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Formal Report

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Fluctuations, Correlations and RHIC Low Energy Runs

October 3-5, 2011

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. 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 and the RBRC Experimental Group consists of a total of 25-30 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 ~100 graduates of which 27 theorists and 14 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. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are one hundred and five 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. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. The next generation computer in this sequence, QCDCQ (400 Teraflops), will become operational in the winter of 2011.

N. P. Samios, Director
October 2011

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CONTENTS

Preface to the Series

Introduction i

Study QCD Phase Structure in STAR Experiment
N. Xu 1

PHENIX Overview
J. Mitchell 7

Non-Gaussian Fluctuations at the QCD Critical Point
M. Stephanov 13

Cumulants of Conserved Charges and QCD Phase Structure
M. Asakawa 19

Revealing Baryon Number Fluctuations in Heavy Ion Collisions
M. Kitazawa 25

Charge Fluctuations in Effective Chiral Models
V. Skokov 31

Three Quarks for Muster Mark--- Lessons Learned from Susceptibilities
J. Liao 37

Fluctuations of Conserved Charges within Dynamic Models of Heavy-ion Collisions
M. Nahrgang 43

Lattice Calculation of QCD Critical Point with the Canonical Ensemble
K-F. Liu 49

Study of QCD Phase Transition at Finite Density by a Histogram Method
S. Ejiri 55

The Cumulants of Net-proton Multiplicity Distribution at RHIC
L. Chen 61

Recent Results on Correlations and Fluctuations from the Wuppertal-Budapest Lattice QCD Collaboration
C. Ratti 67

Fluctuations and Correlations: Lattice QCD vs. HRG
P. Hegde 73

Finite Size Scaling on the Phase Diagram of QCD
S. Gupta 79

Higher Moments of Hadronic Fluctuations and QCD Critical Behavior from Lattice Simulations
C. Schmidt 85

Probability Distributions of Conserved Charges and the QCD Phase Transition
K. Redlich 91

Flow at Low Energies (PHENIX)
Y. Gu 97

Flow at Lower RHIC Energies
P. Sorensen 103

The Freeze-out Source Shape: Recent Results from the STAR Energy Scan
M. Lisa 109

J/Psi Results from PHENIX
A. Sen 115

Status of Fluctuation Studies in NA49 at CERN SPS Energies
P. Seyboth 121

Current Results for Dynamical K/pi, p/pi, and K/p Fluctuations from the STAR Experiment
T. Tarnowsky 127

More or Less a Summary
V. Koch 133

List of Registered Participants 139

Agenda 141

Additional RIKEN BNL Research Center Proceeding Volumes 143

Contact Information

Introduction

Most of our visible universe is made up of hadronic matter. Quantum Chromodynamics (QCD) is the theory of strong interaction that describes the hadronic matter. However, QCD predicts that at high enough temperatures and/or densities ordinary hadronic matter ceases to exist and a new form of matter is created, the so-called Quark Gluon Plasma (QGP). Non-perturbative lattice QCD simulations shows that for high temperature and small densities the transition from the hadronic to the QCD matter is not an actual phase transition, rather it takes place via a rapid crossover. On the other hand, it is generally believed that at zero temperature and high densities such a transition is an actual first order phase transition. Thus, in the temperature-density phase diagram of QCD, the first order phase transition line emanating from the zero temperature high density region ends at some higher temperature where the transition becomes a crossover. The point at which the first order transition line turns into a crossover is a second order phase transition point belonging to three dimensional Ising universality class. This point is known as the QCD Critical End Point (CEP).

For the last couple of years the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been performing experiments at lower energies in search of the elusive QCD CEP. In general critical behaviors are manifested through appearance of long range correlations and increasing fluctuations associated with the presence of mass-less modes in the vicinity of a second order phase transition. Experimental signatures of the CEP are likely to be found in observables related to fluctuations and correlations. Thus, one of the major focuses of the RHIC low energy scan program is to measure various experimental observables connected to fluctuations and correlations. On the other hand, with the start of the RHIC low energy scan program, a flurry of activities are taking place to provide solid theoretical background for the search of the CEP using observables related to fluctuations and correlations. While new data are pouring in from the RHIC low energy scan program, many recent advances have also been made in the phenomenological and lattice gauge theory sides in order to have a better theoretical understanding of the wealth of new data.

This workshop tried to create a synergy between the experimental, phenomenological and lattice QCD aspects of the fluctuation and correlation related studies of the RHIC low energy scan program. The workshop brought together all the leading experts from related fields under the same forum to share new ideas among themselves in order to streamline the continuing search of CEP in the RHIC low energy scan program.

Study QCD Phase Structure in STAR Experiment

Nu Xu

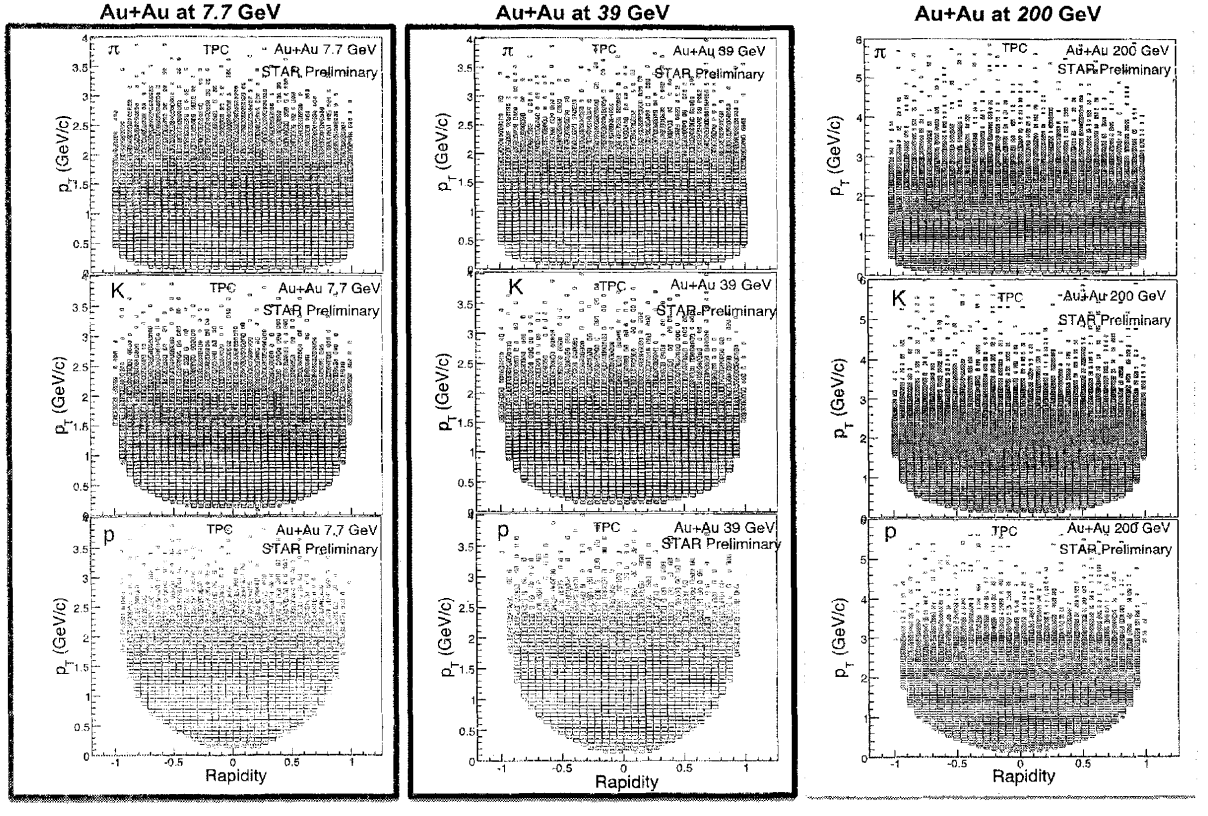
(1) *Nuclear Science Division, Lawrence Berkeley National Laboratory, USA*

(2) *College of Physical Science & Technology, Central China Normal University, China*

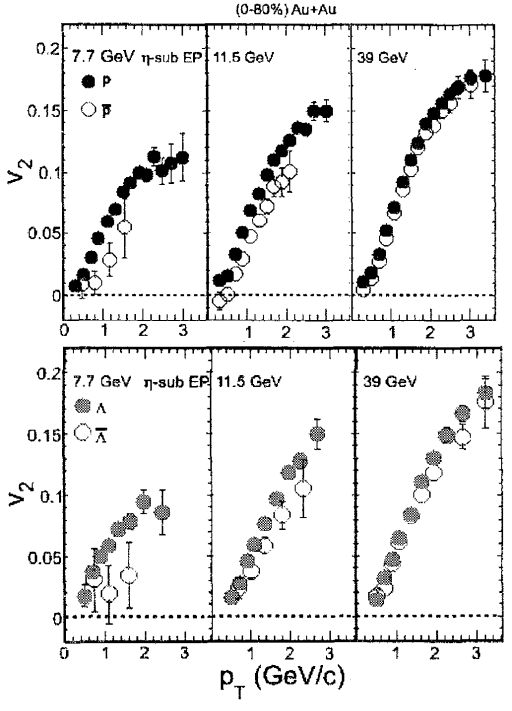
Outline:

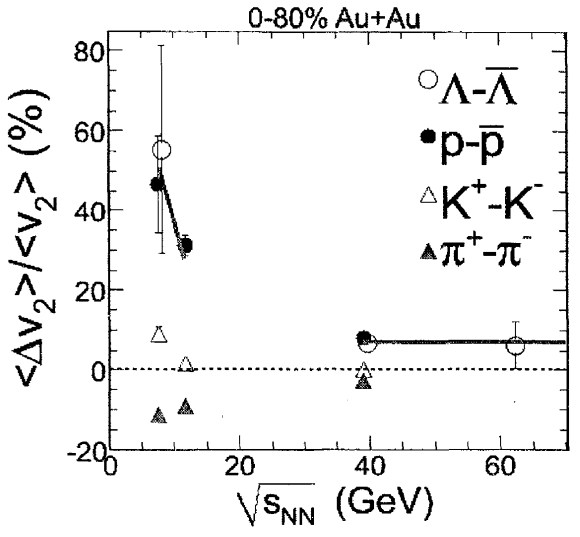
1) Introduction
   - Physics programs at STAR
2) RHIC Beam Energy Scan
   - Status at STAR
3) Summary

STAR PID: 7.7, 39, 200 GeV ($\pi^{\pm}$, $K^{\pm}$, p)



(anti-)Particle v_2 vs. $\sqrt{s_{NN}}$





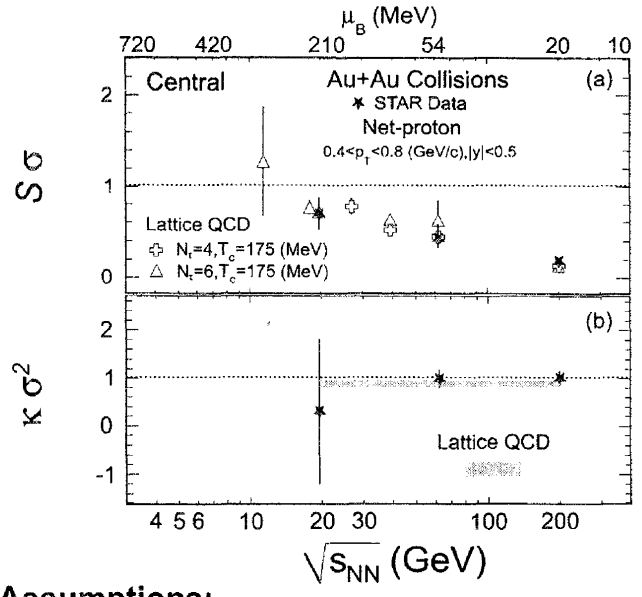
At $\sqrt{s_{NN}} \leq 11.5$ GeV:

- v_2(baryon) > v_2(anti-baryon)
- v_2(π^+) < v_2(π^-)
- v_2(K^-) < v_2(K^+)

STAR: Quark Matter 2011

Hadronic interactions appear dominant

Comparing with LGT Results



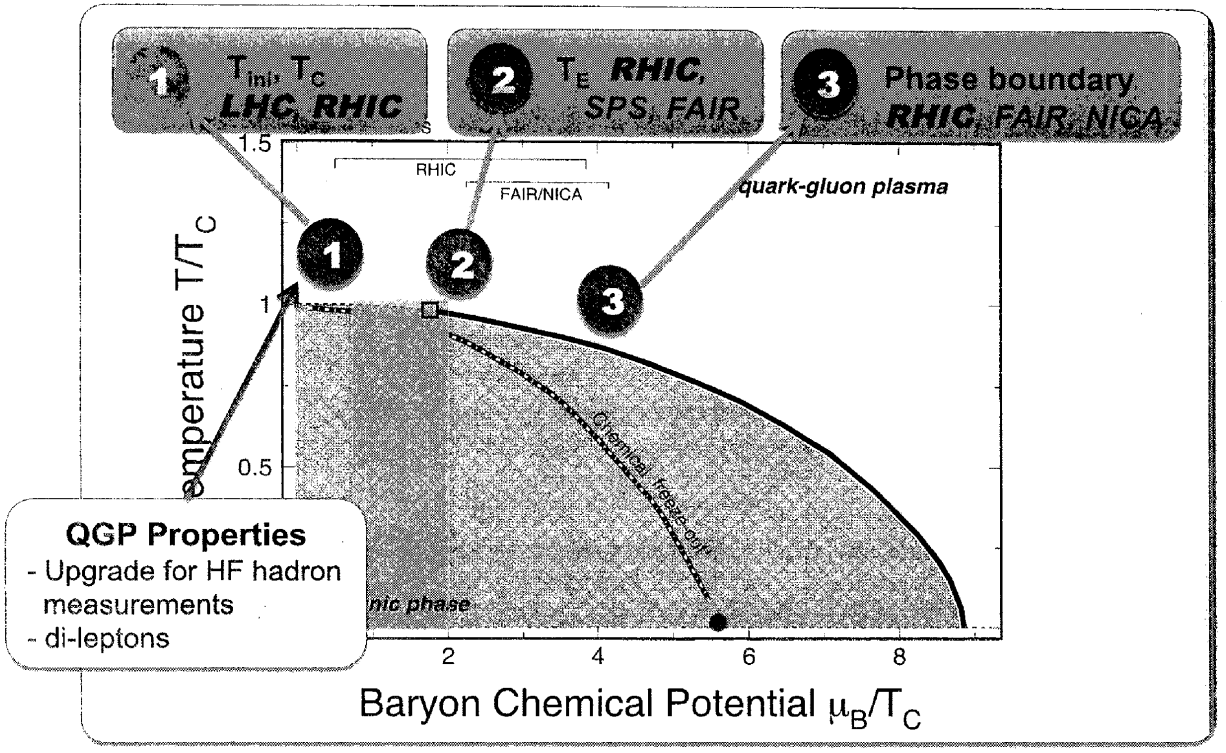
References:
- STAR, *PRL105, 22303(10)*
- R.V. Gavai and S. Gupta: *PLB696, 459(11)*

Assumptions:

(a) Freeze-out temperature is close to LGT T_C
(b) Thermal equilibrium reached in central collisions
(c) Taylor expansions, at $\mu_B \neq 0$, on LGT results are valid

➔ Lattice results are consistent with data for 60 < $\sqrt{s_{NN}}$ < 200 GeV

RHIC: (7.7, 11.5, 15.5, 19.6, 27, 39,62, 200 GeV)



QGP Properties
- Upgrade for HF hadron measurements
- di-leptons

Summary

(1) In collisions at RHIC top energy, hot and dense ***matter, with partonic degrees of*** **freedom and collectivity, has been formed**

(2) RHIC BES: Preliminary results indicate

$\mu_B < 110$ *(MeV):* **partonic interactions dominant**

$\mu_B > 320$ (MeV): **hadronic interactions dominant**

(3) Near future physics program:

- BES: 'Comb' the QCD phase diagram;
  Complete analysis for 7.7/11.5/**15.5**(?)/19.6/27/39 GeV and 200 GeV, e.g. C_6, C_8, …;
- Heavy flavor, di-lepton: study QGP properties

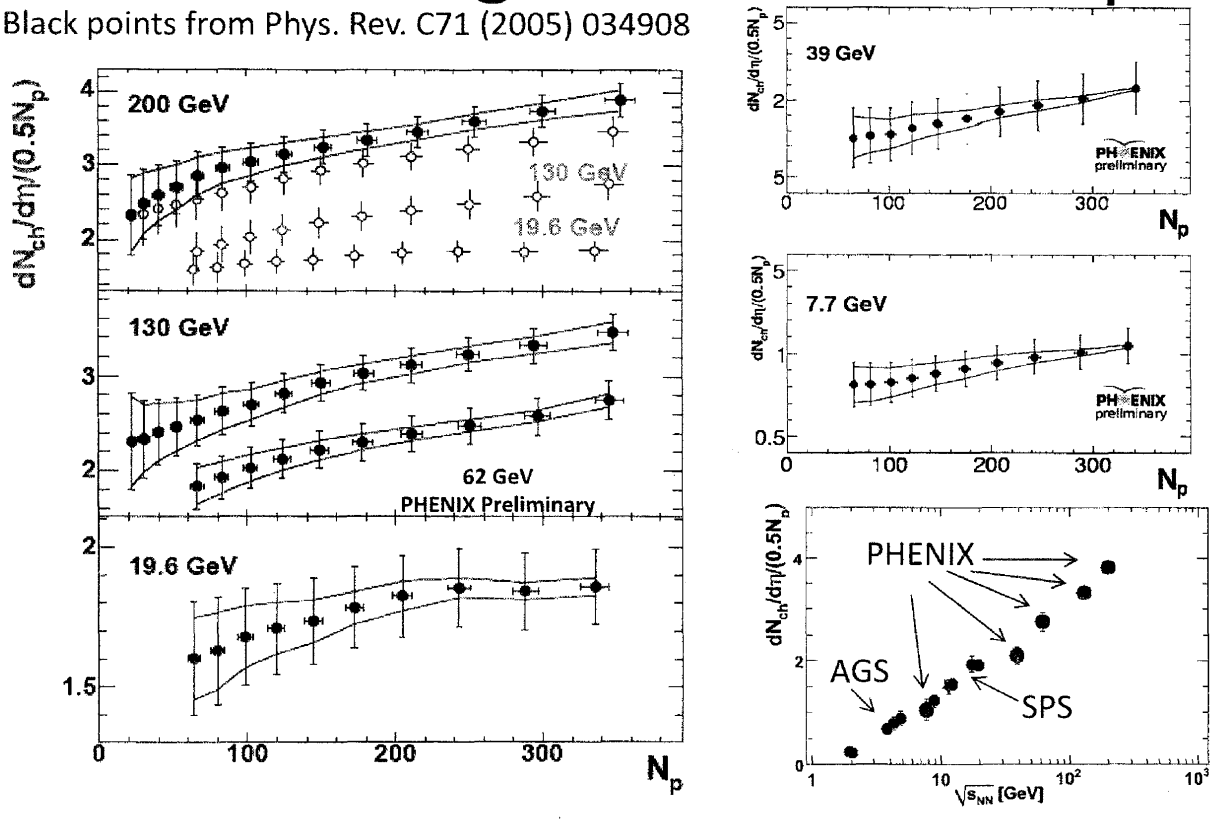
An Overview of PHENIX Low Energy Results

Jeffery T. Mitchell (Brookhaven National Laboratory) for the PHENIX Collaboration

Summary: The Relativistic Heavy Ion Collider (RHIC) has initiated a program to probe the QCD phase diagram in the vicinity of a possible critical point with a beam energy scan. During 2010, RHIC provided Au+Au collisions to PHENIX at sqrt(s_{NN}) 200 GeV, 62.4 GeV, 39 GeV, and 7.7 GeV. Measurements of $dN/d\eta$ per participant pair show a linear dependence on log(sqrt(s_{NN})). The R_{AA} of the π^0 shows suppression in central collisions in 62.4 and 39 GeV collisions. A significant suppression of the J/Ψ is also observed in 62.4 and 39 GeV collsions. However, there is no significant suppression of the f meson in 62.4 GeV collisions. Measurements of v_2, v_3, and v_4 show a saturation of the values of all 3 variables above 39 GeV. The value of v_2 in 7.7 GeV collisions is below that in 39 GeV collisions. Consitituent quark number scaling of identified particle v_2 still holds in 62.4 and 39 GeV collisions. Many more PHENIX results from the RHIC beam energy scan program will be available soon.

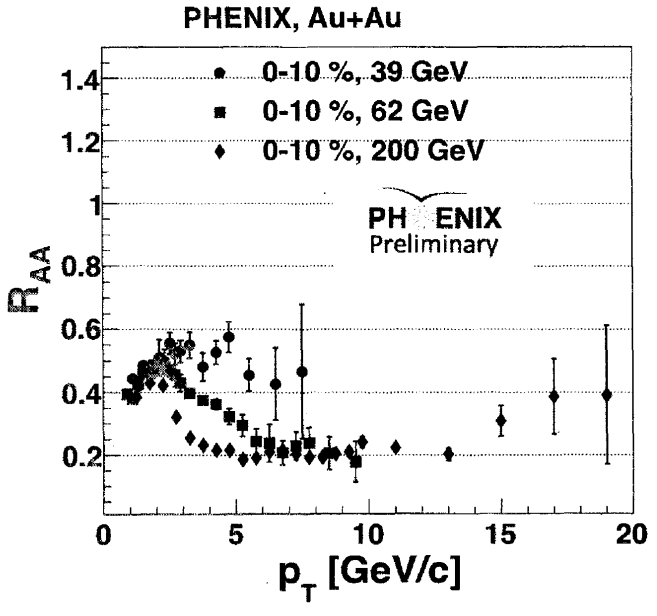
Au+Au Charged Particle Multiplicity

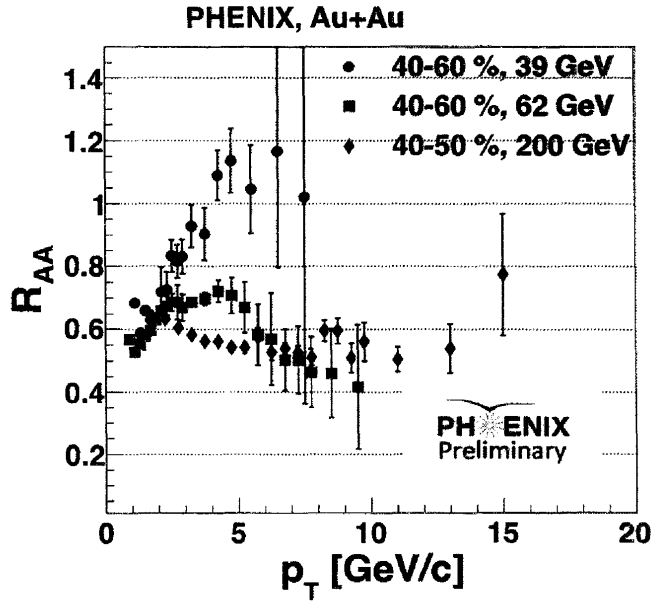
Black points from Phys. Rev. C71 (2005) 034908



Error bars represent the systematic errors. The lines represent the "tilt" error due to the uncertainty in the trigger cross section. The multiplicity per participant pair increases linear with log(sqrt(s_{NN})).

π^0 R_{AA} in Au+Au at 39 and 62 GeV



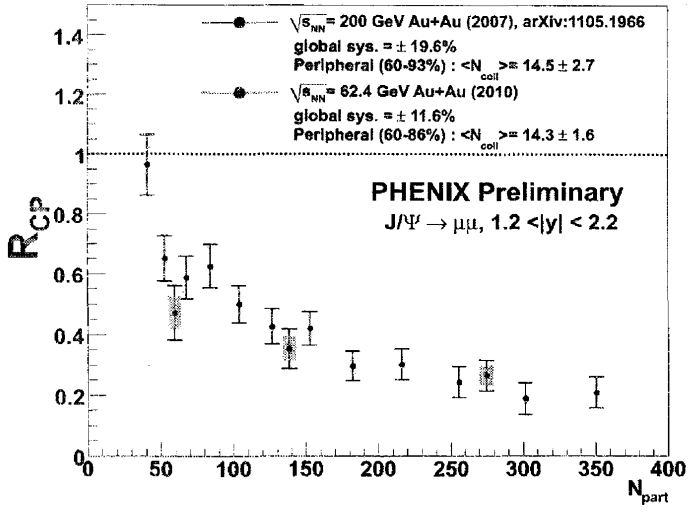


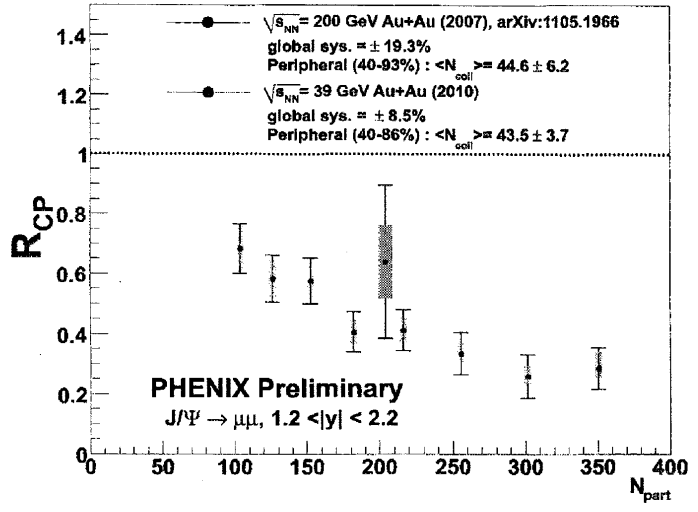
π^0 R_{AA} as a function of p_T in PHENIX at $\sqrt{s_{NN}}$ = **39, 62** and **200** GeV.

- Still observe a strong suppression (factor of 2) in the most central $\sqrt{s_{NN}}$ = 39 GeV collisions.
- R_{AA} from $\sqrt{s_{NN}}$ = 62 GeV data is comparable with the R_{AA} from $\sqrt{s_{NN}}$ = 200 GeV for p_T 6 >GeV/c.
- Peripheral $\sqrt{s_{NN}}$ = 62 and 200 GeV data show suppression, but the $\sqrt{s_{NN}}$ = 39 GeV does not.

Energy dependence of J/ψ R_{CP}

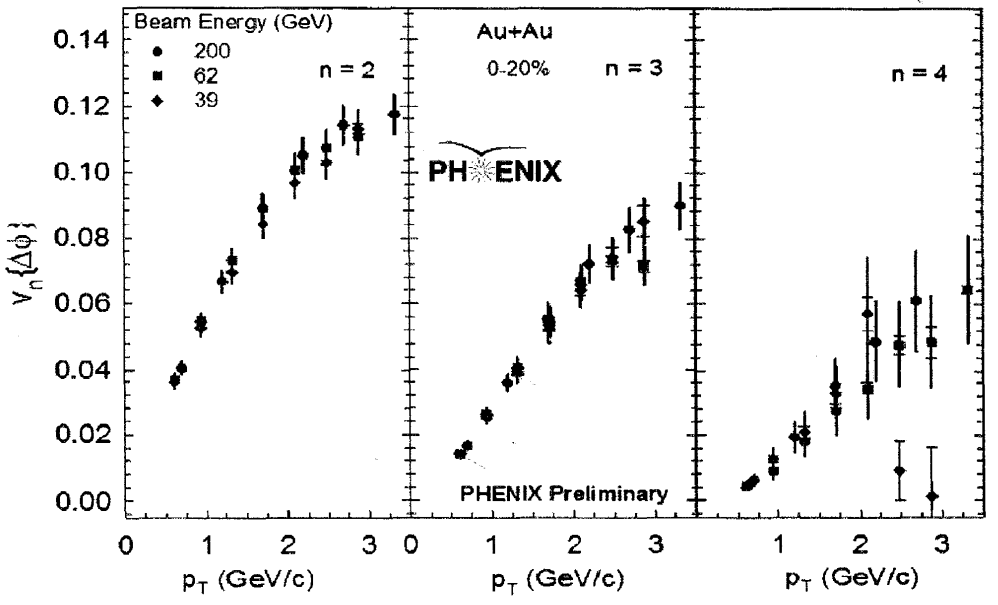
Rapidity 1.2 <|y| <2.2

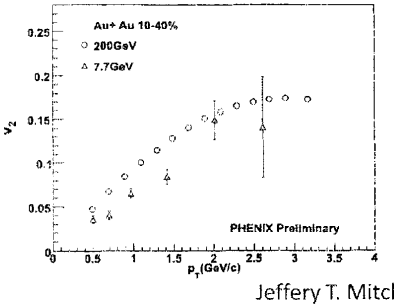




- PHENIX does not yet have a p+p reference at 62 and 39 GeV.
- Lacking a reference, R_{CP} can still give us insight about the suppression level.
- The suppression is at a similar level at all energies.

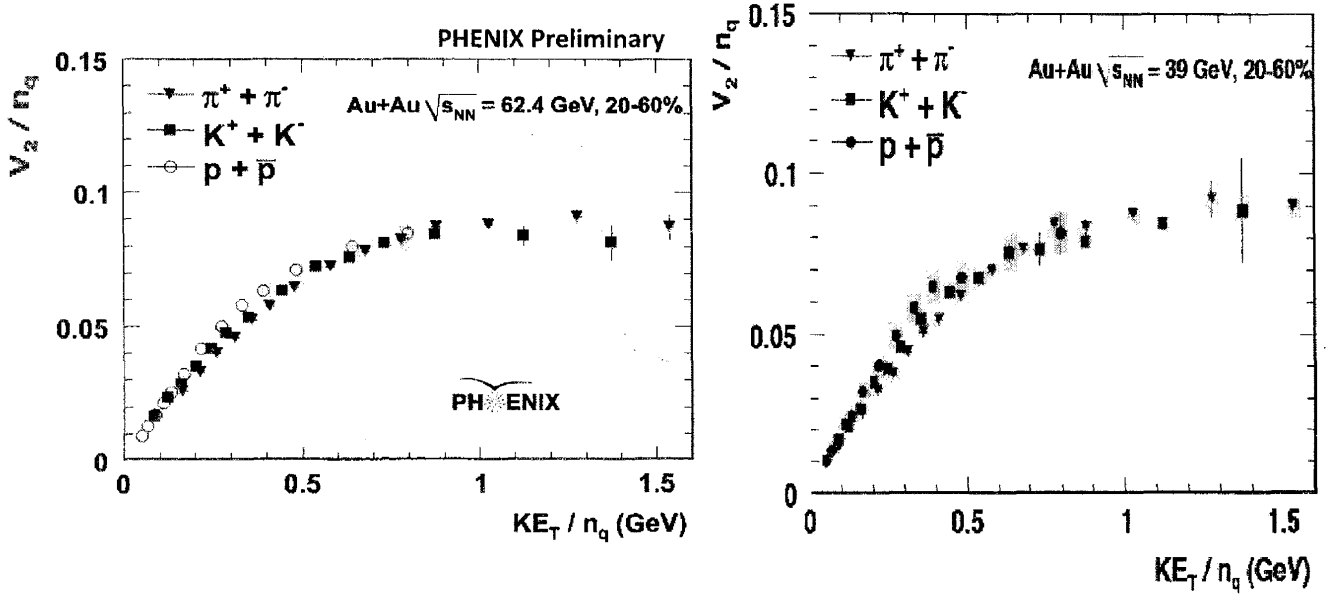
v_2, v_3, v_4 as a function of $\sqrt{s_{NN}}$





v_2, v_3, v_4 are independent of $\sqrt{s_{NN}}$ for 39, 62.4, 200 GeV. v2 at 7.7 GeV is lower in magnitude.

Identified hadron v_2 in 62.4 and 39 GeV Au+Au Collisions



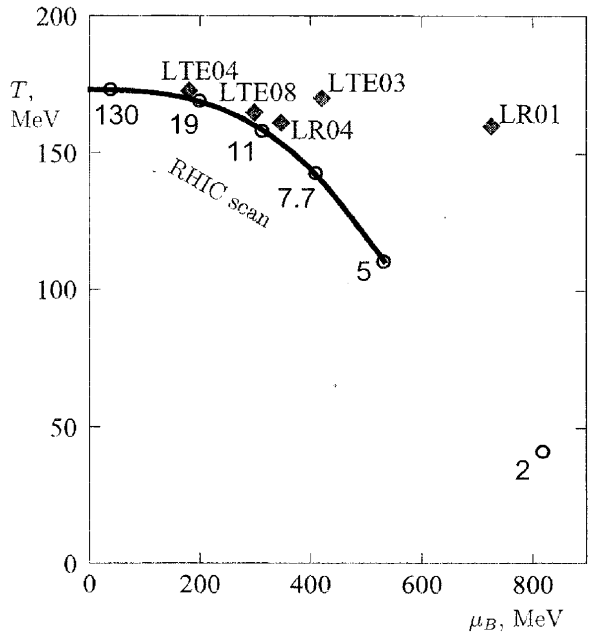
Partonic collective flow is observed down to 62 GeV and 39 GeV.

Non-gaussian fluctuations at the QCD critical point

M. Stephanov

U. of Illinois at Chicago

What do we need to discover the critical point?



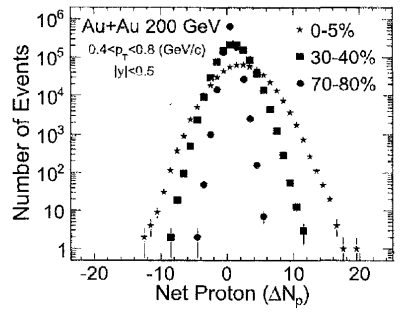
- Key: scan phase diagram by changing collision energy. Experiments: RHIC, NA61(SHINE), FAIR/GSI, NICA
- Reliable lattice predictions, understanding of systematic errors (tackle "sign problem").
- Find experimental signatures most sensitive to the critical point.

Fluctuation signatures

- Experiments measure multiplicities N_π, N_p, ..., mean p_T, etc.

  These quantities fluctuate event-by-event.

  - Fluctuation magnitude is quantified by e.g., $\langle(\delta N)^2\rangle$,$\langle(\delta p_T)^2\rangle$.



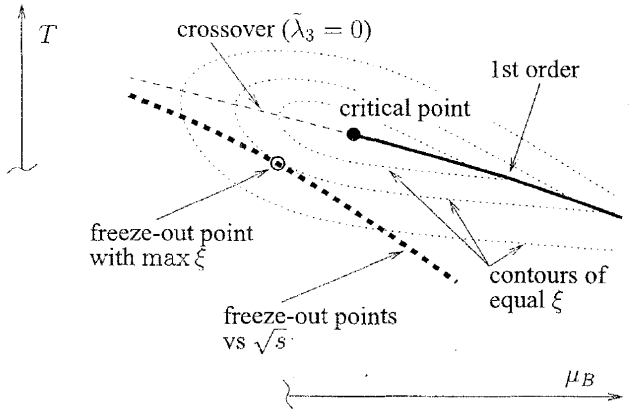
- What is the magnitude of these fluctuations near the QCD C.P.? (Rajagopal-Shuryak-MS, 1998)
- Universality tells us how it grows at the critical point: $\langle(\delta N)^2\rangle \sim \xi^2$.
- Magnitude of ξ is limited $< \mathcal{O}$(2–3 fm) (Berdnikov-Rajagopal).

- "Shape" of the fluctuations can be measured: non-Gaussian moments. As $\xi \to \infty$ fluctuations become less Gaussian.
- Higher cumulants show even stronger dependence on ξ (PRL 102:032301,2009):

$$\langle(\delta N)^3\rangle \sim \xi^{4.5}, \qquad \langle(\delta N)^4\rangle - 3\langle(\delta N)^2\rangle^2 \sim \xi^7$$

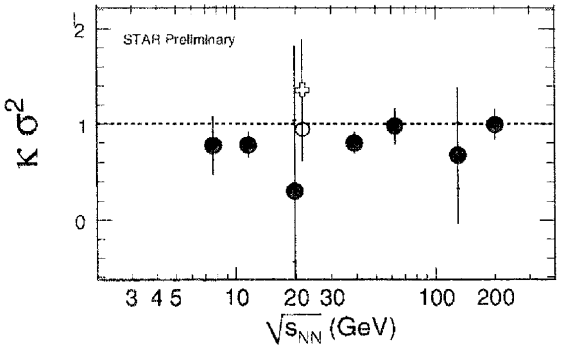
which makes them more sensitive signatures of the critical point.

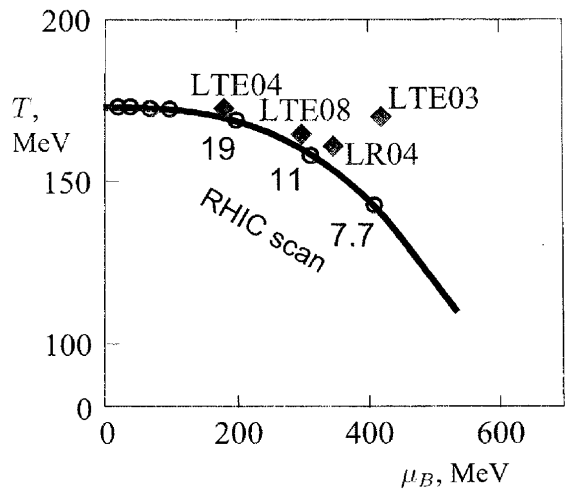
Energy scan and fluctuation signatures: notes



- Higher moments provide more sensitive signatures.
- As usual, there is a price:
  - Harder to predict – more theoretical uncertainties.
  - Signal/noise is worse for higher moments.
- But there is more information in higher moments and one can, e.g., combine various higher moments to optimize or eliminate uncertainties.
  Athanasiou, Rajagopal, MS (2010)

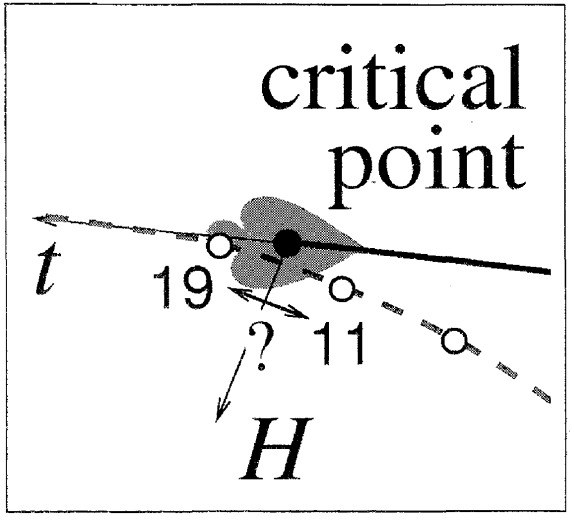
Early data from RHIC energy scan

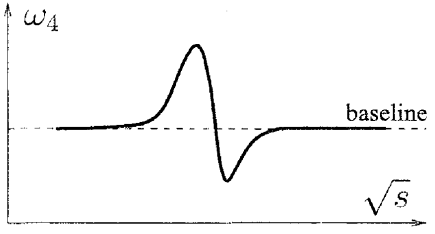




- On the crossover side, for $\sqrt{s} = 19$ GeV: $\omega_{4p} - 1 \approx -\mathcal{O}(1)$ at $\xi \approx 1.5$ fm.

A scenario





- If the kurtosis stays significantly below Poisson value in 19 GeV data, the logical place to take a closer look is between 19 and 11 GeV.

Cumulants of Conserved Charges and QCD Phase Structure

Masayuki Asakawa

Department of Physics, Osaka University

We discuss the effects of the critical end point in QCD on experimental observables, the significance of odd power cumulants of conserved charges in the diagnosis of the system created in high energy heavy ion collisions, and the relation between net baryon number cumulants and net proton number cumulants.

October 2011

@ Fluctuations, Correlations and RHIC Low Energy Runs

Odd Power Fluctuation Moments

- Fluctuation of Conserved Charges: not subject to final state interactions
  - Usually even power fluctuations such as $\langle (\delta Q)^2 \rangle$ have been considered

One of exceptions: Stephanov (2008) in conjunction with CEP

  - Usual Fluctuations such as $\langle (\delta Q)^2 \rangle$: positive definite

$\Longrightarrow$ Absolute values carry information of states (D-measure)

Asakawa, Heinz, Müller, Jeon, Koch

On the other hand,

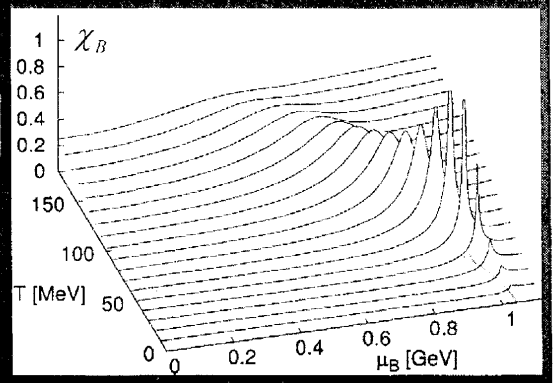
✓ Odd power fluctuations : NOT positive definite

- In general, do not vanish (exception, $\langle \delta A \rangle$)
- *Sign also carry information of states*

Physical Meaning of 3rd Fluc. Moment

χ_B : Baryon number susceptibility

in general, has a peak along phase transition



$\Rightarrow$ $\dfrac{\partial \chi_B}{\partial \mu_B}$ changes the sign at QCD phase boundary !

- In the Language of fluctuation moments:

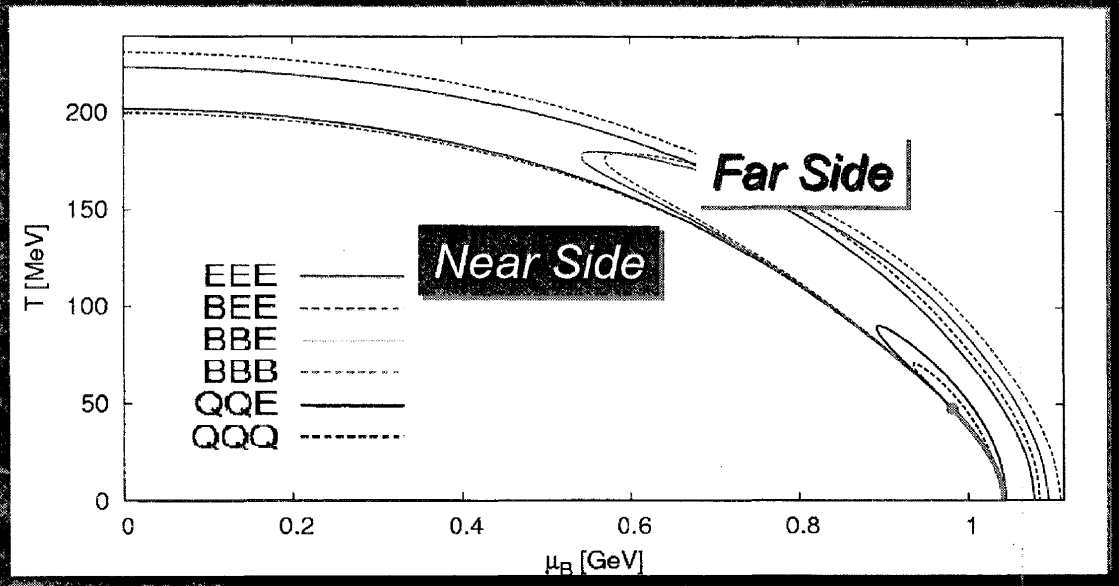
$$\chi_B = -\frac{1}{V}\frac{\partial^2 \Omega}{\partial \mu_B^2} = \frac{\langle (\delta N_B)^2 \rangle}{VT}$$

$$\frac{\partial \chi_B}{\partial \mu_B} = -\frac{1}{V}\frac{\partial^3 \Omega}{\partial \mu_B^3} = \frac{\langle (\delta N_B)^3 \rangle}{VT^2} \equiv m_3(\mathrm{BBB})$$

more information than usual fluctuation

M. Asakawa (Osaka University)

Comparison of Various Moments



2-flavor NJL with standard parameters

G=5.5GeV^{-2}
m_q=5.5MeV
Λ=631MeV

- Different moments have different regions with negative moments

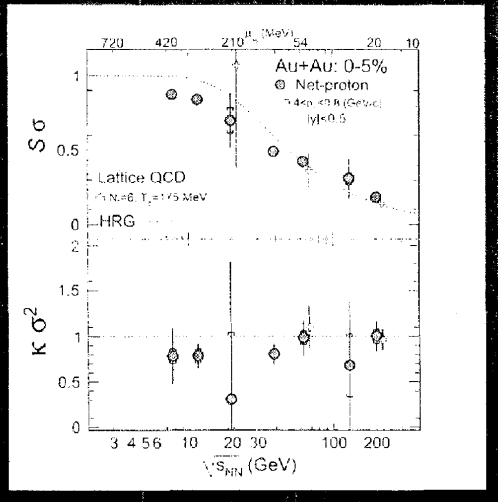
⇨ By comparing the signs of various moments, possible to pin down the origin of moments

- Negative m_3(EEE) region extends to T-axis (in this particular model)
- Sign of m_3(EEE) may be used to estimate heat conductivity

M. Asakawa (Osaka University)

Recent Progress: Proton Cumulants

- Proton Fluctuation has been attracting a lot of interest because it can be observed experimentally
- Proton Fluctuation diverges at CEP Hatta and Stephanov, 2003
- Comparisons of experimental results and lattice predictions have been done (e.g. Gupta et al., Science 2011)



$$\chi_B^{(n)}\left(\frac{T}{T_c},\frac{\mu_B}{T}\right)=\frac{1}{T^n}\frac{\partial^n}{\partial(\mu_B/T)^n}P\left(\frac{T}{T_c},\frac{\mu_B}{T}\right)\Bigg|_{T/T_c}$$

$$S\sigma=\frac{T\chi_B^{(3)}}{\chi_B^{(2)}}$$

$$\kappa\sigma^2=\frac{T^2\chi_B^{(4)}}{\chi_B^{(2)}}$$

STAR, QM2011

Experiment: Net Proton
Theory: Net Baryon

Is this legitimate?

Kitazawa's Talk

M. Asakawa (Osaka University)

Summary

- Final State Interaction and Critical Slowing Down

  ➡ Usual observables
  such as large fluctuation, critical opalescence, ...etc. do not work

- Conserved Charges and Higher Moments:

  i) Third Fluctuation Moments of Conserved Charges
  take negative values in regions on the FAR SIDE of Phase Transition
  (more information!)

  ii) Different Moments have different regions with negative moments

  By comparing different moments, possible to pin down the origin
  of hot matter, get an idea about heat conductivity...etc.

- Proton Number Cumulants and Baryon Number Ones:

  will be discussed in Kitazawa's talk

Revealing Baryon Number Fluctuations in Heavy Ion Collisions

Masakiyo Kitazawa

(Osaka U.)

Baryon number cumulants are invaluable tools to diagnose the primordial stage of heavy ion collisions if they can be measured. In experiments, however, proton number cumulants have been measured as substitutes. In fact, proton number fluctuations are further modified in the hadron phase and different from those of baryon number. We show that the isospin distribution of nucleons at kinetic freezeout is binomial and factorized. This leads to formulas that express the baryon number cumulants solely in terms of proron number fluctuations, which are experimentally observable.

MK, M. Asakawa, arXiv:1107.2755[nucl-th]

$$\langle \delta N_p^n \rangle \overset{?}{\Longleftrightarrow} \langle \delta N_{\mathrm{B}}^n \rangle$$

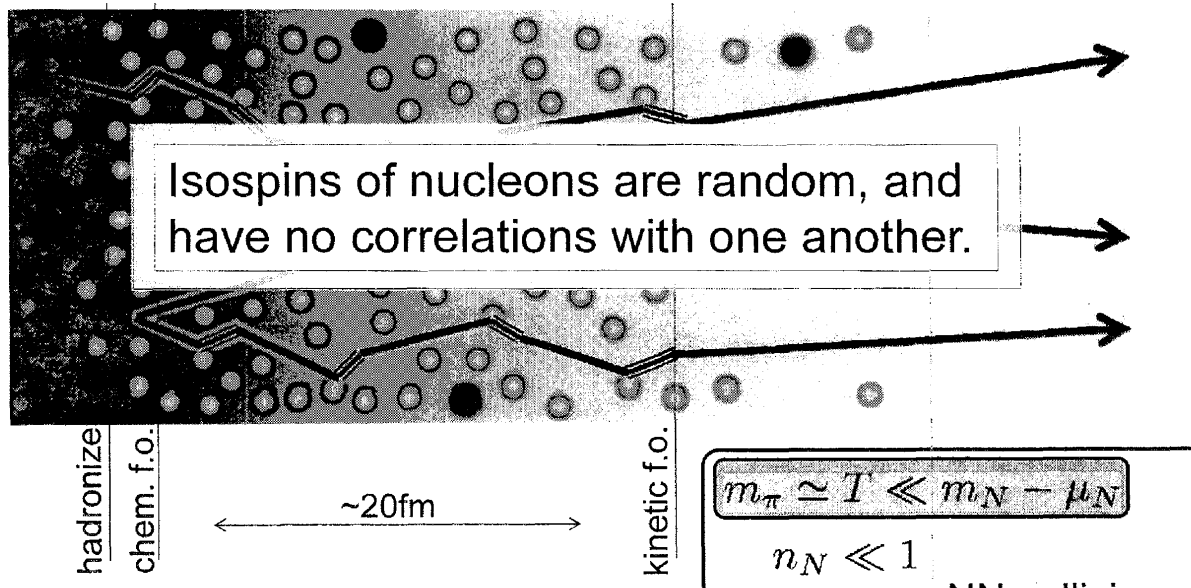
- In free nucleon gas in equilibrium,

$$\langle \delta N_{\mathrm{B}}^n \rangle_c = 2 \langle \delta N_p^n \rangle_c$$

- If the medium is not equilibrated,

$$\langle \delta N_{\mathrm{B}}^n \rangle_c \neq 2 \langle \delta N_p^n \rangle_c$$

Nucleons in Hadronic Phase



Isospins of nucleons are random, and have no correlations with one another.

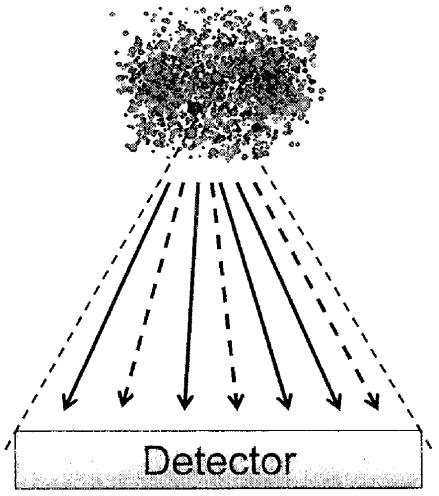
$p, \bar{p}$
$n, \bar{n}$
$\Delta(1232)$
mesons
baryons

$m_\pi \simeq T \ll m_N - \mu_N$

$n_N \ll 1$
- rare NN collisions
- no quantum corr.

$n_N \ll n_\pi$
- many pions

Probability Distribution $\mathcal{P}(N_p, N_n, N_{\bar{p}}, N_{\bar{n}})$



- N_N nucleons
- $N_{\bar{N}}$ anti-nucleons

$\Rightarrow F(N_N, N_{\bar{N}})$

- N_N $\begin{cases} N_p \text{ protons} \\ N_n \text{ neutrons} \end{cases}$

$\Rightarrow B(N_p; N_N)$

binomial distribution func.

$$\mathcal{P}(N_p, N_n, N_{\bar{p}}, N_{\bar{n}}) = F(N_N, N_{\bar{N}}) B(N_p; N_N) B(N_{\bar{p}}; N_{\bar{N}})$$

- for any phase space in the final state.

Effect of Isospin Distribution

(1) $N_B^{(\mathrm{net})} = N_B - N_{\bar{B}}$ deviates from the equilibrium value.

(2) Boltzmann (Poisson) distribution for $N_B, N_{\bar{B}}$.

$$\Rightarrow \begin{cases} 2\langle(\delta N_p^{(\mathrm{net})})^2\rangle = \frac{1}{2}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^2\rangle + \frac{1}{2}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^2\rangle_{\mathrm{free}} \\ 2\langle(\delta N_p^{(\mathrm{net})})^3\rangle = \frac{1}{4}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^3\rangle + \frac{3}{4}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^3\rangle_{\mathrm{free}} \\ 2\langle(\delta N_p^{(\mathrm{net})})^4\rangle_c = \frac{1}{8}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^4\rangle_c + \frac{7}{8}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^4\rangle_{c,\mathrm{free}} \end{cases}$$

genuine info. noise

For free gas

$$2\langle(\delta N_p^{(\mathrm{net})})^n\rangle_c = \langle(\delta N_{\mathrm{N}}^{(\mathrm{net})})^n\rangle_c$$

Summary

- **Baryon and proton number fluctuations are different** in nonequilibrium medium. To see non-thermal contribution, baryon number is better.
- Formulas to reveal baryon # cumulants in experiments.
- Experimental analysis of baryon # fluctuations may verify
  - signals of QCD phase transition
  - speed of baryon number diffusion in the hadronic stage.

Future Work

- Refinement of the formulas to incorporate
  nonzero isospin density / low beam energy region
- Discussion on time evolution of fluctuations @STAR

Charge fluctuations in effective chiral models

Vladimir Skokov

Brookhaven National Laboratory Upton, NY 11973, USA

in collaboration with B. Friman, F. Karsch, and K. Redlich

3.10.2011

Modeling QCD

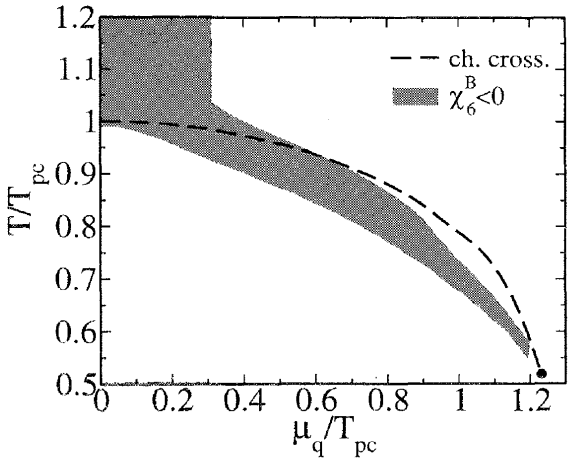
Main properties required from models

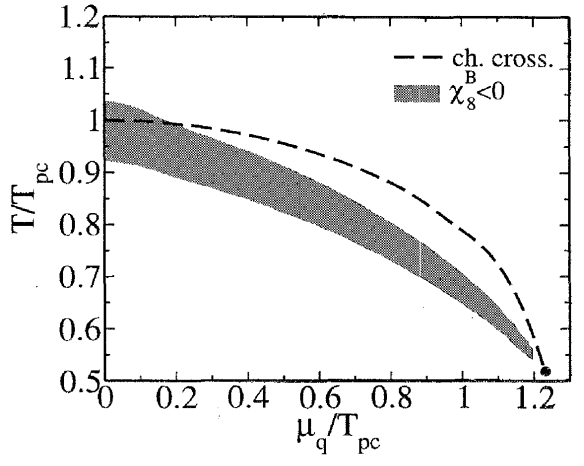
- **O(4) symmetry in limit of vanishing mass for light quarks**
- simulation of confinement properties (ratios of cumulants are sensitive to degrees of freedom)
- **Beyond mean-field**

  $\rightsquigarrow$ non-trivial critical exponents

Higher order baryon cumulant

Temperature interval of negative cumulants closest to hadronic phase:

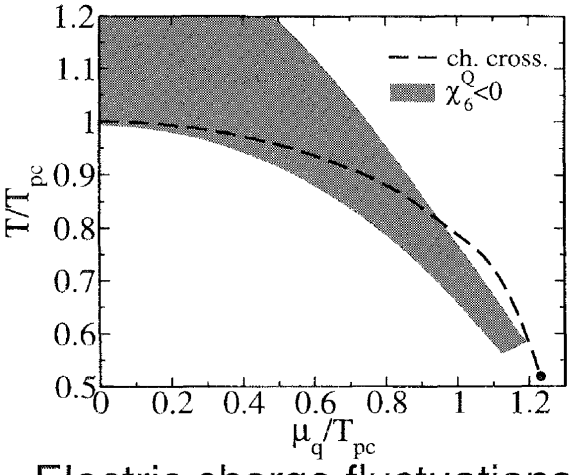




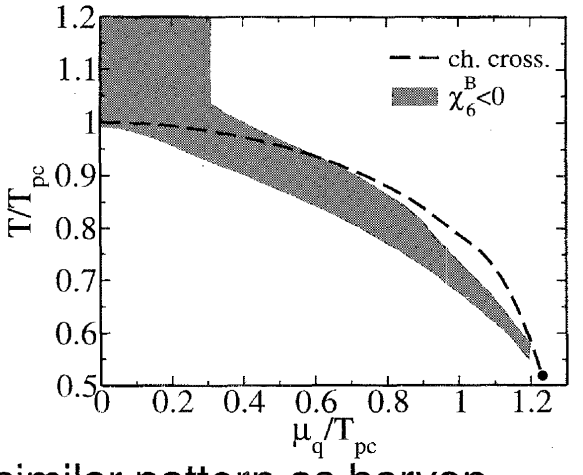
- Negative values (in broken phase!) of high-order cumulants: indicates proximity of freeze-out to crossover

Electric charge fluctuations

Electric charge:

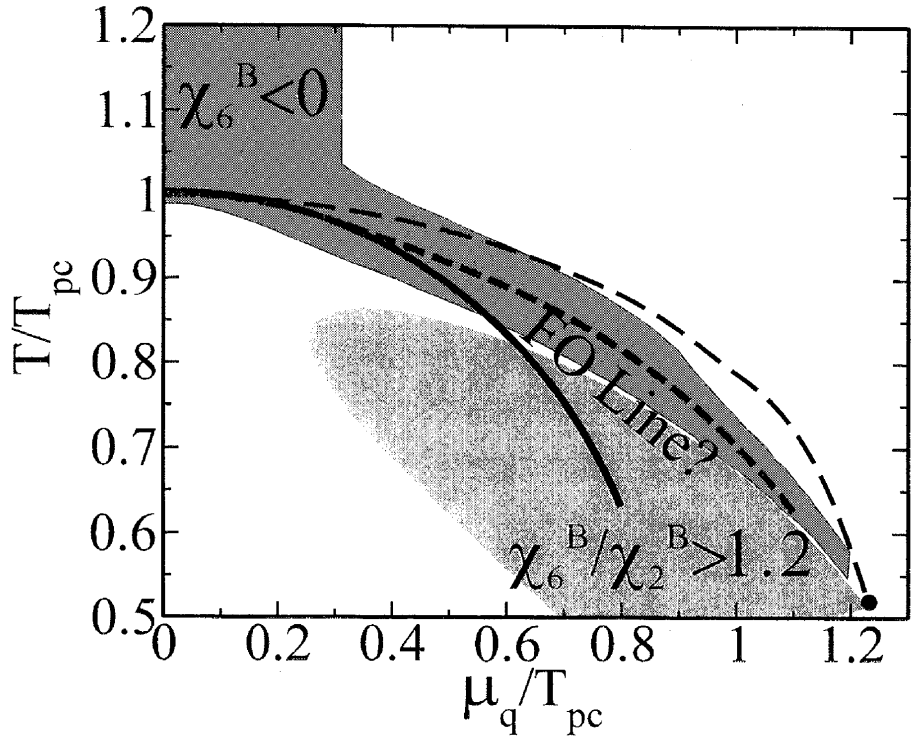


Baryon charge:



Electric charge fluctuations follow similar pattern as baryon fluctuations

FO SCENARIOS



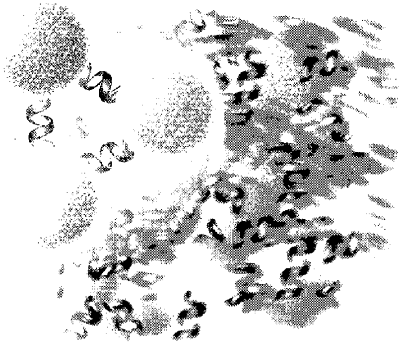
- Models are unable relate FO line and PT line
- Low energies: cumulants might be affected by conservation laws

Conclusions

- **Fluctuations** of conserved charges are **sensitive** probes of the phase structure. They carry information about deconfinement and chiral phase transitions. Fluctuations can be used to identify order and universality class of phase transition.
- **Negative** χ_6^B and χ_8^B can serve as indication of proximity of chemical freeze-out to crossover line.
- Chiral crossover $\rightsquigarrow$ qualitative differences from Hadron Resonance Gas

Talk @ Workshop on Fluctuations, Correlations and RHIC Low Energy Run
Brookhaven OCT.3rd, 2011

"Three Quarks for Muster Mark"
--- Lessons Learned from Susceptibilities



Jinfeng Liao
Indiana University, Physics Dept. & CEEM
RIKEN BNL Research Center

Quasi-particle Models

Free gas of quark quasi-particles with medium generated mass: M(T , \mu)

$$d_2 = \frac{\partial(n_B/T^3)}{\partial\tilde{\mu}}\bigg|_{\mu=0} = -\frac{2g}{2\pi^2}\int dx x^2 n^2 F^{(1)}(\epsilon_0),$$

$$d_4 = \frac{\partial^3(n_B/T^3)}{\partial\tilde{\mu}^3}\bigg|_{\mu=0}$$
$$= -\frac{2g}{2\pi^2}\int dx x^2\Big[n^4 F^{(3)}(\epsilon_0) + 3n^2 F^{(2)}(\epsilon_0)\frac{\tilde{m}_0}{\epsilon_0}$$
$$\times\left(\frac{\partial^2\tilde{m}}{\partial\tilde{\mu}^2}\bigg|_{\mu=0}\right)\Big],$$

$$d_6 = \frac{\partial^5(n_B/T^3)}{\partial\tilde{\mu}^5}\bigg|_{\mu=0}$$
$$= -\frac{2g}{2\pi^2}\int dx x^2\Big[n^6 F^{(5)}(\epsilon_0) + 10n^4 F^{(4)}(\epsilon_0)\frac{\tilde{m}_0}{\epsilon_0}$$
$$\times\left(\frac{\partial^2\tilde{m}}{\partial\tilde{\mu}^2}\bigg|_{\mu=0}\right) + 15n^2 F^{(3)}(\epsilon_0)\frac{\tilde{m}_0^2}{\epsilon_0^2}\left(\frac{\partial^2\tilde{m}}{\partial\tilde{\mu}^2}\bigg|_{\mu=0}\right)^2$$
$$+ 5n^2 F^{(2)}(\epsilon_0)\left(\frac{\tilde{m}_0}{\epsilon_0}\left(\frac{\partial^4\tilde{m}}{\partial\tilde{\mu}^4}\bigg|_{\mu=0}\right)\right.$$
$$\left.+\frac{3x^2}{x^2+\tilde{m}_0^2}\left(\frac{\partial^2\tilde{m}}{\partial\tilde{\mu}^2}\bigg|_{\mu=0}\right)^2\right)\Big].$$

The main message:

$$\boxed{\begin{array}{l} d_2\ (T) \rightarrow \{M\}_{T,\mu=0} \\ d_4\ (T) \rightarrow \\ \quad \left\{M,\ \dfrac{d^2 M}{d\mu^2}\right\}_{T,\mu=0} \\ d_4\ (T) \\ \rightarrow \left\{M,\ \dfrac{d^2 M}{d\mu^2},\ \dfrac{d^4 M}{d\mu^4}\right\}_{T,\mu=0} \end{array}}$$

(*JL & Shuryak, Phy. Rev. D 73(2006)014509.*

Susceptibilities from Holography

Thermodynamics of QGP phase in Sakai-Sugimoto Model:

$$P_{\rm QGP}[T, d(T,\mu)] = \left[\frac{2}{7}\Gamma_A d^{\frac{7}{5}} + \frac{2}{7}u_T\left(d^2+u_T^5\right)^{\frac{1}{2}} - \frac{2}{7}u_T d\, {}_2\mathrm{F}_1\left(\frac{1}{5},\frac{1}{2};\frac{6}{5};-\frac{u_T^5}{d^2}\right)\right],$$

$$\Gamma_A d^{\frac{2}{5}} - u_T\, {}_2\mathrm{F}_1\left(\frac{1}{5},\frac{1}{2};\frac{6}{5};-\frac{u_T^5}{d^2}\right) - \mu = 0, \quad \Gamma_A = \frac{\Gamma(\frac{3}{10})\Gamma(\frac{6}{5})}{\sqrt{\pi}}.$$

Results for susceptibilities in QGP phase from such a holographic model of QCD:

$$d_n = \xi_n N_s N_c N_f \left(\frac{1}{\lambda\tilde{T}}\right)^{n-3}$$

$$\lambda = g^2 N_c$$

$$\tilde{T} = T / T_c$$

$$\boxed{\frac{d_2}{N_s N_f N_c} \approx 0.012\cdot\lambda\tilde{T}, \qquad \frac{d_4}{N_s N_f N_c} \approx \frac{0.37}{\lambda\tilde{T}}, \qquad \frac{d_6}{N_s N_f N_c} \approx -\frac{26}{\lambda^3\tilde{T}^3}.}$$

Very interesting dynamical feature:

- **alternating signs (beyond 6-th order as we checked)**
- **strong coupling suppressing higher fluctuations while enhancing leading order**
- **temperature dependence is unusual as well**

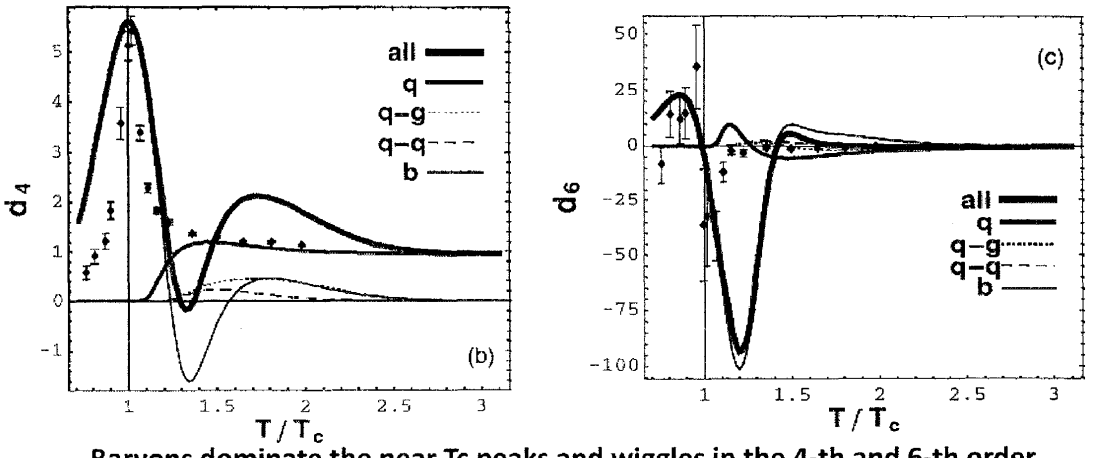
Kim & JL, Nucl. Phys. B 822(2009)201.

Susceptibilities: Baryons v.s. Quarks

Thermal factor : $e^{-M_q/T}$ **v.s.** $e^{-M_B/T}$

Charge factor : $\left(B_q = \frac{1}{3}\right)^n$ **v.s.** $\left(B_B = \frac{1}{3}\right)^n$

Baryons, or baryonic correlations, can contribute much more prominently in higher order susceptibilities, particularly the *4-th and 6-th orders*!



Baryons dominate the near Tc peaks and wiggles in the 4-th and 6-th order.

JL & Shuryak, Phy. Rev. D 73(2006)014509.

Cross-Flavor Susceptibilities

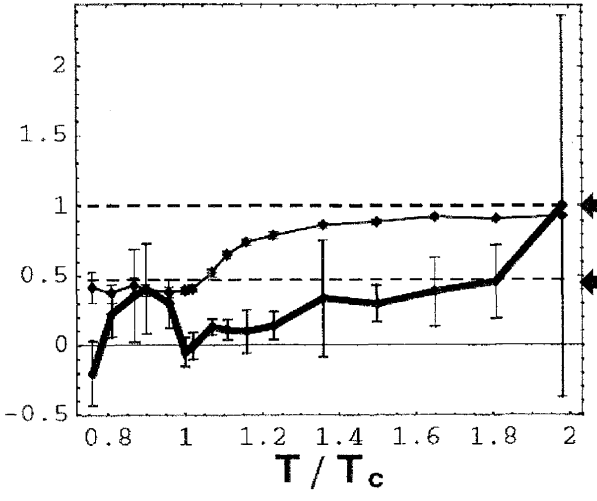
There are more conserved charges (within QCD): Baryon , Isospin , Strangeness
→ Provides additional probes of charge carriers

N : I = 1 / 2 , B = 1

Δ : I = 3 / 2 , B = 1

Q (u, d) :

I = 1 / 2, B = 1 / 3



An example of mixed-susceptibilities

$$\frac{d_4{}^I}{d_4} \sim \frac{I^2}{B^2} \qquad \frac{d_6{}^I}{d_6} \sim \frac{I^2}{B^2}$$

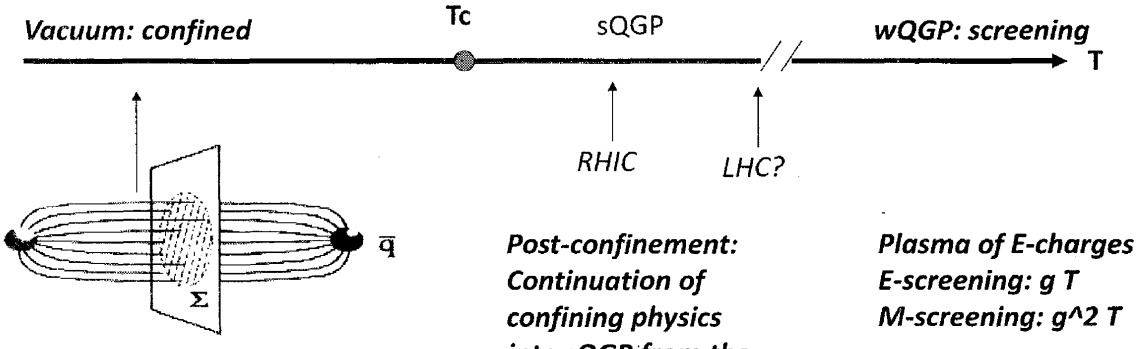
QUARKs

BARYONs

Baryonic correlations are alive, as seen from high-order susceptibilities!

Other example: B-S correlations by Koch, et al.

"Three Quarks for Muster Mark" in a New Context: Near-Tc QGP



Electric Flux Tube:
Magnetic Condensate

Susceptibilities from BARYONs: colorless combination of THREE (constituent) quarks

Post-confinement:
Continuation of confining physics into sQGP from the magnetic component
--- the magic of THREE still at work !

--- would be great to see it gone at LHC!

Plasma of E-charges
E-screening: g T
M-screening: g^2 T

Susceptibilities from individual colorful QUARKs

JL & Shuryak, PRC2007,PRL2008

Fluctuations of conserved charges within dynamic models of heavy-ion collisions

Marlene Nahrgang

SUBATECH, Nantes & FIAS, Frankfurt

We present studies of fluctuations in dynamic models of heavy-ion collisions and focus on two different aspects. First, we investigate the development and evolution of fluctuations of the order parameter of chiral symmetry, the sigma field, in a dynamic environment. For this we use nonequilibrium chiral fluid dynamics. We find an enhancement of the fluctuations at the phase transition. Second, we apply the relativistic transport model UrQMD to study the fluctuations of conserved charges. It turns out that experimental centrality selection and the exact eventwise baryon charge conservation leads to negative values of the net-baryon kurtosis. The net-proton kurtosis is influenced by the baryon charge conservation only at lower energies. We show results for central Pb+Pb/Au+Au collisions from $E_{\rm lab} = 2A$ GeV to $\sqrt{s_{\rm NN}} = 200$ GeV.

Subatech

FIAS Frankfurt Institute for Advanced Studies

Nonequilibrium chiral fluid dynamics

- Langevin equation for the sigma field: damping and noise from the interaction with the quarks

$$\partial_\mu \partial^\mu \sigma + \frac{\delta U}{\delta \sigma} + g\rho_s + \eta \partial_t \sigma = \xi$$

- Fluid dynamic expansion of the quark fluid = heat bath

$$T_{\mathrm{q}}^{\mu\nu} = (e+p)u^\mu u^\nu - pg^{\mu\nu}$$

- Energy and momentum exchange

$$\partial_\mu T_{\mathrm{q}}^{\mu\nu} = S^\nu = -\partial_\mu T_\sigma^{\mu\nu}$$

$\Longrightarrow$ Selfconsistent approach within the two-particle irreducible effective action!

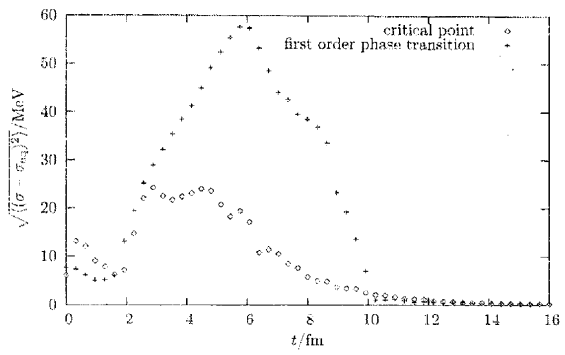
(MN, S. Leupold, C. Herold, M. Bleicher, PRC **84** (2011))

Intensity of sigma fluctuations

$$\frac{\mathrm{d}N_\sigma}{\mathrm{d}^3k} = \frac{(\omega_k^2|\sigma_k|^2 + |\partial_t\sigma_k|^2)}{(2\pi)^3 2\omega_k}$$

$$\omega_k = \sqrt{|k|^2 + m_\sigma^2}$$

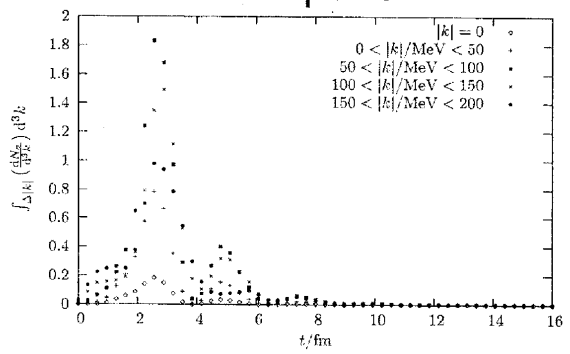
$$m_\sigma = \sqrt{\partial^2 V_{\mathrm{eff}}/\partial\sigma^2|_{\sigma=\sigma_{\mathrm{eq}}}}$$



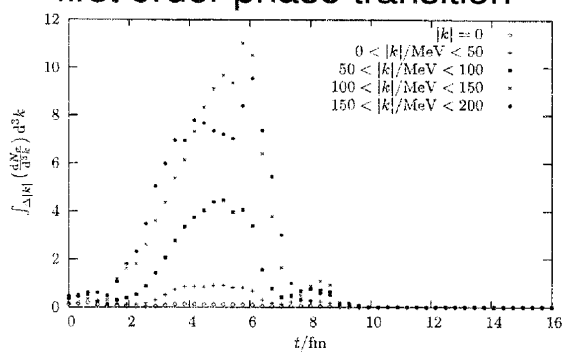
deviation from equilibrium

(MN, M. Bleicher, S. Leupold, I. Mishustin, arXiv:1105.1962)

critical point



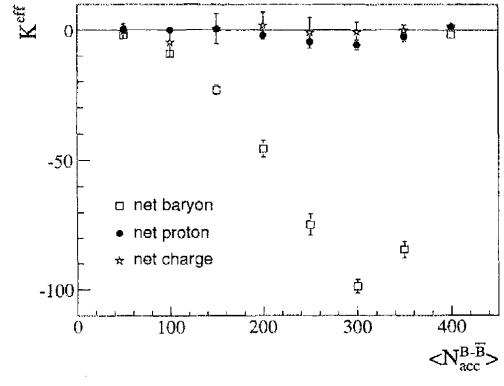
first order phase transition



Rapidity window dependence of the effective kurtosis

- Same qualitative behavior of the net-baryon kurtosis as expected from the analytic toy model.

- $E_{\mathrm{lab}} = 158A\mathrm{GeV}$
- The net-proton kurtosis only slightly follows this trend.
- The net-charge kurtosis is not influenced, but error bars are larger.

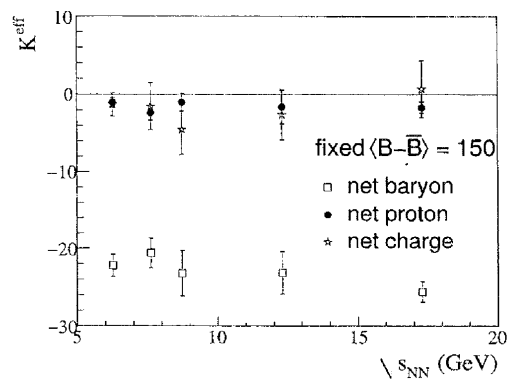


- For small net-baryon numbers in the acceptance, the values of net-baryon, net-proton and net-charge kurtosis are compatible with values of $0 - 1$.

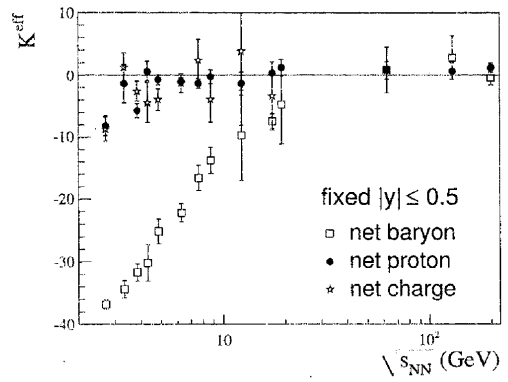
(T. Schuster, MN, M. Mitrovski, R. Stock, M. Bleicher, [arXiv:0903.2911 [hep-ph])

Energy dependence of the effective kurtosis

- adapting the rapidity window to fix the mean net-baryon number
- net-baryon effective kurtosis does not show an energy dependence



- fixed rapidity cut
- the net-baryon number varies with $\sqrt{s}$
- for lower $\sqrt{s}$ K^{eff} becomes increasingly negative
- at $E_{\mathrm{lab}} = 2A$GeV: $\langle N_{B-\bar{B}} \rangle \simeq 240$

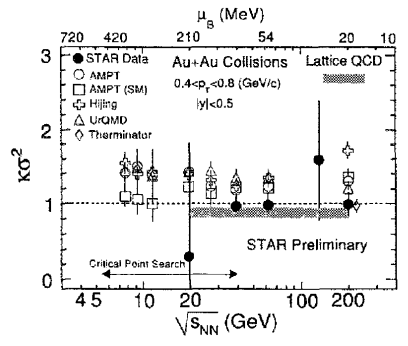


(T. Schuster, MN, M. Mitrovski, R. Stock, M. Bleicher, [arXiv:0903.2911 [hep-ph]])

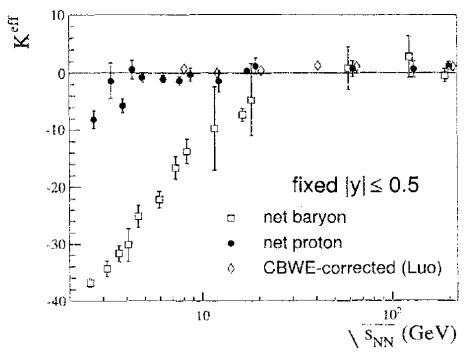
Effects of centrality selection

Suggestion by STAR to reduce centrality bin width effects:

- calculate moments for each fixed N_{charge} in one wider centrality bin
- take the weighted average



(STAR collaboration, Nucl.Phys. A862-863 (2011))



(MN et al., QM 2011 proceedings)

problems:

- (anti-) protons constitute a larger fraction of all charged particles with decreasing energy
- fixing N_{charge} puts a bias on the fluctuations

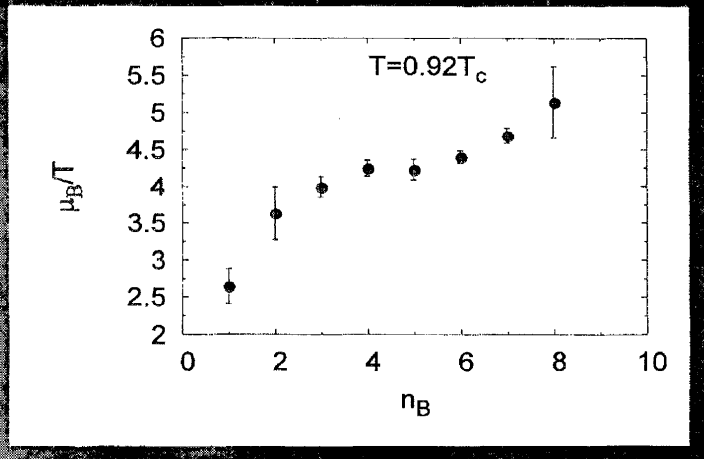
Lattice Calculation of QCD Critical Point with the Canonical Ensemble

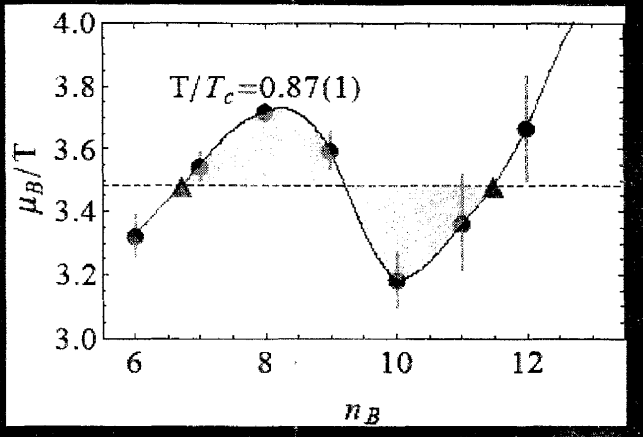
- Keh-Fei Liu
- Dept. of Physics and Astronomy University of Kentucky, Lexington, KY 40502

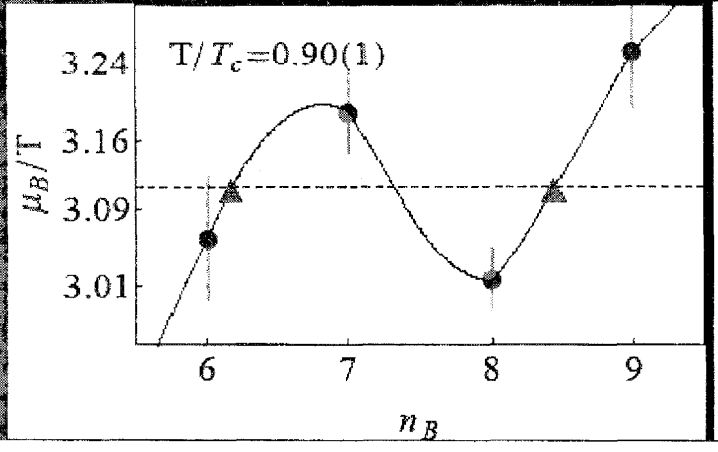
- Summary: The canonical ensemble approach to the finite density calculation is adopted to search for the critical point in 3-flavor QCD. We clearly see a first order phase transition on the small lattice with relatively large quark mass. Using Maxwell's construction, we determine the critical temperature and chemical potential. We will work on smaller quark mass and larger volume and a higher cutoff to have more realistic results. This result is accepted for publication in PRD (A. Li, A. Alexandru, and K.F. Liu, arXiv:1103.3045).

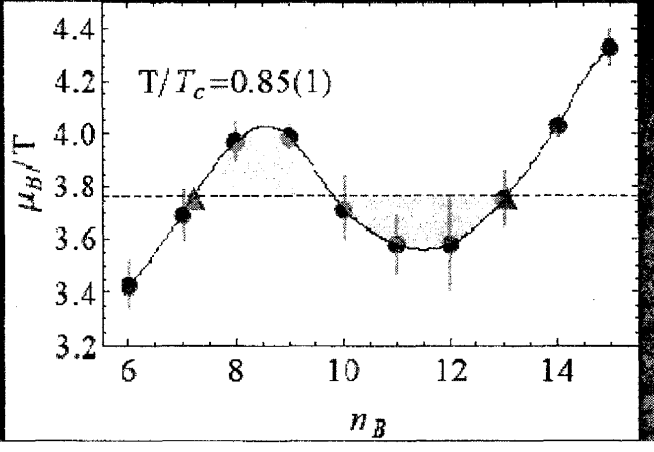
Three flavor case
(m_π ~ 0.7 GeV, a~ 0.3 fm)

$6^3 \times 4$ lattice,
Clover fermion



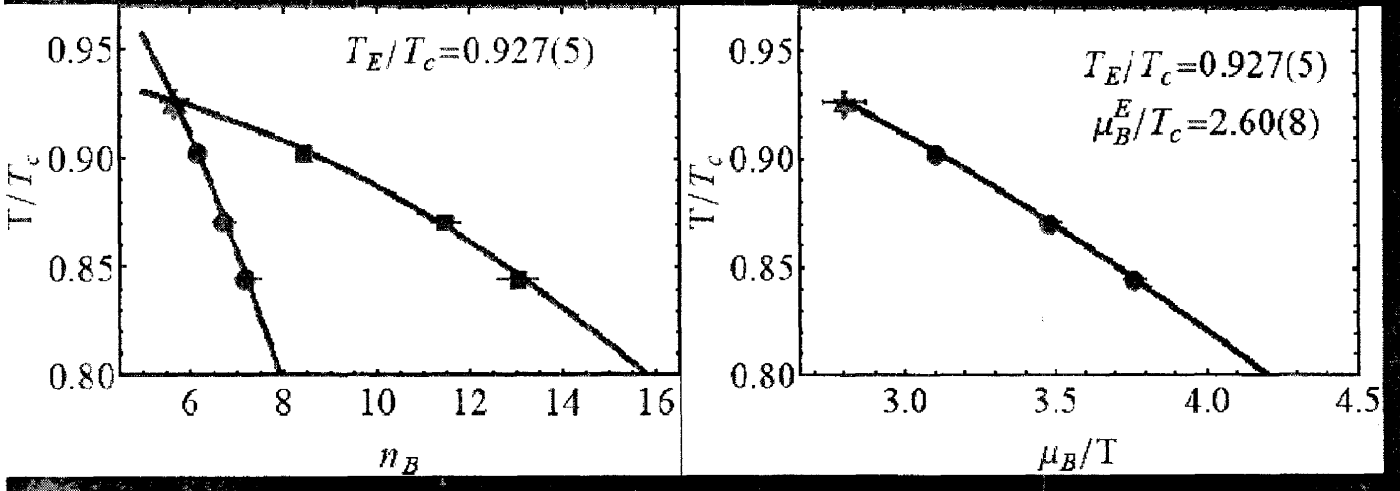






Critial Point of N_f = 3 Case

m_π ~ 0.7 GeV, 6^3 x 4 lattice, a ~ 0.3 fm



T_E = 0.927(5) T_c (~ 157 MeV)
μ_B^E = 2.60(8) T_c (~ 441 MeV)

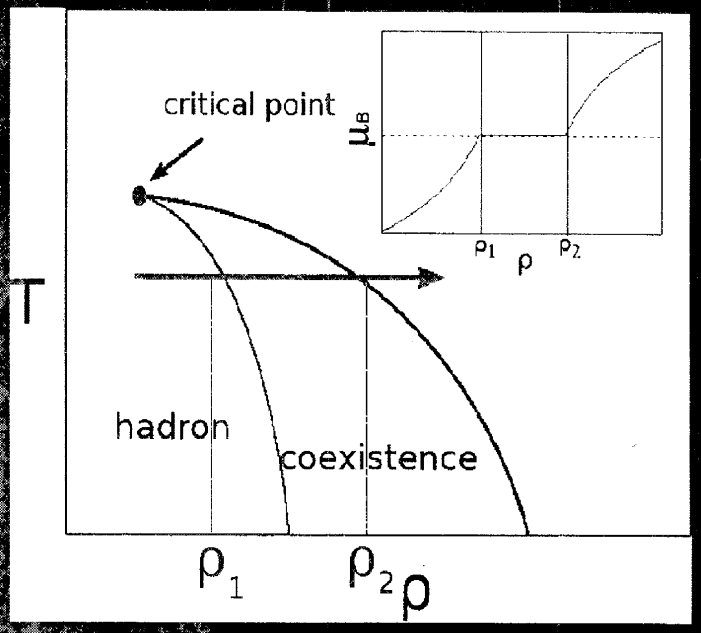
Transition density ~ 5-8 ρ_{NM}

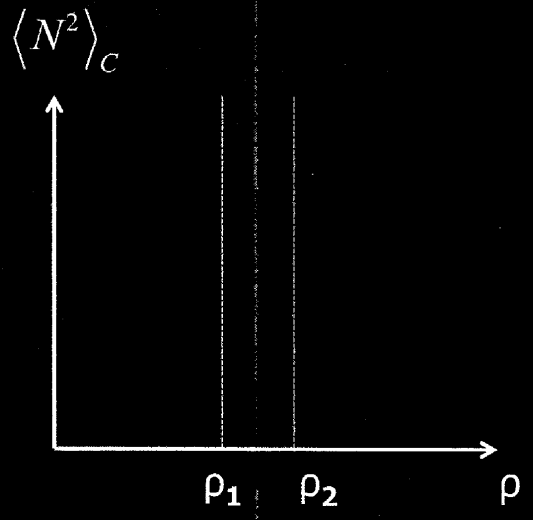
Nature of phase transition

UK, 2007, page 3

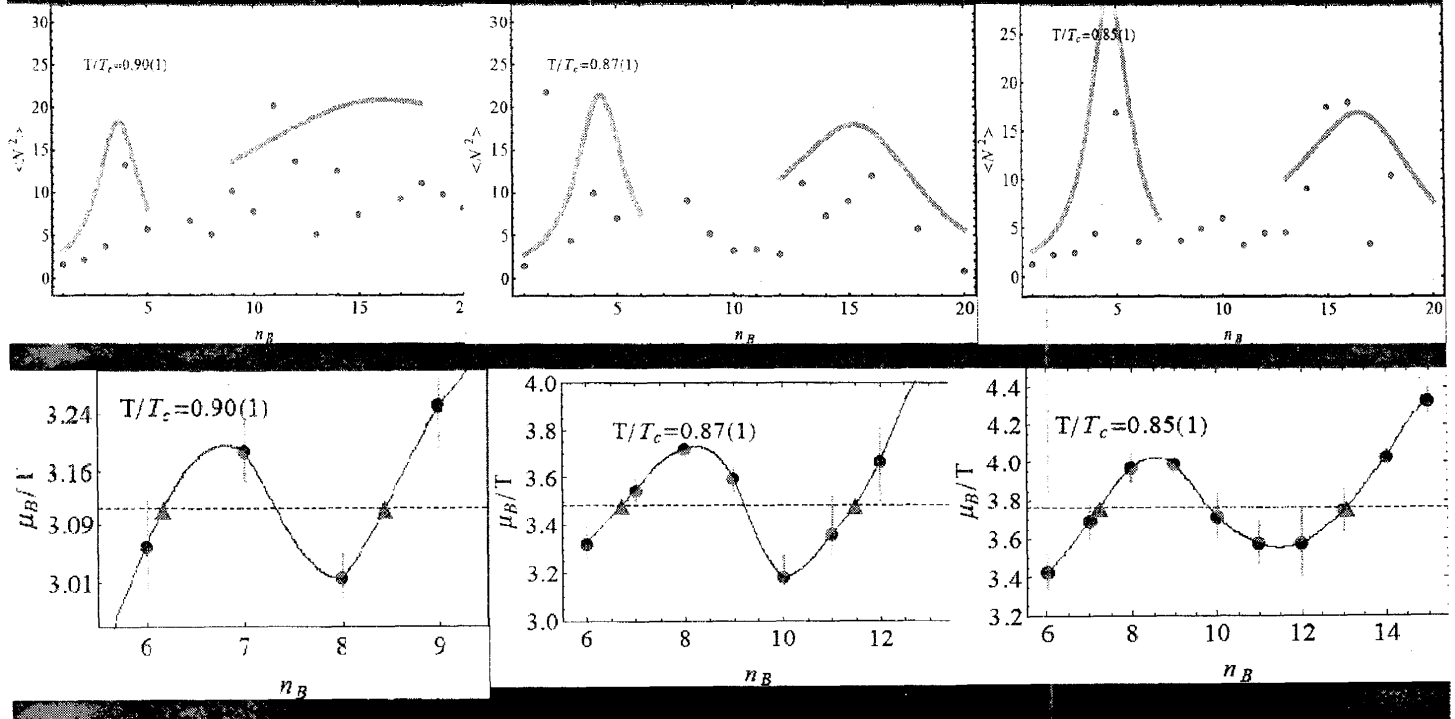
Variance

$$\langle N^2 \rangle_c = T \left(\frac{\partial \mu}{\partial N} \right)^{-1}$$



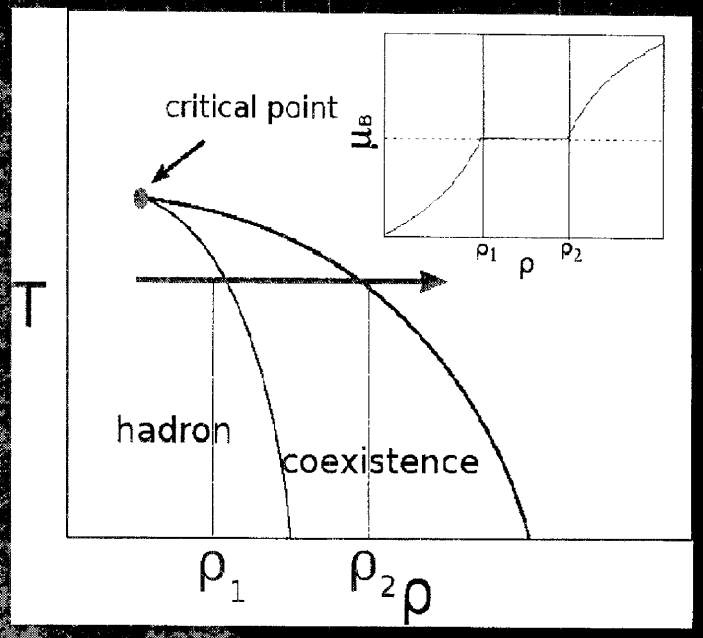


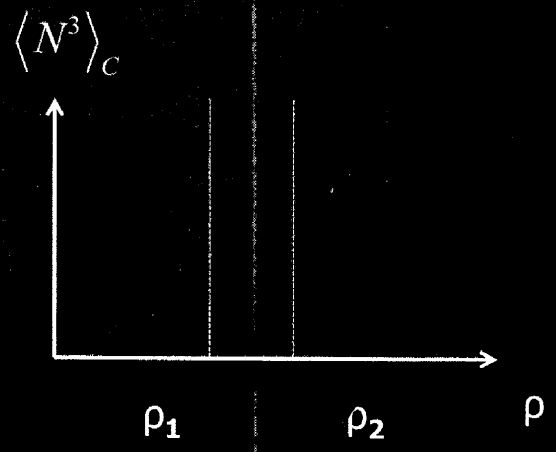
Second moment <N²>



Skewness

$$\langle N^3 \rangle_c = T \left(\frac{\partial \mu}{\partial N} \right)^{-3} \frac{\partial^2 \mu}{\partial N^2}$$





Study of QCD Phase Transition at Finite Density by a Histogram Method

Shinji Ejiri, Niigata University

WHOT-QCD collaboration: S. Ejiri[1], S. Aoki[2], T. Hatsuda[3,4], K. Kanaya[2], Y. Maezawa[5], Y. Nakagawa[1], H. Ohno[2,5], H. Saito[2], and T. Umeda[6]

[1]Niigata Univ., [2]Univ. of Tsukuba, [3]Univ. of Tokyo, [4]RIKEN, [5]BNL, [6]Hiroshima Univ.

Abstract:
We propose a new approach to finite density lattice QCD based on a histogram method and discuss the QCD phase transition at high temperature and density. Because the quark determinant is complex at finite density, the Monte-Carlo method cannot be applied directly. We use a reweighting method and try to solve the problems which arise in the reweighting method, i.e. the sign problem and the overlap problem. We discuss the quark mass and chemical potential dependence of the probability distribution function and examine the applicability of the approach.

Fluctuations, Correlations and RHIC Low Energy Runs, BNL, October 3-5, 2011

Problems in simulations at $\mu \neq 0$

- Problem of Complex Determinant at $\mu \neq 0$
  - Boltzmann weight: complex at $\mu \neq 0$
    - Monte-Carlo method is not applicable.
    - Configurations cannot be generated.
- Density of state method (Histogram method)

  X: <u>order parameters</u>, <u>total quark number</u>, <u>average plaquette</u> etc.

$$Z(m,T,\mu) = \int dX \, \underbrace{W(X,m,T,\mu)}_{\text{histogram}}$$

$$W(X',m,T,\mu) \equiv \int DU \delta(X\text{-}X') \left(\det M(m,\mu)\right)^{N_f} e^{-S_g}$$

- Expectation values

$$\langle O[X] \rangle_{(m,T,\mu)} = \frac{1}{Z} \int dX \, O[X] W(X,m,T,\mu)$$

- Sign problem: $\det M$ changes its sign $\rightarrow$ the error of W: large.

Distribution function in the light quark region

WHOT-QCD, in preparation

- We perform phase quenched simulations with the weight:

$$\left|\det M(m,\mu)\right|^{N_f} e^{-S_g}$$

$$\boxed{\begin{aligned} W(P',F',\beta,m,\mu) &= \int DU\ \delta(P-P')\delta(F-F')\left(\det M(m,\mu)\right)^{N_f} e^{-S_g} \\ &= \int DU\ \delta(P-P')\delta(F-F')e^{i\theta}\left|\det M(m,\mu)\right|^{N_f} e^{-S_g} \\ &= \underbrace{\left\langle e^{i\theta}\right\rangle_{P',F'}}_{\text{expectation value with fixed } P,F} \times \underbrace{W_0(P',F',\beta,m,\mu)}_{\text{histogram}} \end{aligned}}$$

P: plaquette $\quad F(\mu) = N_f \ln\left|\frac{\det M(\mu)}{\det M(0)}\right| \quad \theta \equiv \mathrm{Im}\ln\det M$

Distribution function of the phase quenched.

$$W_0(P',F') = \int DU\ \delta(P-P')\delta(F-F')\left|\det M\right|^{N_f} e^{6N_{\mathrm{site}}\beta P}$$

Avoiding the sign problem

(SE, Phys.Rev.D77,014508(2008), WHOT-QCD, Phys.Rev.D82, 014508(2010))

θ: complex phase $\qquad \theta \equiv \mathrm{Im}\ln\det M$

- Sign problem: If $e^{i\theta}$ changes its sign,

$$\left\langle e^{i\theta}\right\rangle_{P,F\ \mathrm{fixed}} \ll \text{(statistical error)}$$

- Cumulant expansion $\qquad$ $\langle..\rangle_{P,F}$: expectation values fixed F and P.

$$\left\langle e^{i\theta}\right\rangle_{P,F} = \exp\left[\underbrace{\cancel{i\langle\theta\rangle_C}}_{\to 0} - \frac{1}{2}\left\langle\theta^2\right\rangle_C - \underbrace{\cancel{\frac{i}{3!}\left\langle\theta^3\right\rangle_C}}_{\to 0} + \frac{1}{4!}\left\langle\theta^4\right\rangle_C + \cancel{\cdots}\right]$$

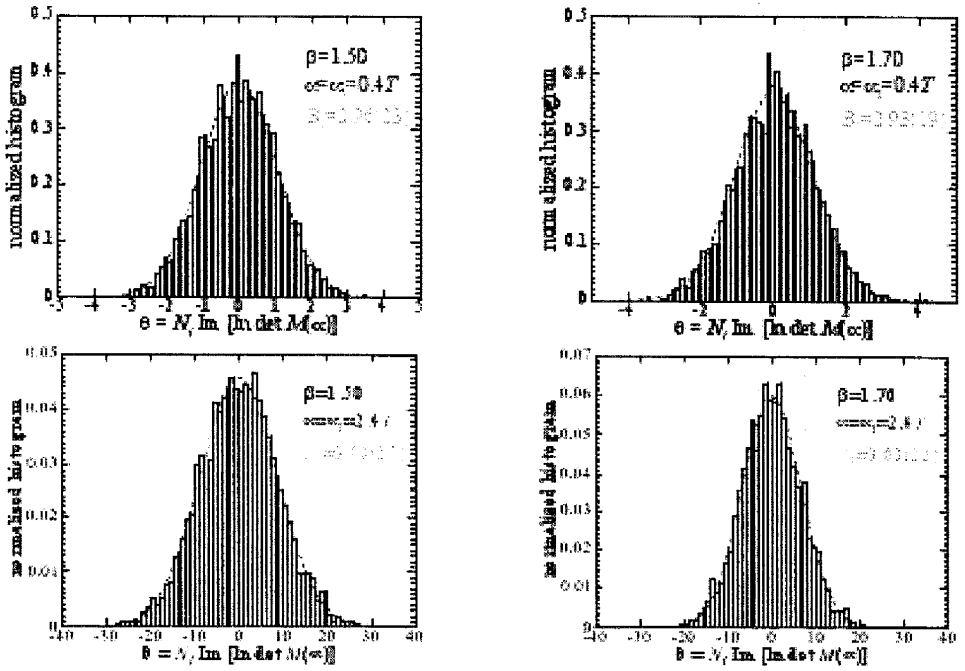
cumulants

$$\langle\theta\rangle_C = \langle\theta\rangle_{P,F},\ \left\langle\theta^2\right\rangle_C = \left\langle\theta^2\right\rangle_{P,F} - \langle\theta\rangle_{P,F}^2,\ \left\langle\theta^3\right\rangle_C = \left\langle\theta^3\right\rangle_{P,F} - 3\left\langle\theta^2\right\rangle_{P,F}\langle\theta\rangle_{P,F} + 2\langle\theta\rangle_{P,F}^3,\ \left\langle\theta^4\right\rangle_C = \cdots$$

– <u>Odd terms</u> vanish from a symmetry under $\mu \leftrightarrow -\mu$ ($\theta \leftrightarrow -\theta$)
Source of the complex phase

If the cumulant expansion converges, No sign problem.

Distribution of the complex phase

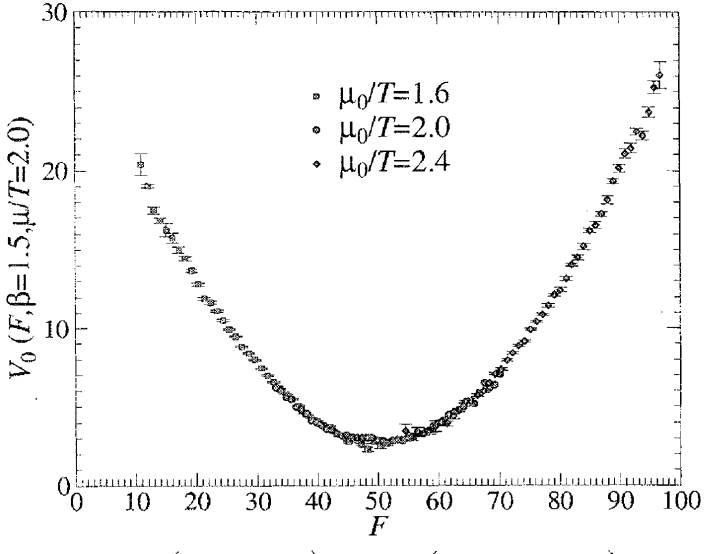


- Well approximated by a Gaussian function.
- Convergence of the cumulant expansion: good.

Overlap problem

Reweighting method W_0: distribution function in phase quenched simulations.

$$R(P,F)=\frac{W_0(P,F,\mu)}{W_0(P,F,\mu_0)}=\left\langle\left|\frac{\det M(\mu)}{\det M(\mu_0)}\right|^{N_f}\right\rangle_{P,F\ \text{fixed}}$$



- Perform phase quenched simulations at several points.
  - Range of F is different.
- Change μ by reweighting method.
- Combine the data.

⬇

Distribution in a wide range: obtained.

- The error of R is small because F is fixed.

$$-\ln W_0(P,F,\mu_0)-\ln R(P,F,\mu,\mu_0)=-\ln W_0(P,F,\mu)$$

The Cumulants of Net-proton Multiplicity Distribution at STAR

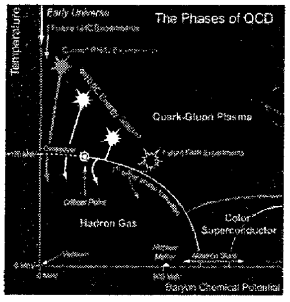
Lizhu Chen (for the STAR Collaboration)
Institute of Particle Physics, Central China Normal University, China

The ratios of different order cumulants of conserved quantities have become important observables for probing the QCD phase diagram as they are independent of the volume and directly related to the ratios of the susceptibilities from the theory calculation. The STAR experiment with large acceptance, excellent particle identification capability and high event statistics collected in year 2010, has given us a good chance to study the cumulants of net-proton up to sixth order. In this talk, we report the preliminary results about the ratios of sixth to second and fourth to second cumulants of the net-proton multiplicity at mid-rapidity ($|y| < 0.5$) measured in Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV and 200 GeV.

Outline

- **Motivation**
- **STAR Detecting System**
- **Results and Discussions**
  - Centrality dependence
  - Energy dependence
- **Summary**

Motivation



- Lattice QCD: $\mu_B = 0$, Crossover.
  Y. Aoki et al., Nature 443, 675-678(2006).
- QCD based Model,
  T≈0 and larger μ_B, first order transition.
  eg: S. Ejiri, Phys. Rev. D 78, 074507 (2008); H. Saito, et al., (WHOT-QCD Collaboration). hep-lat/1106.0974.
- Experiment approach:
  ✓RHIC Beam Energy Scan Program: The search for signatures of phase boundary and critical point.
  http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493, arXiv: 1007.2613.
  ✓High event statistics collected at RHIC top energy.

Important observable: The cumulants ratios of conserved quantities.
Direct connection between theory calculation and experiment.

Ratios of cumulants of net-proton multiplicity

1:The net-proton multiplicity fluctuation can reflect the net-baryon number fluctuation.
Y. Hatta et al,PRL 91, 102003 (2003)

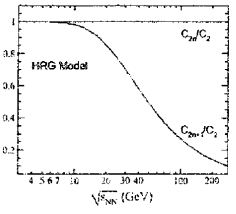
2: Related to the ratios of the susceptibilities directly.

$$\chi_3^B/\chi_2^B \approx \left(\frac{1}{VT^3}C_3\right)/\left(\frac{1}{VT^3}C_2\right) = S\sigma$$
$$\chi_4^B/\chi_2^B \approx \left(\frac{1}{VT^3}C_4\right)/\left(\frac{1}{VT^3}C_2\right) = C_4/C_2 = \kappa\sigma^2$$
$$\chi_6^B/\chi_2^B \approx \left(\frac{1}{VT^3}C_6\right)/\left(\frac{1}{VT^3}C_2\right) = C_6/C_2$$

✓Cancel the volume effect.

3: Hadron Resonance Gas expectation:
$$\frac{C_{2nel}}{C_2} = \tanh(\mu_B/T),\quad \frac{C_{2n}}{C_2} = 1 \quad (n = 1, 2, 3 \cdots)$$
F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011)

$$C_2 = \langle \delta N_{p-\bar{p}}^2 \rangle \quad C_3 = \langle \delta N_{p-\bar{p}}^3 \rangle$$
$$C_4 = \langle \delta N_{p-\bar{p}}^4 \rangle - 3\langle \delta N_{p-\bar{p}}^2 \rangle^2$$
$$C_6 = \langle \delta N_{p-\bar{p}}^6 \rangle - 15\langle \delta N_{p-\bar{p}}^4 \rangle \langle \delta N_{p-\bar{p}}^2 \rangle - 10\langle \delta N_{p-\bar{p}}^3 \rangle^2 + 30\langle \delta N_{p-\bar{p}}^2 \rangle^3$$



Ratios of cumulants of net-proton multiplicity

4: Sensitive to the correlation length

$$\langle \delta N^k \rangle \sim \xi^{2.5k-3} \Longrightarrow \begin{array}{l} \langle \delta N^3 \rangle \sim \xi^{4.5} \\ \langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2 \sim \xi^7 \end{array}$$

M.A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009). arXiv:1104.1627

✓ The correlation length away from the CP (Critical Point): $\xi \sim 0.5 - 1 fm$

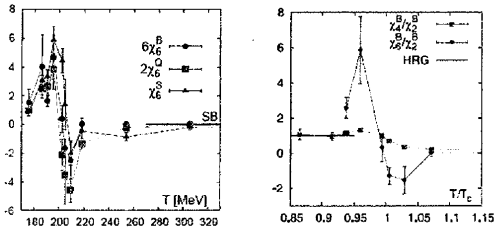
✓Near the CP, due to the critical slowing down:
Magnitude of ξ is limited: $\xi \sim 2 - 3 fm$
B. Berdnikov, K. Rajagopal, Phys. Rev. D 61, 105017 (2000).

✓Higher moments are more sensitive to the critical point.

✓ **Non-monotonic signal as function of energy is expected to be observed near CP.**

Ratios of cumulants of net-proton multiplicity

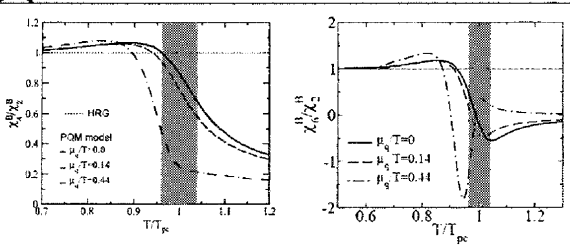
5: Sensitive to the QCD Critical Temperature Tc



Cheng et al, Phys.Rev. D79 (2009) 074505. Prog Theor Phys.Suppl. 186 (2010) 363-366

➢ Both χ_6^B/χ_2^B and χ_4^B/χ_2^B deviate from unity near the Tc.
➢ The χ_6^B/χ_2^B are much more sensitive to the Tc.
➢ Lattice Prediction: At LHC and RHIC high energy, the experiment may observe the negative χ_6^B/χ_2^B if the freeze-out curve close to the phase transition line.

Ratios of cumulants of net-proton multiplicity

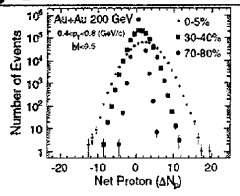


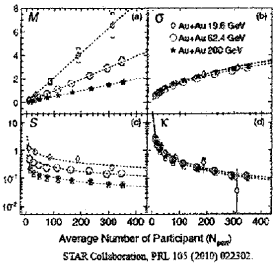
➢ The Polyakov loop extended quark meson (PQM) model is an effective model to study the thermodynamics near the chiral phase transition.

➢The structure of the fluctuation in PQM model are similar with Lattice QCD for both χ_6^B/χ_2^B and χ_4^B/χ_2^B.

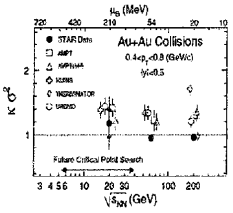
B. Friman, F. Karsch, K. Redlich and V. Skokov, Eur Phys. J. C71, 1694 (2011)

First result on higher moments of net-proton



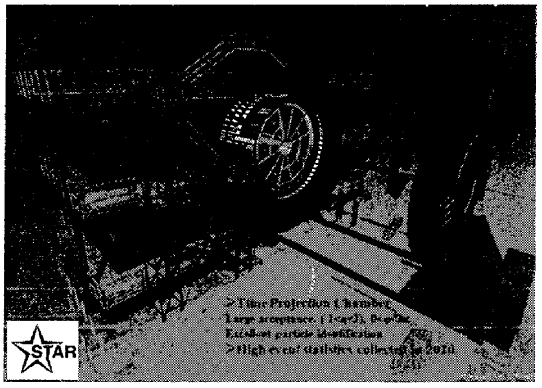


STAR Collaboration, PRL 105 (2010) 022302.



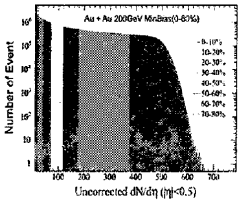
- STAR first results on higher moments analysis are up to fourth order.
- Using ratios used to establish base line measurements for the QCD critical point search.
- **This talk:** C_5 / C_2 **and** C_2 / C_2.

STAR Detecting System



Analysis Detail

- The centrality definition and data collection



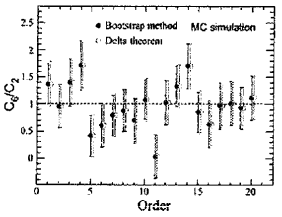
- ✓ 200 GeV: 404 Million totally*
- ✓ 39 GeV: 125 Million MB
- ✓ 11.5 GeV: 14 Million MB
- ✓ 7.7 GeV: 4.2 Million MB

*For Central collisions of 200 GeV, the data are from MinBias and central-triggered datasets.

Kinematic range of protons:
- Midrapidity: $|y| < 0.5$
- p_T : 0.4 - 0.8 GeV/c

Analysis Detail

➢ Statistical error propagation method study

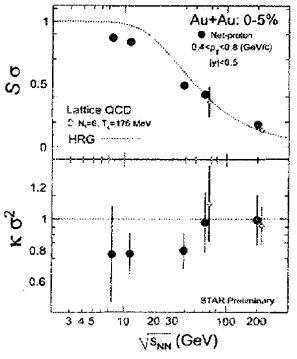


(a): The 20 samples are from MC simulation based on the Skellam distribution.
(b): Input parameter for MC simulation:
mean value: $\mu_1 = 4.0$, $\mu_2 = 3.0$,
Number of event for each sample: 30 Million.

- Trying different methods for data analysis
  (a) Sub-group method.
  (b) Bootstrap method.
  (c) Delta theorem method.
- The statistical error estimated by sub-group method is unstable.
- The bootstrap method and delta theorem give the consistent result for statistical error estimation.
- Using bootstrap method for data analysis.

Bradley Efron, http://www.jstor.org/pss/2030104.
X. Luo, arXiv:1109.0593

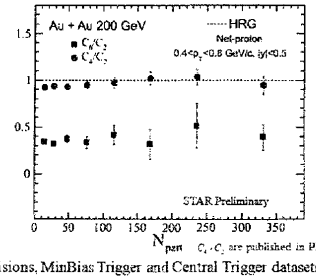
Results (I): Energy dependence of product moments



➢ Data are compared with HRG and Lattice QCD.

X. Luo, SQM 2011

Results (II): Au + Au 200 GeV



C_4/C_2 are published in PRL 105 (2010) 022302

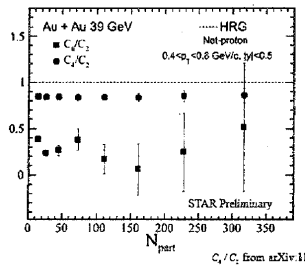
➢ Central collisions, MinBias Trigger and Central Trigger datasets.

➢ The centrality dependence is small.

➢ C_4/C_2 are consistent with unity for central collisions.

➢ First results of C_6/C_2

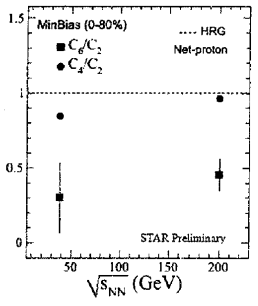
Results (III): Au + Au 39 GeV



C_4/C_2 from arXiv:1106.2926

- C_4/C_2 deviate from the unity.
- C_6/C_2 show similar trends with Au + Au 200 GeV. But larger error in central collisions.

Results (IV): Energy dependence



- Data:
  The deviation for C_4/C_2 from HRG at lower energy.
- Theory:
  The deviation from the HRG results grow with increasing energy.

P. Braun-Munzinger, B. Friman, et al. arXiv: 1107.4267

Summary

- The cumulant ratio of conserved quantities provide a directly connection between theory calculation and experiment. It is an important observable for studying the QCD phase diagram.
- We report the first results of net-proton C_6/C_2 in Au + Au collisions at 39 and 200 GeV.

Outlook: Au + Au Collisions at 19.6, 27 and 62.4 GeV data are under analysis.

Claudia Ratti

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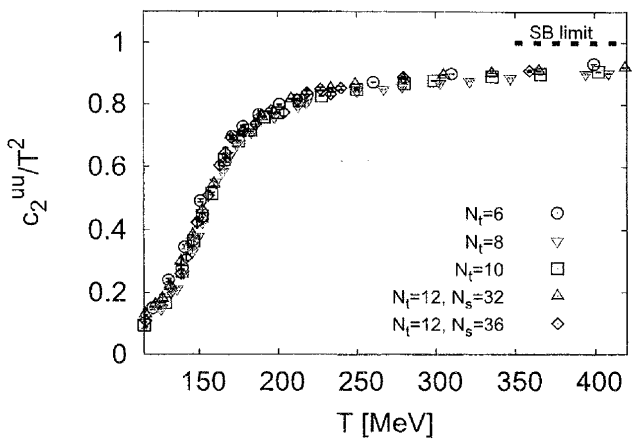
Recent Results on Correlations and Fluctuations from the Wuppertal-Budapest Lattice QCD Collaboration

We present the new results of the Wuppertal-Budapest lattice QCD collaboration on flavor diagonal and non-diagonal quark number susceptibilities with 2+1 staggered quark flavors, in a temperature regime between 120 and 400 MeV. A Symanzik improved gauge and a stout-link improved staggered fermion action is utilized; the light and strange quark masses are set to their physical values. Lattices with Nt=6, 8, 10, 12 are used. We perform a continuum extrapolation of those observables for which the scaling regime is reached, and discretization errors are under control. Preliminary results on the (partial quenched) charm susceptibilities are also shown. The possibility of bound states above Tc is discussed.

Results: light quark susceptibilities

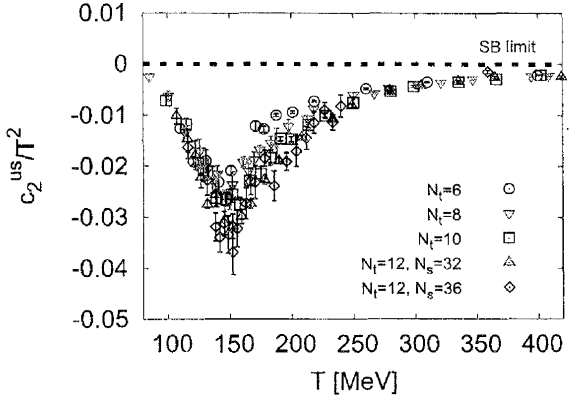
$$c_2^{uu} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_u \partial\mu_u}\bigg|_{\mu_i=0}$$



- quark number susceptibilities exhibit a rapid rise close to T_c
- at large T they reach $\sim 90\%$ of the ideal gas limit

Results: nondiagonal susceptibilities

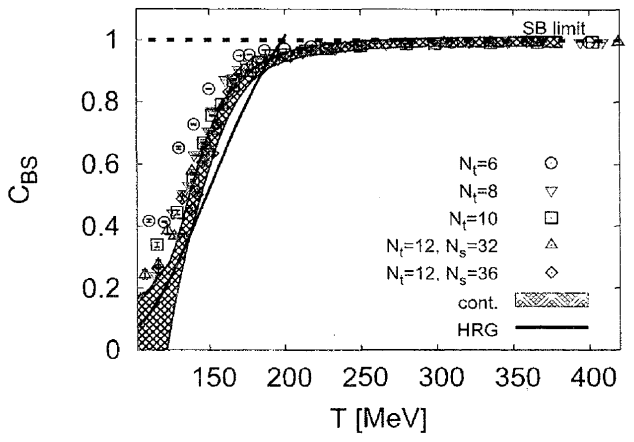
$$c_2^{us} = c_2^{ds} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_u \partial\mu_s}\bigg|_{\mu_i=0}$$



- non-diagonal susceptibilities look at the linkage between different flavors
- in the hadronic phase they are non-zero
- they exhibit a strong dip in the vicinity of T_c
- they vanish in the QGP phase at large temperatures

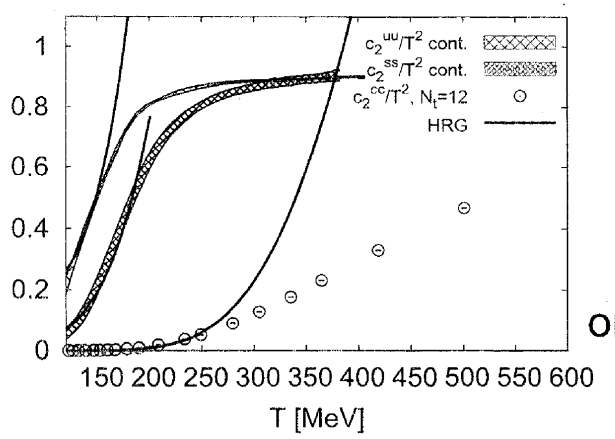
Results: baryon-strangeness correlator

$$C_{BS} = 1 + \frac{c_2^{us} + c_2^{ds}}{\chi_2^s}$$

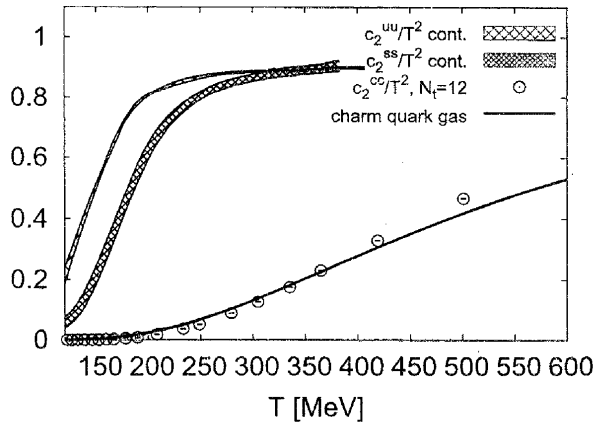


- C_{BS} indicates the possibility of bound states in a certain window above T_c
- there is a window of about 100 MeV above the transition where $C_{BS} < 1$

Possible interpretations



or



- survival of open charm hadrons up to $T \simeq 2T_c$?
- HRG results agree with the lattice up to the inflection point in the data

- thermal excitation of charm quarks takes place at larger temperatures
- ideal gas of charm quarks agrees with lattice

need for non-diagonal quark number susceptibilities

Conclusions

- study of diagonal and non-diagonal quark number susceptibilities for $N_f = 2 + 1$ dynamical flavors
- diagonal quark number susceptibilities: signals of QCD phase transition
  - ⇝ rapid rise close to T_c
  - ⇝ susceptibilities of different flavors show their rise at different T
- correlations between different flavors are large immediately above T_c
  - ⇝ possibility of bound states survival in the QGP
- diagonal charm quark susceptibilities rise at much larger temperatures
- they don't allow to distinguish between HRG and free charm gas
  - ⇝ need for non-diagonal correlators

Fluctuations and Correlations: Lattice QCD vs. HRG

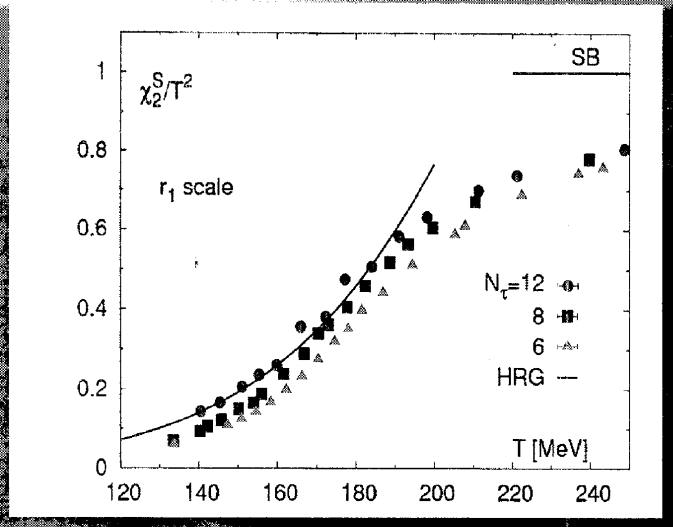
Prasad Hegde (BNL)

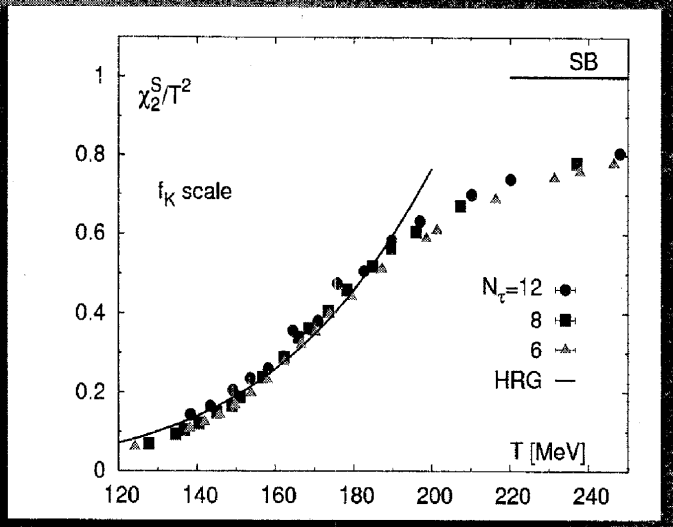
[for the HotQCD Collaboration]

4th October 2011.

Fluctuations, Correlations and the RHIC Low-Energy Runs, Oct 3-5

Choice of Observable: r_1 vs. f_K





- Smaller cutoff dependence when f_K is used to set the scale.

Hadron Resonance Gas

$$\frac{P}{T^4} = \frac{1}{\pi^2} \sum_i d_i K_2 \left(\frac{m_i}{T}\right) \left(\frac{m_i}{T}\right)^2 \cosh\left[B_i \mu_B + Q_i \mu_Q + S_i \mu_S\right]$$

- We have included all resonances upto ~ 2.5 GeV.
- Satisfactory description for temperatures below the transition.
- P, χ_n etc. increase monotonically with T.
- Deviations from HRG would constitute a signal for non-trivial dynamics.

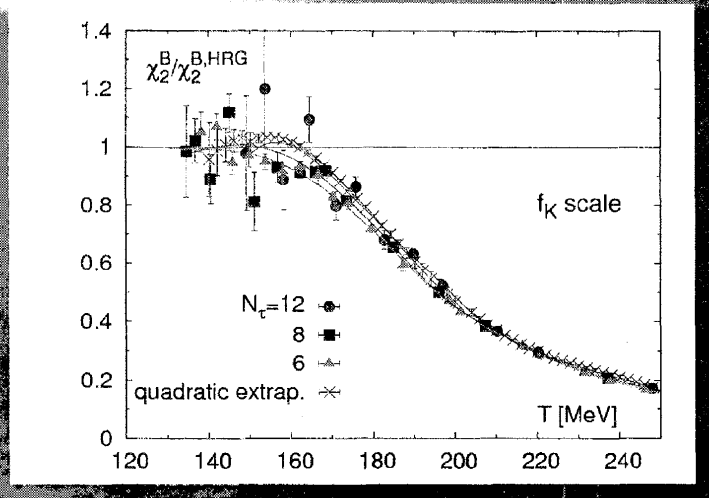
Continuum Extrapolations

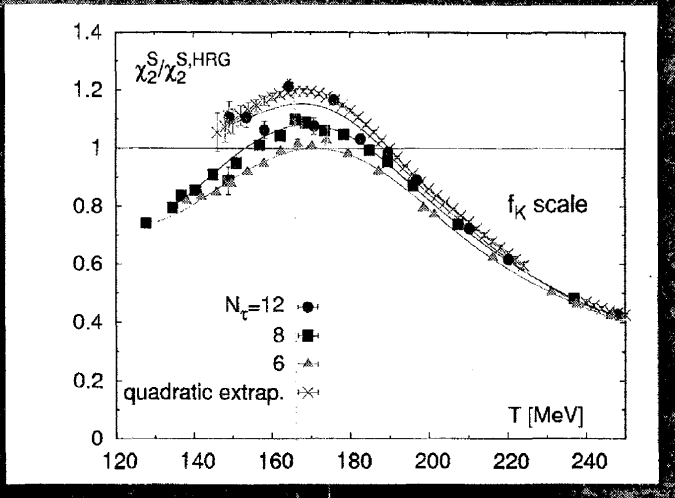
- We also attempted a continuum extrapolation.
- We assumed a polynomial scaling ansatz viz.

$$\mathcal{O}(N_\tau) = \mathcal{O}_{\text{cont.}} + \frac{A}{N_\tau^2}$$

- The extrapolated results were compared to the HRG predictions for T below ~160 MeV.
- Good agreement for baryon number and strangeness.
- Electric charge sensitive to the value of m_π .

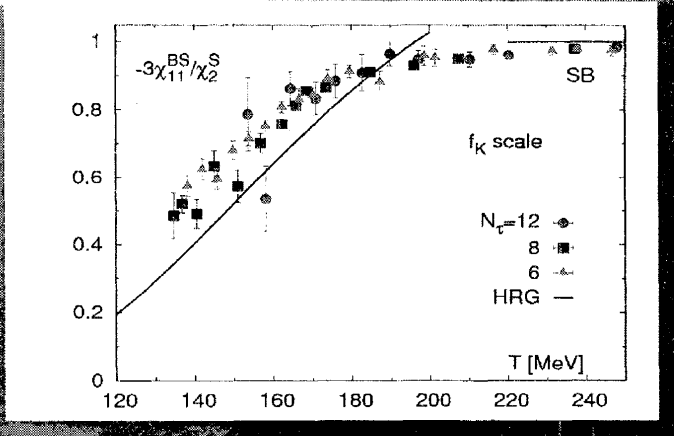
Baryon Number and Strangeness

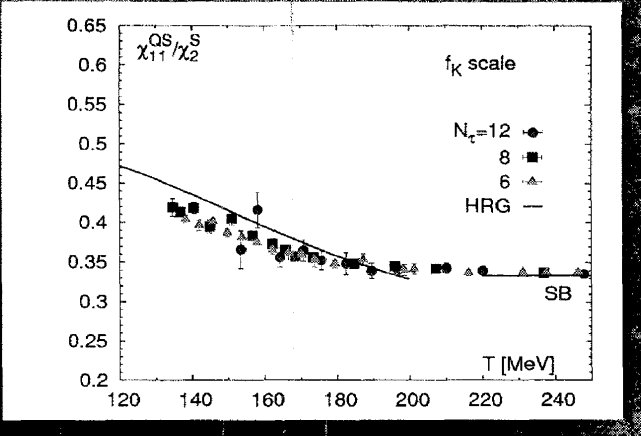




- Strangeness exceeds HRG predictions. For baryon number, HRG predicts that ratio of cumulants should be unity. This holds from T < ~170 MeV.

ios: Off-diagonals to Diagonals





- These two ratios (V. Koch et al., PRL95, 182301) satisfy $-2\frac{\chi_{11}^{BS}}{\chi_2^S}+\frac{\chi_{11}^{QS}}{\chi_2^S}=1$ at all temperatures.

- In the case of the ratios, the perturbative contributions start at $O(g^6 \ln g)$.

Finite Size Scaling on the Phase Diagram of QCD

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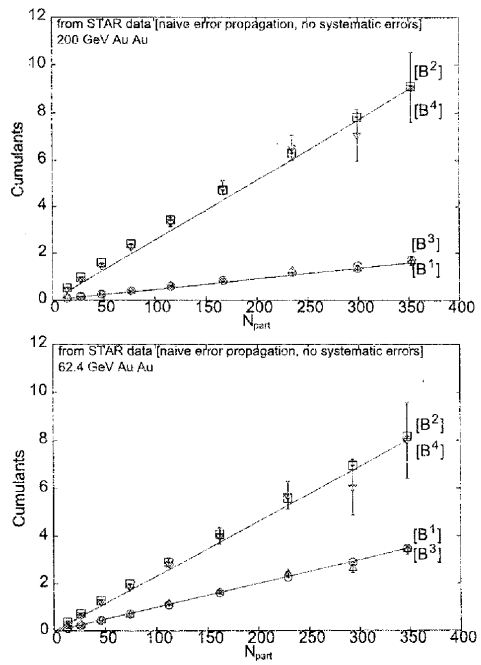
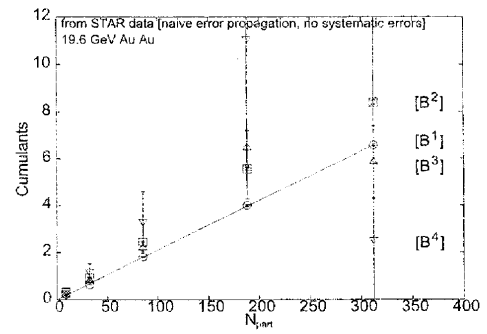
Finite Size Scaling on the Phase Diagram of QCD

1. Scale of the persistence of memory, $V_{fireball}$. When $V_{fireball}/V_{obs} \gg 1$ then total charge of the system forgotten. May not hold at small $\sqrt{S}$.
2. Shortest length scale ξ, defined by transport: the diffusion constant. Scale at which baryon number transport becomes important.
3. Scale of observation volume, V_{obs}. Set by the detector. Thermodynamics and finite size scaling applicable for $V_{obs}/\xi^3 \gg 1$. Comparison to lattice works when $\xi^3 \ll V_{obs} \ll V_{fireball}$.
4. Peclet scale, $\lambda = \xi/M$ (where M is the Mach number). Controls freeze out of fluctuations.
5. Volume per unit baryon number, $\zeta^3 = V_{obs}/B_+$. Events with $\zeta \simeq \xi$, may not be observed at thermodynamic frequency because of slow diffusion.

Evolution of shape





Plots show scaling to central limit theorem, ie, $\xi^3 \ll V_{obs}$ at these $\sqrt{S}$

Thermodynamics in the grand canonical ensemble works when three scales are distinct: $\xi^3 \ll V_{obs} \ll V_{fireball}$. Then distributions of conserved quantities are Gaussian except near a critical point.

When does thermodynamics break down?

Out of control diffusion

If fireball static, then control of diffusion requires the hierarchy $\xi^3 \ll V_{obs} \ll V_{fireball}$. When $\sqrt[3]{V_{obs}} \simeq \xi$ then microscopic physics of transport controls observed distributions. This happens in the critical regime. Also turbulent?

Persistence of memory

If $V_{obs} \simeq V_{fireball}$ then conserved baryon number is seen and fluctuations are due to initial state fluctuations. May be important at low $\sqrt{S}$.

Other scales?

But plasma ball is not static, and new length scales become important.

Diffusion-advection phenomena

Entropy content in B or S small compared to entropy content of full fireball. Coupled relativistic hydro and diffusion equations can then be simplified to diffusion-advection equation.
Which is more important— diffusion or advection? Examine Peclet's number

$$\mathrm{Pe} = \frac{\lambda v}{D} = \frac{\lambda v}{\xi c_s} = M\frac{\lambda}{\xi}.$$

When $\mathrm{Pe} \ll 1$ diffusion dominates. When $\mathrm{Pe} \gg 1$ advection dominates. Crossover between these regimes when $\mathrm{Pe} \simeq 1$.

Advective length scale

New length scale: defines when advection becomes comparable to diffusive evolution—

$$\lambda \simeq \frac{\xi}{M}.$$

Bhalerao and SG, 2009

Finite volumes: density sets a scale

When the total number of baryons (baryons + antibaryons) detected is B_+, the volume per detected baryon is $\zeta^3 = V_{obs}/B_+$. If $\zeta \simeq \xi$ then system may not be thermodynamic: controlled when $V_{obs}/\xi^3 \to \infty$.

Events which (by chance) have large B_+ may take longer to come to chemical equilibrium. However, this subclass of events involve interesting transport properties. Can one selectively study these rare events?

On cumulant order

In central Au Au collisions, the measurement of $[B^6]$ involves $\zeta/\xi \simeq 2$. Could it be used to study transport? Probe this by separating out samples with large B_+ and studying their statistics.

Higher Moments of Hadronic Fluctuations and QCD Critical Behavior from Lattice Simulations

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Spontaneous breaking of the $SU_L(n_f) \times SU_R(n_f)$ chiral symmetry, which is manifest in the massless QCD Lagrangian, is the key ingredient to our understanding of the QCD phase structure. Quite general renoramlization group arguments [1] suggest that the nature of the chiral phase transition in QCD with two massless quark flavor is of second order. This is believed to persist also in the presence of a heavy strange quark mass. The expected universality class of this transition is $O(4)$, or with staggered fermions at finite lattice spacing: $O(2)$.

We have performed a sequence of lattice simulations with improved staggered fermions on $N_\tau = 4$ lattices at fixed physical strange quark mass (m_s) but varying light quark masses (m_l) in a wide range of $m_l/m_q \in [0.0125, 0.4]$ [2]. We find good $O(N)$ scaling of the chiral order parameter (M) already at $m_l/m_s = 0.05$, *i.e.* the physical point lies in the scaling region of the critical point. From an analysis of the magnetic equation of state we determine the non universal parameter that govern the transition temperature T_c and its quark mass dependence. Preliminary results by the HotQCD Collaboration, obtained with highly improved staggered quarks (hisq action) on much finer lattices ($N_\tau = 6, 8, 12$) enable us to perform the continuum extrapolation of T_c in the chiral limit and at the physical point [3]. We obtain the curvature of the phase transition line at zero quark masses by a scaling analysis of the mixed susceptibility that involves the derivatives with respect to the chemical potential and the light quark mass [4]. This analysis has been performed with $N_\tau = 4$ and 8 lattices, which indicate that the cutoff effects are small, a firm continuum extrapolation is, however, still missing. Current results suggest that the curvature of the phase transit on line is smaller than that of the experimentally determined freeze-out curve.

Furthermore, we study derivatives of the partition function with respect to baryon (B), electric charge (Q)and strangeness (S) chemical potentials. These quantities define moments of the B, Q, S fluctuations and can also be connected to the critical behavior of QCD in the chiral limit [5]. The second moment behaves like the energy density and is thus dominated by regular parts. The fourth moment develops a kink in the chiral limit, while the sixth moment is divergent. In general, higher and higher moments become more and more sensitive to the critical behavior. Previous results of hadronic fluctuations have been obtained with the p4 action on $N_\tau = 4, 6$ lattices [6]; preliminary results are obtained with the hisq action on $N_\tau = 6, 8, 12$ lattices. While the second order moments and correlations already allow for a controled continuum extrapolation [3, 7] the higher moments [9] still have large statistical errors, which makes the discussion more qualitative than quantitative. However, in general we find that all moments follow the pattern that is dictated by the critical behavior [5], which is also observed in model calculations [8]. Moreover, they are close to the hadron resonance gas results right below the transition temperature at $T \lesssim 160$ MeV. An exception are the electric charge fluctuations since they are sensitive to the light pion sector, which is disturbed on the lattice due to the flavor symmetry breaking, which is inherent to staggered fermions.

In order to compare moments of baryon number charge fluctuations to the experimental results [10] we follow a Taylor expansion approach. As input we use the temperature and chemical potential values obtained by statistical model fits to the experimental data. We find, that the data can be reasonably good described by the so obtained lattice data for collision energies of $\sqrt{s} \gtrsim 20$ GeV [11]. For lower energies, statistical and systematic errors increase drastically. In Future, it will be possible to obtain the freeze-out parameters in a model independent manor, using continuum extrapolated results of higher order baryon number fluctuations.

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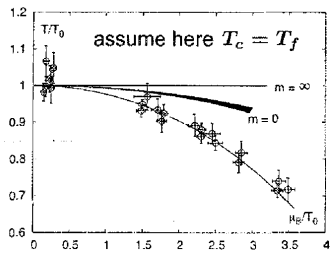
[1] R. Pisarski and F. Wilczek, Phys. Rev. **D29**, 338 (1984).
[2] S. Ejiri *et al.*, Phys. Rev. **D80**, 094505 (2009).
[3] HotQCD in preparation.
[4] O. Kaczmarek *et al.*, Phys. Rev. **D83**, 014504 (2011).
[5] S. Ejiri, F. Karsch, K. Redlich, Phys. Lett. **B633**, 275-282 (2006).
[6] M. Cheng *et al.*, Phys. Rev. **D79**, 074505 (2009).
[7] See the contribution by P. Hegde to this proceedings.
[8] B. Friman *et al.*, Eur. Phys. J. **C71** 1694 (2011); V. Skokov, this proceedings.
[9] RBC-Bielefeld Collaboration in preparation.
[10] Aggarwal *et al.*, Phys. Rev. Lett. 022302 (2010).
[11] C. Schmidt, Prog. Theor. Phys. Suppl. **186** 563 (2010).

2) Analyzing QCD critical behavior

1

Critical line vs. freeze-out line:

- Statistical models are very successful in describing particle abundances observed in heavy ion collision; use a parametrization of the freeze-out curve



statistical model:

$$\frac{T_c}{T} = 1 - 0.023\left(\frac{\mu_B}{T}\right)^2 - d\left(\frac{\mu_B}{T}\right)^4$$

Cleymans, et al., PRC 73 (2006) 034905

lattice:

$$\frac{T_c}{T} = 1 - 0.0066(7)\left(\frac{\mu_B}{T}\right)^2$$

Kaczmarek *et al.*, PRD 83 (2001) 014504

$\Longrightarrow$ **curvature of the freeze-out curve seems to be larger**

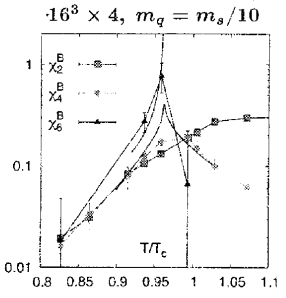
- **open issues**: continuum limit, strangeness conservation, nonzero electric charge

2) Analyzing QCD critical behavior

2

Analyzing baryon number fluctuation $\chi_n^B = \frac{\partial^n (p/T^4)}{\partial(\mu_B/T)^n}$

- higher moments of baryon number fluctuations are more and more sensitive to the critical behavior.



scaling analysis:

scaling field (chiral limit):

$$t = \frac{1}{t_0}\left(\frac{T - T_c}{T_c} + \kappa\left(\frac{\mu_B}{T}\right)^2\right)$$

free energy:

$$f = A_\pm |t|^{2-\alpha} + \text{regular}$$

critical exponent:

$$-0.15 < \alpha < -0.11$$

$$\chi_2^B \sim \mp 2A_\pm(2-\alpha)\kappa\,|t|^{1-\alpha} + \text{regular}$$

$$\chi_4^B \sim -12A_\pm(2-\alpha)(1-\alpha)\kappa^2\,|t|^{-\alpha} + \text{regular} \longrightarrow \text{kink (chiral limit)}$$

$$\chi_6^B \sim \mp 120A_\pm(2-\alpha)(1-\alpha)(-\alpha)\kappa^3\,|t|^{-1-\alpha} + \text{regular} \longrightarrow \text{divergent (chiral limit)}$$

3) Baryon number fluctuations: lattice vs. HRG

3

hadron resonance gas:

$$\ln Z(T,V,\mu_B,\mu_S,\mu_Q) = \sum_{i\in hadrons} \ln Z_{m_i}(T,V,\mu_B,\mu_S,\mu_Q)$$

$$\sum_{i\in mesons} \ln Z^B_{m_i}(T,V,\mu_S,\mu_Q) + \sum_{i\in baryons} \ln Z^F_{m_i}(T,V,\mu_B,\mu_S,\mu_Q)$$

mesons:

$$\frac{p_i}{T^4} = \frac{d_i}{\pi^2}\left(\frac{m_i}{T}\right)^2 \sum_{l=1}^{\infty}(+1)^{l+1} l^{-2} K_2(lm_i/T)\cosh(lS_i\mu_S/T + lQ_i\mu_Q/T)$$

baryons:

$$\frac{p_i}{T^4} = \frac{d_i}{\pi^2}\left(\frac{m_i}{T}\right)^2 \sum_{l=1}^{\infty}(-1)^{l+1} l^{-2} K_2(lm_i/T)\cosh(lB_i\mu_B/T + lS_i\mu_S/T + lQ_i\mu_Q/T)$$

Boltzmann approximation

ratios are independent of spectrum and volume

→ possibly large parts of cut-off effects cancel

3 ratios:

$$\frac{\chi_4^B}{\chi_2^B} = \kappa\sigma^2 = \frac{B^4}{B^2} = 1$$

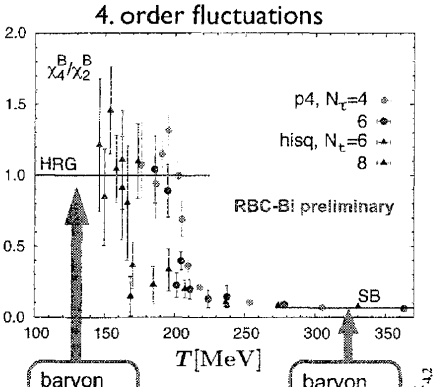
$$\frac{\chi_3^B}{\chi_2^B} = S\sigma = \frac{B^3}{B^2}\tanh(\mu_B/T)$$

$$\frac{\chi_2^B}{\chi_1^B} = \sigma^2/N_B = \frac{B^2}{B^1}\coth(\mu_B/T)$$

3) Baryon number fluctuations: lattice vs. HRG

4

4. order fluctuations



baryon number carried by **hadrons**

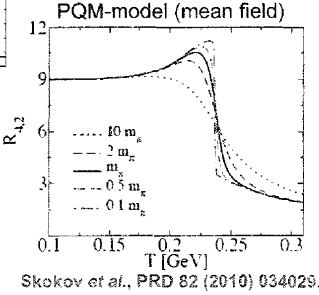
baryon number carried by **quarks**

⇒ cutoff dependence of Tc

⇒ pronounced step function indicating deconfinement

kink at Tc from critical behavior?

PQM-model (mean field)

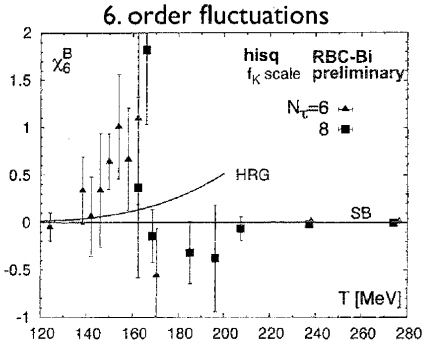


Skokov *et al.*, PRD 82 (2010) 034029.

3) Baryon number fluctuations: lattice vs. HRG

5

6. order fluctuations

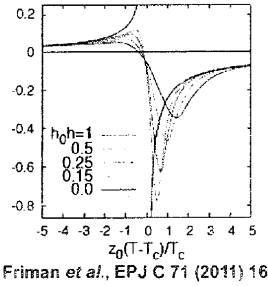


notice for $T < T_c$:

⇒ fluctuations increase over HRG

⇒ fluctuations stay positive

O(4) scaling function



Friman *et al.*, EPJ C 71 (2011) 1694.

3) Q and S fluctuations: lattice vs. HRG

6

hadron resonance gas:

$$\ln Z(T,V,\mu_B,\mu_S,\mu_Q) = \sum_{i\in hadrons} \ln Z_{m_i}(T,V,\mu_B,\mu_S,\mu_Q)$$
$$\sum_{i\in mesons} \ln Z^B_{m_i}(T,V,\mu_S,\mu_Q) + \sum_{i\in baryons} \ln Z^F_{m_i}(T,V,\mu_B,\mu_S,\mu_Q)$$

mesons:

$$\frac{p_i}{T^4} = \frac{d_i}{\pi^2}\left(\frac{m_i}{T}\right)^2 \sum_{l=1}^{\infty}(+1)^{l+1} l^{-2} K_2(l m_i/T) \cosh(l S_i \mu_S/T + l Q_i \mu_Q/T)$$

baryons:

$$\frac{p_i}{T^4} = \frac{d_i}{\pi^2}\left(\frac{m_i}{T}\right)^2 \sum_{l=1}^{\infty}(-1)^{l+1} l^{-2} K_2(l m_i/T) \cosh(l B_i \mu_B/T + l S_i \mu_S/T + l Q_i \mu_Q/T)$$

$$\frac{\chi_4^Q}{\chi_2^Q} = \frac{F^{(Q=\pm1)} + 16F^{(Q=\pm2)}}{F^{(Q=\pm1)} + 4F^{(Q=\pm2)}}$$

contributions from double charged particles, dominated by charged pions for low T

$$\frac{\chi_4^S}{\chi_2^S} = \frac{F^{(S=\pm1)} + 16F^{(S=\pm2)} + 81F^{(S=\pm3)}}{F^{(S=\pm1)} + 4F^{(S=\pm2)} + 9F^{(S=\pm3)}}$$

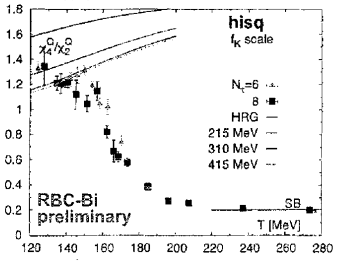
contributions from double and triple strange particles, dominated by Kaons for low T

⇒ deviations from unity for $T \gtrsim 100$ MeV

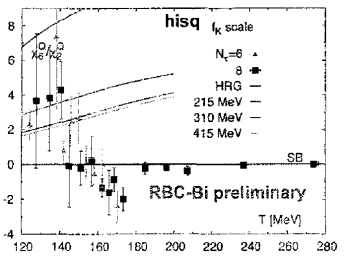
3) Electric charge fluctuations: lattice vs. HRG

7

4. order fluctuations



6. order fluctuations



⇒ negative fluctuations above Tc

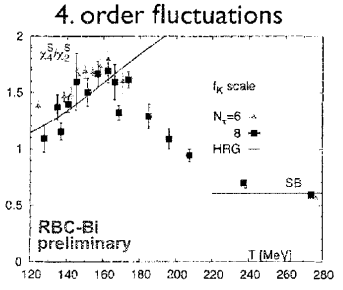
⇒ electric charge fluctuations are sensitive to the light pion sector (which is distorted on the lattice)

⇒ continuum extrapolations for higher moments of electric charge fluctuations become increasingly difficult

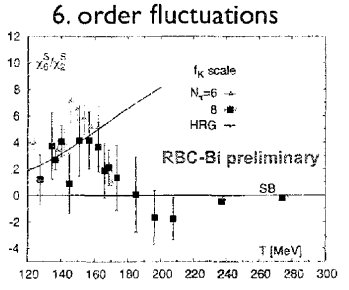
3) Strangeness fluctuations: lattice vs. HRG

8

4. order fluctuations



6. order fluctuations



⇒ negative fluctuations above Tc

⇒ close to HRG for $T \lesssim 160$ MeV (approach from above)

3) Hadronic fluctuations: lattice vs. experiment

9

Approaching a critical end-point at $\mu_B > 0$?

- a Taylor expansion approach:

$$p/T^4 = c_0 + c_2(\mu/T)^2 + c_4(\mu/T)^4 + c_6(\mu/T)^6 + \cdots$$

$$\Rightarrow \quad \frac{\chi_2}{\chi_1} = \frac{2c_2 + 12c_4(\mu/T)^2 + 30c_6(\mu/T)^4 + \cdots}{2c_2(\mu/T) + 4c_4(\mu/T)^3 + 6c_6(\mu/T)^5 + \cdots}$$

$$= \left(\frac{\mu}{T}\right)^2 \frac{1 + 6(c_4/c_2)(\mu/T)^2 + 15(c_6/c_2)(\mu/T)^4 + \cdots}{1 + 2(c_4/c_2)(\mu/T)^2 + 3(c_6/c_2)(\mu/T)^4 + \cdots}$$

$\Rightarrow$ similar expansions for χ_4/χ_2, χ_3/χ_2

can be used to get a model independent freeze out line, input: continuum extrapolated c4/c2 from lattice QCD

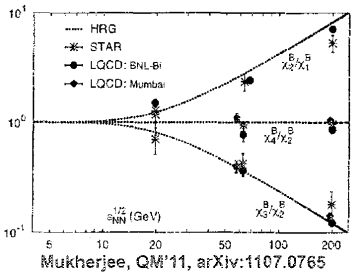
- **for now**: use parametrization of freeze-out line from statistical models in terms of the center of mass energy

3) Hadronic fluctuations: lattice vs. experiment

10

Approaching a critical end-point at $\mu_B > 0$?

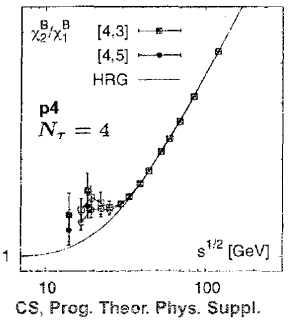
- analyze ratios of moments of baryon number fluctuations
  $\Rightarrow$ **independent of the spectrum, simple dependence on μ_B**
- use parametrization of freeze-out line in the center of mass energy



Mukherjee, QM'11, arXiv:1107.0765

STAR data:
Aggarwal *et al.*, PRL (2010) 022302

$\Rightarrow$ net-proton number fluctuations are close to HRG and lattice QCD (using HRG input)



CS, Prog. Theor. Phys. Suppl. 186 (2010) 563

$\Rightarrow$ systematic and statistical errors increase for $\sqrt{s} \leq 20$ GeV

Probability distribution of conserved charges and the QCD phase transition

OUTLINE:

- QCD phase boundary, its O(4) „scaling" & relation to freezeout in HIC
- Moments and probablility distributions of conserved charges as probes for proximity to O(4) criticality
- STAR data & expectiations

K. Redlich, University of Wroclaw, Poland

With: P. Braun-Munzinger, B. Friman
F. Karsch, V. Skokov

O(4) scaling of net-baryon number fluctuations

- The fluctuations are quantified by susceptibilities

$$\chi_B^{(n)} = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n} := c_n \qquad \text{with} \qquad P = P_{reg} + P_{Singular}$$

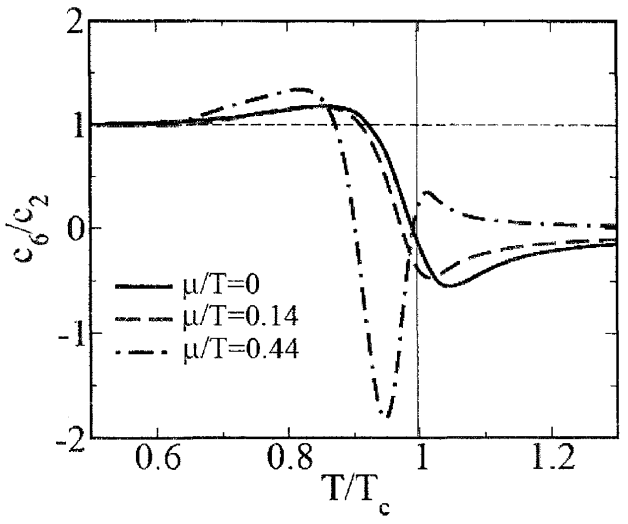
- From free energy and scaling function one gets

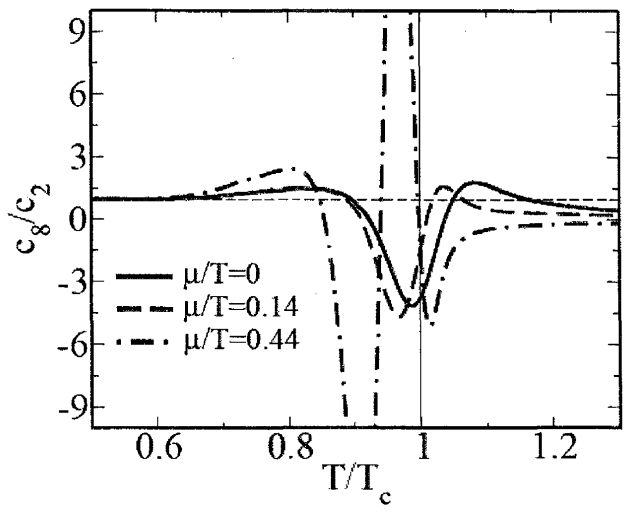
$$\chi_B^{(n)} \approx \chi_r^{(n)} + c\, h^{2-\alpha-n/2} f_\pm^{(n/2)}(z) \quad for \;\; \mu = 0 \;\; and \;\; n \;\; even$$

$$\chi_B^{(n)} \approx \chi_r^{(n)} + c_\mu\, h^{2-\alpha-n} f_\pm^{(n)}(z) \quad for \;\; \mu \neq 0$$

- Resulting in singular structures in n-th order moments which appear for $n \geq 6 \;\; at \;\; \mu = 0$ and for $n \geq 3 \;\; at \;\; \mu \neq 0$ since $\alpha \approx -0.2$ in O(4) univ. class

Ratio of higher order cumulants at finite density





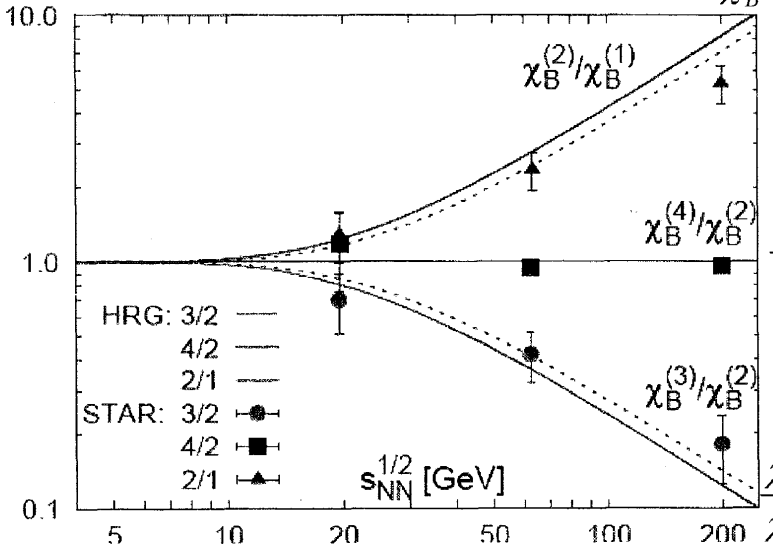
Deviations of the ratios from their asymptotic, low T-value, are increasing with the order of the cumulant order and with increasing chemical potential

Properties essential in HIC to discriminate the phase change by measuring baryon number fluctuations !

Coparison of the Hadron Resonance Gas Model with STAR data

- Frithjof Karsch & K.R.

$$\frac{\chi_B^{(2)}}{\chi_B^{(1)}} \approx \coth(\mu_B / T)$$



$$\frac{\chi_B^{(4)}}{\chi_B^{(2)}} = 1$$

$$\frac{\chi_B^{(3)}}{\chi_B^{(2)}} \approx \tanh(\mu_B / T)$$

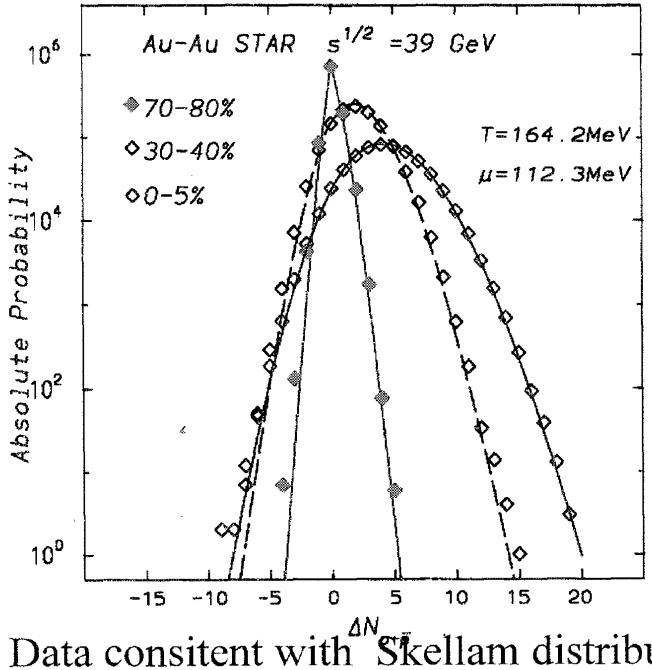
- RHIC data follow generic properties expected within HRG model for different ratios of the first four moments of baryon number fluctuations

deviations between HRG model and data for the variance ($\chi_B^{(2)}$)?

Error Estimation for Moments Analysis: Xiaofeng Luo arXiv:1109.0593v

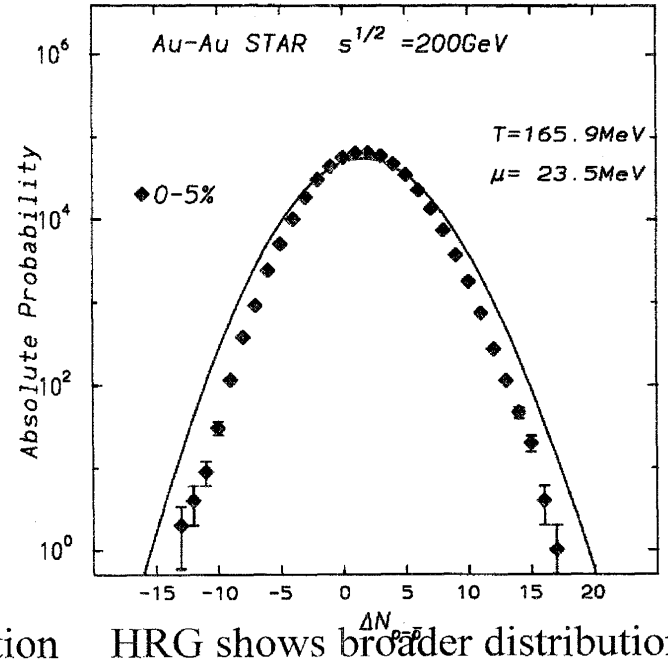
Centrality dependence at $\sqrt{s_{NN}}$ = 39 and 200 GeV

Preliminary STAR data



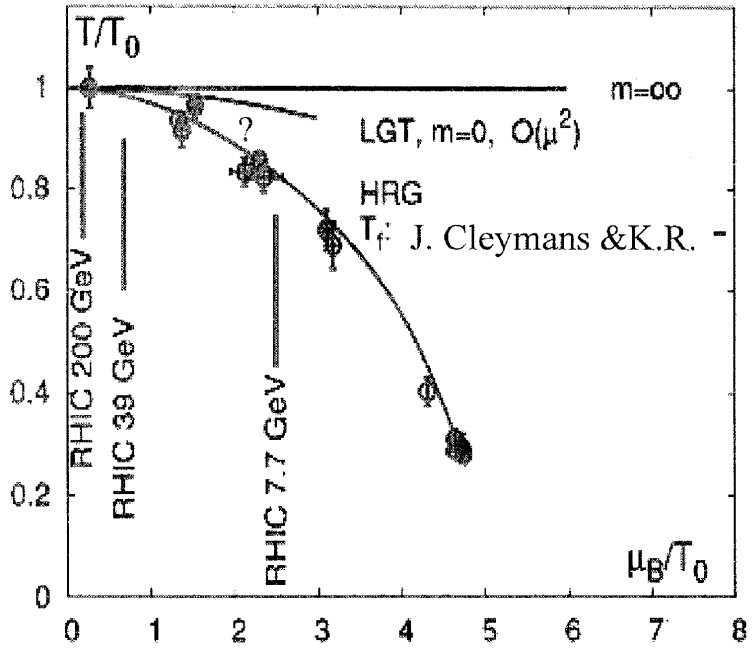
Data consitent with Skellam distribution

STAR data-efficiency uncorected



HRG shows broader distribution

Conclusions:



freeze-out line and chiral phase transition

J. Cleymans et al, PRC73, 034905 (2006)

BNL-Bielefeld-GSI, arXiv:1011.3130

- Higher order moments and probability distributions are excellent probes of criticality in HIC
- The 6th and 8th order moments negative already at the LHC
- Deviation of P(N) sets in at $\sqrt{s} > 39GeV$ and increases with centrality:

  remnant of O(4) criticality

  This might indicate that critical line decouples from the freezeout line near $\sqrt{s} > 39GeV$

  The above need to be checked with efficiency corrected data

PHENIX Flow at Low Energies

Yi Gu (for the PHENIX Collaboration)
Chemistry Department, State University of New York,
Stony Brook, NY 11794-3400, USA

Oct 3rd, 2011

Abstract

To map out the QCD phase diagram, and to further investigate the properties of the different phases, RHIC has recently embarked on an energy scan program. PHENIX results from this program will be presented with emphasis on the anisotropic flow coefficients v_n for n=2,3,4, extracted from Au+Au collisions at the lower beam collision energies of $\sqrt{s_{NN}}$= 7.7GeV, 39GeV,62.4GeV. The measurements, which employ both the Event Plane method and the long-range Two Particle Correlation method, show good consistency and suggest a saturation of these flow coefficients for $\sqrt{s_{NN}}$= 39 - 200 GeV. Measurements for several particle species show that the empirical quark number scaling ansatz still holds for the lower collision energy of 39GeV, suggesting an important role for partonic flow at this lower collision energy. The flow excitation function shows a fairly rapid decrease of v_2 for the lowest collision energy of 7.7GeV, reflecting the demise of partonic flow and the rise of hadronic-driven flow.

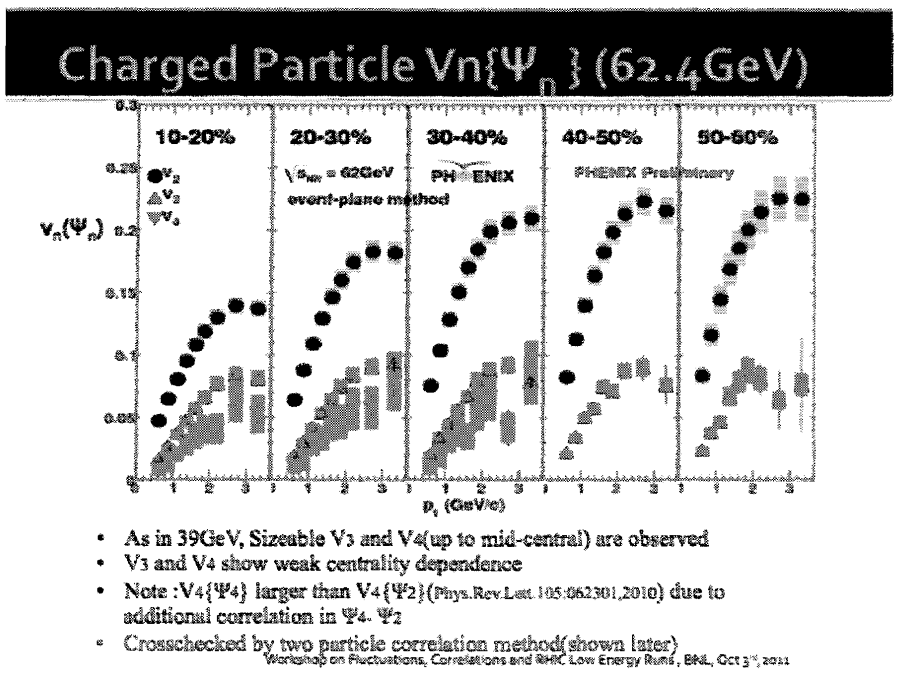


Figure 1: v_n,n=2,3,4 at 62.4GeV, obtained by Event Plane method

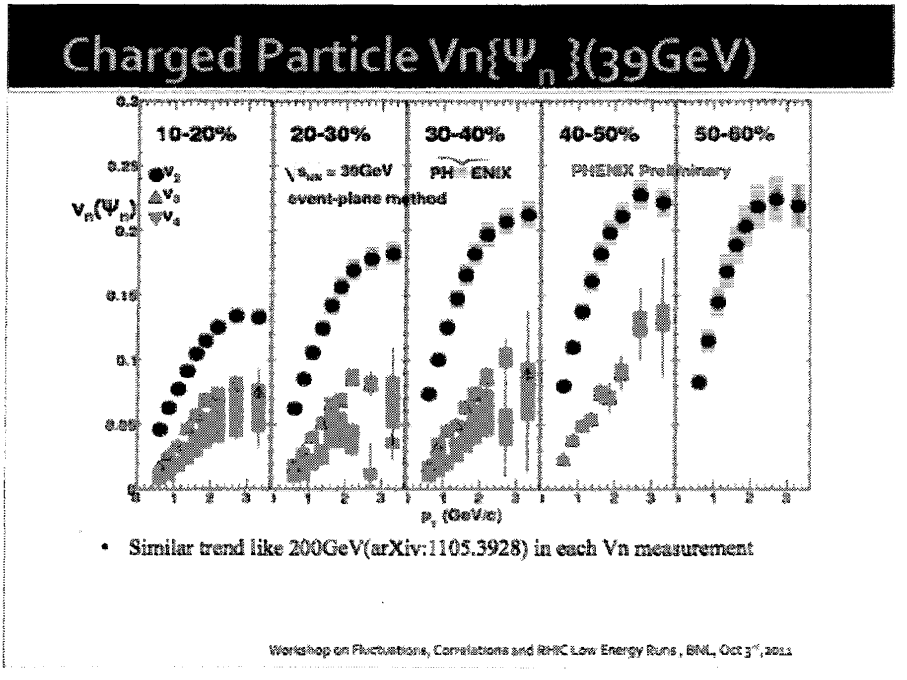


Figure 2: v_n,n=2,3,4 at 39GeV, obtained by Event Plane method

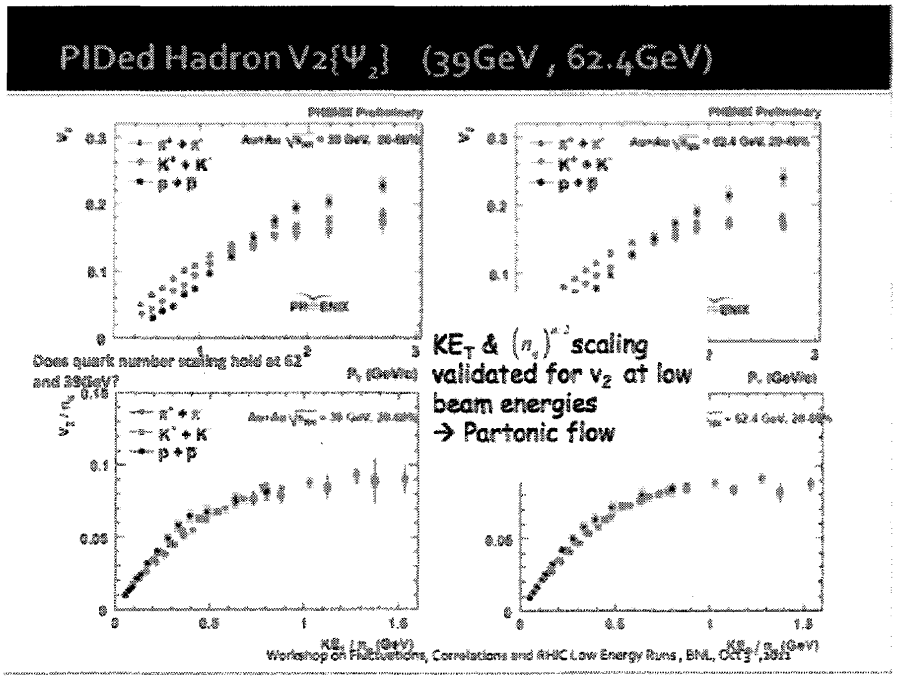


Figure 3: Quark number scaling ansatz still holds, which suggests partonic flow expansion at low beam energies

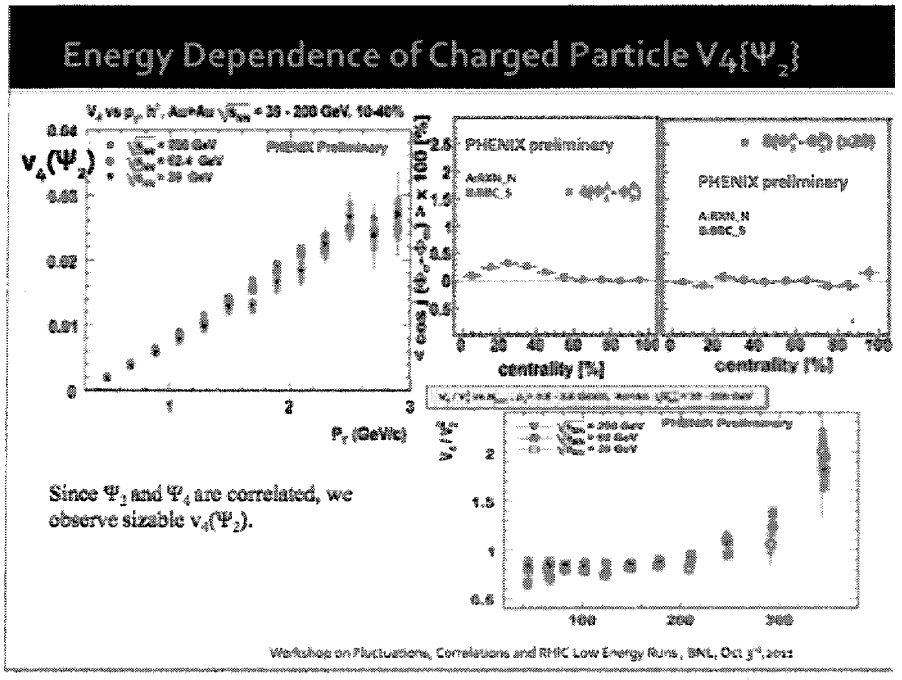


Figure 4: Flow at mixed-order even plane at low energies

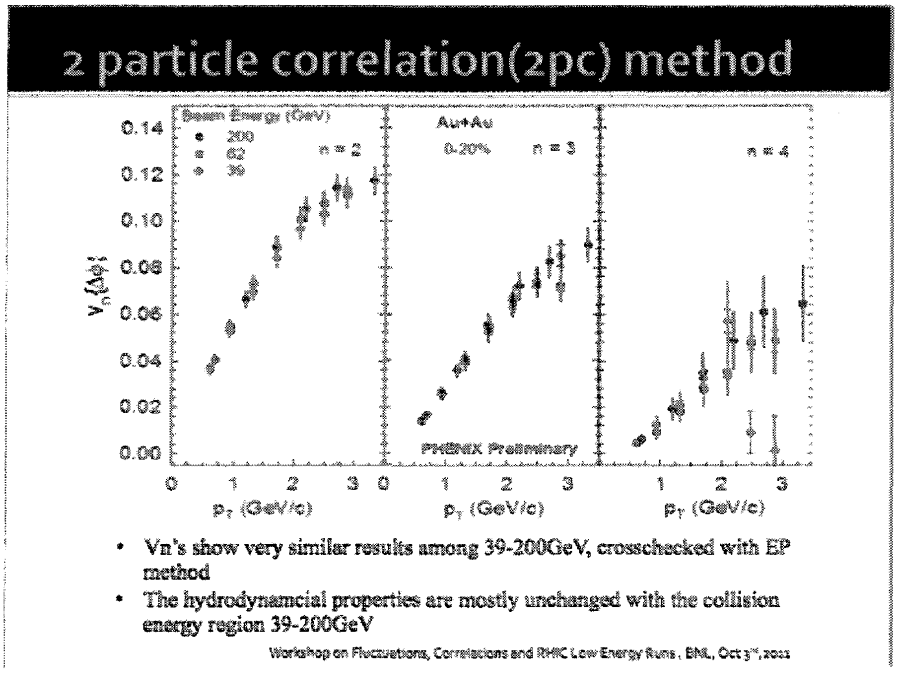


Figure 5: v_n,n=2,3,4 saturate from 200GeV down to 39GeV

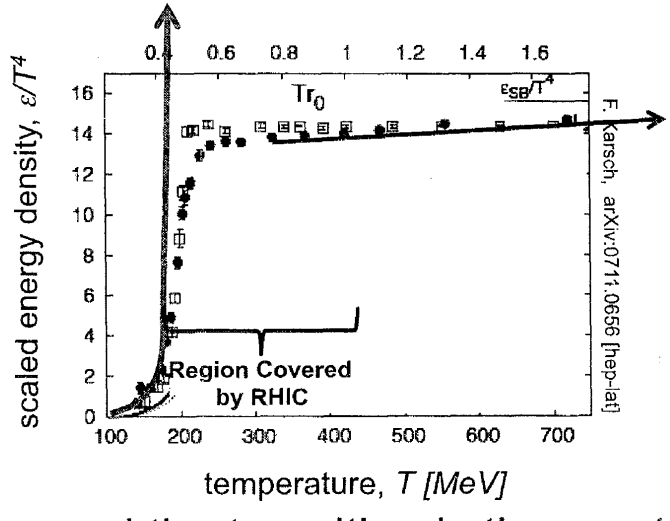
Flow at Lower RHIC Energies

Paul Sorensen (BNL)

Thermodynamics of QCD

Quantum Chromodynamics shows a rapid crossover to QGP above a critical T: ε/T^4 ($\propto$ # degrees-of-freedom) plateaus when quarks and gluons become the relevant degrees of freedom

Hadron Gas:
maximum T

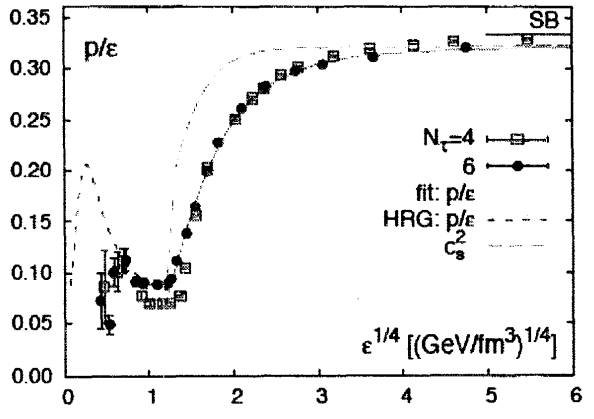


QGP: no maximum
adding energy increases T, instead of creating heavier hadrons

The region around the transition is the most interesting, not the asymptotic limit

Thermodynamics of QCD

Quantum Chromodynamics shows a rapid crossover to QGP above a critical T: ε/T^4 ($\propto$ # degrees-of-freedom) plateaus when quarks and gluons become the relevant degrees of freedom



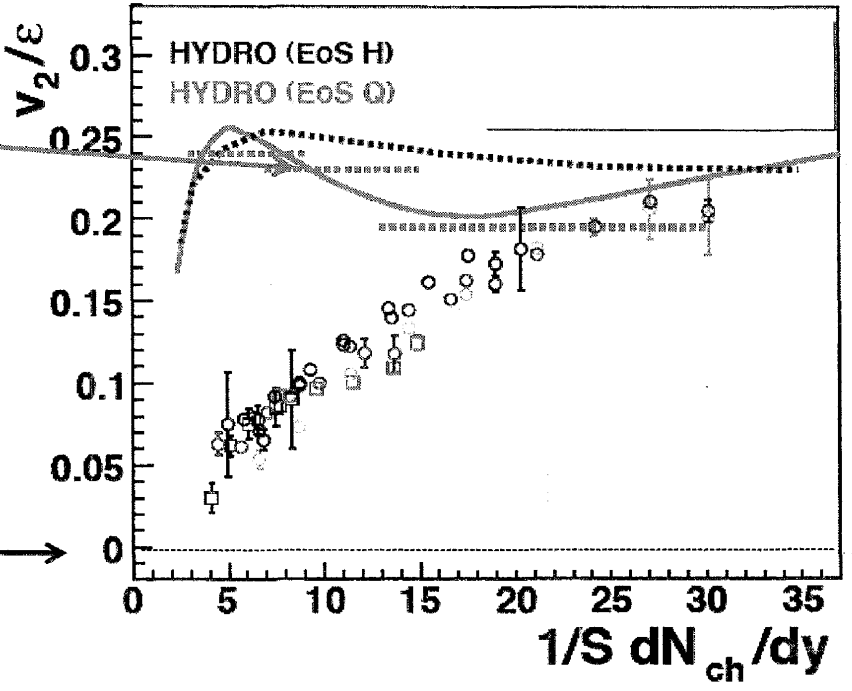
The region around the transition will exhibit significant changes in pressure. Can we study these?

Conversion of Initial Spatial Distortion

S. Voloshin, J.Phys.G34:S883-886,2007

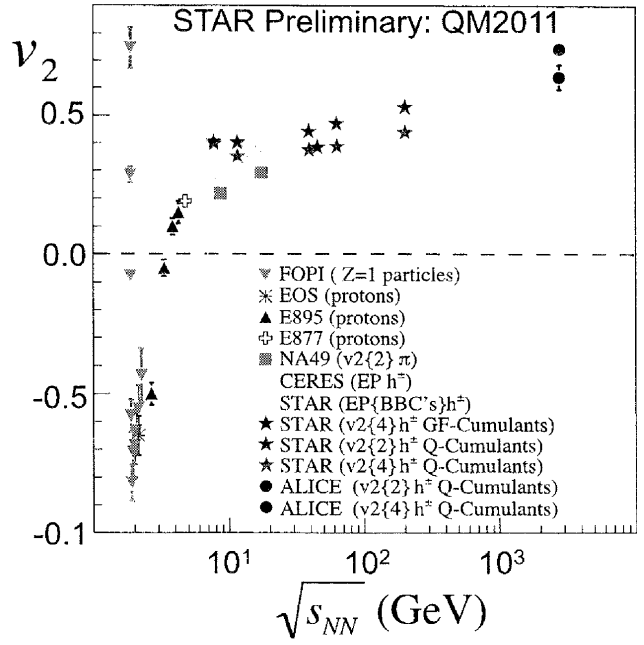
zero mean-free-path limit

Ballistic expansion



The strategy is to study quantities related to pressure vs something related to energy density

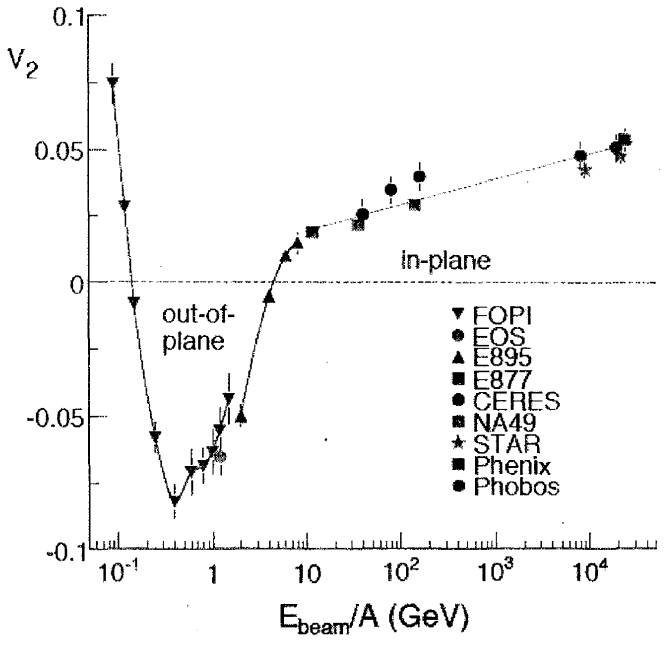
v_2 Over Three Orders of Magnitude

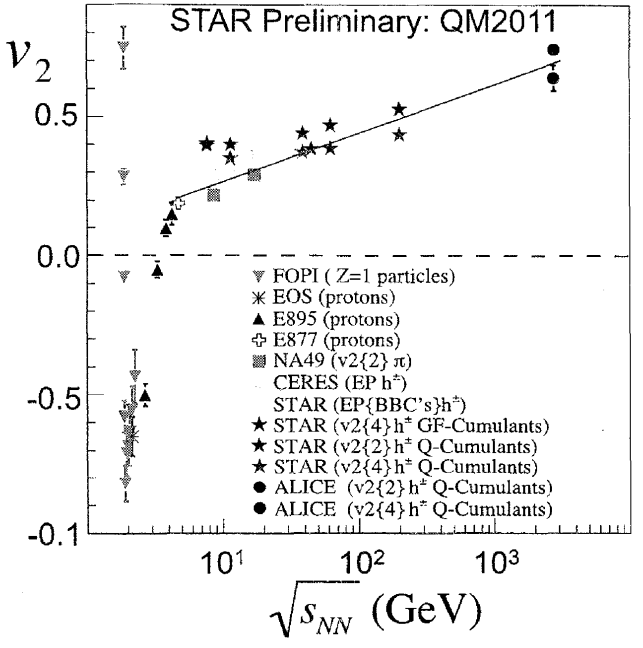


RHIC covers exactly the range where softening is expected

STAR data on $v_2\{2\}$ and $v_2\{4\}$ follows smooth trends but better systematics may reveal more detail…

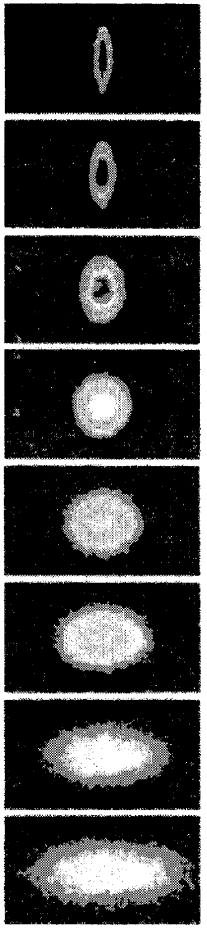
v_2 Over Three Orders of Magnitude





RHIC covers exactly the range where softening is expected

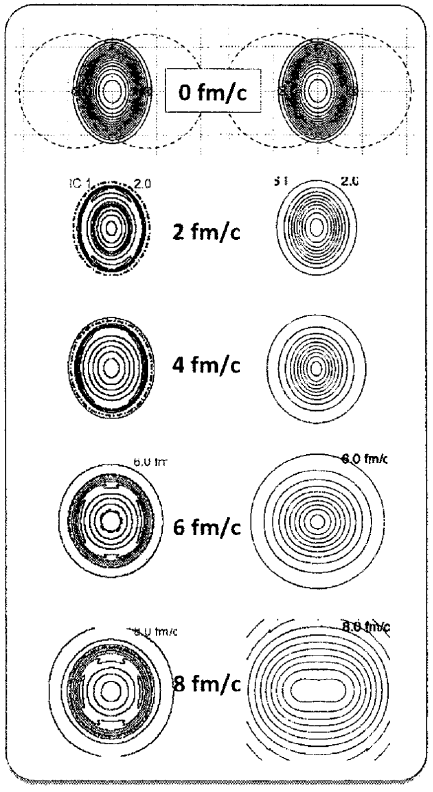
Log linear curve does not describe new data; Old compilation was a hodge-podge of techniques, PIDs, and acceptances



The freeze-out source shape: recent results from the STAR energy scan

Mike Lisa (Ohio State University)
for the STAR Collaboration

phi- the sexy direction



evolution from initial "known" shape depends on

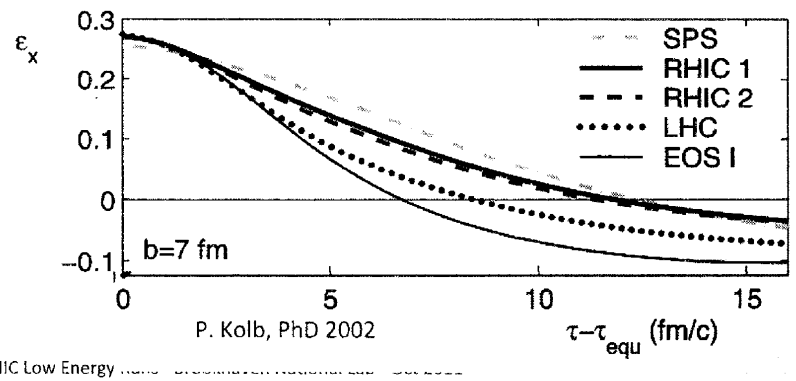
- pressure anisotropy ("stiffness")
- lifetime

Both are interesting!

We will measure a convolution over freezeout

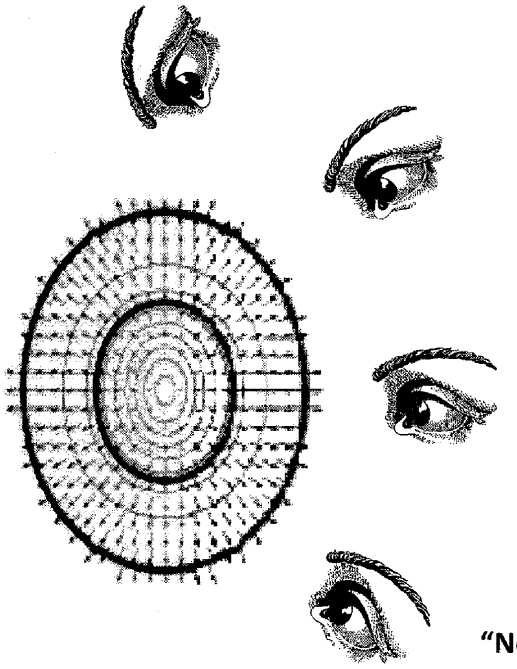
- model needed

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

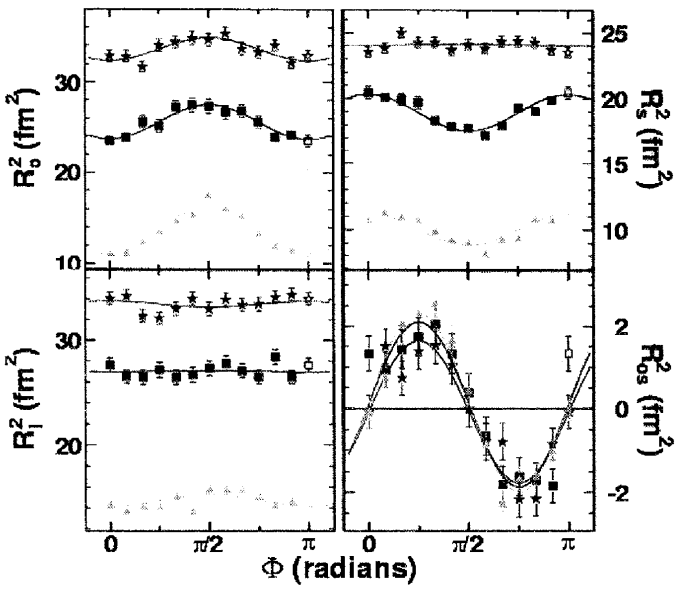


P. Kolb, PhD 2002

Azimuthal dependence of HBT radii at RHIC



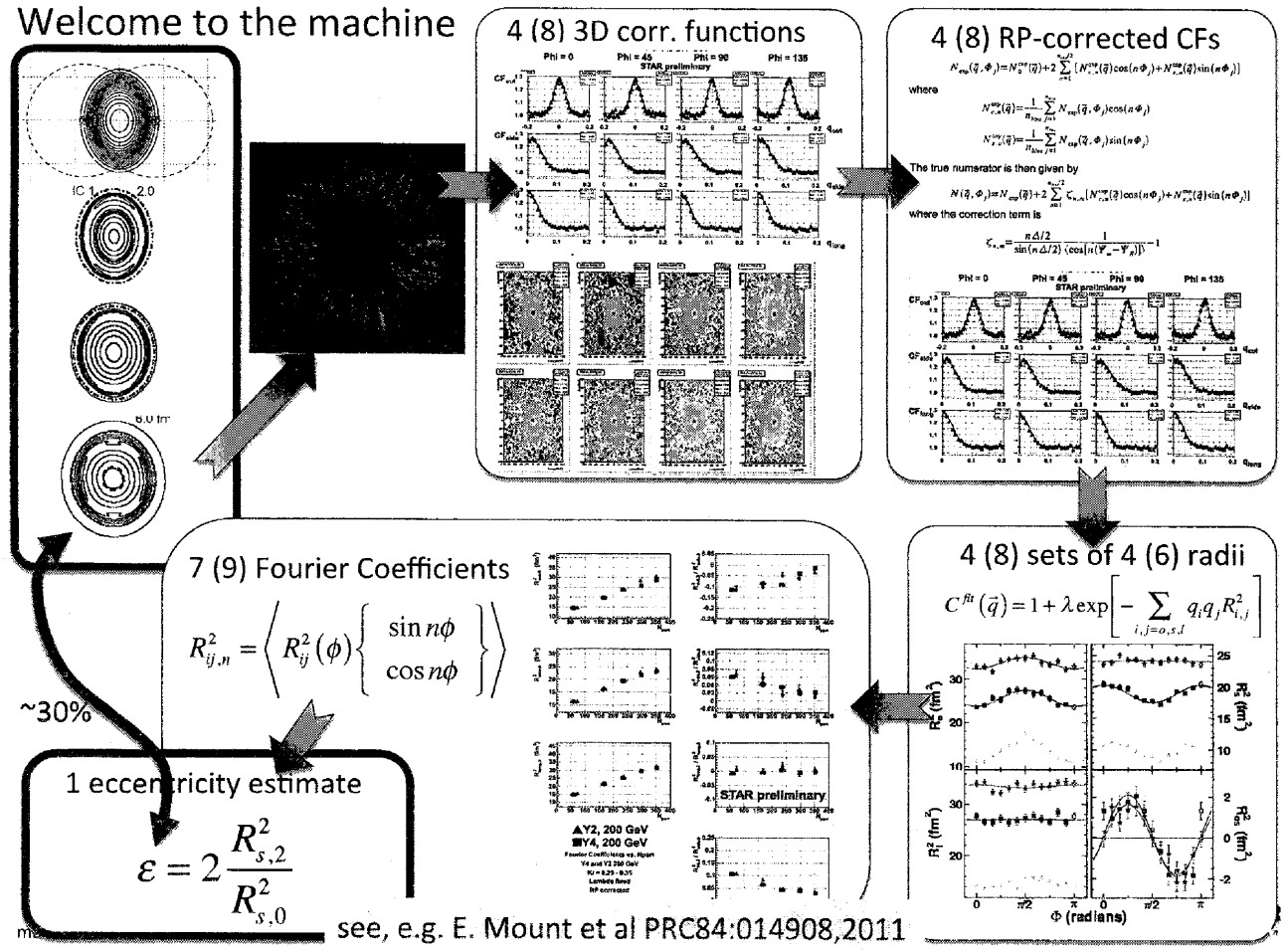
STAR, PRL93 012301 (2004)



"No-flow formula" estimated good within ~ 30% (low pT)

Retiere&MAL PRC70 (2004) 044907
Mount et al, PRC84:014908,2011

$$R_{s,n}^2 \equiv \left\langle R_s^2(\phi)\cdot\cos(n\phi)\right\rangle \qquad \varepsilon \approx 2\frac{R_{s,2}^2}{R_{s,0}^2} \approx 2\frac{R_{os,2}^2}{R_{s,0}^2} \approx -2\frac{R_{o,2}^2}{R_{s,0}^2}$$


Welcome to the machine
4 (8) 3D corr. functions
Phi = 0
Phi = 45
Phi = 90
Phi = 135
STAR preliminary
4 (8) RP-corrected CFs
where
The true numerator is then given by
where the correction term is
4 (8) sets of 4 (6) radii
$C^{fit}(\vec{q}) = 1 + \lambda \exp\left[-\sum_{i,j=o,s,l} q_i q_j R^2_{i,j}\right]$
Φ (radians)
7 (9) Fourier Coefficients
$R^2_{ij,n} = \left\langle R^2_{ij}(\phi) \left\{ \begin{matrix} \sin n\phi \\ \cos n\phi \end{matrix} \right\} \right\rangle$
Y2, 200 GeV
Y4, 200 GeV
STAR preliminary
~30%
1 eccentricity estimate
$\varepsilon = 2\frac{R^2_{s,2}}{R^2_{s,0}}$
see, e.g. E. Mount et al PRC84:014908,2011

10+ years of asHBT systematics

2000 : E895/AGS
PLB496 1 (2000)

2004: STAR/RHIC
200 GeV
PRL93 012301 (2004)

2008: CERES/SPS
PRC78 064901 (2008)

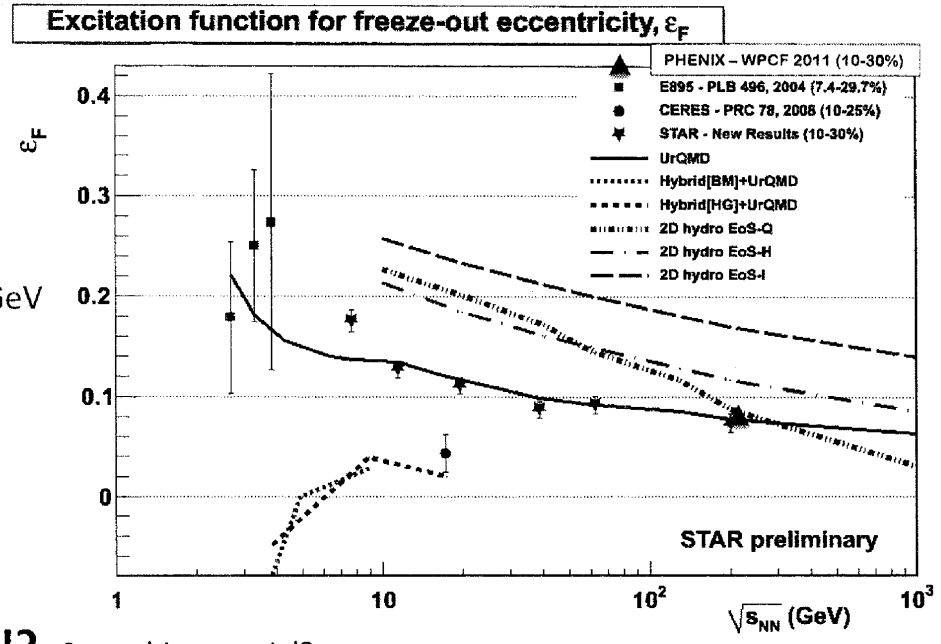
2010 (WPCF Kiev):
STAR/RHIC 62.4 GeV

2011 (QM Annecy):
STAR/RHIC
7.7, 11.5, 39 GeV
arXiv:1107.1527

2011 (WPCF Tokyo)
STAR/RHIC
19.6 GeV

2011 (WPCF Tokyo)
PHENIX/RHIC
200 GeV

Soon: ALICE/LHC

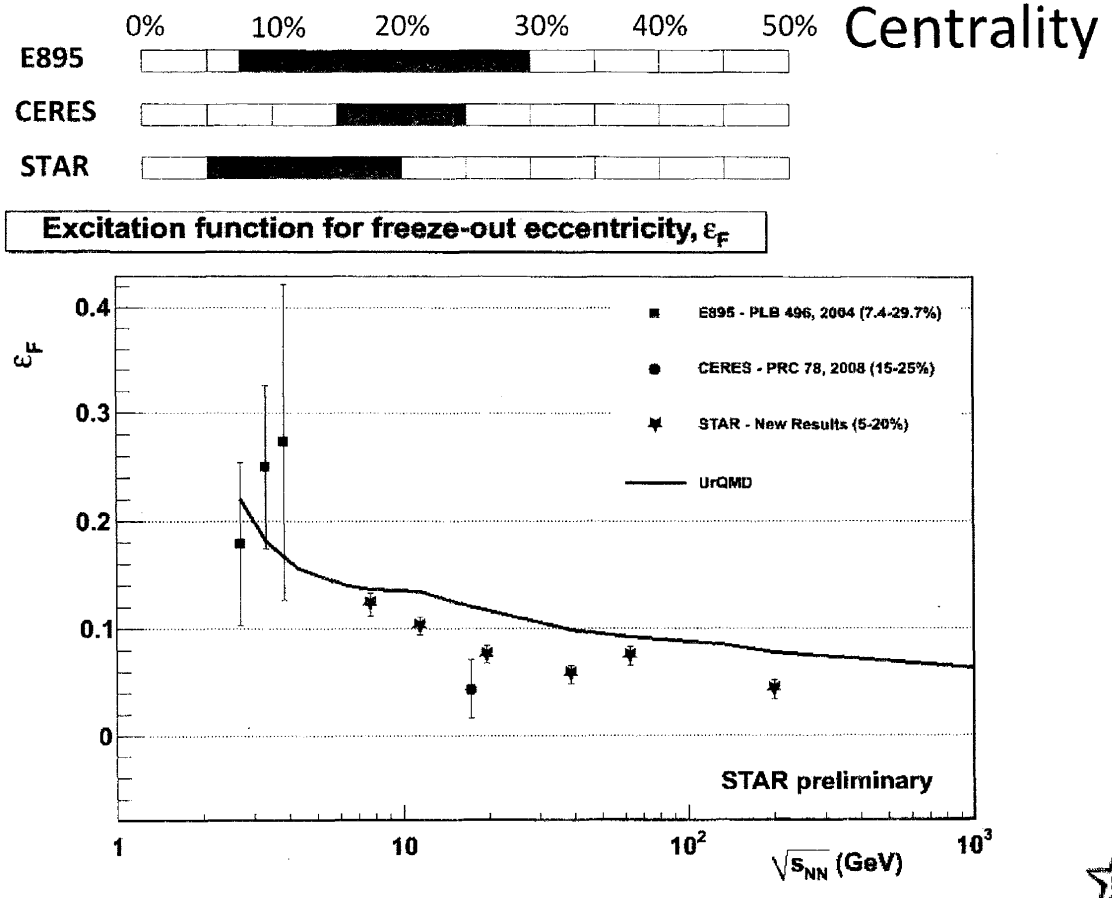


!? Something special?

!? A real minimum? – speculation of P.T. (Lisa et al, New J. Phys 2011)

!!!? A real **sharp** minimum at the "special" kink/horn/step energy?

Uh-oh


0%
10%
20%
30%
40%
50%
Centrality
E895
CERES
STAR
Excitation function for freeze-out eccentricity, ε_F
ε_F
0.4
0.3
0.2
0.1
0
E895 - PLB 496, 2004 (7.4-29.7%)
CERES - PRC 78, 2008 (15-25%)
STAR - New Results (5-20%)
UrQMD
STAR preliminary
1
10
10^2
10^3
$\sqrt{s_{NN}}$ (GeV)

J/ψ Results from PHENIX

Abhisek Sen

Georgia State University

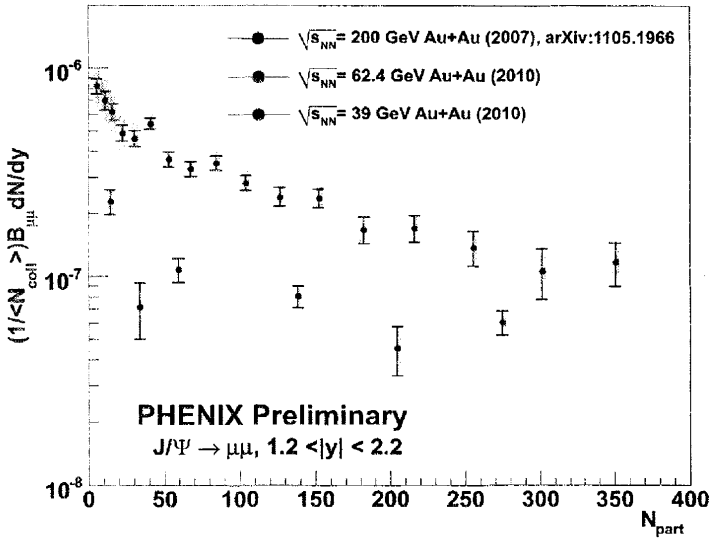
Fluctuations, Correlations and RHIC Low Energy Runs workshop

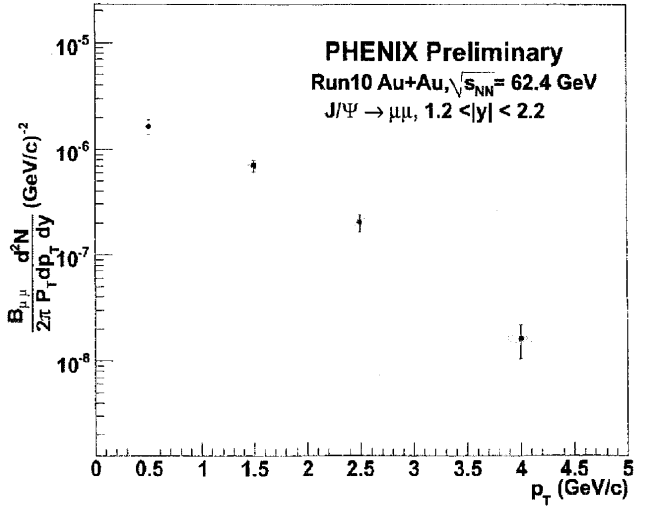
BNL, USA

October 5, 2011

Quarkonia suppression is one of the highly cited signatures of quark gluon plasma (QGP) formed in relativistic heavy ion collisions. PHENIX observed a high suppression of J/Ψ production in Au+Au collisions at √s = 200 GeV. However, theoretical predictions remain diverse due to lack of precise knowledge of heavy flavor meson production, suppression, regeneration in hot and dense medium and other cold nuclear effects. In order to separate these effects the PHENIX collaboration also measured J/Ψ production in d+Au collisions at √s = 200 GeV for isolating coldnuclear effects and Au+Au collisions at low energies (√s = 62 GeV and 39 GeV) to study the onset of the nuclear phase transition to QGP. The measurement of J/Ψ nuclear modification factors at different center of mass energies may elucidate this transition and supplement our understanding of the energy dependence of cold nuclear matter effects.

J/ψ Invariant yields in Au+Au collision



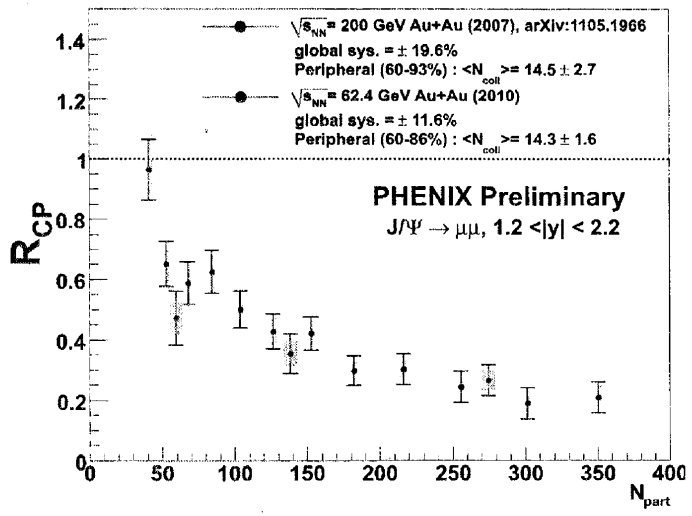


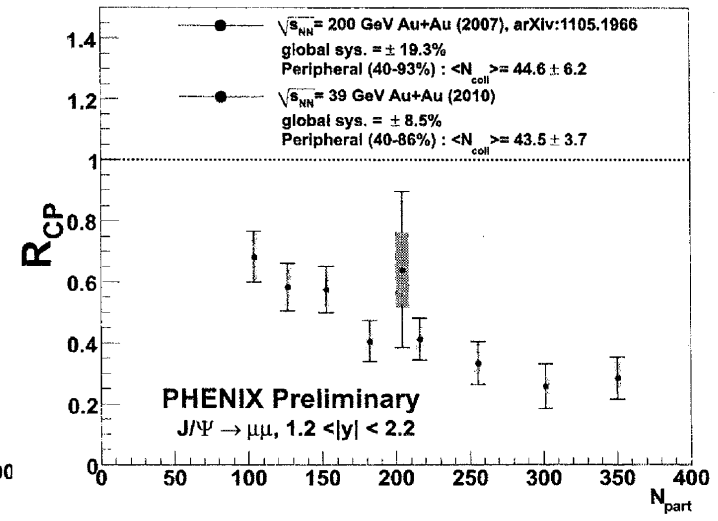
- In 2010 PHENIX collected 700M (200M) MB events from 62.4 GeV (39 GeV) Au+Au collision.
- Total No of J/ψ's
  - ✓ **62 GeV: 1130.4 +/− 172.7(stat)**
  - ✓ **39 GeV: 169.1 +/− 82.7(stat)**

Rapidity 1.2 <|y| <2.2

Energy dependence of J/ψ R_{CP}

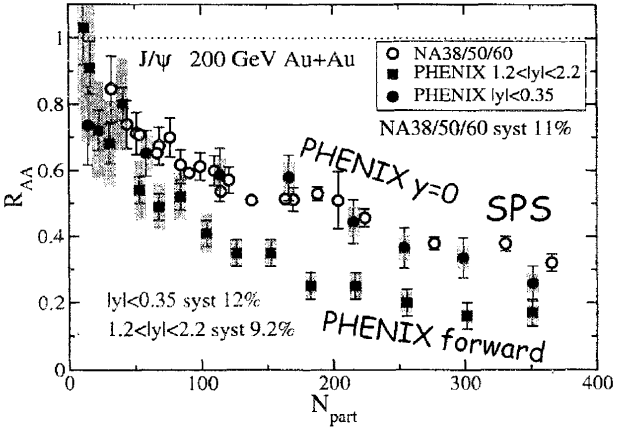
Rapidity 1.2 <|y| <2.2



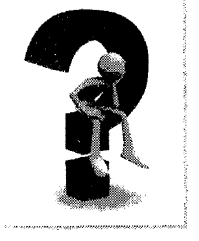


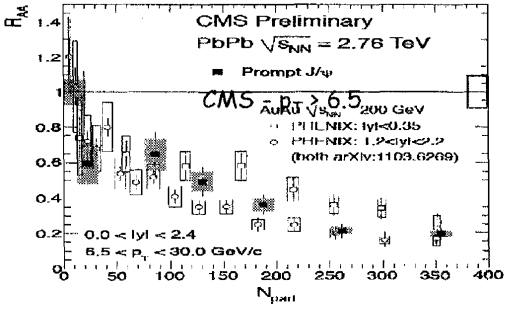
- ❑PHENIX doesn't have a p+p reference at 62 and 39 GeV.
- ❑ Rcp will give us an insight about the suppression level.
- ❑ Suppression is of similar level within uncertainties.

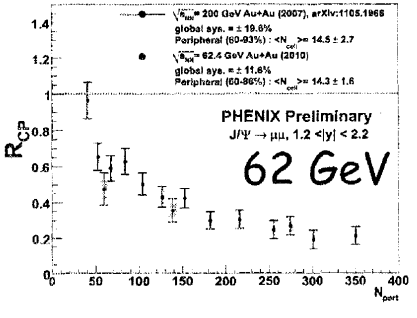
Quarkonia Suppression Similarity in √s

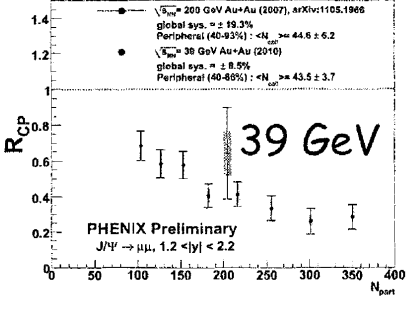


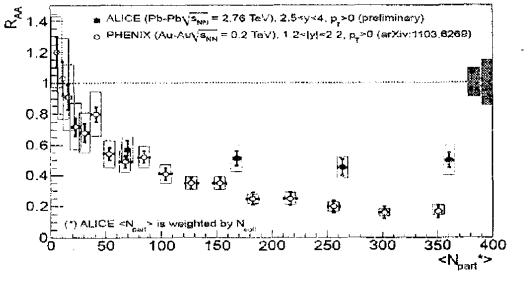
Overall suppression of J/ψ is nearly "similar" between RHIC, SPS, & LHC ?



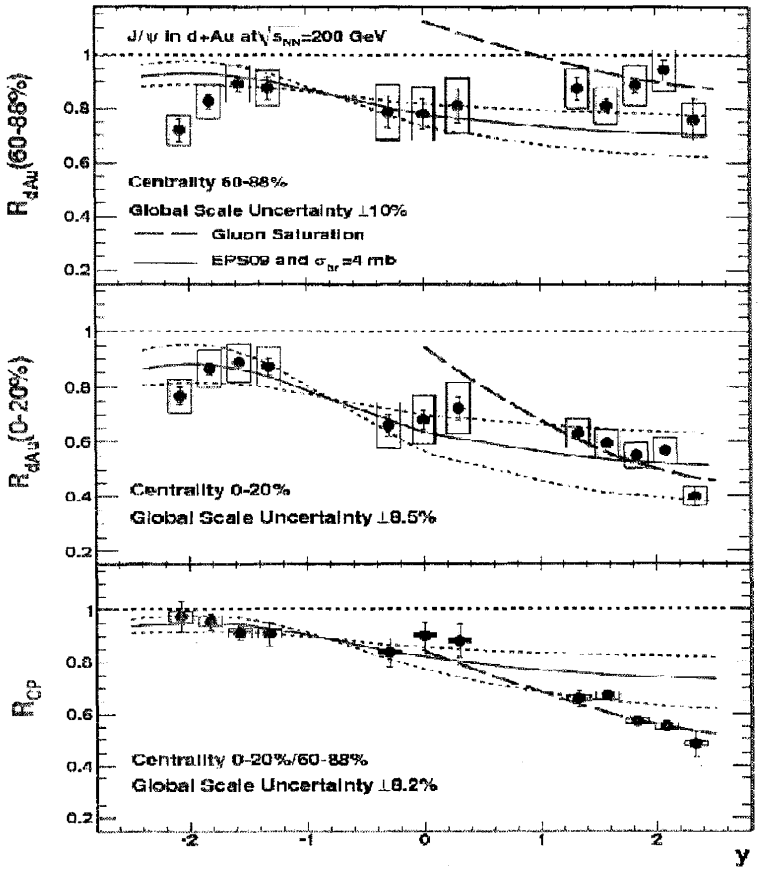








J/ψ suppression in d+Au (200 GeV)



- (Solid Red curves) A reasonable aggreement with EPS09 nPDF + σ_{br} = 4 mb for central collisions but not peripheral.
- (Dashed green line) CGC calculations can't reproduce mid-rapidity. (Nucl. Phys. A 770(2006) 40)

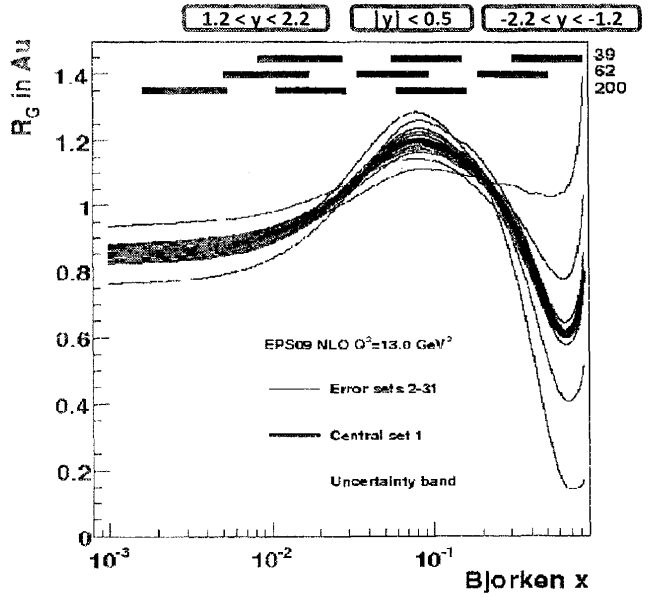
What about Rcp ?

EPS09 with assumed linear thickness dependence fails to describe centrality dependence of forward rapidity region.

PhysRevLett.107.142301

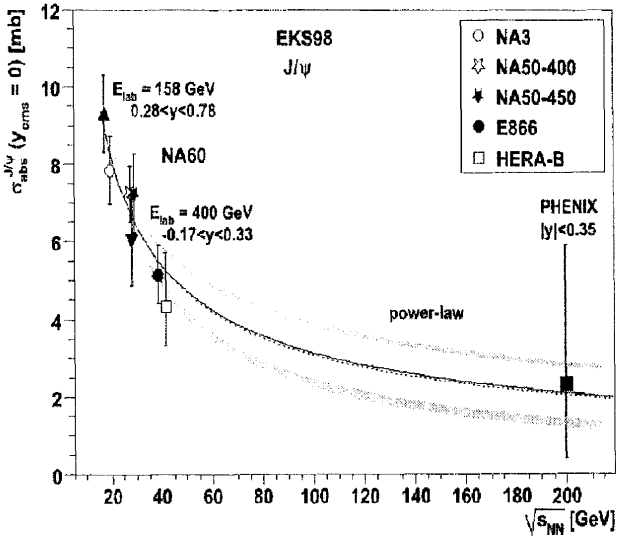
Energy dependence of CNMs

R_G for J/ψ production at RHIC



A systematic analysis at y~0 using EKS98 + $\sigma_{breakup}$ showed a clear **collision energy dependence** of $\sigma_{breakup}$.

JHEP 0902:014 (2009)



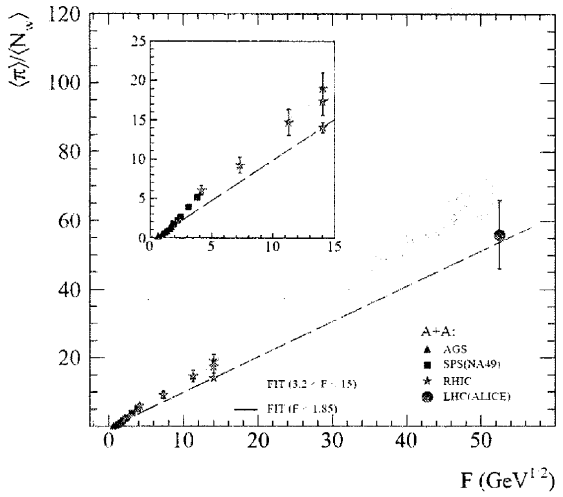
Status of Fluctuation Analysis in NA49 at CERN SPS Energies

P. Seyboth
Max-Planck-Institut für Physik, München
and
Jan Kochanowski University, Kielce
(for NA49/NA61 collaborations)

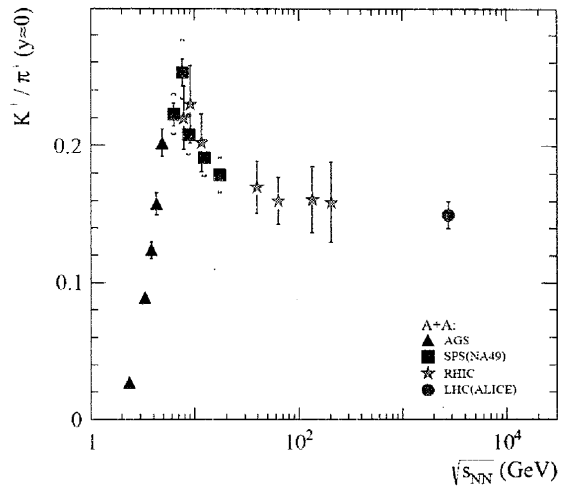
- confirmation of onset of deconfinement
- results on fluctuations
  - particle ratios , NA49/STAR disagreements
  - search for critical point of strongly interacting matter
- future programs

confirmation by recent STAR and ALICE results (2)

the kink



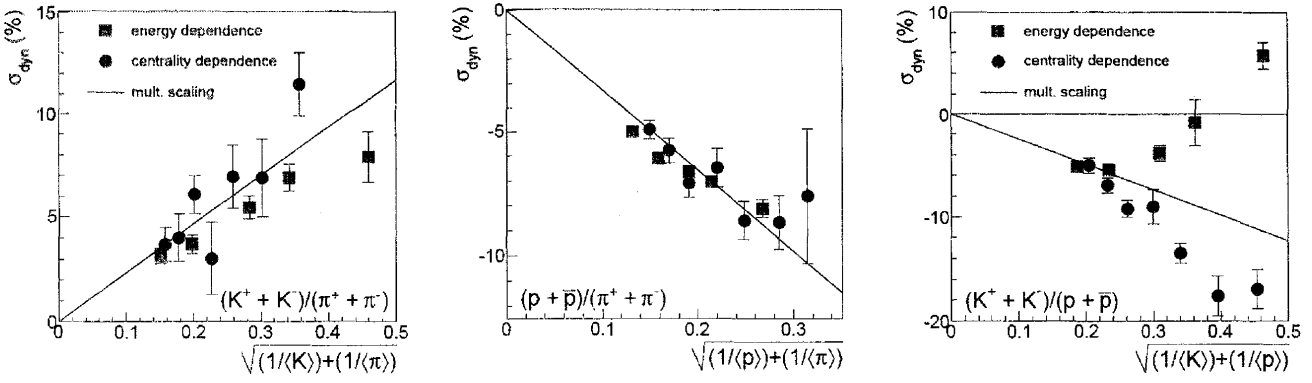
the horn



- estimate obtained from ALICE data not inconsistent with extrapolation
- preliminary STAR results confirm horn
- K/π constant above SPS as expected

onset of deconfinement at 30A GeV remains the most natural scenario

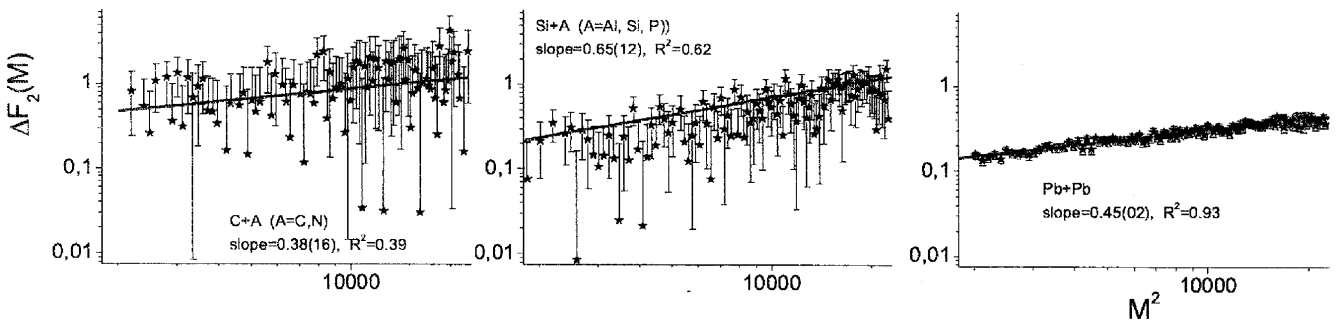
test of simultaneous multiplicity scaling
for energy and centrality dependence

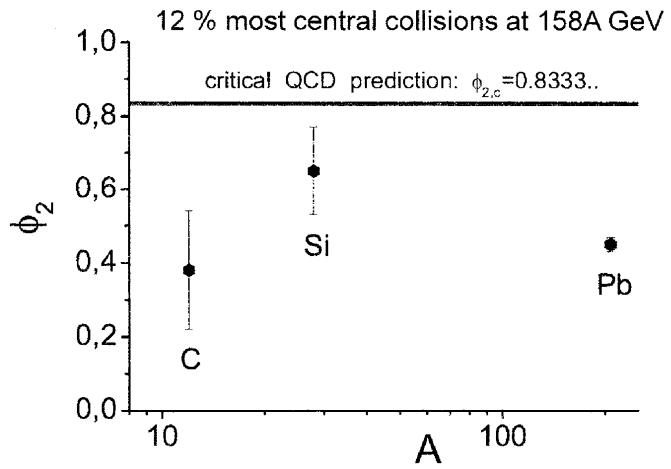


generic scaling
- works for K/π and p/π fluctuations
- cannot describe K/p fluctuations

proton intermittency analysis (preliminary results)

(N.Davis, Univ.of Athens)

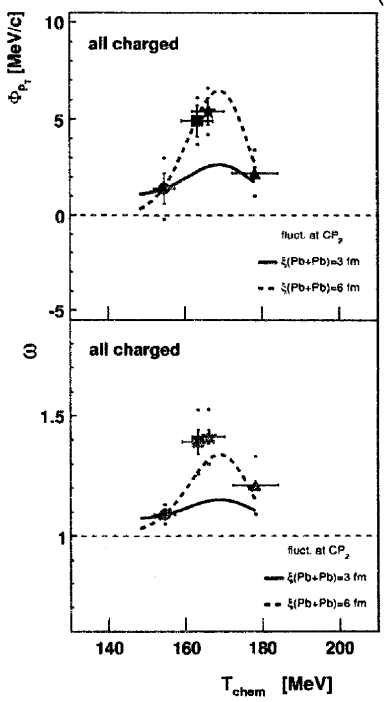


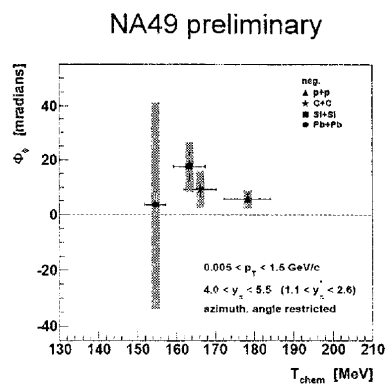


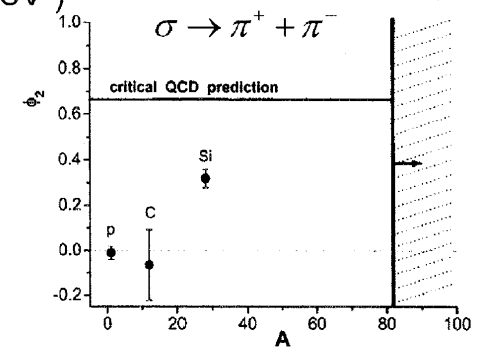
suggestive of maximum in p intermittency for central Si+Si collisions at 158A GeV

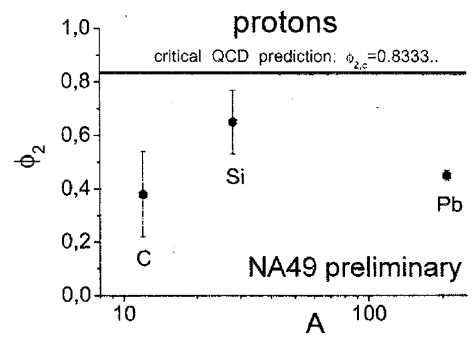
Conclusion from the critical point search in NA49

(central collisions at 158A GeV)





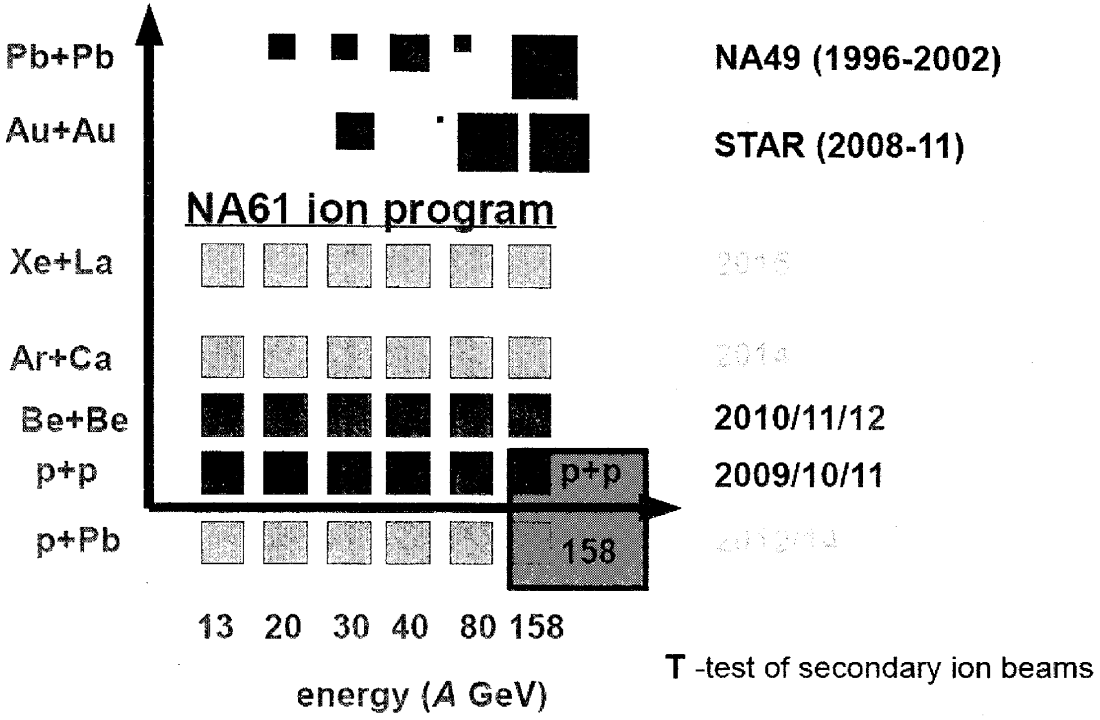




fluctuations of $\langle p_T \rangle$, N_{ch}, $\langle \phi \rangle$, intermittency of $\pi^+\pi^-$,p tend to a maximum in Si+Si collisions at 158A GeV

first hint of the hill of fluctuations ??

Status and plans for ion collisions at SPS energies



T -test of secondary ion beams

SHINE NA61

P.Seyboth: Status of Fluctuation Studies at CERN SPS Energies
BNL Workshop on Fluctuations, 3-5/10/2011

Current Results for Dynamical K/π, p/π, and K/p Fluctuations from the STAR Experiment

Terence J Tarnowsky

(for the STAR Collaboration)

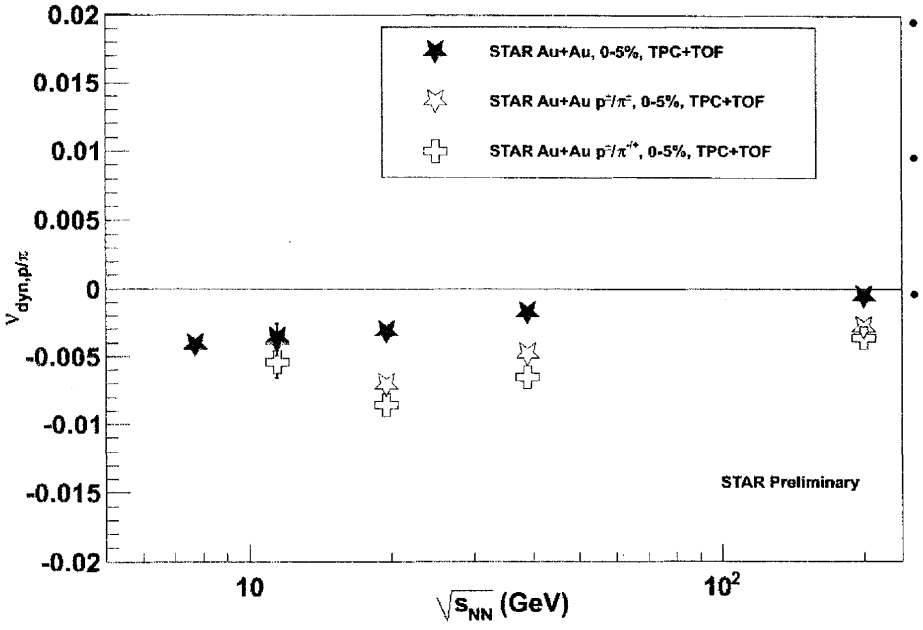
Michigan State University

RIKEN-BNL Workshop on Fluctuations, Correlations and RHIC Low Energy Runs

October 5, 2011

Dynamical fluctuations in global conserved quantities such as baryon number, strangeness, or charge may be observed near a QCD critical point. Charge dependent results from new measurements of dynamical K/π, p/π, and K/p ratio fluctuations are presented. The STAR experiment has performed a comprehensive study of the energy dependence of these dynamical fluctuations in Au+Au collisions at the energies $\sqrt{s_{NN}}$ = 7.7-200 GeV using the observable, ν_{dyn}. These results are compared to previous measurements and to theoretical predictions. Various proposed scaling scenarios that attempt to remove the intrinsic volume dependence of ν_{dyn} and to simplify comparisons between experimental measurements are also considered. Constructing an intensive quantity allows for a direct connection to thermodynamic predictions.

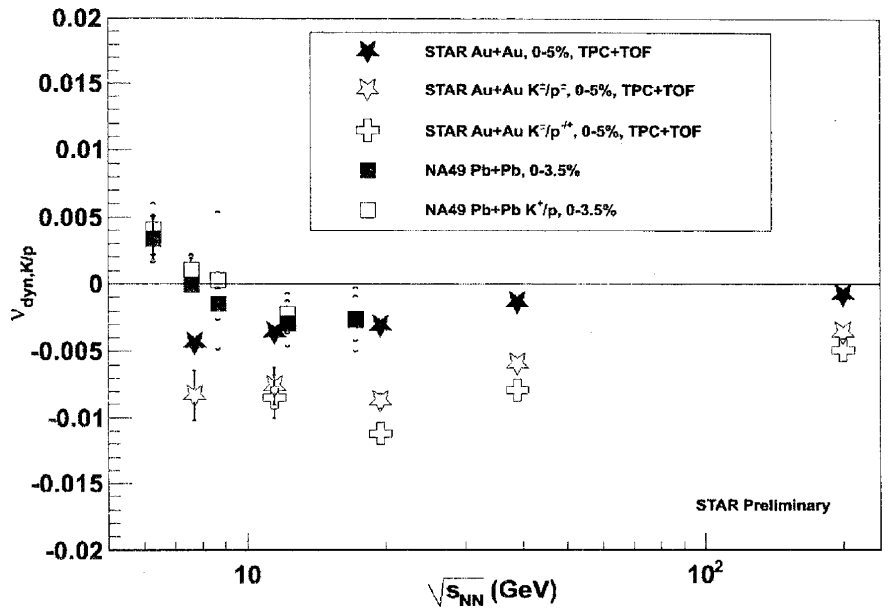
Charge Dependent Excitation Function for $\nu_{\mathrm{dyn},p/\pi}$



- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- Like-sign and opposite-sign charge combinations are similar at 200 GeV.
- Differences arise at lower energies.

Charge Dependent Excitation Function for $\nu_{dyn,K/p}$

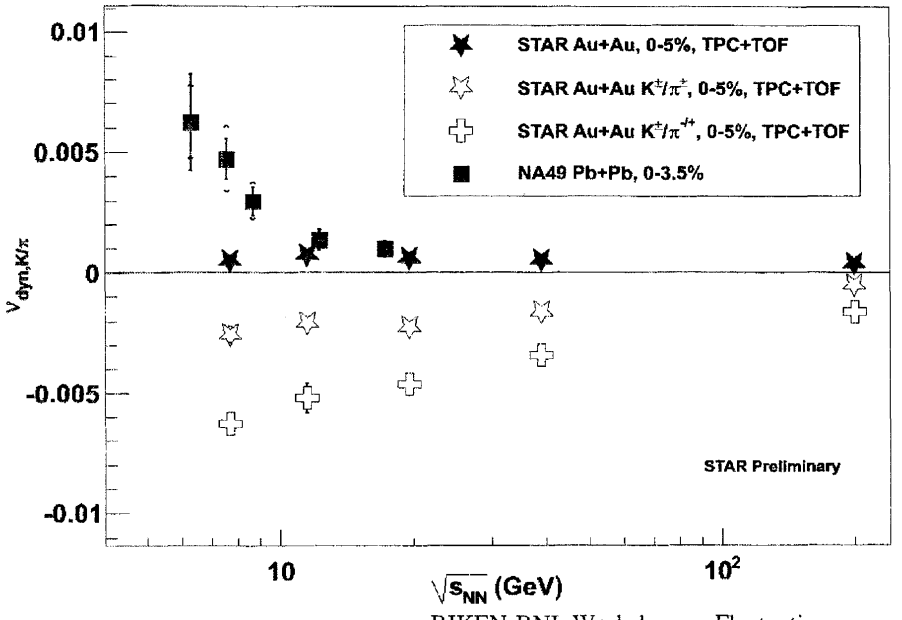
- NA49 $\sigma_{dyn,K/p}$ converted to $\nu_{dyn,K/p}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



- TPC+TOF (GeV/c):
  - K : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- Like-sign and opposite-sign charge combinations are similar at 200 GeV.
- Like for $\nu_{dyn,p/\pi}$, also see that differences arise at lower energies.

Charge Dependent Excitation Function for $\nu_{dyn,K/\pi}$

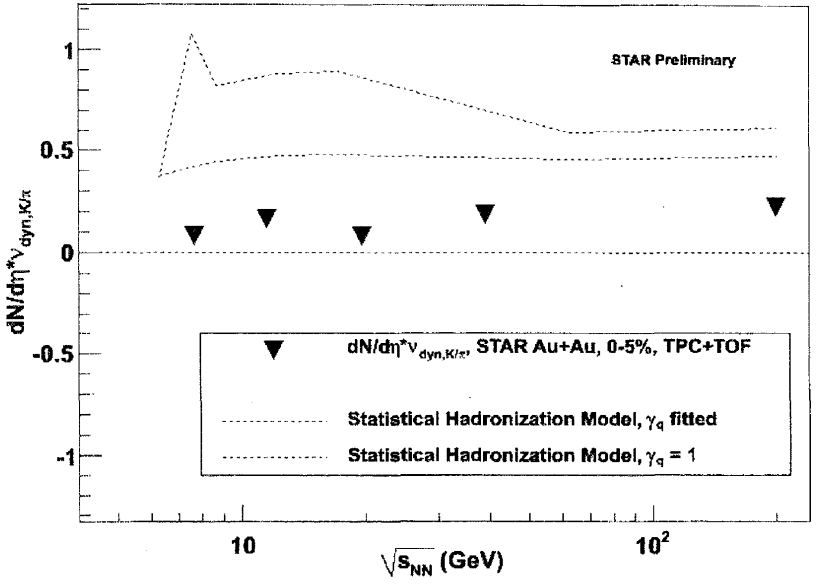
- NA49 $\sigma_{dyn,K/\pi}$ converted to $\nu_{dyn,K/\pi}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - K : $0.2 < p_T < 1.4$
- Growing difference between same- and opposite-sign combinations with decreasing energy.
- Opposite-sign charge fluctuations tend to be lower for all ratios due to decays of neutral resonances.

B.I. Abelev et al. [STAR Collab.], Phys. Rev. Lett. 103, 92301 (2009)

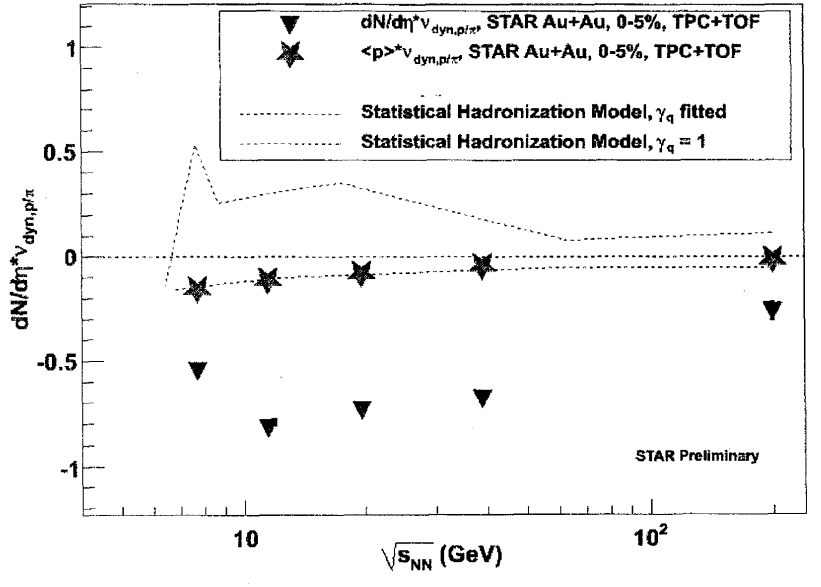
Multiplicity Scaling of $\nu_{dyn,K/\pi}$



- 0-5% Au+Au $\nu_{dyn,K/\pi}$ scaled by measured $dN/d\eta$.
- Approximate increase with energy.
- Compared to Statistical Hadronization model prediction:
  - γ_q = light quark phase space occupancy.
    - = 1, equilibrium.
    - Fitted: fit to ratio yields, etc.
  - Scaled by $dN/d\eta$ from the model
- Uncorrected experimental multiplicities.

Multiplicity Scaling of $\nu_{dyn,p/\pi}$

- 0-5% Au+Au $\nu_{dyn,p/\pi}$ scaled by measured $dN/d\eta$.
- More negative from 7.7-11.5 GeV, then decreases toward zero.
- Compared to Statistical Hadronization model prediction:
  - γ_q = light quark phase space occupancy.
    - = 1, equilibrium.
    - Fitted: fit to ratio yields, etc.
  - Scaled by $dN/d\eta$ from the model
- Scaling by <p> (p+pbar) approaches zero smoothly with increasing energy.
- Uncorrected experimetal multiplicities.



More or less a Summary !

Volker Koch
LBNL
Berkeley, CA 94720

This talk is an attempt at summarizing the workshop

Higher moments (cumulants) and ξ

- Consider probability distribution for the order-parameter field:

$$P[\sigma] \sim \exp\{-\Omega[\sigma]/T\}\,,$$

$$\Omega = \int d^3x \left[\frac{1}{2}(\nabla\sigma)^2 + \frac{m_\sigma^2}{2}\sigma^2 + \frac{\lambda_3}{3}\sigma^3 + \frac{\lambda_4}{4}\sigma^4 + \ldots\right]. \qquad \Rightarrow \quad \xi = m_\sigma^{-1}$$

- Moments (connected) of $q = 0$ mode $\sigma_V \equiv \int d^3x\,\sigma(x)$:

$$\kappa_2 = \langle\sigma_V^2\rangle = VT\,\xi^2\,; \qquad \kappa_3 = \langle\sigma_V^3\rangle = 2VT^2\,\lambda_3\,\xi^6\,;$$

$$\kappa_4 = \langle\sigma_V^4\rangle_c \equiv \langle\sigma_V^4\rangle - 3\langle\sigma_V^2\rangle^2 = 6VT^3\,[\,2(\lambda_3\xi)^2 - \lambda_4\,]\,\xi^8\,.$$

- Tree graphs. Each propagator gives ξ^2.

- Scaling requires "running": $\lambda_3 = \tilde{\lambda}_3 T(T\xi)^{-3/2}$ and $\lambda_4 = \tilde{\lambda}_4(T\xi)^{-1}$, i.e.,

$$\kappa_3 = \langle\sigma_V^3\rangle = 2VT^{3/2}\,\tilde{\lambda}_3\,\xi^{4.5}\,; \quad \kappa_4 = 6VT^2\,[\,2(\tilde{\lambda}_3)^2 - \tilde{\lambda}_4\,]\,\xi^7\,.$$

Stepha

Effect of Isospin Distribution

(1) $N_B^{(\mathrm{net})} = N_B - N_{\bar{B}}$ deviates from the equilibrium value.

(2) Boltzmann (Poisson) distribution for $N_B, N_{\bar{B}}$.

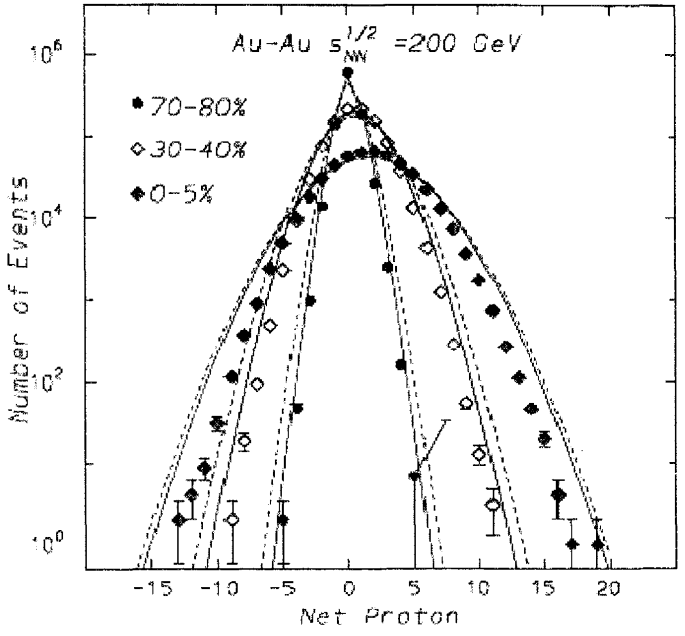
$$\Rightarrow \begin{cases} 2\langle(\delta N_p^{(\mathrm{net})})^2\rangle = \frac{1}{2}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^2\rangle + \frac{1}{2}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^2\rangle_{\mathrm{free}} \\ 2\langle(\delta N_p^{(\mathrm{net})})^3\rangle = \frac{1}{4}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^3\rangle + \frac{3}{4}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^3\rangle_{\mathrm{free}} \\ 2\langle(\delta N_p^{(\mathrm{net})})^4\rangle_c = \frac{1}{8}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^4\rangle_c + \frac{7}{8}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^4\rangle_{c,\mathrm{free}} \end{cases}$$

genuine info. noise

For free gas

$$2\langle(\delta N_p^{(\mathrm{net})})^n\rangle_c = \langle(\delta N_{\mathrm{N}}^{(\mathrm{net})})^n\rangle_c$$

Kitiza



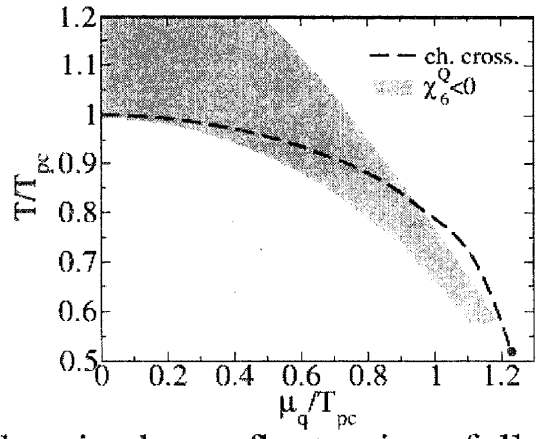
$$\frac{\langle(\delta N_p)^2\rangle_{binomial}}{\langle N_p\rangle_{binomial}} = (1-\frac{1}{2}p)$$

Peripheral collisions:
p <<1
Expect close to Poisson

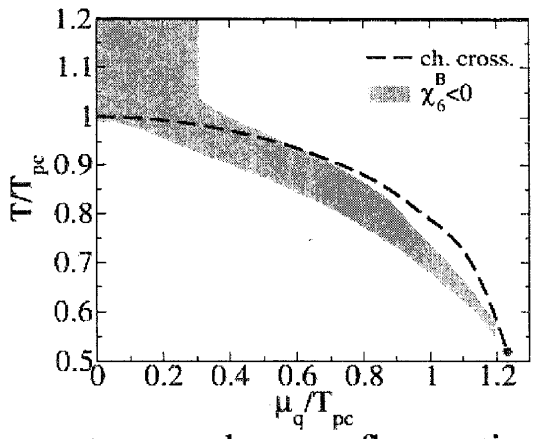
Needs to be checked more quantitatively

Electric charge fluctuations

Electric charge:



Baryon charge:



Electric charge fluctuations follow similar pattern as baryon fluctuations

Things to do

- Account for conservation of Baryon number etc
- Understand proton vs Baryon
- Understand effect of multiplicity selection on cumulants
- Understand the relevant length scales in MOMENTUM space
  - Is there an optimal system size???
- Understand initial state fluctuations

- Can we access the density fluctuations directly???

Fluctuations, Correlations and RHIC Low Energy Runs

Attendees

Masayuki	Asakawa	Osaka University
Chin-Hao	Chen	Stony Brook University
Lizhu	Chen	Brookhaven National Laboratory
William	Christie	Brookhaven National Laboratory
Michael	Creutz	Brookhaven National Laboratory
Ramiro	Debbe	Brookhaven National Laboratory
Heng-Tong	Ding	Brookhaven National Laboratory
Shinji	Ejiri	Niigata University
Yi	Gu	Stony Brook University
Sourendu	Gupta	Tata Institute of Fundamental Research
Wlodek	Guryn	Brookhaven National Laboratory
Prasad	Hegde	Brookhaven National Laboratory
Andrew	Hirsch	Purdue University
Zhongbo	Kang	RBRC/BNL
Frithjof	Karsch	Brookhaven National Laboratory
Dmitri	Kharzeev	Stony Brook University
Masakiyo	Kitazawa	Osaka University
Volker	Koch	Lawrence Berkeley National Laboratory
Toru	Kojo	Bielefeld University
JINFENG	LIAO	IU & RBRC
Michael	Lisa	Ohio State University
Keh-Fei	Liu	University of Kentucky
W	LLOPE	Rice University

Jeff	Mitchell	Brookhaven National Laboratory
Berndt	Mueller	Duke University
Swagato	Mukherjee	Brookhaven National Laboratory
Marlene	Nahrgang	Frankfurt Inst for Advanced Studies & SUBATECH, Nantes
Grazyna	Odyniec	Lawrence Berkeley National Laboratory
Rob	Pisarski	Brookhaven National Laboratory
Krishna	Rajagopal	MIT
Claudia	Ratti	Torino University - Italy
Krzysztof	Redlich	University of Wroclaw
Nihar	Sahoo	Variable Energy Cyclotron Centre
Takao	Sakaguchi	Brookhaven National Laboratory
Christian	Schmidt	Frankfurt Institute for Advanced Studies
Abhisek	Sen	Georgia State University
Peter	Seyboth	Max-Planck-Institut fuer Physik
Vladimir	Skokov	BNL and GSI, Darmstadt
Paul	Sorensen	Brookhaven National Laboratory
Mkhail	Stephanov	University of Illinois
Michael	Tannenbaum	Brookhaven National Laboratory
Terence	Tarnowsky	Michigan State University
Flemming	Videbaek	Brookhaven National Laboratory
Gary	Westfall	Michigan State University
Nu	Xu	Lawrence Berkeley National Laboratory
Zhangbu	Xu	Brookhaven National Laboratory
Ho-Ung	Yee	Stony Brook University

Fluctuations, Correlations and RHIC Low Energy Runs

Hamilton Seminar Room, Chemistry, Bldg. 555
October 3-5, 2011

Monday, October 3

		Chair: S. Mukherjee
08:30-08:45		Registration
08:45-09:00	N. Samios	Welcome
09:00-09:45	N. Xu	Study QCD Phase Structure in STAR Experiment
09:45-10:30	J. Mitchell	PHENIX Overview
		~ ~ *Coffee* ~ ~
11:00-11:30	M. Stephanov	Non-Gaussian Fluctuations at the QCD Critical Point
11:30-12:00	M. Asakawa	Cumulants of Conserved Charges and QCD Phase Structure
		~ ~ *Lunch* ~ ~
		Chair: R. Pisarski
14:00-14:30	M. Kitazawa	Revealing Baryon Number Fluctuations in Heavy Ion Collisions
14:30-15:00	V. Skokov	Non-perturbative Dynamics and Charge Fluctuations in Effective Chiral Models
		~ ~ *Coffee* ~ ~
15:30-16:00	J. Liao	Three Quarks for Muster Mark--- Lessons Learned from Susceptibilities
16:00-16:30	M. Nahrgang	Fluctuations of Conserved Charges within Dynamic Models of Heavy-ion Collisions

Tuesday, October 4

		Chair: K. Rajagopal
09:00-09:30	K-F. Liu	Lattice Calculation of QCD Critical Point with the Canonical Ensemble
09:30-10:00	S. Ejiri	Study of QCD Phase Transition at Finite Density by a Histogram Method
10:00-10:30	L. Chen	Probing the QCD Phase Transition Using Cumulants of Net-proton Multiplicity at RHIC
		~ ~ *Coffee* ~ ~
11:00-11:30	C. Ratti	Recent Results on Correlations and Fluctuations from the Wuppertal-Budapest Lattice QCD Collaboration
11:30-12:00	P. Hegde	Fluctuations and Correlations: Comparing Lattice QCD to the Hadron Resonance Gas Model
		~ ~ *Lunch* ~ ~

Tuesday, October, 4 (afternoon)

		Chair: D. Kharzeev
13:45-14:15	S. Gupta	TBA
14:15-14:45	C. Schmidt	Higher Moments of Hadronic Fluctuations and QCD Critical Behavior from Lattice Simulations
14:45-15:15	K. Redlich	Probing QCD Phase Boundary with Charge Fluctuations and their Probability Distributions

~ ~ Coffee ~ ~

15:45-16:45 **Chair: N. Xu**: Discussion Session: Theory, Experiments and Lattice QCD

~ ~ Workshop Dinner, 18:00-19:30, Berkner Hall ~ ~

Wednesday, October 5

		Chair: M. Stephanov
09:00-09:30	Y. Gu	Flow at Low Energies (PHENIX)
09:30-10:00	P. Sorensen	Flow at Low Energies (STAR)
10:00-10:30	N. R. Sahoo	Higher Moments of Net-charge Fluctuations (STAR)

~ ~ Coffee ~ ~

11:00-11:30	M. Lisa	The Energy Dependence of the Freeze-out Source Shape Measured by Azimuthally-sensitive HBT in STAR
11:30-12:00	A. Sen	J/Psi Results at 39 & 62 GeV (PHENIX)

~ ~ Lunch ~ ~

13:45-14:30	P. Seyboth	Status of Fluctuation Studies in NA49 at CERN SPS Energies
14:30-15:00	T. Tarnowsky	Current Results for Dynamical K/pi, p/pi, and K/p Fluctuations from the STAR Experiment
15:00-16:00	V. Koch	Summary & More

~ ~ Coffee; Workshop Ends ~ ~

Additional RIKEN BNL Research Center Proceedings:

Volume 105 – Opportunities for Polarized He-3 in RHIC and EIC, September 28-30, 2011 – BNL-xxxxx-2011 (Rachel/Elke/CAD)
Volume 104 – Brookhaven Summer Program on Quarkonium Production in Elementary and Heavy Ion Collisions, June 6-18, 2011 – BNL-96171-2011
Volume 103 – Opportunities for Drell-Yan Physics at RHIC, BNL, May 11-13, 2011 – BNL-95236-2011-2011
Volume 102 – Initial State Fluctuations and Final-State Particle Correlations, BNL, February 2-4, 2011 – BNL-94704-2011
Volume 101 – RBRC Scientific Review Committee Meeting, October 27-29, 2010 – BNL-94589-2011
Volume 100 – Summer Program on Nucleon Spin Physics, BNL, July 14-27, 2010 – BNL-96163-2011
Volume 99 – The Physics of W and Z Bosons, BNL, June 24-25, 2010 – BNL-94287-2010
Volume 98 – Saturation, the Color Glass Condensate and the Glasma: What Have we Learned from RHIC?, BNL – May 10-12, 2010 – BNL-94271-2010
Volume 97 – RBRC Scientific Review Committee Meeting, October 21-22, 2009 – BNL-90674-2009
Volume 96 – P- and CP-Odd Effects in Hot and Dense Matter, April 26-30, 2010 – BNL-94237-2010
Volume 95 – Progress in High-pT Physics at RHIC, March 17-19, 2010 – BNL-94214-2010
Volume 94 – Summer Program on Nucleon Spin Physics at LBL, June 1-12, 2009
Volume 93 – PHENIX Spinfest School 2009 at BNL - July 1-31, 2009. BNL-90343-2009
Link: PHENIXSpinfestSchool2009@BNL
Volume 92 – PKU-RBRC Workshop on Transverse Spin Physics, June 30-July 4, 2008, Beijing, China, BNL-81685-2008
Volume 91 – RBRC Scientific Review Committee Meeting, November 17-18, 2008 – BNL-81556-2008
Volume 90 – PHENIX Spinfest School 2008 at BNL, August 4-8, 2008 - BNL-81478-2008
Volume 89 – Understanding QGP through Spectral Functions and Euclidean Correlators, April 23-25, 2008 – BNL-81318-2008
Volume 88 – Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, April 21-22, 2008 – BNL-81307-2008
Volume 87 – RBRC Scientific Review Committee Meeting, November 5-6, 2007 – BNL-79570-2007
Volume 86 – Global Analysis of Polarized Parton Distributions in the RHIC Era, October 8, 2007 – BNL-79457-2007
Volume 85 – Parity-Violating Spin Asymmetries at RHIC-BNL, April 26-27, 2007 – BNL-79146-2007
Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 – BNL 77857-2007
Volume 83 – QCD in Extreme Conditions, July 31-August 2, 2006 – BNL-76933-2006
Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
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-79763-2008
Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, Dec 12-14, 2005 – BNL-76915-2006
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 – RBRC Scientific 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
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

Additional RIKEN BNL Research Center Proceedings:

Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)–BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized pp Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
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
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Fluctuations, Correlations and RHIC Low Energy Runs

October 3-5, 2011

Li Keran

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

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Speakers

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