisayuki Torii, MGP, Wei Xie)

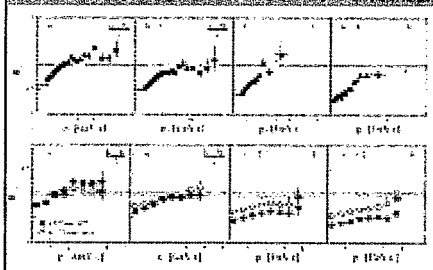
→ selection of π^0 in d-Au collisions at high rates makes control experiment possible.

RBRC (hardware):
Yujie Goto, Kensuke Okada, Hisayuki Torii, MGP, Wei Xie



Is the Initial State in Heavy Ion Collisions Determined by Saturation Effects in the Gluon Field ?

BRAHMS d+Au Results as Function of Rapidity and Centrality

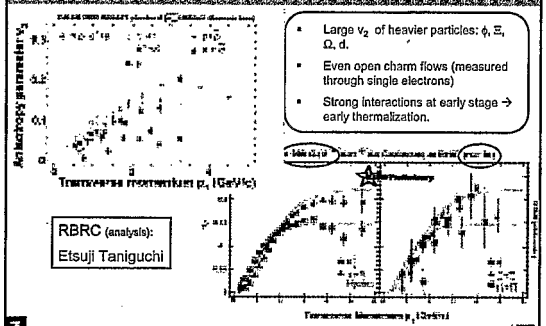


$$R_{dAu} = \frac{Y_{dAu}}{N_{coll} Y_{pp}}$$

Hadron production is suppressed at large rapidity consistent with saturation effects at low x in the Au gluon densities → CGC

Elliptic Flow
Strong Evidence for sQGP
PDFs (partonic degrees of freedom)?!

v_2 Large for all Particles



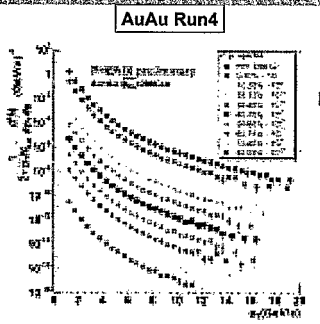
- Large v_2 of heavier particles: ϕ, Ξ, Ω, d.
- Even open charm flows (measured through single electrons)
- Strong interactions at early stage → early thermalization.

RBRC (analysis):
Etsuji Taniguchi

High p_T
Suppression

π^0 p_T spectra at $\sqrt{s_{NN}}$ = 200 GeV

AuAu Run4

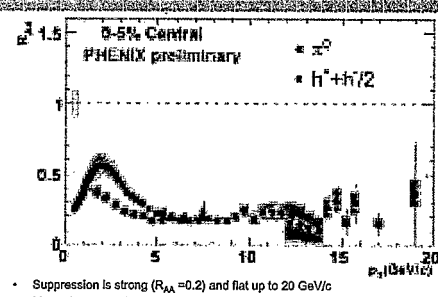


High quality data:

9 centrality bins
36 p_T bins
high statistics!

RBRC (analysis):
Hisayuki Torii,
Wei Xie, Etsuji
Taniguchi

Suppression Extends to 20 GeV/c



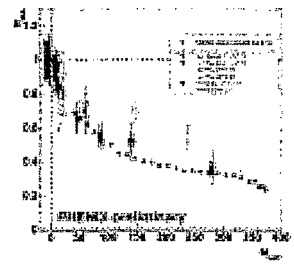
- Suppression is strong (R_{AA} =0.2) and flat up to 20 GeV/c
- Matter is extremely opaque
- The data should provide a *lower bound* on the initial gluon density

Heavy Flavor Physics

RBRC (theory):
Dima Kharzeev et al.,
Peter Petreczky

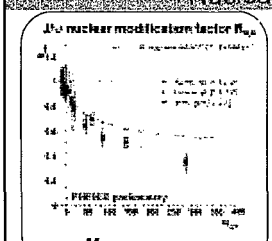
R_{AA} vs N_{part}: PHENIX and NA50

J/ψ nuclear modification factor R_{AA}

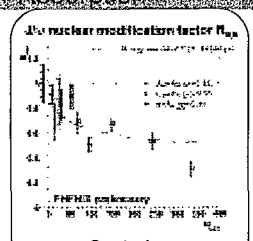


- NA50 data normalized to NA50 p+p point.
- Suppression level is similar in the two experiments, although the collision energy is 10 times higher (200GeV in PHENIX wrt 17GeV in NA50)

Comparison to Theory (I): Nuclear Absorption



Muon arm



Central arm

Vogt (nucl-th/0507027) → Cold nuclear matter absorption model in agreement with dAu: Tendency to underpredict suppression in most central events

Summary

- o Enormous effort and advances to build RHIC with it's detectors as the first facility optimally adapted for Heavy Ion Physics.
- o Discovery of the strongly interacting quark gluon plasma. Many independent channels. Among the most important:
  - → strong elliptic flow
  - → large suppression
  - → large energy densities
- o Enter second phase of the experimental program at RHIC to survey the sQGP.
- o Additional tools: detector upgrades in PHENIX and STAR; electron cooling in RHIC.

Perfect fluid QGP or CGC?

Tetsufumi Hirano

Institute of Physics, University of Tokyo, Komaba, Tokyo 153-8902, Japan

Keywords: quark gluon plasma, relativistic heavy ion collisions, perfect fluid, color glass condensate
PACS: 24.85.+p,25.75.-q,24.10.Nz

We investigate, based on hydrodynamics, how robust the conclusion of discovery for perfect fluid QGP at RHIC is. In hydrodynamic simulations, one needs to model (1) initial conditions, (2) equations of state, and (3) decoupling/freezeout. The conclusion was obtained essentially based on a particular set of the above three models. So it is very important to check whether the conclusion remains valid even by changing model assumptions. If chemical freezeout is considered in hydrodynamics, the slope of differential elliptic flow turns out to be deviated from the data. On the other hand, ideal hydrodynamics followed by a kinetic description based on hadronic cascade models can reproduce particle ratio, spectra, and elliptic flow parameters. We find that two canceling effects, namely, chemical freezeout and dissipation in the hadron phase which are missing in conventional hydrodynamic simulations, cause an accidental reproduction of the elliptic flow data. So the dissipation in the hadron phase is turned out to be important as long as we employ the Glauber-type initial conditions. We find that the color glass condensate (CGC), whose cases are growing in deep inelastic scattering at HERA, gives a larger eccentricity for produced gluon distributions and in turn leads to a larger momentum anisotropy than the conventional Glauber model does. Whether the perfect fluid QGP is discovered depends strongly on the modeling of initial states in relativistic heavy ion collisions.

REFERENCES

1. T. Hirano and M. Gyulassy, Nucl. Phys. A **769**, 71 (2006).
2. T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, and Y. Nara., Phys. Lett. B **636**, 299 (2006).

"RHIC Physics in the Context of the Standard Model"
RBRC workshop on Heavy Ion Physics

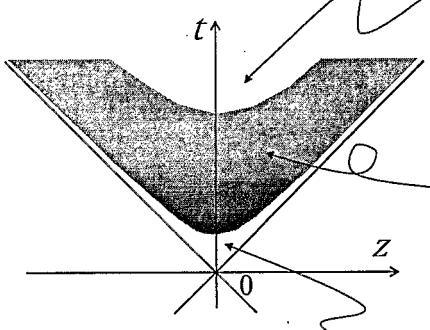
Perfect Fluid QGP or CGC?

Tetsufumi Hirano*
Institute of Physics, University of Tokyo

* Visiting scientist at RBRC

References:
T.Hirano and M.Gyulassy, Nucl.Phys.A **769**(2006)71.
T.Hirano, U.Heinz, D.Kharzeev, R.Lacey, Y.Nara, Phys.Lett.B **636** (2006)299; work in progress.

Three Inputs for Hydrodynamic Models



Final stage:
Free streaming particles
→ Need decoupling prescription

Intermediate stage:
Hydrodynamics can be valid as far as local thermalization is achieved. → Need EoS $P(e,n)$

Initial stage:
Particle production, pre-thermalization, instability?
→Instead, initial conditions are put for hydro simulations.

Need modeling
(1) EoS, (2) Initial cond., and (3) Decoupling

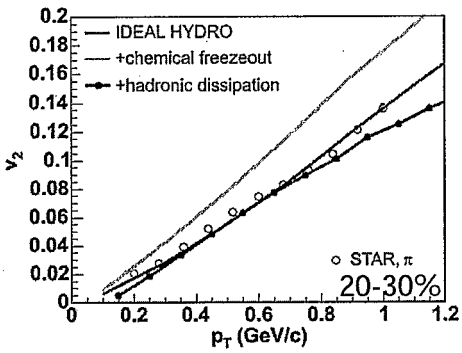
Note on Hydrodynamic Results

Obviously, final results depend on modeling of

1. Equation of state
2. Initial condition
3. Freezeout

So it is indispensable to check sensitivity of conclusion to model assumptions and try to reduce model parameters.
In this talk, I will cover 2 and 3.

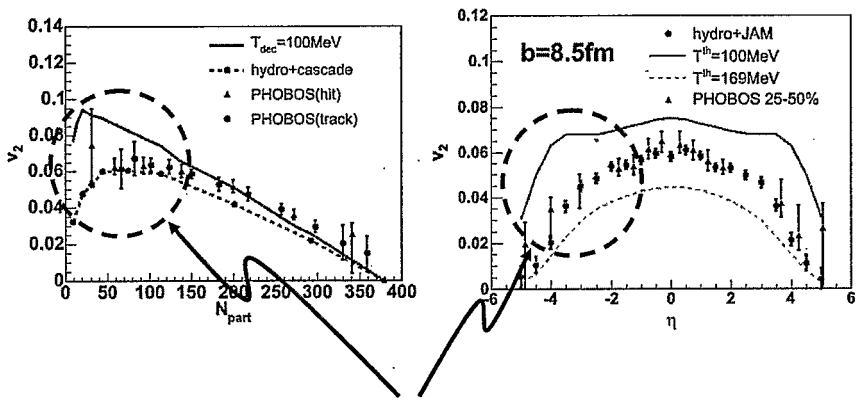
$v_2(p_T)$ for Different Freezeout Prescriptions



2000 (Heinz, Huovinen, Kolb...)
Ideal hydro w/ chem.eq.hadrons
2002 (TH,Teaney,Kolb...)
+Chemical freezeout
2002 (Teaney...)
+Dissipation in hadron phase
2005 (BNL)
"RHIC serves the perfect liquid."

Why so different/similar?

$v_2(N_{part})$ and $v_2(eta)$



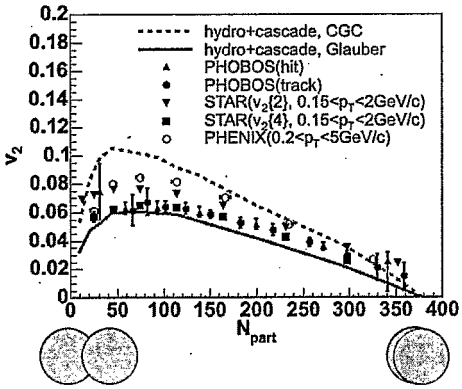
Significant Hadronic Viscous Effects
at Small Multiplicity!

Summary So Far

- When we employ Glauber-type initial conditions, hadronic dissipation is indispensable.
- Perfect fluid QGP core and dissipative hadronic corona

TH et al.('06)

$v_2(N_{part})$ from QGP Hydro + Hadronic Cascade



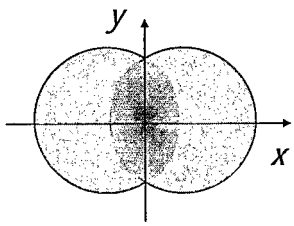
Glauber:
- ✓ Early thermalization
- ✓ Mechanism?

CGC:
- ✓ No perfect fluid?
- ✓ Additional viscosity is required in QGP

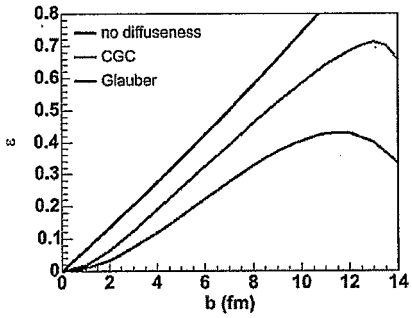
Importance of better understanding of initial condition

Large Eccentricity from CGC Initial Condition

Hirano and Nara('04), Hirano et al.('06)
Kuhlman et al.('06), Drescher et al.('06)



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

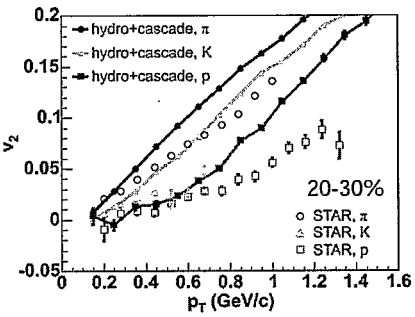


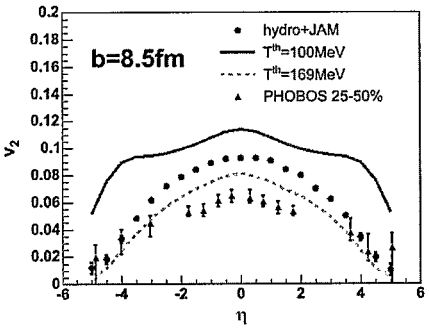
Pocket formula (ideal hydro):

$v_2 \sim 0.2\varepsilon$ @ RHIC energies

Ollitrault('92)

$v_2(p_T)$ and v_2(eta) from CGC initial conditions





v_2(model) > v_2(data)

Summary and Outlook

Initial Condition	Glauber-type	Color Glass Condensate
Freezeout		
Sudden freezeout	Dis... "P... Liquid"	Not a relevant picture
Hadronic rescattering	Discovery of "Perfect Liquid"	Non-perfect fluid of QGP???

FAKE!

- Much more studies needed for initial states
- Still further needed to investigate EOS dependence
- To be or not to be (consistent with hydro), that is the question!

Some topics about Color Glass Condensate

Kazunori Itakura

Institute of Particle and Nuclear Studies, KEK, Japan

Abstract

Recent progress in the theoretical description of the Color Glass Condensate (CGC) was briefly reported. The CGC is a universal state of matter which appears in the limit of large scattering energy. It is made of gluons having **colors**, which are created by almost frozen color sources (a situation similar to a spin **glass**). Besides, the density of gluon is very high, and the state is like a **condensation**. The standard theoretical description of the CGC is given by the Balitsky-Kovchegov (BK) equation, which is a result of the mean-field approximation. We know this equation has a variety of interesting phenomena, including saturation (unitarization) of the scattering amplitude and the emergence of a new scale "saturation scale." There are several experimental supports which are consistent with the CGC picture.

However, recently, it has been recognized that the mean-field picture is not valid at very high transverse momenta. In this regime, the mean-field picture should be drastically changed due to fluctuation. This notion came from the remarkable observation that the BK equation is essentially equivalent to the F-KPP equation which is a famous equation describing the reaction-diffusion system such as chemical reaction. Since the F-KPP equation too is obtained in the mean-field picture, it has the same problem. I have discussed the importance of fluctuation in the F-KPP equation and presented the second-quantization method which produces a field theory containing all the information of the reaction-diffusion system, including the effects of fluctuation.

Some topics about Color Glass Condensate

Kazunori Itakura

IPNS, KEK

At the RBRC Alumni workshop

19th June, 2006

Plan

- Introduction
- Theoretical framework for the CGC
- Mean-field picture
  - -- The Balitsky-Kovchegov equation
  - -- Reaction-diffusion dynamics (F-KPP equation)
- Beyond mean-field picture
  - -- Reaction-diffusion dynamics: exact implementation
  - -- Fluctuation & Stochastic F-KPP equation
  - -- Back to the saturation physics
- Summary

Introduction

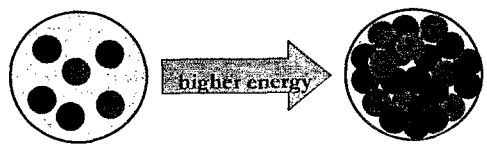
High-energy limit of QCD is the Color Glass Condensate (CGC)!!

Named by Iancu, Leonidov, & McLerran (2000)

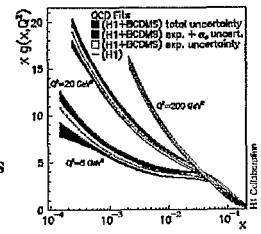
Color : A matter made of gluons with colors.

Glass: Almost "frozen" random color source creates gluon fields

Condensate: High density. Occupation number ~ $O(1/\alpha_s)$



Dilute gas **CGC: high density gluons**



Experimental supports:

Enhancement of gluon distribution in a proton at small x

Geometric scaling at DIS and eA

Suppression of R_{dAu} at forward rapidity in deuteron-Au collisions, etc,...

Mean-field picture (2/4)

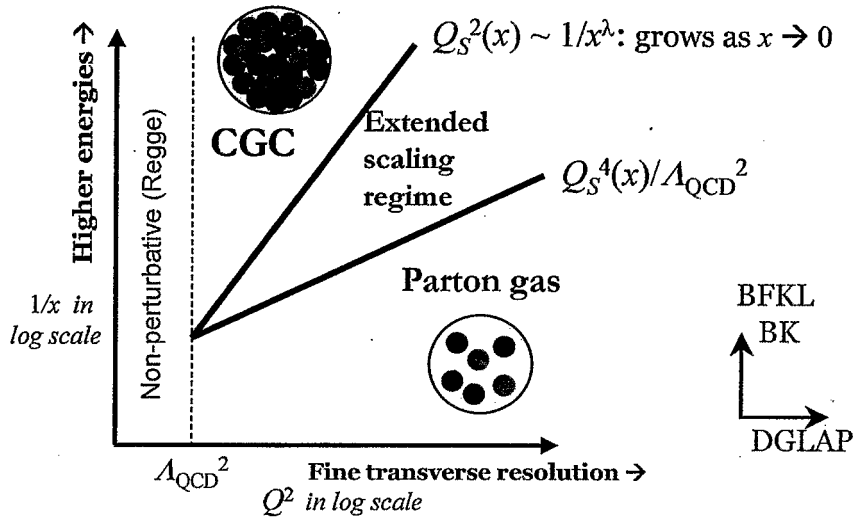
The Balitsky-Kovchegov equation

$$\partial_Y \langle T_{xy} \rangle = \frac{\bar{\alpha}}{2\pi} \int d^2 z \frac{(x-y)^2}{(x-z)^2 (z-y)^2} \left[\langle T_{xz} \rangle + \langle T_{zy} \rangle - \langle T_{xy} \rangle - \langle T_{xz} \rangle \langle T_{zy} \rangle \right]$$

Consequences

- BFKL + non-linear term
  - → $\langle T_{xy} \rangle_Y$ saturates (unitarizes) at fixed $b = (x+y)/2$: $\langle T_{xy} \rangle_Y \leq 1$
- Saturation scale $Q_s(Y)$
  - → typical $\perp$ size of gluons when $\perp$ area is occupied: $1/Q_s(Y)$
  - → increases with rapidity Y : $Q_s^2(Y) \sim e^{\lambda Y}$
- Geometric Scaling
  - → amplitude $\langle T_{xy} \rangle_Y$ is a function of $(x-y)Q_s(Y)$
- Approximate scaling persists even outside of the CGC regime

Emerging picture



The Reaction-Diffusion dynamics

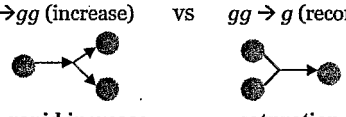
Munier & Peschanski (2003~)

Within a reasonable approximation, the BK equation in momentum space is rewritten as <u>the F-KPP equation</u> (Fisher, Kolmogorov, Petrovsky, Piscounov)

$$\partial_t u = \partial_x^2 u + u - u^2 \quad \text{where } t \sim \tau, \quad x \sim \ln k^2 \text{ and } u(t,x) \sim N_t(k).$$

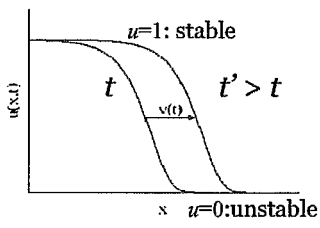
FKPP = "logistic" + "diffusion"

- **<u>Logistic</u>** : "reaction" part
  $g \to gg$ (increase) vs $gg \to g$ (recombination)



rapid increase saturation

- **<u>Diffusion</u>** : expansion of stable region



<u>Traveling wave solution</u>

Wave front : $x(t)=vt$ → saturation scale
Translating solution: $u(x-vt)$ → geometric scaling

Lessons from the reaction-diffusion dynamics

1. **The FKPP equation is *not complete*:**

   It is for an averaged number density in the continuum limit

   $$u(x,t) = \lim_{N\to\infty}\langle n_i(t)/N\rangle$$

   and is valid when allowed number of particles N is *quite large.*

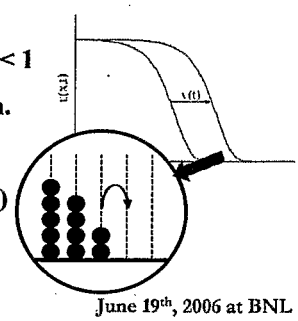
2. **Fluctuation (discreteness) becomes important when the number of particles are *few*.**

   → At the tail of a traveling wave : $u(x,t) \sim 1/N \ll 1$

   → large effect: Diffusion controls the propagation.

   The velocity of a traveling wave is reduced.

   (Linear growth does not work without "seeds")



Field-theory representation

<u>Second quantization method</u> Doi '76 , Peliti '85, Cardy & Tauber '98

a useful technique for a system with creation and annihilation of particles

Introduce bosonic operators a_i^+ creates a particle at site i.

$[a_i, a_j^+] = \delta_{ij}$ $[a_i, a_j] = [a_i^+, a_j^+] = 0$

"Hamiltonian" is defined for a "probability vector"

$$-\partial_t|\Phi(t)\rangle = H|\Phi(t)\rangle, \quad |\Phi(t)\rangle = \sum_{\{n\}} P(\{n\};t)|\{n\}\rangle$$

For A→AA and AA→A, the master equation is <u>exactly</u> reproduced by

$$H = \frac{D}{h^2}\sum_{<i,j>}(a_i^+ - a_j^+)(a_i - a_j) - \lambda_s\sum_i\left((a_i^+)^2 a_i - a_i^+ a_i\right) - \frac{\lambda_m}{2}\sum_i\left(a_i^+ a_i^2 - (a_i^+)^2 a_i^2\right)$$

Can construct a "field theory" by using coherent state path-integral

$$S = \int dxdt\ \bar{\phi}(\partial_t - D\nabla^2)\phi - g_s(\bar{\phi}\phi + \bar{\phi}^2\phi) + g_m(\bar{\phi}\phi^2 + \bar{\phi}^2\phi^2)\Big]$$

where ϕ is a coherent state eigen-value of annihilation operator, $g_s = \lambda_s$, $g_m = \lambda_m h/2$

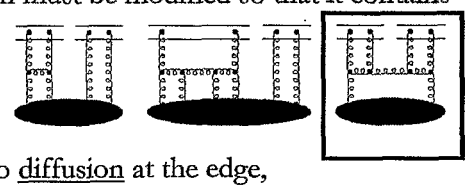
cf) Reggeon field theory (but diffusion is in the impact parameter space)

Back to saturation physics

1. Difference btw Balitsky and BK eqs. becomes significant when gluon (dipole) number is small (high transverse momentum).

$$\langle T(r) \rangle_Y \approx \alpha_s^2 \, n(r,Y) \;<<\; \alpha_s^2$$

2. Inclusion of full fluctuation replaces the F-KPP equation by the **stochastic** F-KPP equation.
   → Even the Balitsky equation must be modified so that it contains dipole splitting.
   → Pomeron loop



3. Saturation scale becomes
   slowly increasing due to <u>diffusion</u> at the edge,
   stochastic variable due to fluctuation term in sFKPP eq.

By Mueller, Shoshi, Iancu, Munier, Tryantafyllopoulos, Soyez, ...

Summary

- **Theoretical description of the Color Glass Condensate is improving. Analogy with the reaction-diffusion dynamics is very useful.**
- **In particular, the effects of fluctuation beyond the mean-field BK picture have been recognized to be significant in dilute regime (at high transverse momentum)**
- **Slowly-growing and stochastic saturation scale is obtained.**
- **Deeper understanding of the reaction-diffusion system is necessary. The field-theory representation will be useful.**

Quarkonium production and propagation in partonic media

Hirotsugu Fujii
(*University of Tokyo*)

RBRC RA: 1997.9 – 1999.3

Abstract

Three related topics are discussed; quarkonium interaction with hadrons at low energies, quarkonium attenuation in nuclear target at high energies, and quarkonium production in high-energy proton-nucleus collisions. Especially, we shall apply the color glass condensate approach to the quarkonium production in dense partonic media, and show phenomenological implications.

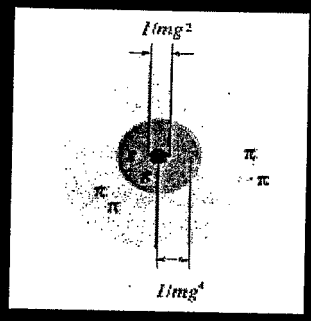
Onium interaction at low energy

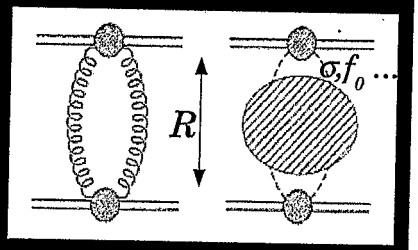
- Short time scale($\tau c = 1/\alpha_s^2 m$) as compared with $1/\Lambda_{QCD}$
- Multipole expansion: separation of long & short distance parts

$$\sum_i c_i O_i \sim d_2 \frac{g^2}{2} E^2 + \cdots$$

- Matching onto chiral theory using anomaly relation -->

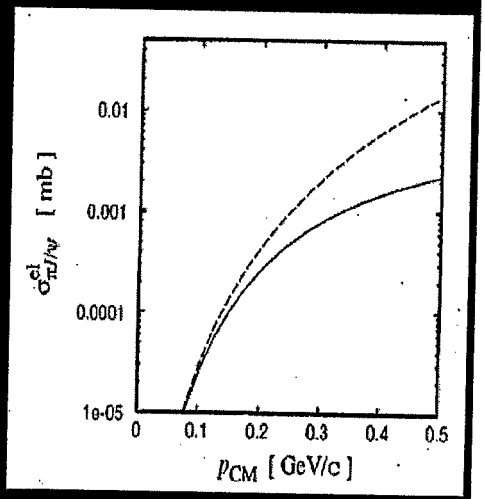
'van der Waals force' of QCD





Onium interaction at low energy

- Onium coupling to soft ext ernal field is weak ~ r^2/ε_0
- Effects of hadron gas on oniua expected small
- Recent lattice atempt

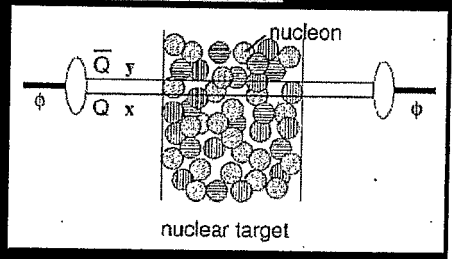


dashed = w/o FormFactor

Onium projected on a nucleus at high energy

- When we boost the onium to higher energy, coherence time τc (= 1/B.E. ~ 0.3 fm for J/ψ) is no longer short:

$$\tau_c \gamma = 30\,fm(RHIC),\ 600\,fm(LHC) > R$$

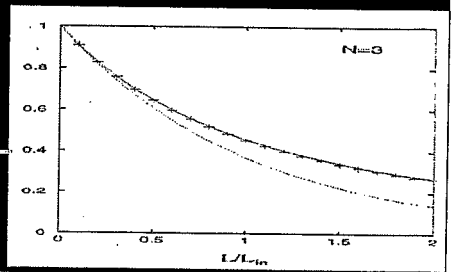


Onium projected on a nucleus at high energy

- The model:
  - Nucleus = random gauge field config.
  - Frozen color dipole traversing straight through a nucleus --> eikonal approx.

$$S(x,y;A) = \frac{1}{N} Tr[\hat{U}(x;A)\ \hat{U}^{\dagger}(y;A)]$$

- Multiple scatterings of Q, Q^{bar}
  - Momentum diffusion
- S=1 for x=y;
  color transparency
- Survival probability = $|(\varphi|S|\varphi)|^2$
  - Non-exponential behavior



Quarkonium production in pA collisions from the CGC

- Extension of onium attenuation model
  - Needs heavy pair production part..
    we have no onium beam anyway
  - Energy dependence

- Use the CGC framework

Quarkonium production in pA collisions from the CGC

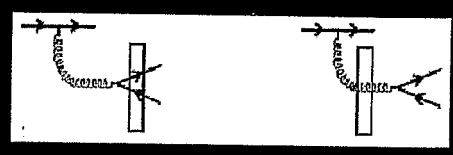
- A dilute proton probes a 'saturated' nucleus
  - Solution known to $O(\rho_p^{\,1}\,\rho_A^{\,\infty})$ in the MV model
  - Need to know 4-pt fn, and integrate numerically

$$\frac{d\sigma_{q\bar{q}}}{d^2\vec{p}_\perp d^2\vec{q}_\perp dy_p dy_q} = \frac{\alpha_s^2 N}{8\pi^4 d_A} \int_{\vec{k}_{1\perp},\vec{k}_{2\perp}} \frac{\delta(\vec{p}_\perp + \vec{q}_\perp - \vec{k}_{1\perp} - \vec{k}_{2\perp})}{k_{1\perp}^2 k_{2\perp}^2}$$

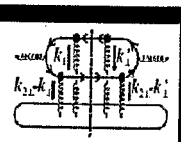
$$\times \Big\{ \int_{\vec{k}_\perp,\vec{k}'_\perp} \mathrm{tr}\Big[(\not{q}+m)T_{q\bar{q}}(\vec{k}_\perp)(\not{p}-m)T^*_{q\bar{q}}(\vec{k}'_\perp)\Big]\phi_A^{qq,q\bar{q}}(\vec{k}_{2\perp}|\vec{k}_\perp,\vec{k}'_\perp)$$

$$+ \int_{\vec{k}_\perp} \mathrm{tr}\Big[(\not{q}+m)T_{q\bar{q}}(\vec{k}_\perp)(\not{p}-m)L^* + \mathrm{h.c.}\Big]\phi_A^{q\bar{q},g}(\vec{k}_{2\perp}|\vec{k}_\perp)$$

$$+\mathrm{tr}\Big[(\not{q}+m)L(\not{p}-m)L^*\Big]\varphi_A^{g,g}(\vec{k}_{2\perp})\Big\}\varphi_p(\vec{k}_{1\perp})$$

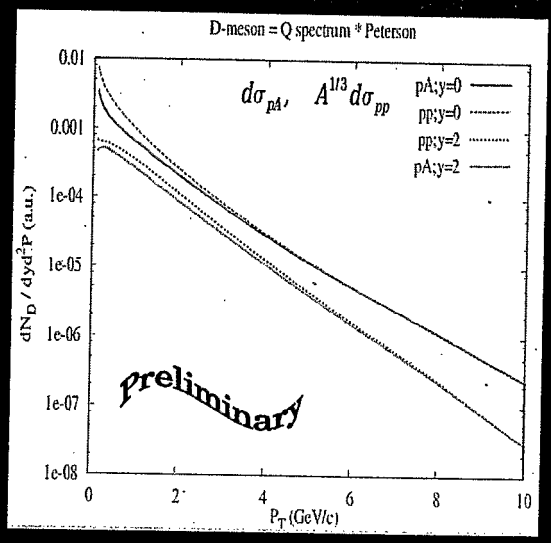


$\phi_A^{qq,q\bar{q}} \sim \mathrm{FT}\ \mathrm{tr}(\tilde{U}^\dagger t^a \tilde{U}^\dagger \tilde{U} t^a \tilde{U}) \propto$



Open charm production

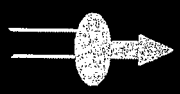
- Comparison btwn pp & pA in our model
- 'Saturation' effect seen only for $p_T \lesssim Q_S$; suppression in pA
- Higher p_T, pA = sum of pp

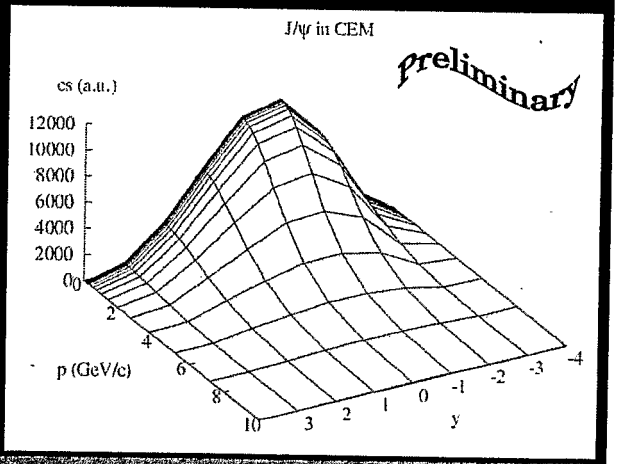


J/Ψ production

- use Color Evaporation Model (CEM) to convert pair cross section to quarkonium cross section

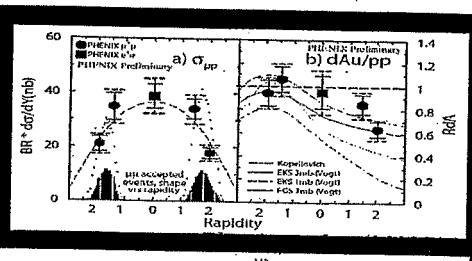
$$\frac{dN_{J/\psi}}{dY d^2P_\perp}\bigg|_{CEM} = F_{J/\psi} \int_{4m^2}^{4m_D^2} dM^2 \frac{dN}{dY d^2P_\perp dM^2}$$

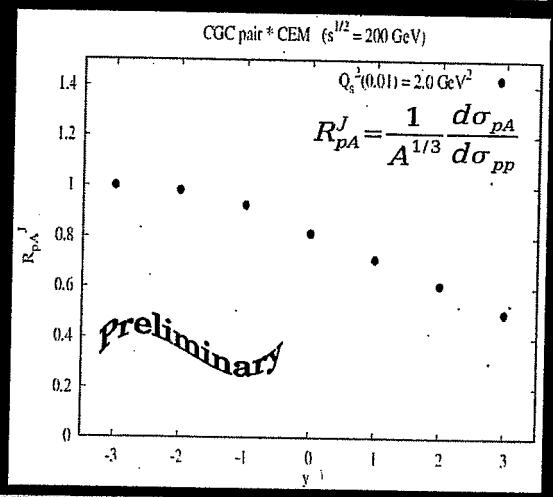




J/Ψ production

- Y-dependence of normal suppression
- Comparison with data in progress – no parameter search yet
- Other production mechanisms than CEM to be studied as well





Remarks

- Quarkonia are good test ground to apply perturbative/non-perturbative methods in QCD
  - Van der Waals force of QCD, CGC approach, ...
- In CGC framework, we can now compute $Q\bar{Q}$ production including both the effects of multiple scatterings and gluon saturation
  - Systematic parameter scan is underway

Charm production at high parton densities

Kirill Tuchin [a,b]

[a] *Department of Physics and Astronomy,*

Iowa State University, Ames, IA 50011

[b] *RIKEN BNL Research Center, Upton, NY 11973-5000*

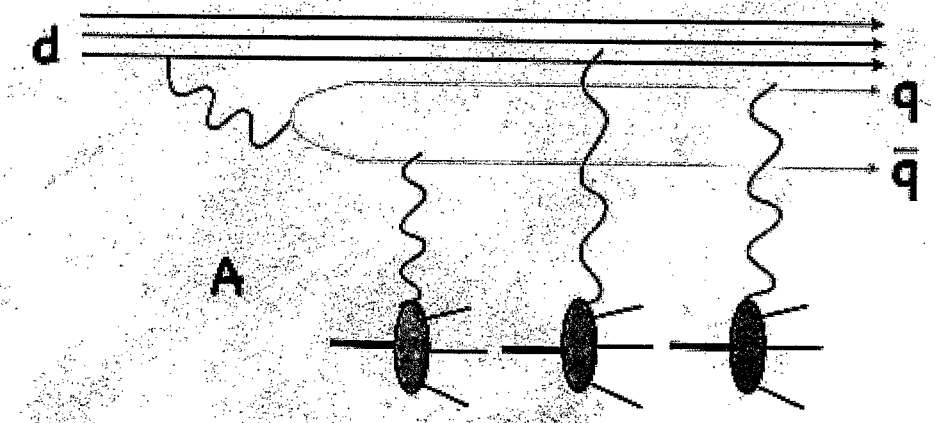
We discuss open and hidden charm production in p(d)A collisions in High Parton Density QCD in quasi-classical approximation and including low-x quantum evolution. We argue that the coherence length of charm production at RHIC becomes much larger than the nuclear radius at forward rapidities. This allows us to use the dipole model and calculate the open charm production including effects of multiple rescatterings and quantum evolution. We also suggest a simple model for J/Ψ production which is in the reasonable agreement with experimental data.

Heavy Quark Production in pA collisions

- coherence length of qq pair

$$l_c \approx \frac{E_g}{(2m_q)^2} = \frac{1}{2M_N x_2}$$

where $x_2 = \frac{m_T}{\sqrt{s}} e^{-y}$

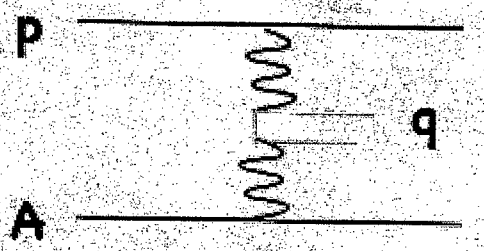


- For charm at RHIC $l_c = 15 e^y \,\mathrm{fm}$
- At forward rapidity $l_c \gg R_A$

- Dipole model: color dipoles diagonalize the scattering matrix.

Single inclusive quark cross-section

KT;
Kovchegov, KT



Size of the initial dipole

Number of dipoles in proton

Total rapidity Quark rapidity

$$\frac{d\sigma}{d^2k\,dy_1\,dy_2}(z_{01}) = \frac{1}{2(2\pi)^4}\int d^2z_0'\,d^2z_1'\,n_1(\underline{z}_0,\underline{z}_1;\underline{z}_0',\underline{z}_1';Y-y)\,d^2x_1\,d^2x_2\,d^2y_1\,e^{-i\underline{k}\cdot(\underline{x}_1-\underline{y}_1)}$$

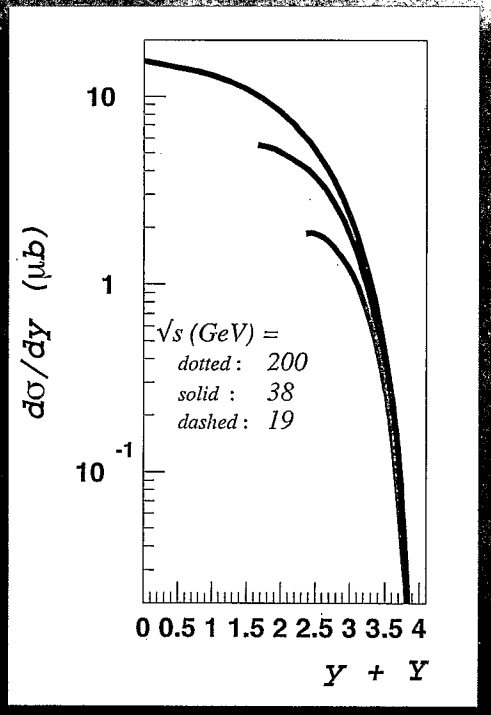
$$\times\int_0^1 d\alpha\sum_{i,j=1}^{3}\sum_{k,l=0}^{1}(-1)^{k+l}\,\Phi_{ij}(\underline{x}_1-\underline{z}_k,\underline{x}_2-\underline{z}_k;\underline{y}_1-\underline{z}_l,\underline{x}_2-\underline{z}_l;\alpha)\,\Xi_{ij}(\underline{x}_1,\underline{x}_2,\underline{z}_k;\underline{y}_1,\underline{x}_2,\underline{z}_l;\alpha,y)$$

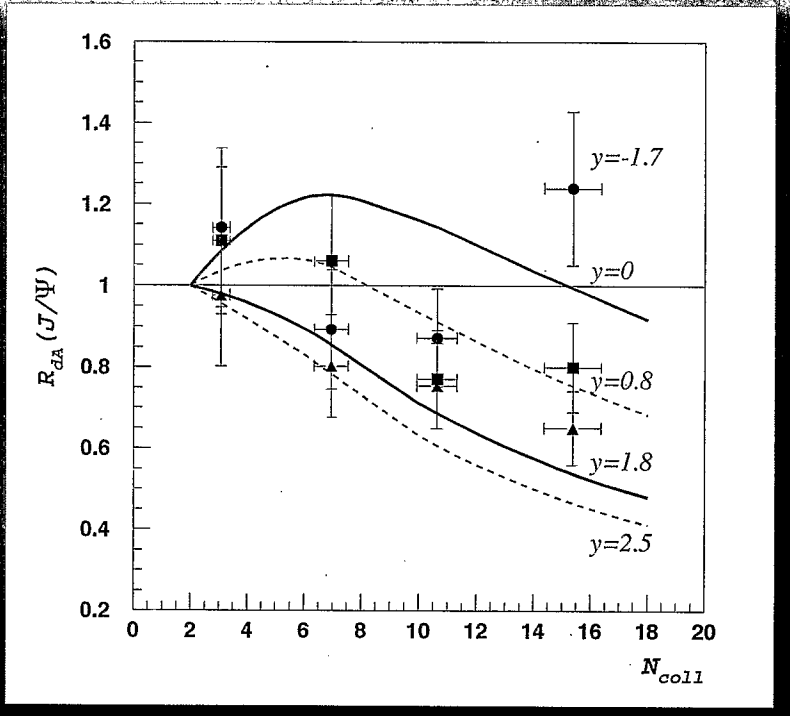
qq wave functions for different time orderings

Rescattering factors

see also Blaizot,
Gelis, Venugopalan

Our model vs data (by PHENIX)



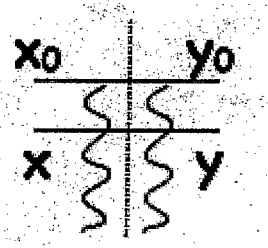


Cold nuclear matter absorption at low energies $S=\exp(-\sigma_{\psi N}\rho L)$

Onset of suppression: $Q_s > M_\psi$

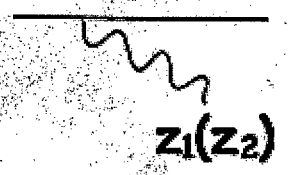
J/ψ at forward rapidities

- cc scattering amplitude projected on the color singlet state (large N_c)



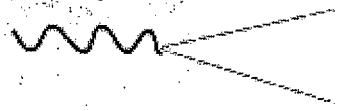
$$\mathcal{M}_1(\underline{x},\underline{x}_0,\underline{y},\underline{y}_0) = \frac{1}{4}\left(\frac{Q_s^2}{4}\right)^2 \left[(\underline{x}-\underline{y})^2 + (\underline{x}_0-\underline{y}_0)^2\right]^2$$

- light cone wave function of a proton

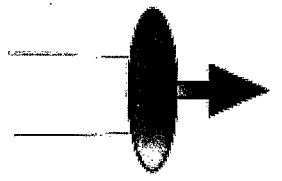


$$\Phi(\underline{z}_1,\underline{z}_2) = \frac{\alpha_s C_F}{2\pi}\frac{\underline{z}_1\cdot\underline{z}_2}{\underline{z}_1^2\underline{z}_2^2}$$

- light cone wave function of a virtual gluon



- projection on a hadron wave function



$$\Psi_\psi \otimes \Psi_{g^*}(\underline{r},\alpha=1/2) = \sqrt{\frac{3\Gamma_{ee}M_\psi}{48\alpha_{em}\pi}}\,\frac{m^3\underline{r}^2}{4}\,K_2(mr)$$

Beyond a quasi-classical approximation

- This resummation amounts to replacement of the Glauber exponent by a solution of the BK evolution equation (Kovchegov, K.T.):

$$e^{-\frac{1}{4}(\underline{x}_0-\underline{x}_1)^2 Q_s^2 \ln(1/|\underline{x}_0-\underline{x}_1|\mu)} \longrightarrow N(\underline{x}_0, \underline{x}_1, Y)$$

$$\partial_y N(\underline{x}_{01}) = \frac{\alpha_s}{2\pi}\int d^2x_2 \frac{\underline{x}_{01}^2}{\underline{x}_{12}^2\,\underline{x}_{20}^2}\left(N(\underline{x}_{12}) + N(\underline{x}_{20}) - N(\underline{x}_{01}) - N(\underline{x}_{12})N(\underline{x}_{20})\right)$$

Balitski-Kovchegov

also JIMWLK

- The saturation scale acquires the energy dependence

$$Q_s^2 = \Lambda^2 A^{1/3} e^{\lambda y} e^{\lambda s/2}$$

- Number of dipoles in proton (deuteron) evolves according to the BFKL equation.

Strangeness Physics at RHIC

Jürgen Schaffner–Bielich

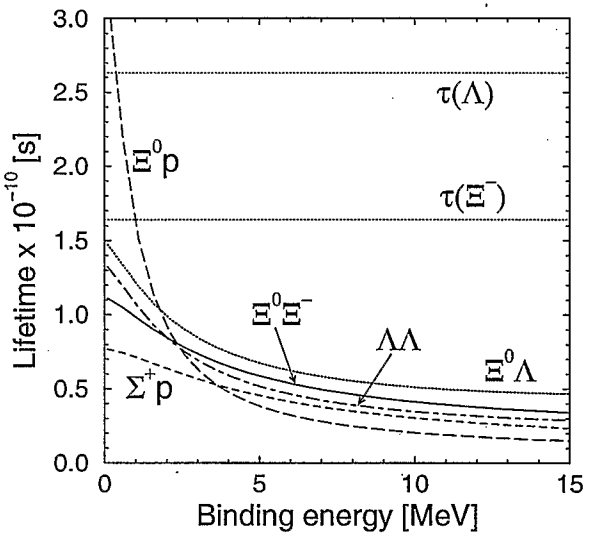
Institute for Theoretical Physics/Astrophysics

JOHANN WOLFGANG GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

RHIC Physics in the Context of the Standard Model:
A Workshop and Symposium
RIKEN BNL Research Center, BNL, New York, USA, June 18–23, 2006
(partly based on topical review in JPG 30 (2004) R245)

range Dibaryons – Candidates and Lifetime

(JSB, Mattiello, Sorge, PRL 84 (2000) 4305)

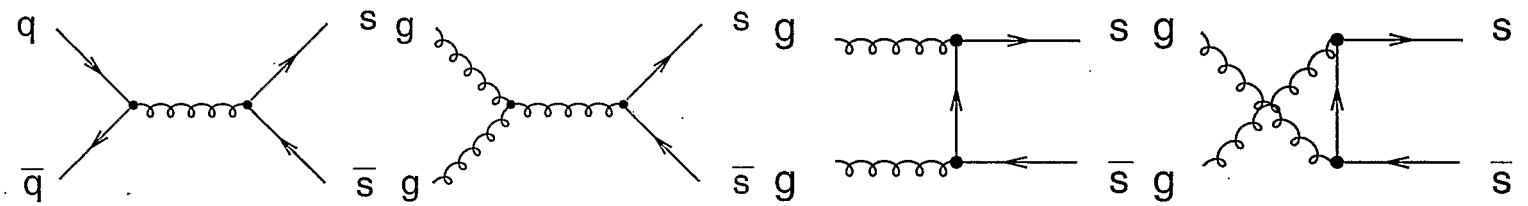


$$_{\text{weakSU(3)}} = D\mathrm{Tr}\bar{B}B\,[P,\lambda_6] + F\mathrm{Tr}\bar{B}\,[P,\lambda_6]\,B + G\mathrm{Tr}\bar{B}P\gamma_5 B\lambda_6 + H\mathrm{Tr}\bar{B}\lambda_6\gamma_5 BP + J\mathrm{Tr}\bar{B}\{P,\lambda_6\}\gamma_5 B$$

- best observable dibaryon decay products: p, Λ, Ξ^- only!
- corresponding bound candidates: $(\Sigma^+ p)_b \to p + p$, $(\Xi^0 p)_b \to \Lambda + p$, $(\Lambda\Xi^0)_b \to \Lambda + \Lambda$ or $\Xi^- + p$, $(\Xi^-\Xi^0)_b \to \Xi^- + \Lambda$
- lifetime estimates: $c\tau = 1 - 5$ cm (only slightly smaller than hyperon lifetimes) depending on binding energy

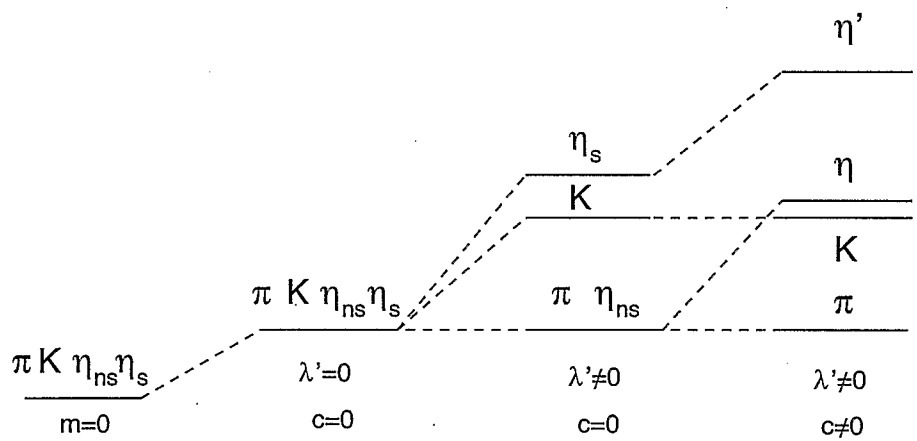
rangeness enhancement in the quark-gluon plasma

(J. Rafelski and B. Müller, PRL 48 (1982) 1066)



- producing strangeness via quarks: $q + \bar{q} \leftrightarrow s + \bar{s}$, $q = u, d$ quarks
- and gluons: $g + g \leftrightarrow s + \bar{s}$
- Q-value of reaction: $Q_{qgp} = 2m_s \approx 200$ MeV, comparable to critical temperature T_c!
- Q-value for hadron gas (associated production): $NN \rightarrow N\Lambda K$, $Q_{hg} = m_\Lambda + m_K - m_N \approx 670$ MeV!

U(3) chiral effective Lagrangian at $T \neq 0$ (Lenaghan, Rischke, JSB)

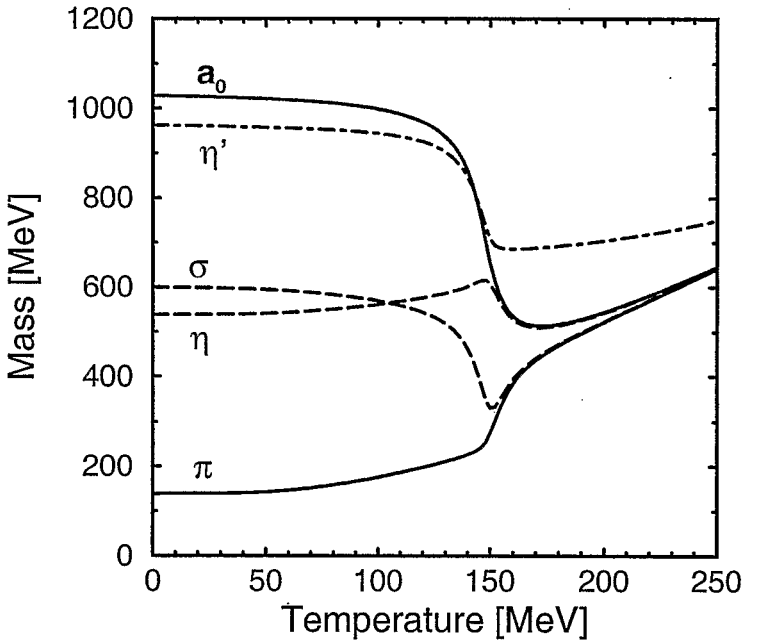


$$= \mathcal{L}_{\rm kin} + \frac{1}{2}\mu^2 {\rm Tr} M^\dagger M - \lambda \cdot \left({\rm Tr} M^\dagger M\right)^2 - \lambda' \cdot {\rm Tr}\left(M^\dagger M\right)^2 + c \cdot \left(\det M + \det M^\dagger\right) + \epsilon \cdot \sigma + \epsilon' \cdot \zeta$$

- hadrons involved: pseudoscalar mesons (π,K,η,η') and their chiral partners, the scalar mesons (σ,κ,a_0,f_0)
- mass splittings: complete degeneracy without mass or interaction terms
- $\lambda' \neq 0$ breaks O(18) symmetry, mass splitting according to strangeness
- the $U_A(1)$ anomaly ($c \neq 0$) breaks $\eta_{ns} - \pi$ degeneracy, heavy η'!

hiral symmetry restoration II

(JSB, PRL 84 (2000) 3261)



- η' becomes degenerate with a_0, not η!
- reflects the fact, that η' is mainly nonstrange
- level crossing visible between η and η' around T_c
- the mesons η and η' switch roles at T_c! (η' enhancement at and above T_c)

ummary: A Strange Puzzle and a Strange Conclusion?

- enhanced strangeness production in QGP and in chirally restored phase
- issue is not fully addressed in resummed calculations and/or with effects from CGC or sQGP!
- SU(3) chiral symmetry restoration predicts huge effects on mass spectrum for mesons
- but measured particle ratios as in (free) phase-space statistical approaches
- where is the interaction? where is chiral symmetry restoration?
- solution 1: there is no deconfined/chirally restored matter formed (we do not want that)
- solution 2: final particle production happens out of equilibrium (but strong collective behaviour observed, elliptic flow)
- $\Longrightarrow$ need a collective out-of-equilibrium process! (reminds one of the physics of the very early universe)

Fluctuations in Hot and Dense Matter

Sangyong Jeon

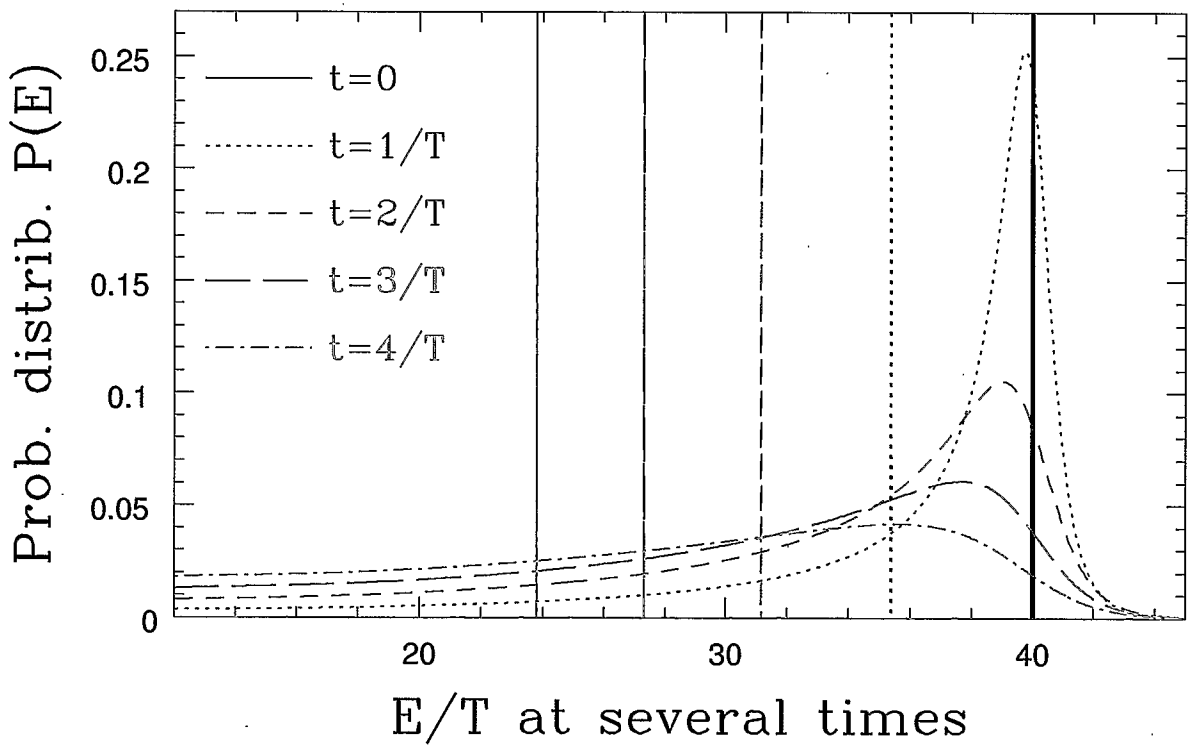
McGill University,
RBRC-BNL RHIC Fellow (Jan.2001 – Dec.2005)

Abstract

In the QGP phase, net charge fluctuations per entropy is small due to the fact that quarks have fractional charges and gluon contribution to the entropy is as important as quark contribution. If the system produced by RHIC collisions is inhomogeneous, this effect should be observable using a local measure of charge fluctuations, namely, the charge transfer fluctuations.

Why fluctuations?

- Average can be (quite) misleading – I



Evolution of jet $P(E)$. (Jeon and Moore, PRC71:034901, 2005)

Net Charge Fluctuations

- Motivations [Jeon & Koch + Asakawa, Heinz & Muller, PRL **85**, 2000]
  - * Quarks carry fractional charges
  - * Gluons are abundant
  - * In QGP (with appropriate degeneracy factors (12+12+16))

$$\left\langle \Delta Q^2 \right\rangle = (9/4) \left\langle \Delta N_u^2 \right\rangle + (9/1) \left\langle \Delta N_d^2 \right\rangle$$

and invoking 'parton-hadron duality'

$$\langle N_{\text{ch}} \rangle \approx (2/3)(\langle N_u \rangle + \langle N_d \rangle + \langle N_g \rangle)$$

we get (and Lattice confirms it)

$$\frac{\left\langle \Delta Q^2 \right\rangle}{\langle N_{\text{ch}} \rangle} \approx 1/4 - 1/3$$

Charge Transfer Fluctuations

$$\kappa(y) \equiv \frac{D_u(y)}{dN_{\text{ch}}/dy} \propto \lambda(y)$$

Constant $\kappa(y)$: Thomas-Chao-Quigg Relationship

- Measure of the *local* charge correlation length

  [Net charge fluct. and Balance func : Averaged inside the obs. window]

- In elementary particle collisions, $\kappa(y) \approx$ const

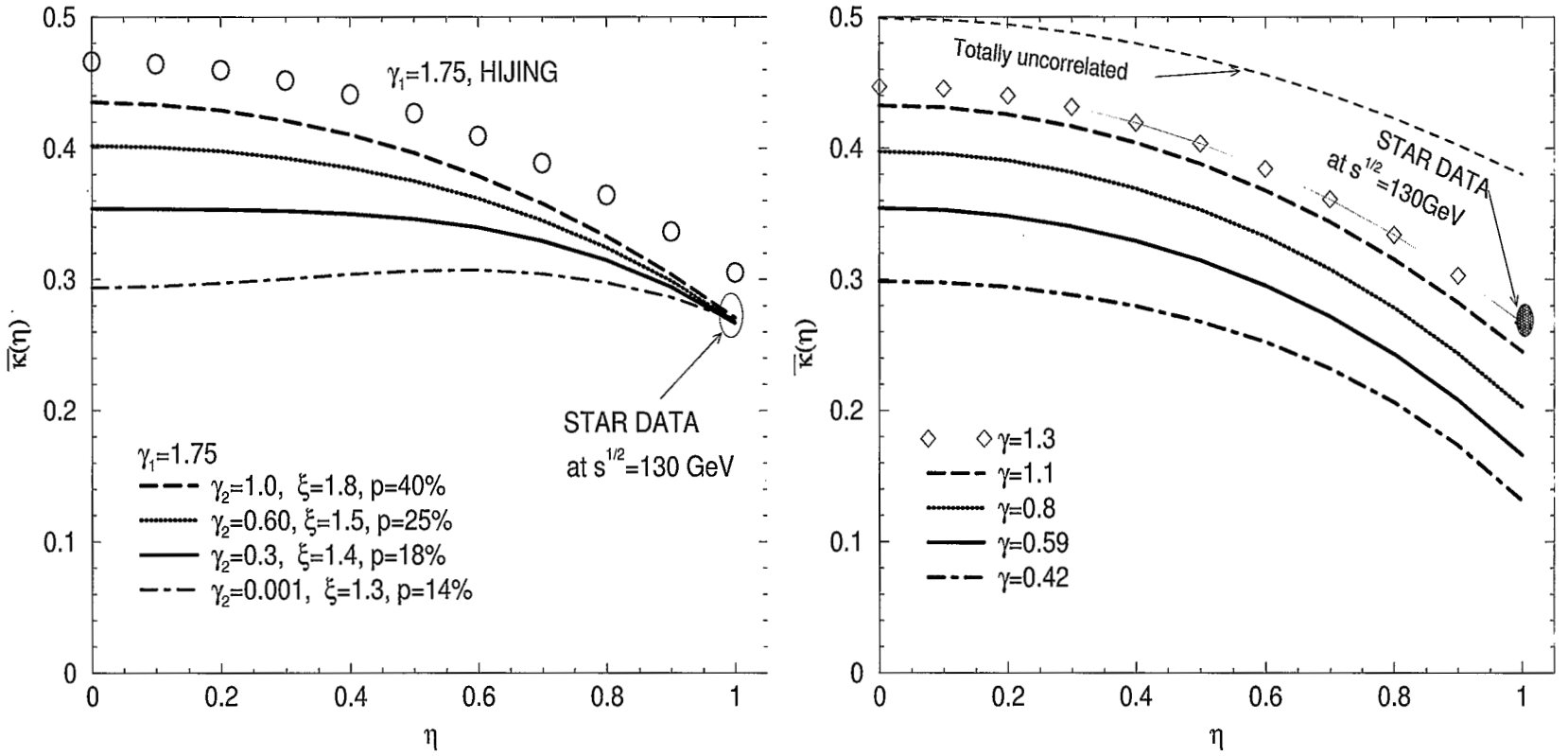
- If QGP has a much smaller λ, its presence should be reflected in $\kappa(y) \Longrightarrow$Captures *inhomogeneity*.

  * $\kappa_{AA} < \kappa_{PP}$

  * $\kappa_{AA}(y)$: Significantly different from constant if QGP is made only locally

HG + QGP – STAR acceptance

End point fixed by $\left\langle \Delta Q^2 \right\rangle / N_{\mathrm{ch}}$



Left: 2-comp. results. Right: Single comp. results.

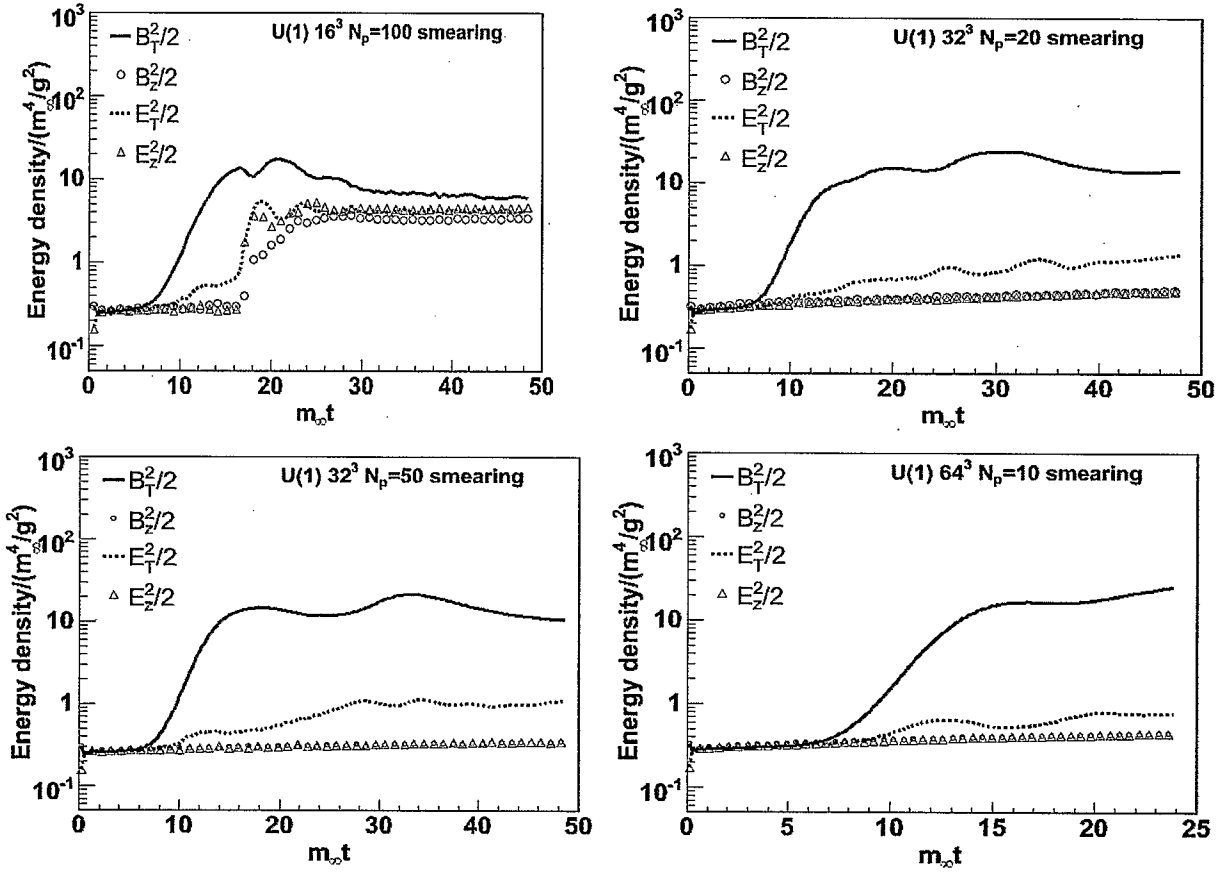
Numerical Studies of Thermalization

Yasushi Nara
Johann Wolfgang Goethe University,
Frankfurt am Main

We present solutions of coupled particle-field evolution in classical U(1) and SU(2) gauge theories in real time on three-dimensional lattices. For strongly anisotropic particle momentum distributions, we find qualitatively different behavior for the two theories when the field strength is high enough that non-Abelian self-interactions matter for SU(2). It appears that the energy drained by a Weibel-like plasma instability from the particles does not build up exponentially in transverse magnetic fields but instead returns, isotropically, to the hard scale via a rapid avalanche into the ultraviolet.

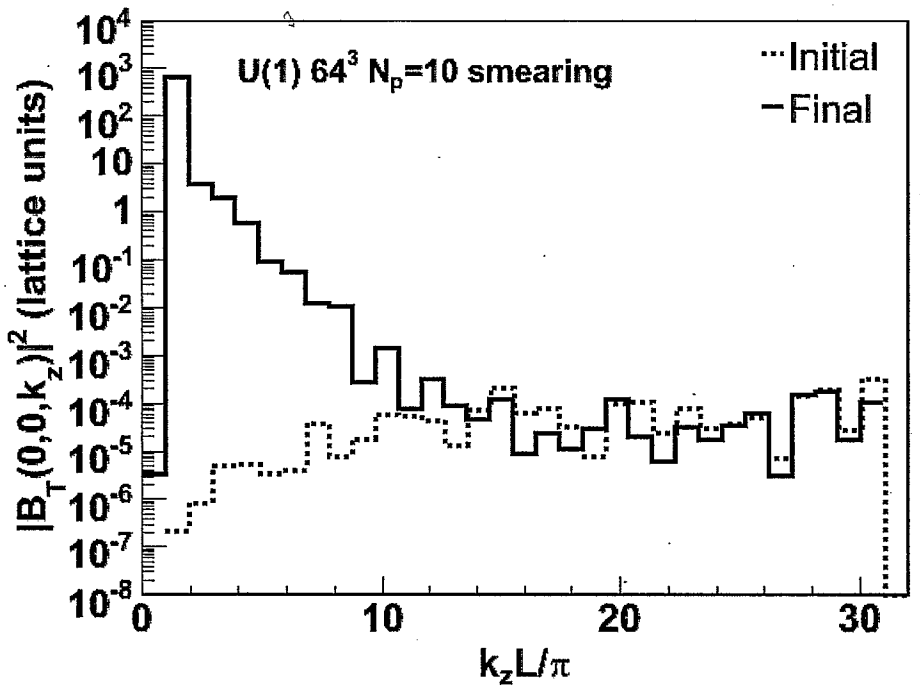
Adrian Dumitru and Y. N, Phys. Lett. B621,89 (2005).
Adrian Dumitru, Y.N. , Mike Strickland, hep-ph0604149.

U(1) results for 3D+3V: good!



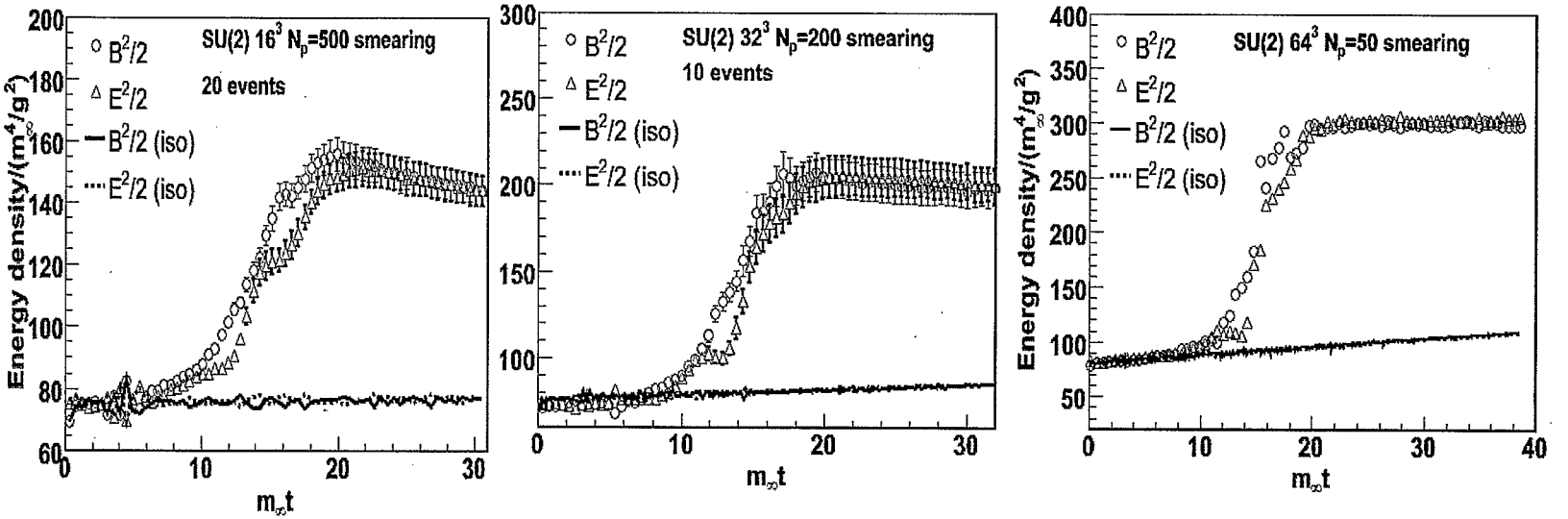
- Exponential growth of magnetic field. independent of lattice spacing.

Fourier transform of the transverse magnetic field in U(1)



No UV problem in U(1). Soft modes unstable, hard modes stable.

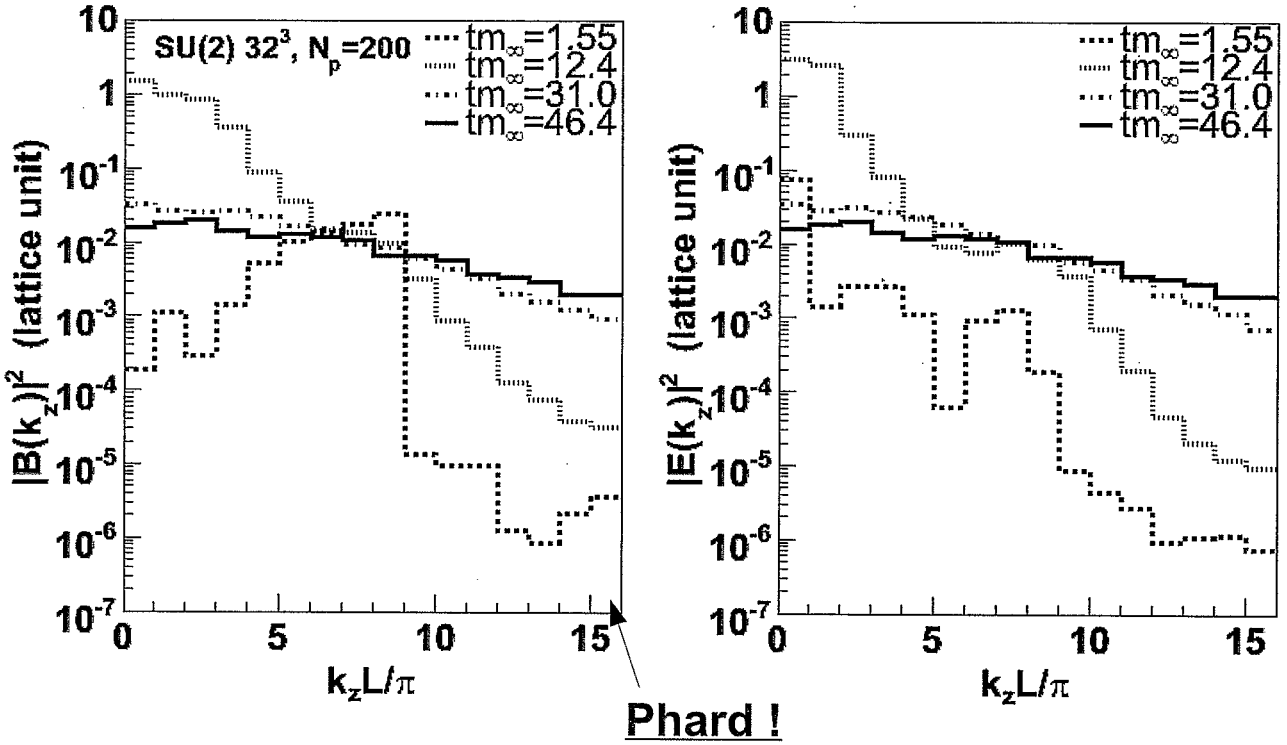
SU(2) for 3D+3V



We have developed a particle in cell simulation method by introducing current smearing in SU(2) case.

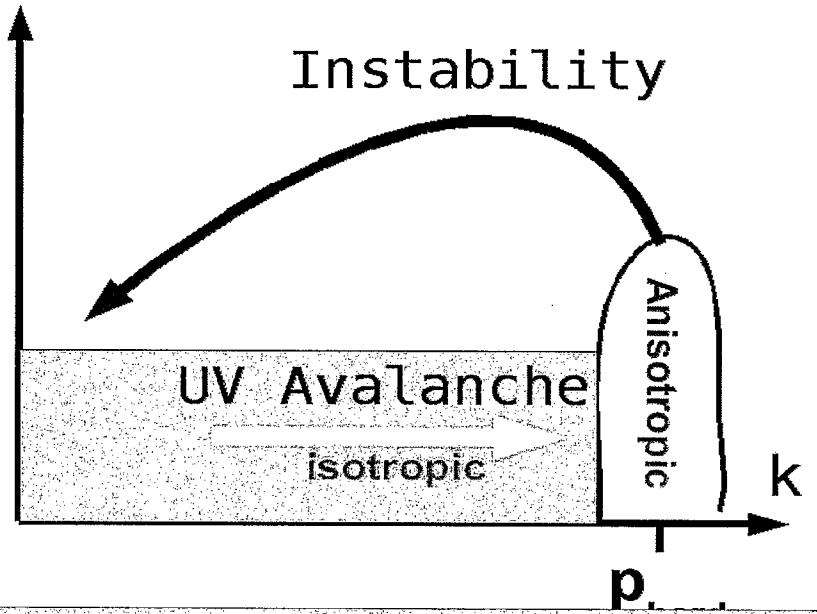
Field strength grow with inverse lattice spacing!

Time evolution of the Fourier transformed fields in SU(2) 3D+3V



Soft fields rapidly avalanche to the UV

Collective process driving thermalization at RHIC/LHC ?



☆ Proper definition of classical dynamics of soft+hard modes in gauge theories beyond the hard-loop approx. is lacking !

Electric Dipole Moment Searches in Nuclei, Atoms, and Molecules

A permanent electric dipole moment (EDM) of a fundamental particle would violate parity and time-reversal symmetries. Standard model predictions for EDMs are typically well below current experimental sensitivities, but theories of physics beyond the standard model often predict dramatically enhanced EDMs within the sensitivity of a new generation of EDM experiments.
In the presentation, a few of these next-generation experiments and their prospects are described.

Dave Kawall : RIKEN-BNL Research Center and University of Massachusetts at Amherst

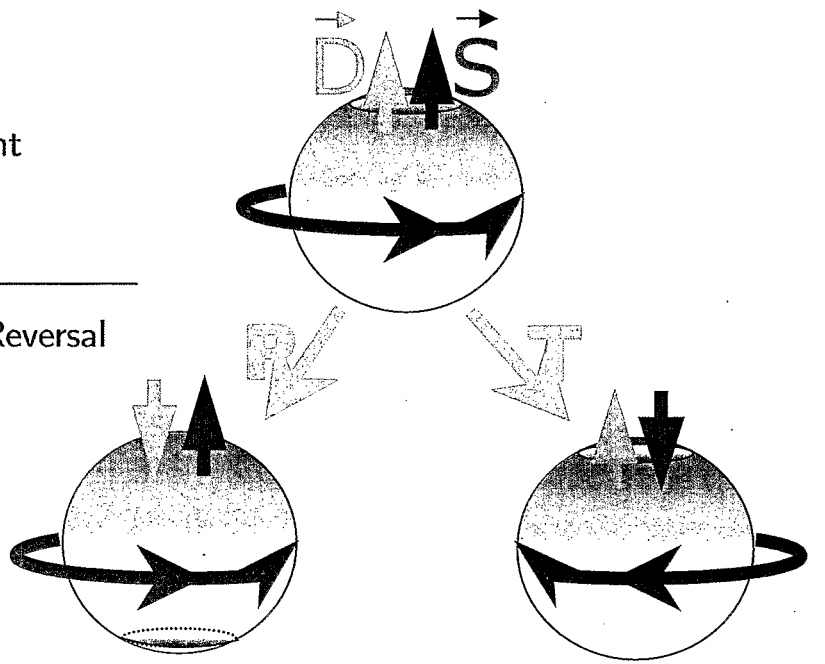
What is a Permanent Electric Dipole Moment (EDM) ?

- Non-rel. Hamiltonians of bare spin 1/2 particle with EDM $\vec{d}$ and magnetic moment $\vec{\mu}$

$$H_{\text{Magnetic Dipole}} = -\vec{\mu}\cdot\vec{B} \;=\; -\mu\vec{\sigma}\cdot\vec{B}$$

$$H_{\text{Electric Dipole}} = -\vec{d}\cdot\vec{E} \;=\; -d\vec{\sigma}\cdot\vec{E}$$

- EDM is an analog of a magnetic dipole moment
- Manifests itself as a linear Stark effect



Behavior of Moments under Parity and Time Reversal

	$\vec{\sigma}\sim\vec{r}\times\vec{p}$	$\vec{B}\sim\vec{j}\times\vec{r}/\lvert\vec{r}\rvert^3$	$\vec{E}\sim-\vec{\nabla}V$
P	even	even	odd
T	odd	odd	even

- $H_{\text{Magnetic Dipole}}$ is P-even and T-even
- $H_{\text{Electric Dipole}}$ is P-odd and T-odd !!!

$\Rightarrow$ For fundamental particle to have EDM P and T must be violated

Effective Low Energy MSSM CP-violating Lagrangian

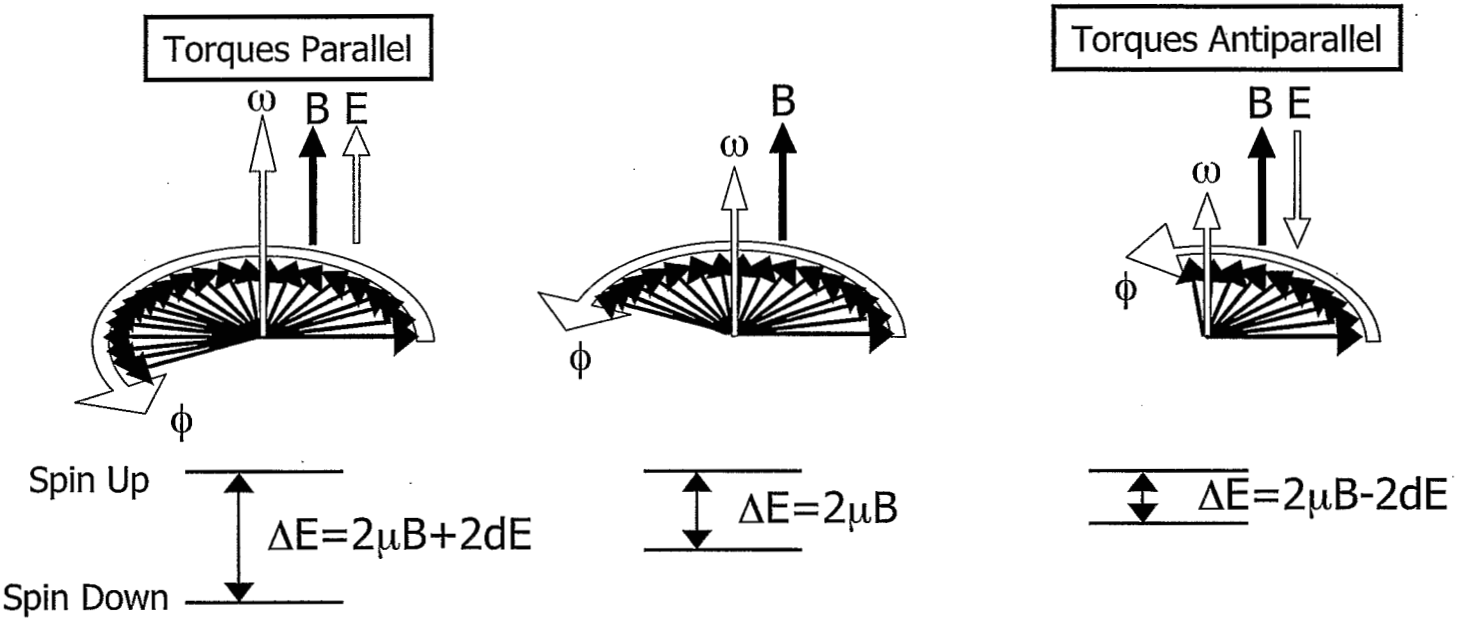
(From D. Demir *et al.*, Nucl. Phys. B **680**, 339 (2004))

$$\mathcal{L}_{\text{eff}} = \frac{g_s^2}{32\pi^2}\bar{\Theta}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3}w f^{abc}G^a_{\mu\nu}\tilde{G}^{\nu\beta,b}G^{\mu,c}_{\beta} - \frac{i}{2}\sum_{i=e,u,d,s} d_i\bar{\Psi}_i\gamma_5\sigma^{\mu\nu}\Psi_i F_{\mu\nu} - \frac{i}{2}\sum_{i=e,u,d,s} d_i^c\bar{\Psi}_i g_s\gamma_5\sigma^{\mu\nu}\lambda^a\Psi_i G^a_{\mu\nu}$$

- Contributions : $\bar{\Theta}$, Weinberg 3-gluon, EDMs of e and quarks d_i, chromo-edms of quarks d_i^c
- $|d_{Hg}|$ limits $\rightarrow$ $\bar{\Theta} < 1.5 \times 10^{-10}$, *a priori* $\bar{\Theta} \approx 0 - 2\pi$
  - If Peccei-Quinn axions exist $\bar{\Theta} \rightarrow 0$
  - Radiative corrections to $\bar{\Theta}$ may induce non-negligible EDM
- The CP-odd term cubic in $G^a_{\mu\nu}$ seldom dominates the EDM of a nucleon
- For given manner of SUSY breaking w, d_i, d_i^c can be calculated
  - From quark level to nucleon level involves nuclear models : w, $d_{u,d,s}$, $d^c_{u,d,s}$ $\Rightarrow$ d_n
  - $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u$
  - $d_n = \eta\left(\Delta_d d_d + \Delta_u d_u + \Delta_s d_s\right)$, ...
- Experimental limits interpreted in terms of these parameters
  - d_e "easily" extracted from EDM, d_A, observed in atom or molecule

Algorithm for finding an EDM

- Put system with unpaired spin in parallel E and B fields
- Spin polarize system perpendicular to fields (superposition of spin up and down)
- Torques from E and B lead to precession through angle ϕ in coherence time τ
- Flip E wrt B, look for change in ϕ (i.e. look for energy shift)



- Look for precession frequency shift $\Delta\nu \sim 4dE/h$
- For E=100 kV/cm, $d_e = 1 \times 10^{-27}$ e cm $\Rightarrow \Delta\nu \sim 20$ nHz <--> $\Delta B \sim$ few $\times 10^{-14}$ G
- Only works for neutral systems

LANL/SNS Neutron EDM Experiment (M. Cooper, S. Lamoreaux)

- One of 3 new neutron EDM experiments (SNS,ILL,PSI)
- Aims for 2 orders of magnitude improvement $d_n \approx 6 \times 10^{-26}$ e cm $\Rightarrow 6 \times 10^{-28}$ e cm.

Strategy

- Make mixture of neutrons in superfluid ^{4}He at 300 mK, $\rho \approx 2.2 \times 10^{22}$ cm^{-3}
- Impose external $\mathbf{B_0}$ to precess n spins in plane $\perp$ to $\mathbf{B_0}$
- Impose external $\mathbf{E_0} \parallel$ to $\mathbf{B_0}$
- Measure n precession frequency, flip $\mathbf{E_0}$, look for difference :

$$h\nu_n = -2\mu_n B_0 \pm 2d_n E_0 \Rightarrow h\nu_n = -2\mu_n B_0 \mp 2d_n E_0 \Rightarrow |\Delta\nu| = 4d_n E_0/h$$

What's so hard about that?

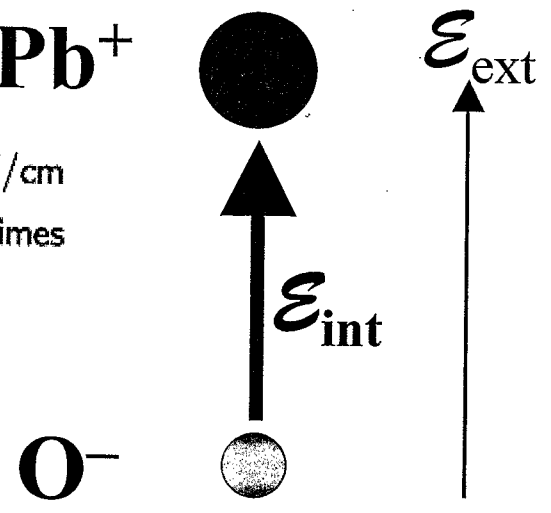
- $\mathbf{B_0} \approx 1$ mG, $\mathbf{E_0} \approx 50$ kV/cm, $d_n = 4 \times 10^{-27}$ e cm $\Rightarrow \Delta\nu = 0.19\mu$Hz (<1 ppm of ν_n)
- Record setting UCN density would be 500 cm^{-3} : in 2 cells of 4000 cm^3, only 4×10^6 neutrons/measurement cycle
- How do you measure spin precession rate of 4 million neutrons?

Search for the Electron EDM in Metastable PbO (D. DeMille, Yale)

⇒ Polar molecules with heavy atom & unpaired spin good candidates for d_e search
⇒ Valence electron feels $E_{\rm int} \approx Z^3\alpha^2 e/a_0^2$ along internuclear axis $\hat{n}$
⇒ To harness this : align $\vec{E}_{\rm int}$ along $\vec{E}_{\rm ext}$
⇒ Align electron spin parallel/antiparallel to $E_{\rm int}$ look for energy shift $d_e \times E_{\rm int}$

- PbO can be used in a vapor cell ⇒ high count rates
- For PbO* : $E_i - E_j \approx 10$ MHz (Ω-doubling)
- $\vec{E}_{\rm int}$ of PbO* fully polarized along $\vec{E}_{\rm ext} \approx 15$ V/cm
- Valence electron feels $E_{\rm int} \approx Z^3\alpha^2 e/a_0^2 \approx$ 20-60 GV/cm
- Stark shift induced by d_e amplified hundreds of times compared to atoms

⇒ $d_e \approx 10^{-27}$ e·cm ⇔ 10-30 mHz
⇒ $d_e \approx 10^{-29}$ e·cm ⇔ 100-300 μHz
⇒ Find those shifts !



QCD at the High Energy/Density Frontier

D.E. Kharzeev

Nuclear Theory Group,

Physics Department,

Brookhaven National Laboratory,

Upton, NY 11973-5000, USA

This talk is an attempt to review the current status of the theoretical studies of QCD at the high energy/density frontier, and to catalog the successes and failures of theory in describing the variety of phenomena observed at RHIC. I argue that there is a mounting evidence that RHIC has created new states of matter – strongly correlated Quark-Gluon Plasma and the Color Glass Condensate, even though a number of important questions still remain unanswered. This is also an occasion to review the variety of profound contributions to the theory of strong interactions made by the former and current members of the RIKEN-BNL Research Center.

Fundamental questions

addressed at RHIC

1. What are the phases of QCD matter?
2. What is the wave function of the proton?
3. What is the wave function of a heavy nucleus?
4. What is the nature of non-equilibrium processes in a fundamental theory?

QCD phase diagrams, early XXI century

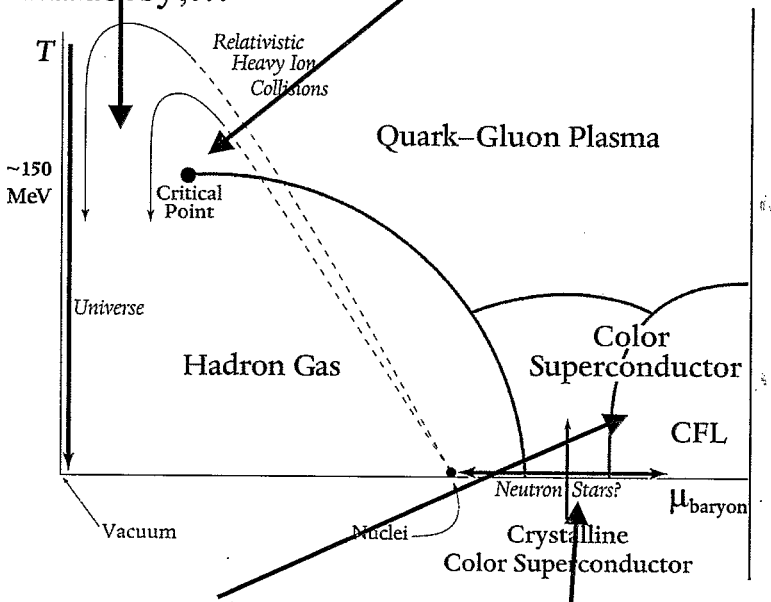
Lattice: P.Petreczky, S.Aoki,…(and RBRC alumni)
T.Hirano, Y.Nara;
D.Bodeker; S.Jeon;
S.Bass; T.Wettig;
A.Mocsy;…

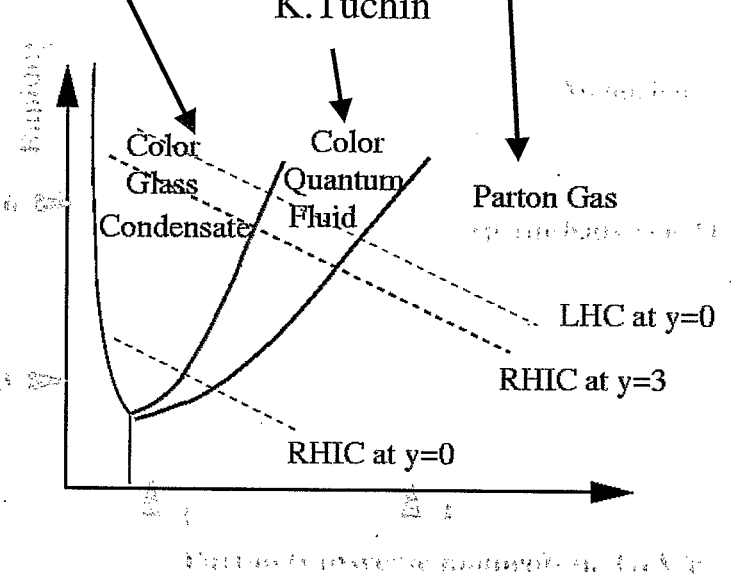
M.Stephanov

R.Venugopalan;
H.Fujii, Y.Hatta,
K.Fukushima,…

K.Itakura,
K.Tuchin

W.Vogelsang;
D.Boer;
S.Kretzer;…



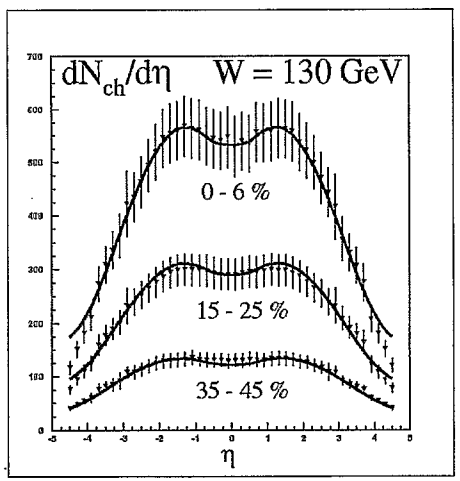


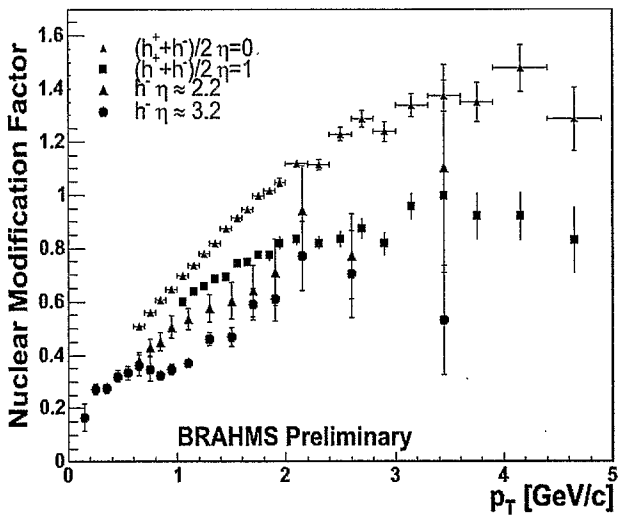
R.Pisarski, D.Rischke;
D.Son; T.Schaefer;

J.Schaffner-Bielich

What have we learned from RHIC so far ?

I. "Small" hadron multiplicities +
suppression of high p_T particles at forward rapidities =>
coherent interactions in the initial state, consistent
with the presence of parton saturation/Color Glass Condensate





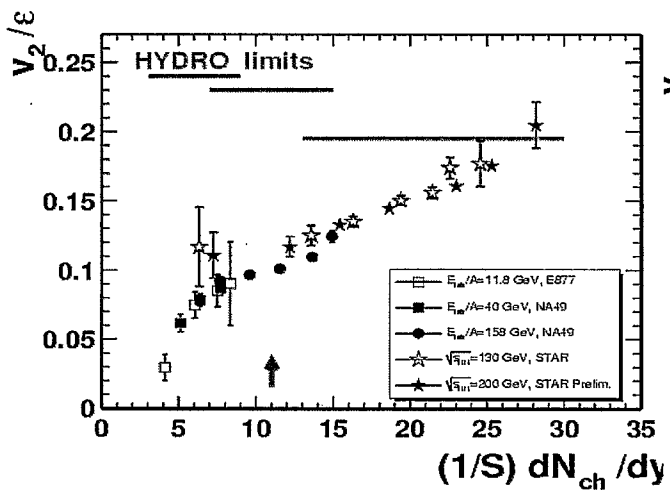
Do we see the QCD matter at RHIC ?

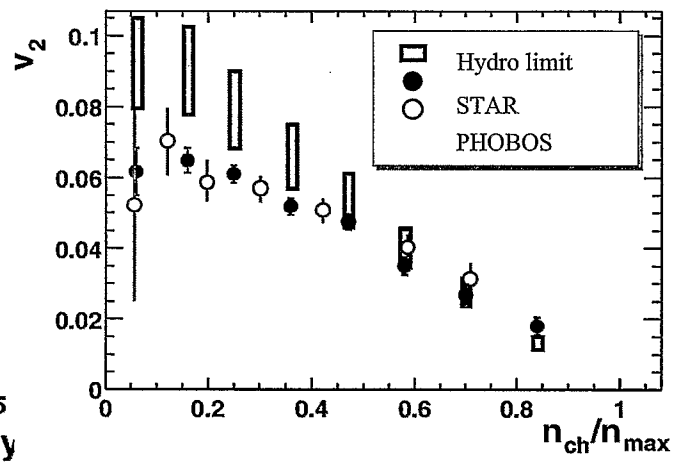
II. Collective flow =>

Au-Au collisions at RHIC produce strongly interacting matter

shear viscosity - to - entropy ratio

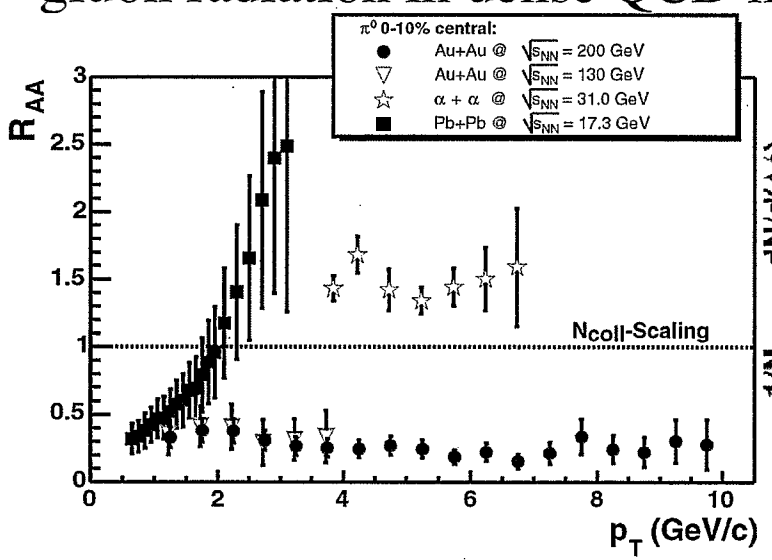
hydrodynamics: QCD liquid is more fluid than water

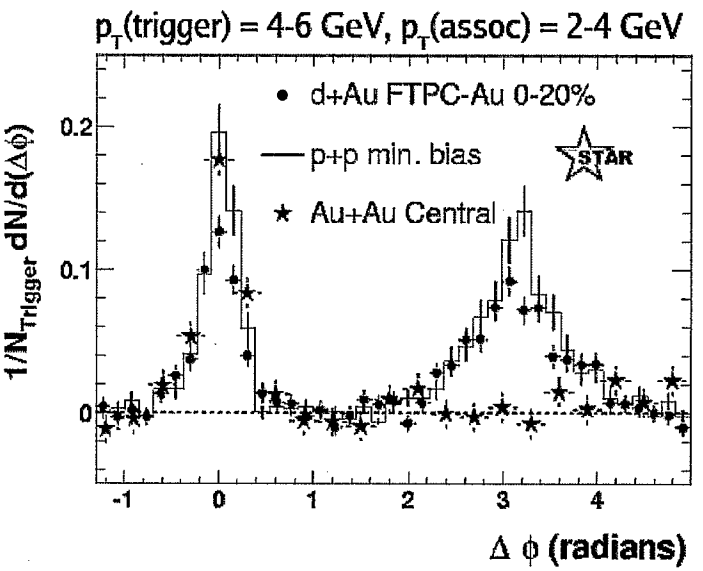




What have we learned from RHIC so far ?

III. Suppression of high p_T particles =>
consistent with the predicted jet energy loss from induced gluon radiation in dense QCD matter (but: heavy quarks?)





Experiments at RHIC: Exciting Discoveries & Future Plans

Barbara V. Jacak, Dept. of Physics & Astronomy, Stony Brook University

The matter created at RHIC shows collective flow, which is developed early. Quarks & gluons are the likely d.o.f. The flow magnitude implies that QGP is a liquid with very low viscosity, similar to other strongly coupled plasmas. The QGP is very opaque to color charged probes, and even charm quarks lose energy and flow. J/ψ are suppressed, but only partially. This has been posited to be due to screening + recombination from thermal bath, or alternatively, as a result of sequential melting of the χ and ψ`. The observed behaviors are as expected for a plasma.

The next step is to use RHIC II tofigure out the plasma physics of this new kind of matter. Compelling properties to probe are the temperature, transport properties, collective excitations, expansion dynamics, density waves, screening length and existence of possible instabilities. Addressing these will require detector upgrades (planning and construction are now well underway), the order of magnitude higher luminosity to be provided by electron cooling of RHIC II, and precision measurements of low σ probes, as well as scanning these properties as a function of colliding nuclei & beam energy.

Implications of $\lambda_D \sim 0.3$ fm

- can use to estimate Coupling parameter, Γ
- $\Gamma = \langle PE \rangle / \langle KE \rangle$ but also $\Gamma = 1/N_D$

  for $\lambda_D = 0.3$fm and $\varepsilon = 15$ GeV/fm^3

  $V_D = 4/3\ \pi\ \lambda_D^3 = 0.113$ fm^3

  $E_D = 1.7$ GeV

  to convert to number of particles, use gT or g^2T

  for $T \sim 2T_c$ and $g^2 = 4$

  get $N_D = 1.2 - 2.5$

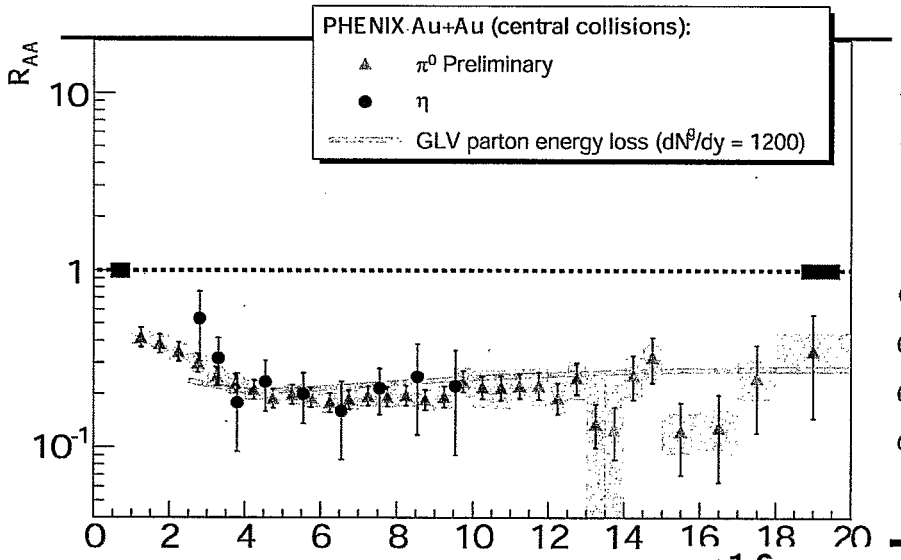
  $\Gamma \sim 1$
- NB: for $\Gamma \sim 1$

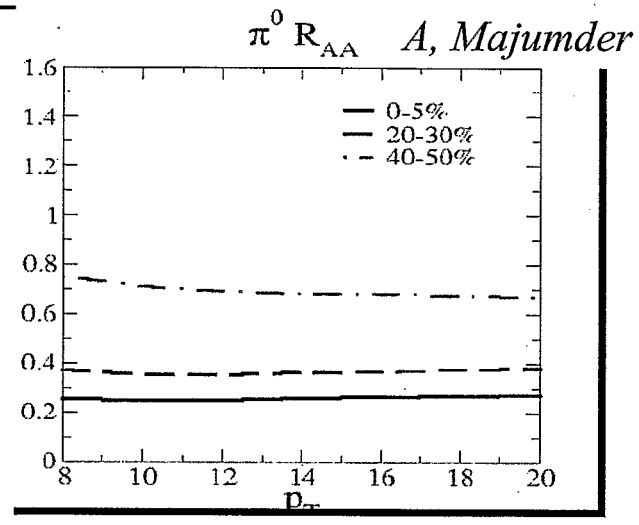
  plasma is NOT fully screened – it's strongly coupled!

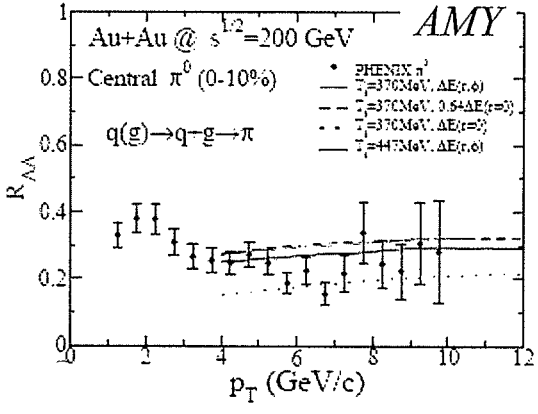
  other strongly coupled plasmas behave as liquids, even crystals for $\Gamma \geq 150$

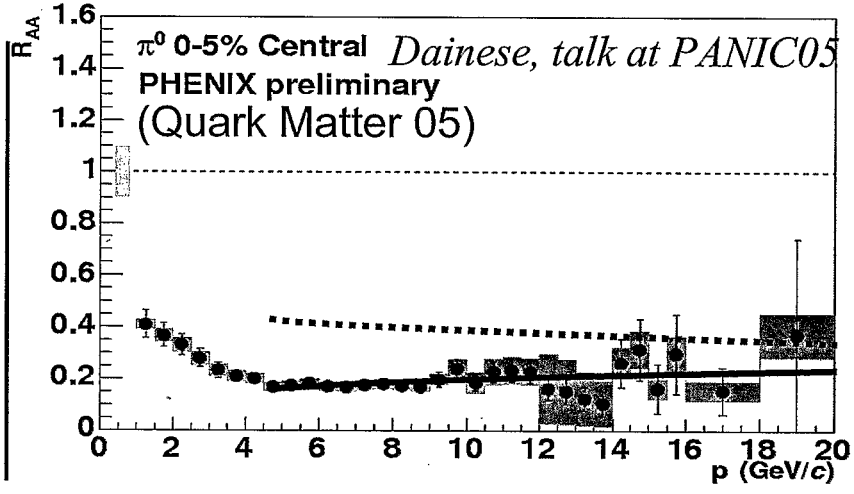
  dusty plasmas, cold atoms+ions , warm dense matter

flat R_{AA} via radiative energy loss only

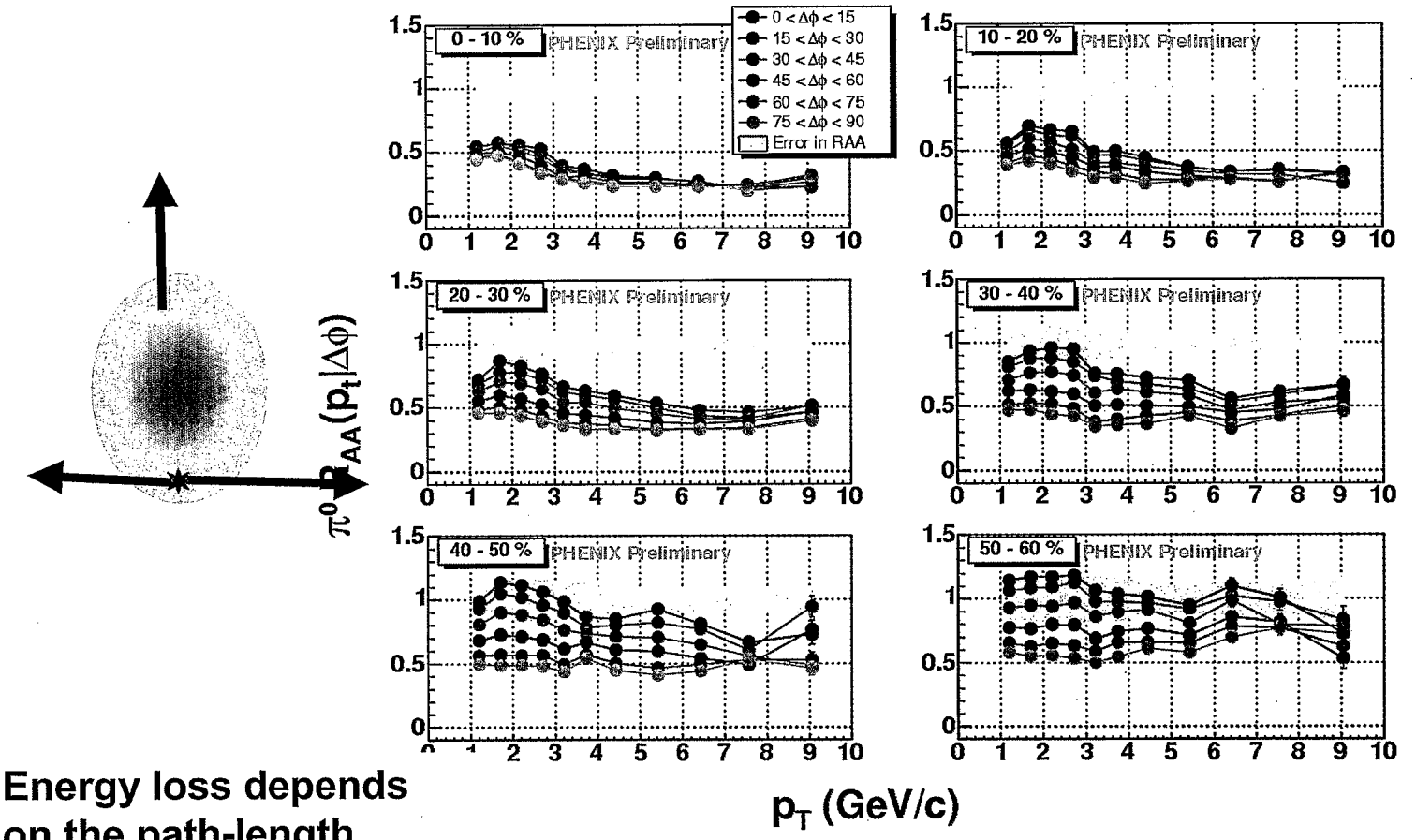








R_{AA} wrt reaction plane – more discriminating



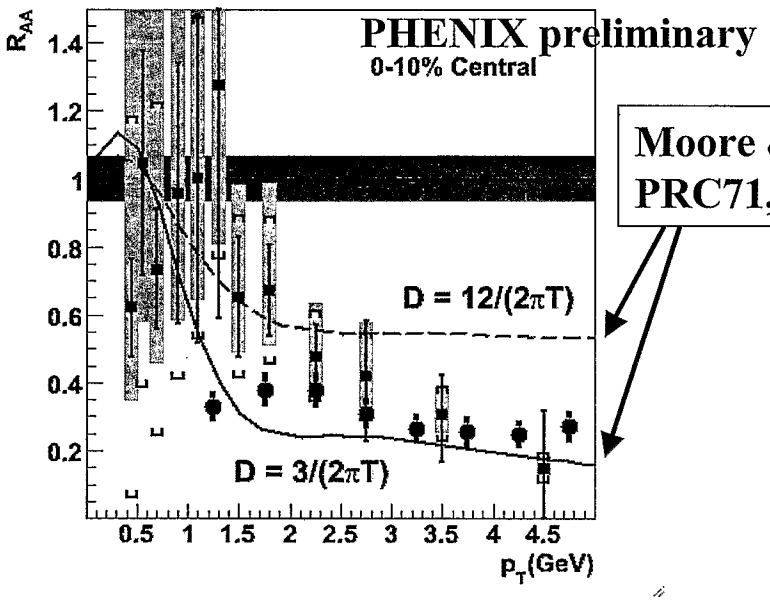
Energy loss depends on the path-length, expansion, collisions(?)

diffusion = transport of particles by collisions

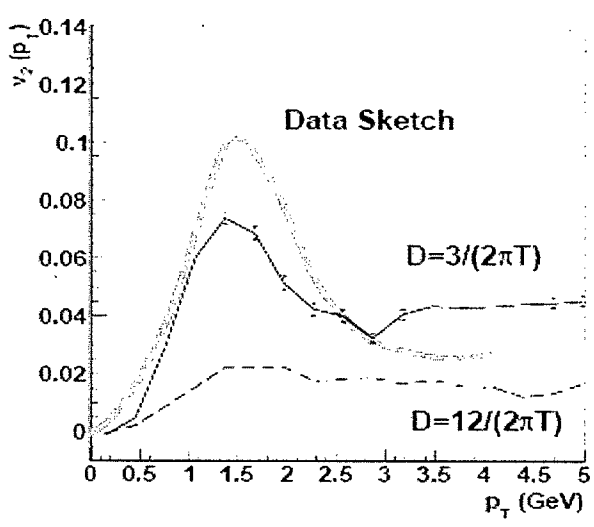
$D = 1/3 \langle v \rangle \lambda_{mfp} = \langle v \rangle / 3\rho\sigma$

$D \propto$ collision time

→ relaxation time



Moore & Teaney
PRC71, 064904, '05



$D \sim 3/(2\pi T)$ is small!

→ strong interaction of c quarks

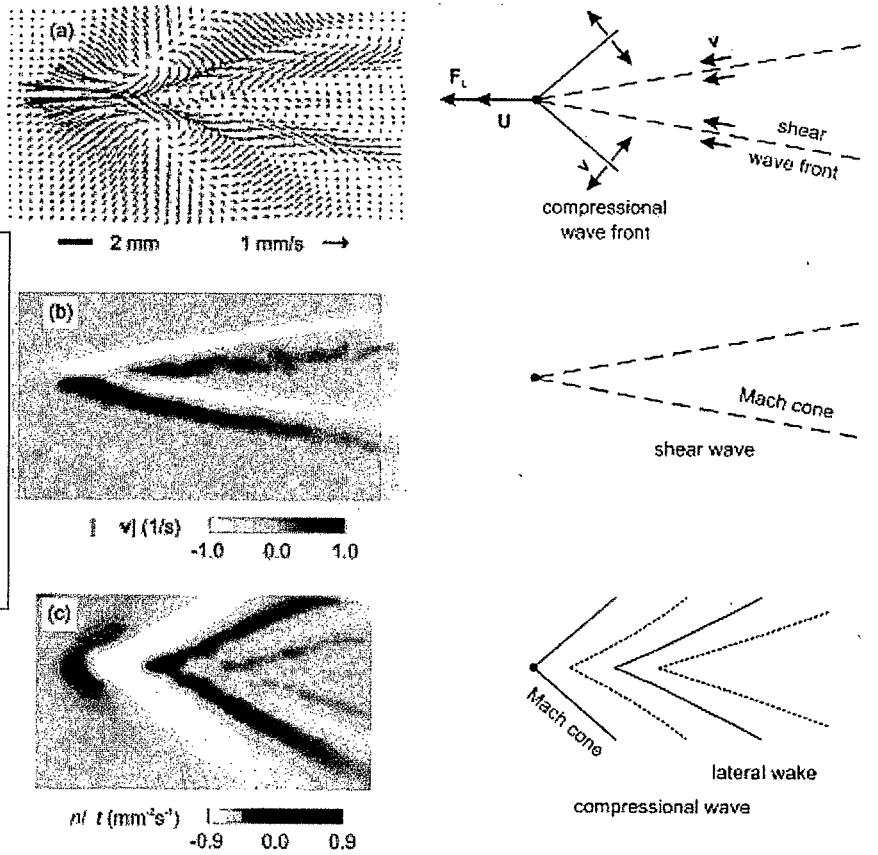
larger D → less charm e loss

fewer collisions, smaller v_2

Compressional and shear wakes in a two-dimensional dusty plasma crystal

NOSENKO *et al.* PHYSICAL REVIEW E 68, 056409 (2003)

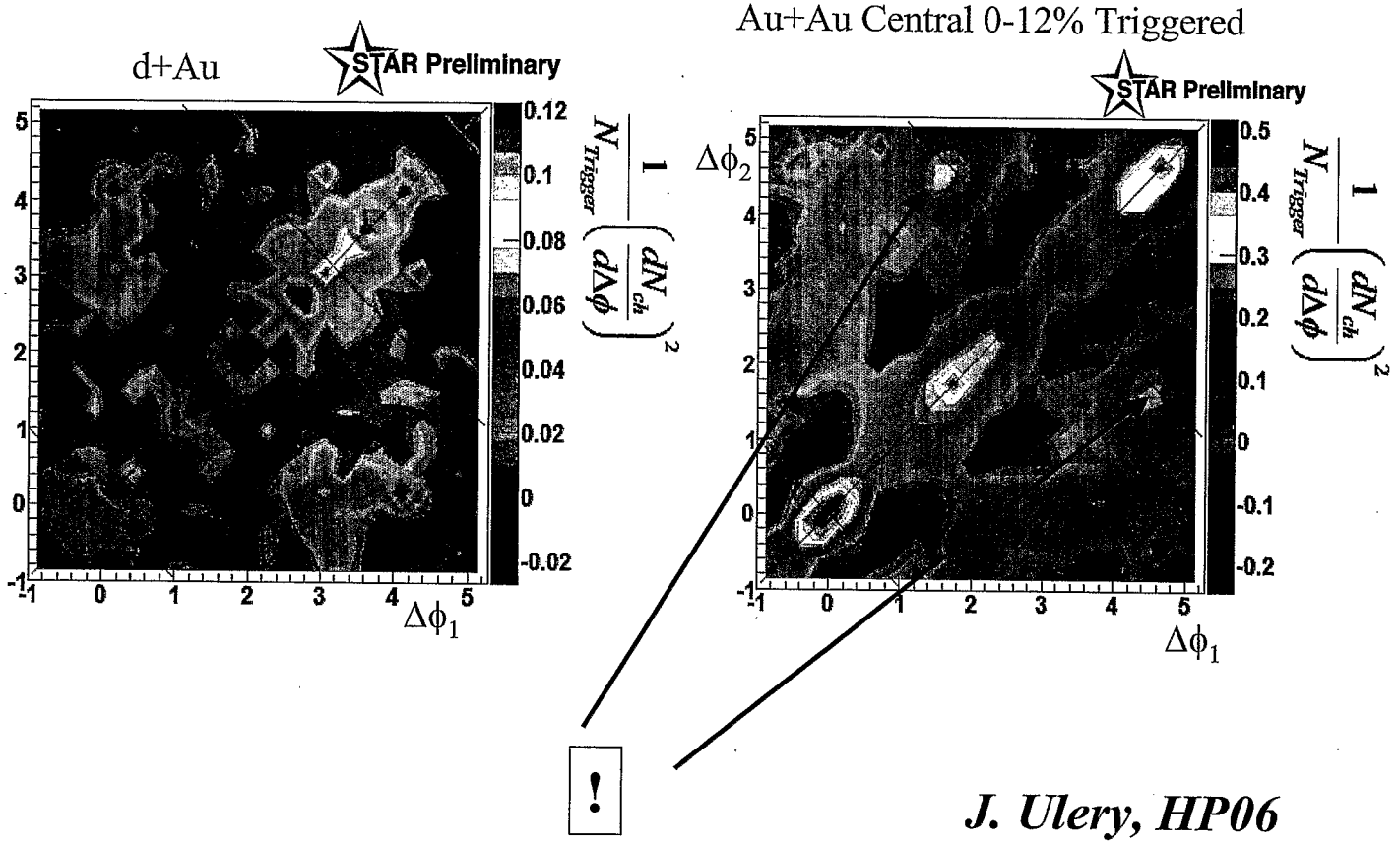
Mach cones CAN BE and HAVE BEEN observed in strongly coupled plasmas!!



shear waves are generally a phenomenon in crystals but not liquids

FIG. 4. The compressional- and shear-wave Mach cones, excited simultaneously. The scanning speed U is higher than the sound speed for both the compressional and shear waves. Maps are shown for (a) particle velocity $\mathbf{v}$, (b) vorticity $|\nabla \times \mathbf{v}|$, and (c) $\partial n/\partial t$, where n is the particle areal number density.

3 particle correlations support cone-like structure



J. Ulery, HP06

Spin: Some Answers Many Questions

The issues raised by the "spin crisis" of the 1990's have been around for nearly two decades.

Much has been learned
Some conclusions can (tentatively) be drawn
Some old questions (for both theorists and experimenters) persist
Some new questions come to the fore

R. L. Jaffe
Workshop RHIC Physics in the Context of the Standard Model, RBRC, BNL, June 2006

- Is there a gauge invariant description of <u>all the components</u> of the nucleon spin in terms of (in principle) observables?

  Not one, but two! And neither is experimentally accessible.

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + L_Q(Q^2) + J_G(Q^2)$$

DIS

RLJ & Manohar, Ji, Hoodbhoy & Ji

$$\frac{1}{2} = \int_0^1 dx \left[\frac{1}{2}\Delta\Sigma(x,Q^2) + \Delta G(x,Q^2) + \mathcal{L}_Q(x,Q^2) + \mathcal{L}_G(x,Q^2)\right]$$

DIS **DIS** **???** **???**

Bashinsky & RLJ, Hagler & Schafer Harindranath & Kundu

- Is the OZI rule badly violated --- do strange quarks play a significant role in the nucleon?

  NO $|\langle N|\mu_s|N\rangle| \sim 0 \quad \left|\langle N|r_s^2|N\rangle\right| \sim 0$ SAMPLE, HAPPEX, A4, G0 @ JLab

  - Does the strange quark carry a small, significant, negative fraction of the nucleon spin?

    Yes, but?
  - Does the quark spin carry a mere 30% of the nucleon spin?

    Yes, but?
  - Can single particle inclusive DIS unravel flavor/spin correlations?

    We'll see Sum rules and SIDIS disagree at this point...
  - Is there significant SU(3)-flavor symmetry violation in the axial charges?

    Perhaps??
  - Can this question be answered on the lattice?

    Yes, Now!

R. L. Jaffe, RHIC Physics in the Context of the Standard Model, BNL, June 2006

- Is the gluon spin associated with a well-defined, gauge invariant operator?

  Yes

$$\Delta G\,(x_{\rm Bj}, Q^2) \;=\; i\int \frac{d\xi^-}{4\pi x_{\rm Bj} P^+}\, e^{i x_{\rm Bj} P^+ \xi^-} \langle PS|\, F^{+\lambda}(0)\mathcal{I}(0,x^-)\tilde{F}^+_\lambda(\xi^-)\Big|_{Q^2}|PS\rangle$$

Not as complicated as it looks!

- Is the gluon spin operator related to the axial anomaly?

  No!

- What about the old assertion that an anomalously large gluon spin could somehow restore the quark spin content of the nucleon to ~100%?

  It's dead theoretically and on life support experimentally

- Can the gluon spin contribution to the nucleon spin be computed on the lattice?

  No ~ not without major breakthroughs

- What is the relation among all the effects in DIS that vanish for on-shell, collinear, NRQM quarks?

  Transversity and the tensor charge
  Orbital angular momentum
  Sivers distribution function
  Magnetic moments

  No one knows!

R. L. Jaffe, RHIC Physics in the Context of the Standard Model, BNL, June 2006

- What is the leading twist physics of transverse spin?

  Transversity — Collins & Soper; RLJ & Ji, Artru & Mekhfi, Ralston & Pire

  Collins fragmentation function — Collins

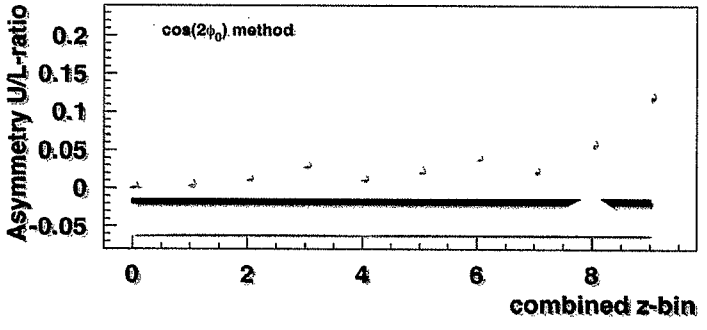
  Sivers distribution function — Sivers

- Can transversity be measured?

  Yes, with the aid of the Collins function, or in transverse Drell-Yan

- But is the Collins function non-zero? Is there any transverse resolving power in fragmentation?

  Yes



Ogawa, Gabbert, Gross-Perdekamp, Seidl & Hasuko @ BELLE

- But I thought the Sivers function is zero by time-reversal invariance?

  NO the gluon field of the nucleon dresses the initial state with a phase "borrowed" from the final state. — Sivers, Brodsky, Hwang, and Schmidt

- What does all this have to do with single transverse spin asymmetries in DIS?

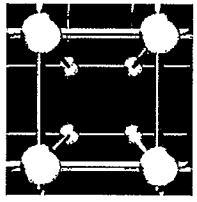
  We don't yet know for sure!

R. L. Jaffe, RHIC Physics in the Context of the Standard Model, BNL, June 2006

Conclusion

Compute

$$\mathbf{Ys}_\mu = \langle \mathbf{Ns} | \bar{\mathbf{q}} \lambda_8 \gamma_\mu \gamma_5 \mathbf{q} | \mathbf{Ns} \rangle$$



with enough accuracy to detect SU(3) symmetry violation:

- It's a renormalization group invariant, local, non-singlet operator, just analogous to g_A.
- Must compute in unquenched QCD with realistic quark masses.
- Would be extremely useful, equivalent to original motivation for elastic neutrino scattering experiment LSND!

Final Thoughts on Angular Momentum

Rest frame quark Dirac wavefunction

$$q(\vec{x},t) = \begin{pmatrix} f(r)\,\varphi_{\kappa j}(\Omega) \\ ig(r)\,\vec{\sigma}\cdot\hat{r}\,\varphi_{\kappa j}(\Omega) \end{pmatrix} \begin{array}{l} \text{Orbital angular momentum } \ell = j \pm 1/2 \\ \text{Orbital angular momentum } \ell' = \ell \pm 1 \end{array}$$

Things that depend on the lower components of the Dirac wavefunction, or quark excitation beyond ground state orbital -- "relativistic" effects...

- Difference between quark helicity and transversity distributions
- Deviation of nucleon axial charge from NRQM 5/3
- Difference between nucleon's axial charge and its tensor charge
- Quark orbital angular momentum
- Correlation between transverse momentum and transverse spin

Lacking any model independent connection between these things!

R. L. Jaffe, RHIC Physics in the Context of the Standard Model, BNL, June 2006

RHIC Spin Experiments
current status and future prospects

Naohito Saito
(Kyoto University, Department of Physics/ RIKEN BNL Research Center)

The structure of the nucleon reflects the complicated quark-gluon dynamics as a result of quark confinement. Its mass, magnetic moment, and spin cannot be easily constructed from the characteristics of the quarks and gluons. Especially the spin of the proton was found to be hardly explained from its constituent quark spin, which is known as *the proton spin crisis.*

At RHIC, we have been investigating the spin structure by utilizing electro-magnetic, strong, and weak interactions. These interactions are sensitive to electric charge squared, color charge, and weak charge (~flavor), respectively, and the full picture of the spin-flavor structure of the proton can be obtained by using all interactions.

Particularly the constraints on the gluon polarization from inclusive hadron production have been obtained. The production is a mixture of gluon-gluon, gluon-quark, and quark-quark interactions, therefore the double helicity asymmetry A_{LL} for pion production is sensitive to the $\Delta g/g$. When we include the PHENIX results from year of 2005 in the global QCD analysis together with inclusive DIS data, the uncertainty on the $\Delta g/g(x)$ has been reduced significantly; the first moment of the polarized gluon distribution was extracted to be 0.3 ± 0.3 at Q^2=1 GeV^2. This should be compared with the previously obtained value 0.5 ± 1.0. Now we think the large gluon polarization scenario is unlikely, but a modest value of gluon polarization (~0.3) is still possible. This size of gluon polarization is enough to compensate the deficit in the spin sum rule, but significantly smaller than the initial expectation basing on the axial anomaly concept to fill the gap between naïve expectation and observed small quark contributions.

The RHIC has just started to show its powerfulness to probe the spin structure of the nucleon. It will continue to provide crucial information including sea-structure of the nucleon using W production and transverse spin effects. With the newly obtained data, a qualitatively new picture of the nucleon is emerging and it will lead us to a deeper understanding of the strong interaction, therefore the standard model.

First Crisis?

- Proton has gone through many crisis
  - Mass : m_u~5 MeV/c^2, m_d~10 MeV/c^2
    - Saved by constituent quark model
  - Momentum : $\sum_q \int xq(x)dx \approx 0.5$
    - Saved by gluon momentum
  - Spin : $\Delta\Sigma \approx (0.1 \pm 0.3)$, $\sum_q \int \Delta q(x)dx \approx 0.1 \pm 0.3$
    - Helicity SR:

$$\frac{1}{2}^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

- Theory guideline for separation (nf=3) (Ji, Tang, and Hoodboy)

$$\frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\frac{3n_f}{3n_f+16} = 0.18 \qquad \Delta g + L_g = \frac{1}{2}\frac{16}{3n_f+16} = 0.32$$

Gluon is expected to be Polarized

- To compensate the Spin SR: (not necessarily)

$$\frac{1}{2}^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

Δg~0.3 would be enough

- To recover QM expectation thru axial anomaly

$$\Delta\Sigma \Rightarrow \Delta\Sigma - \frac{N_f \alpha_s}{2\pi}\Delta g$$

Δg~2 required

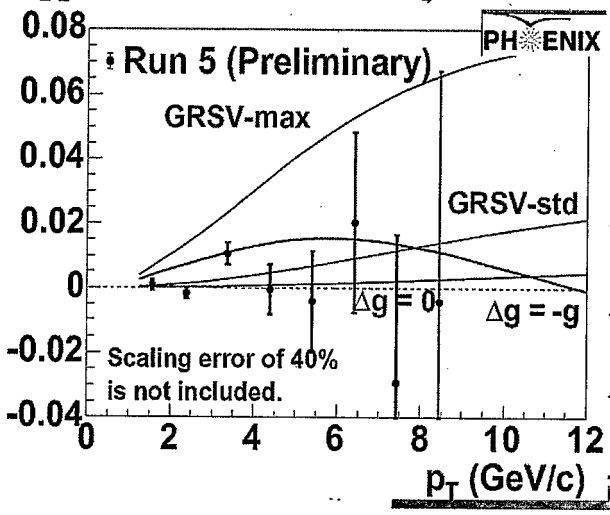
- Through Q^2 evolution: $\Delta\Sigma$ and Δg mix

$$\frac{d}{d\log(Q^2)}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix}0 & 0 \\ \frac{3}{2}C_F & \frac{\beta_0}{2}\end{pmatrix}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix}$$

Q^2 evolution of the 1st Moment

Constraints on $\Delta g(x)$ w/ π^0 Prod.

n $pp \rightarrow \pi^0 \; X$ ♦♫■♦♦♦♫❖♫ ♦□



Theory model	C.L. (%)
GRSV-std	21.7-17.1
*GRSV-max (Δg=g)	0.0-0.0
*GRSV Δg=0	16.7-18.4
*GRSV Δg=−g	0.7-0.0

AAC updates

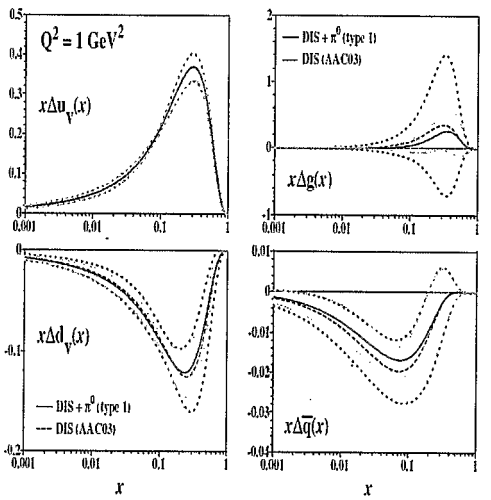
(S.Kumano, M. Hirai, NS hep-ph/0603213)

n Include J-Lab, HERMES, COMPASS new data

n Trial inclusion of PHENIX π^0-A_{LL} data

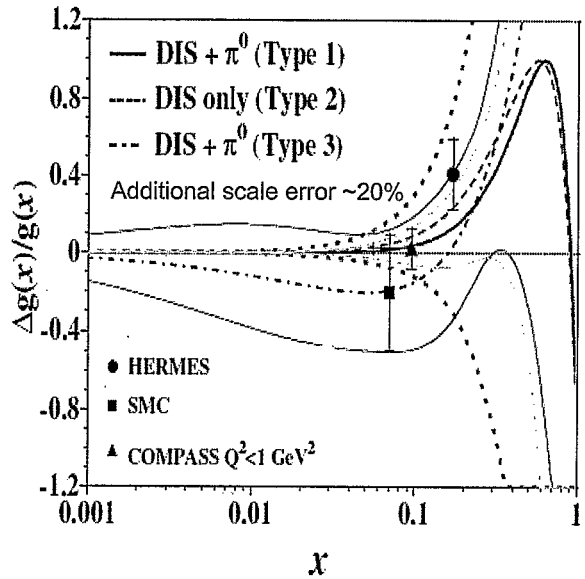
n K-factor method à la CTEQ

n Gluon Uncertainty significantly reduced!



Gluon Polarization

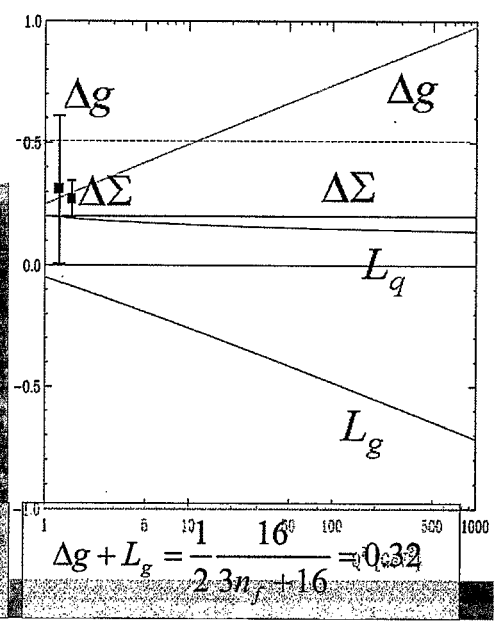
- $\Delta g>0$ preferred at large-x
  - HERMES and COMPASS A_1^d data
  - Higher-twist effects?
- $\Delta g=0.3\pm0.3$
  - Additional scale error of ~20%
  - previously 0.5 ± 1.3
  - If no π^0 data 0.5 ± 1.1



Improved Constraints

- Newly obtained 1st moments (Q^2=1 GeV^2)
  - Δg = 0.3±0.3
    - With additional scale error of ~20%
  - $\Delta\Sigma$ = 0.27±0.07
- Still need to improve precision
  - Δg
  - L_q and L_g, too!
    - GPD
- Compare with Ji, Tang, Hoodboy Expectation

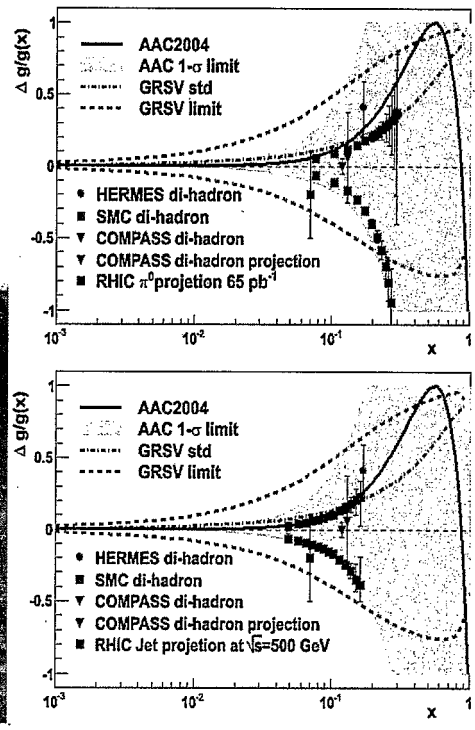
$$\frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\frac{3n_f}{3n_f+16} = 0.18$$



$$\Delta g + L_g = \frac{1}{2}\frac{16}{3n_f+16} = 0.32$$

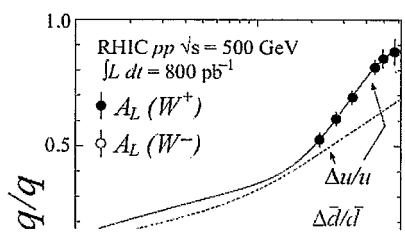
Extend x Range

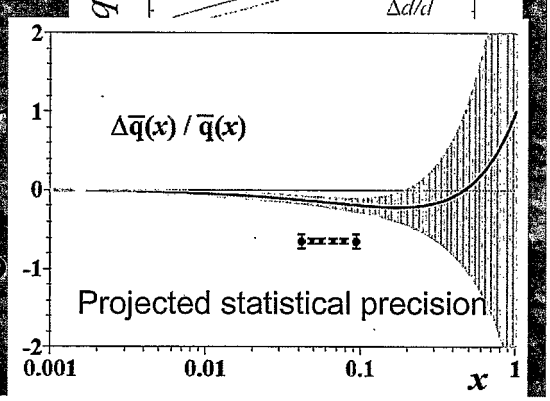
- $A_{LL}(\pi^0)$ from Run 6/7 (65 pb^{-1}) will extend x range to larger x.
- STAR jet measurement also provides precision data
- 500 GeV run will cover smaller x-range
- FWD rapidity coverage also useful for smaller x region



Sea Constraints: RHIC W Prospects

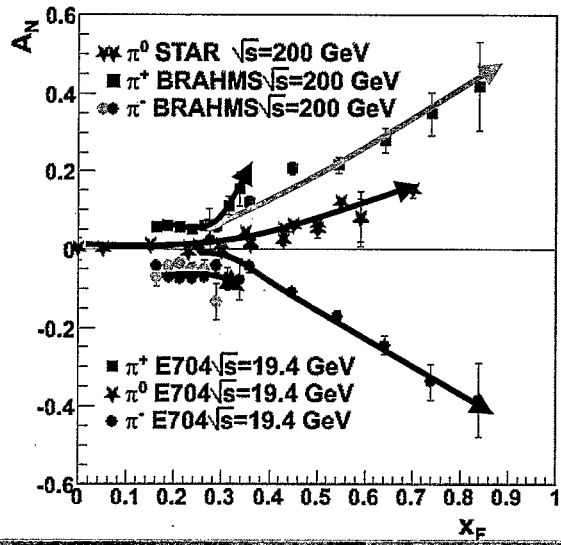
- Clear flavor separation
  - Weak charge ~ flavor
- Clear spin information
  - Left handed current only
- Start in 2009!
  - The 1st Commissioning starts tomorrow!



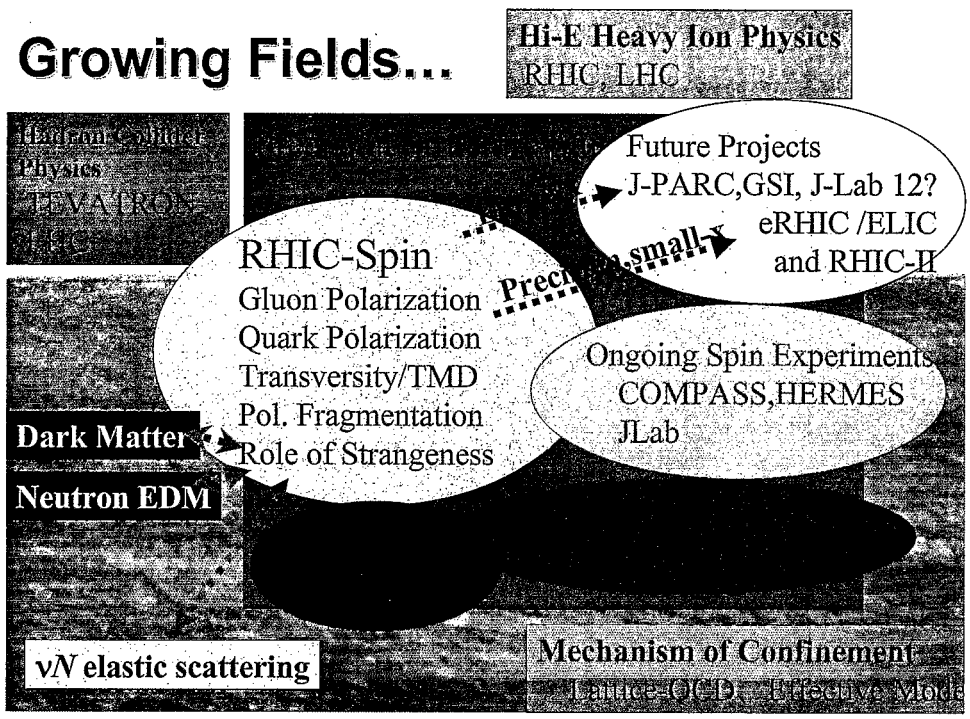


BRAHMS Results on A_N

- BRAHMS observed Large A_N in charged pion production
- Similar Trend to E704, but deviation from ZERO starts earlier?
- Need to explore further!



Growing Fields...



Lattice QCD: Past, Present and Future

Norman H. Christ
Columbia University
New York, NY 10027

Understanding, computing and in some cases predicting the properties of Quantum Chromodynamics (QCD) at low energy presents a major physics challenge. This is a strongly-coupled, relativistic and therefore many-body problem with no known analytic solution or tractable systematic approximation scheme. However, the explicit calculation of masses and matrix elements by Monte Carlo evaluation of the discretized, field-theoretic Feynman path integral (lattice QCD) provides an increasingly successful technique for making these computations and predictions.

This has proven to be a very demanding task. It is only through spectacular advances in computer technology, remarkable developments in the lattice formulation and enormous advances in numerical algorithms that we can claim increasing control over all of the systematic errors present in such a first-principles calculation.

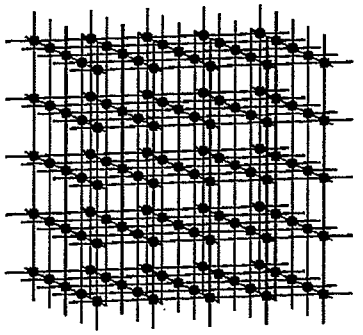
The RBRC, 10 Teraflops QCDOC computer provides the large-scale resources for competitive lattice QCD calculations. The domain wall fermion formulation, developed to a large extent within the lattice QCD program of the RBRC, allows fermions to be treated in a numerical simulation in a fashion that reflects the flavor and chiral symmetries of Nature with a controlled accuracy. This permits a wide range of quantities from CP violation in K meson decays to nucleon structure to be studied. The rational hybrid Monte Carlo method, invented by our UKQCD collaborators and tested and refined on the QCDOC machines at the RBRC and the University of Edinburgh has increased the speed of demanding full QCD calculations by at least a factor of three.

The present, joint computational program of the RBC (RIKEN, BNL, Columbia) and UKQCD collaborations gives a good view into the future. Large scale calculations have been underway for more than one year on both $16^3 \times 32$ and $24^3 \times 64$ volumes with a single lattice spacing, $1/a = 1.6$ GeV, including dynamical up, down and strange quarks. In the present calculation light quarks with masses as small as 1/4 of the strange quark mass are being studied. These calculations will be followed in a few months by a second series at the smaller lattice spacing of $1/a = 2.1$ GeV. The resulting ensembles of gauge configurations will form the basis of a series of RBC and UKQCD calculations which should have a major impact on particle and nuclear physics.

An example of what has become possible is shown in the final slide below. The quantity B_K relates the CP violating phase in the CKM matrix with the indirect CP violation measured in the K meson system. The domain wall formulations provides the best method to compute this quantity and the 2+1 flavor lattice ensembles described above will permit its calculations to unprecedented accuracy. The graph shows the matrix element of the weak interaction operator located at a time t between the operator creating the K meson (at $t = 59$) and the operator destroying the resulting $\overline{K}^0$ (at $t = 5$). The broad plateau demonstrates the absence of excited state contamination and provides a highly accurate volume average promising results with small statistical errors. (See the talk of Jun Noaki for a further description.)

Lattice QCD

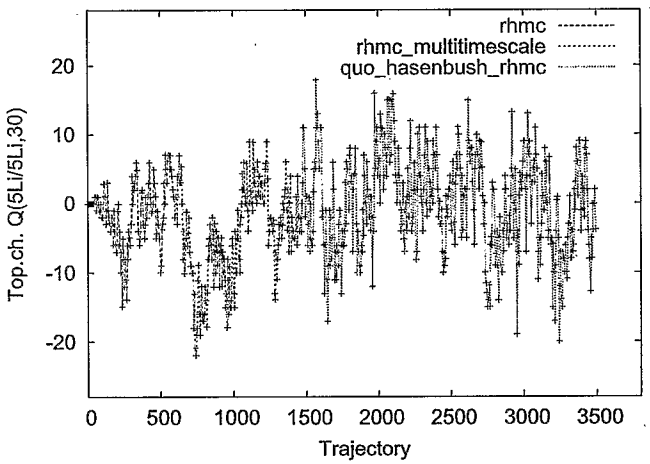
- Introduce a space-time lattice.
- Perform the Euclidean Feynman path integral.
  - Precise non-perturbative formulation.
  - Capable of numerical evaluation.



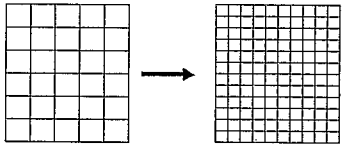
$$\sum_n \langle n|e^{-Ht}\mathcal{O}|n\rangle = \int d[U_\mu(n)]e^{-\mathcal{A}[U]_{\text{gauge}}}\det(D+m)\mathcal{O}[U]$$

- Evaluate using Monte Carlo, importance sampling, with hybrid molecular dynamics/Langevin evolution.
- "First principles" ability to determine the consequences of QCD with controlled errors.

Well understood sources of error:

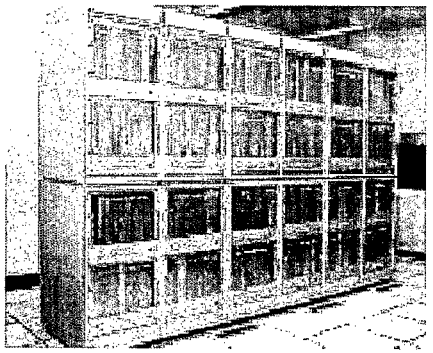
•Finite Volume:	*Kinematic:* $p = 2\pi n/L$ *Dynamic,* $\langle r \rangle < L$: *errors* $\sim e^{-L/r}$ *Compare different volumes,* *Effort ~ ln(Error)*
• Quenching:	*Include det(D+m)* ! *Effort* ~ 100X
• Finite MC statistics:	*Search for long-time Autocorrelations* *(A. Hart, UKQCD)* *Effort* ~ $1/(Error)^2$ 

Sources of error:

• Perturbation theory:	*Step scaling:* $a \sim (0.5)^N$, $g^4 \sim 1/N^2$  *Effort* $\sim 1/\mathrm{Error}^{1/2}$
• Non-zero lattice spacing:	*Symanzik improvement:* $L_{cont} + \Sigma_i\, c_i L_i^{dim\ 5} + \ldots \Rightarrow$ $\langle q \ldots q\bar{q} \ldots \bar{q} \rangle_{\mathrm{lattice}}$ *Tune action to make* c_i *to vanish.* *Effort* $\sim 1/(\mathrm{Error})^{8/n}$
• Quark masses too large:	*Effort* $\sim 1/(\mathrm{Error})^2 + 1/(\mathrm{Error})^{8/n}$

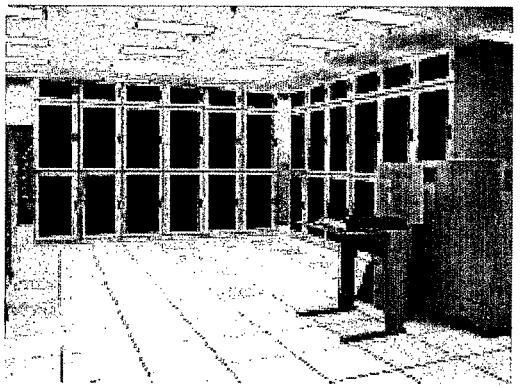
RBRC Computers

- QCDSP
  - 0.6 Tflops
  - Completed 1998
  - Gordon Bell Prize



- QCDOC
  - 10 Tflops
  - Completed 2005
  - Parent of Bluegene

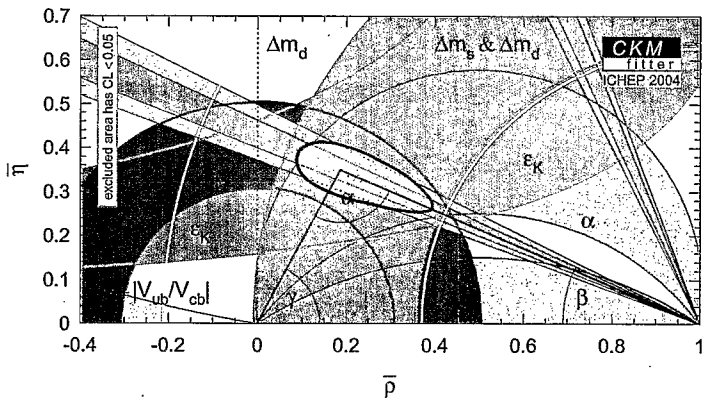
    Overview of the QCDSP and QCDOC computers, IBM Research Journal, Vol 49, No. 2/3, p 351 (2005)

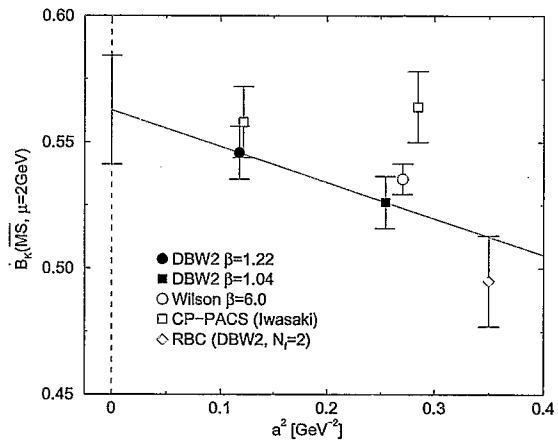


$K^0 - \overline{K}^0$ Mixing (B_K)

(Chris Dawson, Saul Cohen, Jun Noaki)

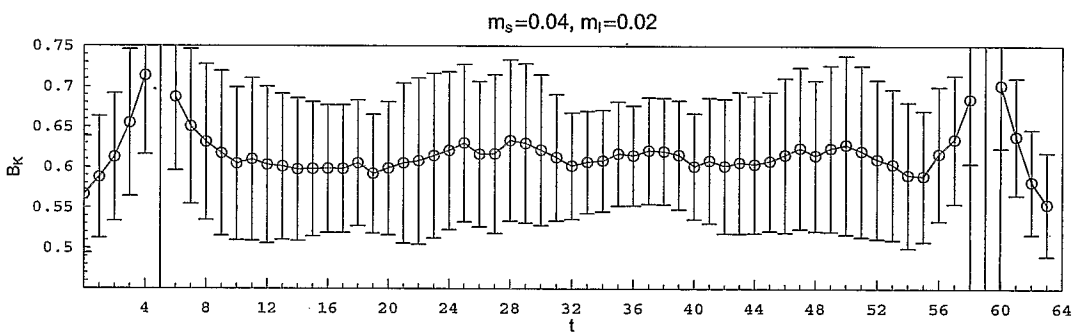
CKM matrix





New Nf=2+1 data:

- $1/a = 1.6$ GeV
- $24^3 \times 64$, $L_s = 16$
- 16 configurations (Saul Cohen)



Chiral symmetry restoration and in-medium hadron properties

Dirk H. Rischke

Institut für Theoretische Physik
and
Frankfurt Institute for Advanced Studies
of the
Johann Wolfgang Goethe – Universität Frankfurt am Main

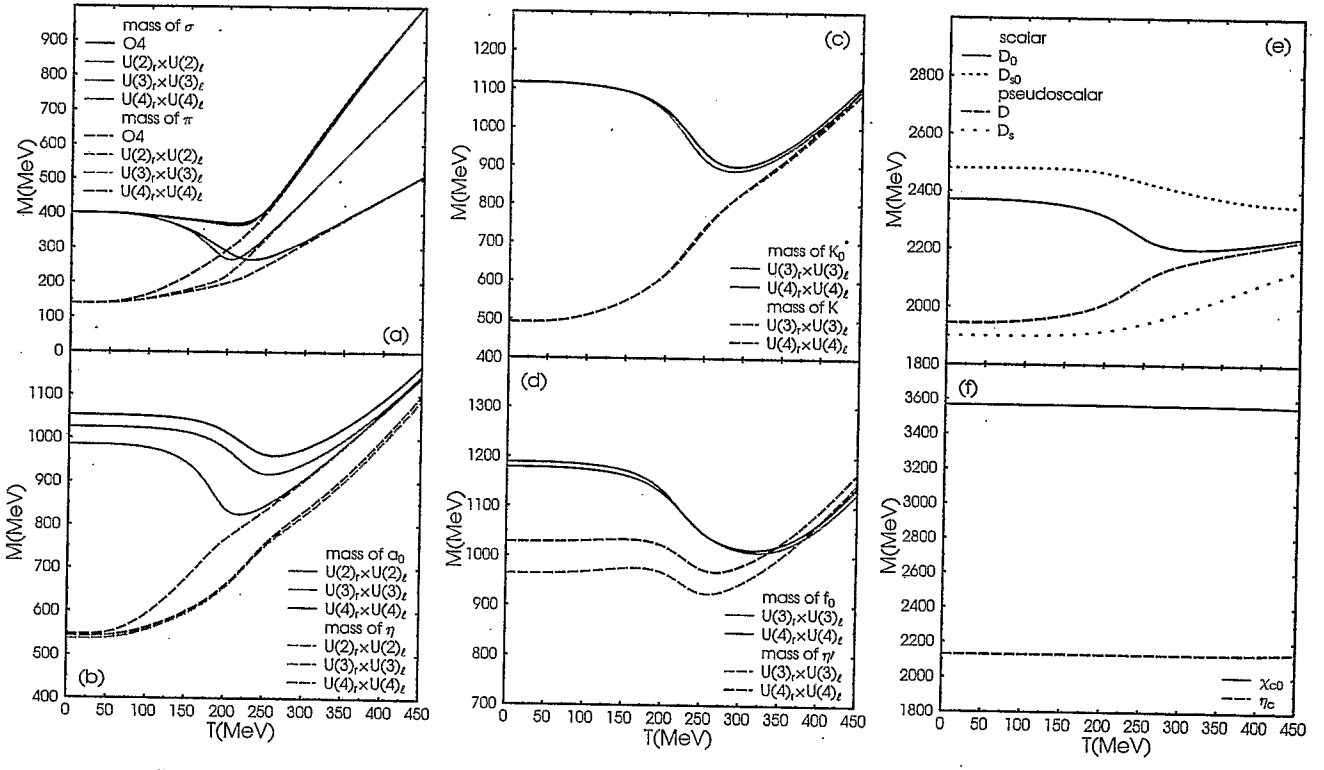
I study linear sigma models with chiral $U(N_f)_r \times U(N_f)_l$ symmetry and compute the masses of scalar, pseudoscalar, vector, and axialvector mesons selfconsistently in the Hartree-Fock approximation around the chiral symmetry restoration temperature.

I also go beyond the Hartree-Fock approximation and compute scalar and pseudoscalar spectral functions selfconsistently including a nonzero decay width.

I point out the direction for future studies which should comprise an extension to vector meson and baryonic degrees of freedom and a calculation of the invariant dilepton mass spectrum.

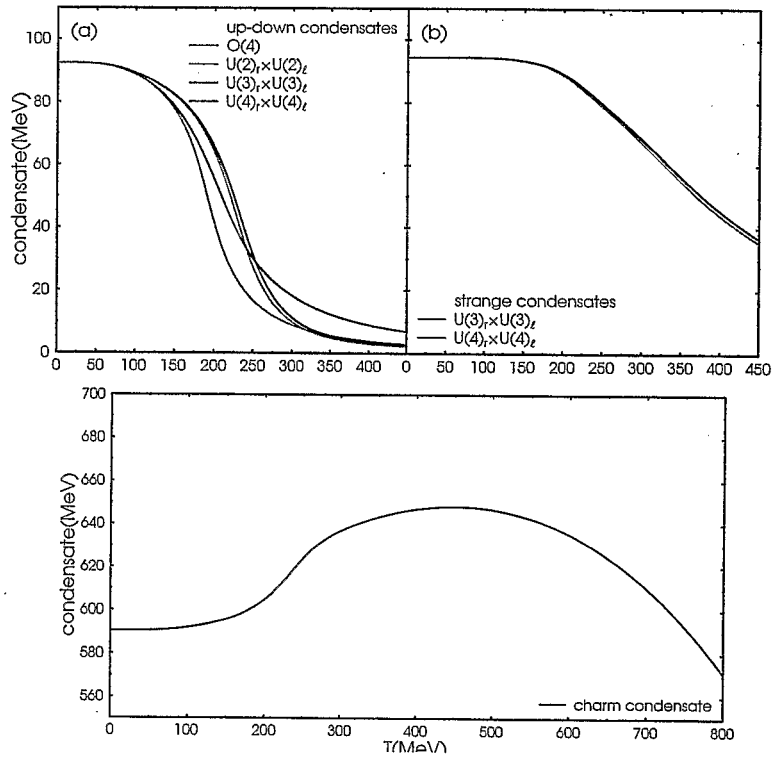
Linear Sigma Models (IV)

Masses in HF approximation: Dirk Röder, Jörg Ruppert, DHR, PRD 68 (2003) 016003



Linear Sigma Models (V)

Condensates in HF approximation: Dirk Röder, Jörg Ruppert, DHR, PRD 68 (2003) 016003



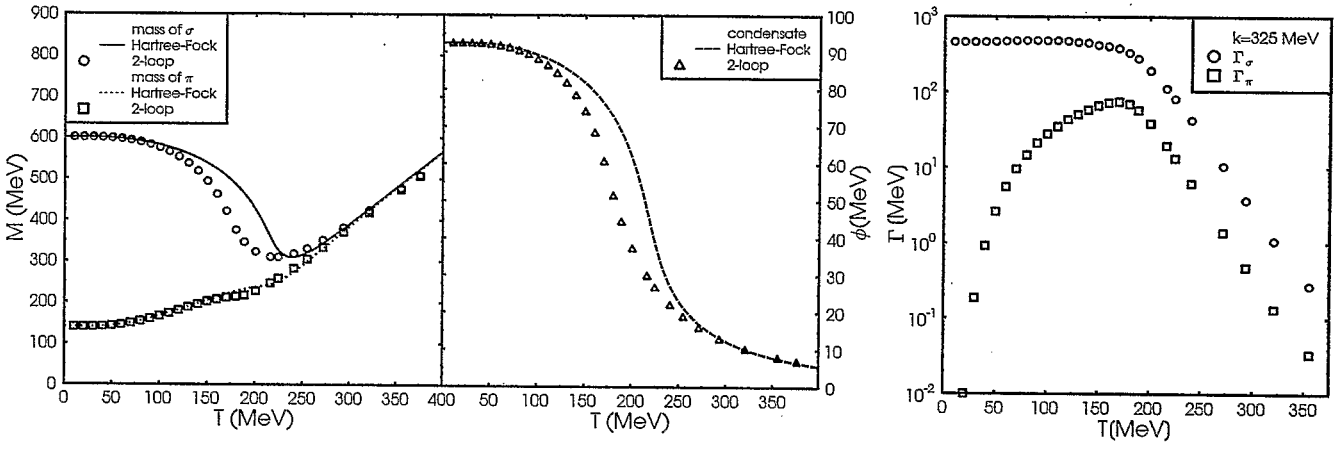
Linear Sigma Models (IX)

2-loop approximation for $O(4)$ model ($\mathrm{Re}\,\Pi \equiv \Pi_{\mathrm{tadpole}}$):

$\Longrightarrow$ mass $M^2 = M^2_{\mathrm{tree-level}} + \Pi_{\mathrm{tadpole}}\,,\quad \Pi_{\mathrm{tadpole}} \sim \int d\omega\, d^3k\, \rho(\omega,k)\, \dfrac{1}{e^{\omega/T}-1}$

$\Longrightarrow$ on-shell energy $\omega(k) = \sqrt{k^2+M^2}$

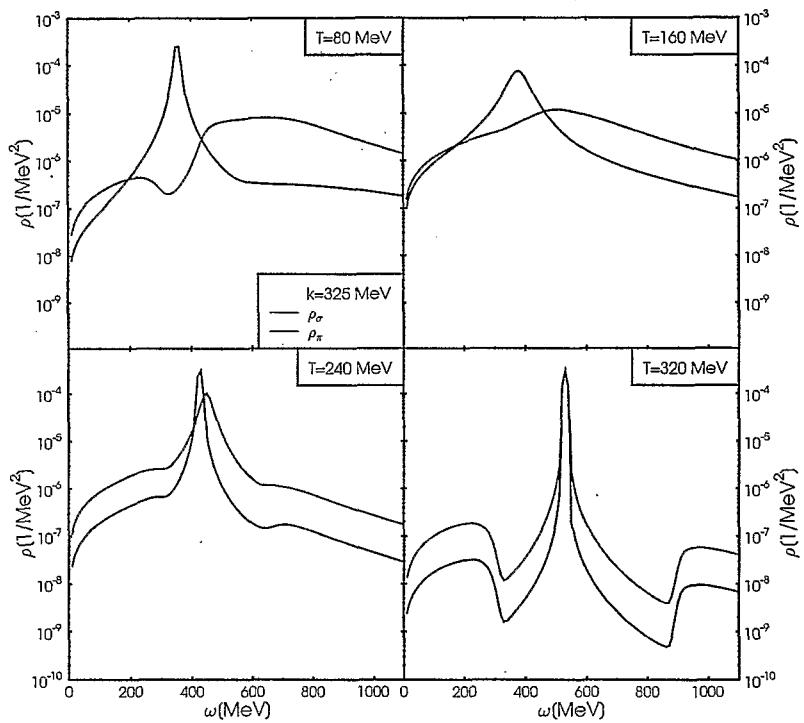
$\Longrightarrow$ decay width $\Gamma(k) \equiv \dfrac{\mathrm{Im}\,\Pi(\omega(k),k)}{\omega(k)}$



Dirk Röder, Jörg Ruppert, DHR, hep-ph/0503042 (NPA, to be published)

Linear Sigma Models (XI)

Spectral densities in 2-loop approximation for $O(4)$ model:



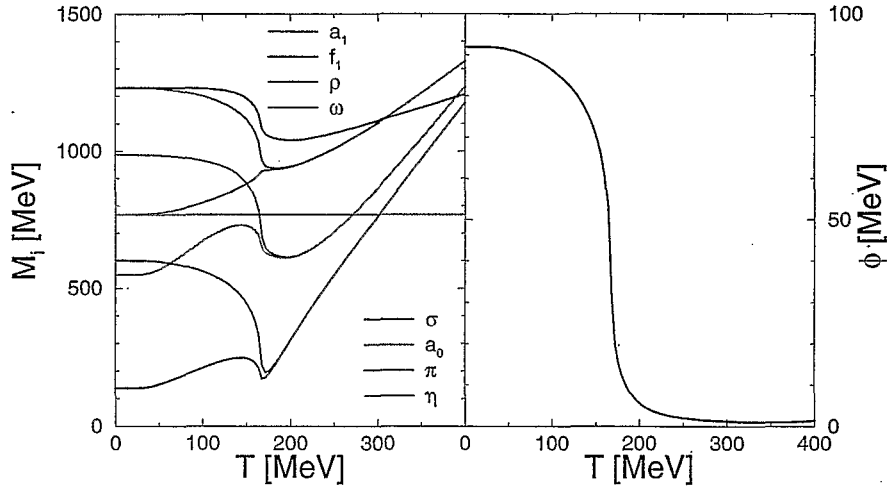
Dirk Röder, Jörg Ruppert, DHR, hep-ph/0503042 (NPA, to be published)

Vector Mesons (II)

Particle content of $U(2)_r \times U(2)_\ell$ model:

scalars σ_a	σ, (a_0^+, a_0^0, a_0^-)
pseudoscalars π_a	η, (π^+, π^0, π^-)
vectors V_μ^a	ω, (ρ^+, ρ^0, ρ^-)
axial vectors A_μ^a	f_1, (a_1^+, a_1^0, a_1^-)

Hartree-Fock approximation:



Stefan Strüber,
DHR,
in preparation

The State of the Universe

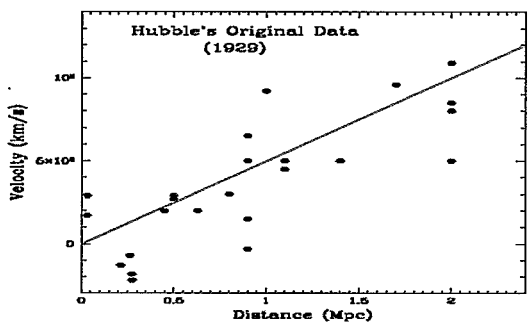
John Huchra
Harvard-Smithsonian Center for Astrophysics
RBRC Symposium, BNL, June 2006

COSMOLOGY is a modern subject: The basic framework for our current view of the Universe rests on ideas and discoveries (mostly) from the early 20th century.

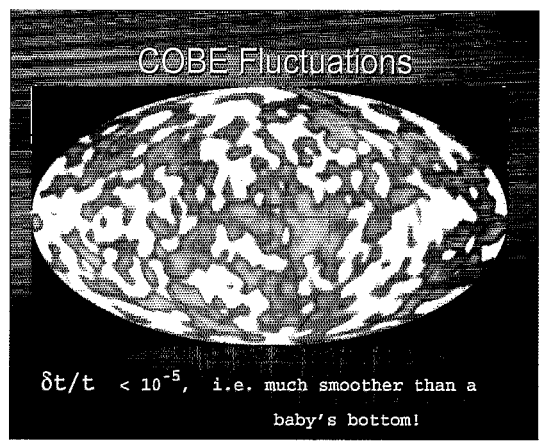
The Absolute Basics are: Einstein's General Relativity & The Copernican Principle
There are four Fundamental Observations & a few Fundamental Principles on which our view (model) is based:

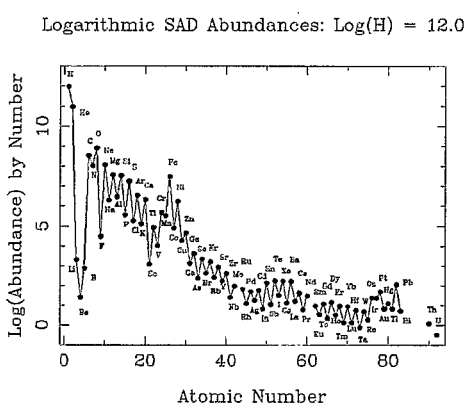
Fundamental Observations:

The Sky is Dark at Night (Olber's Paradox)
The Universe is Homogeneous on large scales (eg. the Cosmic Background)
The Universe is generally Expanding (Hubble's Law)
The Universe has Stuff in it, and the stuff is consistent with a hot origin: $T_{cmb} = 2.725^{o}$

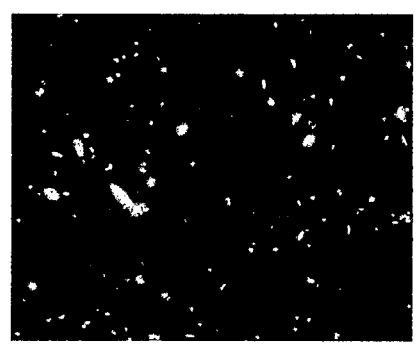


Hubble's Expansion Law





Olber's Paradox Hubble UDF



Basic Principles:

Cosmological Principle: (a.k.a. the Copernican principle).

There is no preferred place in space --- the Universe should look the same from anywhere → The Universe is HOMOGENEOUS and ISOTROPIC.

Perfect Cosmological Principle: The Universe is also the same in time.

This leads to the STEADY STATE Model which we're sure is wrong (XXX)

Anthropic Cosmological Principle: We see the Universe in a preferred state (time etc.) i.e. when Humans can exist. This is distained by theorists but has some predictive power and does represent e bit of a conundrum

Relativistic Cosmological Principle: The Laws of Physics are the same everywhere and everywhen. This is absolutely necessary (!!!) and we check it often

Taken together these principles imply a geometry for the Universe: the Friedman-Robertson-Walker metric is the most general description of space and time that is "Homogeneous," "Isotropic," and "Non-Static:"

$$ds^2 = c^2dt^2 - R^2(t)(dx^2 + dy^2 + dz^2)/(1+kr^2/4)$$

or in spherical coordinates and simplifying,

$$ds^2 = c^2dt^2 - R^2(t)[dr^2/(1-kr^2) + r^2(d\theta^2 + sin^2\theta\, d\phi^2)]$$

Remember: This is just geometry!

What about the scale factor R(t)? R(t) is specified by <u>*Physics*</u> Einstein's equations plus Friedman's equation.

Cosmology is now the search for three numbers + the geometry:

The Expansion Rate = Hubble's Constant H_0 N.B. $H_0 = dR(t)/dR$

The Mean Matter Density = Ω (matter) = Ω_M

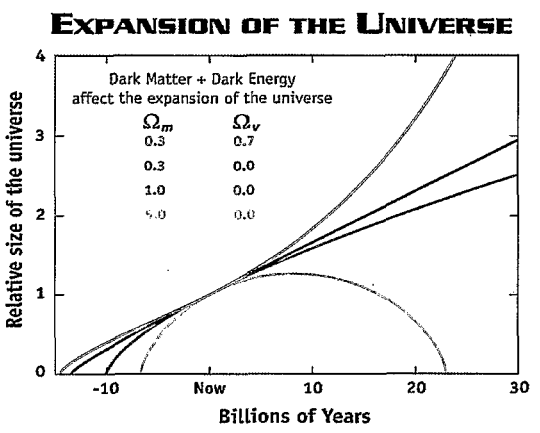
The Cosmological Constant = Ω (lambda)= Ω_Λ

The geometric constant $k = -1, 0, +1$

Taken together, these numbers describe the geometry of space-time and its evolution. They also give you the Age of the Universe, and how its geometry evolves with time.

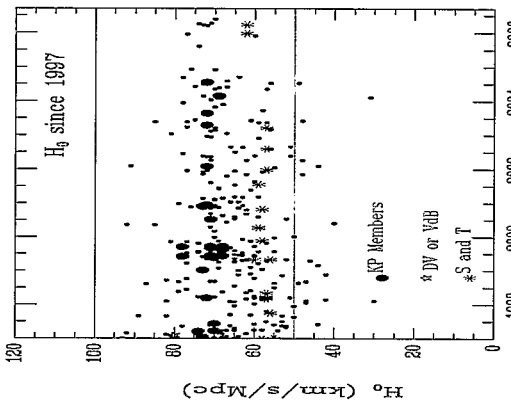
The best routes to the first two are in the Nearby Universe: H_0 is determined by measuring distances and redshifts to galaxies. It changes with time in real FRW models so by definition it must be measured locally. Ω_M is determined locally by (1) a census, (2) topography, or (3) gravity versus the velocity field (how things move in the presence of lumps).

The best current value of H_0 comes from the HST Key Project and is ~ 70 km/s/Mpc.

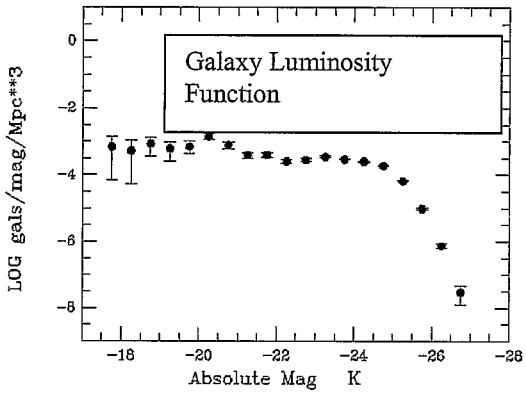


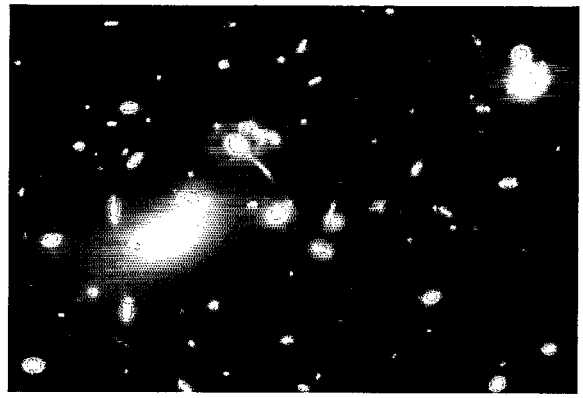
Omega(matter) Ω_M is determined by counting and/or weighing things plus theory.

0. Baryons from Nucleosynthesis
1. Sum up Starlight (count stars and/ or count galaxies)
2. Count and Weigh Galaxies
   Dynamics, lensing ....
3. Use Global techniques:
   Large Scale Structure
   Large Scale Flows



← 70 km/s/Mpc





From Stars	Ω_M	~ 0.01	counts
From Baryon Genesis		~ 0.044	theory+
From Rotation Curves		~ 0.08	gravity
From Galaxy Groups		~ 0.20	gravity
From Clusters		~ 0.22	gravity
From Flows		~ 0.25	gravity
From Large Scale Structure		~ 0.27	theory

Cosmological Constant = Lambda Λ is measured by observing the geometry of the Universe at large redshift (distance). There are two main methods

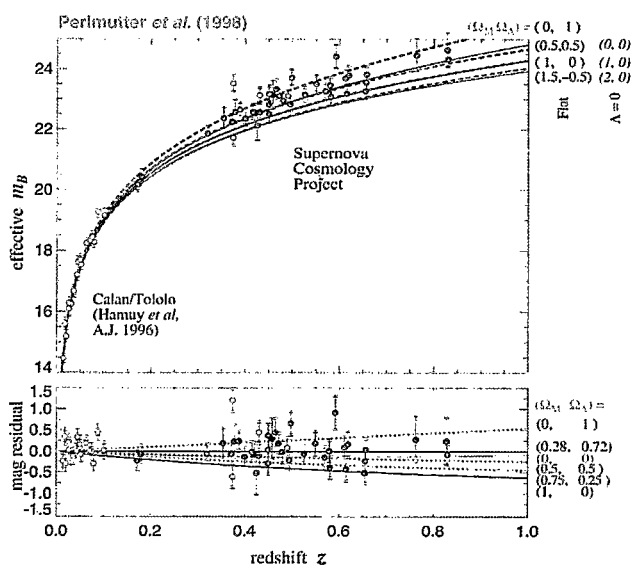
1. Supernovae as standard candles (the SN Ia Hubble Diagram)
2. The comparison of CMB Fluctuations and Models

Levels of Certainty in Science:

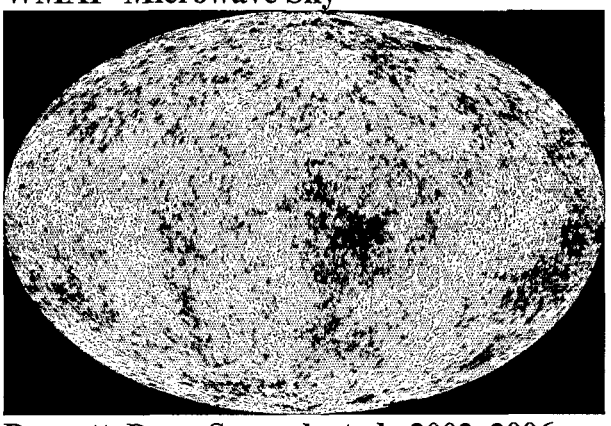
You bet:

A Dime	=	\$0.1
Your Dog	=	\$100
Your House	=	\$100,000

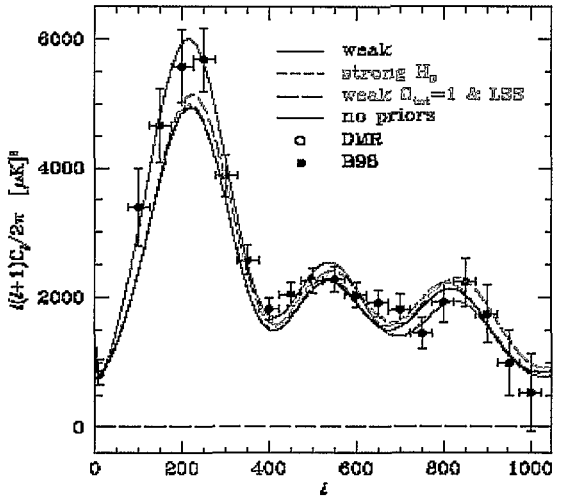
Your Firstborn = \$100,000,000 ....
each is x 1000
(except in New York and Boston where everything is x 10!!!)



WMAP Microwave Sky



Bennett, Page, Spergel, et al. 2003, 2006



From CMB Fluctuations matched to constrained models, the positions and amplitudes of peaks give estimates of the cosmological parameters. The model has 20+ fit parameters, and a strong dependence on priors (Tegmark '05).

Large scale geometry:

CMB Fluctuations as measured by WMAP indicate Ω(total) = Ω_T is very nearly unity (1.026 +/- 0.03 for the k-unconstrained OCDM model, 3 years of data) thus the Universe is ***probably*** FLAT, k = 0, and

$$\Omega_\Lambda = \Omega_T - \Omega_M = \sim 0.73$$

With that we can finally write down for the contents:

Ω (stars) =0.005 +/- 0.002
Ω (baryons) = 0.044 +/- 0.004 (which includes the stars)
Ω (neutrinos) < 0.008
Ω (CDM) = 0.23 +/- 0.04
Ω (matter) = 0.27 +/- 0.04 (which includes baryons, neutrinos, CDM ...)
Ω (Dark Energy) = 0.73 +/- 0.04
Ω (Total) = 1 (of course, as an assumption)

Age of the Universe: The age of the Universe is estimated in two ways:

1. Cosmological Expansion Age is $(1/H_0)$ x geometric factors
2. Ages of the Oldest Things: stars, galaxies, star clusters, whatever.

The Age of Flat Universes

H_0/Ω_Λ	0.0	0.6	0.7	0.8
55	11.9	15.1	17.1	18.5
65	10.0	12.7	14.5	16.2
70	9.4	11.9	**13.6**	15.1
75	8.7	11.1	12.6	14.0

Where Ω_{total} = 1.000, and the Ω_Λ = 0 model is the Standard CDM models in Gigayears

JPH's Favorite Guess Today:

H_0 = 70 +/- 5 km/s/Mpc
The Universe is going to expand forever
Its current age is around **14 Billion Years**, and
There is a good chance its **FLAT** with a Cosmological constant = $\Omega_\Lambda \sim 0.7$
(or the equivalent)

This is called the **"Concordance Cosmology."**

But Big Open Questions Remain:

1. Is the Universe really FLAT? If so, is that due to a Cosmological Constant? Quintessense? Dark Energy? Or something else?? What is the equation of state of DE?
2. How much Dark Matter exists? What exactly is the Dark Matter?
3. How did Large Scale Structure form? When did it form?
4. When and how did galaxies form? *("semianalytic" models cute, but contain no physics)* Is the distribution of ordinary matter different from that of dark matter? How different? Why?
5. Can we understand baryon aysmmetry?
6. What made the chemical elements? (P.S. The Sun isn't average)
7. Are we absolutely sure the laws of physics are not space and/or time dependent?
8. Do we have the right laws of physics?!

Its quite a hoot to think that 95.5% of the Universe has never been physically seen or detected in a laboratory and at the same time that we have solved it all! (a.k.a. chutzpah)

Some Cautions:

Gold's Law: Complex problems often have simple, easy to understand, **wrong** solutions.

Yogi's Caution: It ain't what you don't know, Its what you know that ain't so. (originally M. Twain) Beware of Myths and Biases. Or, "Traditional Wisdom" can lead you down the garden path.

Tarzan's Dilemma: Don't miss the forest for the trees. Keep the Big Picture in mind. Ask clear questions. Know why you asked them. Remember your assumptions! (and communicate them to your colleagues)

Electroweak Physics

William J. Marciano
Brookhaven National Laboratory
Upton, NY 11973-5000

Summary

An overview of electroweak physics is given. The role of precision measurements for constraining the Higgs mass and probing for "new physics" is discussed. Examples where lattice calculations can be very valuable are described. Disagreement between the two best measurements of the weak mixing angle is shown to suggest very different interpretations (supersymmetry versus Technicolor). Future possibilities for resolving that discrepancy are mentioned.

W. Marciano
6/21/06

Electroweak Physics

$SU(3)_c$ QCD is a perfect theory - No Free Parameters!

Rich Dynamics: Confinement, Asy Freedom, Spectroscopy...

BNL is a QCD Laboratory

RHIC - Pol. pp - Lattice Gauge Th.

$SU(2)_L \times U(1)_Y$ EW is not a perfect theory

but very accommodating!

Many Arbitrary Parameters

$g_1, g_2 \rightarrow \alpha, \sin^2\theta_W$

$\mu^2, \lambda \rightarrow m_H, v \simeq 250\,\text{GeV}$

Higgs Yukawa $\rightarrow$ 72 Parameters - 20 observables + ...

CKM Unitarity: $|V_{ud}|^2 + |V_{us}|^2 + \underbrace{|V_{ub}|^2}_{\sim 1\times 10^{-5}\ \text{tiny}} = 1$

$0^+ \to 0^+$ Beta Decays $\quad V_{ud} = 0.97377(11)(15)(19)_{RC}$

$\to V_{us} = \sin\theta_c = 0.2275(11)$ Indirect

$K \to \pi \ell \nu_\ell \quad (K_{\ell 3}) \to V_{us} = 0.2261(8)\left(\frac{0.961}{f_+(0)}\right)$ Vector

$\frac{K \to \mu\nu}{\pi \to \mu\nu} \left(\frac{K_{\mu 2}}{\pi_{\mu 2}}\right) \to V_{us} = 0.2245(5)\left(1.198\frac{f_\pi}{f_K}\right)$ Axial

Also, Hyperon Decays, $\tau \to \nu_\tau s\bar{u}$

Now a lattice problem: $f_+(0)$ & f_K/f_π

I will concentrate on $\sin^2\theta_W(m_Z)_{\overline{MS}} \to m_H$ & "New Physics"

The Most Important EW Parameter!

Natural Relations: $\sin^2\theta_W^0 = \frac{e_0^2}{g_{2_0}^2} = 1 - (m_W^0/m_Z^0)^2$ SU(2) Custodial sym.

Radiative Corrections (finite & calculable)

$$\Delta r(m_t, m_H, \text{new phys}) = 1 - \frac{\pi\alpha}{\sqrt{2}G_\mu m_W^2(1 - m_W^2/m_Z^2)}$$

$$\Delta\hat{r}(m_t, m_H, \text{new phys}) = 1 - \frac{2\sqrt{2}\,\pi\alpha}{G_\mu m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{MS}}}$$

The Weak Mixing Angle Problem (Mini-Crisis)

Two Best Z Pole Determinations

$$\left.\begin{array}{ll} A_{LR} \ \text{SLD} \rightarrow & \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2307(3) \\ A_{FB}(Z\to b\bar{b}) \rightarrow & \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2320(3) \end{array}\right\} 3\sigma!$$

Discrepency Lost in Averaging $\rightarrow 0.2312(2)$

Very Different Implications

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2307(3) \rightarrow \underline{m_H = 35^{+26}_{-17}\ \text{GeV}}$ Ruled Out!

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2320(3) \rightarrow \underline{m_H = 480^{+350}_{-230}\ \text{GeV}}$ Heavy!

S Parameter

$$S = 118\left[2\,\frac{m_W - 80.366\,\text{GeV}}{80.366\,\text{GeV}} + \frac{\sin^2\theta_W(m_Z)_{\overline{MS}} - 0.23117}{0.23117}\right]$$

use $\underline{m_W = 80.410(32)\ \text{GeV}}$

Standard Model + SUSY $\rightarrow$ $S \simeq 0$ Expected

Heavy Fermion Chiral Doublets $\rightarrow$ $S \simeq +\frac{1}{6\pi} N_D \simeq 0.05 N_D$

How will $\sin^2\theta_W(m_Z)_{\overline{MS}}$ discrepency be resolved?

* LHC? $pp \to Z \to \mu^+\mu^-$ FB Asym Hard (± 0.00008)

ILC? Giga Z Factory (Z pole) A_{LR} in e^+e^-

$\Delta \sin^2\theta_W \to \pm 0.00002$ Pol. $\pm 0.1\%$? Hard

Other $\to \pm 0.0002$ (Long Wait ~15yr)

What about low Q^2 experiments?

Atomic Parity Violation $Q_W(Cs) = -72.66(46)$

Pol. Electron Scattering $e^-e^- \to e^-e^-$ Moller $A_{LR} \simeq 1.3\times10^{-7}$

($\propto (1-4\sin^2\theta_W)$) $e^-p \to e^-p$ $Q_W(p)$ A_{LR}

Current Status (After Rad. Corr.)

APV $\longrightarrow$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2290(20)$

Moller (E158) $\longrightarrow$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2330(14)$

$\Big\}$ 1.5σ

Again below and above world average

Nice confirmation of SM Quantum Loops & Running

But Errors Not Competitive With Z Pole

Constraints: $m_{Z_\chi} > 1\,\text{TeV}$

$m_{comp.} \gtrsim 10\,\text{TeV}$

$g^2/m_{H^{--}}^2 < 0.01\,G_F$

$\vdots$

Together

$S \simeq 0.4(6)$

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2317(12)$

Conclusion: $\sin^2\theta_W(m_Z)$ most important parameter for:

Higgs Mass (via loops)
S Parameter
Grand Unification
⋮

Present Situation Unacceptable

Need $Q_W(p)$, e^-e^- at JLab

e^-e^- + Giga Z at ILC $\rightarrow \Delta s^2 \simeq \pm 0.00006, 0.00002$

+ LHC + other e^+e^- efforts

Very Complementary to Direct "New Physics" Discovery

Lattice:

vs $e^+e^- \rightarrow$ hadrons data

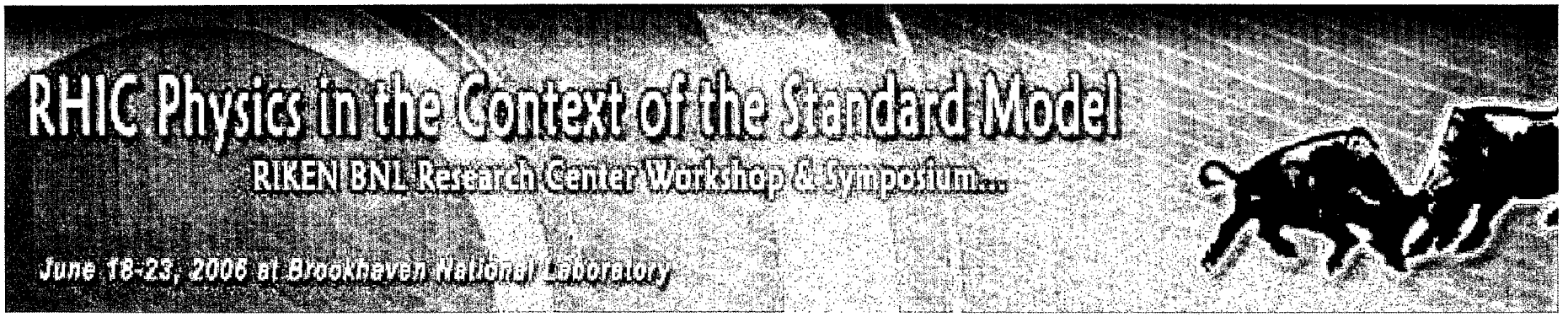
easier than $g_\mu - 2$

LHC: $pp \rightarrow Z + X$ $\quad Z \rightarrow \mu^+\mu^- \rightarrow$ $\delta \sin^2\theta_W \simeq \pm 0.00008$

(Best Bet)

Can Pol pp help overcome had. unc $\rightarrow \pm 0.0002$?

or Z/W at LHC



BNL, June. 2006

Neutrino Oscillation Experiments

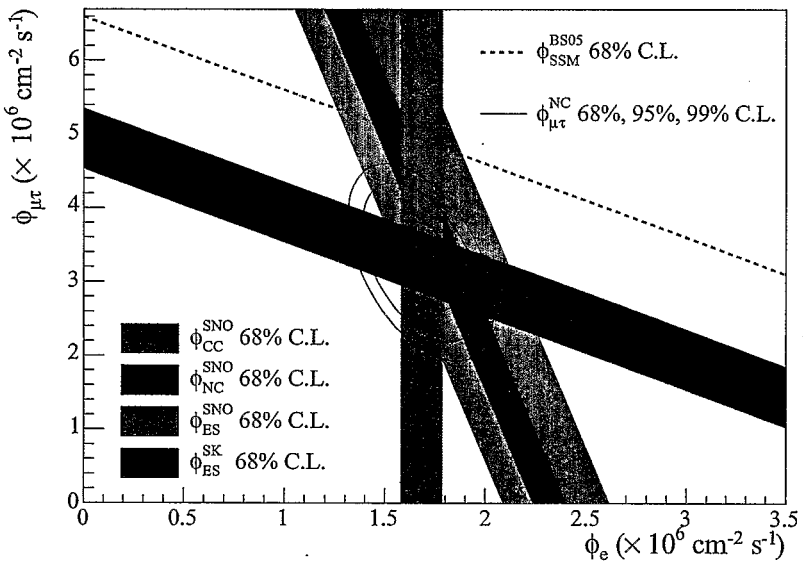
- present and future -

Takaaki Kajita

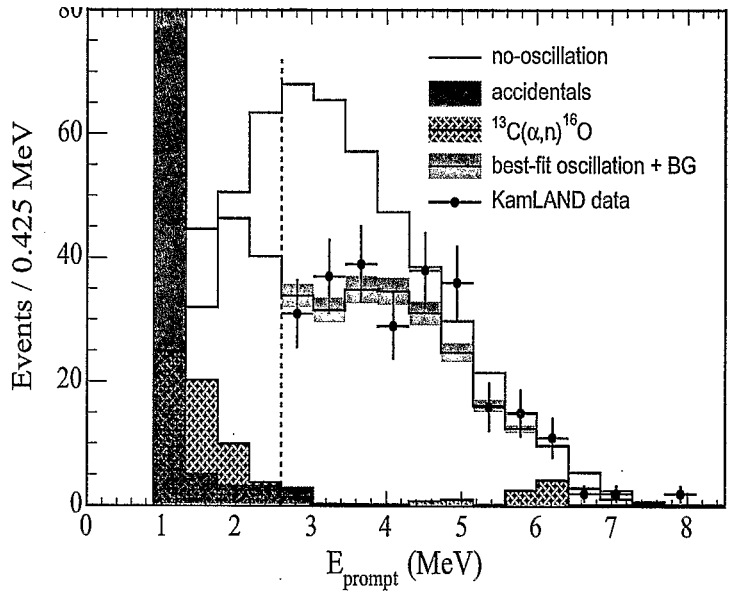
ICRR, Univ. of Tokyo

Results from various neutrino oscillation experiments are summarized. Although the dominant oscillations are understood well by the present experiments, there are still unknowns. Prospects for the future neutrino oscillation experiments are discussed.

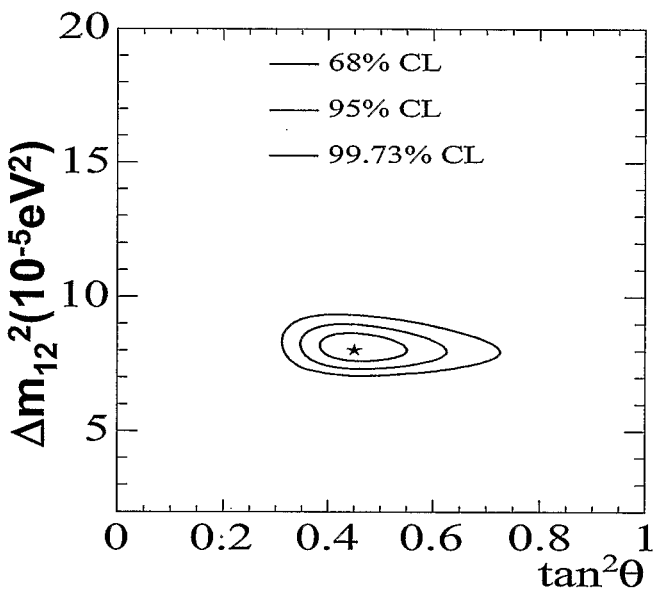
Results from solar and KamLAND experiments



Solar neutrino measurements by SNO and Super-K. The observations clearly show non-zero $\nu_\mu + \nu_\tau$ flux. (This figure is taken from SNO collab. Phys. Rev. C72: 055502, 2005.)

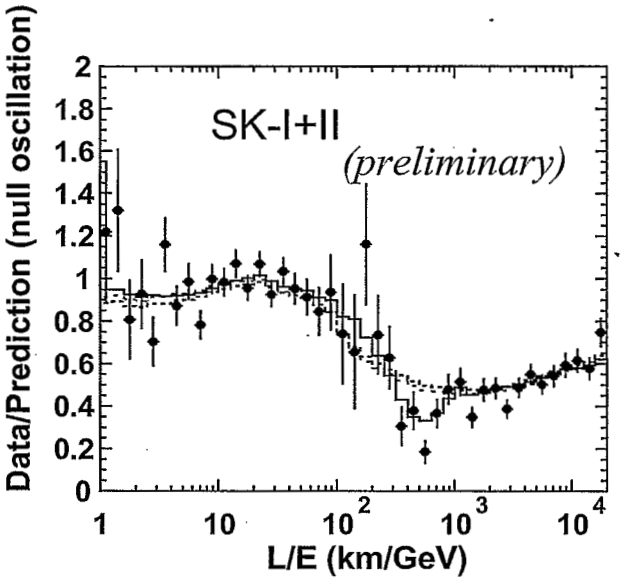


Observed energy spectrum of reactor neutrinos by KamLAND. The energy dependent deficit of events constrains the oscillation parameters. (This figure is taken from KamLAND collab. Phys. Rev. Lett. 94: 081801, 2005.)

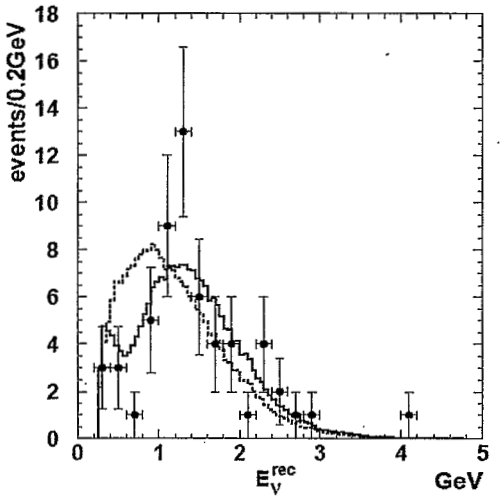


Allowed neutrino oscillation parameter region from solar and KamLAND experiments. (This figure is taken from SNO collab. Phys. Rev. C72: 055502, 2005.)

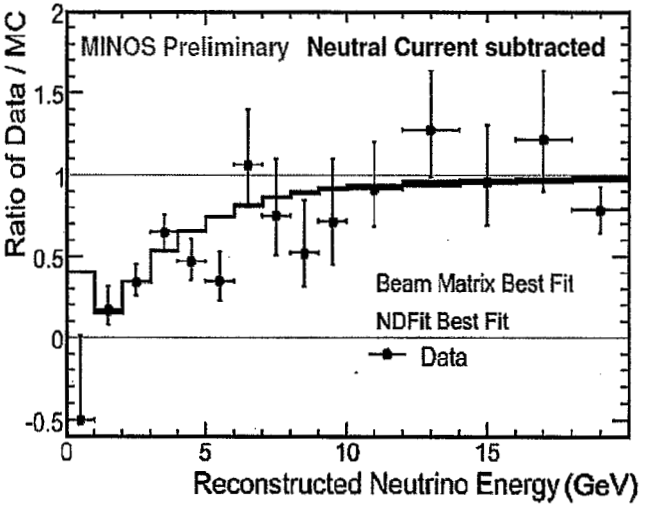
SK atmospheric, K2K and MINOS results



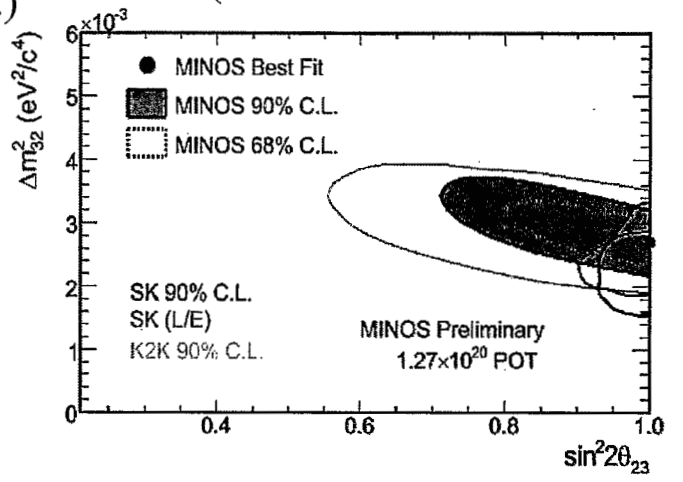
L/E analysis of the Super-K-I+II(141ktonyr) data. The data favor oscillation (blue). The decay (green) and decoherence models are excluded at about 5σ level. (SK collab. Neutrino2006, poster)



Final K2K result on ν_μ disappearance. The energy dependent deficit is clearly seen. (This figure is taken from K2K collab. hep-ex/0606032.)



New MINOS result on ν_μ disappearance. The energy dependent deficit is clearly seen. (MINOS collab. Neutrino2006)



Allowed neutrino oscillation parameter region from atmospheric, K2K and MINOS experiments. (This figure was presented in Neutrino 2006 by the MINOS collab. The SK allowed regions are slightly old.)

Future neutrino oscillation experiments

Search for non-zero θ_{13}

• Reactor experiments. ➔ They search for anti-neutrino disappearance. Pure measurement of $\sin^2 2\theta_{13}$. It is very important to control systematics. There are several projects going on. The typical sensitivities are $\sin^2 2\theta_{13} = 0.01 - 0.03$.

•Long Baseline Accelerator experiments. ➔ They search for electron neutrino appearance. The size of the appearance signal depends not only on θ_{13} but also on CP phase, mass hierarchy and θ_{23}. T2K and Nova experiments. The expected sensitivities are about $\sin^2 2\theta_{13} = 0.01$ or slightly smaller.

Beyond θ_{13} ➔ CP violation, mass hierarchy

• If $\sin^2 2\theta_{13}$ is near the present limit, collaborative work between T2K and Nova together with more neutrino events will be useful to understand the mass hierarchy, since Nova has longer baseline than T2K.

• In order to measure the CP violation and mass hierarchy, much larger scale, long baseline neutrino oscillation experiments are discussed. These include BNL or Fermilab to DUSEL and T2K phase-II (with and without a detector in Korea). These experiments have high sensitivities on these measurements, if $\sin^2 2\theta_{13}$ is larger than ~ 0.01.

Summary

Present

- Dominant oscillations (Δm_{23}^2, $\sin^2\theta_{23}$) and (Δm_{12}, $\sin^2\theta_{12}$) ➔ already in the precision study phase.

Future

- The key parameter is θ_{13}.
- Future reactor and LBL experiments intend to search for non-zero θ_{13} with a factor 10-20 better sensitivity than the present limit.
- If non-zero θ_{13} is observed, the neutrino community hopes to proceed to the next phase for the measurement of the leptonic CP violation and the determination of the mass hierarchy.

Using AdS/CFT to explore the Strong Coupling Regime of Gauge Theories: I

Steve Gubser
Princeton University

RBRC Symposium, Brookhaven National Laboratory

June 21, 2006

1. Introduction

A recent string theory computation of drag force on a heavy quark moving through a thermal plasma of $\mathcal{N} = 4$ super-Yang-Mills theory gives

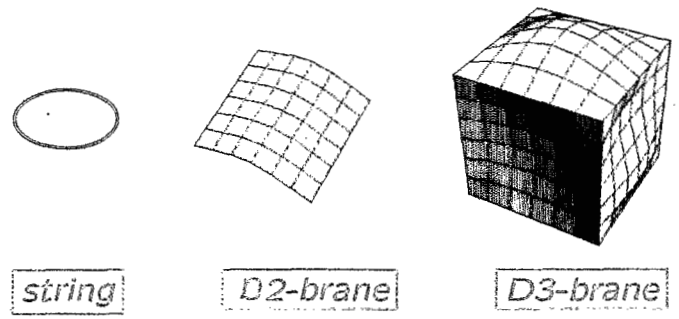
$$F \equiv \frac{dp}{dt} = -\frac{\pi\sqrt{g_{YM}^2 N}}{2} T^2 \frac{p}{m} \,. \tag{1}$$

My aims are

- To summarize relevant aspects of string theory (i.e. AdS/CFT).
- To caution you that string theorists have not yet solved QCD!
- To explain where (1) comes from.
- To describe further calculations that give evidence for a "wake" of gluons and their superpartners.
- To speculate about the possible relevance to jet-quenching at RHIC.

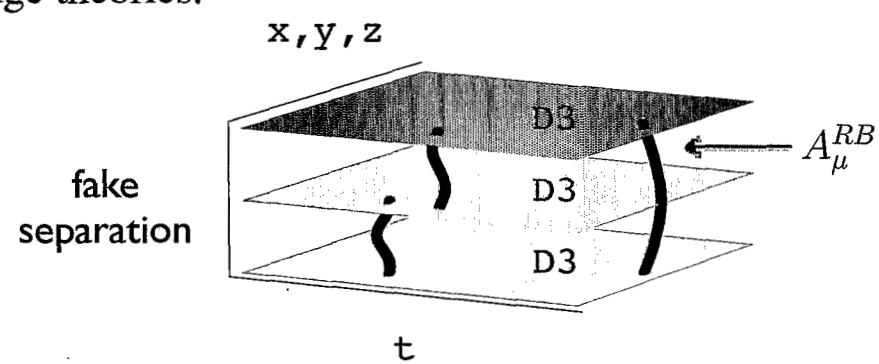
2. String theory and $\mathcal{N} = 4$ super-Yang-Mills

Strings can't exist without higher-dimensional objects: D-branes.



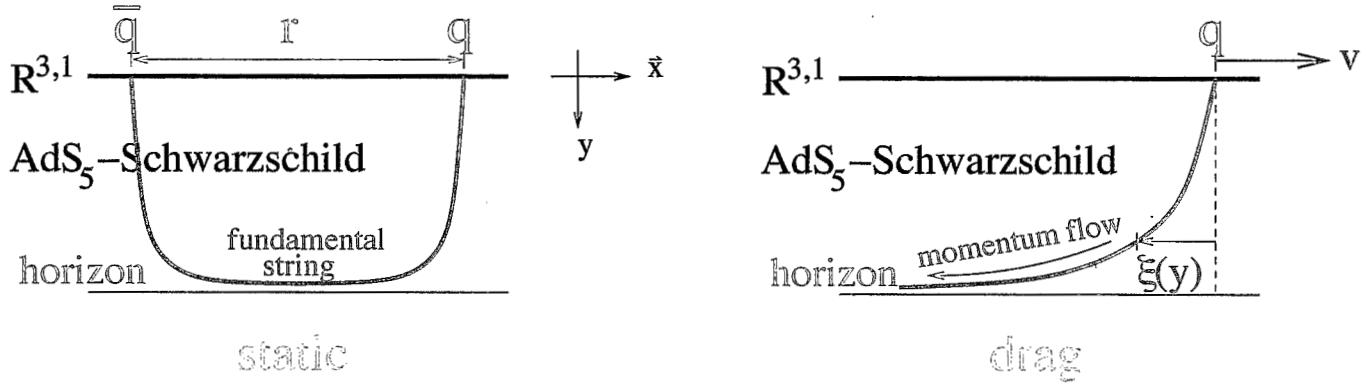
D-branes can be defined as locations where strings can end.

○ One one hand, strings ending on D3-branes act as gluons for interesting four-dimensional gauge theories.



4. A drag force computation

$G_{tt} \longrightarrow 0$ at the horizon of AdS-Schwarzschild, so the *static force* between quarks goes to zero as separation increases. But *drag force* on a moving quark is finite.



We need to know the shape of the trailing string and the momentum flow down it. We assume a "co-moving" ansatz:

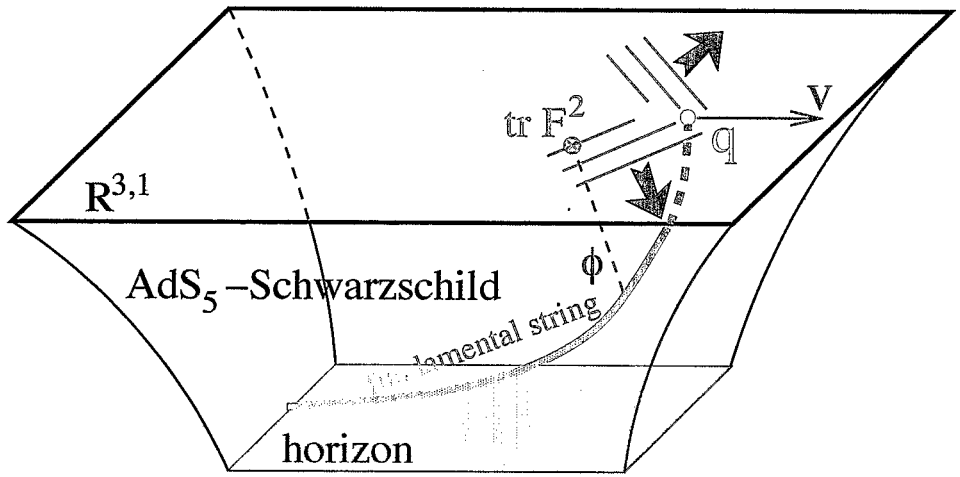
$$x^1(t,y) = vt + \xi(y) \tag{7}$$

The AdS_5-Schwarzschild background is

$$ds^2 = \frac{L^2}{z_H^2 y^2}\left(-hdt^2 + d\vec{x}^2 + z_H^2 \frac{dy^2}{h}\right) \qquad \boxed{h \equiv 1 - y^4} \qquad z_H = \frac{1}{\pi T}. \tag{8}$$

5. A wake generated by the moving quark

The string "casts a shadow" on the boundary, and that shadow is the wake of the moving quark.



We can learn about color singlet VEV's by further string theory computations.

- Easiest is the dilaton, which relates to $\langle \mathrm{tr}\, F^2 + (\text{superpartners}) \rangle$ on the boundary. Worked out in `hep-th/0605292`.
- Graviton is harder but tells us about $\langle T_{mn} \rangle$, in paritcular the Poynting vector. Work in progress.

7. Conclusions

- AdS/CFT gives us a lot of computational power over $\mathcal{N} = 4$ super-Yang-Mills at large N and large $g_{YM}^2 N$. Maybe this is useful to RHIC physicists.
- A drag force $F \sim \sqrt{g_{YM}^2 N}\, T^2$ comes out of a trailing string picture.
- The "shadow" on $\mathbf{R}^{3,1}$ of the trailing string is the QCD string stretching out and widening in a wake around and behind the quark.
- This wake involves high-momentum fields.
- More theoretical information soon, in the form of $\langle T_{mn} \rangle$.
- A question for the experimentalists: Is energy dissipated through a wake of coherent low-energy fields, or are high-energy particles involved in an important way?

Using AdS/CFT to explore the strong coupling regime of gauge theories: II

Dam T. Son (Institute for Nuclear Theory, University of Washington)

We show how the AdS/CFT correspondence can be used to compute the shear viscosity of strongly coupled plasma. In theories with gravity duals, the ratio of the shear viscosity and the entropy densith is equal to a universal number, $\hbar/(4\pi)$.

Viscosity: Kubo's formula

For our goal, it is best to start from Kubo's formula for viscosity:

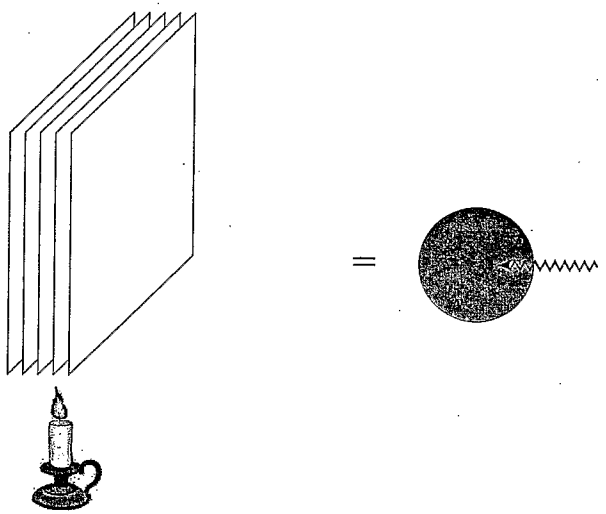
$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t, \mathbf{x}),\, T_{xy}(0, \mathbf{0})] \rangle$$
$$= - \lim_{\omega t \to 0} \lim_{\mathbf{q} \to 0} \operatorname{Im} G_{xy,xy}(\omega, \mathbf{q})$$

retarded Green's function of T_{xy}

Similar relations exist for other kinetic coefficients (diffusion constants, conductivities...)

Gravity counterpart of Kubo's formula

Consider a graviton that falls on this stack of N D3-branes
Will be absorbed by the D3 branes.
The process of absorption can be looked at from two different perspectives
(Klebanov; Gubser, Klebanov, Tseytlin 1996-1997):



Absorption by D3 branes = absorption by black hole, calculable classically

Viscosity as absorption

From optical theorem: absorption cross section of graviton is proportional to the imaginary part of the correlator of stress-energy tensor of gauge theory (coupling: $h_{\mu\nu}T^{\mu\nu}$).

$$\sigma_{\text{abs}} = -\frac{2\kappa^2}{\omega}\,\text{Im}\,G^R(\omega), \qquad \kappa = \sqrt{8\pi G}$$
$$= \frac{\kappa^2}{\omega}\int d^4x\, e^{i\omega t}\langle[T_{xy}(x),\, T_{xy}(0)]\rangle$$

Viscosity = absorption cross section of low-energy gravitons

$$\eta = \frac{\sigma_{\text{abs}}(0)}{2\kappa^2} = \frac{\sigma_{\text{abs}}(0)}{16\pi G}$$

Two theorems

The computation of the absorption cross section σ_{abs} is made easy by two theorems, valid for a wide class of backgrounds:

- Equation for h_{xy} is the same as of a minimally coupled scalar
- For a minimally coupled scalar

$$\lim_{\omega \to 0} \sigma_{\text{abs}} = \text{Area of the event horizon}$$

Das, Gibbons, Mathur

As a consequence of these theorems

$$\eta = \frac{\sigma_{\text{abs}}(0)}{16\pi G} = \frac{\text{Horizon area}}{16\pi G}$$

Universality of η/s

So we found

$$\eta = \frac{\text{Horizon area}}{16\pi G}$$

However the entropy density is

$$s = \frac{\text{Horizon area}}{4G}$$

Therefore

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

This result is valid for *all* theories with gravity duals: universal, but within a restrictive class of theories, including $\mathcal{N} = 4$ SYM theory at infinite 't Hooft coupling and deformations (less SUSY, non-conformal).
(also proven by Buchel and and Liu)

QCD Thermodynamics

Jean-Paul Blaizot*

ECT, Villa Tambosi, strada delle Tabarelle 286, 38050 Villazzano (TN), Italy*

Abstract

The ideal quark-gluon plasma, a weakly interacting gas of quarks and gluons, was predicted on the basis of QCD asymptotic freedom. Lattice calculations provide evidence that thermodynamic functions go over those of ideal massless particles at high temperature. However RHIC data have forced us to look more carefully into the region of moderate temperatures, $T \gtrsim T_c$, where the quark-gluon plasma seems to behave more like a liquid than a gas, showing behavior reminiscent of that of strongly coupled plasmas. The region $T_c \lesssim T \lesssim 3T_c$ is still poorly understood theoretically. However, above $3T_c$, an accurate description of the thermodynamics can be obtained using weak coupling techniques. In this talk I argue that in spite of the fact that perturbation theory is ill behaved, weak coupling techniques can provide useful information on the thermodynamics, even in regimes where the coupling constant gets of order unity. I present in particular results from dimensional reduction, and skeleton expansion, and show in the later case that a good description of lattice data is achieved for temperatures above $3T_c$. Finally I suggest that the functional renormalization group can provide insights into what happens when the various scales characterizing the quark-gluon plasma start to mix.

*Member of CNRS; Electronic address: `blaizot@ect.it`

Ideal QGP

Asymptotic freedom $\alpha_s = \frac{g^2}{4\pi} \approx \frac{2\pi}{b_0 \ln\left(\mu/\Lambda_{QCD}\right)}$

$(\mu \approx 2\pi T)$

First predictions for existence of ideal quark matter (1975)

Preparation of heavy ion program, and proposed « signatures », were (mostly) based on this simple picture

RHIC forces us to look into a region Where theory is hard

Some important findings at RHIC

- -large energy density
- -Collective behavior
- -ideal hydro flows (low viscosity)
- -suppression of jets
- -etc

Leading to the suggestion that matter created in nucleus-nucleus collisions at RHIC behaves as a « perfect liquid » or a « strongly coupled quark-gluon plasma »

Region above Tc not well understood

$$T_c \le T \le 2.5T_c$$

Degrees of freedom ?

Bound states ? (Shuryak, Zahed, hep-ph/0405127)

Heavy quark bd states appear to survive well above Tc
(Asakawa, Hatsuda hep-ph/0208024)

But charge (baryon, flavor) carriers seem to be quarks

(Ejiri, Karsch, Redlich, hep-ph/0509051 - Gavai, Gupta hep-lat/0510044 ----)

..... Controversial issue

Remnants of confinment ?

Role of Z(3) symmetry and Polyakov loop

Strong coupling ?

QCD plasma

g Dimensionless gauge coupling

Thermal fluctuations $\sqrt{\langle A^2 \rangle_{\kappa T}} \approx \sqrt{\kappa} T$

		Kinetic energy $\partial_{\kappa T} \approx \kappa T$	Interaction energy $g\sqrt{\langle A^2 \rangle_{\kappa T}} \approx g\sqrt{\kappa} T$
Hard	$\kappa \approx 1$	T	gT
Soft	$\kappa \approx g$	gT	$g^{3/2}T$
Ultrasoft	$\kappa \approx g^2$	g^2T	g^2T

Effective theory.

Weak coupling techniques

-provide physical understanding of the regime of high temperature, and allow controlled extrapolations
-not limited to perturbation theory; in fact weak coupling techniques can be used to study non perturbative phenomena (many degenerate degrees of freedom, strong fields)
-present understanding of the transition from partonic w.f. (color glass) to matter produced in heavy ion collisions relies on weak coupling techniques

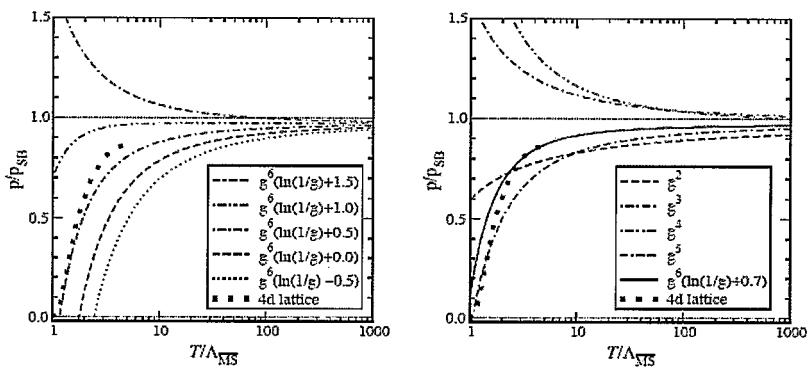
Effective theories- Dimensional reduction

Skeleton expansion

Insights from the functional renormalisation group

$$p = T^4 \left[c_0 + c_2 g^2 + c_3 g^3 + (c_4' \ln g + c_4)\, g^4 + c_5 g^5 + c_6 g^6 \right]$$

$$c_6 = N_c^3 \frac{N_c^2 - 1}{(4\pi^4)} \left[\left(\frac{215}{12} - \frac{805}{768}\pi^2 \right) \ln \frac{1}{g} + 8\delta \right]$$



K. Kajantie, M. Laine, K. Rummukainen, and Y. Schröder, *Phys. Rev. Lett.* 86 (2001) 10 , *Phys. Rev.* D 65 (2002) 045008 , *Phys. Rev.* D 67 (2003) 105008 , *JHEP* 0304 (2003) 036

Skeleton expansion

Pressure in terms of dressed propagators
(2PI formalism)

$$P[G]$$

Stationarity property

$$\frac{\delta P}{\delta G} = 0$$

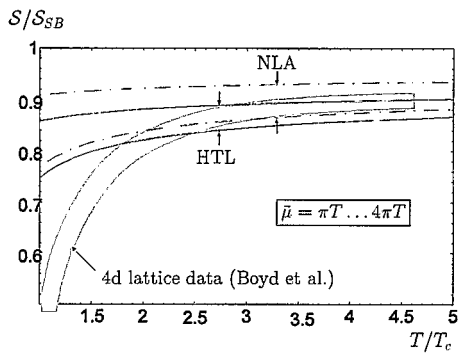
Entropy is simple!

$$S = \frac{dP}{dT} = \left.\frac{dP}{dT}\right|_G$$

State of the art

- Compare Lattice – 2PI

from J.-P. B., E. Iancu, A. Rebhan: Nucl.Phys.A698:404-407,2002

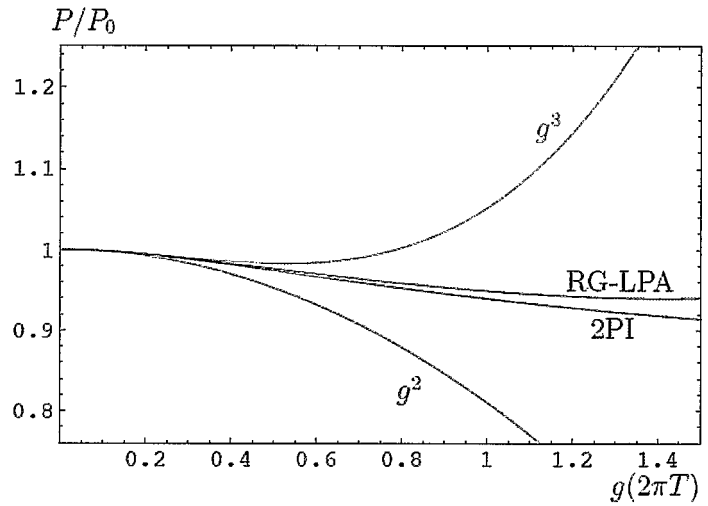


pure-glue SU(3) Yang-Mills theory

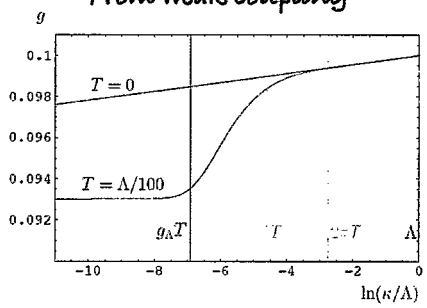
- J.-P. B., E. Iancu, A. Rebhan: Phys.Rev.D63:065003,2001
- F. Karsch, Nucl.Phys.A698:199-208,2002;
- G. Boyd *et al.*, Nucl. Phys. B469, 419 (1996).

Insights from the functional renormalization group

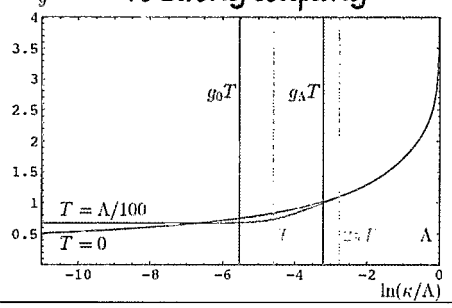
J.-P. B, A. Ipp, R. Mendez-Galain, N. Wschebor(work in progress)



From weak coupling



To strong coupling



Instabilities in non-abelian plasmas

Dietrich Bödeker (Bielefeld U), Kari Rummukainen (Oulu U & CERN)

RBRC Symposium, Brookhaven 2006

Abstract

I first give a brief review of recent work on QCD plasma instabilities and their potential role in thermalization in heavy ion collisions. Then I describe a numerical lattice study of instabilities in strongly anisotropic SU(2) plasmas. We find that the energy grows quasi-exponentially beyond the naive saturation bound for weak field initial conditions. The growth appears to stop only due to the finite lattice spacing. The lattice spacing dependence of the final energy density indicates that the continued growth is due to rapid energy transfer into high momentum modes which are not unstable in the weak field regime. This behavior is also seen in the gauge field spectrum in Coulomb gauge.

Simulation of strongly anisotropic plasmas

system with "hard" classical particles + soft classical fields

neglect backreaction on hard particle momentum distribution $\bar{f}(\mathbf{p})$ "hard loop effective theory"

$$(D_\mu F^{\mu\nu})^a = g \int \frac{d^3p}{(2\pi)^3} v^\nu f^a,$$

$$(v \cdot Df)^a + g v^\mu F^a_{\mu i} \frac{\partial \bar{f}}{\partial p^i} = 0$$

we use the W field method, SU(2) gauge group

$$W^a(x, \mathbf{v}) \equiv 4\pi g \int_0^\infty \frac{dp p^2}{(2\pi)^3} f^a(x, \mathbf{v}p)$$

- weak sphaleron rate in thermal equilibrium (isotropic $\bar{f}$) [Bödeker,Moore,Rummukainen]
- plasma instabilities in SU(2) [Arnold,Moore,Yaffe]

Simulation of strongly anisotropic plasmas

we expand W, $\bar{f}$ in spherical harmonics

$$\bar{f}(p\mathbf{v}) = \sum_{l}^{L_{\text{asym}}} \bar{f}_l(p) Y_{l0}(\mathbf{v})$$

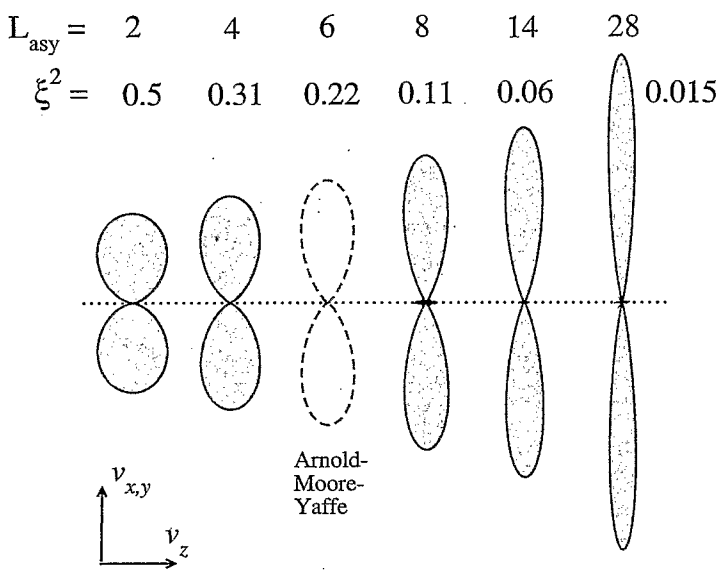
$$W(x, \mathbf{v}) = \sum_{l,m}^{L_{\max}} W_{lm}(x) Y_{lm}(\mathbf{v})$$

we use similar techniques as Arnold, Moore, Yaffe but

- 5 different values for the anisotropy, both weaker and much stronger
- large lattices (up to 240^3) with a large number of W-fields (up to $L_{\max} = 240$, i.e., 14250 fields in addition to A_i^a)

Simulation of strongly anisotropic plasmas

for each L_{asym} we try to maximally localize the distribution along the xy-plane



propellor shaped distribution

asymmetry parameter

$\xi^2 \equiv \frac{v_z^2}{\mathrm{v}^2}$

$\xi = 0.5, \ldots, 0.015$

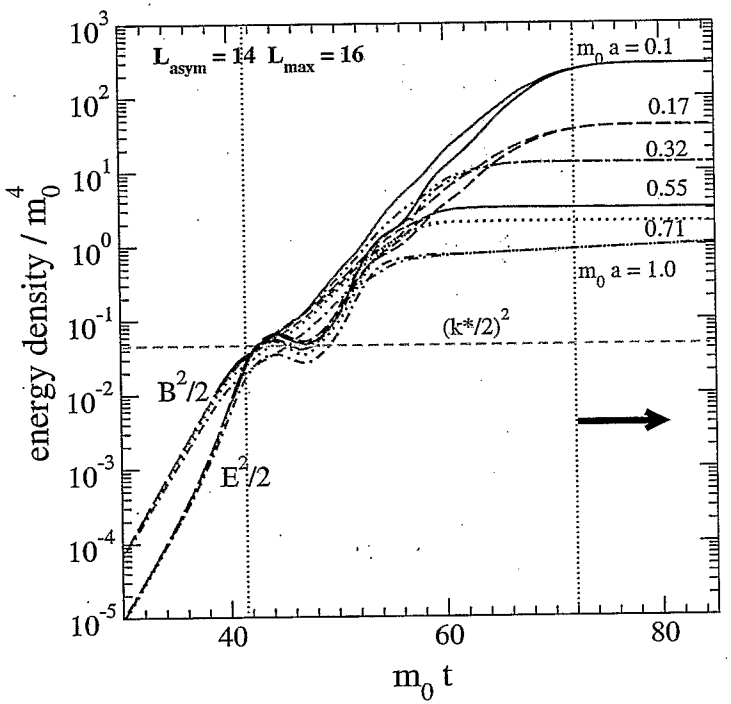
one needs $L_{\max} > L_{\mathrm{asym}}$

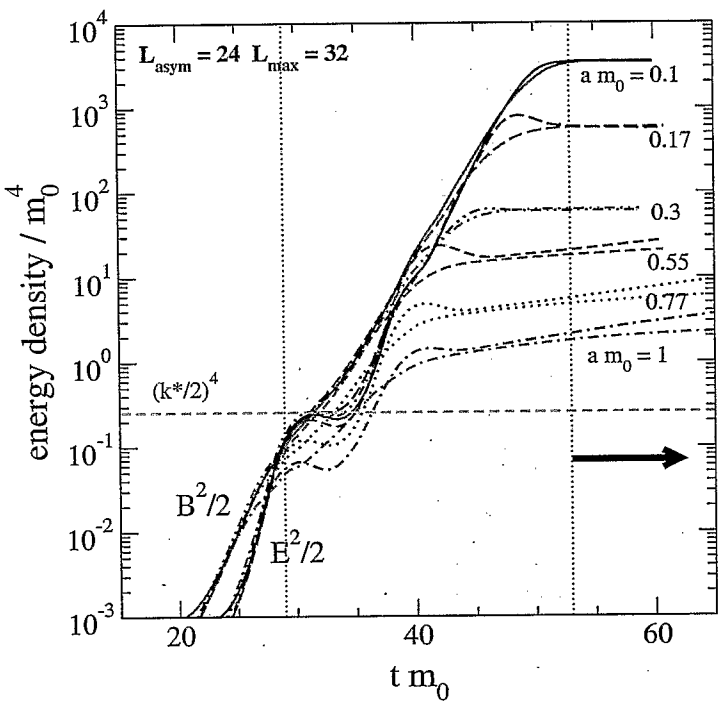
Results: growth of energy for strong anisotropy

quasi-exponential growth beyond weak field regime

stops when lattice UV modes saturate, $aA \sim 1$

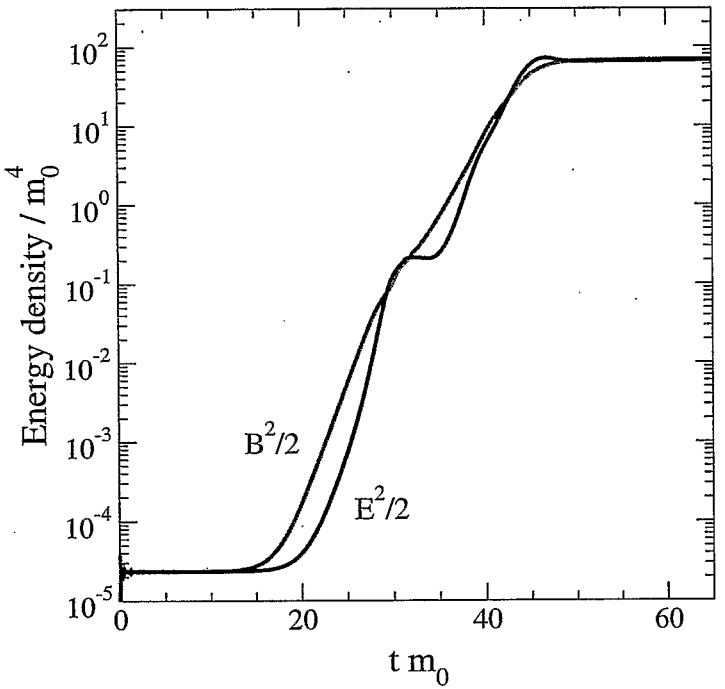
how far does it continue when $a \to 0$?



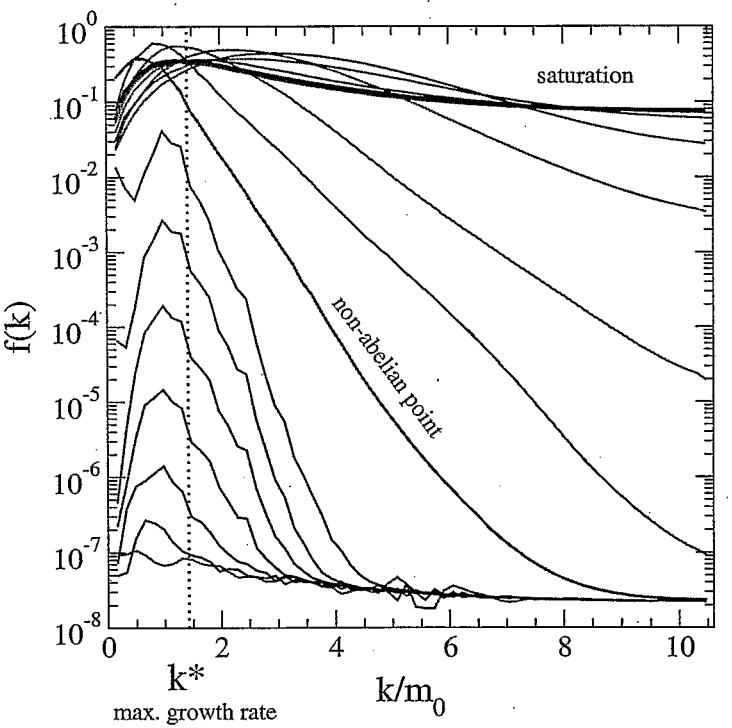


Coulomb gauge spectrum

gauge fixed to Coulomb gauge, $f_{\text{soft}}(\mathbf{k}) \propto kA(\mathbf{k})$



Fri May 5 10:35:40 2006



QCD phase diagram

M. Stephanov

U. of Illinois at Chicago

RBRC 1999-2004

QCD thermodynamics

- Applications:
  - Neutron stars (large density, low T)
  - Heavy-ion collisions (large T, large density)
- QCD allows first principle calculations
- Questions: phases, phase diagram, as function of T, μ_B, ...

- Early expectations $\Rightarrow$

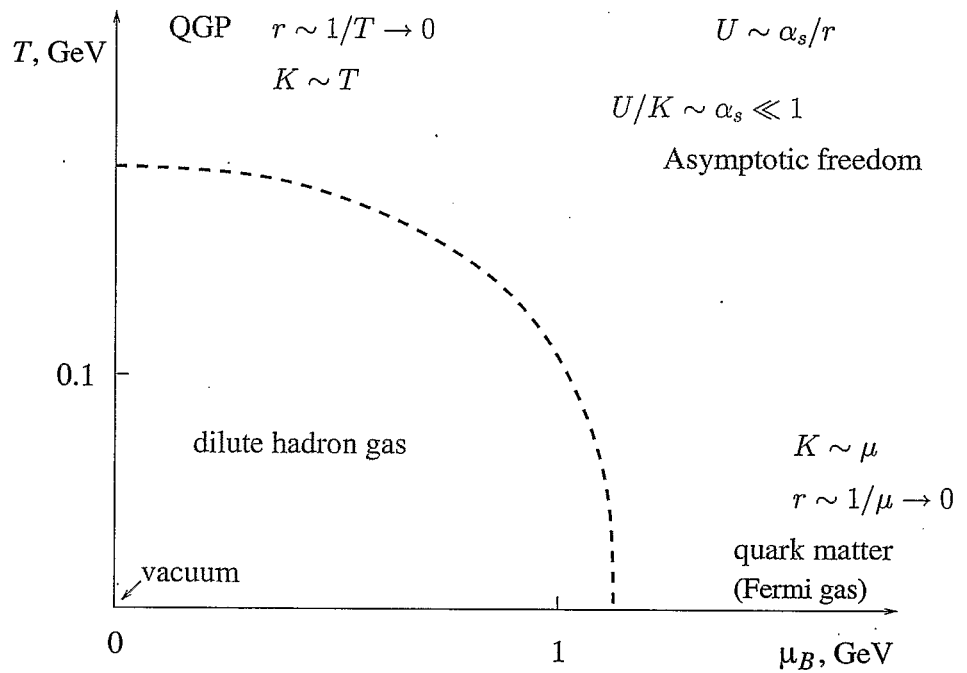
Natural scale:

$$kT \sim \frac{\hbar c}{1\text{fm}} = 0.2 \text{ GeV}.$$

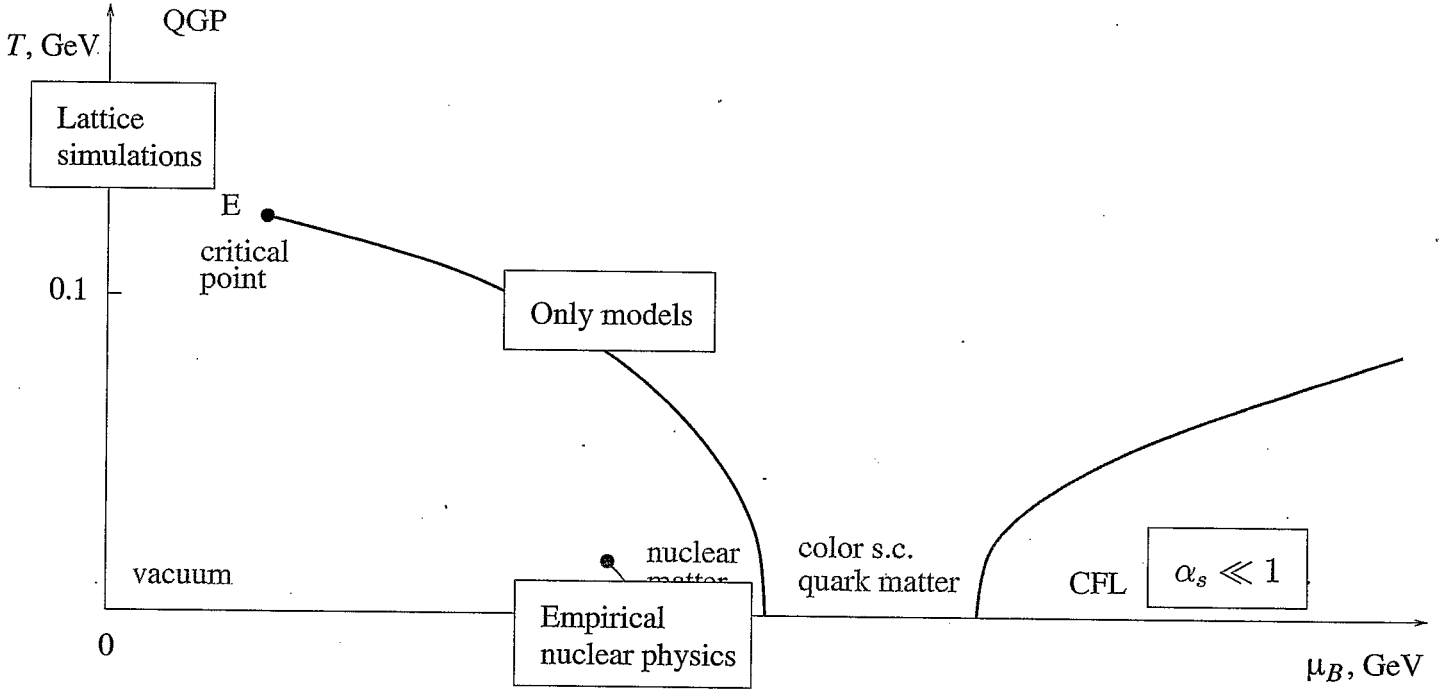
$$(T \sim 10^{12} K)$$

or

$$\rho_B \sim 1\text{fm}^{-3}.$$

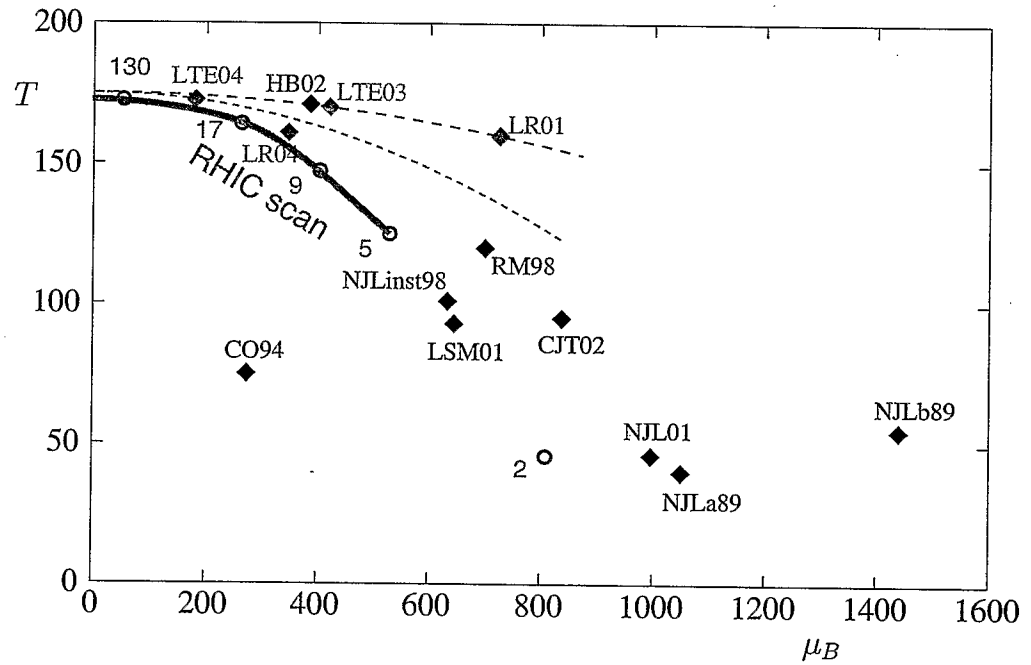


Contemporary view



"Minimal" phase diagram

Locating the QCD critical point

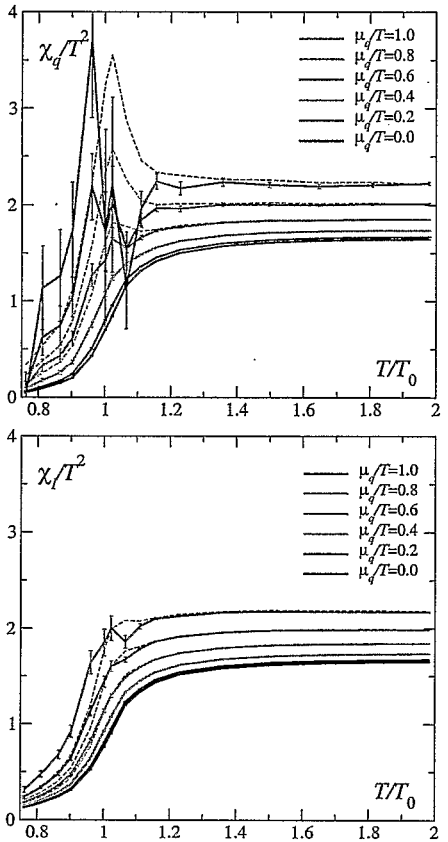


Experiments can scan the phase diagram by changing $\sqrt{s}$: RHIC.

Signatures: event-by-event fluctuations.

Susceptibilities diverge $\Rightarrow$ fluctuations grow towards the critical point.

Critical point on the lattice



Allton, *et al*: peak in χ_B, but not in χ_I

Several approaches:

- Reweighting: Fodor-Katz
  - 2001: $\mu_B \sim 725$ MeV
  - 2004: $\mu_B \sim 360$ MeV (smaller m_q and V)
- Taylor expansion: Bielefeld-Swansea (to μ^6)
  - 2003: $\mu_B \sim 420$ MeV
  - 2005: 300 MeV $\lesssim \mu_B \lesssim$ 500 MeV
- Taylor expansion: Gavai-Gupta (to μ^8)
  - $\mu_B \sim 180$ MeV (more precisely > 180 MeV)
- Imaginary μ: Philipsen-deForcrand, Lombardo, *et al*
  - Sensitive to m_s, perhaps $\mu_B \gg$ 300 MeV
- Fixed density: deForcrand, Kratochvila
  - ? ($N_f = 4$, small volumes)

Current status and summary notes

- Phase diagram of QCD at nonzero baryon density is under active theoretical investigation: much progress in lattice calculations.

  Still a lot to be done to narrow down the prediction for the critical point.

- Heavy ion collision experiments can discover the critical point by observing non-monotonous signatures.

- Needed:
  - Accelerator with variable $\sqrt{s}$ to scan phase diagram
  - Detector with sufficient acceptance and p.id. at $p_T \lesssim 500$ MeV to
    - measure fluctuations (of mean p_T, ratios, etc.);
    - measure μ_B, T of freezeout.

- RHIC is the ideal machine to do this

Static/Dynamic Correlations in Hot QCD

T. Hatsuda
Phys. Dept., Univ. of Tokyo
hatsuda@phys.s.u-tokyo.ac.jp

After briefly summarizing one of the big questions in modern physics, namely the "origin of the masses" in particle, nuclear and astrophysics, I discuss the following topics closely related to the strong correlation inside the hot QCD plasma.

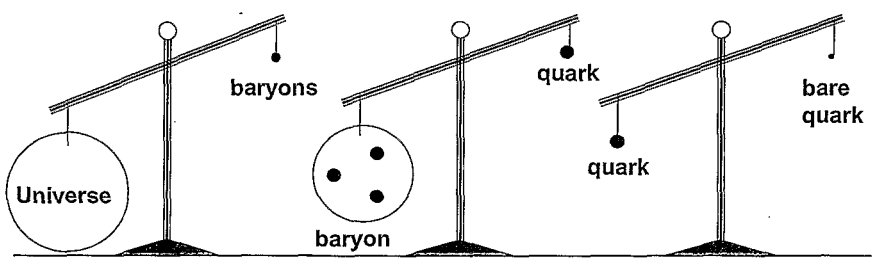
[1] QCD Phase Structure
-- similarity to High Tc superconductivity
– anomaly induced critical point at high density

[2] QCD Phase Transition and the Hagedorn's slope

[3] Strongly Correlated QCD Plasma
-- plasma screening and viscosity
-- heavy flavor as a probe

	Big Bang	Little Bang
Initial state	Inflation ? (10^{-36} sec)	Color glass ? (< 10^{-1} fm)
Thermalization	Inflaton decay	decoherence
Expansion	$R^{\mu\nu} - \frac{1}{2}Rg^{\mu\nu} = 8\pi G T^{\mu\nu}$	$\partial_\mu T^{\mu\nu} = 0$ $\partial_\mu J^\mu = 0$
Freezeout	(T = 1.95 K neutrino) T = 2.73 K photon	T_{chem} ~ 170 MeV T_{therm} ~ 120 MeV
Observables	CMB & anisotropy (C ν B, CGB & anisotropy)	Collective flow & anisotropy Jets, leptons, photons
Parameters to be determined	**8~10** cosmological parameters • Initial density fluctuation • Cosmological const. Λ etc	QGP parameters • Initial energy density • Equation of state etc
Evolution Code	CMBFAST	3D-hydro

"Origin of masses" ⟺ *Structure of the vacuum*



4% = baryons	$m_q \simeq$ 10 MeV	$m_0 = 0$
23% = dark matter	$m_N \simeq$ 1000 MeV	$m_q \simeq$ 10 MeV
73% = dark energy		

Cosmological constant	**"Chiral" condensate**	**"Higgs" condensate**
Einstein (1917)	Nambu (1960)	Anderson (1963) Englert-Brout, Higgs (1964)
WMAP (2001-), Planck (2007-)	**RHIC (2000-), LHC (2007-)**	**LHC(2007-)**

$$T^{\mu\nu} = \varepsilon_{\rm vac}\, g^{\mu\nu} \leftrightarrow \varepsilon_{\rm vac} = -P_{\rm vac}$$

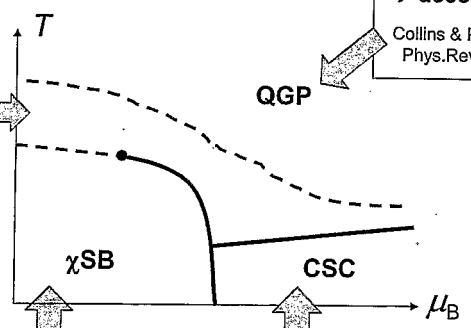
Origin of each "phase"

strong residual force
→ **pre-formed pairs**

Hatsuda & Kunihiro, Phys.Rev.Lett. 55 (1985)
DeTar, PRD32 (1985)

Asymptotic freedom
+ Debye screening
→ **deconfinement**

Collins & Perry, Phys.Rev.Lett. 34 (1975)



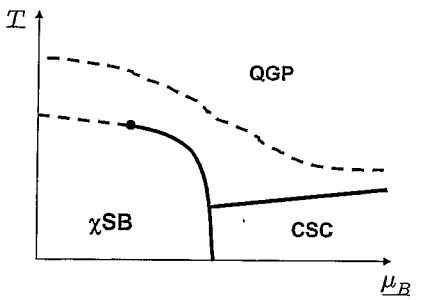
quark - anti-quark pairing
→ **chiral instability**

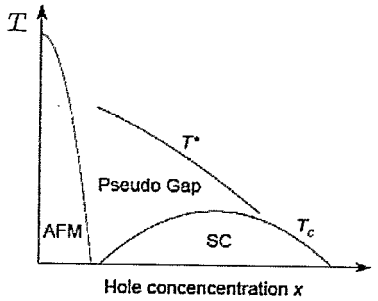
Nambu & Jona-Lasinio, Phys.Rev. 122 (1961)

quark-quark pairing
→ **Cooper instability**

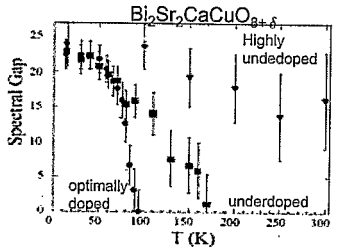
Bailin & Love, Phys.Rep.107 (1984)

Similarity with high T_c superconductivity





1. Competing order parameters
2. strong coupling effect
   → pre-formed pairs in $T_c < T < T^*$
   T_c = decoherence temp.
   T^* = dissociation temp.

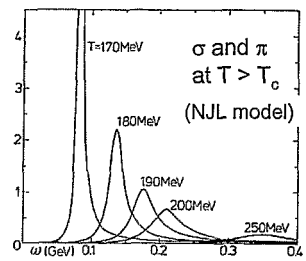


HTS – BEC – QCD connection ?

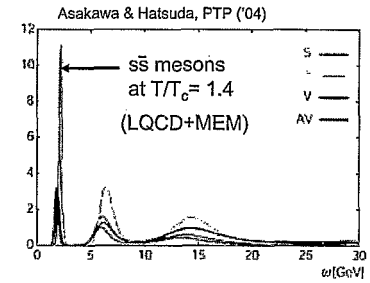
- Babaev, PRD ('00)
- Abuki, Itakura & Hatsuda, PRD ('02)
- Kitazawa, Koide, Kunihiro & Nemoto, PRD ('02)
- Chen, Stajic, Tan & Levin, Phys. Rep. ('05)

Pre-formed pairs (PFP) for $T_c < T < T^*$

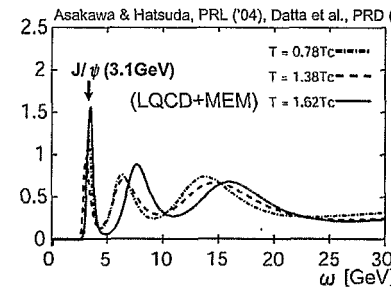
Hatsuda & Kunihiro, PRL ('85)



Asakawa & Hatsuda, PTP ('04)



Asakawa & Hatsuda, PRL ('04), Datta et al., PRD ('04)



T_c : absence of coherence

T^* : dissociation of PFP

Anomaly Induced Critical Point

Most General Ginzburg-Landau Potential with the symmetry:

$$SU(3)_L \times SU(3)_R \times U(1)_B \times \cancel{U(1)_A} \times SU(3)_C$$

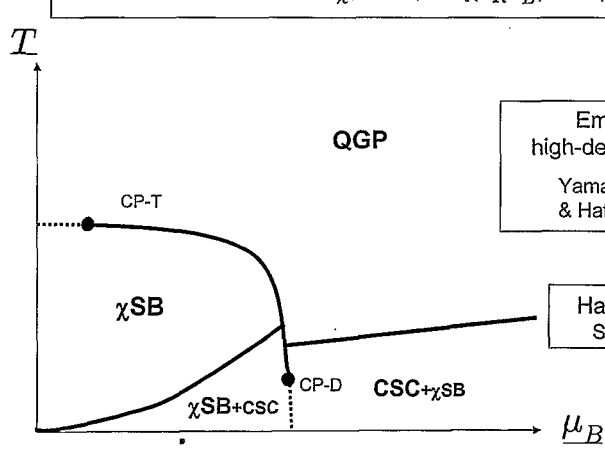
$$\longrightarrow \quad \Omega_{\chi d} = \gamma_1 \, \mathrm{tr}[(d_R d_L^\dagger)\Phi + (d_L d_R^\dagger)\Phi^\dagger] + \cdots$$

Emergence of a high-density critical point (CP-D)

Yamamoto, Tachibana, Baym & Hatsuda, hep-ph/0605018.

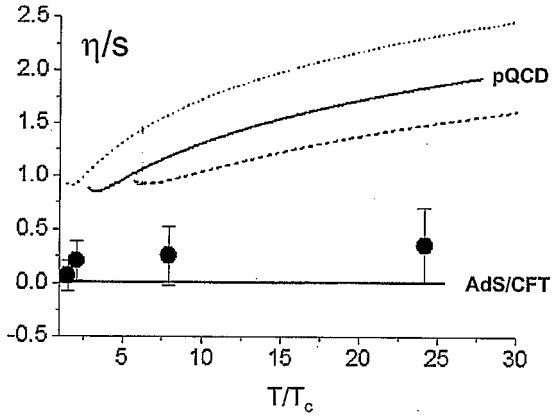
Hadron-quark continuity

Schafer & Wilczek ('99)



Viscosity updated
(quenched QCD)

$$\Leftrightarrow \quad \left\langle \mathrm{R}\, T_{\mu\nu}(t,\vec{x}) T_{\lambda\rho}(0,0) \right\rangle$$

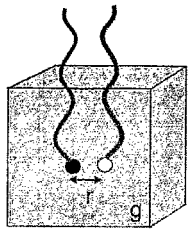


Baym, Monien, Pethick & Ravenhall ('90)
Arnold, Moore & Yaffe, ('03)

Kovtun, Son & Starinets ('04)

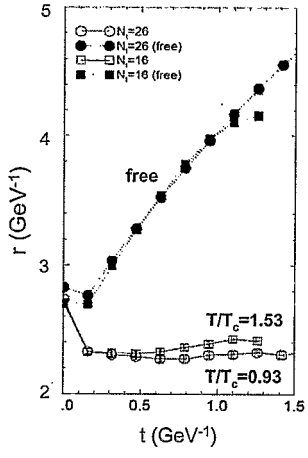
24x24x24x8
Nakamura & Sakai, Phys.Rev.Lett.94:072305,2005
updated: hep-lat/0510100

Charmonium "Wave Function" at Finite T (quenched QCD)



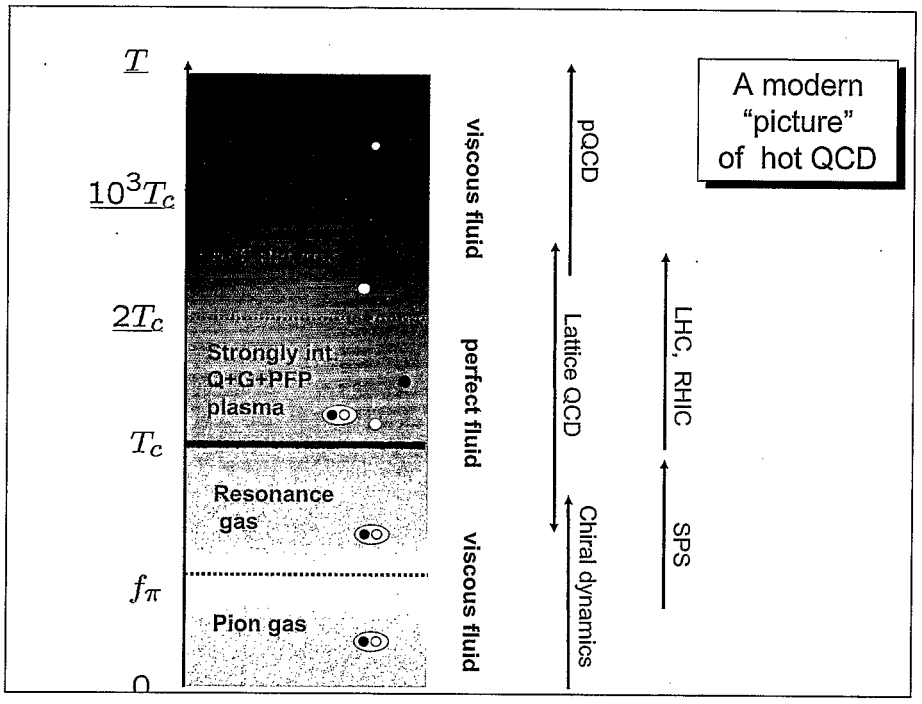
$$w_M(\vec{r},t) = \sum_{\vec{x}} \langle \bar{q}(\vec{x}+\vec{r},t)\gamma_M q(\vec{x},t)\mathcal{O}_M^\dagger(0)\rangle$$

$$\phi_M(\vec{r},t) = \frac{w_M(\vec{r},t)}{w_M(\vec{0},t)}$$



quenched, 16^2x24x(96,26,22,16)
x=3.95, a_s=0.12 fm, a_t=0.03 fm

Umeda, Katayama, Miyamura & Matsufuru,
Int.J.Mod.Phys.A16 (2001) 2215 [hep-lat/0011085]



Summary

1. Hot QCD is strongly interacting: $T_c < T^*$?

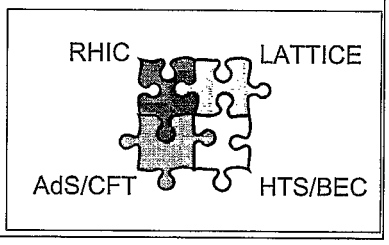
   Just like { high T_c superconductor
   BEC regime of systems of atomic fermions

2. Several critical points in (T, μ)-plane ?

   Chiral CP at high T, Chiral-super CP at high μ, Liquid-gas CP at low μ

3. Progress in spectral analysis on the lattice

   Heavy and light bound states above T_c
   Small viscosity even up to 30 T_c ?
   Full QCD study is started

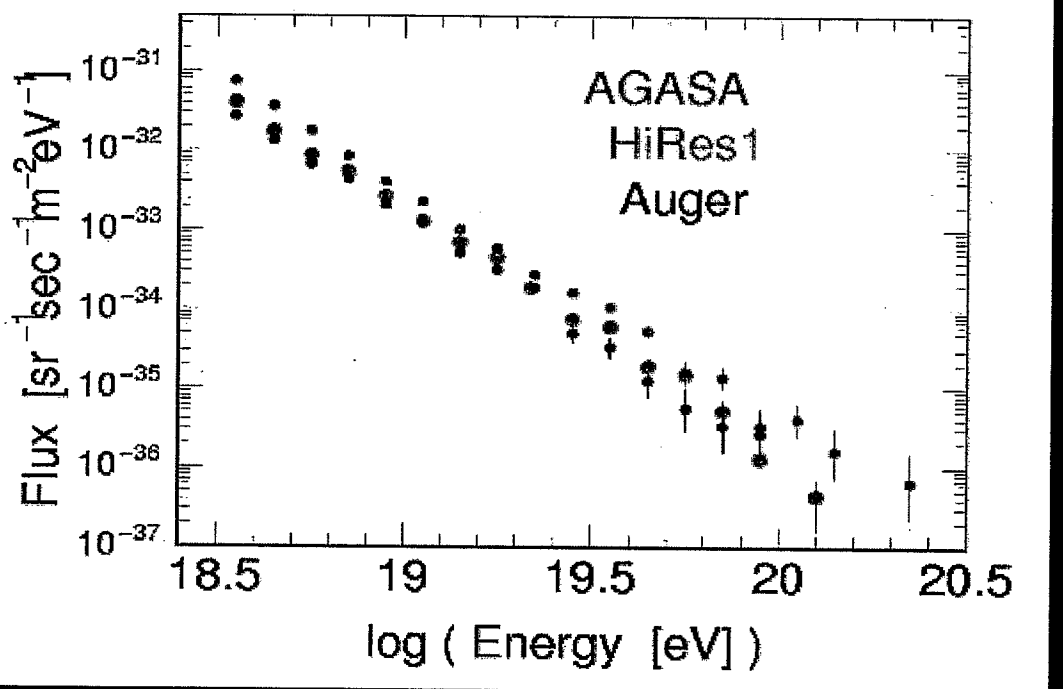


Physics of ultrahigh-energy cosmic rays

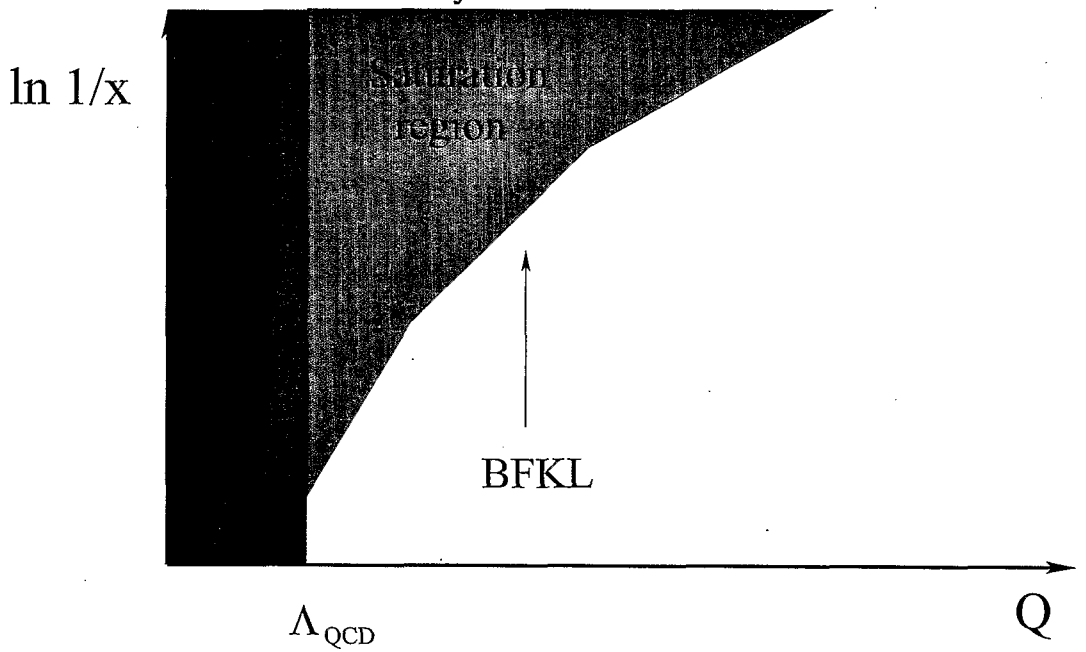
Alexander Kusenko
Department of Physics and Astronomy
University of California
Los Angeles, CA 90095-1547

Ultrahigh-energy cosmic rays can teach us about the astrophysics of the most powerful objects in the universe. In addition, they provide an opportunity to study the physics of strong interactions at the extreme values of the center-of-mass energy and for some very small x. Measurements of neutrino-nucleon cross section at $\sqrt{s} \sim 10^5$ GeV can shed light on the small-x behavior of parton distribution functions, as well as new physics.

Comparison with HiRes1, AGASA

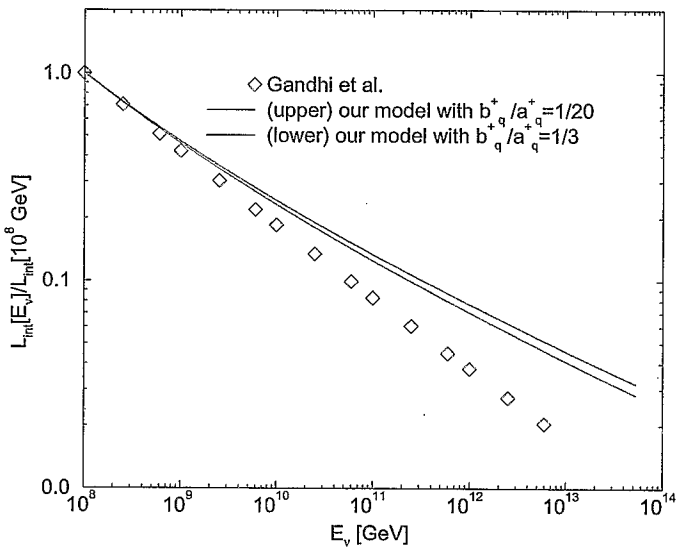


LO and saturation effects may affect the cross section



The cross section σ_{ν_N} **decreases** [R. Fiore, L.L. Jenkovszky, A. Kotikov, F. Paccanoni, A. Papa, E. Predazzi]

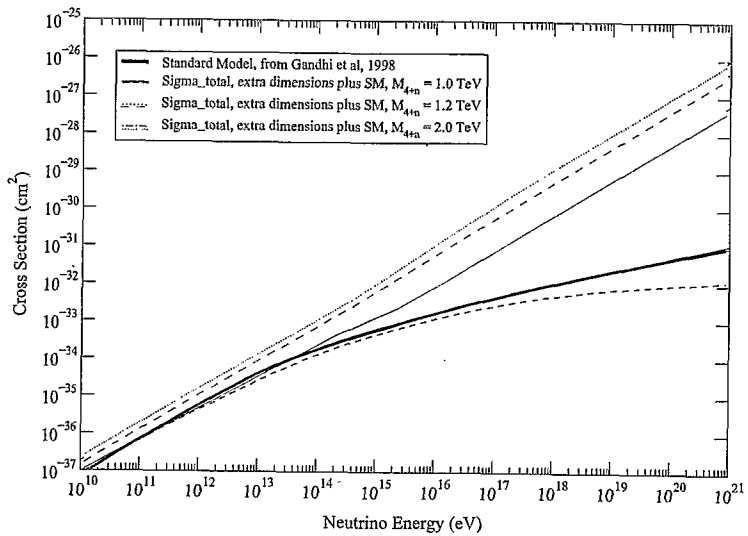
LO and saturation effects may affect the cross section



The cross section σ_{ν_N} **decreases** [R. Fiore, L.L. Jenkovszky, A. Kotikov, F. Paccanoni, A. Papa, E. Predazzi]

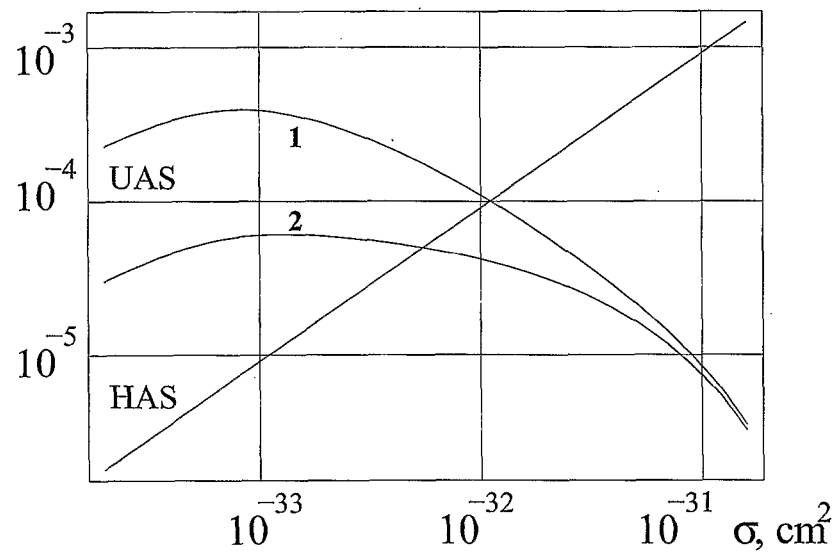
Neutrino-nucleon cross section at $\sqrt{s} \sim 10^6$GeV

Calculations necessarily use extrapolations of PDF and standard model parameters.



SM calculation [Quigg et al.] is most likely right, but we want to **measure** this cross section.

The shower probability per incident neutrino:



The energy threshold for detection of UAS was assumed $E_{\rm th} = 10^{18}$eV for curve 1 and $E_{\rm th} = 10^{19}$eV for curve 2. Additional UAS events, not included here, can be detected by EUSO or OWL via Cerenkov radiation of tau leptons.

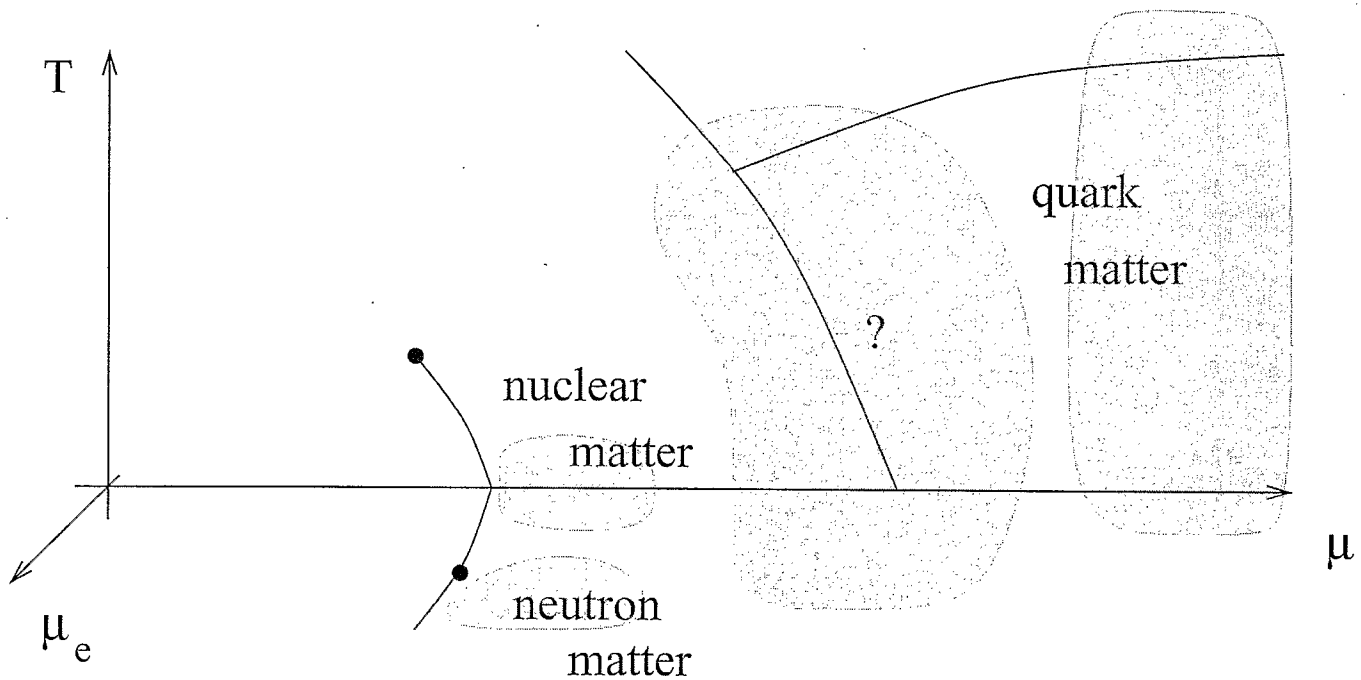
Non-perturbative Methods in QCD

at finite μ and T

Thomas Schaefer, North Carolina State

We discuss effective field theories of dense baryonic matter. We concentrate on the regime of very low density, where effective theories of point-like non-relativistic nucleons are appropriate, and the regime of very high baryon density, where the relevant degrees of freedom are quarks and gluons.

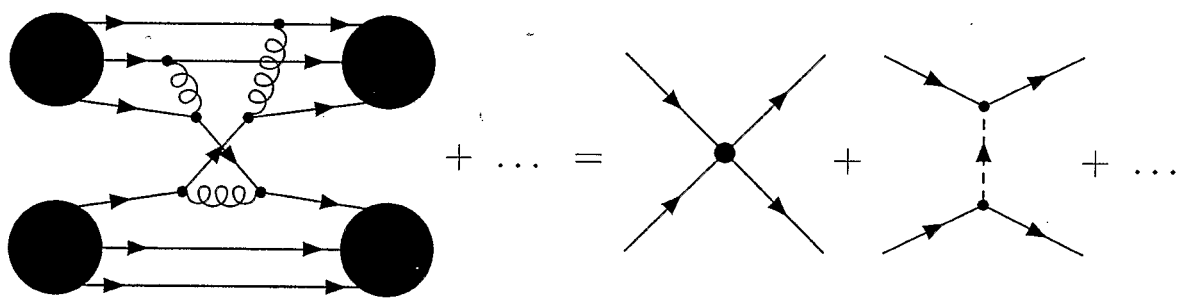
More modest: Systematic approaches to dense matter



Low Density: Nuclear Effective Field Theory

Low Energy Nucleons:

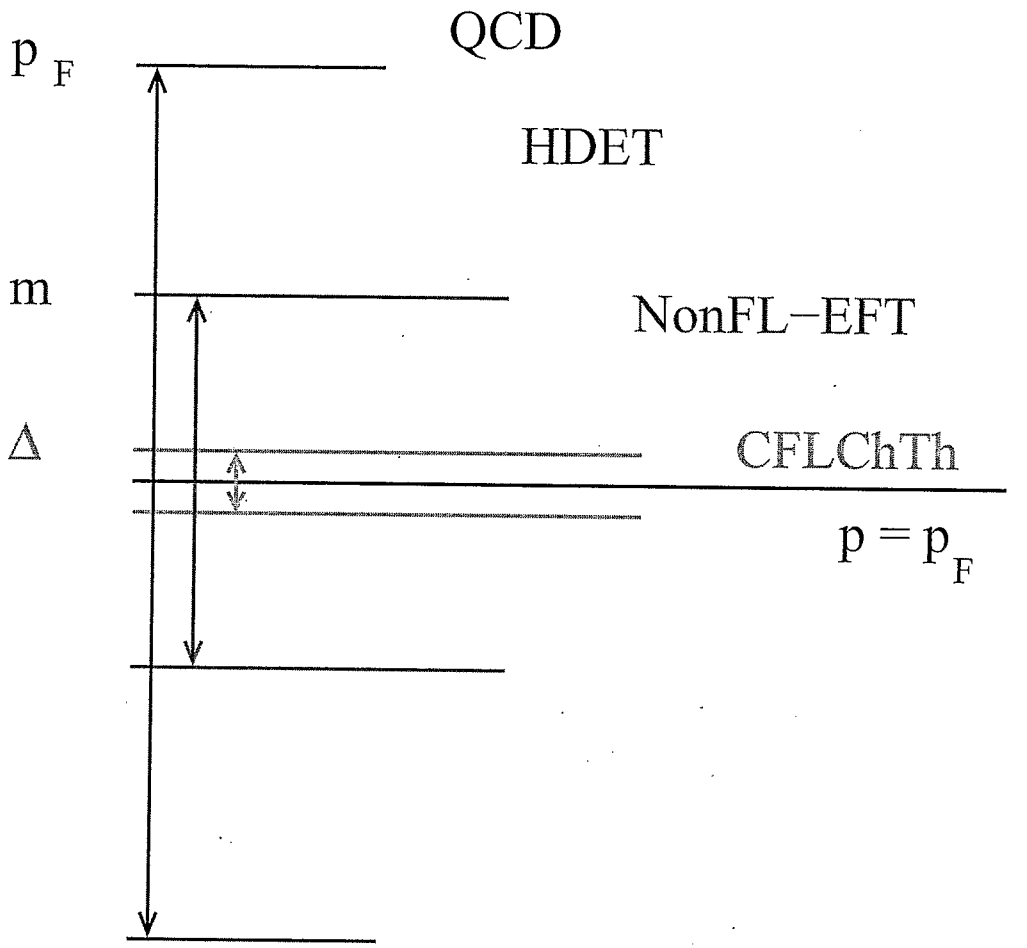
- Nucleons are point particles
- Interactions are local
- Long range part: pions



Advantages:

- Systematically improvable
- Symmetries manifest (Chiral, gauge, ...)
- Connection to lattice QCD

Very Dense Matter: Effective Field Theories



Effective Theory for $l < m$

$$\mathcal{L} = \psi_v^\dagger \left(iv \cdot D - \frac{D_\perp^2}{2\mu} \right) \psi_v + \mathcal{L}_{4f} - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \mathcal{L}_{HDL}$$

$$\mathcal{L}_{HDL} = -\frac{m^2}{2} \sum_v G^a_{\mu\alpha} \frac{v^\alpha v^\beta}{(v \cdot D)^2} G^b_{\mu\beta}$$

Transverse gauge boson propagator

$$D_{ij}(k) = \frac{\delta_{ij} - \hat{k}_i \hat{k}_j}{k_0^2 - \vec{k}^2 + i\frac{\pi}{2} m^2 \frac{k_0}{|\vec{k}|}},$$

Scaling of gluon momenta

$$|\vec{k}| \sim k_0^{1/3} m^{2/3} \gg k_0 \quad \text{gluons are very spacelike}$$

EFT in the CFL Phase

Consider HDET with a CFL gap term

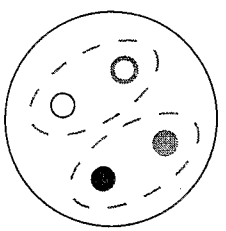
$$\mathcal{L} = \mathrm{Tr}\left(\psi_L^\dagger (iv\cdot D)\psi_L\right) + \frac{\Delta}{2}\left\{\mathrm{Tr}\left(X^\dagger \psi_L X^\dagger \psi_L\right) - \kappa\left[\mathrm{Tr}\left(X^\dagger\psi_L\right)\right]^2\right\} + (L \leftrightarrow R, X \leftrightarrow Y)$$

$$\psi_L \to L\psi_L C^T,\ X \to LXC^T, \qquad \langle X\rangle = \langle Y\rangle = \mathbb{1}$$

Quark loops generate a kinetic term for X, Y

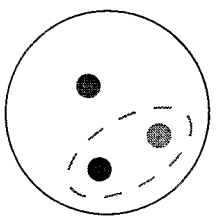
Integrate out gluons, identify low energy fields ($\xi = \Sigma^{1/2}$)

$$\Sigma = XY^\dagger$$



[8]+[1] GBs

$$N_L = \xi(\psi_L X^\dagger)\xi^\dagger$$



[8]+[1] Baryons

Light Quarks on the Lattice

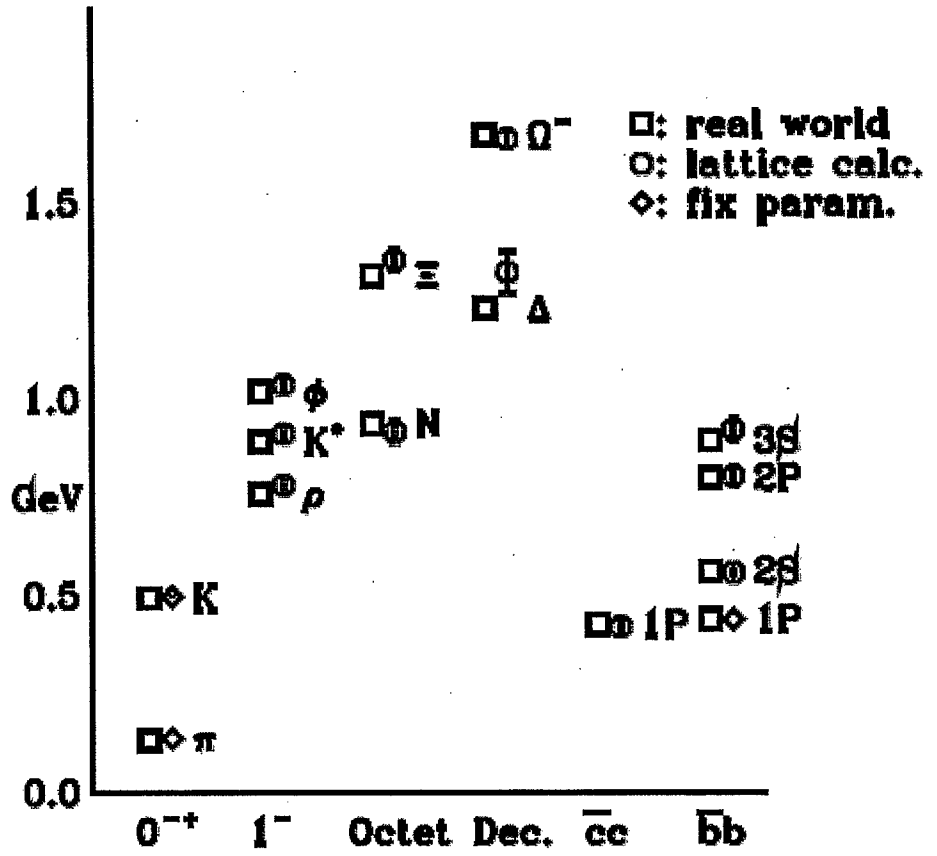
Sinya AOKI
University of Tsukuba and RBRC

In this talk, I will review on-going full QCD simulations with light quarks by several groups including my own in a rather critical way. In particular I focus on advantages and shortcomings of various lattice fermion formulation employed in simulations, which includes staggered by MILC, Wilosn-type by CP-PACS/JLQCD, domain-wall by RBC and overlap by JLQCD2.

Staggered Fermions

- Advantages
  - exact non-singlet U(1) chiral symmetry
  - single component/site simulations are easier
  - $O(a^2)$ scaling violations
- Shortcomings
  - 4 taste --> 4-th root trick
  - large taste breaking

Gottlieb, ILFTN2006



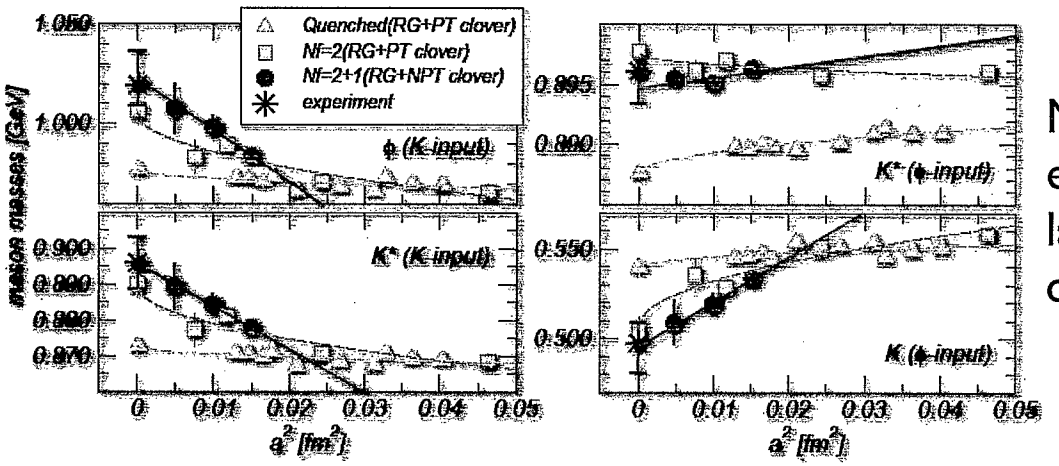
3-flavor lattice QCD reproduces Nature !?

Wilson-type fermions

- Advantages
  - well-defined formulation (locality, no doubling,...)
  - straight-forward interpretation
  - reasonable computational cost
- Shortcoming
  - O(a) scaling violation
  - explicit violation of chiral symmetry
  - no protection against small eigenvalues
    large cost for small quark mass

O(a) improvement (Clover)

Improved Algorithm



Meson masses agree with experimental values within large errors after continuum extrapolations.

New project using DDHMC

PACS-CS collaboration

New cluster at University of Tsukuba
14 TFlops peak

Target

- RG action/non-perturbative Clover (same as before)
- DDHMC + (UV-filtered) PHMC
- a=0.1, 0.07 fm
- L= 2.4 fm or 3.2fm
- much lighter quark masses $m_\pi/m_\rho = 0.4,\ 0.3,\ 0.2\ (?)$
- 10000 trajs. for 100 independent configurations

$N_f = 2+1$

Cost estimates based on test runs

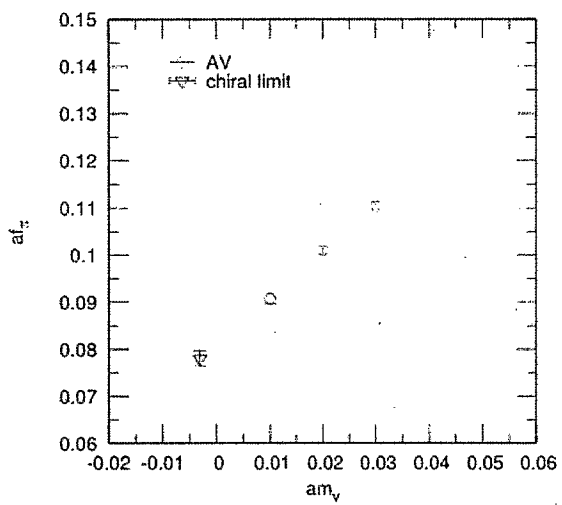
$a = 0.1\text{fm},\ La = 3.2\ \text{fm}$

	m_π/m_ρ	m_π (MeV)	SR11000	PACS-CS	SAP+GCR
volume			$16^3 \times 32$	$32^3 \times 64$	
sustained speed			13.8 Gflops	4 Tflops	
days for 10000 trajs.	0.62	660	96	11	8
	0.5	480	148	16	11
	0.4	350	243	27	17
	0.3	250	333	37	20
total days			820	91	56

Domain-wall Fermion

- Advantages
  - exact chiral symmetry at $N_s \to \infty$ (size of 5th dimension)
    - no O(a) scaling violation
    - renormalization is simple, no extra operator mixings
    - small quark mass
- Shortcomings
  - large computational cost $\simeq N_s \times$ ordinary fermions
  - at $N_s \neq \infty$, small chiral symmetry violation $\sim e^{-cN_s}$

f_π



$$f_\pi = 0.781(17) \simeq 125 \text{ MeV}$$

(linear chiral extrapolation)

Overlap Fermion

$$D_{ov} = 1 + \gamma_5 \mathrm{sign}(H_W) = 1 + \gamma_5 \frac{H_W}{\sqrt{H_W^2}}$$

H_W: negative mass Wilson op.

- satisfies GW relation
  - equivalent to domain-wall fermion at $N_s \to \infty$
  - exact "lattice" chiral symmetry
- low eiganmodes of H_W (main problem)

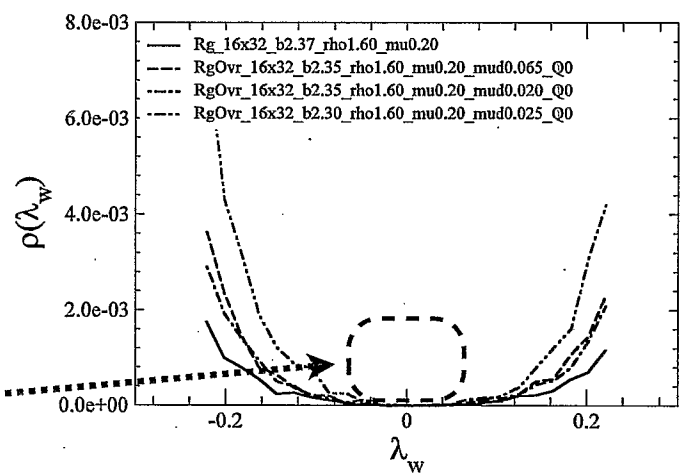
Overlap project (JLQCD2 Collaboration)

Blue Gene/L at KEK (10 racks, 57.3 TFlops)

Fixed topology by topology conserving action(Iwasaki+$\det H_W$) to suppress small eiegn-modes

eigenvalue distributions with dynamical overlap

No small eigen-modes



RBRC Symposium
June 22, 2006

Semi-leptonic decays on the lattice

- from CKM unitarity to Proton spin problem -

Shoichi Sasaki
(RBRC/U. of Tokyo)

The computation of weak matrix elements in lattice QCD is now progressing with steadily increasing accuracy by utilizing domain wall fermions (DWF), which have a big advantage in dealing with both the flavor symmetry and the axial symmetry. In this talk, I mainly review the present status of semi-leptonic decays: K_{l3} decays and hyperon beta decays, in DWF simulations of lattice QCD.

Semi-leptonic decays

- Kaon semi-leptonic decay (K_{l3} decay)

$$\langle \pi(p)|\bar{s}\gamma_\mu u|K(p')\rangle = f_+(q^2)(p'+p)_\mu + f_-(q^2)(p'-p)_\mu$$

SU(3) symmetry: $f_+(0) = 1,\ f_-(q^2) = 0 \qquad \Gamma_{\text{expt.}} \propto |f_+(0)|^2|V_{us}|^2$

- Hyperon beta decay $B' \to B + l^\pm + \nu_l(\bar{\nu}_l)$

$$\langle B|V_\alpha - A_\alpha|B'\rangle = \bar{u}_B(p)[f_1(q^2)\gamma_\alpha + \frac{f_2(q^2)}{M_{B'}}\sigma_{\alpha\beta}q_\beta + \frac{f_3(q^2)}{M_{B'}}q_\alpha \qquad \frac{g_1(0)}{f_1(0)} = \frac{g_A}{g_V}$$

$$+g_1(q^2)\gamma_\alpha\gamma_5 + \frac{g_2(q^2)}{M_{B'}}\sigma_{\alpha\beta}\gamma_5 q_\beta + \frac{g_3(q^2)}{M_{B'}}q_\alpha\gamma_5]u_{B'}(p')$$

SU(3) symmetry: $f_3(q^2) = 0,\ g_2(q^2) = 0 \qquad \Gamma_{\text{expt.}} \propto (|f_1(0)|^2 + 3|g_1(0)|^2)\,|V_{us}|^2$

Semi-leptonic decays

The simpler weak matrix elements:

✓ Vector and Axial symmetry play important roles

- SU(3) breaking effects ($|\Delta s|=1$ process)
  - CKM unitarity (KI3, HBD)

✓ described by form factors

- struture of hadrons
  - Proton spin problem (HBD)

- Needs the precise theoretical calculation !

Kl3 decays

- Kl3 decays are described by 2 form factors

pure vector transition

$$\langle \pi(\mathbf{p})|\bar{s}\gamma_\mu u|K(\mathbf{k})\rangle = f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu$$

✓ SU(3) limit : $f_+(0) = 1,\ f_-(q^2) = 0$

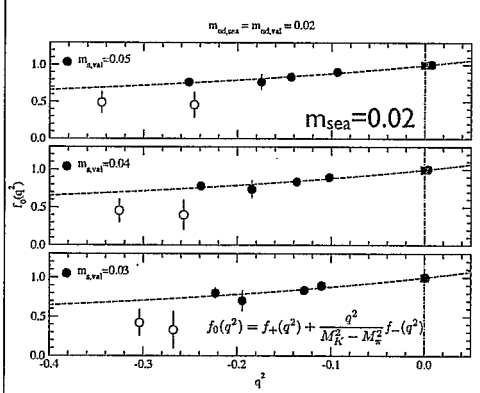
decay rate:

$$\Gamma = \frac{G_F^2}{192\pi^2} M_K^5 C^2 |f_+(0)|^2 |V_{us}|^2 I S_{\rm ew}(1+\delta_{\rm em})$$

To determine $|V_{us}|$

Γ from experiment
$f_+(0)$ from theory

K_{l3} ($K \to \pi$) form factor



- DWF-DBW2 (Nf=2 dynamical)

  La~2.0 fm, a^{-1}=1.7 GeV

  m_{sea}=0.02 (QCDSP & QCDOC)

  m_{sea}=0.03, 0.04 (QCDOC)

T. Kaneko, C. Dawson, T. Izubuchi, S. Sasaki, A. Soni

$f_+(0)(=f_0(0))=0.968(9)(6)$

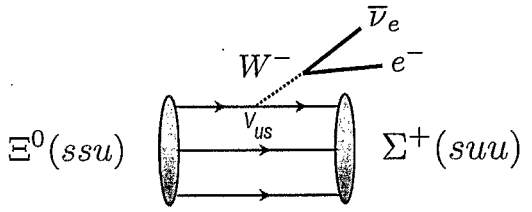
combine with the experimental data $|V_{us}f_+(0)|=0.2173(8)$

→ CKM matrix $|V_{us}| = 0.2245(8)_{\rm expt}(26)_{\rm theory}$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \delta \qquad \delta = 0.0013(16)$$

Hyperon beta decay ($\Xi^0 \to \Sigma^+$)

$\Xi^0 \to \Sigma^+$ is the direct analogue of $n \to p$ under $d \leftrightarrow s$



highly sensitive to SU(3) breaking

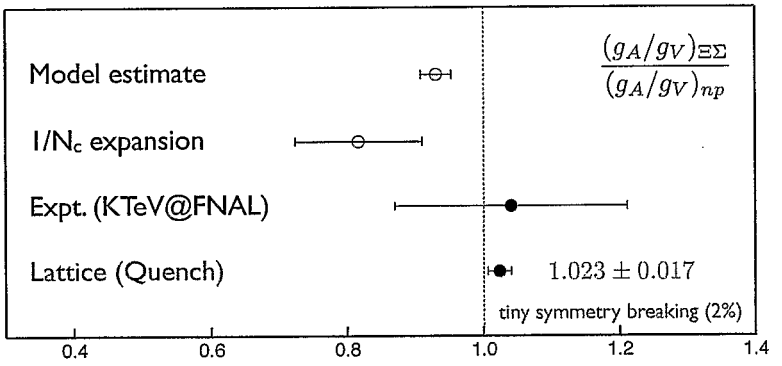
Center of mass correction approach (Ratcliffe)

$(g_A/g_V)_{np} > (g_A/g_V)_{\Xi\Sigma}$ 8-10%

$1/N_c$ expansion approach (Flores-Mendieta-Jenkins-Manohar)

$(g_A/g_V)_{np} > (g_A/g_V)_{\Xi\Sigma}$ 20-30%

SU(3) breaking effect on g_1 / f_1 (g_A/g_V)



* Center-of-mass correction approach (with a bag model)
Ratcliffe, Phys. Rev. D59 (1999) 014038

* 1/Nc expansion approach
R. Flores-Mendieta, E. Jenkins, A.V. Manohar, Phys. Rev. D58 (1998) 094028

2nd-class form factors

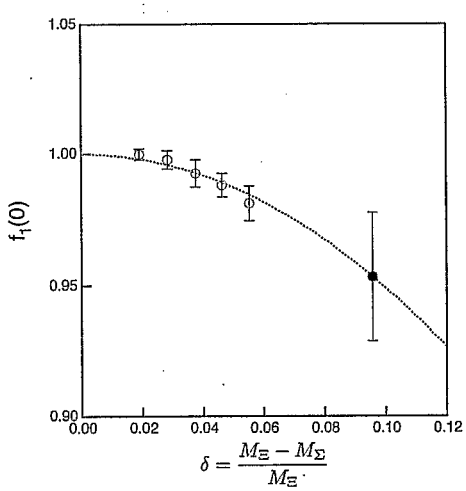
✓ Lattice results (quenched lattice QCD)

$$\frac{g_2(0)}{f_1(0)} = -0.757 \pm 0.057 \qquad \frac{f_3(0)}{f_1(0)} = +0.250 \pm 0.022$$

✳ KTeV@FNAL

$$\frac{g_2(0)}{f_1(0)} = -1.7 \pm 2.0 \pm 0.5 \qquad \frac{f_3(0)}{f_1(0)} = N/A$$

SU(3) breaking effect on $f_1(0)$



Ademollo-Gatto theorem

$$|1 - f_1(0)| \propto \delta^2$$

2nd order symmetry breaking

$$f_1(0) = 0.953(24)$$

Combined with

$$|f_1(0)V_{us}| = 0.209(27) \text{ (KTeV)}$$

$$|V_{us}|_{\Xi^0 \to \Sigma^+} = 0.219(27)_{\text{expt}}(5)_{\text{theory}}$$

Summary of $|V_{us}|$

✓ Kl3 decay: $f_+(0) = 0.960(5)_{\rm stat}(7)_{\rm syst}$ 2 flavor DWF

✓ Hyperon decay: $f_1(0) = 0.953(24)_{\rm stat}$ quench DWF

$$|V_{us}|_{K_{l3}} = 0.2245(8)_{\rm expt}(26)_{\rm theory}$$

$$|V_{us}|_{\Xi^0\to\Sigma^+} = 0.219(27)_{\rm expt}(5)_{\rm theory}$$

$$|V_{us}|_{\rm unitarity} = 0.2274(21)$$

agreement with the CKM unitarity

Summary of SU(3) breaking effects

- $f_1(0)$ has about 5% negative breaking effects
- $f_2(0)$ has about 20% positive breaking effects
- $f_3(0)$ is large positive: about 1/4 of $f_1(0)$

  1st-order breaking (20-25%), 2nd-order breaking (~5%)
- $g_2(0)$ is large negative: about 3/5 of $g_1(0)$
- $g_1(0)/f_1(0)$ is suprisingly tiny breaking around 2%
  - This doesn't conflict with Cabibbo-model fits for HBD
  - However, this doesn't mean that an estimation of Δs is reliable.

QCD spin physics - a theoretical overview

Daniël Boer

Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

QCD spin physics is about defining and extracting universal nonperturbative quantities that capture aspects of the proton spin. These quantities are hadronic matrix elements of operators of the quark and gluon fields. For the sum of the contributions of the quarks and antiquarks to the proton spin, a local operator matrix element can be defined, that is straightforward to interpret and can be (and has been) extracted from polarized Deep Inelastic Scattering (DIS). In contrast, for the contribution of the gluons the operator is intrinsically nonlocal along the lightcone. It only becomes local in a lightcone gauge and after a partial integration upon neglect of the boundary contributions. The latter contributions may be very relevant however and this issue was part of a long debate. Experimentally the polarized gluon distribution Δg can be obtained from DIS or from hadron-hadron collisions, such as performed at RHIC. Knowledge of Δg provides information on the contribution from orbital angular momentum (OAM) of the quarks and gluons. The question of how to separately treat the quark and gluon OAM is a longstanding issue and seems to require either the choice of a gauge or of a preferred frame in which to interpret the different operators. This problem gave rise to the investigation of the Deeply Virtual Compton Scattering (DVCS) process and the field of Generalized Parton Densities (GPDs) which yield a more complete picture of the momentum *and* spatial distribution of partons.

OAM requires transverse momentum of the quarks inside a hadron, so it is natural, but theoretically highly nontrivial, to extend the parton distributions (which are functions of the lightcone momentum fraction only) to transverse momentum dependent parton distribution functions (TMDs). The transverse spin dependent TMDs can offer explanations of several observed single spin asymmetries and also of unpolarized azimuthal asymmetries. Despite this successful phenomenology, the proper gauge invariant definition of the TMDs gives rise to theoretical questions. This definition contains operators that are nonlocal *off* the lightcone and that are dependent on the color flow of the scattering process. This means that TMDs are sensitive to the process as a whole, which is not the case in standard collinear factorization of high energy scattering processes. The process dependence does not imply lack of predictability however, since it is a calculable process dependence. Nevertheless, factorization theorem proofs of processes involving a small, observed transverse momentum, and studies of the Q^2 evolution properties of TMDs need to be revisited. Despite these unresolved issues, the TMDs are the main candidates to describe the spin-orbit coupling effects that lead to single (transverse) spin asymmetries and the phenomenology of TMDs has led to several successes, in which several people and workshops of the RBRC played an important role.

Several people have started to investigate a possible connection between the TMDs and the GPDs, for example via the introduction of quantum phase space (Wigner) distributions, but thus far this has not resulted in new insights or proposals for new experiments that may shed light on such relations.

The large asymmetries that have been observed in polarized Λ production in hadron-hadron collisions were discussed as an example of how a full understanding of spin asymmetries can be used to turn them into diagnostic tools for indicating changes in underlying physics. For example, asymmetries in proton-nucleus scattering at large energies and baryon number can be sensitive to saturation effects and in nucleus-nucleus collisions to the formation of a quark-gluon plasma.

Measuring the Sivers effect: two examples

One can probe the k_T-dependence of the Sivers function directly in "jet SIDIS"

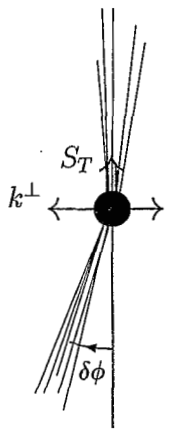
$$\frac{d\sigma(e\,p^\uparrow \to e'\,\text{jet}\,X)}{d\phi^e_{\text{jet}}\,dk_T^2} \propto |\boldsymbol{S}_T|\,\sin(\phi^e_{\text{jet}} - \phi^e_S)\,\frac{k_T}{M} f_{1T}^\perp(x,k_T^2), \qquad k_T^2 = |\boldsymbol{P}_\perp^{\text{jet}}|^2$$

D.B. & Mulders, PRD 57 (1998) 5780

Upon integration over the transverse momentum of the jet: no SSA remains
Christ & Lee, PR 143 (1966) 1310

Asymmetric jet or hadron correlations in $p^\uparrow\,p \to h_1\,h_2\,X$

D.B. & Vogelsang, PRD 69 (2004) 094025
Bacchetta *et al.*, PRD 72 (2005) 034030



Reductions of Wigner distributions

Fourier transforms of GPD's are obtained as follows:

$$\int \frac{d^2\boldsymbol{k}_T}{(2\pi)^2}\left[\int \frac{dk^-}{2\pi} W_{\gamma^+}(\vec{r},k)\right]$$

$$\propto \text{F.T.}\left\{H_q(x,\xi,t)\,\bar{u}(\vec{q}/2)\gamma^+ u(-\vec{q}/2) + E_q(x,\xi,t)\,\bar{u}(\vec{q}/2)\frac{i\sigma^{+i}q_i}{2M}u(-\vec{q}/2)\right\}$$

TMDs can also be seen as reductions of Wigner distributions

$$q(x,\boldsymbol{k}_T) = \int \frac{d^3r}{(2\pi)^3}\left[\int \frac{dk^-}{2\pi} W_{\gamma^+}(\vec{r},k)\right]$$

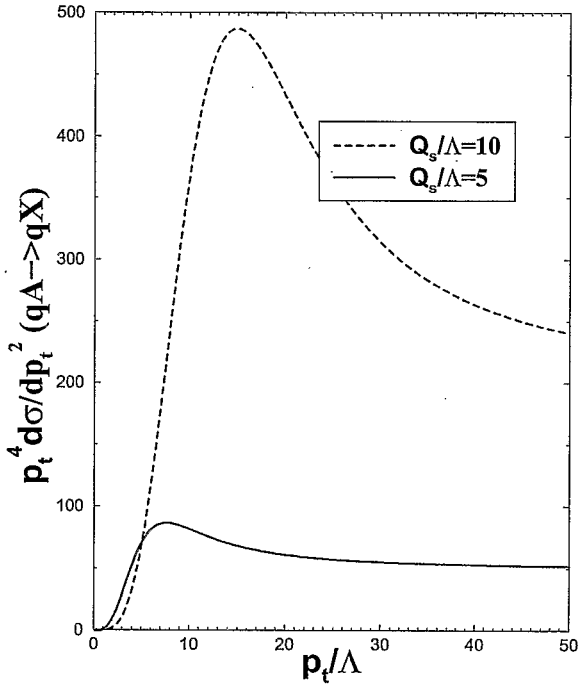
The six-dimensional phase space quantity: just a definition or measurable?

$$f_{\gamma^+}(\vec{r},x,\boldsymbol{k}_T) \equiv \int \frac{dk^-}{2\pi} W_{\gamma^+}(\vec{r},k)$$

Note: $\boldsymbol{k}_T$ and $\boldsymbol{r}_T$ are not each other's Fourier conjugates

Saturation effects in $p + A \to \Lambda + X$

Asymmetries can also be used to indicate changes in underlying physics



At high p_T, leading twist pQCD predicts:

$$\frac{d\sigma(q\,A \to q\,X)}{d\boldsymbol{p}_T^2} \sim \frac{1}{\boldsymbol{p}_T^4}$$

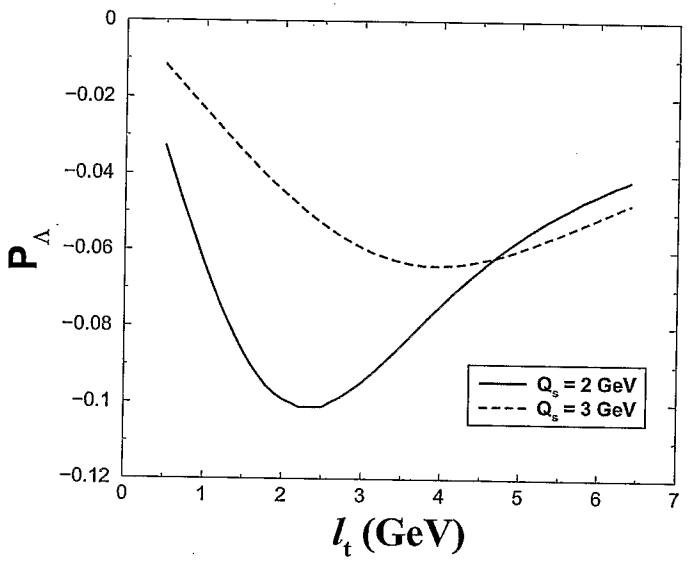
For $p_T \lesssim Q_s$ saturation effects modify the cross section

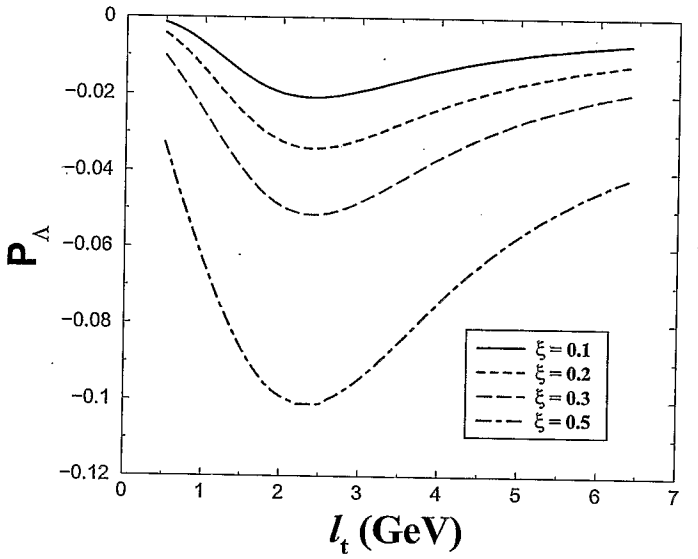
Figure: cross section (times $\boldsymbol{p}_T^4$) in the McLerran-Venugopalan model (large A & $\sqrt{s}$)

Since $D_{1T}^{\perp}$ is $\boldsymbol{k}_T$-odd, it essentially probes the derivative of the partonic cross section

Λ polarization in $p + A \to \Lambda^{\uparrow} + X$

$pA \to \Lambda^{\uparrow} X$: at large A & $\sqrt{s}$ the asymmetry is sensitive to gluon saturation (Q_s)





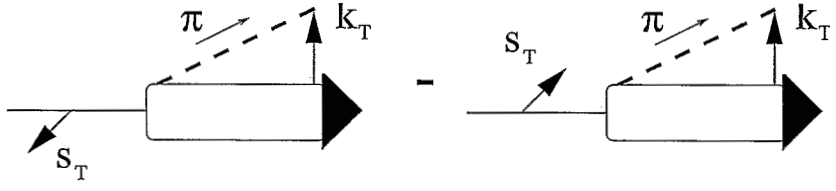
D.B. & Dumitru, PLB 556 (2003) 33

[going beyond classical saturation is in progress]

Chiral-odd TMDs

Besides $f_{1T}^{\perp}$ and $D_{1T}^{\perp}$, there are two other, equally interesting k_T-odd functions

One is called the Collins fragmentation function:

$H_1^{\perp} =$ 

Collins, NPB 396 (1993) 161

It can be extracted from $e^+ e^- \to \pi^+ \pi^- X$: $\langle \cos(2\phi) \rangle \propto (H_1^{\perp})^2$
D.B., Jakob & Mulders, NPB 504 (1997) 345

Matthias Grosse Perdekamp (around 2000): use off-resonance BELLE data

EXPERIMENTAL OVERVIEW

Douglas E. Fields
University of New Mexico/RBRC

Being the lowest energy baryon state, one would, with good foundation, expect that the quarks that make up the proton would be in an s-state. The naive expectation then, is that there is no orbital angular momentum contribution to the proton spin. However, measurements of the quark spin contribution to the proton spin, $\Delta\Sigma$, have determined that only a small fraction of the proton spin is due to quark polarization. Recent measurements of ΔG, the gluon polarization inside the proton, are still statistically limited, but may have excluded large values of gluon polarization. Forthcoming data from RHIC should place tighter constraints on ΔG, and perhaps will solve the spin-puzzle. However, progress in the quark and gluon spin distributions has rekindled interest in orbital angular momentum. In fact, it has been shown recently, in a model independent way that the proton anomalous magnetic moment *requires* orbital angular momentum of the quarks, although *net* orbital angular momentum may be zero.

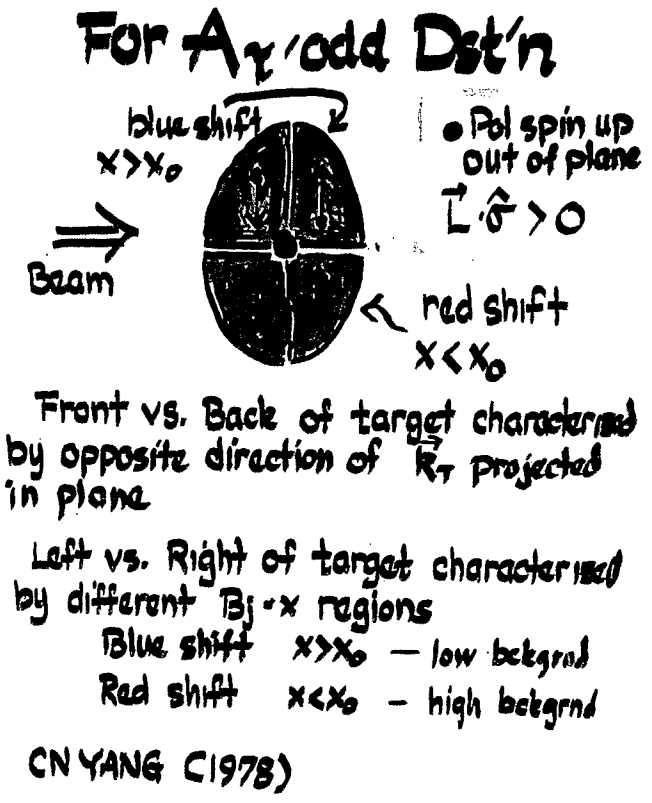
The history of the theoretical interest in orbital angular momentum inside hadrons can be traced to a paper by Chou and Yang in 1976, describing hadronic matter current inside a polarized hadron. Later, Meng Ta-chung et al. proposed two experiments to access hadronic matter currents, one in semi-inclusive deep inelastic scattering of unpolarized leptons on transversely polarized protons, and the second in collisions of longitudinally polarized protons. It is the latter which is the theoretical basis for this discussion.

In the late 1990's, Ji proposed a method to access *quark* orbital angular momentum via Deeply-Virtual Compton Scattering. Several groups have pursued this experimentally challenging path. The concept upon which the present analysis is based is complementary, as it should access both quark and gluon orbital angular momentum, depending upon the process which dominates the hard scattering.

We have proposed a method to probe the spin-correlated transverse momentum of partons involved in hard collisions of longitudinally polarized protons leading to jet events at RHIC. The basic picture is that if some part of the transverse momentum of partons is correlated to the (longitudinal) spin direction, as it would be in the case of orbital angular momentum, then hard collisions involving these rotating partons may lead to jets with more or less average transverse momentum k_T, depending upon the relative orientation of the spin directions and the centrality of the collision. Since, at present, there is no good experimental tool to determine the collision centrality in $p+p$ collisions, one must determine if the effect remains when the impact parameter is undetermined. It has been found that by integrating over the entire range of impact parameters, a net overall effect is still found.

Sivers Effect in Double Spin?

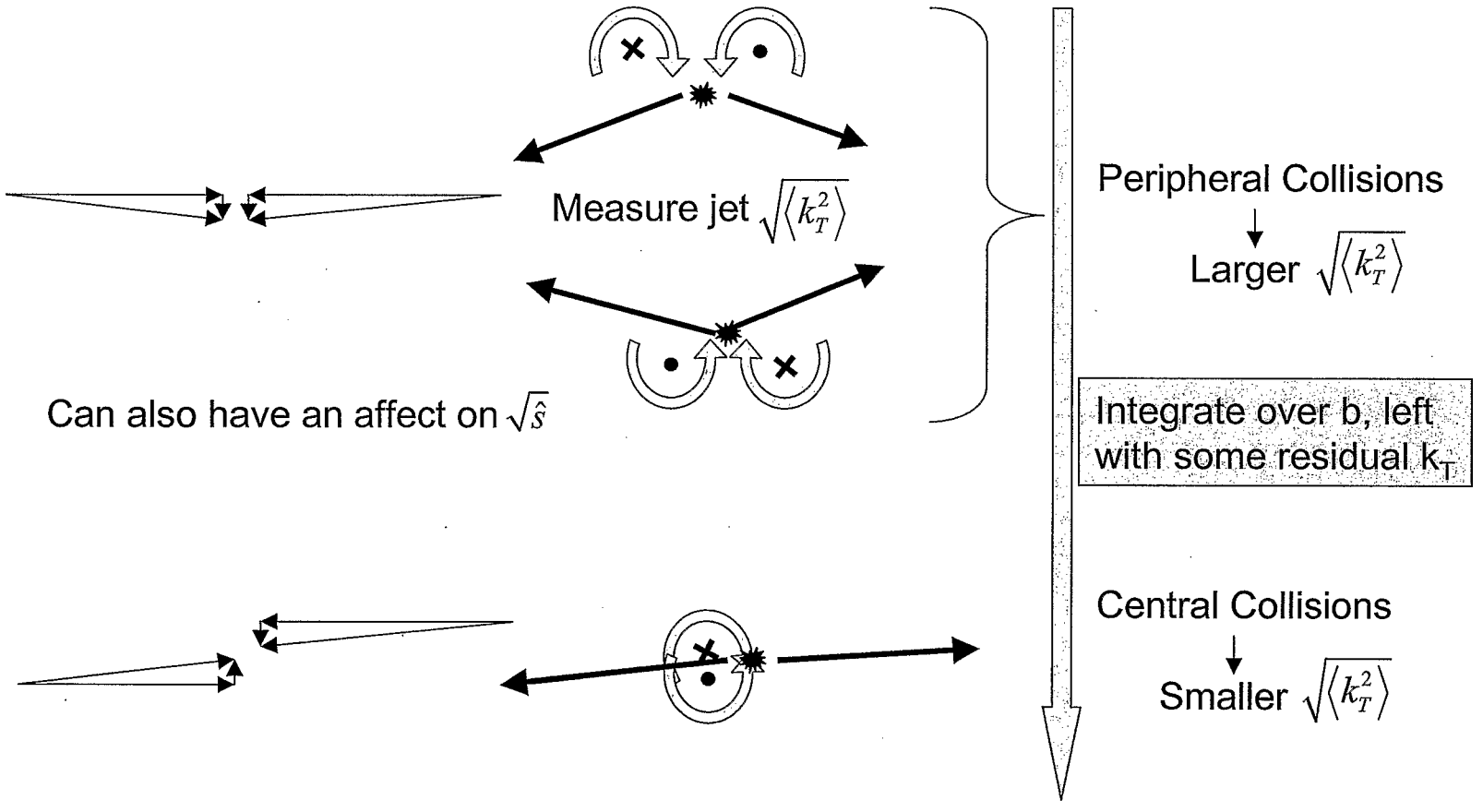
- Front vs. back: effect adds.
- Left vs. right also adds for central collisions,
- But for peripheral collisions, it cancels.
- Impact parameter dependence reduces the effect on average.
- Can double spin asymmetries differentiate these two effects?



From D. Sivers

Like Helicity

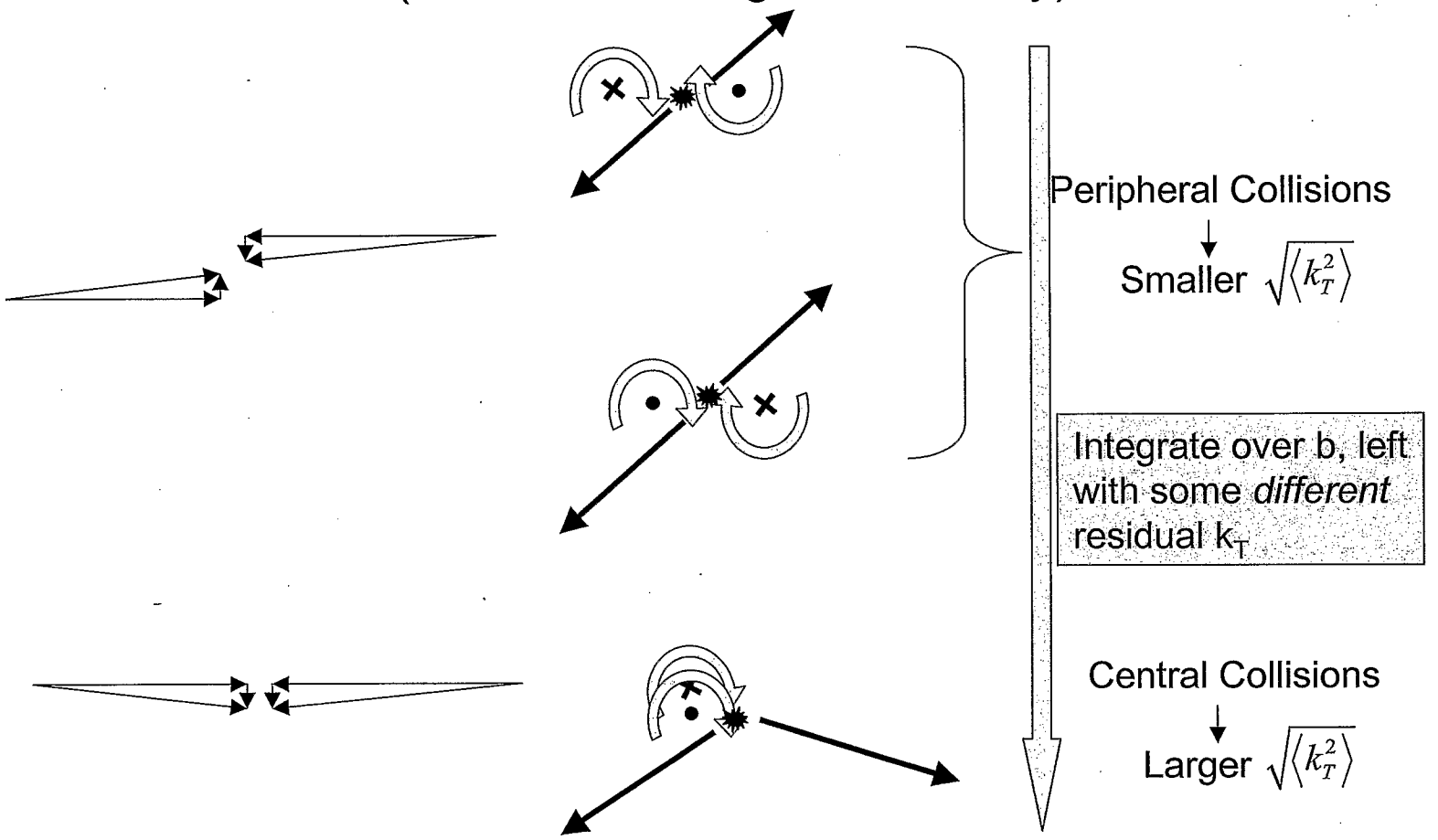
(Positive on Positive Helicity)



Can also have an affect on $\sqrt{\hat{s}}$

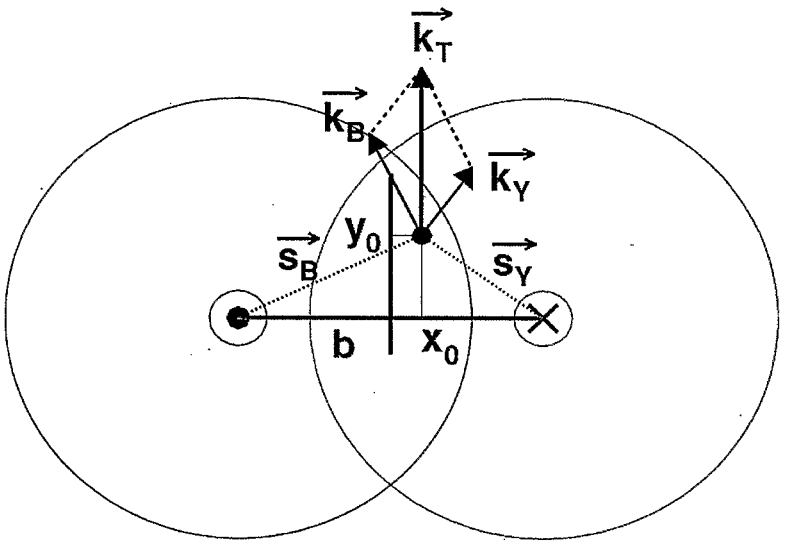
Un-like Helicity

(Positive On Negative Helicity)



Impact Parameter Dependence

- Have followed Ta-Chung's calculation to determine if effect remains when the impact parameter is undetermined.
- Assume constant angular velocity of partons, p_θ, regardless of distance to the proton center.
- We set (arbitrarily) the maximum transverse momentum of the partons to be 300 Mev at the radius of the proton equal to 1.3 fm.
- Basically independent of transverse density distribution.
- k_T difference ranges from 0.3 to 0.6 times the initial momentum.



R. Hobbs, PhD Thesis, UNM (2006).

Summary

- RHIC Spin program has made much progress, and has great promise in the near future.
- Deliverables are not "easy", but so far we have been successful in overcoming difficulties.
- Jet k_T may probe partonic orbital angular momentum…
  - In single transverse spin (Sivers).
  - In double transverse spin???
    - Could be tested with existing data from RHIC.
  - In double longitudinal spin?
    - Some data have been shown, more coming.
- These may be sensitive to orbital angular momentum.
- Need theoretical guidance…

Parity-Odd Asymmetry in W-Jet Events

Hiroshi Yokoya

Dept. of Physics, Niigata University, Niigata 950-2181, Japan

Parity-odd asymmetries in the decay angular distribution of a W boson produced with a hard jet in $p\bar{p}$ collisions arise only from QCD rescattering effects. If observed, these asymmetries provide a first demonstration that perturbative QCD calculation is valid for the absorptive part of scattering amplitudes. We propose a simple observable to measure these asymmetries and perform realistic Monte Carlo simulations at Tevatron energies. It is shown that the Tevatron Run-II should provide sufficient statistics to test the prediction. We also give a simulation on RHIC pp collider and discuss the possibility of measuring the parity-odd quantities.

References

[1] K. Hagiwara, K. Hikasa and N. Kai,Phys. Rev. Lett. **52**,1076 (1984); **67**, 931(E) (1991).

[2] K. Hagiwara, K. Hikasa and H. Yokoya, arXiv:hep-ph/0604208.

[3] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **73**, 052002 (2006).

[4] E. Mirkes, Nucl. Phys. B **387**, 3 (1992).

[5] D. Boer and W. Vogelsang, arXiv:hep-ph/0604177.

Lepton Angular Distributions

- Rich information on the polarization of W-boson, i.e. the details of production mechanism can be investigated

$$
\begin{aligned}
\frac{d^4\sigma}{dq_T^2 d\cos\hat{\theta} d\cos\theta d\phi} &= F_1(1+\cos^2\theta) + F_2(1-3\cos\theta^2) \\
&+ F_3 \sin 2\theta \cos\phi + F_4 \sin^2\theta \cos 2\phi \\
&+ F_5 \cos\theta + F_6 \sin\theta \cos\phi \\
&+ F_7 \sin\theta \sin\phi + F_8 \sin 2\theta \sin\phi \\
&+ F_9 \sin^2\theta \sin 2\phi
\end{aligned}
$$

P-even

P-odd

F_i : structure functions

$\hat{\theta}$: scattering angle in W-jet c.m. frame

θ, ϕ : lepton decay angles in Collins-Soper frame

Lepton Angular Distributions

- pQCD calculation :

$$F_i(q_T^2, \cos\widehat{\theta}) = \sum_{a,b} \int dY\, f_{a/p}(x_+, \mu_F^2) f_{b/\bar{p}}(x_-, \mu_F^2) \widehat{F}_i^{ab\to W^- j}$$

P-even parts : LO (tree-level) Chaichian,Hayashi,Yamagishi('82)

NLO (one-loop) Mirkes,Korner,Schuler('91),Mirkes('92)

P-odd parts : LO (one-loop) Hagiwara,Hikasa,Kai('84)

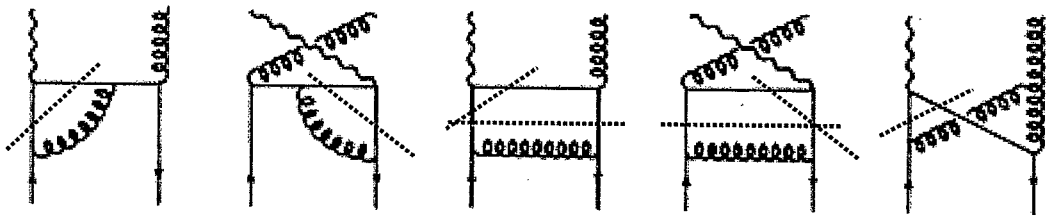
One-loop calculation

Hagiwara,Hikasa,Kai('84)

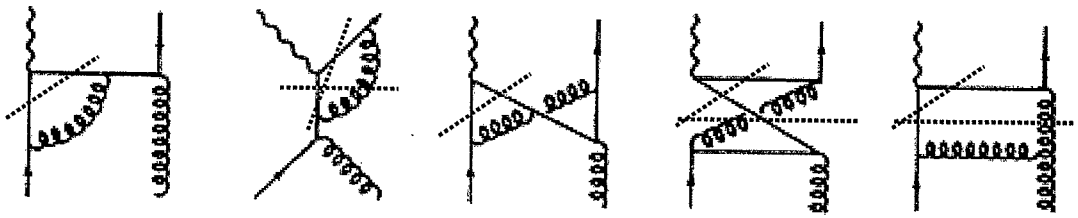
- one-loop calculation in pQCD
  on the absorptive part of scattering amplitude

$$A_{fi} = \sum_n T^*_{nf} T_{ni} (2\pi)^4 \delta^4(P_n - P_i)$$

$q\bar{q}' \to Wg$



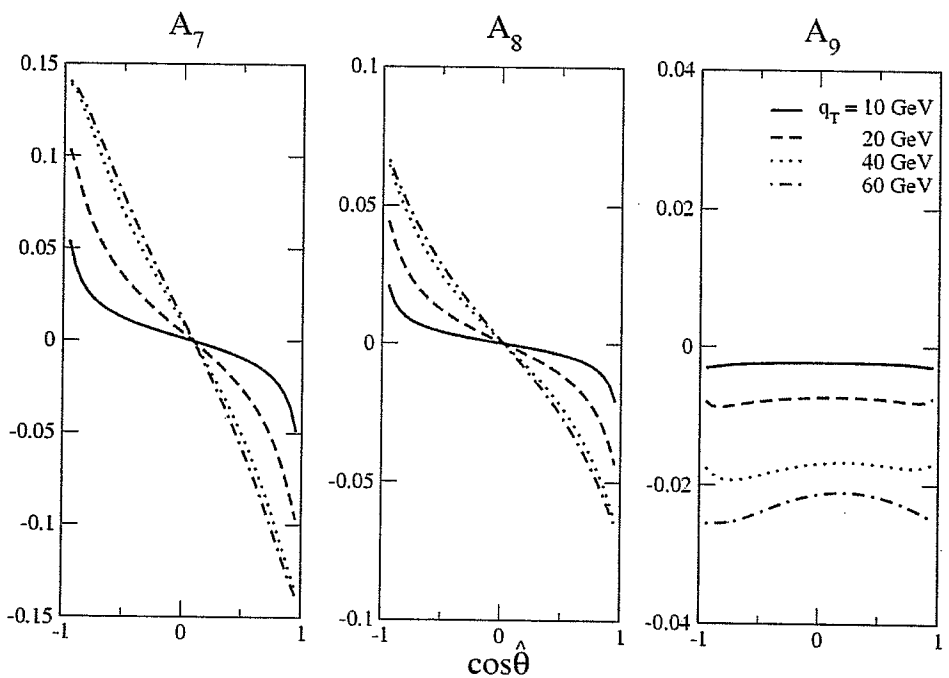
$qg \to Wq'$
$(\bar{q}g \to W\bar{q}')$



One-loop calculation

Hagiwara,Hikasa,Kai('84)

$$A_i(q_T^2, \cos\hat{\theta}) = F_i \,/\, F_1 \text{ for } i = 7, 8, 9$$



$\sin\theta \sin\phi$ $\sin 2\theta \sin\phi$ $\sin^2\theta \sin 2\phi$

$p\bar{p}$, $\sqrt{S} = 1.96$ TeV

with CTEQ6M

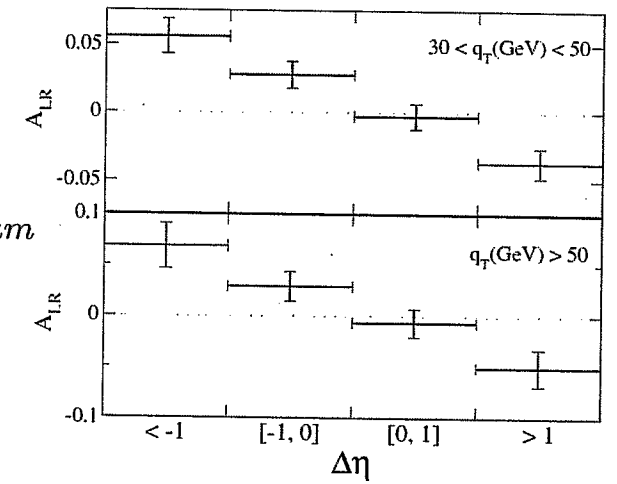
Results : Observable P-odd asymmetries

- Left-right asymmetry $\longleftrightarrow$ A_7

$$A_{LR}(\Delta\eta, q_T) = [N(p_y^\ell > 0) - N(p_y^\ell < 0)]/N_{sum}$$

$\sim$ 5% at large $\Delta\,\eta$

more than 5σ deviation
from zero-asymmetry is expected

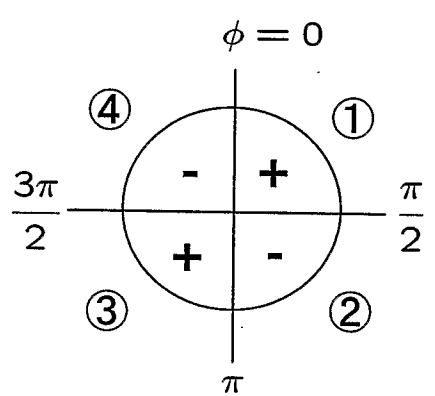


- sign(sin2ϕ) asymmetry $\longleftrightarrow$ A_9

$$A_Q = [① - ② + ③ - ④]/N_{sum}$$

$\sim -0.9\% \pm 0.5\ (1.8\sigma)$

(combining all Δy and q_T)



RHIC Physics in the Context of the Standard Model: A Workshop
and Symposium
BNL June 18-23, 2006

Structure Functions on the Lattice

Kostas Orginos
College of William and Mary / JLab

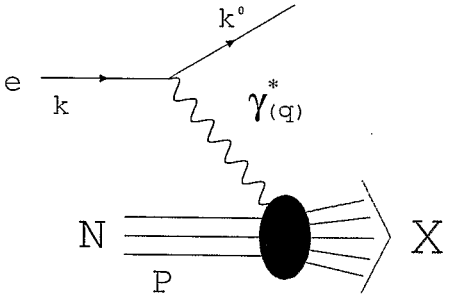
In this talk I present lattice calculations of moments of nucleon structure functions with lattice QCD. In particular I present the first lattice calculations done with domain wall fermions. The main results of these calculations are two. First we demonstrated the finite volume sensitivity of the nucleon axial charge g_A, explaining the reason why older lattice calculations seemed to disagree with experiment. Our result for g_A is consistent with the experimental value with in the errors of our calculation. Second we investigated the chiral behavior of the first moment of the quark density and the helicity distribution functions. Down to 400MeV pion masses we observe no evidence of chiral curvature that would reconcile the lattice results with the experimental expectations. However, we observed that the ratio of the two moments is consistent with experiment. This was the first time this observation was made. The use of domain wall fermions is central in accurately determining this ratio. Finally, I present some new results for the first few moments of the nucleon structure functions in the context of mixed action lattice calculations. We use Kogut-Susskind fermions to represent the quark determinant and domain wall fermions for the valence sector. I discuss the details of these type of mixed action calculations and present our result (LHPC) for the g_A, which is the most accurate up to day lattice calculation of this quantity.

Moments of Structure Functions

$$2\int_0^1 dx x^{n-1} F_1(x,Q^2) \longrightarrow \langle x^n \rangle_q$$

$$2\int_0^1 dx x^{n} g_1(x,Q^2) \longrightarrow \langle x^n \rangle_{\Delta q}$$

$$2\int_0^1 dx x^{n} g_2(x,Q^2) \longrightarrow \langle x^n \rangle_{\Delta q}, d_n$$



- $\langle x^n \rangle_q$, $\langle x^n \rangle_{\Delta q}$, d_n Nucleon matrix elements of local operators $\langle P,S|\mathcal{O}|P,S\rangle$

$$\mathcal{O}^q_{\{\mu_1\mu_2\cdots\mu_n\}} = \overline{q}\left[\left(\frac{i}{2}\right)^{n-1} \gamma_{\mu_1} \overleftrightarrow{D}_{\mu_2} \cdots \overleftrightarrow{D}_{\mu_n} - trace\right] q$$

$$\mathcal{O}^{5q}_{\{\mu_1\mu_2\cdots\mu_n\}} = \overline{q}\left[\left(\frac{i}{2}\right)^{n-1} \gamma_5\gamma_{\mu_1} \overleftrightarrow{D}_{\mu_2} \cdots \overleftrightarrow{D}_{\mu_n} - trace\right] q$$

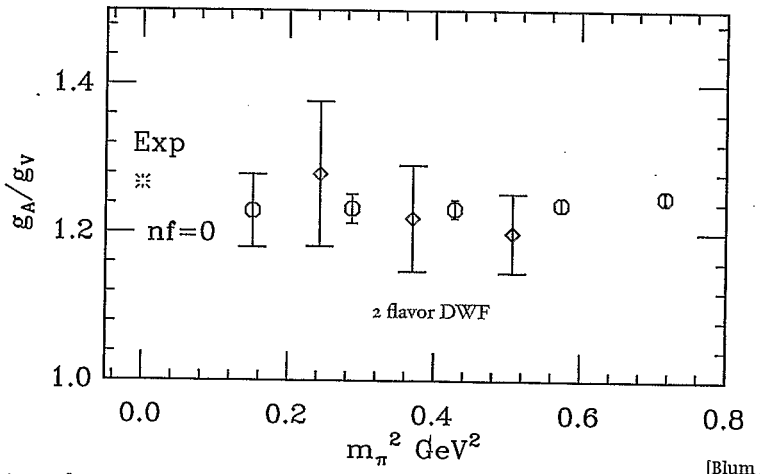
Transversity

$$\int_0^1 dx x^n h_1(x,Q^2) \longrightarrow \langle x^n \rangle_{\delta q}$$

$$\mathcal{O}^{\sigma q}_{\rho\nu\mu_1\mu_2\cdots\mu_n} = \overline{q}[\left(\frac{i}{2}\right)^{n} \gamma_5\sigma_{\rho\nu} \overleftrightarrow{D}_{\mu_1} \cdots \overleftrightarrow{D}_{\mu_n} - traces]q$$

RHIC spin program

Nucleon Axial Charge



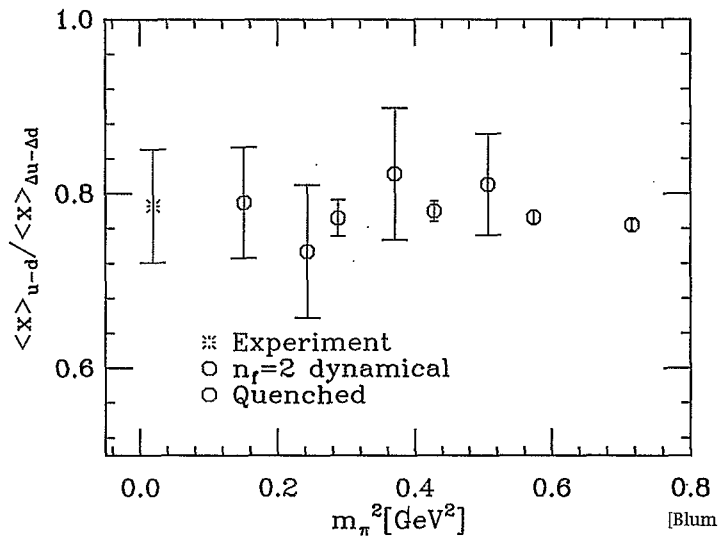
[Blum KO Ohta Sasaki]

- Finite volume effect
- Experimental value: 1.2695(29)
- Quenched DWF: $1.212(24)_{stat}(27)_{norm}$ (linear fit)

- New dynamical result on the way (2 flavor and 2+1) [Blum, Lin, Sasaki, ...]

Ratio of first moments

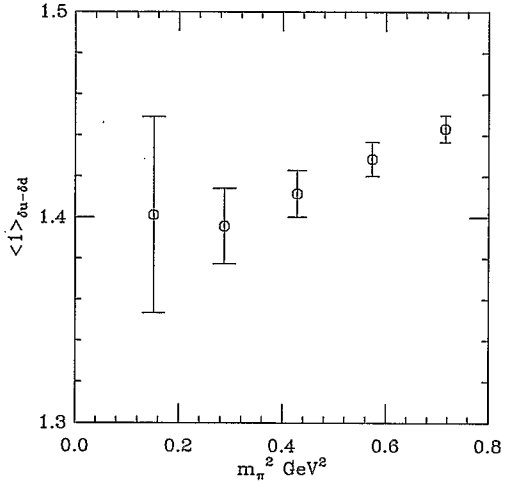
(polarized and unpolarized)

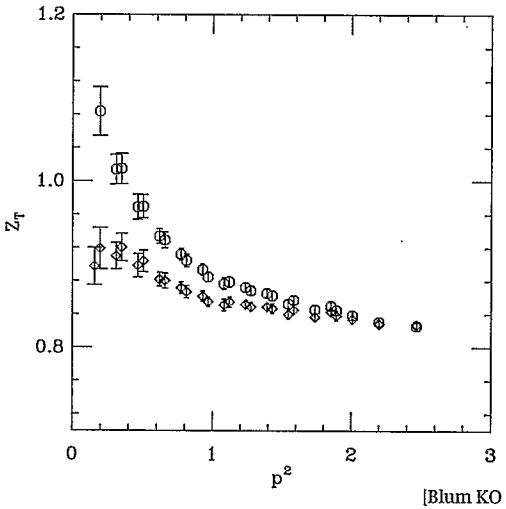


[Blum KO Ohta '05]

- No curvature observed down to **400MeV** pions (Quenched)
- Renormalization constant cancels in the ratio for DWF
- Ratio agrees with experimental expectations

Transversity



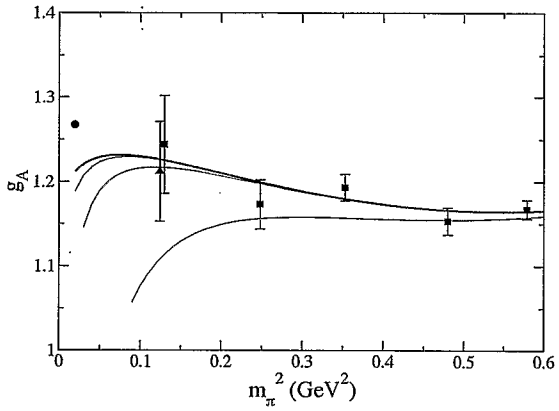


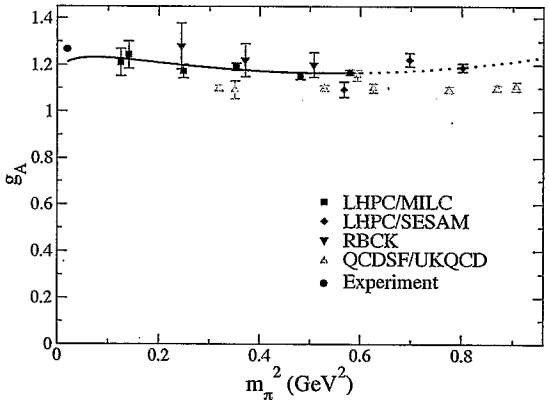
[Blum KO Ohta '05]

- Linear extrapolation: 1.193(30) at 2GeV $\overline{\text{MS}}$

Nucleon Axial charge

LHPC





- Non-perturbatively renormalized
- $g_A(m_\pi = 140\text{MeV}) = 1.22(8)$

Electromagnetic splittings of Hadrons, and calculations towards $g_\mu - 2$ light-by-light contribution.

Taku Izubuchi

RIKEN BNL Reserch Center

Kanazawa University

Having precise lattice QCD calculations with dynamical quarks, QED effects on Hadron physics become more important ingredient for reducing systematic errors. Isospin (and $SU(3)_F$) breaking of Hadron mass spectrum due to the Electro-magnetic effects calculated from QCD+QED simulations are reported. Also novel ideas to combine perturbative (QED part) and non-perturbative (QCD part) aspects of nature are presented, which will be useful towards the exciting calculation, Hadronic light-by-light contribution to the muon anomalous magnetic moment.

based on a collaborations with [RBC, RBC-UKQCD collaboration]

T. Blum, T. Doi, M. Hayakawa, N. Yamada
Koichi Hashimoto

QCD + QED simulations

(T. Blum, T. Doi, 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.

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

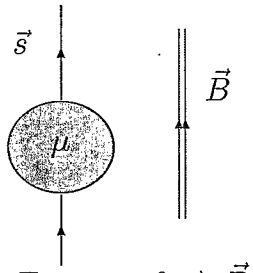
- Hadron mass differences due to isospin breaking are measured very accurately in experiments:

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

- 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.

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



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

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

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

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

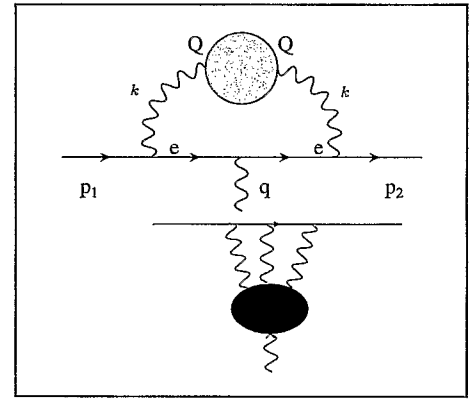
- Hadronic contributions dominates theory error.

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

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

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

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



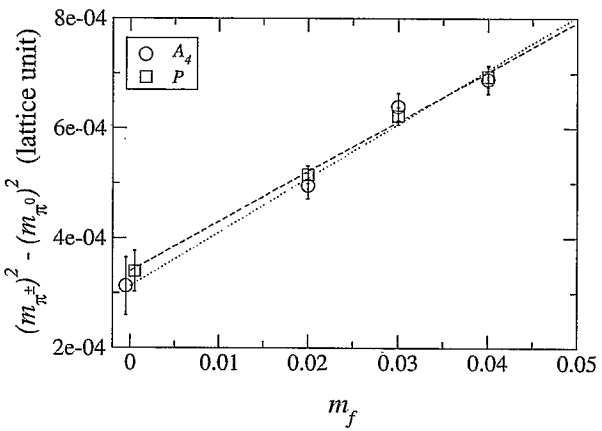
$a_\mu^{\text{Had,HO}}$ was explored by T. Blum in PRL 91, 2003,
C. Aubin & T. Blum new analysis using SChPT.

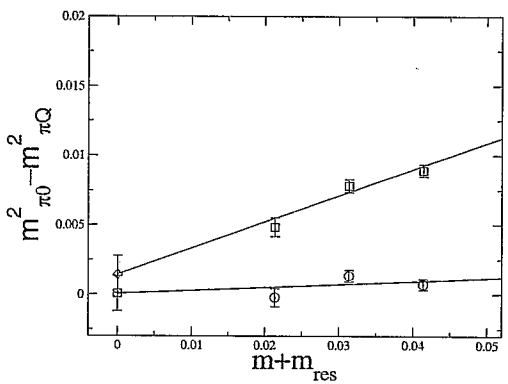
ΔM_π^2, Dashen's theorem

- Mass splitting of Π_0 and $\Pi_\pm$ with fixed quark mass.
- preliminary results $m_\pi^\pm - m_\pi^0 = 3.5(6)MeV(4.43exp)$ $m_d - m_u = 2.6(3)$MeV
- Breaking of 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 $m_{\pi\pm}, m_\pi^0, m_{K\pm}, m_{K^0}$.





non-perturbative technique with perturbative one

- In Lattice QCD calculations, perturbative treatment is often used.
- If the expansion paramter is enough small why not rely on perturbative methods if it extends the reach to a new region ! Perturbation is nice, intuitive, particle picture....
-

  [answer] = [pertubative vlue] $*$ [non-pertubative value]

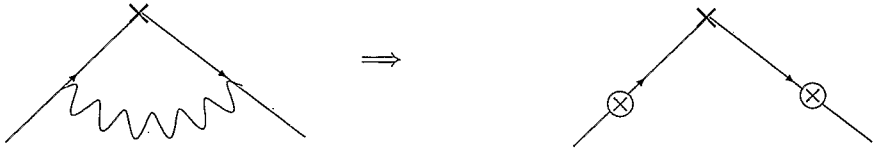
  '$*$' could be a simple operation (multiplication) or a compilcated operation (integrals):

answer	pertubative	non-perturbative	*
$\Gamma(\pi \to e\bar{\nu}_e)$	$G_F V_{ud} m_\mu$	F_π	mult.
ϵ_K $(K_0 - \overline{K_0})$	$\propto G_F^2 M_W^2$ [$V_{qq'}F$'s]	B_K	lin. comb.
$O(\alpha^2)g-2$	kernel $f(q^2)$	$\Pi_{\mu\nu} = \langle V_\mu V_\nu \rangle (q)$	fit & integ.
EM splits	Photon prop. $G_{\mu\nu}(q)$	$\langle H \vert V_\mu(q) V_\nu(-q) \vert H \rangle$	M.C. integral

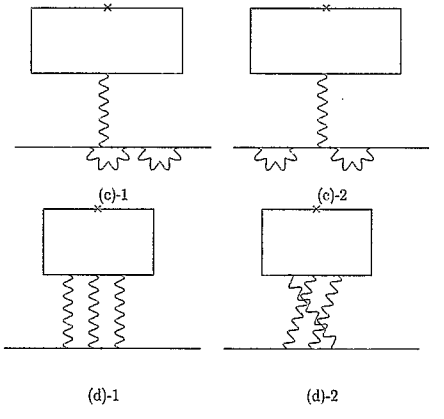
(K_{l3} : (Shoichi's talk) , SF (NEDM!) : (Kostas' talk) , B_K : (Jun's talk))

Future prospects

- EM splittings using non-perturbative QED.
- Nucleon mass splittings in progress (Takumi Doi) . (important !)
- EM splittings using the direct calculation of the QED diagrams.
- $\mathcal{O}(\alpha)$ contribution to $g_\mu - 2$ (pure QED).



- Auxially small uniform E/M field on lattice.
- $\mathcal{O}(\alpha^3)$ contribution (light-by-light) to $g_\mu - 2$.



Lattice and Effective Field Theory for Cold Fermionic Atoms

Matthew Wingate
Institute for Nuclear Theory
University of Washington

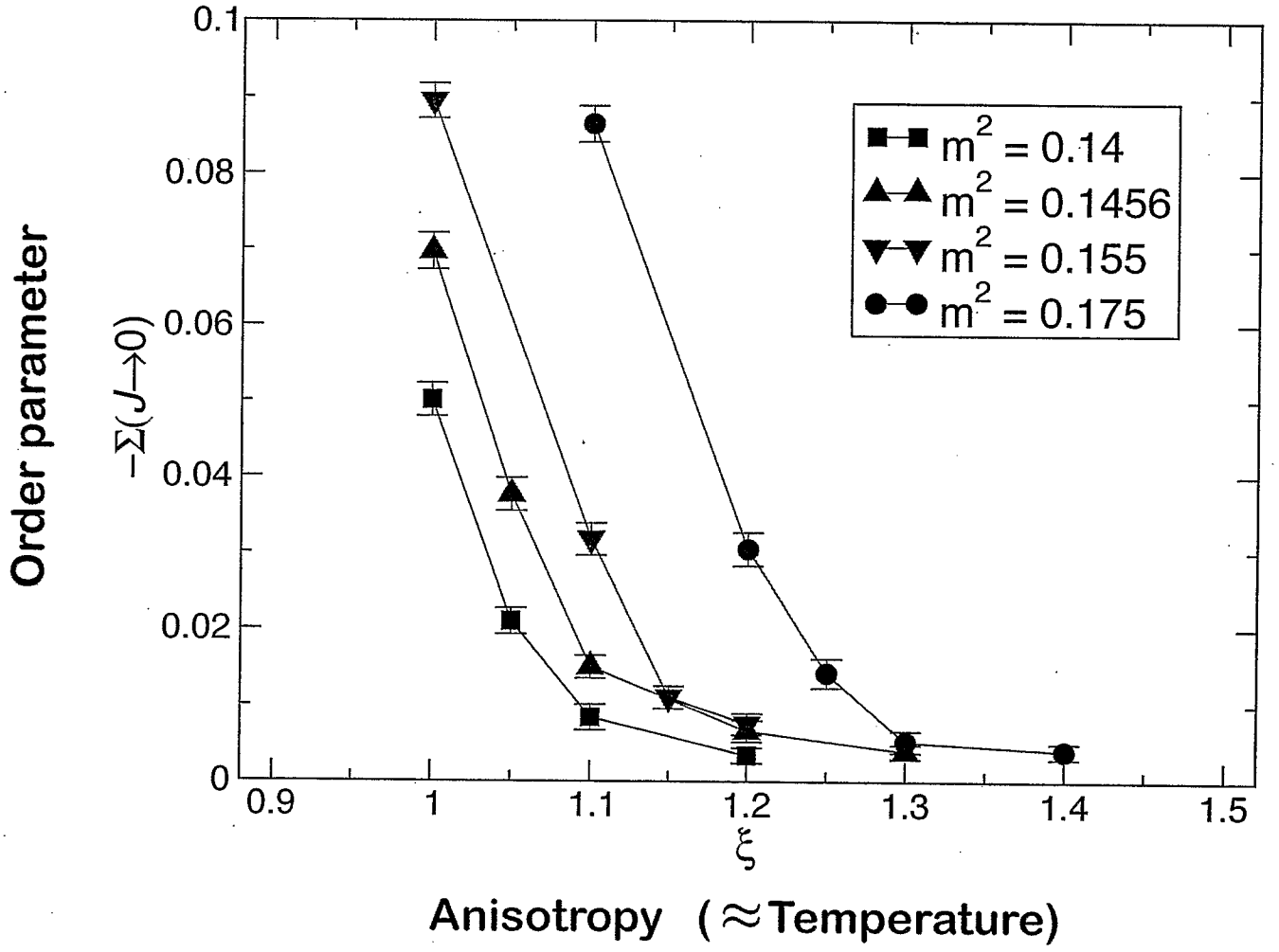
Trapped and cooled gases of alkali atoms can be manipulated to exhibit a variety of interesting phenomena. For example, dilute gases of fermionic atoms, in 2 hyperfine states, can be cooled to temperatures where they become superfluid. An external field can be applied to tune the scattering length a. When $|a|$ exceeds the interparticle spacing, nonperturbative tools are needed to study the system theoretically. The unitary limit, $|a| \to \infty$, is particularly interesting due to its universality and symmetry. Lattice field theory and effective field theory can be used to systematically calculate properties of this system.

I discuss the formulation of the problem on the lattice and present results of Monte Carlo computations of the critical temperature between normal and superfluid states. Then I turn to zero temperature and discuss the effective field theory from which corrections to superfluid hydrodynamics can be calculated. A by-product of this work was the realization that this unitary Fermi gas possesses nonrelativistic general coordinate and conformal invariance.

Cold Fermionic Atoms - Outline

- **General motivation, specific system**
- **Lattice Field Theory & Monte Carlo calculation**
  - ☆ First results -- superfluid/normal phase transition
  - ☆ Road to understanding and reducing uncertainties
  - ☆ (see M.W., cond-mat/0502372)
- **Symmetries & Low Energy Effective Field Theory**
  - ☆ All cold atoms: general coordinate invariance
  - ☆ Unitary Fermi gas: scale and conformal invariance
  - ☆ (see D.T. Son & M.W., cond-mat/0509786, Ann. Phys. 321, 197 (2006))
- **Future directions**

Phase transition



Introducing external sources

$$\mathcal{L} = \frac{i}{2}\psi^\dagger \boxed{\overleftrightarrow{D_t}}\psi - \frac{\boxed{g^{ij}}}{2m}\boxed{D_i}\psi^\dagger \boxed{D_j}\psi + q_0\psi^\dagger\psi\sigma - \frac{1}{2}\boxed{g^{ij}}\partial_i\sigma\partial_j\sigma - \frac{\sigma^2}{2r_0^2}$$

U(1) gauge field $D_\mu\psi = (\partial_\mu + iA_\mu)\psi$ 3D metric tensor g^{ij}

$$\exp\{iW[A_0, A_i, g_{ij}]\} = \int \mathcal{D}\psi\mathcal{D}\psi^\dagger \exp\{i\mathcal{S}[\psi, \psi^\dagger, A_0, A_i, g_{ij}]\}$$

number density

$$n = -\frac{\delta W}{\delta A_0}$$

number current

$$j^k = -\frac{\delta W}{\delta A_k}$$

momentum density

$$T_{0k} = -mg_{ik}\frac{\delta W}{\delta A_i} + A_k\frac{\delta W}{\delta A_0}$$

stress tensor

$$T^i_k = 2g_{kj}\frac{\delta W}{\delta g_{ij}} - \delta^i_k W + A_k\frac{\delta W}{\delta A_i}$$

Phonon Lagrangian to NLO

General coordinate invariance yields the combination

$$\mathcal{L} = P(X) \qquad X = D_t\theta - \frac{(D_i\theta)^2}{2m}$$

$$+ \partial_i X \partial_i X f_1(X) + (\partial_i D_i \theta)^2 f_2(X)$$

$$+ \left(-m\partial_i E_i + \frac{1}{4}F_{ij}F_{ij} - \partial_i F_{ij} D_j \theta\right) f_3(X)$$

all gases

Conformal invariance tells us the functional form

$$\mathcal{L} = c_0 m^{3/2} X^{5/2} + c_1 \sqrt{m}(\partial_i X \partial_i X) X^{-1/2}$$

$$+ \frac{c_2}{\sqrt{m}}\left[(\partial_i D_i \theta)^2 + 9m\partial_i E_i - \frac{9}{4}F_{ij}F_{ij} + 9\partial_i F_{ij} D_j \theta\right] X^{1/2}$$

unitary Fermi gas

Applying the EFT

Equation of state

$$\frac{E}{N} = \xi \frac{E_{\text{free}}}{N} \qquad c_0 = \frac{2^{5/2}}{15\pi^2\xi^{3/2}}$$

Dispersion relation

$$\omega(q) = \sqrt{\frac{\xi}{3}} v_F\, q \left[1 - \pi^2\sqrt{2\xi}\left(c_1 + \frac{3}{2}c_2\right)\frac{q^2}{k_F^2}\right] + O(q^5 \ln q)$$

Static density response function

$$\chi(q) = -\frac{m k_F}{\pi^2 \xi}\left[1 + 2\pi^2\sqrt{2\xi}\left(c_1 - \frac{9}{2}c_2\right)\frac{q^2}{k_F^2}\right] + O(q^4 \ln q)$$

Static transverse response function

$$\chi^T(q) = -9\, c_2 \sqrt{\frac{\xi}{2}}\, v_F q^2 + O(q^4 \ln q)$$

Thermodynamics at $\mu = 0$ on the lattice

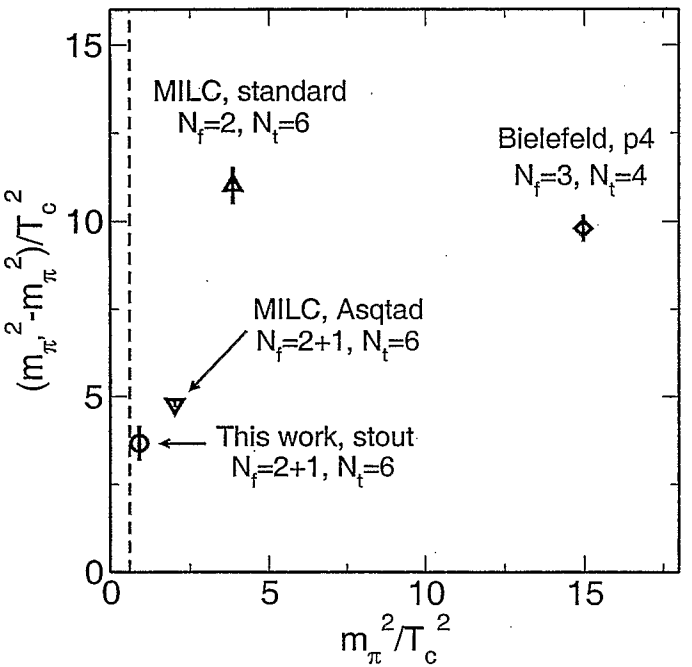
Y. Aoki
University of Wuppertal

QCD thermodynamics at vanishing chemical potential with three light flavors is investigated. The aim of these works are to control most of the systematic uncertainties in the lattice simulation with staggered fermions. Tree-level improved Symanzik gauge and stout-link improved fermion action is employed, which results in substantial reduction of the taste symmetry breaking of staggered fermions. The exact fermion algorithm, RHMC is used. We tune the quark masses to be the physical ones for the finite temperature simulation. Zero temperature simulation which is needed to renormalize the finite temperature quantity employs physical s quark and slightly heavier u, d quarks than the reality, which are used to extrapolate to the physical point. Equation of state at $\mu = 0$ is calculated with $N_t = 4$ and 6 lattices. Further study with $N_t = 8$, which is a simple extension of this work is needed for the reliable continuum extrapolation. Order of the transition at the physical quark masses is studied employing the finite size scaling. Peak height of the properly renormalized chiral susceptibility of u, d quarks is extrapolated to the continuum limit using $N_t = 4$, 6, 8, 10 results, showing the transition is a crossover.

Equation of state has been studied with Z. Fodor, S.D. Katz, K.K. Szabó, and published in JHEP 0601:089,2006 [hep-lat/0510084].

The order of the transition is being studied with G. Endrődi, Z. Fodor, S.D. Katz, K.K. Szabó.

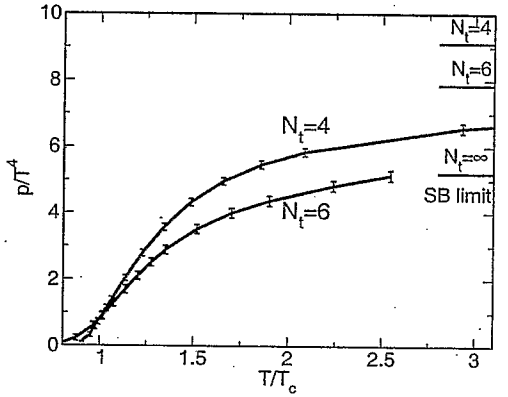
How close to the physical and continuum limit ?

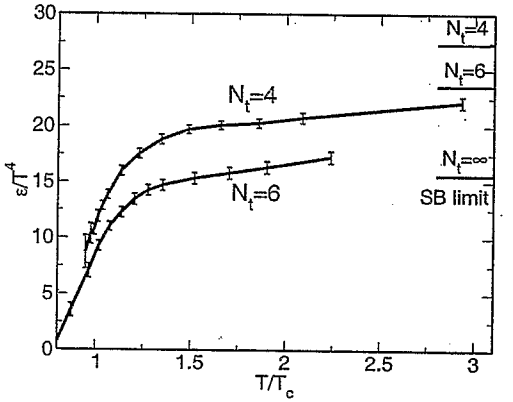


$$\Delta'_\pi = \frac{m_{\pi'}^2 - m_\pi^2}{T_c^2} = (m_{\pi'}^2 - m_\pi^2) N_t^2$$

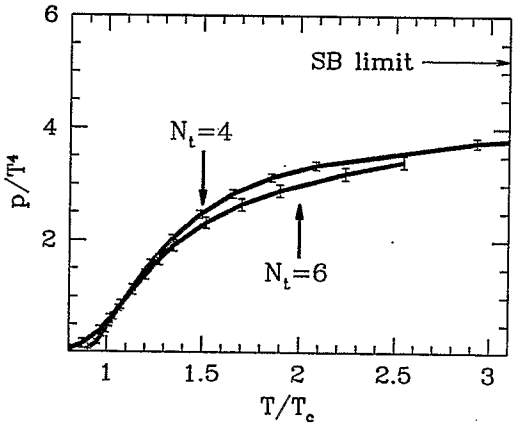
($T = 0$ masses, measured at $\beta_c(N_t)$)

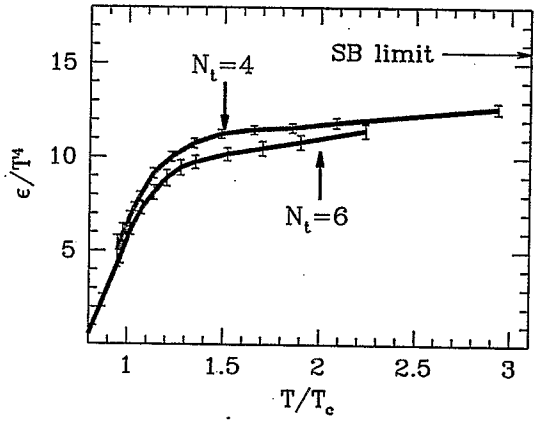
EoS





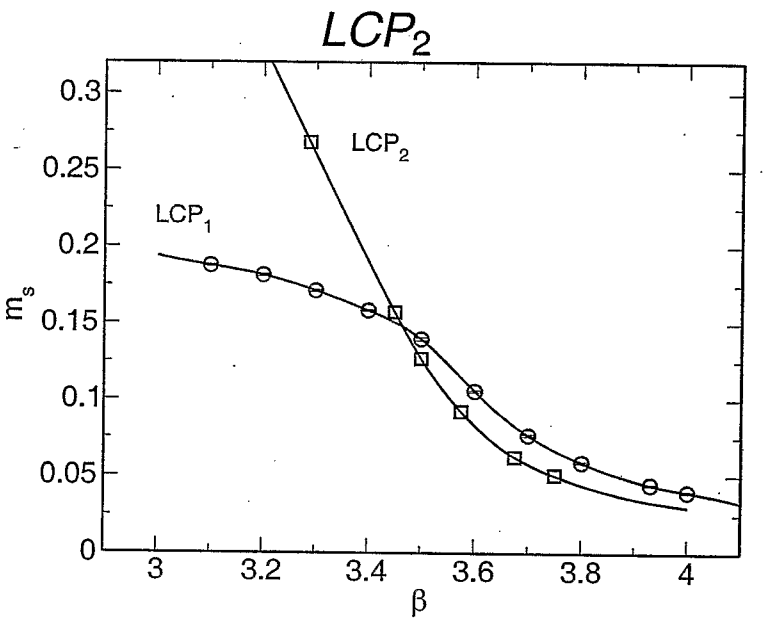
Multiplied with c_{SB}/c_{N_t} ($c_{SB} = \lim_{N_t\to\infty} c_{N_t}$), $N_t = 4$(red), 6(blue).





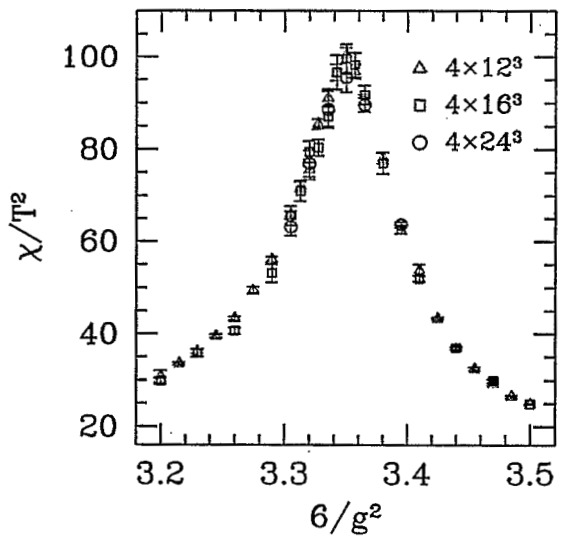
Strategy

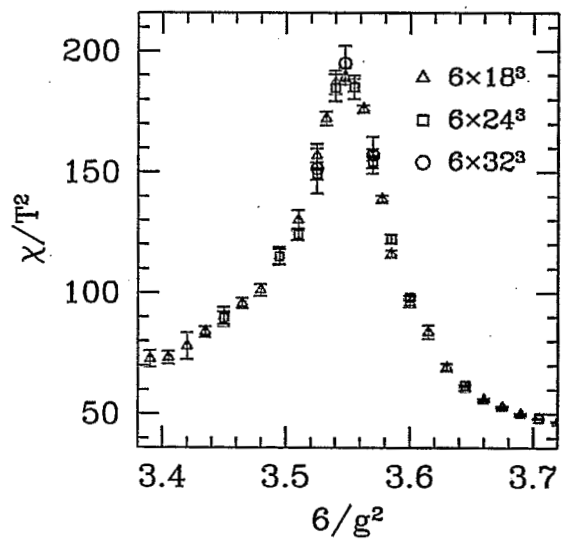
- Exact algorithm (RHMC)
- Finite size scaling
- Correct quark masses
  - tune m_s and m_u so that ratios of m_π, m_K, f_K take physical values.
  - LCP_2: $m_u = m_s/27.3$, $m_s \to$
- Continuum limit



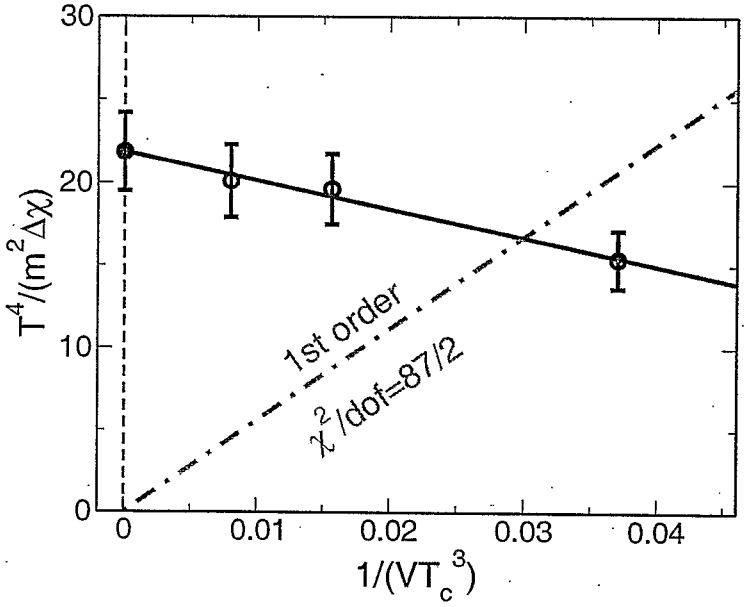
Finite Size Scaling of chiral susceptibility χ_{ud}

- $N_s/N_t = 3 - 5(6)$.
- No volume dependence found.
- How about in the continuum limit ?





Finite Size Scaling after continuum extrapolation



- Susceptibility does not diverge as $V \to \infty$
- $\to$ Crossover

Kaon physics in the full domain-wall QCD

Jun Noaki

野秋淳一

RBC+UKQCD Collaboeations

University of Southampton

Summary: The RBC and UKQCD joint collaborations started a new project of generating the $N_f = 2 + 1$ domain-wall QCD gauge configurations. Using configurations generated so far, UKQCD calculated spectrum and kaon B-parameters. These results are very promising and signal the coming of new age of lattice QCD simulations.

June 23, 2006

Introduction
Numerical simulation
Parameters and strategy
Basic parameters
Spectrum & decay constants
technical issues
chiral extrapolation
B-parameter
plateaus
NPR
chiral extrapolation
Summary

Brief history of DWQCD

1992 Domain-Wall fermion
Kaplan, Shamir

1994 Domain-Wall QCD
Fürman & Shamir

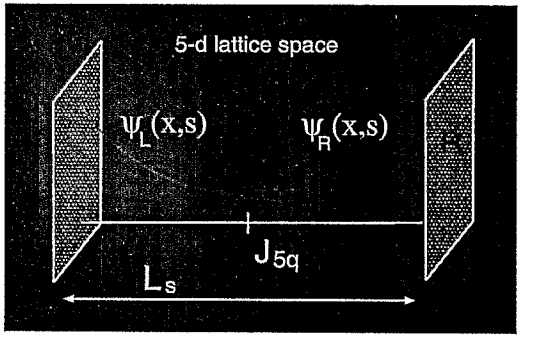
1997 First quenched simulation
Blum & Soni, RBC

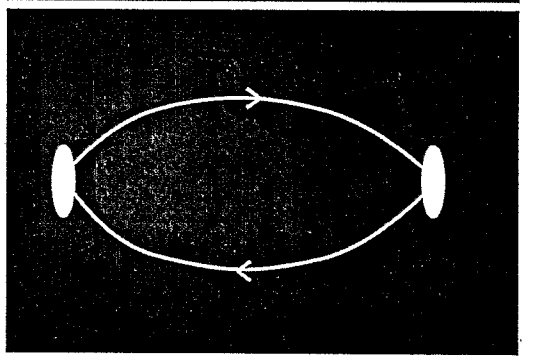
2000 RG improvement + DWF
CP-PACS

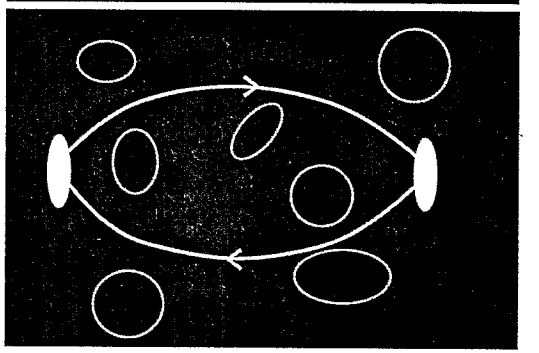
2001 $B_K, \epsilon'/\epsilon$ CP-PACS, RBC

2005 $N_f = 2$ simulation
RBC

2006~ $N_f = 2 + 1$ simulation
RBC+UKQCD

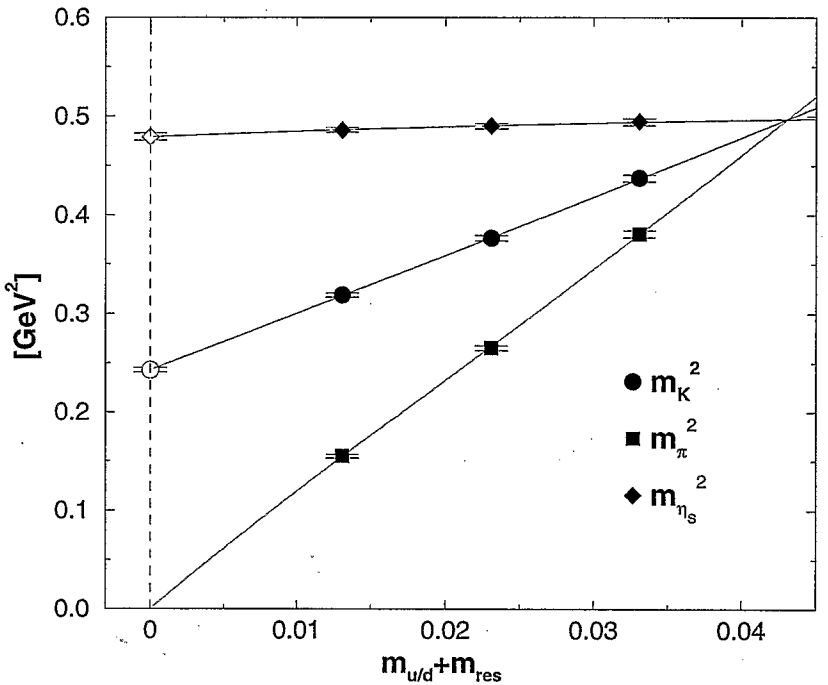






Introduction
Numerical simulation
Parameters and strategy
Basic parameters
Spectrum & decay constants
technical issues
chiral extrapolation
B-parameter
plateaus
NPR
chiral extrapolation
Summary

PS meson masses



- Reproduces PCAC relation very well.
- $m_K \simeq 495$ MeV at chial limit.
- Too few data points to check chiral property.

Introduction

Numerical simulation

Parameters and strategy

Basic parameters

Spectrum & decay constants

technical issues

chiral extrapolation

B-parameter

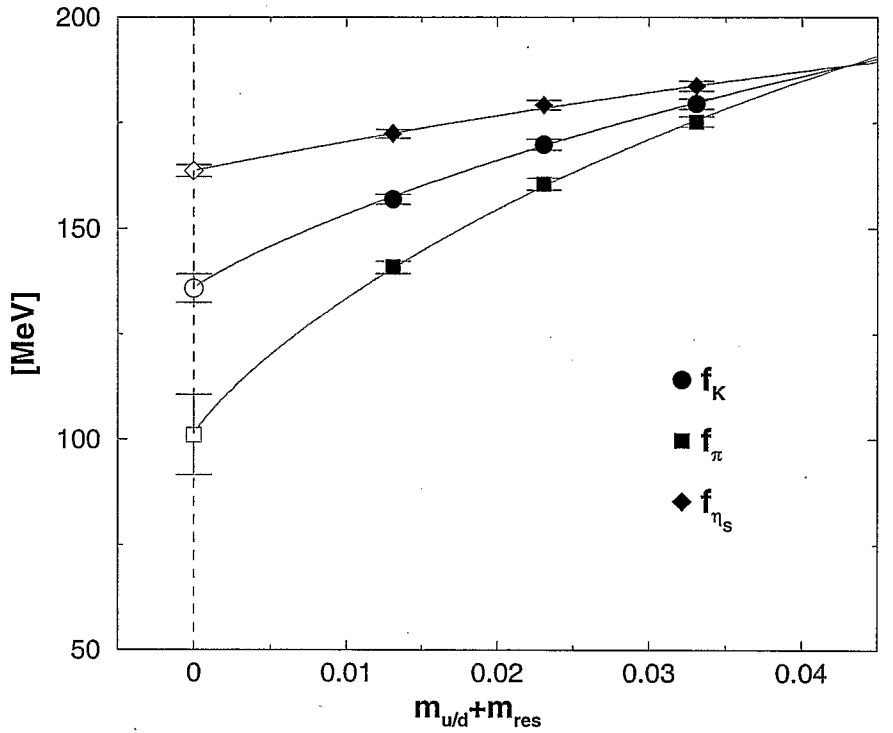
plateaus

NPR

chiral extrapolation

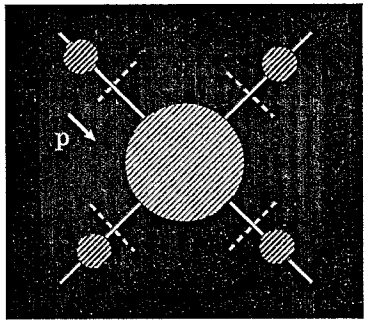
Summary

Decay constants



- $f_K \simeq 135$ MeV, $f_\pi \simeq 101$ MeV at the chiral limit
- $f_K/f_\pi \simeq 1.31$ at the chiral limit
- B_0 is inconsistent with m_π^2's higher order effect?

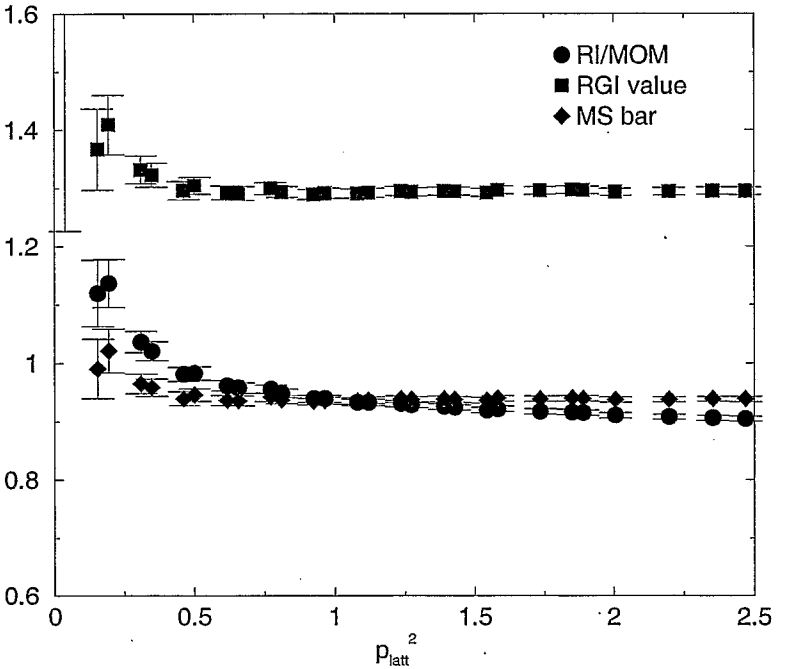
Non-perturbative Renormalization



- **Rome-Southampton method**

$$Z_q^{-2} Z_O \Gamma_O^{(\mathrm{latt})} = \Gamma_O^{(\mathrm{tree})}$$

for Landau gauge (RI/MOM)



$$Z_{B_K}^{\mathrm{RI/MOM}} = Z_O / Z_A^2$$

$$Z_{B_K}(\overline{\mathrm{MS}}\ \mathrm{NDR},\ \mu = 2\,\mathrm{GeV}) = 0.9382(13)$$

Introduction

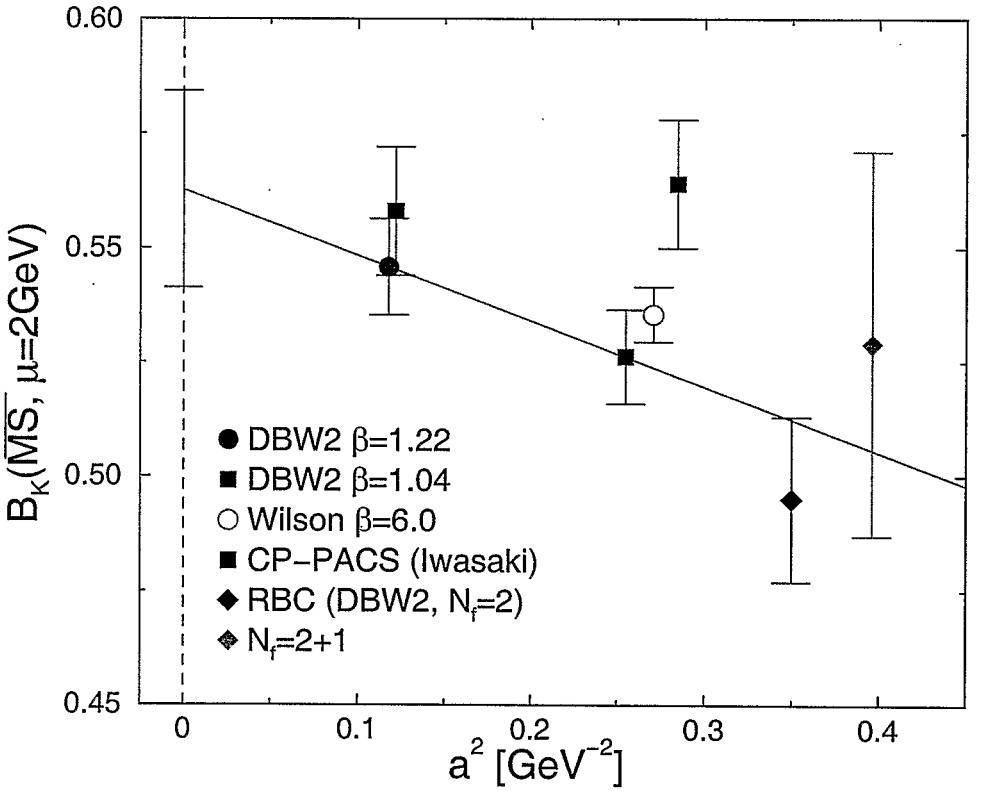
Numerical simulation
- Parameters and strategy
- Basic parameters

Spectrum & decay constants
- technical issues
- chiral extrapolation

B-parameter
- plateaus
- NPR
- chiral extrapolation

Summary

Current status of B_K



Good starting point, isn't it?

Light hadron spectrum in 2+1 flavor QCD with Wilson quarks

Tomomi Ishikawa

CP-PACS and JLQCD Collaborations

University of Tsukuba

tomomi@ccs.tsukuba.ac.jp

SUMMARY

CP-PACS and JLQCD collaborations are performing simulations of 2+1 flavor full QCD using the non-perturbatively $O(a)$ improved Wilson-clover quark formalism. We have completed HMC runs at three lattice spacings, $a \sim 0.07$, 0.10 and 0.122 fm, keeping the physical volume constant at $(2.0\text{fm})^3$. On the generated gauge configurations we calculate light meson spectrum, light quark masses and PS decay constants. The light meson spectrum is consistent with experiment and obtained ud and strange quark masses are $m_{ud}^{\overline{MS}}(\mu = 2\text{GeV}) = 3.50(14)(^{+26}_{-15})$ MeV and $m_s^{\overline{MS}}(\mu = 2\text{GeV}) = 91.8(3.9)(^{+6.8}_{-4.1})$ MeV.

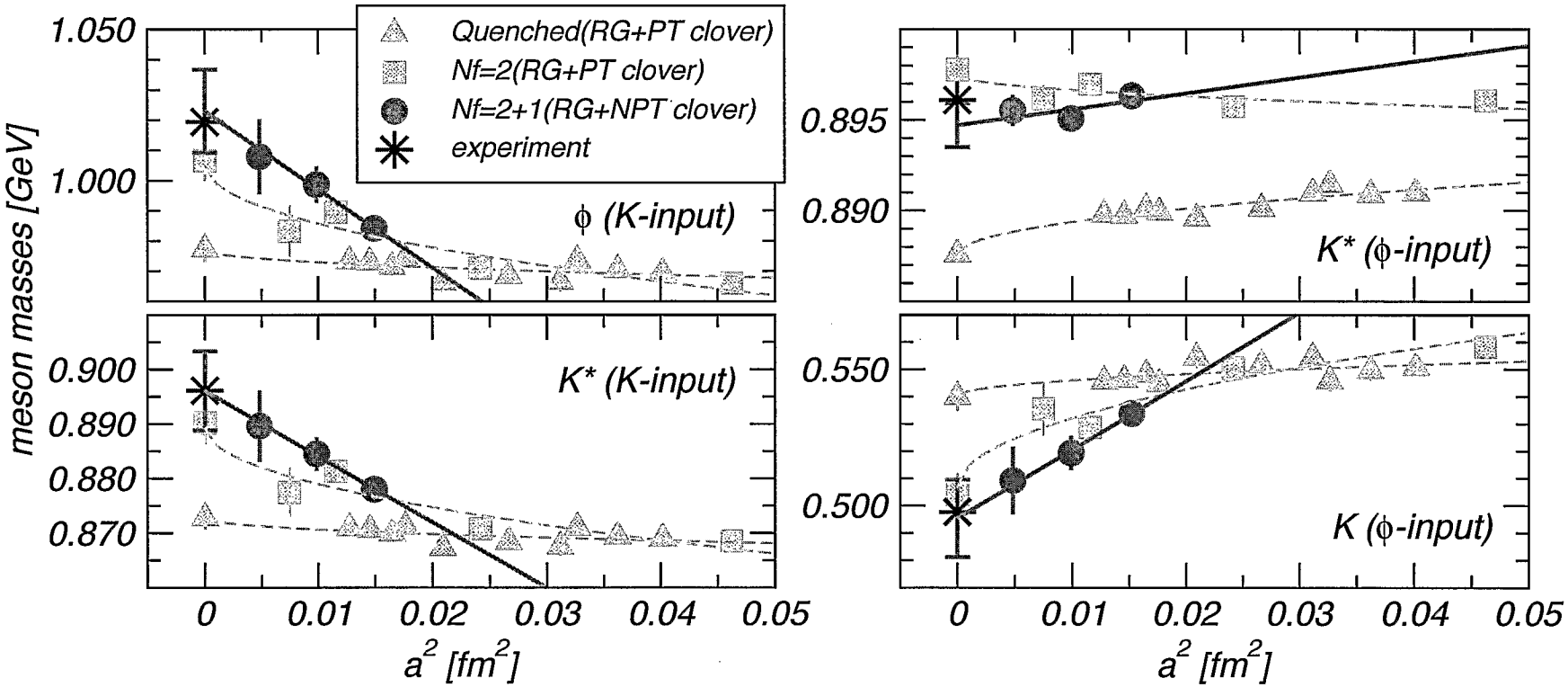
Simulation and Analysis

- Wilson quark formalism
  - Iwasaki gauge action + NP clover quark action
- Dynamical up, down and strange quarks
  - Up and down have a degenerate mass, strange has a distinct mass.
- Algorithm
  - HMC for ud quarks, PHMC for strange quark
- Simulation palameters
  - $\beta = 2.05\ (a \sim 0.07\mathrm{fm}),\ L^3 \times T = 28^3 \times 56,\ \mathrm{HMC\ traj.} = 6000 - 6500$
    $\beta = 1.90\ (a \sim 0.10\mathrm{fm}),\ L^3 \times T = 20^3 \times 40,\ \mathrm{HMC\ traj.} = 5000 - 9000$
    $\beta = 1.86\ (a \sim 0.12\mathrm{fm}),\ L^3 \times T = 16^3 \times 32,\ \mathrm{HMC\ traj.} = 7000 - 8600$
  - 5 ud quark mass parameters $(m_{PS}/m_V \sim 0.60 - 0.78)$
    2 strange quark mass parameters $(m_{PS}/m_V \sim 0.7)$
- Chiral extrapolation
  - Polynomial fit in quark masses up to quadratic order

Light meson spectrum

Results

- In the continuum, meson spectrum is consistent with experiment.
- The statistical error in the continuum limit is large.



Light quark masses

Renormalization

$$m_q^{LAT}(a^{-1}) \longrightarrow m_q^{\overline{MS}}(\mu = 2\ \mathrm{GeV})$$

- tad-pole improved 1-loop matching
- 4-loop running to 2 GeV

Results

$$m_{ud}^{\overline{MS}} = 3.50(14)(^{+26}_{-15})\ \mathrm{MeV}$$

$$m_s^{\overline{MS}} = 91.8(3.9)(^{+6.8}_{-4.1})\ \mathrm{MeV}$$

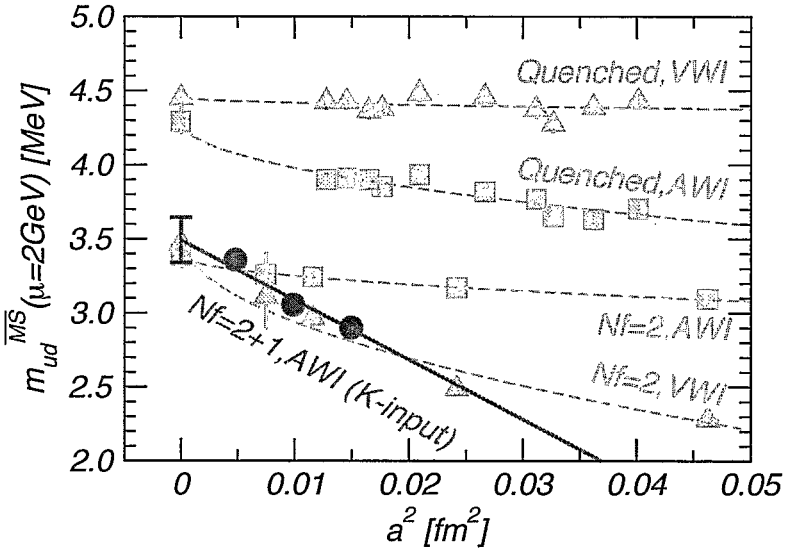
(AWI, combined K with ϕ-input)

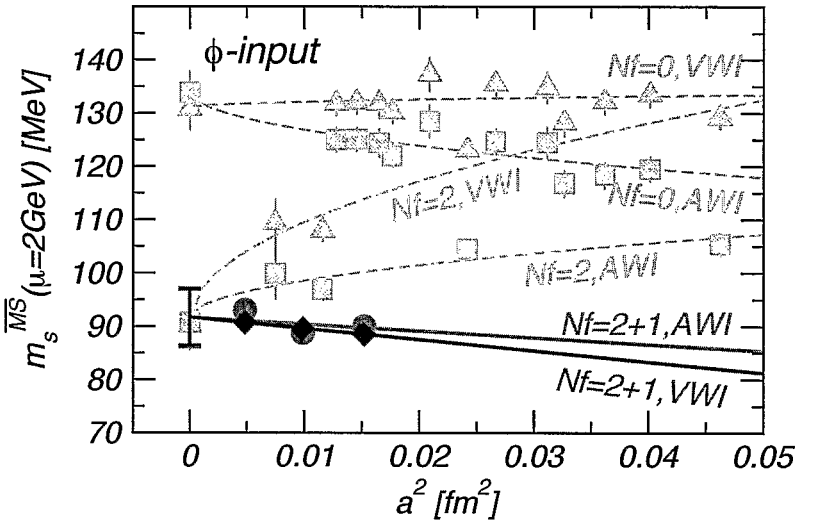
consistent with Nf=2

MILC staggered (2-loop matching)

$$m_{ud}^{\overline{MS}} = 3.2(0)(2)(2)(0)\ \mathrm{MeV}$$

$$m_s^{\overline{MS}} = 87(0)(4)(4)(0)\ \mathrm{MeV}$$





(Nf=2, 0 : RG+clover(PT))

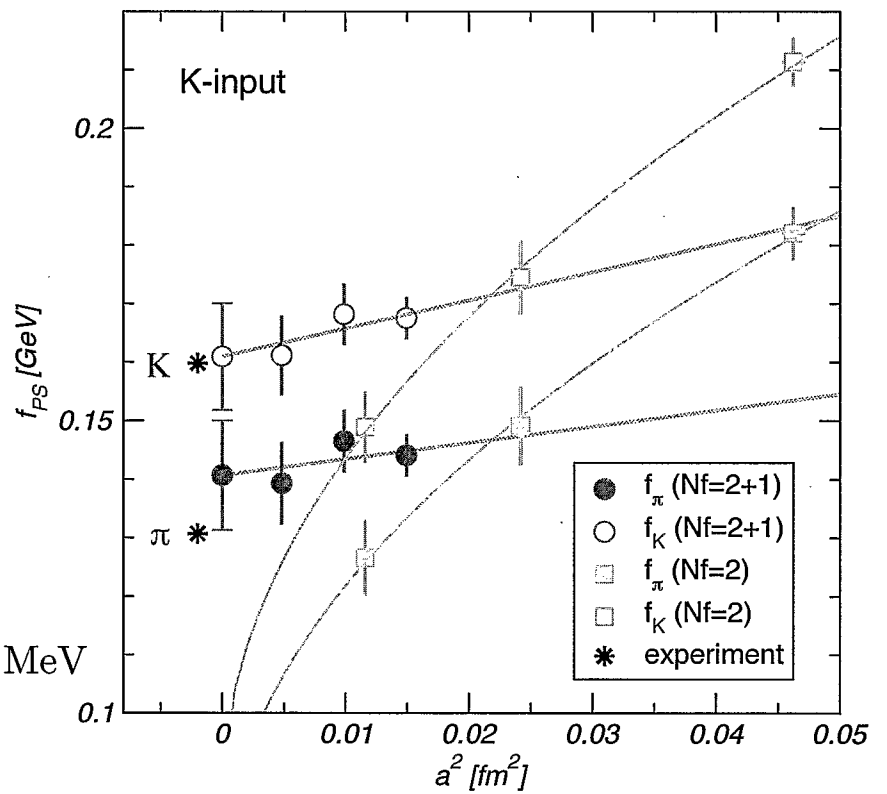
PS meson decay constants

- PS decay constant f_π, f_K

$$\langle 0|A_4|\pi\rangle = f_\pi m_\pi$$

- Renormalization
  - tad-pole improved 1-loop renormalization factor
- Results

$$f_\pi = 140.7(9.3)\ \mathrm{MeV}$$
$$f_K = 160.9(9.1)\ \mathrm{MeV}$$
$$f_K/f_\pi = 1.142(17)$$
(K-input)



experiment

$f_\pi = 130.7(0.4)\ \mathrm{MeV}, \quad f_K = 159.8(1.5)\ \mathrm{MeV}$

$f_K/f_\pi = 1.223(12)$

Next direction - lighter quark mass -

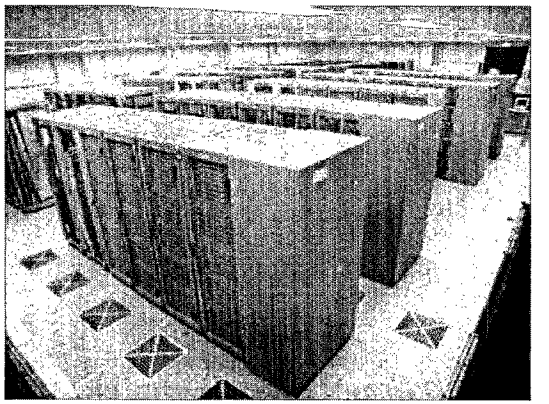
- PACS-CS collaboration
  - clover quark with domain decomposed HMC (Luscher, 2004)
  - We wish go down to light quark mass :

$$m_\pi/m_\rho \approx 0.4 \;\; (m_{ud}/m_s \approx 0.2) \quad \text{or less ...}$$

  - PACS-CS @ CCS, Univ. of Tsukuba

    to be installed soon !! (July 1st, 2006)

    - cluster, 16x16x10=2560 nodes
    - 14.3 Tflops peak



By this simulation we hope that the ambiguity in the chiral extrapolation will be removed !

RHIC Physics in the Context of the Standard Model

June 18-23, 2006
Physics Department Large Seminar Room

Registered Participants

Name	Affiliation	E-Mail Address
Sinya Aoki	University of Tsukuba	saoki@het.ph.tsukuba.ac.jp
Yasumichi Aoki	University of Wuppertal	aoki@theorie.physik.uni-wuppertal.de
Anthony Baltz	BNL	baltz@bnl.gov
Jean-Paul Blaizot	ECT* & CNRS	blaizot@ect.it
Dietrich Bodeker	Bielefeld University	bodeker@physik.uni-bielefeld.de
Daniel Boer	Free University Amsterdam	D.Boer@few.vu.nl
Norman Christ	Columbia University	nhc@phys.columbia.edu
Michael Creutz	BNL	creutz@bnl.gov
Abhay Deshpande	SUNY, Stony Brook & RBRC	abhay@bnl.gov
Takumi Doi	RBRC	doi@quark.phy.bnl.gov
Hideto En'yo	RIKEN	enyo@riken.go.jp
Douglas Fields	RBRC & University of New Mexico	fields@unm.edu
Hirotsugu Fujii	University of Tokyo	hfujii@phys.c.u-tokyo.ac.jp
Kenji Fukushima	RBRC	fuky@quark.phy.bnl.gov
Yuji Goto	RIKEN & RBRC	goto@bnl.gov
Matthias Grosse Perdekamp	UIUC & RBRC	mgp@uiuc.edu
Steven Gubser	Princeton University	ssgubser@Princeton.EDU
Tetsuo Hatsuda	University of Tokyo	hatsuda@phys.s.u-tokyo.ac.jp
Yoshitaka Hatta	RBRC	hatta@quark.phy.bnl.gov
Tetsufumi Hirano	University of Tokyo	hirano@nt1.c.u-tokyo.ac.jp
John Huchra	Harvard University	huchra@cfa.harvard.edu
Tomomi Ishikawa	University of Tsukuba	tomomi@ccs.tsukuba.ac.jp
Kazunori Itakura	KEK	kazunori.itakura@kek.jp
Taku Izubuchi	Kanazawa University / RBRC	izubuchi@bnl.gov
Barbara Jacak	SUNY, Stony Brook	jacak@skipper.physics.sunysb.edu
Robert Jaffe	MIT	jaffe@mit.edu
Sangyong Jeon	McGill University	jeon@physics.mcgill.ca
Takaaki Kajita	University of Tokyo	kajita@icrr.u-tokyo.ac.jp
David Kawall	RBRC & University of Massachusetts	kawall@physics.umass.edu
Dmitri Kharzeev	BNL	kharzeev@bnl.gov
Alexander Kusenko	UCLA	kusenko@ucla.edu
William Marciano	BNL	marciano@bnl.gov
Melvin McKenzie Jr	C-AD, BNL	melnsel@optonline.net
Larry McLerran	BNL	mclerran@bnl.gov
Agnes Mocsy	RBRC	mocsy@bnl.gov
Itaru Nakagawa	RIKEN & RBRC	itaru@bnl.gov
Yasushi Nara	J.W. Goethe University	ynara@th.physik.uni-frankfurt.de
Junichi Noaki	University of Southampton	noaki@phys.soton.ac.uk
Shigemi Ohta	IPNS/KEK & RBRC	shigemi.ohta@kek.jp
Kostas Orginos	College of William and Mary	kostas@wm.edu
Peter Petreczky	BNL	petreczk@quark.phy.bnl.gov
Rob Pisarski	BNL	Pisarski@quark.phy.bnl.gov
Dirk Rischke	J.W. Goethe University	drischke@th.physik.uni-frankfurt.de
Naohito Saito	Kyoto University	saito@nh.scphys.kyoto-u.ac.jp

RHIC Physics in the Context of the Standard Model

June 18-23, 2006
Physics Department Large Seminar Room

Registered Participants

Name	Affiliation	E-Mail Address
Nicholas Samios	BNL	Samios@bnl.gov
Shoichi Sasaki	RBRC	ssasaki@bnl.gov
Thomas Schaefer	North Carolina State University	thomas_schaefer@ncsu.edu
Jurgen Schaffner -Bielich	University of Frankfurt	schaffner@astro.uni-frankfurt.de
Dam Son	Institute for Nuclear Theory	son@phys.washington.edu
Misha Stephanov	UIC	misha@uic.edu
Larry Trueman	BNL	trueman@bnl.gov
Kirill Tuchin	Iowa State University & RBRC	tuchin@iastate.edu
Raju Venugopalan	BNL	raju@bnl.gov
Werner Vogelsang	BNL	wvogelsang@bnl.gov
Matthew Wingate	University of Washington	wingate@phys.washington.edu
Wei Xie	BNL	Xiewei@bnl.gov
Hiroshi Yokoya	Niigata University	yokoya@nt.sc.niigata-u.ac.jp
Feng Yuan	RBRC	fyuan@quark.phy.bnl.gov

RHIC Physics in the Context of the Standard Model: A Workshop and Symposium

Physics Department Large Seminar Room
June 18-23, 2006

Organizers:

Abhay Deshpande (SUNY, Stony Brook & RBRC)
[RIKEN BNL Fellow 2/2000 to 12/2003; RHIC Physics Fellow 1/2004 to present]

Dmitri Kharzeev (BNL)
[RIKEN BNL Fellow 08/1997 to 9/1999; RHIC Physics Fellow 10/1999 to 3/2000]

Raju Venugopalan (BNL)
[RHIC Physics Fellow 10/2000 to 6/2003]

Werner Vogelsang (BNL)
[RIKEN BNL Fellow 4/2000 to 9/2003; RHIC Physics Fellow 10/2003 to 3/2006]

Sun, June 18 **Welcome Reception**, Brookhaven Center South Room and Patio (6:00 – 7:30 pm)

Mon, June 19 **Workshop on Heavy Ion Physics**

[Session Chair: Anthony Baltz, BNL]

08:30 – 09:00 Registration
09:00 – 09:15 Welcome & Introduction (Nick Samios, Director, RBRC)
09:15 – 10:00 Experimental Overview (Matthias Perdekamp, U of IL at Urbana Champaign & RBRC)
[RIKEN BNL Fellow 1/1999 to 8/2002; RHIC Physics Fellow 9/2002 to present]
10:00 – 10:30 Ideal Hydrodynamics (Tetsufumi Hirano, University of Tokyo)
[Research Associate 3/2003 to 8/2004; Visiting Scientist 9/2004 to present]

10:30-11:00 **Coffee Break**

11:00 – 11:30 Color Glass Condensate (Kazunori Itakura, KEK)
[Research Associate 6/2002 to 5/2003]
11:30 – 12:00 Quarkonia I (Hiro Fujii, University of Tokyo)
[Research Associate 9/1997 to 9/1999]

12:00 – 2:00 **Lunch Break**

[Session Chair: Yasuyuki Akiba, RIKEN & RBRC]

02:00 – 02:30 Quarkonia II (Kirill Tuchin, Iowa State University & RBRC)
[RHIC Physics Fellow 9/2005 to present]
02:30 – 03:00 Strangeness (Jurgen Schaffner-Bielich, University of Frankfurt)
[Research Associate 9/1998 to 10/2001]
03:00 – 03:30 Charge Fluctuations (Sangyong Jeon, McGill University)
[RHIC Physics Fellow 1/2001 to 12/2005]

03:30 – 04:00 **Coffee Break**

04:00 – 04:30 Numerical Studies of Thermalization (Yasushi Nara, University of Frankfurt)
[Research Associate, 10/1999 to 9/2002]
04:30 – 05:00 Electric Dipole Moment Searches in Nuclei, Atoms, and Molecules
(David Kawall, U of MA & RBRC)
[RIKEN BNL Fellow 6/2004 to 1/2005; RHIC Physics Fellow 1/2005 to present]

Tues, June 20	**RBRC Symposium**
	[Session Chair: Hideto En'yo, RIKEN & RBRC]
09:00 - 09:15	Opening Remarks (Nick Samios, Director, RBRC)
09:15 - 10:00	RHIC HI Theory (Dima Kharzeev, BNL) [RIKEN BNL Fellow 8/1997 to 9/1999; RHIC Physics Fellow 10/1999 to 3/2000]
10:00 - 10:45	RHIC HI Experiment (Barbara Jacak, SUNY, Stony Brook)
10:45 - 11:00	**Coffee Break**
11:00 - 11:45	Spin: Some Answers, Many Questions (Robert Jaffe, MIT)
11:45 - 12:30	RHIC Spin Experiment (Naohito Saito, Kyoto University) [RIKEN Special Postdoc Fellow 4/1995 to 3/1996; RIKEN/RBRC Researcher 4/1996 to 3/2001; RIKEN Spin Program Researcher 4/2001 to 3/2002; RSP Visiting Scientist 3/2002 to present]
12:30 - 2:00	**Lunch Break**
	[Session Chair: Larry Trueman, BNL]
02:00 - 02:45	Past, Present & Future of Lattice Gauge Theory (Norman Christ, Columbia University)
02:45 - 03:30	Chiral Symmetry Restoration and In-Medium Hadron Properties (Dirk Rischke, U of Frankfurt) [RIKEN BNL Fellow 9/1997 to 9/2000; RHIC Physics Fellow 10/2000 to 1/2001]
03:30 - 04:00	**Coffee Break**
04:00 - 05:00	The State of the Universe (John Huchra, Harvard University)

Wed, June 21	**RBRC Symposium**
	[Session Chair: Michael Creutz, BNL]
09:00 - 09:10	Introduction (Sam Aronson, Interim Director, BNL)
09:10 - 09:55	Electroweak Physics (Bill Marciano, BNL)
09:55 - 10:40	Neutrino Experiments (Takaaki Kajita, University of Tokyo)
10:40 - 11:00	**Coffee Break**
11:00 - 11:45	Using AdS/CFT to explore the Strong Coupling Regime of Gauge Theories: I (Steve Gubser, Princeton University)
11:45 - 12:30	Using AdS/CFT to explore the Strong Coupling Regime of Gauge Theories: II (Dam Son, INT, University of WA) [RHIC Physics Fellow 10/1999 to 3/2002]
12:30 - 02:00	**Lunch Break**
	[Session Chair: Rob Pisarski, BNL]
02:00 - 02:45	QCD Thermodynamics I (Jean-Paul Blaizot, ECT* and CNRS)
02:45 - 03:30	QCD Thermodynamics II (Dietrich Bodeker, Bielefeld University) [RHIC Physics Fellow 12/2000 to 12/2001]
03:30 - 04:00	**Coffee Break**
04:00 - 04:45	Phase Structure of QCD at Finite T and mu (Misha Stephanov, University of IL, Chicago) [RHIC Physics Fellow 10/1999 to 9/2004]
04:45 - 05:30	Static and Dynamic Correlations in Hot QCD (Tetsuo Hatsuda, University of Tokyo)
07:00 - 10:00	**Symposium Banquet**, Veranda Room at the Inn at East Wind in Wading River

Thurs, June 22 **RBRC Symposium**

[Session Chair: Shigemi Ohta, KEK and RBRC]

09:00 - 09:45 Ultrahigh Energy Cosmic Rays (Alex Kusenko, UCLA)
[RHIC Physics Fellow 10/1999 to 9/2004]

09:45 - 10:30 Non-Perturbative Methods in QCD at finite T and mu (Thomas Schaefer, NC State University)
[RHIC Physics Fellow 1/2000 to 12/2002 and 1/2003 to 12/2004]

10:30 - 11:00 Coffee Break

11:00 - 11:45 Light Quarks on the Lattice (Sinya Aoki, University of Tsukuba)
[RHIC Physics Fellow 4/2004 to present]

11:45 - 12:30 Semileptonic Decays on the Lattice (Shoichi Sasaki, University of Tokyo & RBRC)
[Research Associate 9/1998 to 9/2000; RIKEN BNL Fellow 10/2004 to present]

12:30 - 02:00 Lunch Break

FREE AFTERNOON FOR DISCUSSIONS

Fri, June 23	**Workshop on Spin & Lattice**
	[Session Chair: Gerry Bunce, BNL]
09:00 – 09:45	QCD Spin Physics - A Theoretical Overview (Daniel Boer, Free University, Amsterdam) [Research Associate 10/1998 to 6/2001]
09:45 – 10:30	Experimental Overview (Doug Fields, University of NM & RBRC) [RHIC Physics Fellow 9/2001 to present]
10:30 – 11:00	Parity Odd Asymmetries (Hiroshi Yokoya, Niigata University) [RSP Young Researcher 4/2003 to 3/2005]
11:00 – 11:30	**Coffee Break**
11:30 – 12:00	Structure Functions on the Lattice (Kostas Orginos, College of William and Mary) [Research Associate 10/2000 to 8/2003]
12:00 – 12:30	Weak Matrix Elements (Taku Izubuchi, Kanazawa Univeristy & RBRC) [RHIC Physics Fellow 4/2003 to present]
12:30 – 02:00	**Lunch Break**
	[Session Chair: Peter Petreczky, BNL & RBRC]
02:00 – 02:30	Cold Atoms on the Lattice (Matt Wingate, University of WA) [Research Associate 9/1997 to 9/2000]
02:30 – 03:00	Lattice Thermodynamics (Yasumichi Aoki, University of Wuppertal) [Research Associate 5/2000 to 4/2003; Visiting Scientist 4/2003 to 7/2003]
03:00 – 03:30	Kaon Physics in Full Domain-Wall QCD (Junichi Noaki, University of Southampton) [Research Associate 7/2001 to 6/2004]
3:30 – 4:00	**Coffee Break**
04:00 – 04:30	Dynamical Wilson Fermions (Tomomi Ishikawa, University of Tsukuba)
04:30 – 04:45	Concluding Remarks (Larry McLerran, BNL & RBRC)

Additional RIKEN BNL Research Center Proceedings:

Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-

Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL-75692-2006

Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-

Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, December 12-14, 2005 – BNL-

Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649-2005

Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005

Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005

Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005

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

Additional RIKEN BNL Research Center Proceedings:

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
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 –

Additional RIKEN BNL Research Center Proceedings:

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

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

For information please contact:

Ms. Pamela Esposito
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

Phone: (631) 344-3097
Fax: (631) 344-4067
E-Mail: pesposit@bnl.gov

Ms. Jane Lysik
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

(631) 344-5864
(631) 344-2562
lysik@bnl.gov

Homepage: http://www.bnl.gov/riken

RIKEN BNL RESEARCH CENTER

RHIC Physics in the Context of the Standard Model

June 18-23, 2006

Li Keran

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

Copyright©CCASTA

Speakers:

Sinya Aoki	Ysumichi Aoki	Jean-Paul Blaizot	Detrich Bodeker	Daniel Boer
Norman Christ	Douglas Fields	Hirotsugu Fujii	Matthias Grosse Perdekamp	Steven Gubser
Tetsuo Hatsuda	Tetsufumi Hirano	John Huchra	Tomomi Ishikawa	Kazunori Itakura
Taku Izubuchi	Barbara Jacak	Robert Jaffe	Sangyong Jeon	Takaaki Kajita
David Kawall	Dmitri Kharzeev	Alexander Kusenko	William Marciano	Yasushi Nara
Junichi Noaki	Kostas Orginos	Dirk Rischke	Naohito Saito	Shoichi Sasaki
Thomas Schaefer	Jurgen Schaffner –Bielich	Dam Son	Misha Stephanov	Kirill Tuchin
Matthew Wingate	Hiroshi Yokoya			

Organizers: Abhay Deshpande, Dmitri Kharzeev, Raju Venugopalan and Werner Vogelsang