BNL-75692-2006
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 80

Can We Discover the QCD Critical Point at RHIC?

March 9-10, 2006

Organizers:

T. Ludlam, H. Ritter, G. Stephans, M. Gazdzicki, B. Friman, F. Videbaek,
T. Satogata, K. Rajagopal, L. McLerran

RIKEN BNL Research Center

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

DISCLAIMER

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

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

Preface to the Series

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

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

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

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

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

N. P. Samios, Director
October 2005

CONTENTS

Preface to the Series

Introduction
T. Ludlam and H-G. Ritter i

Can We Discover the QCD Critical Point at RHIC
K. Rajagopal 1

Lattice Results on the QCD Critical Point
F. Karsch 9

QCD Critical Point and Correlations
M. Stephanov 15

Can We Discover the QCD Critical Point at RHIC – Experimental Overview
G. Roland 21

Prospects for RHIC Low-Energy Operations
T. Satogata 27

Energy Dependence of Pb+Pb Collisions at the CERN SPS
P. Seyboth 33

Four Special Points of the High-mu RHIC
E. Shuryak 39

Soft Mode of the QCD Critical Point
H. Fujii 45

Baryon Number Fluctuation Near the Critical Point
Y. Hatta 51

Hydrodynamical Evolution Near the QCD Critical Point
C. Nonaka 57

Prospects of a New Ion Program at the CERN SPS
M. Gazdzicki 63

PHENIX Capabilities for the Low-Energy RHIC Run
P. Steinberg 69

The Search for the Critical Point of QCD: STAR Capabilities for Low $\sqrt{s_{NN}}$ Running
T. Nayak 75

Low Energy Operation of RHIC; AGS Low Energy Extraction Performance
N. Tsoupas 81

Luminosity Monitoring Issues for Low-Energy RHIC Operations
A. Drees 87

Electron Cooling in RHIC at Low Energies
A. Fedotov 93

Energy Dependence of Thermal Parameters in Heavy Ion Collisions
K. Redlich 99

Observable Power Laws at the QCD Critical Point
N. Antoniou 105

The Compressed Baryonic Matter Experiment at FAIR
P. Senger 113

Excitation Function; Experimental Perspective – Search for the Native Hadronic Shore
N. Xu 119

Experience with CERES
H. Appelshäuser 125

Critical Point at SPS?
R. Stock 131

Lattice Calculations at Finite Baryon Potential
Z. Fodor 137

Fluctuations
V. Koch 143

Strangeness and Phase Changes in Relativistic Heavy Ion Collisions
J. Rafelski 149

Can We Discover the First-Order Phase Transition at RHIC?
J. Randrup 155

v1- & v2-Flow: BAROMETRY @ HiMu-RHIC – Pinning Down the Order of the Phase Transition
H. Stöcker 161

List of Registered Participants 167

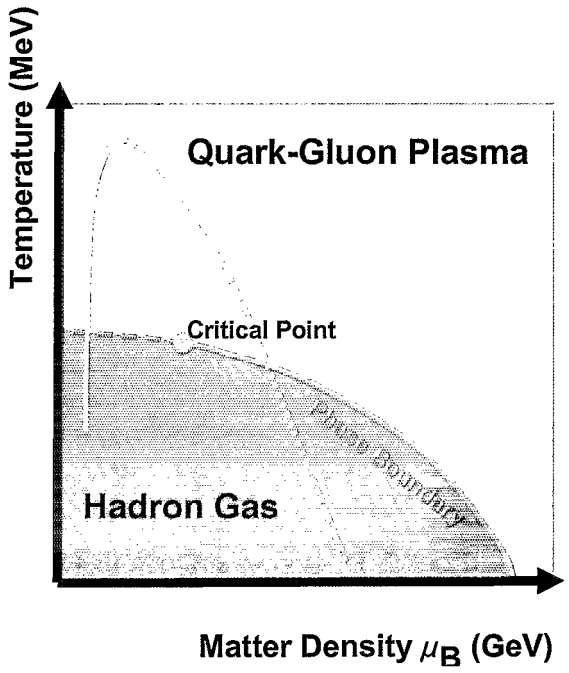
Agenda 169

Additional RIKEN BNL Research Center Proceeding Volumes 171

Contact Information

Can we discover the QCD critical point at RHIC?
Report from the workshop
March 9-10, 2006
T. Ludlam and H.-G. Ritter

Experiments with high energy heavy ion collisions, and accompanying theoretical work, are now exploring a rich landscape across the phase diagram of bulk QCD matter. A recent example, of wide interest and significance, is the "perfect liquid" behavior observed in matter created at high temperature ($T \geq 170$MeV) and near-zero baryo-chemical potential ($\mu_B \leq 50$ MeV). Experiments at smaller collision energies explore larger values of μ_B. Theoretical work, including recent results from lattice gauge calculations, indicates that the phase boundary between hadronic matter and the quark gluon plasma consists of a line of first order phase transition at large μ_B, ending at a critical point whose location is predicted to be in the range μ_B= 100-500 MeV, which is above the range currently being explored by the RHIC experiments, but within the range where the SPS and AGS experiments have been carried out.



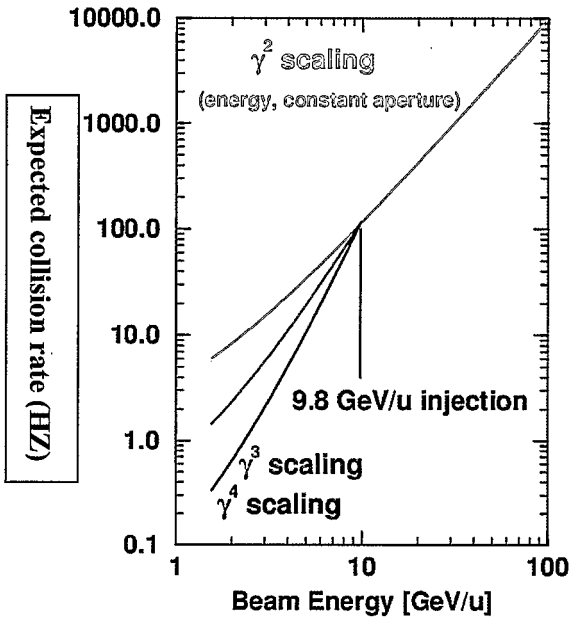
In this picture the matter produced in top-energy RHIC experiments, as it cools, undergoes a rapid cross-over from quark gluon plasma to a hadron gas, but does not undergo a first-order phase transition. Direct evidence for a first-order phase transition, and measurement of the existence and properties of the critical point, would provide an essential quantitative understanding of the phase diagram, and would be a major step forward in the effort to determine the properties of QCD at high temperature and density.

This workshop brought leading theorists in the field together with experimentalists from the SPS, the RHIC program, and the planned FAIR facility, along with RHIC accelerator scientists, to examine the current understanding from data and theory, and to see if an experimental search should be carried out with the RHIC colliding beams and the PHENIX and STAR detectors.

Experimental searches focus on rapid changes, as a function of collision energy, in particle production ratios, collective behavior, and enhanced fluctuations in multiplicity, transverse momentum, or particle ratios near the critical point. Data consistent with such signatures have been found in experiments at the SPS, but no definitive conclusions have yet been possible. One of the main experimental difficulties is the fact that, in fixed target experiments, the interesting range of μ_B spans beam energies from ~10 GeV/n to

~160 GeV/n. Even for detector systems with very large angular coverage, such as NA 49, the kinematic acceptance over this range changes enormously, as do the systematic errors due to detector resolution, as the mid-rapidity range is focused into a forward cone that narrows with increasing beam energy. By contrast, in a colliding beam geometery, the same energy range can be spanned by beam energies from 2.5+2.5 GeV/n to 10+10 GeV/n ($\sqrt{S_{nn}}$ = 5 – 20 GeV), and the detector acceptance in rapidity is independent of energy.

Estimates presented at this workshop indicate that the energy-scan results from NA 49 could be reproduced at RHIC, with a factor of ~4 improvement in the statistical error, with ~100,000 central collisions at each energy point (~1 million minimum-bias events). The lowest energy at which RHIC has been operated so far is at the injection energy (10+10 GeV/n). At this point, the rate of minimum-bias Au-Au collisions is ~100/sec. The RHIC accelerator staff express confidence that useful collision ratges can be achieved at beam energies as low as 2.5 GeV/n, but this is very much unexplored territory. Many technical issues need to be studied, such as magnet performance at low current, power supply regulation, beam lifetimes, tuning issues, etc. It is expected that the collision rate, at energies below injection, will fall as a power law somewhere between $1/\gamma^3$ and $1/\gamma^4$, where γ is the Lorentz factor. The corresponding collision rates are shown in the accompanying figure.



Even in the "pessimistic" scenario, a useful scan could be carried out in a relatively small number of weeks of running. Nonetheless, a definitive assessment of the prospects for collisions in this range will require some studies with beam during machine operation. It is estimated that the required study time is ~1 day. It could be accomplished with proton beams (i.e., during the current RHIC run).

For the longer term, electron beam cooling could increase the luminosity by a factor of ~100, provide a narrow, vertex distribution, and allow beam stores of long duration. This is similar in principle to the e-cooling at full energy that is now being developed for RHIC II, but would be accomplished with much lower energy electrons.

The PHENIX and STAR collaborations have expressed enthusiastic support for these measurements, and have begun to study the experimental issues. Considerations of triggering modes, luminosity monitoring, extended vertex distributions, and beam lifetime are under study, and these, along with refined projections for the expected luminosity, will feed into specific requests in forthcoming beam use proposals.

In the closing discussion, the participants in the workshop reached consensus on the following points:

- Can we discover the QCD critical point at RHIC? Experimental and theoretical indications are extremely promising; it appears that such a program can be carried out with a very modest impact on the current planning for RHIC experiments; a successful outcome would rank among the major scientific achievements at RHIC.
- Experiments in the collider mode, with large-acceptance detectors, are ideal for such a program.
- A RHIC program to discover and locate the critical point is seen as complementary to future fixed-target experiments, such as CBM at FAIR, which can carry out detailed studies with rare probes.
- The community represented at the workshop strongly endorses the proposal to carry out machine studies at low beam energies during the current RHIC run. These are estimated to require approximately one day. A detailed plan and time estimate should be prepared and presented to Brookhaven management as soon as possible.
- We should aim at an initial program of about 10 weeks. The specific energy points to aim for initially are $\sqrt{S_{nn}}$= 6.3, 7.6, and 8.8 GeV. These correspond to the NA 49 measurements.
- The organizing committee for this workshop will be expanded to a Working Group, including members from the STAR and PHENIX collaborations. This group will prepare for a follow-up meeting in the July-August time frame, at the time when beam use proposals are being prepared for presentation to BNL's Program Advisory Committee as input for planning the RHIC run schedule for 2007 and beyond.

CAN WE DISCOVER THE QCD CRITICAL POINT AT RHIC?

KRISHNA RAJAGOPAL

MIT + LBNL

BNL, March 9, 10 2006

We have motivation-a-plenty. So....

CAN RHIC FIND THE CRITICAL POINT?

- Gunther Roland will describe the advantages of using a collider vs. fixed target for study of event-by-event fluctuations at varying $\sqrt{s}$.
- I will focus on "what needs to be done". Later speakers (experimental and accelerator physicists) will address what can be done. The goal for the workshop is to understand how best to maximize the intersection.

WHAT NEED BE MEASURED AT EACH ENERGY

- Enough ⟨particle ratios⟩ to first evaluate μ_B — ie you have to know where you are freezing out — and then see whether $\langle K\rangle/\langle\pi\rangle$ enhanced — ie as a bonus confirm(?) the "horn."
- Event-by-event fluctuations in:
  - $\langle p_T\rangle$, with equal or smaller error bars as in CERES data
  - in $\langle K\rangle/\langle\pi\rangle$ and $\langle p\rangle/\langle\pi\rangle$, with smaller error bars than in NA49 data
  - All fluctuation analyses done for $p_T < p_T^{cut}$ for several choices of p_T^{cut} down to $p_T^{cut} \sim 500$ MeV
- v_2 of π + p.

WHAT RANGE OF $\sqrt{s}$, ie μ_B?

- I suggest RHIC explore $\mu_B \lesssim 500$ MeV.
- Want to test NA49 observation of K/π fluctuations at $\mu_B \sim 400-450$.
- Why stop at $\mu_B \sim 500$?
  - If $\mu_B^{\bullet} < 3T_c \sim 500$ MeV, plausibly the different lattice calculations will converge as each improves in the next few years. If $\mu_B^{\bullet} > 500$ MeV, a quantitative comparison with theory is harder to envision.
  - If $\mu_B^{\bullet} > 500$ MeV, it will also be tough to find experimentally. (Low $T_{freeout}$; equilibration ???)
- NB: if $\bullet$ is <u>found</u> with $\mu_B^{\bullet} < 500$ MeV, this will give strong motivation for study of non-eq'bm signatures of first order transition at larger μ_B, eg at FAIR.

WHAT SPACING BETWEEN μ_B's ?

- In the vicinity of a discovery, will want μ_B's separated by ~50 MeV.
- A scan with steps $\lesssim$ 100 MeV should allow to make discoveries.
- Other than calculating $\mu_B^{\bullet}$, second most important quantity we would like to learn from lattice QCD is width in μ_B of region where $\xi > 2$ fm. Or, say, where $\dfrac{\chi_B}{\chi_B(T_c, \mu=0)} > 4$.

A "STRAW MAN" CHOICE OF ENERGIES

[$\sqrt{s} \leftrightarrow \mu_B$ taken from Cleymans et al's hep-ph/0511094 compilation of data where available and empirical fit where there is none.]

	$\sqrt{s}$ (AGeV)	μ_B (MeV)	
	5	550	
	6.27	470	largest fluctuations in $\langle K \rangle / \langle \pi \rangle$
peak of "horn" →	7.62	410	
	8.77	380	
	12.3	300	
	18	220	
	28	150	
done at RHIC	60	75	
	130	40	
	200	30	

CAN WE DISCOVER THE QCD CRITICAL POINT AT RHIC?

YES, IF:

- Accelerator & detector capabilities permit measurement of the event-by-event fluctuations of the hadronic observables I described, at a sequence of energies like that I described
- Nature is kind, and puts $\mu_B^0 < 500$ MeV

IF YES:

- The landmark discovered. Our map of the QCD phase diagram then anchored by experiment.
- Assuming reasonable progress in lattice QCD, quantitative comparison between theory & experiment for μ_B^0
- FAIR (and RHIC) can study the first order phase transition

Lattice results on the QCD critical point

Frithjof Karsch, Physics Department, BNL

- calculations for non-vanishing chemical potential ($\mu_q > 0$) show a rapid transition from a HRG to a QGP; signaled by sudden changes in EoS and susceptibilities
- fluctuations on the crossover line increase with increasing baryon chemical potential
  - strongly suggests the existence of a critical point
- WE have no convincing quantitative result on the location of the QCD critical point... so far
  - a large critical value, $\mu_B^{crit} \gtrsim 300$ MeV, is favored
  - a value below $\mu_B^{crit} \lesssim 600$ MeV is likely

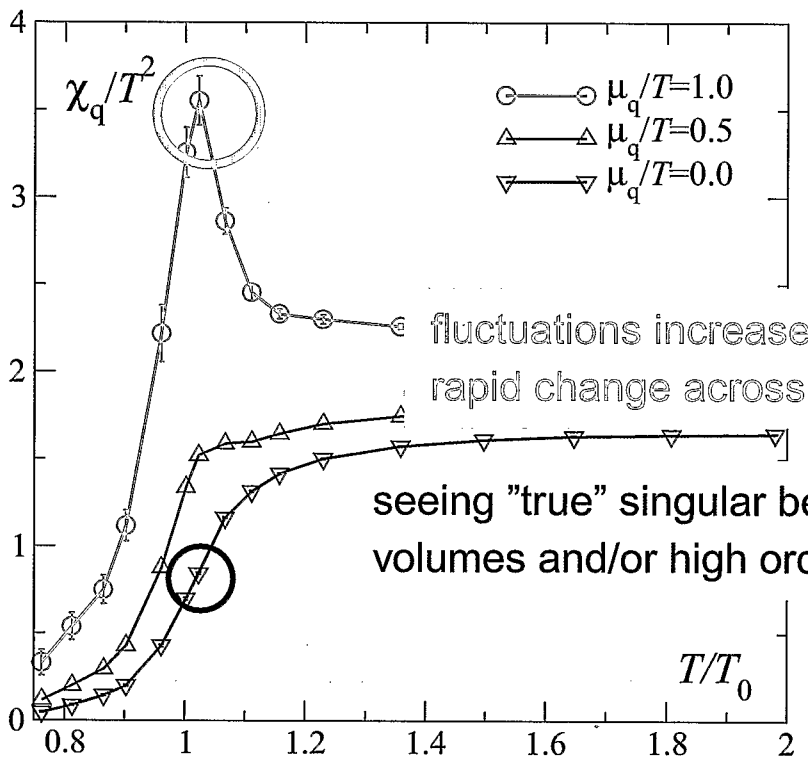
Fluctuations of the baryon number density ($\mu \geq 0$)

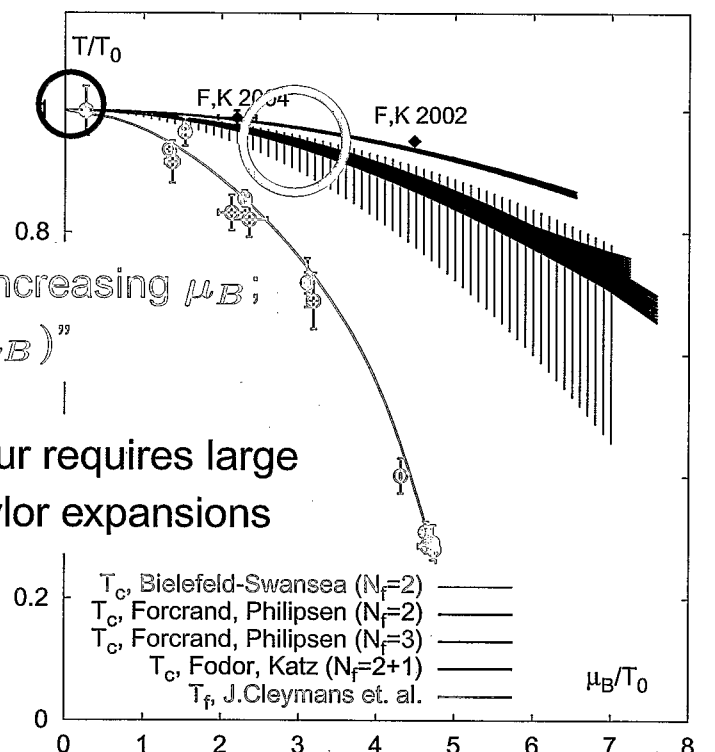
baryon number density fluctuations:
(Bielefeld-Swansea, PRD68 (2003) 014507;
PRD71 (2005) 054508

$$\mu \geq 0, n_f = 2$$

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

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





fluctuations increase with increasing μ_B;
rapid change across "$T_c(\mu_B)$"

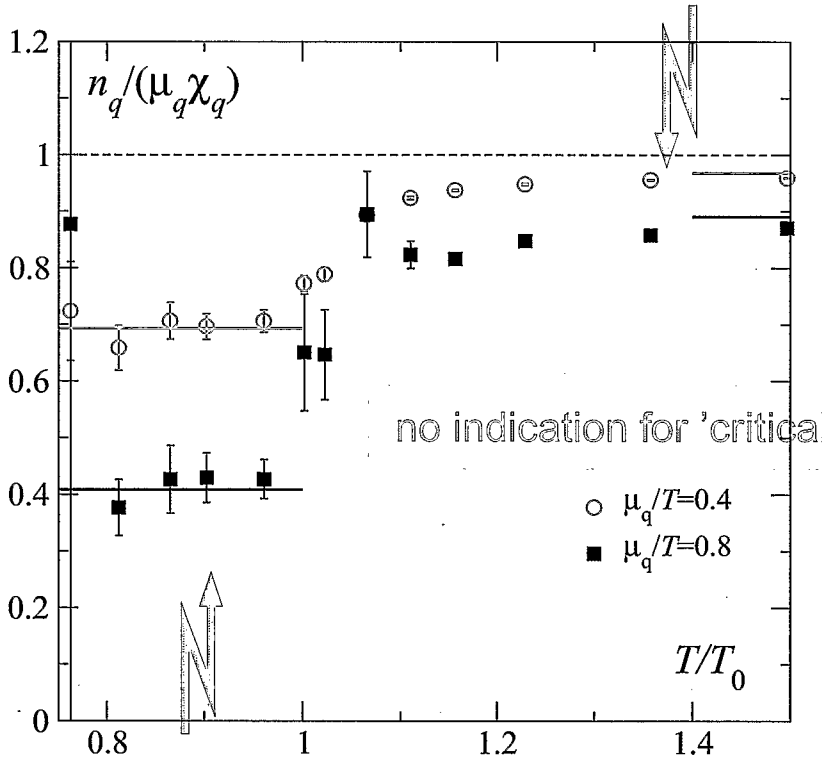
seeing "true" singular behaviour requires large volumes and/or high order Taylor expansions

Isothermal compressibility of the quark gluon plasma

inverse compressibility:

$$\kappa_T^{-1} = \frac{n_q}{\chi_q} = \left(\frac{\partial p}{\partial n_q}\right)_{T \text{ fixed}}$$

ideal $q\bar{q}$ gas



resonance gas

high-T, massless limit: polynomial in (μ_q/T)

$$\frac{n_q}{\chi_q} = \mu_q + \mathcal{O}\left(\left(\frac{\mu_q}{T}\right)^3\right)$$

large density fluctuations for $\mu_q > 0$, $T < T_c$

"saturated" by fluctuations in a resonance gas

no indication for 'critical' fluctuations

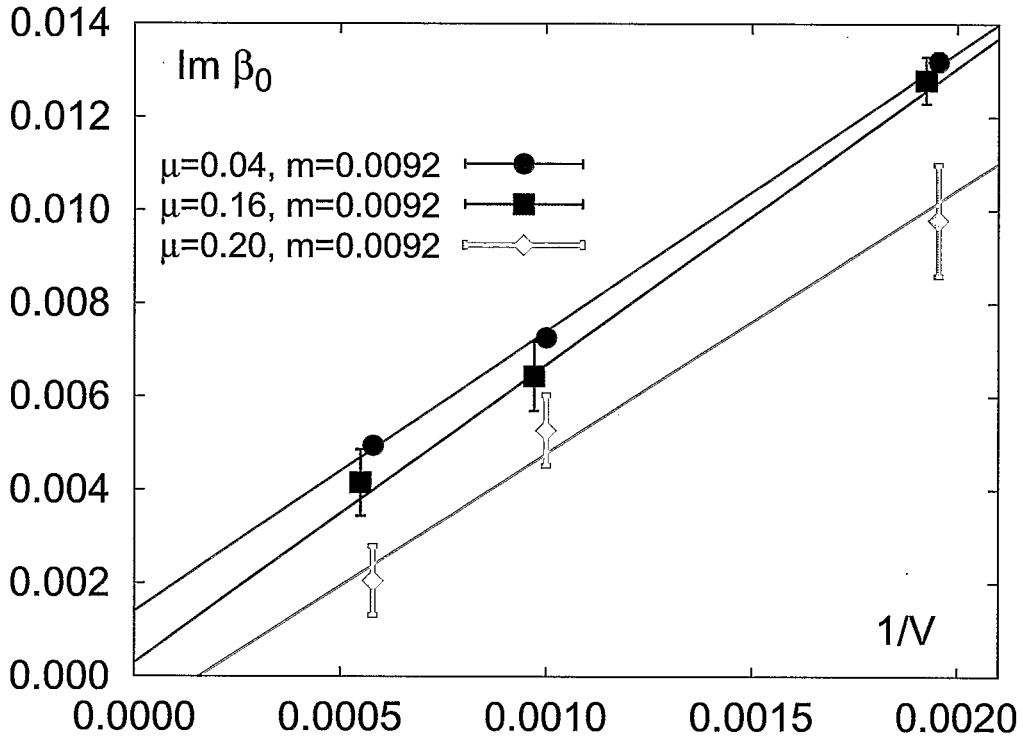
expect: $\left(\frac{\partial p}{\partial n_q}\right)_T = \frac{n_q}{\chi_q} = 0$

at chiral critical point

$m_\pi \simeq 770$ MeV, smaller m_q or larger V needed??!!

Volume and quark mass dependence of Lee-Yang zeroes

strong volume dependence ⇒ fit sensitive to fitting range



$$\mu_q^{crit} = 0.1825(75)$$

$$\Downarrow$$

$$\mu_B^{crit}/T = 2.19(9)$$

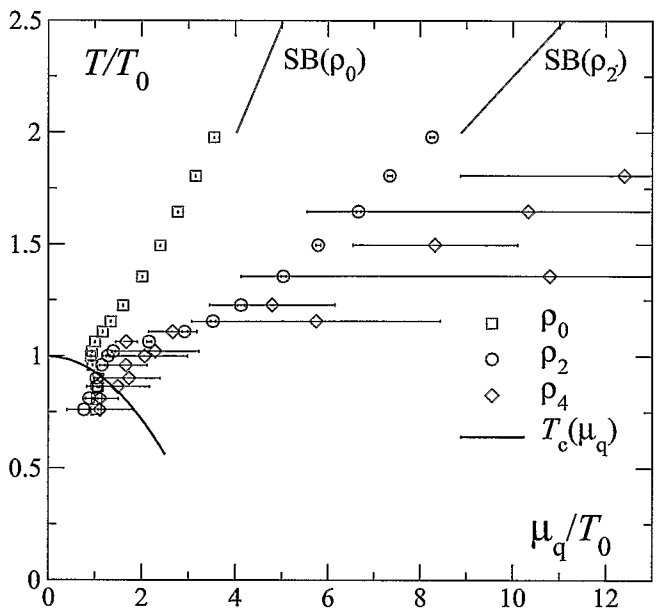
F+K 2004

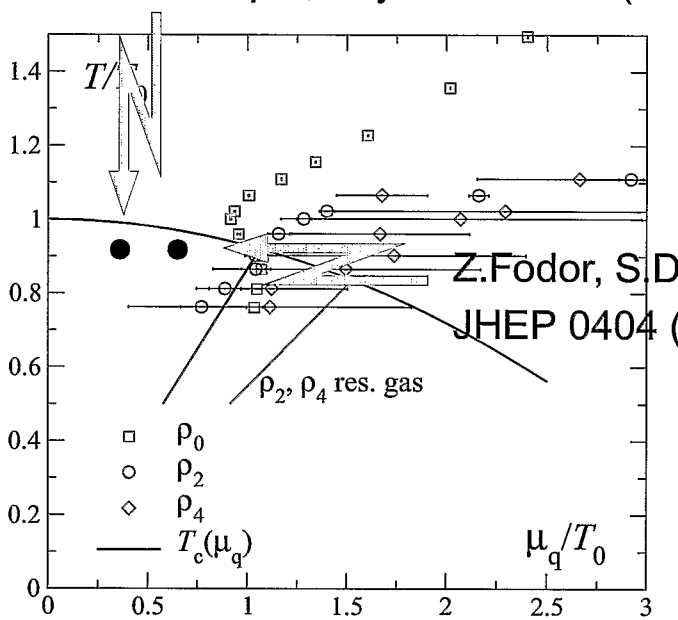
$V \to \infty$ limit difficult to control, S. Ejiri, hep-lat/05006023
the sign problem pops up again

Radius of convergence: lattice estimates vs. resonance gas

- Taylor expansion $\Rightarrow$ estimates for radius of convergence $\rho_{2n} = \sqrt{\left|\frac{c_{2n}}{c_{2n+2}}\right|}$

R.V. Gavai, S. Gupta, Phys. Rev. D71 (2005) 114014





Z.Fodor, S.D.Katz
JHEP 0404 (2004) 050

$T < T_0$: $\rho_n \simeq 1.0$ for all n $\Rightarrow$ $\mu_B^{crit} \simeq 500$ MeV

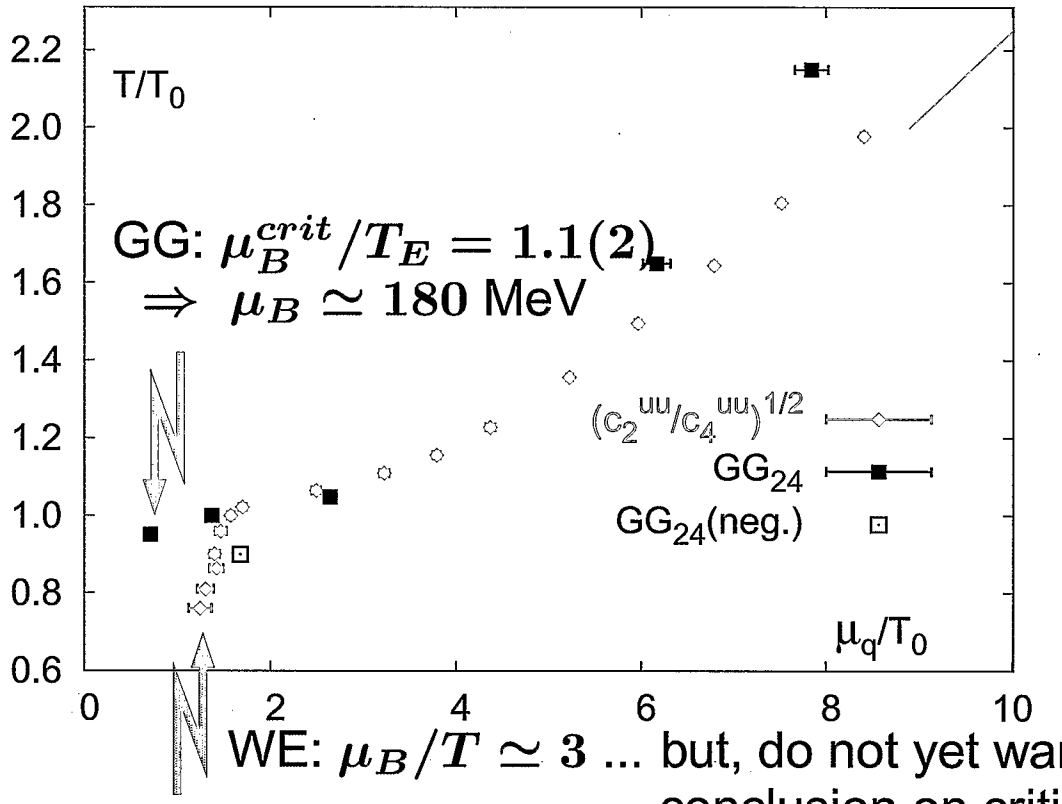
HOWEVER still consistent with resonance gas!!!

HRG analytic, LGT consistent with HRG $\Rightarrow$ infi nite radius of convergence not yet ruled out

Estimator for radius of convergence

$$\left(\frac{\mu_q}{T}\right)_{crit} \simeq \sqrt{\left|\frac{c_2^{uu}}{c_4^{uu}}\right|}$$

(Gavai, Gupta also analyze $\sqrt{|c_4/c_6|}$ and $\sqrt{|c_6/c_8|}$)



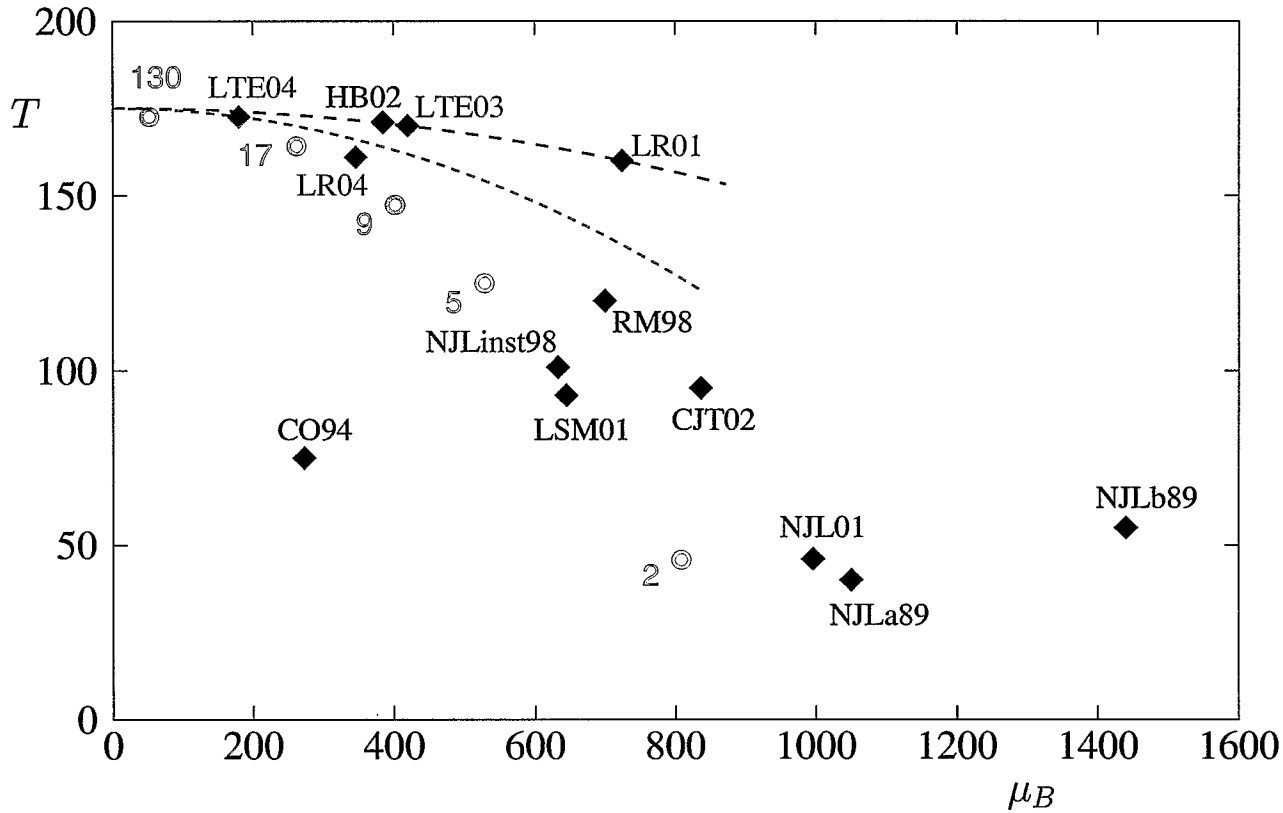
WE: $\mu_B/T \simeq 3$ ... but, do not yet want to draw a conclusion on critical behavior

QCD critical point and correlations

M. Stephanov

U. of Illinois at Chicago (and RIKEN-BNL Center)

Locating the QCD critical point

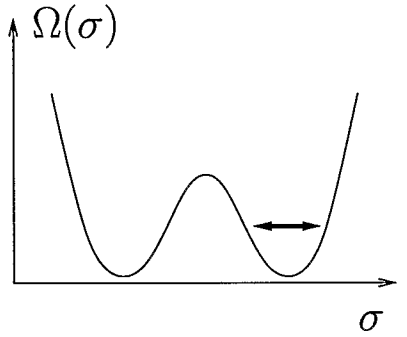


Signatures: event-by-event fluctuations.

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

Critical mode and equilibrium fluctuations

$\boxed{1}$

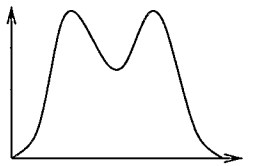


$\mu > \mu_E$

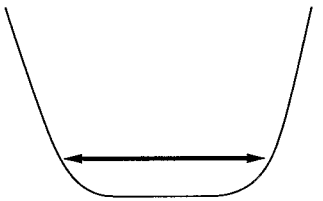
$\boxed{\langle\bar{\psi}\psi\rangle = \sigma}$

$\langle\sigma^2\rangle \sim (\Omega'')^{-1}$

think $e^{-\Omega}$:



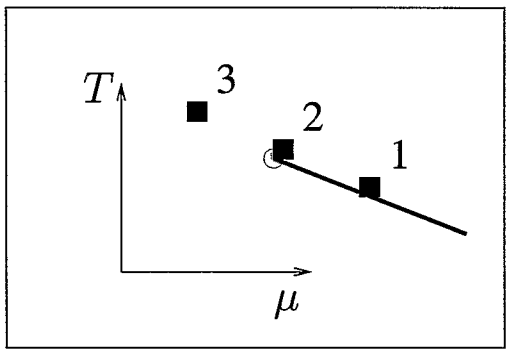
$\boxed{2}$



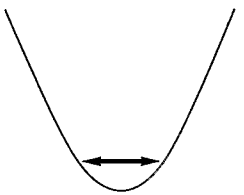
$\mu = \mu_E$

$(\Omega'')^{-1} \to \infty$

large equilibrium fluctuations



$\boxed{3}$



$\mu < \mu_E$

Relation to correlation length:

$$\langle\sigma(\boldsymbol{x})\sigma(\mathbf{0})\rangle \sim \begin{cases} e^{-|\boldsymbol{x}|/\xi}, & \text{for} \quad |\boldsymbol{x}| \gg \xi \\ 1/|\boldsymbol{x}|, & \text{for} \quad |\boldsymbol{x}| \ll \xi \end{cases} \qquad \langle\sigma^2\rangle = \int d^3\boldsymbol{x}\langle\sigma(\boldsymbol{x})\sigma(\mathbf{0})\rangle \sim \xi^2$$

n_B, T^{00} are also critical? – Mix. Only *one* linear combination is critical (Fujii's talk)

Fluctuations and correlations

Basic idea:

$$\chi_B \equiv \frac{1}{V}\frac{\partial B}{\partial \mu_B} = \frac{1}{TV}\langle(\delta B)^2\rangle \to \infty \qquad \text{at c.p.}$$

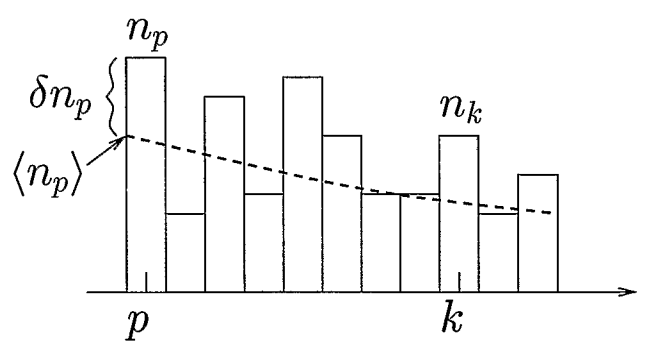
- Susceptibilities diverge $\Rightarrow$ fluctuations grow towards the critical point.
- Fluctuations can be measured in heavy ion collision experiments.
- Finite (and experiment-dependent) acceptance
- Separate acceptance from physics?

18

Most fluct. measures can be expressed through two-particle correlator

$$\langle \delta n_p \delta n_k \rangle$$

where $\delta n_p = n_p - \langle n_p \rangle$.

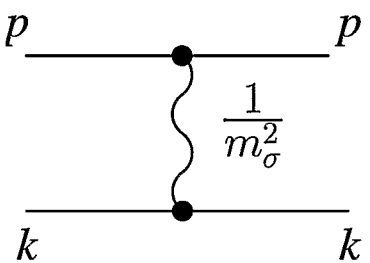


E.g., $Q = \sum_{p,\alpha} q(\alpha) n_p^\alpha$ means:

$$\langle(\delta Q)^2\rangle = \sum_{pk,\alpha\beta} q(\alpha)q(\beta)\,\langle \delta n_p^\alpha \delta n_k^\beta \rangle$$

Critical point

The 2-particle correlator measures 4-point function at $q = 0$ (for $p \neq k$).
Singularity appears at $q = 0$ due to vanishing σ screening mass $m_\sigma \to 0$.
(or $\xi = 1/m_\sigma \to \infty$).



$$\langle \delta n_p \delta n_k \rangle_\sigma = \frac{1}{T} \frac{f_p(1+f_p)}{\omega_p} \frac{f_k(1+f_k)}{\omega_k} \frac{G^2}{m_\sigma^2} \, .$$

$\langle \delta n_p \delta n_k \rangle = \langle n_p n_k \rangle - \langle n_p \rangle \langle n_k \rangle > 0$ — attraction

Consider baryon number susceptibility:

$$\langle \delta B \delta B \rangle_\sigma = \langle (\delta N_p - \delta N_{\bar{p}} + \delta N_n - \delta N_{\bar{n}})^2 \rangle_\sigma = \langle \delta N_p \delta N_p \rangle_\sigma + \ldots$$

Each term is $\sim \dfrac{1}{m_\sigma^2}$, $\quad \Rightarrow \quad \langle \delta B \delta B \rangle \sim 1/m_\sigma^2 = \xi^2$.

Enough to measure $\langle \delta N_p \delta N_p \rangle$ (Hatta's talk)

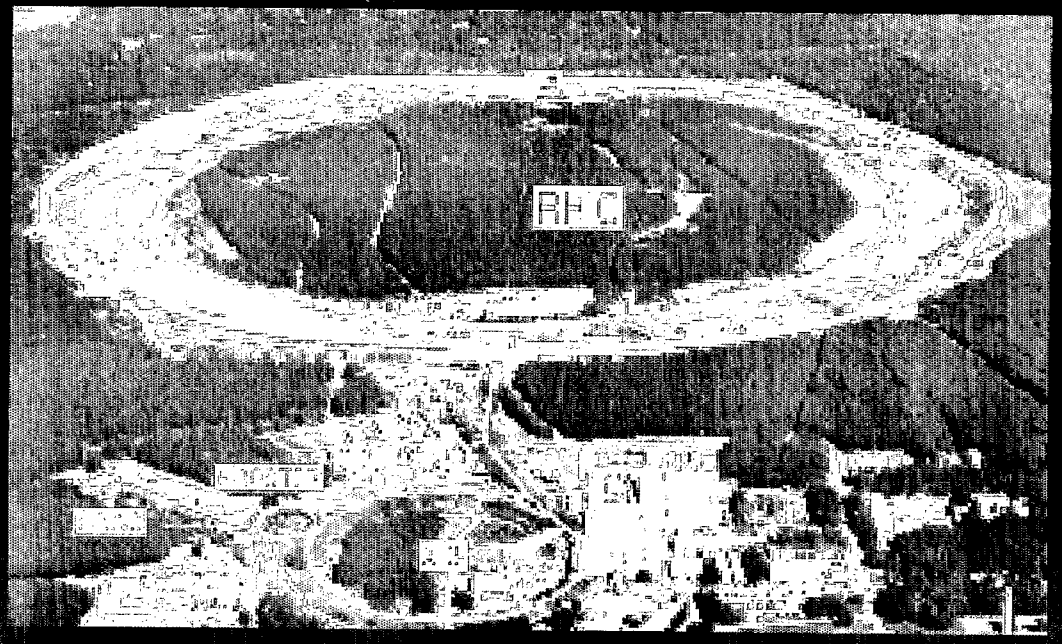
Current status and summary notes

- Nontrivial fluctuations are seen. Both magnitude and energy/centrality dependence are non-trivial. (Roland's talk).

- To understand what is observed – address this:
  - what is physics and what is acceptance, etc?
    - For small acceptance intensive measures $\sim$ (acceptance)^1.
  - what is physics of the critical point and what is jets, initial state fluctuations, bubbles, etc. ?

    To resolve:
    - p_T: jets – high p_T, critical $\Rightarrow$ low p_T.
    - $\sqrt{s}$ dependence: critical $\Rightarrow$ non-monotonous.
    - non-equlibrium effects – might turn on 1st order side of the c. point. Use measures which are less sensitive to these, e.g., Φ_{pT} or particle ratios.

Can we discover the critical point at RHIC?



Experimental Overview

BNL
March 9 2006

Gunther Roland

Thanks to
Burak Alver, Ed Wenger,
Siarhei Vaurynovich, Wei LI

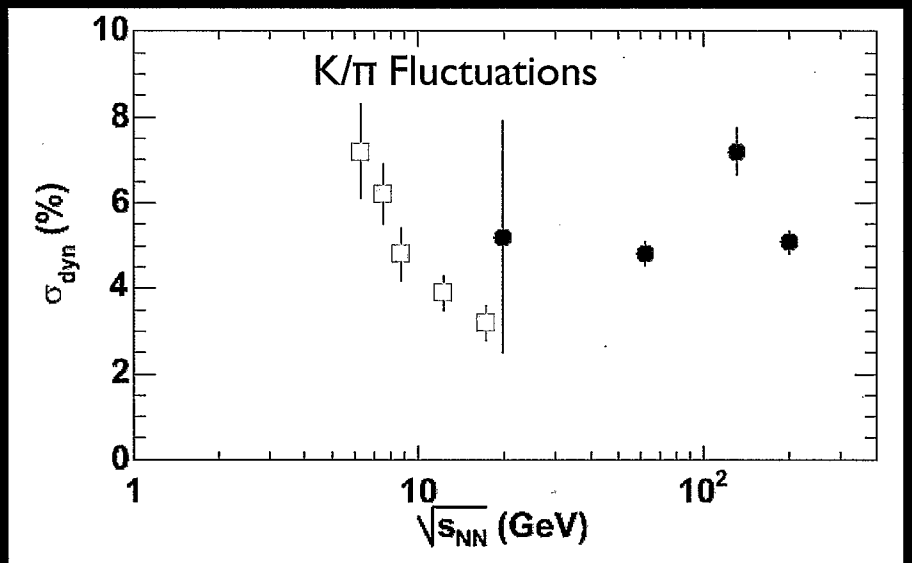
Experimental Search for the Critical Point

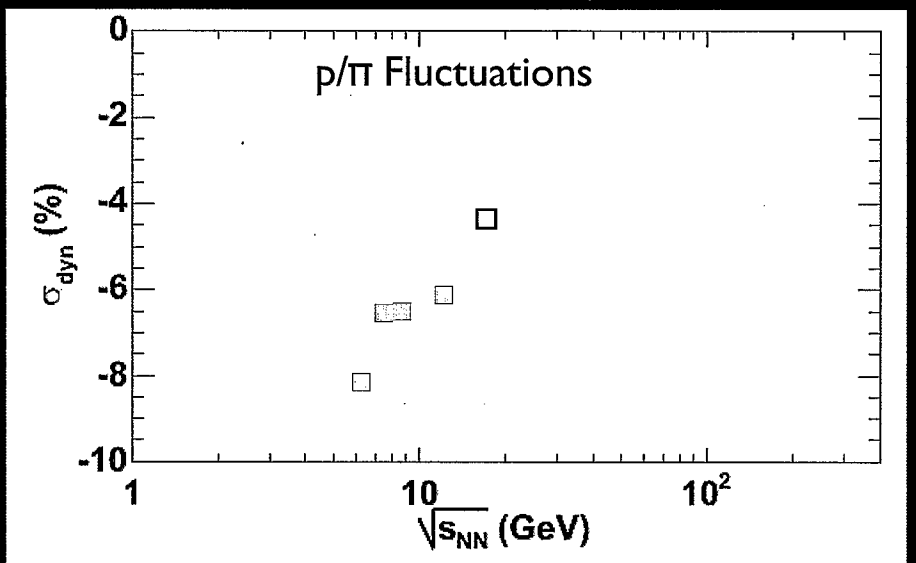
- Theoretical guidance is limited
- Experimental strategy:
  - Search in different observables, correlate observables ➡NA49
  - Maximize experimental sensitivity
  - Fine grained exploration of μ_B, T space
- Side effect:
  - Sensitivity to critical phenomena at 1st order transition, Onset of Deconfinement, EOS softest point, changes in bulk dynamics etc

Why use a collider?

Can RHIC low-√s scan improve on SPS measurements?

NA49, Christof Roland, QM'04

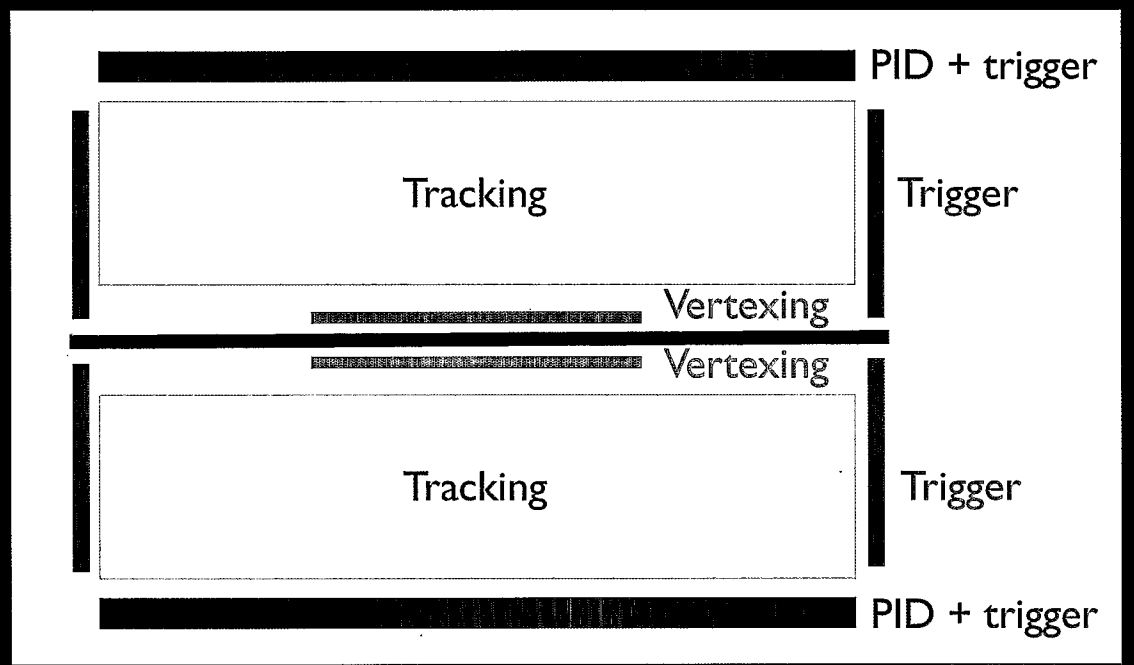




Use particle ratio fluctuations as case study

What can be achieved at RHIC?

"Ideal Detector"



* >80% tracking + PID efficiency from 0.1 < pT < 2.0 GeV/c, over 2+ units of rapidity
* Large acceptance trigger/centrality counters
* High resolution vertexing

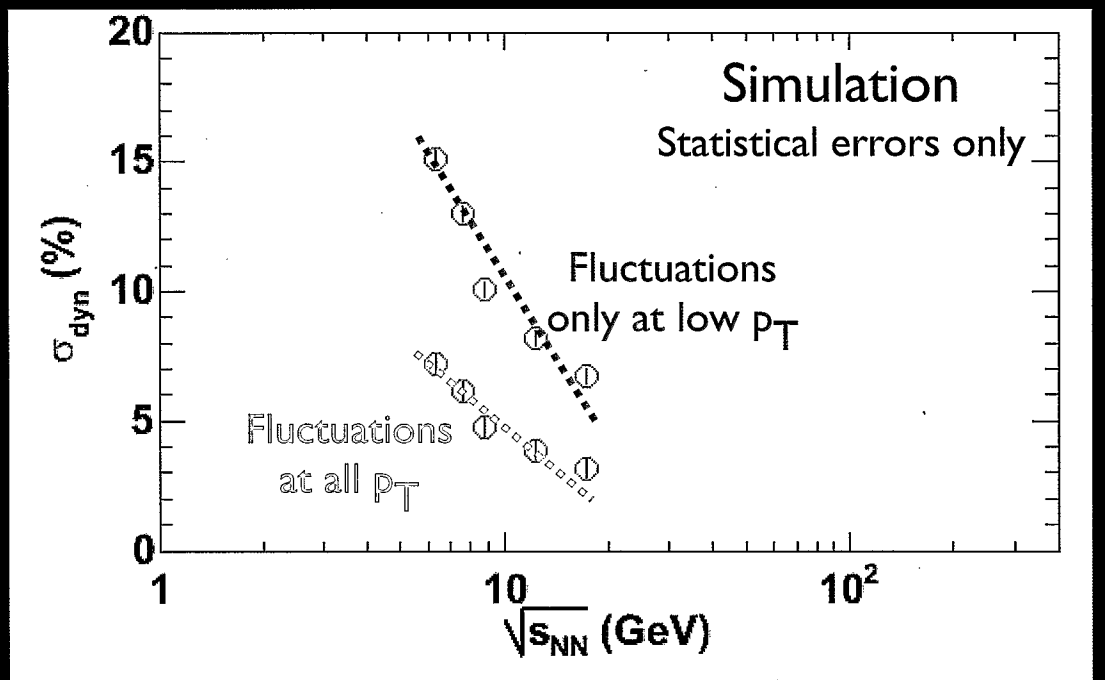
Assume 100k central sample at each $\sqrt{s}$

* 2π ToF PID coverage near y=0 possible
* Acceptance in (pT,y) independent of $\sqrt{s}$
* Track density grows logarithmically with $\sqrt{s}$
* Consistent centrality determination from N_{ch}

But: give up very low p_T, luminosity vs fixed target

Low p_T K/π Fluctuations at √s RHIC

Assumptions:
* Ideal RHIC detector (see above)
* 100k central Au+Au at each √s
* K/π Fluctuations from NA49 are correct
* $0.1 < p_T < 0.5$ GeV/c



Conclusion:
RHIC low-√s scan should allow precision measurement of (low p_T) K/π fluctuations

Summary

- Strong theoretical motivation for A+A at $\sqrt{s}$ from 5-50 GeV
- Rich existing data set in this range
  - Non-trivial structure/change in yields, ratios, fluctuations/correlations
- Limited statistical/systematic significance
- Low-$\sqrt{s}$ scan at RHIC could confirm and <u>improve</u> experimental results

Prospects for RHIC Low-Energy Operations

Todd Satogata
Brookhaven National Laboratory

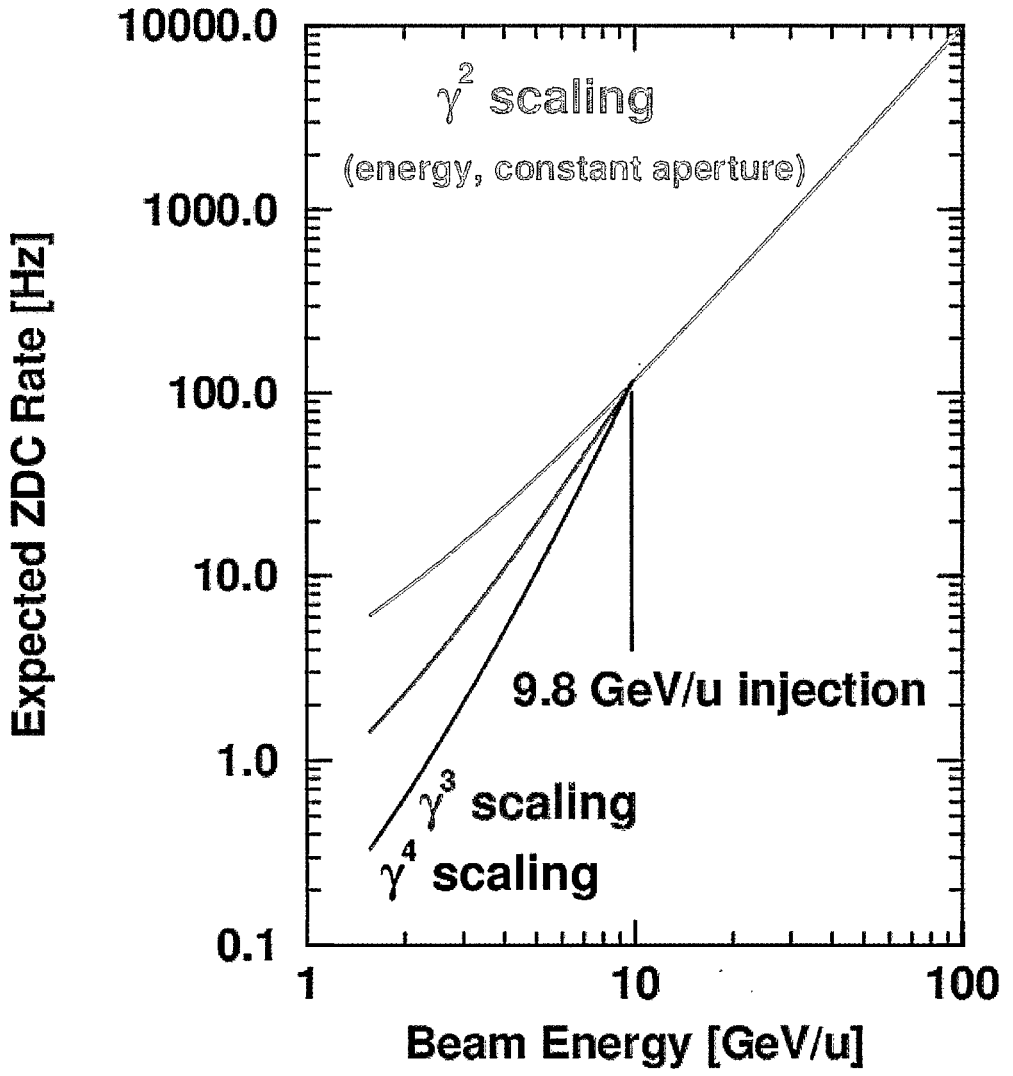
Summary:

- No apparent show-stoppers for RHIC collisions at 5-50 GeV/u
- Luminosity scales as γ^2 down to nominal injection energy
  - Modify lattice transition energy if necessary
- Luminosity likely degrades as γ^{3-4} below 9.8 GeV/u
  - Uncertainty dominated by field quality, power supplies
  - Should measure magnet field quality at very low currents
- Request a ~1 day study in run preceding low-energy operations
  - Identify power supply, lifetime, tuning issues/limitations
- Low-energy cooling is feasible in the 2 year timescale

BROOKHAVEN
NATIONAL LABORATORY

Initial Machine Projections

- Scaling laws apply above injection energies
- When aperture dominated:
  - Peak luminosity $\alpha\ \gamma^2$
- No clear scaling laws apply below injection energies
  - Injected beam already fills aperture
  - Magnetic field quality degrades very quickly
  - Power supply regulation is an issue
- Strawman model
  - Peak luminosity $\alpha\ \gamma^{3\text{-}4}$



Initial Machine Projections

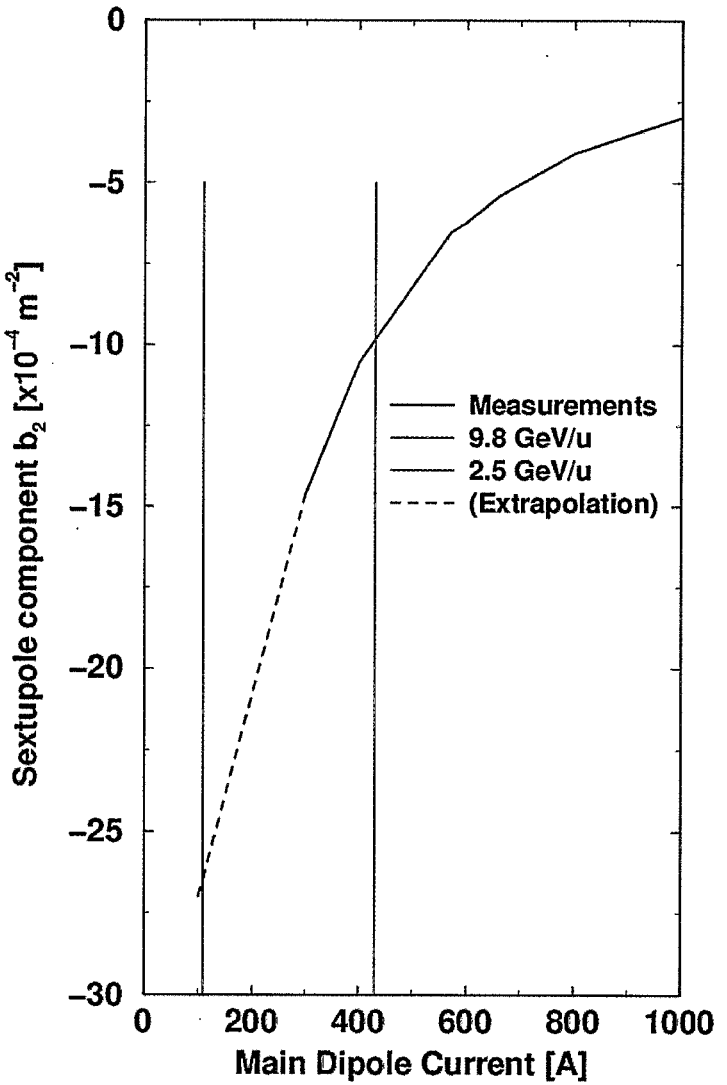
Mode	Beam Energy [GeV/u]	$N_{bunches}$	Ions/bunch [10^9]	β^* [m]	Emittance [μm]	L_{peak} [$cm^{-2}s^{-1}$]
Au-Au 2001-2	9.8	55	0.6	3	15	8.0×10^{24}
Au-Au 2003-4	31.2	45	1.0	3	15-30	1.2×10^{26}
Au-Au	9.8	55	1.2	10	15-40	1.0×10^{25}
Au-Au	2.5	55	1.0	10	15-30	1.1×10^{23}
Au-Au	25	55	1.2	3	15-40	2.0×10^{26}

- Assumes expected luminosity scaling as γ^3 below 9.8 GeV/u
- β^*/aperture and integrated luminosity tradeoffs must be studied
- Projections do not include potential improvements
  - Electron and stochastic cooling (peak and integrated luminosity)
  - Lattice modifications to mitigate IBS (integrated luminosity)
  - Total bunch intensity from vacuum improvements (peak luminosity)
- Small set of specific energies (and species?) should be a workshop deliverable for planning

Low-Energy Magnetic Field Quality

Total Energy	γ	$B\rho$	Dipole Current
9.8 GeV/u	10.52	81.11	430 A
2.5 GeV/u	2.68	20.69	110 A

- Magnet currents scale with rigidity $B\rho$ which scale with γ
- Field quality deteriorates rapidly at very low currents
- Currently have no magnet measurements at very low currents, few at low energy
  - Must extrapolate field behavior for simulations
  - Low-current magnet measurements are a priority



Beam Studies for Low-Energy Injection

- ~1 day of studies required in preceding run

- Initial studies
  - Trivially scale nominal injection to lower energies
  - Provides reality check of power supplies, optics
  - Test injection, establish circulating beam, optimize lifetime
  - Initial global optics measurements, field quality, tune scans
  - IBS growth time study require 3-6 hours extra time
    - All but IBS growth evaluation can be done with Run6 p

- Later studies
  - IBS modification lattice development
  - Field quality and detailed optics measurement/correction

Summary

- No apparent show-stoppers for RHIC collisions at 5-50 GeV/u
  - Lattice modifications to suppress IBS should be studied
- For energies 2.5-10 GeV/u, luminosity scaling is uncertain
  - Field quality at very low currents should be measured/modeled
  - β^*=10m likely required for reasonable lifetime/aperture
  - A ~1 day study period in preceding run will be very beneficial
    - Identify power supply, lifetime, tuning issues/limitations
- Above 10-12 GeV/u, luminosity scales as γ^2 with constant aperture
  - Study transition energy changes
    - Required to avoid ~3 GeV transition "hole" around 20-23 GeV/u
  - Very similar to normal heavy ion operations
- Low-energy cooling
  - Stochastic Palmer cooling under development, unknown cooling time
  - Electron cooling is quite promising (see A. Fedotov's talk)

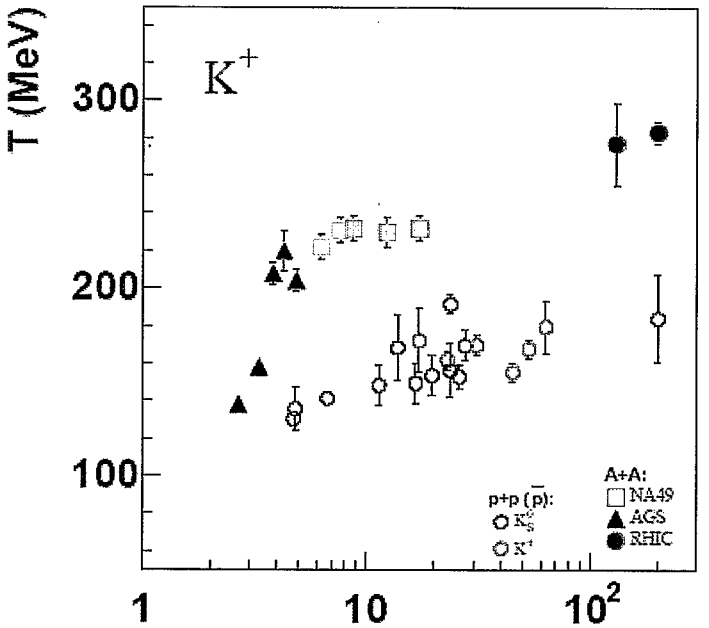
Energy Dependence of Pb+Pb collisions at the CERN SPS

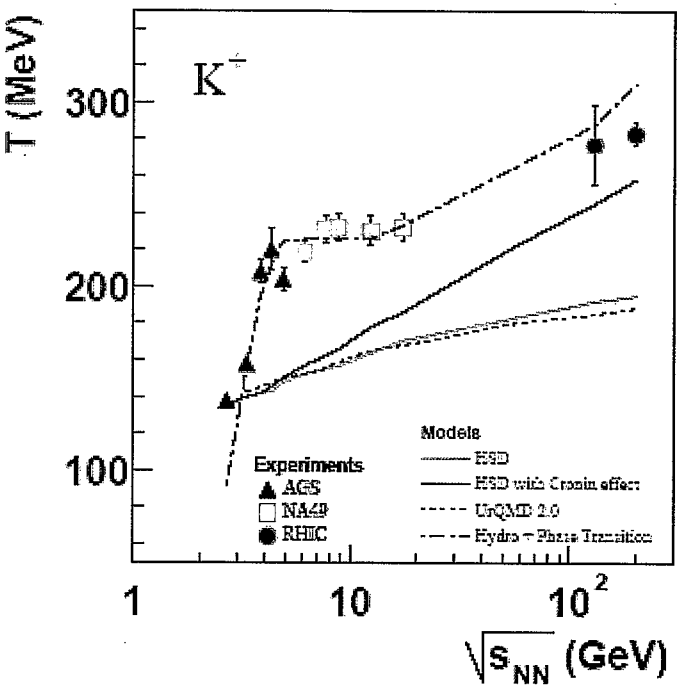
P.Seyboth, MPI für Physik, München
for the NA49 Collaboration

Summary

- Strong collective behavior in Pb+Pb (Au+Au) reactions:
  increasing radial and anisotropic flow AGS → SPS → RHIC
- Initial energy density reaches range of deconfinement at SPS
- Structure in the energy dependence of mT spectra and
  of pion and strangeness production indicate
  onset of deconfinement at low SPS energy
- No convincing signals of a phase transition or critical point
  in correlations and fluctuations yet, search continues
- Further experimental studies preferentially with an improved
  detector should be done to explore the possible existence
  of the critical point of QCD

Energy dependence – inverse slope parameters

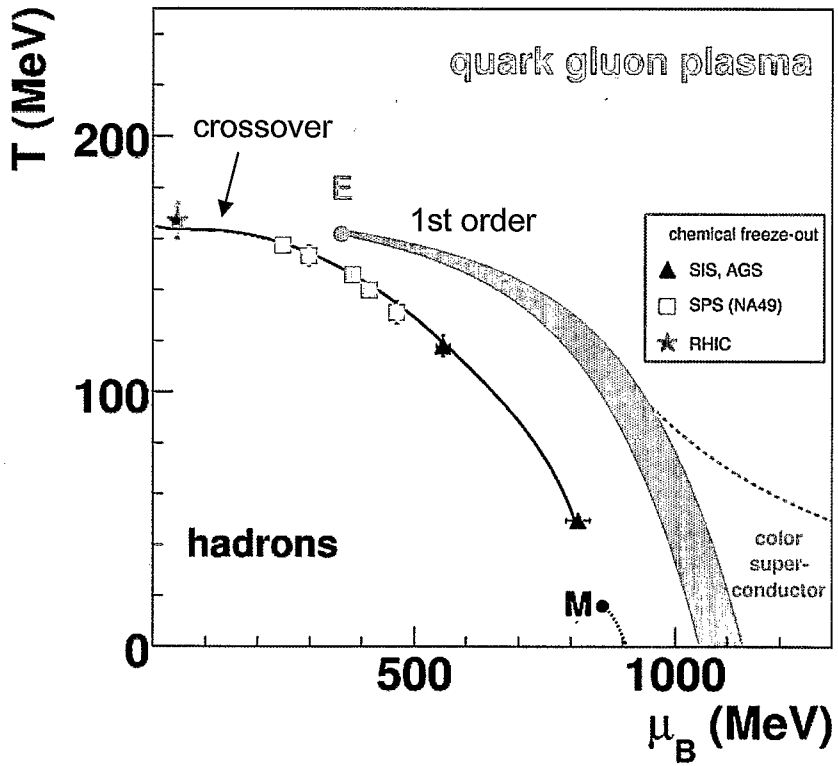




- the step-like feature is not seen for pp collisions and models without phase transition do not show it
- consistent with approximately constant pressure and temperature in a mixed phase system

(L.van Hove, PLB89(1982)253; M.Gorenstein et al.,PLB567(2003)175)
model curve SPheRIO S.Hama at al., Braz.J.Phys,34,322 (2004)

Global view - Phase diagram



(Lattice-QCD phase boundary: Fodor,Katz JHEP04(2004)050)

- statistical model describes yields from SIS to RHIC energy
- T of "hadrochemical" freeze out increases SIS → RHIC
- μ_B decreases (increase of pion production)

- freeze out line E ≈ 1 GeV / particle

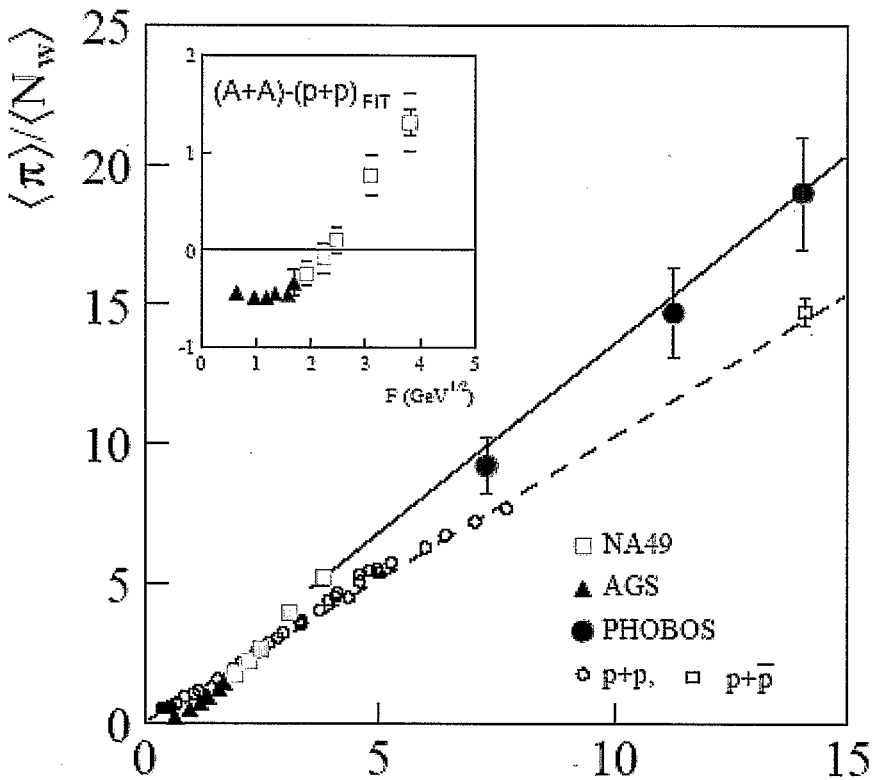
(Cleymans and Redlich, PRL 81(1998) 5284)

hadrochemical freeze out parameters approach the phase boundary at SPS

Energy dependence - π yields

- increase of $<\pi>/<N_W>$ with energy gets steeper in the SPS range
- π deficit changes to enhancement compared to p+p

$$<\pi> = 1.5 \cdot (<\pi^+> + <\pi^->)$$



$F\,(\mathrm{GeV}^{1/2}) \approx s_{NN}^{1/4}$

- pions are most abundant produced particle species
  → measure of entropy in statistical models

SMES: statistical model of the early stage

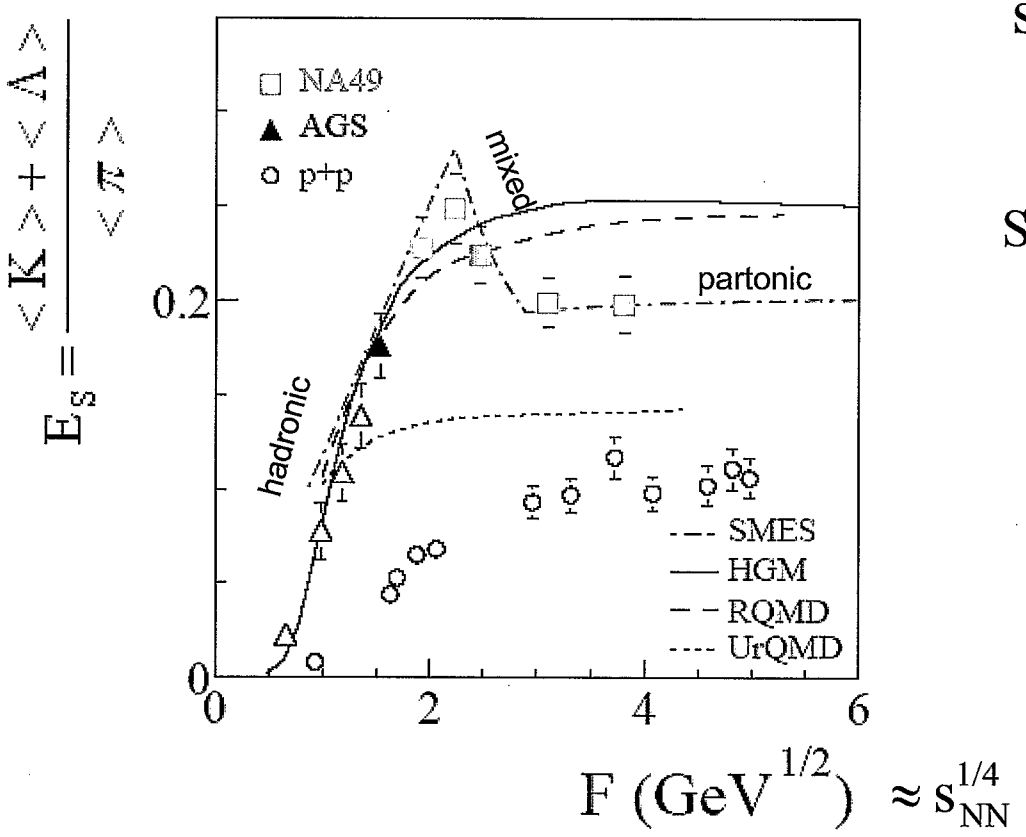
$$\frac{\langle \pi \rangle}{N_w} \propto \frac{S}{N_w} \propto g^{1/4} F$$

$$F = \frac{(\sqrt{s} - 2m_p)^{3/4}}{\sqrt{s}^{1/4}}$$

(Gazdzicki,Gorenstein : Acta Phys.Pol. B30(1999)2705)

Increase of initial d.o.f . g between AGS and SPS ?

Energy dependence – ratio of strange hadrons to pions



strangeness to pion ratio peaks sharply at the SPS

SMES explanation:

- entropy, number of s,sbar quarks conserved from QGP to freezeout
- ratio of strange/nonstrange d.o.f. rises rapidly with T in hadron gas
- E_s drops to predicted constant level above the deconfinement threshold

$$E_S \approx \frac{<N_S + N_{\bar{S}}>}{<\pi>} = \frac{0.74\, g_s}{g_u + g_d + g_g}$$

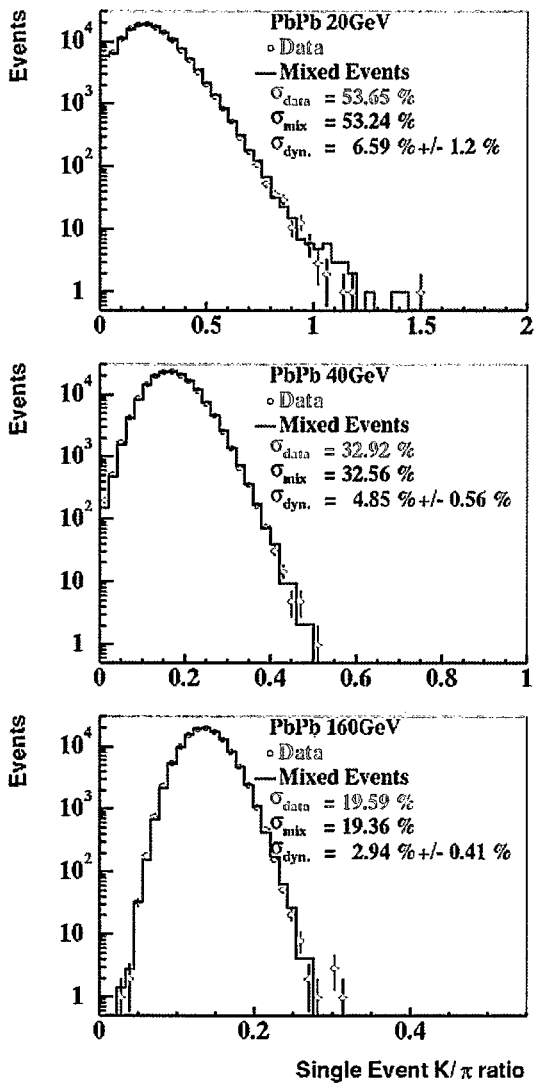
$$\approx 0.21$$

note: $<K> = 2(<K^+> + <K^->) = 4<K_S^0>$

suggests onset of deconfinement at SPS

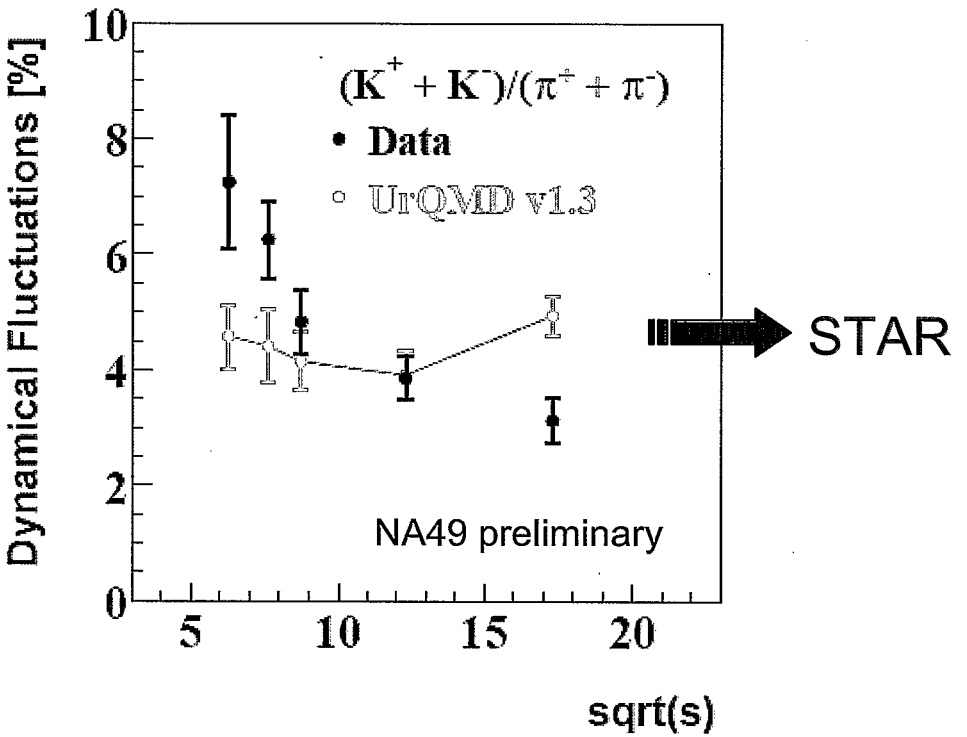
The Event-by-Event K/π ratio

Beam Energy



max.likelihood fit for each event

$$\sigma^2_{dyn} = \sigma^2_{data} - \sigma^2_{mixed}$$



Increased fluctuation signal at lower beam energies

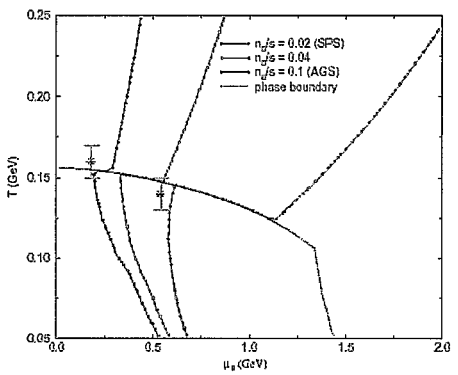
P.Seyboth: Energy dependence of Pb+Pb collisions at the CERN SPS
Workshop: Can We Discover the QCD critical Point at RHIC ? BNL, 9/3/2006

Four special points of the high-mu RHIC

Edward Shuryak
Department of Physics and Astronomy
State University of New York
Stony Brook NY 11794 USA

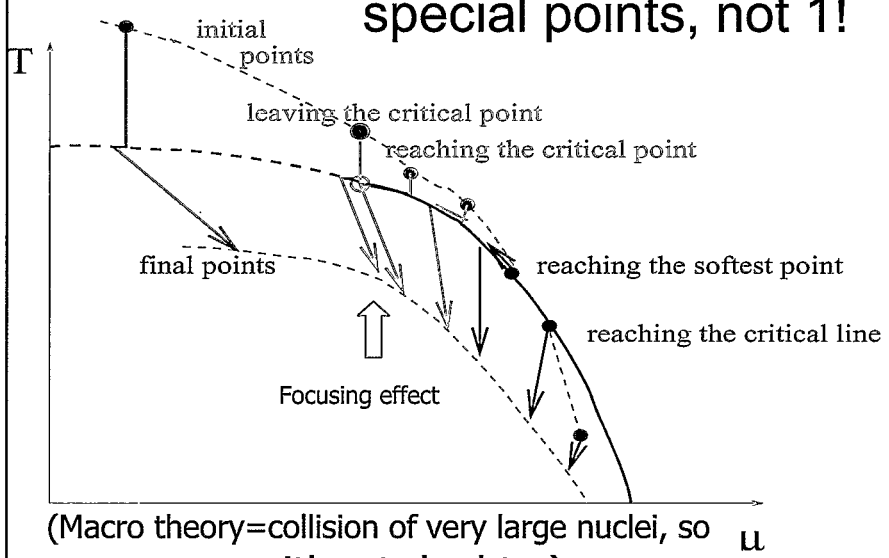
The zigzags on the phase diagram

- Both bar.charge and entropy are conserved: n_b/s=const(t)
- In resonance gas and QGP different formulae: curves do not meet at the critical line
- Of course they are connected inside the mixed phase –heating while expanding due to latent heat



A decade old plot
From C.M.Hung and ES, hep-ph/9709264,PRC

Macro theory expects 4 special points, not 1!



(Macro theory=collision of very large nuclei, so Hydro is valid without doubt...)

In passing: does (ideal) hydro work at low energy?

- Yes, radial flow (which is less influenced by viscosity) is OK
- Important point: one has to do dynamical freezeout for each species and each system size!
- (not done by most hydro even for RHIC, important for s,y-dependences)

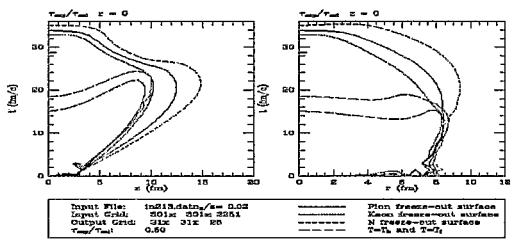
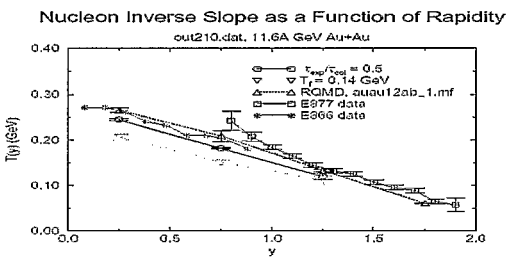
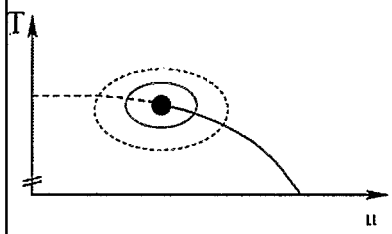


FIG. 12. Freeze-out surfaces for 160A GeV Pb+Pb



Pion-pion interaction



Inside the dashed line

$$m_\sigma < 2E_\pi$$

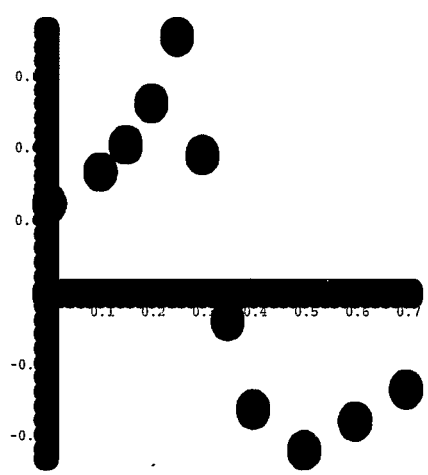
Pion-pion interaction gets repulsive

$$m_\sigma < 2m_\pi$$

At the boundary of the the shaded region sigma acts as the Feshbach resonance for cold atoms, making pion gas a liquid!

Pion potential induced by sigma

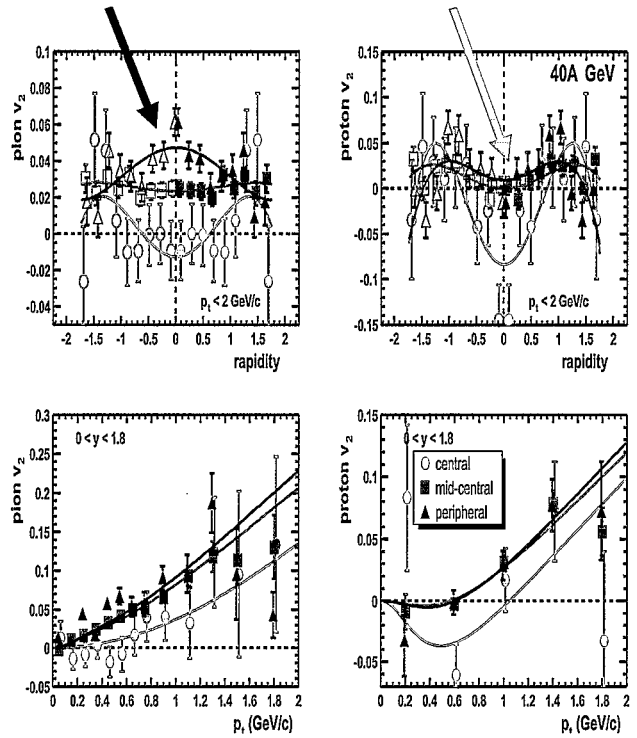
- Re(V_eff(p=0,m_sigma)) [GeV] vs the sigma mass [GeV]
- Change from attraction to repulsion!
- Note: a singularity at 2m(pion)



Now we go to 40 GeVA, NA49

Note the collapse of the N flow at midrapidity

Is it so?



Baryons go from light to heavy because quark quasiparticles are heavy

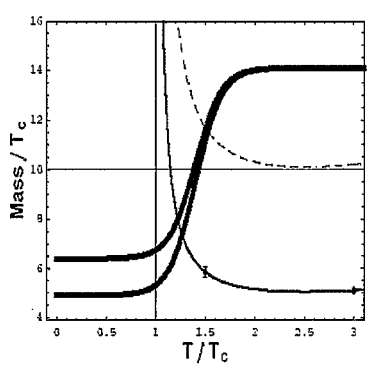


FIG. 5. Masses of various states studied in this work. The thin solid line is for quark and the dashed line is twice quark mass which is roughly for quark-gluon and diquark. The lower thick solid line is for nucleon states and the upper one for Δ states. These masses are used for calculation of Fig.7.

Unlike colored objects, Such as q, qg, qq etc, Baryons (N...) should Evolve through the QCD phase transition Continuously

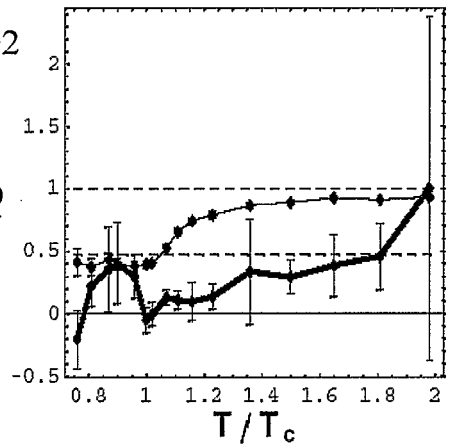
Their mass must grow Into the sQGP side

This will generate T and mu derivatives! M″ has a ``wiggle″!

Baryons, not quarks dominate d4 and d6

$\partial^2\mu I$ / $\partial^2\mu$ = ((2I_3) / B)^2

Derivatives work like this:
- **For quarks d_In/d_n=1**
- **For N and Delta+, Delta0=1/9**
- **For Delta ++ and Delta -=1**
- **For 4 N and 16 Delta = .466**



.46
N+Δ

FIG. 6. The susceptibilities ratios d_4^I/d_4 (the thin solid) and d_6^I/d_6 (the thick solid). The dashed lines correspond to ideal quark gas (upper) and ideal baryonic gas (lower).

Summary

- **4 special points expected**
- **2 are related with 1st order line**
- **2 with the critical point**

○ The softest point corresponds to the logest lived fireball => horn?

•Near critical point one expects a massless (sigma-omega) mode

=>V(pions) gets repulsive

=> Walecka cancellation is violated

=> stronger NN and rhoN attraction

•affect N and pion flows in opposite direction. Is it what is happening at 40 GeV according to NA49?

○ Heavy baryons in QGP?

Soft mode of the QCD critical point

H. Fujii

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

In this talk I will focus on the soft mode associated with the QCD critical point, which is expected as an endpoint of the 1st order line in the T-μ phase diagram.

In the case of n_f=2 massless quarks, the chiral-symmetry broken phase in low T/μ region is separated from the symmetry restored phase by a boundary line of singularity. Here we assume a tri-critical point where the nature of transition changes from the 2nd to the 1st order although for a proof we would need dynamical information beyond symmetry-based arguments. At the tri-critical point the entropy and baryon number densities start to have gap, and accordingly their susceptibility diverge in addition to the scalar susceptibility.

We may extend the phase space to T-μ-m_{ud}. As the quark mass value m_{ud} is increased, the 2nd order line is smeared out and an edge line of the 1st-order 'wing' surface originates from the tri-critical point. We call this endpoint singularity the QCD critical point. At this point, the susceptibilities of T, μ and m_{ud} all diverge with the same singularity exponent.

We know that mode softening generally accompanies with a critical point. When m_{ud}=0, the sigma meson is regarded as the soft mode which degenerates with the pions at $T \geq T_c$.

What is the soft mode associated with the QCD critical point with $m_{ud} \neq 0$? Regarding the singularity, the scalar channel is not special than the other baryon number and entropy channels. Furthermore, it is known that the susceptibility of conserved density is completely given by the 'hydro'-mode spectrum whose characteristic frequency vanishes as the wavenumber q goes to zero, irrespective of whether we are near or away from the critical point. Hence we expect that the 'hydro'-mode should bear critical behavior near the QCD critical point.

We demonstrate this general argument by computing the mode spectrum within the NJL model, and give a brief discussion about the dynamica critical behavior associated to the QCD critical point. The effects of the coupling between the critical hydro-mode and other degrees of freedom, e.g., pions, are left open for further study.

References

1. H. Fujii, Phys. Rev. D67, 094018 (2003).
2. H. Fujii and M. Ohtani, Phys. Rev. D70, 014016 (2004).
3. D. Son and M. Stephanov, Phys. Rev. D70, 056001 (2004).

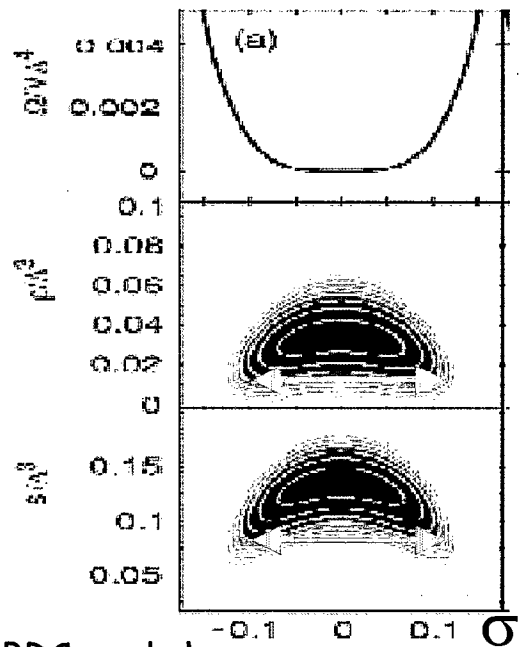
Introduction

$\Omega(\sigma, n_B, s)$ at critical points in NJL model

Chiral critical point
- σ is the flat direction

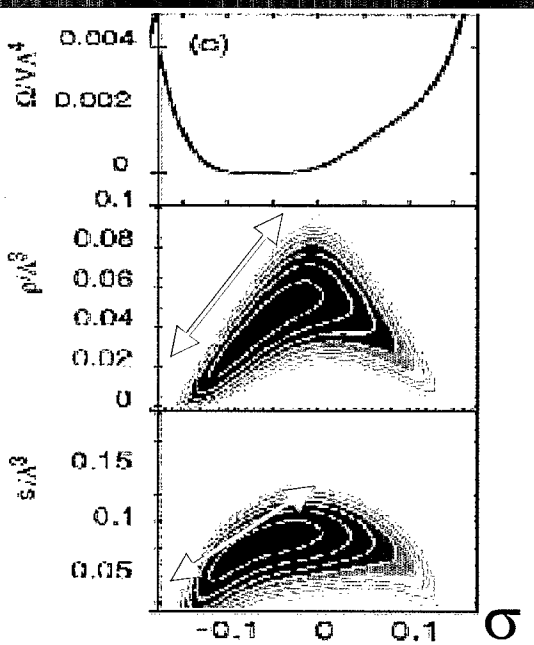
χ_m is divergent !

$m_{screen} = 4\chi_m \lambda^2 = 0$



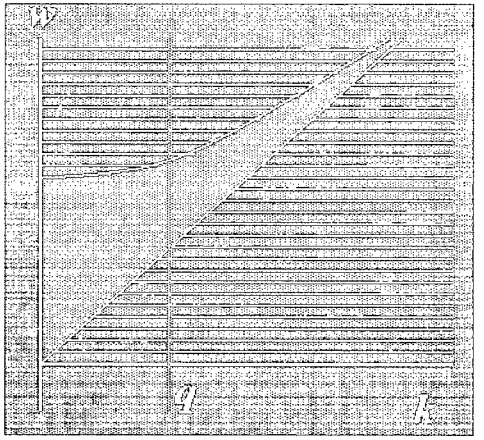
QCD critical point
- A valley in (σ, n_B, s) space

Screening masses vanish in all these channels



Divergence at a critical point accompanies mode softening

$$\chi = \lim_{q\to 0} \chi(0,q) = \int \frac{d\omega}{2\pi} \frac{\rho(\omega,q)}{\omega}$$



- Chiral critical point → χ_m diverges
  → softening of σ meson (and π)

- QCD critical point (endpoint of 1st order line)
  → C, χ_μ and χ_m diverge
  → What is the critical mode there?

Cf.Scavenius et al. PRC64,2001
Fukushima-Ohnishi

N.B. $(m_\sigma^{screen})^2 = 1/\chi_m$ and m_σ^{dyn} are different quantities

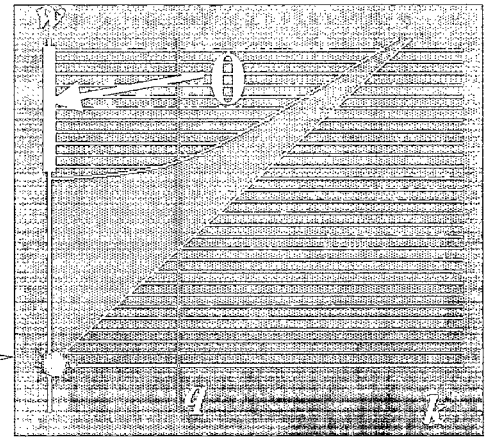
Ans: A hydrodynamic mode

Hydrodynamic modes

Long-wavelength fluctuations of conserved density dists.

- e.g. Energy, Baryon number, ..., etc.
  - Inherent to in-medium dynamics
  - Low-lying mode due to conservation :

$$\omega n = q.j$$



From a textbook (e.g., Forster),

Susceptibility of conserved density is completely given by the modes whose $\omega \to 0$ as $q \to 0$.

This is always true ➔

Enhanced C & χ_μ near critical point must be caused by modes

s.a. sound $\omega = cq$, thermal diffusion $\omega = iaq^2$, ... etc.

Lesson from model result

Hydro-mode is low-lying due to conservation

Chiral case:

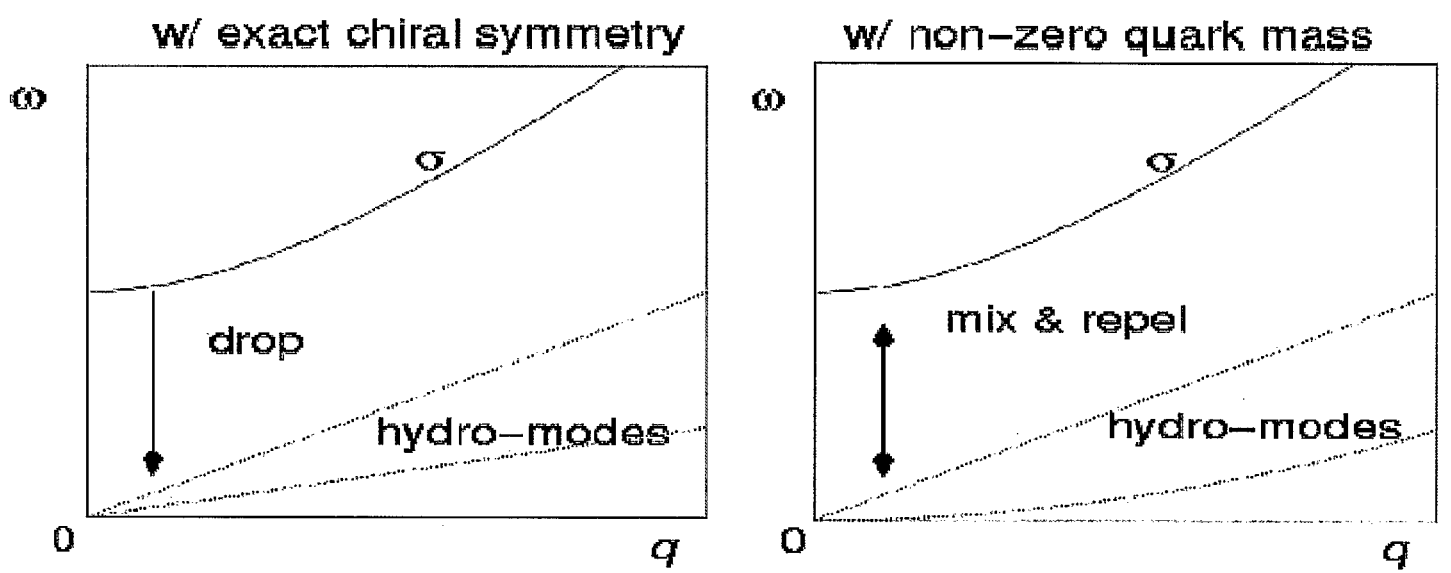
effective action is a function of σ^2

→ no linear mixing btwn σ and others

QCD critical point:

linear mixing occurs among s, n_B and σ

Schematic representation of the solution



Slow dynamics near QCD critical point

HF, PRD67,2003
HF-Ohtani, PTPS153,2004
Son-Stephanov, PRD70,2004

σ meson decouples:

slow dynamics of $T^{\mu\nu}$ & n_B → the same as liq.-gas

known facts:

thermal diffusion $\omega \sim q^z$, $z \sim 3$

thermal conductivity $\lambda \sim q^{-18\varepsilon/19}$,

shear viscosity $\eta \sim q^{-\varepsilon/19}$

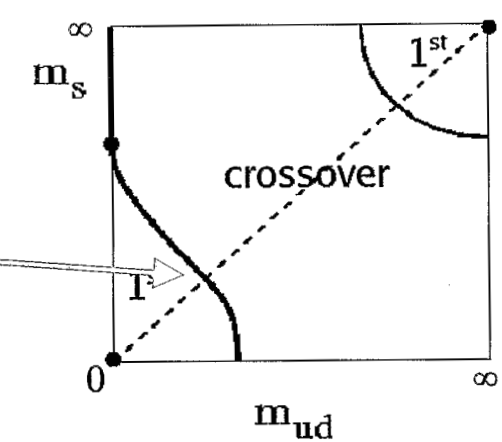
Other critical points:

Critical point with finite iso-spin density

($T^{\mu\nu}$ & n_B & n_I)

Critical point on T-axis

$T^{\mu\nu}$



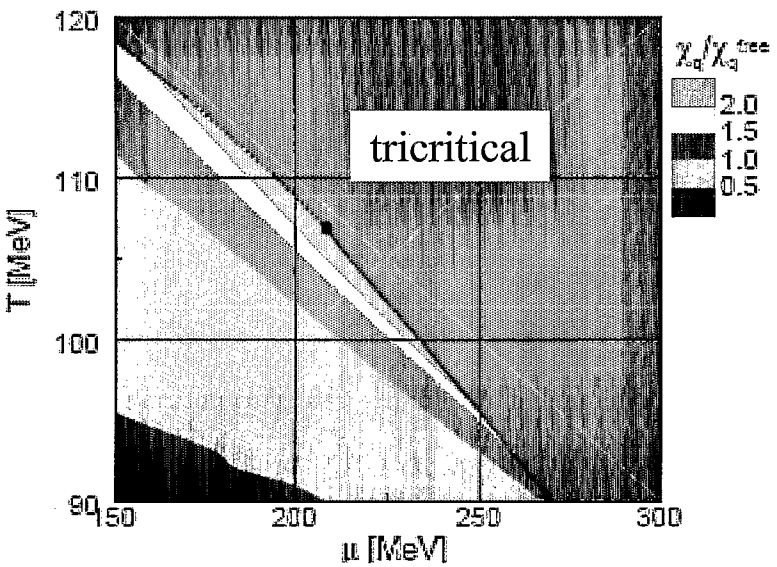
Baryon number fluctuation near the critical point

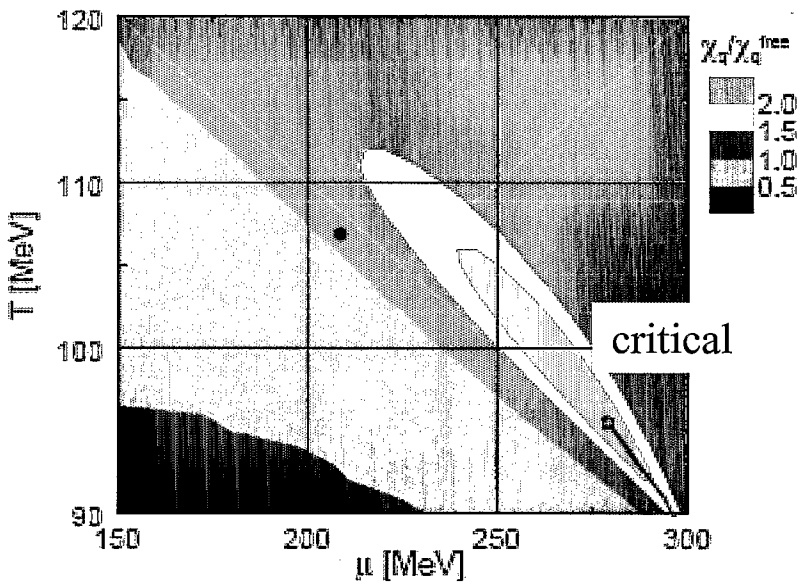
Yoshitaka Hatta
(RIKEN BNL)

In the first part of this talk, we demonstrate that the baryon number fluctuation is enhanced in a large region in the T-\mu plane.
In the second part we propose the proton number fluctuation as a signal of the critical point.

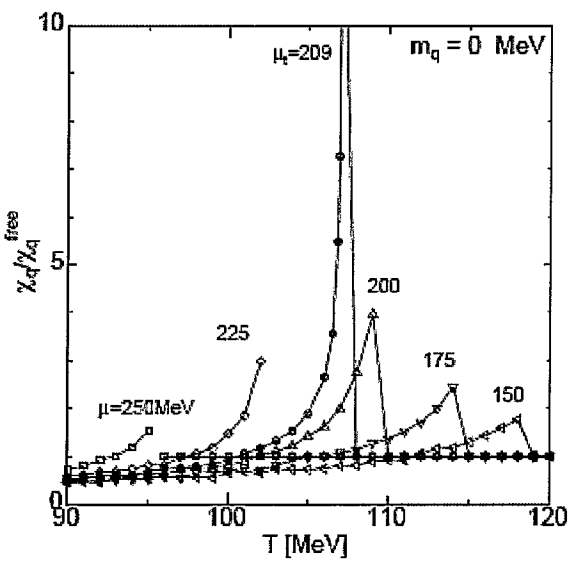
Refs. Y. H . and T. Ikeda, Phys. Rev. D 67 014028 (2003)
Y. H. and M. Stephanov, Phys. Rev. Lett. 91 102003 (2003)

The quark number susceptibility near the (tri)critical point





$$m_q = 0$$



$$m_q = 5\text{MeV}$$

Our model:

CJT effective potential in the improved ladder approximation

Quark-mass scaling

Quark mass dependence of the critical point

$$T_c(m_q) - T_t \propto m_q^{2/5}$$

$$\mu_c(m_q) - \mu_t \propto m_q^{2/5}$$

Susceptibilities

$$\chi_{chiral} \propto m_q^{-16/15} \, |\mu - \mu_c(m_q)|^{-\varepsilon}$$

$$\chi_B, C \propto m_q^{2/15} \, |\mu - \mu_c(m_q)|^{-\varepsilon}$$

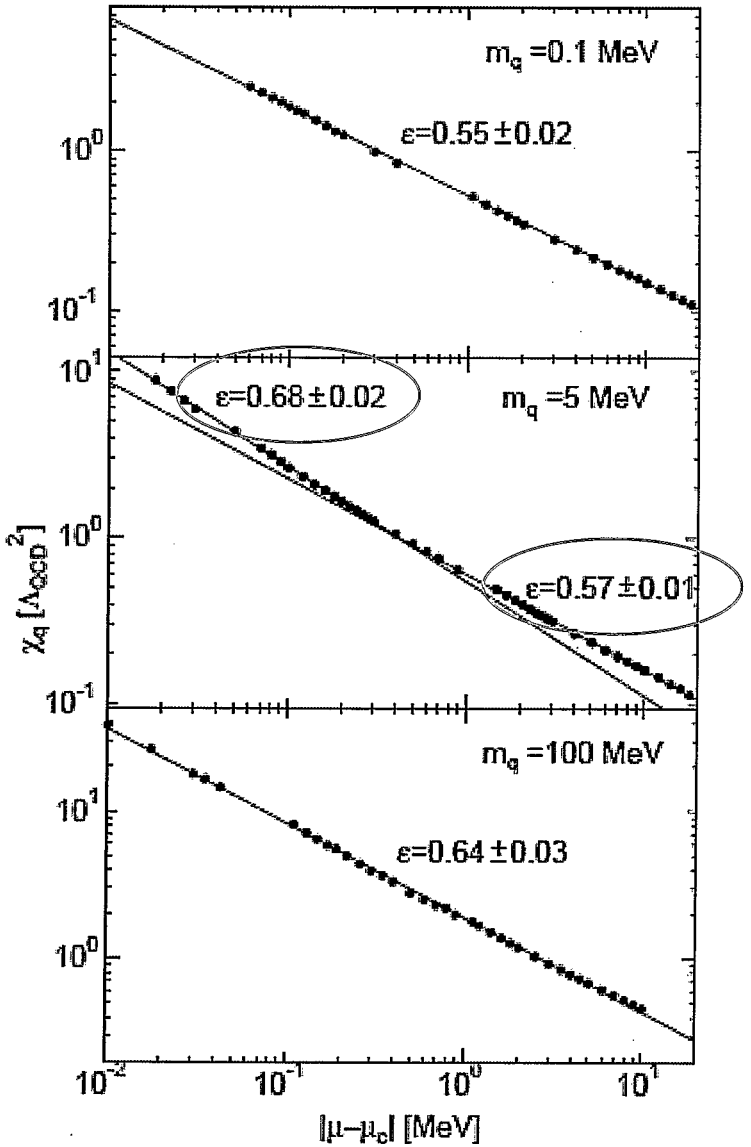
$$\varepsilon = \frac{\gamma}{\beta\delta} = \frac{2}{3}$$

Size of the critical region

$$\propto m_q^{4/5}$$

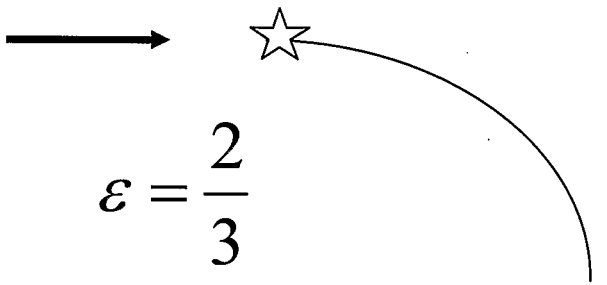
$\longrightarrow$ Mean field approximation is good

Crossover of two universality classes



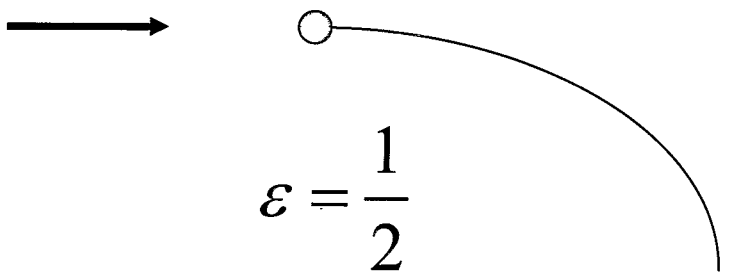
critical vs. tricritical

Critical ($m_q \neq 0$)



$$\varepsilon = \frac{2}{3}$$

Tricritical ($m_q = 0$)



$$\varepsilon = \frac{1}{2}$$

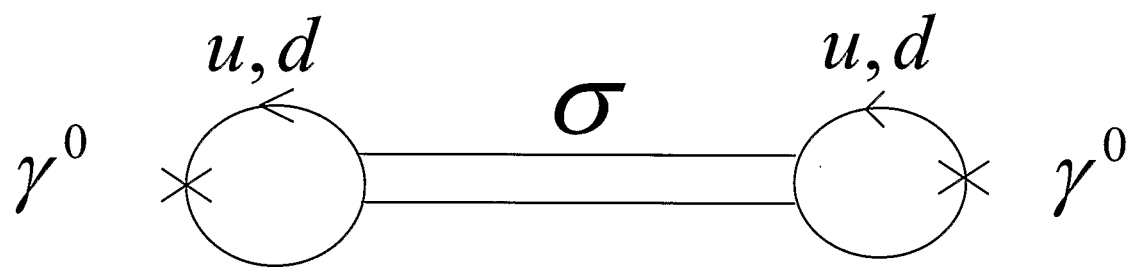
The order parameter is isospin blind

The baryon number fluctuation is divergent, but the isospin fluctuation is not.

$$(\mu_I = 0)$$

$$\chi_B = <(\bar{u}\gamma^0 u + \bar{d}\gamma^0 d)^2> \rightarrow \infty$$

$$\chi_I = <(\bar{u}\gamma^0 u - \bar{d}\gamma^0 d)^2> \rightarrow \text{finite}$$



Divergence comes from disconnected quark-loop diagrams.

Proton number fluctuation

Isospin blindness implies

Y. H. and M. Stephanov, '03

$$< PP >=< NN >=< PN >$$

$$< P\pi^{+} >=< P\pi^{-} >=< N\pi^{+} >=< N\pi^{-} >$$

$$\chi_B = 4 < PP >$$

$$\chi_I = 0$$

$$\chi_{EM} =< PP >$$

Divergence comes from protons!

Hydrodynamical evolution near the QCD critical point

Chiho Nonaka

School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, U.S.A.

Masayuki Asakawa

Department of Physics, Osaka University, Toyonaka 560-0043, Japan

Hydrodynamical calculations have been successful in describing global observables in ultrarelativistic heavy ion collisions, which aim to observe the production of the quark-gluon plasma. On the other hand, recently, a lot of evidence that there exists a critical point (CP) in the QCD phase diagram has been accumulating. Nevertheless, so far, no equation of state with the CP has been employed in hydrodynamical calculations. Here, we construct the equation of state with the CP on the basis of the universality hypothesis and show that the CP acts as an attractor of isentropic trajectories. We also consider the time evolution in the case with the CP and discuss how the CP affects the final state observables, such as the correlation length, fluctuation, chemical freezeout, kinetic freezeout, and so on. Finally, we argue that the anomalously low kinetic freezeout temperature at the BNL Relativistic Heavy Ion Collider suggests the possibility of the existence of the CP.

Reference: Phys. Rev. C **71**, 044904 (2005)

EoS with QCD CP

- Singular Part near CP + Non-singular Part
  1. Singular part of EoS near CP

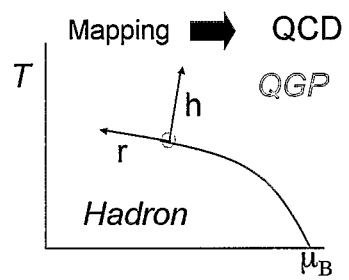
     assumption:

     3d Ising Model ⟷ **QCD**

     $r = \frac{T - T_C}{T_C}$ Same Universality Class T, μ_B

     h: extermal magnetic field $(r, h) \longleftrightarrow (T, \mu_B)$

     - Mapping: $(r, h) \longleftrightarrow (T, \mu_B)$
  2. Singular Part + Non-Singular Part
     - Matching with known *QGP* and *Hadronic* entropy density
  3. Thermodynamical quantities
     - Entropy density



Chiho NONAKA

Singular +Non Singular

Entropy Density

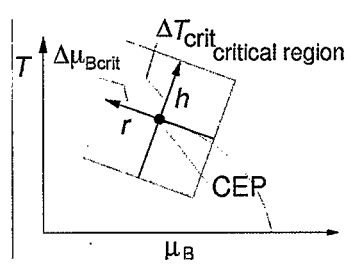
$$S_{\text{real}}(T, \mu_B) = \frac{1}{2}\{1 - \tanh[S_c(T, \mu_B)]\} S_H(T, \mu_B) + \frac{1}{2}\{+\tanh[S_c(T, \mu_B)]\} S_Q(T, \mu_B)$$

- $S_H(T, \mu_B)$: Hadron Phase (excluded volume model)

  $S_Q(T, \mu_B)$: QGP phase
- Dimensionless parameter: S_c

  $S_c(T, \mu_B) = s_c \sqrt{(\Delta T_{\text{crit}})^2 + (\Delta \mu_{\text{crit}})^2} \times D$

  Critical domain
- Choice of parameters: $\Delta T_{\text{crit}}, \Delta \mu_{\text{crit}}, D$



Thermodynamical inequalities

$$\left(\frac{\partial S}{\partial T}\right)\Big|_{V,N} \geq 0, \quad \left(\frac{\partial P}{\partial V}\right)\Big|_{T,N} \geq 0, \quad \left(\frac{\partial \mu}{\partial N}\right)\Big|_{T,V} \geq 0$$

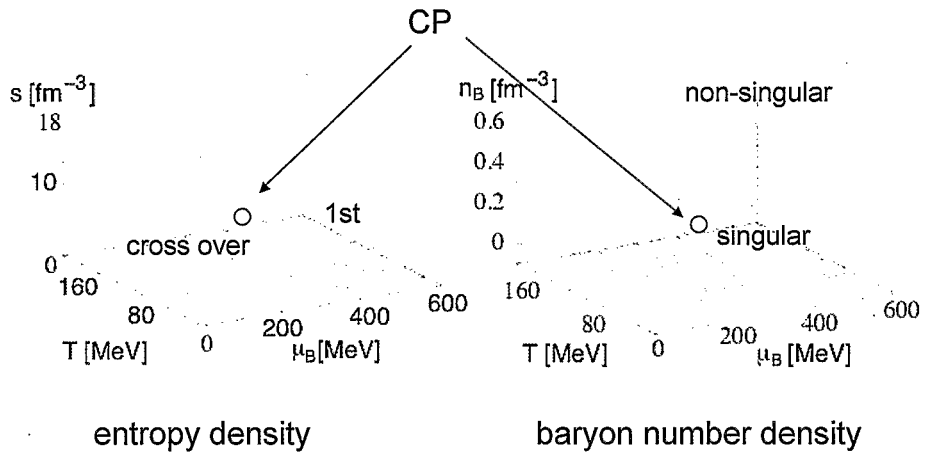
Critical exponent near CP keeps correctly.

Chiho NONAKA

Equation of State

Location of QCD CP: parameter

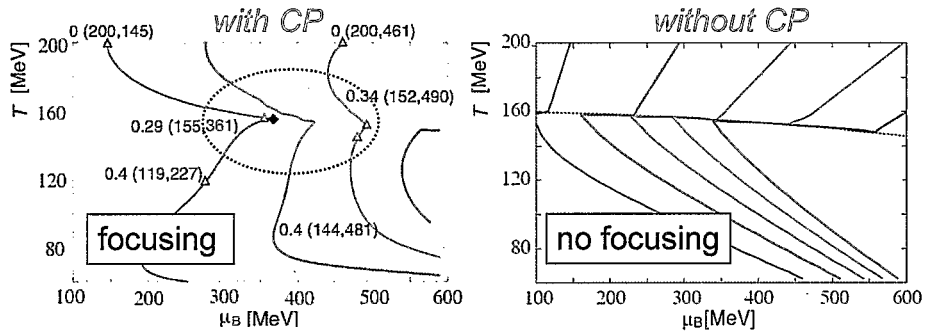
ex. $T_E = 154.7$ [MeV], $\mu_E = 367.7$ [MeV]

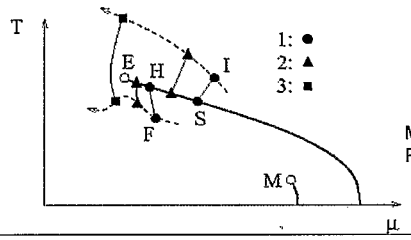


Chiho NONAKA

focusing

- Isentropic trajectories: s/n_B=const.





M. Stephanov, K. Rajagopal, and E.Shuryak, PRL81 (1998) 4816

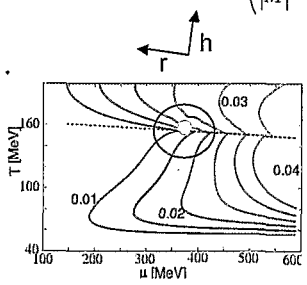
Chiho NONAKA

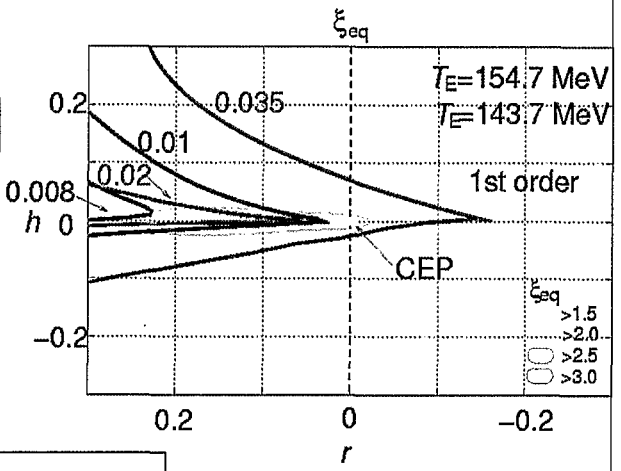
Correlation Length in Equilibrium

■ ξ_{eq}

Widom's scaling low

$$\xi_{eq}^2(r,M) = f^2 M^{-2\nu/\beta} g\left(\frac{|r|}{|M|^{1/\beta}}\right)$$





- Max. ξ_{eq} depends on n_B/s.
- Trajectories pass through the region where ξ_{eq} is large. (focusing)
- n_B/s ← non-critical component of the EOS

Chiho NONAKA

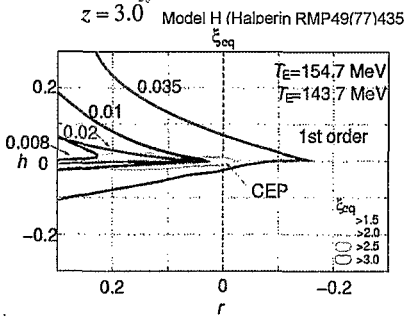
Dynamical Correlation Length

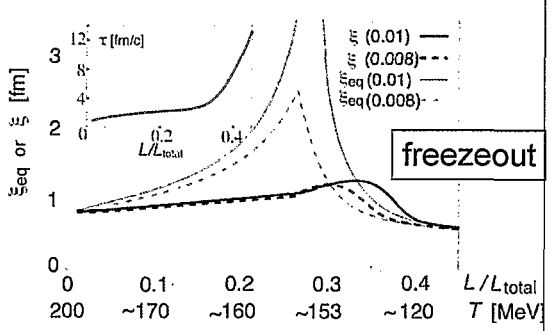
■ ξ : time evolution (1-d)

$$\frac{d}{d\tau} m_\sigma(\tau) = -\Gamma[m_\sigma(\tau)]\left(m_\sigma(\tau) - \frac{1}{\xi_{eq}(\tau)}\right)$$

$$\Gamma(m_\sigma) = \frac{a}{\xi_0}(m_\sigma \xi_0)^\gamma, \quad m_\sigma(\tau) = 1/\xi(\tau)$$

$z = 3.0$ Model H (Halperin RMP49(77)435





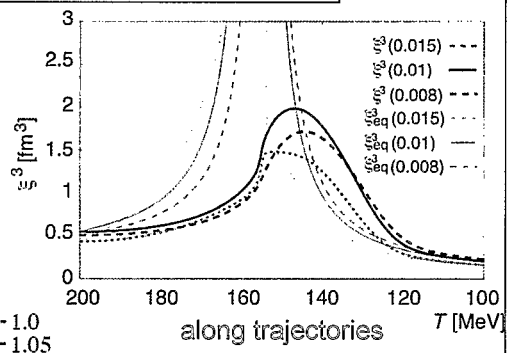
- ξ is larger than ξ_{eq} at T_f. ← Critical slowing down
- Differences among ξs on n_B/s are small.
- In 3-d, the difference between ξ_{eq} and ξ becomes large due to transverse expansion.

Chiho NONAKA

Fluctuation, Shear Viscosity

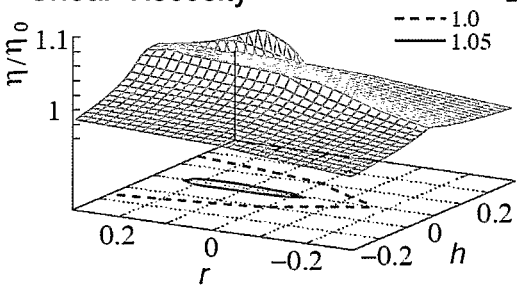
- Fluctuation ~ ξ^3

• There is a possibility that the fluctuation shows some enhancement.



along trajectories

- Shear Viscosity



$$\frac{\eta}{\eta_0} = \left(\frac{\xi_{eq}}{\xi_{eq,0}}\right)^{(\frac{1}{10}\epsilon + O(\epsilon^2))}$$

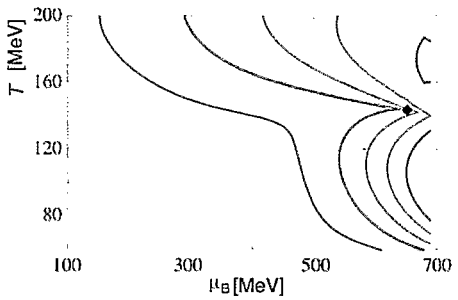
ε=4−d

• Entropy production is expected small.

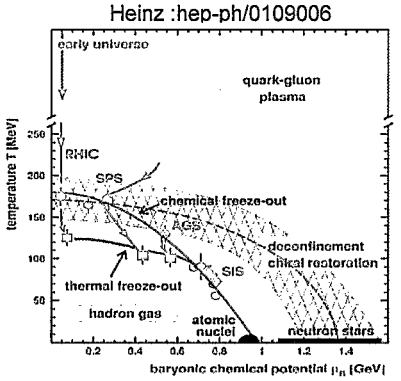
Chiho NONAKA

Chemical Freezeout

- Hadron ratios



Heinz :hep-ph/0109006



Chemical freezeout point is focused?

➔ Not necessarily

•Statistical Model
Free resonance gas model

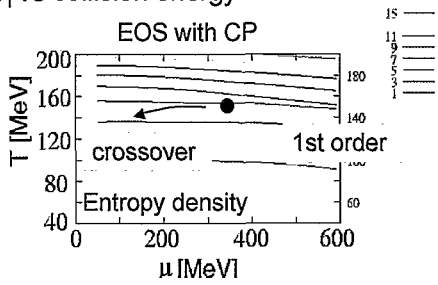
⇕

•At chemical freeze-out
Quasi-particle state
Csorgo, Gyulassy, Asakawa PRL99

Chiho NONAKA

Thermal Freezeout

- T_f vs collision energy

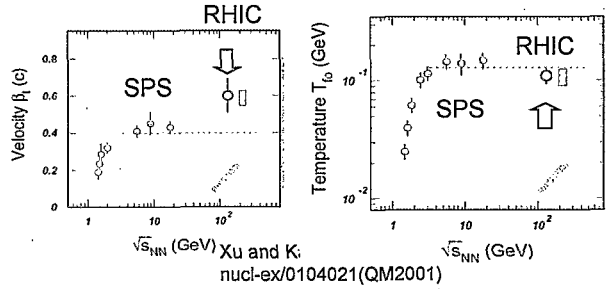


Thermal freezeout takes place at lower T_f at RHIC?

Yes!
QCD CP may exist between RHIC and SPS collision energy.

- Thermal freezeout
  - Expansion rate RHIC > SPS
  - Collision rate, HBT SPS ~ RHIC

- T_f(RHIC) > T_f(SPS)



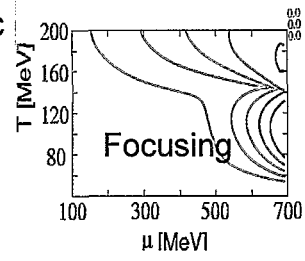
Xu and K
nucl-ex/0104021(QM2001)
BRAHMS nucl-ex/0404011

Chiho NONAKA

CP and Its Consequences

- Focusing in isentropic trajectories
  Fine tune collision energy is not necessary.
- Consequence:
  fluctuations,
  low thermal freezeout temperature at RHIC

Existence and location of CP in phase diagram: Collision energy dependent experiments are indispensable.



Future task

- Realistic time evolution (ex. 3-d hydro calculation) with critical point

Chiho NONAKA

Prospects of a new ion program at the CERN SPS

M. Gazdzicki for NA49-future
Frankfurt, Kielce

- Physics goals
- NA49-future
- Experimental landscape

Based on Letter of Intent of NA49-future Collaboration:
"Study of Hadron Production in Collisions of Protons and Nuclei at the CERN SPS",
CERN-SPSC-2006-001

- Physics goals

  - Study the properties of the onset of deconfinement:
    -is it possible to observe the predicted signals of deconfinement in fluctuations and anisotropic flow?
    -what is the nature of transition from the anomalous energy dependence measured in heavy ion collisions to the smooth dependence seen in p+p interactions?

  - Search for the critical point of strongly interacting matter:
    -does the critical point of SIM exist in nature and, if it does, where is it located?

NA49-future

today

NA49-future = a proto-collaboration which intends to use the upgraded NA49 detector at the CERN SPS for:

-measurements of hadron production in A+A collisions, in particular fluctuations and long range correlations, with the aim to identify the properties of the onset of deconfinement and search for the critical point of SIM

-measurements of hadron production in p+p and p+A interactions needed as a reference data for better understanding of A+A reactions, in particular correlations, fluctuations and high transverse momenta will be the focus of this study

-measurements of hadron production in hadron-nucleus interactions needed for neutrino and cosmic ray experiments

The NA49-future Proto-Collaboration:

80 physicists from 20 institutes and 14 countries

Project status:

Letter of Intent "Study of Hadron Production in Collisions of Protons and Nuclei at the CERN SPS", CERN-SPSC-2006-001, submitted to the SPSC in January 2006

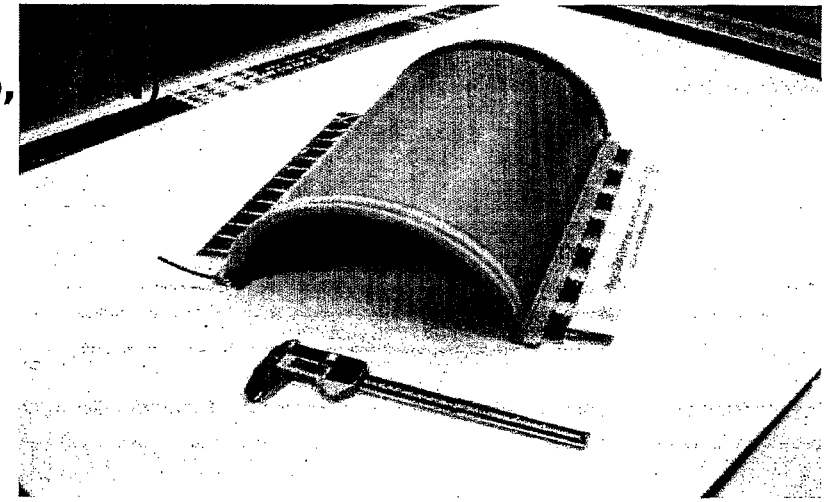
An recommendation of the SPSC expected in May 2006

A one week long test run (p-beam) scheduled for August 2006

Two running R&D projects:

-a high resolution Projectile Spectator Detector (INR Moscow, together with CBM),

-semi-cylindrical GEM detectors (Gas Detector Development Group,



Beam requirements:

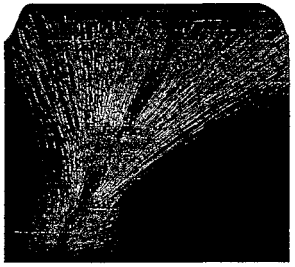
	beam	energy (*A* GeV)	#days
2006:	**protons**	**200**	**7**
2007:	**protons**	**30**	**30**
2008:	**hadrons**	**30-158**	**45**
2009:	**indium**	**10-158**	**30**
2010:	**silicon**	**10-158**	**30**
2011:	**carbon**	**10-158**	**30**

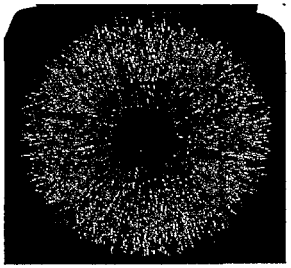
Ions for fixed target program at SPS possible only after the first, 2008, ion run at LHC

Experimental landscape

Physics comparison: SPS vs RHIC-low

	SPS (NA49-future)	RHIC-CP (STAR+...)
energy	5-20	5(?)-200 ⊕ ⊕
acceptance	4π (inclusive) ⊕ limited (e-by-e)	mid-rapidity (inclusive) 2π mid-rapidity (e-by-e) ⊕
event rate	30 Hz ⊕	1(?) Hz at low E
centrality control	a full measurement of N^{proj}_{spec} (PSD) ⊕	(?)





NA49-future:
- perfect for a fast energy-system size scan,
- very good for a study of properties of the deconfinement,
- ideal to study fluctuations of extensive quantities

RHIC-CP
- very broad energy range, perfect for a search for the critical point,
- excellent for a study of anisotropic flow and other azimuthal correlations (e.g. at high transverse momentum)

⬇

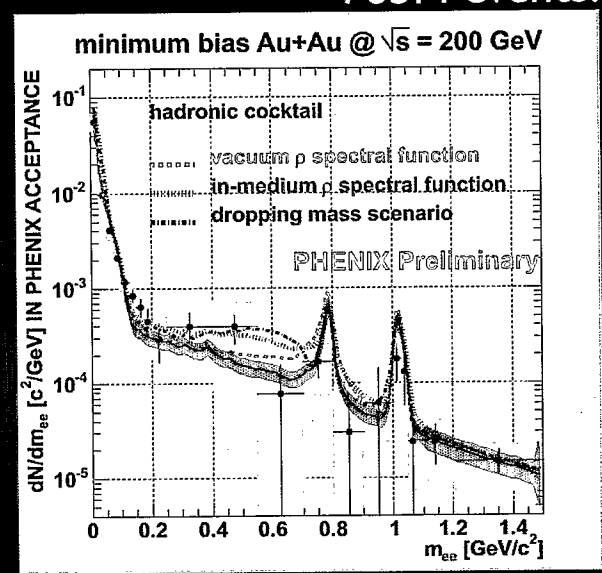
We need both RHIC-CP and NA49-future running soon

PHENIX Capabilities for the Low-Energy RHIC Run

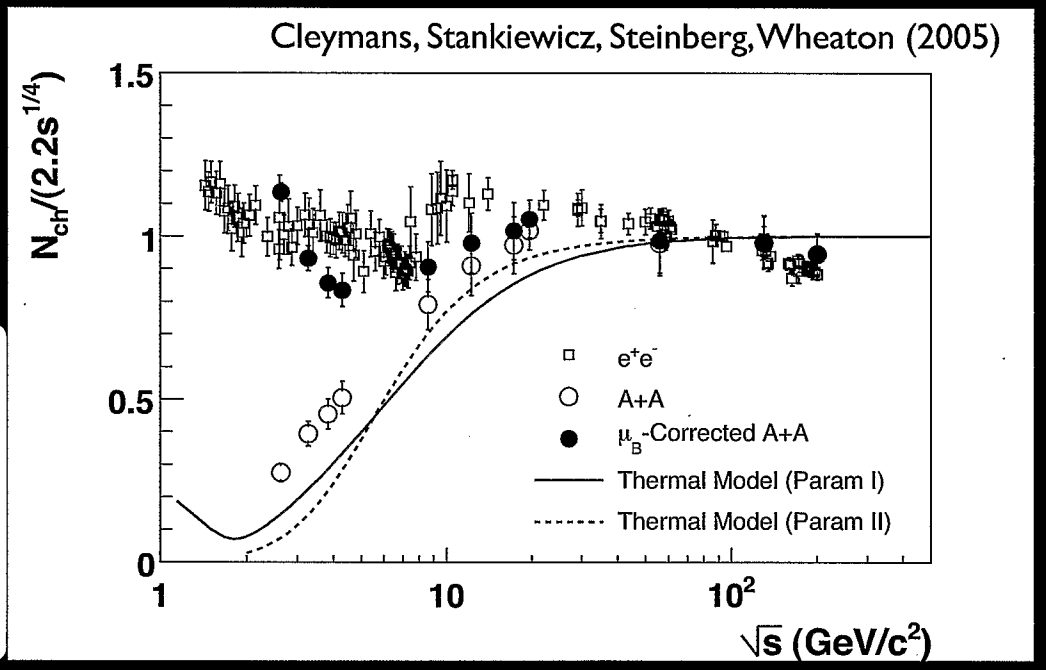
Peter Steinberg, BNL Chemistry Department

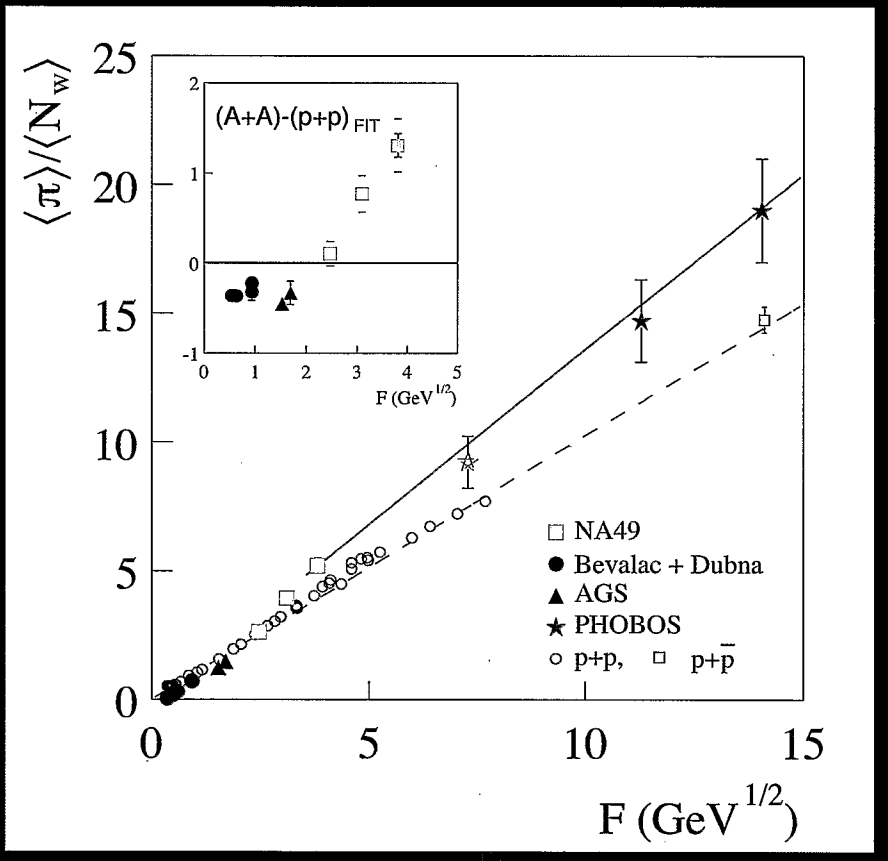
- Unprecedented opportunity to study strongly-interacting matter over 2 orders of magnitude in excitation energy!
- How does baryon density affect dynamics?
- PHENIX will provide a broad and deep menu of observables
  - Bulk observables (entropy, flavor, dynamics)
  - Correlations & Fluctuations
  - Rare probes (iff a long, dedicated run)
- High return to modest investment

765M events!



Baryons suppress entropy?





$$S = \frac{E + PV}{T} - \frac{\mu_B N_B}{T}$$

$$\Delta \frac{N_{ch}}{N_{part}/2} \propto \frac{\mu_B}{T}$$

A change in the number of degrees of freedom?...

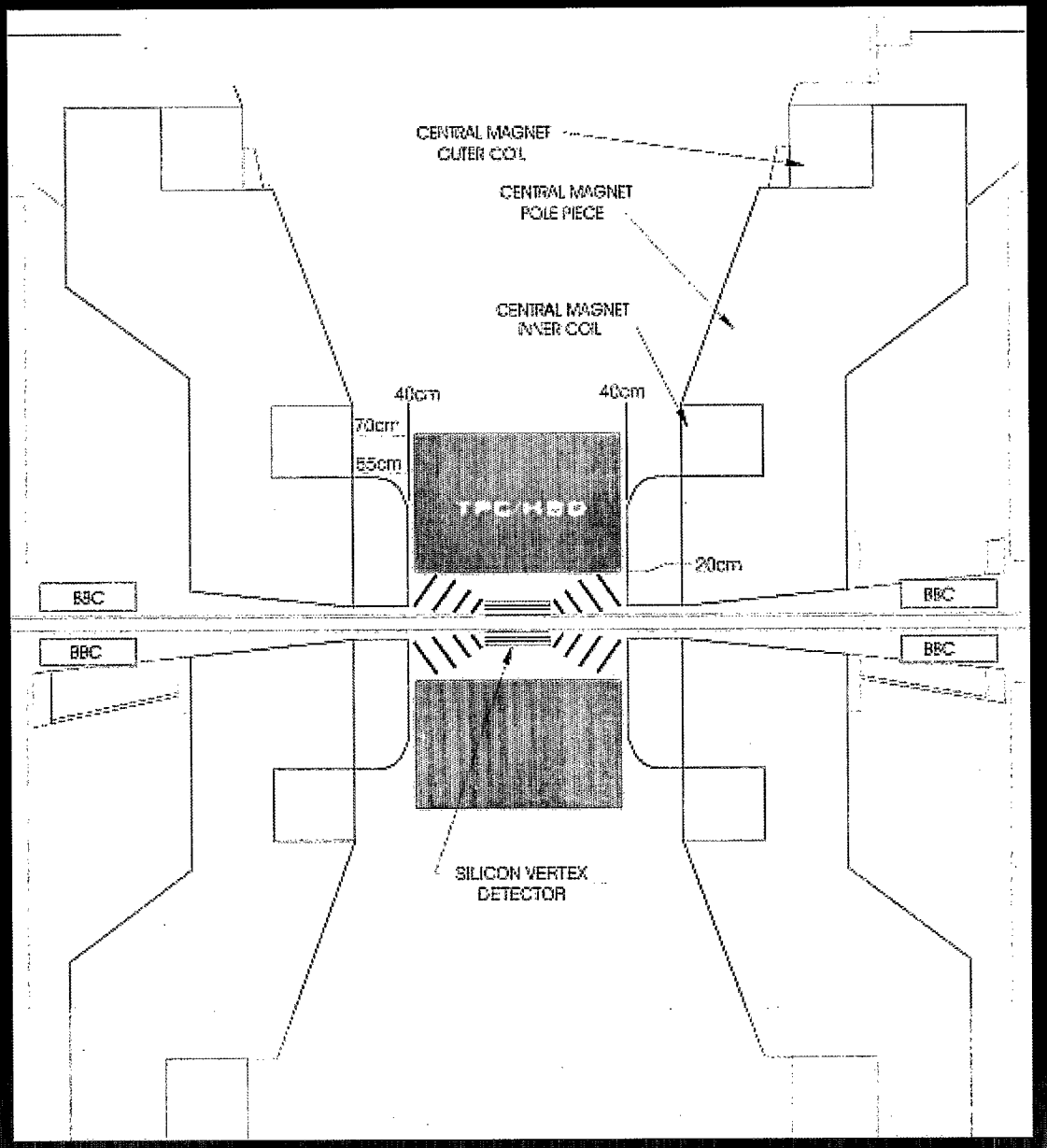
...or just leaving out the non-pion contributions to the total?

Rapidly-changing baryon density leads to interesting physics!

Triggering & Acceptance

- ZDC - at low energy?
- BBC - $3<|\eta|<4$
  - Will be of limited use for low energy running
- Need a high-efficiency trigger scheme

- Central arm has $|\eta|<0.35$
- BUT lots of forward capability and <u>upgrades</u>
  - Muon arms $1<|\eta|<2$
  - VTX $|\eta|<2$
  - NCC
  - MPC
  - Other low-E specific detectors



Transverse Dynamics

PHENIX White Paper

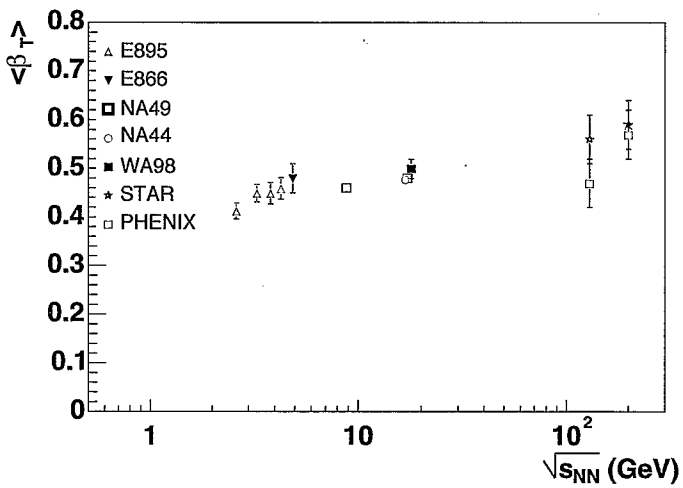
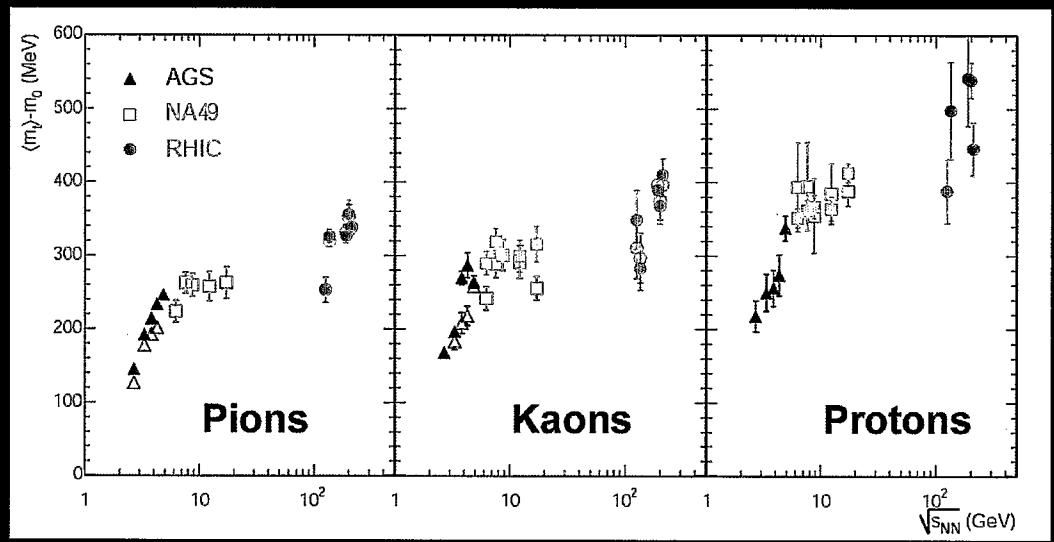


Fig. 13. Beam-energy dependence of the extracted mean transverse expansion velocity as a function of beam energy from simultaneous fits to spectra of different mass [97,98,99,100,101,48,102].

NA49, Hoehne QM2005

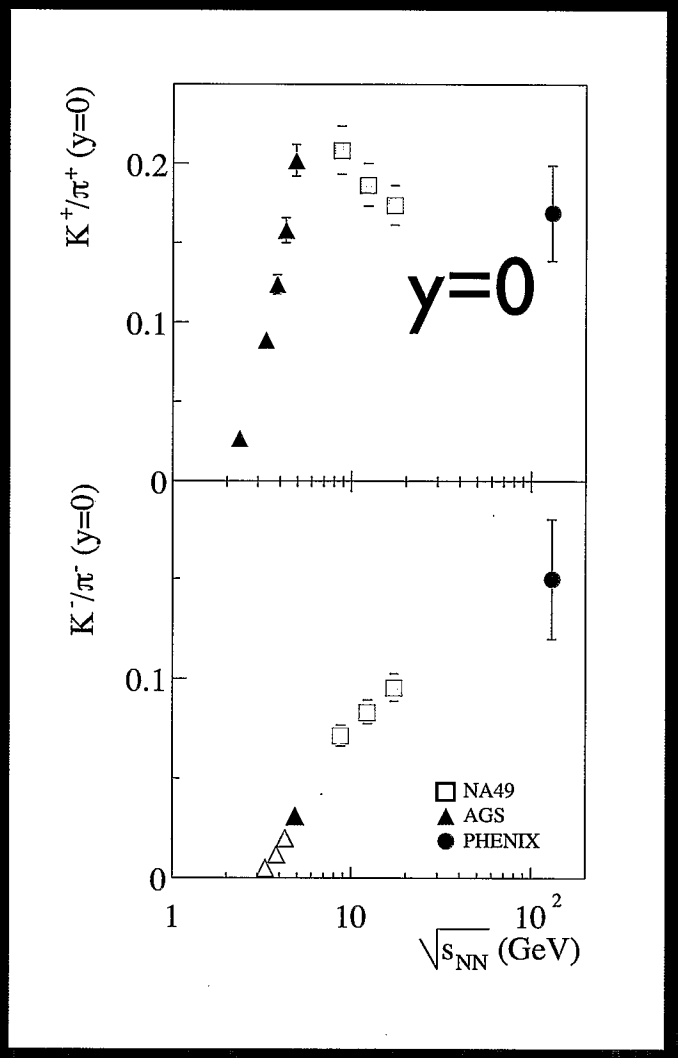


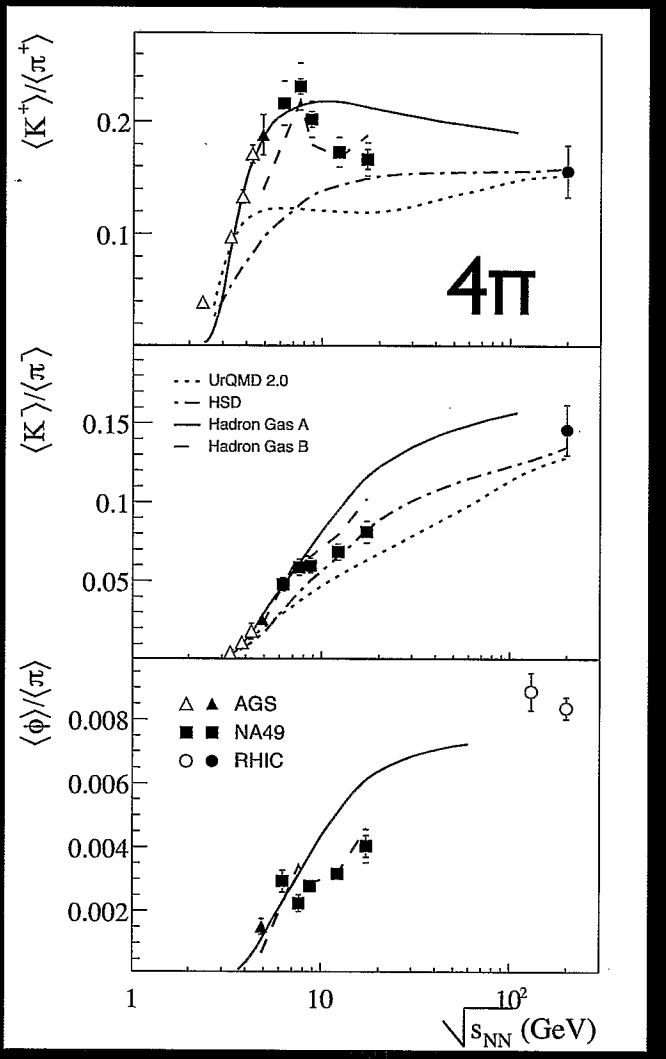
Energy dependence of radial expansion?...

...or a dramatic change in $\langle m_T \rangle$ right where baryon density is changing!

How does baryon density affect transverse activity?

K/π Horns





Shows up at mid-rapidity and in 4π results: comparison of PHENIX & STAR will be important

Elliptic Flow

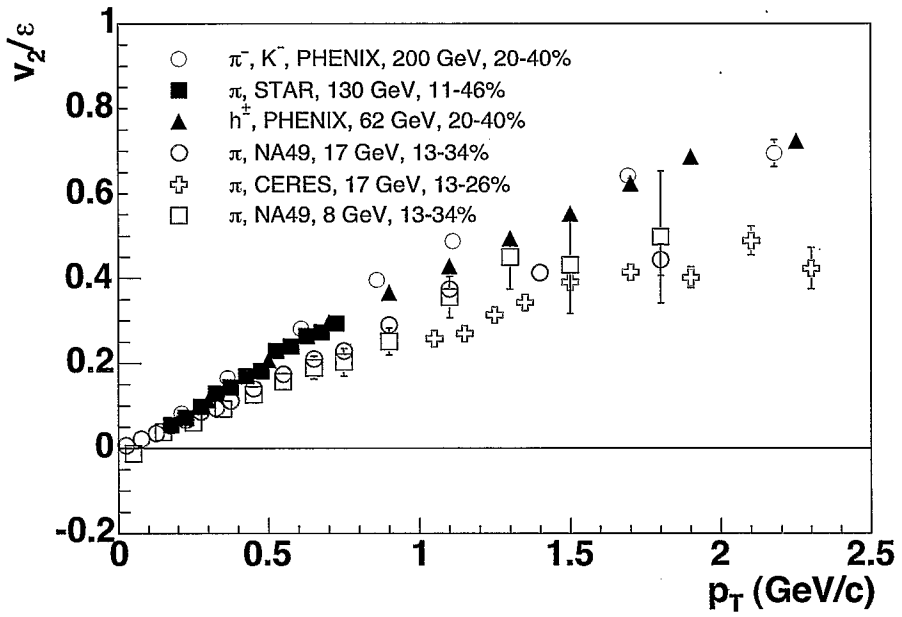


Fig. 16. $v_2(p_T)/\varepsilon$ vs. p_T for mid-central collisions at RHIC (filled symbols) and SPS (open symbols). Dividing by eccentricity removes to first order the effect of different centrality selections across the experiments [50,103,70,104,105].

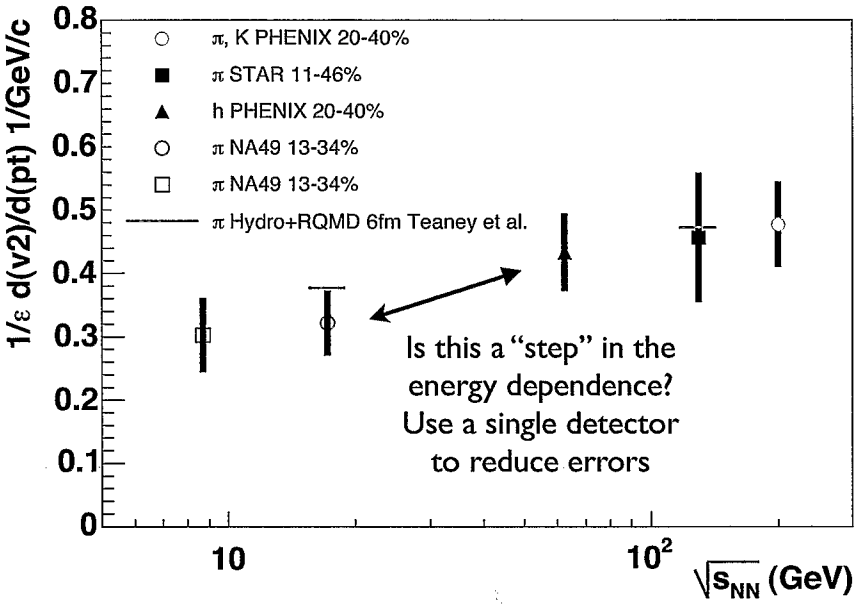


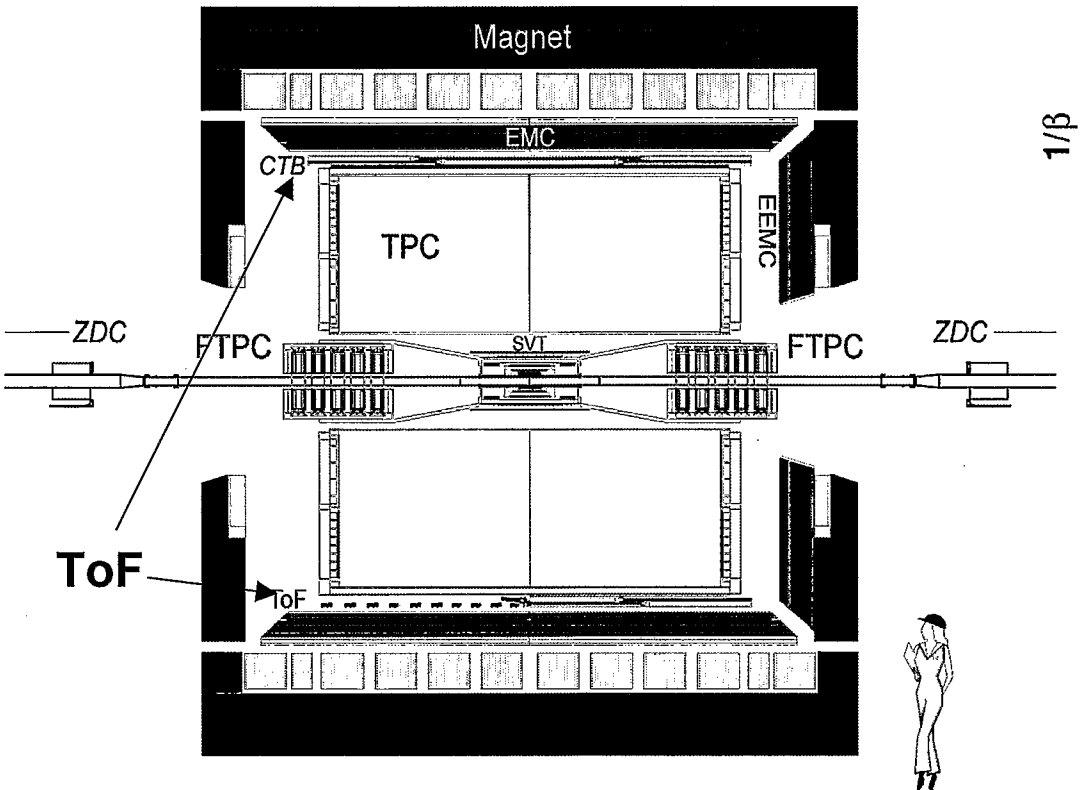
Fig. 17. The slope of the scaled elliptic flow, $(dv_2/dp_T)/\varepsilon$, for mid-central collisions at RHIC (filled symbols) and the SPS (open symbols). The slope is calculated from the data in Fig. 16 for the data $p_T < 1$ GeV/c. The solid error bars represent the total systematic error including the systematic error on v_2 and ε [50,103,70,104].

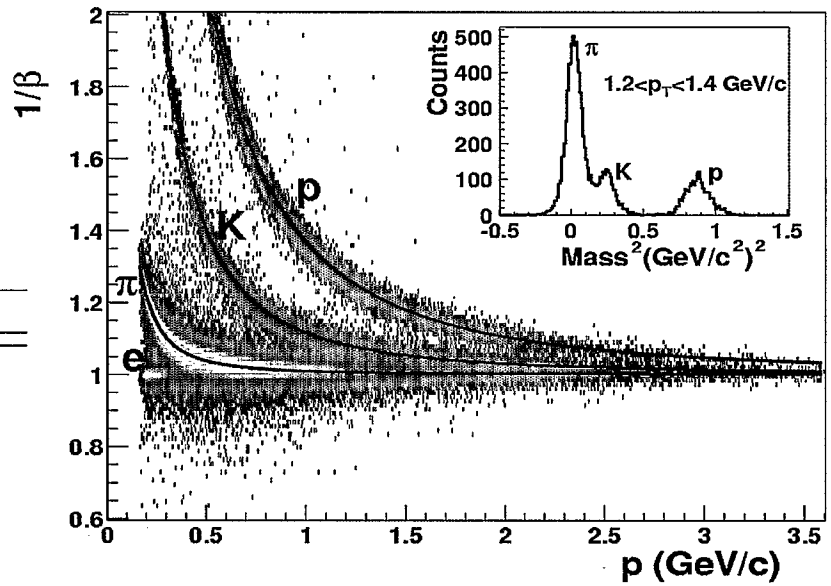
The Search for the Critical Point of QCD: STAR Capabilities for Low $\sqrt{s_{NN}}$ Running

Tapan Nayak
CERN, Geneva, Switzerland
and
Variable Energy Cyclotron Centre, Kolkata, India

(for the STAR Collaboration)

The STAR experiment: inclusion of ToF detector



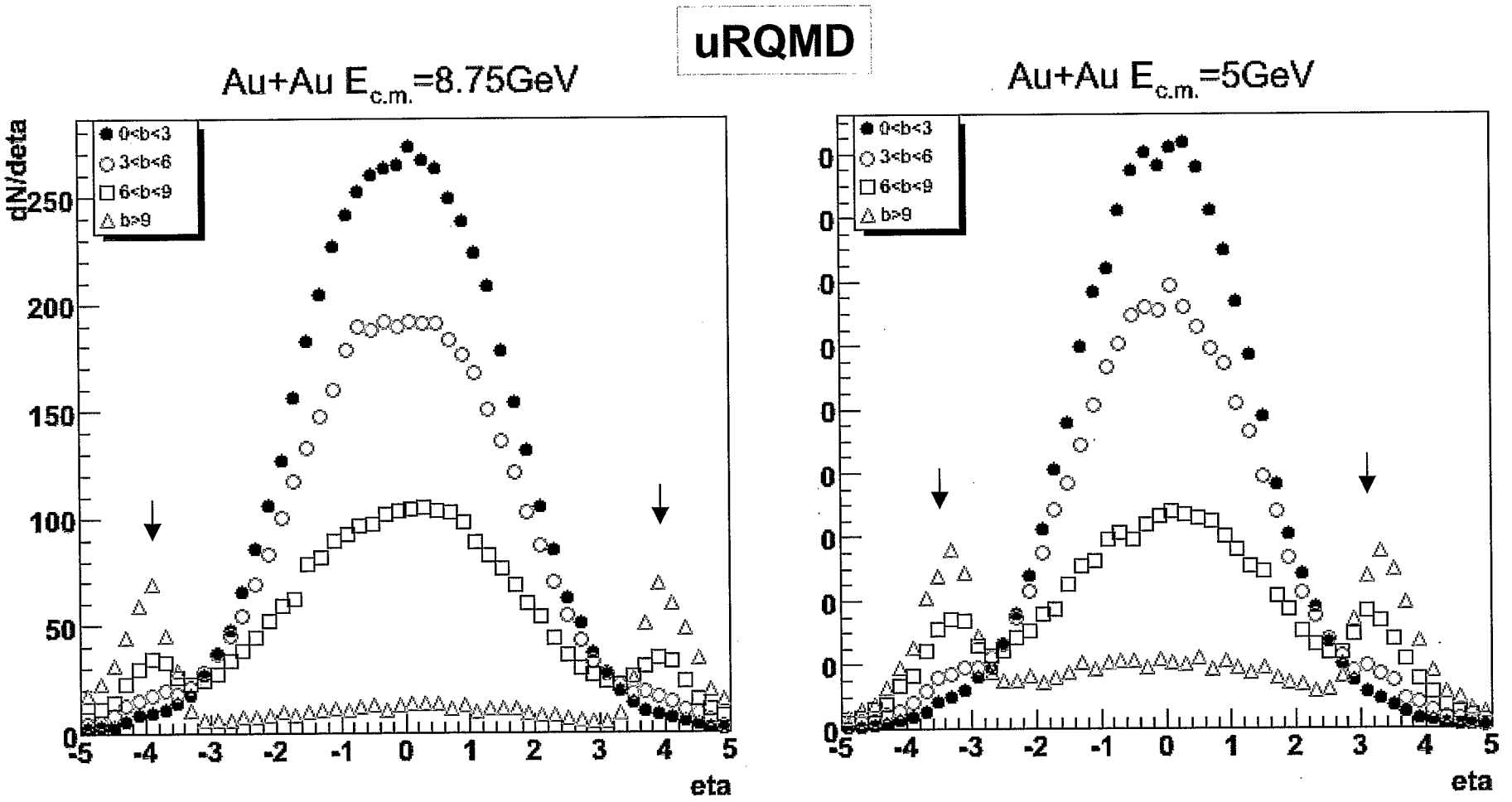


Hadron identification:
STAR Collaboration, *nucl-ex/0309012*

Fabrication of MRPC based Time-of-Flight (ToF) detector for STAR is in progress. It is scheduled to be installed for RHIC RUN-9.

The STAR experiment (with the inclusion of TOF) is an ideal detection device to search for the Critical Point of QCD and to carry on a systematic study of majority of the physics topics being addressed.

Particle production at low $\sqrt{s_{NN}}$ energies



Pseudo-rapidity distribution of charged particles at 4 different centralities.

Triggering with STAR Beam-Beam Counter (BBC)

STAR uses two BBCs wrapped around the beampipe: one on either side of the TPC. Each counter consists of two rings of hexagonal scintillator tiles: an outer ring composed of large tiles and an inner ring composed of small tiles. Internally, each ring is divided into two separate sub-rings of 6 and 12 tiles each.

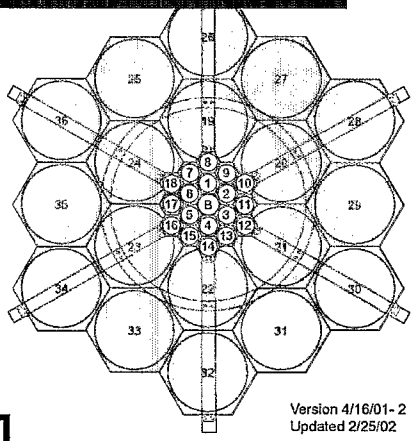


Table below gives the #of particles within BBC coverage for two c.m. energies and four different centralities:

Centrality (b in *fm*) ↓	AuAu $E_{c.m.}$= 5 GeV		AuAu $E_{c.m.}$= 8.75 GeV	
	BBC Inner $3.3<\eta<5.0$	BBC Outer $2.1<\eta<3.3$	BBC Inner $3.3<\eta<5.0$	BBC Outer $2.1<\eta<3.3$
b<3	5	27	12	54
3<b<6	11	30	21	57
6<b<9	22	35	39	40
b>9	44	30	66	8

BBC is sensitive down to single MIP falling on the detector.

BBC can effectively be used for triggering for low energy runs.

Beam-time estimation for a basic energy scan

March 10, 2006

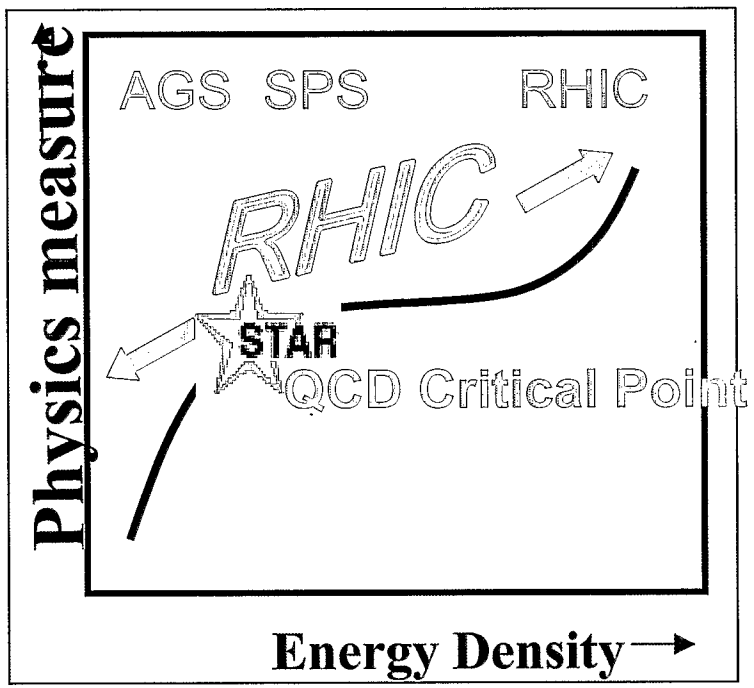
$E_{c.m.}$	μ_B	BBC Coin Rate	#of days/1M (1day=10 hr)	#of events needed	#of days of beam
4.6	570	3	9	5M	45
6.3	470	7	4	5M	20
7.6	410	13	2	5M	10
8.8	380	20	1.5	5M	7.5
12	300	54	0.5	5M	2.5
18	220	>100	0.25	5M	1.5
28	150	>100	0.25	5M	1.5

- cleanup
- vertex
- efficiency

- Gunter: 200K 0-5%, minbias:4M

5M events: 12.5 weeks: JUST enough,
Errors factor 2-4 better than NA49

Summary



- The QCD phase boundary is worthy of study, including that of the tri-critical point.
- STAR experiment with the inclusion of TOF will be the ideal place for this study.
- **Current investigations don't indicate any problem carrying out this program with the STAR detector.**
- The RHIC program looks most promising.

Thanks to STAR Collaborators and in particular:

Paul Sorensen, Bill Christie
Jamie Dunlop, Nu Xu
Zhangbu Xu, Peter Seyboth
Tim Hallman

BROOKHAVEN NATIONAL LABORATORY RHIC Discoveries Ahead

Low Energy operation of RHIC

AGS low energy extraction performance

N. Tsoupas CAD

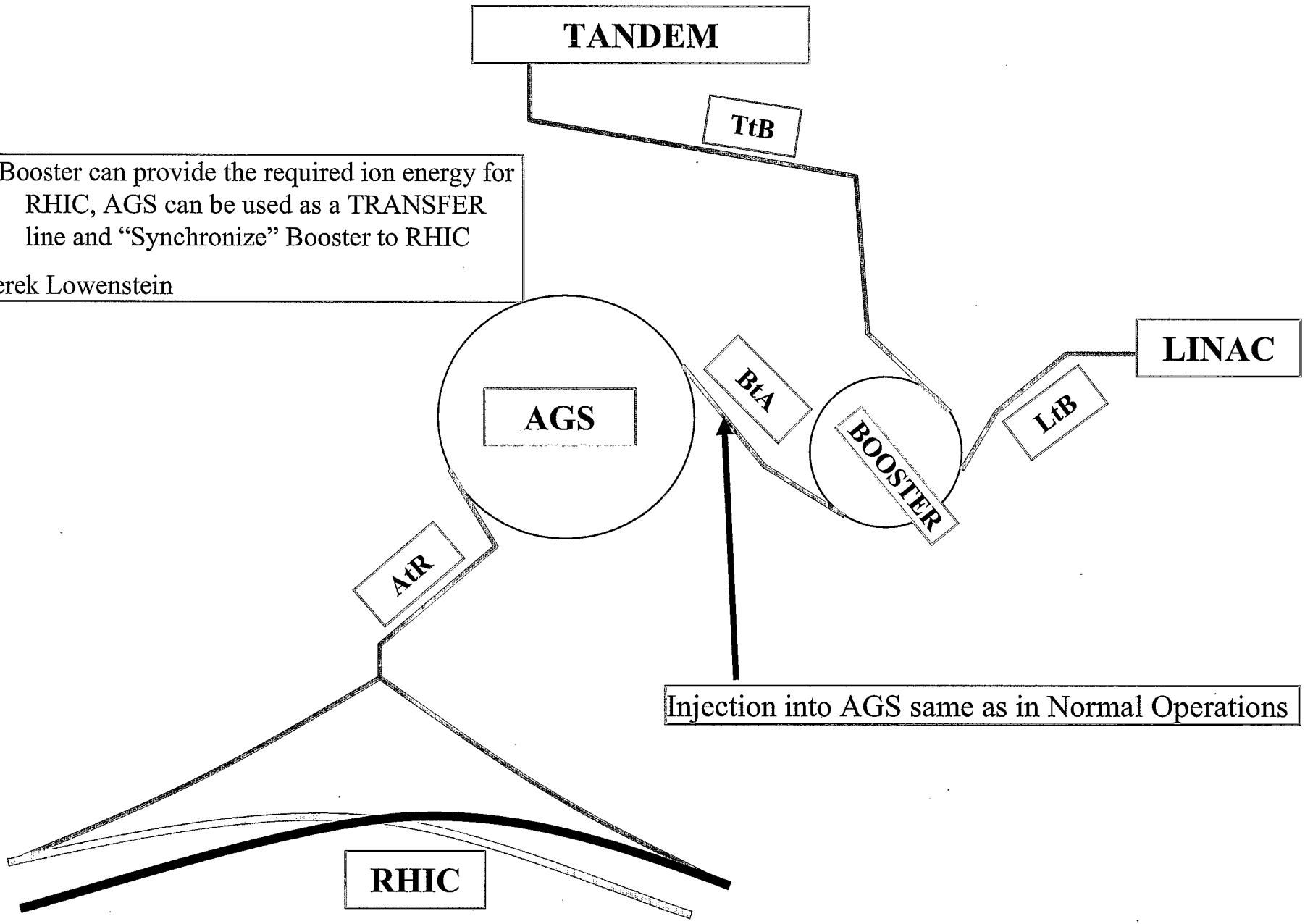
Purpose of the Study

- To identify, and cope with, any issues related to the
  - injection in AGS
  - acceleration
  - extraction from AGS and
  - transport to RHIC

  of p Cu and Au ions of $E_{total} \geq 2.5$ GeV/nucleon.

- If necessary, we may perform measurements to answer any questions relevant to the tasks mentioned above.

Schematic Diagram of the Collider Accelerator Complex



If Booster can provide the required ion energy for RHIC, AGS can be used as a TRANSFER line and "Synchronize" Booster to RHIC

Derek Lowenstein

Injection into AGS same as in Normal Operations

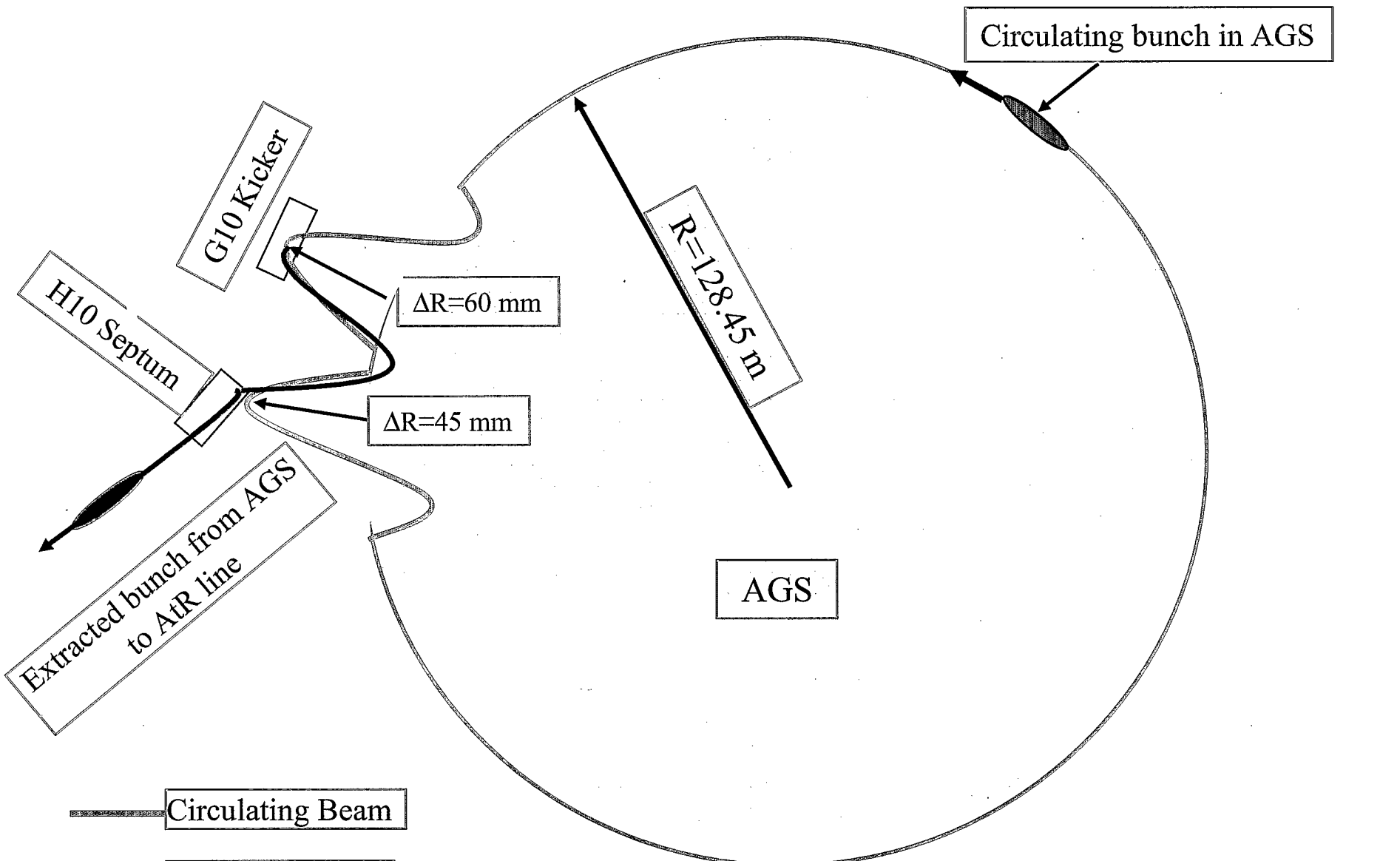
Are there any problem relevant to beam Injection from the Booster to AGS?

- There are no known problems relevant to the beam injection from Booster to the AGS.
- In the past the following ions have been Injected and accelerated in AGS to a rigidity Bρ~85.[T.m]
  - Protons Cu Au

Ion	E_{tot} GeV/n	Ions/bunch	$\varepsilon_{x,y}$ (95%) π[mm.mrad]
p	2.354	2.0×10^{11}	8.7
Cu	1.030	4.0×10^{9}	16.8
Au	1.028	6.0×10^{9}	9.2

Acceptance of AGS at Injection 47 π[mm.mrad]

Schematic Diagram of the Fast Beam Extraction (FEB) from AGS



Acceptance of AGS at Extracion 6.3 π[mm.mrad]

Are there any problems relevant to beam Extraction from AGS at ion Energies 2.5 GeV/nucleon?

- Beam Emittance issue:
  - Beam emittance measurements of p Cu and Au ions during the acceleration show that the Normalized beam emittance is less or equal to the Normalized emittance at Extraction.

Ion	E_{tot}	Ions/bunch	Norm_$\varepsilon_{x,y}$ (95%)	$\varepsilon_{x,y}$ (95%)
	GeV/n		π[mm.mrad]	π[mm.mrad]
p	2.500	1.5×10^{11}	15.0	6.2
Cu	2.500	4.0×10^{9}	15.0	6
Au	2.500	6.0×10^{9}	12.5	5

Acceptance of AGS at Extraction 6.3 π[mm.mrad]

- Bunch length issues:
  - For a Au beam at energy 2.5 GeV/nucleon, and longitudinal emittance of 0.4 eVsec, computer simulations show that "Quad pumping" is required to produce a Au beam with bunch length of 32 nsec.

- In the past, protons of K. E. of 1.7 GeV have been extracted from the AGS and transported to the 'Neutrino Target" tunnel.

Luminosity Monitoring Issues for Low-Energy RHIC Operations

Angelika Drees
Brookhaven National Laboratory

Summary:

- ZDCs seem statistically, acceptance and light limited at low energies
- ZDCs most likely cannot be used reliably for monitoring or steering (and not for triggering)
- We will have to give up the idea of two independent measurement systems
- Can we use the experimental BBCs for luminosity monitoring, and calibrate them?

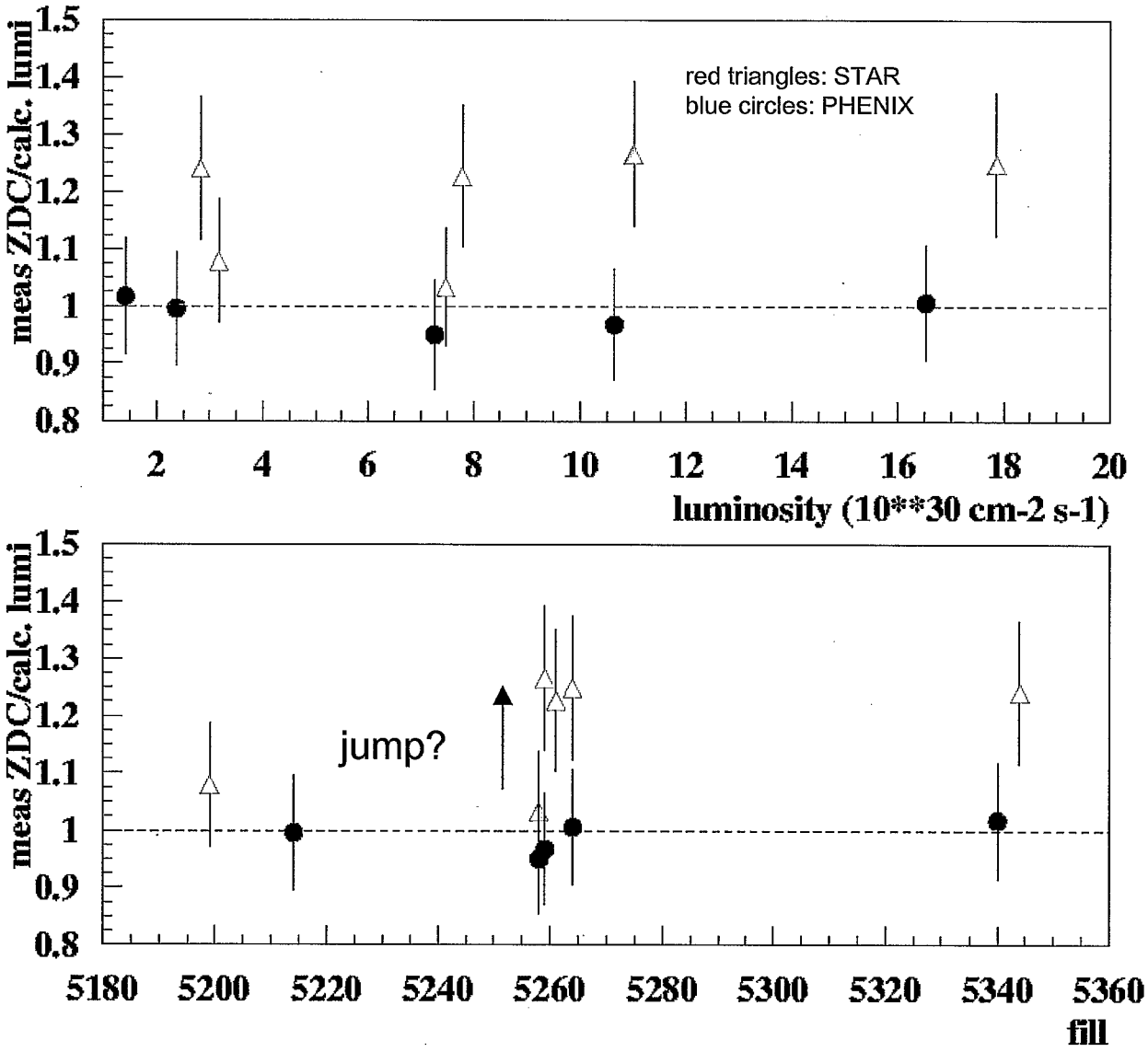
What do we want/need?

- a reliable detector for online monitoring and steering
- a reasonable signal/noise ratio
- calibration (cross section measurement) for book-keeping
- comparison between the different IRs
- small integration times
- independent from vertex distribution and location
- redundancy

ZDC overview

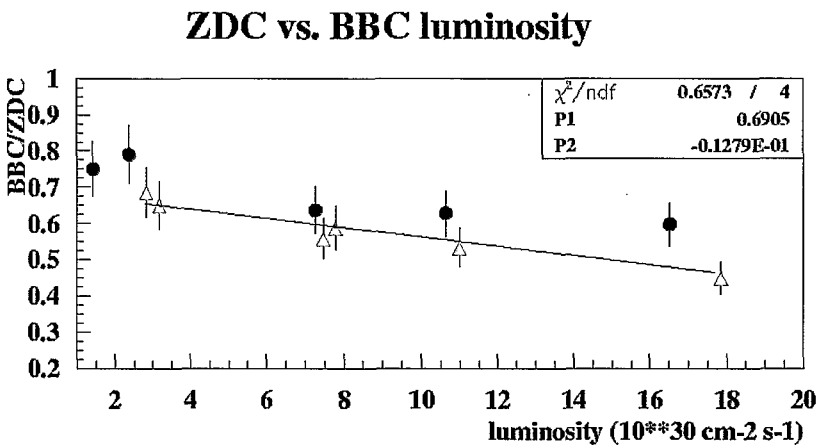
- The ZDCs are sampling hadronic calorimeters with tungsten/fiber layers (27 per module)
- common to all IRs
- Since they are located at +/- 18 m, behind the DX magnets, they 'see' only neutrons
- the mutual forward neutron cross-section is much smaller than the single neutron cross section (about x10 @100 GeV)
- if used as a collision monitor in coincidence mode the signal/noise ratio is very good (typically very low background)
- they see all collisions, regardless of the vertex position and distribution

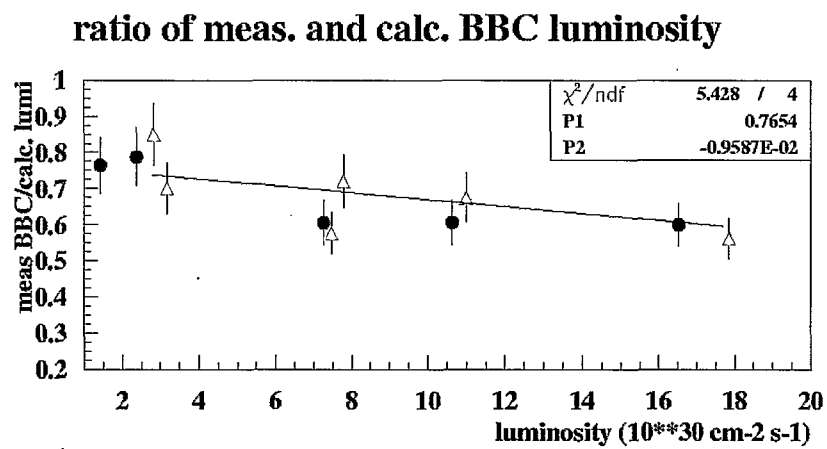
ratio of ZDC meas. and calc. luminosity



Luminosity from collision rates in the ZDC (calibration from 2002) divided by the luminosity calculated from beam parameters (size & bunch current). Beam parameters are derived from vernier scans. This ratio should be constant and about 1. Should not depend on luminosity.

Why does it help to have redundant measurements?





Luminosity from collision rates measured by the STAR (triangles) and PHENIX (circles) BBCs divided by the luminosity from the ZDCs. This ratio should not depend on the luminosity but should be constant and about 1. Calibration used is from 2002.

Luminosity from collision rates (calibration from 2002) as measured by the BBC divided by the luminosity from beam parameters (calculated). Beam parameters are derived from vernier scans. This ratio should be constant and about 1.

Calorimeter limitations

- limit of production of cherenkov light in the fibers: $\beta > 1/n$
- n for the fibers = 1.4 => 1/n = 0.7
- for $\beta = p/E = 2.3/3.5 = 0.65$
- assume coulomb dissociation of the neutrons: $E_{neutron} \sim E_{beam} \sim E_{show.prod.}$
- depending on the beam energy we are just at the limit
- increase tube voltage, decrease discriminator voltage => new calibration …
- acceptance drop due to fermi motion $1/p^2_{beam}$

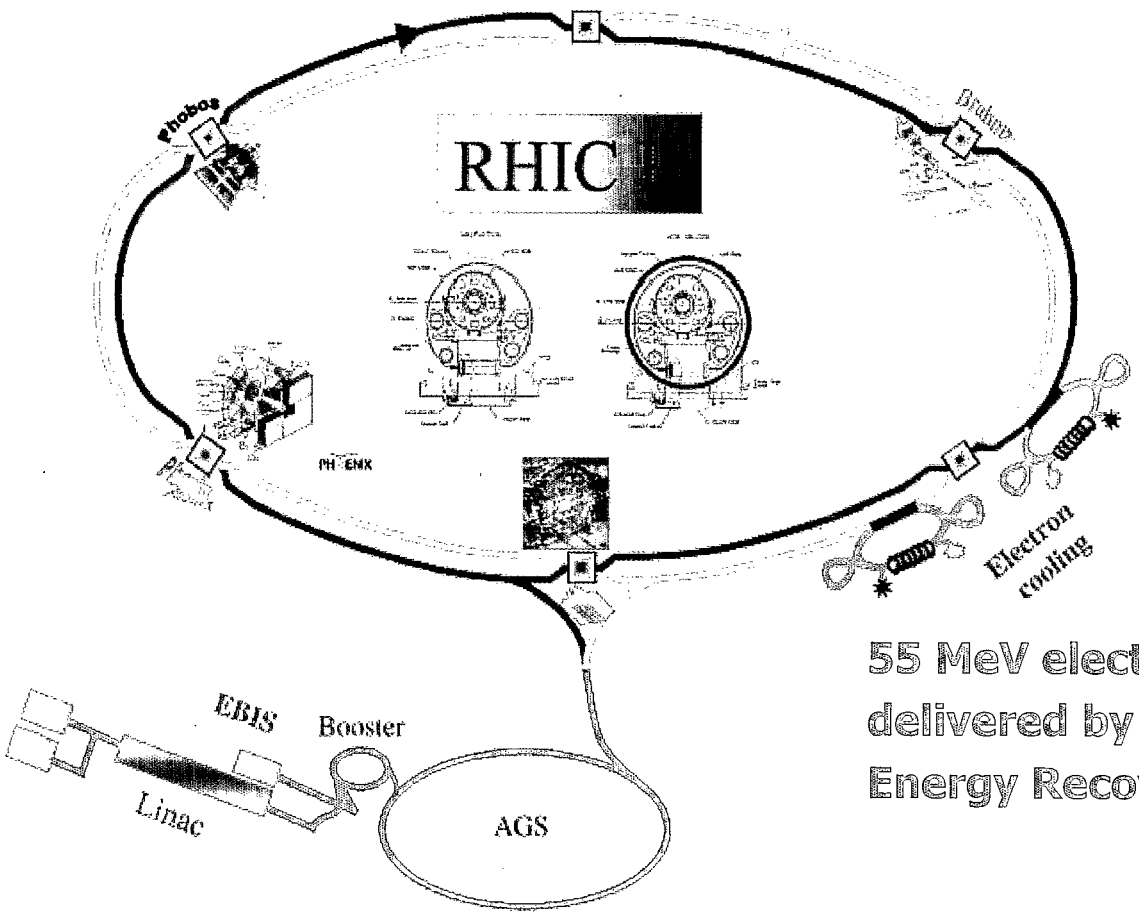
"Electron Cooling in RHIC at Low Energies"

Alexei Fedotov, Collider-Accelerator Department, BNL

Summary of principle points:

- Electron cooling was considered for low-energies in RHIC (below present injection energy).
- Electron beam was assumed to be produced by ½ cell RF gun of the ERL which is presently under construction at BNL/C-AD.
- It was found that cooling is effective both for the rms emittances and rms bunch length of ions.

High-energy (55 MeV electrons) cooling - to cool Au ions at 100 GeV/u energies in RHIC



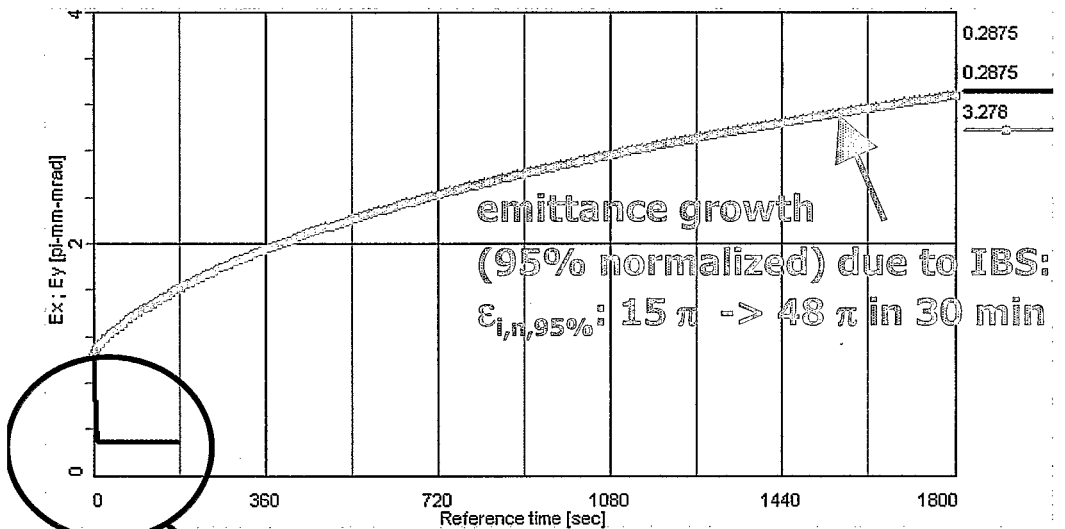
55 MeV electrons delivered by Energy Recovery Linac (ERL)

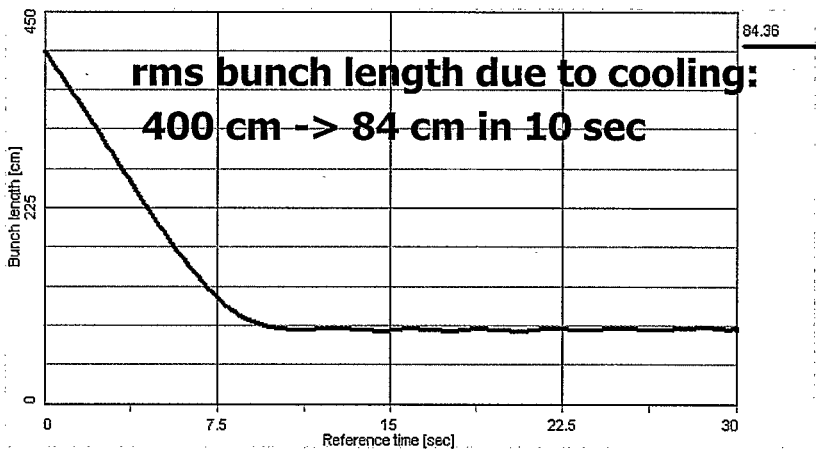
BROOKHAVEN NATIONAL LABORATORY

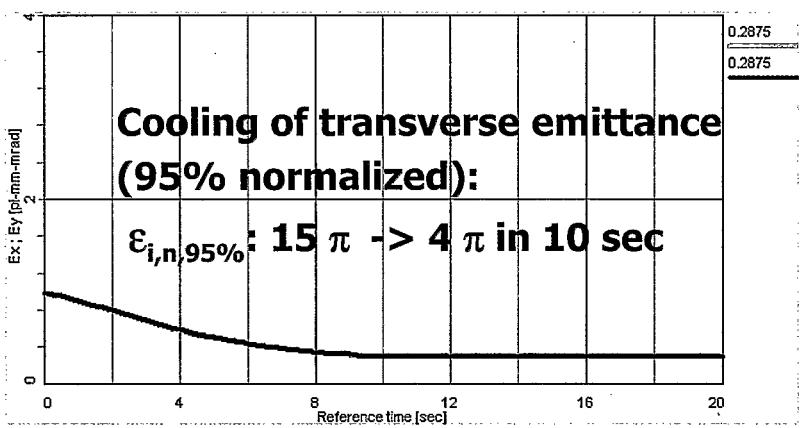
Alexei Fedotov

RHIC

Cooling Au ions at 1.5 GeV/u (γ=2.61)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=15μm, σ_p=1e-3, L=80m
(Figs: plotted emittance is rms unnormalized)



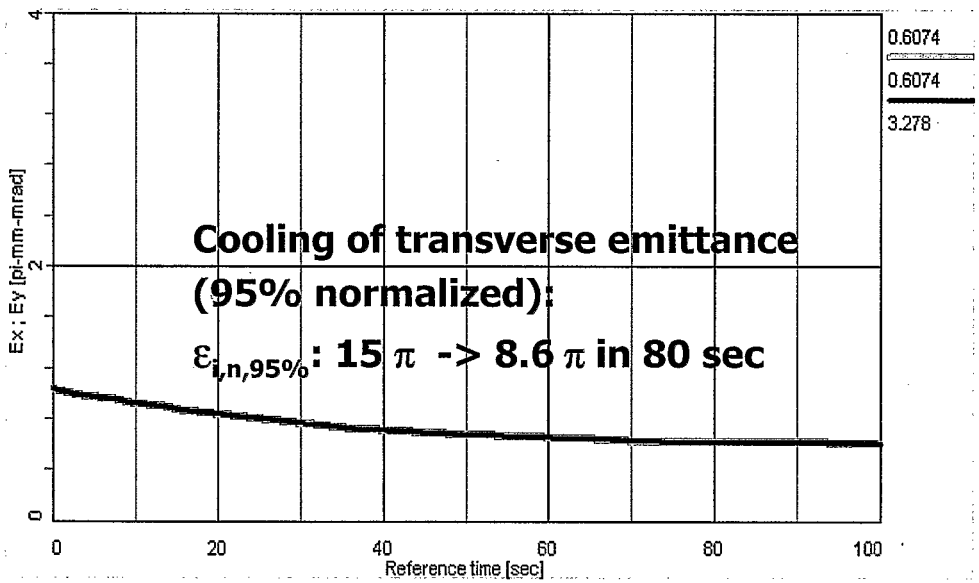


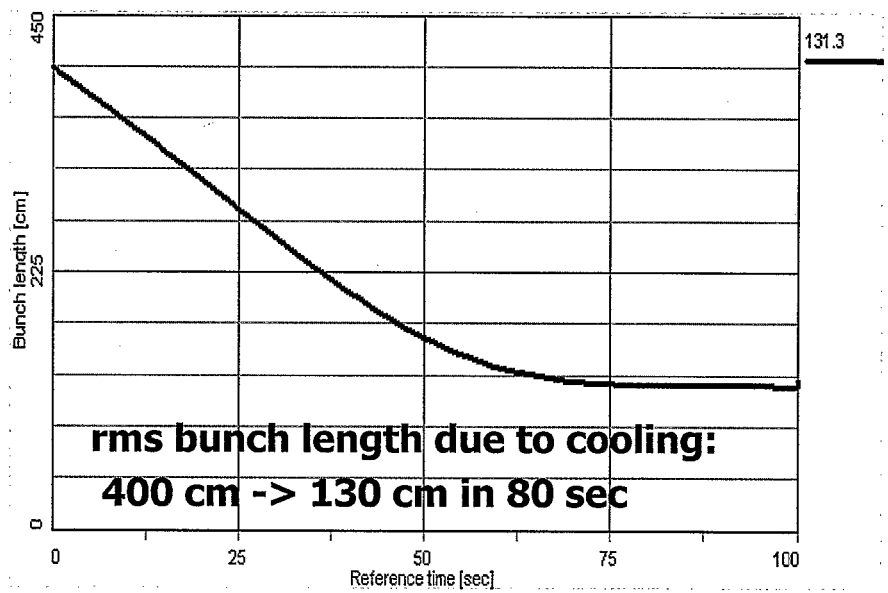


Cooling section length: L=80m

BROOKHAVEN NATIONAL LABORATORY
Alexei Fedotov
RHIC

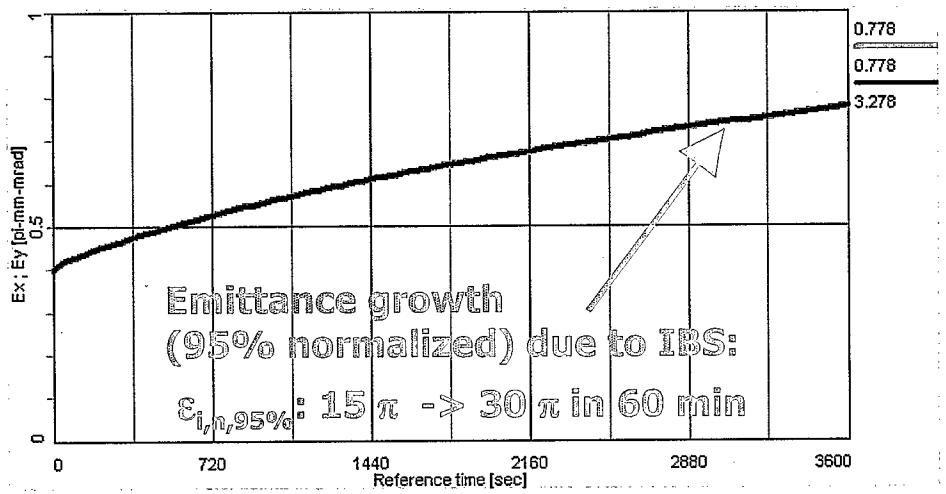
Cooling Au ions at 1.5 GeV/u (γ=2.61)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=15μm, σ_p=1e-3, L=10m
(Figs: plotted emittance is rms unnormalized)

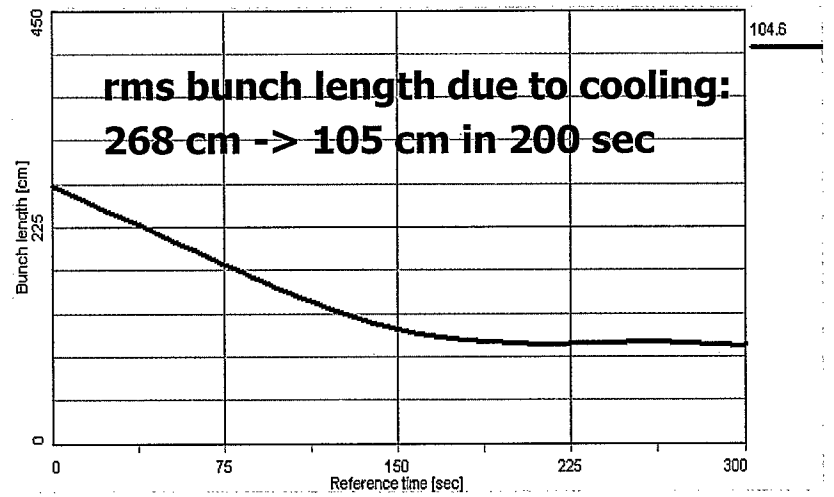


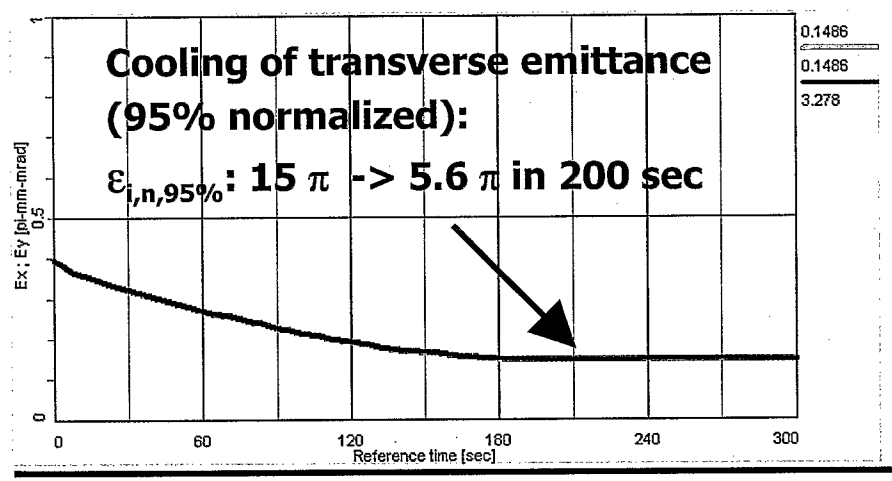


Cooling section length: L=10m

Cooling Au ions at 5 GeV/u (γ=6.37)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=10μm, σ_p=1e-3, L=10m
(Figs: plotted emittance is rms unnormalized)



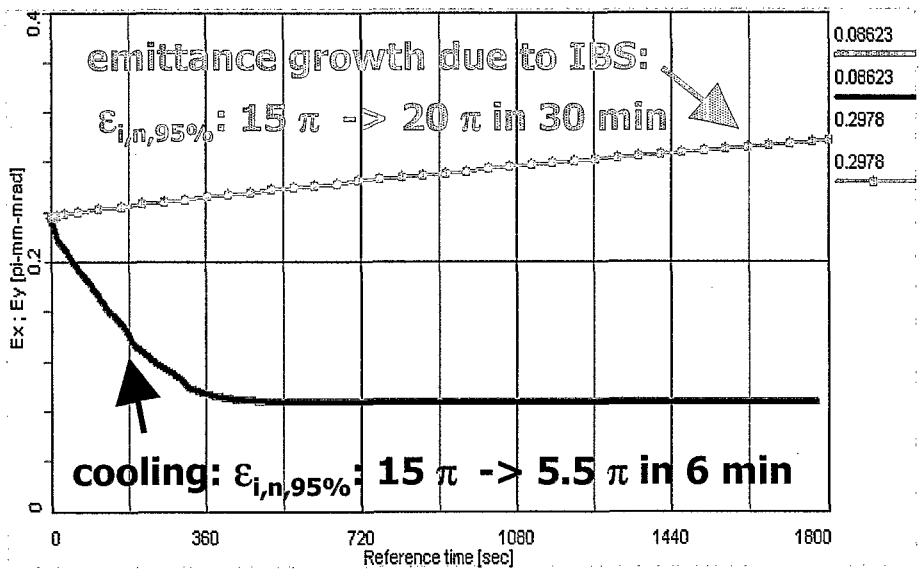


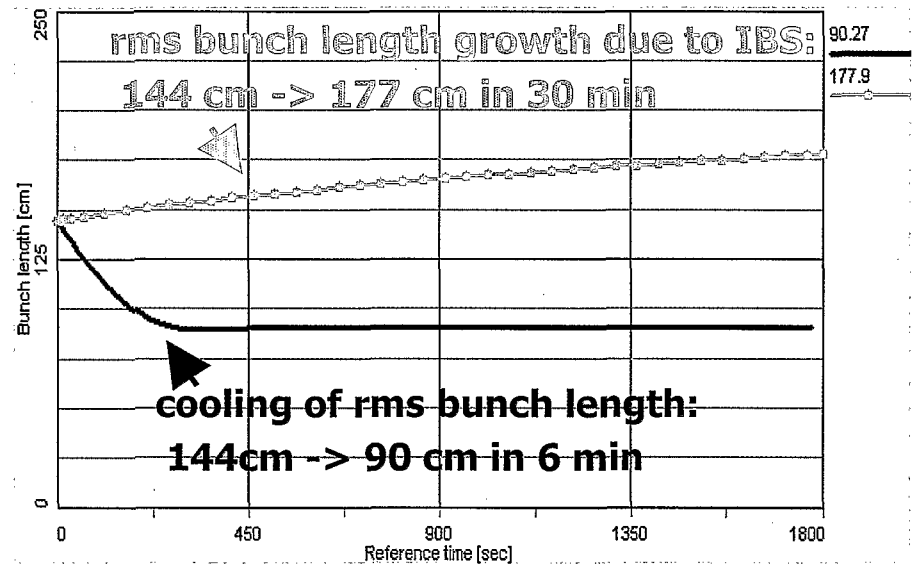


Cooling section length: L=10m

BROOKHAVEN NATIONAL LABORATORY
Alexei Fedotov

Cooling of Au ions at 9 GeV/u (γ=10.66)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=10μm, σ_p=1e-3, L=10m
(Figs: plotted emittance is rms unnormalized)



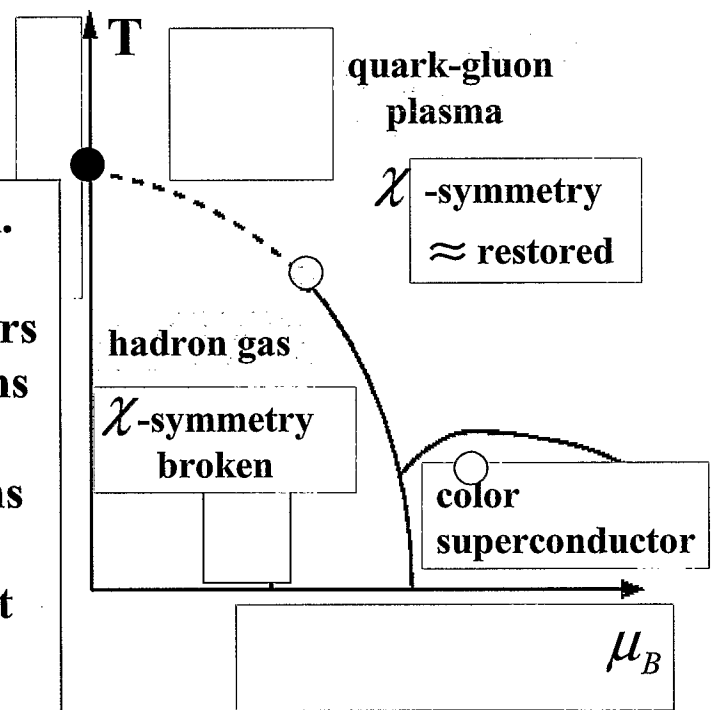


cooling at present RHIC injection energy just with L=10 m cooling section

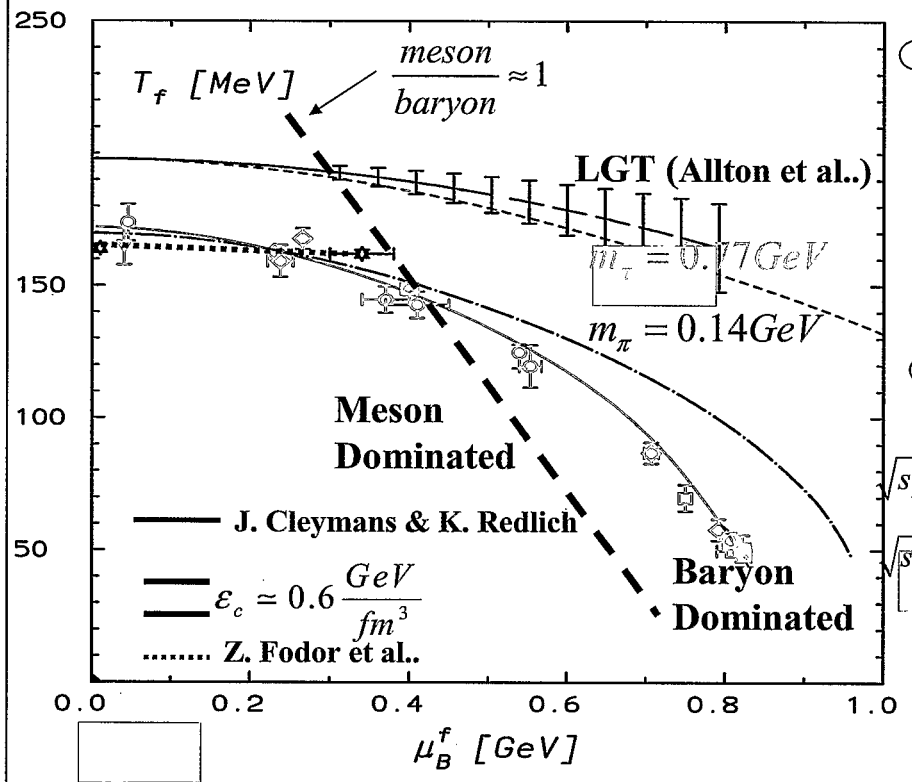
Energy Dependence of Thermal Parameters in Heavy Ion Collisions

Krzysztof Redlich
University of Wroclaw

- Chemical Freeze-out in A-A col.
  - freeze-out conditions and $\sqrt{s_{NN}}$ dependence of parameters
  - particles excitation functions
- Freeze-out $\Longleftrightarrow$ critical conditons
- Charge fluctuations below and at deconfinement transition



Phase boundary of the fixed energy density versus chemical freezeout



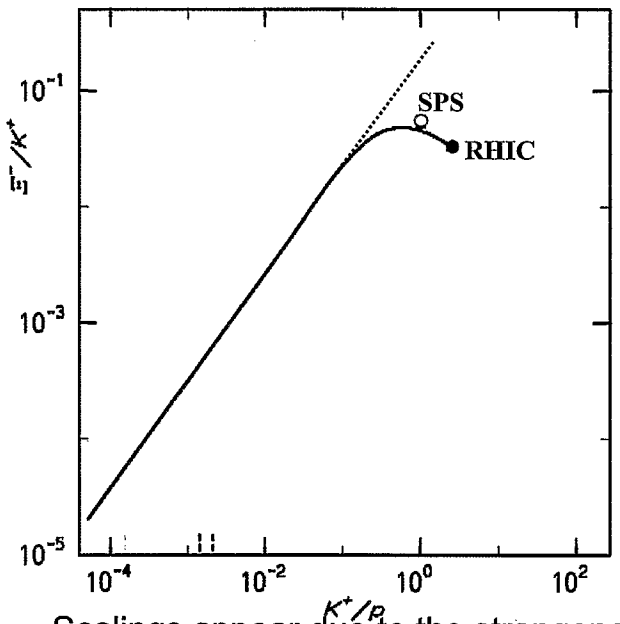
- Splitting of the chemical freeze-out and the phase boundary surface appears when the densities of mesons and baryons are comparable?
- particles production processes

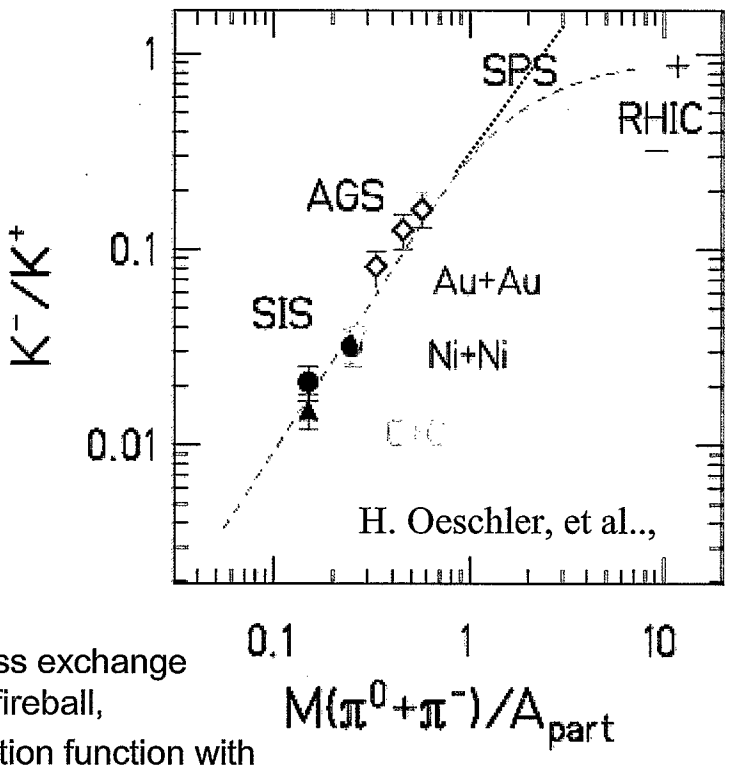
$\sqrt{s_{NN}} > (6-8)\ GeV$: QGP hadronization

$\sqrt{s_{NN}} < (6-8)\ GeV$: Hadronic rescattering

Scaling properties of particle production yields

A. Andronic, P. Braun-Munzinger &K.R.





- Scalings appear due to the strangeness exchange production processes in the hadronic fireball, that are correctly treated in the partition function with an exact implementation of the strangeness conservation

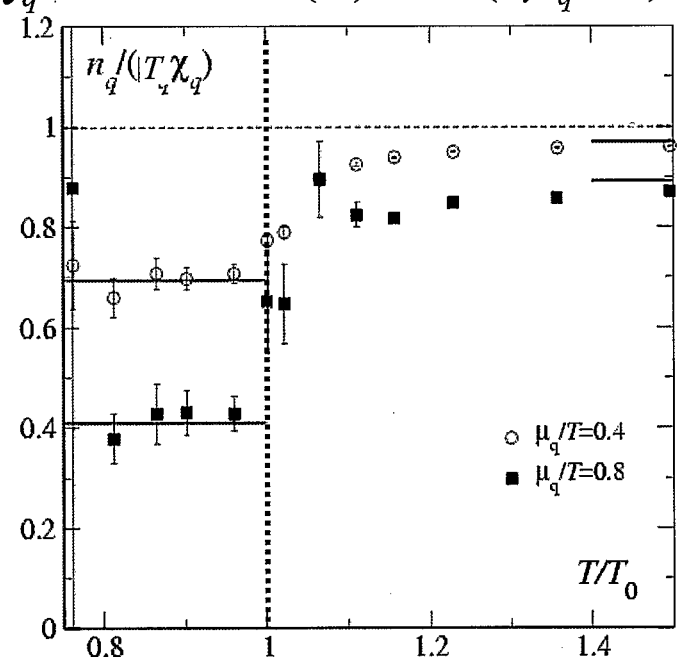
μ/T factorization on the Lattice as in HRG

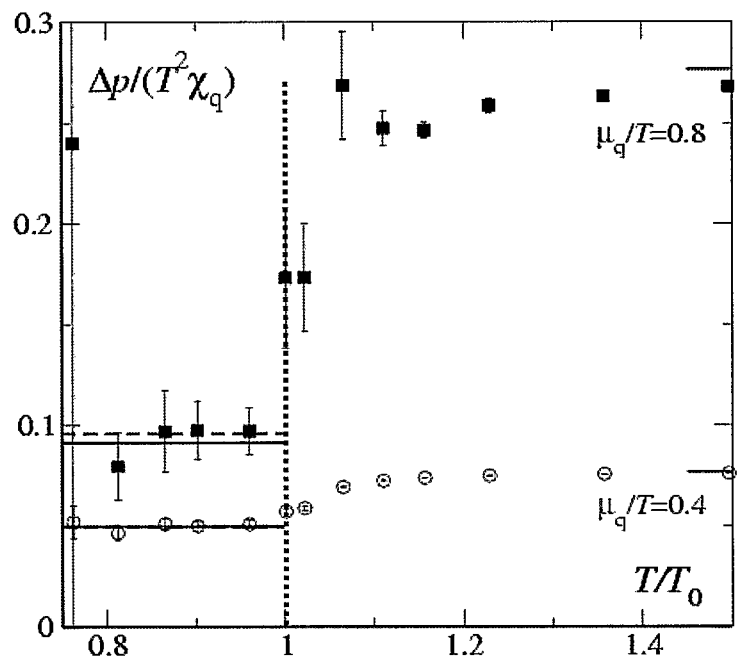
HRG-partition function: $P = P^{meson} + F^B(T)\cosh(3\mu_q/T)$

$$n_q = 3T^{-1}F^B(T)\sinh(3\mu_q/T)$$

$$\chi_q T = 9T^{-1}F^B(T)\cosh(3\mu_q/T)$$

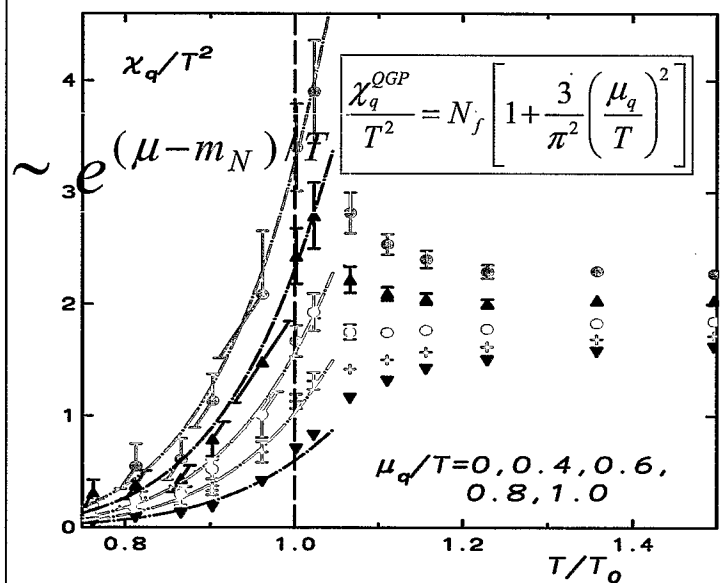
$\frac{\mu_q}{T}$ = **fixed** ⇨ **ratios of baryonic observables independent of** T



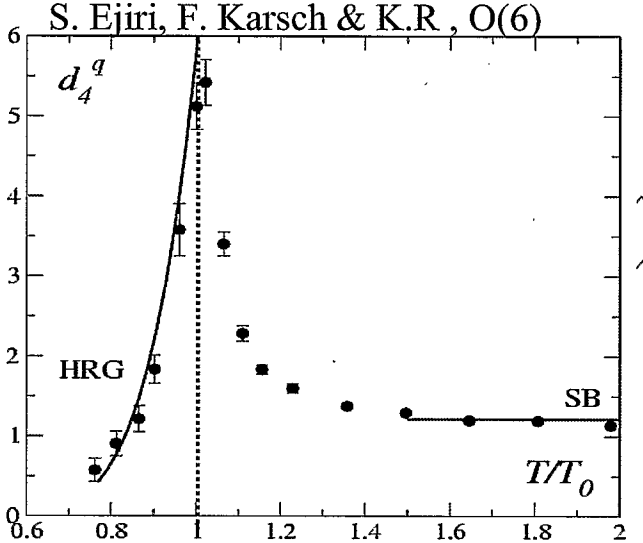


paris

The Hadron resonance gas model and net-quark fluctuations

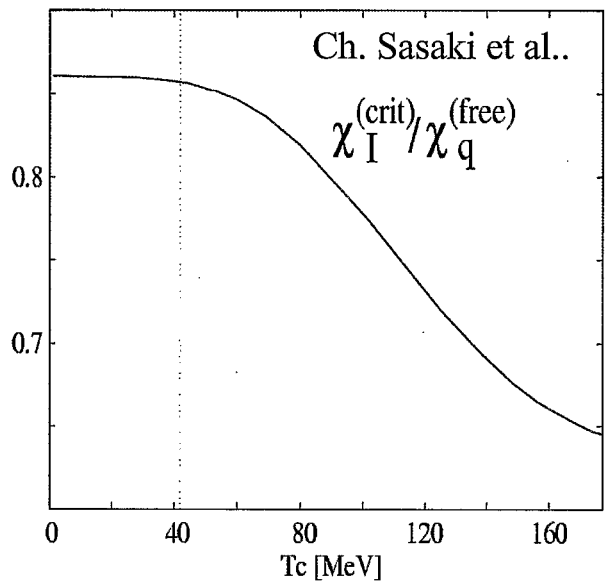


S. Ejiri, F. Karsch & K.R , O(6)

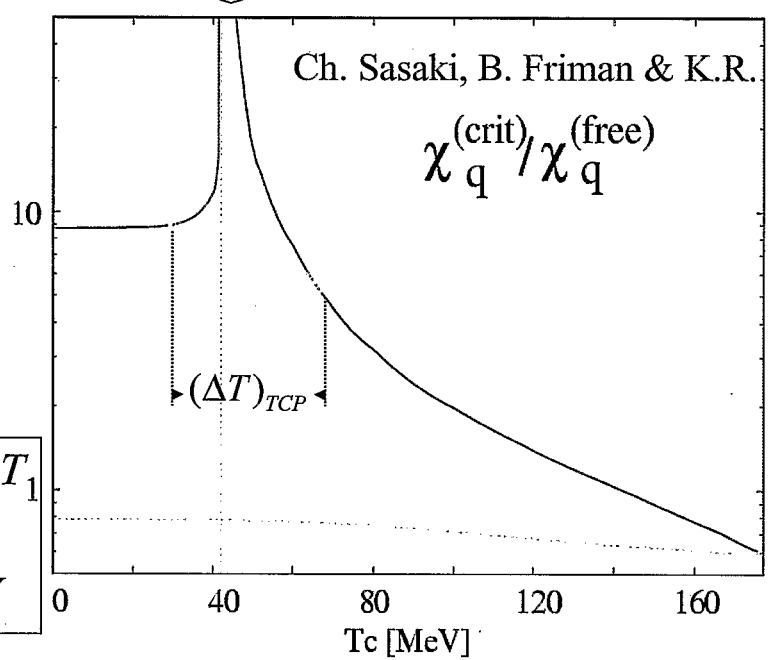


The phenomenological partition function of hadron resonance gas describes the net quark number fluctuation and their higher moments in the region for $T < T_c$. An increase of susceptibility with μ/T is not sufficient to claim being in the vicinity of 2d order end point.

Quark and isovector susceptibilities along the critical curve in the NJL model



Non-monotonic behavior of the net quark susceptibility in the vicinity to TCP



Crude estimate of the critical region ΔT_1 in $\sqrt{s_{NN}}$ using chemical freeze-out condition gives: $\Delta(\sqrt{s_{NN}})_{TCP} \approx 0.7\ GeV$

paris

Can We Discover the QCD Critical Point at RHIC ?

RIKEN BNL Research Center Workshop

March 9-10, 2006 at Brookhaven National Laboratory

Observable power laws at the QCD critical point

Nikos Antoniou

University of Athens, Department of Physics

Outline

1. Critical QCD phenomena
2. The order parameter
3. Self-similar solutions
4. Critical opalescence in QCD
5. Factorial moments (power laws)
6. Preliminary studies with NA49 data
7. Summary

Critical QCD phenomena

At the critical point ($\mu = \mu_c,\ T = T_c$) we expect:

1. **A second order phase transition:**

   (compressibility) $\sim \xi^{2-\eta}$

   (compressibility) $\sim \frac{\partial n_B}{\partial \mu_B} = \int d^3\vec{x} \langle n_B(\vec{x}) n_B(0) \rangle$

2. **Universality class:**

   $3D$ Ising ; $\delta \simeq 5$, $\eta \simeq 0$ (critical exponent)

3. **Order parameter:** Effective field: $m(\vec{x}) \sim \sigma(\vec{x})$; $n_B(\vec{x})$

4. **The free energy (effective action)** in $2D$ after integrating in rapidity and rescaling the basic variables $(m, \vec{x})$:

$$\Gamma_c = C \int d^2\vec{x}_\perp \left[|\nabla_\perp m|^2 + G C^{\delta-1} |m|^{\delta+1} \right]$$

$$C \equiv [2T_c \tau_c \sinh(\frac{\delta y}{2})]^{-1}, \quad G \approx 2$$

5. **The partition function:**

$$Z \approx \sum_s e^{-\Gamma_c[m^{(s)}]} \quad ; \quad \nabla_\perp^2 m^{(s)} - (\delta+1)GC^{\delta-1}[m^{(s)}]^\delta = 0$$

$m^{(s)}$: singular solutions of the Euler-Lagrange equation.

6. **The final result:**

Generation of self-similar critical cluster in $2D$ transverse space (fractals). In the σ-mode or in the baryon sector the correlators obey the power laws:

$$\langle \rho_\sigma(\vec{x})\rho_\sigma(0)\rangle \sim |\vec{x}_\perp|^{d_F^{(\sigma)}-2} \quad ; \quad d_F^{(\sigma)} = \frac{2(\delta-1)}{\delta+1} \approx \frac{4}{3}$$

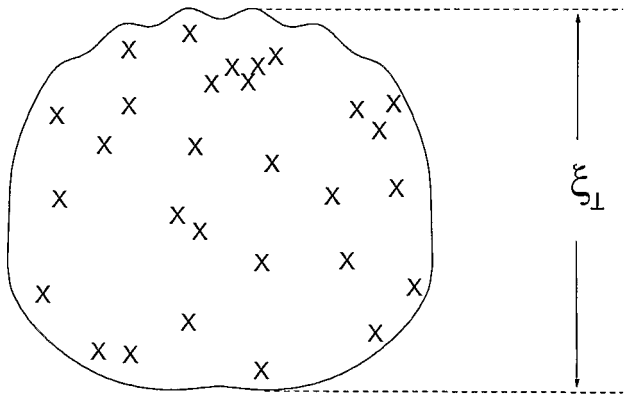
$$\langle \rho_B(\vec{x})\rho_B(0)\rangle \sim |\vec{x}_\perp|^{d_F^{(B)}-2} \quad ; \quad d_F^{(B)} = \frac{2\delta}{\delta+1} \approx \frac{5}{3}$$

In momentum space these power laws are observable

(critical opalescence $\simeq$ critical intermittency)

Critical Clusters

σ - cluster

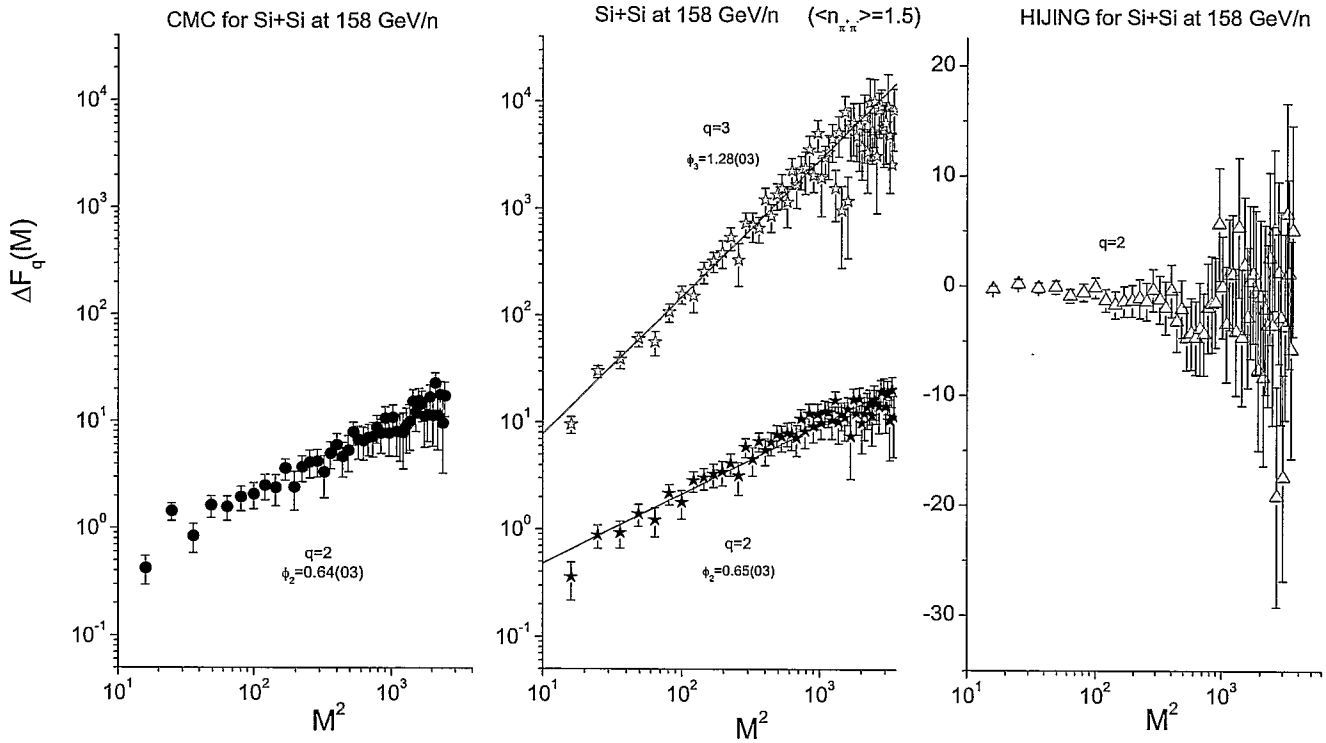


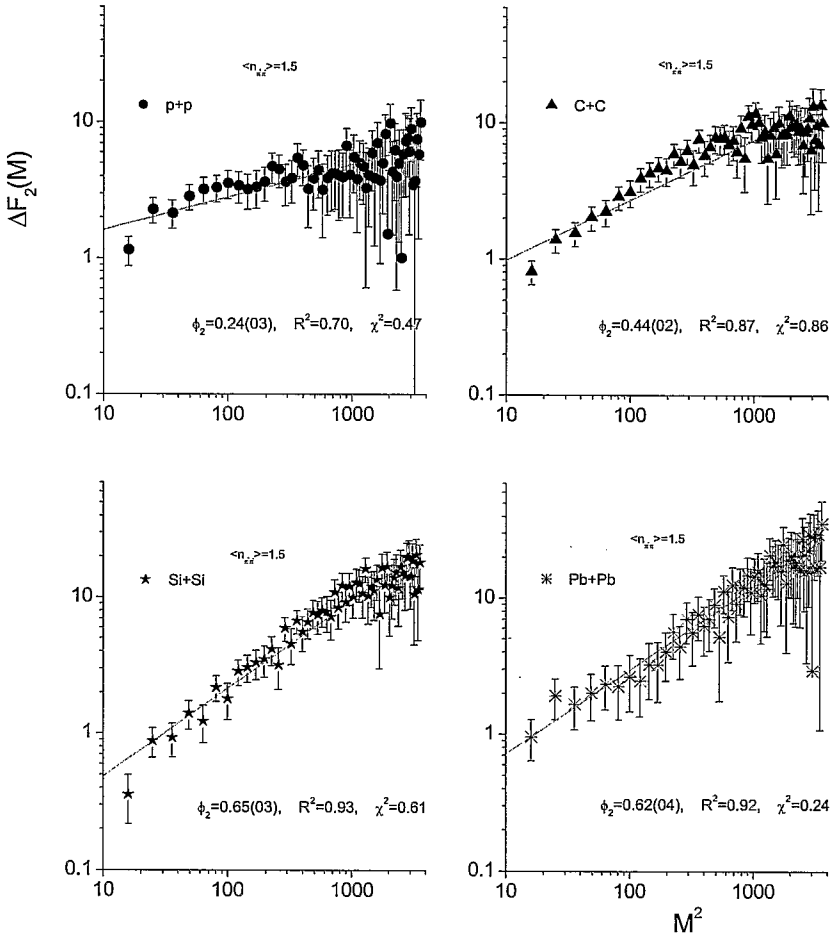
$$(a) \qquad \langle \rho(\vec{x}_\perp)\rho(0)\rangle \sim |\vec{x}_\perp|^{d_F - d}$$

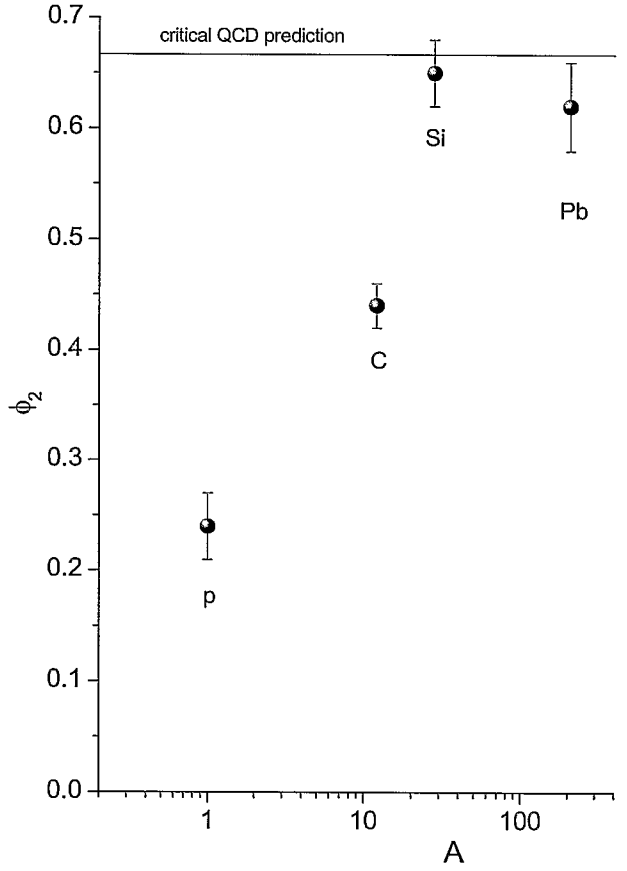
$$(b) \qquad \xi_\perp \simeq \frac{\pi\tau_c}{8}\sinh\left(\frac{\delta y}{2}\right)$$

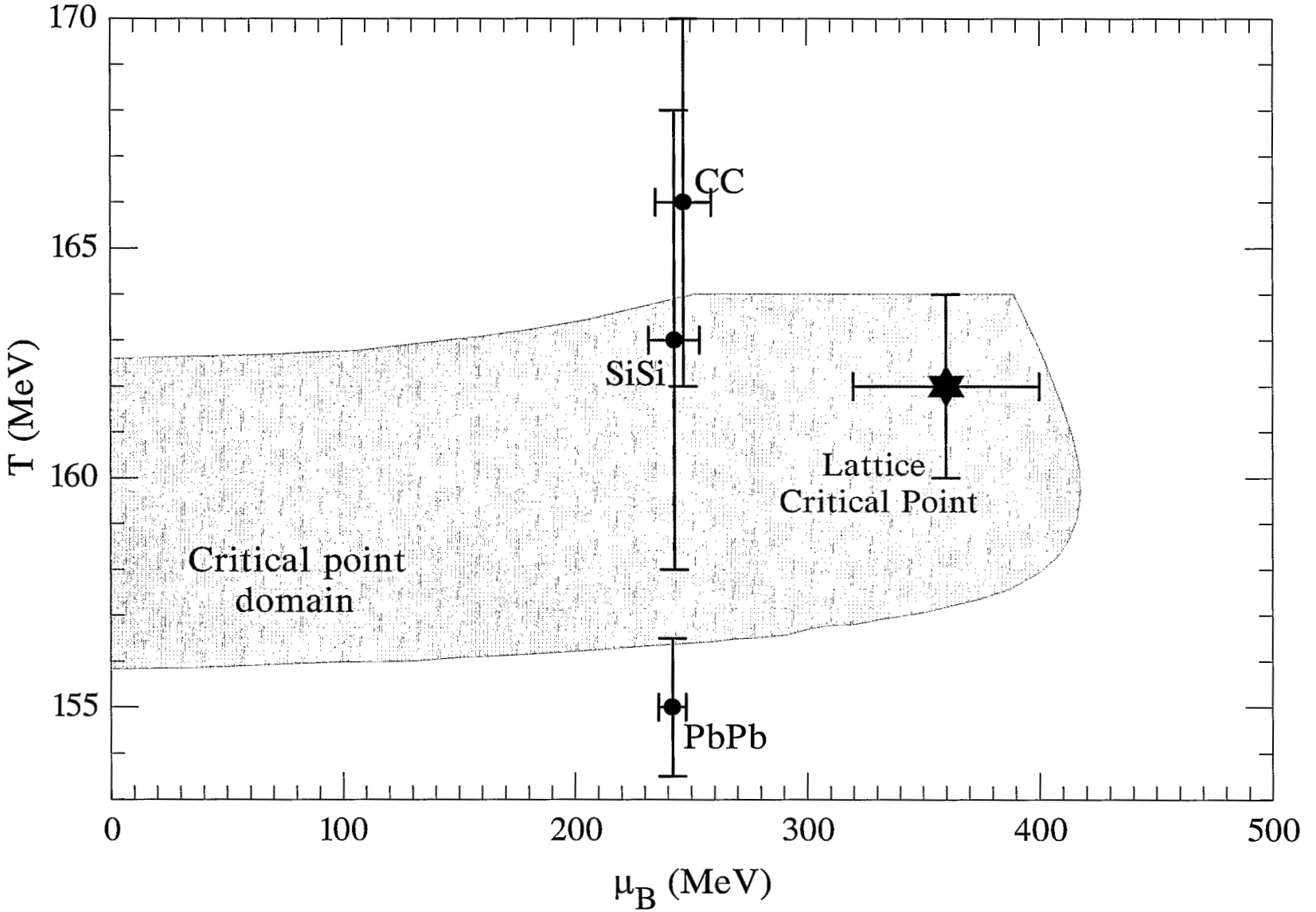
$$(c) \qquad d_F = \frac{2(\delta - 1)}{\delta + 1}$$

N.G. Antoniou, Y.F. Contoyiannis, F.K. Diakonos and C.G. Papadopoulos, Phys. Rev. Lett. **81**, 4289 (1998); N.G. Antoniou, Y.F. Contoyiannis and F.K. Diakonos, Phys. Rev. **62**, 3125 (2000).


CMC for Si+Si at 158 GeV/n
Si+Si at 158 GeV/n (<n_ππ>=1.5)
HIJING for Si+Si at 158 GeV/n
ΔF_q(M)
M^2
q=2
φ_2=0.64(03)
q=3
φ_3=1.28(03)
q=2
φ_2=0.65(03)
q=2


p+p
C+C
Si+Si
Pb+Pb
ϕ_2=0.24(03), R^2=0.70, χ^2=0.47
ϕ_2=0.44(02), R^2=0.87, χ^2=0.86
ϕ_2=0.65(03), R^2=0.93, χ^2=0.61
ϕ_2=0.62(04), R^2=0.92, χ^2=0.24
$\Delta F_2(M)$
M^2


critical QCD prediction
p
C
Si
Pb
ϕ_2
A

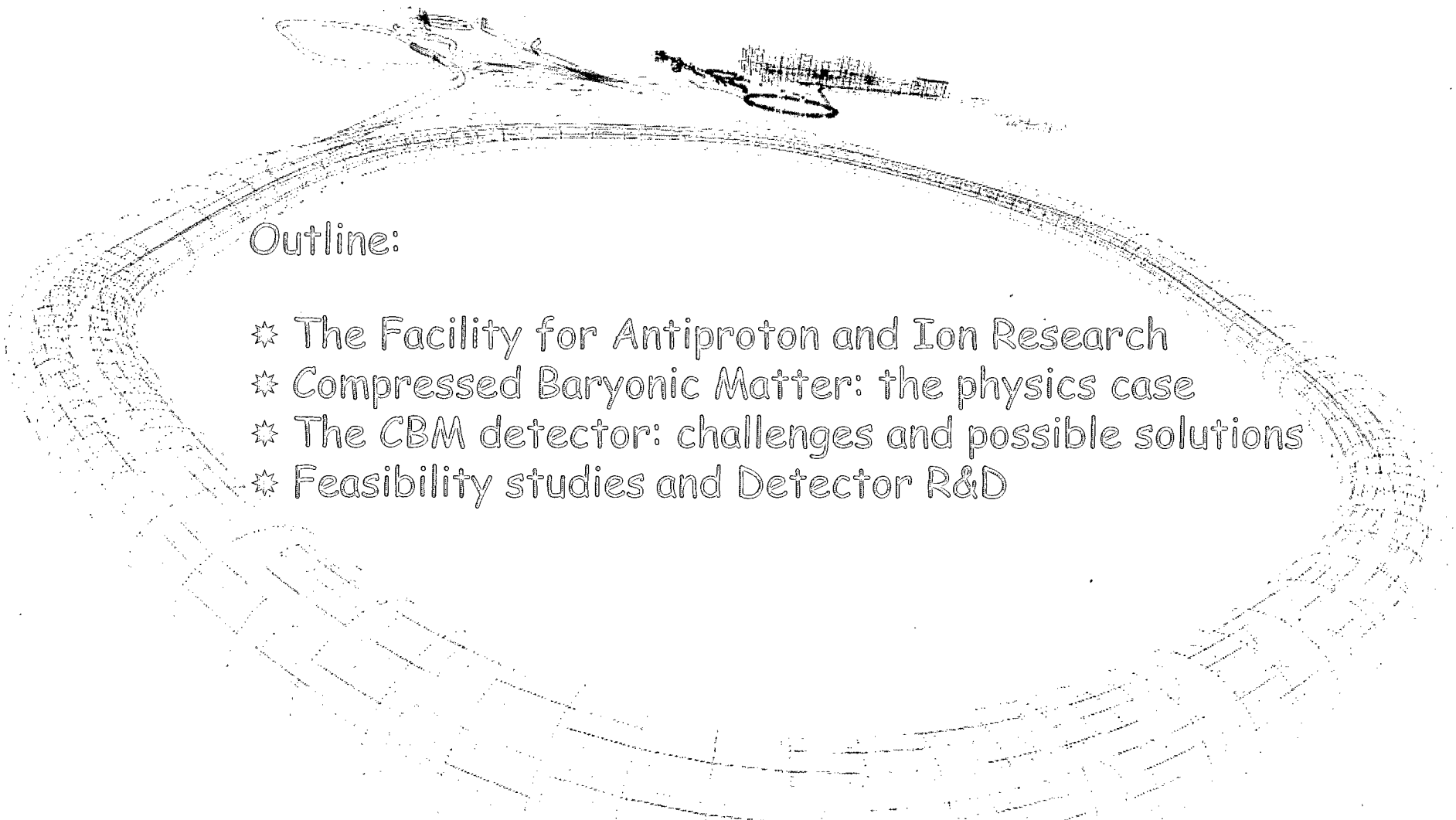


- N. G. Antoniou, F. K. Diakonos, A. S. Kapoyannis, Nucl. Phys. A **759** (2005) 417, [hep-ph/0503176]
- Z. Fodor, S. D. Katz, JHEP 0404 (2004) 050, [hep-lat/0402006]
- F. Becattini, J. Manninen, M.Gazdzicki, hep-ph/0511092

The Compressed Baryonic Matter Experiment at FAIR

Peter Senger

GSI



Outline:

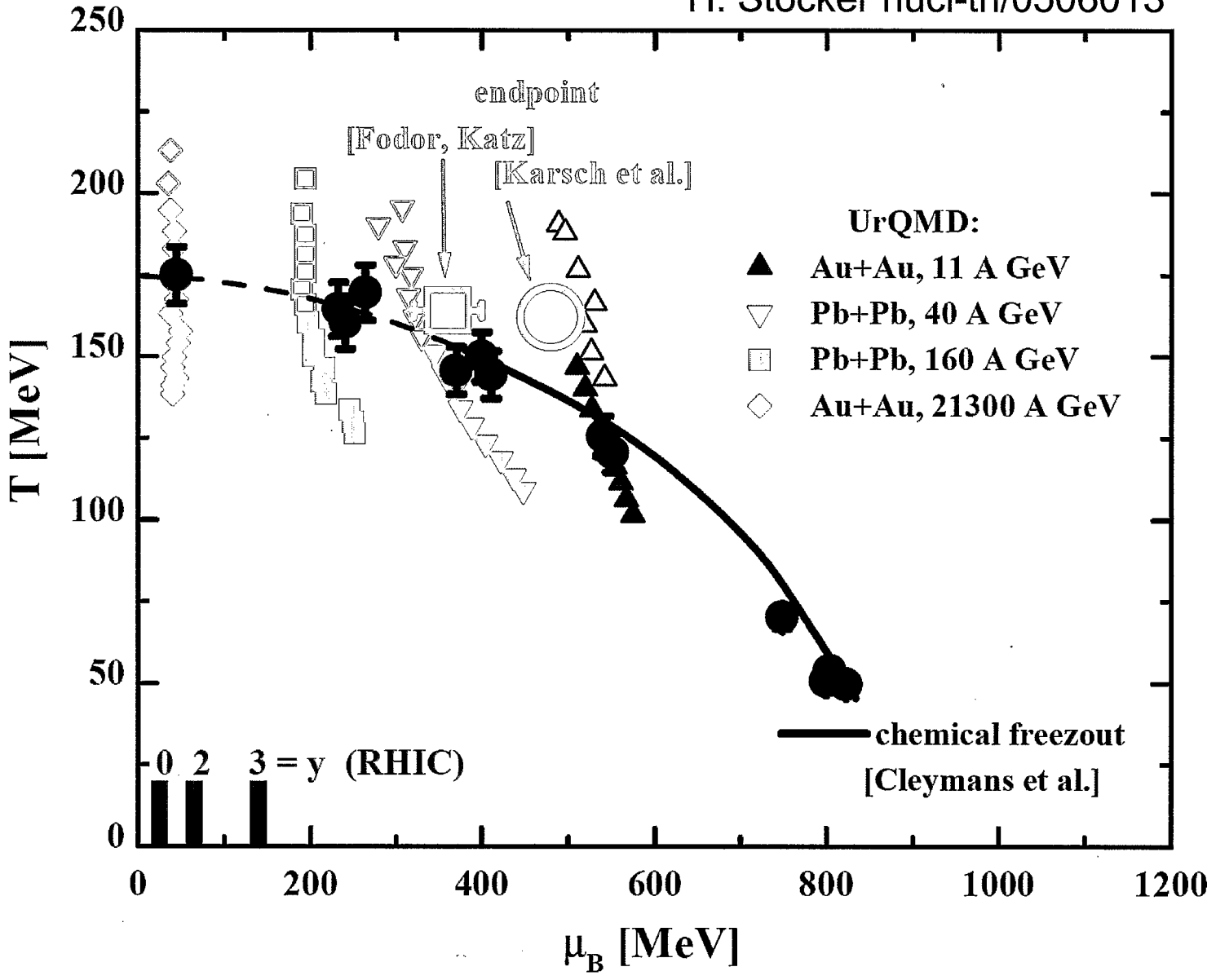
- The Facility for Antiproton and Ion Research
- Compressed Baryonic Matter: the physics case
- The CBM detector: challenges and possible solutions
- Feasibility studies and Detector R&D

Can we discover the QCD critical point at RHIC ? BNL, March 9-10, 2006

Mapping the QCD phase diagram with heavy-ion collisions

"Trajectories" from UrQMD

H. Stöcker nucl-th/0506013



Compressed Baryonic Matter: physics topics and observables

Probing the equation-of-state at high ρ_B

Observables: collective flow of hadrons,
particle production at threshold energies (open charm)

Search for the deconfinement phase transition at high ρ_B

- enhanced strangeness production ?

  Observables: K, Λ, Σ, Ξ, Ω
- anomalous charmonium suppression ?

  Observables: charmonium (J/ψ, ψ'), open charm (D^0, $D^{\pm}$)

Search for the critical endpoint

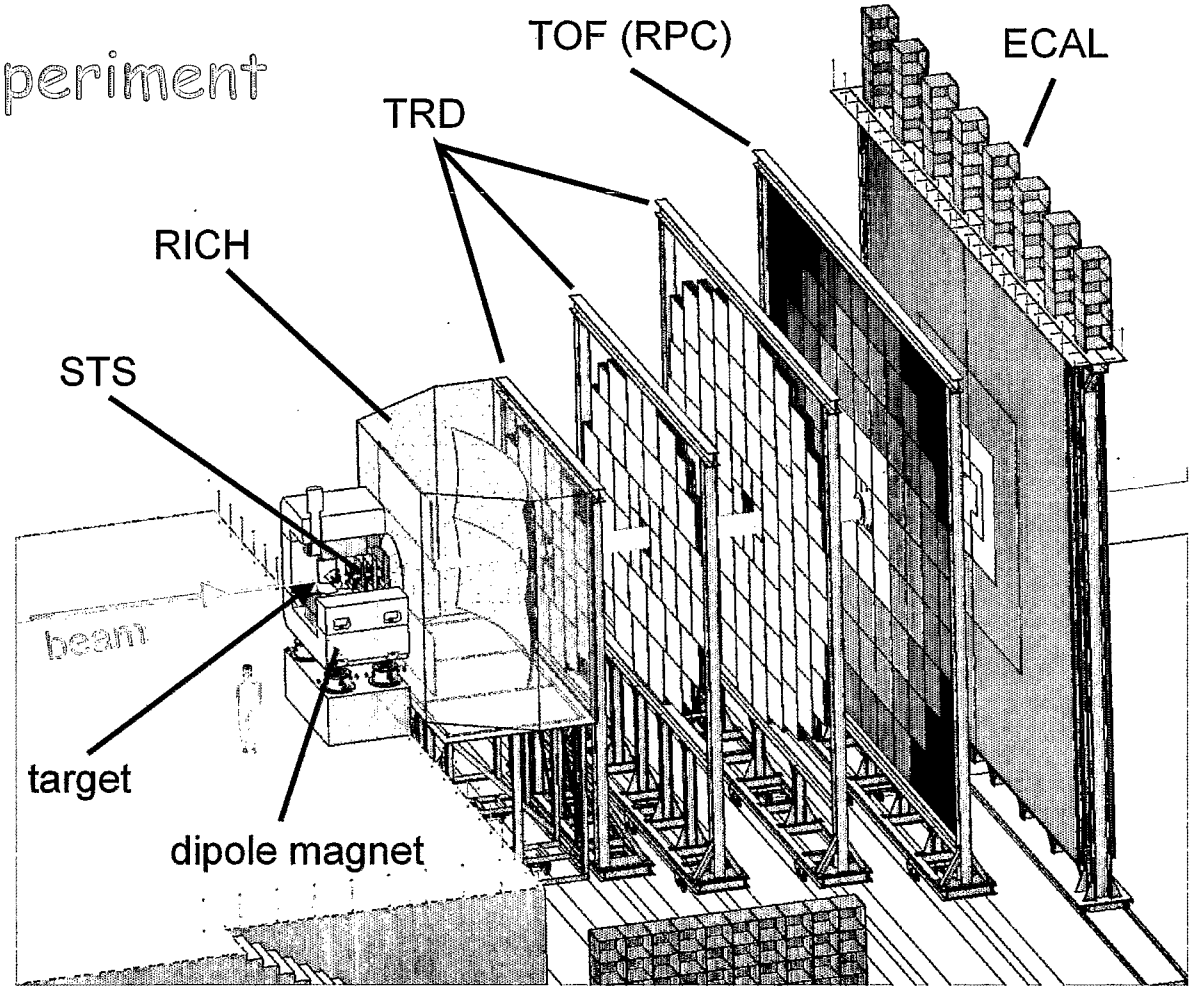
Observable: event-by-event fluctuations (K/π, p_T, ...)

Search for chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons

  Observables: ρ, ω, ϕ $\rightarrow$ e^+e^- , open charm, ...

The CBM Experiment

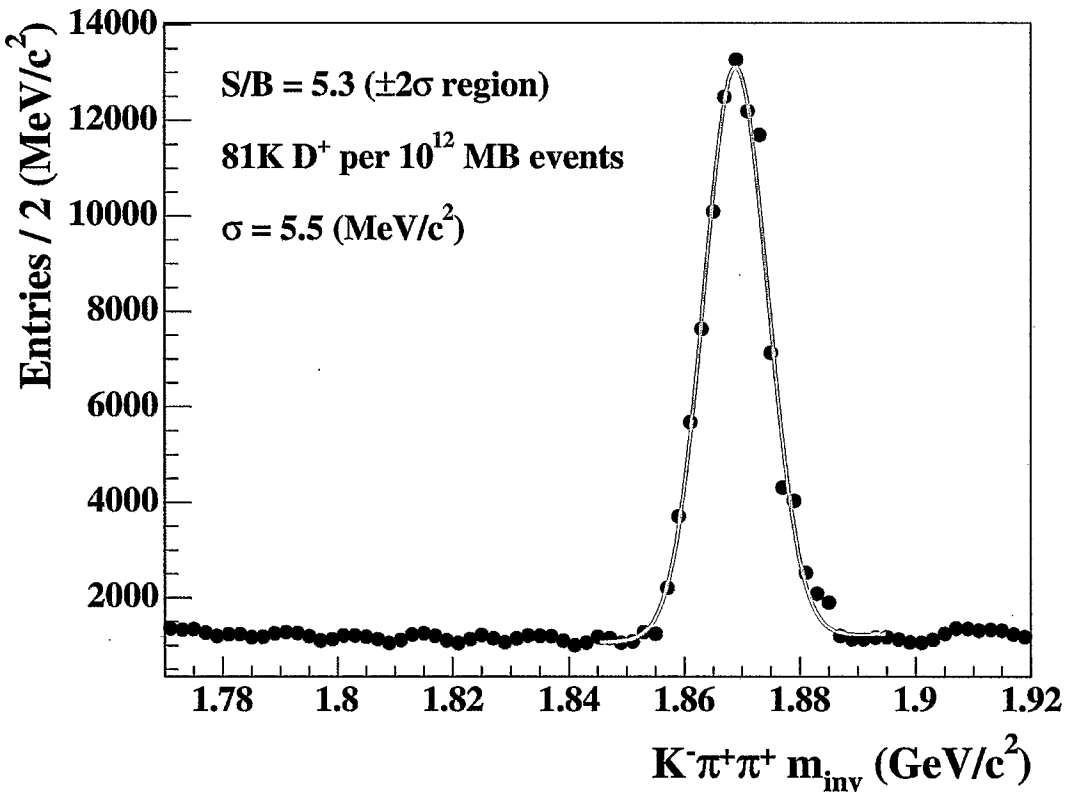


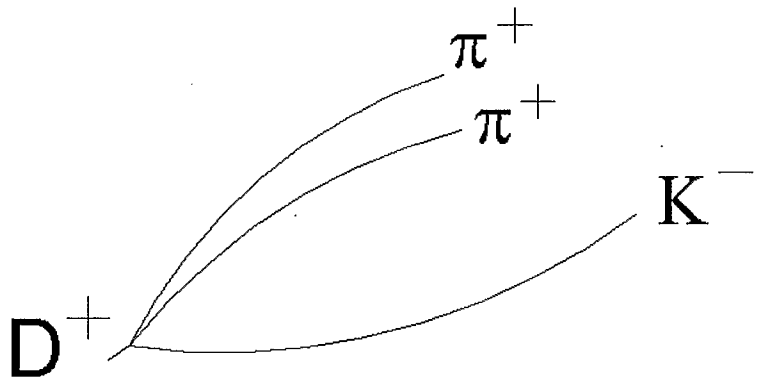
- Radiation hard Silicon (pixel/strip) Tracking System in a magnetic dipole field
- Electron detectors: RICH & TRD & ECAL: pion suppression better 10^4
- Hadron identification: TOF-RPC
- Measurement of photons, π, η, and muons: electromagn. calorimeter (ECAL)
- High speed data acquisition and trigger system

D^+ mesons from Au+Au collisions at 25 AGeV

Track reconstruction:
realistic magnetic field,
7 pixel detectors (no strips yet),
no particle ID required

D^+ production cross section from HSD
25 AGeV Au+Au from UrQMD

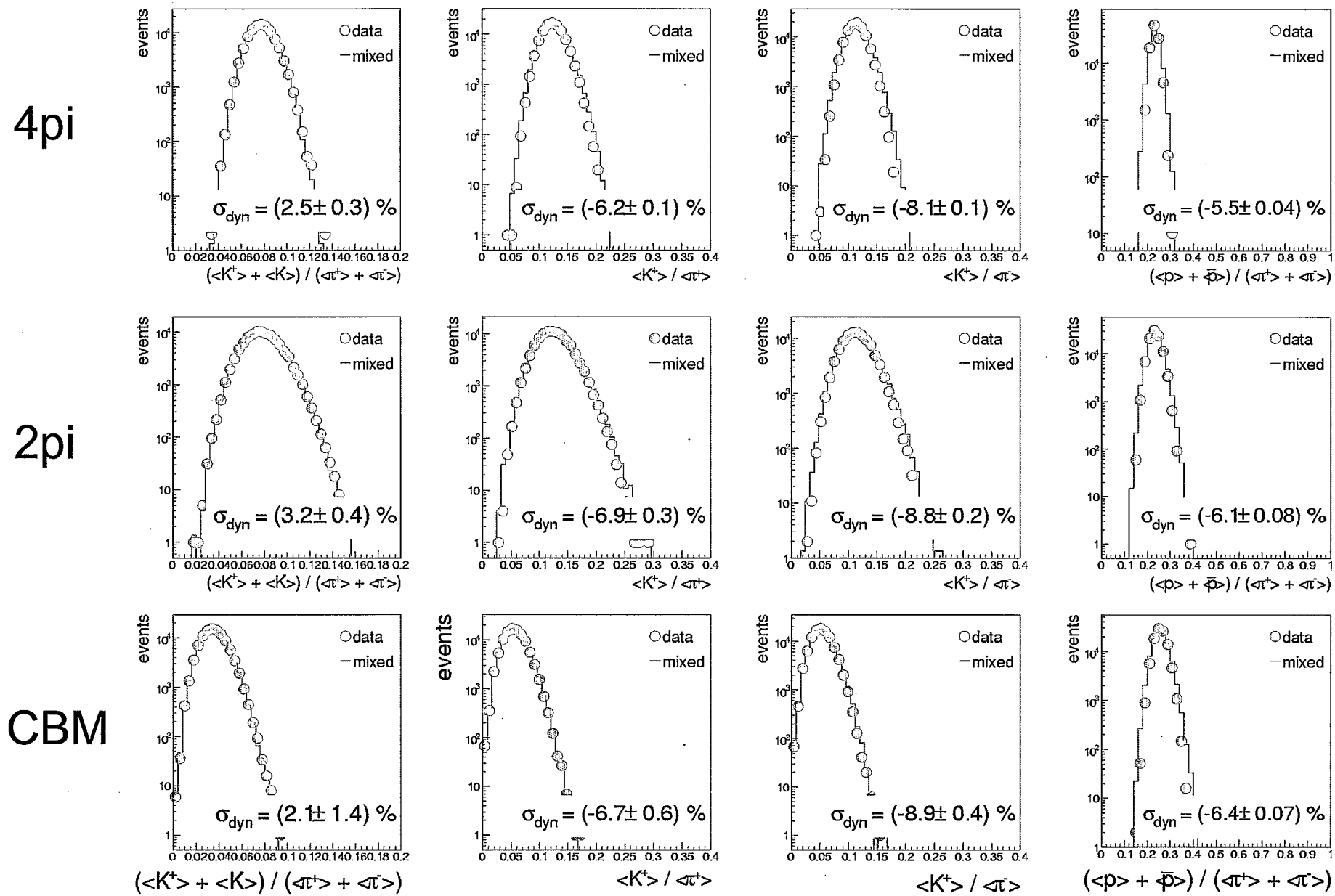




81000 D^+ mesons registered in 10^{12} min. bias Au+Au collisions at 25 AGeV
→ 1 day run with fast and rad hard vertex detector and tracking trigger
→ 100 days run with todays MAPS vertex detector without trigger

E-by-E dynamical fluctuations of particle ratios in UrQMD

Simulations by D. Kresan (GSI), M. Bleicher (Frankfurt)



Excitation Function Experimental Perspective

-- search for the native hadronic shore

Nu Xu

Lawrence Berkeley National Laboratory

Many thanks to organizers
and

V. Koch, J. Randrup, H. Ritter, Z. Xu

Outline

- **Motivation**
- **What we have learned at 200GeV**
  Some systematic from 1 - 200 GeV
- **Energy scan at RHIC - search for native hadronic shore**

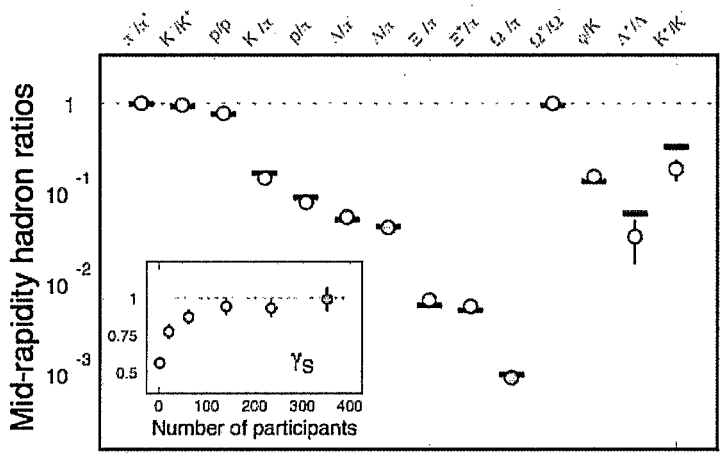
High-Energy Nuclear Collisions

Goals:

(1) Identify the bulk-matter (EOS) with partonic d.o.f
(2) Study the properties of the partonic matter

(3) *Demonstrate* the transition between partonic and hadronic worlds

Yields ratio results

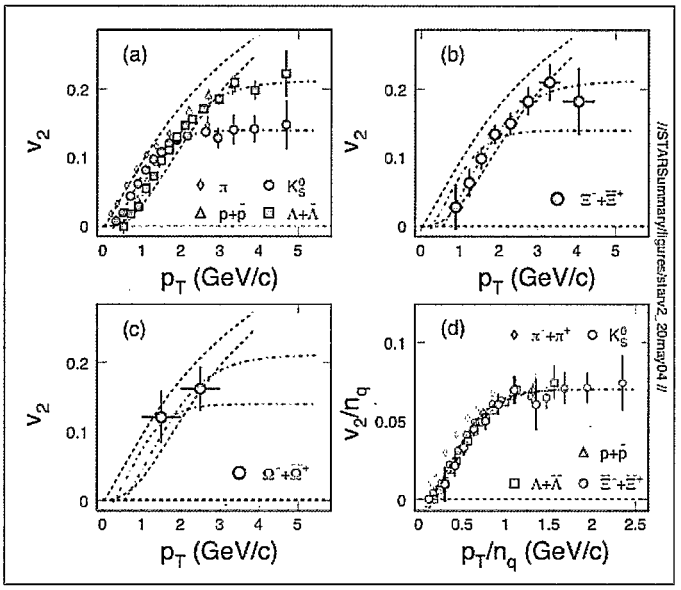


200 GeV ^{197}Au + ^{197}Au central collision

- In central collisions, thermal model fit well with $\gamma_S = 1$. **The system is thermalized at RHIC.**
- Short-lived resonances show deviations. **There is life after chemical freeze-out.**

RHIC white papers - 2005, Nucl. Phys. A757, STAR: p102; PHENIX: p184.

Collectivity, Deconfinement at RHIC



- v_2, spectra of light hadrons and multi-strange hadrons
- scaling of the number of constituent quarks

At RHIC, I believe we have achieved:

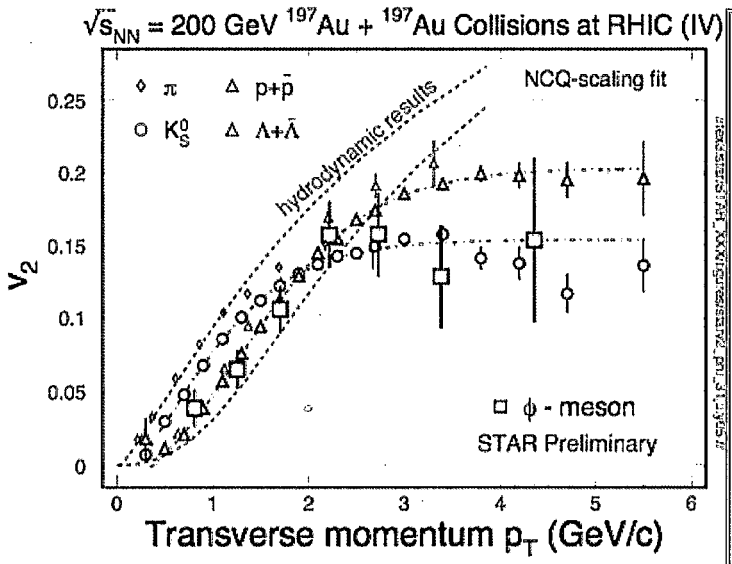
⇨ Partonic Collectivity

⇨ Deconfinement

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
....

ϕ-meson flows



STAR Preliminary, QM05 conference

RHIC results mean:

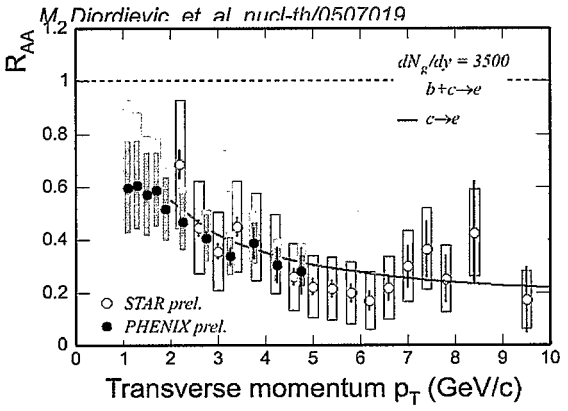
- Partonic EoS
- Particle productions dominated via partonic introduction

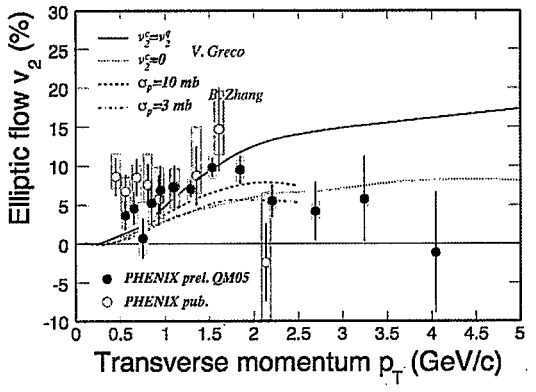
⇒ The system started beyond hadronic matter

Is there a boundary that can be observed?
Where is the boundary?

Experimental issue!
Systematic approach

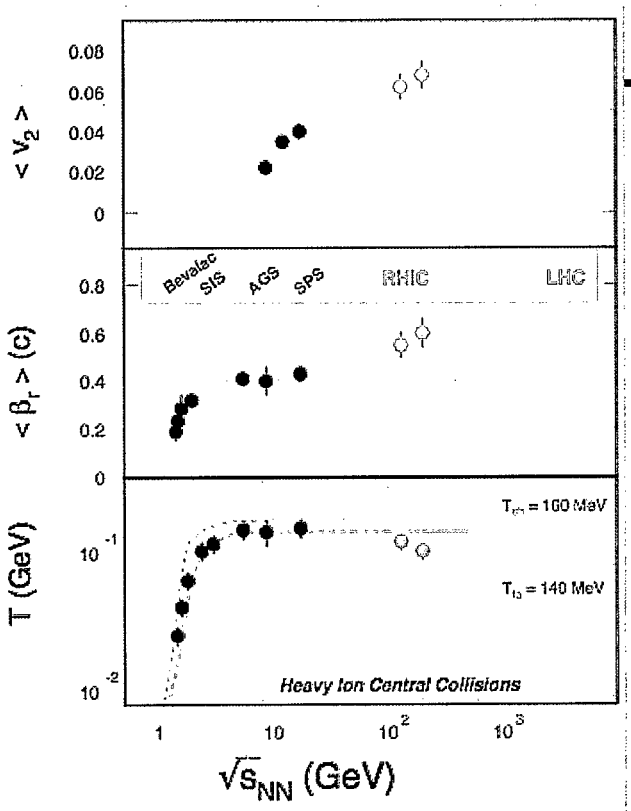
Non-photonic electron spectra & v_2





Partonic energy loss - necessary for the plasma formation !

Charm flows - a hint for partonic thermalization at RHIC!



Freeze-out systematic

At freeze-out:

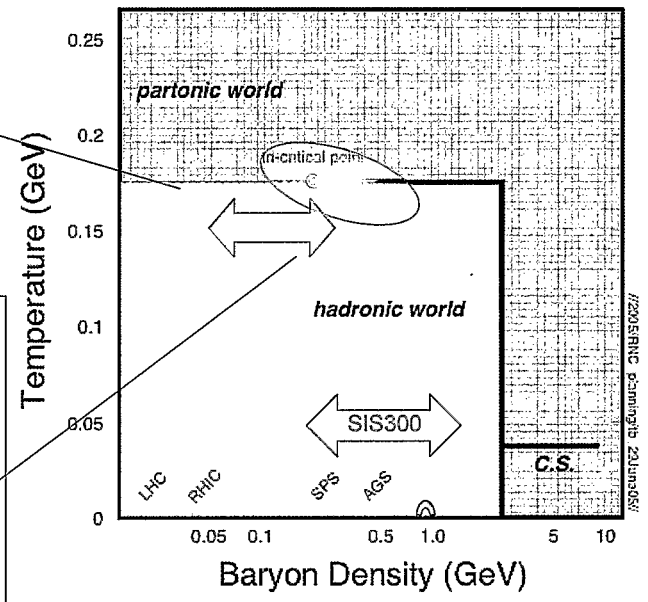
The 'temperature' parameters T_{fo} seem to be around 100 - 140 MeV.

v_2 continuously rise with beam energy. A clear increase in averaged velocity parameters β_r - increase of the 'pressure' in the system at RHIC.

When v_2 crosses zero, a plateau appears for T_{fo} and β_r at beam energy ~ 5 GeV.

Nuclear Phase Diagram

High excitation
Partonic d.o.f. dominant
"Tsunami at deep ocean"
Null effect!!!



Energy scan:

Turn off partonic activities
- ϕ,Ω, D-meson $v_2 \Rightarrow 0$
- jet-quching disappear

Look for our
"Native hadronic shore"

Systematic study of correlation/fluctuations
Systematic of di-lepton signal

U+U collisions
Large acceptance with collider environment

Detector system

Clean environment - colliding mode
Large acceptance
Good resolutions for particle PID

STAR TPC
STAR TOF(08) ideal for the scan program
STAR HFT(10)
PHENIX HBD ideal for di-lepton program

Important for RHIC-II future programs

<u>Heavy flavor program</u>:
partonic EoS study

<u>Energy scan</u>:
phase boundary and possible critical point

Experience with CERES

Dynamical pt fluctuations in central Pb-Au collisions at SPS are of order 1%, similar to measurements at RHIC.
This might be related to KNO-scaling of the multiplicity distributions in pp-collisions observed in this energy range.
In this case, the energy-independent pt fluctuations are not a trivial observation, but rather a consequence of the non-Poissonian nature of particle production in hadronic collisions. However, indications of a non-monotonic behaviour which might be related to critical fluctuations have not been observed.
Deeper insight into the origin of the observed pt fluctuations in AA can be obtained by a scale-dependent analysis, employing the pt correlator $<\Delta pt \Delta pt>$. A systematic study of the correlator in Pb-Au reactions at 158 AGeV is presented. The data exhibit a strong short range component presumably related to HBT correlations and a weaker back-to-back correlation. The $\Delta\phi$ and the centrality dependence show features similar to elliptic flow, however, a quantative estimate of the flow contribution can not describe the data. Rather, a connection to jet-induced high-pt correlation is suggested. This can be substantiated by a study of pt-pt correlations of particle pairs, expressed by the cumulant pt variable x(pt). Indeed, the observed short-range correlation is located along the diagonal at small pt and opening angles, pointing to HBT correlations. In contrast, the back-to-back correlations are located at high-pt, as expected for correlations arising from jet fragmentation.
Using the pt correlator formalism, different contributions to pt fluctuations could be assigned to known physical effects. Beyond that, no indication for critical fluctuations are observed.

Harald Appelshäuser, Johann-Wolfgang-Goethe-University Frankfurt

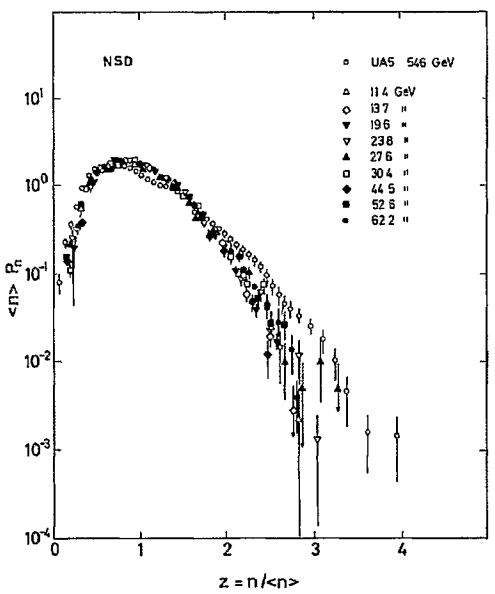
JOHANN WOLFGANG GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

KNO-scaling and p_t fluctuations in pp

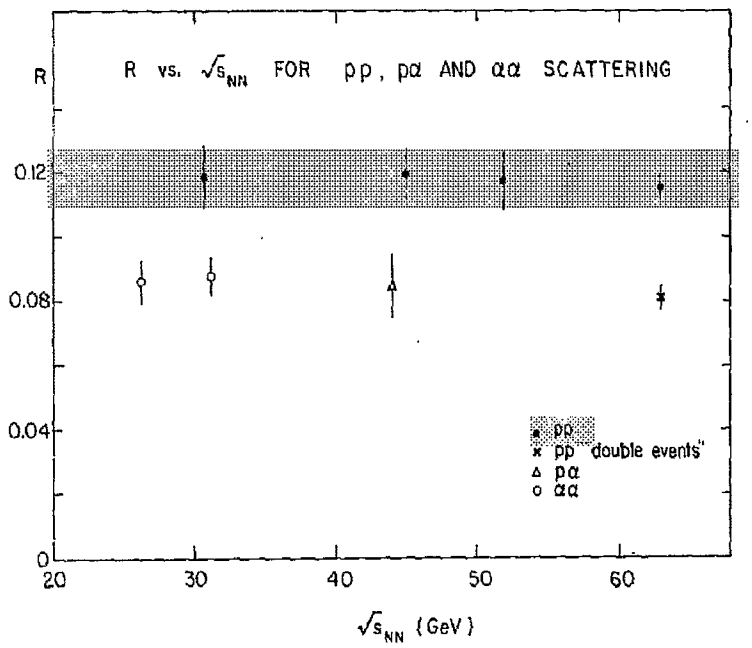
For constant *total* p_t per event, expect for p_t fluctuations:

$$\frac{\sigma(M_{pt})}{\langle M_{pt}\rangle} \sim \frac{\langle N\rangle}{\langle N\rangle^2}\sigma(N) = \sigma\left(\frac{N}{\langle N\rangle}\right)$$

UA5 Phys.Rep. 154 (1987)



Braune et al. Phys.Lett. 123B (1983)



~12%

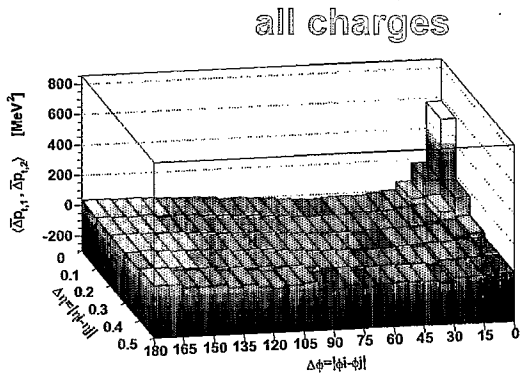
KNO-scaling: scaled multiplicity distributions collaps to a universal function → $\sigma(N/\langle N\rangle) = const$

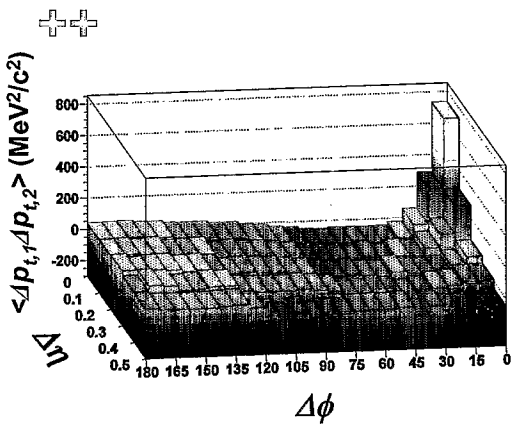
→ beam energy-*independent* M_{pt} fluctuations related to KNO-scaling in pp
→ in AA: a remnant of pp physics?

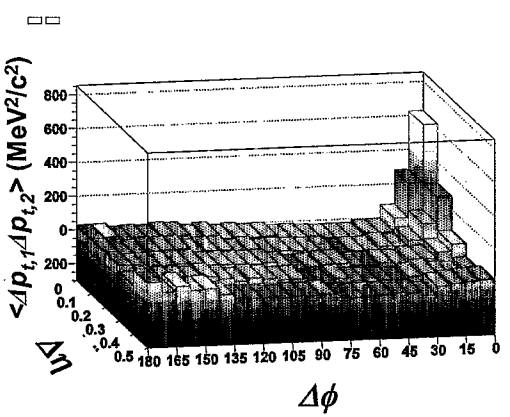
Scale dependent analysis

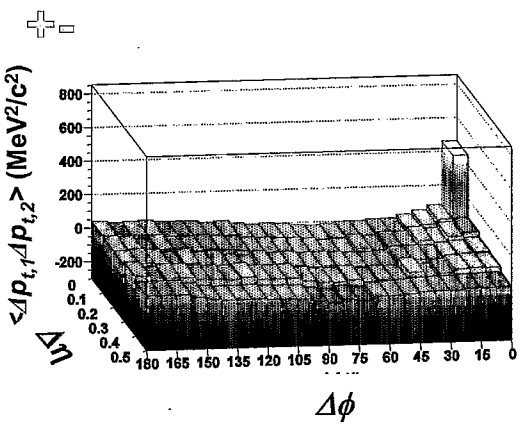
158 AGeV Pb-Au central

CERES preliminary







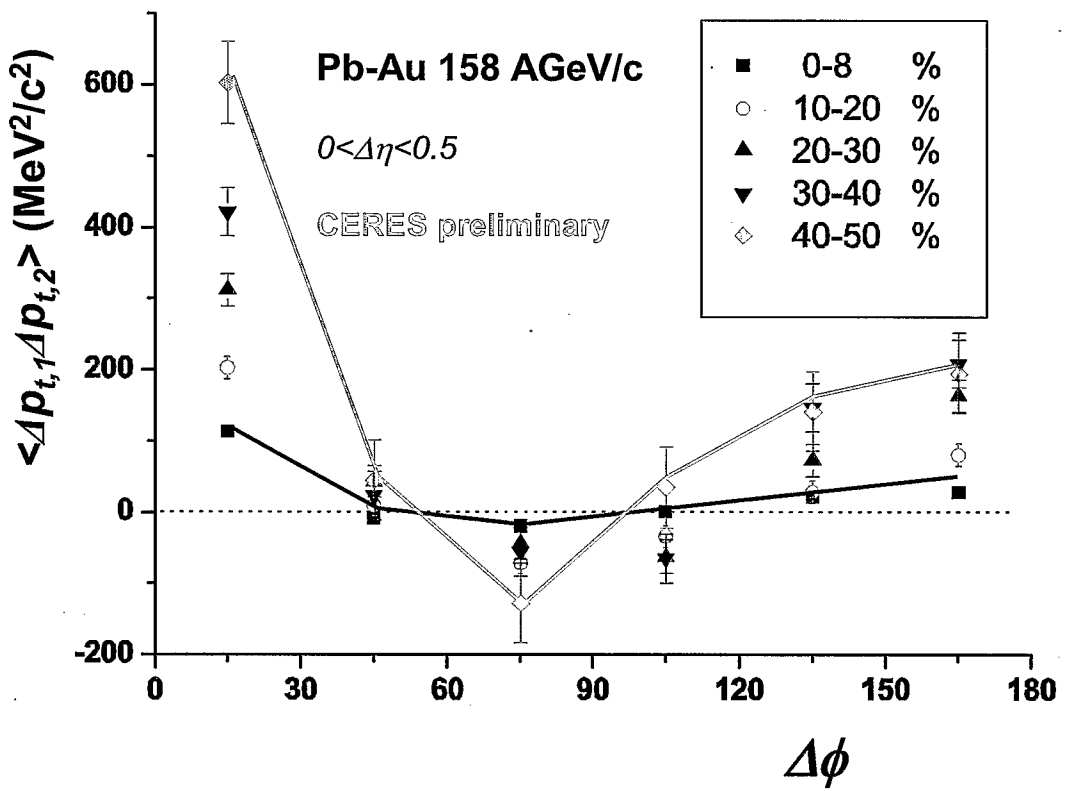


G. Tsiledakis, PhD

- short range component from quantum correlations
- very short range component from Coulomb, e^+e^-
- weak bump from resonances
- back-to-back component

Harald Appelshäuser, Johann-Wolfgang-Goethe-University Frankfurt

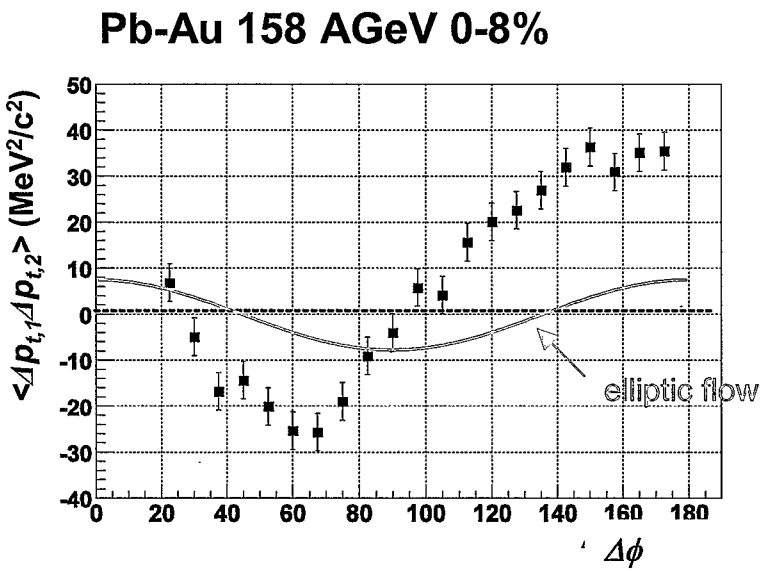
Centrality dependence

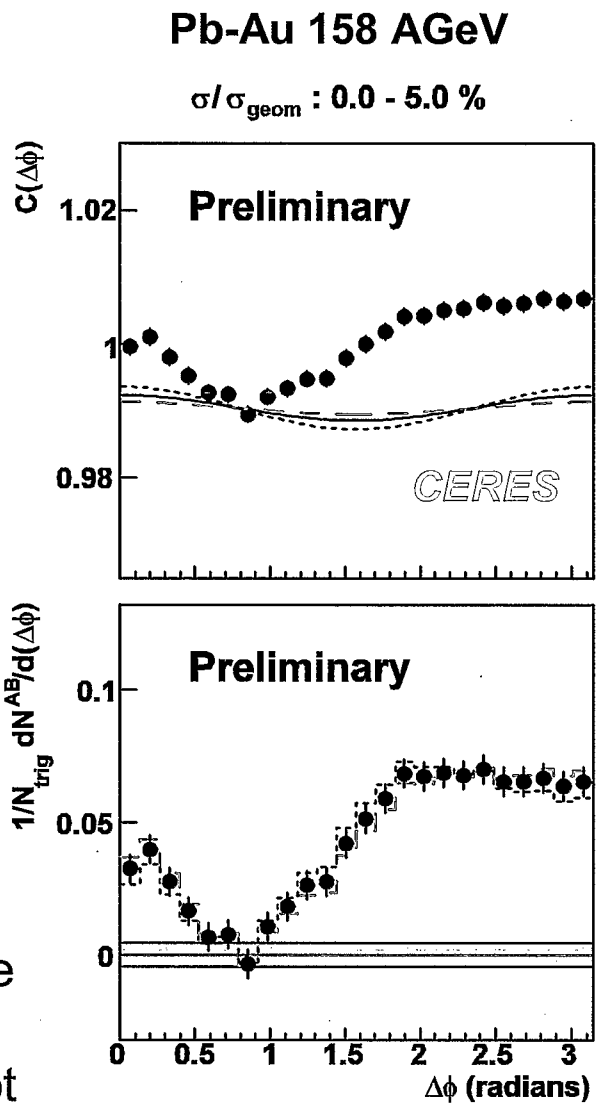


G. Tsiledakis, PhD

- angular dependence increases towards peripheral collisions

Elliptic flow contribution



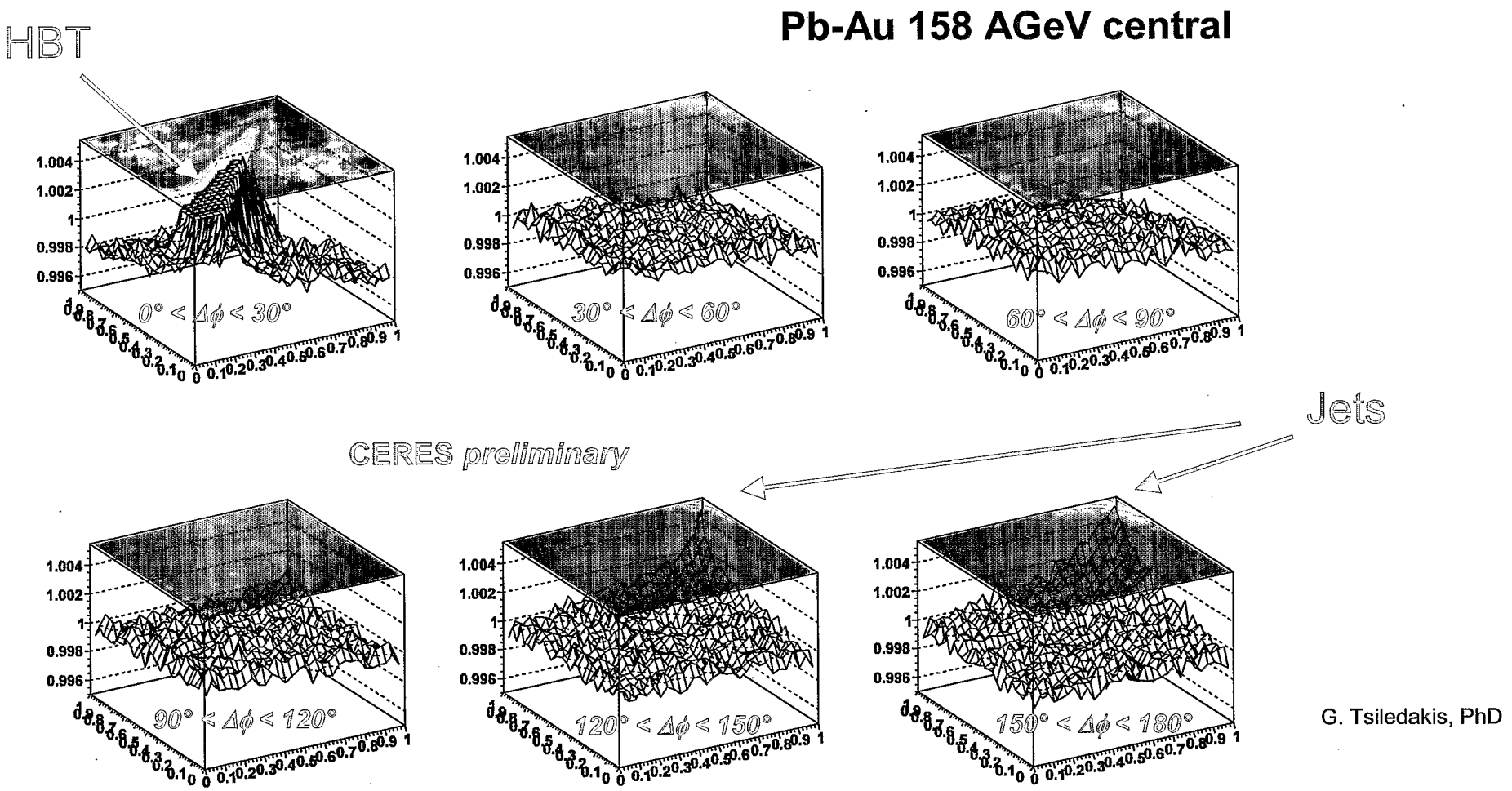


M. Ploskon
QM05

- measured elliptic flow explains neither shape nor magnitude of the measured correlations
- observed pattern looks very similar to high-pt correlations

p_t^{trig} >2.5 GeV/c
1.2 < p_t^{asso} < 2.5 GeV/c

p_t-p_t correlations - azimuthal dependence



G. Tsiledakis, PhD

Harald Appelshäuser, Johann-Wolfgang-Goethe-University Frankfurt

Critical Point at SPS?

Reinhard Stock, Univ. of Frankfurt

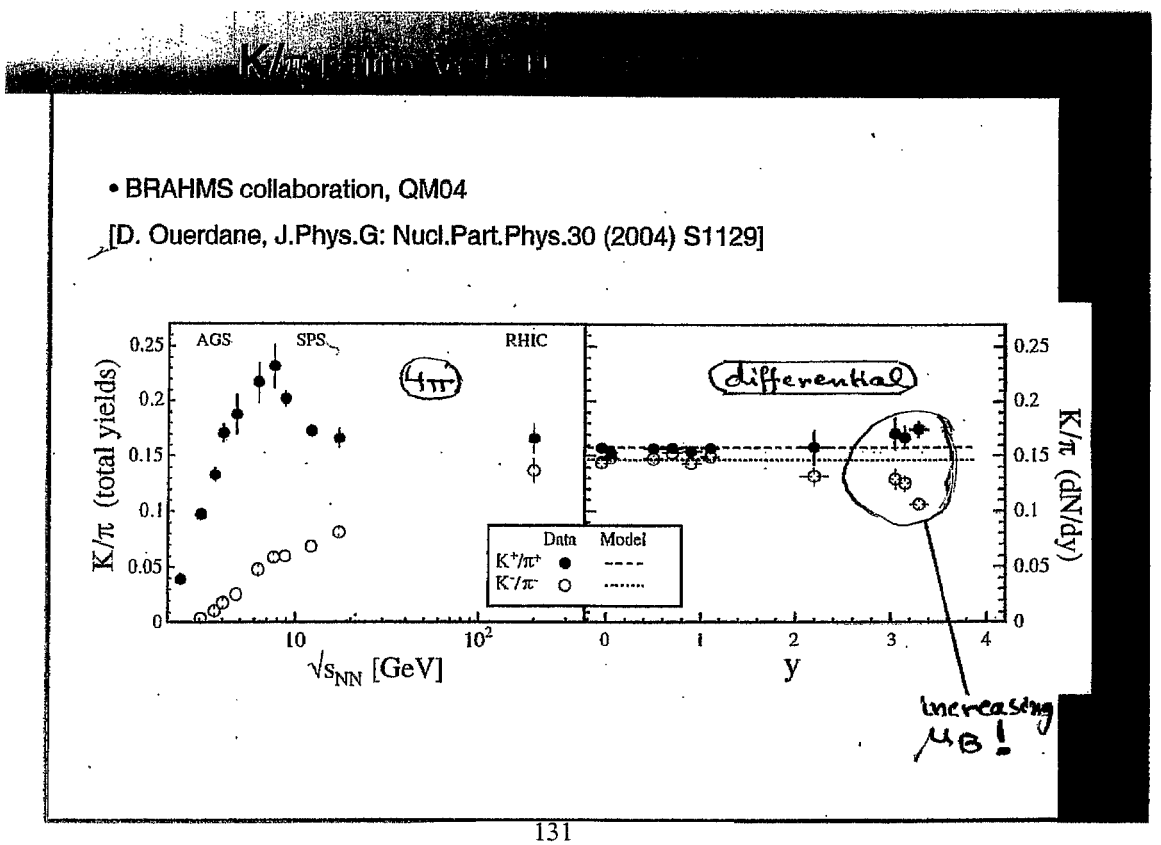
Interesting and seemingly "non-trivial" data at the low energy end of the SPS domain are discussed:

(a) In the framework of the Statistical Model "The γ_s - problem", the Wróblewski ratio

(b) With regard to quark susceptibilities from Lattice QCD.

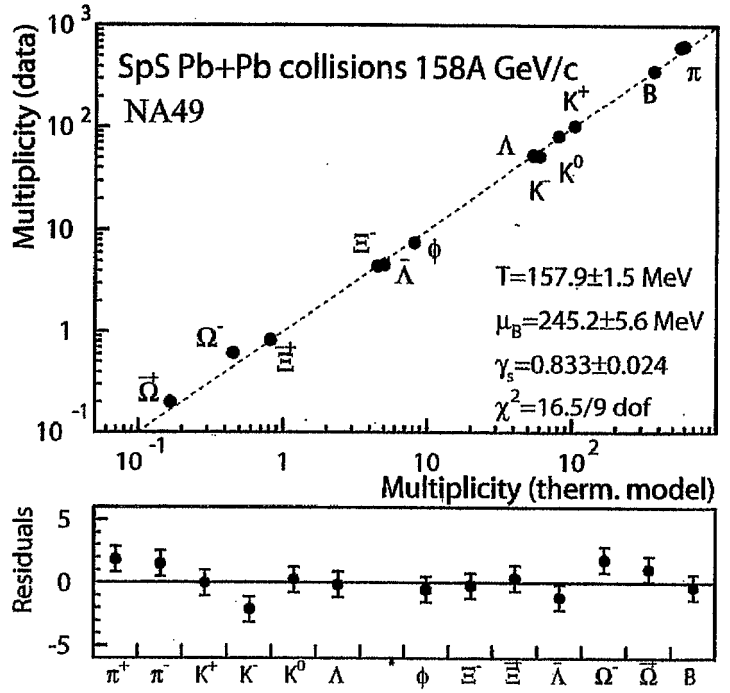
→ justification of the Gavai-Gupta-Formula (and extension to finite μ_B)?

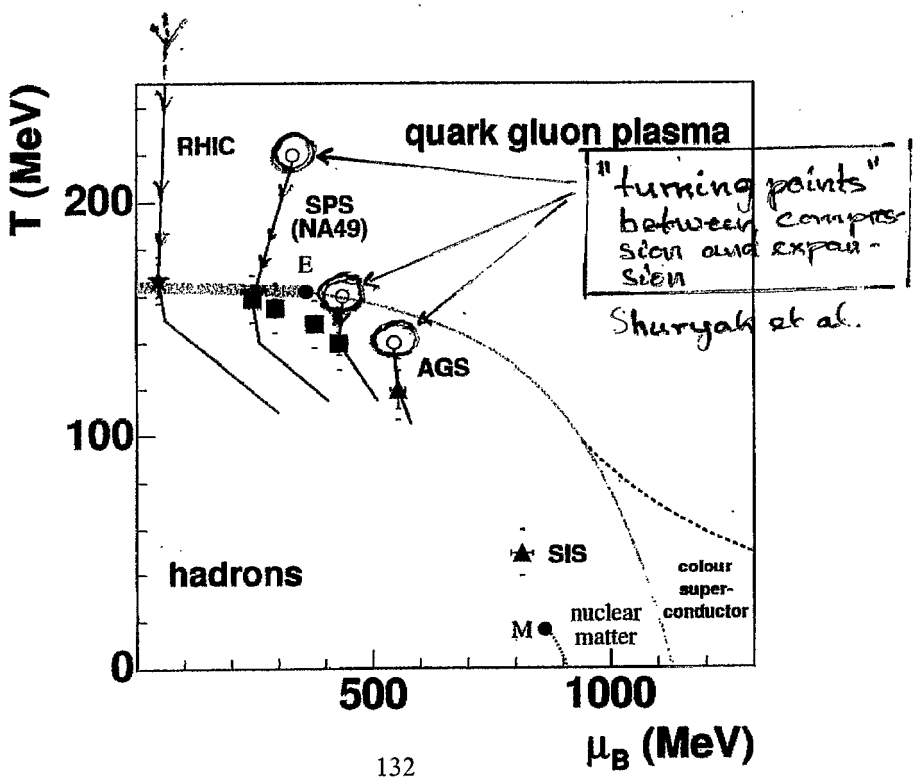
→ relation of the light quark susceptibility peak at $T = 150$ MeV, $\mu_B = 450$ MeV observed by Bielefeld-Swansea to K/π "horn" and ebye-fluctuation?



Grand Canonical statistical hadronization

Becattini, Braun-Munzinger, Claymans, Öschler, Tounsi, Redlich, Stachel, Stock et al.





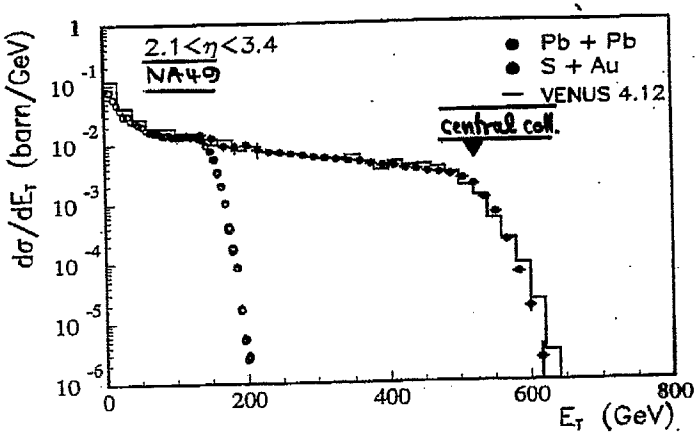
"turning points" between compression and expansion

Shuryak et al.

Signal I:

Calorimetric Measurement of Total Transverse Energy Production in Pb+Pb at 158 GeV/A

WA98, NA49



1. Extrapolate to 4π: $E_T^{total} \simeq 1.2$ TeV in head-on collisions

2. Use J.D. Bjorken-prescription which relates E_T density in rapidity (p_{long}) space to energy density ϵ in reaction volume: $\epsilon \gtrsim 2.5\ \mathrm{GeV/fm^3}$

Strangeness vs. Grand Canonical Ensemble

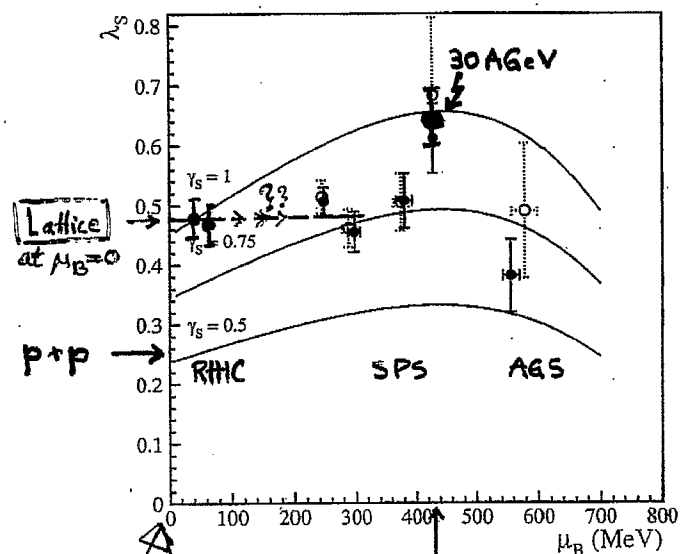
The "Wroblewski-Ratio":

$$\lambda_s = \frac{2(\langle s\rangle + \langle \bar{s}\rangle)}{\langle u\rangle + \langle \bar{u}\rangle + \langle d\rangle + \langle \bar{d}\rangle} \stackrel{!}{=} \frac{2X_s}{X_u + X_d}$$

[Gavai et al. QM04]

from quark counting in GC ensemble

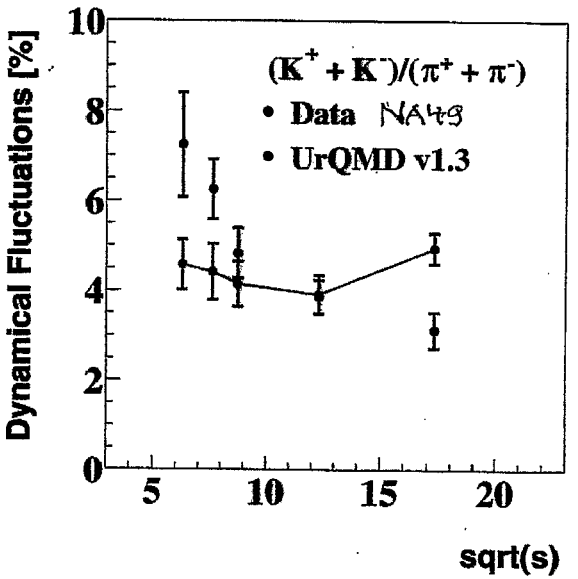
from Lattice extrapolation



F. Becattini et al. PRC 69 (2004) 24905 ⇝ $\mu_B \approx 440$ MeV

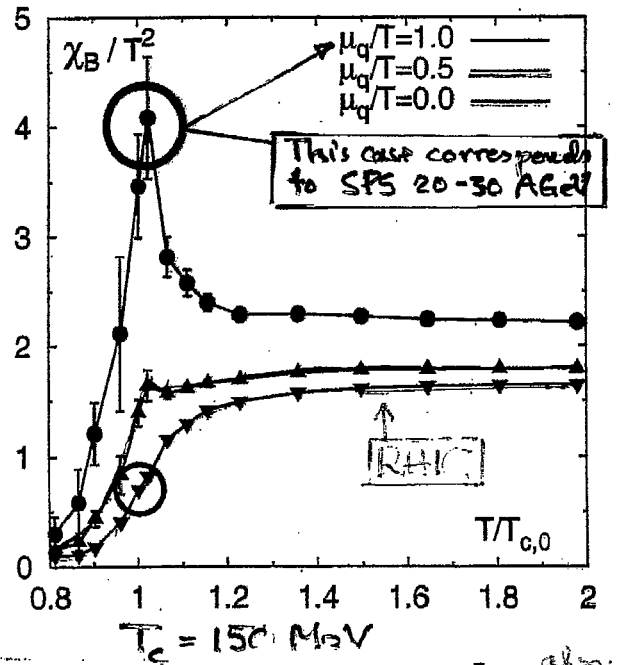
$\mu_{u,d} = \frac{1}{3}\mu_B \approx 150$ MeV

Ch. Roland, QM04



Recent Lattice QCD Success:

- Calculation at finite baryochemical potential
  i.e. at $\rho(u-\bar{u}, d-\bar{d}) > 0$
- Find QCD "critical point" !!
  baryon number density fluctuations:
  (Bielefeld-Swansea, in preparation)



S. Ejiri et al., Poster QM04
F. Karsch talk "

Discussion:

1. The Gavai - Gupta - estimate for the Wroblewski - Ratio

$$\lambda_s \equiv \frac{2\,(n_s + n_{\bar{s}})}{n_u + n_{\bar{u}} + n_d + n_{\bar{d}}} \approx \frac{2\,\chi_s}{\chi_u + \chi_d}$$

- works well at $\mu_B \to 0$
- how to be extended to $\mu_B > 0$?
- then perhaps to reproduce the K^+/π^+ data??
  (from 2+1 flavour Lattice ?) at finite μ_B

2. Explanation of the Bielefeld-Swansea lattice peak at $\mu_Q/T = 1$, i.e. $\mu_B \approx 450\,\mathrm{MeV}$?

- does it indicate the vicinity of a crit. point, near $T = 150\,\mathrm{MeV}$, $\mu_B = 450\,\mathrm{MeV}$??
- whether or not :
  $\longrightarrow$ observable consequences ?
- can we expect a corresponding peak of χ_s/T^2 in lattice 2+1 ?
  $\longrightarrow$ explaining event-by-event K/π fluctuation ?

Can we discover the QCD critical point at RHIC?
Lattice calculations at finite baryon potential

Zoltán Fodor
University of Wuppertal & University of Budapest

1. Standard picture of the phase diagram and its uncertainties

2. Lattice results (staggered fermionic actions with fourth root)

   a. Existence of the critical point: transition at μ=0
   b. Location of the critical point: L_t=4, a=0.25 fm results
   c. Density of state method: three phases for n_f=4

3. Conclusions

- Is our picture correct? (cross over $\longrightarrow$ critical point)

What can we really say about the physical point (cross-over)?

$\Longrightarrow$ physical quark masses: m_π=140 MeV, m_K= 500 MeV
$\Longrightarrow$ continuum limit: extrapolation to vanishing lattice spacings

in "usual" lattice simulations these two limits are missing

quark masses are important for the order of the transition:
n_f=2+1 theory with m_q=0 or ∞ gives a first order transition
for intermediate quark masses we have an analytic cross over

F. Karsch et al., Nucl. Phys. Proc. 129 (2004) 614

continuum limit is important for the order of the transition:
n_f=3 case (standard action, μ=0, L_t=4): critical $m_\pi \approx$300 MeV
with different discretization error (p4 action): critical $m_\pi \approx$70 MeV
the physical pion mass is just between these two values

do physical quark masses result in a cross-over in the continuum?

for the critical point at μ>0 we need a cross-over at μ=0

Order of the transition at μ=0: physical m_q-s in the continuum

G. Endrodi, Z. Fodor, S.D. Katz, M. Nagy, K.K. Szabo, WU-06-01

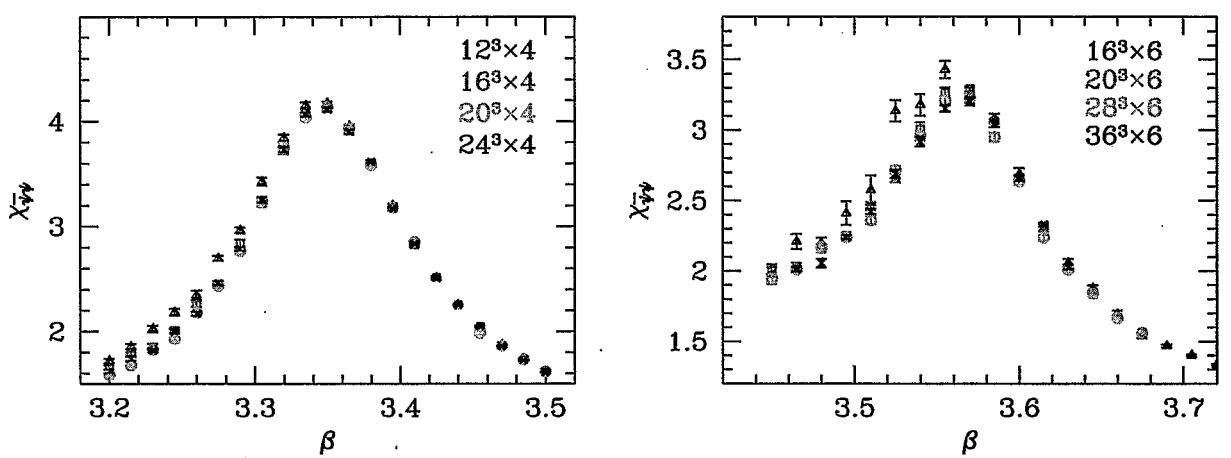
- Finite size scaling of the transition, L_t=4,6,8,10

(Symanzik improved gauge, stout improved fermionic action)

Chiral susceptibilities: $\chi=(T/V)\partial^2 \log Z/\partial m^2$

first order transition $\Longrightarrow$ peak width $\propto$ 1/V, peak height $\propto$ V

cross over $\Longrightarrow$ peak width $\propto$ constant, peak height $\propto$ constant



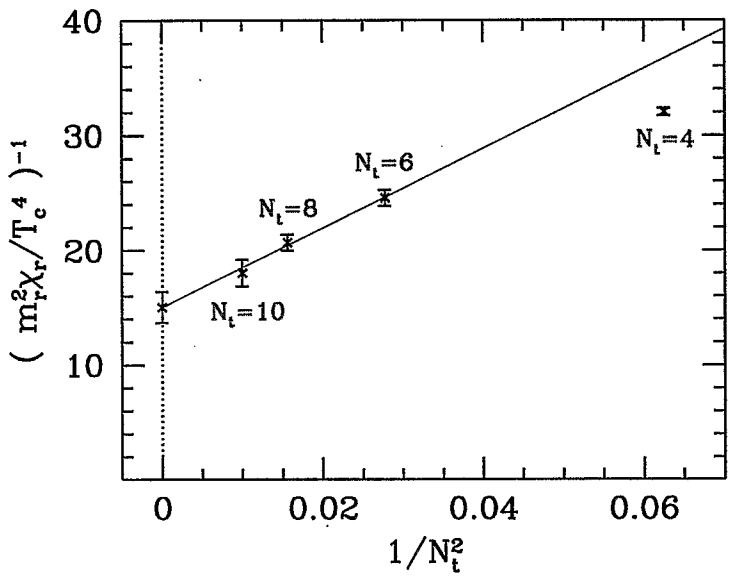
for aspect ratios 3–6 (an order of magnitude larger volumes)

volume independent scaling $\Longrightarrow$ cross-over

- we need a continuum extrapolation (width, height)

calculate $m^2[\chi(T\neq 0)-\chi(T=0)]$ at the transition point

continuum limit: L_t=4,6,8,10 (6,8,10 in the a^2 scaling regime)

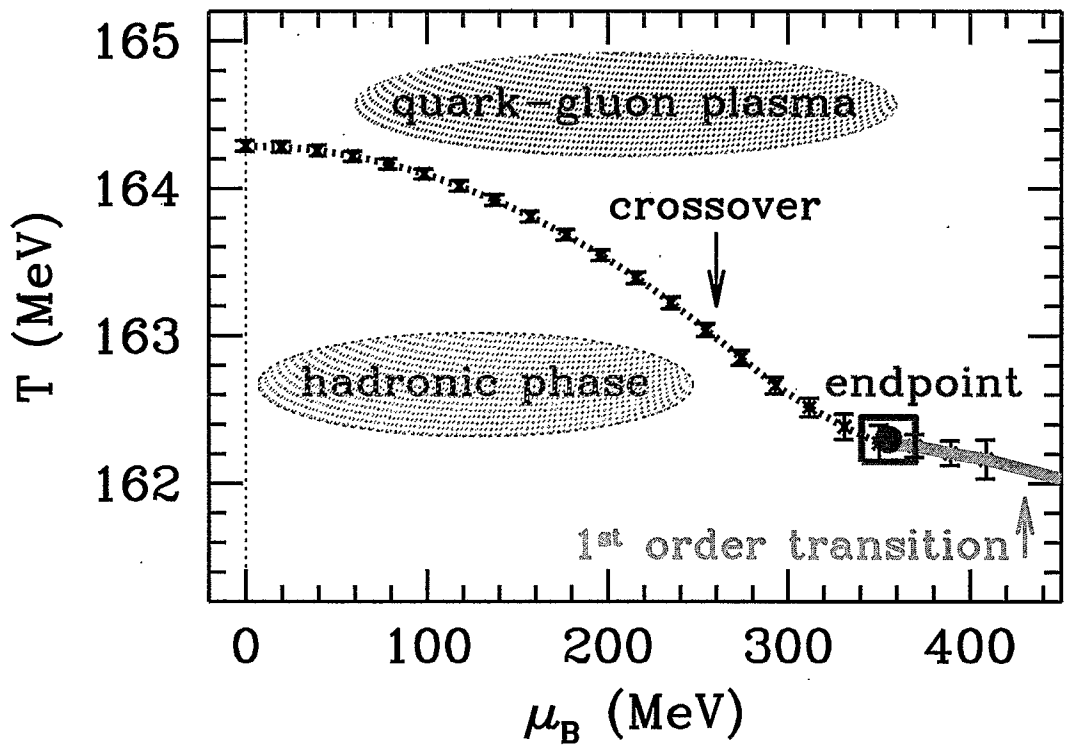


continuum extrapolation is more than 10 sigma away for zero continuum result with physical quark masses in staggered QCD

the QCD transition at μ=0 is a cross-over

$\Longrightarrow$ Condition for the critical point is fulfilled

- T as a function of the baryonic chemical potential μ_B



- lattice result for physical quark masses at $L_t = 4$

endpoint: $T_E = 162 \pm 2$ MeV, $\mu_E = 360 \pm 40$ MeV

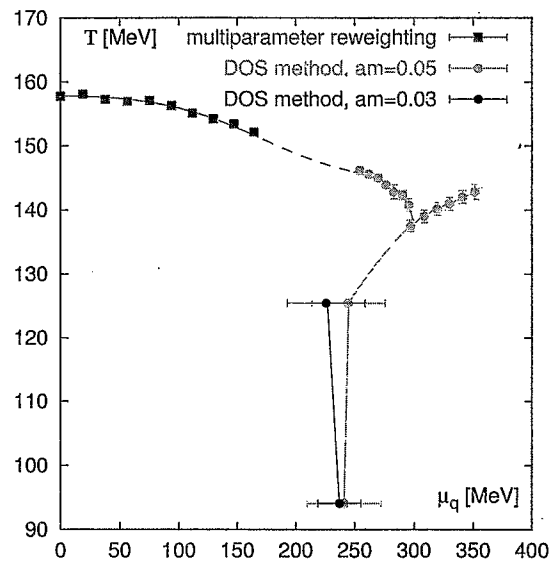
$$T/T_c = 1 - C\mu_B^2/T_c^2 \text{ wit C=0.0032(1)}$$

errors are only statistical (no continuum extrapolation)

Results for QCD at large μ

Z. Fodor, S.D. Katz, C. Schmidt, hep-lat/0510087

$N_f = 4$ staggered QCD on 6^4, $8 \cdot 6^3$ lattices



existence of a triple point around $\mu_q \approx$ 300 MeV and T $\lesssim$ 135 MeV

Note, L_t=6 lattices: smallest T is 73 MeV (if m_ρ fixes the scale)

Mass dependence checked:
small T transition point does not depend on pion mass

Fluctuations

V. Koch
Lawrence Berkeley National Laboratory

Baryon Number fluctuations are the most obvious observable for the critical point . However, Baryon number conservation might make this measurement difficult at low energies, since the correlation length as well as corrections due to scattering in the hadronic phase might be as large as the system in rapidity space.

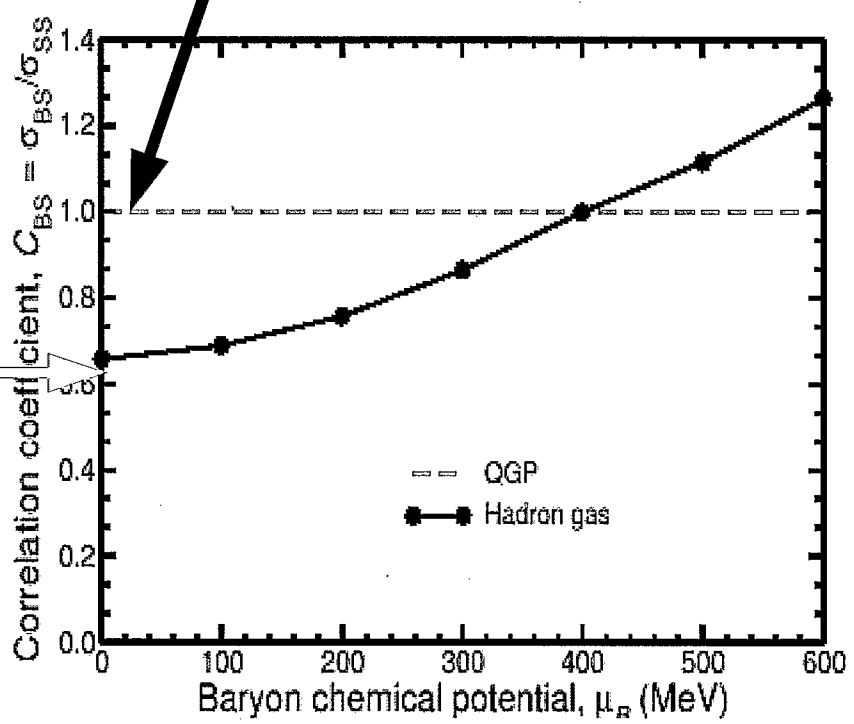
The measured K/pi ratio by NA49 is qualitativeley consistent with spinodal breakup. However, it is not yet understood why the proton/pion fluctuations are in agreement with UrQMD. A detailed study needs to address this.

The physics case for a low energy run at RHIC is very convincing. And while the experiments ramp up, theorist need to work on more practical observables

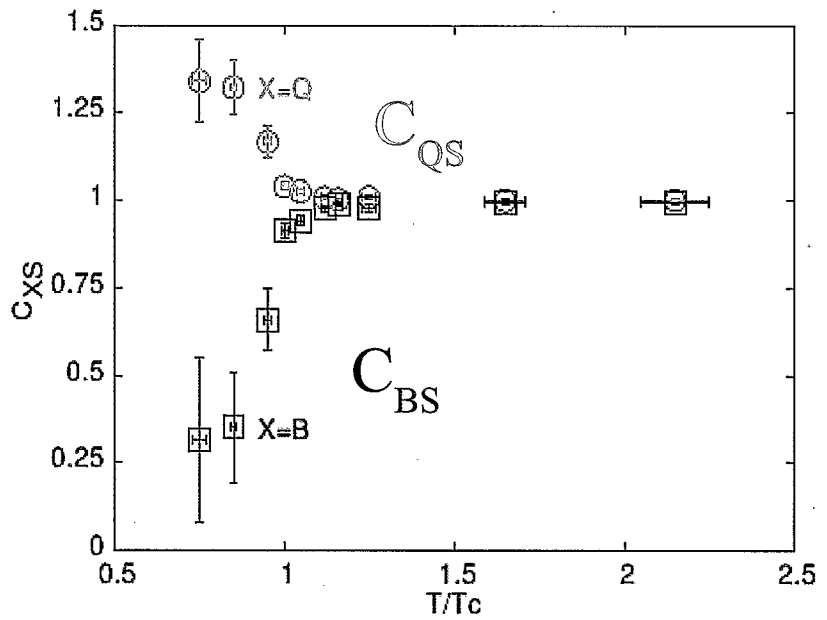
Something new: <BS> , <QS>

Independet quarks and
LATTICE QCD for T>1.1T_c

Bound state
QGP



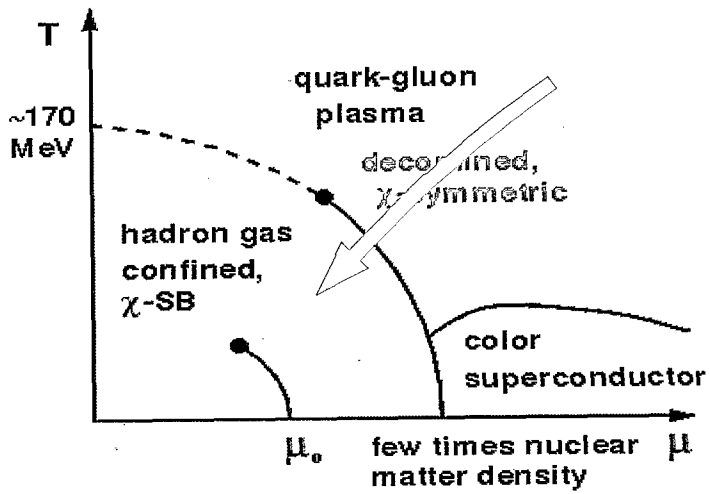
$$C_{QS} = -3\frac{\langle QS \rangle}{\langle S^2 \rangle}$$



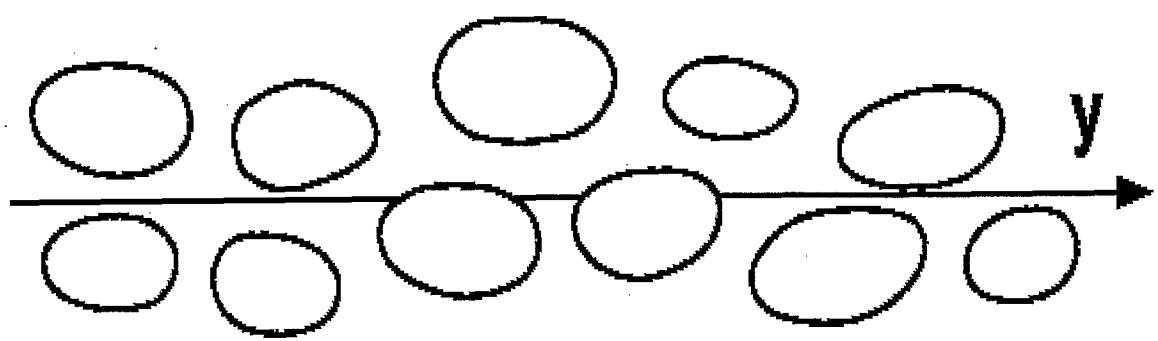
V.K, Majumder, Randrup PRL95:182301,2005

Gavai,Gupta, hep-lat/0510044

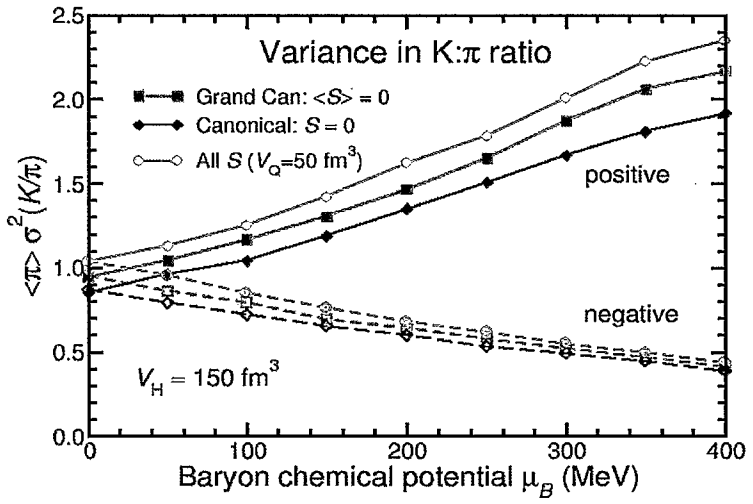
Spinodal breakup

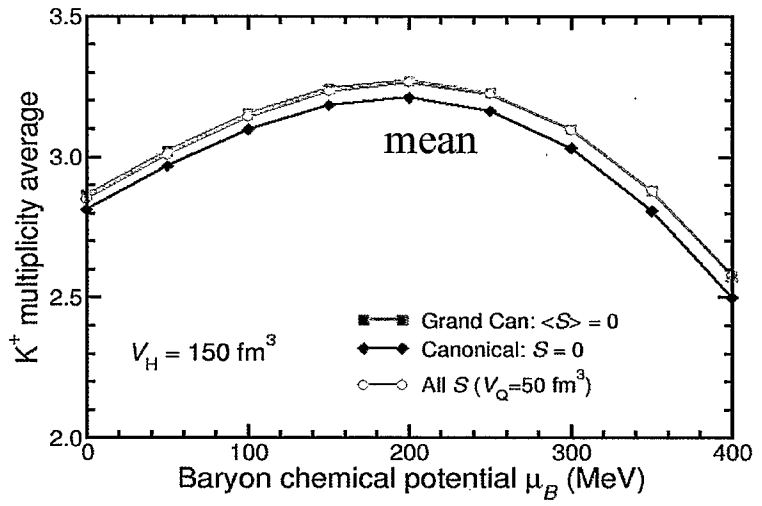


Spinodal decomposition:
- general phenomenon
- dynamical process
- typical "blob" size
  - depends on details of interaction



Strangeness and spinodal breakup





Variance: enhanced by ~10 %

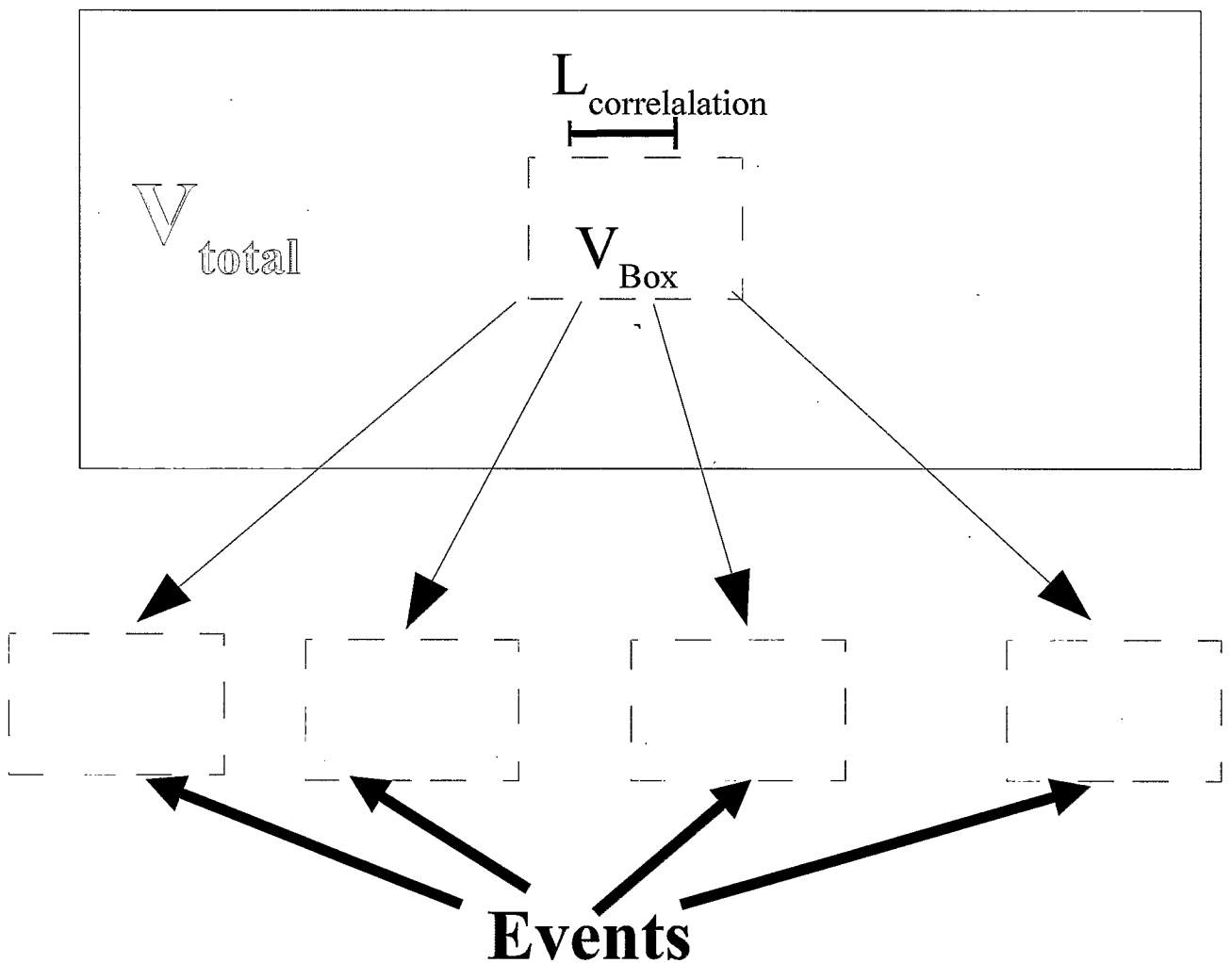
$V_{QGP} = 50\ fm^3$

$V_{hadron} = 150\ fm^3$

$T = 170\ MeV$

Generally: variance is more enhanced than mean

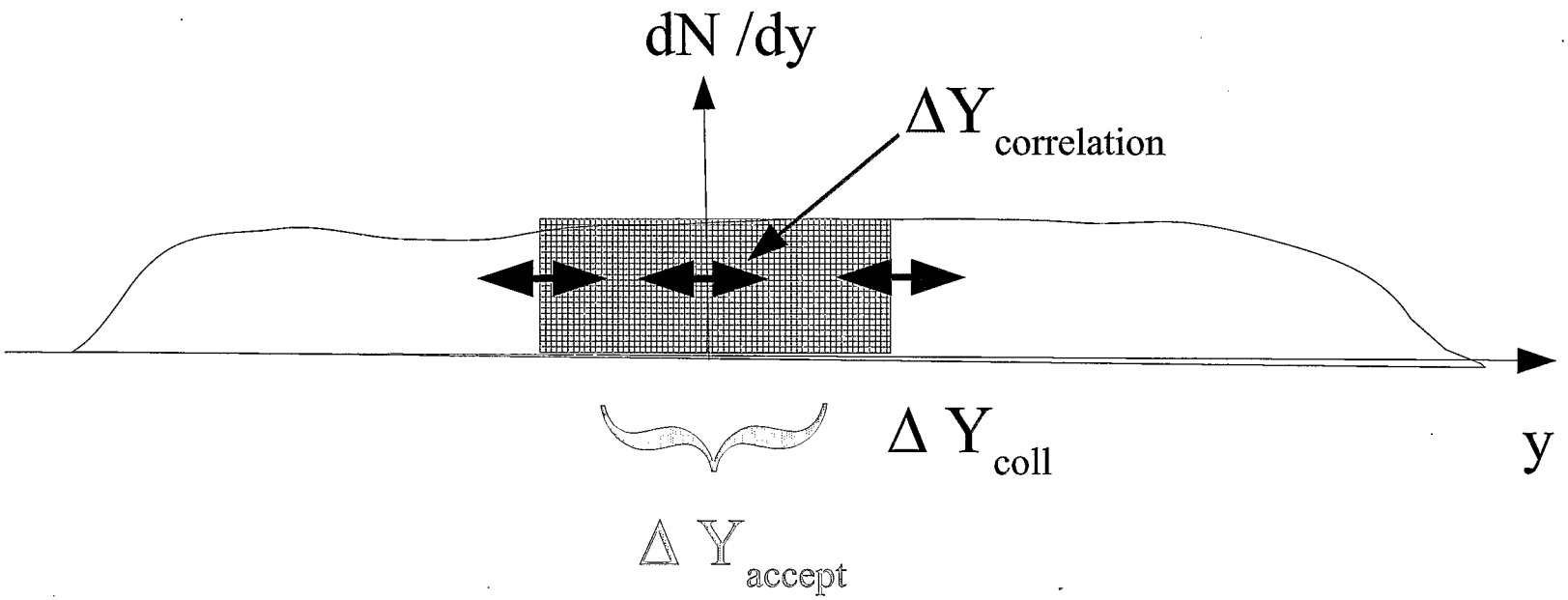
"Charge" Fluctuations



$V_{box} << V_{total}$

$L_{correlation} << V_{box}^{1/3}$

“Charge” fluctuations



Condition for “charge” fluctuations:

1) $\Delta Y_{corrrelation} << \Delta Y_{accept}$

3) $\Delta Y_{total} >> \Delta Y_{accept} >> \Delta Y_{coll}$

Strangeness and Phase Changes in Relativistic Heavy Ion Collisions

QCD Critical Point BNL-9/10 March, 2006, Presented by J. Rafelski

Strangeness flavor is the natural observable of the baryon-rich deconfined quark-gluon state of matter. We discuss here how deviation from chemical equilibrium of strangeness in QGP impacts phase structure. We show hoe one can interpret the NA49-Horn by allowing chemical nonequilibrium among hadrons.

1. MATTER-ANTIMATTER PRODUCTION MECHANISM
2. RISE OF STRANGENESS YIELD MOVES PHASE BOUNDARY $n_f = 2 + \gamma_s^{\rm QGP}$
3. THEORETICAL INTERPRETATION OF THE NA49 'HORN'
4. PHYSICAL PROPERTIES OF THE FIREBALL

See also nucl-th/0504028, nucl-th/0511016 by J.Letessier and J.Rafelski

---

Supported by a grant from the U.S. Department of Energy, DE-FG02-04ER41318

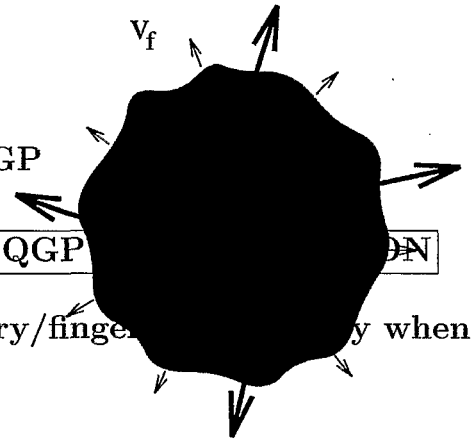
1. MATTER-ANTIMATTER PRODUCTION MECHANISM

For the past 15 years experiments demonstrate symmetry of $m_\perp$ spectra of strange baryons and antibaryons in baryon rich environment.

Interpretation: Common matter-antimatter particle formation mechanism, little antibaryon re-annihilation in sequel evolution.

Appears to be free-streaming particle emission by a quark source into vacuum. Such fast hadronization confirmed by other observables: e.g. reconstructed yield of hadron resonances. Note: within HBT particle correlation analysis: nearly same size pion source at all energies

Practically no hadronic 'phase'!
No 'mixed phase' either!
Direct emission of free-streaming
hadrons from exploding filamentary QGP



Develop analysis tools viable in SUDDEN QGP [illegible]ON

Proposed reaction mechanism: filamentary/finge[illegible]y when in expansion pressure reverses.

SUDDEN HADRONIZATION DOES NOT APPLY TO LOW $\sqrt{s}$

We only have evidence for sudden hadronization at reaction energies ABOVE the horn. It is likely that at $\sqrt{s}$ below the horn hadronization is NOT SUDDEN. To test for this RHIC-critical should measure asymmtry of spectra of strange baryons and antibaryons. Recall that in NN reactions spectra of baryons B, and antibaryons $\overline{B}$ are completely different.

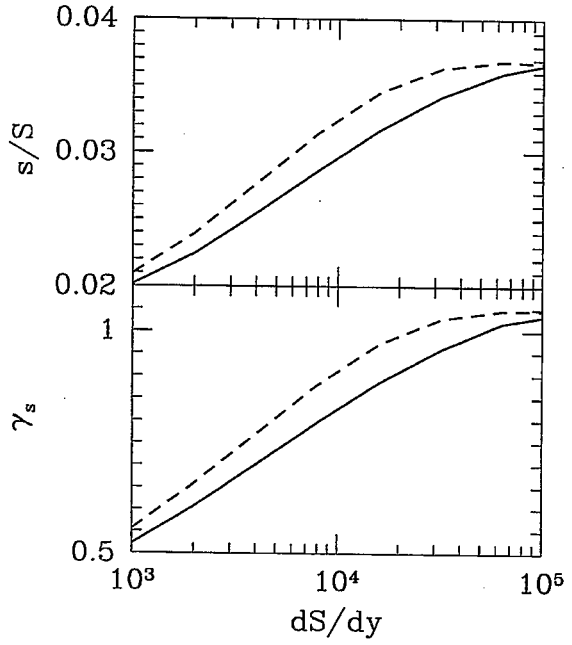
2. RAPID RISE OF STRANGENESS YIELD MOVES PHASE BOUNDARY

Temperature of phase transition depends on available degrees of freedom

- For 0 flavor theory $T > 200$ MeV
- For 2 flavors: $T \to 170$ MeV more importantly 1st order turns into 2nd order
- For 2+1 flavors: $T = 162 \pm 3$ and appearance of minimum μ_B we need extra quarks to reach a 1st order transition
- For 3, 4 flavors further drop in T.

At low heavy ion reaction energy low value of γ_s and thus effectively 2 flavor phase limit. This means we need a much greater μ_B to reach the tri-critical point. An easy way to test for this using QCD lattice is to consider large values of m_s and see how the value of $\mu_b^{\rm cr}$ moves as function of m_s.

A first look at energy dependence



Solid, bulk QGP expansion, dashed donut expansion.

Since the main parameter controlling the reaction energy dependence is the value of entropy (hadron multiplicity) produced, this model calculation shows that in QGP γ_s changes rapidly – diminishing with decreasing entropy and thus energy content.

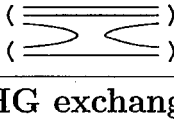
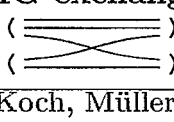
3. INTERPRETATION OF THE NA49 'HORN'

First there is a fast rise of strangeness yield which on the other side of the horn is rivaled by faster rise of entropy. In order to be able to describe the behavior of the horn we thus must have both γ_s, γ_q

ANALYSIS OF DATA: STATISTICAL HADRONIZATION

Fermi (micro canonical)-Hagedorn (grand / canonical) particle 'evaporation' from hot fireball:particles produced into accessible phase space, yields and spectra thus predictable.

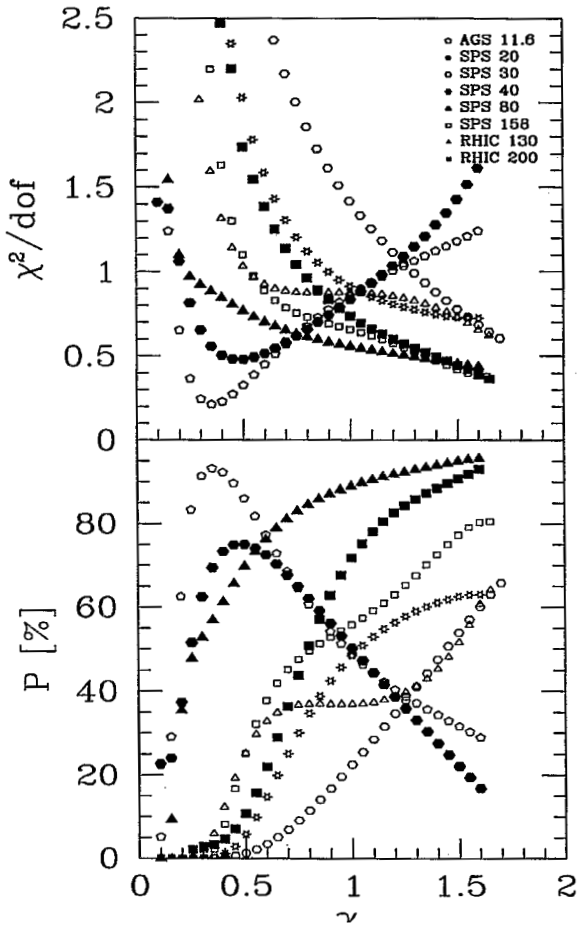
FOUR QUARKS: $s, \overline{s}, q, \overline{q} \rightarrow$ FOUR CHEMICAL PARAMETERS

γ_i controls overall abundance of quark ($i = q, s$) pairs	Absolute chemical equilibrium	HG production 
$\lambda_i = e^{\mu_i/T}$ controls difference between strange and light quarks ($i = q, s$)	Relative chemical equilibrium	HG exchange 

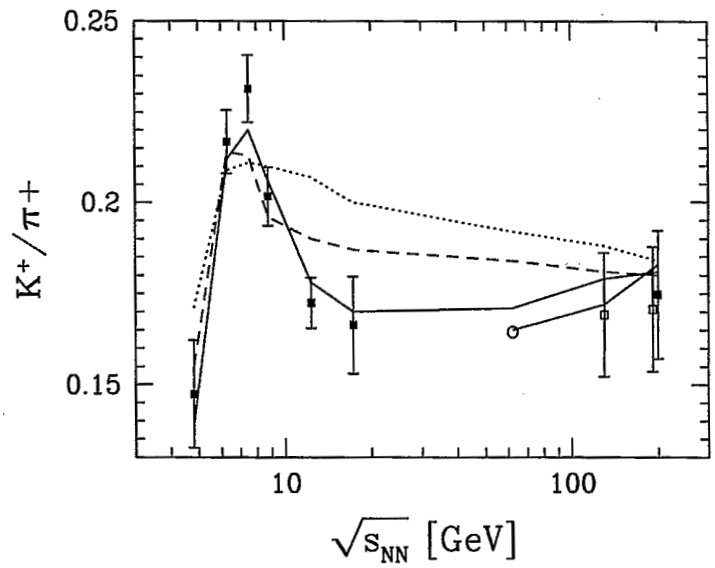
See Physics Reports 1986 Koch, Müller, JR

Boltzmann gas: $\gamma \equiv \frac{\rho(T,\mu)}{\rho^{\rm eq}(T,\mu)}$

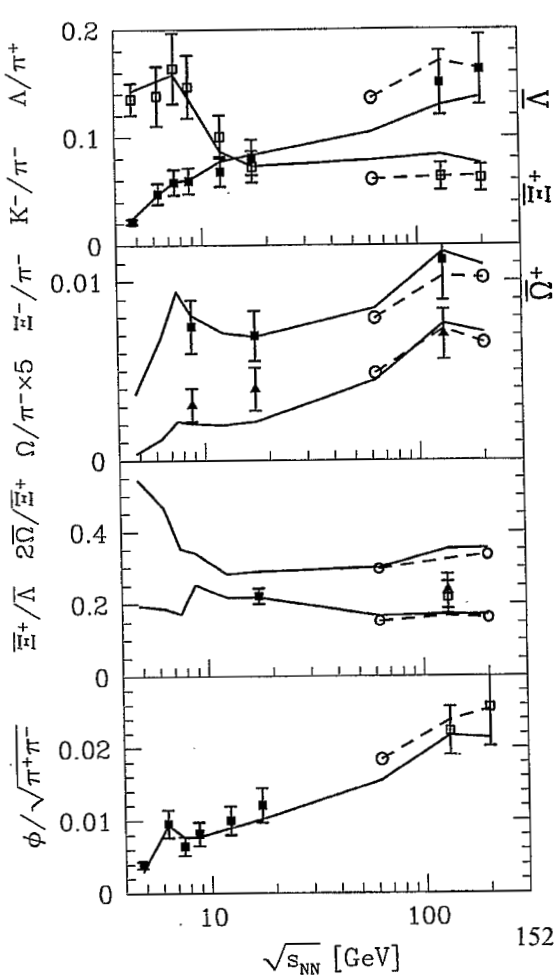
Fit particle yields at every energy: WE DESCRIBE THE HORN

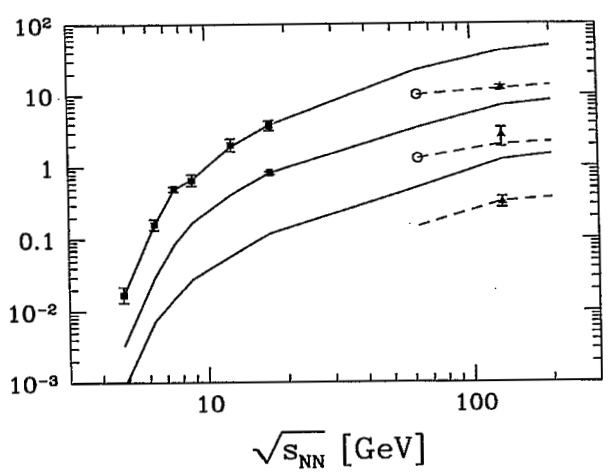


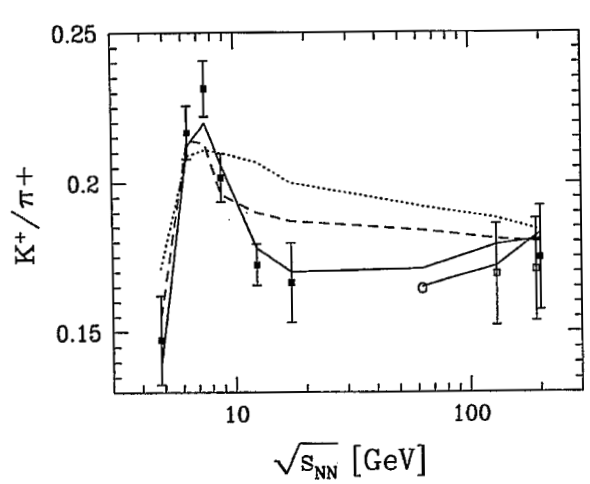
Allowing chemical nonequilibrium we see that between 20 and 30GeV the fit jumps from highly unsaturated to fully saturated: from $\gamma_q < 0.5$ to $\gamma_q > 1.5$. This produces the horn (below). The fits have reasonable quality, in particular those relevant to understanding how the horn is created. ENTROPY DENSITY SURGES



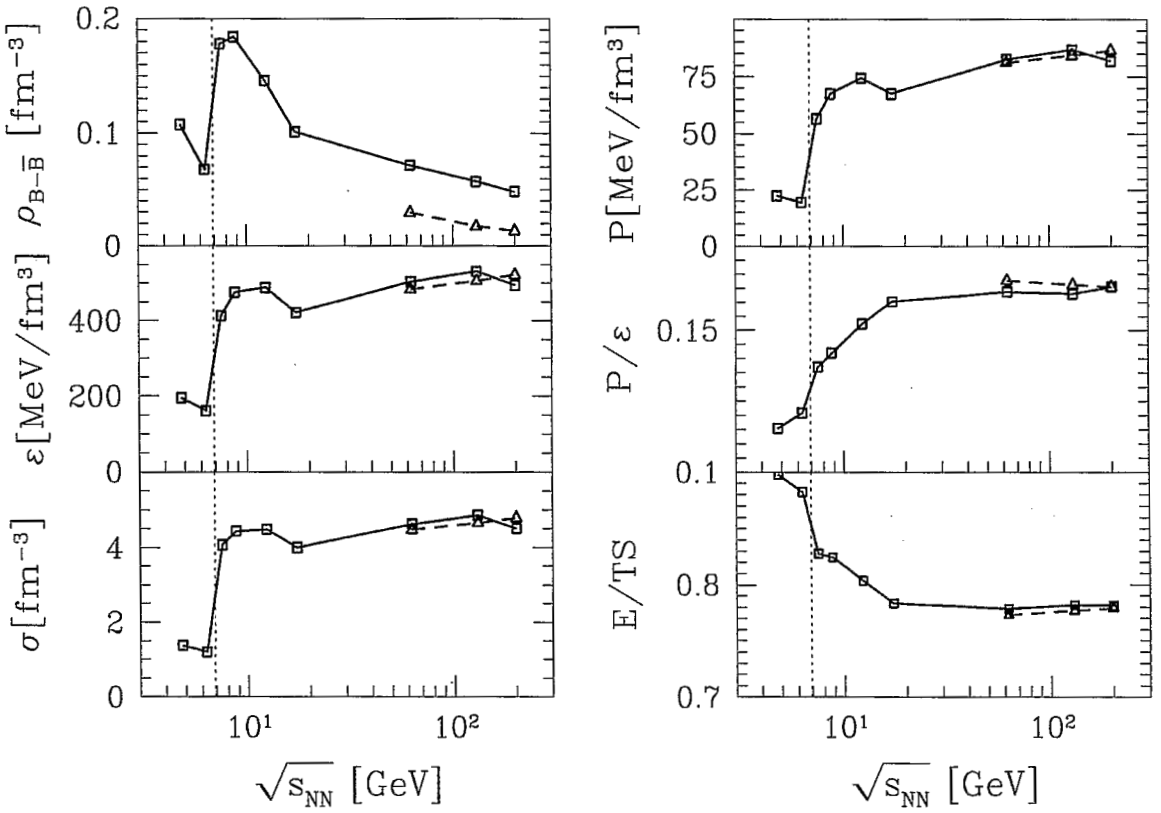
Particle yield systematics





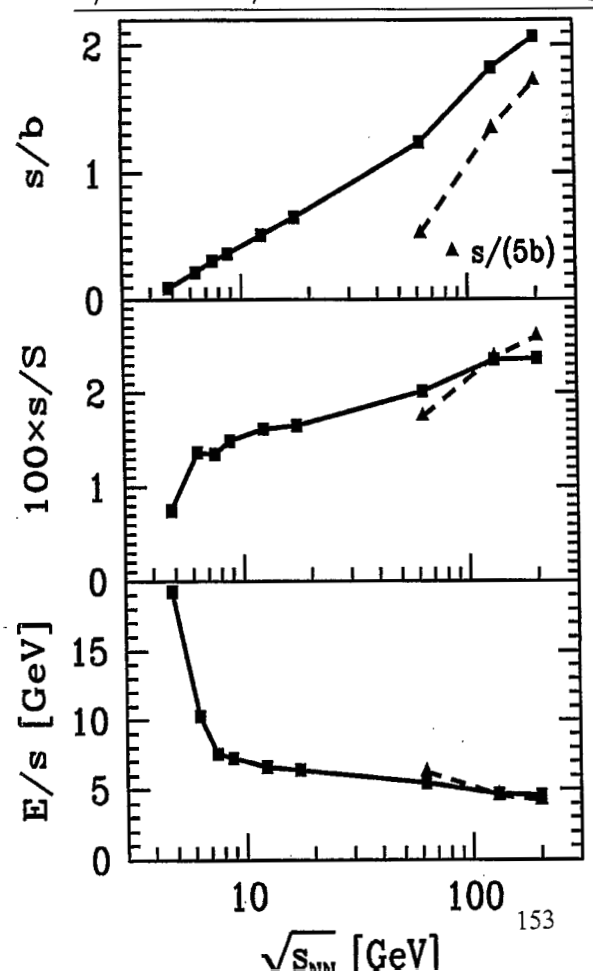


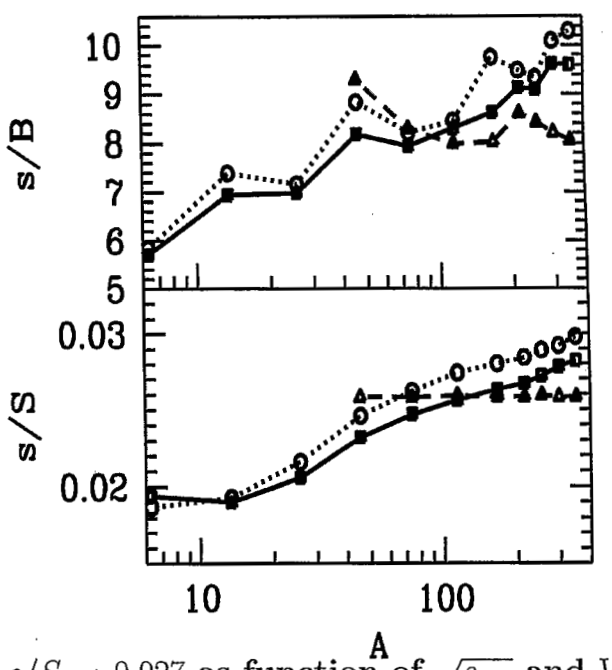
4. PHYSICAL PROPERTIES OF THE FIREBALL



Note the large jumps by factor 2–3 in densities (to left) and pressure (on right) as the collision energy changes from 20 GeV to 30 GeV. There is clear evidence of change in reaction mechanism. There no difference between top SPS and

s/b and s/S rise with energy and centrality E/s falls

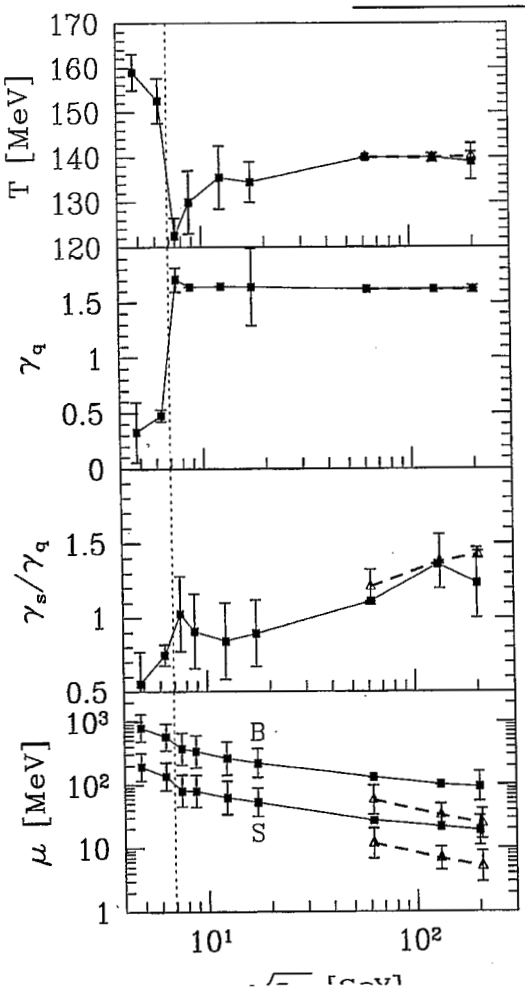


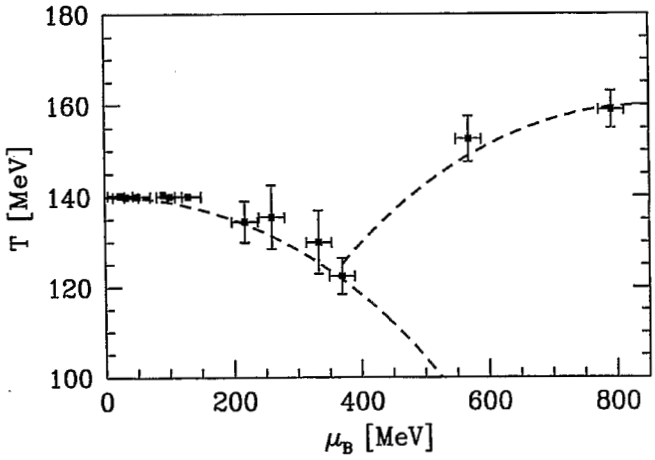


$s/S \to 0.027$ as function of $\sqrt{s_{NN}}$ and V: INITIAL QGP!

Energy/strangeness breaks at $\sqrt{s_{NN}^{cr}}$
Different cost → different mechanism!

Statistical parameters

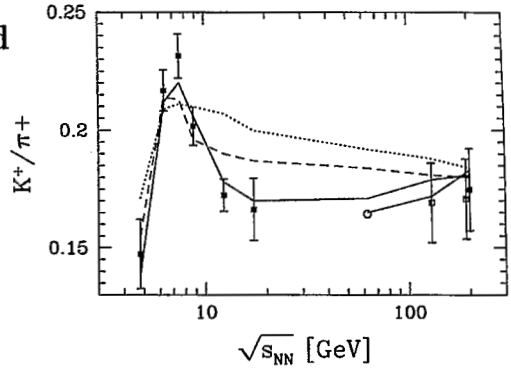




STRANGENESS, ENTROPY, THE HORN, AND QGP DISCOVERY

1. Strange hadrons probe phase properties and phase dynamics; additional task: measure (multi) strange baryons and antibaryons.
2. Deconfinement in baryon rich phase influenced by presence of the third flavor, QCD matter system exceptionally fine tuned.
3. Full analysis of energy excitation functions and centrality dependence is now available
4.

   Structure between 20 and 30 GeV understood within chemical nonequilibrium model, same type of sudden behavior change as is seen in centrality dependence.

   The gambler and his horn

5. Two different phases hadronize - see phase diagram.
   - At high energy and volume, an entropy rich phase with the count of degrees of freedom expected from QGP ($s/S \to 0.027$).
   - At low collision energy we find a high energy cost to produce strangeness, and phase space under-saturated
6. At high energy and volume as expected if QGP fireball: strangeness nearly equilibrated at hadronization. Overpopulates HG phase space.

Can we discover the first-order phase transition at RHIC?

Jørgen Randrup, LBNL

This presentation addresses two issues of key relevance to the prospects for probing the first-order hadronization phase transition in nuclear collision experiments.

1) The well-established hadronic freeze-out exhibits a systematic dependence on the collision energy. At the current beam energies at RHIC the temperature is high while the net baryon density is very small. As the beam energy is lowered, the baryon density increases (while the temperature decreases only slowly) until it reaches a maximum value and it then drops back towards zero. On the basis of established fits to data taken in various energy regimes (at different facilities), one is led to the expectation that the maximum freeze-out density is obtained for RHIC beam energies of 3-5 GeV per nucleon (corresponding to beam kinetic energies of 15-50 GeV/N for a stationary target).

2) In order to probe the first-order phase transition, it is necessary to bring the bulk of the system into the region of phase coexistence. Using results obtained with a number of different dynamical models in conjunction with simple estimates of the phase boundaries, we have sought to determine the most suitable beam energies for this purpose. Remarkably, the different dynamical models yield rather similar phase trajectories, when these are expressed in terms of the net baryon density and the total energy density, and the results suggest that the optimal RHIC beam energies would be 2-4 GeV/N (corresponding to beam kinetic energies of 5-30 GeV/N for a stationary target).

Can We Discover the QCD Critical Point at RHIC ?

RIKEN BNL Research Center Workshop...

March 9-10, 2006 at Brookhaven National Laboratory

Can we discover the first-order phase transtion at RHIC?

Jørgen Randrup

LBNL

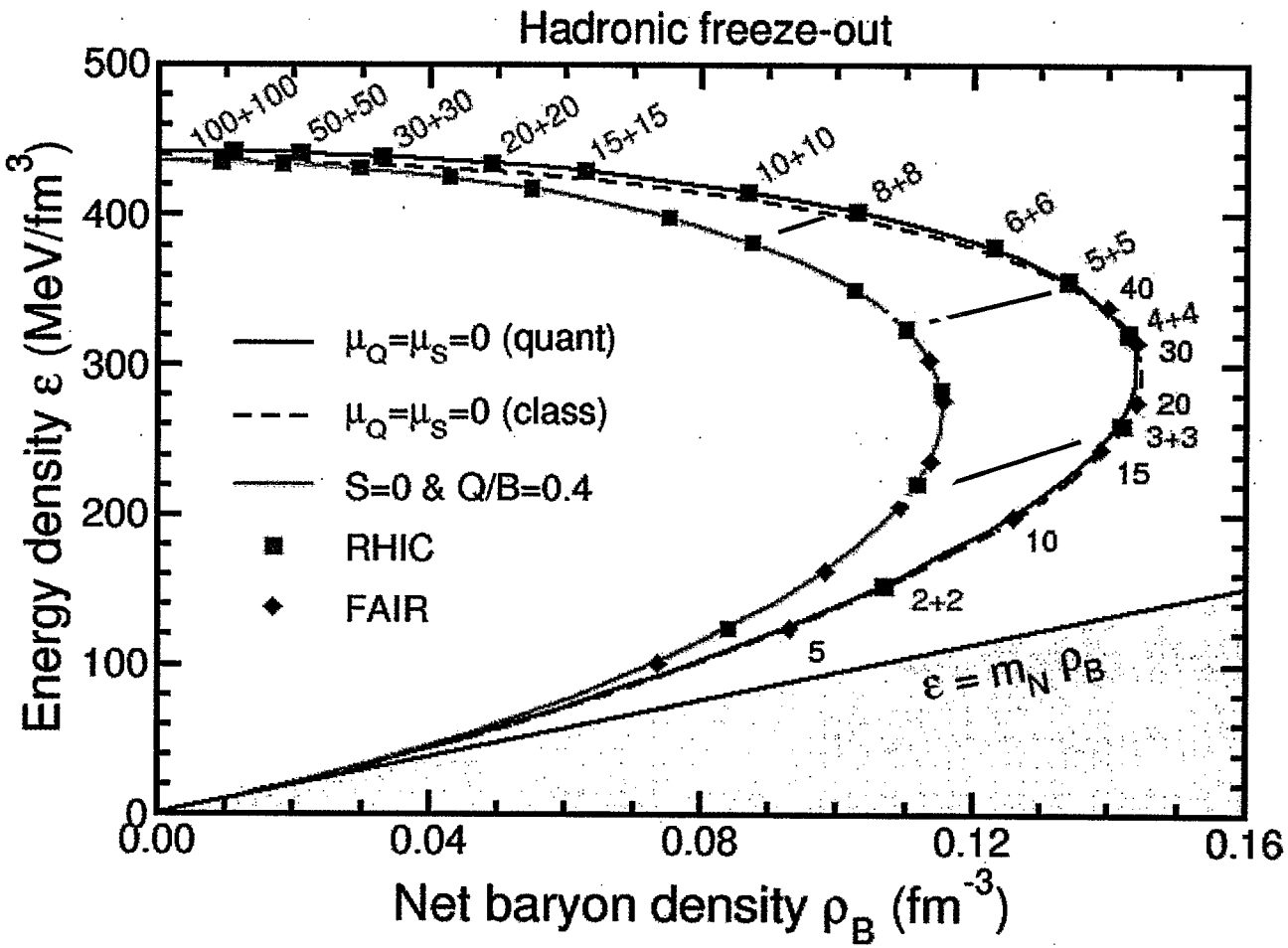
1) Hadronic freeze-out: maximum baryon density

2) Phase coexistence region: how to get there?

BNL 9-10 March 2006

[Randrup & Cleymans]

Energy density: $\varepsilon(T,\{\mu\}) = -\dfrac{\partial \ln \mathcal{Z}}{\partial \beta}$



Baryon density: $\rho_B(T,\{\mu\}) = T\,\dfrac{\partial \ln \mathcal{Z}}{\partial \mu_B}$

μ, T versus ρ, ε

Temperature: $T = 1/\beta$

Chemical potentials: μ_B, μ_Q, μ_S

... are *not* order parameters:
$p(\mu,T)$ is multi-valued

... do *not* obey conservation laws:
can change spontaneously

... exist *only* in equilibrium

Energy density: ε

Charge densities: ρ_B, ρ_Q, ρ_S

... *are* order parameters:
$p(\varepsilon,\rho)$ is single-valued

... *do* obey conservation laws:
$$\partial_\mu T^{\mu\nu} = 0 \ , \ \ \partial_\mu j^\mu = 0$$

... *always* exist

=> are well suited for dynamics

Contributors (so far):

3-fluid: *Yuri Ivanov et al.*

PHSD: *Wolfgang Cassing et al.*

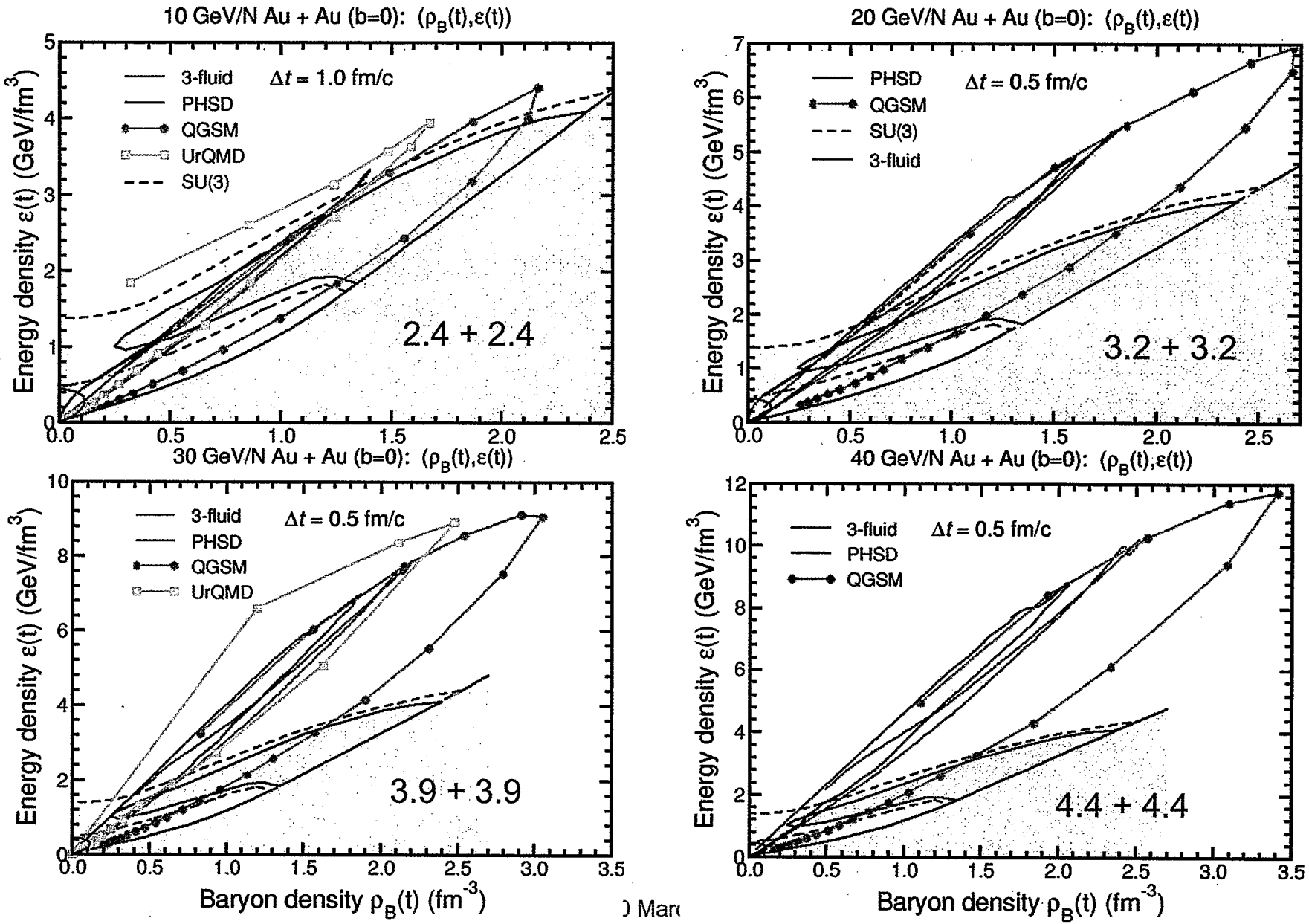
QGSM: *Viatchelav Toneev* et al.

UrQMD: *Ionut Arsene, Larissa Bravina et al.*

SU(3): *Gebhard Zeeb & Detlef Zchiesche* (adiabatic expansion)

... plus in contact with others (the more the merrier)

Dynamical trajectories in the ρ - ε phase plane



) Mar

v1- & v2-Flow: BAROMETRY @ HiMu-RHIC
— pinning down the Order of the Phase Transition

Horst Stöcker, FIAS Frankfurt Institute for Advanced Studies and ITP,
Barbara Betz Gebhard Zeeb
in Collaboration with: Marcus Bleicher Adrian Dumitru Kerstin Paech (now NSCL, MSU)
Hannah Petersen Dirk Rischke Stefan Schramm (also CSC, Frankfurt) Detlef Zschiesche
ITP Institute for Theoretical Physics, Frankfurt University
Elena Bratkovskaya (FIAS-Junior Fellow), Xianglei Zhu (FIGSS-Student, also Tsinghua Univ.)

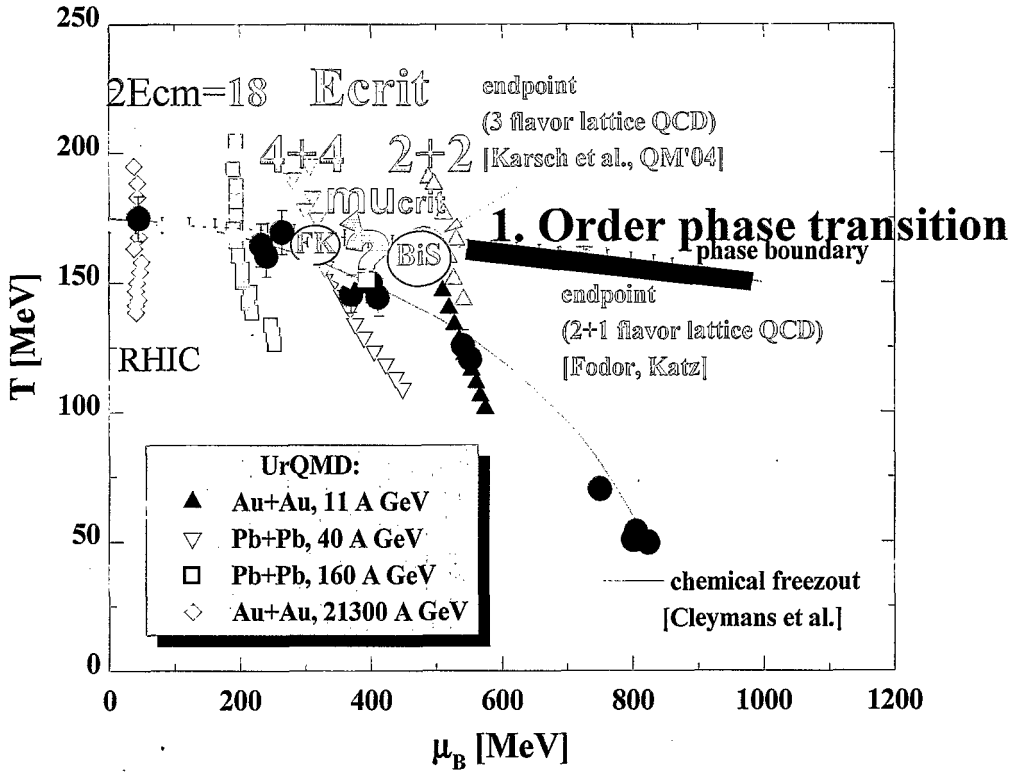
1 Outreach to hi-mu=300 - 600MeV@HiMu-RHIC
2 v1, v2- Flow change sign at critical point:
  1. & 2. Order Phase Transition (T, mu)-critical
3 v1 Bounce-Off Excitation Fct. Collapse @ 40 AGeV
4 v2 Squeeze-Out Exc. Fct.: 2+2 to 8+8 AGeV
5 Machshock-angles measure speed of sound:
  The case for asymmetric collisions

Horst Stöcker, RIKEN BNL Research Center Workshop, March 10, 2006

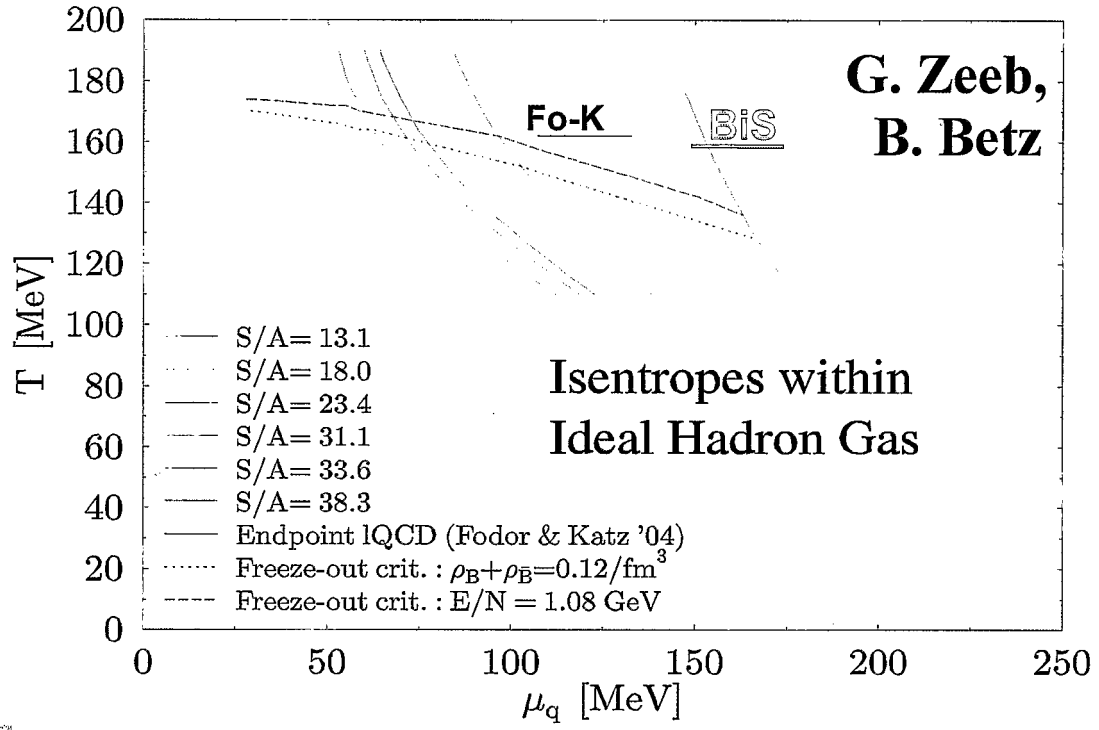
Time-Evolution UrQMD

◦RHIC-Time evolution in T-Mu_B Plane

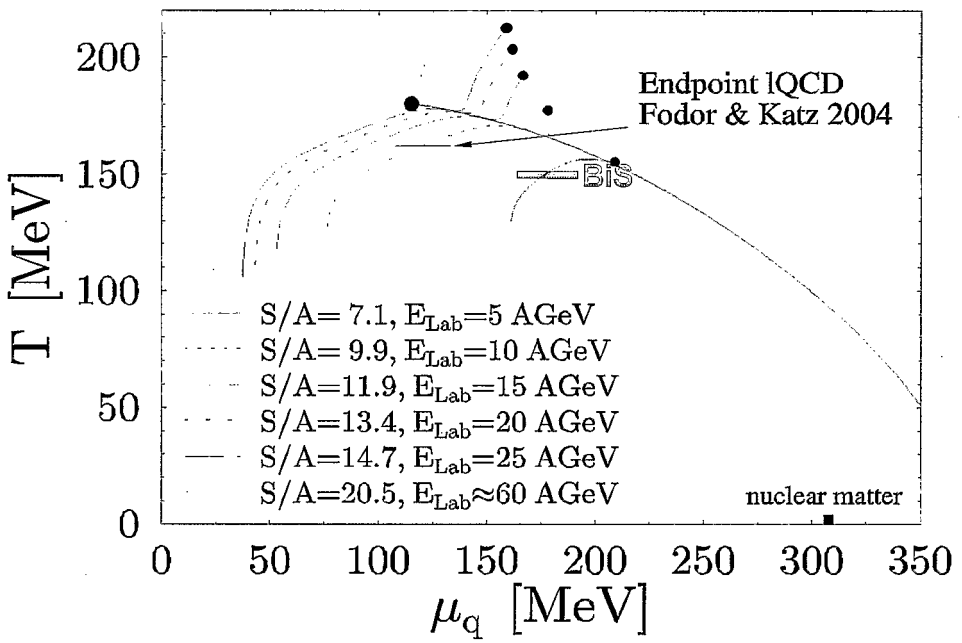
UrQMD Bravina - looks thermal after 5 fm/c!



◦Ideal Hadron Gas: mu-crit@S/A=13-18!

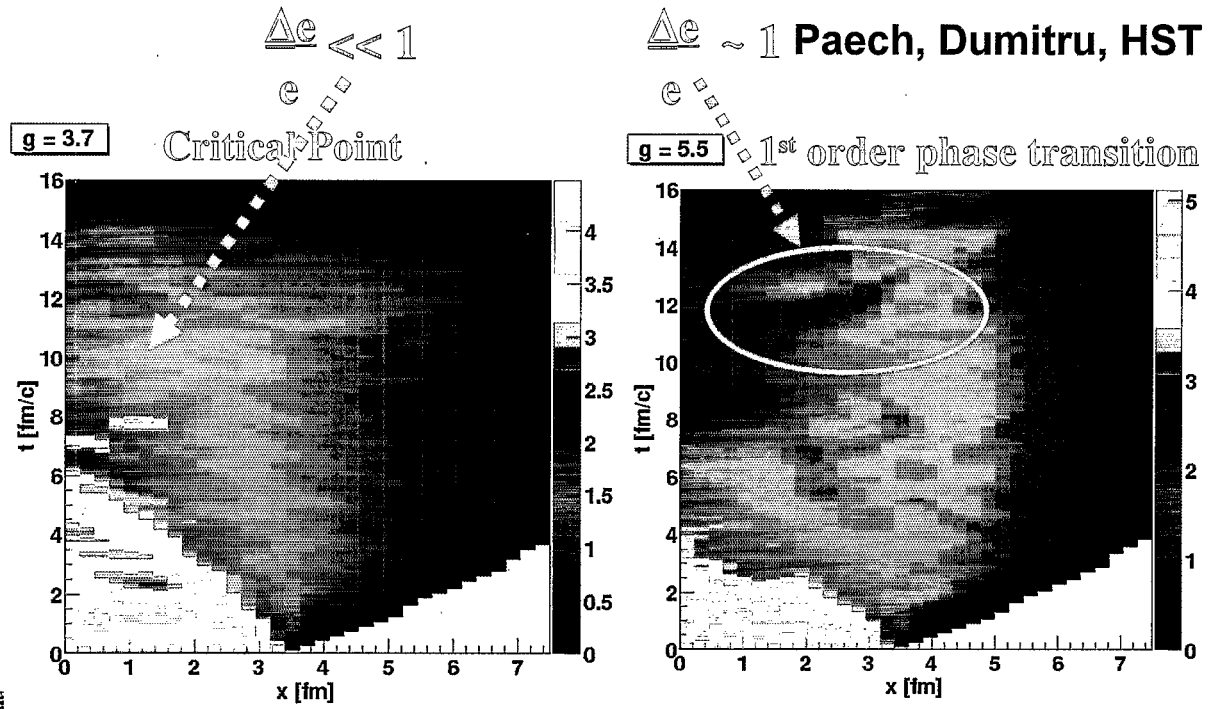


◦IG-Results differ strongly from Chiral SU(3) hadron model mu-crit@S/A=7-10!



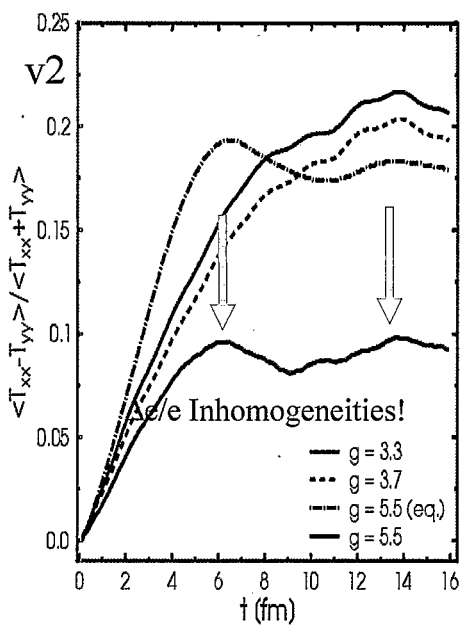
D.Zschiesche, G.Zeeb, S.Schramm `nucl-th/0602073`

◦Huge Fluctuations in Energy-(Baryon-?) Density

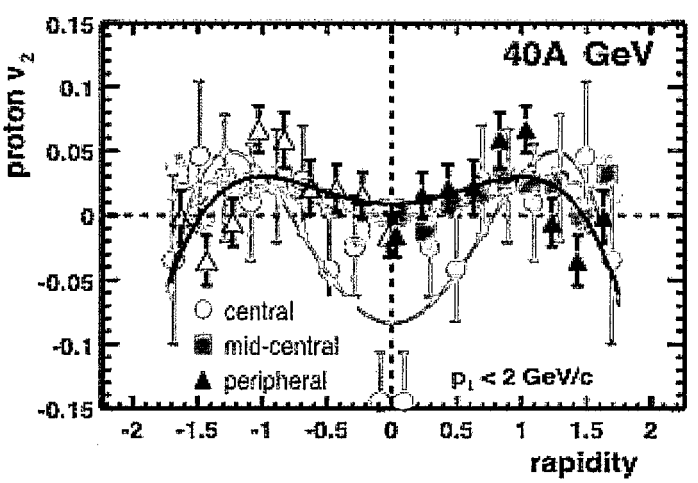


◦V_2 : Fluctuations and Exitation Fct.

Paech+Dumitru



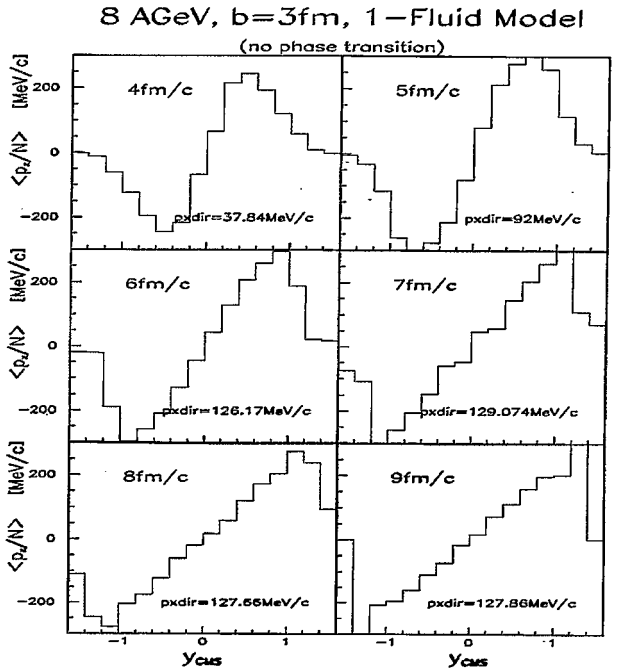
NA49 PRC C68 034903 (2003)



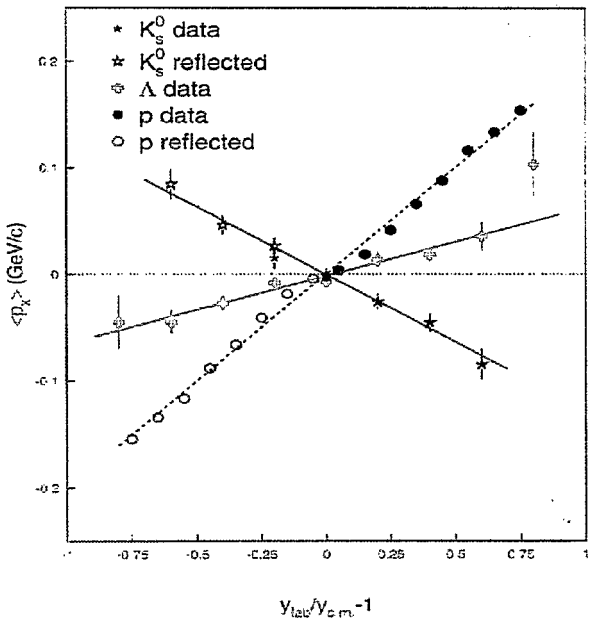
Collapse of proton flow at 40AGeV?
provides universal scaling

◦ Flow v1=px/pt

Brachmann, Paech, Dumitru

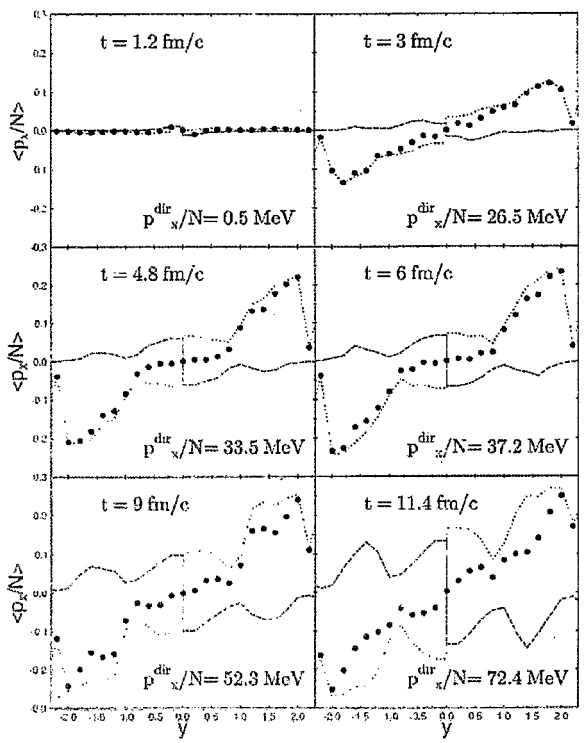


6 AGeV (E895)



◦E_Lab > 40 A GeV - above critical point...

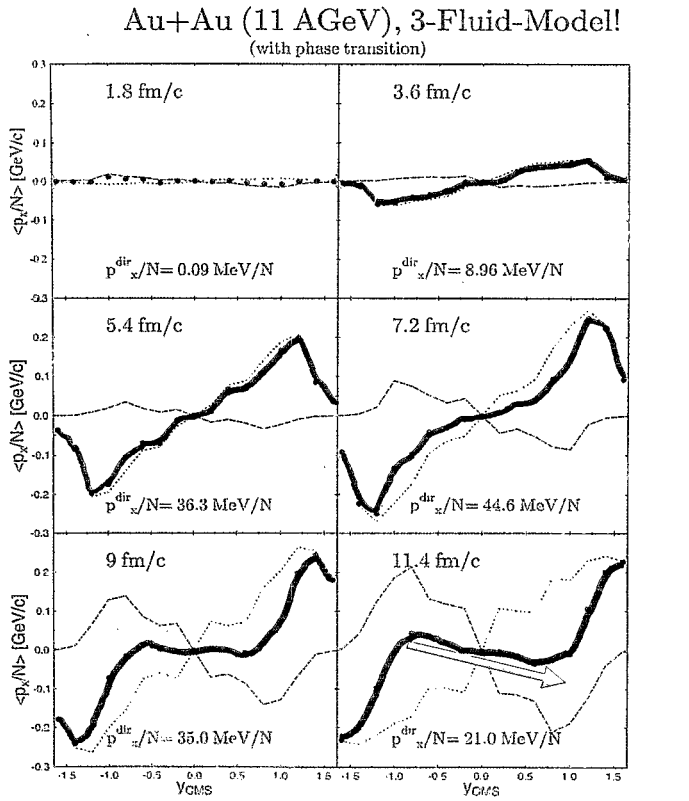
mu < mu-crit: NO PT-> crossing! Recover Positive v1-Flow!



Directed Flow

- hydro higher E: mu > mu-crit: 1.order transition line crossed -> Negative v1-flow = Anti-Flow of protons at > 11 AGeV

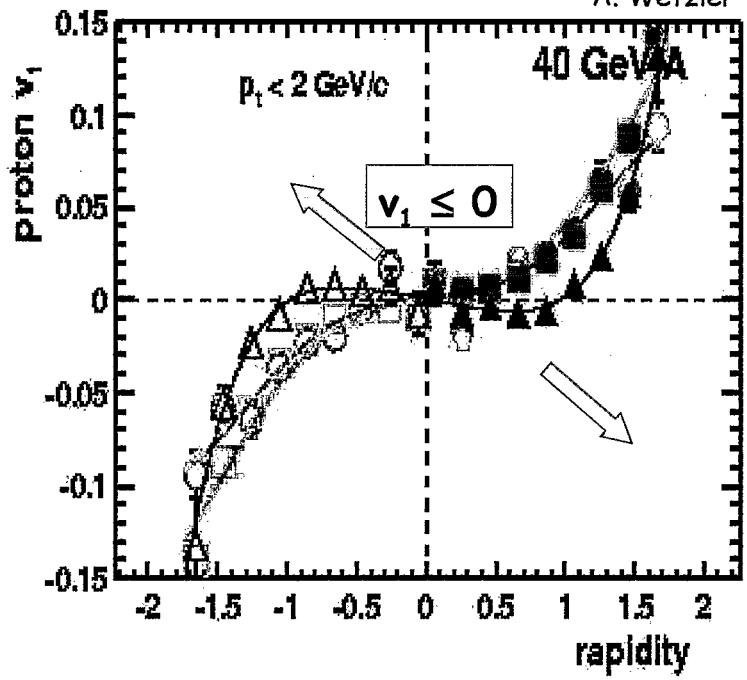
It is in the protons !



Proton "Anti-Flow" observed in Pb+Pb@ 40AGeV by NA49 ?

NA 49 Preliminary

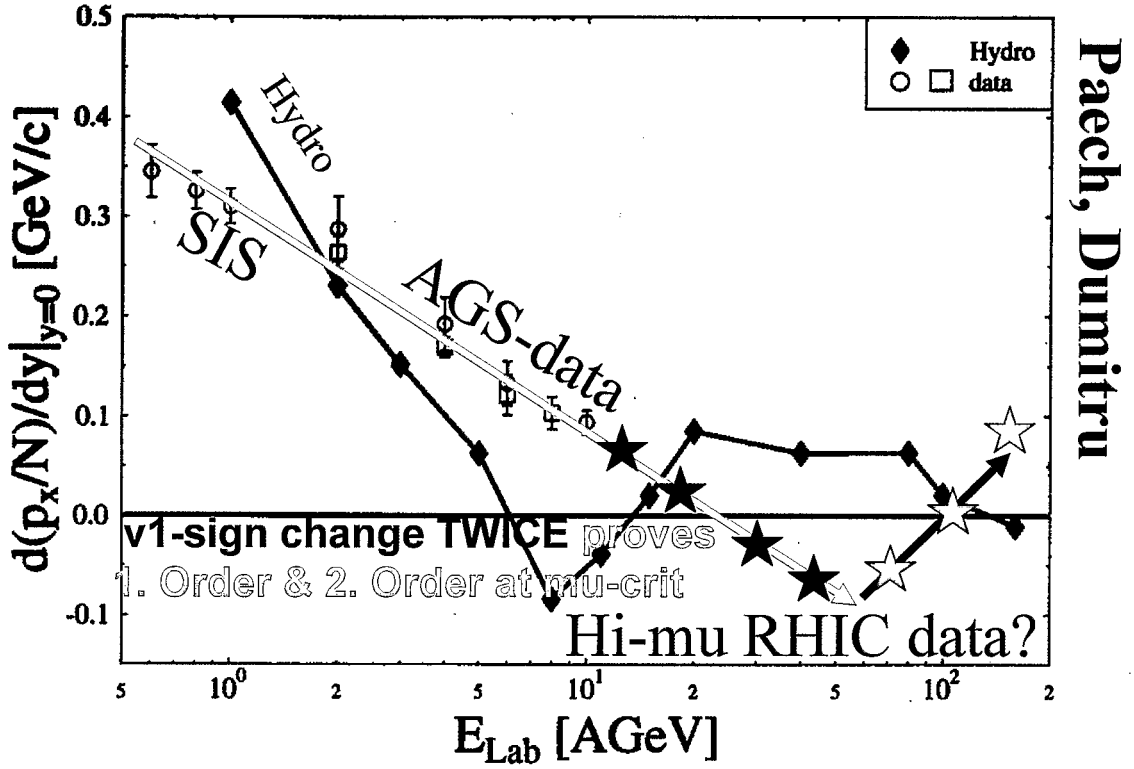
A. Wetzler



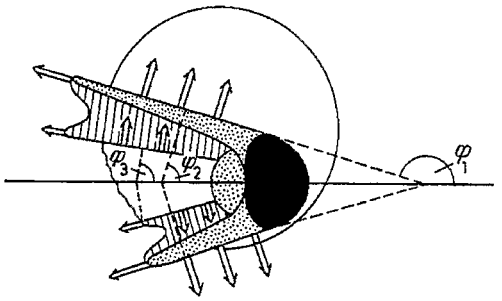
"Anti-Flow" discovered! -> 1. Order Phase Transition!

◦V1 proton 3DHydro: PROTONAnti-Flow FAIR, Hi-muRHIC

Extrapol. Data: Anti-Flow@20-40AGeV: Hi-muRHIC DATA!

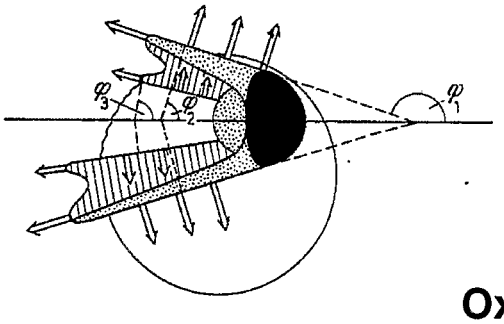


◦ Hi-mu Mach shock cones compress nuclei
-the case for asymmetric collisions



Baumgardt, Schott, Sakamoto, Schopper, Stöcker, Hofmann, Scheid, Greiner, Z. Phys. A273 (1975) 359

$$\varphi_2 = \arccos \frac{v_{Mach\,s.w.}}{v_{Head\,s.w.}}$$



$$v_{Mach\,s.w.} \approx 3\,c_s \approx 0.57\,c \quad (K = 300\,MeV)$$
$$v_{Head\,s.w.} \approx 0.95\,c \quad (E_{Lab} = 21\,AGeV)$$

$$\Rightarrow \quad \varphi_2 \approx 0.93\,rad \approx 53\,°$$

Oxygen cause Mach cone in Nuclei

Can We Discover the QCD Critical Point at RHIC?

March 9-10, 2006
Physics Department Large Seminar Room
(Registered Participants as of March 6, 2006)

Name	Affiliation	E-Mail Address
Nikos Antoniou	University of Athens	nantonio@phys.uoa.gr
Harald Appelshaeuser	University of Frankfurt	appels@ikf.uni-frankfurt.de
Mark Baker	Brookhaven National Laboratory	mark.baker@bnl.gov
Peter Barnes	Brookhaven National Laboratory	pdbarnes@bnl.gov
Adrian Cho	Science Magazine	acho@aaas.org
William Christie	Brookhaven National Laboratory	christie@bnl.gov
Angelika Drees	Brookhaven National Laboratory	drees@bnl.gov
Alexei Fedotov	Brookhaven National Laboratory	fedotov@bnl.gov
Zoltan Fodor	University of Wuppertal	fodor@bodri.elte.hu
Hiro Fujii	University of Tokyo	hfujii@phys.c.u-tokyo.ac.jp
Marek Gazdzicki	Frankfurt Univeristy and Swietokrzyska Academy	Marek.Gazdzicki@cern.ch
Stephen Gushue	ORYX Consulting, Inc.	gushue@buoy.com
Yoshitaka Hatta	RIKEN BNL Research Center	hatta@bnl.gov
Peter Jones	University of Birmingham	p.g.jones@bham.ac.uk
Frithjof Karsch	Brookhaven National Laboratory	karsch@bnl.gov
Volker Koch	Lawrence Berkeley National Laboratory	vkoch@lbl.gov
Mike Lisa	Ohio State University	lisa@mps.ohio-state.edu
Thomas Ludlam	Brookhaven National Laboratory	ludlam@bnl.gov
Zbigniew Majka	Jagiellonian Unversity	ufmajka@cyf-kr.edu.pl
Christina Markert	Kent State University	markert@star.physics.yale.edu
Larry McLerran	Brookhaven National Laboratory	mclerran@bnl.gov
Alice Mignerey	University of Maryland	mignerey@umd.edu
Jeffery Mitchell	Brookhaven National Laboratory	mitchell@bnl.gov
Agnes Mocsy	RIKEN BNL Research Center	mocsy@bnl.gov
Tapan Nayak	CERN	nayak@mail.cern.ch
Matthew Nguyen	SUNY Stony Brook	manguyen@bnl.gov
Chiho Nonaka	University of Minnesota	nonaka@physics.umn.edu
Shigemi Ohta	IPNS/KEK and RBRC/BNL	shigemiohta@mac.com
Johann Rafelski	University of Arizona	rafelski@physics.arizona.edu
Krishna Rajagopal	Massachusetts Institute of Technology	krishna@lns.mit.edu
Jorgen Randrup	LBNL	JRandrup@LBL.gov
Krzysztof Redlich	University of Wroclaw & CERN	redlich@ift.uni.wroc.pl
Hans Georg Ritter	LBNL/Univ. Heidelberg	hgritter@lbl.gov
Gunther Roland	Massachusetts Institute of Technology	rolandg@mit.edu
Tom Roser	BNL	roser@bnl.gov
Todd Satogata	Brookhaven National Laboratory	satogata@bnl.gov
Christian Schmidt	Brookhaven National Laboratory	cschmidt@bnl.gov
Kai Schweda	University of Heidelberg	kschweda@cern.ch
Peter Senger	GSI	p.senger@gsi.de
Peter Seyboth	Max-Planck-Institut fuer Physik	pxs@mppmu.mpg.de
Edward Shuryak	Stony Brook University	shuryak@tonic.physics.sunysb.edu
Paul Sorensen	Brookhaven National Laboratory	prsorensen@bnl.gov
Peter Steinberg	Brookhaven National Laboratory	peter.steinberg@bnl.gov
Misha Stephanov	University of Illinois at Chicago	misha@uic.edu
George Stephans	Massachusetts Institute of Technology	gsfs@mit.edu
Reinhard Stock	University of Frankfurt	stock@ikf.uni-frankfurt.de
Horst Stoecker	University of Frankfurt	stoecker@th.physik.uni-frankfurt.de
Terence Tarnowsky	Purdue University and Brookhaven National Lab	tjt@physics.purdue.edu
Nicholaos Tsoupas	Brookhaven National Laboratory	tsoupas@bnl.gov
Flemming Videbaek	Brookhaven National Laboratory	videbaek@bnl.gov
Nu Xu	Lawrence Berkeley National Laboratory	NXu@lbl.gov
Robert Zaballa	Georgia State University	rzaballa1@student.gsu.edu

Can We Discover the QCD Critical Point at RHIC?
March 9 – 10, 2006, Physics Department, Bldg. 510
Workshop Agenda

Thursday, March 9

8:30 – 9:00	*Registration*	
Chair: T. Ludlam		
9:00 – 9:10	Welcome	T. Ludlam (10)
9:10 – 9:50	Introduction and overview	K. Rajagopal (35+5)
9:50 – 10:25	Lattice results on the QCD critical point	F. Karsch (30+5)
10:25	*Break (15)*	
10:40 – 11:05	Fluctuations at the critical point	M. Stephanov (20+5)
11:05 – 11:40	Experimental overview & prospects for RHIC	G. Roland (30+5)
11:40 – 12:15	RHIC machine considerations	T. Satogata (30+5)
12:15	*Lunch*	
Chair: George Stephans		
1:30 – 2:00	Excitation function – NA 49 results	P. Seyboth (25+5)
2:00 – 2:30	Excitation function—onset of deconfinement	E. Shuryak (25+5)
2:30 – 2:50	Soft mode of the QCD critical point	H. Fujii (15+5)
2:50 – 3:10	Baryon number fluctuation near the critical point	Y. Hatta (15+5)
3:10	*Break (15)*	
3:25 – 3:55	Hydro evolution near the QCD critical point	C. Nonaka (15+5)
3:55 – 4:25	Future prospects for the CERN SPS	M. Gazdzicki (25+5)
4:25 – 5:00	Experiments with PHENIX near the critical point	P. Steinberg (25+10)
5:00 – 5:35	Experiments with STAR near the critical point	T. Nayak (25+10)
6:15	*Reception and dinner*	

Friday, March 10

Chair: F. Videbaek		
8:30 – 9:30	Low energy operation of RHIC: AGS low energy extraction performance	N. Tsoupas (15+5)
	Luminosity monitoring issues	A. Drees (15+5)
	Low energy electron cooling	A. Fedotov (15+5)
9:30 – 10:00	Energy dependence of temperature and baryochemical potential	K. Redlich (25+5)
10:00 – 10:25	Observable power laws at the QCD critical point	N. Antoniou (20+5)
10:25	*Break (15)*	
10:40– 11:10	The CBM experiment at FAIR	P. Senger (25+5)
11:10 – 11:35	Excitation function – experimental perspective	N. Xu (20+5))
11:35 – 12:00	Experience with CERES	H. Appelshauser (20+5)
12:00 – 12:25	Critical point at SPS energy?	R. Stock (20+5)
12:25	*Lunch*	
Chair: L. McLerran		
2:00 – 2:30	Lattice calculations at finite baryon potential	Z. Fodor (25+5)
2:30 – 3:00	Fluctuations and correlations	V. Koch (25+5)
3:00 – 3:25	Hadron production and phase changes	J. Rafelski (20+5)
3:25 – 3:45	Can we discover the first-order phase transition at RHIC?	J. Randrup (15+5)
3:45	*Break (15)*	
4:00 – 4:20	Signals of the first order phase transition	H. Stoecker (15+5)
4:20 – 5:30	Summary/discussion – prospects for experiments at RHIC	*Discussion Leaders* : H.-G. Ritter & T. Roser
5:30	*Adjourn*	

Additional RIKEN BNL Research Center Proceedings:

Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-

Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, December 12-14, 2005 – BNL-

Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649

Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005

Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005

Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005

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

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

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

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

Volume 69 – Review Committee – BNL-73546-2004

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Additional RIKEN BNL Research Center Proceedings:

Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560

Additional RIKEN BNL Research Center Proceedings:

Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299

Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559

Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116

Volume 10 – Physics of Polarimetry at RHIC – BNL-65926

Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762

Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634

Volume 7 – RHIC Spin Physics – BNL-65615

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

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

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

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

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

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

For information please contact:

Ms. Pamela Esposito
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

Phone: (631) 344-3097
Fax: (631) 344-4067
E-Mail: pesposit@bnl.gov

Ms. Jane Lysik
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

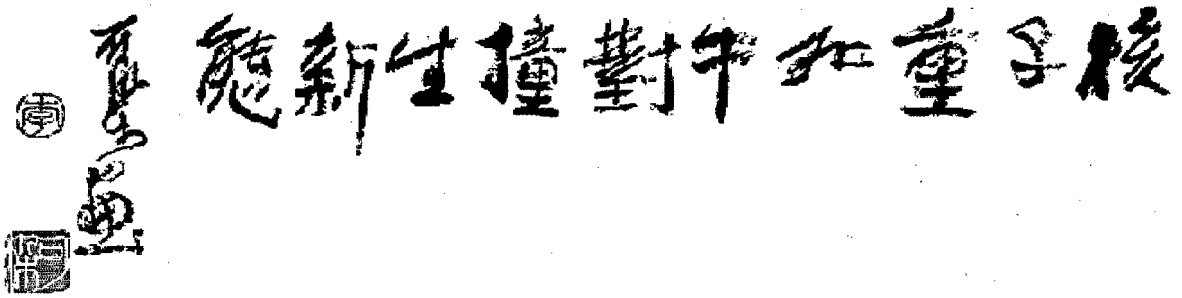
(631) 344-5864
(631) 344-2562
lysik@bnl.gov

Homepage: http://www.bnl.gov/riken

RIKEN BNL RESEARCH CENTER

Can We Discover the QCD Critical Point at RHIC?

March 9-10, 2006



Li Keran

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

Copyright©CCASTA

Speakers:

Nikos Antoniou	Harald Appelshaeuser	Angelika Drees	Alexei Fedotov	Zoltan Fodor
Hiro Fujii	Marek Gazdzicki	Yoshitaka Hatta	Frithjof Karsch	Volker Koch
Tapan Nayak	Chiho Nonaka	Johann Rafelski	Krishna Rajagopal	Jørgen Randrup
Krzysztof Redlich	Gunther Roland	Todd Satogata	Peter Senger	Peter Seyboth
Edward Shuryak	Peter Steinberg	Misha Stephanov	Reinhard Stock	Horst Stöcker
Nicholaos Tsoupas	Nu Xu			

Organizers: T. Ludlam, H. Ritter, G. Stephans, M. Gazdzicki, B. Friman, F. Videbaek, T. Satogata, K. Rajagopal, L. McLerran