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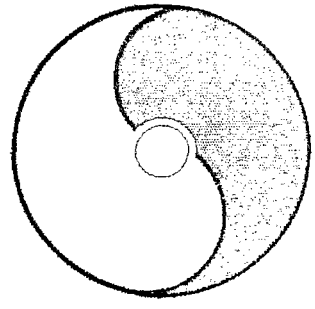
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 62

New Discoveries at RHIC

May 14-15, 2004



Organizers:

Wit Busza, MIT
Miklos Gyulassy, Columbia University
Larry McLerran, BNL

RIKEN BNL Research Center

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

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Preface to the Series

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

During the first year, the Center had only a Theory Group. In the second year, an Experimental Group was also established at the Center. At present, there are four Fellows and eight Research Associates in these two groups. During the third year, we started a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program, with six positions in the first academic year, 1999-2000. This program had increased to include ten theorists and one experimentalist in academic year, 2001-2002. With five fellows having already graduated, the program presently has eleven theorists and three experimentalists. Of these eleven RHIC Physics Fellows, five have been awarded/offered tenured positions, and this will be their final year in the program.

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 62 proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998. A 10 teraflops QCDOC computer in under development and expected to be completed this year.

N. P. Samios, Director
April 1, 2004

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

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Overview

The Strongly Interacting Quark Gluon Plasma and Future Physics

T. D. Lee

May 15, 2004 (RBRC/BNL)

Q E D

↓

Coulomb Interaction + Schroedinger Eq.

↓

- atomic and molecular physics
- condensed matter physics (superfluidity superconductivity, quantum Hall effect, ..)
- chemistry
- biology

Superconductivity and Superfluidity

1911 Kamerlingh Onnes : Superconductivity

1924 " " & Boks : λ transition of He

1924 Bose - Einstein transition

1938 Two Fluid Model of liquid He (F. London

1957 BCS Theory

late 1980's High T_c Superconductivity

- Knowing the Eq'n ≠ knowing the Solutions

QCD

↓

quarks, gluons and the strongly interacting QGP

↓

- QGP Physics and Dark Energy
- " " at LHC and beyond

QGP Physics and Dark Energy

TDL astro-ph/040-4601

Λ = cosmological constant :

its energy density is "negative", with

$$|\rho_\Lambda| \sim 3 - 7 \times 10^{-6} \text{ GeV/cm}^3$$

vs

the critical density ρ_c,

$$\rho_c \sim 1 \times 10^{-5} \text{ GeV/cm}^3$$

Questions : 1. <u>origin</u> of ρ_Λ

2. Why should ρ_Λ & ρ_c be the <u>same order of magnitude</u> ?

THE MEANING OF RELATIVITY

Third edition, revised, including
THE GENERALIZED THEORY OF GRAVITATION

By ALBERT EINSTEIN

INSTITUTE FOR ADVANCED STUDY

PRINCETON UNIVERSITY PRESS · 1950
PRINCETON NEW JERSEY

from First Edition
ceton U. Press (1922), based on 4 lectures
n in May 1921.

follows. Matter consists of electrically charged particles. On the basis of Maxwell's theory these cannot be conceived of as electromagnetic fields free from singularities. In order to be consistent with the facts, it is necessary to introduce energy terms, not contained in Maxwell's theory, so that the single electric particles may hold together in spite of the mutual repulsions between their elements, charged with electricity of one sign. For the sake of consistency with this fact, Poincaré has assumed a pressure to exist inside these particles which balances the electrostatic repulsion. It cannot, however, be asserted that this pressure vanishes outside the particles. We shall be consistent with this circumstance if, in our phenomenological presentation, we add a pressure term. This must not, however, be confused with a hydrodynamical pressure, as it serves only for the energetic presentation of the dynamical relations inside matter. In this sense we put

$$T_{\mu\nu} = g_{\mu\alpha}g_{\nu\beta}\sigma\frac{dx_\alpha}{ds}\frac{dx_\beta}{ds} - g_{\mu\nu}p. \tag{122}$$

In our special case we have, therefore, to put

$$\begin{aligned} T_{\mu\nu} &= \gamma_{\mu\nu}p \text{ (for } \mu \text{ and } \nu \text{ from 1 to 3)} \\ T_{44} &= \sigma - p \\ T &= -\gamma^{\mu\nu}\gamma_{\mu\nu}p + \sigma - p = \sigma - 4p. \end{aligned}$$

Observing that the field equation (96) may be written in the form

$$R_{\mu\nu} = -\kappa(T_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}T)$$

we get from (96) the equations,

$$\begin{aligned} +\frac{2}{a^2}\gamma_{\mu\nu} &= \kappa\left(\frac{\sigma}{2} - p\right)\gamma_{\mu\nu} \\ 0 &= -\kappa\left(\frac{\sigma}{2} + p\right). \end{aligned}$$

motion of the stars. One can arrange it so that the mean velocity of matter relative to this system shall vanish in all directions. There remain the (almost random) motions of the individual stars, similar to the motions of the molecules of a gas. It is essential that the velocities of the stars are known by experience to be very small as compared to the velocity of light. It is therefore feasible for the moment to neglect this relative motion completely, and to consider the stars replaced by material dust without (random) motion of the particles against each other.

The above conditions are by no means sufficient to make the problem a definite one. The simplest and most radical specialization would be the condition: The (naturally measured) density, ρ of matter is the same everywhere in (four-dimensional) space, the metric is, for a suitable choice of coordinates, independent of x_4 and homogeneous and isotropic with respect to x_1, x_2, x_3.

It is this case which I at first considered the most natural idealized description of physical space in the large; it is treated on pages 103–108 of this book. The objection to this solution is that one has to introduce a negative pressure, for which there exists no physical justification. In order to make that solution possible I originally introduced a new member into the equation instead of the above mentioned pressure, which is permissible from the point of view of relativity. The equations of gravitation thus enlarged were:

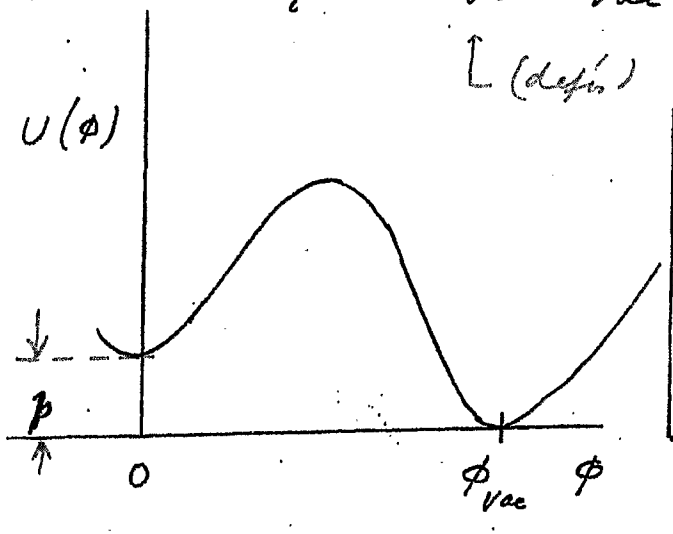
$$(R_{ik} - \tfrac{1}{2}g_{ik}R) + \Lambda g_{ik} + \kappa T_{ik} = 0 \tag{1}$$

where Λ is a universal constant ("cosmologic constant"). The introduction of this second member constitutes a complication of the theory, which seriously reduces its logical simplicity. Its introduction can only be justified

Any Spin 0 field, fundamental or composite (σ-model, Higgs, Q&P-composed) is coupled to vacuum; therefore it is always connected to the <u>inertia</u> of <u>any particle i</u>

Write $m_i \equiv g_i \phi_{vac}$, $\phi = \phi(x)$ spin 0 field

(defn) g_i = coupling to i

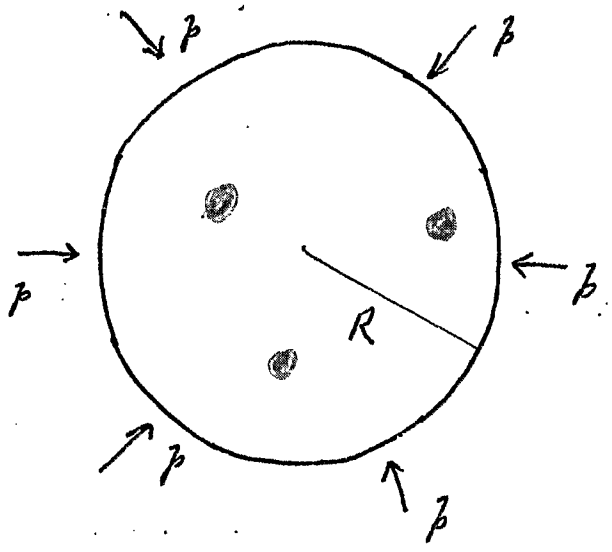


<u>transformation</u>:

$\phi(x)$ from $\phi_{vac} \to 0$,

mass of i at x : $m_i \to 0$.

∞ MIT/Dirac bag model of a "negative pressure"



$N_Q = 3$

$$E - \frac{4\pi}{3} R^3 p = \underbrace{N_Q \frac{2.0428}{R}}$$

$$\therefore \quad 4\pi R^2 p = \frac{1}{R} \quad ''$$

$$\rho_E \equiv \frac{E}{4\pi R^3/3} = 4p$$

$$\rho_Q \equiv N_Q \frac{2.0428}{4\pi R^4/3} = 3p$$

Dirac Proc. R. Soc. A268, 57 (1962)

Chodos et al Phys Rev D9, 3471 (1974)

Date: Tue, 23 Mar 2004 13:47:40 -0400 (EDT)
From: charles.baltay@yale.edu
Subject: Message to TD
To: rae@bnl.gov
X-yahMAIL: YAHMAIL AXP-1.6.4 (MIME) (PMDF) (CGILIB AXP-1.6.5/OBJ)
X-BNL-MailScanner-Information: Please contact the ISP for more information
X-BNL-MailScanner: Found to be clean
X-MailScanner-From: charles.baltay@yale.edu

Dear Rae

Would you please pass on this message to TD Lee for me. For Omega Lambda=0.7 and the Hubble constant=65 km/sec/Mparsec, the currently preferred values, the energy density associated with the Cosmological Constant is

ρ_Λ = rho(lambda)=3 E-6 Gev per cubic cm = $3 \cdot 10^{-6}$ Gev/cm^3

I would be happy to talk to him in more detail if that were useful.

with Best Regards

Charlie

Assume our Universe to be a large bag

$$\mathcal{E} - \frac{4\pi}{3} R^3 \rho_\Lambda \cong \frac{\text{Const}}{R} \quad \left(\equiv \frac{4\pi}{3} R^3 \rho_M \right)$$

$$\frac{\partial \mathcal{E}}{\partial R} = 0 \quad \text{gives}$$

$$\rho_M \cong 3 \rho_\Lambda \cong 9 \times 10^{-6} \text{ Gev/cm}^3$$

$$\rho_{\mathcal{E}} = \mathcal{E} / \frac{4\pi}{3} R^3 \cong 4 \rho_\Lambda \cong 1.2 \times 10^{-5} \frac{\text{Gev}}{\text{cm}^3}$$

Both are same order as

$$\text{critical density} = \rho_c \cong 1 \times 10^{-5} \text{ Gev/cm}^3$$

2. ASTROPHYSICAL CONSTANTS

Table 2.1. Revised 2001 by D.E. Groom (LBNL). The figures in parentheses after some values give the one-standard deviation uncertainties the last digit(s). Physical constants are from Ref. 1. While every effort has been made to obtain the most accurate current values of the list quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference.

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	$299\,792\,458$ m s^{-1}	defined[2]
Newtonian gravitational constant	G_N	$6.673(10) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[3]
astronomical unit (mean ⊕–⊙ distance)	au	$149\,597\,870\,660(20)$ m	[4, 5]
tropical year (equinox to equinox) (2001.0)	yr	$31\,556\,925.2$ s	[4]
sidereal year (fixed star to fixed star) (2001.0)		$31\,558\,149.8$ s	[4]
mean sidereal day (2001.0)		$23^{\rm h}\,56^{\rm m}\,04^{\rm s}.090\,53$	[4]
Jansky	Jy	10^{-26} W m^{-2} Hz^{-1}	
Planck mass	$\sqrt{\hbar c/G_N}$	$1.2210(9) \times 10^{19}$ GeV/c^2 $= 2.176\,7(16) \times 10^{-8}$ kg	[1]
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,7(4) \times 10^{16}$ m $= 3.262\ldots$ ly	[6]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,1\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,08$ km	[7]
solar mass	$M_\odot$	$1.988\,9(30) \times 10^{30}$ kg	[8]
solar equatorial radius	$R_\odot$	6.961×10^8 m	[4]
solar luminosity	$L_\odot$	$(3.846 \pm 0.008) \times 10^{26}$ W	[9]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,056\,22$ mm	[10]
Earth mass	$M_\oplus$	$5.974(9) \times 10^{24}$ kg	[11]
Earth mean equatorial radius	$R_\oplus$	$6.378\,140 \times 10^6$ m	[4]
luminosity conversion	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_{\rm bol}}$ W ($M_{\rm bol}$ = absolute bolometric magnitude = bolometric magnitude at 10 pc)	[12]
flux conversion	$\mathscr{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\,m_{\rm bol}}$ W m^{-2} ($m_{\rm bol}$ = apparent bolometric magnitude)	from above
$v_\odot$ around center of Galaxy	Θ_o	$220(20)$ km s^{-1}	[13]
solar distance from galactic center	R_o	$8.0(5)$ kpc	[14]
Hubble expansion rate†	H_0	$100\,h$ km s^{-1} Mpc^{-1} $= h \times (9.778\,13$ Gyr$)^{-1}$	[15]
normalized Hubble expansion rate†	h	$(0.71 \pm 0.07)\times^{1.15}_{0.95}$	[16, 17]
critical density of the universe†	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h^2\,M_\odot$Mpc^{-3} $= 1.879(3) \times 10^{-29}\,h^2$ g cm^{-3} $= 1.053\,9(16) \times 10^{-5}\,h^2$ GeV cm^{-3}	
local disk density	$\rho_{\rm disk}$	3–12×10^{-24} g cm$^{-3} \approx 2$–7 GeV/c^2 cm^{-3}	[18]
local halo density	$\rho_{\rm halo}$	2–13×10^{-25} g cm$^{-3} \approx 0.1$–0.7 GeV/c^2cm^{-3}	[19]
pressureless matter density of the universe†	$\Omega_M \equiv \rho_M/\rho_c$	$0.15 \lesssim \Omega_M \lesssim 0.45$	[16, 20]
baryon density of the universe	$\Omega_B \equiv \rho_B/\rho_c$	$0.0095 \lesssim \Omega_B h^2 \lesssim 0.023$	[21]
scaled cosmological constant†	$\Omega_\Lambda = \Lambda c^2/3H_0^2$	$0.6 \lesssim \Omega_\Lambda \lesssim 0.8$	[16]
scale factor for cosmological constant†	$c^2/3H_0^2$	$2.853 \times 10^{51}\,h^{-2}$ m^2	
$\Omega_M + \Omega_\Lambda + \ldots$ [22]	$\Omega_{\rm tot}$ [22]	see footnote [23]	
age of the universe†	t_0	12–18 Gyr	[16]
cosmic background radiation (CBR) temperature†	T_0	2.725 ± 0.001 K	[24, 25]
solar velocity with respect to CBR		371 ± 0.5 km s^{-1} towards $(\alpha, \delta) = (11.20^{\rm h} \pm 0.01^{\rm h}, -7.22^\circ \pm 0.08^\circ)$ or $(\ell, b) = (264.31^\circ \pm 0.17^\circ, 48.05^\circ \pm 0.10^\circ)$	[25]
Local group velocity with respect to CBR	$v_{\rm LG}$	627 ± 22 km s^{-1} towards $(\ell, b) = (276^\circ \pm 3^\circ, 30^\circ \pm 3^\circ)$	[25]
energy density of CBR	ρ_γ	$4.641\,7 \times 10^{-34}\,(T/2.725)^4$ g cm^{-3} $= 0.260\,38\,(T/2.725)^4$ eV cm^{-3}	[12, 25]
energy density of relativistic particles (CBR + ν)	$\rho_{\rm rel}$	$7.804\,2 \times 10^{-34}\,(T/2.725)^4$ g cm^{-3} $= 0.437\,78\,(T/2.725)^4$ eV cm^{-3}	[12, 25]
	$\Omega_{\rm rel} = \rho_{\rm rel}/\rho_c$	$4.153\,4 \times 10^{-5} h^{-2} (T/2.725)^4$	
number density of baryons	n_B	$2.6 \times 10^{-10} < n_B/n_\gamma < 6.2 \times 10^{-10}$	[21]
entropy density/Boltzmann constant	s/k	$2\,889.2\,(T/2.725)^3$ cm^{-3}	[12]

† Subscript 0 indicates present-day values.

Crude Approximation

1. no non-Euclidean geometry
2. no short wave length matter energy
3. no expansion

Yet, order of magnitude agreement.

So the nucleon is a tiny bag
" nucleus is a little bag
our universe is a larger bag!

Implications

1. Through RHIC expt. p and $\partial p/\partial \rho$ of the Quark-Gluon-Plasma can be measured.

2. In the bag model, p is exerted by the space outside. Likewise, Λ may also be due to the space outside the radius of our Universe.

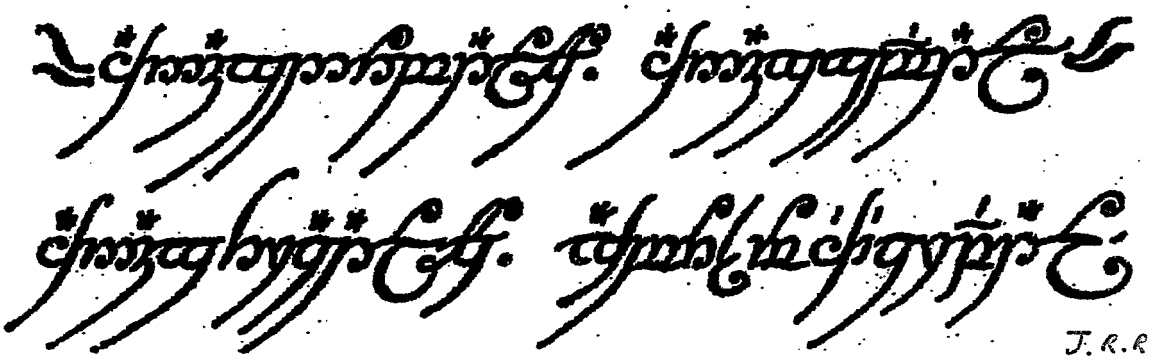
3. Λ, like p, is not a constant, but space-time dependent. Its variation can also be measured.

QGP Physics at LHC and beyond

- QGP is contained within each nucleon
  and " " nucleus
- QGP will be produced at LHC abundently, and will dominate LHC physic ∵ its strong interaction.
- At small distance r, $g(r)$ is weak but QCD is nonlinear; one expects soliton solutions with amplitude $\sim \frac{1}{g(r)}$ to exist.
- These soliton-like QGP excitations can be <u>high energy</u>, depending on r, and may be described <u>approximately</u> by a <u>phenomenological super-symmetrical field</u>, with sym. <u>violations</u>.
- Need early RHIC II to supplement LHC
  Also, e-RHIC to differentiate QED vs QCD

Eight Gluons for the Universe,
To set her gauge.
Six Quarks for Humankind,
Searching for the Truth.
One Plasma with superstrength,
One Plasma to find them.
Through Dark Energy,
One Plasma to quench them.
And from the Big Bang,
One Plasma to shape them all.

TOL

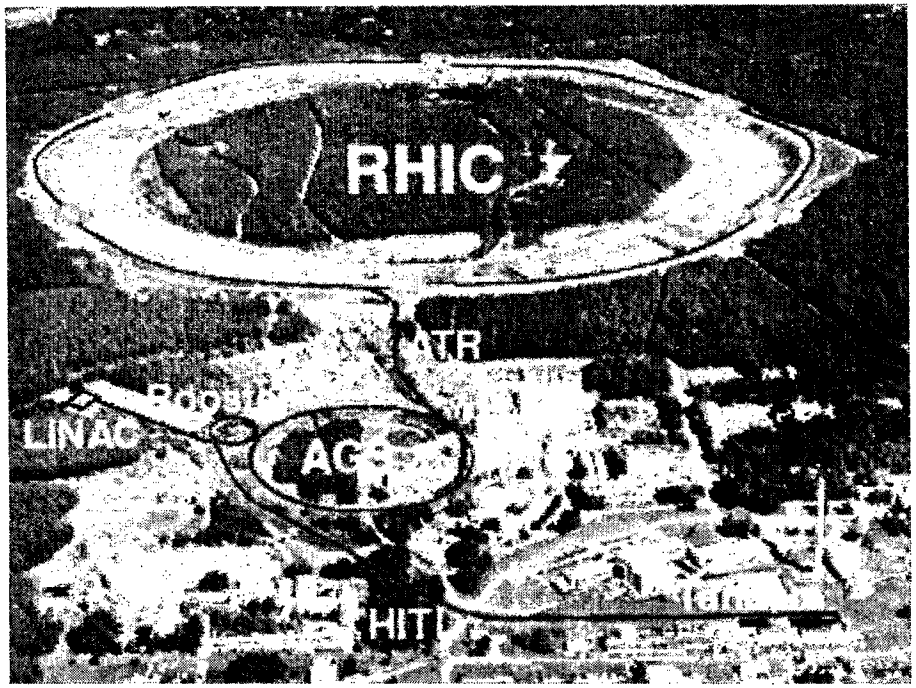


J.R.R. Tolkien

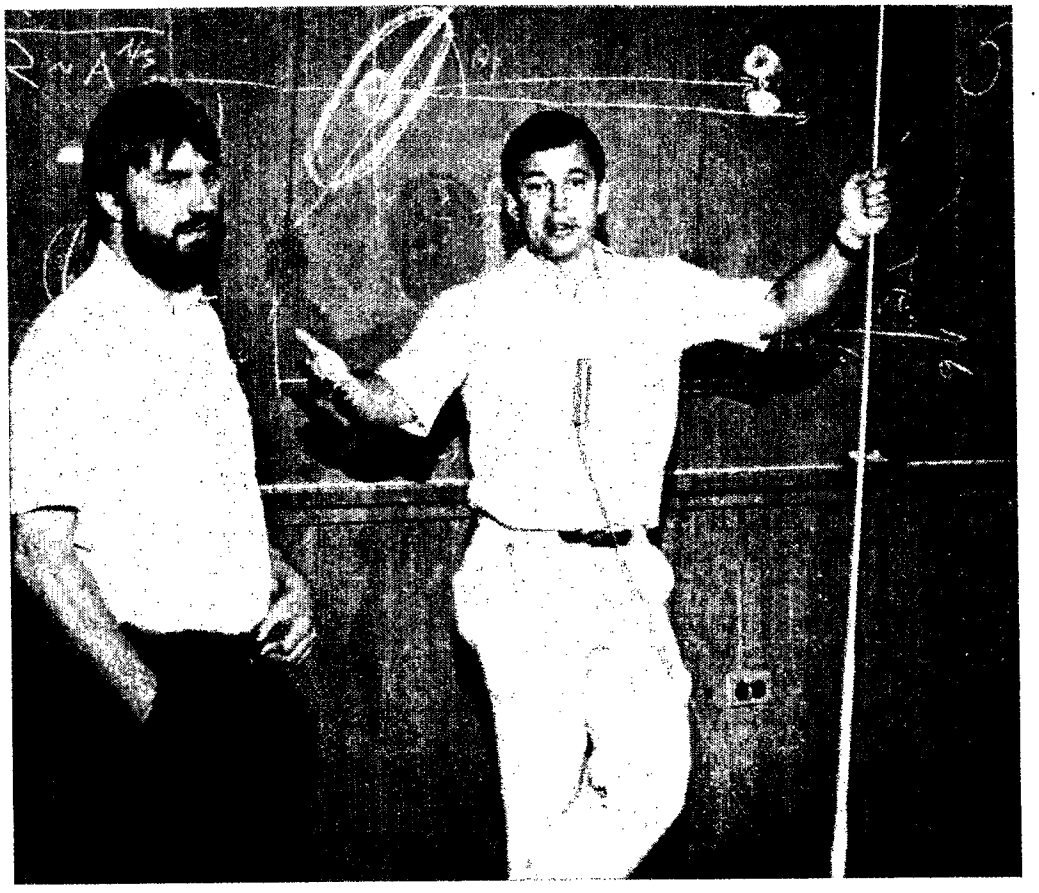
Experimental results from the early measurements at RHIC

T. Ludlam

New Discoveries at RHIC
RBRC Workshop
May 15, 2004



The early days at RHIC



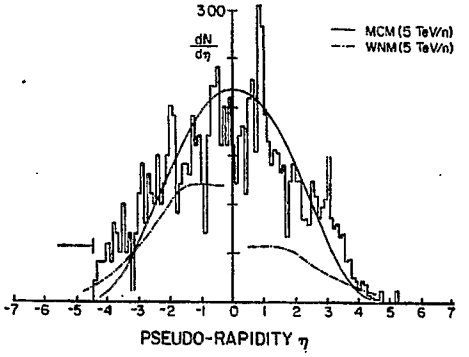
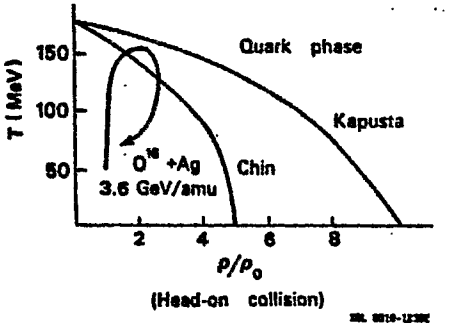
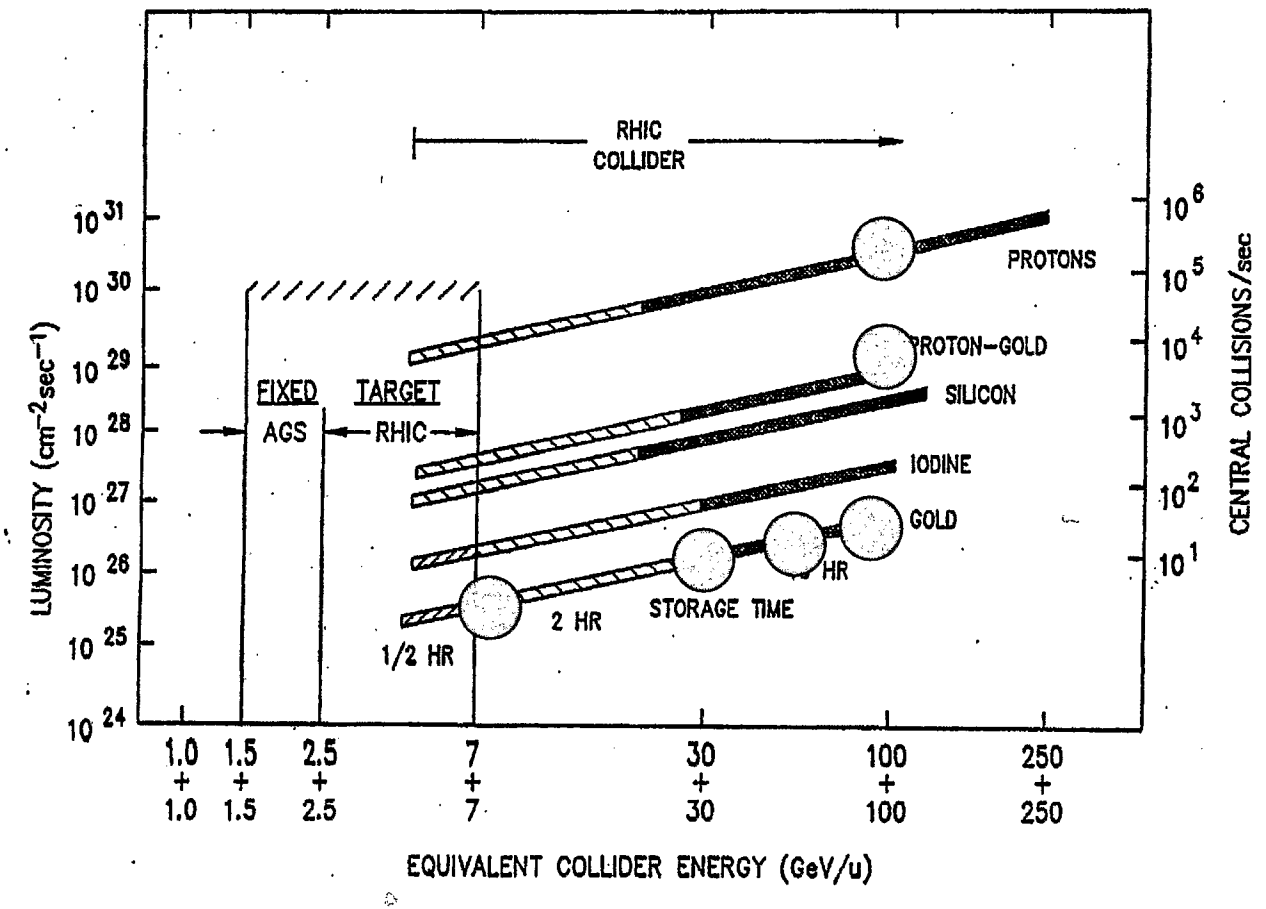


Fig. 15 Pseudorapidity distribution of Si + AgBr event



The Key design parameters for RHIC
c. 1983



RHIC Bulletin
Brookhaven National Laboratory May 1991
Volume II, Number 2

Construction begins: January 1991

Beginning of RHIC Construction Celebrated at Brookhaven

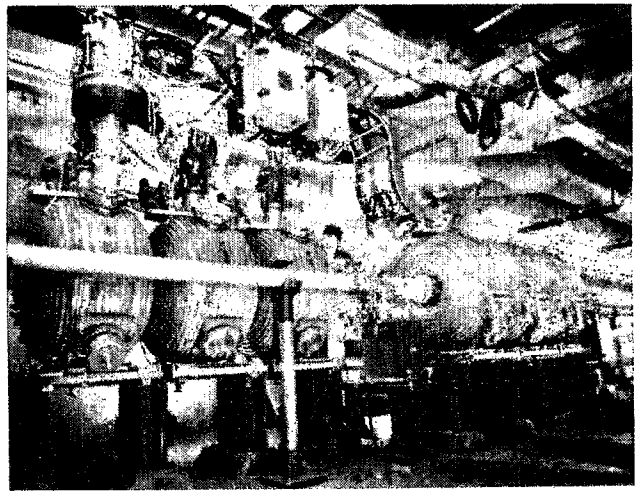
On April 12, under breezy blue skies, a crowd of 500 BNL employees and visitors gathered to celebrate the beginning of construction of the Relativistic Heavy Ion Collider. Hosting the ceremony, which was held atop the RHIC ring, was Laboratory Director Nicholas Samios. "We thought this would be an appropriate time," he declared, "to express our thanks and gratitude to the many individuals who have made RHIC possible, and, further, to acknowledge the efforts and dedication of those who are bringing RHIC into operation and fruition."

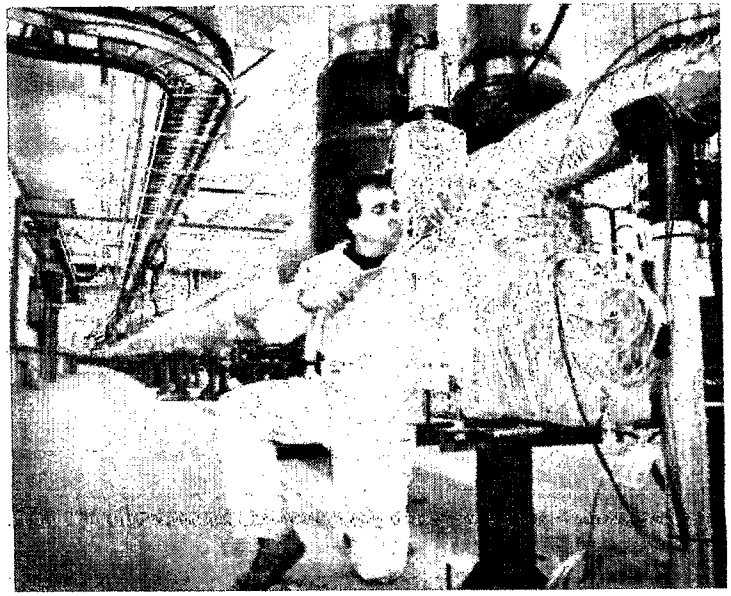
On hand were many of the scientists, legislators, officials of the Department of Energy, and members of

(Continued on page 4)

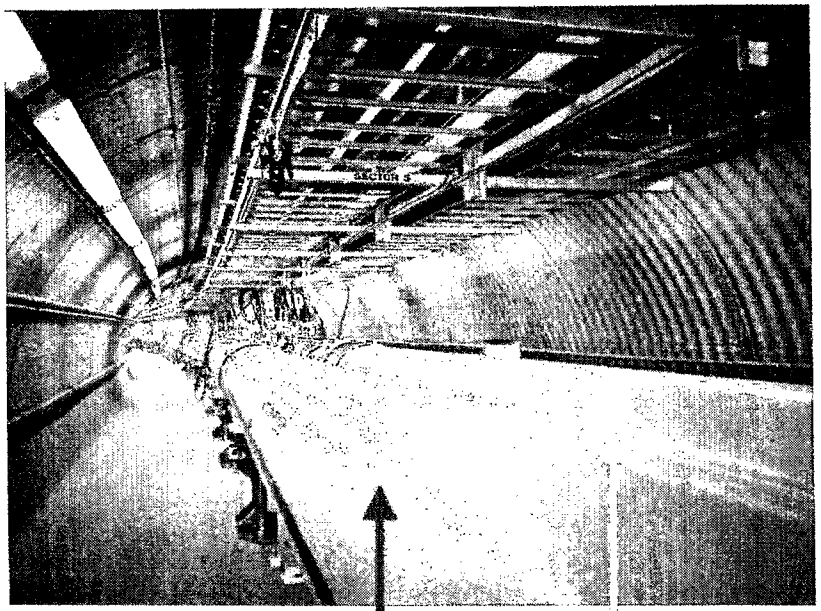
Satoshi Ozaki, RHIC Project Head, seated on the flatbed of the truck bearing a RHIC dipole magnet.

Cutting the ribbon to mark the start of construction of the Relativistic Heavy Ion Collider (RHIC) are: (from left) Suffolk County Executive Patrick Halpin, Presidential Science Advisor D. Allan Bromley, Senator Alfonse D'Amato, BNL Director Nicholas Samios and Congressman George Hochbrueckner. On the flatbed truck behind them is a full-length RHIC dipole magnet, about to be ceremonially delivered to the RHIC tunnel.





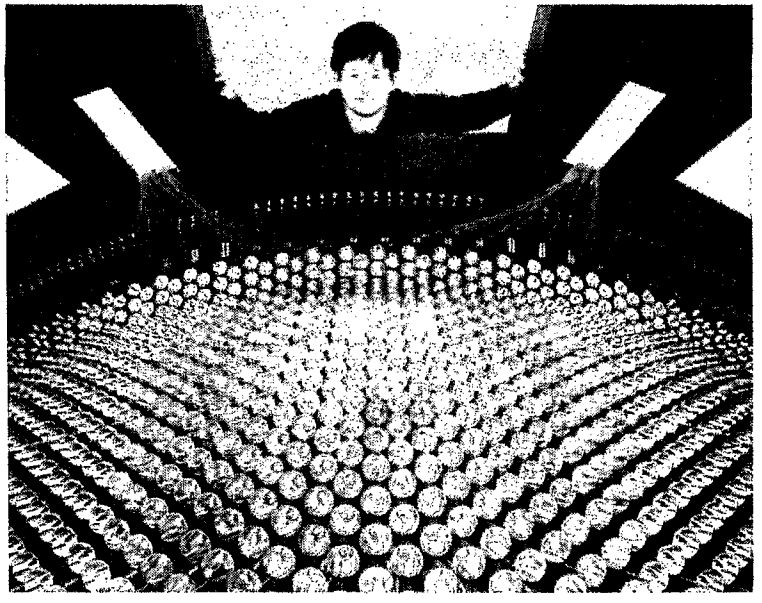
Nine long years

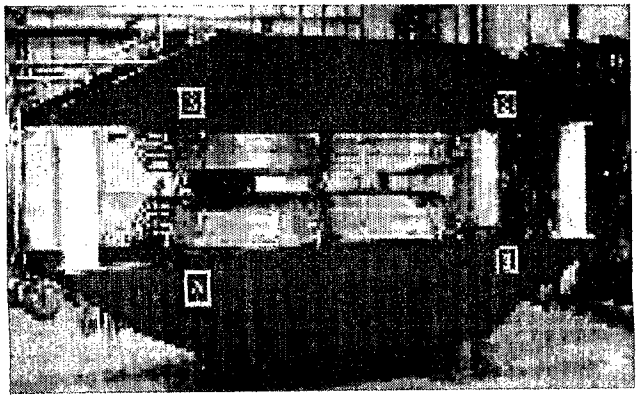


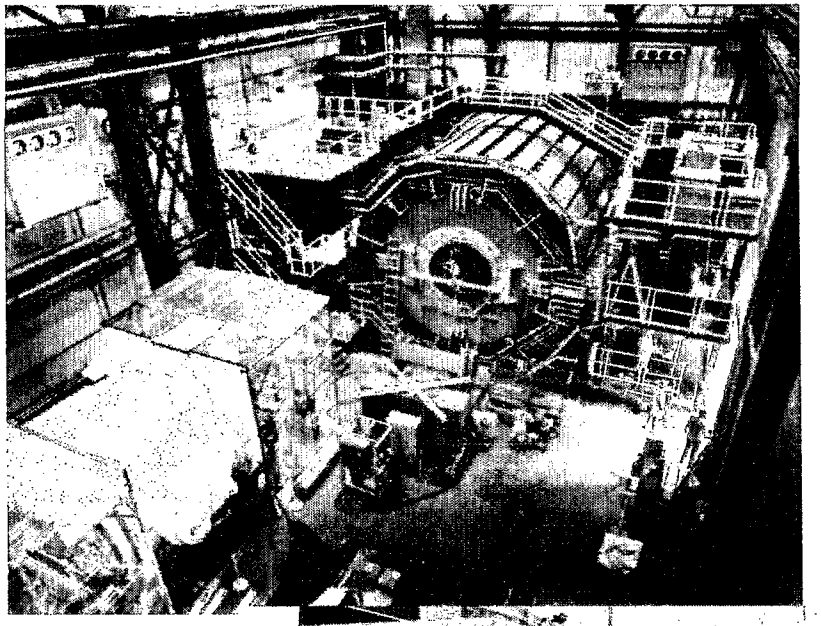
Arc

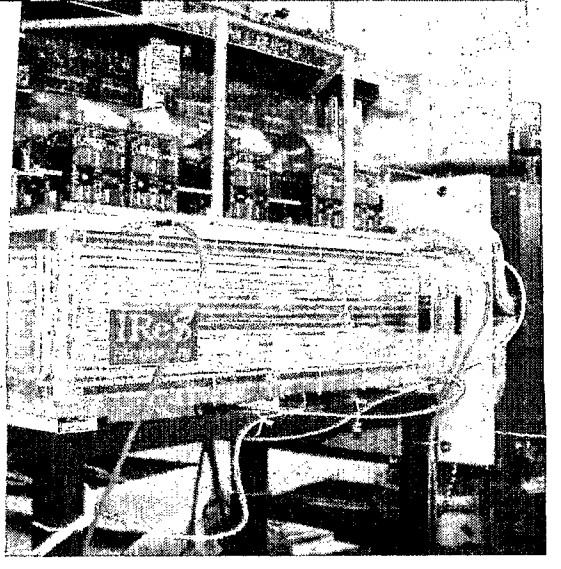
Blue Ring
(Clockwise)

Detectors too...

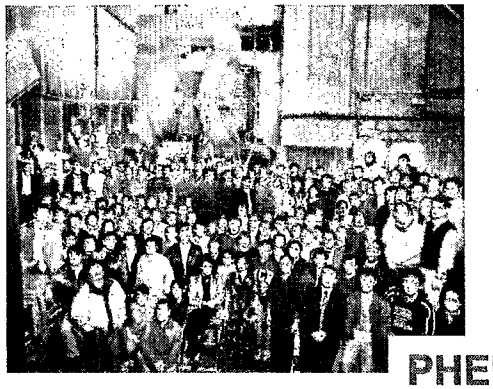




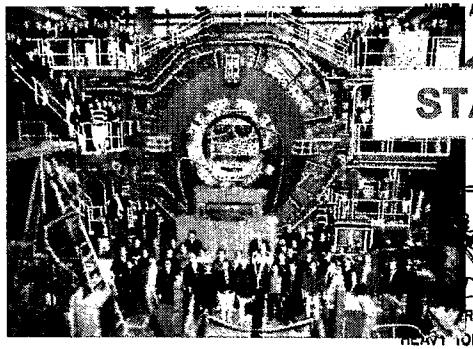




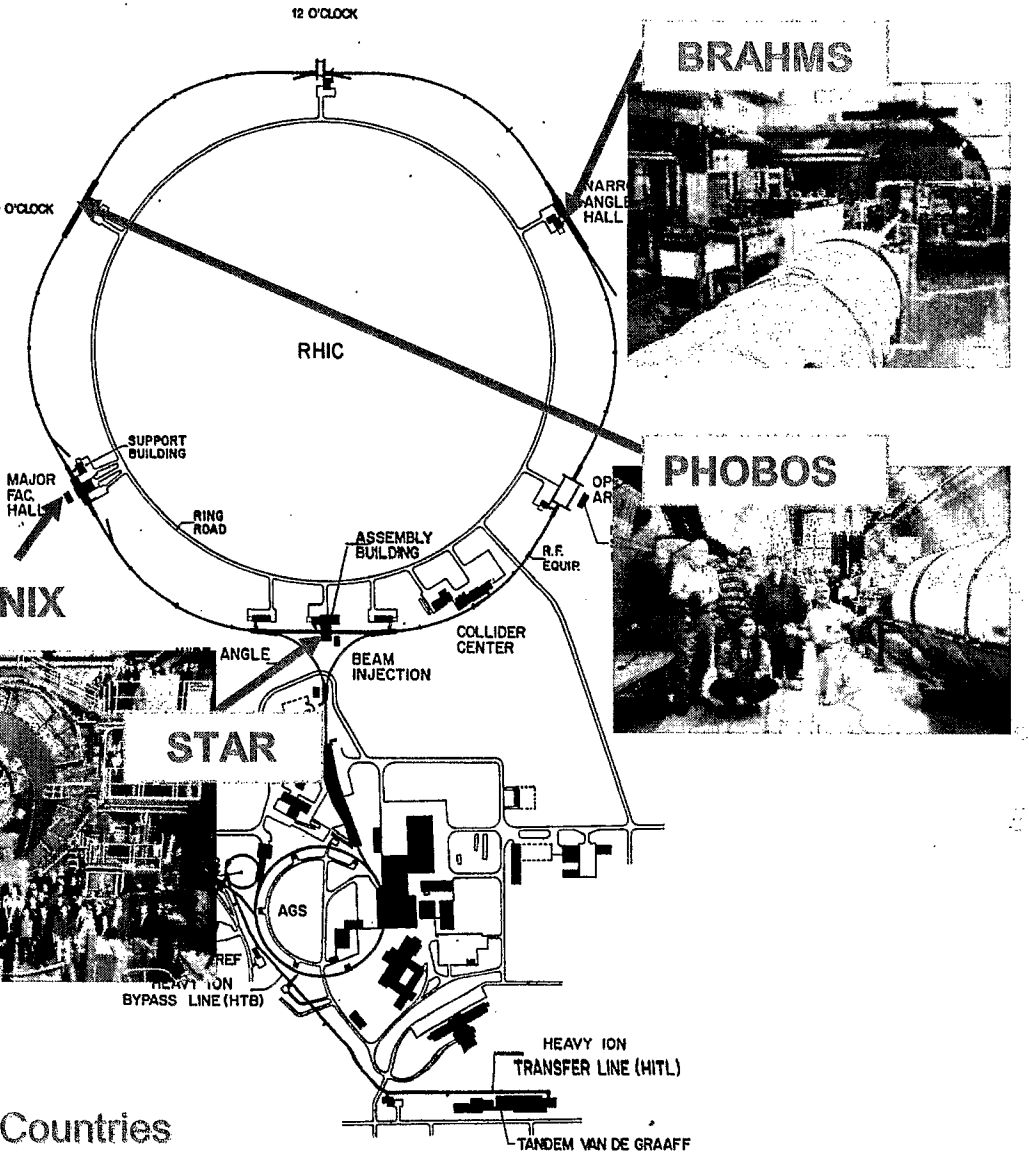
Detector suite at turn-on



PHENIX



STAR



BRAHMS

PHOBOS

2 Large Detectors
- STAR
- PHENIX

2 "Small" Detectors
- PHOBOS
- BRAHMS

All Participated in FY 2000 Data Runs

~900 Participants, ~90 Institutions, 19 Countries

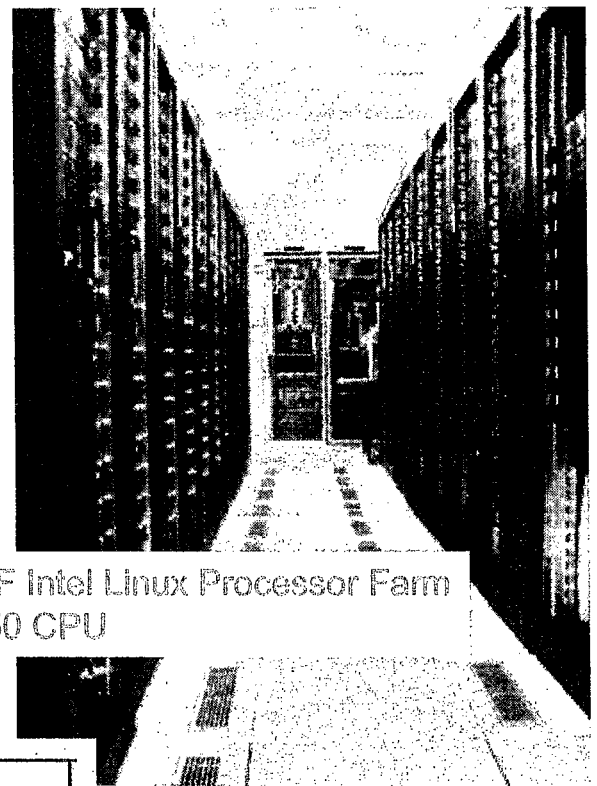
RHIC Computing Facility...

430 Terabytes of raw data recorded during FY 2004 runs.

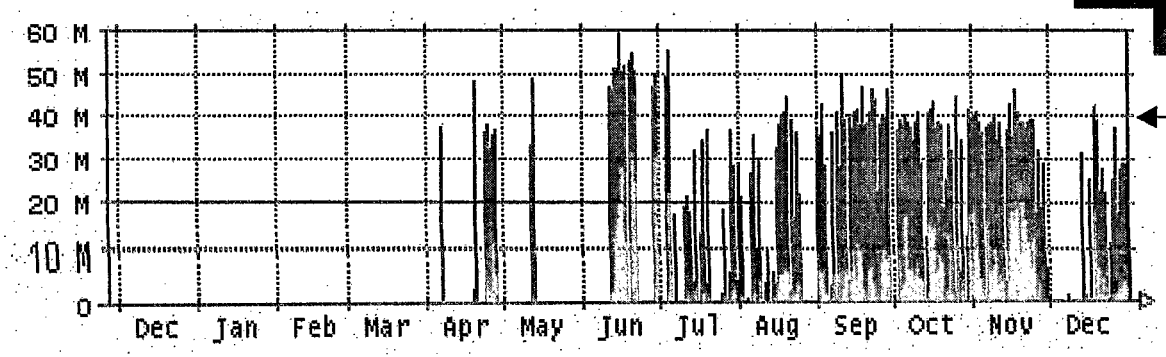
FY 2003 capacity:

- 99,000 SPECint95 cpu processing (~2 Tflops)
- 118 Tbytes disk storage
- 4500 Tbytes robotic tape storage
- 2200 Mbyte/sec disk I/O capacity

Data Transfer and processing from all four experiments.

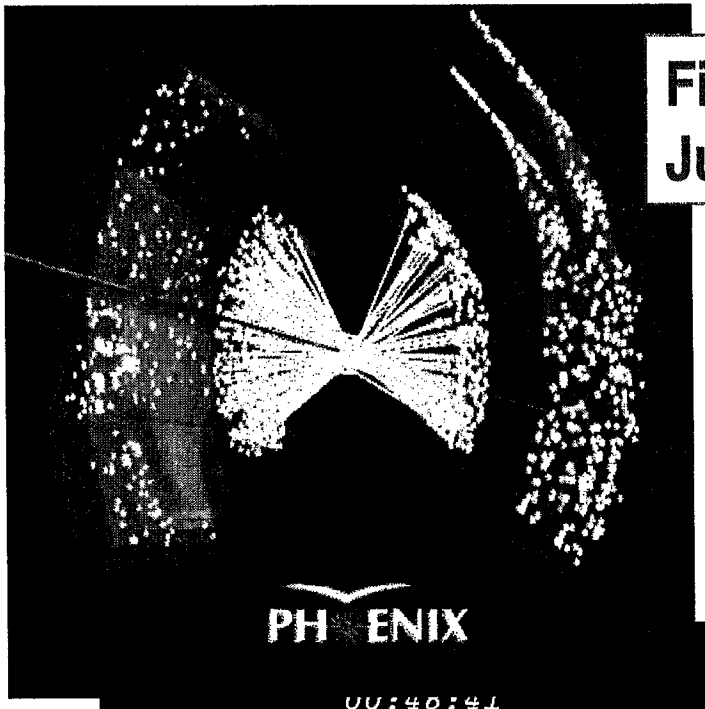


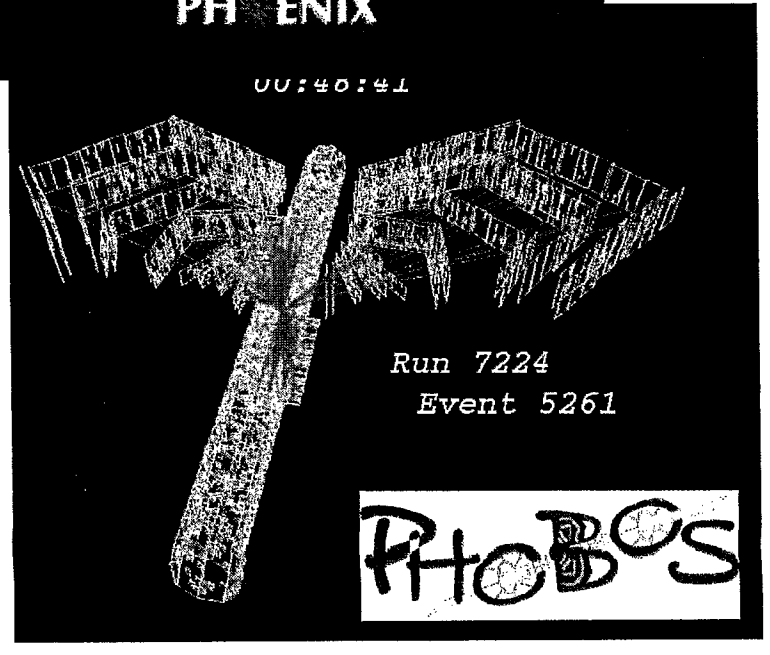
Raw Data Recording Rate for STAR during 2001

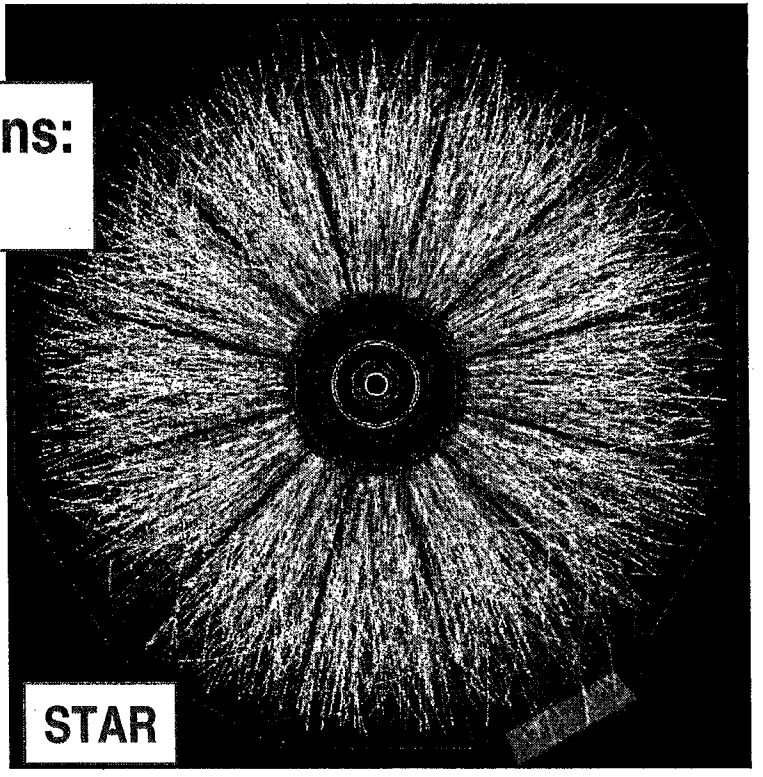


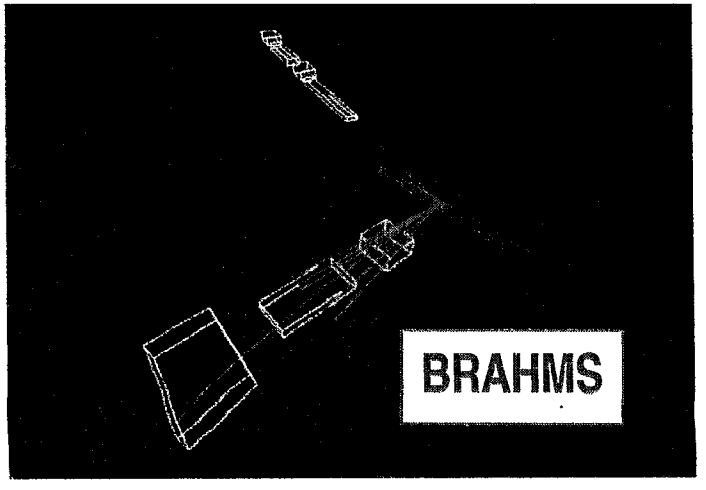
40 Mbyte/sec

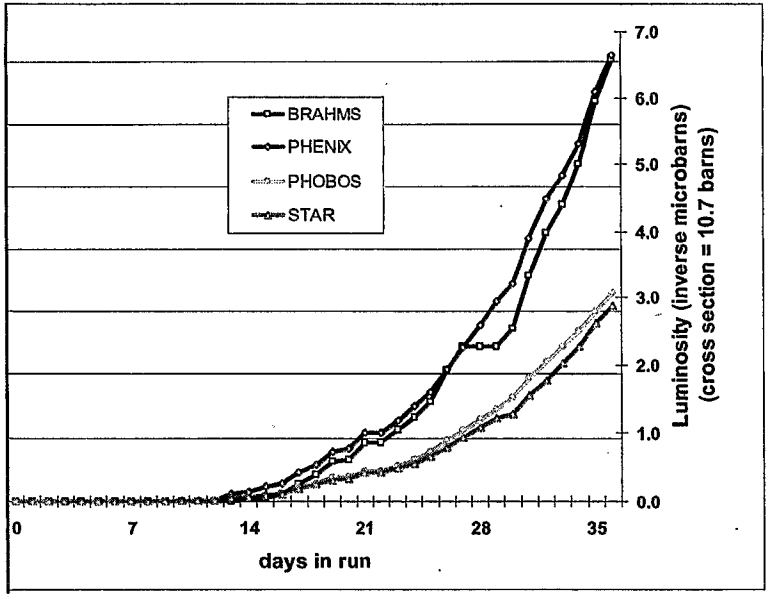
First collisions: June 2000







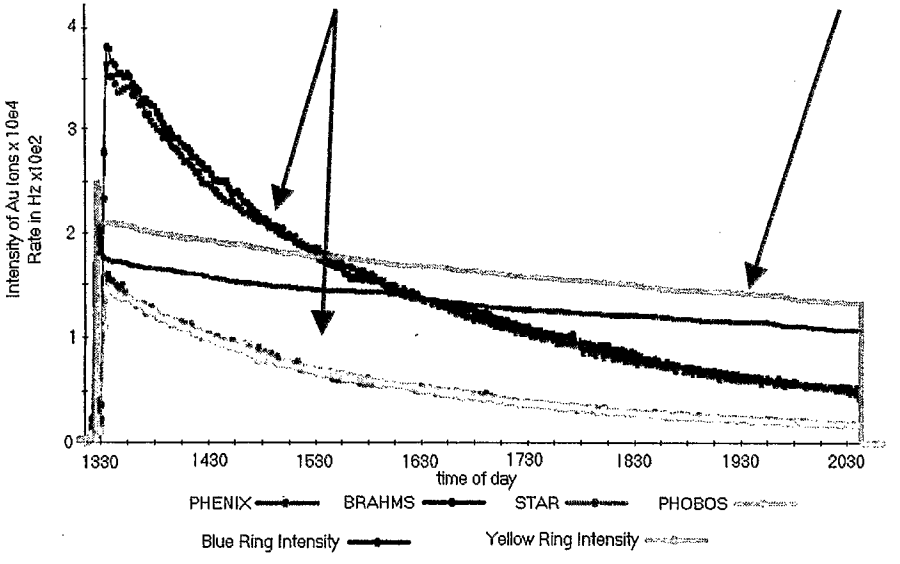


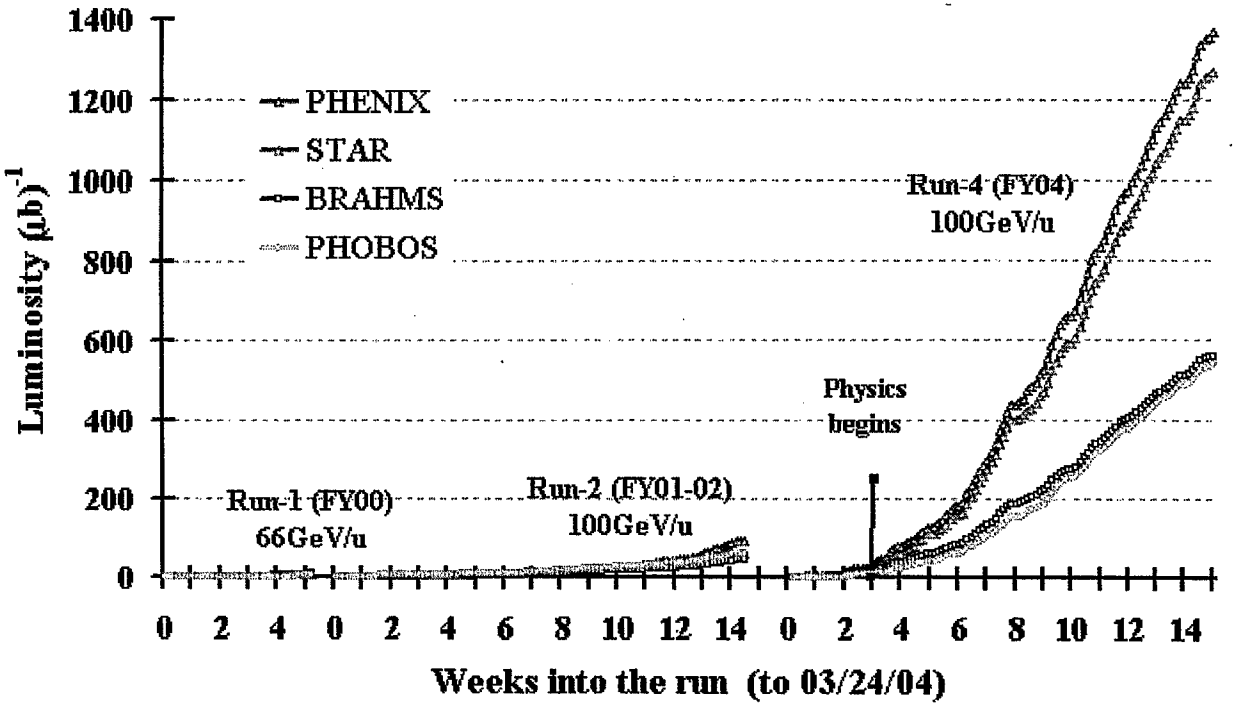


Run 1: FY 2000
130 GeV/u Au-Au

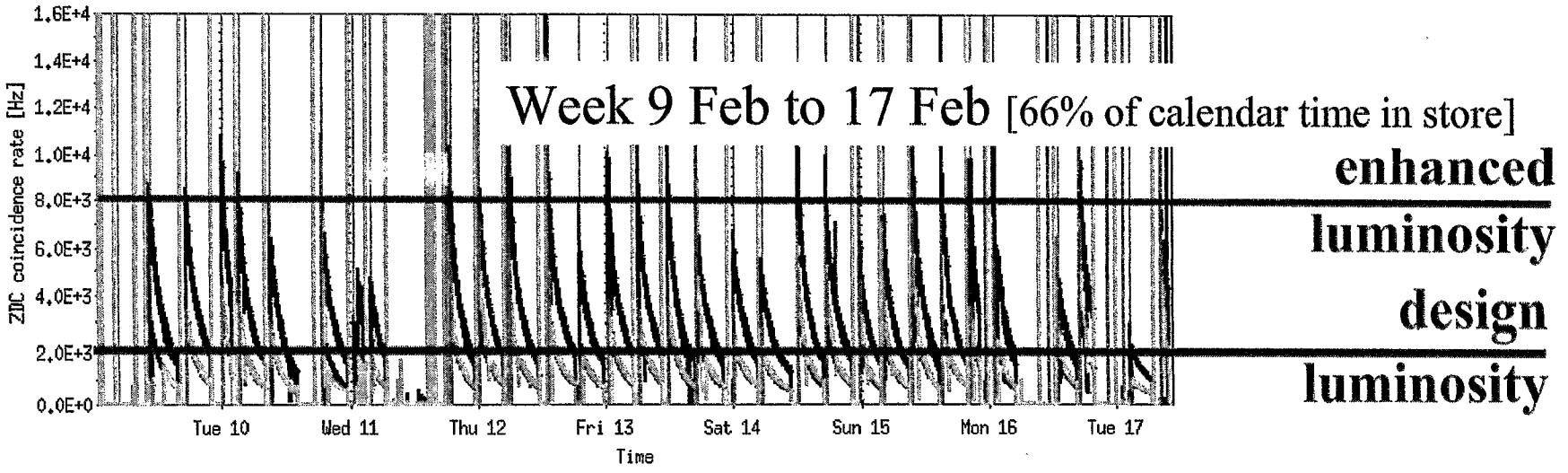
Collision Rates and Stored Beam Intensities

"Typical" Store
Run 1

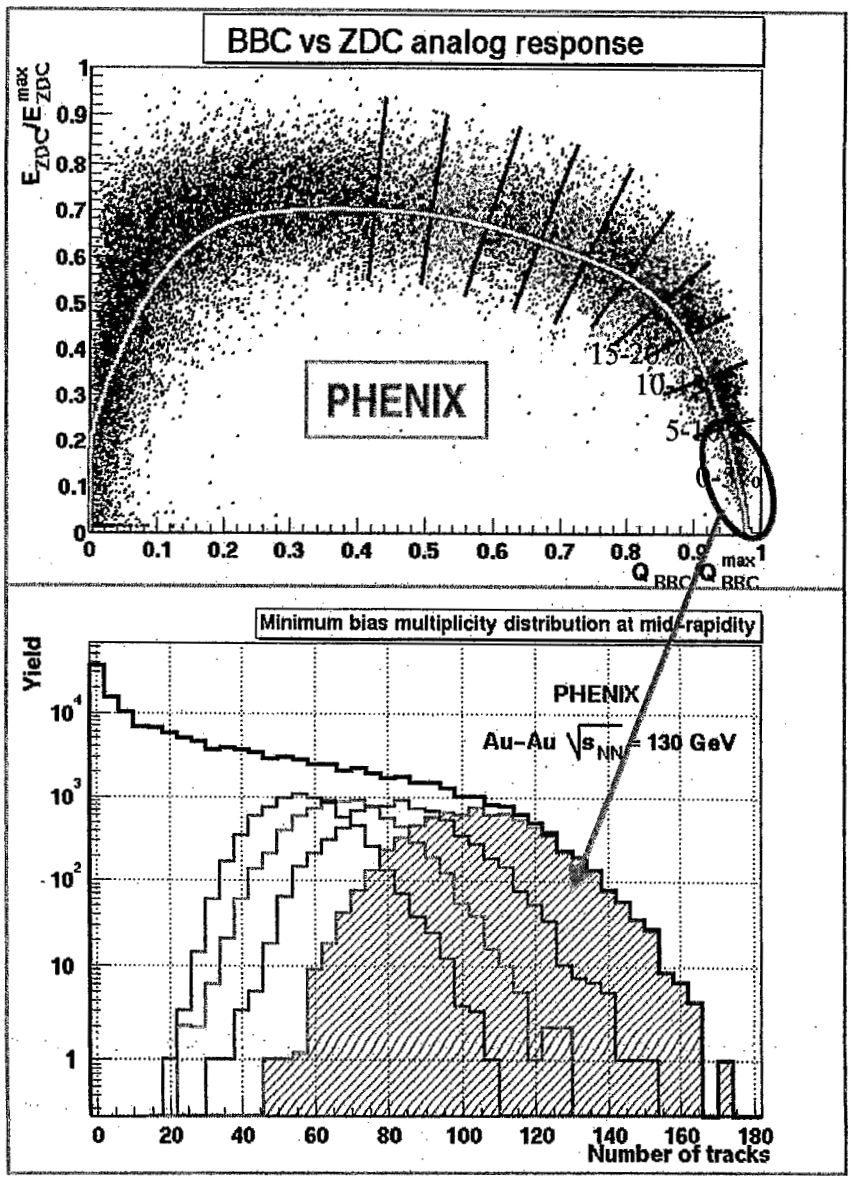


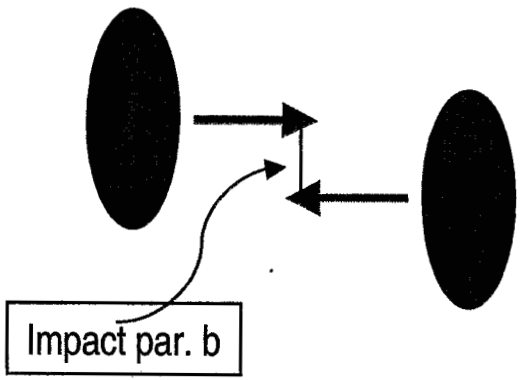


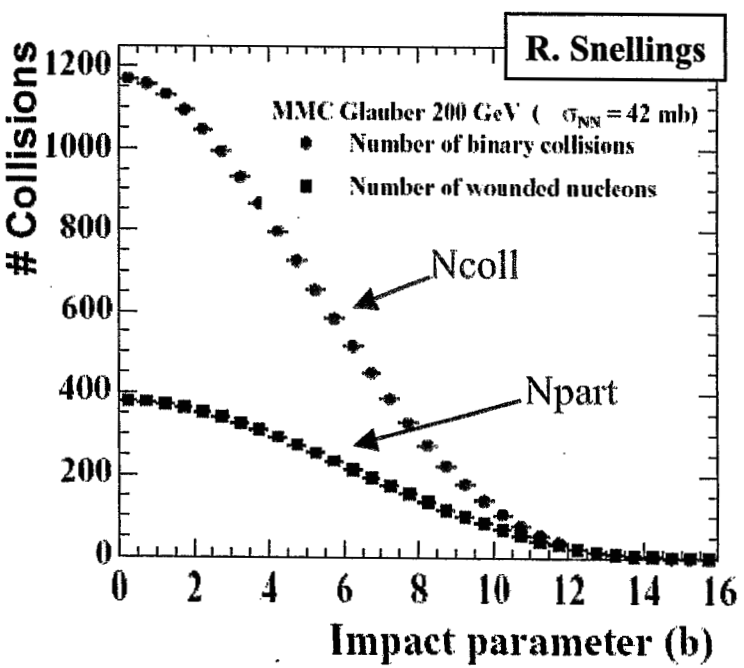
The integrated luminosity delivered to each of the four experiments during the three Au+Au running periods to date.

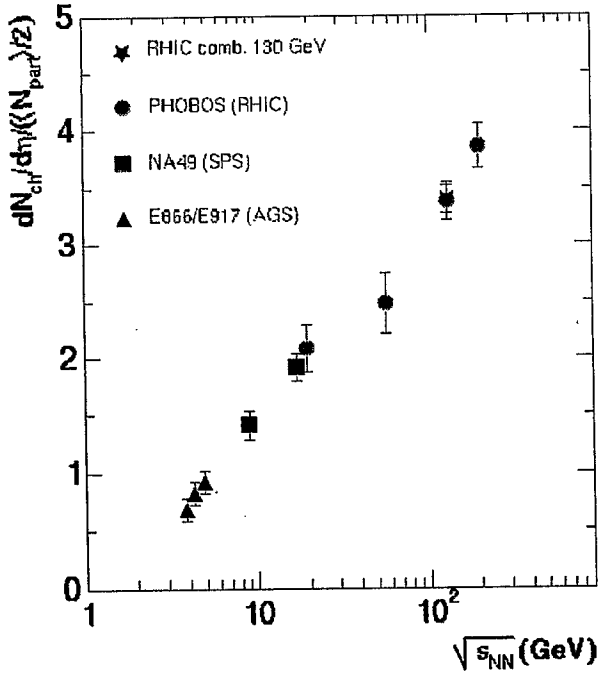


Geometry of nuclear collisions: Centrality



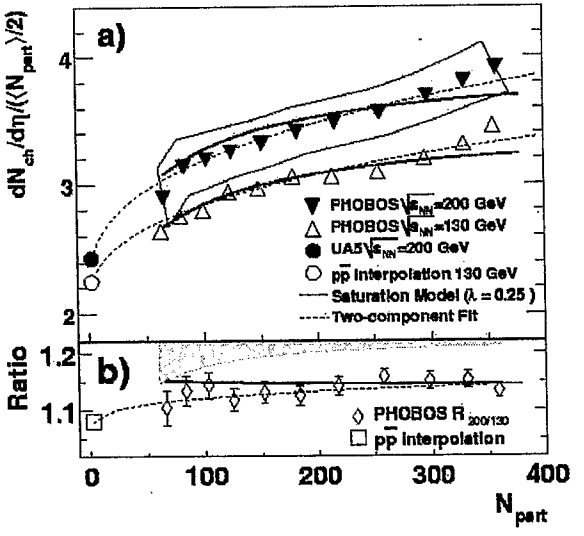






The multiplicity data: PHOBOS

*B. Back et al., PRL **88**, 022302 (2002)*
*PR **C65**, 061901R (2002)*

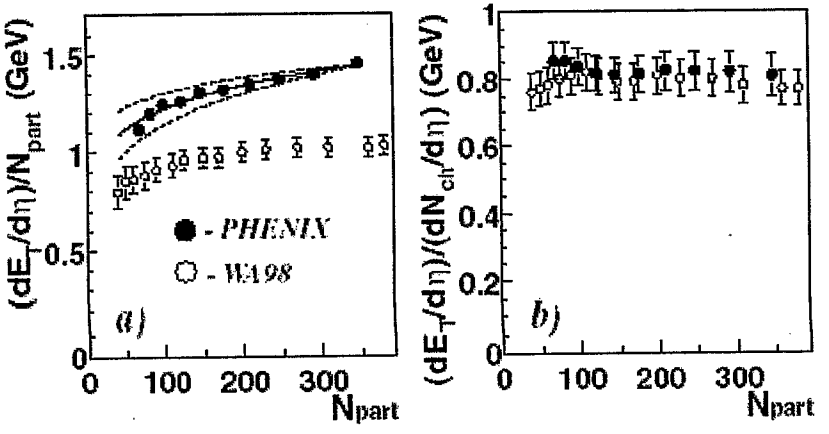


PHENIX E_T results:

ε_{BJ} = 4.6 GeV/fm^3

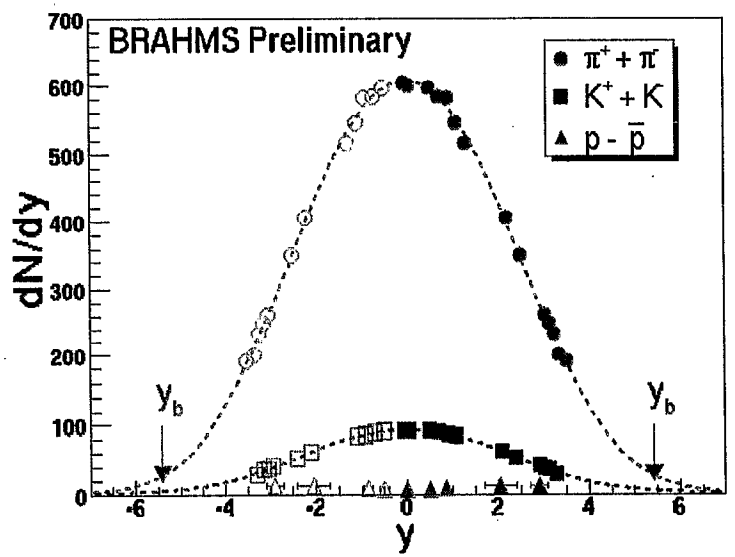
τ_0 = 1 fm/c

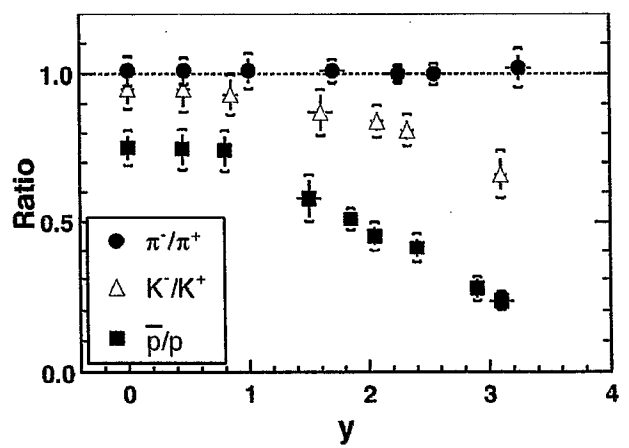
K. Adcox et al,
*PRL **87**, 052301 (2001)*



Rapidity distributions....

- Central region is nearly baryon-free
- No Plateau

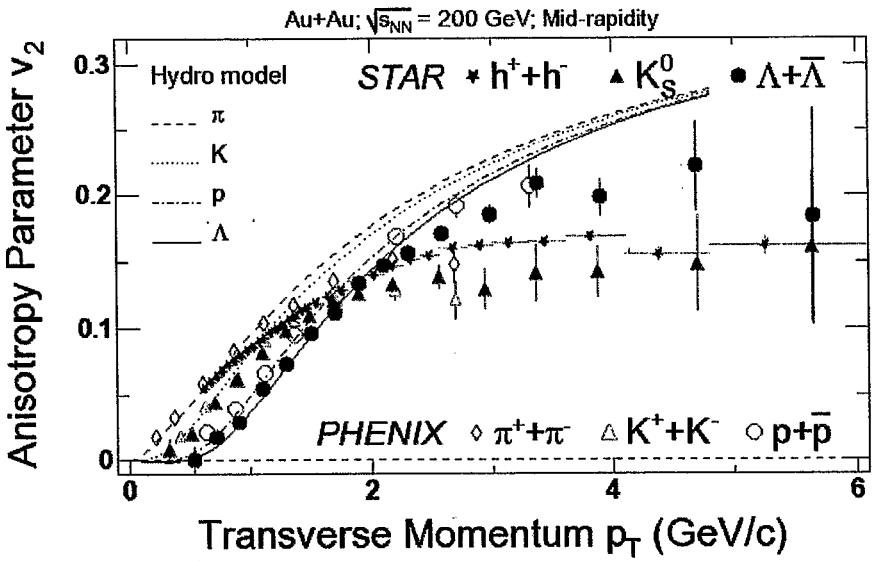




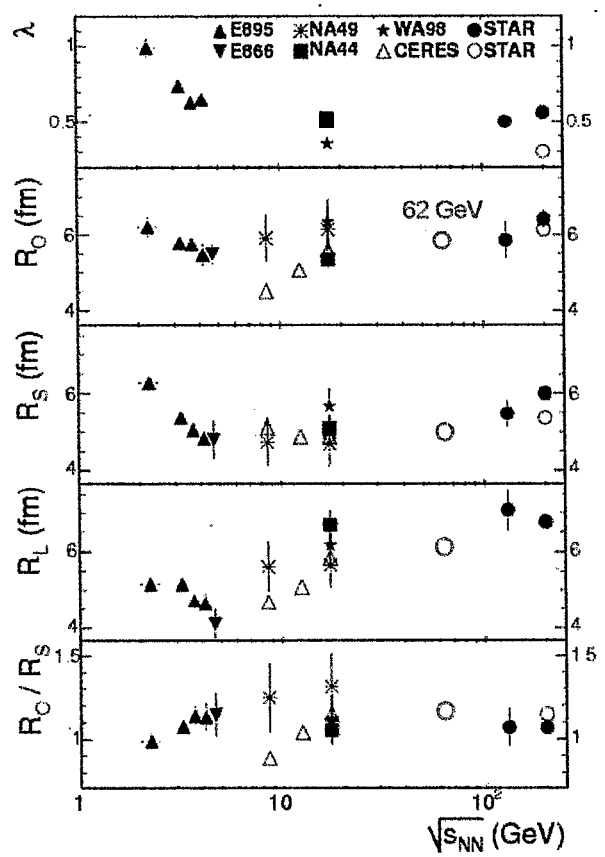
BRAHMS 200 GeV/u

*I. Bearden et al., PRL **90**, 102301 (2003)*

Flow; Hydrodynamics; HBT

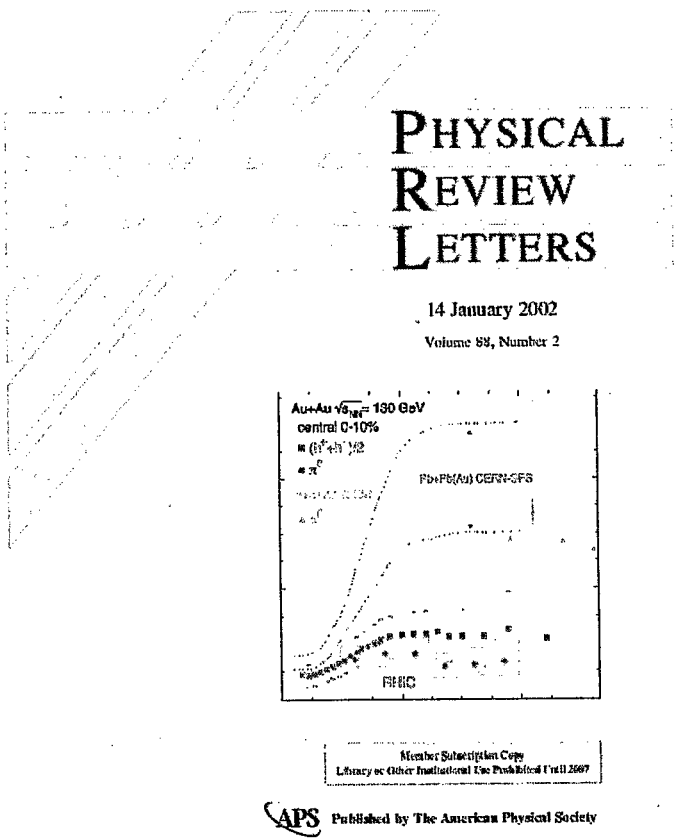


*PHENIX, S. Adler et al., PRL **91**, 172301 (2003)*
*STAR, J. Adams et al., PRL **92**, 052302 (2004)*



*STAR, C. Adler et al., PRL **87**, 082301 (2001)*

Hard Scattering…
The Silver Bullet of RHIC



schematic view of jet production

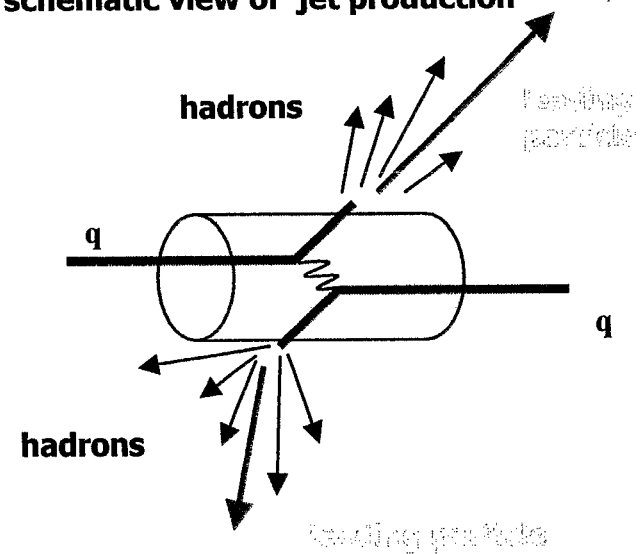
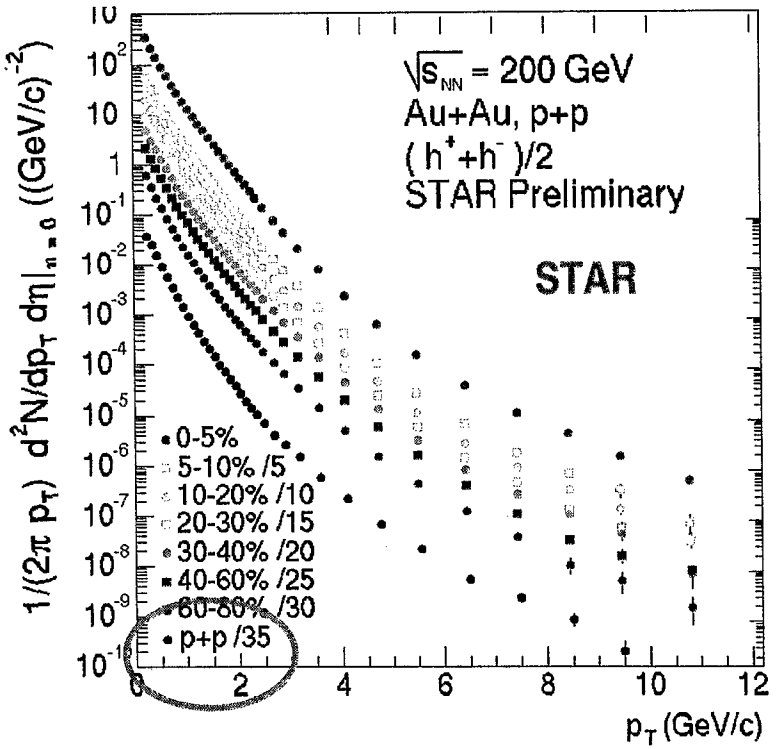
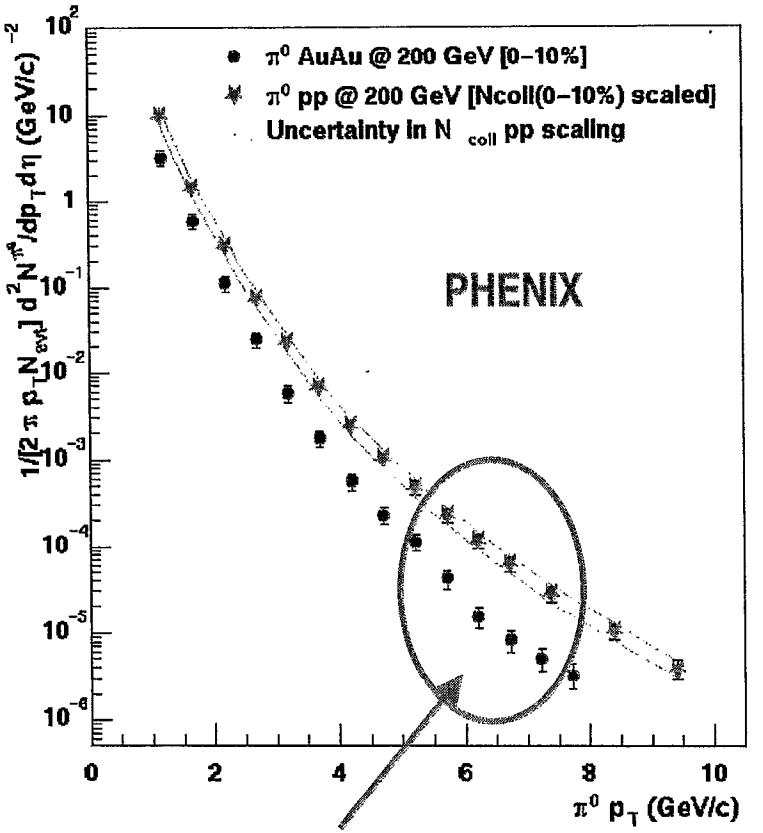


Figure 5

High P_t Data

Well measured, as function of centrality, to p_t > 10 GeV/c.
Calibration data from p – p collisions in the same detectors.

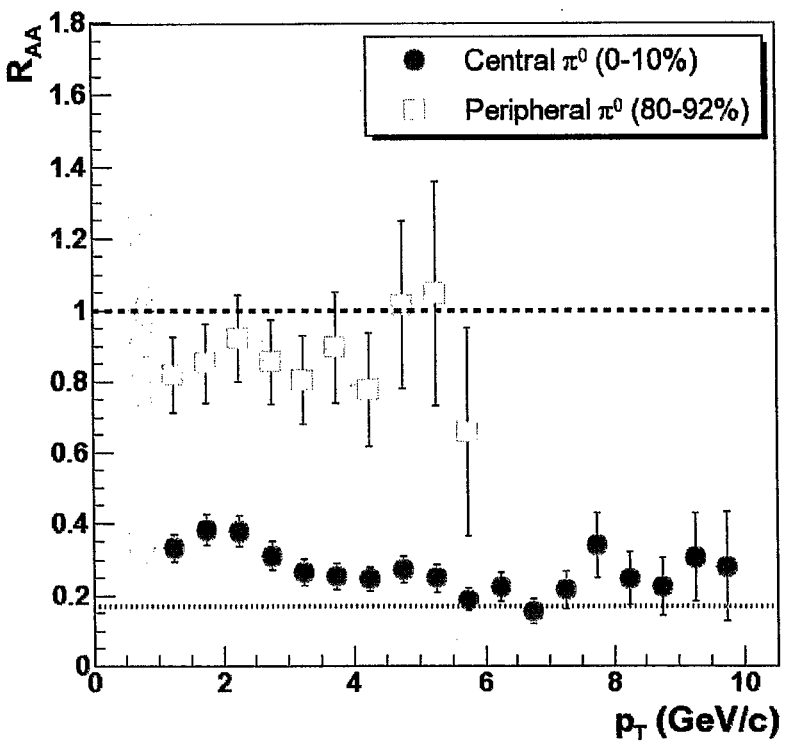




Clear suppression in central Au-Au relative to p – p at large p_t

Suppression of leading hadrons in RHIC data

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

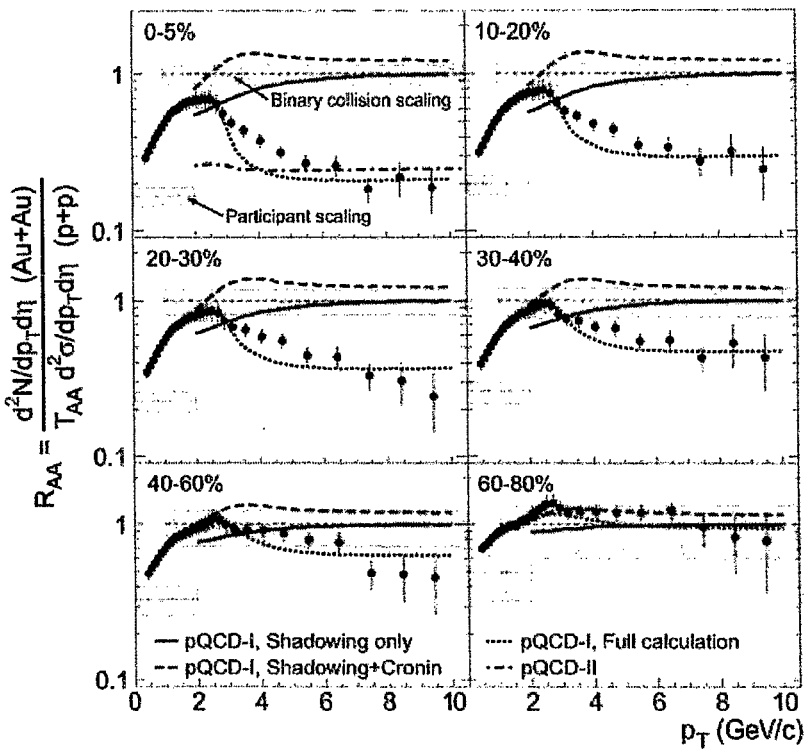


PHENIX:

Inclusive π^0 in central & peripheral collisions

*S. Adler et al., PRL **91**, 072301 (2003)*

$\sqrt{S_{nn}}$=200: Au+Au



STAR Charged hadrons:

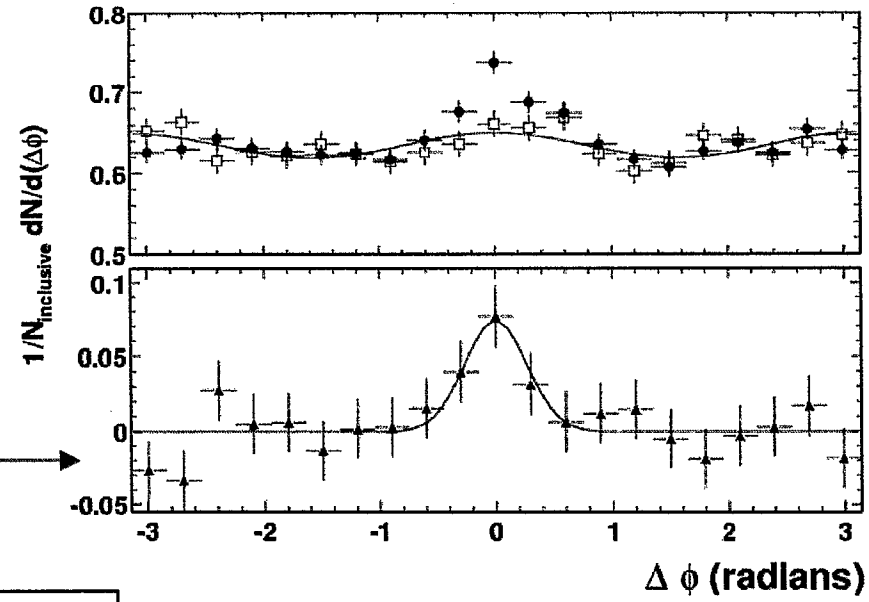
Dependence on centrality

*J. Adams et al., PRL **91**, 172302 (2003)*

Jet structure in Au-Au collisions at 200 GeV/u: Two Particle Correlations at High p_T

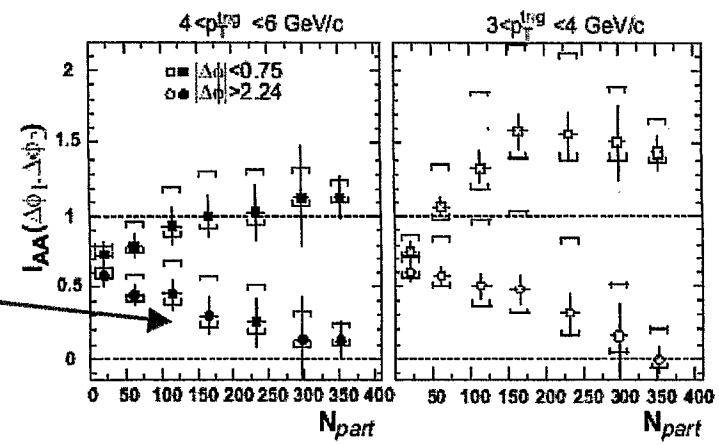
- Trigger particle pT>4 GeV/c
- look at azimuthal correlations for pT>2 GeV/c
- v_2 contributes: subtract correlation at $|\eta_1 - \eta_2|>0.5$
  - also eliminates the away-side correlations

what remains has jet-like structure ⇒ direct evidence for jets at RHIC!

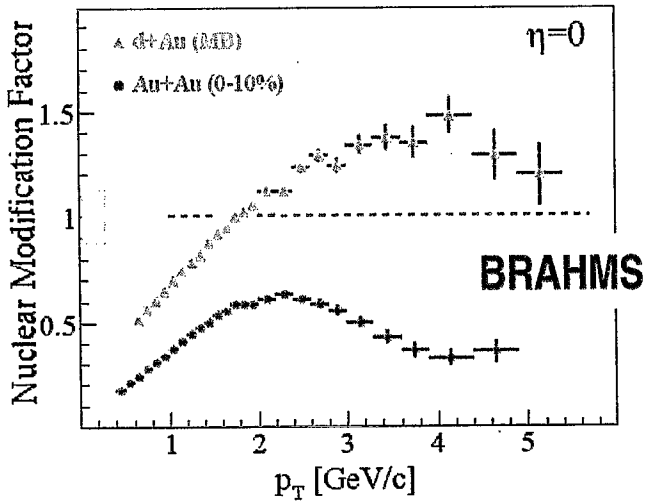


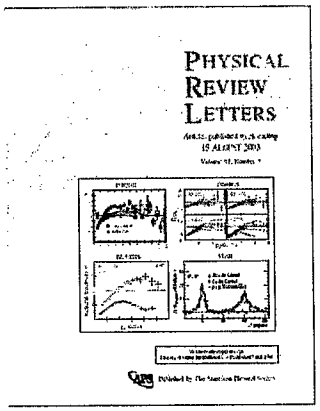
*STAR, C. Adler et al., PRL **90**, 082302 (2003)*

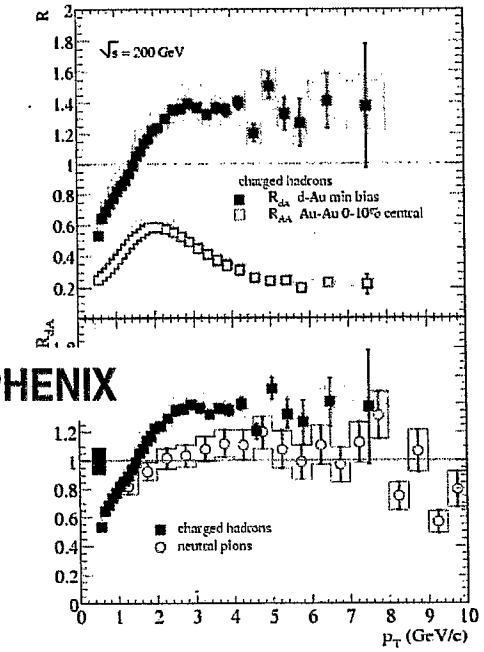
Back-to-back correlations disappear
With increasing centrality

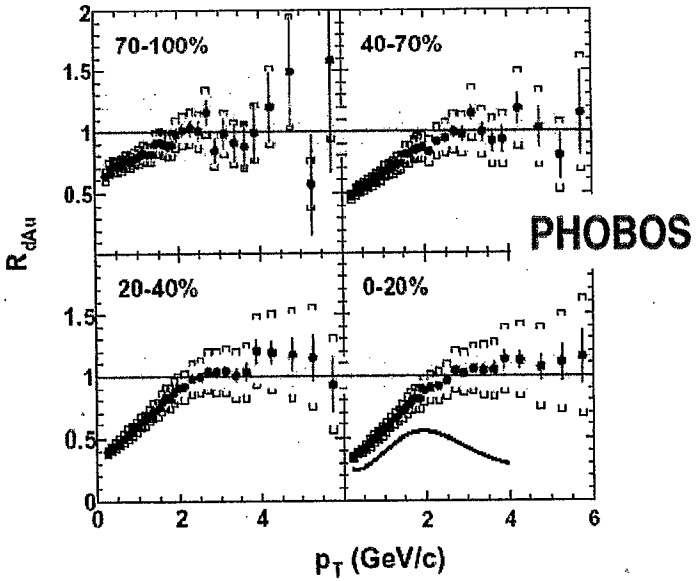


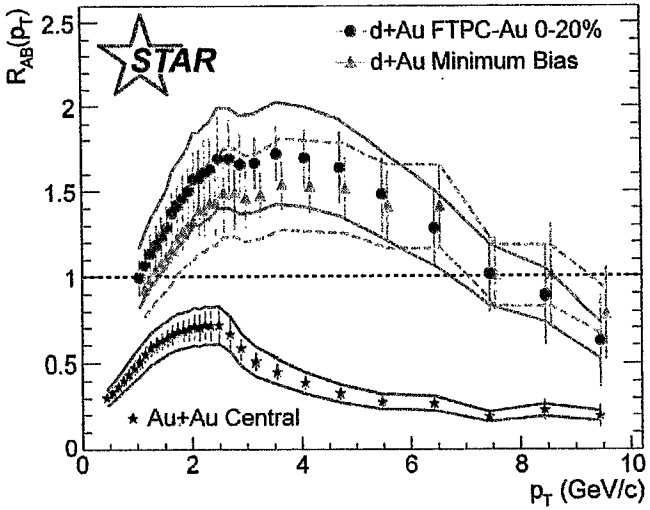
The Color Glass alternative & d – Au data

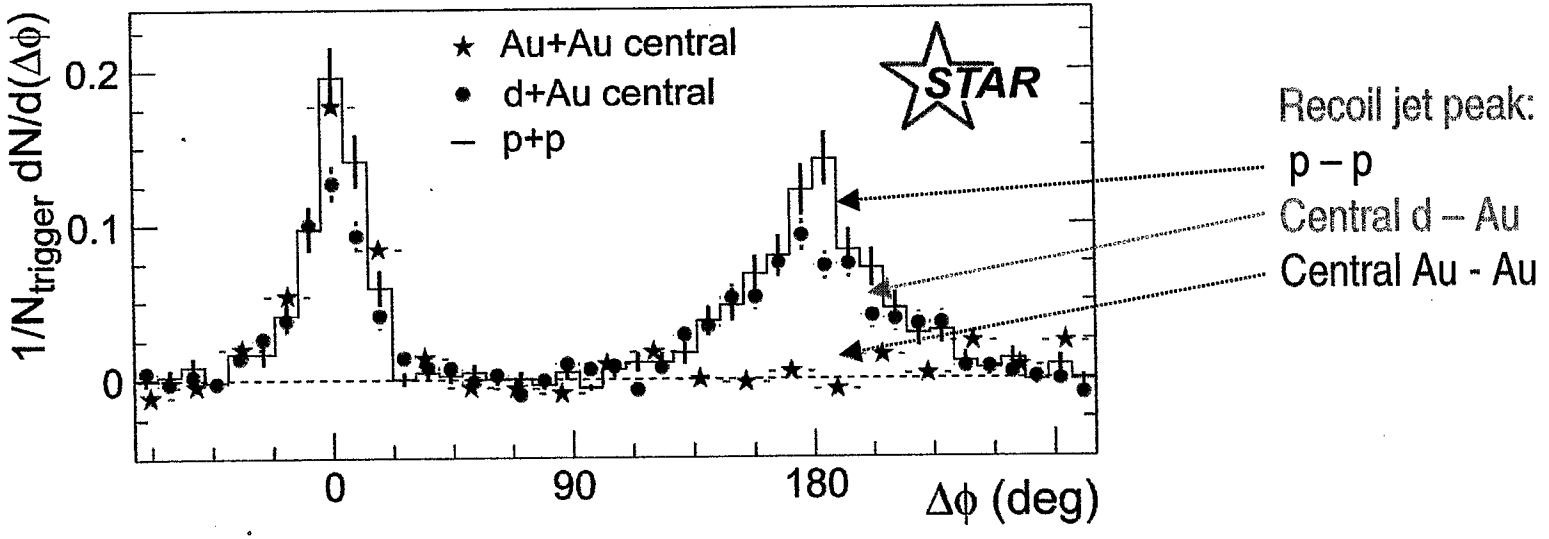






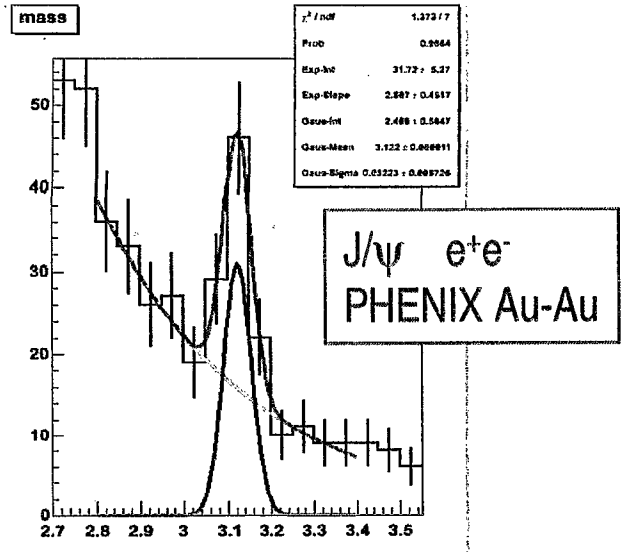


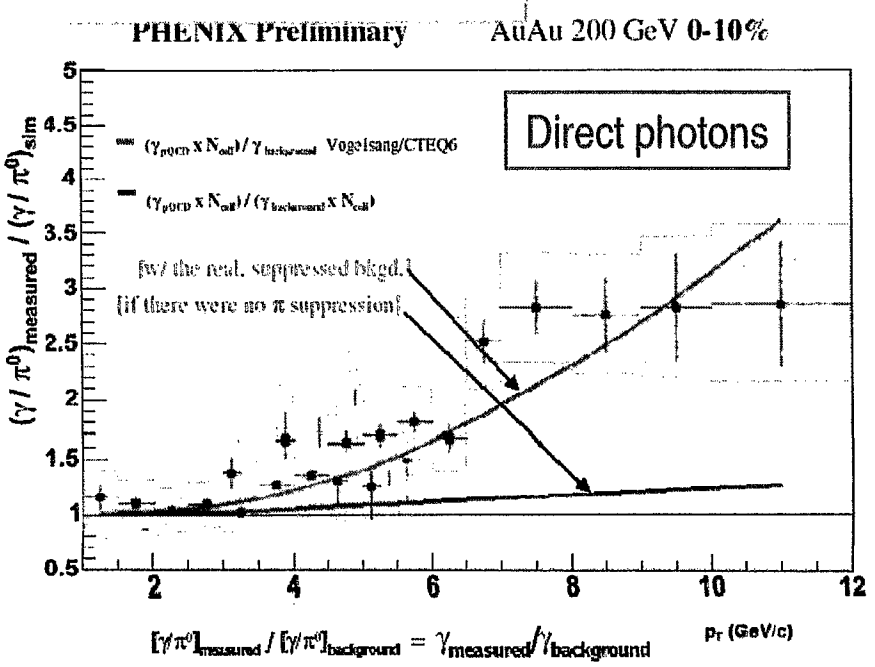


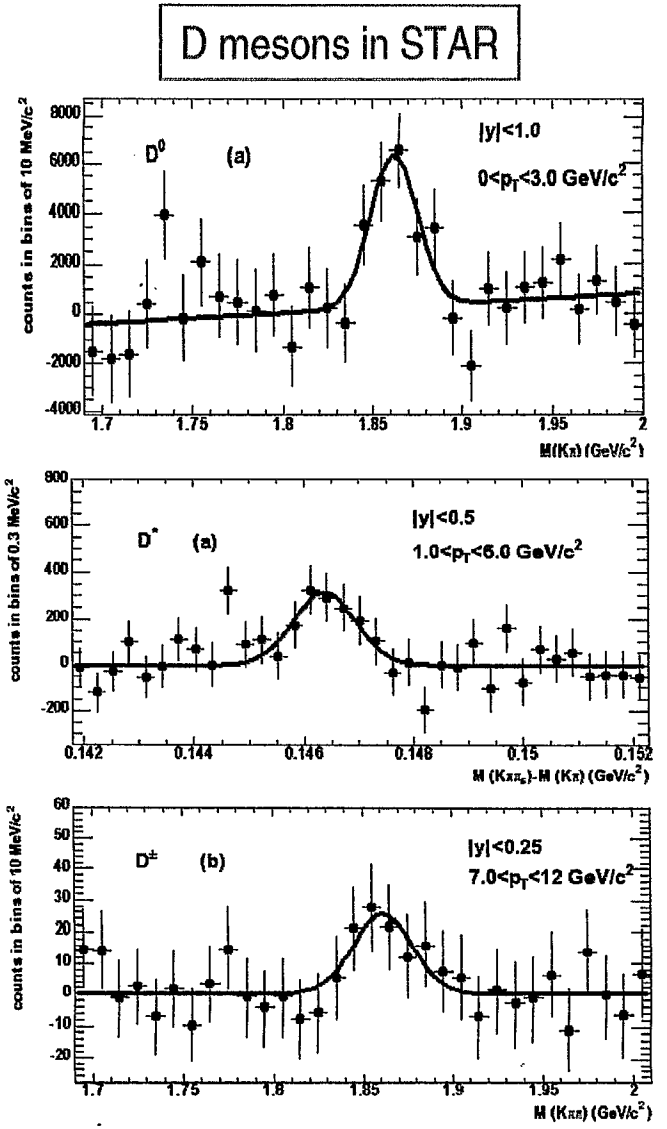


The data indicate a hot, dense medium of final state particles that is characterized by strong collective interactions at very high energy densities.

A Glimpse of future probes







In Summary

The early days at RHIC are over...

- High energy nuclear collisions have achieved temperatures and densities predicted to melt the QCD vacuum

- Direct comparisons can be made between experiment and theory (QCD)... not dependent on an array of phenomenological models

- The observed final particles are the product of an intermediate form of matter that has the earmarks of the Quark Gluon Plasma. We are left to discuss the adjectives.

Beginning a new chapter in Nuclear/ Particle/Condensed Matter Physics

Of course, there may be further surprises!

"...HOLD STILL, LARRY. IT'S TAKING ANOTHER PICTURE..."

Thanx to Jeff Mitchell

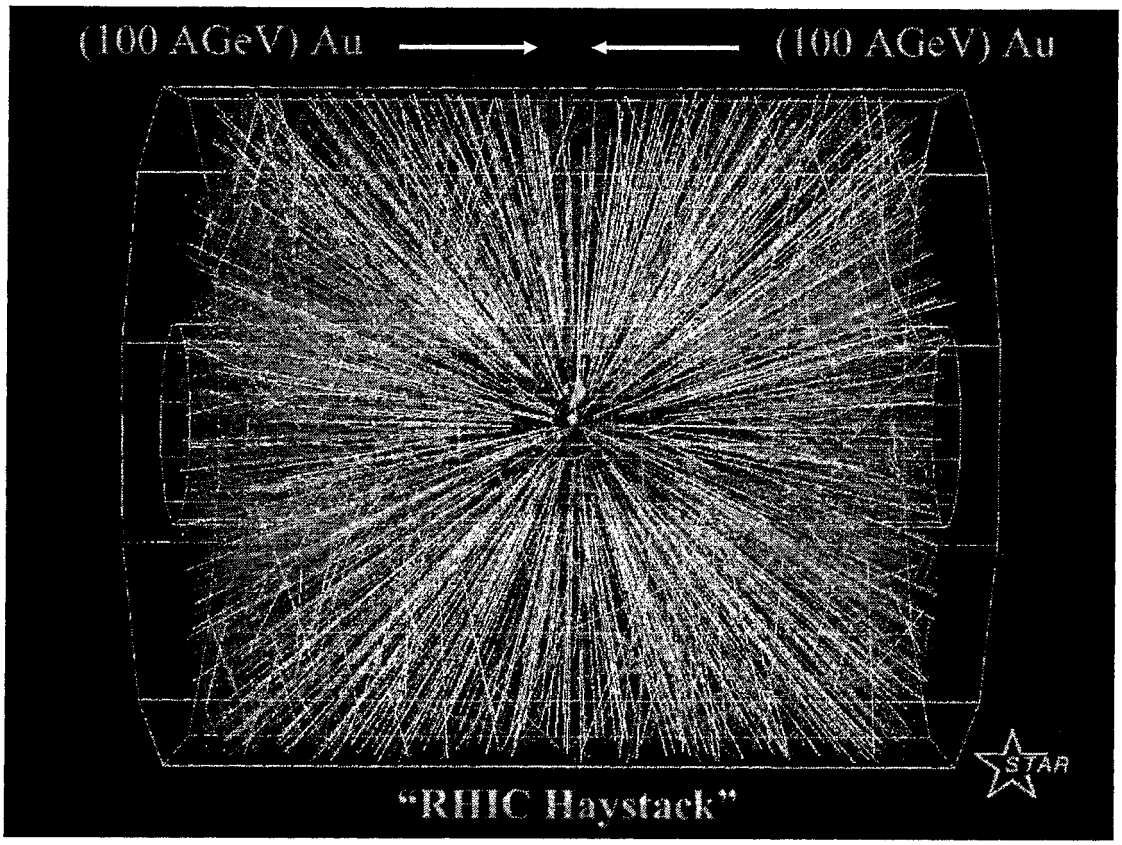
New Forms of QCD Matter
Discovered at RHIC

The Current Case for
1. Quark Gluon Plasma: sQGP
2. Color Glass Condensate: CGC

M.Gyulassy and L. McLerran

RBRC Scientific Articles Vol.9
nucl-th/0405013

RBRC/BNL 5/15/04 MGLM 1



"RHIC Haystack"

Mining some of the new physics from the

first 275 RHIC publications

22 (4 PRL) from BRAMHS

92 (15 PRL) from PHENIX

34 (6 PRL) from PHOBOS

127 (21 PRL) from STAR

Together with extensive SPS/CERN data base
E_{cm}=5 - 20 AGeV

(108 NA49/35, 69 NA50/38, 26 CERES/NA45,

79 WA98/80, 32 na57/wa97)

Theoretical Mining Tools using Rigorous but idealized Limits of the Standard Model

1. **Asymptotic free perturbative pQCD**
   short wavelength (high p_T)

2. **High temperature/density thermodynamics**
   nonperturbative Lattice QCD
   Long Wavelength (low p_T)

3. **High energy light cone QCD**
   Color Glass Condensate (small x)

The Empirical Evidence for QGP @ RHIC

- **Unique long wavelength collective properties**
  - **Elliptic flow ⇔ P_{QCD}**
- **Unique short wavelength dynamical properties**
  - **Jet Quenching ⇔ pQCD**
- **Conclusive Null Control with D+Au**

Big Surprise: exp. QGP = sQGP

Growing case for CGC

- **HERA e+p small x scaling ⇔ gluon saturation scale**
- **Energy and Nuclear Geometry dependence of Entropy production in Au+Au**
- **Deep gluon shadowing in high y D+Au**

What is a QGP?
Theoretical limit of Ultra-Hot Matter

1975 QCD Predicts

QGP

Asymptotic Freedom
Deconfinement
Chiral Symmetry

$$P_{QCD} \sim \tfrac{1}{3} K_{QCD} T^4 - B_{vac}$$ **TDL**

$$e_{QCD} \sim K_{QCD} T^4 + B_{vac}$$

$$c_s^2 = dP/d\varepsilon$$

Equation of State

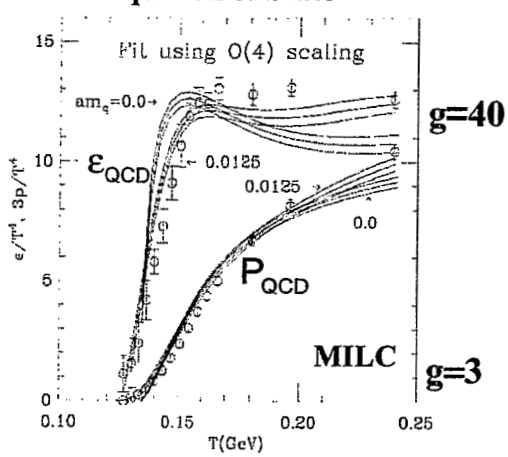


Figure 10: The $am_q = 0$ equation of state from a fit to the data that includes the O(4) universal scaling function. Also shown is the data and the fit at $am_q = 0.0125$ for comparison. Again, there is only a weak mass dependence. The "bump" just after the transition is likely an artifact of the extrapolation. The solid lines correspond to the central value and a one standard deviation above and below this result (statistical errors only).

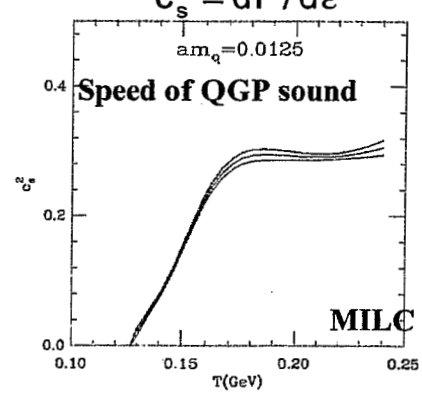


Figure 11: The speed of sound squared from a fit to the data that includes the O(4) universal scaling function. c_s^2 rises rapidly in the crossover region and then approaches the free gas result, 1/3. The low temperature result is probably not accurate (see text). The solid lines correspond to the central value and a one standard deviation above and below this result (statistical errors only).

MI 7

What is a CGC?
Theoretical limit of High energy Matter

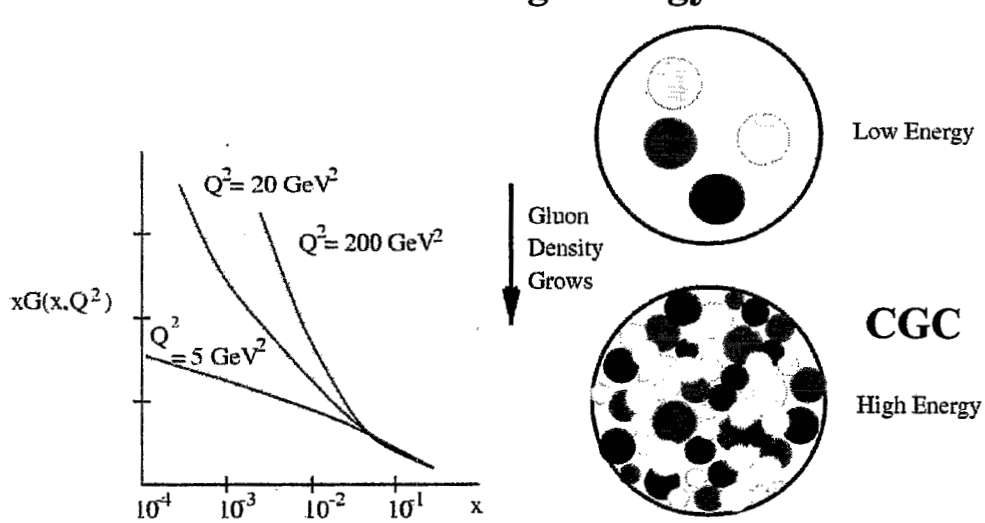
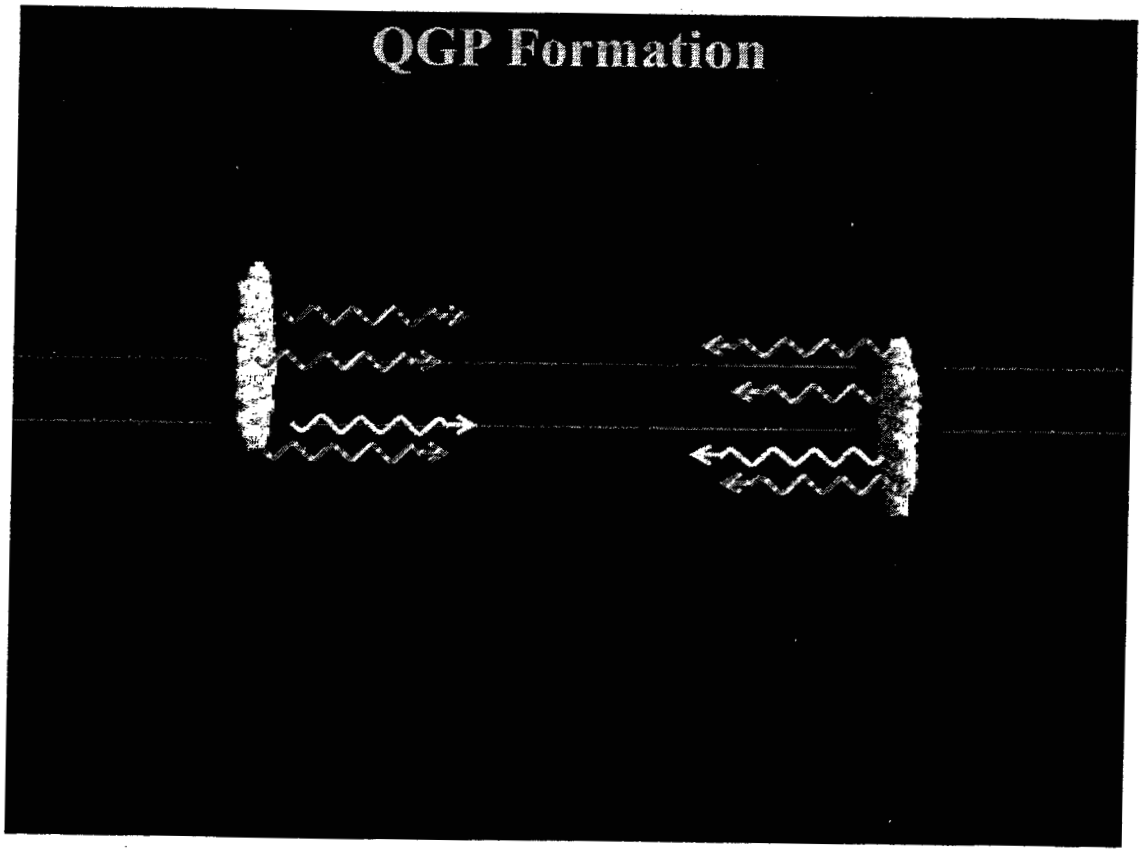


Figure 3: (a)The HERA data for the gluon distribution function as a function of x for various values of Q^2. (b) A physical picture of the low x gluon density inside a hadron as a function of energy

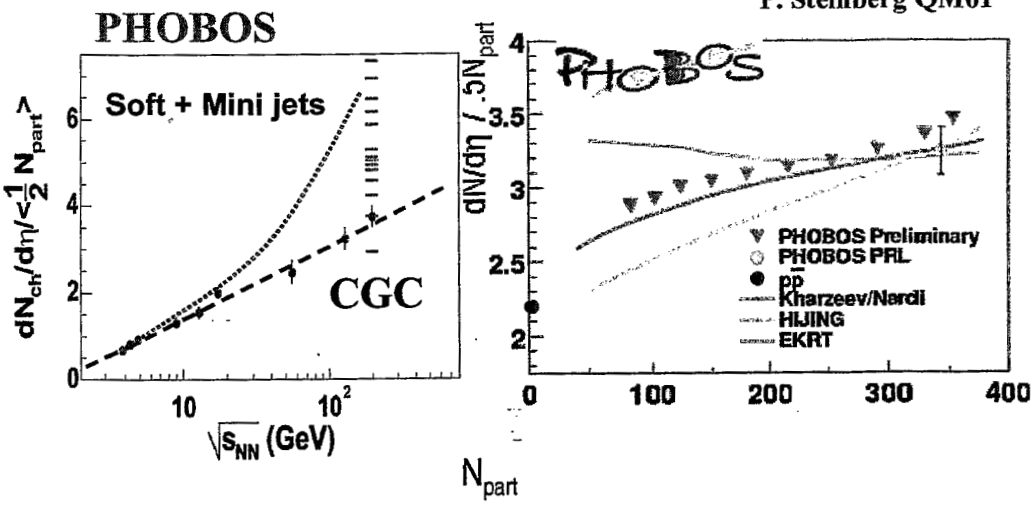
Gribov et al, McLerran Venugopalan ... (see Blaizot)



Entropy Production at RHIC

Slow Centrality and Energy Depend. of dN_{ch}/dy => CGC

P. Steinberg QM01

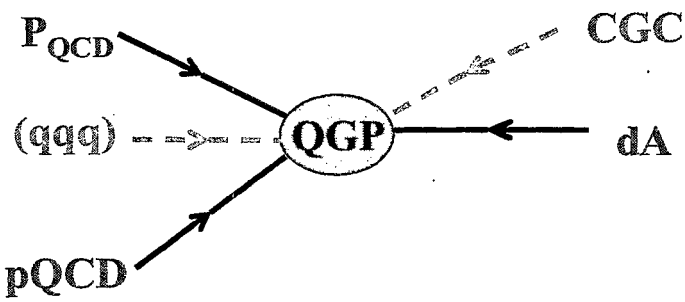


dN_g/dy~200 HIJING " r_{glue} (t_0=0.2 fm/c) » 5/fm^3

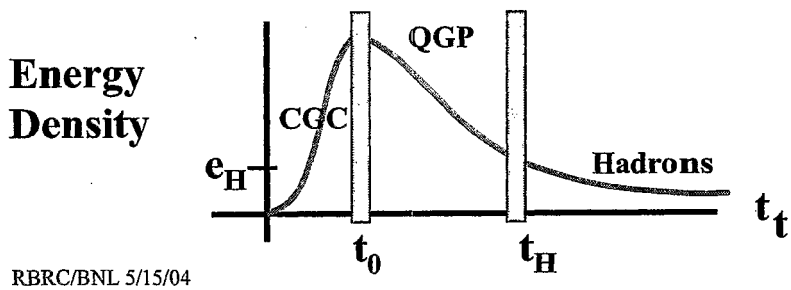
dN_g/dy~1000 CGC " r_{glue} (t_0=0.2 fm/c) » 25/fm^3

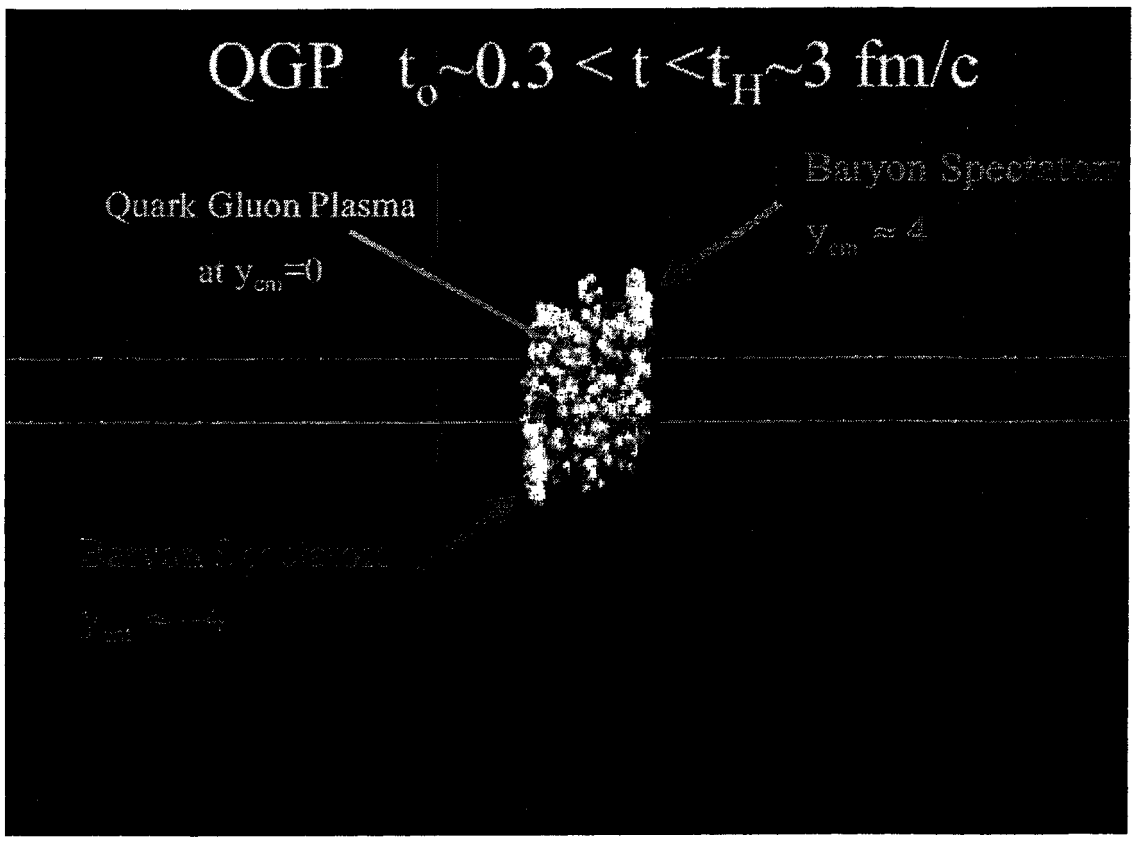
XNWang, MG, PRL86(01)3496

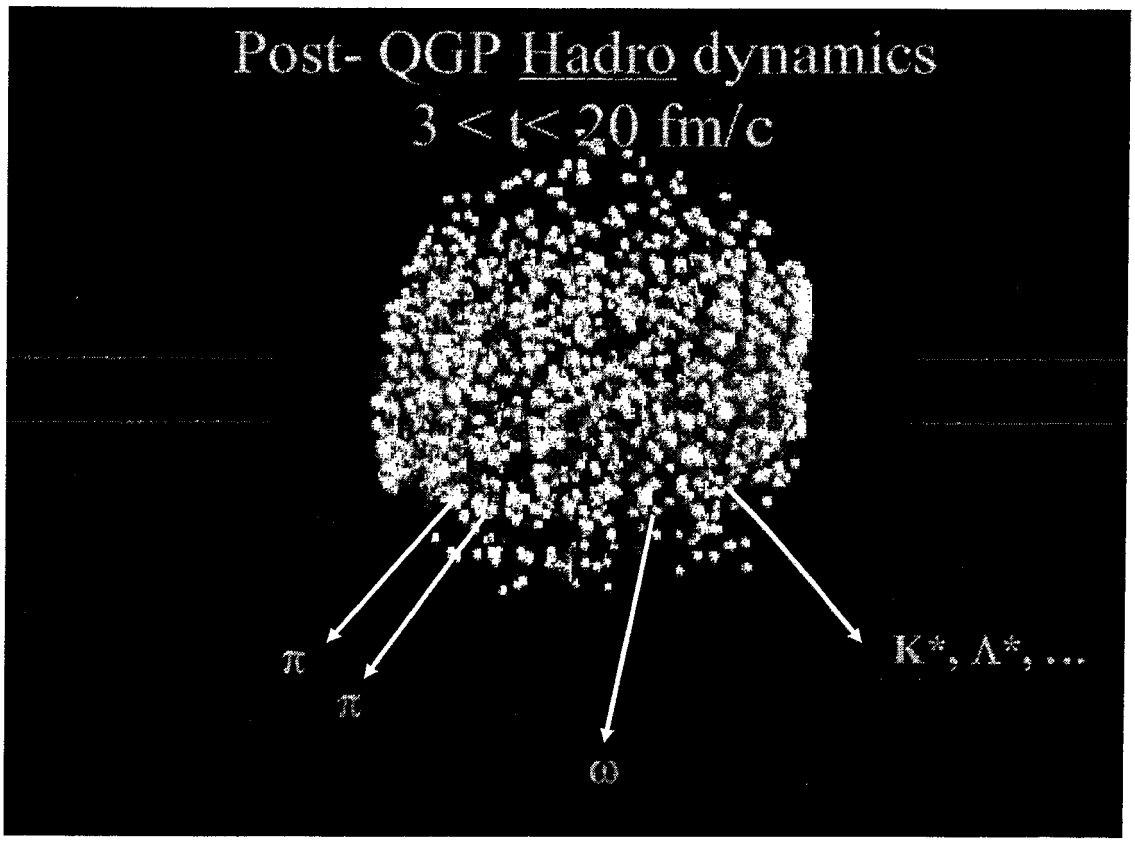
Finding the needles in the Haystack

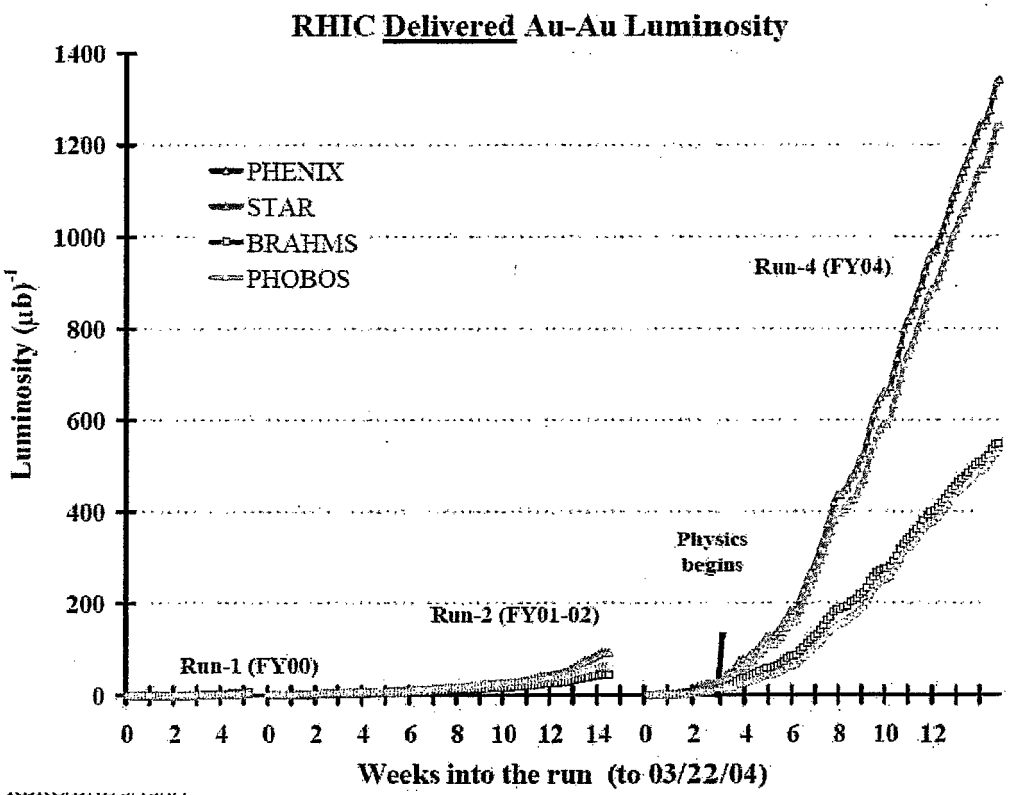


Haystack = *pre* - QGP Formation dynamics
+ *post* - QGP Hadronic dynamics






Post- QGP Hadro dynamics
3 < t< 20 fm/c
π
π
ω
K*, Λ*, ...


RHIC Delivered Au-Au Luminosity
Luminosity (μb)-1
1400
1200
1000
800
600
400
200
0
PHENIX
STAR
BRAHMS
PHOBOS
Run-4 (FY04)
Physics begins
Run-2 (FY01-02)
Run-1 (FY00)
0 2 4 0 2 4 6 8 10 12 14 0 2 4 6 8 10 12
Weeks into the run (to 03/22/04)

Bulk Collective Flow of QCD matter

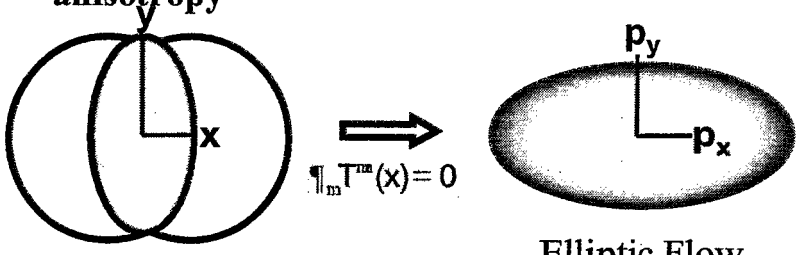
$$\P_m T^{mn} = \P_m \{u^m u^n (e(T) + P(T)) - g^{mn} P(T)\} = 0$$

QCD EOS

W. Greiner, H. Stocker(1974)
...
P.Kolb, U. Heinz et al (2000)
D.Teany, E. Shuryak
T. Hirano, Y. Nara

Initial *spatial* **anisotropy**

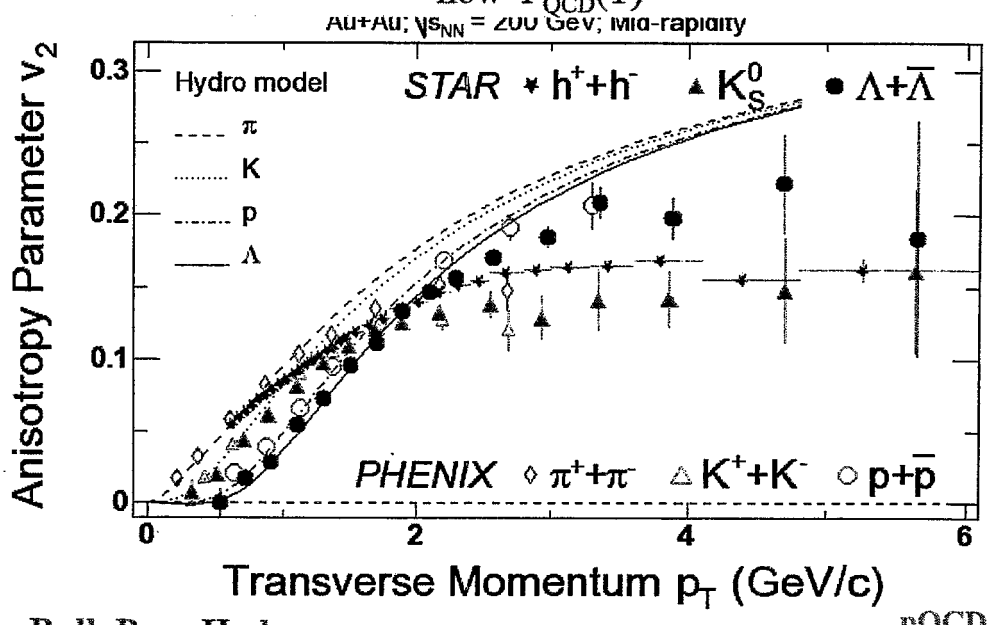
Final ***momentum*** **anisotropy**



Elliptic Flow

$$\frac{dN}{dy\,dp_T^2\,d\phi} = \rho(y, p_T)\{1 + 2v_2(p_T)\cos(2\phi) + L\}$$

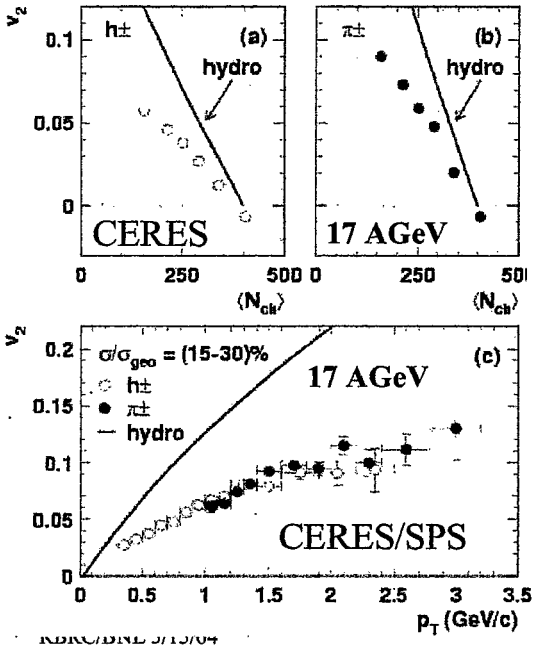
The QGP Fingerprint at RHIC = Fine Structure of collective flow $P_{QCD}(T)$



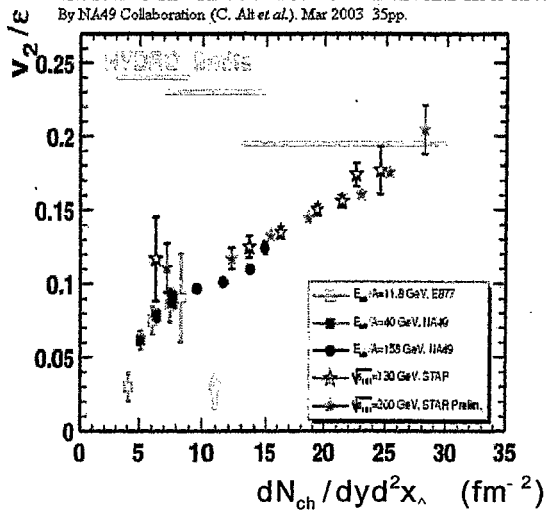
Bulk P_{QCD} Hydro ⟷ **qqq Coalescence** ⟶ **pQCD Jets**

Below RHIC energies, QCD hydro over-predicts elliptic flow!

$v_2(E_{cm}) \Longrightarrow$ QGP hydro only works at RHIC



2) DIRECTED AND ELLIPTIC FLOW OF CHARGED PIONS AND PROTONS IN PB + PB COLLISIONS AT 40-A-GEV AND 158-A-GEV.
By NA49 Collaboration (C. Alt et al.). Mar 2003 35pp.



Conclusive evidence for
Long wavelength flow with unique fine structure

$v_2(p_T, m_h, b)$ consistent with $P_{QCD}(T)$

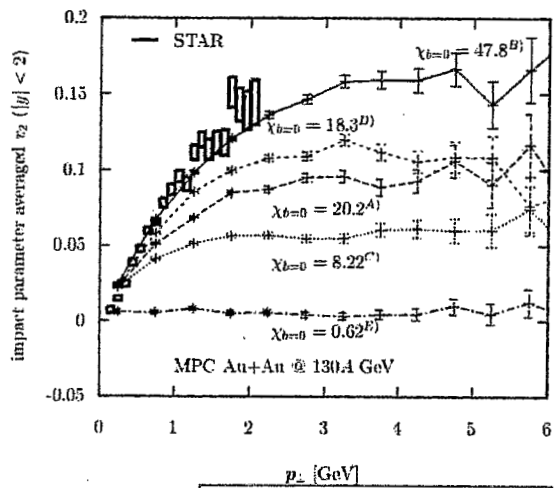
But how could Euler ideal fluid work?

It never worked on nuclear scale before!!

The QGP is almost a perfect fluid !

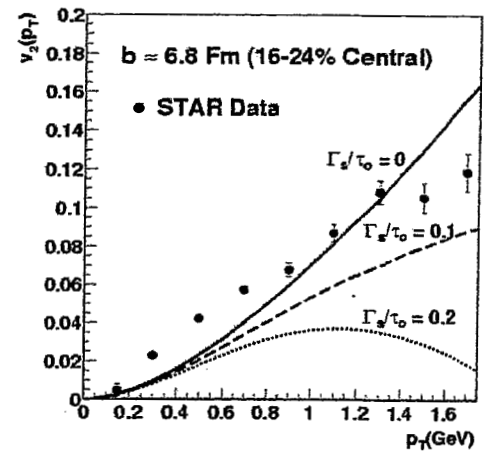
Gluon Transport

Molnar, MG (01)



Navier-Stokes

Teaney (03)

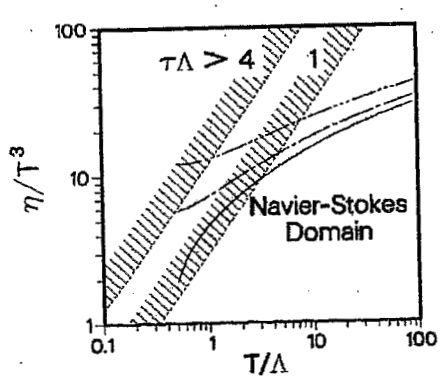


Opacity $\chi = \int d\tau\, \sigma \rho \approx \frac{dN_g}{dy} \frac{\sigma_g}{\pi R^2}$

Viscosity / Entropy density of QGP

$$\frac{\eta}{\sigma} \approx \frac{1}{3}\frac{\rho}{\sigma}\langle p\rangle \lambda \approx \frac{1}{12}\langle p\rangle \lambda \approx \frac{T\lambda}{4}$$

Ultra-rel. $\sigma = 4\rho\,,\ \langle p\rangle = 3T$



pQCD

Danielewicz, MG (85)

$$\frac{\eta}{\sigma} \approx \frac{\pi}{g^4 \log 1/g} \ ?\ 1$$

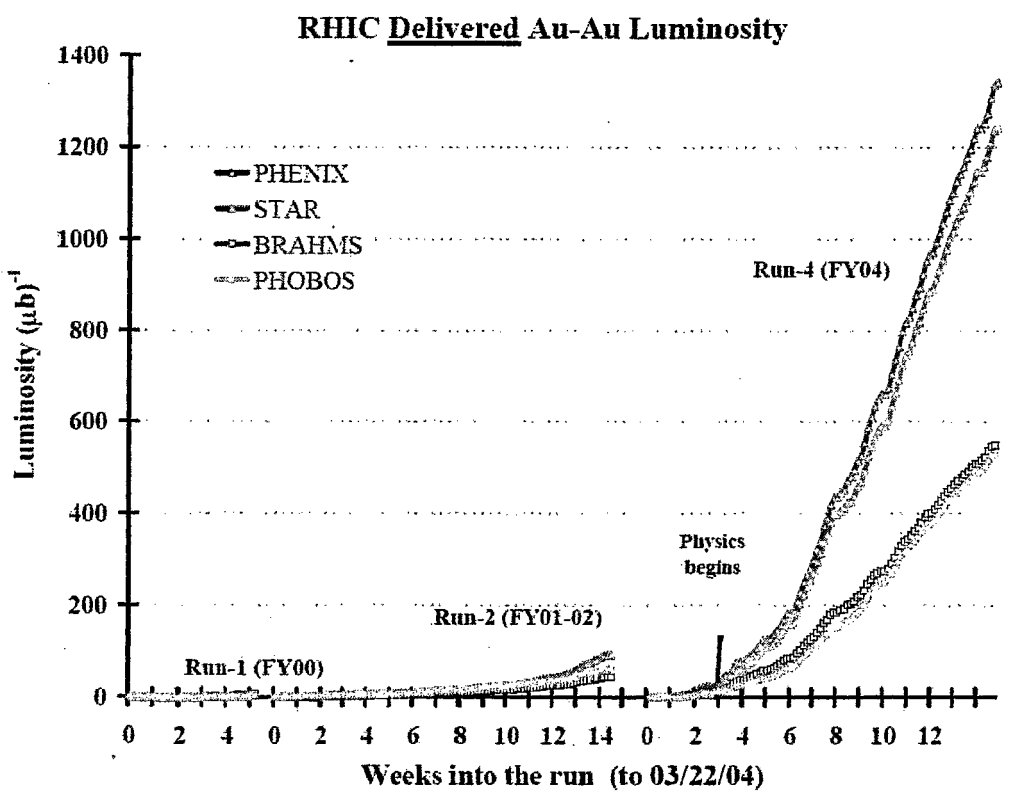
Conclusion 1

Not only does P_{QCD} account quantitatively for the fine structure (p_T , m_h) of elliptic flow at RHIC

But, also the QGP at $T<3T_c$ saturates the *minimal* viscosity bound!

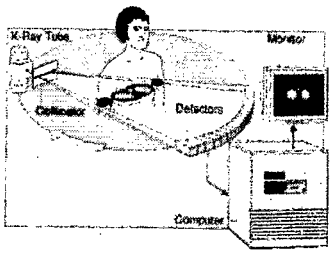
QGP found at RHIC = new form of strongly coupled plasma sQGP

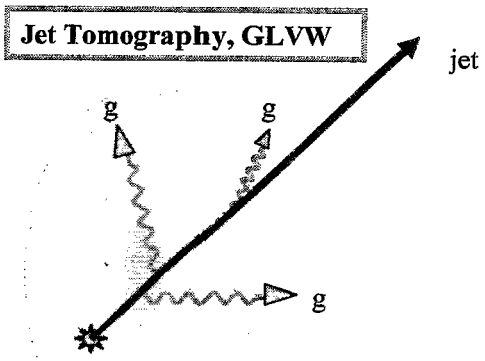
RBRC/BNL 5/15/04 MG,LM 21



Jet Quenching

MG, P. Levai, I.Vitev, X.N. Wang **(see Wang)**



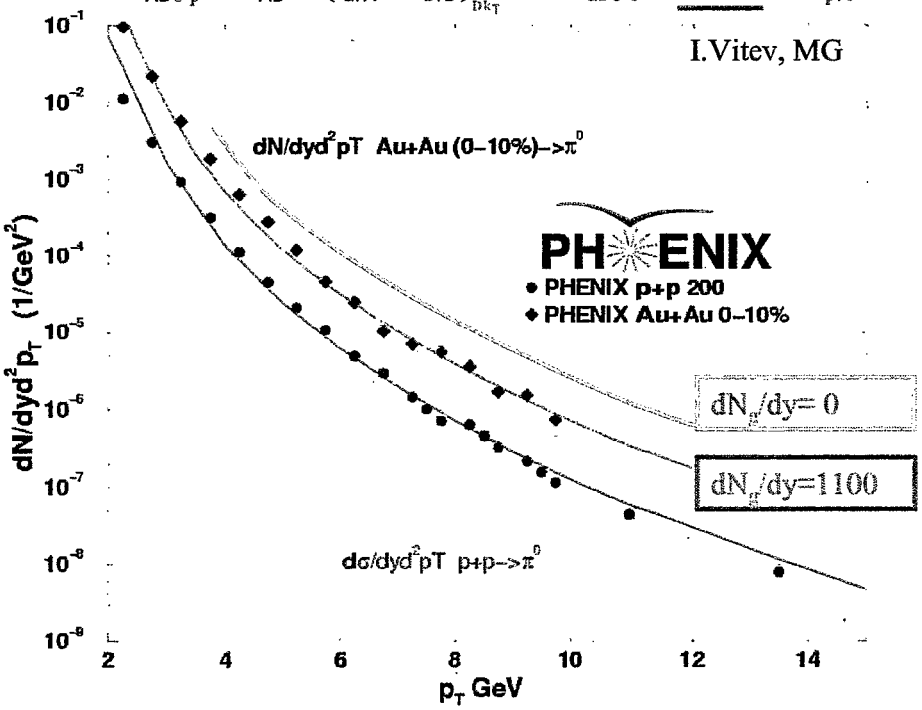


$$\Delta E_{GLV} : C_2 \alpha_s^3 E_0 \int d\tau \, \tau \rho_{glue}(\tau, r(\tau))$$

$$dN_{AB\to p} = T_{AB} \otimes (f_{a/A} \otimes f_{b/B})^{shad}_{Dk_T} \otimes ds_{ab\to c} \otimes \underline{P(DE)} \otimes D_{p/c}$$

GRV
EKS
BKK
GLV

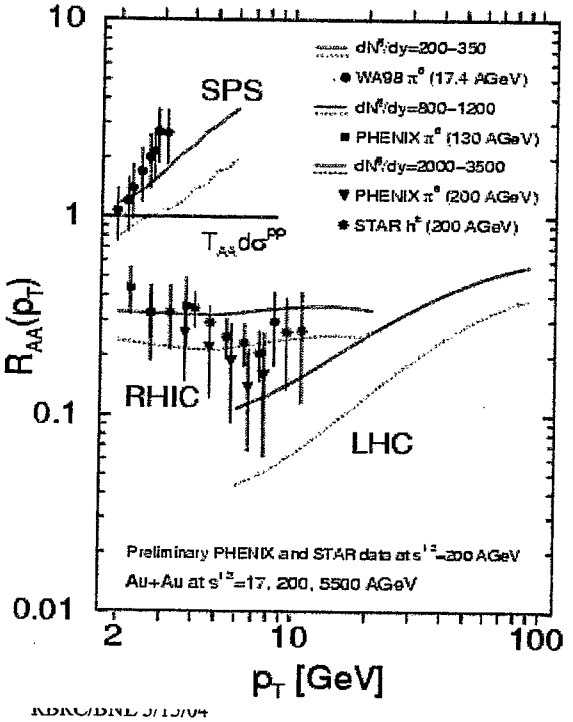
I.Vitev, MG



Absolute scale pQCD jet tomography

Single Hadron Tomography from SPS, RHIC, LHC

Ivan Vitev and MG, PRL 89 (2002)



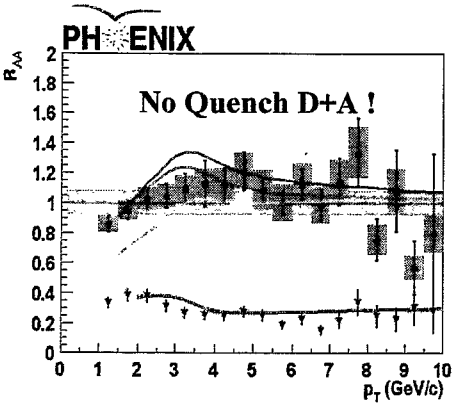
1) **Cronin *enhancement* dominates at SPS**

2) **Cronin+Quench+Shadow conspire to give ~ flat $R_{AA} \sim N_{part}/N_{bin}$ at RHIC**
$dN_g/dy \sim 1000 \rightarrow r_g \sim 100\ r_0$

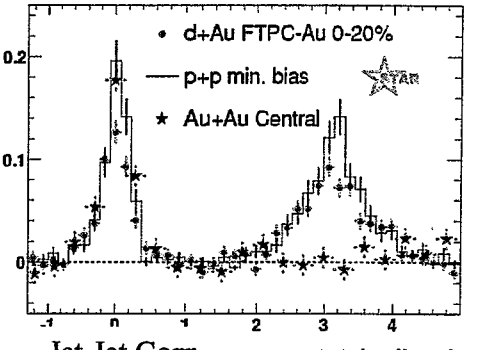
3) **Predict sub N_{part} quench, positive p_T slope of R at LHC**

Third Line of Evidence at RHIC

" Return of the Jeti "



Strong Quench A+A



Jet-Jet Corr. $\Delta\phi$ (radians)

dA=Critical Control Experiment

Conclusion 2

The nearly perfect fluid QGP seen through long wavelength collective flow

Has a predicted pQCD high opacity To short wavelength $2p/p_T << 1$ fm probes

Seen through jet quenching

(1) $P_{QCD} = v_2(p_T, m_h, b)$

(2) $pQCD = R_{AA}(p_T, b) + I_{AA}(f, p_T, b)$

RBRC/BNL 5/15/04

MG,LM 27

Four independent calibrations of Initial QGP density

$$e(t_0) \gg 100\, e_0 = 15\ \mathrm{GeV/fm^3}$$

1. Bjorken Backward extrapolation

$$E_T/N_p = 0.5\ \mathrm{GeV},\quad dN_p/dy = 1000,$$
$$t_0 = 1/p_0 = 0.2\ \mathrm{fm/c},\quad V = (0.2\ \mathrm{fm})pR^2 = 30\ \mathrm{fm}^3$$
$$e_{Bj} = 500\ \mathrm{Gev}/30\ \mathrm{fm}^3 = 100\, e_0$$

2. Hydrodynamic initial condition needed for $v_2(p_T)$

$$e_{Hydro} : e_{Bj} : 100\, e_0$$

KHH
TS
HN

3. Jet Tomography: $dN_g/dy = 1000$

$$e_{Jets} \gg e_{Bj} \gg 100\, e_0$$

GLV
WW

4. Gluon saturation $p_T < Q_s$ predicted
$dN_g/dy = 1000$ at $Q_{sat} = 1$ GeV at $y=0$

MB
McV
EKRT

RBRC/BNL 5/15/04

MG,LM 28

Conclusions:

Overwhelming <u>empirical</u> evidence for a new form of matter sQGP with unexpected properties

Growing evidence that its source is a Gluon saturated CGC

Many puzzles remain (baryon/pi , HBT, ...)

Theoretical understanding is improving

RIKEN-BNL ``discoveries" workshop, May 15 2004

Strongly coupled quark-gluon plasma (sQGP)

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

Outline of the talk

Motivations:

- **Reduced scale => enhanced coupling**
- **Hydro works and QGP seem to have remarkably small viscosity**
- **Lattice bound states and large potentials**

New spectroscopy

(the bulk of the talk)

•Multiple bound states, 90% of them colored? If so, it explains several puzzles related to lattice results:

•Why resonances in correlators (MEM)?

•How rather heavy quasiparticles can create high pressure already at T= 1.5-2 Tc?

(Outline continued)

What can we learn from other strongly coupled systems?

Trapped Li atoms at Feshbach resonance

N=4 SUSY YM at strong coupling

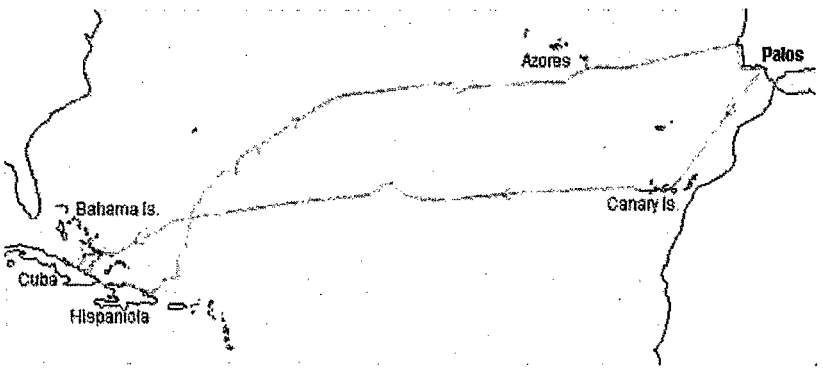
New ideas

Vectors in QGP and dileptons

Jet quenching due to ``ionization" of new bound states

Digression 1: One may have an absolutely correct theory and still make accidental discoveries…

Columbus believed if he goes west he should eventually come to India

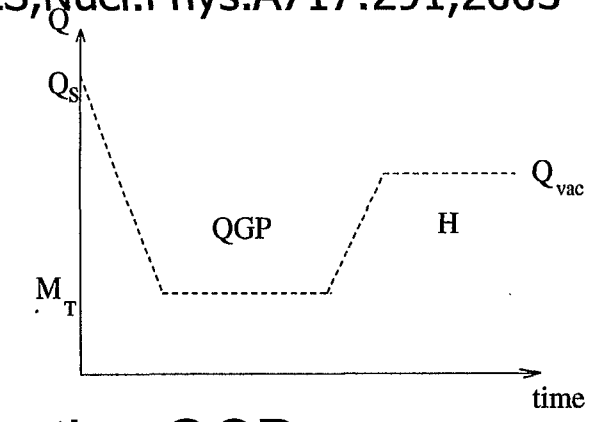


But something else was on the way…

We believed if we increase the energy density, we should eventually get weakly interacting QGP. But something else was found on the way…

Motivation 1: How far does the coupling run in QGP? (general ideas)

ES,Nucl.Phys.A717:291,2003



- In a QCD vacuum the domain of perturbative QCD (pQCD) is limited by non-pert. phenomena, e.g. by the Q(chiral) of about 1 GeV , as well as by confinement etc.: $\alpha_s < 0.3$ 0r so
- At high T we get weak coupling because of screening $\alpha < \alpha(gT)$ ¿ 1 (the Debye mass M_d» gT sets the scale)
- In between, $T_c < T <$ few T_c, there is no chiral/conf. scales

While Md is not yet large: here $\alpha(M_d)$ may be » 1 (?) (M_d¼ 2T» 350-400 MeV only)

Motivation 2: RHIC produces ``matter", not a fireworks of partons

What it means?

$l << L$

(the micro scale) << (the macro scale)

(the mean free path) << (system size)

(relaxation time) << (evolution duration)

- Good equilibration (including strangeness) is seen in particle rations (as at SPS)

- **the zeroth order in l/L is called an ideal hydro with a local stress tensor.**

- **Viscosity** is the **first order O(l/L) effect, » velocity gradients.** Note that η» l» $1/\sigma$ n is inversely proportional to the cross section and is (the oldest) **strong coupling expansion tool**

Digression 2, a 1980's motivation why we thought we should collide heavy ions, or:

The QCD vacuum vs the QGP

- The ``physical vacuum" is very complicated, dominated by ``topological objects", Vortices, monopoles and instantons
- Among other changes it shifts its energy down as compared to an "empty" vacuum,

The Bag terms, $p=\#T^4-B$

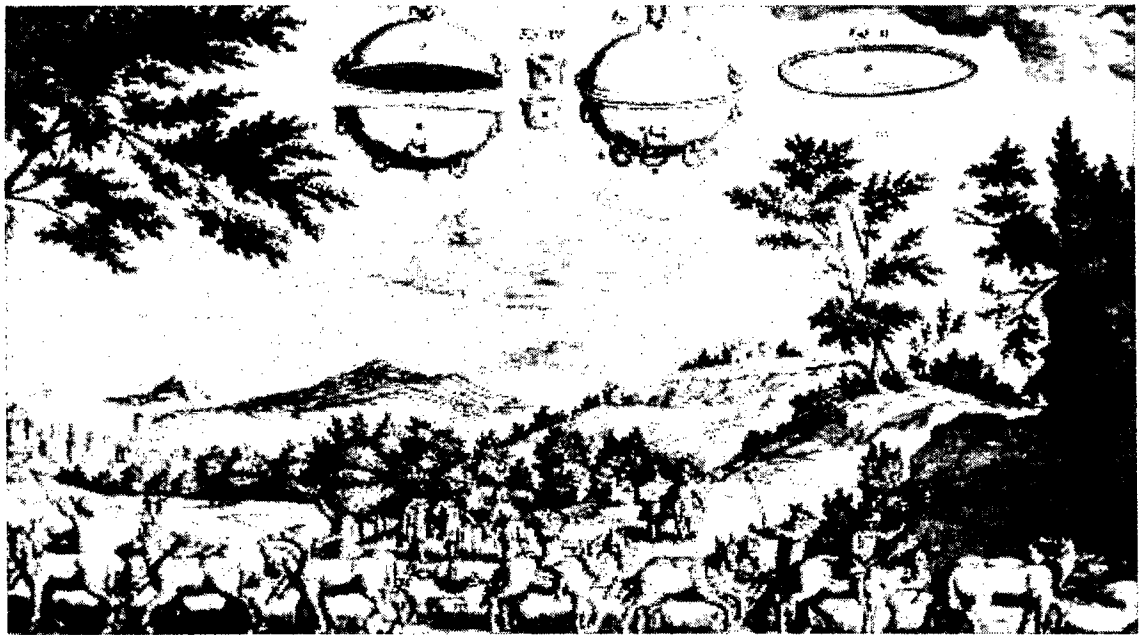
$\varepsilon=\#T^4+B$

- The QGP, as any plasma, screens them, and is nearly free from them
- So, when QGP is produced, the vacuum tries to expel it

(recall here pumped out Magdeburg hemispheres

By von Guericke in 1656 we learned at school)

Magdeburg hemispheres 1656

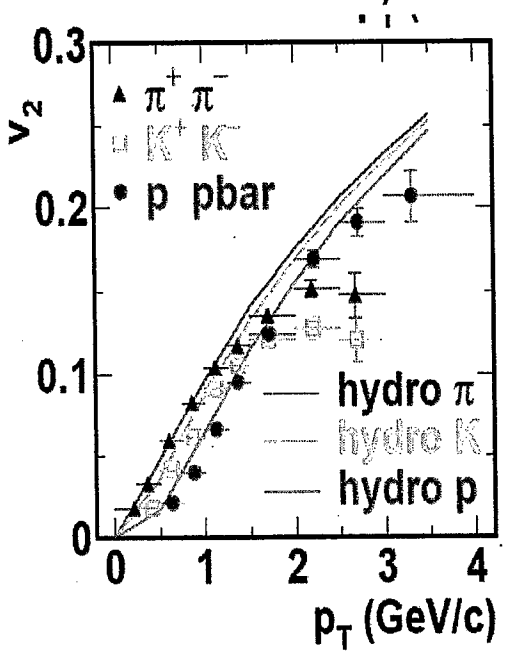


- **We cannot pump the QCD vacuum out, but we can pump in something else, namely the Quark-Gluon Plasma**

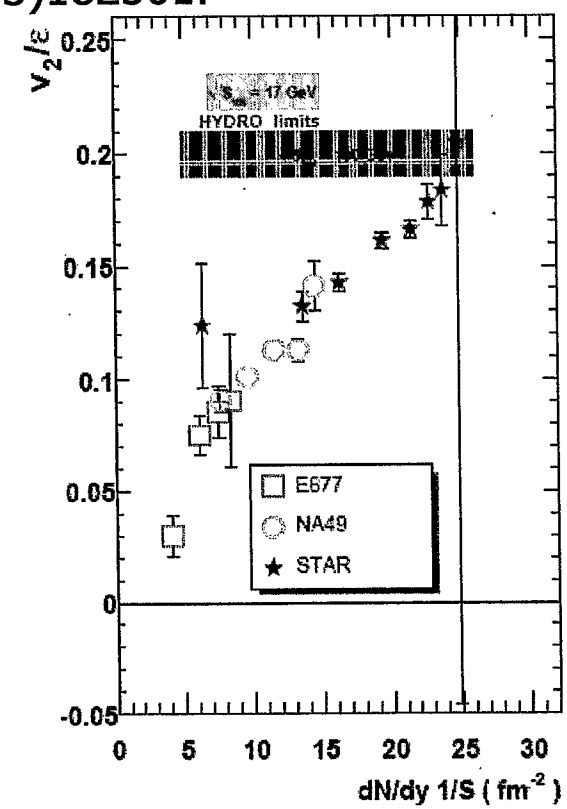
- **QGP was looked at as a much simpler thing, to be described by pQCD. We now see it is also quite complicated matter, sQGP...**

(Back to the main track)
Flows, especially the Elliptic Flow

PHENIX, PRL91('03)182301.



STAR, PRC66('02)034904

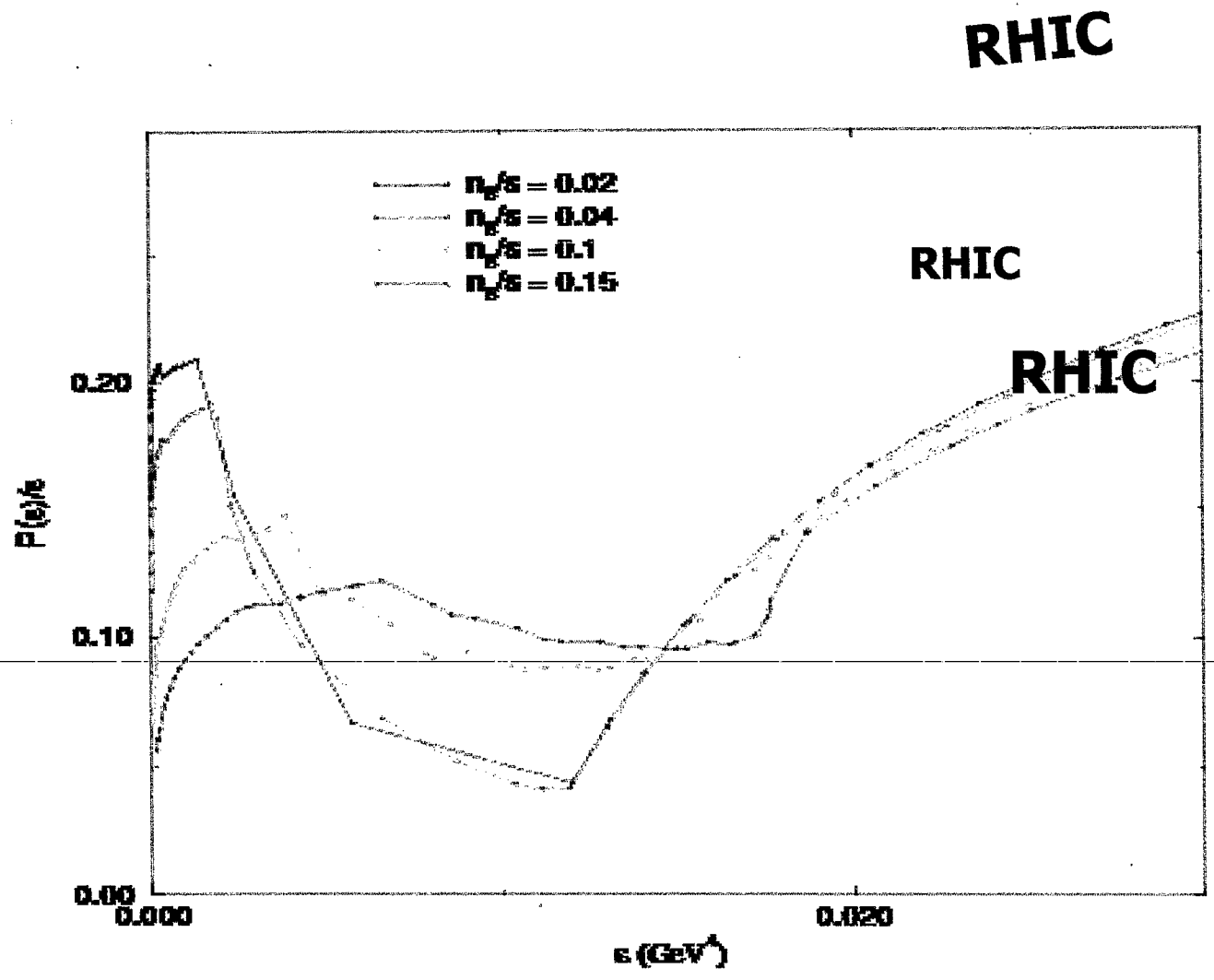


Elliptic flow rapidly rises with energy Because we have surpassed ``The softest point" and Entered the QGP with high p/ε ratio!

See details in a review by P.Kolb and U.Heinz, nucl-/0305084

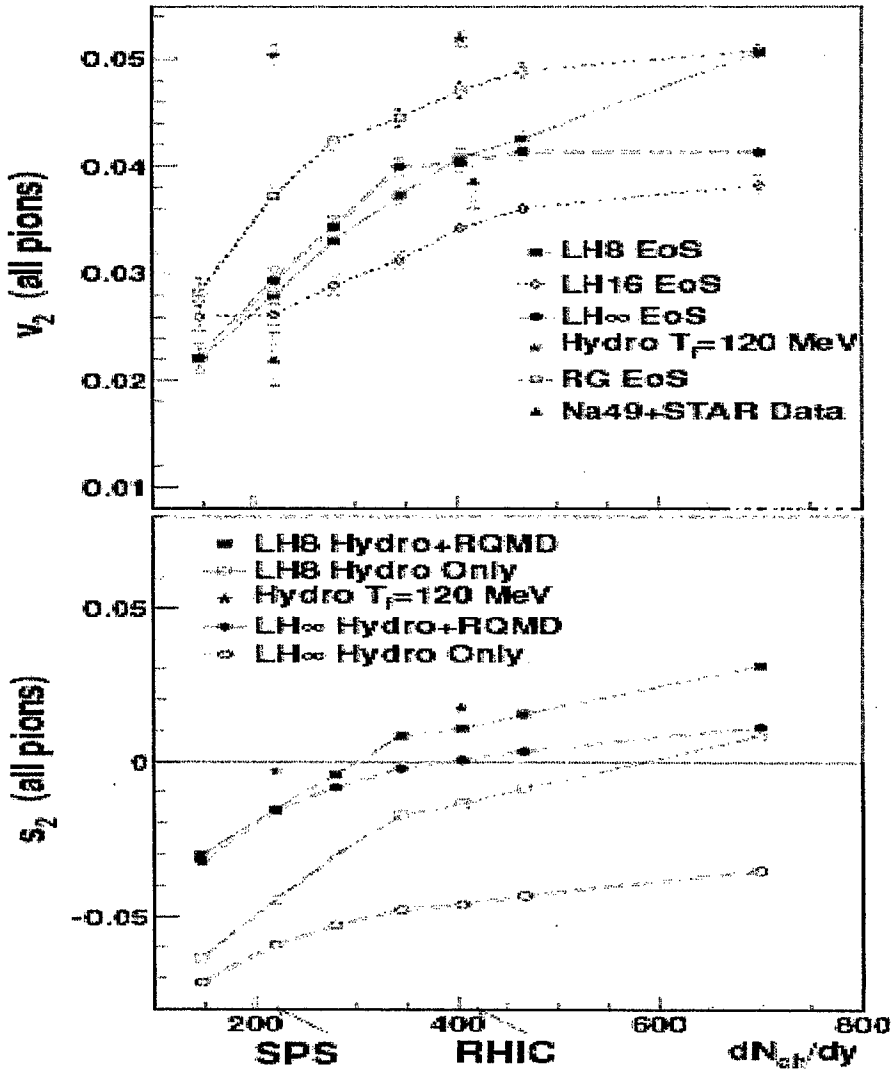
EoS along fixed n_B/s lines

M.Hung,ES,hep-ph/9709264,prc.



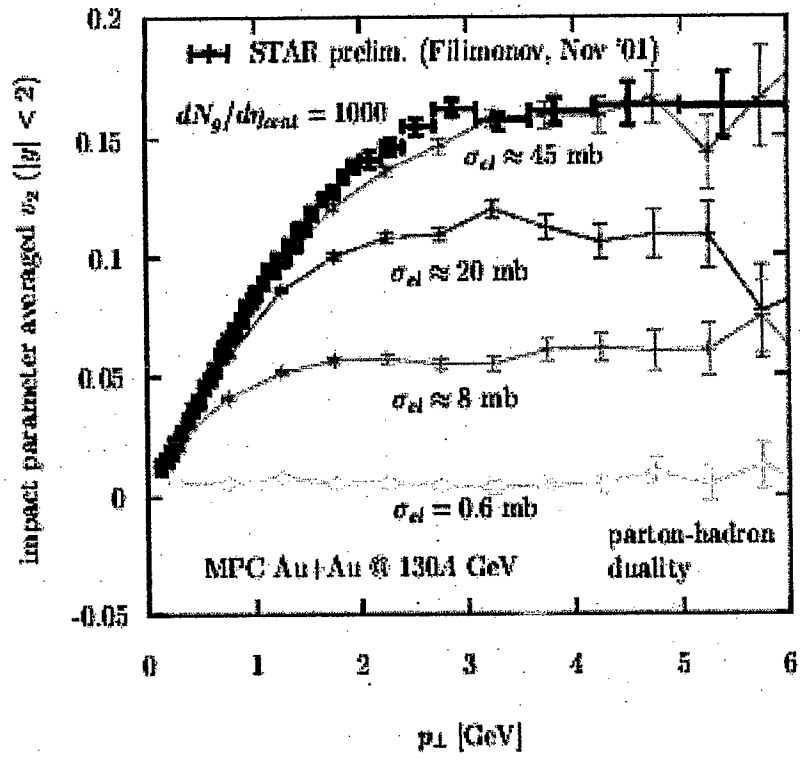
How to determine Eos p(ε) and viscosity η(ε)?

- To study all flows as function of collision energy and centrality



(Hydro+RQMDgives a better description Of energy dependence than pure hydro D.Teaney et al.('01)) because viscosity of hadronic matter and correct freezeout are included

Very large cross sections are needed to reproduce the magnitude of v_2!



parton transport solutions via MPC 1.6.0 [D.M. & Gyulassy, NPA 697 ('02)]

$$p^\mu \partial_\mu f_i = S_i + C_i^{2\to 2}[f] + \ldots$$

minijet initial conditions

$1g \longrightarrow 1\pi$ hadronization

Huge cross sections!!

- **saturation pattern can be reproduced with elastic $2 \to 2$ interactions, requires large opacities $\sigma_{el} \times dN_g/d\eta \approx 45000$ mb $\gg$ pQCD (3 mb $\times 1000$)**
  - **large opacities also suggested by pion HBT data** [D.M & Gyulassy, nucl-th/0211017]

Viscosity of QGP (D.Teaney,2003)

QGP at RHIC seem to be the most ideal fluid ever observed

Water would not flow if only a drop with 1000 trillion cells be made

- viscous corrections

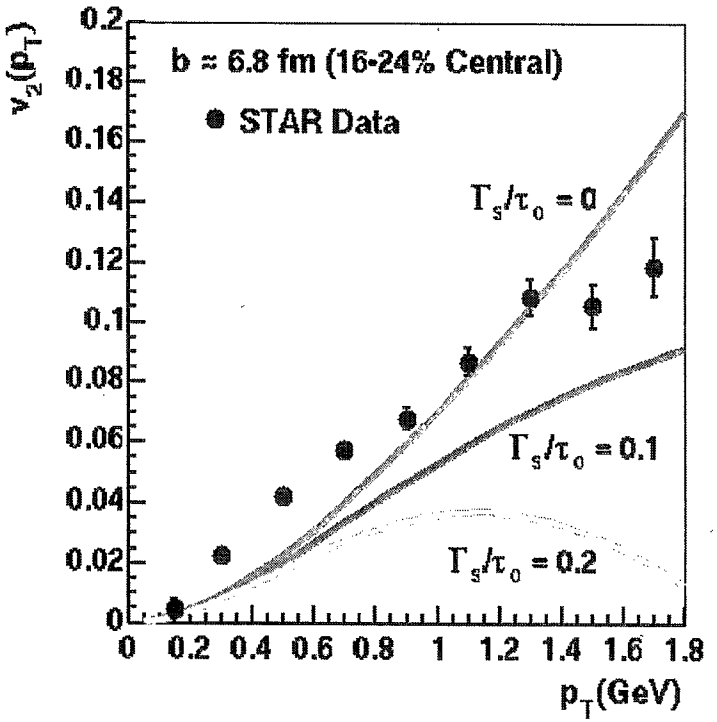
1st order correction to dist. fn.:

$$\text{Corr} \propto (\eta/s)p_t^2$$

Γ_s :Sound attenuation length

$$\Rightarrow \eta/s \approx 1/10$$

Nearly ideal hydro !?



Motivation 3: lattice puzzles

- Since Matsui-Satz and subsequent papers it looked like even heavy charmonium dissolves in QGP (thus the QGP signal)
- And yet recent works (Asakawa-Hatsuda,Karsch et al) have found, using correlators and MEM, that it survives up to about T=2Tc . What was wrong?

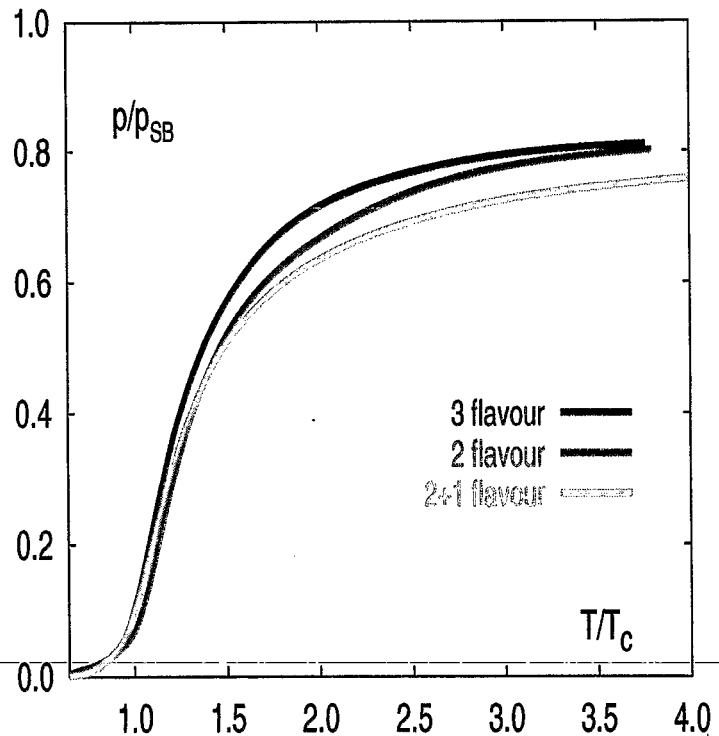
Resolved by correct treatment with entropy removed (see below, when we put it into Schr. Or KG)

- The lattice potentials come from a correlator of static quarks. Then the free energy

  exp[-F(T;R)] =< L(T)L+(0) > should be related to potential energy V (r) = F - TS where the latter entropy part is just a derivative over T
- This simple fact (pointed out only recently by the Bielefeld group) **makes potentials much deeper and the effective coupling stronger**.

The pressure puzzle

(GENERAL)



Well known lattice prediction (numerical calculation, lattice QCD, Karsch et al) the pressure as a function of T (normalized to that for free quarks and gluons)

- **This turned out to be the most misleading picture we had, fooling us for nearly 20 years**

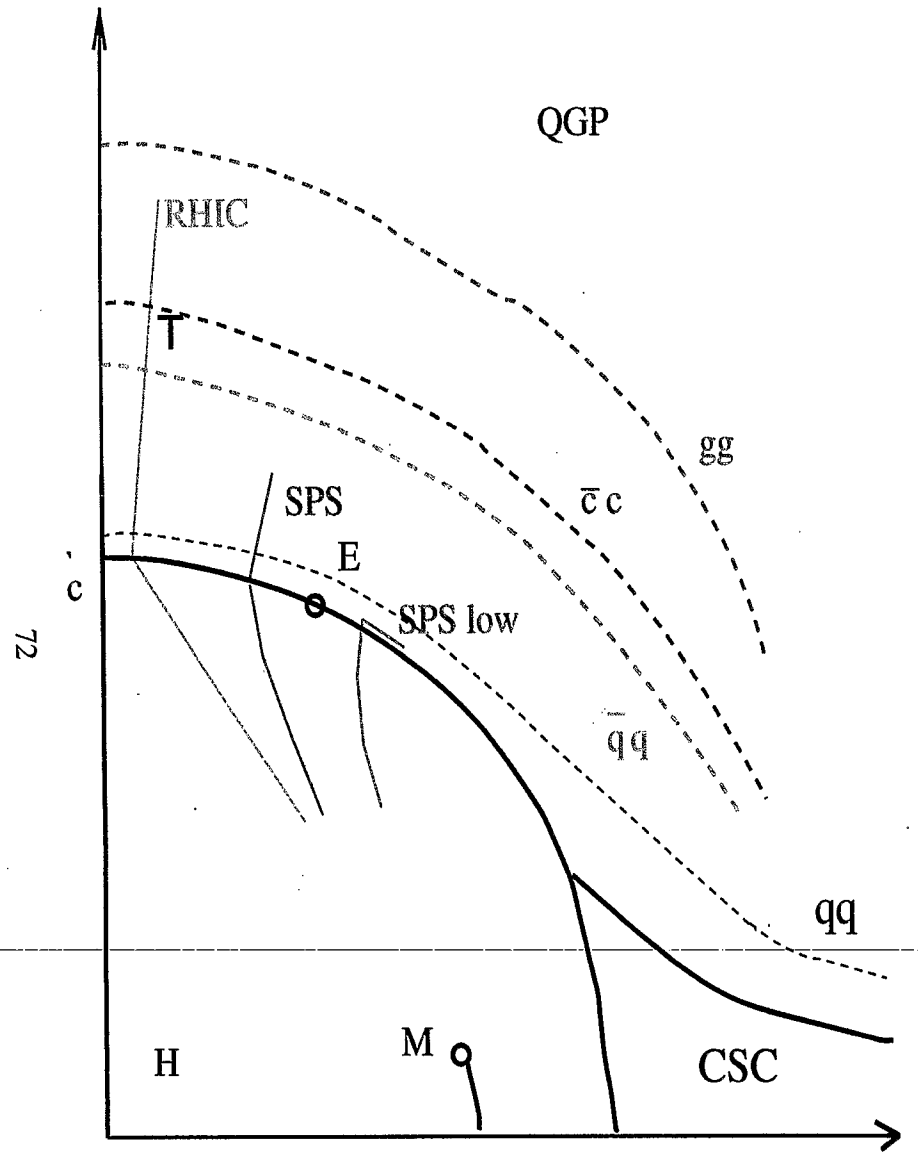
- p/p(SB)=.8 from about .3 GeV to very large value. Interpreted as an argument that interaction is relatively weak (0.2) and can be resumed, although pQCD series are bad...

BUT: we recently learned that storng coupling leads to about 0.8 as well!

(The pressure puzzle, cont.)

- How quasiparticles, which according to direct lattice measurements are heavy (Mq,Mg = 3T) (Karsch et al) can provide enough pressure? (exp(-3)»1/20)
- (The same problems appears in N=4 SUSY YM, where it is parametric, $\exp(-\lambda^{1/2})$ for large λ´ g^2N_cÀ 1)

New QCD Phase Diagram, which includes ``zero binding lines" (ES+I.Zahed hep-ph/030726)



The lines marked RHIC and SPS show the paths matter makes while cooling, in Brookhaven (USA) and CERN (Switzerland)

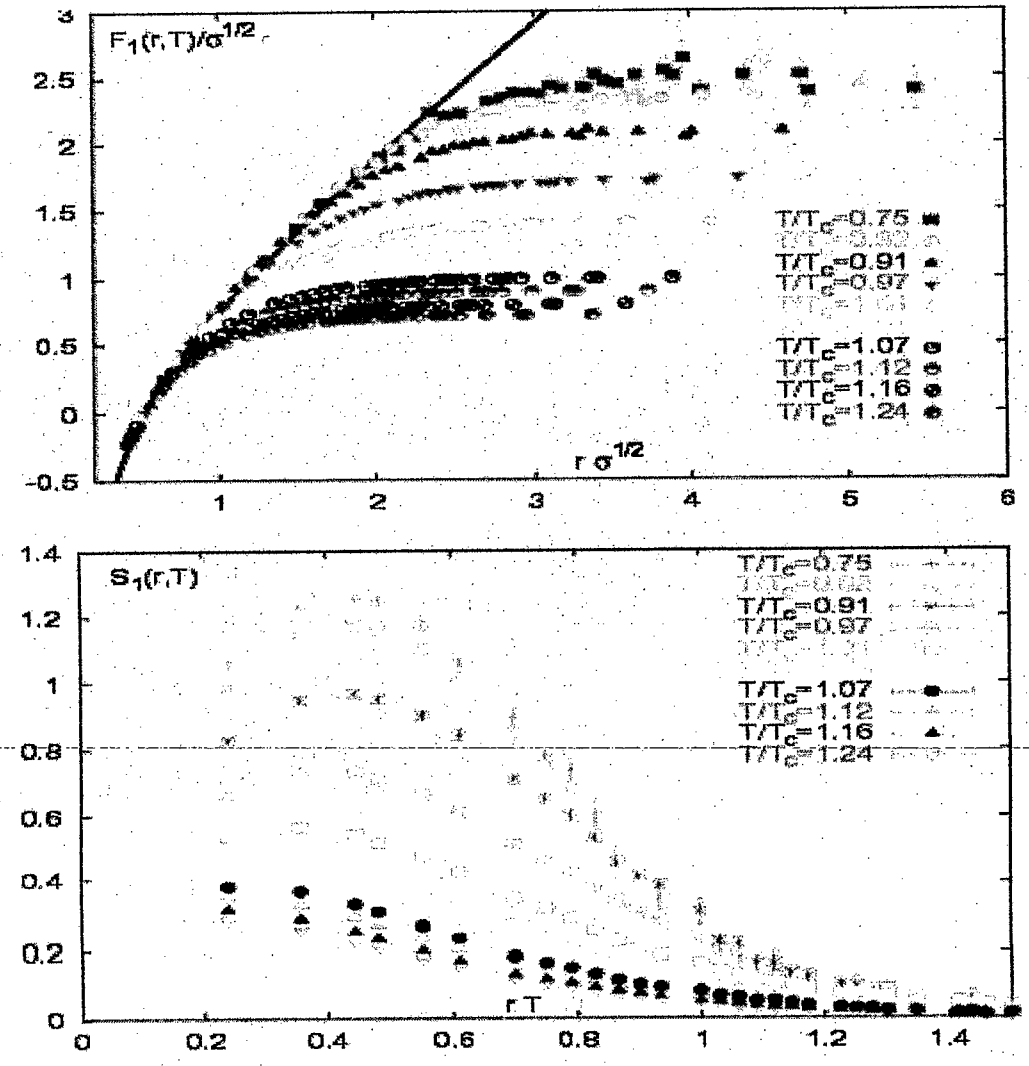
Chemical potential μ_B related to baryon charge

For a screened Coulomb potential, a simple condition for a bound state

- $(4/3)\alpha_s\ (M/M_d) > 1.68$
- M(charm) is large, M_d is only about 2T
- If $\alpha(M_d)$ indeed runs and is about ½-1, it is large enough to bind charmonium till about $T=2T_c=340$ MeV

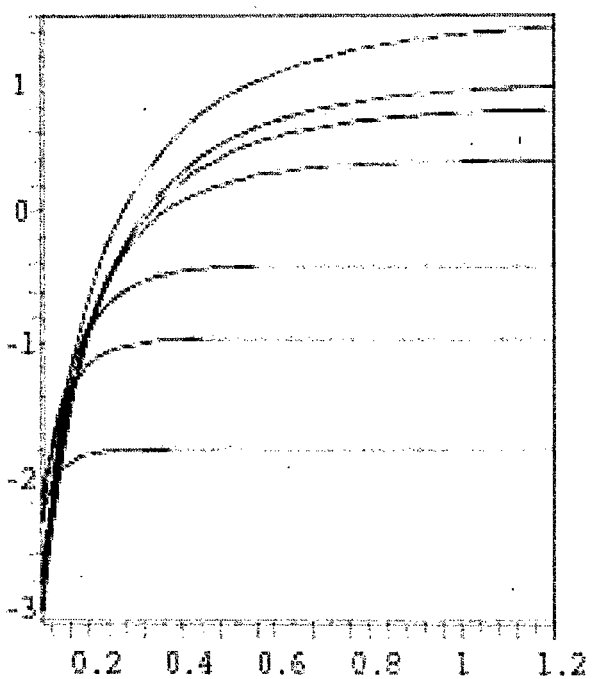
(accidentally, the highest T at RHIC)

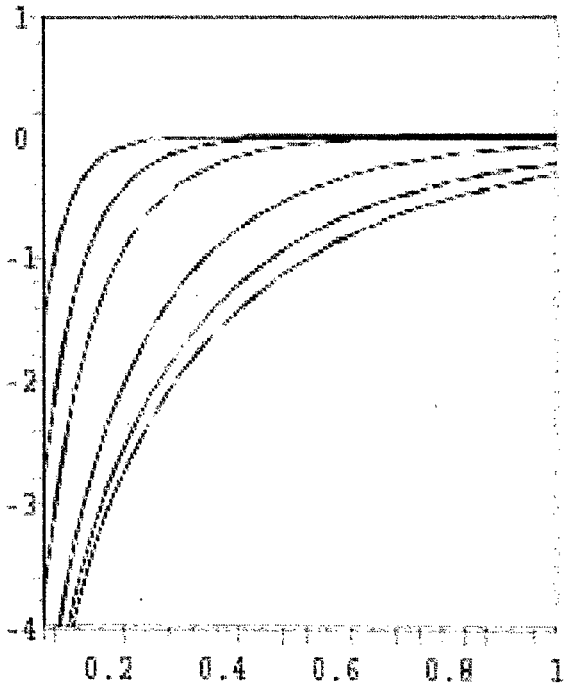
New ``free energies" for static quarks (from Bielfeld)



- **Upper figure is normalized at small distances: one can see that there is large ``effective mass" for a static quark at T=Tc.**
  - **Both are not yet the potentials!**
- **The lower figure shows the effective coupling constant**

New potentials (cont): after the entropy term is subtracted, potentials become much deeper





this is how potential I got look like for T = 1; 1.2; 1.4; 2; 4; 6; 10Tc, from right to left, from ES,Zahed hep-ph/0403127

Solving for the bound states ES+I.Zahed, hep-ph/0403127

- **In QGP there is no confinement => Hundreds of colored channels may have bound states as well!**

channel	rep.	charge factor	no. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

- gg color 8*8=64=27+2*10+2*8+1: only the 2 color octets $(gg)_8$ have (16$*$ $3_s * 3_s = 144$) states.

Digression 3:

Relativistic eqns have a critical Coulomb coupling for falling onto the center (known since 1920's)

What happens is that the particle starts falling towards the center. Indeed, ignoring at small r all terms except the V^2 term one finds that the radial equation is

$$R'' + \frac{2}{r}R' + \frac{\alpha^2}{r^2}R = 0 \qquad (10)$$

which at small r has a general solution

$$R = Ar^{s+} + Br^{s-}, \qquad s_\pm = -1/2 \pm \sqrt{1/4 - \alpha^2} \qquad (11)$$

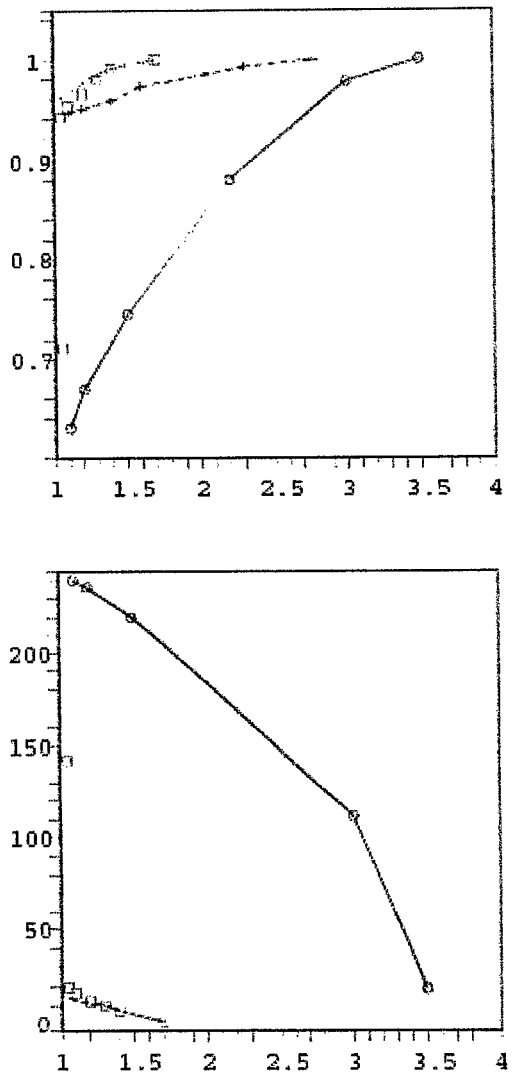
that for $\alpha \longrightarrow 1/2$ is just $1/r^{1/2}$. At the critical coupling *both* solutions have the same (singular) behavior at small r. For $\alpha > 1/2$ the falling starts, as one sees from the complex (oscillating) solutions.

- $(4/3)\alpha_s = 1/2$ is a critical value for Klein-Gordon eqn, at which falling onto the center appears. (It is 1 for Dirac).

Here is the binding and |psi(0)|^2

- Our results (IZ+ES,hep-ph/0403...) for binding then reproduce the binding region from Asakawa-Hatsuda and Bielefeld group (using the Maximal Entropy Method MEM), found bound $J/\psi, \eta_c$ till $2.2T_c$:

(a) The energy of the bound state $E/2M$ vs T/T_c from $V(T,r)$, for charmonium (crosses and dashed line), singlet light quarks $\bar{q}q$ (solid line) and gg (solid line with circles). Squares show the relativistic correction to light quark, a single square at $T = 1.05T_c$ is for $\bar{q}q$ with twice the coupling, which is the maximal possible relativistic correction. (b) $|\psi(0)|^2/T_c^3$ of the bound states vs T/T_c.



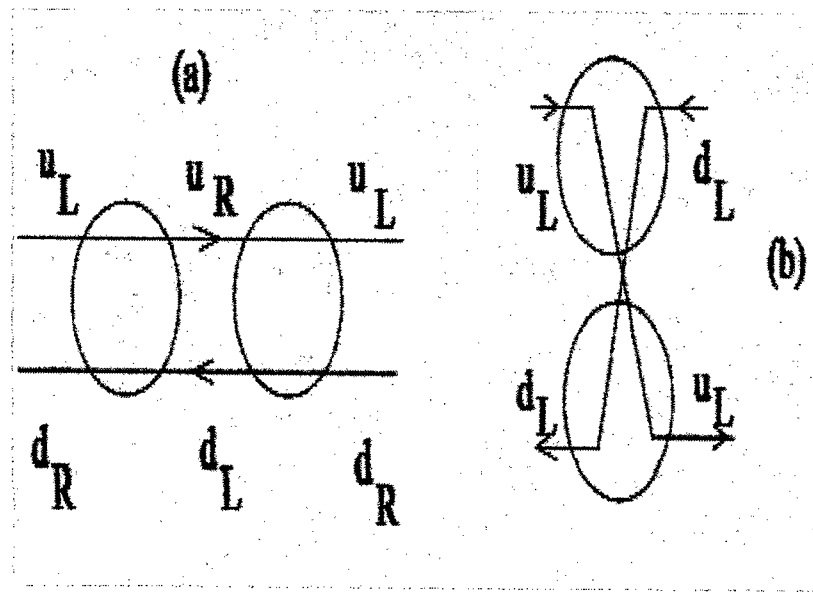
If a Coulomb coupling is too strong, falling onto the center may occur: but it is impossible to get a binding comparable to the mass

But we need massless pion/sigma at T=>Tc

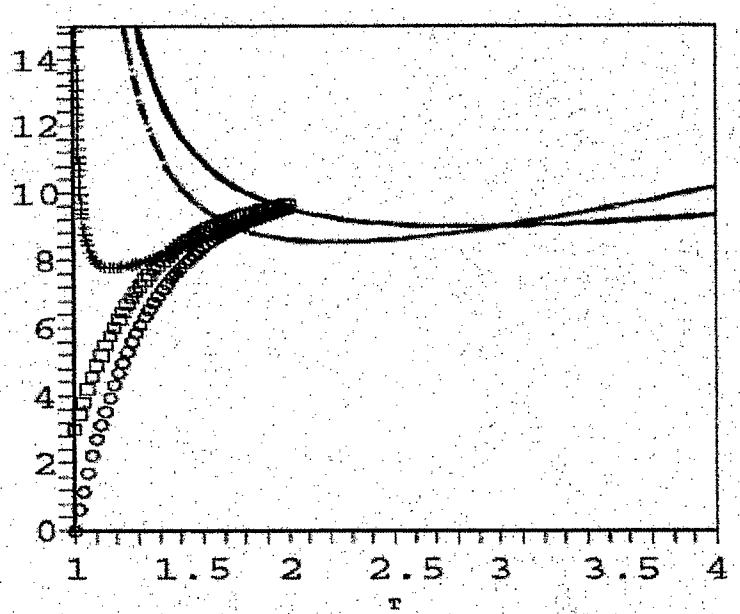
- Brown,Lee,Rho,ES hep-ph/0312175 : near-local interaction induced by the ``instanton molecules"

(also called ``hard glue" or ``epoxy", as they survive at $T>T_c$

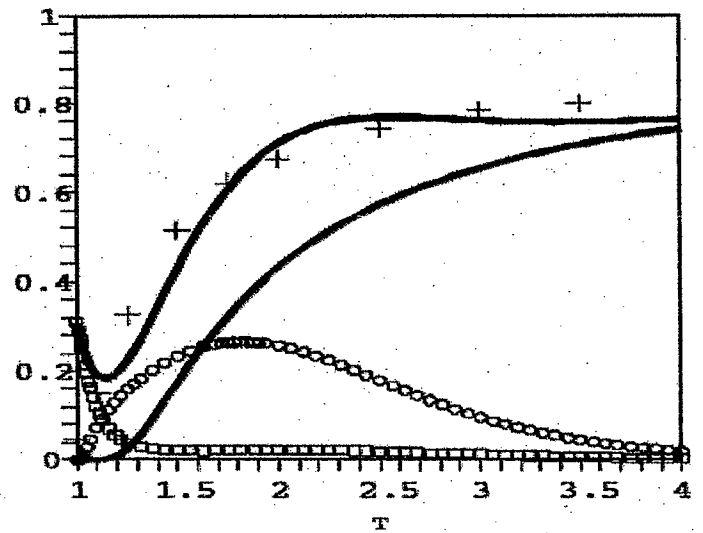
- Their contribution is » $|\psi(0)|^2$ which is calculated from strong Coulomb problem



The pressure puzzle is resolved!



$2M_q(T), 2M_g(T)$ fitted to (Karsch et al) quasiparticle masses, as well as example of "old" $M_\pi(T)$ and "new" octet $M^8_{gg}(T)$



The QGP pressure: crosses are lattice thermodynamics for $N_f = 2$ (Bielefeld,2000), the lines represent the contributions of $q + g$ quasiparticles, "mesons" $\pi - \rho$..., colored exotics (gg_3, qg_3) and total (the upper curve).

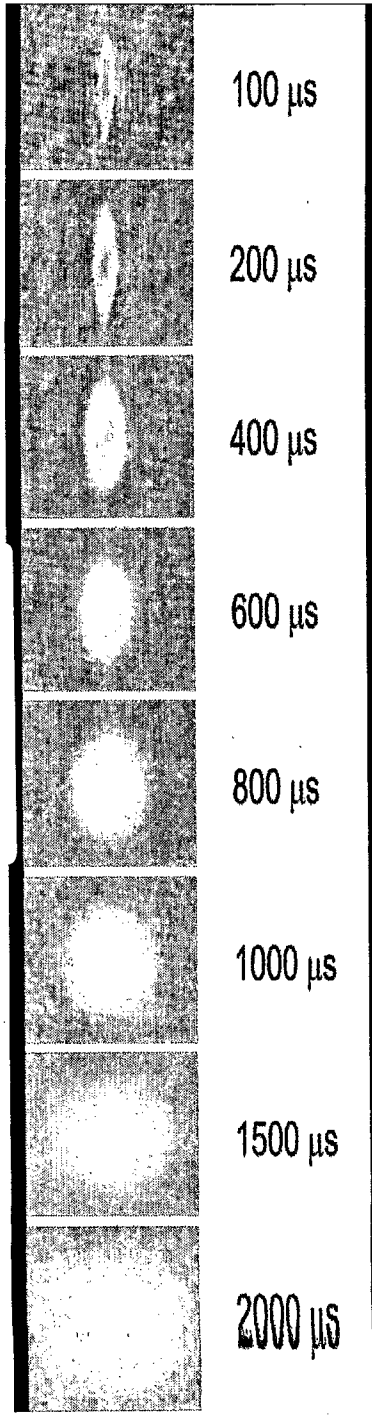
Resonance enhancement near zero binding lines: Explanation for large cross section? (ES+Zahed,03)

This is how small mean free path (viscosity) and zero binding lines and can be related!
(SZ) (q.p.+ q.p. <=> bound state): a resonance

$$\sigma(k) \sim \frac{4\pi}{k^2} \frac{\Gamma_i^2/4}{(E-E_r)^2 + \Gamma_t^2/4}$$

For $E - E_r \approx 0$ the in- and total widths approximately cancel: the resulting "unitarity limited" scattering is determined by the quasiparticle wavelengths which can be very large.

Can this scenario work?



The coolest thing on Earth, T=10 nK or 10^(-12) eV can actually produce a

Micro-Bang !

Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime

The system is extremely dilute, but can be put into a hydro regime, with an elliptic flow, if it is specially tuned into a strong coupling regime via the so called Feshbach resonance

- **Although the cross section changes by huge (» 10^6) factor, the EoS is only changed by (once again!) 20%!**

The phenomenon of the Adiabatic capture

- Very recent important discovery with trapped Li atoms

J.Cubizolles et al, cond-mat/0308018, K.Strecker et al,cond-mat/0308318 all in PRL

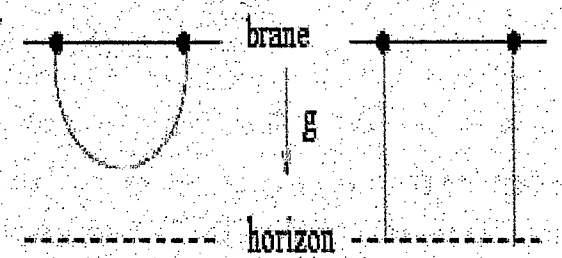
- If one changes the magnetic field so that the molecular level moves from unbound into bound domain, nearly all atoms (~ 85 percents) are turned into Li_2 molecules, all of course in the same relative state near zero.
- Only a bit more cooling is needed to get BEC of molecules
- The phenomenon is reversible which proves that no entropy is produced: going back one finds molecules dissolved
- Going further into the bound region one finds that binding energy goes into heating the gas

- The adiabatic path in heavy ion collision also crosses the no-biding line in this direction.
- the reheating was predicted as a zig-zag path on the phase diagram
- Can the "hadronization" happen at this line, not at $T = T_c$?
- At least that would be enough to explain why we do not see large fluctuations related to quasi-first order transition: no "clumps", the matter remains homogeneous at all times

Unexpected help from the string theorists, AdS/CFT correspondence

- The $\mathcal{N}$=4 SUSY Yang Mills gauge theory is conformal (CFT) (the coupling does not run). At finite T it is a QGP phase at ANY coupling. If it is weak it is like high-T QCD => gas of quasiparticles. What is it like when the coupling gets strong $\lambda = g^2 N_c \gg 1$?
- AdS/CFT correspondence by Maldacena turned the strongly coupled gauge theories to a classical problem of gravity in 10 dimensions
- Example: a modified Coulomb's law (by Maldacena)

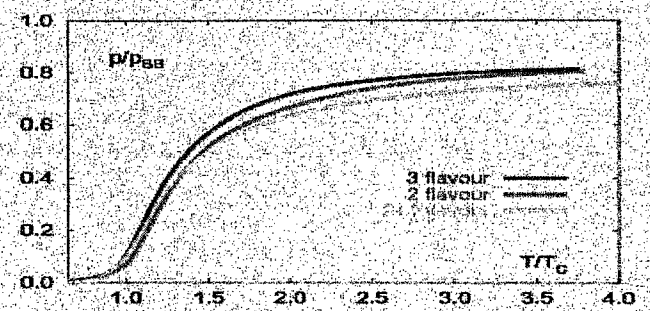
$$V(L) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{L}$$



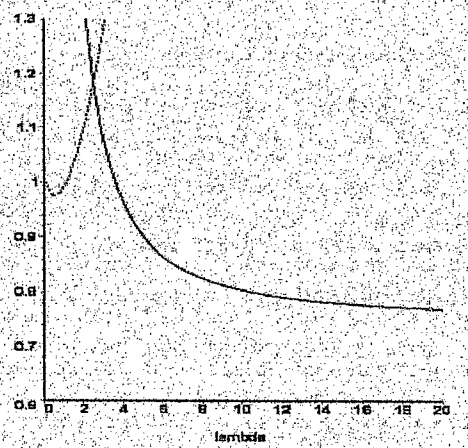
- becomes a sreened potential at finite T

The famous .8 again:

- CFT free energy at large λ is $F = (3/4 + O(1/\lambda^{3/2}))F_{free}$ (I.Klebanov et al 1996...)



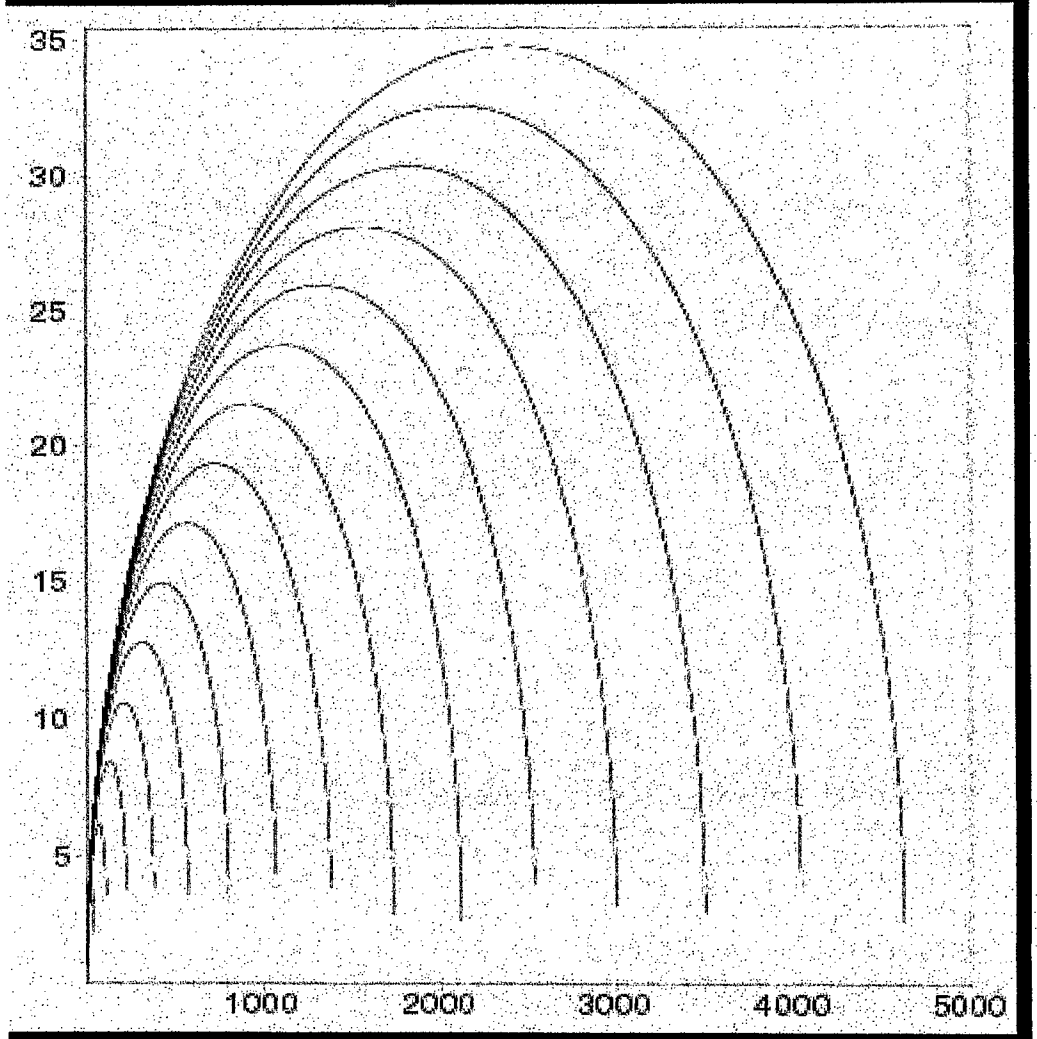
- Lattice results (Bielefeld group) for QCD thermodynamics: pressure normalized to Stephan-Boltzmann value



- Weak (5 terms) vs. strong $(3/4 + const/\lambda^{3/2})$ coupling for the CFT: the ratio of the pressure to Stephan-Boltzmann value vs the 't Hooft coupling $\lambda = g^2 N$.

The viscosity/entropy => $\eta/s = 1/4\pi$ (Policastro,Son,Starinets, 2003) is very small

Light bound states exist for any coupling (Zahed and ES, 2003, the formula is from Darwin, Gordon, 1928)



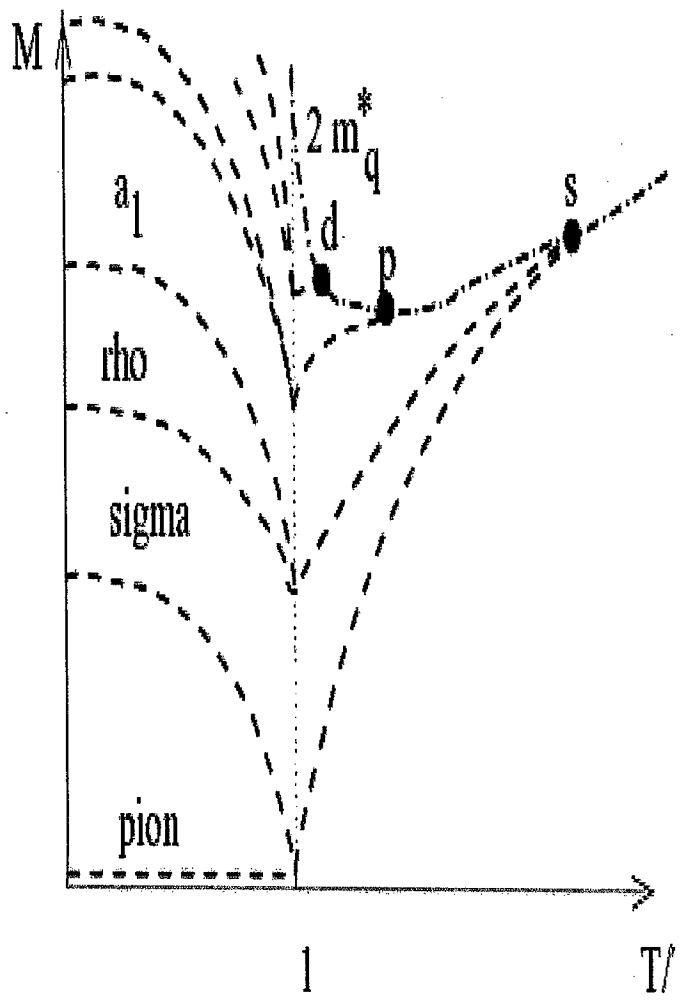
$$V = -\frac{C}{r}$$

$$E_{nl} = m\left[1+\left(\frac{C}{n+1/2+\sqrt{(l+1/2)^2-C^2}}\right)^2\right]^{-1/2}$$

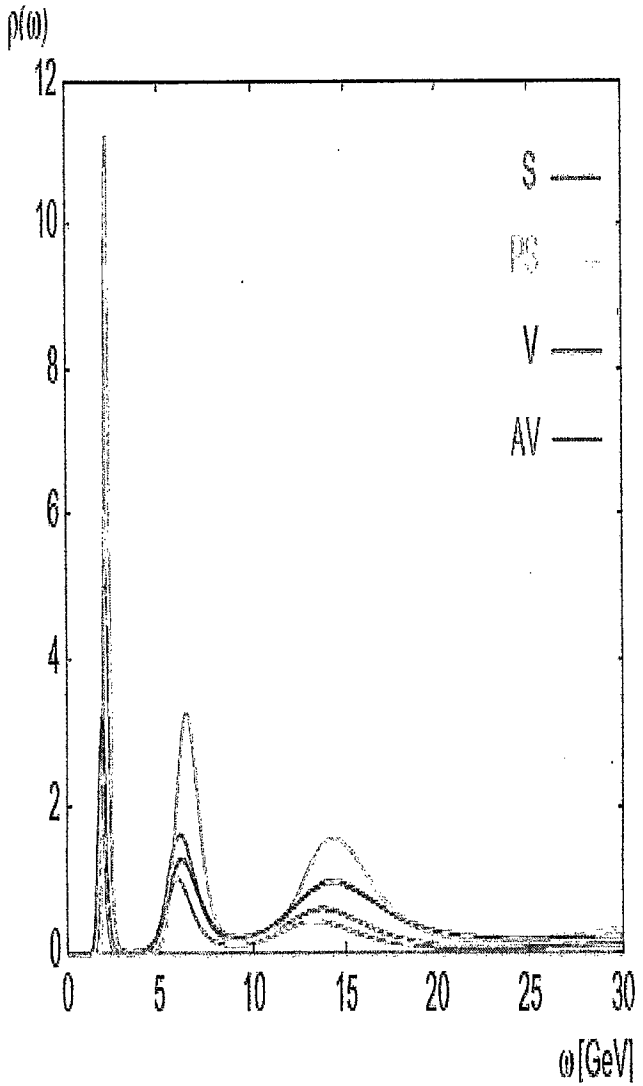
Small C - nonrelat. atoms, Balmer series... New regime at large $C >> 1$: families of relativistic deeply bound states, with large orbital momentum balancing the supercritical Coulomb

Dileptons from new bound states in QGP?

- However the only states we can observe from the early stages are still only those which decay straight into dileptons. A continuation of ρ, ω, ϕ into QGP is now expected to start with $M \approx .5GeV$ at $T = T_c$ but then reach $M \approx 2GeV \approx 2m_q^{eff}$ at the endpoint. Suggestion: have a very good look at new mass window $m_\rho - 2\,GeV$



Asakawa-Hatsuda, $T=1.4T_c$



Karsch-Laerman, T=1.5 and 3 Tc

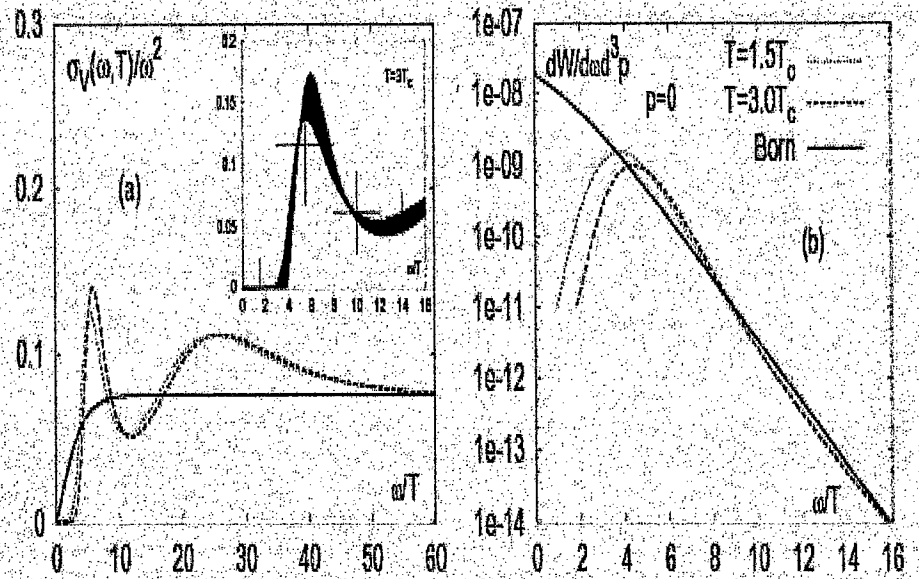


Figure 2: Reconstructed vector spectral function σ_V in units of ω^2 at zero momentum (a) and the resulting zero momentum differential dilepton rate (b) at $T/T_c = 1.5$ (doted line) and 3 (dashed line). The solid lines give the free spectral function (a) and the resulting Born rate (b). The insertion in (a) shows the error band on the spectral function at $3T_c$ obtained from a jackknife analysis and errors on the average value of $\sigma_V(\omega,T)/\omega^2$ in four energy bins (see text).

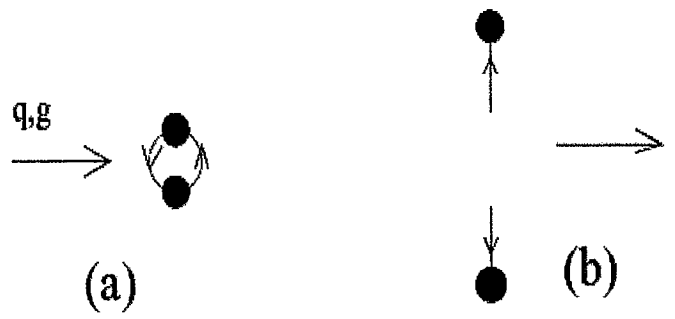
Jet quenching by ``ionization" of new bound states in QGP?

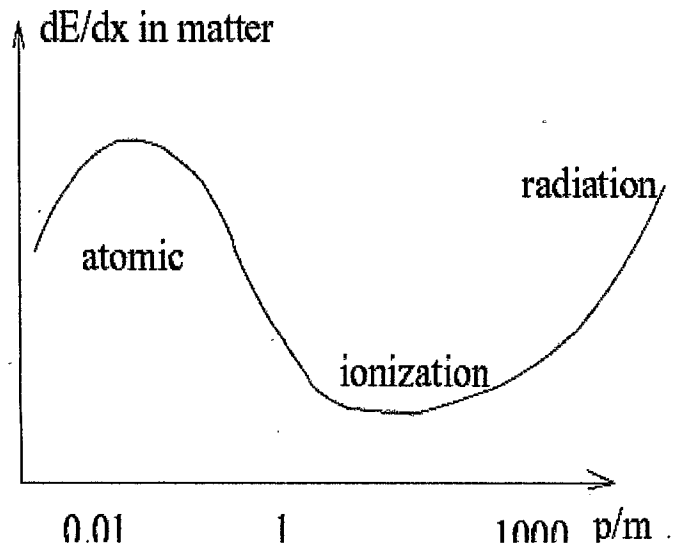
- Can we observe (much more multiple) colored states directly?

Very recent idea (IZ+ES) of ''ionization losses'' for minijets at $p_t \sim few\, GeV$.

Cannot work in hadronic phase - cofinement

If it is true, the ''lost energy'' can never be recovered (unlike for radiative losses)





Conclusions:

we found at RHIC not what we expected but more (as Columbus)

- **QGP as a "matter" in the usual sense, not a bunch of particles, has been produced at RHIC**
  - Lattice EoS is about confirmed, $\Delta\varepsilon$ ¼ .8 GeV/fm^3
  - QGP seems to be the most ideal fluid known

    η/s » .1
  - => QGP at RHIC is in a strong coupling regime.

    New spectroscopy: many old mesons plus hundreds of exotic colored binary states.
- **Instructuve analogies with other strongly coupled systems – atomic and field theory (AdS/CFT)**

Searching Evidence for the Color Glass Condensate at RHIC

New Discoveries at RHIC
BNL, May 14-15, 2004

J.-P. Blaizot and F. Gelis, SPhT, CEA Saclay and CNRS

Quantum ChromoDynamics

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} + \sum_f \bar{\psi}_f(i\not{D} - m_f)\psi_f$$

$$D_\mu = \partial_\mu - igA_\mu$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + gf^{abc}A^b_\mu A^c_\nu$$

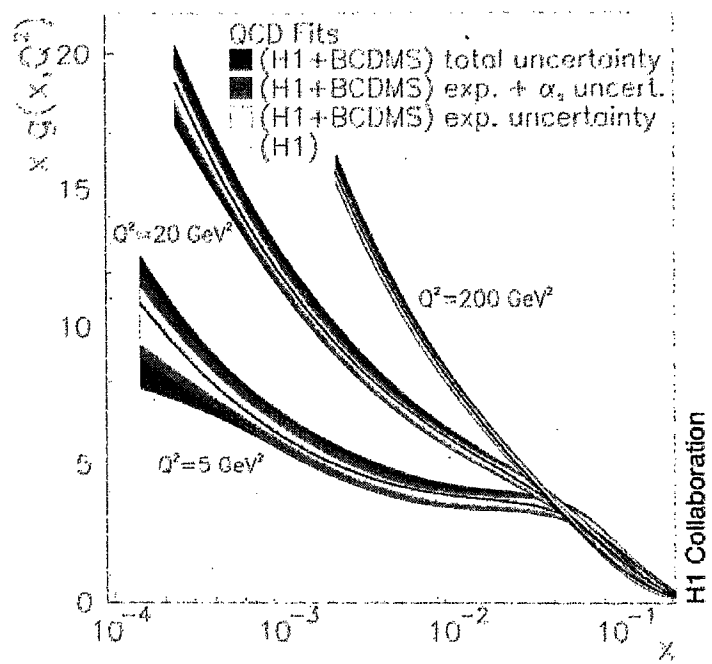
Non linear effects become important when

$$\langle(\partial A)^2\rangle \sim g^2\langle A^4\rangle \sim g^2\langle A^2\rangle^2$$

Gluon saturation

a regime with weak coupling, many cooperating degrees of freedom, strong fields.

$$\langle A^2 \rangle \approx \frac{xG(x,Q^2)}{\pi R^2}$$



Non linear effects important when

$$\langle (\partial A)^2 \rangle \sim g^2 \langle A^2 \rangle^2$$

$$Q^2 \sim g^2 \langle A^2 \rangle$$

Saturation scale

$$Q_s^2 \approx \alpha_s \frac{xG(x,Q^2)}{\pi R^2}$$

Gribov, Levin, Ryskin 83
Mueller, Qiu 86

High density partonic systems

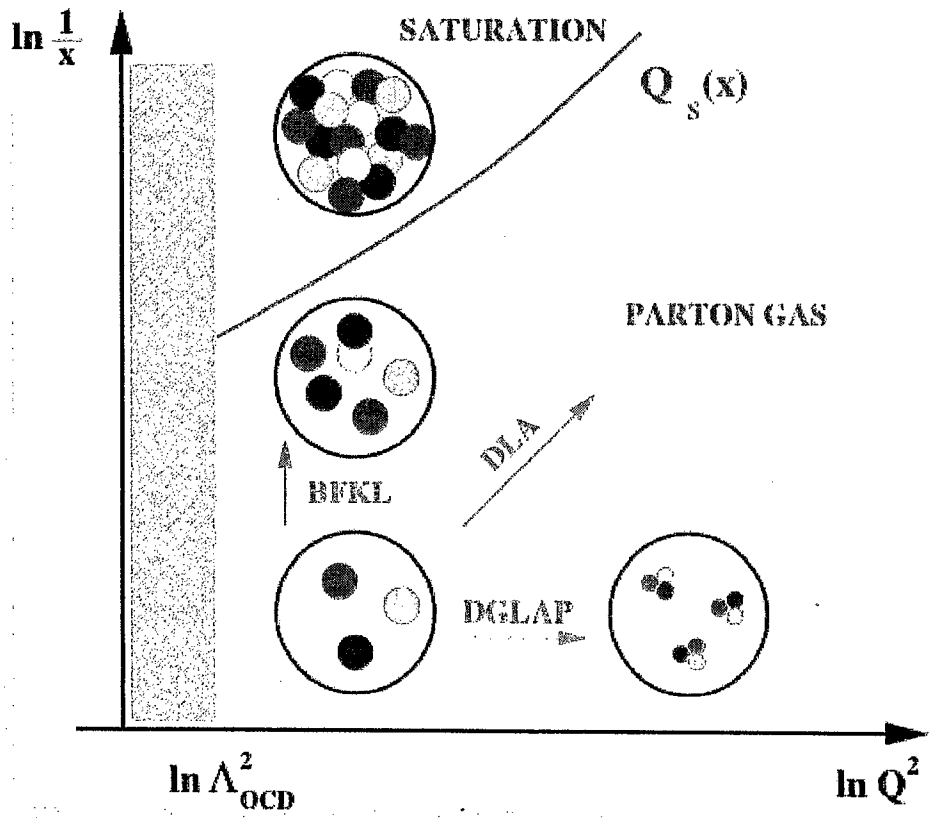
$$Q_s^2 \approx \alpha_s \frac{xG(x,Q^2)}{\pi R^2}$$

Large occupation numbers

$$n \sim \frac{xG(x,Q^2)}{\pi R^2}$$

$$\frac{\pi}{Q_s^2} n \sim \frac{\pi}{\alpha_s}$$

Classical fields



The saturation scale Q_s

From fit to DIS (HERA)

$$Q_s^2(x) \equiv Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda} \qquad Q_0 = 1\mathrm{GeV} \qquad x_0 = 3 \times 10^{-4} \qquad \lambda \approx 0.3$$

In a nucleus $$\frac{xG_A(x,Q^2)}{\pi R^2} \sim A^{1/3}$$

$$Q_0^2 \to Q_0^2 A^{1/3} \qquad x = 10^{-2} \to Q_s^2 \approx 2\mathrm{GeV}^2 \qquad (\mathrm{for}\, A = 200)$$

The conditions in the central rapidity of a nucleus-nucleus collision at RHIC are similar to those at HERA

Early stages of a nucleus-nucleus collision

Partons set free have typical tranverse momenta $k_T \sim Q_s$

They are set free at (proper) time $\tau \sim Q_s^{-1}$

At that time

$$\frac{\mathrm{d}N}{\mathrm{d}y} = 2AxG(x, Q_s) \qquad \frac{\mathrm{d}E_T}{\mathrm{d}y} = 2Q_S AxG(x, Q_s)$$

(J.-P. B., A. Mueller, 87)

Momentum distributions

$k_\perp \leq Q_s$ (saturated regime)

$k_\perp \geq Q_s$ (dilute regime)

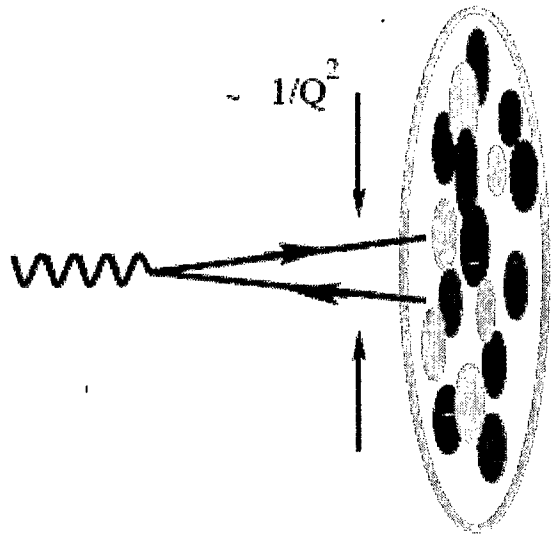
NON LINEAR EVOLUTION EQUATIONS

BALITSKY-KOVCHEGOV EQUATION

COLOR GLASS CONDENSATE
AND JIMWLK(*) EQUATION

(*) Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

High energy scattering. Small x gluons



$$\sigma_{\gamma^* A}(x, Q^2) = \int dz \int d^2\boldsymbol{r} \; \underbrace{|\psi(z, \boldsymbol{r}; Q^2)|^2}_{QED} \; \underbrace{2 \int d^2\boldsymbol{b} \; (1 - S_\tau(\boldsymbol{x}, \boldsymbol{y}))}_{\sigma_{dipole}}$$

$$S_\tau(\boldsymbol{x}, \boldsymbol{y}) = \langle \mathrm{tr}(U^\dagger(\boldsymbol{x}) U(\boldsymbol{y})) \rangle_\tau \qquad \tau \equiv \ln(1/x) \sim \ln s$$

$$U^\dagger(\boldsymbol{x}) \equiv \mathrm{P} \exp\left(\mathrm{i}g \int dx^- A_a^+(x^-, \boldsymbol{x}) t^a \right)$$

Wilson line operators and the U–representation

Calculate change in expectation values, $\partial_\tau \langle \mathrm{tr}(U_{\boldsymbol{x}}^\dagger U_{\boldsymbol{y}})\rangle_\tau$, rather than the expectation values themselves. Focus on the evolution of the dipole

$$\partial_\tau \langle \mathrm{tr}(U_{\boldsymbol{x}}^\dagger U_{\boldsymbol{y}})\rangle_\tau =$$

$$-\frac{\alpha_s}{2\pi^2}\int d^2\boldsymbol{z}\,\frac{(\boldsymbol{x}-\boldsymbol{y})^2}{(\boldsymbol{x}-\boldsymbol{z})^2(\boldsymbol{y}-\boldsymbol{z})^2}\left\langle N_c \mathrm{tr}(U_{\boldsymbol{x}}^\dagger U_{\boldsymbol{y}}) - \mathrm{tr}(U_{\boldsymbol{x}}^\dagger U_{\boldsymbol{z}})\mathrm{tr}(U_{\boldsymbol{z}}^\dagger U_{\boldsymbol{y}})\right\rangle_\tau$$

$$\langle U_{\boldsymbol{x}_1}^{(\dagger)} \ldots U_{\boldsymbol{x}_n}^{(\dagger)}\rangle_\tau = \int [\mathrm{d}\mu(U)]\; U_{\boldsymbol{x}_1}^{(\dagger)} \ldots U_{\boldsymbol{x}_n}^{(\dagger)}\; Z_\tau[U]$$

$$\boxed{\partial_\tau Z_\tau[U] = \frac{1}{2}\nabla_{\boldsymbol{x}}^a \chi_{\boldsymbol{xy}}^{ab}[U]\,\nabla_{\boldsymbol{y}}^b Z_\tau[U]}$$

$$\chi_{\boldsymbol{xy}}^{ab}[U] \equiv \frac{1}{\pi}\int \frac{d^2\boldsymbol{z}}{(2\pi)^2}\,\mathcal{K}_{\boldsymbol{xyz}}\left[(1-U_{\boldsymbol{x}}^\dagger U_{\boldsymbol{z}})(1-U_{\boldsymbol{z}}^\dagger U_{\boldsymbol{y}})\right]^{ab}$$

$$\mathcal{K}_{\boldsymbol{xyz}} \equiv \frac{(\boldsymbol{x}-\boldsymbol{z})\cdot(\boldsymbol{y}-\boldsymbol{z})}{(\boldsymbol{x}-\boldsymbol{z})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$

The Colour Glass Condensate

A model for the hadron wavefunction — explicit calculation of expectation values. Soft gluons (xP^+) treated as classical fields. Fast partons ($k^+ \gg xP^+$) create a source $\rho_a(x^-, \boldsymbol{x})$ for the soft fields. $\rho_a(x^-, \boldsymbol{x})$ is a **random variable**

$$(D_\nu F^{\nu\mu})_a(x) = \delta^{\mu+}\rho_a(x^-, \boldsymbol{x})$$

Renormalization group procedure $\rho \longrightarrow \rho + \delta\rho$

$$\langle \delta\rho \rangle \sim \sigma \qquad \langle \delta\rho\delta\rho \rangle \sim \chi \qquad \sigma = \frac{1}{2}\frac{\delta\chi}{\delta\rho}$$

$$\langle \mathrm{tr}(U^\dagger_{\boldsymbol{x}} U_{\boldsymbol{y}}) \rangle_\tau = \int [\mathrm{d}\rho]\, W_\tau[\rho]\, \langle \mathrm{tr}(U^\dagger_{\boldsymbol{x}}[\rho] U_{\boldsymbol{y}})[\rho] \rangle$$

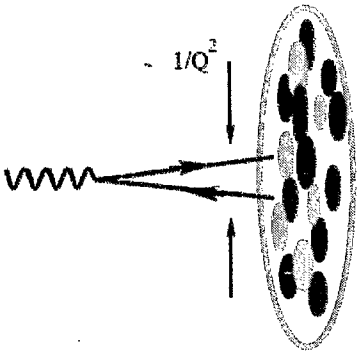
$$\boxed{\partial_\tau W_\tau[\rho] = \frac{1}{2}\frac{\delta}{\delta\rho^a_\tau(\boldsymbol{x})}\chi^{ab}_{\boldsymbol{xy}}[\rho]\frac{\delta}{\delta\rho^b_\tau(\boldsymbol{y})} W_\tau[\rho]}$$

EXPERIMENTAL TESTS

DEEP INELASTIC SCATTERING

Geometrical scaling

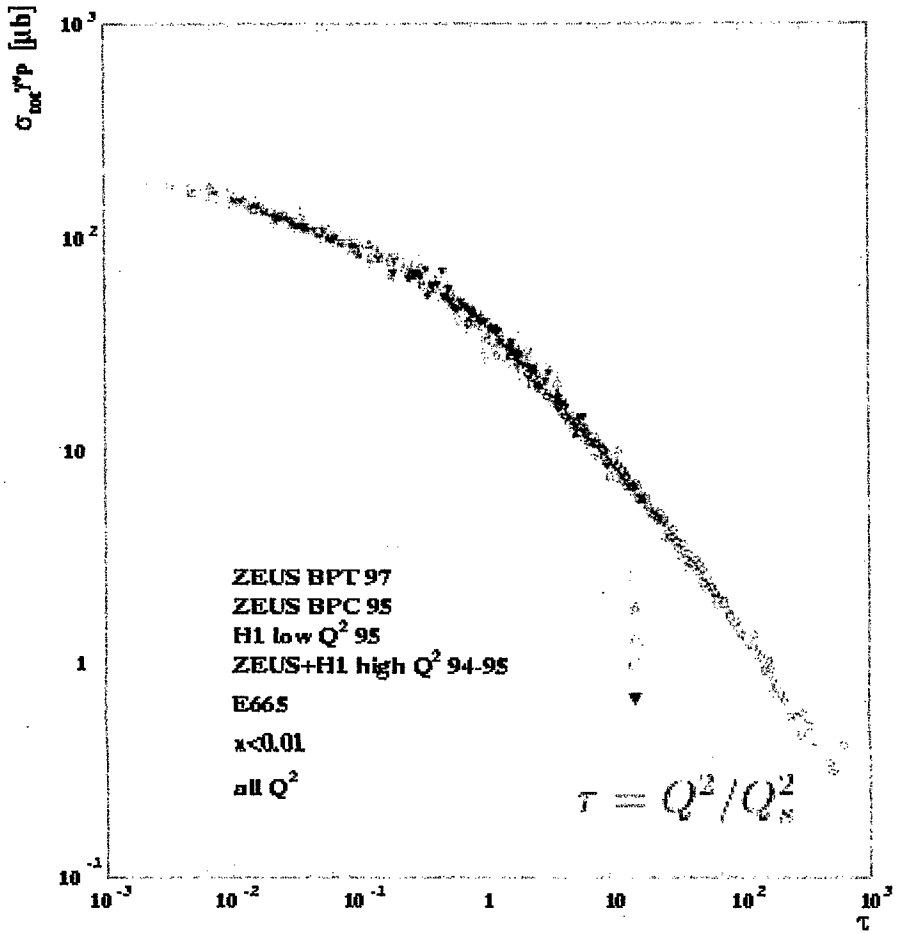
$$\sigma_{\gamma^* A}(x,Q^2) = \int dz \int d^2\boldsymbol{r}\ \underbrace{\left|\psi(z,\boldsymbol{r};Q^2)\right|^2}_{QED}\ \underbrace{2\int d^2\boldsymbol{b}\ (1-S_\tau(\boldsymbol{x},\boldsymbol{y}))}_{\sigma_{dipole}}$$



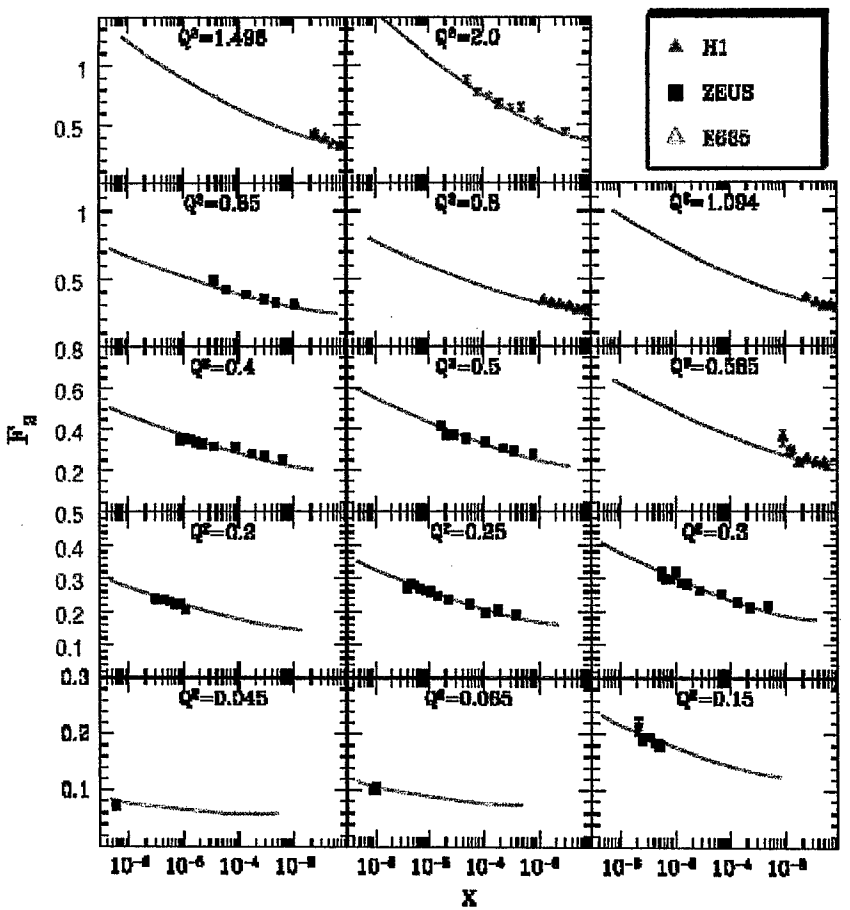
$$\sigma_{dip} = \sigma_0\left[1-\exp(-r_\perp^2 Q_s(x)^2)\right]$$

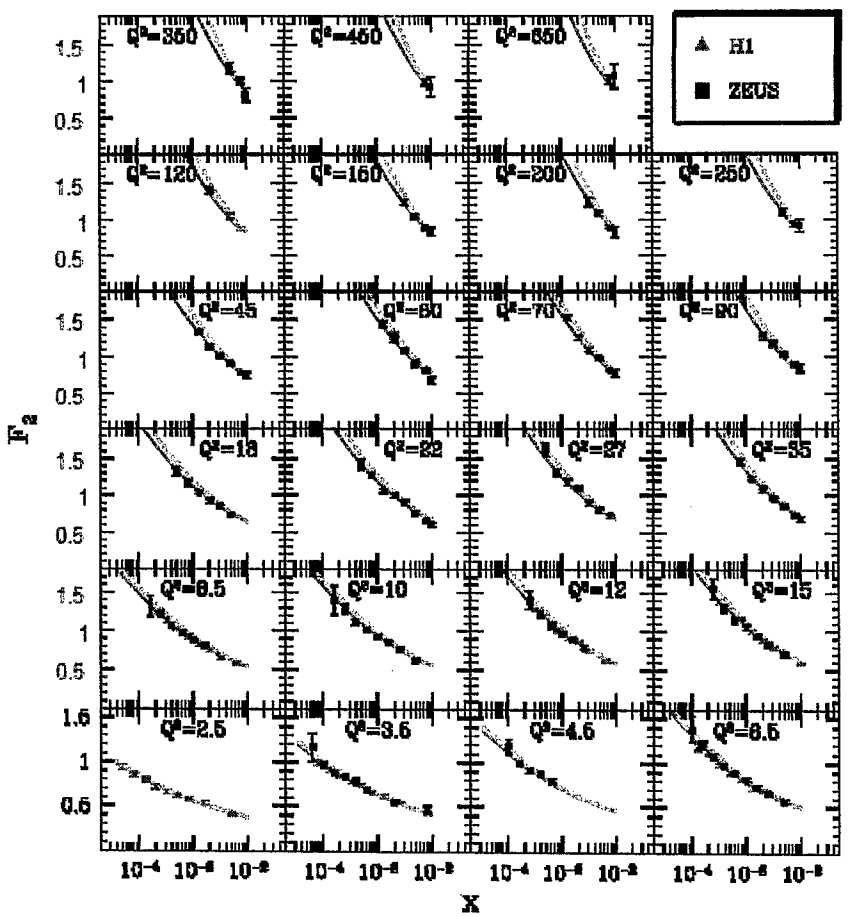
$$Q_s^2(x) \equiv Q_0^2\left(\frac{x_0}{x}\right)^\lambda$$

(Golec-Biernat,Kwiecinski,Stasto)

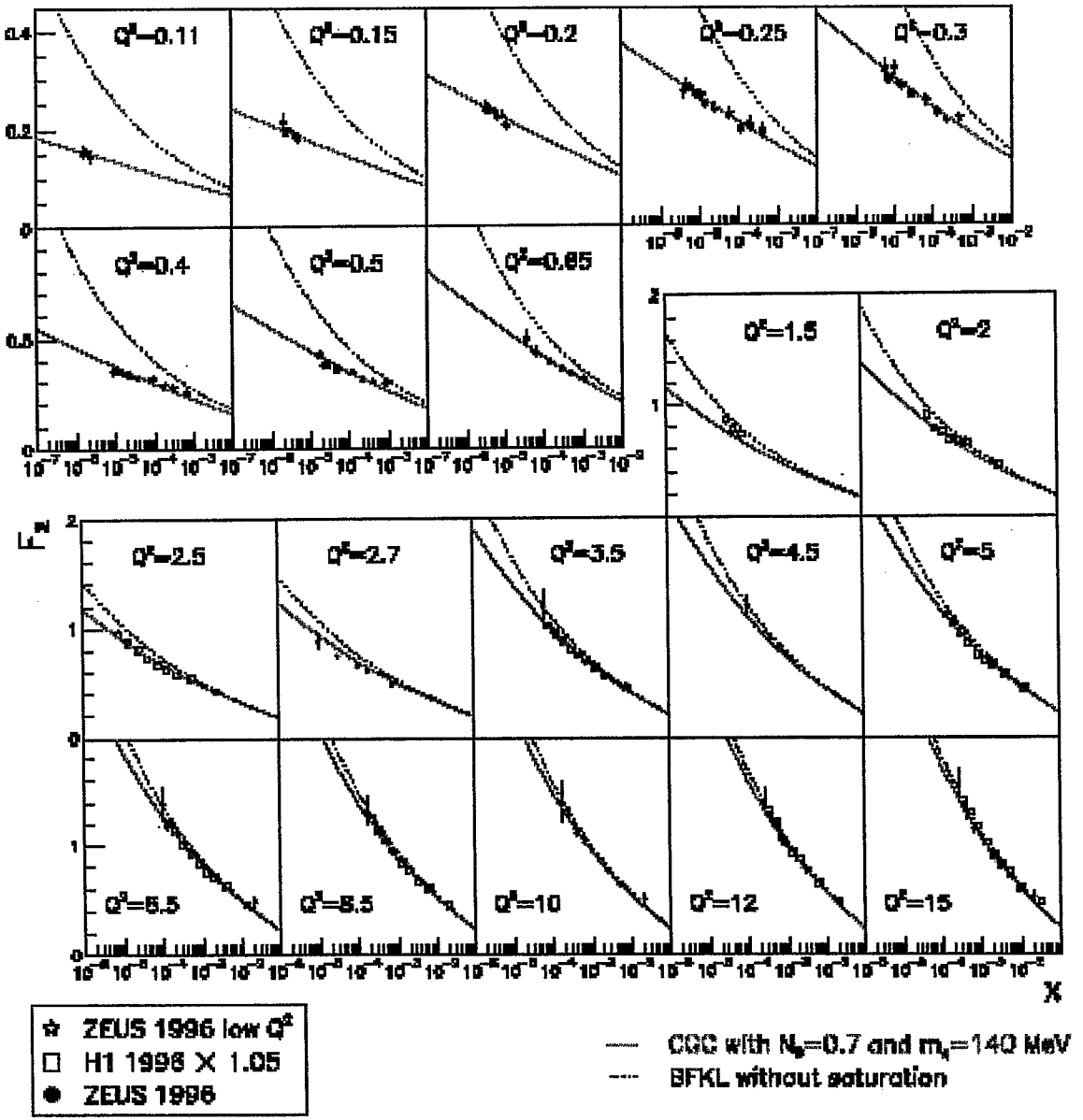


Numerical solution of the BK equation + DGLAP corrections





(Gotsman, Levin, Lublinsky, Maor hep-ph/0209074)

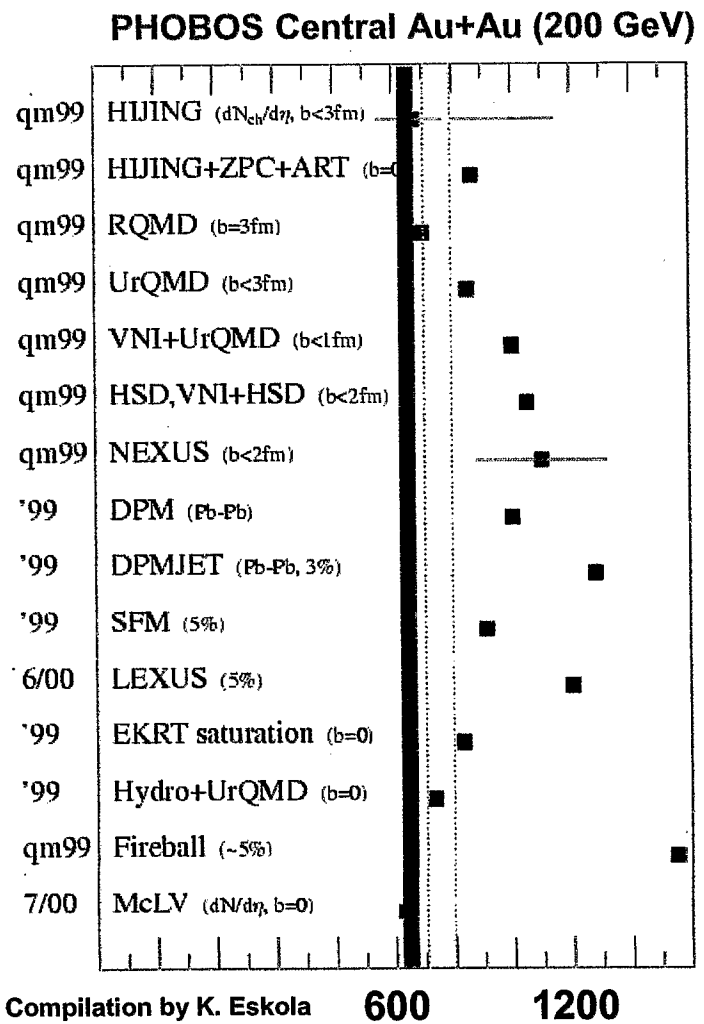


(Iancu, Itakura, Munier hep-ph/0310338)

RHIC

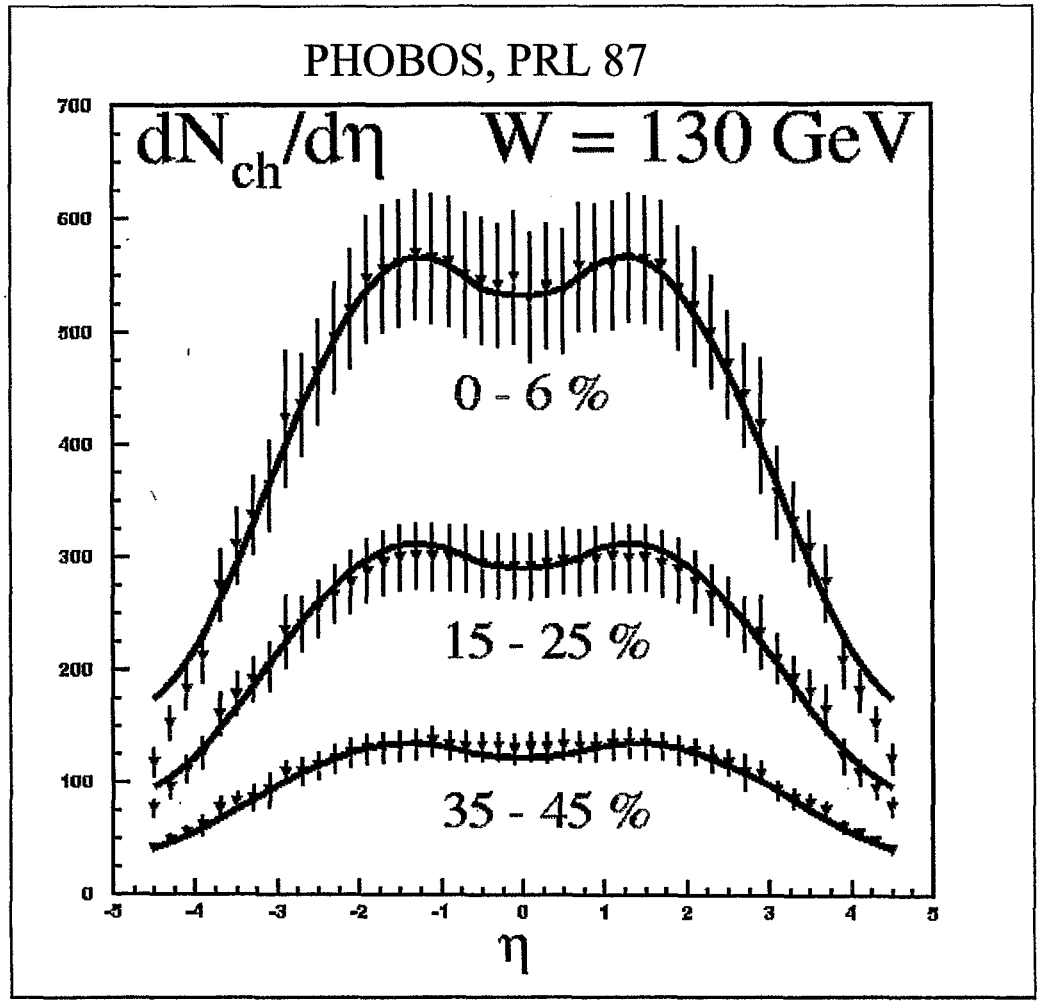
PARTICLE MULTIPLICITIES

Total multiplicities



$$\frac{1}{N_{\rm part}}\frac{dN}{d\eta} \sim \frac{1}{\alpha_s(Q_s^2)} \sim \ln(Q_s^2/\Lambda_{QCD}^2)$$

QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

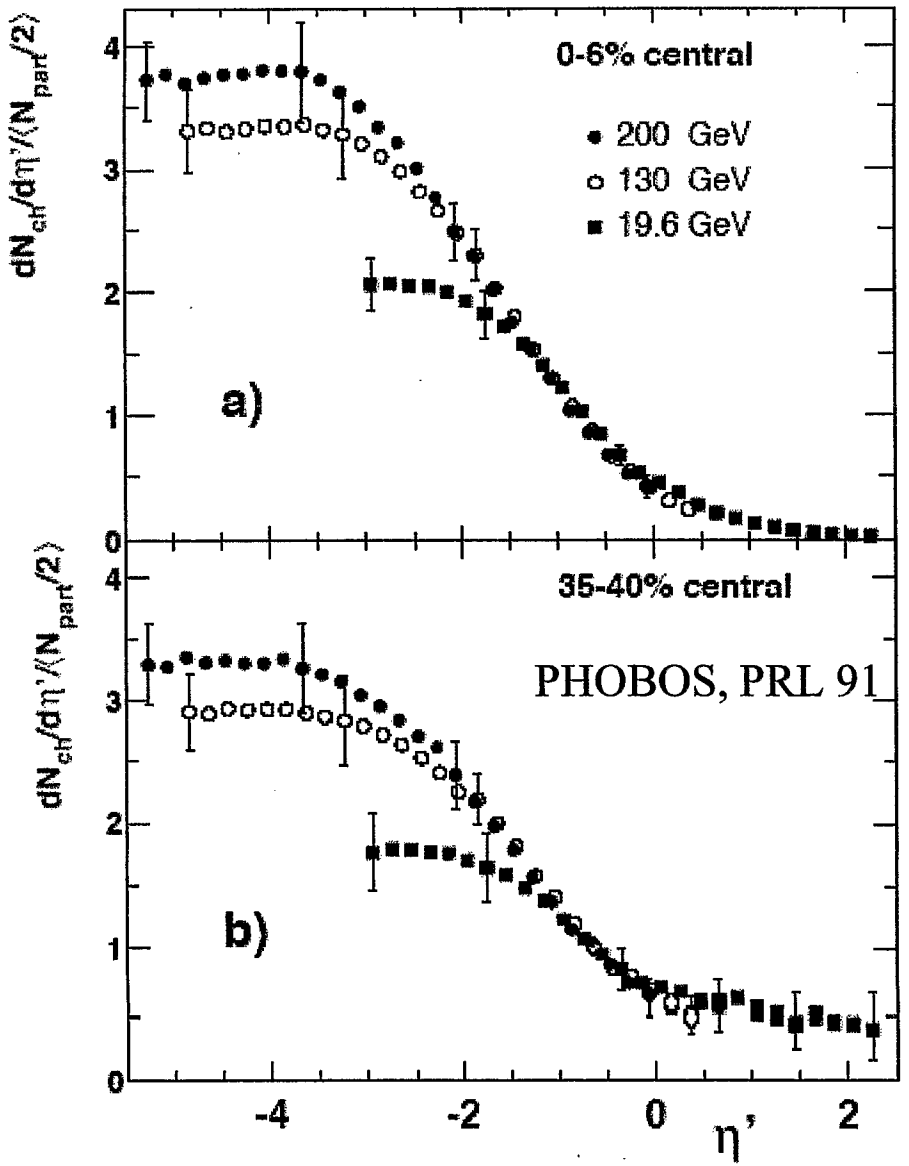


Kharzeev & Levin, Phys. Lett. B523 (2001) 79

QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

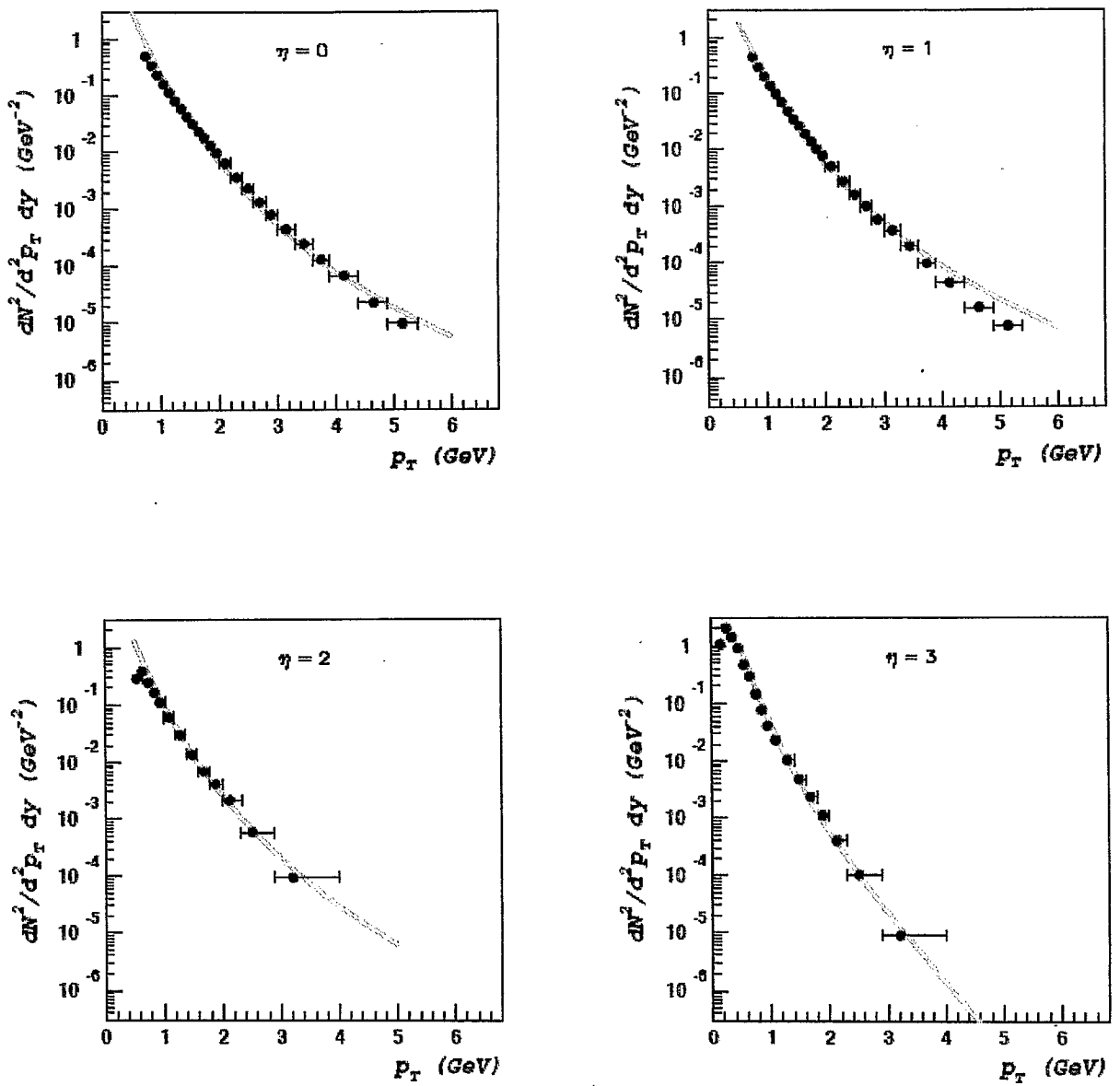
(Kharzeev, Levin, Nardi hep-ph/0212316)

« Limiting fragmentation »



Interpretation in the color glass picture:
J. Jalilian-Marian, nucl-th/0212018

SPECTRA



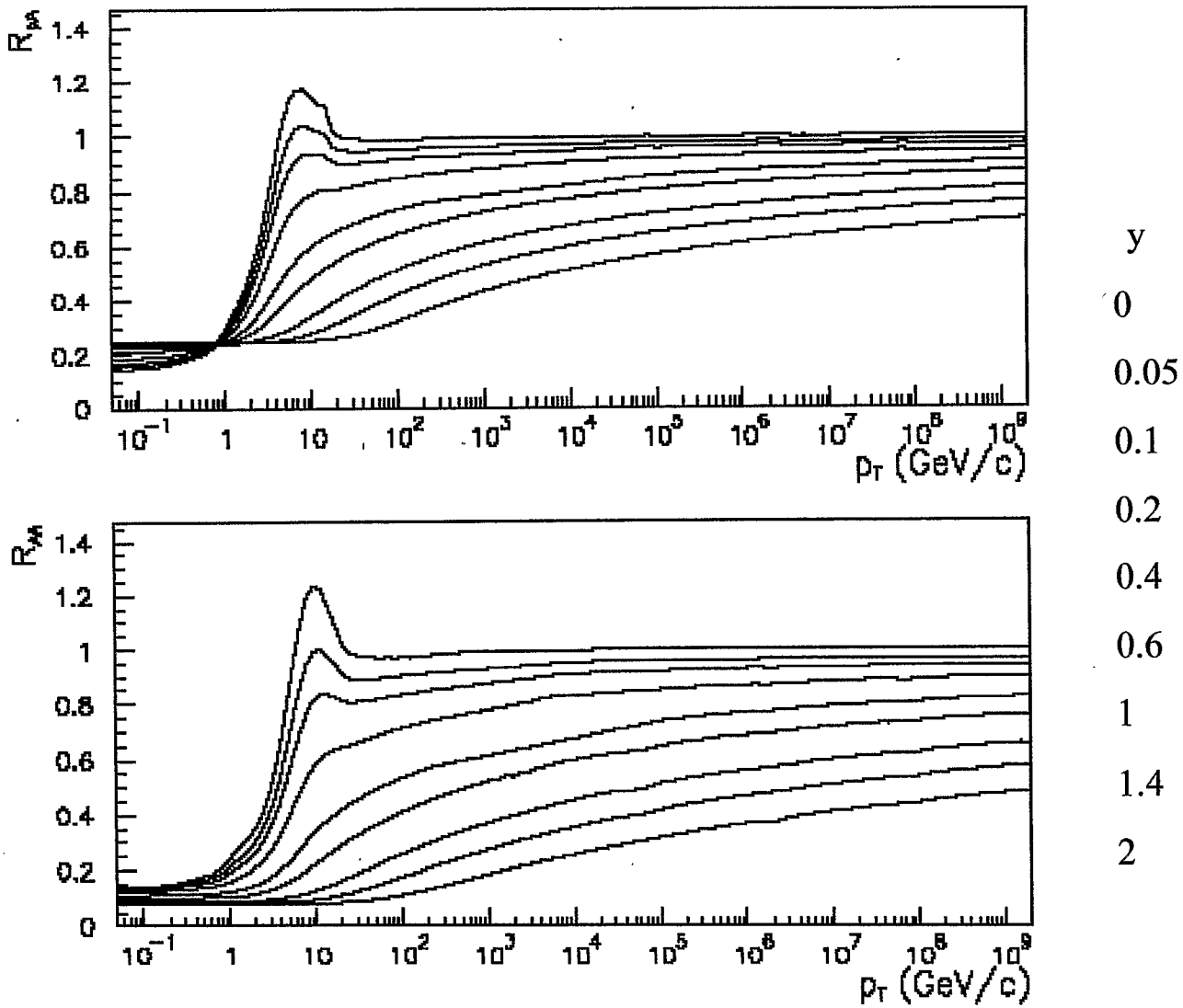
(Kharzeev, Kovchegov, Tuchin, hep-ph/0405045)

RATIOS OF SPECTRA

$$R_{dA} \equiv \frac{\left.\frac{dN}{dy d^2 \mathbf{p}_\perp}\right|_{dA}}{N_{\mathrm{coll}} \left.\frac{dN}{dy d^2 \mathbf{p}_\perp}\right|_{pp}}$$

QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

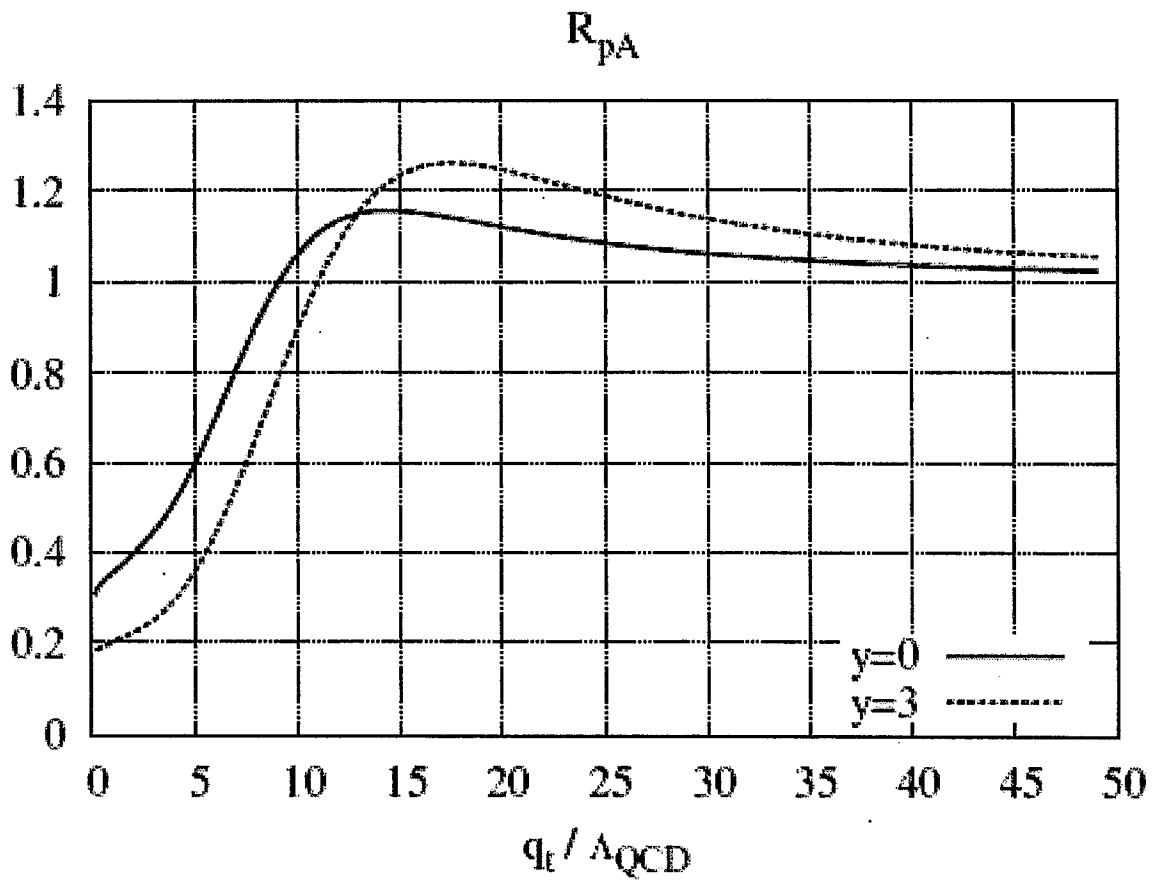
I. Arsene, et al., BRAHMS collaboration, nucl-ex/0403005



Albacete et al, hep-ph/0307179

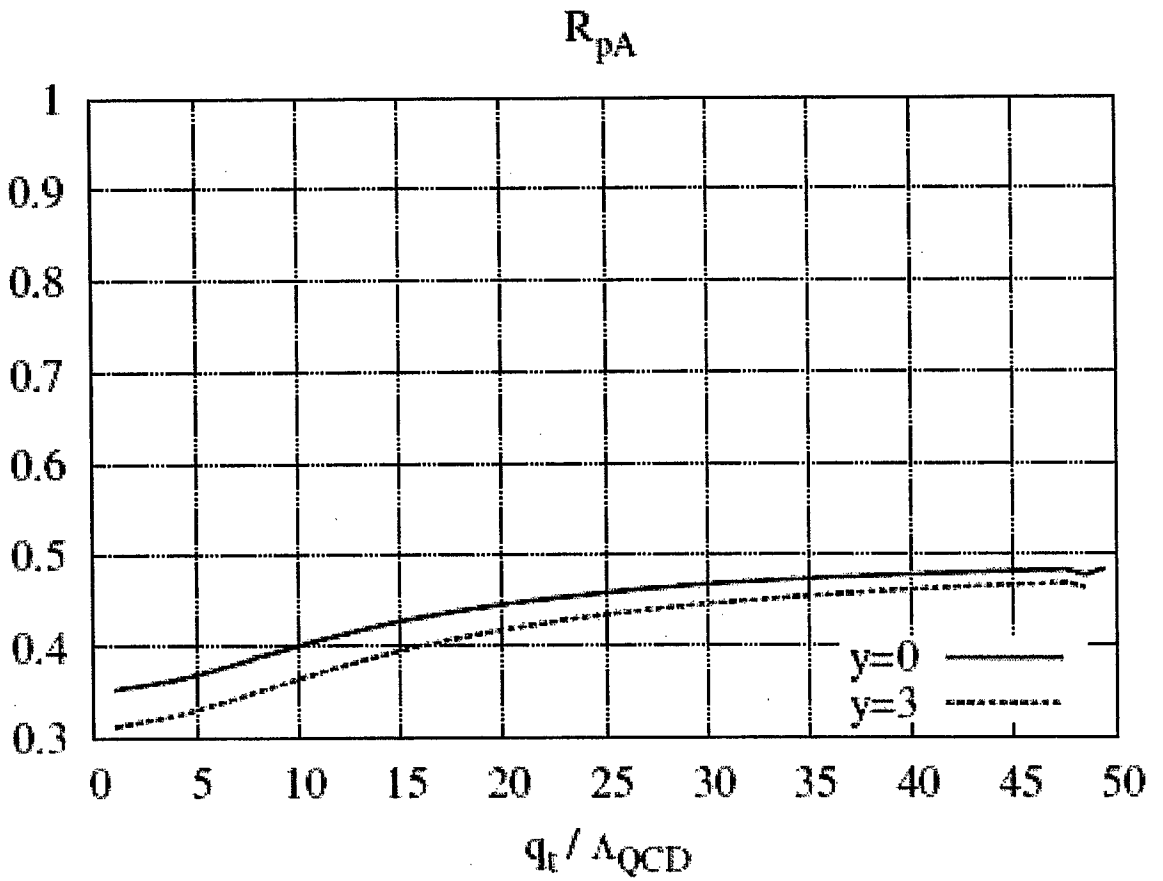
(Related analytical work by Iancu, Itakura, Triantafyllopoulos hep-ph/0403103)

$$W_{x_0}[\rho] = \exp\left[-\int_{\mathbf{x}_\perp} \frac{\rho(x_\perp)\rho(x_\perp)}{2\mu^2} \right]$$

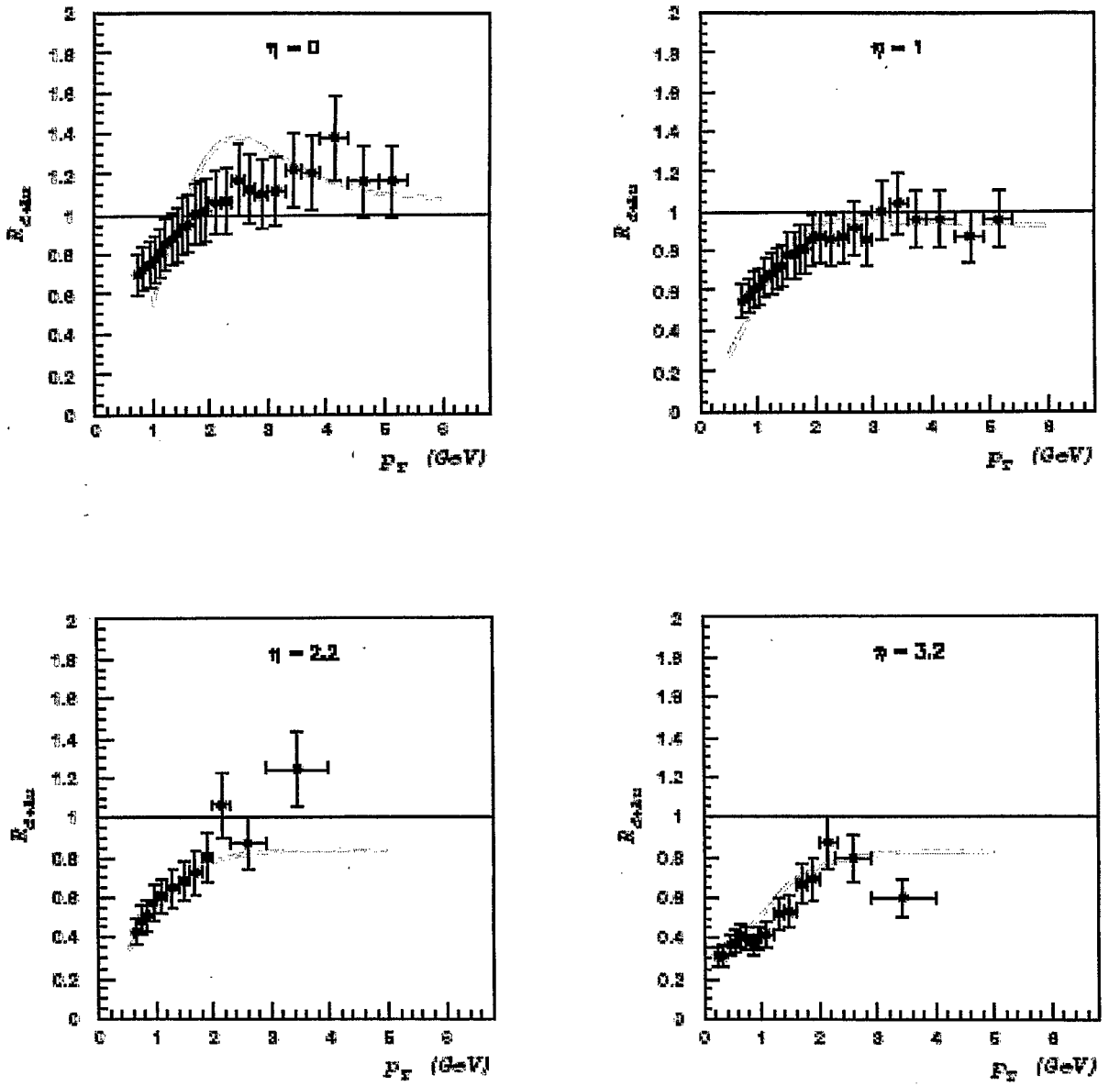


(J.-P. B, F. Gelis, R. Venugopalan, hep-ph/0402256)

$$W_{x_0}[\rho] = \exp\left[-\int_{x_\perp, y_\perp} \frac{\rho(x_\perp)\rho(y_\perp)}{2\mu^2(x_\perp - y_\perp, x_0)}\right]$$



(J.-P. B, F. Gelis, R. Venugopalan, hep-ph/0402256)



(Kharzeev, Kovchegov, Tuchin, hep-ph/0405045)

CONCLUSIONS AND OUTLOOK

- Saturation picture (color glass condensate) does provide a successful phenomenology, both at RHIC and at HERA.

- Saturation manifests itself at lower energy in nucleus-nucleus collisions than in proton-proton collisions

- Color glass only provides initial conditions. Because of final state interactions, AA collisions do not allow for direct tests.

- dA are much better. Going to forward rapidity one gets a chance to « see » evolution of parton densities.

- Phenomena should be more visible at the LHC

$$\sqrt{s} = 5.5\mathrm{TeV} \qquad x \sim 5 \times 10^{-4} - 10^{-5} \qquad Q_s^2 \sim 5 - 14\mathrm{GeV}^2$$

Why is it important to search for the color glass condensate ?

- **Saturation is a genuine, characteristic, QCD effect**

- **Important to get a complete control of the initial conditions**

- **May well turn into an essential piece in the chain of arguments leading to the identification of the quark-gluon plasma**

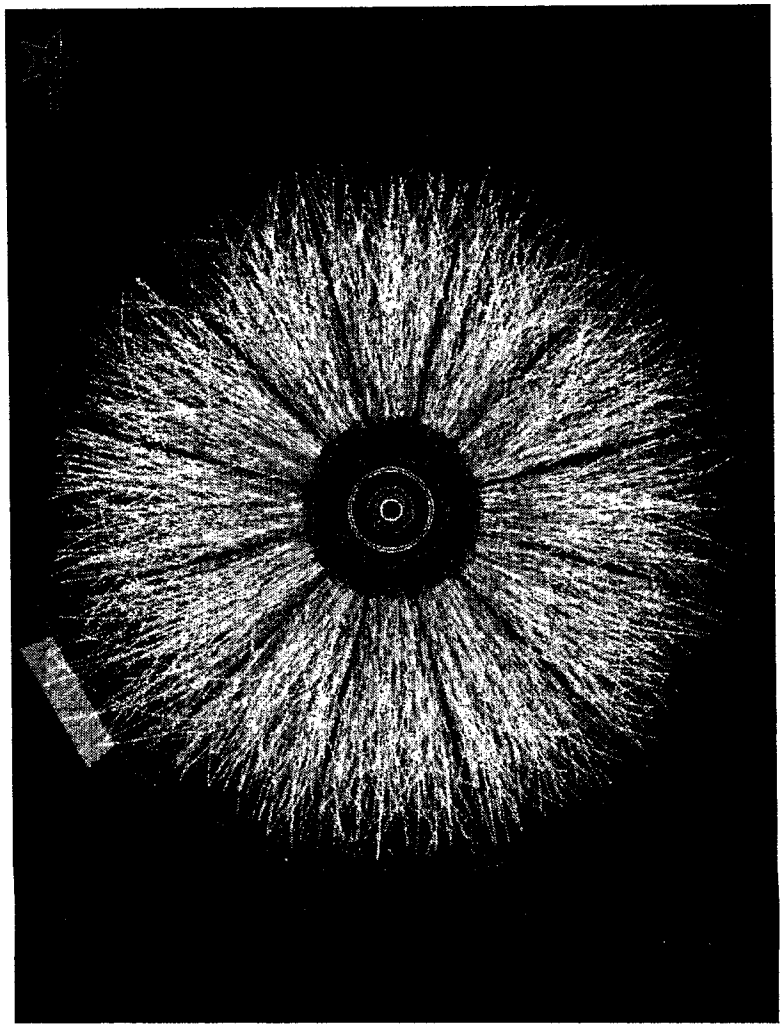
Hadronic Signals of Deconfinement at RHIC

Berndt Müller
Duke University

Riken-BNL "Discovery" Workshop

May 14-15, 2004

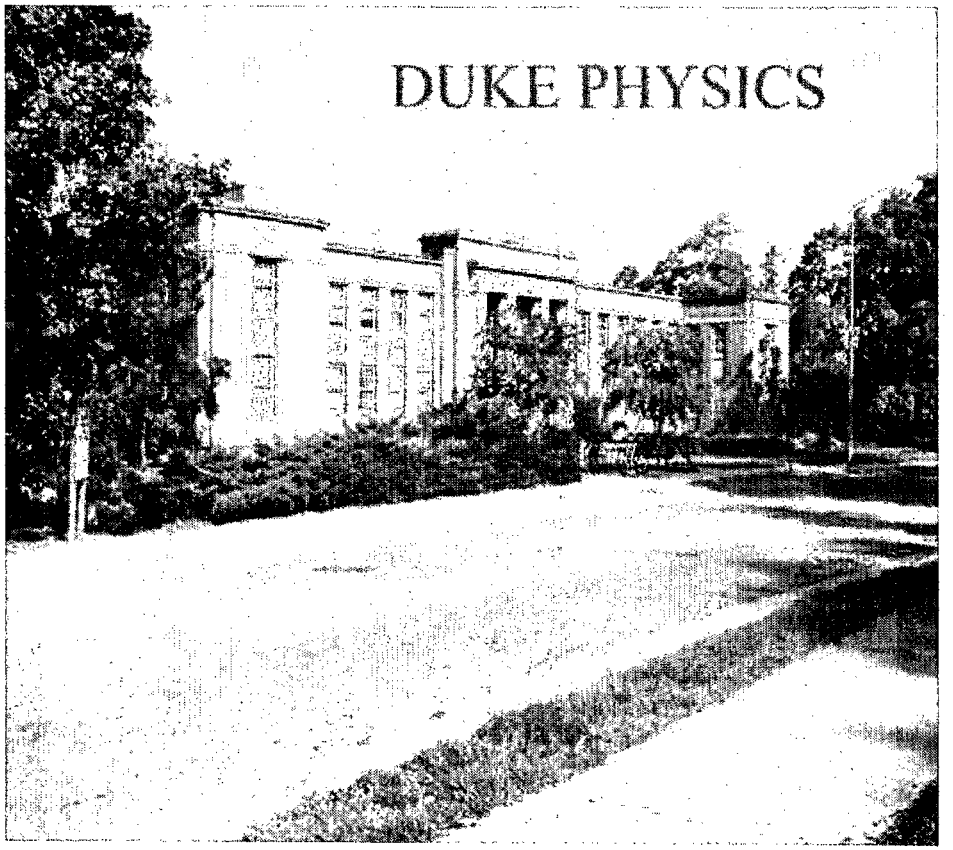
Hadrons encode essential properties of the partonic phase of dense, hot matter created in RHI reactions.



Special thanks to…

- M. Asakawa
- S.A. Bass
- R.J. Fries
- C. Nonaka
- T. Renk

- PRL 90, 202303
- PRC 68, 044902
- PLB 583, 73
- PRC 69, 031902
- nucl-th/0404015



What would it really take…?

Question (from a friend):

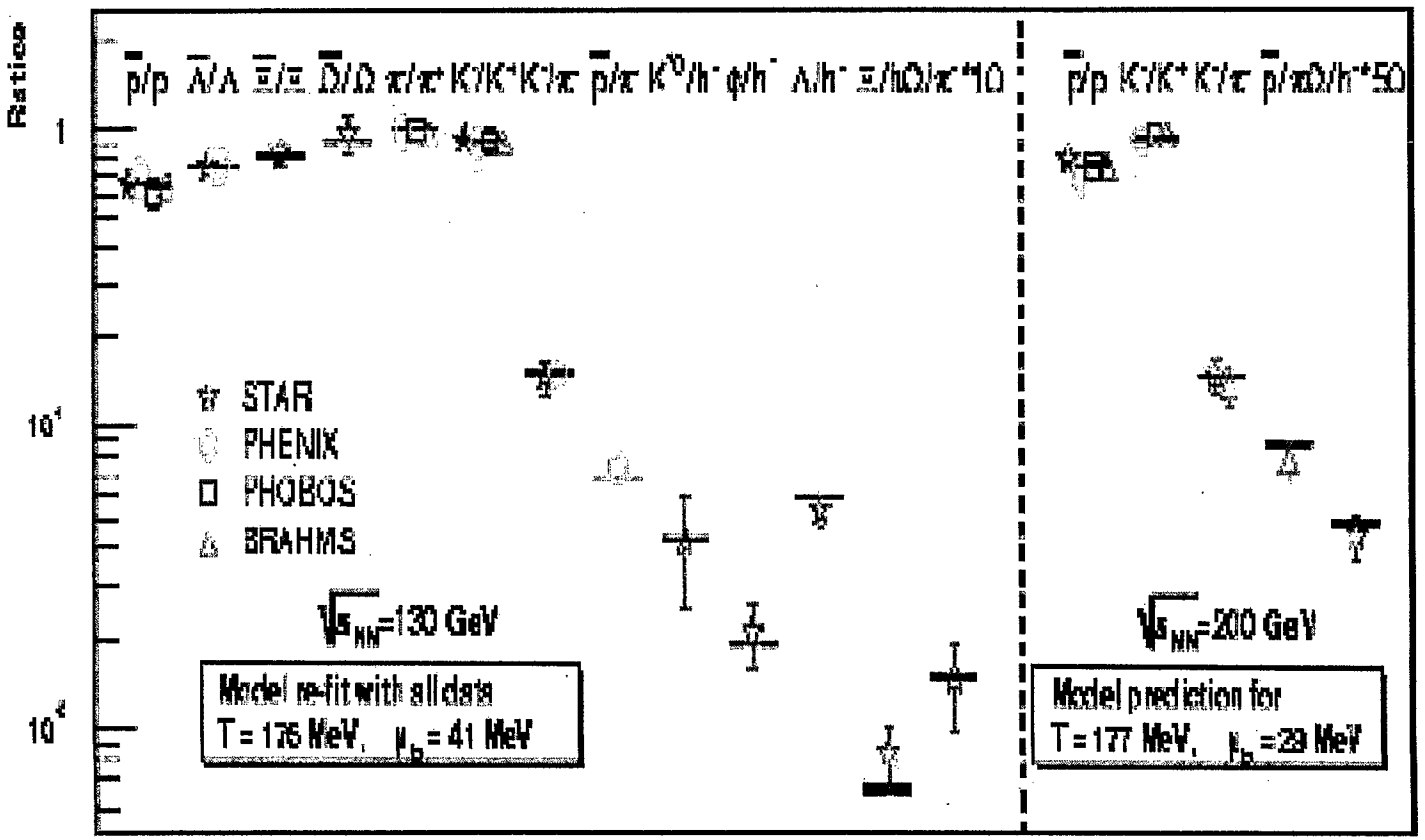
What would it take to convince you that the quark-gluon plasma has been discovered at RHIC?

Answer – If we could show that:

- *Hadrons are emitted in universal equilibrium abundances;*
- *Hadrons are produced by recombination of quarks;*
- *Hadrons show clear evidence of collective flow* (v_0 *and* v_2);
- *Flow pattern is not universal for hadrons, but universal for the constituent quarks.*

Chemical equilibrium – not new, but…

T_{ch} does not grow from SPS to RHIC !



Braun-Munzinger et al., PLB 518 (2001) 41 D. Magestro (updated July 22, 2002)

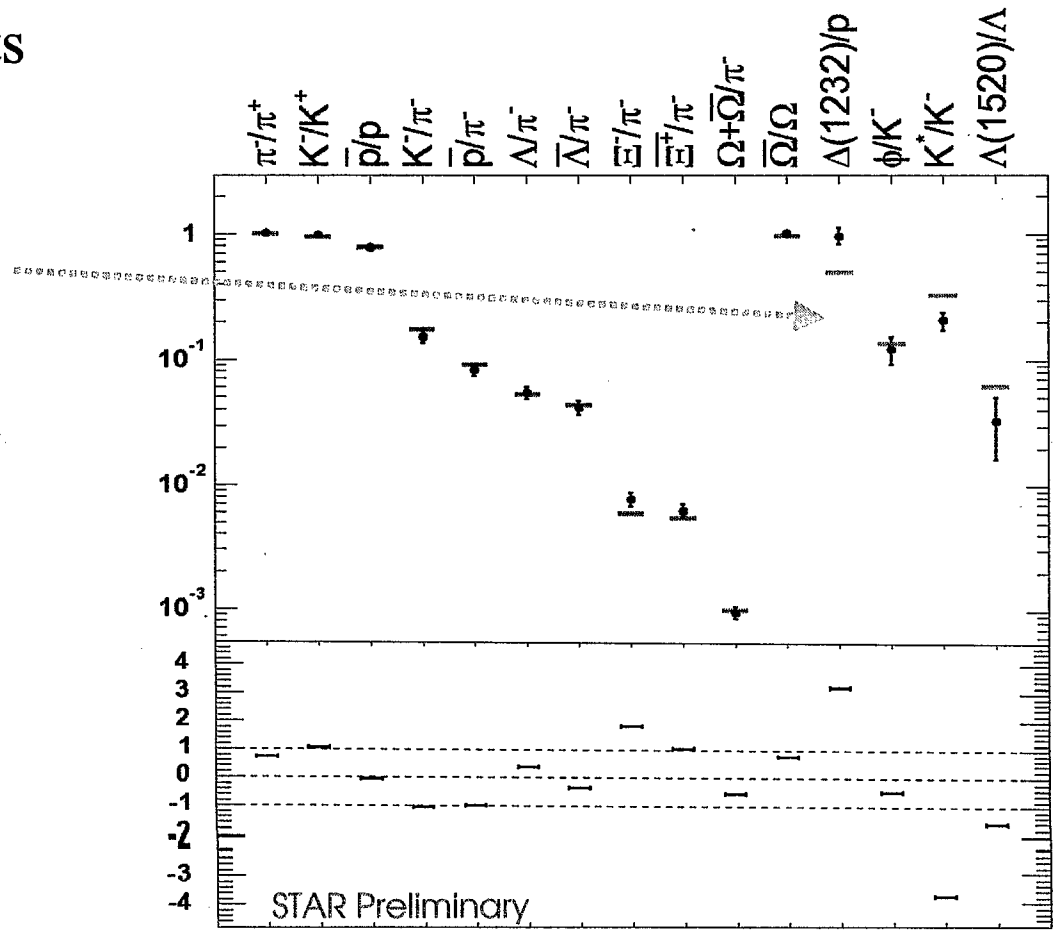
Equilibrium fits work…

- Chemical equilibrium fits work, *except* where they should not (resonances with large rescattering).

RHIC Au+Au @ 200 GeV

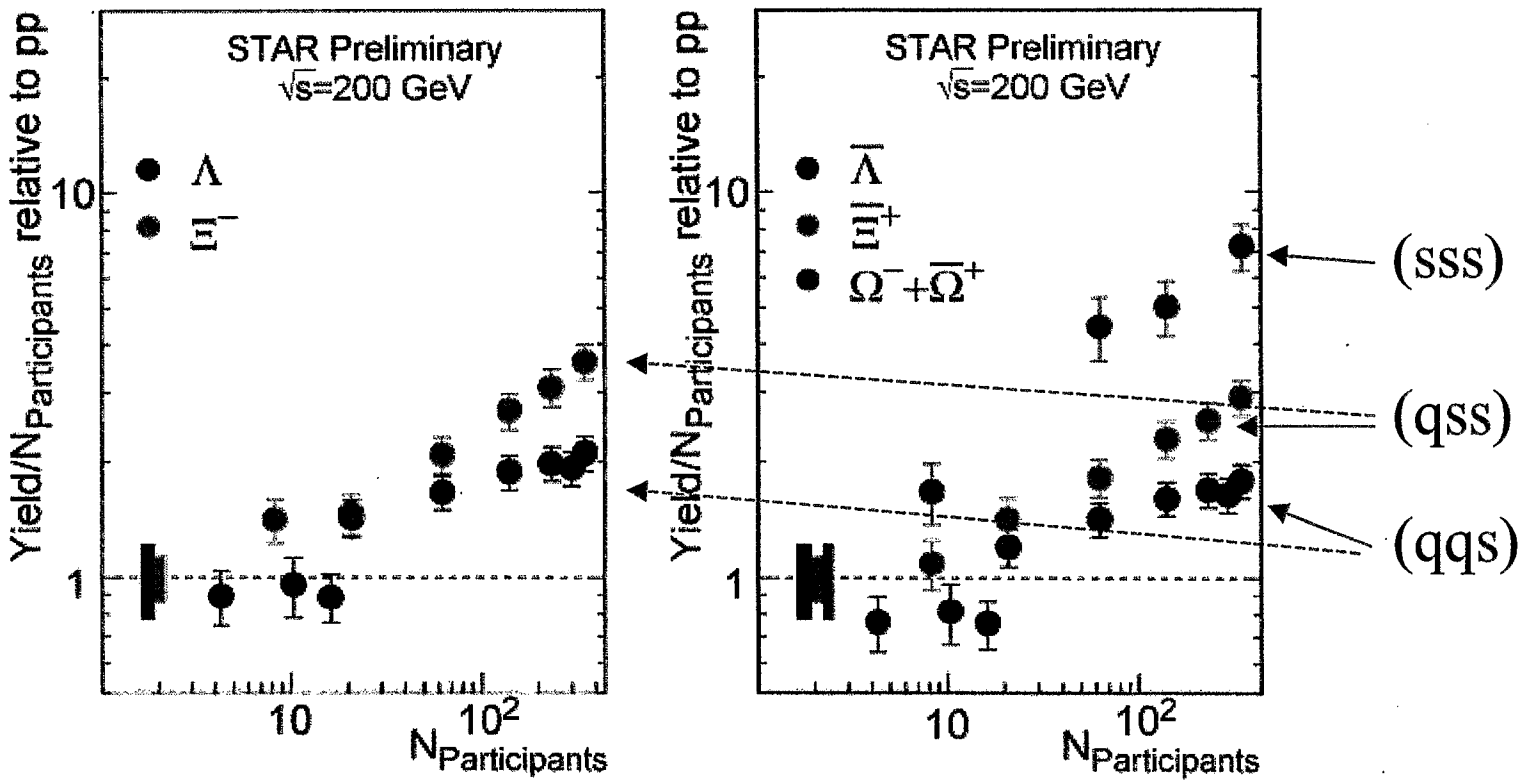
- $T_{ch} = 160 \pm 10$ MeV
- $\mu_B = 24 \pm 5$ MeV

(STAR Preliminary)



Strangeness in Au+Au at RHIC

The strangeness "enhancement" is less than at SPS energy, as expected from chemical equilibrium paradigm!



Conclusions (1)

- Clear evidence for a *universal* hadronization temperature $T_{ch} \equiv T_c$ is seen in RHIC data;
- Already visible at SPS, but only RHIC data make the evidence compelling;
- Strangeness equilibration is critical discriminator between phase space dominance (pp, e^+e^-) and equilibration (AA).

Issues to be clarified...

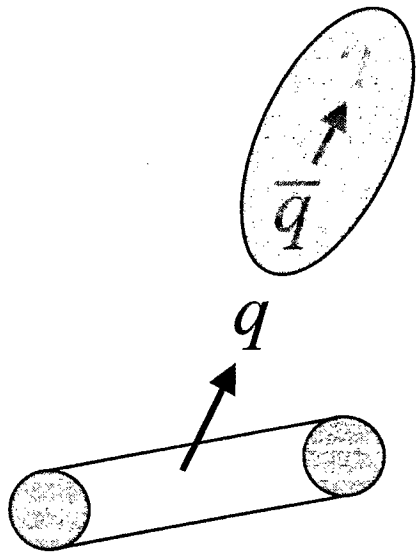
- Are hadron abundances described by *universal* parameters [$T_c = T_c = T_c(\mu)$] or by A- and E_{CM}-dependent parameters describing chemical freezeout conditions?

- If the hadron abundances are determined by equilibrium at T_c, then only the *deviations* from equilibrium should be non-universal. Do the data confirm this?

- Can these deviations from equilibrium be *quantitatively* described by microscopic models of final-state hadronic rescattering (e.g. by UrQMD)?

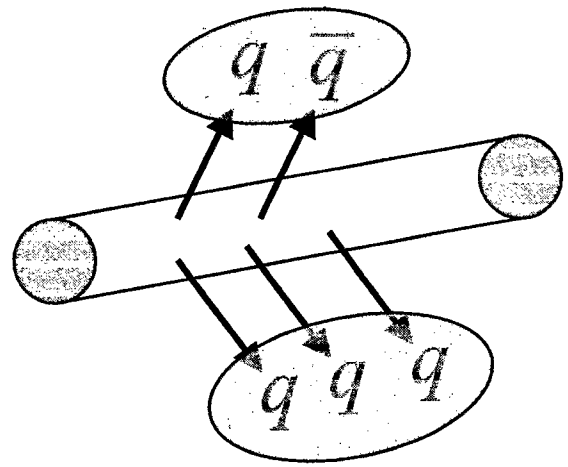
Hadronization mechanisms

Recombination was predicted in the 1980's – but a surprise after all



Fragmentation

$$\frac{\text{Baryon}}{\text{Meson}} = 1$$



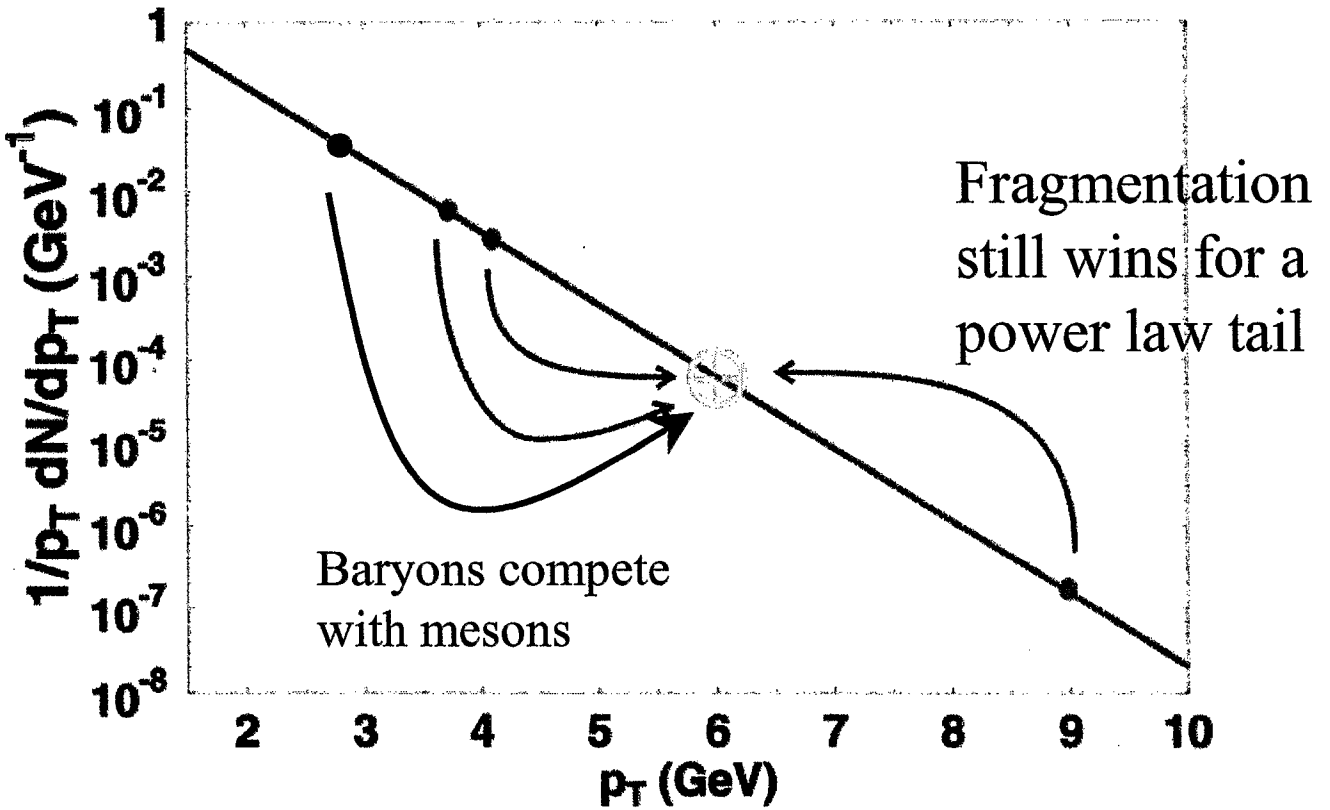
Recombination

$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

$$p_M \approx 2p_Q \quad p_B \approx 3p_Q$$

Recombination "wins" …

… always for a thermal source



Recombination of thermal quarks

Relativistic formulation using hadron light-cone frame:

$w_\alpha(r,p) =$ Quark distribution function at "freeze-out"

$$E\frac{dN_{\mathrm{M}}}{d^3P} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3}\sum_{\alpha,\beta}\int dx\, w_\alpha(R,xP^+)\bar{w}_\beta(R,(1-x)P^+)\left|\bar{\phi}_{\mathrm{M}}(x)\right|^2$$

$$E\frac{dN_{\mathrm{B}}}{d^3p} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3}\sum_{\alpha,\beta,\gamma}\int dx dx'\, w_\alpha(R,xP^+)w_\beta(R,x'P^+)w_\gamma(R,(1-x-x')P^+)\left|\bar{\phi}_{\mathrm{B}}(x,x')\right|^2$$

For a thermal distribution, $w(r,p):\ \exp(-p\cdot u/T)$

hadron wavefunctions can be integrated out, eliminating the model dependence of predictions.

Recombination vs. Fragmentation

Recombination: $$E\frac{dN_{\mathrm{M}}}{d^3P} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3}\sum_{\alpha,\beta}\int dx\, w_\alpha(R,xP^+)\overline{w}_\beta(R,(1-x)P^+)\left|\overline{\phi}_{\mathrm{M}}(x)\right|^2$$

Fragmentation: $$E\frac{dN_{\mathrm{h}}}{d^3P} = \int d\sigma \frac{P\cdot u}{(2\pi)^3}\int_0^1 \frac{dz}{z^3}\sum_\alpha w_\alpha(r,\tfrac{1}{z}P)D_{\alpha\to\mathrm{h}}(z)$$

Recombination… $$w_\alpha(r,xP^+)\overline{w}_\beta(r,(1-x)P^+) = \exp\left(-P\cdot u/T\right) \quad \text{Meson}$$

$$w_\alpha(r,xP^+)w_\beta(r,x'P^+)w_\gamma(r,(1-x-x')P^+) = \exp\left(-P\cdot u/T\right) \quad \text{Baryon}$$

…always wins over fragmentation for an exponential spectrum (z<1):

$$\exp(-P\cdot u/T) \quad > \quad \exp(-P\cdot u/zT)$$

… but loses at large p_{T}, where the spectrum is a power law ~ $(p_{\mathrm{T}})^{-b}$

Recombination & statistical model

In stat. model, hadron distributions at freeze-out are given by:

$$E\frac{d^3N_i}{d^3P} = \int_\sigma f_i(P\cdot u)\,P^\lambda d\sigma_\lambda \quad \text{with}$$

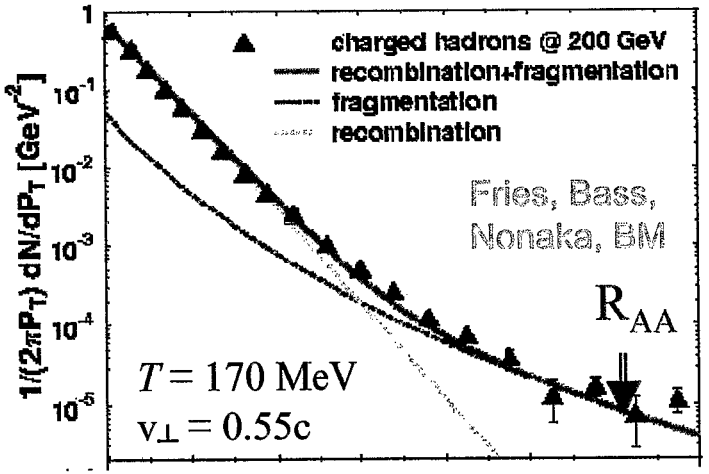
$$f_i(P\cdot u) = \frac{g_i}{(2\pi)^3}\left(\exp\left[\left(P\cdot u - \mu_B B_i - \mu_s S_i - \mu_I I_i\right)/T \pm 1\right]\right)^{-1}$$

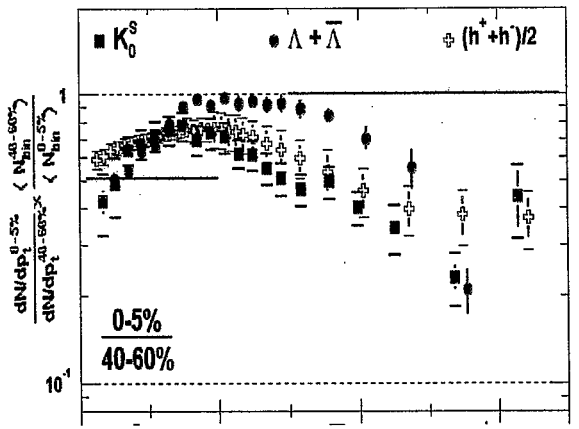
For $p_t \to \infty$, hadron ratios are identical to those in recombination!
(only determined by hadron degeneracy factors & chem. pot.)

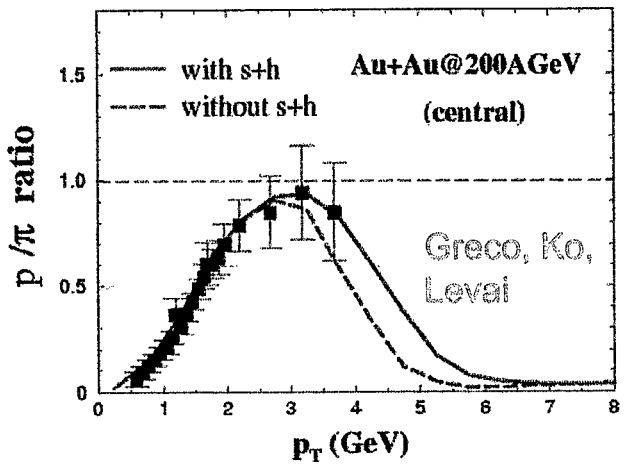
- recombination provides a microscopic basis for the apparent chemical equilibration among hadrons at (moderately) large p_t

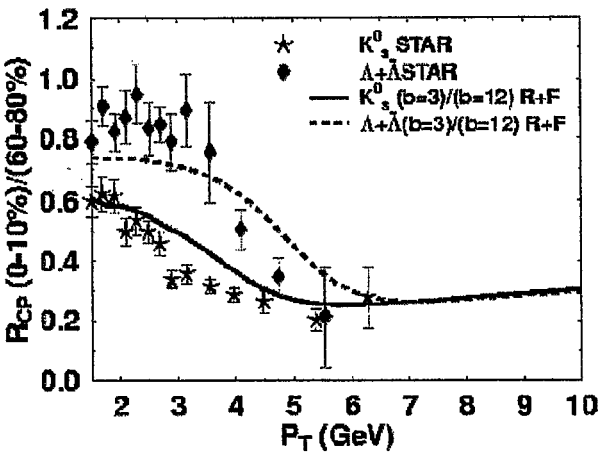
But: The elliptic flow velocity is approximately additive in valence quark number, showing partonic, rather than hadronic origin of the elliptic flow.

Recombination vs. Fragmentation

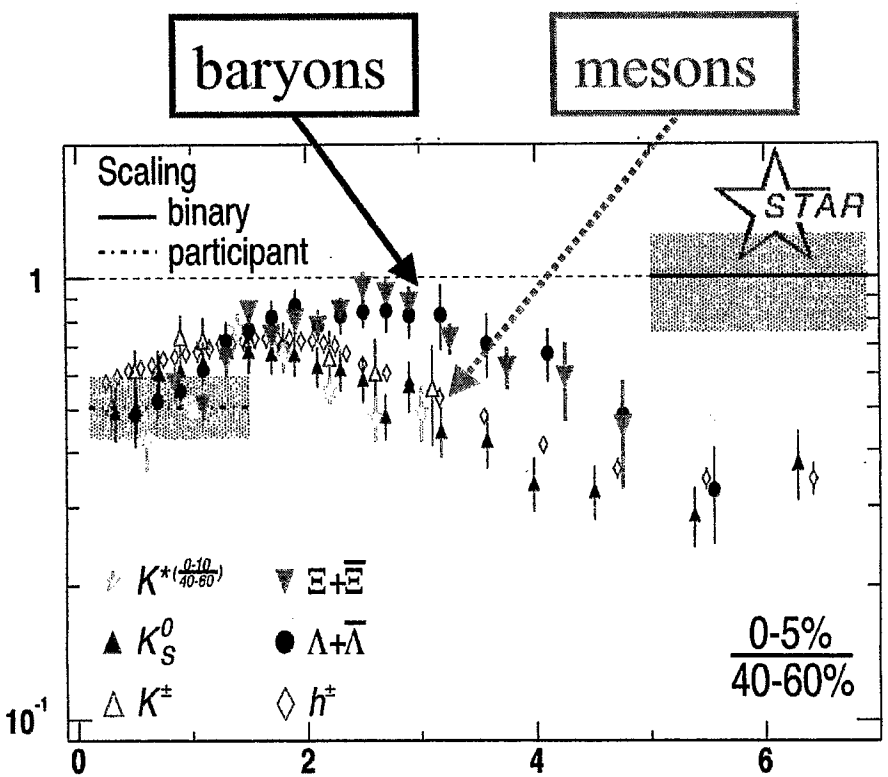


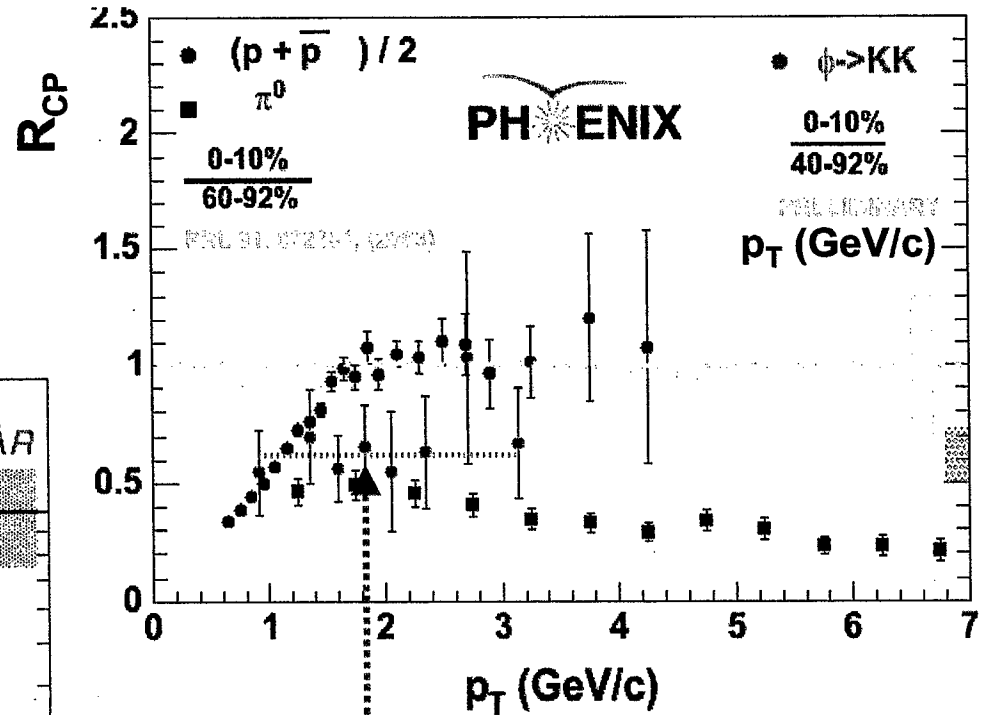






Suppression: Baryons vs. mesons





ϕ behaves like meson ?

(also η-meson)

Conclusions (2)

- Strong evidence for dominance of hadronization by quark recombination from a thermal, deconfined phase comes from:
  - Large baryon/meson ratios at moderately large p_T;
  - Compatibility of measured abundances with statistical model predictions;
  - Collective flow (v_0) still visible at large p_T.
- Φ-meson is an excellent test case (if not from $KK \rightarrow \Phi$).

Parton Number Scaling of Elliptic Flow

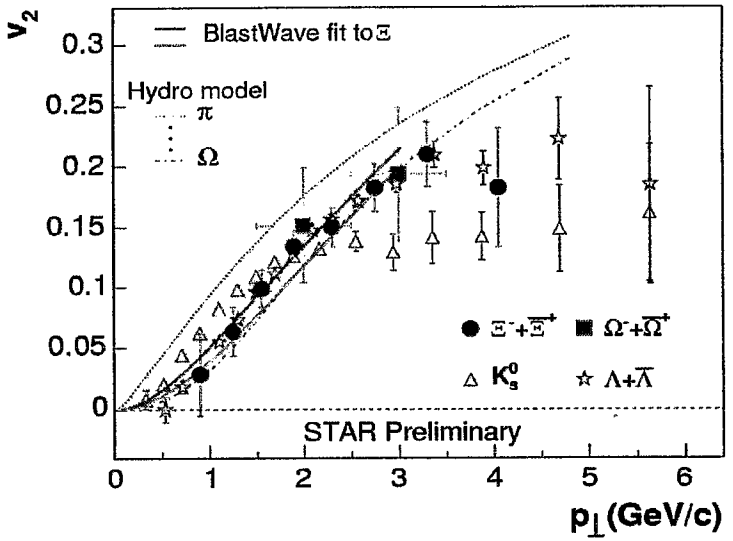
In the recombination regime, meson and baryon v_2 can be obtained from the parton v_2 :

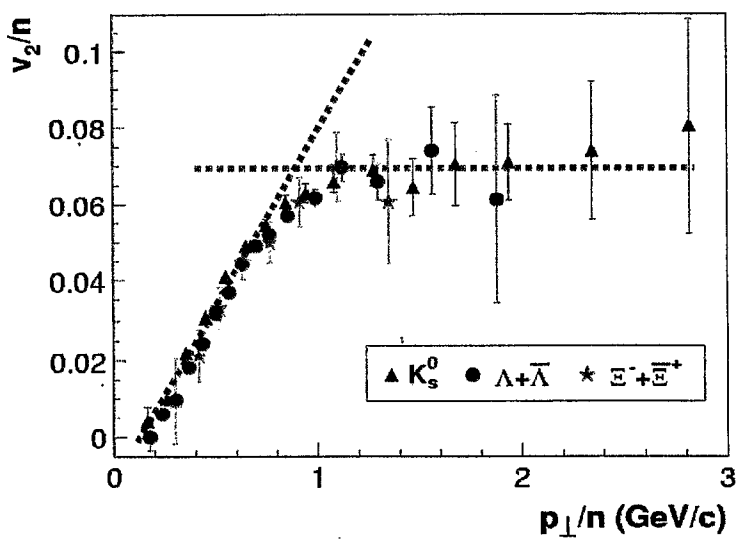
$$v_2^M(p_t) = \frac{2v_2^p\left(\frac{p_t}{2}\right)}{1+2\left(v_2^p\left(\frac{p_t}{2}\right)\right)^2} \quad \text{and} \quad v_2^B(p_t) = \frac{3v_2^p\left(\frac{p_t}{3}\right)+3\left(v_2^p\left(\frac{p_t}{3}\right)\right)^3}{1+6\left(v_2^p\left(\frac{p_t}{3}\right)\right)^2}$$

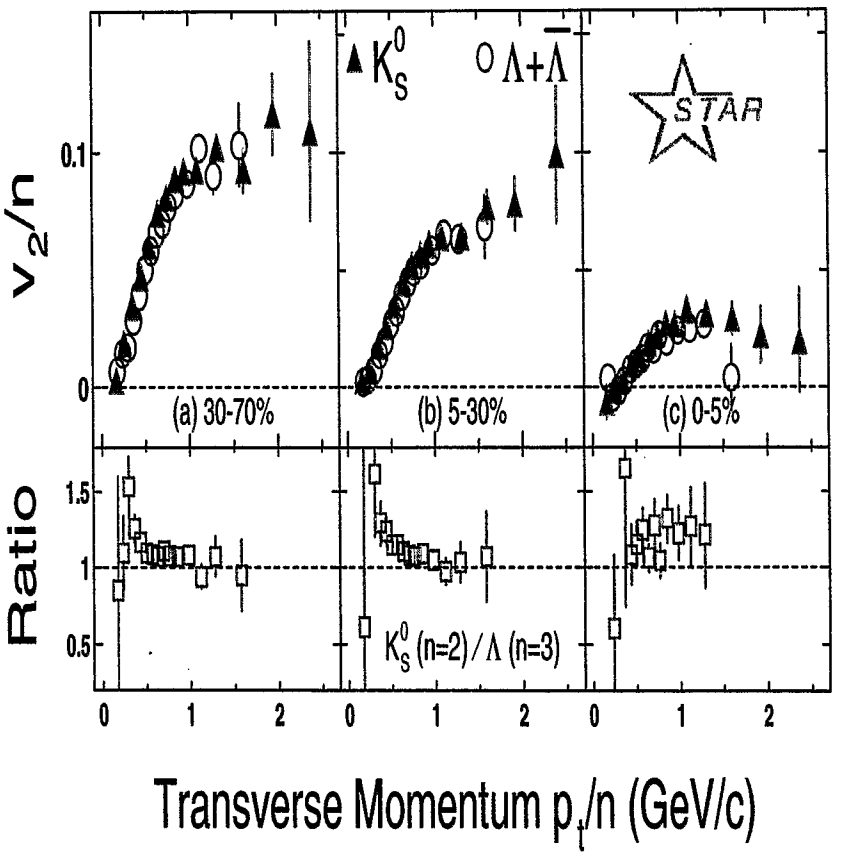
Neglecting quadratic and cubic terms, a simple scaling law holds:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

Hadron v_2 reflects quark flow !

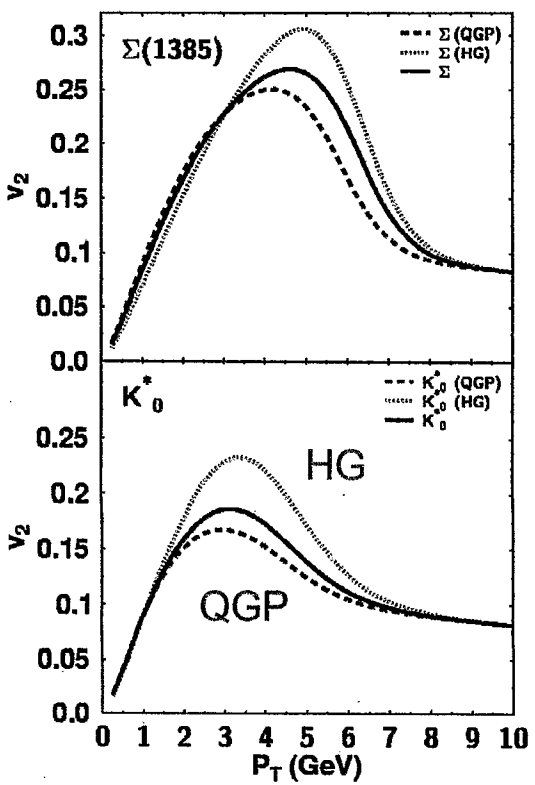




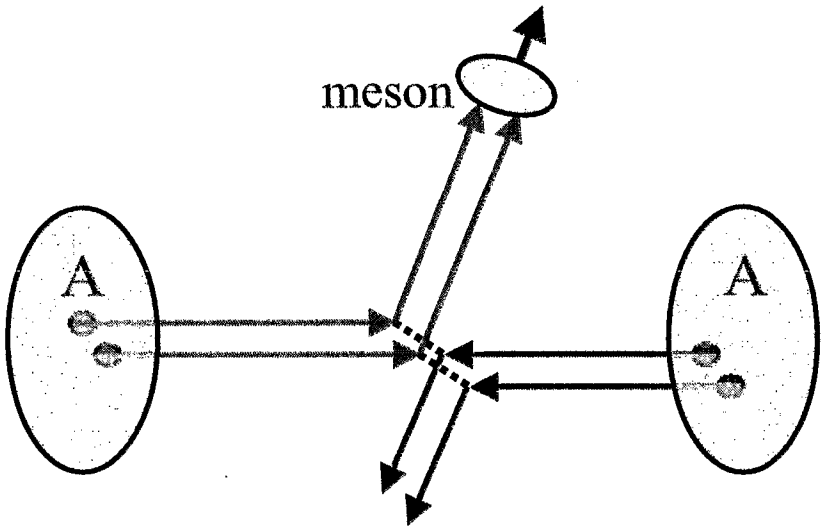


Conclusions (3)

- Recombination model works nicely for v_2:
  - $v_2(p_T)$ curves for different hadrons collapse to *universal* curve for constituent quarks;
  - Saturation value of v_2 for large p_T is *universal* for quarks and agrees with expectations from anisotropic energy loss;
  - Vector mesons (Φ, K^*) permit test for influence of mass versus constituent number (but note the *effects of hadronic rescattering on resonances*!)



Issues to be clarified…



T. Ochiai, Prog. Theor. Phys. 75 (1986) 1184

The "pQCD approach" to parton recombination

Double parton scattering:

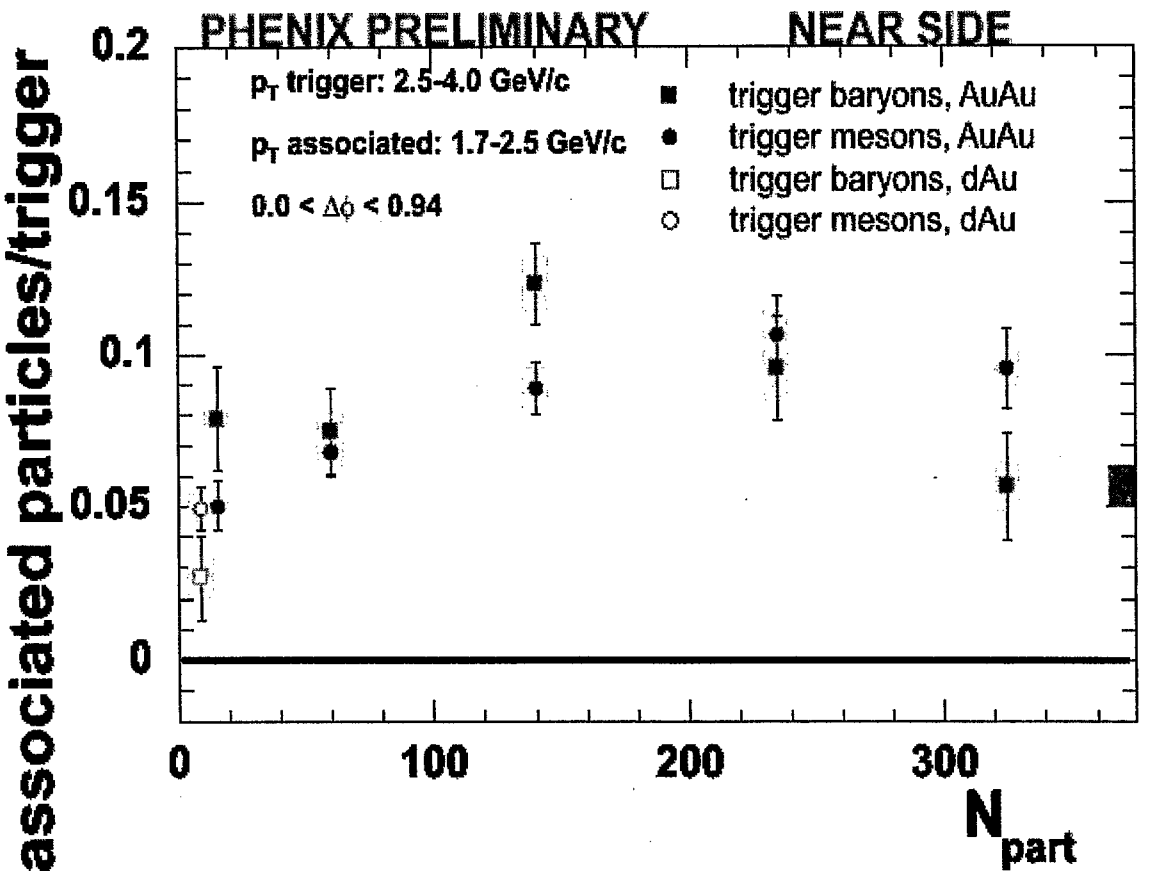
$$\frac{\mathrm{DPS}}{\mathrm{SPS}} : \left(\frac{16\alpha_s A^{1/3} \Lambda^2}{z p_T^2} \right)^2$$

Baryon enhancement by two-quark scattering and di-quark formation is possible, **but** does **not** naturally imply a statistical ratio of hadron yields (baryons vs. mesons).

Recombination from a **thermal** quark ensemble does!

Hadron-hadron correlations

The fly in the ointment… ?



"Jet"-like correlations persist in the recombination regime, for baryons and mesons!

How serious is this?

- Not a "theorist's excuse":
  - Existing recombination models are based on the assumption of a one-body quark density. Two-hadron correlations are determined by quark correlations, which are not included (except by Hwa et al.).

- Two- and multi-quark correlations are a natural result of jet quenching by energy loss of fast partons.

- Incorporation of quark correlations is straightforward, but introduces many new parameters: $C(p_1, p_2)$.

Parton correlations ...

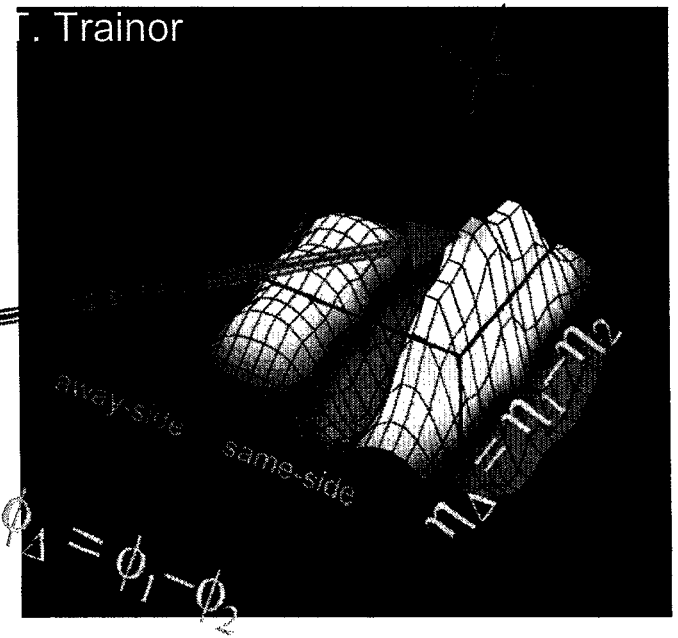
...provide a simple way out?

Parton correlations trivially translate into hadron correlations.

Soft-hard recombination naturally gives such correlations.

Parton correlations even in the thermal regime?

Two-point velocity correlations among 1-2 GeV/c hadrons



Correlations - formalism

2-meson production:

$$\frac{dN_{MM}}{d^3P_1 d^3P_2} = \frac{V^2}{(2\pi)^6} \int d^3q_1 d^3q_2 |\phi(q_1)|^2 |\phi(q_2)|^2 W_4\left(\frac{1}{2}P_1 + q_1, \frac{1}{2}P_1 - q_1, \frac{1}{2}P_2 + q_2, \frac{1}{2}P_2 + q_2\right)$$

$$W_n(p_1, \mathrm{K}, p_n) = \prod_n w(p_i)\left(1 + \sum_{i<j} C_{qq}(p_i, p_j)\right)$$

Partons with pairwise correlations

$$\Rightarrow \frac{dN_{MM}}{d^3P_1 d^3P_2} = \frac{V^2}{(2\pi)^6} w^2\left(\frac{1}{2}P_1\right) w^2\left(\frac{1}{2}P_2\right)\left[1 + 2C_0 + 4C_{qq}\left(\frac{1}{2}P_1, \frac{1}{2}P_2\right)\right]$$

Meson-meson, baryon-baryon, baryon-meson correlations

$$C_{BB} = 9C_{qq}, \quad C_{MB} = 6C_{qq}, \quad C_{MM} = 4C_{qq}$$

Model studies are in progress; please stay tuned…

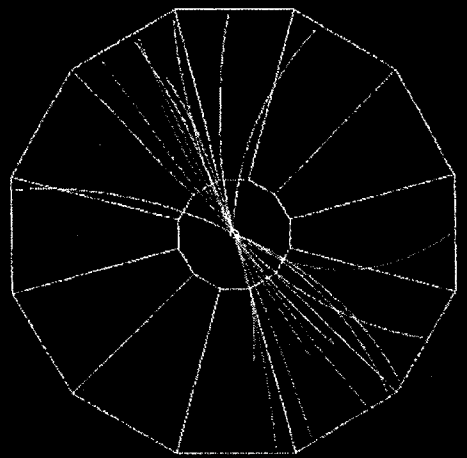
Conclusions – at last!

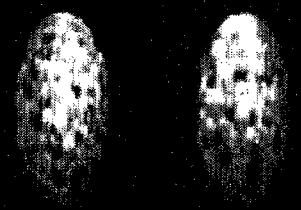
How the Q(G)P ("a deconfined phase of QCD matter") was discovered at RHIC:

- ✓ *Hadrons are emitted in* ***universal*** *equilibrium abundances;*
- ✓ *Most hadrons are produced by* ***recombination of quarks****;*
- ✓ *Hadrons show evidence of* ***collective flow*** (v_0 *and* v_2);
- ✓ *Flow pattern* (v_2) *is not universal for hadrons, but* ***universal for the constituent quarks****.*

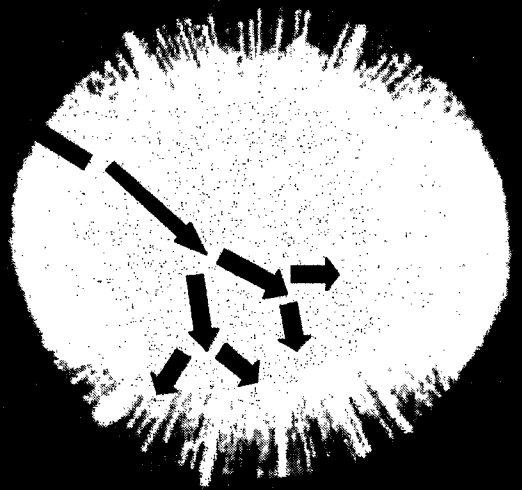
THE END

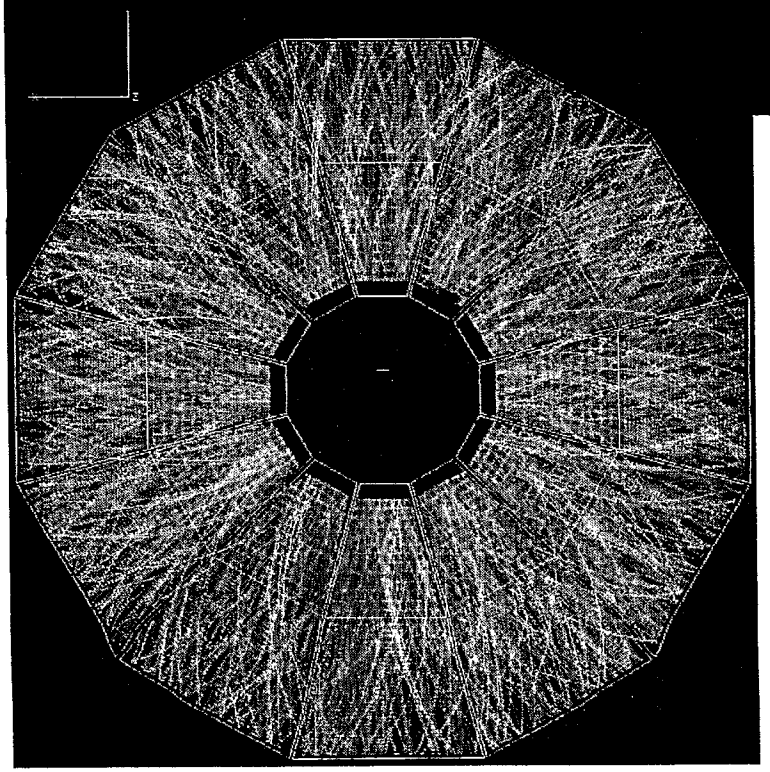
Discovery of Jet Quenching and Beyond

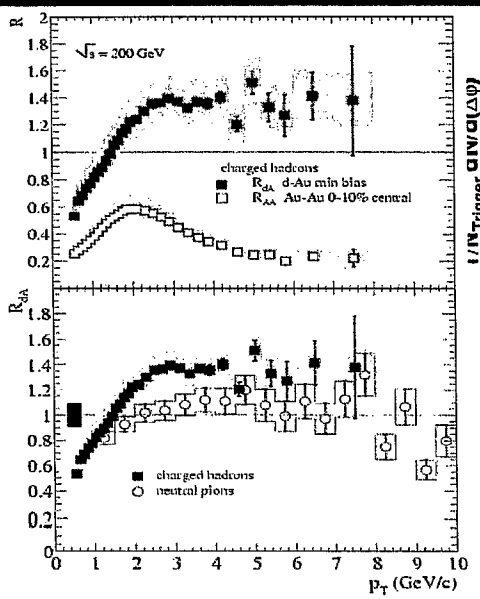


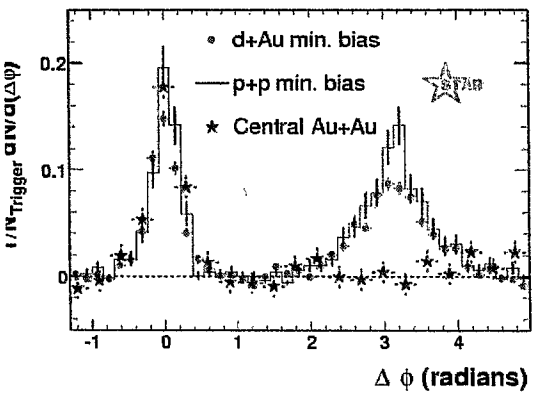


Jet









Xin-Nian Wang

LBNL, May 15, 04

Discovery of Jet Quenching and Beyond

RBRC Workshop on: New Discoveries at RHIC

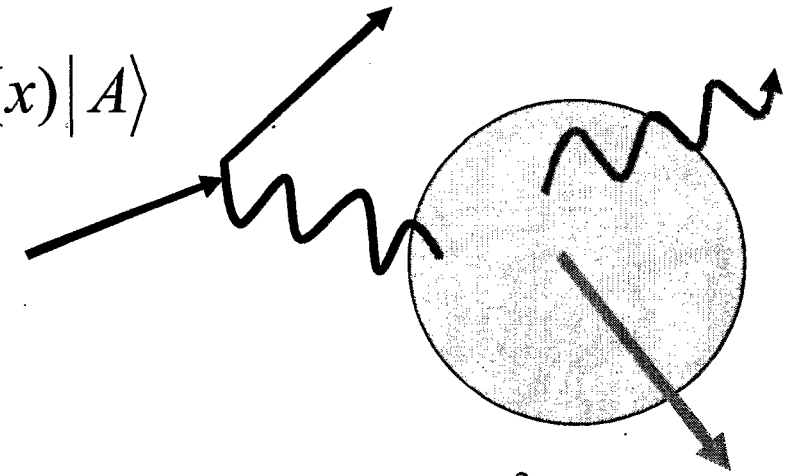
BNL/RIKEN, May 15, 2004

- Introduction: Jet Quenching
- Single hadron: Jet quenching and initial effects
- Dihadron: Modified fragmentation function
- Why the observed energy loss is partonic?
- Beyond the discovery of jet quenching

Xin-Nian Wang (LBNL)

Jet Tomography

$$W_{\mu\nu}(q) = \frac{1}{4\pi}\int d^4x e^{iq\cdot x}\left\langle A\middle| j_\mu^{em}(0) j_\nu^{em}(x)\middle| A\right\rangle$$



$$W_{DIS}^{\mu\nu} \equiv -\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)F_1(x_B) + \frac{1}{p\cdot q}\left(p^\mu - \frac{p\cdot q}{q^2}q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2}q^\nu\right)F_2(x_B)$$

$$x_B = -\frac{q^2}{2p\cdot q}$$

Dynamic System: Photon or dilepton emission

J/Ψ suppression

QCD Response: $j_\mu^{em}(x) \rightarrow j_\mu(x)$ Quark scattering

A Chronicle of Jet Quenching

- 1982, Bjorken (unpublished): elastic dE/dx too small
- 1990,Gyulassy, Pluemer: Evoking inelastic dE/dx
- 1992, Gyulassy, XNW: Suppression of leading hadrons due to jet quenching
- 1994, Gyulassy, XNW: First calculation of radiative parton energy loss with LPM
- 1995, Gyulassy, Pluemer, XNW: Estimate of mono-jet rate in AA at RHIC
- 1996, Huang, Sarcevic, XNW: Medium modified fragmentation function & gamma tagged jet quenching
- 1996, Zakharov: Path integral formulation of dE/dx
- 1997, Baier et al: non-abelian LPM in QCD- interaction with gluonic clouds

A Chronicle- Con' d

- 2000, XNW: First estimate of Cronin at RHIC
- 2000, Gyulassy, Levai, Vitev: Opacity expansion I.
- 2001, Wiedemann: Opacity expansion II
- 2001, Guo, XNW: Higher-Twist expansion and calculation of modified frag. function.
- 2001, XNW, GVW: high p_T v_2 due to jet quenching
- 2002: Suppression of high p_T hadron in Au+Au
- 2003: v_2 at high pt observed
- 2003: Suppression of back-side jet
- 2003, June 18: d+Au results announced
- 2004, azimuthal dependence of away-side jet

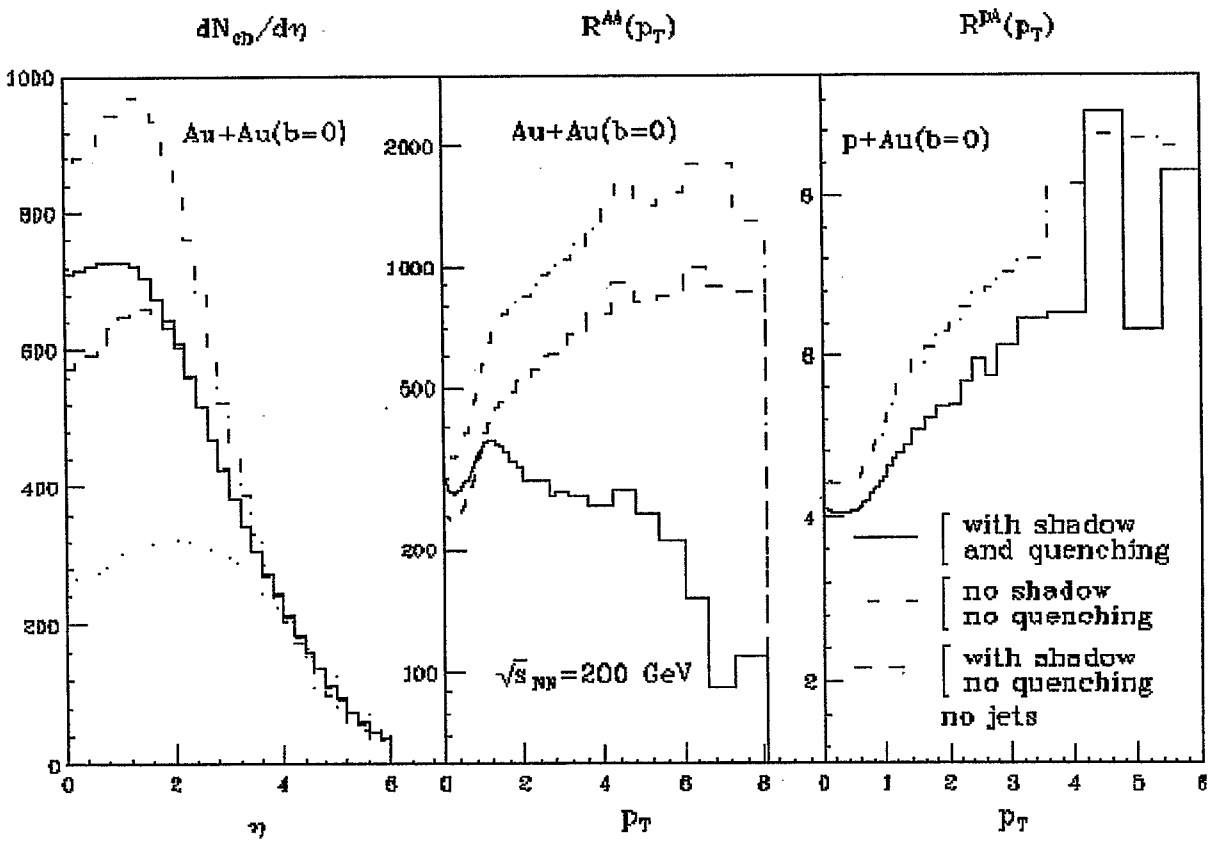
Jet Quenching

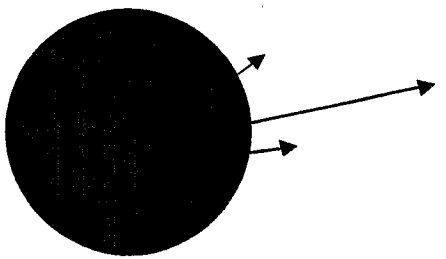
- Jet Quenching – Suppression of high p_T jet in dense medium
- Experimentally:
  - Medium modification of jet fragmentation function (FF)
  - Suppression of the leading hadrons in FF
- Theoretically:
  - Parton energy loss before hadronization
  - Or absorption of leading hadrons from jets

Single Spectra Suppression

Phys. Rev. Lett. **68**, 1480 (1992) **XNW and M. Gyulassy**

Gluon Shadowing and Jet Quenching in A+A Collisions at \sqrt{s}=200 AGeV



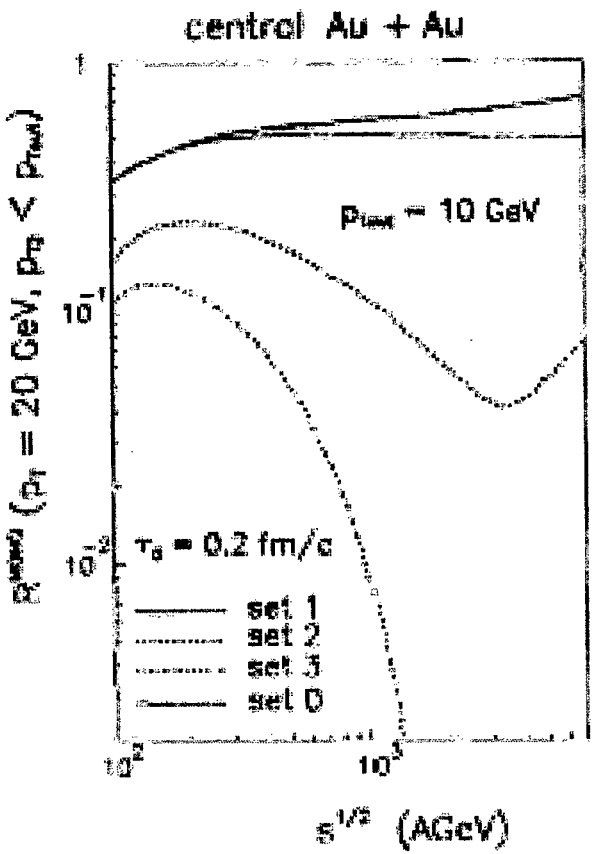


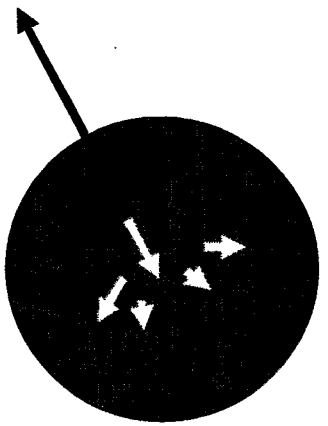
Away-side suppression or Mono-jet

NIL
LISFVII-8
Nuclear Physics A590 (1995) 511c-514c
NUCLEAR PHYSICS A

Jet Quenching and Monojet Rates in Ultrarelativistic Nucleus-Nucleus Collisions*

M. Plümer[a], M. Gyulassy[b] and X.N. Wang[c]

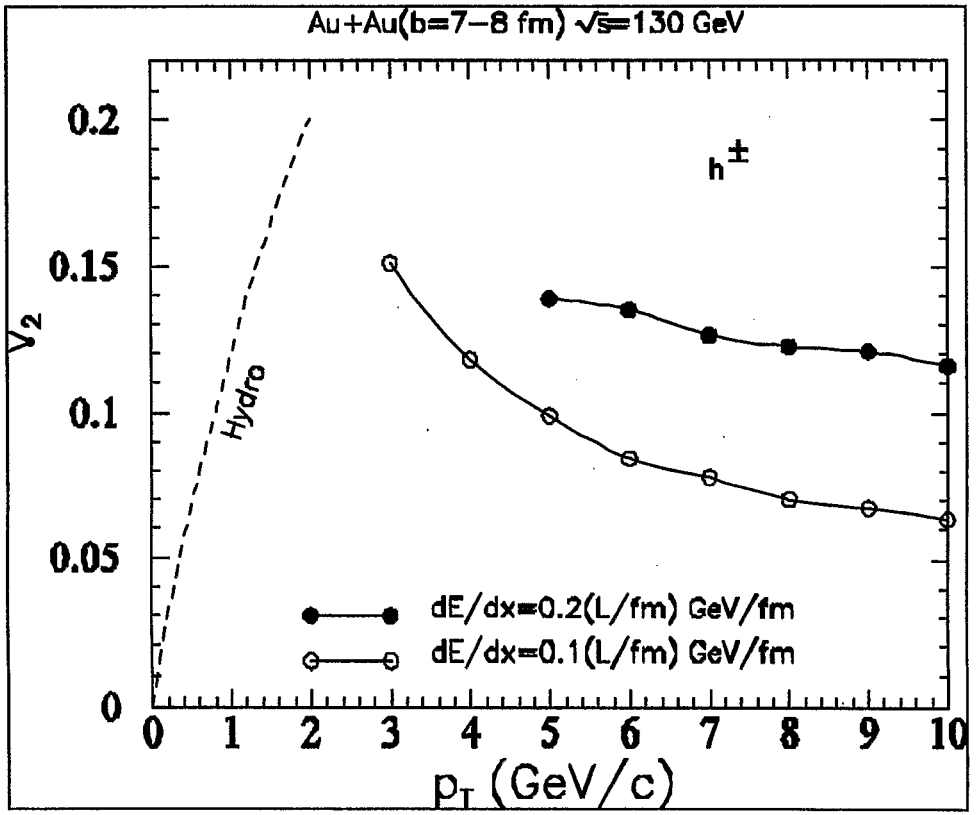


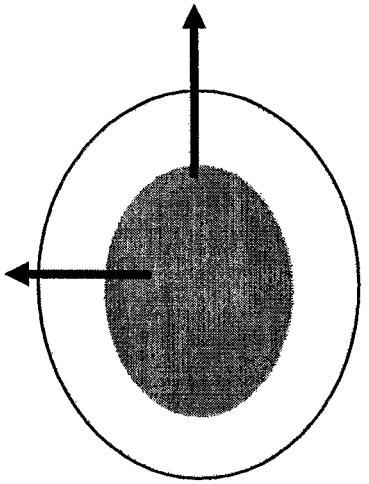


Azimuthal Anisotropy

Phys. Rev. C **63**, 054902 (2001) **XNW**

Jet Quenching and Azimuthal Anisotropy of Large p_T Spectra in Non-central High-energy Heavy-ion Collisions

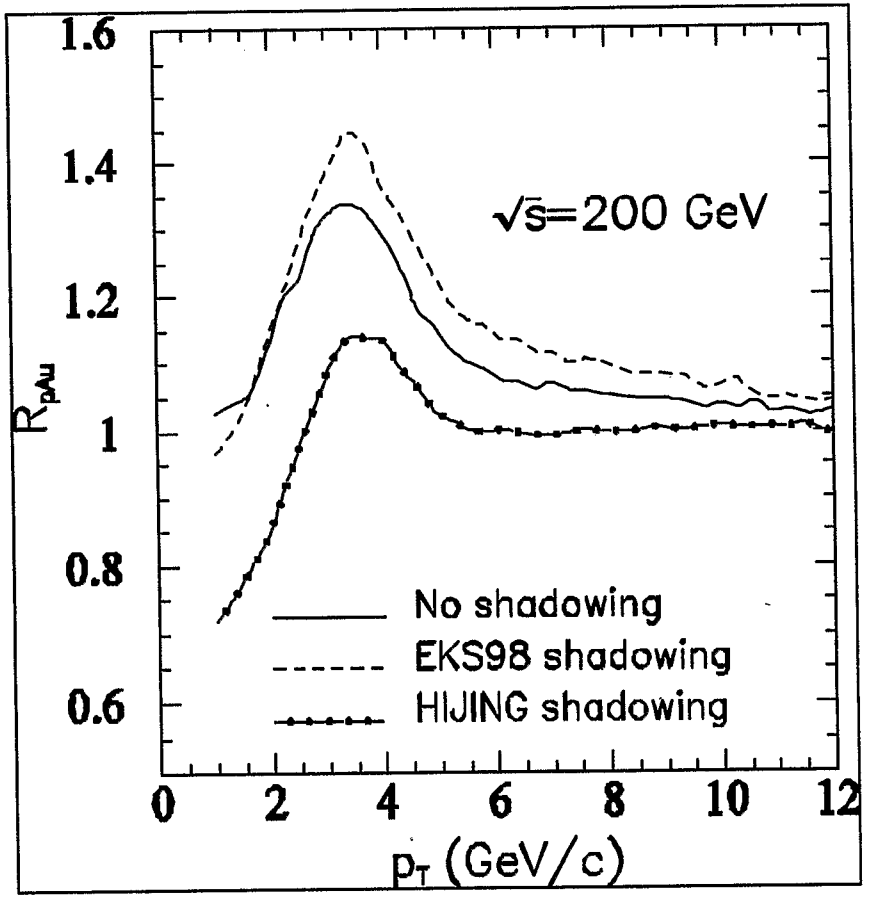


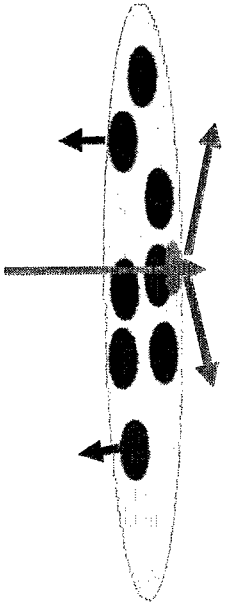


Non-suppression in p+A

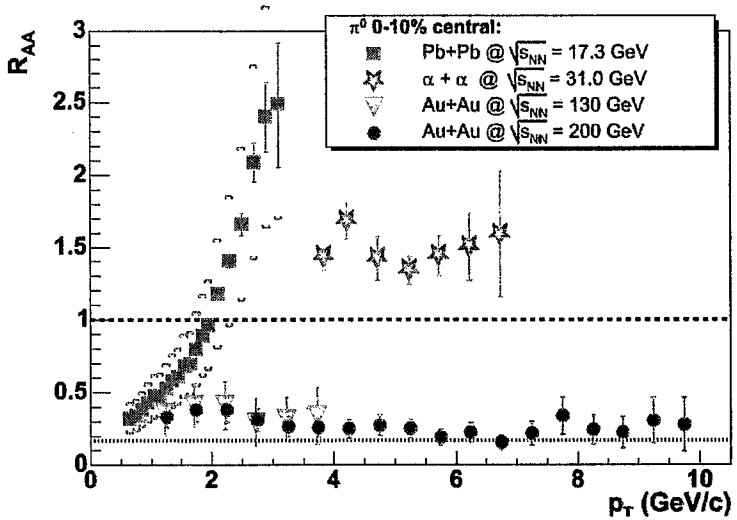
Systematic study of high p(T) hadron spectra in p p, p A and A A collisions from SPS to RHIC energies

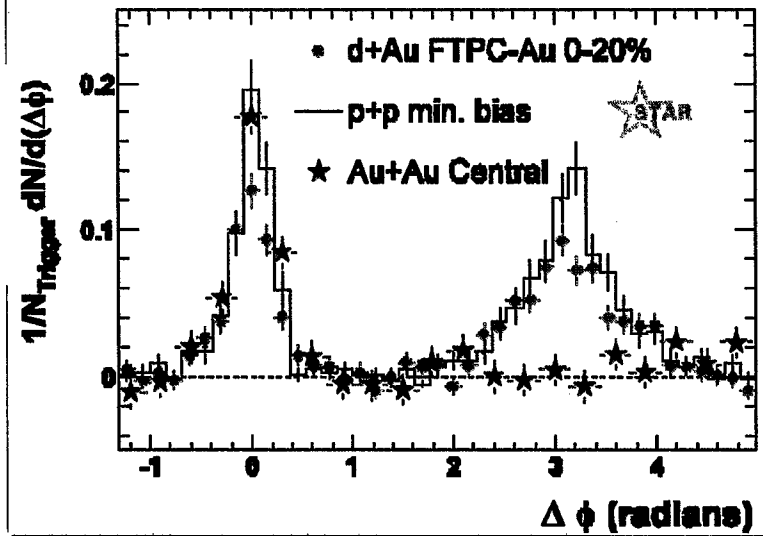
Phys. Rev. C **61**, 064910 (2000) hep-ph/9812021, XNW

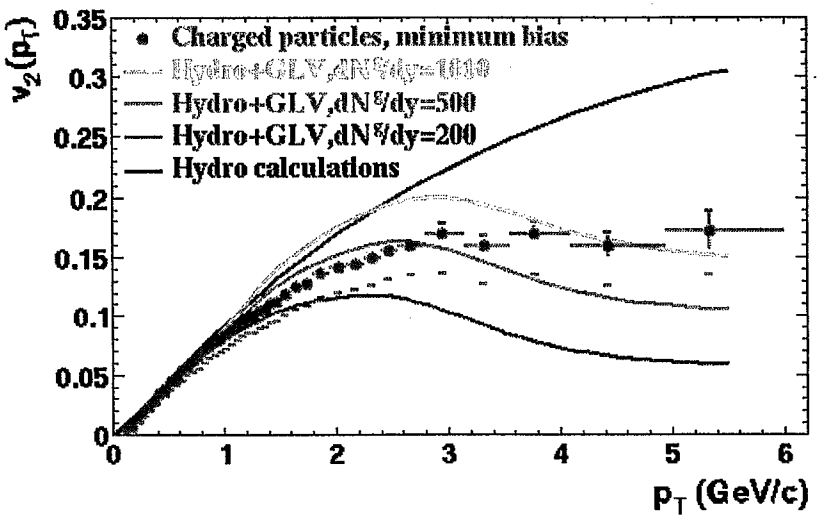


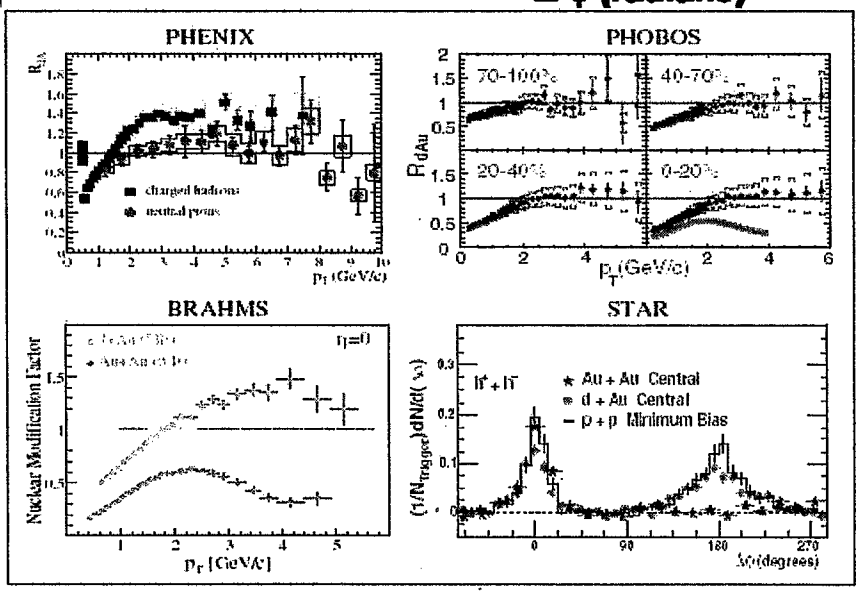


Experimental Evidence

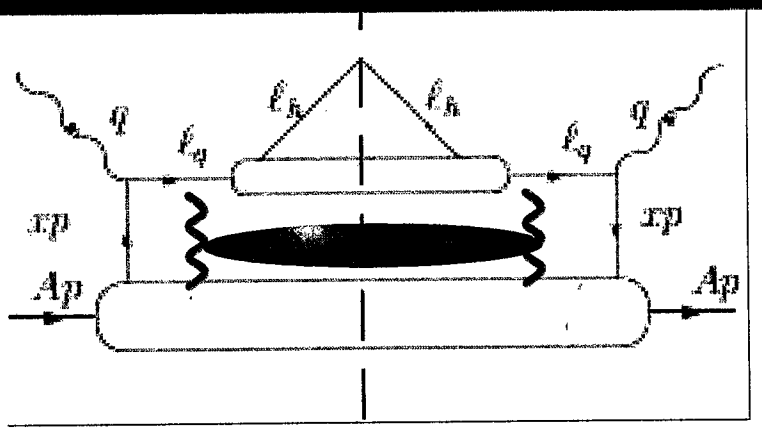


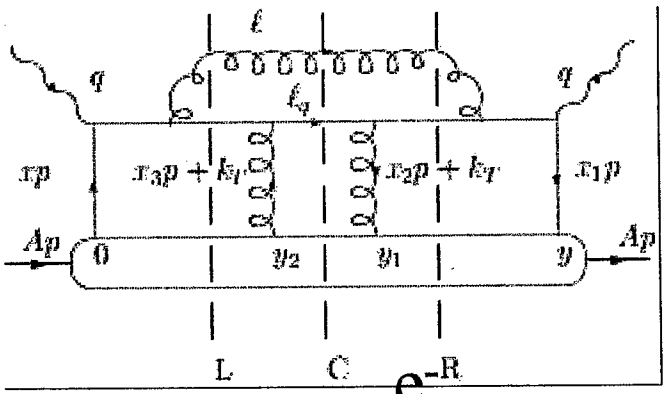


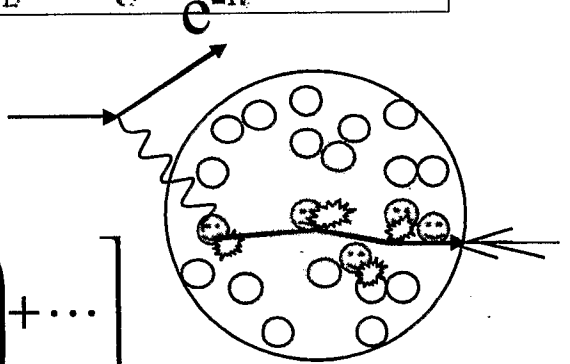




Modified Fragmentation Function







$$\tilde{D}(z_h, Q^2) = D(z_h, Q^2) + \Delta D(z_h, Q^2)$$

$$\Delta D_{q\to h}(z_h, Q^2) = \frac{\alpha_S}{2\pi}\int_0^{Q^2}\frac{d\ell_\perp^2}{\ell_\perp^4}\int_{z_h}^{1}\frac{dz}{z}\left[\Delta\gamma(z, x_L) D_{q\to h}\left(\frac{z_h}{z}\right) + \cdots\right]$$

Modified splitting functions

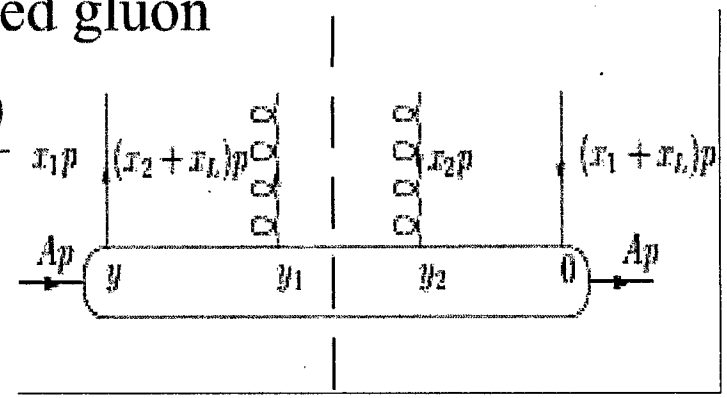
Guo & XNW'00

$$\Delta\gamma(z, x_L) = \frac{1+z^2}{(1-z)_+}\frac{C_A 2\pi\alpha_S}{N_c}\frac{T_{qg}^A(x, x_L)}{f_q^A(x)} + \cdots(\text{virtual})$$

Energy Loss & q_T Broadening

Quark energy loss = energy carried by radiated gluon

$$\langle \Delta z_g \rangle = \int_0^{Q^2} d\ell_T^2 \int_0^1 dz \frac{1+(1-z)^2}{\ell_T^2\left(\ell_T^2+\langle k_T^2\rangle\right)} \frac{C_A\alpha_s^2}{N_c} \frac{T_{qg}^A(x,x_L)}{f_q^A(x)}$$



Two-parton correlation:

$$T_{qg}^A(x,x_L) = \int \frac{dy^-}{2\pi} dy_1^- dy_2^- e^{-ix_Bp^+y^-} \langle A|\bar{\psi}(0)\frac{\gamma^+}{2}\psi(y^-)F_\sigma^{+}(y_1^-)F^{+\sigma}(y_2^-)|A\rangle \theta(y^- - y_1^-)$$

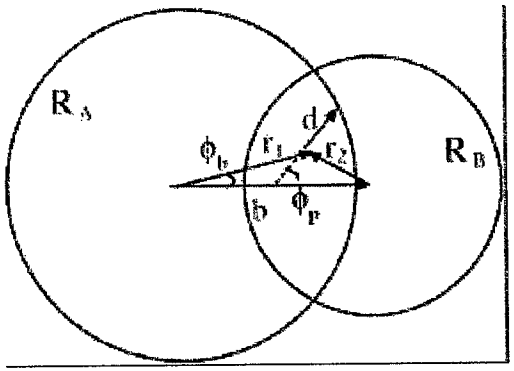
$$\times\left(1-e^{-ix_Lp^+y_2^-}\right)\left(1-e^{ix_Lp^+(y_1^- - y^-)}\right)\theta(-y_2^-)$$

$$\frac{T_{qg}^A(x,x_L)}{f_q^A(x)} \sim \int dy \mu^2 \sigma_g \rho(y)\left[1-\cos\frac{y}{\tau_f}\right]$$

$$\Delta E = \pi C_a C_A \alpha_s^3 \int_{\tau_0}^{R} d\tau \rho(\tau)(\tau-\tau_0)\ln\left(\frac{2E}{\tau\mu^2}\right)$$

BDPM
Gyulassy Vitev Levai
Wang & Wang
Wiedemann; Zakharov

Single spectra in A+A collisions



$$\Delta E(b,r,\phi) = \left\langle \frac{dE}{dx} \right\rangle_{1d} \int_{\tau_0}^{\tau_0+\Delta L} d\tau \frac{\tau-\tau_0}{\tau_0\rho_0} \rho(\tau,b,\vec{r}+\vec{n}\tau)$$

$$\rho(\tau,b,r) = \frac{\tau_0\rho_0}{\tau} n_{part}(b,r)$$

Participant Density

Single spectra

$$\frac{d\sigma_{AB}}{dyd^2p_T} = K\int d^2b \int d^2r_1 d^2r_2 t_A(r_1) t_B(r_2) \sum_{abcd} \int dx_a d^2k_{\perp a} dx_b d^2k_{\perp b}$$

$$f_{a/A}(x_a,k_{\perp a},r_1) f_{b/B}(x_b,k_{\perp b},r_2) \frac{d\sigma_{ab\to cd}}{dt} \frac{1}{z_c\pi} D_{h/c}(z_c)$$

Dihadron spectra

$$\frac{D_{h/c}(z_c,\Delta E_c)}{z_c^2} \frac{D_{h/d}(z_d,\Delta E_d)}{z_d^2}$$

Nuclear Modification Factor

$$R^{AB} = \frac{\sigma_{AB}}{\langle N_{\text{binary}} \rangle_{AB} \langle \sigma_{NN} \rangle} \qquad \langle N \rangle_{bin} \equiv \int d^2 b T_{AB}(b)$$

Wang&Wang 2001

Initial state effect: Shadowing & pt broadening: XNW, PRC61(00)064910

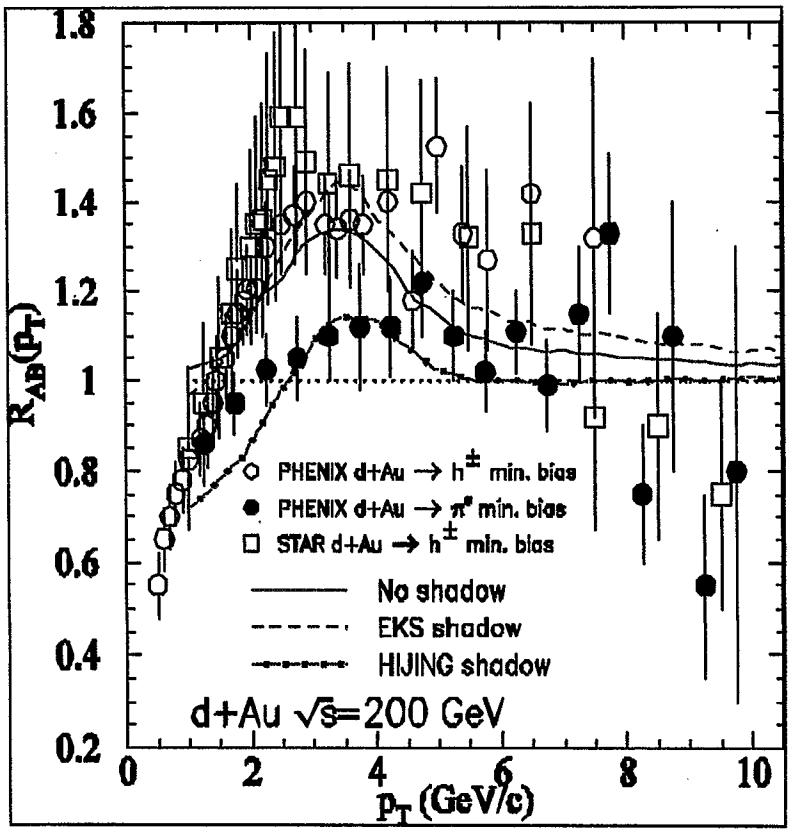
Fai, Papp, and Levai (02)

Vitev & Gyulassy (02)

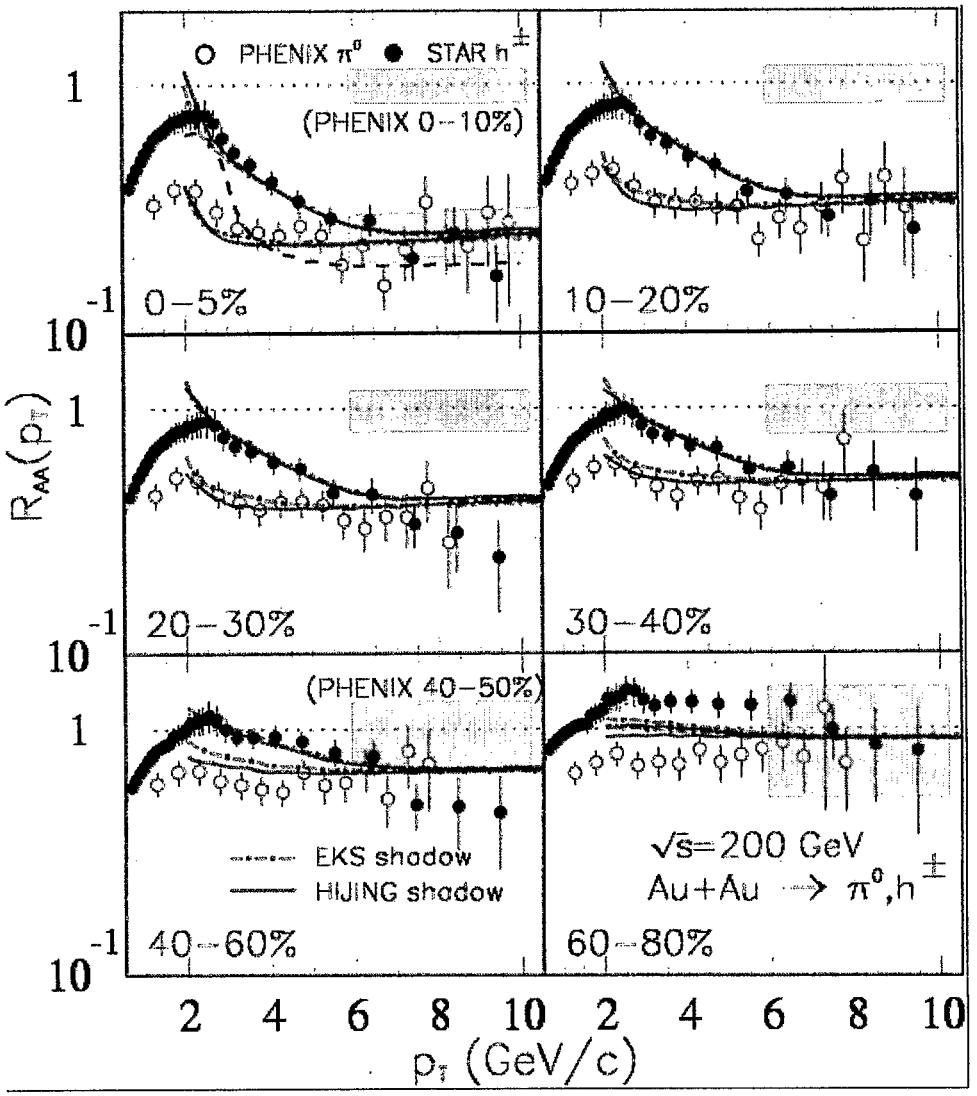
Vitev (03)

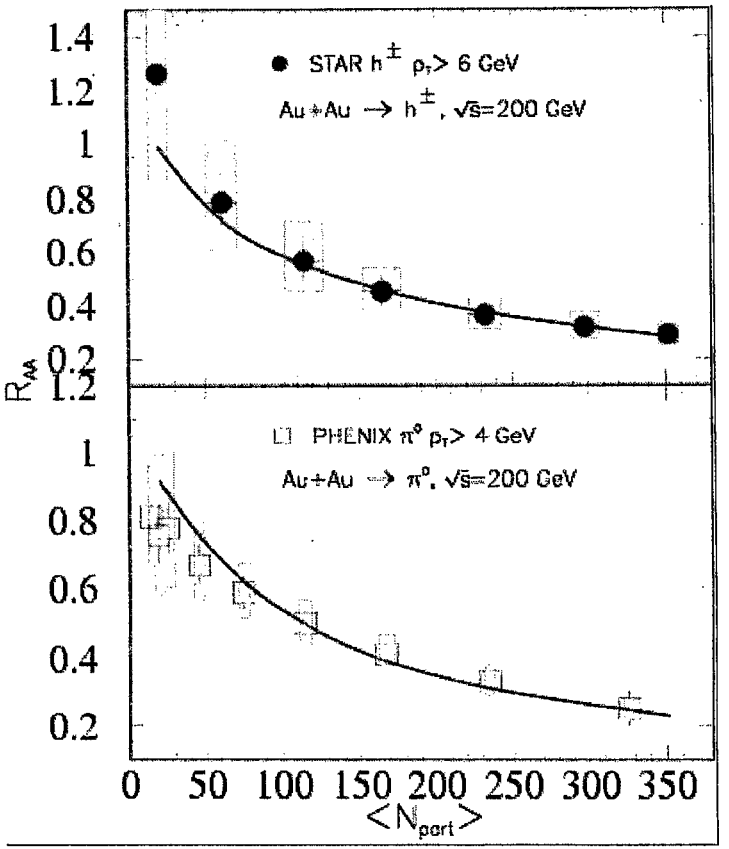
LP model
Alberto Accardi (01)

Color dipole model
Kopeliovich et al (02)

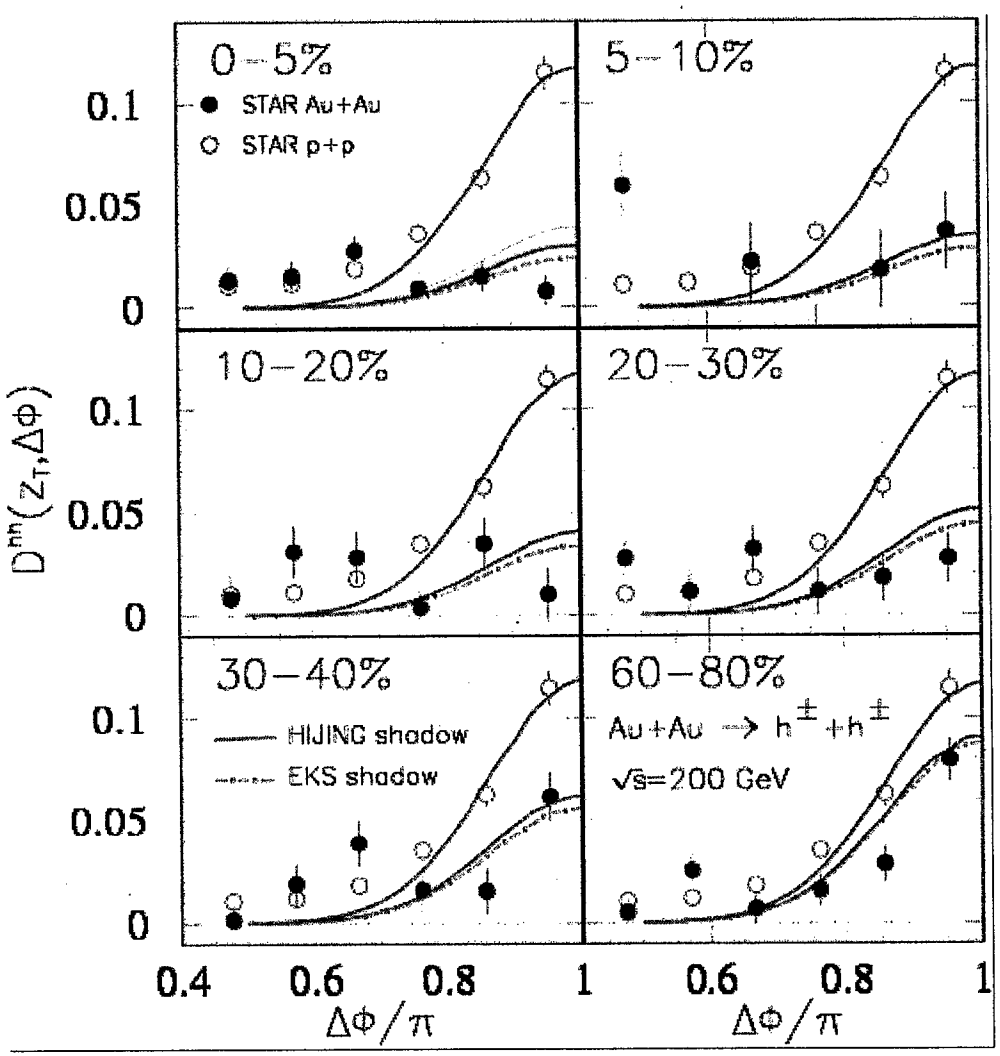


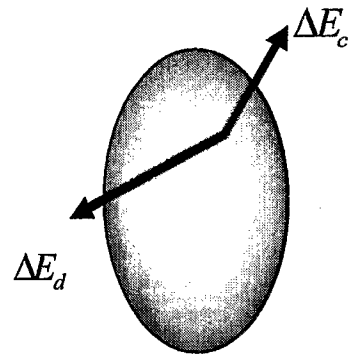
Single hadron suppression

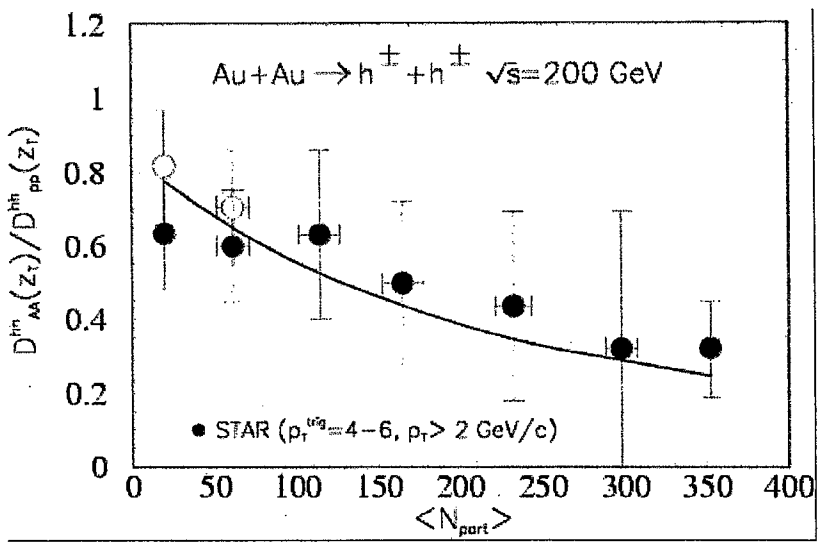




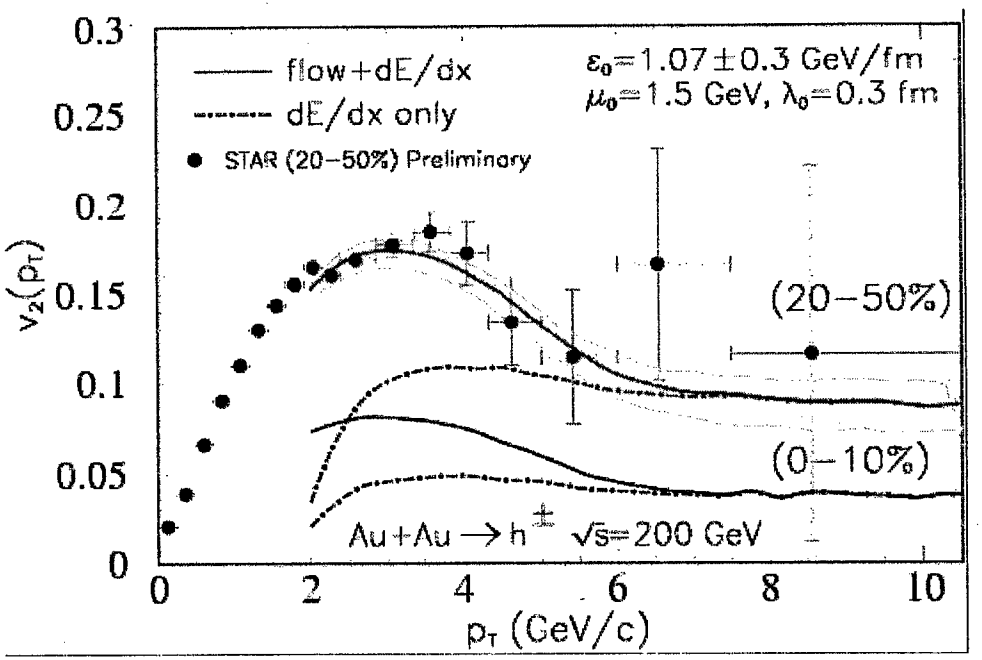
Suppression of away-side jet



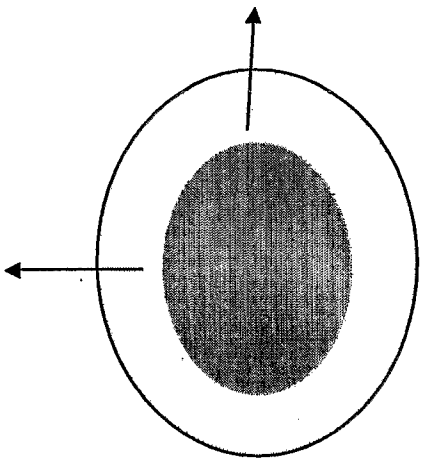




Azimuthal Anisotropy



Single hadron



Intermediate p_T: effects of parton coalescence

Partonic Energy Loss at RHIC

$$\Delta E = \frac{\Delta E_{1d}}{\rho_0 \tau_0 R} \int_{\tau_0}^{R} d\tau \rho(\tau)(\tau - \tau_0)$$

$$\rho(\tau, r) = \rho_0(r) \frac{\tau_0}{\tau} \theta(R - r)$$

E=10 GeV $\tau_0 = 0.2$ fm/c

$$\Delta E = 5.5 \pm 1.6 \quad \text{GeV}$$

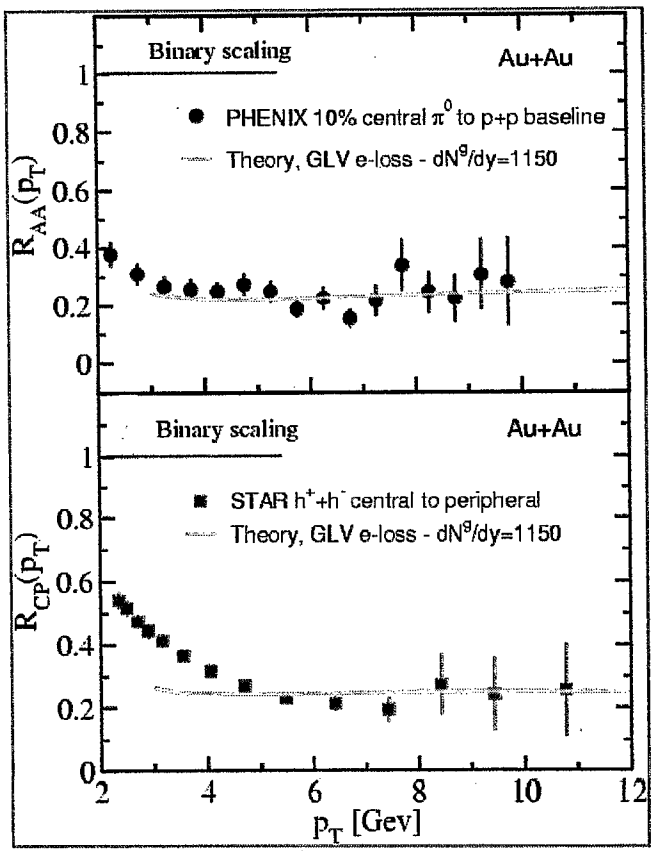
$$\left(\frac{dE}{dx}\right)_0 \approx 13.8 \pm 3.9 \text{ GeV/fm}$$

$$\left(\frac{dE}{dx}\right)_{\text{cold matter}} \approx 0.5 \text{ GeV/fm}$$

Gyulassy & Vitev;
Barnafoldi et al
Muller
Jeon et al

$$\frac{dN_g}{dy} = 1150$$

$$\rho_0 = 40 \text{ /fm}^3$$

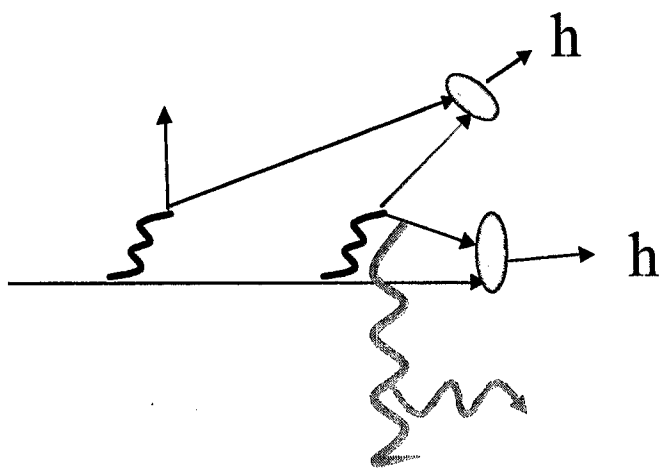


Quenching is parton energy loss!

Could it be caused by hadronic absorption or rescattering? **NO!**

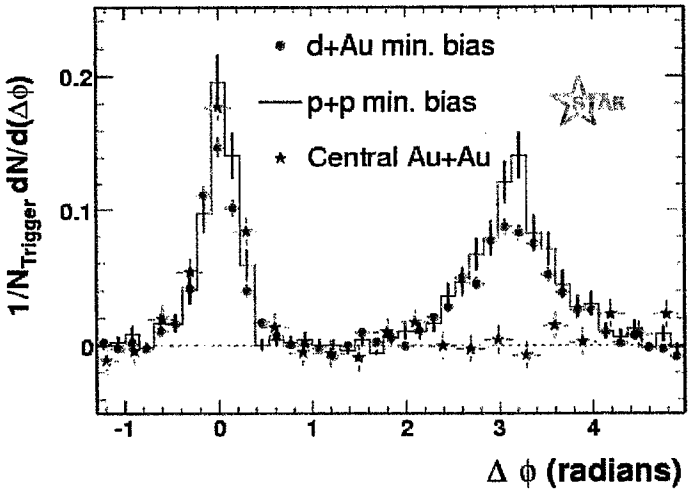
Hadron formation time: Uncertainty principle:

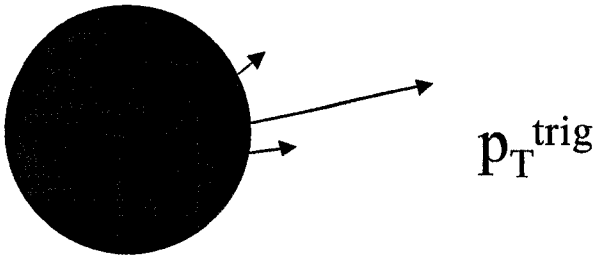
$$\tau_f = 70 \text{ fm} \quad \text{for E=10 GeV pion} \qquad \tau_f = r_h \frac{E}{m}$$

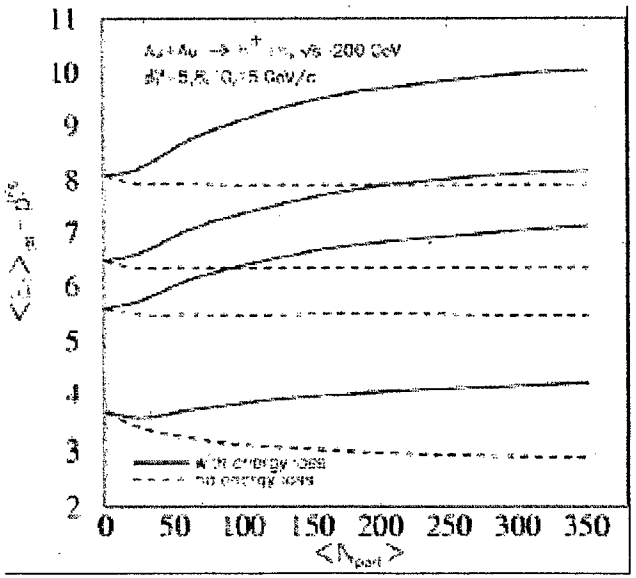


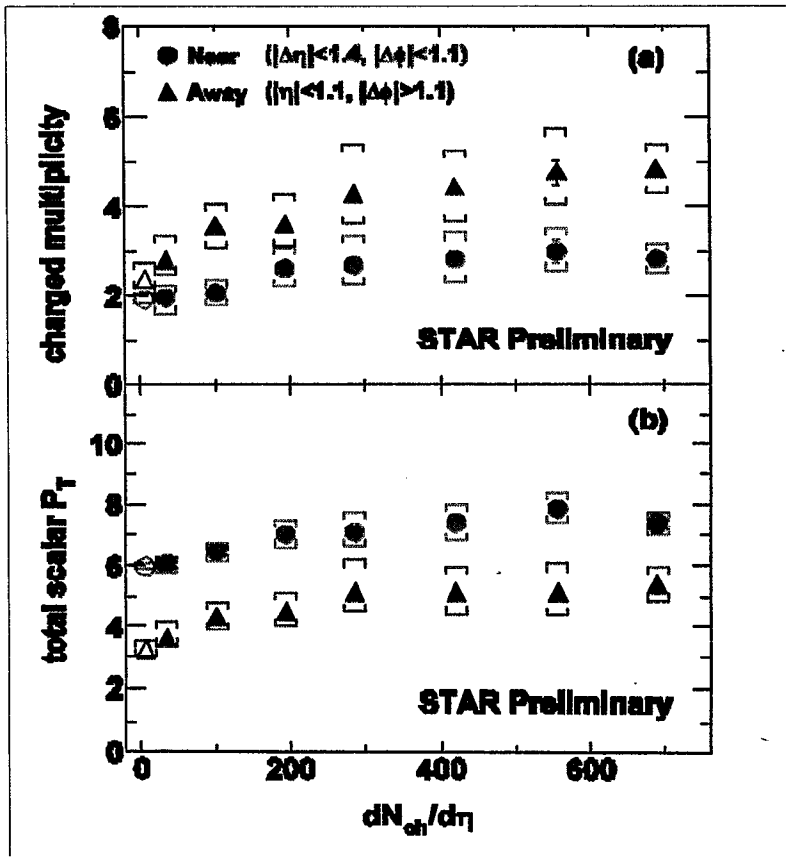
- Energy dependence of jet quenching
- Large v2 → early stage
- Same-side jet profile

Measuring Parton Energy Loss



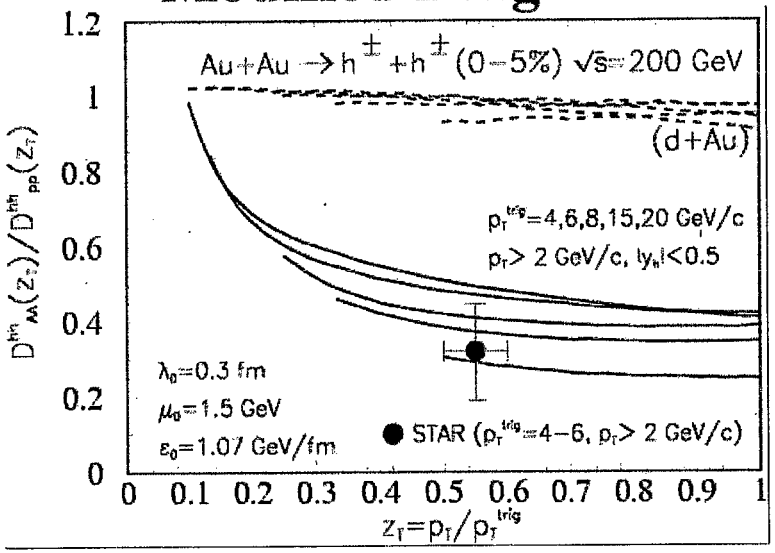


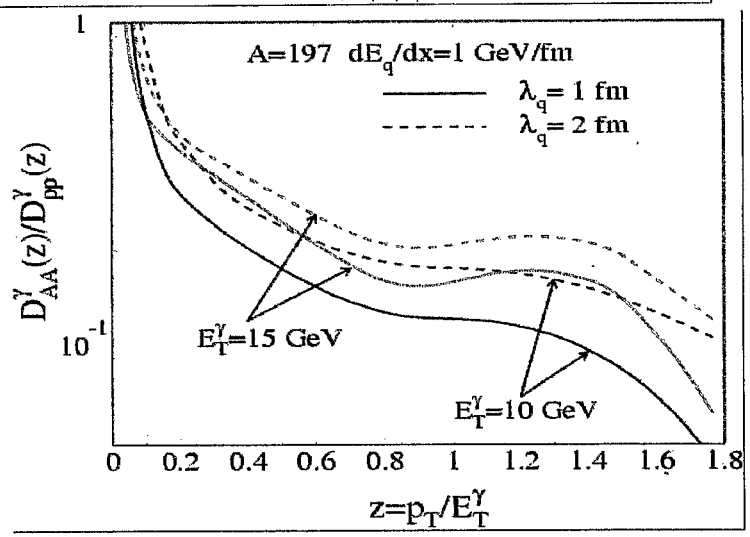


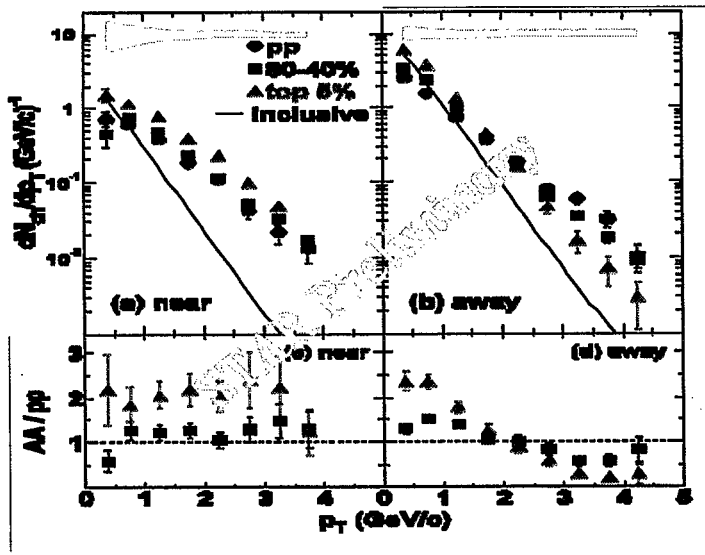


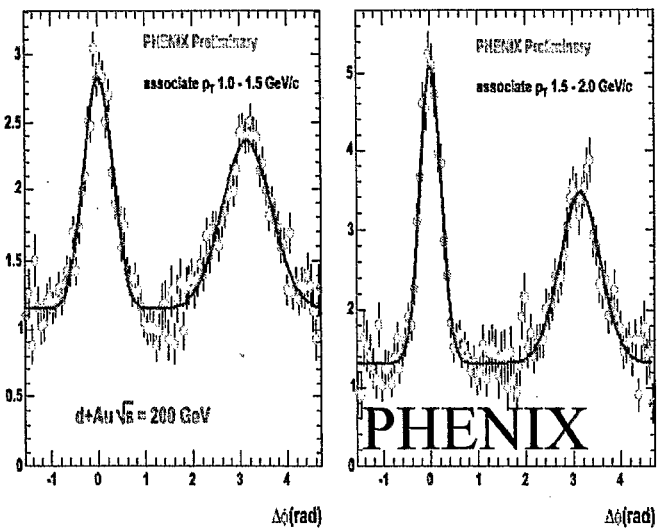
Beyond the discovery I

Modified Fragmentation



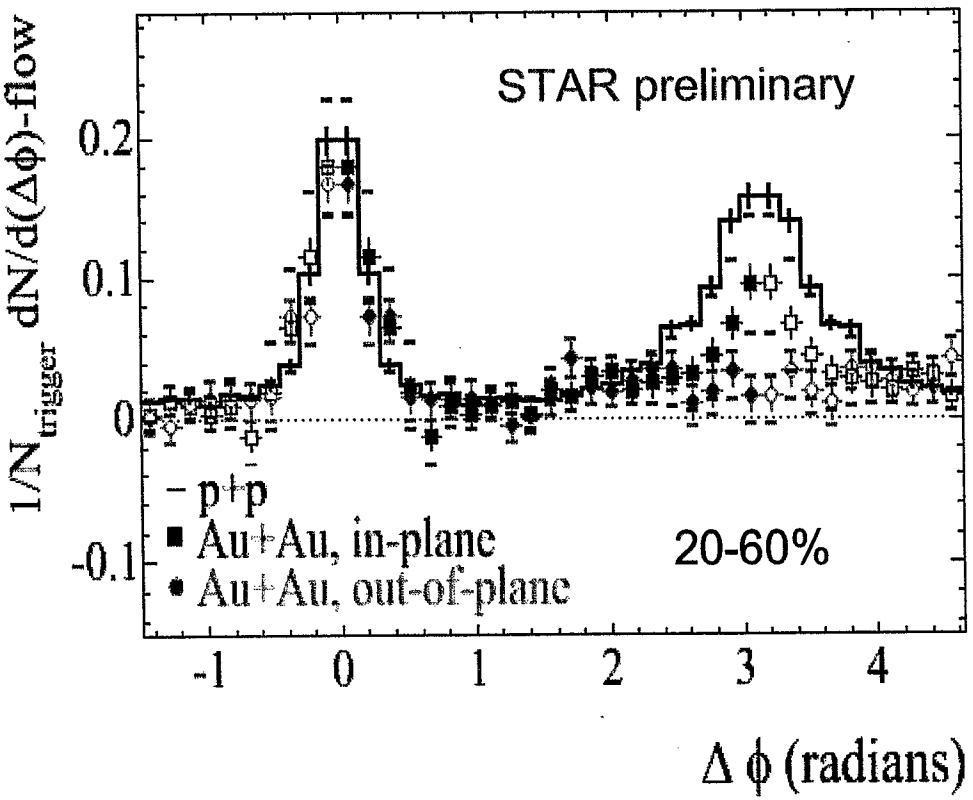


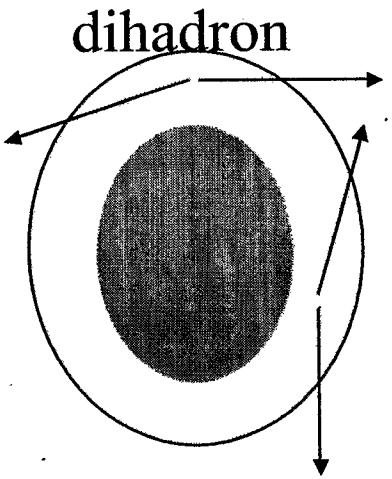


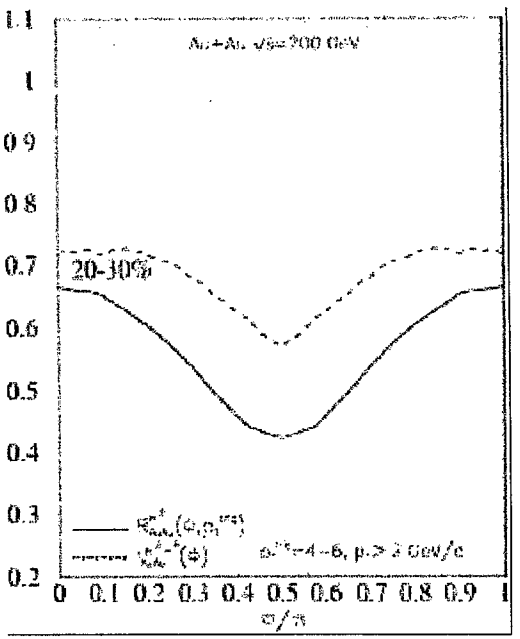


Beyond the Discovery II

Azimuthal Mapping of jet quenching

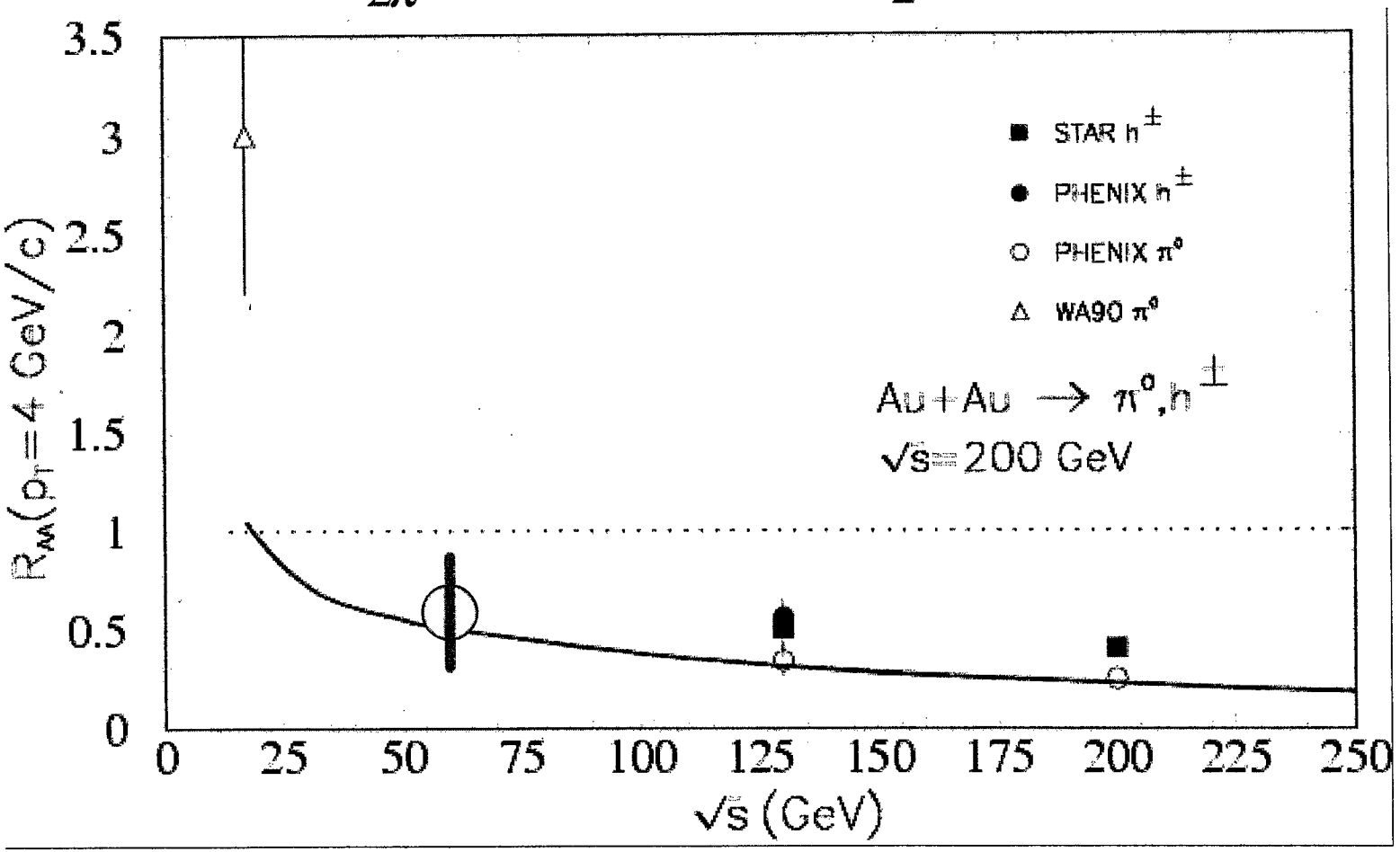




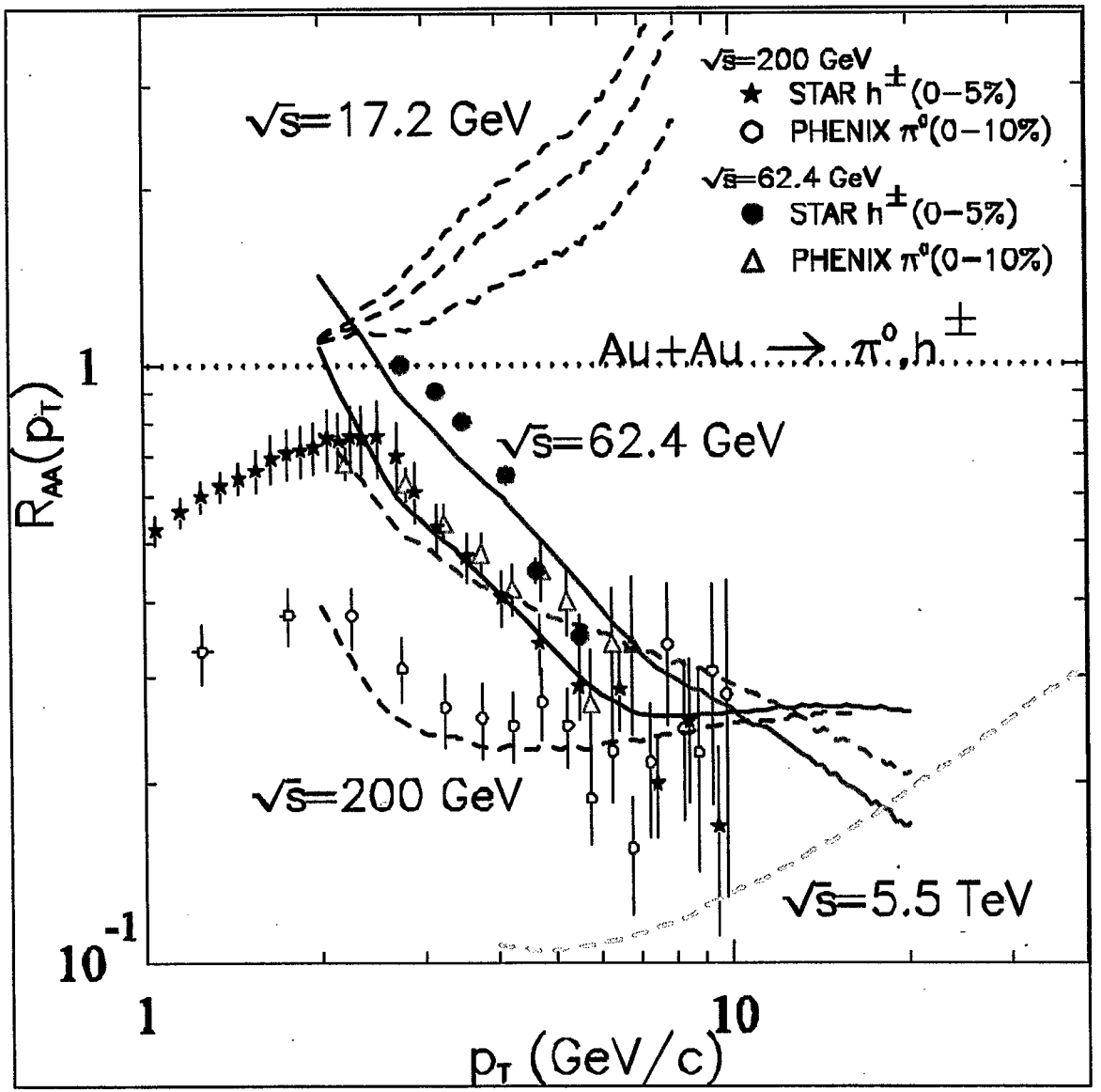


Beyond the discovery III

$$T_{qg}^{A}(x,x_L)=\int\frac{dy^-}{2\pi}dy_1^-dy_2^-e^{-ix_Bp^+y^-}\left\langle A\left|\bar{\psi}(0)\frac{\gamma^+}{2}F_\sigma^+(y_1^-)F^{+\sigma}(y_2^-)\psi(y^-)\right|A\right\rangle$$



Degree of thermalization?



XNW
Adil & Gyulassy
Vitev

Summary

- Discovery of Jet Quenching proves that dense matter is formed
- Jet quenching is caused by partonic energy loss
- Dense matter at RHIC is 30 times higher than cold nuclei
- The matter is strongly interactive
- Jet tomography become useful and power tool for studying properties of dense matter

High Definition Jet Tomography

SPS

QGP

RHIC

QGP

LHC, RHIC II

Collective Flow signals the Quark Gluon Plasma *

H. Stöcker
Institut für Theoretische Physik, Johann Wolfgang Goethe - Universität, Robert Mayer Str. 8-10, 60054 Frankfurt am Main, Germany and Frankfurt Institute for Advanced Studies (FIAS), Robert Mayer Str. 8-10, 60054 Frankfurt am Main, Germany

A critical discussion of the present status of the CERN experiments on charm dynamics and hadron collective flow is given. We emphasize the importance of the flow excitation function from 1 to 50 A·GeV: here the hydrodynamic model has predicted the collapse of the v_1-flow and of the v_2-flow at ~ 10 A·GeV; at 40 A·GeV it has been recently observed by the NA49 collaboration. Since hadronic rescattering models predict much larger flow than observed at this energy we interpret this observation as potential evidence for a first order phase transition at high baryon density ρ_B. A detailed discussion of the collective flow as a barometer for the equation of state (EoS) of hot dense matter at RHIC follows. Here, hadronic rescattering models can explain $< 30\%$ of the observed elliptic flow, v_2, for $p_T > 2$ GeV/c. This is interpreted as evidence for the production of superdense matter at RHIC with initial pressure far above hadronic pressure, $p > 1$ GeV/fm^3. We suggest that the fluctuations in the flow, v_1 and v_2, should be measured in future since ideal hydrodynamics predicts that they are larger than 50 % due to initial state fluctuations. Furthermore, the QGP coefficient of viscosity may be determined experimentally from the fluctuations observed. The connection of v_2 to jet suppression is examined. It is proven experimentally that the collective flow is not faked by minijet fragmentation. Additionally, detailed transport studies show that the away-side jet suppression can only partially ($< 50\%$) be due to hadronic rescattering. We, finally, propose upgrades and second generation experiments at RHIC which inspect the first order phase transition in the fragmentation region, i.e. at $\mu_B \approx 400$ MeV ($y \approx 4-5$), where the collapse of the proton flow should be seen in analogy to the 40 A·GeV data. The study of Jet-Wake-riding potentials and Bow shocks - caused by jets in the QGP formed at RHIC - can give further information on the equation of state (EoS) and transport coefficients of the Quark Gluon Plasma (QGP).

I. OLD AND NEW OBSERVABLES FOR THE QGP PHASE TRANSITION

Lattice QCD results [1, 2] (cf. Fig. 1) show a crossing, but no first order phase transition to the QGP for vanishing or small chemical potentials μ_B, i.e. at the conditions accessible at central rapidities at RHIC full energies. A first order phase transition does occur according to the QCD lattice calculations [1, 2] only at high baryochemical potentials or densities, i.e. at SIS-300 and lower SPS energies and in the fragmentation region of RHIC, $y \approx 4-5$ [3, 4]. The critical baryochemical potential is predicted [1, 2] to be $\mu_B^c \approx 400 \pm 50$ MeV and the critical temperature $T_c \approx 150-160$ MeV. We do expect a phase transition also at finite strangeness. Predictions for the phase diagram of strongly interacting matter for realistic non-vanishing net strangeness are urgently needed to obtain a comprehensive picture of the QCD phase structure. Multi-Strangeness degrees of freedom are very promising probes for the properties of the dense and hot matter [5]. The strangeness distillation process [6, 7] predicts dynamical de-admixture of s and $\bar{s}$ quarks, which yields unique signatures for QGP creation: high multistrange hyperon-/-matter production, strangelet formation and unusual antibaryon to baryon ratios *ect.*

A. Thermodynamics in the $T - \mu_B$ plane

A comparison of the thermodynamic parameters T and μ_B extracted from the UrQMD-transport model in the central overlap regime of Au+Au collisions [9] with the QCD predictions is shown in Fig 1, where the full dots with errorbars denote the 'experimental' chemical freeze-out parameters - determined from fits to the experimental yields - taken from Ref. [10]. The triangular and quadratic symbols (time-ordered in vertical sequence) stand for temperatures T and chemical potentials μ_B extracted from UrQMD transport calculations in central Au+Au (Pb+Pb) collisions at RHIC (21.3 A·TeV), 160, 40 and 11 A·GeV [8] as a function of the reaction time (separated by 1 fm/c steps from

* Supported by DFG, GSI, BMBF, EU, RIKEN and DOE

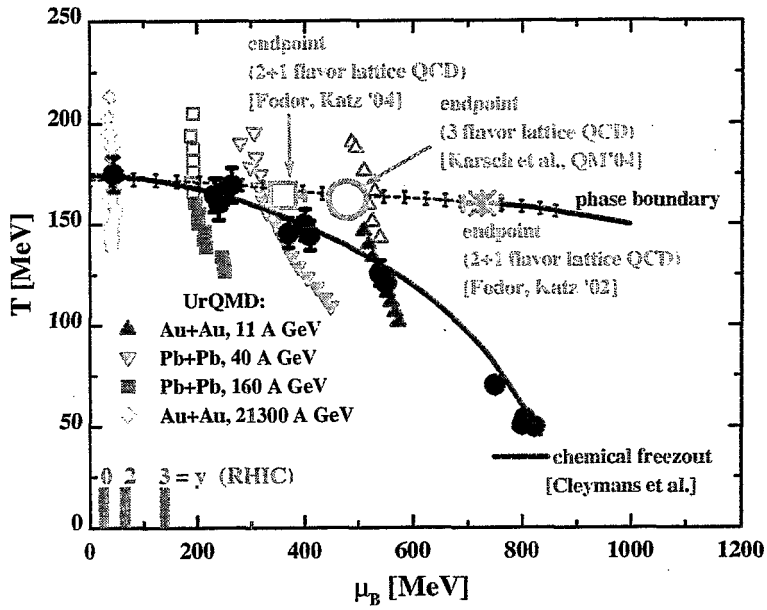


FIG. 1: The new phase diagram with the critical end point at $\mu_B \approx 400$ MeV, $T \approx 160$ MeV as predicted by Lattice QCD. In addition, the time evolution in the $T-\mu$-plane of a central cell in UrQMD calculations [8] is depicted for different bombarding energies. Note, that the calculations indicate that bombarding energies $E_{LAB} \lesssim 40$ A·GeV are needed to probe a first order phase transition. At RHIC (see insert at the μ_B scale) this point is accessible in the fragmentation region only (taken from [9]).

top to bottom). The open symbols denote nonequilibrium configurations and correspond to T parameters extracted from the transverse momentum distributions, whereas the full symbols denote configurations in approximate pressure equilibrium in longitudinal and transverse direction.

During the nonequilibrium phase (open symbols) the transport calculations show much higher temperatures (or energy densities) than the 'experimental' chemical freeze-out configurations at all bombarding energies (≥ 11 A·GeV). These numbers are also higher than the critical point (circle) of (2+1) flavor - Lattice QCD calculations by the Bielefeld-Swansea-collaboration [2] (large open circle) and by the Wuppertal-Budapest-collaboration [1] (the star shows earlier results from [1]). The energy density at μ_c, T_c is in the order of ≈ 1 GeV/fm^3 (or slightly below). At RHIC energies a cross-over is expected at midrapidity, when stepping down in temperature during the expansion phase of the 'hot fireball'. The baryon chemical potential μ_B for different rapidity intervals at RHIC energies has been obtained from a statistical model analysis by the BRAHMS Collaboration based on measured antihadron to hadron yield ratios [11]. For midrapidity one finds $\mu_B \simeq 0$, whereas for forward rapidities μ_B increases up to $\mu_B \simeq 130$ MeV at $y = 3$. Thus, only extended forward rapidity measurement ($y \approx 4-5$) will allow to probe large μ_B at RHIC. The detectors at RHIC at present offer only a limited chemical potential range. To reach the first order phase transition region at midrapidity, the International Facility at GSI seems to be the right place to go. This situation changes at lower SPS (and top AGS) as well as at the future GSI SIS-300 energies: sufficiently large chemical potentials μ_B should allow for a first order phase transition [12] (to the right of the critical point in the (T, μ_B) plane). The transport calculations show high temperatures (high energy densities) in the very early phase of the collisions, only. Here, hadronic interactions are weak due to formation time effects and yield little pressure. Diquark, quark and gluon interactions should cure this problem.

B. Open charm and charmonia at SPS and RHIC

Open charm and charmonium production at SPS and RHIC energies has been calculated within the HSD and UrQMD transport approaches [13] using parametrizations for the elementary production channels including the charmed hadrons $D, \bar{D}, D^*, \bar{D}^*, D_s, \bar{D}_s, D_s^*, \bar{D}_s^*$, $J/\Psi, \Psi(2S), \chi_{2c}$ from NN and πN collisions. The latter parametrizations are fitted to PYTHIA calculations [14] above $\sqrt{s} = 10$ GeV and extrapolated to the individual thresholds, while the absolute strength of the cross sections is fixed by the experimental data as described in Ref. [15]; for previous

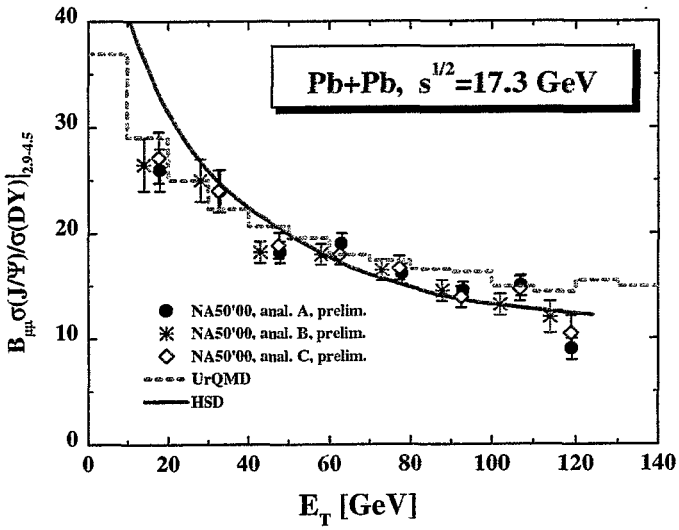


FIG. 2: The J/Ψ suppression as a function of the transverse energy E_T in $Pb + Pb$ collisions at 160 A·GeV. The solid line shows the HSD result within the comover absorption scenario [19]. The different symbols stand for the NA50 data [20] from the year 2000 (analysis A,B,C) while the dashed histogram is the UrQMD result [18].

works see [16–18] Backward channels 'charm + anticharm meson → charmonia + meson' are treated via detailed balance in a more schematic interaction model with a single parameter or matrix element $|M|^2$ that is fixed by the J/Ψ suppression data from the NA50 collaboration at SPS energies (cf. Ref. [19]).

We recall that charmonium suppression had been proposed as "the clearest" QGP-signature and the community has been riding on this folklore for almost two decades. Hence, these detailed comparisons come as a shock: The $Pb + Pb$ results at 160 A·GeV, both from UrQMD and HSD transport calculations are well in line with the data of the NA50 Collaboration in Fig. 2, where the J/Ψ suppression is shown as a function of the transverse energy E_T. The solid line stands for the HSD result within the comover absorption scenario while the various data points reflect the NA50 data from the year 2000 (analysis A,B,C). The data have moved so that they agree now with the HSD and UrQMD calculations [18] (dashed histogram in Fig. 2). We mention that there might be alternative explanations

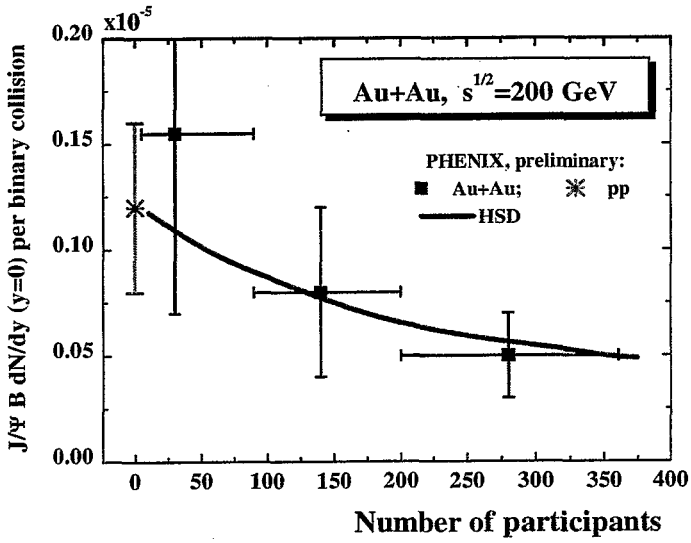


FIG. 3: The calculated J/Ψ multiplicity per binary collision – multiplied by the branching to dileptons – as a function of the number of participating nucleons, N_{part}, in comparison to the preliminary data from the PHENIX collaboration [23] for $Au + Au$ and pp reactions (taken from Ref. [19]).

for J/Ψ suppression, as discussed in Refs. [21, 22] and/or further (dissociation) mechanisms not considered here. However, for the purposes of the present review it is sufficient to point out that

a) no sign of unusual physics can be related to the J/Ψ data and

b) the models employed here (cf. Figs. 6 and 7 in [19]) use upper limits for the dissociation cross sections and do not lead to a sizeable re-creation of charmonia by $D + \bar{D}$ channels at SPS energies.

At RHIC central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV will, however, produce multiplicities of open charm pairs about 2 orders of magnitude larger than at 160 A·GeV, such that a much higher J/Ψ reformation rate ($\sim N_{c\bar{c}}^2$) is expected (cf. Ref. [22]). At RHIC top energy, $\sqrt{s} = 200$ GeV, the J/Ψ comover dissociation may no longer be important, since the charmonia dissociated in this channel are approximately recreated in the backward channels. Hence, the J/Ψ dissociation at RHIC should be less pronounced than at SPS energies.

The preliminary data of the PHENIX Collaboration [23] allow for a first glance at the situation encountered in $Au + Au$ collisions at $\sqrt{s} = 200$ GeV. Fig. 3 shows the J/Ψ multiplicity per binary collision as a function of the number of participating nucleons N_{part} in comparison to the data at midrapidity. The statistics is quite limited; thus no final conclusion can presently be drawn. However, the data neither suggest a dramatic enhancement of J/Ψ production nor a complete 'melting' of the charmonia in the QGP phase.

C. Historical Interlude

Hydrodynamic flow and shock formation has been proposed early [24, 25] as the key mechanism for the creation of hot and dense matter during relativistic heavy-ion collisions. The full three-dimensional hydrodynamical flow problem is much more complicated than the one-dimensional Landau model [26]: the 3-dimensional compression and expansion dynamics yields complex triple differential cross-sections, which provide quite accurate spectroscopic handles on the equation of state. The bounce-off, $v_1(p_T)$, the squeeze-out, $v_2(p_T)$, and the antiflow [27–31] (third flow component [32, 33]) serve as differential barometers for the properties of compressed, dense matter from SIS to RHIC. The most employed flow observables are:

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle \tag{1}$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle . \tag{2}$$

Here, p_x denotes the momentum in x-direction, i.e. the transversal momentum within the reaction plane and p_y the transversal momentum out of the reaction plane. The total transverse momentum is given as $p_T = \sqrt{p_x^2 + p_y^2}$; the z-axis is in the beam direction. Thus, flow v_1 measures the "bounce-off", i.e. the strength of the directed flow in the reaction plane, and v_2 gives the strength of the second moment of the azimuthal particle emission distribution, the so-called "squeeze-out". [24, 25, 27–31]. In particular, it has been shown [25, 27–31] that the disappearence or "collapse" of flow is a direct result of a first order phase transition.

Several hydrodynamic models have been used in the past, starting with the one-fluid ideal hydrodynamic approach. It is well known that the latter model predicts far too large flow effects. To obtain a better description of the dynamics, viscous fluid models have been developed [34–36]. In parallel, so-called three-fluid models, which distinguish between projectile, target and the fireball fluids, have been considered [37]. Here viscosity effects appear only between the different fluids, but not inside the individual fluids. The aim is to have at our disposal a reliable, three-dimensional, relativistic three-fluid model including viscosity [35, 36].

Flow can be described very elegantly in hydrodynamics. However, also consider microscopic multicomponent (pre-) hadron transport theory, e.g. models like qMD [38], IQMD [39], UrQMD [40] or HSD [41], as control models for viscous hydro and as background models to subtract interesting non-hadronic effects from data. If Hydro with and without quark matter EoS, hadronic transport models without quark matter – but with strings – are compared to data, can we learn whether quark matter has been formed? What degree of equilibration has been reached? What does the equation of state look like? How are the particle properties, self energies, cross sections changed?

To estimate systematic model uncertainties, the results of the different microscopic transport models also have to be carefully compared. The two robust hadron/string based models, HSD and UrQMD, are considered in the following.

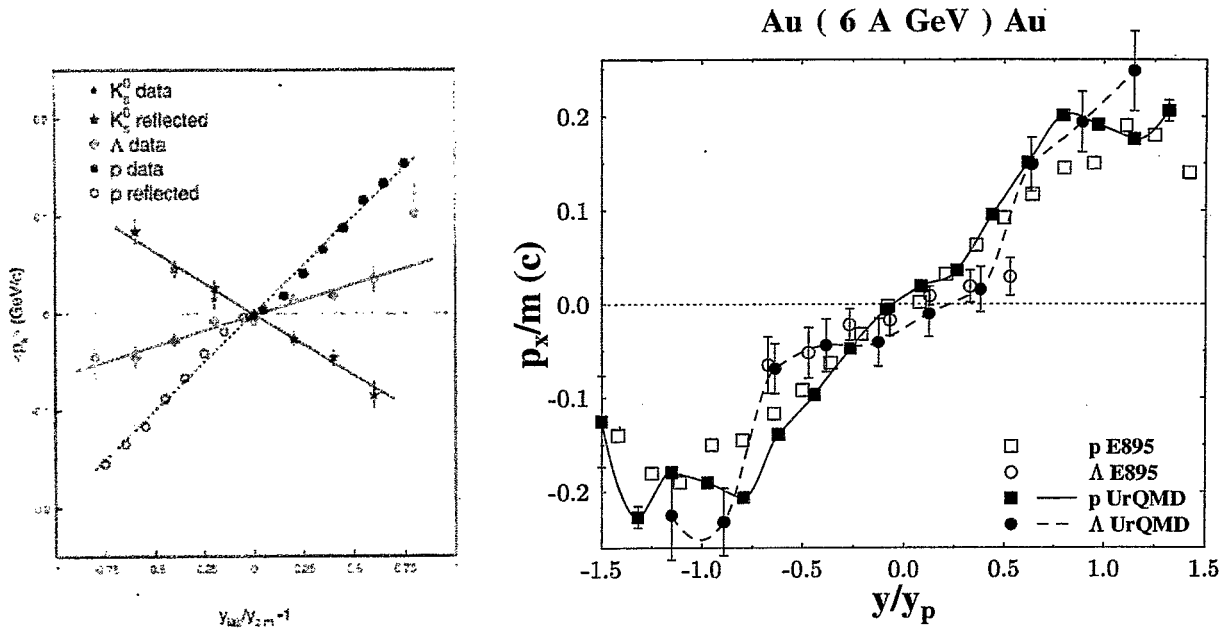


FIG. 4: Left: Sideward flow $p_x = v_1 \cdot p_T$ of K, Λ and p's at 6 A·GeV as measured by E895 in semi-central collisions at the AGS. Right: The same directed flow data for p and Λ compared to UrQMD calculations for $b < 7$ fm [45] .

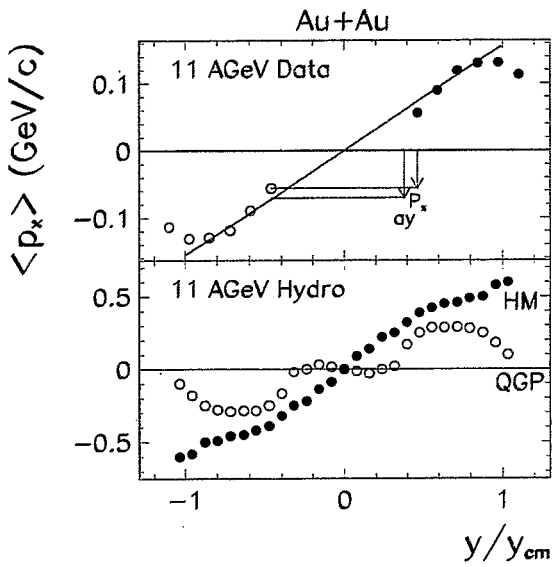


FIG. 5: Directed flow from ideal hydrodynamics with a QGP phase (open symbols) and from the Quark Gluon String Model without QGP phase (full symbols) [32] .

D. Review of AGS and SPS results

Microscopic (pre-)hadronic transport models describe the formation and distributions of many hadronic particles at AGS and SPS rather well [42]. Furthermore, the nuclear equation of state has been extracted by comparing to flow data which are described reasonably well up to AGS energies [32, 43–47]. Ideal hydro calculations, on the other hand, predict far too much flow at these energies [34]. Thus, viscosity effects have to be taken into account in hydrodynamics. In particular, ideal hydro calculations are factors of two higher than the measured sideward flow at SIS [34] and AGS, while the directed flow p_x/m measurement of the E895 collaboration shows that the p and Λ data are reproduced reasonably well [45] (Fig. 4) in UrQMD, i.e. in a hadronic transport theory with reasonable cross-sections, i.e. realistic mean-free-path of the constituents.

Only ideal hydro calculations predict, however, the appearance of a so-called "third flow component" [32] or

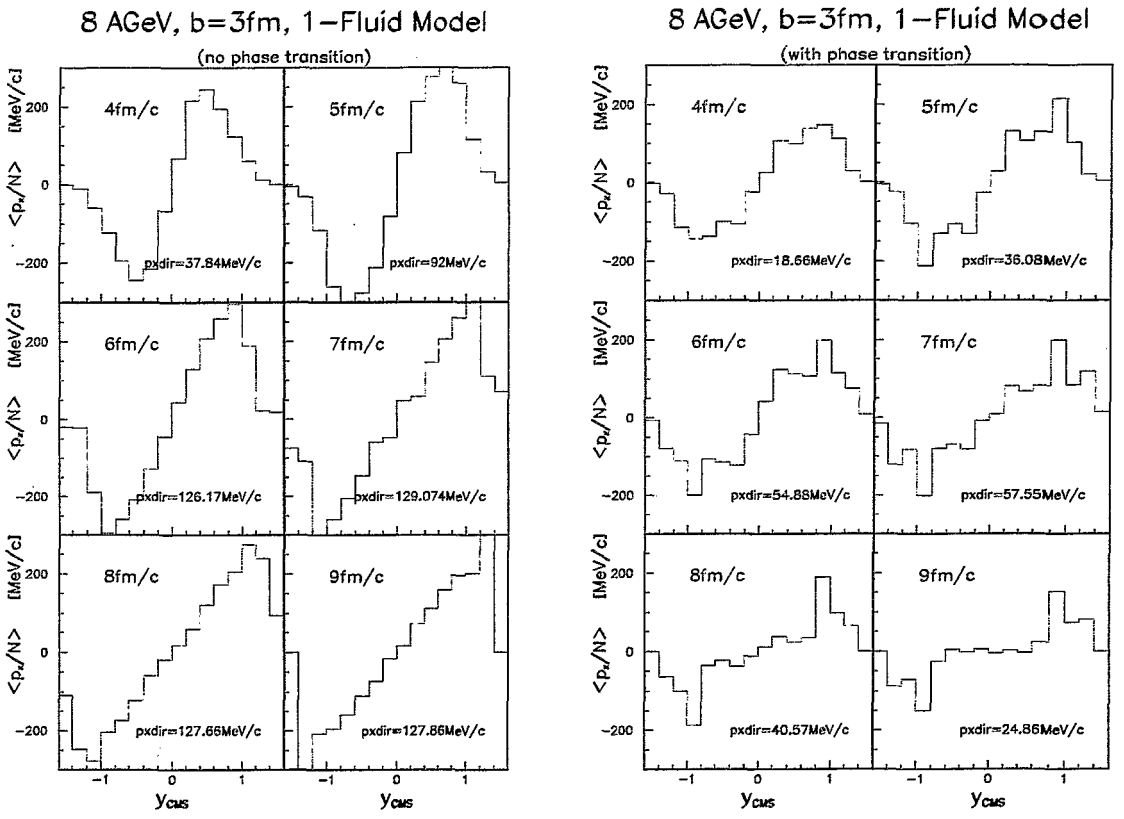


FIG. 6: Time evolution of directed flow p_x/N as a function of rapidity for Au+Au collisions at 8 A·GeV in the one-fluid model. Left: Hadronic EoS without phase transition. Right: An EoS including a first order phase transition to the QGP [48].

"antiflow" [48] in central collisions (cf. Fig. 5). We stress that this only holds if the matter undergoes a first order phase transition to the QGP. The signal is that around midrapidity the directed flow, $p_x(y)$, of protons develops a negative slope! In contrast, a hadronic EoS without QGP phase transition does not yield such an exotic "antiflow" (negative slope) wiggle in the proton flow $v_1(y)$. The ideal hydrodynamic time evolution of the directed flow, p_x/N, for the purely hadronic EoS (Fig. 6 l.h.s.) does show a clean linear increase of $p_x(y)$, just as the microscopic transport theory (Fig. 4 r.h.s.) and as the data (Fig. 4 l.h.s.). For an EoS including a first order phase transition to the QGP (Fig. 6 r.h.s.) it can be seen, however, that the proton flow $v_1 \sim p_x/p_T$ collapses; the collapse occurs around midrapidity.
This observation is explained by an antiflow component of protons, which develops when the expansion from the plasma sets in [49].

The ideal hydrodynamic directed proton flow p_x (Fig. 7) shows even negative values between 8 and 20 A·GeV. An increase back to positive flow is predicted with increasing energy, when the compressed QGP phase is probed. But, where is the predicted minimum of the proton flow in the data? The hydro calculations suggest this "softest point collapse" is at $E_{Lab} \approx 8$ A·GeV. This has not been verified by the AGS data! However, a linear extrapolation of the AGS data indicates a collapse of the directed proton flow at $E_{Lab} \approx 30$ A·GeV (Fig. 7).

Recently, substantial support for this prediction has been obtained by the low energy 40 A·GeV SPS data of the NA49 collaboration [51] (cf. Fig. 8). These data clearly show the first proton "antiflow" around mid-rapidity, in contrast to the AGS data as well as to the UrQMD calculations involving no phase transition (Fig. 9). Thus, at bombarding energies of 30-40 A·GeV, a first order phase transition to the baryon rich QGP most likely is observed; the first order phase transition line is crossed (cf. Fig. 1). This is the energy region where the new FAIR- facility at GSI will operate. There are good prospects that the baryon flow collapses and other first order QGP phase transition signals can be studied soon at the lowest SPS energies as well as at the RHIC fragmentation region $y > 4-5$. These experiments will enable a detailed study of the first order phase transition at high μ_B and of the properties of the baryon rich QGP.

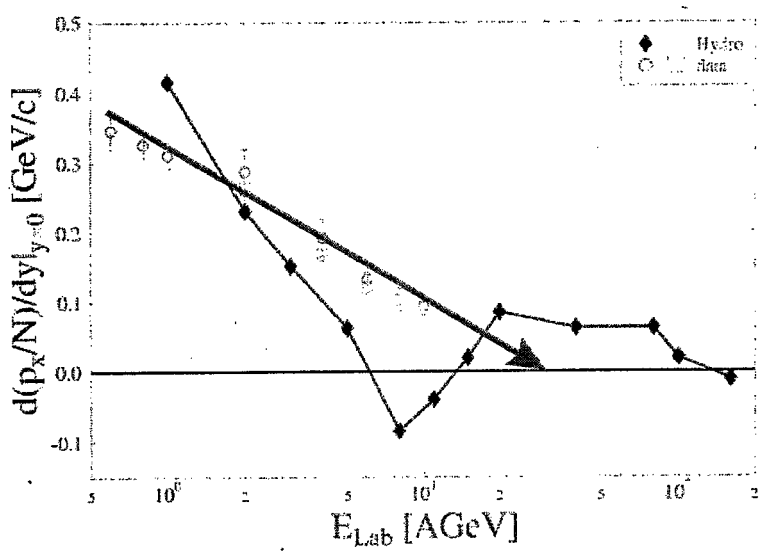


FIG. 7: Measured SIS and AGS proton dp_x/dy-slope data compared to a one-fluid hydro calculation. A linear extrapolation of the AGS data indicates a collapse of flow at $E_{Lab} \approx 30$ A·GeV, i.e. for the lowest SPS- and the upper FAIR- energies at GSI [50].

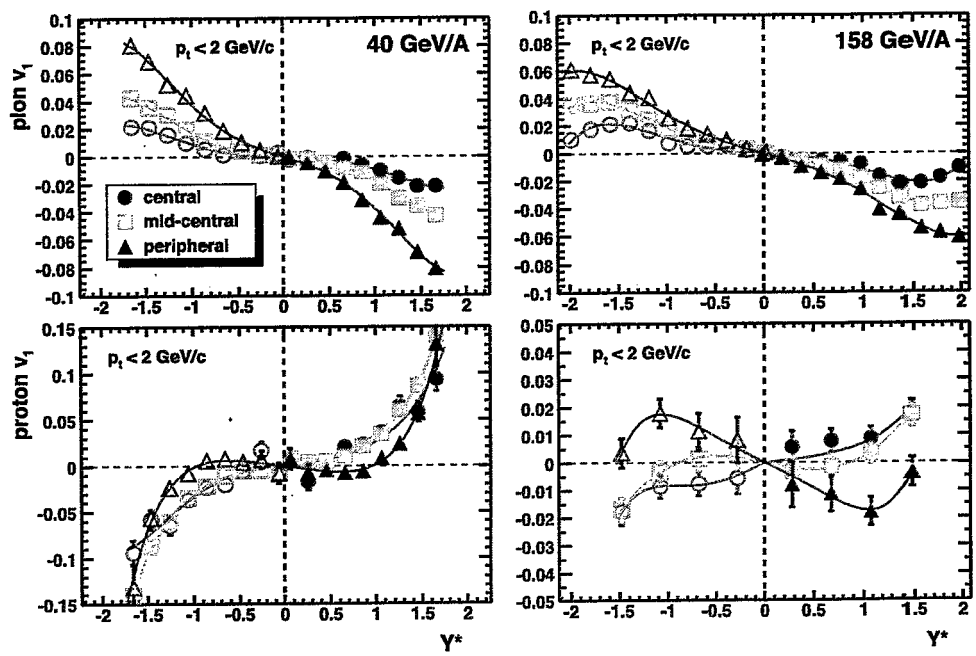


FIG. 8: v_1 at SPS, 40 A·GeV and 158 A·GeV [51] . The proton antiflow is observed in the NA49-experiment even at near central collisions, which is in contrast to the UrQMD-model involving no phase transition (Fig. 9).

II. PROTON ELLIPTIC FLOW COLLAPSE AT 40 A·GEV - EVIDENCE FOR A FIRST ORDER PHASE TRANSITION AT HIGHEST NET BARYON DENSITIES

At SIS energies microscopic transport models reproduce the data on the excitation function of the proton elliptic flow v_2 quite well: A soft, momentum-dependent equation of state [52–54] seems to account for the data. The observed proton flow v_2 below ~ 5 A·GeV is smaller than zero, which corresponds to the squeeze-out predicted by

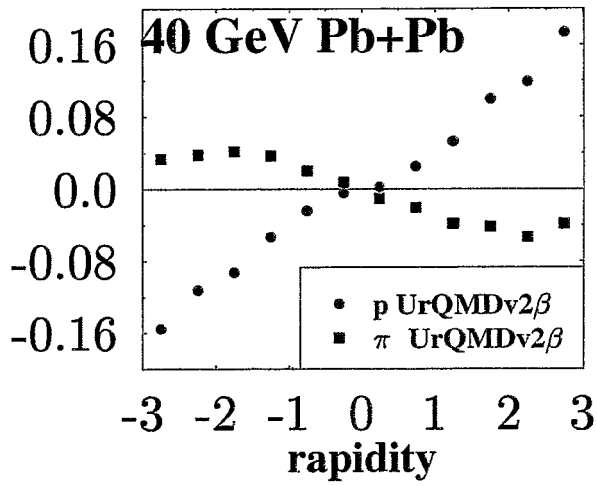


FIG. 9: Proton and pion flow $v_1 = p_x/p_T$ at 40 A·GeV as obtained within the UrQMD model. No proton antiflow is generated in this hadronic transport theory without phase transition.

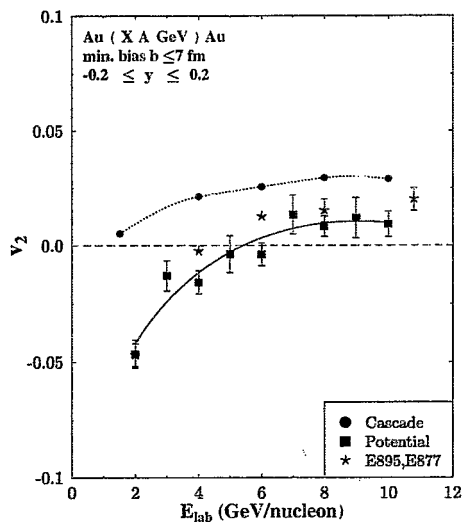


FIG. 10: v_2 excitation function of protons at the AGS. The E895-E877 data show the transition from squeeze-out to in-plane proton elliptic flow at 4-5 A·GeV; the UrQMD calculations show a strong sensitivity to the EoS [45].

hydrodynamics long ago [24, 25, 27–31]. The AGS data (Fig. 10) exhibit a transition from squeeze-out to in-plane flow in the midrapidity region. The change in sign of the proton v_2 at 4-5 A·GeV is in accord with transport calculations (UrQMD calculations in Fig. 10 [45]; for HSD results see [46, 47]). At higher energies, 10-160 A·GeV, a smooth increase of the flow v_2 is predicted from the hadronic transport simulations. In fact, the 158 A·GeV data of the NA49-collaboration suggest that this smooth increase proceeds between AGS and SPS as predicted. Accordingly, UrQMD gives considerable (3%) v_2 flow for midcentral and peripheral protons at 40 A·GeV – Fig. 11 [45].

This is in strong contrast to recent NA49 data at 40 A·GeV (cf. Fig. 12): A sudden collapse of the proton flow is observed for midcentral as well as for peripheral protons. This collapse of v_2 for protons around midrapidity at 40 A·GeV is very pronounced while it is not observed at 158 A·GeV. The UrQMD calculations, without a phase transition, show a robust, but wrong 3% flow of protons - in strong contrast to the data.

A dramatic collapse of the flow v_1 is also observed by NA49 [51], again around 40 A·GeV, where the collapse of v_2 has been observed. This is the highest energy - according to [1, 2] and Fig. 1 - at which a first order phase transition can be reached at the central rapidities of relativistic heavy-ion collisions. We, therefore, conclude that a first order phase transition at the highest baryon densities accessible in nature has been seen at these energies in

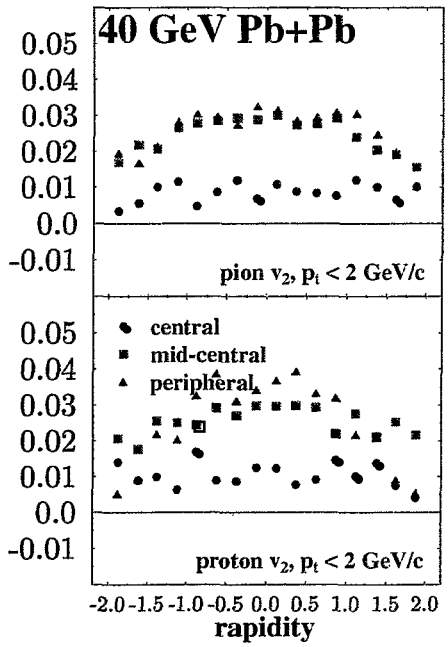


FIG. 11: Elliptic flow v_2 of protons (lower frame) and pions (upper frame) versus rapidity for Pb+Pb collisions at 40 A·GeV from the UrQMD calculations [45].

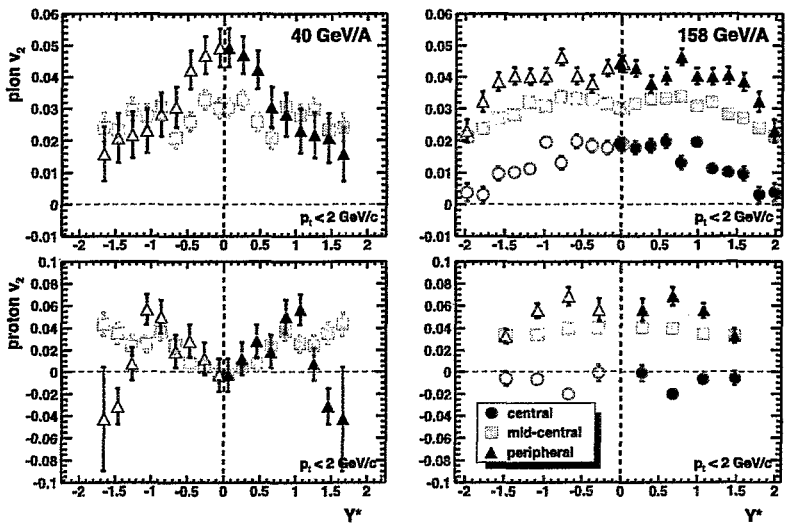


FIG. 12: Elliptic flow v_2 of protons versus rapidity at 40 A·GeV Pb+Pb collisions [51] as measured by NA49 for three centrality bins: central (dots), mid-central (squares) and peripheral (triangles). The solid lines are polynomial fits to the data [51].

Pb+Pb collisions. Moreover, Fig. 13 shows that the elliptic flow clearly distinguishes between a first order phase transition and a crossover.

III. STRONG COLLECTIVE FLOW AT RHIC SIGNALS A NEW PHASE OF MATTER

The rapid three-body thermalization found by Xu and Greiner (cf. Sec. IV.A) justifies *a posteriori* the use of hydrodynamical calculations for the time evolution of the complex four-dimensional expansion of the plasma. However, there is no justification for the use of simple ideal hydrodynamics (i.e. neglecting the important transport coefficients) and simple, smooth initial conditions in hydrodynamics [35, 36, 56]. PHOBOS data at $\sqrt{s}$= 130 GeV

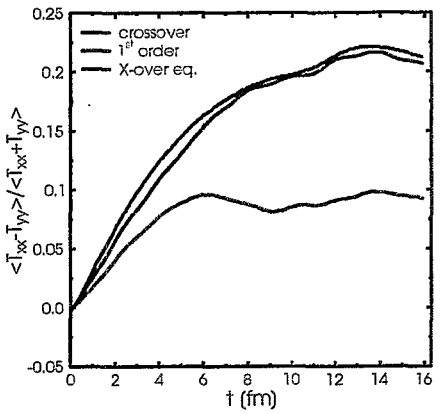


FIG. 13: Time evolution of the momentum anisotropy v_2 for a cross over EoS. Both, in- and off-equilibrium calculations (upper lines) show no drop of the flow v_2. The calculation with a first order phase transition off-equilibrium (lower line) shows - on the other hand - the collapse of v_2-flow of protons. Hence, the collapse is only possible for a first order transition [55].

and 200 GeV suggest energy independent $v_2(\eta)$ distributions. Furthermore, the observed distribution has a triangular shape. This finding is in strong disagreement with Bjorken boost invariant hydro predictions [12, 57], which fit only the midrapidity region. The predicted average proton v_2-values obtained from the SPHERIO hydro code with NEXUS initial conditons (Fig. 14, [58]) are by factors of two higher than simple smooth initial state hydrodynamic calculations. This indicates that ideal hydro with naive smooth initial conditions – as used by many authors – do not describe but rather fit the data. Strong viscosity effects can play a role for particles with $p_T < 1.2$ GeV/c: a decent description of the dynamics requires, however, relativistic viscous hydro simulations [35, 36, 59]. The NexSpherio simulations (Fig. 14, [58]) predict very large event-by-event fluctuations of v_2 caused by the strongly fluctuating initial conditions (given by NEXUS). Is this in accord with data? What about the effect on the event plane determination?

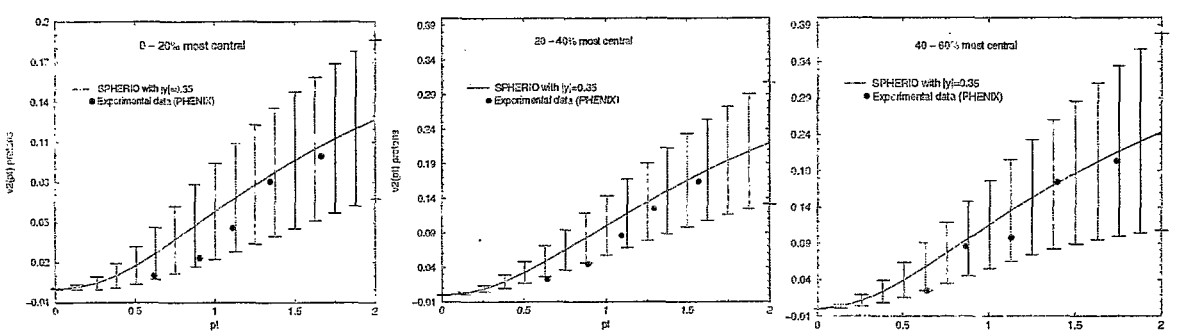


FIG. 14: Elliptic flow v_2 of protons as a function of p_T for different centralities. NexSpherio ideal hydro results exhibit about a factor of two higher proton-v_2-values than the PHENIX data up to $p_T = 1$ GeV/c. Furthermore, the fluctuations in the NEXUS initial conditions for the SPHERIO- ideal hydro simulation reflect > 50 % event-by-event fluctuations of the proton-v_2 values. Only large viscosity effects can damp out the too large v_2 flow itself as well as the fluctuations in v_2.

Microscopic transport simulations of particle yields, dN/dy distributions, etc. give a good description of the RHIC Au+Au data [19]. The HSD and UrQMD transport approaches are based on string, quark, diquark $(q, \bar{q}, qq, \bar{q}\bar{q})$ as well as hadronic degrees of freedom. At RHIC, UrQMD and HSD yield reasonable abundances of light hadrons composed of u, d, s quarks [1]. Do they also predict the collective flow properly? The UrQMD prediction is clearly not compatible with the measured 6% elliptic flow - it is sizeably underestimated [60]. When shortening the formation time [60] one can get the model results closer to the data (Fig. 15) but more additional initial pressure – needed to create the missing extra flow – is not justified in the hadronic transport models. At high transverse momenta ($p_T \approx 2$

[1] For a more recent survey on hadron rapidity distributions from 2 to 160 A·GeV in central nucleus-nucleus collisions within the HSD and UrQMD transport approaches we refer the reader to Ref. [42].

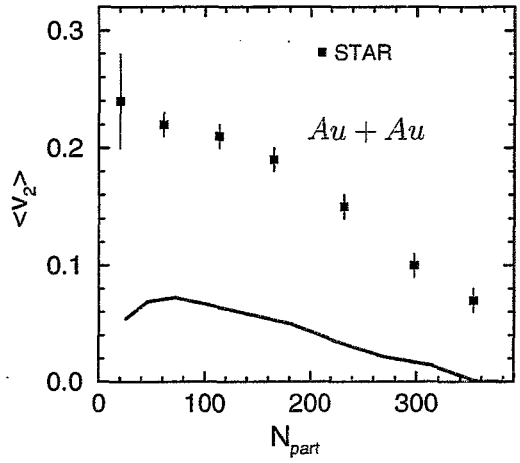


FIG. 15: High p_T- v_2 values as a function of N_{part} as measured by STAR are compared to HSD calculations. The v_2 data are more than 5 times higher than the HSD model predictions for the most central collisions [61].

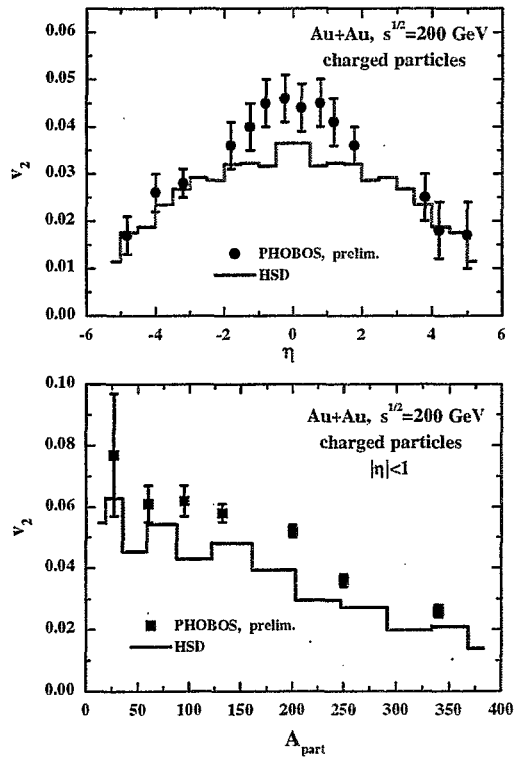


FIG. 16: The elliptic flow v_2 for charged hadrons (HSD, solid lines) as a function of pseudorapidity η (upper part) and as a function of the number of 'participating nucleons' A_{part} for $|\eta| \leq 1$ (lower part) for $Au + Au$ collisions at $\sqrt{s} = 200$ GeV, in comparison to the preliminary 'hit-based analysis' data of the PHOBOS Collaboration [63]. Note, that in spite of the shortened formation, $\tau \approx 0.8$ fm/c, HSD clearly underpredicts the data even at the moderate p_T-values dominating the p_T integrated v_2-values shown here. At higher p_T-values, Fig. 15, the discrepancy to the data is more dramatic.

GeV/c) the v_2-flow is underestimated even by a factor of three (Fig. 15) in the HSD model [61]. We mention that the microscopic quark-gluon-string model inserts in addition short distance vector repulsion in order to achieve high flow values [62].

Is a transport approach - based on strings and hadronic degrees of freedom - adequate in the initial stage of nucleus-nucleus collisions at RHIC energies, where the quark-gluon plasma is formed? Well, the particle abundancies

show a rather smooth evolution from SIS to RHIC energies [64, 65]. However, the effective partonic degrees of freedom in the initial phase are needed to supply the large pressure obviously needed to describe the elliptic flow at RHIC energies. Even 'early' hadron formation – as in HSD with $\tau = 0.8$ fm/c – and 'large' (pre-)hadronic interaction cross sections are insufficient to explain the v_2 flow data. This is demonstrated in Fig. 16, which shows the calculated elliptic flow v_2 from HSD for charged hadrons (solid lines) as a function of the pseudorapidity η (upper part) and as a function of the number of 'participating nucleons' N_{part} (lower part) for $|\eta| \leq 1$ in comparison to the preliminary 'hit-based analysis' data of the PHOBOS Collaboration [63]. The HSD results are very similar to those of the hadronic rescattering model by Humanic et al. [66, 67] and agree with the calculations by Sahu et al. [68] performed within the hadron-string cascade model JAM [69].

IV. EARLY THERMALIZATION AT RHIC - EVIDENCE FOR A NEW PHASE

A. Elastic and inelastic multi-particle collisions in a parton cascade

To describe the early dynamics of ultrarelativistic heavy-ion collisions and to address the crucial question of thermalization and the early pressure build up at RHIC, unexpectedly high elastic parton cross sections have been assumed in parton cascades [70, 71] in order to reproduce the elliptic flow $v_2(p_T)$ seen experimentally at RHIC. These cross sections are about 1/9 of the baryon-baryon total cross section ($\sim$ 45 mb) or 1/6 of the meson-baryon cross section ($\sim$ 30 mb), such that the effective cross section for the constituent quarks and antiquarks is roughly the same in the partonic and hadronic phase, however, tenfold higher than the cross sections calculated in pQCD.

It has been a great puzzle until recently, when Xu and Greiner developed a consistent three-body kinetic parton cascade algorithm [72, 73]. These stochastic inelastic ('Bremsstrahlung') $2 \rightarrow 3$ and $3 \rightarrow 2$ collisions ($gg \leftrightarrow ggg$) drive early thermalization, rather than the two-body elastic collisions, which are too strongly forward peaked. A quantitative understanding of the early dynamical stages of deconfined matter is finally in sight. Parton cascade analyses incorporating only binary $2 \leftrightarrow 2$ pQCD scattering processes can not build up thermalization and early quasi-hydrodynamic behaviour necessary for achieving sufficient elliptic flow. The importance of inelastic reactions was raised in the so called 'bottom-up thermalization' picture [74]; gluon multiplication leads to a much faster equilibration.

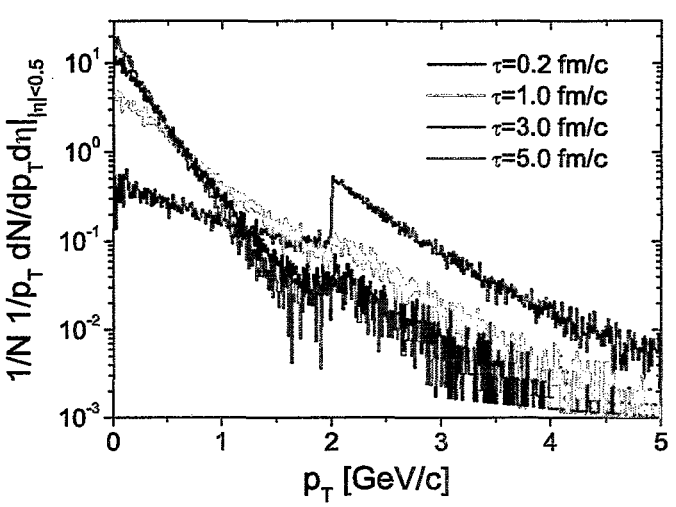


FIG. 17: Time evolution of the midrapidity transverse momentum spectrum for a central RHIC collision from the three-dimensional Xu-Greiner-parton cascade simulation [72, 73] (prelimenary results are from [75] - including transverse expansion). Only partons residing in a central cylinder of radius $R \leq 5$ fm are plotted. The initial off-equilibrium conditions are given by a minijet distribution with corresponding overlap function in space-time. At $t = 0$, only minijets with $p_T > 2$ GeV/c are populated. Energy degradation to lower momenta proceeds by rapid gluon emission within the first fm/c. (Quasi-)kinetic and chemical equilibrium is found up to 4 fm/c. Here longitudinal and transversal hydrodynamic work is at action, resulting in a rapid lowering of the temperature by a factor of two. On the other hand, a small fraction of the initial non-equilibrium high momentum power-law tail of the mini-jet production survives even in this central cell.

Xu and Greiner consider - besides gluon- and quark- two-body elementary parton-parton scatterings - three-body processes $gg \leftrightarrow ggg$ in leading-order pQCD. They employ effective Landau-Pomeranchuk-Migdal suppression and standard screening masses for the infrared sector of the scattering amplitude.

The early stage of gluon production in the Xu-Greiner (X-G) approach (Fig. 17) leads to a rapid kinetic equilibration of the momentum distribution as well as to a rather abrupt lowering of the temperature by soft gluon emission. Detailed balance among gain and loss contributions is reached rapidly, too. The later, slower time evolution is then governed by chemical equilibration of the quark degrees of freedom. The X-G cascade does allow to study in detail RHIC-collisions with various initial conditions like minijets or color glass condensate (CGC). Fig. 17 depicts a preliminary calculation [75] using minijet-initial conditions.

Thermalization and chemical equilibration - as proposed in the bottom-up scenario [74] - can thoroughly be tested within this approach. The impact parameter dependence on the transverse energy is used to understand elliptic and transverse flow at RHIC within this new kinetic parton cascade with inelastic $3 \to 2$ and $2 \to 3$ interactions.

V. HOW MUCH QUENCHING OF HIGH p_T HADRONS IS DUE TO (PRE-) HADRONIC FINAL STATE INTERACTIONS?

A (mini-)jet at RHIC can produce hard particles, with p_T above 5 GeV/c, but must also form soft particles with p_T around 2 GeV/c. Jets produced in the center of the plasma zone have to pass first through the parton phase at very high temperatures, then through the correlated diquark and constituent quarks and finally through the hadronic phase that has build up preferentially close to the surface of the fireball. Very high p_T jets with $\gamma > 10$ materialize only far outside of the plasma. Most of the jets - observed at RHIC - are at $p_T \approx 4-5$ GeV/c. More than 50% of the leading jet particles at $p_T \sim 5$ GeV/c are baryons. Pion jets of 5 GeV have a $\gamma = 35$, i.e., they form far outside the plasma. However, HSD-PYTHIA-calculations [76] show that many pions stem from decaying rho-jets. But, ρ's and protons of 5 GeV have $\gamma = 5$. Thus, ρ and p-jets hadronize with roughly 50% probability [61, 77] while passing through the expanding bulk matter. All partonic and hadronic models have failed by factors of 5-10 to predict the observed high baryon abundance.

The PHENIX [78] and STAR [79] collaborations reported a suppression of meson spectra for transverse momenta p_T above ~ 3 GeV/c. This suppression is not observed in d+Au interactions at the same bombarding energy per nucleon [80, 81] and presents clear evidence for the presence of a new form of matter. However, it is not clear at present how much of the observed suppression can be attributed to (pre-)hadronic interactions (FSI) [77]. (In-)elastic collisions of (pre-)hadronic high momentum states with some of the bulk (pre-)hadrons in the fireball can contribute in particular to the attenuation of $p_T \approx 5$ GeV/c transverse momentum hadrons at RHIC [76]: Most of the medium momentum (pre-)hadrons from a ± 5 GeV/c double jet will materialize inside the dense plasma; their transverse momenta being 0-4 GeV/c. The particles are dominantly ρ's, K's and baryons at $p_T > 2.5$ GeV/c - hence their formation time is $\gamma\tau_F \approx 4$ fm/c in the plasma rest frame. The time for color neutralization can also be very small [82] for the leading particle due to early gluon emission.

The (pre-)hadronic interactions with the bulk of the (pre-)hadronic comovers then must have clearly an effect: they, too, suppress the p_T-spectrum [77]. (In)elastic reactions of the fragmented (pre-)hadrons with (pre-)hadrons of the bulk system cannot be described by pQCD: The relevant energy scale $\sqrt{s}$ is a few GeV. Such (in-)elastic collisions are very efficient for energy degradation since many hadrons with lower energies are produced. On the average, 1 to 2 such interactions can account for up to 50% of the attenuation of high p_T hadrons at RHIC [77]. Hence, the hadronic fraction of the jet-attenuation had to be addressed.

In Ref. [61] the HSD transport approach [41] is employed. Moderate to high transverse momenta (> 1.5 GeV/c) are incorporated by a superposition of $p+p$ collisions described via PYTHIA [14]. In Au+Au collisions, the formation of secondary hadrons is not only controlled by the formation time τ_f, but also by the energy density in the local rest frame. In [61], hadrons are not allowed to be formed if the energy density is above 1 GeV/fm[32]. The interaction of the leading and energetic (pre-)hadrons with the soft hadronic and bulk matter is thus explicitly modeled.

Figs. 18, 19 show the nuclear modification factor [76]

$$R_{\rm AA}(p_T) = \frac{1/N_{\rm AA}^{\rm event}\; d^2N_{\rm AA}/dydp_T}{\langle N_{\rm coll}\rangle\,/\sigma_{pp}^{\rm inelas}\; d^2\sigma_{pp}/dydp_T}\,. \tag{3}$$

for the most central (5% centrality) Au+Au collisions at RHIC. The Cronin enhancement is visible at all momenta. Hadron formation time effects do play a substantial role in the few GeV region, since heavier hadrons (K*'s, ρ's,

[2] This energy density cut is employed in the default HSD approach.

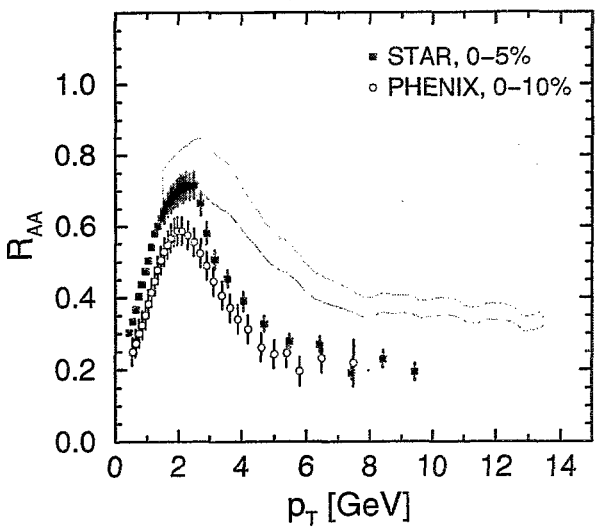


FIG. 18: The suppression factor R_{AA} (3) of charged hadrons at 5% (10%) central $Au + Au$ collisions ($\sqrt{s}$=200 GeV) at midrapidity (hatched band). The experimental data are from Refs. [23, 85] and show clearly that an additional partonic suppression is needed (taken from Ref. [61]).

protons) are formed 7 times earlier than the rather light pions in the cms frame at fixed transverse momentum due to the lower Lorentz boost $\gamma < 5$. It was shown in [61] that for transverse momenta $p_T \geq 6$ GeV/c the interactions of formed hadrons are not able to explain the attenuation observed experimentally. However, the ratio R_{AA} is influenced by interactions of formed (pre-)hadrons in the $p_T = 1 \ldots 5$ GeV/c range [61]. A similar behaviour has also been found in UrQMD simulations [83].

As pointed out before, the suppression seen in the calculation for larger transverse momentum hadrons is due to the interactions of the leading (pre-)hadrons with target/projectile nucleons and the bulk of low momentum hadrons. It is clear that the experimentally observed suppression can not be quantitatively described by the (pre-)hadronic attenuation of the leading particles [61]. The ratio R_{AA} (3) decreases to a value of about 0.5 at 5 GeV for central collisions, whereas the data are around $R_{AA} \approx 0.25$.

To check, how robust this HSD estimate is, alternative models for the leading pre-hadron cross section have been

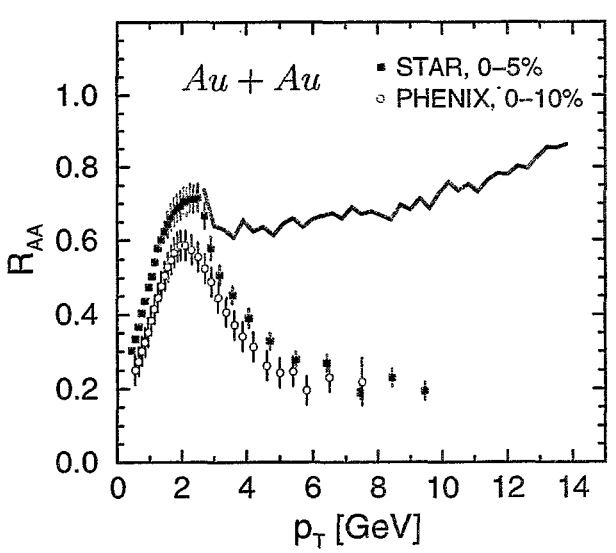


FIG. 19: Same as Fig. 18, but with a leading cross section according to eq. (4) for the perturbative high p_T particles. The observed attenuation is more than double the value!

studied in [61] by adopting a time-dependent, color-transparency-motivated cross section for leading pre-hadrons [84]

$$\sigma_{\rm lead}(\sqrt{s},\tau) = \frac{\tau - \tau_0}{\tau_f}\sigma_{\rm had}(\sqrt{s}) \tag{4}$$

for $\tau - \tau_0 \leq \tau_f$, where τ_0 denotes the actual production time, τ_f the formation time, after which the full hadronic cross section is reached.

Within this scenario the attenuation is 35% at $p_T \sim 5\,\mathrm{GeV}/c$ (see Fig. 19), while the data show more than double the attenuation. Thus, (pre-)hadronic jet interactions cannot provide a quantitative explanation for the jet suppression observed. They do provide, however, a sizable $(30-50\%)$ contribution to the jet quenching.

For particles observable with momenta $p_T \geq 4$ GeV/c, the HSD transport calculation predicts that still 1/3 of the final observed hadrons have suffered one or more interactions, whereas the other 2/3 escape freely, i.e., without any interaction (even for central collisions). This implies that the final high p_T hadrons originate basically from the surface.

A. Angular Correlations of Jets – Can jets fake the large v_2-values observed?

Fig. 20 [76] shows the angular correlation of high p_T particles ($p_T NTrig = 4\ldots6\,\mathrm{GeV}/c$, $p_T = 2\,\mathrm{GeV}\ldots p_T NTrig$, $|y| < 0.7$) for the 5% most central Au+Au collisions at $\sqrt{s} = 200$ GeV (solid line) as well as pp reactions (dashed line) from the HSD-model [76] in comparison to the data from STAR for pp collisions [86]. Gating on high p_T hadrons (in the vacuum) yields 'near-side' correlations in Au+Au collisions close to the 'near-side' correlations observed for jet fragmentation in the vacuum (pp). This is in agreement with the experimental observation [86]. However, for the away-side jet correlations, the authors of Ref. [76] get only a ~50% reduction, similar to HIJING, which has only parton quenching and neglects hadron rescattering. Clearly, the observed [86] complete disappearance of the away-side jet (Fig. 20) cannot be explained in the HSD-(pre-)hadronic cascade even with a small formation time of 0.8 fm/c. Hence, the correlation data provide another clear proof for the existence of the bulk plasma.

Although (pre-)hadronic final state interactions yield a sizable ($\leq 50\%$) contribution to the high p_T suppression effects observed in Au+Au collisions at RHIC, $\sim 50\%$ of the jet suppression originates from interactions in the plasma phase. The elliptic flow, v_2, for high transverse momentum particles is underestimated by at least a factor of 3 in the HSD transport calculations [61] (cf. Fig. 15). The experimentally observed proton excess over pions at transverse momenta $p_T > 2.5$ GeV/c cannot be explained within the CGG approach [61]; in fact, the proton yield at high $p_T \geq 5$ GeV/c is a factor 5-10 too small. We point out that this also holds for partonic jet-quenching models. Further experimental data on the suppression of high momentum hadrons from d+Au and Au+Au collisions, down to $\sqrt{s} =$ 20 GeV, are desperately needed to separate initial state Cronin effects from final state attenuation and to disentangle the role of partons in the colored parton plasma from those of interacting pre-hadrons in the hot and dense fireball.

Can the attenuation of jets of $p_T \geq 5\,\mathrm{GeV}/c$ actually fake the observed v_2-values at $p_T \approx 2\,\mathrm{GeV}/c$? This question comes about since due to fragmentation and rescattering a lot of momentum-degraded hadrons will propagate in the hemisphere defined by the jets. However, their momentum dispersion perpendicular to the jet direction is so large that it could indeed fake a collective flow that is interpreted as coming from the high pressure early plasma phase.

On first sight, Fig. 21 shows that this could indeed be the case: the in-plane v_2 correlations are aligned with the jet axis, the away-side bump, usually attributed to collective v_2 flow (dashed line), could well be rather due to the stopped, fragmented and rescattered away-side jet! However, this argument is falsified by the out-of-plane correlations (circles in Fig. 21). The near-side jet is clearly visible in the valley of the collective flow v_2 distribution. Note that v_2 peaks at $\varphi = \pi/2$ relative to the jet axis! The away-side jet, on the other hand, has completely vanished in the out-of-plane distribution (cf. Fig. 22)!

Where are all the jet fragments gone? Why is there no trace left? Even if the away-side jet fragments completely and the fragments get stuck in the plasma, leftovers should be detected at momenta below 2 GeV/c. Hadronic models as well as parton cascades will have a hard time to get a quantitative agreement with these exciting data!

We propose future correlation measurements which can yield spectroscopic information on the plasma.

1. If the plasma is a colorelectric plasma, experiments will - in spite of strong plasma damping - be able to search for wake-riding potential effects. The wake of the leading jet particle can trap comoving companions that move through the plasma in the wake pocket with the same speed (p_T/m) as the leading particle. This can be particular stable for charmed jets due to the deadcone effect as proposed by Kharzeev et al [87], which will guarantee little energy loss, i.e. constant velocity of the leading D-meson. The leading D-meson will practically have very little momentum degradation in the plasma and therefore the wake potential following the D will be able to capture the equal speed companion, which can be detected [88].

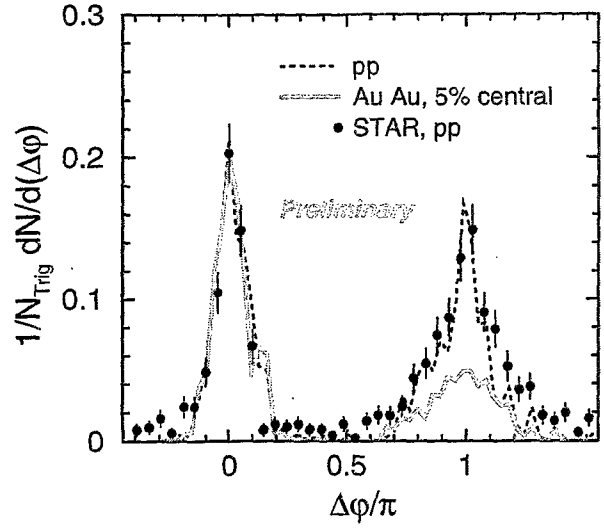


FIG. 20: STAR data on near-side and away-side jet correlations compared to the HSD model for p+p and central Au+Au collisions at midrapidity for $p_T NTrig = 4 \ldots 6\,\mathrm{GeV}/c$ and $p_T = 2\,\mathrm{GeV}/c \ldots p_T NTrig$. [61, 76]

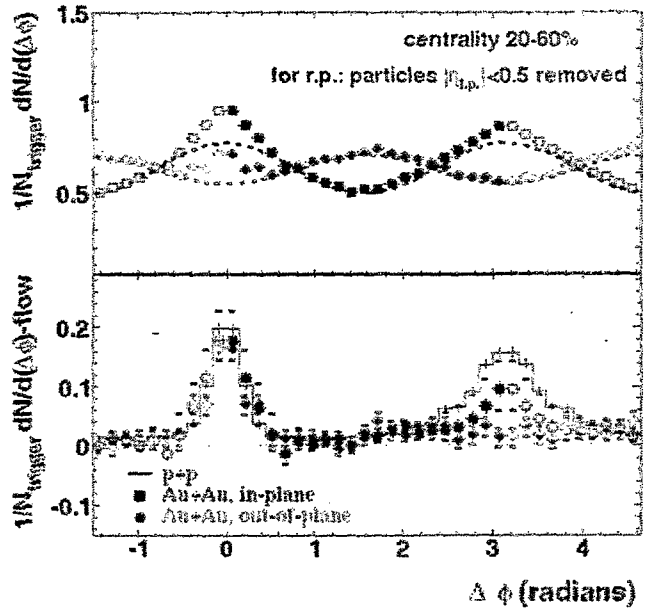


FIG. 21: High p_T correlations: in-plane vs. out-of-plane correlations of the probe (jet+secondary jet fragments) with the bulk (v_2 of the plasma at $p_T > 2\,\mathrm{GeV}/c$), prove the existence of the initial plasma state (STAR-collaboration, preliminary).

2. One may measure the sound velocity of the expanding plasma by the emission pattern of the plasma particles travelling sideways with respect to the jet axis: The dispersive wave generated by the wake of the jet in the plasma yields preferential emission to an angle (relative to the jet axis) which is given by the ratio of the leading jet particles' velocity, devided by the sound velocity in the hot dense plasma rest frame. The speed of sound for a non-interacting gas of relativistic massless plasma particles is $c_s \approx \frac{1}{\sqrt{3}} \approx 57\%\,c$, while for a plasma with strong vector interactions, $c_s = c$. Hence, the emission angle measurement can yield information of the interactions in the plasma.

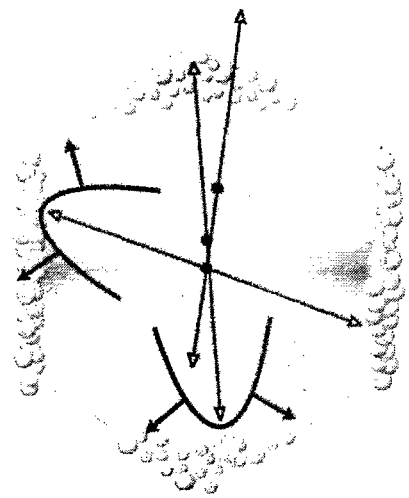


FIG. 22: Illustration of jets traveling through the late hadronic stage of the reaction. Only jets from the region close to the initial surface can propagate and fragment in the vacuum [24, 76, 89, 90]. The other jets will interact with the bulk, resulting in wakes with bow waves travelling transversely to the jet axis.

VI. SUMMARY

The NA49 collaboration has observed the collapse of both, v_1- and v_2-collective flow of protons, in Pb+Pb collisions at 40 A·GeV, which presents first evidence for a first order phase transition in baryon-rich dense matter. It will be possible to study the nature of this transition and the properties of the expected chirally restored and deconfined phase both at the forward fragmentation region at RHIC, with upgraded and/or second generation detectors, and at the new GSI facility FAIR. According to Lattice QCD results [1, 2], the first order phase transition occurs for chemical potentials above 400 GeV. Fig. 13 shows that the elliptic flow clearly distinguishes between a first order phase transition and a crossover. Thus, the observed collapse of flow, as predicted in [24, 25], is a clear signal for a first order phase transition at the highest baryon densities.

A critical discussion of the use of collective flow as a barometer for the equation of state (EoS) of hot dense matter at RHIC showed that hadronic rescattering models can explain $< 30\%$ of the observed flow, v_2, for $p_T > 2$ GeV/c. We interpret this as evidence for the production of superdense matter at RHIC with initial pressure way above hadronic pressure, $p > 1$ GeV/fm^3.

The fluctuations in the flow, v_1 and v_2, should be measured. Ideal Hydrodynamics predicts that they are larger than 50 % due to initial state fluctuations. The QGP coefficient of viscosity may be determined experimentally from the fluctuations observed.

The connection of v_2 to jet suppression is examined. It is proven experimentally that the collective flow is not faked by minijet fragmentation and that the away-side jet suppression can only partially ($< 50\%$) be due to pre-hadronic or hadronic rescattering.

We propose upgrades and second generation experiments at RHIC, which inspect the first order phase transition in the fragmentation region, i.e. at $\mu_B \approx$ 400 MeV ($y \approx 4-5$), where the collapse of the proton flow analogous to the 40 A·GeV data should be seen.

The study of Jet-Wake-riding potentials and Bow shocks caused by jets in the QGP formed at RHIC can give further clues on the equation of state and transport coefficients of the Quark Gluon Plasma.

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Measurements with **BRAHMS**

I.G. Bearden,
Niels Bohr Institute
For
The BRAHMS collaboration

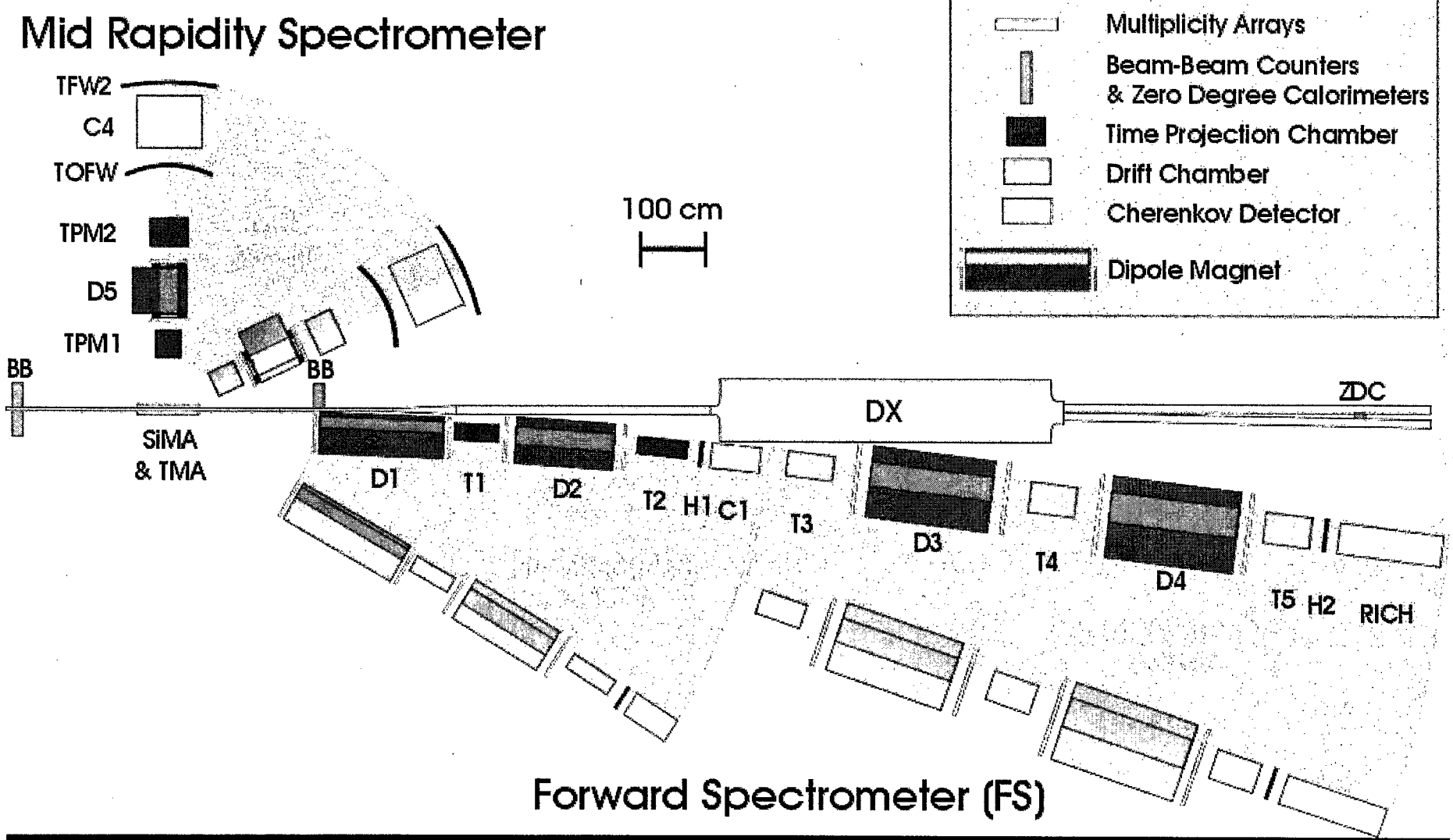
The BRAHMS Collaboration

- 12 institutions-

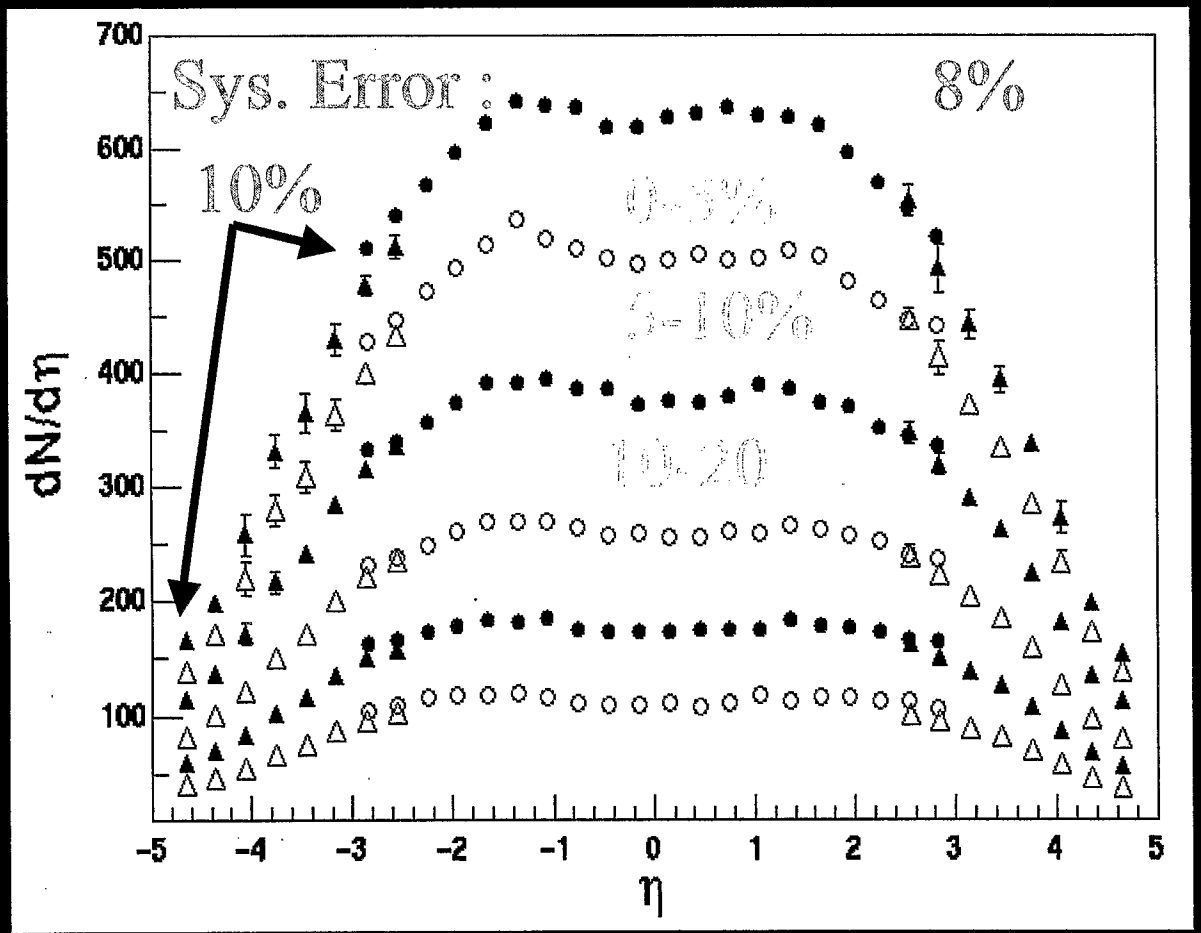
I.Arsene[10],I.G. Bearden[7], D. Beavis[1], C. Besliu[10], Y. Blyakhman[6], J.Brzychczyk[4], B. Budick[6],H. Bøggild[7],C. Chasman[1], C. H. Christensen[7], P. Christiansen[7], J.Cibor[4],R.Debbe[1],J. J. Gaardhøje[7],M. Germinario[7], K. Hagel[8], O. Hansen[7], H. Ito[11], E. Jacobsen[7], A. Jipa[10], J. I. Jordre[10], F. Jundt[2], C.E.Jørgensen[7], E. J. Kim[5], T. Kozik[3], T.M.Larsen[12], J. H. Lee[1], Y. K.Lee[5], G. Løvhøjden[2], Z. Majka[3], A. Makeev[8], B. McBreen[1], M. Murray[8], J. Natowitz[8], B. Neuman[11],B.S.Nielsen[7], K. Olchanski[1], D. Ouerdane[7], R.Planeta[4], F. Rami[2], D. Roehrich[9], B. H. Samset[12], S. J. Sanders[11], I. S. Sgura[10], R.A.Sheetz[1], Z.Sosin[3], P. Staszel[7], T.S. Tveter[12], F.Videbæk[1], R. Wada[8] ,A.Wieloch[3],Z. Yin[9]

[1]Brookhaven National Laboratory, USA, [2]IReS and Université Louis Pasteur, Strasbourg, France
[3]Jagiellonian University, Cracow, Poland, [4]Institute of Nuclear Physics, Cracow, Poland
[5]Johns Hopkins University, Baltimore, USA, [6]New York University, USA
[7]Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Denmark
[8]Texas A&M University, College Station. USA, [9]University of Bergen, Norway
[10]University of Bucharest, Romania, [11]University of Kansas, Lawrence,USA
[12] University of Oslo Norway

BRAHMS Experimental Setup

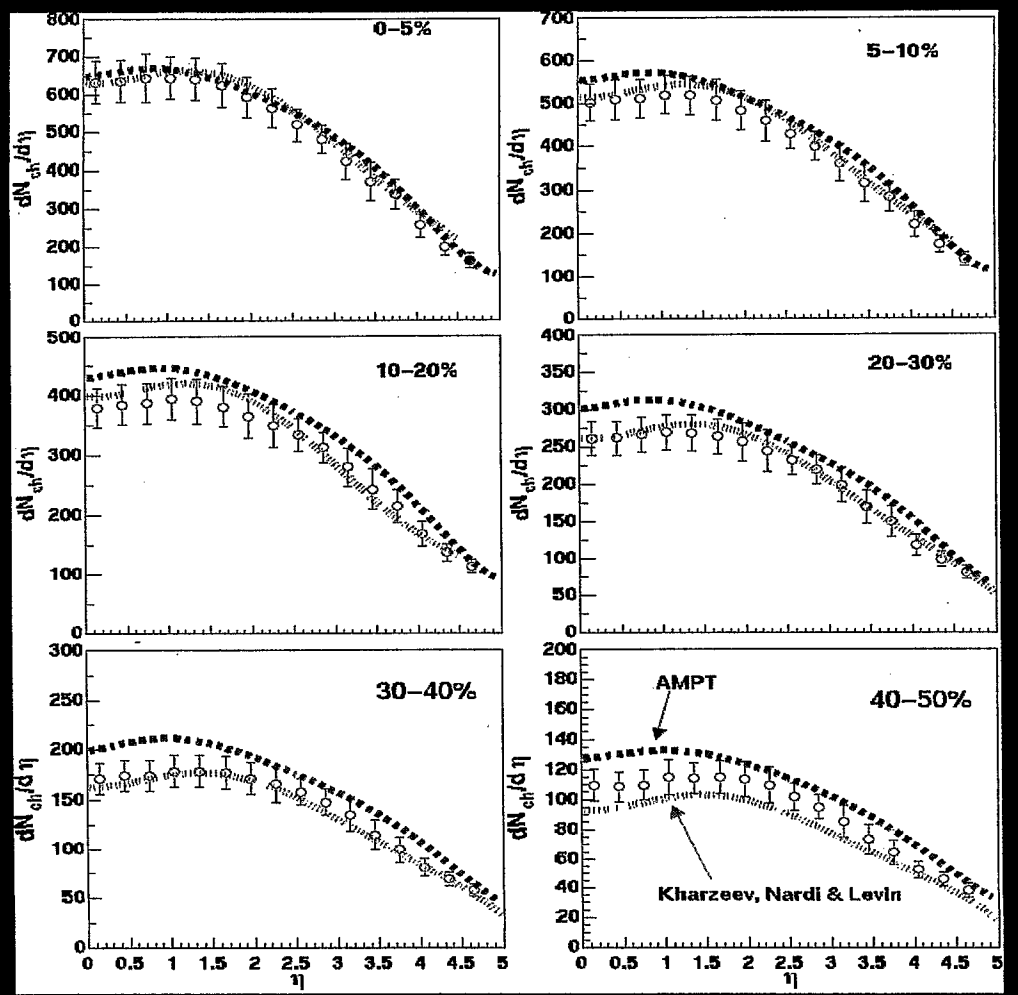


Charged Particle Multiplicity dN/dη



According to Bjorken,

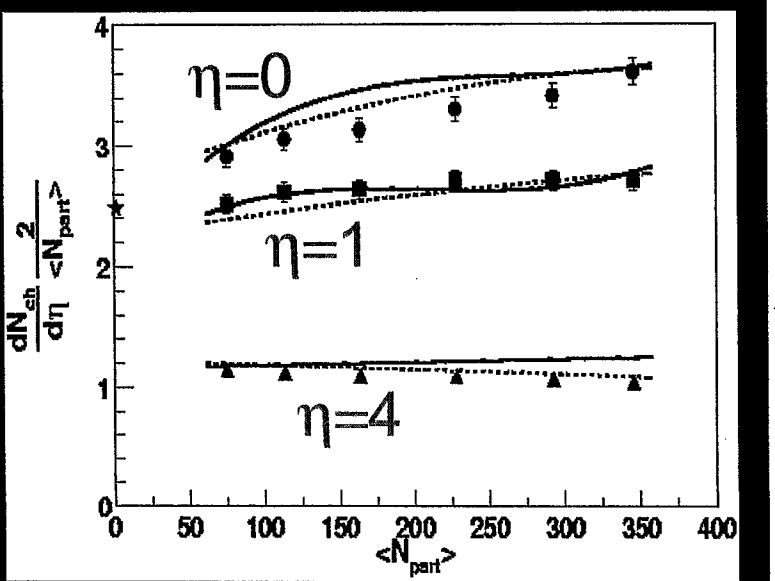
$\varepsilon > 5 GeV/fm^3$



AMPT

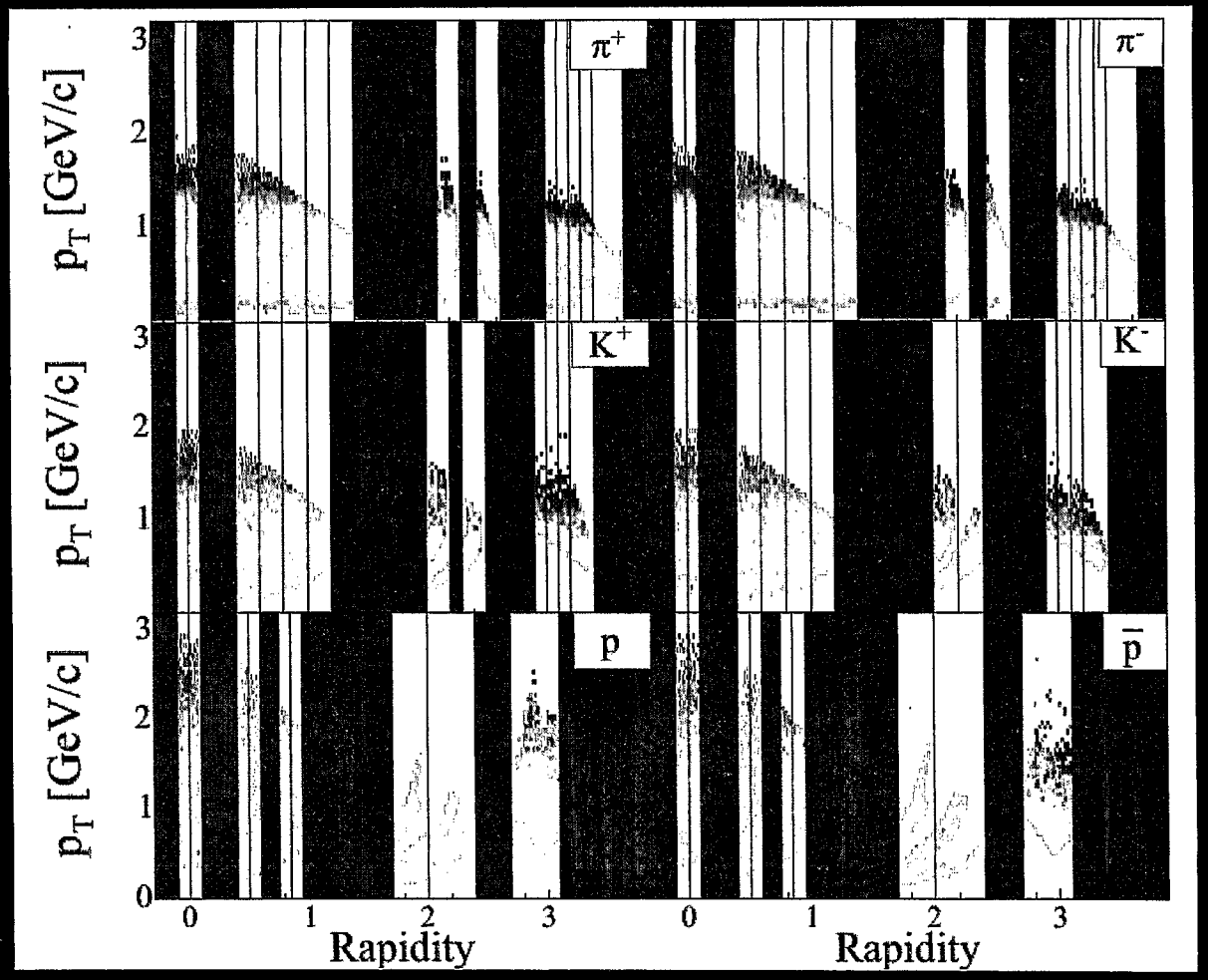
High density QCD gluon saturation

Kharzeev and Levin, PLB523(2001)79



Particle Spectra

After appropriate corrections, we combinine all data sets to obtain final invariant yields over a broad range of rapidity and p_T



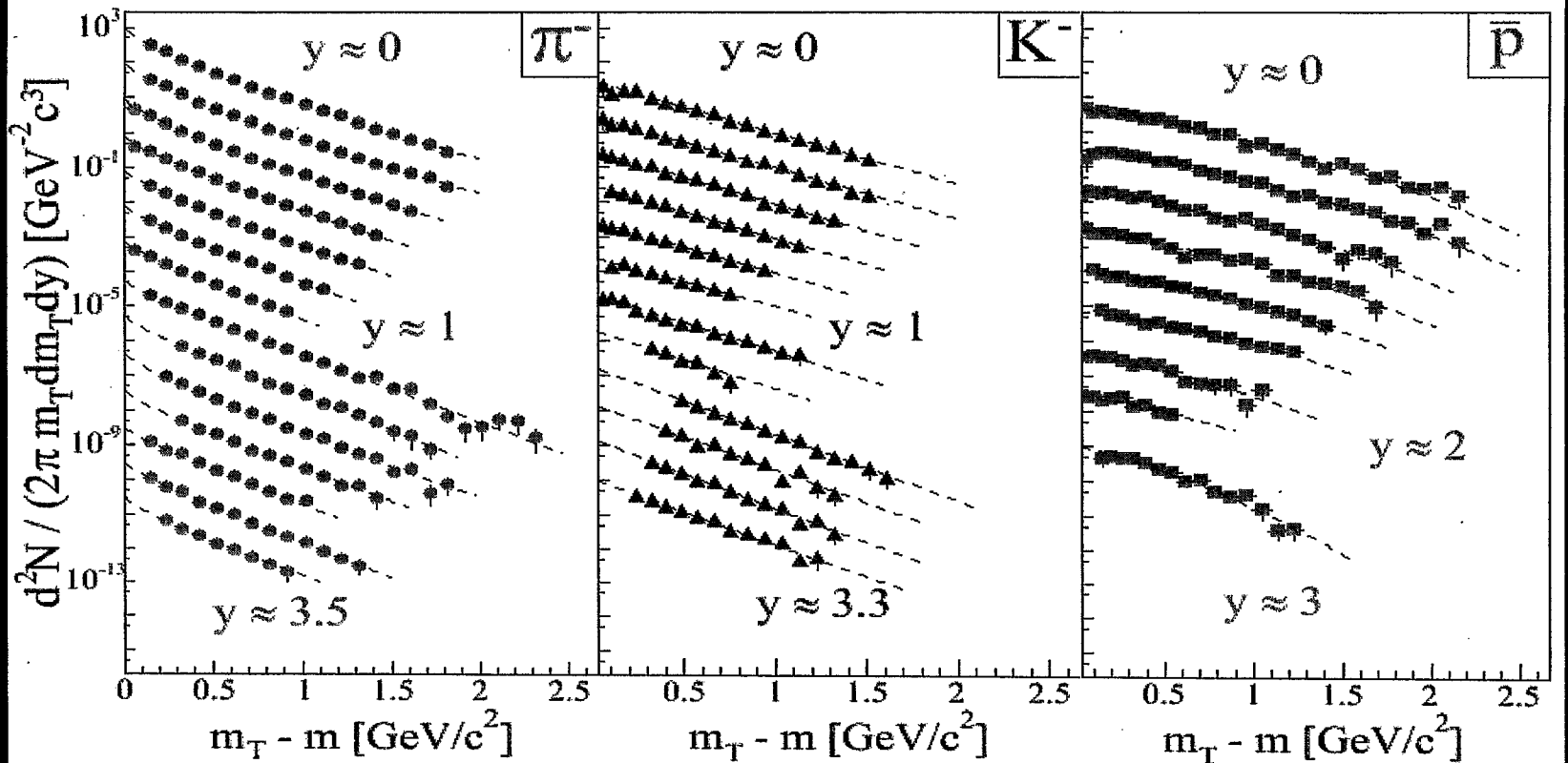
π

K

p

BRAHMS

Top 5% central collisions



Pions: power law

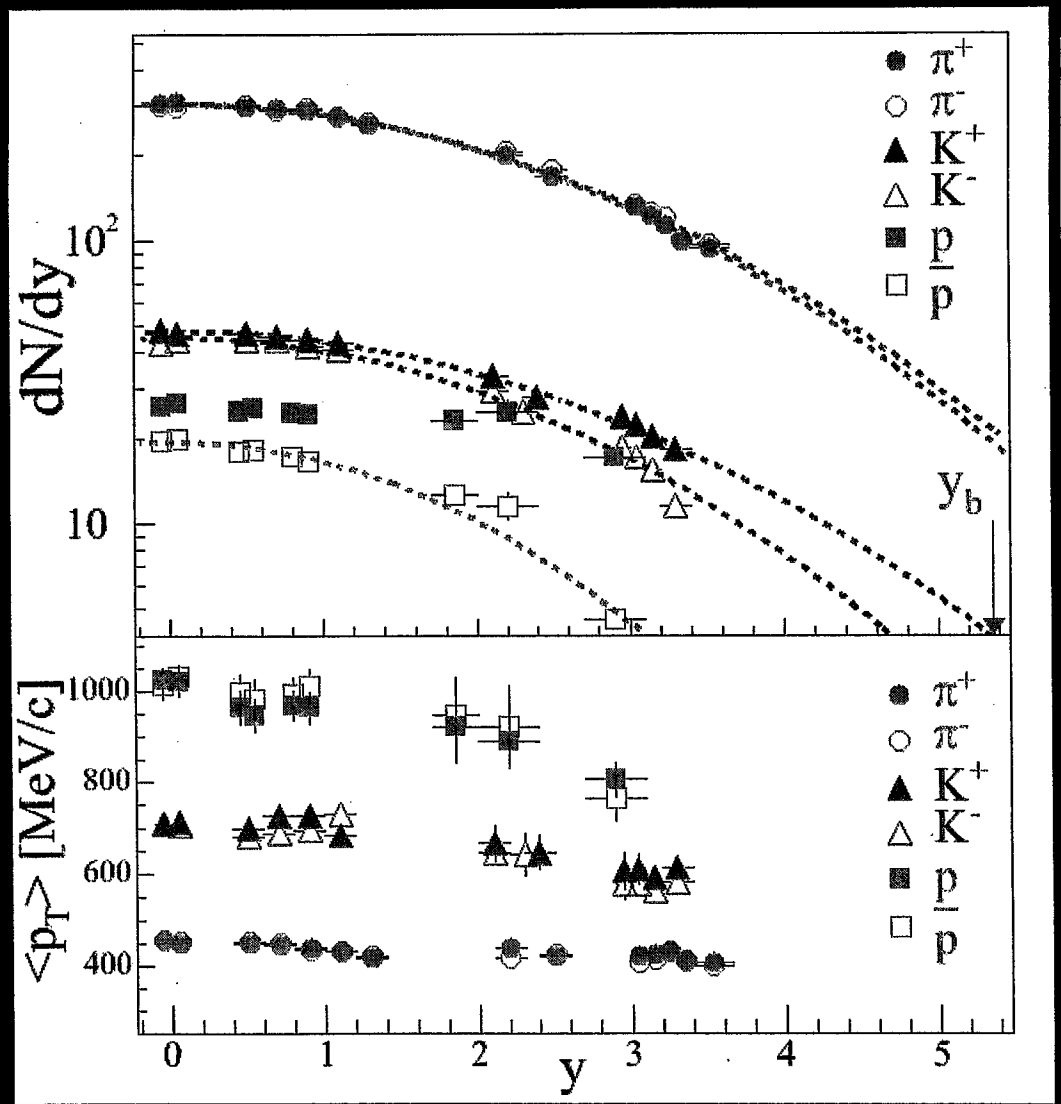
$$A\left(1+\frac{p_T}{p_0}\right)^{-n}$$

Kaons: exponential

$$A\exp\left(-\frac{m_T-m}{T}\right)$$

Protons: Gaussian

$$A\exp\left[-\frac{p_T^2}{2\sigma^2}\right]$$



At y ~ 0, dN/dy is

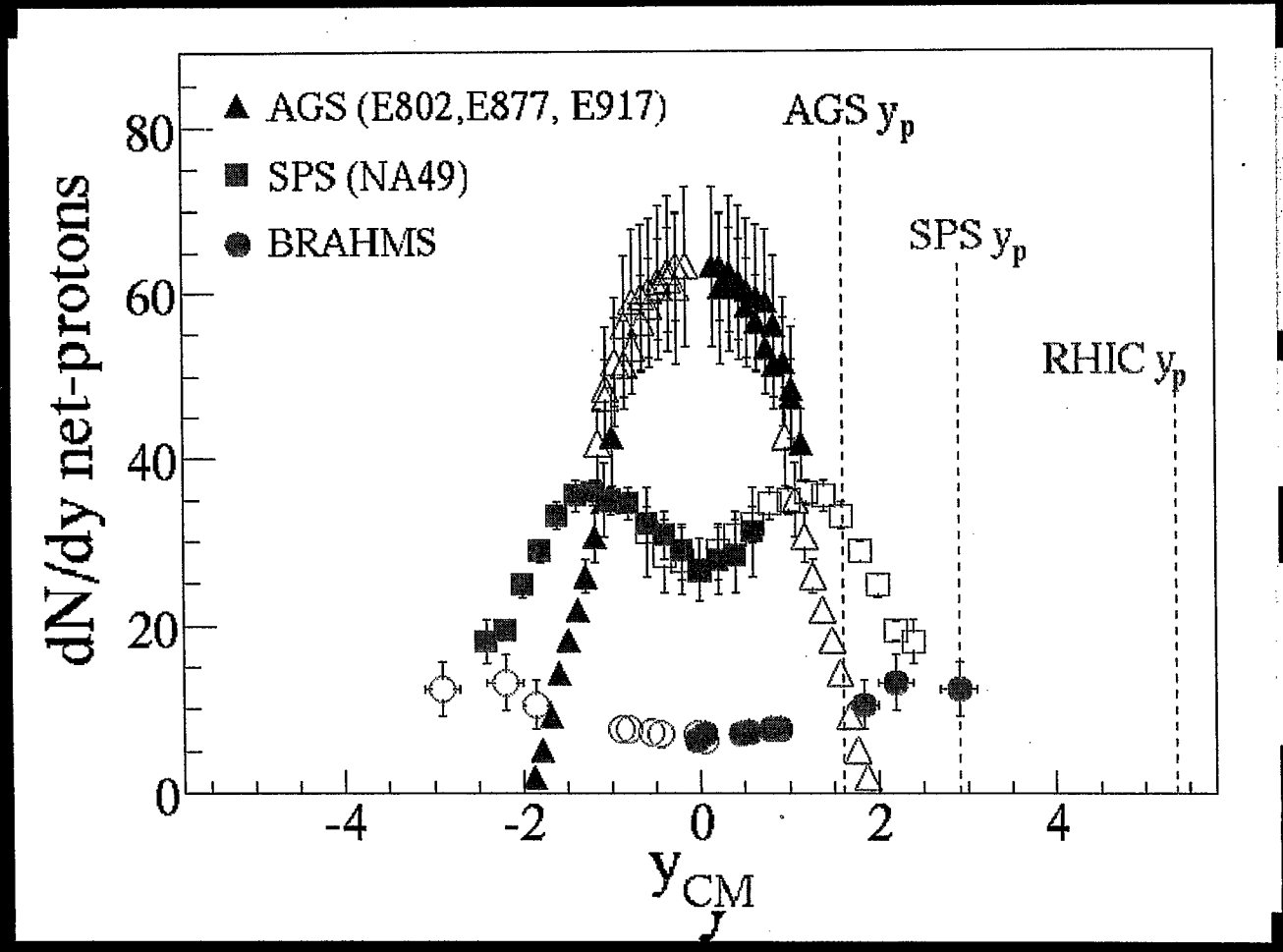
~ 300 (300) for π^+ (π^-)
~ 47 (44) for K^+ (K^-)
~ 27 (20) for p (pbar)

$N(\pi) >> N(K) > N(p)$
$N(\pi^+) = N(\pi^-)$

Integrated multiplicities
(Gaussian fit)

$N(\pi^-)$ ~ 1780 $N(\pi^+)$ ~1760
$N(K^+)$ ~ 290 $N(K^-)$ ~ 240
N(pbar) ~ 85

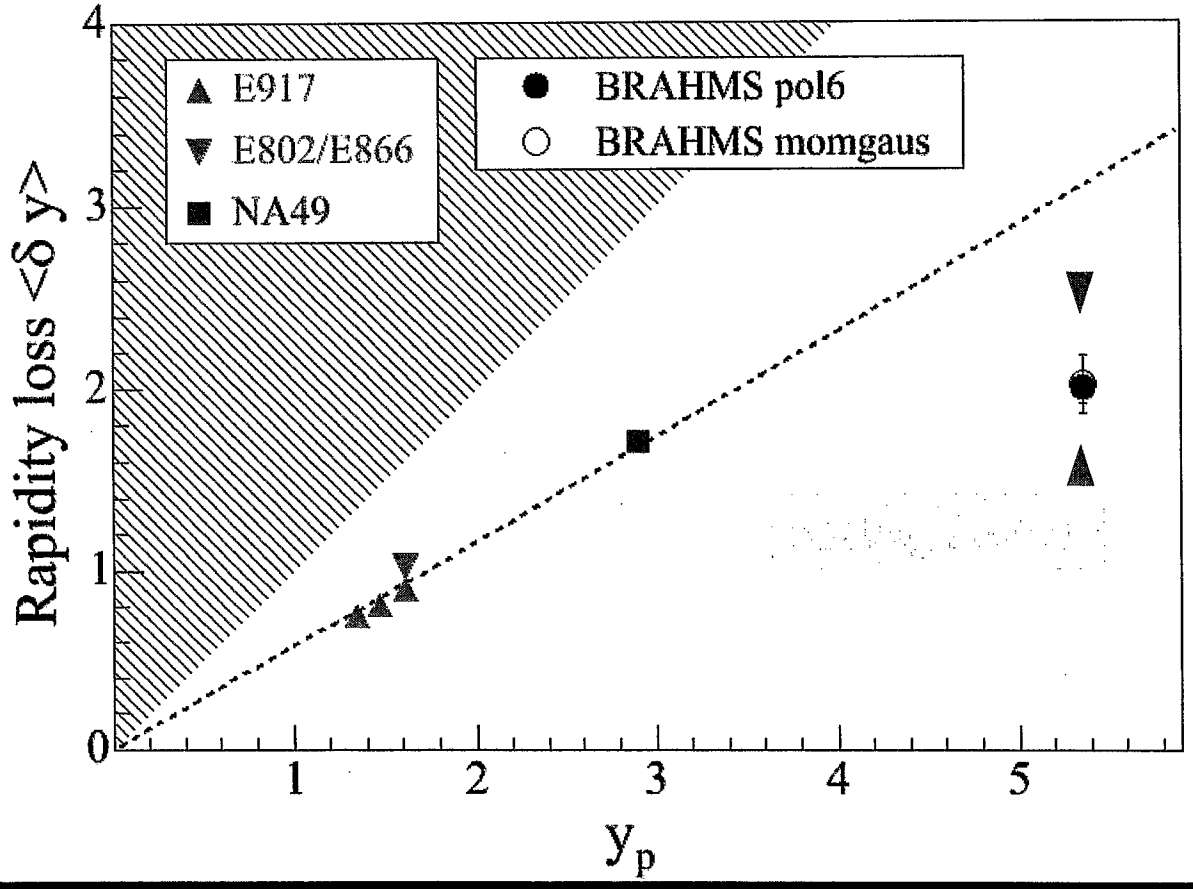
Net-proton rapidity densities (top 5% central collisions)



nucl-ex/0312023

AGS : high stopping
RHIC: more transparent

$$\langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{(B-\bar{B})}}{dy} dy$$



$$\langle \delta y \rangle =$$

$$\langle \delta y \rangle =$$

Total ΔE=25.7±2.1TeV

$$\int_{-y_p}^{y_p} \langle m_T \rangle_y \frac{dN_{(B-\bar{B})}}{dy} \cosh y \, dy$$

Energy Balance

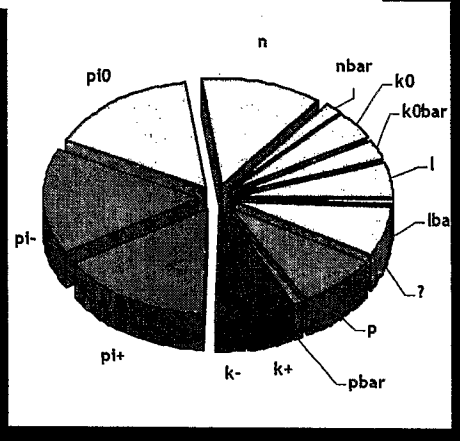
p	: 3108
p	: 428
K^+	: 1628
K^-	: 1093
π^+	: 5888
π^-	: 6117

NB: the method is very sensitive to the tails of the dN/dy dist. (±10-15%)

- Fit π, K and p distributions (dN/dy and $\langle m_T \rangle$ vs y) $\Rightarrow$ total energy of π, K and p
- Assume reasonable distribution for particles we don't detect (π^0,n,Λ...)
- Calculate the total energy...

$$E_{total} = \sum_{specie} \left[\int \frac{dN}{dy} \langle m_T \rangle \cosh(y)\, dy \right]$$

≈35 TeV ($E_{beam} \times N_{part}$) of which ≈25 TeV are carried by produced particles.

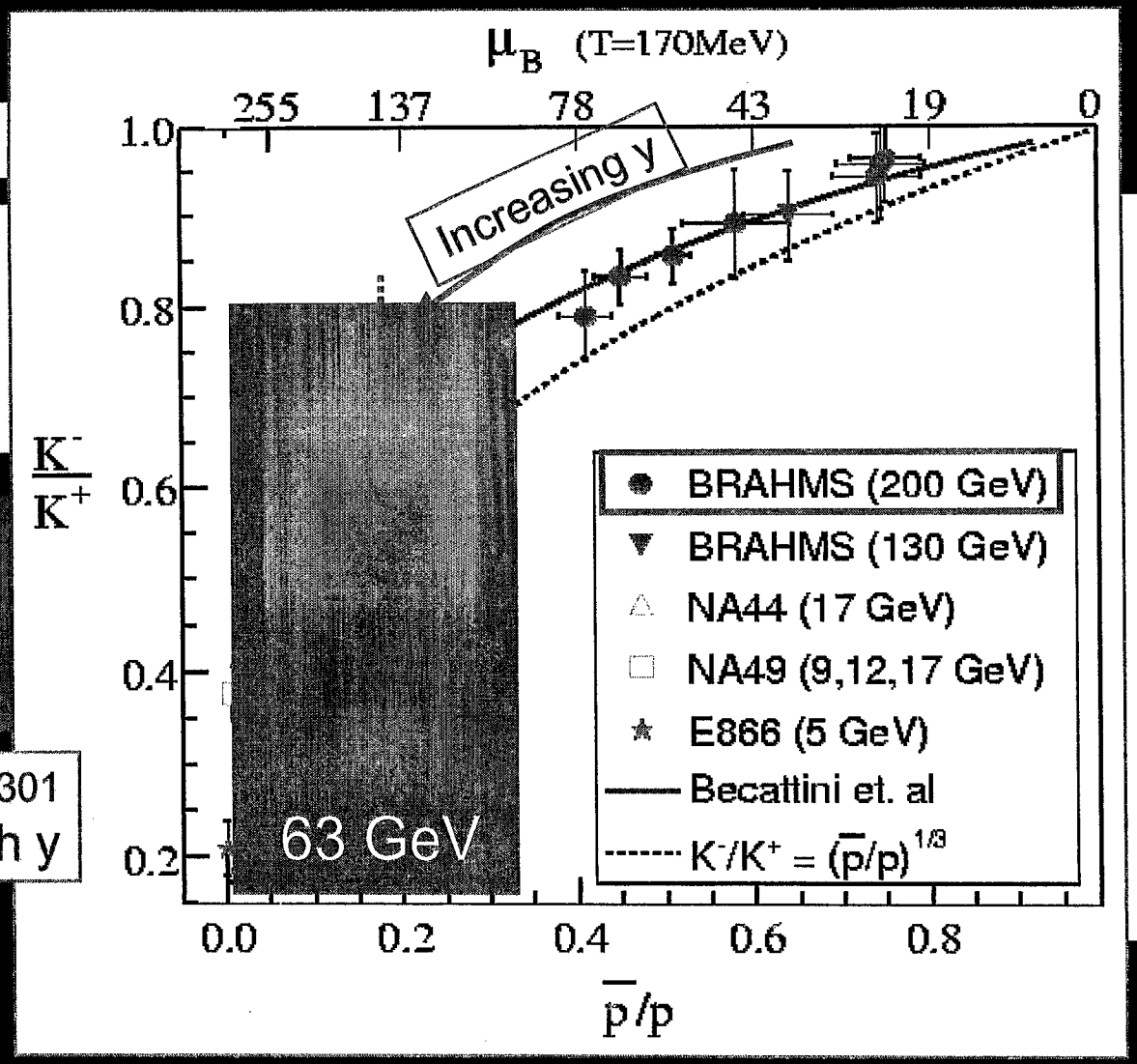


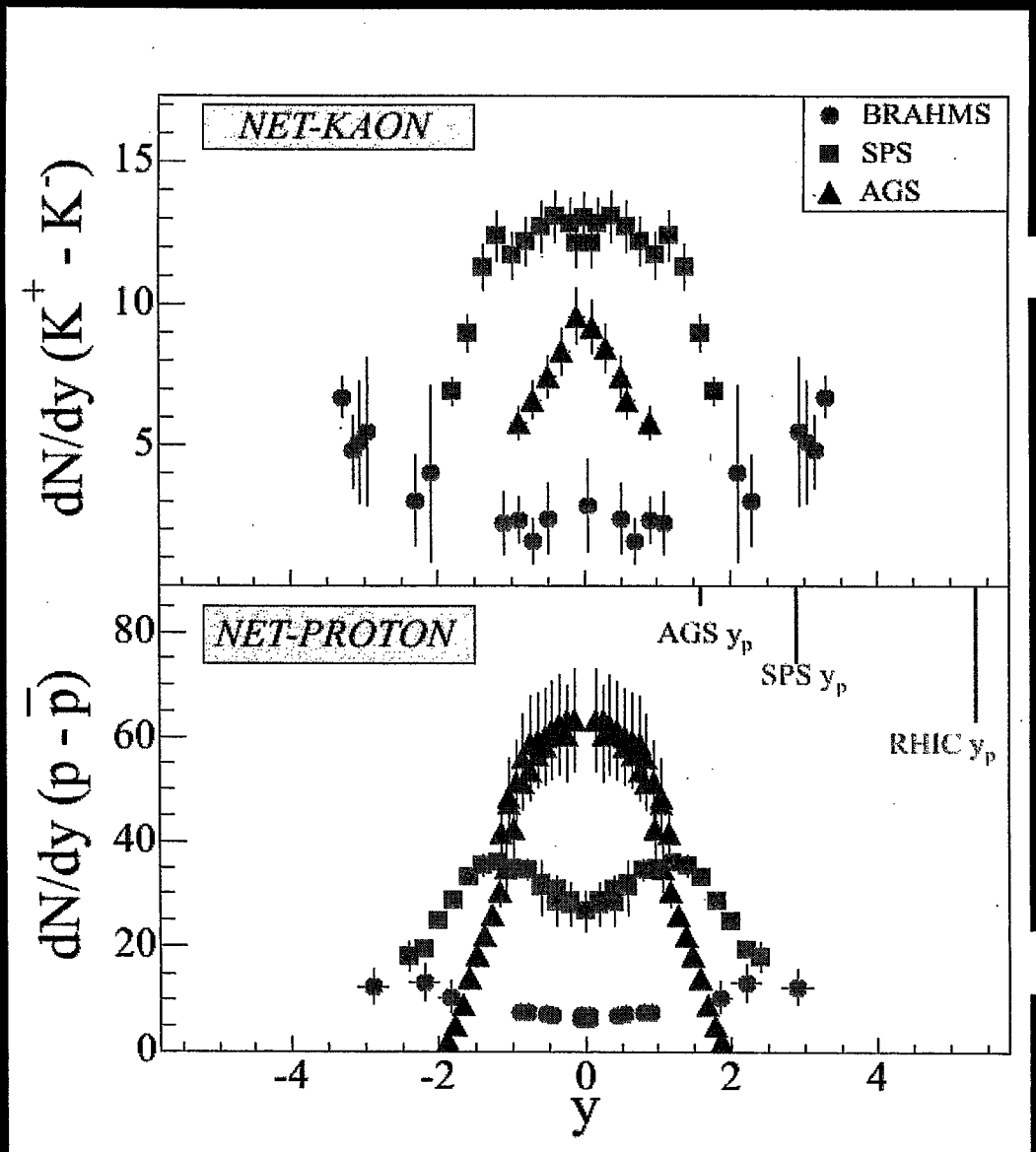
Strangeness with Kaons

RAPIDITY DEPENDENCE

Divergence at higher y :
Associated K^+ production
No single source with
unique T and μ_B

BRAHMS, PRL90 (2003) 102301
T~constant, μ_B varies with y





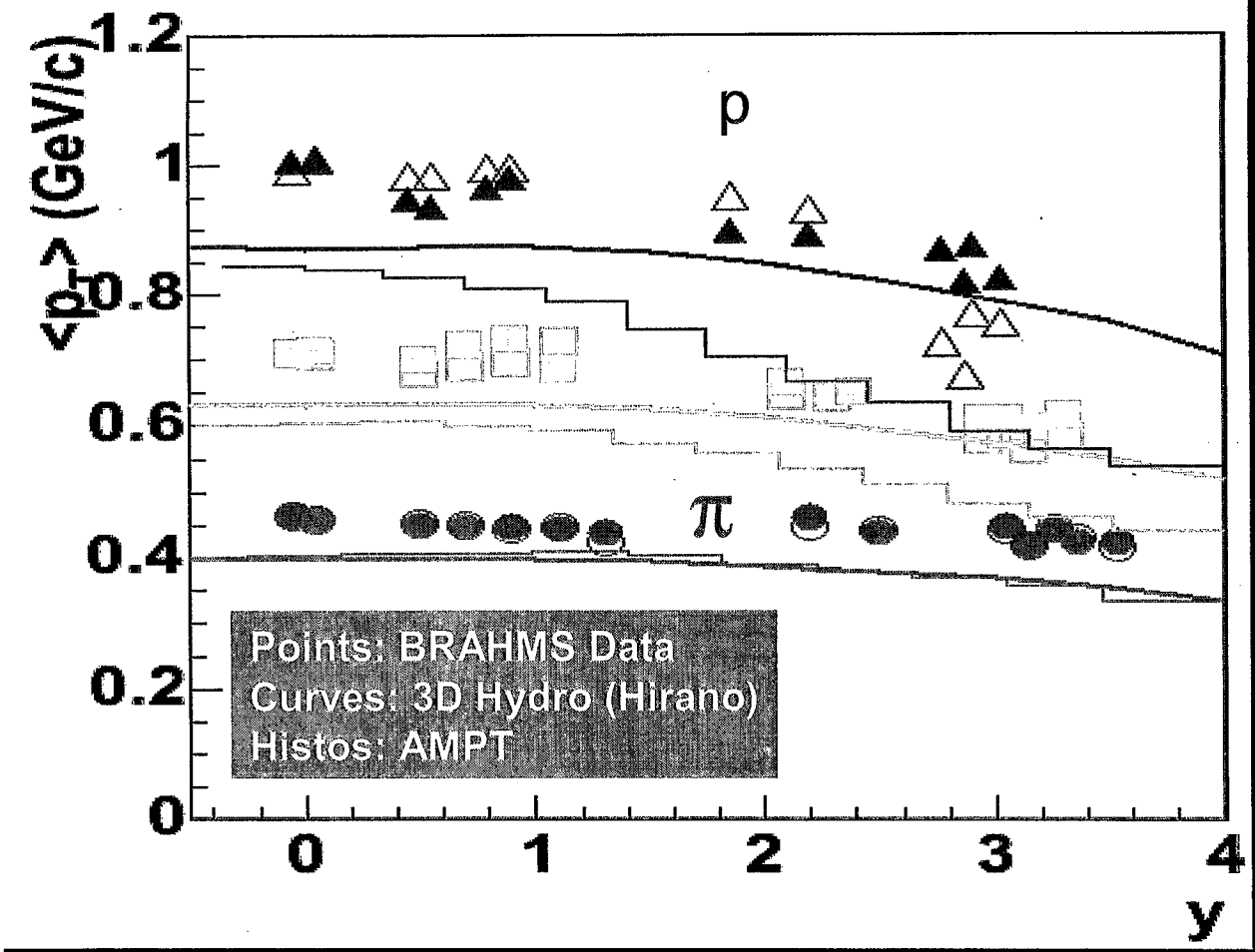
ENERGY DEPENDENCE

At y = 0, ratios converge to ~ 15 %

Over the full phase space
$K^+/\pi^+ = 16.6 \pm 1.5$ % (syst)
$K^-/\pi^- = 13.7 \pm 2.0$ % (syst)

Why this behavior ?
Net-Kaon distribution evolves like net-proton

Transverse Flow...

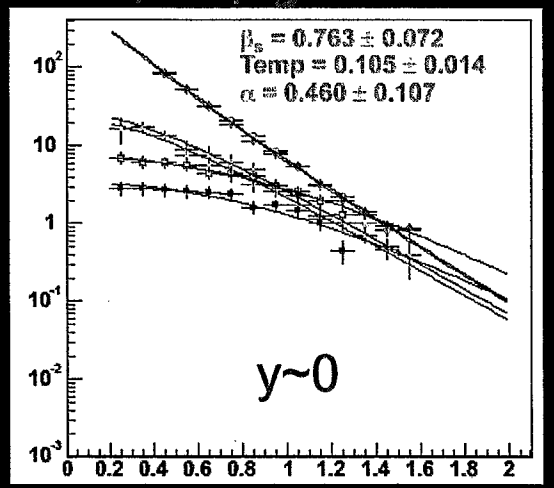


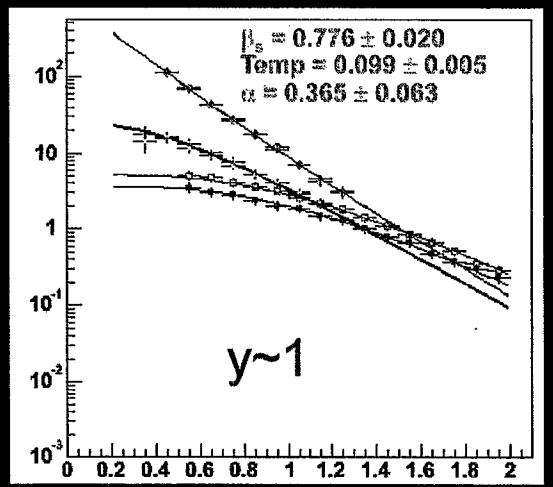
Spectra with BW Fits at y~0,1,2,3

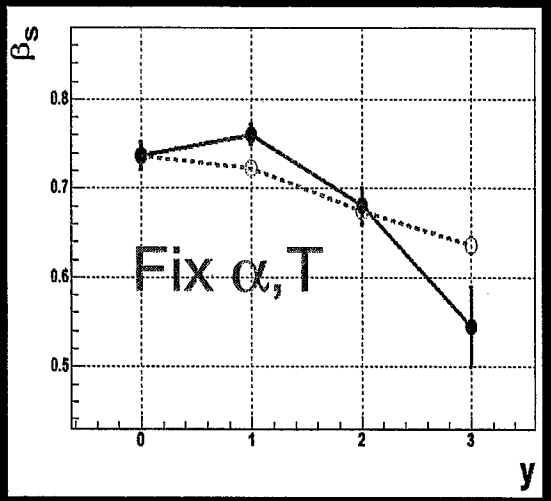
(T, β_s, α in the fit R_{max}=13fm)

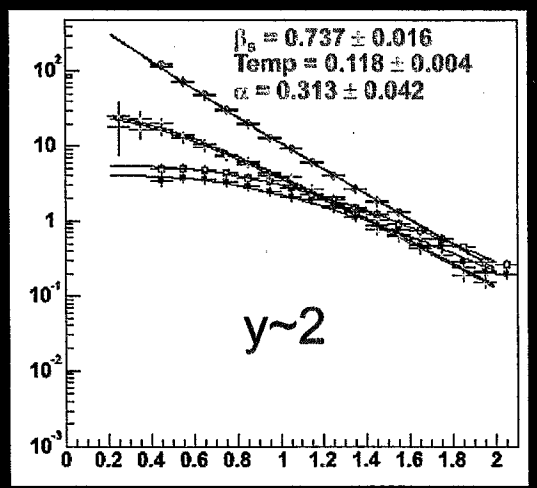
BRAHMS

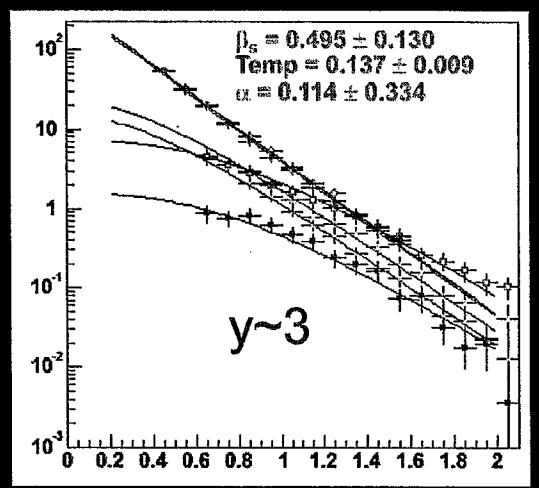
BRAHMS Preliminary

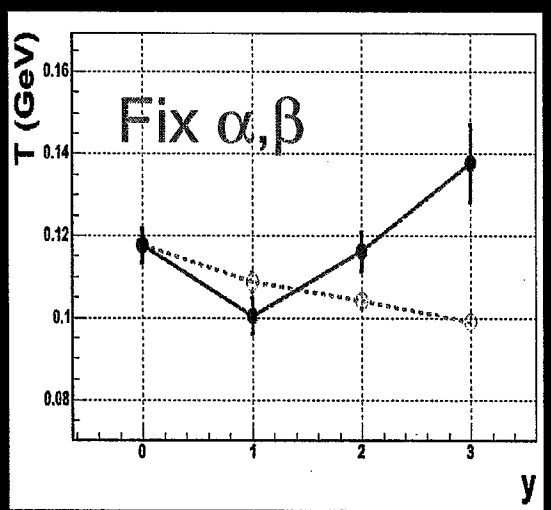






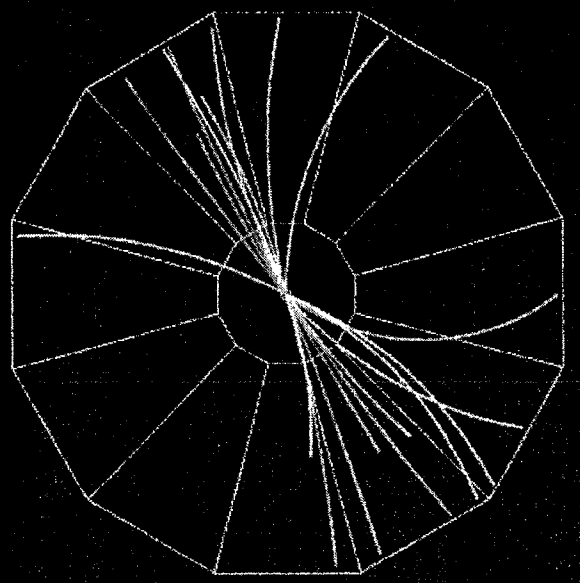






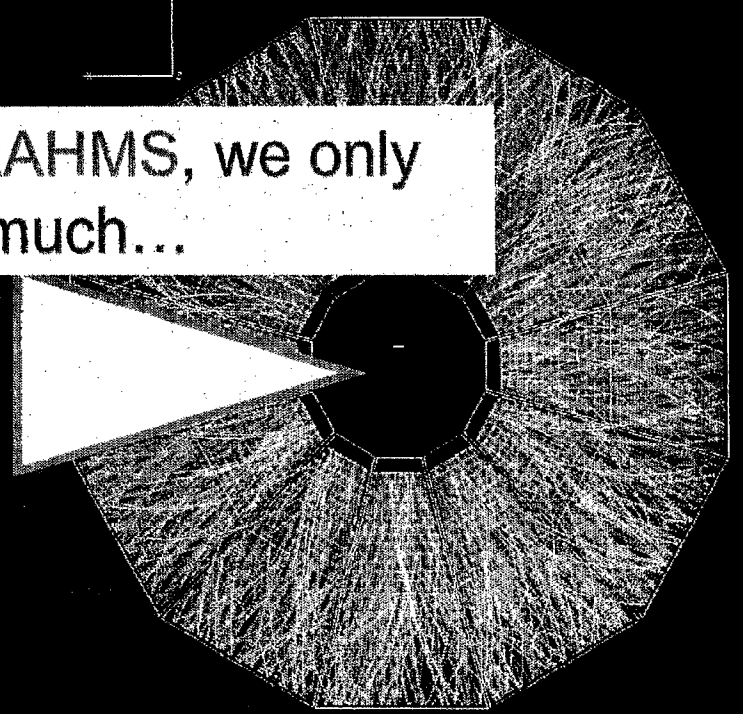
Jets at RHIC

Find this…….in this



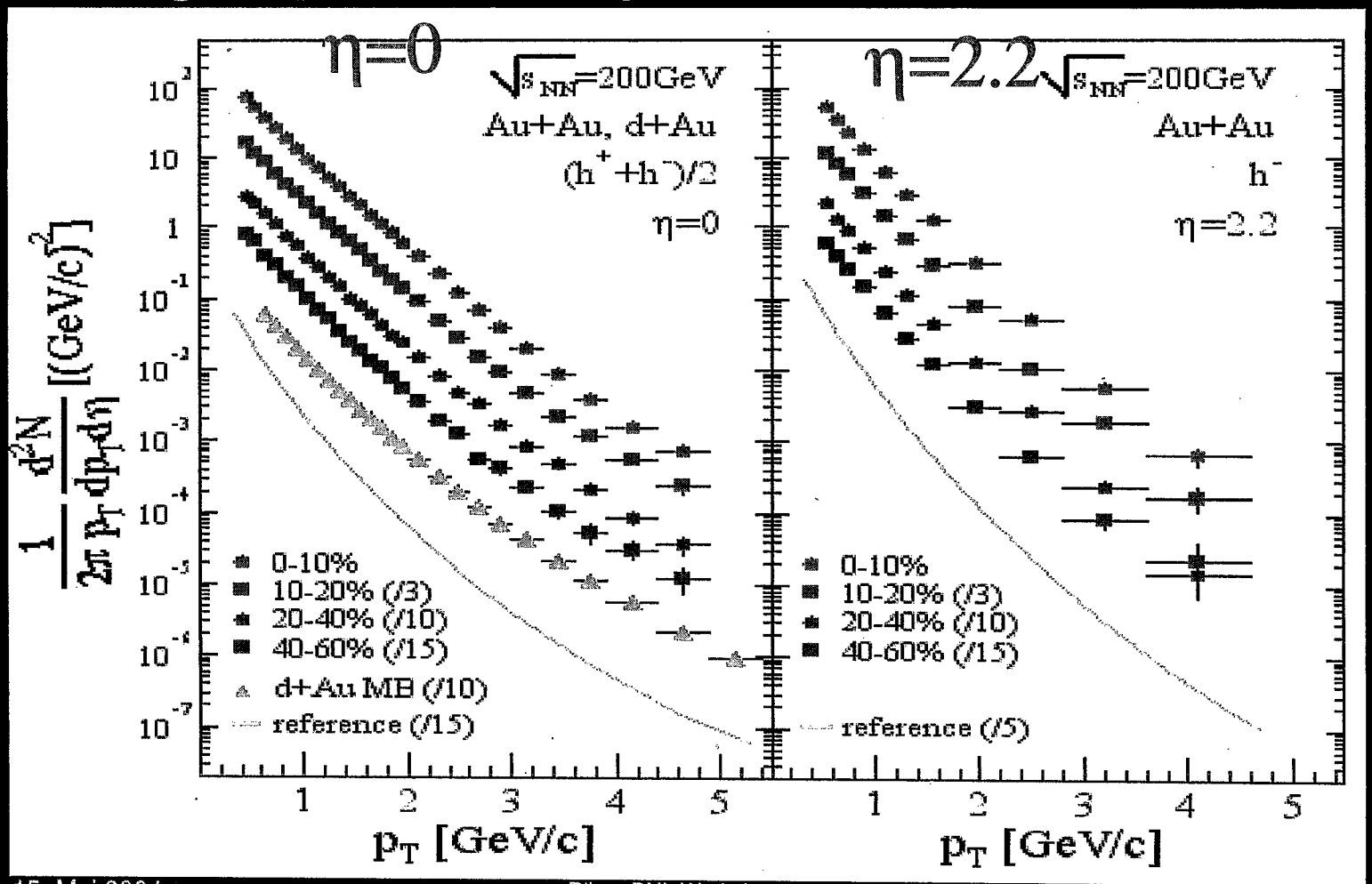
p+p →jet+jet
(STAR@RHIC)

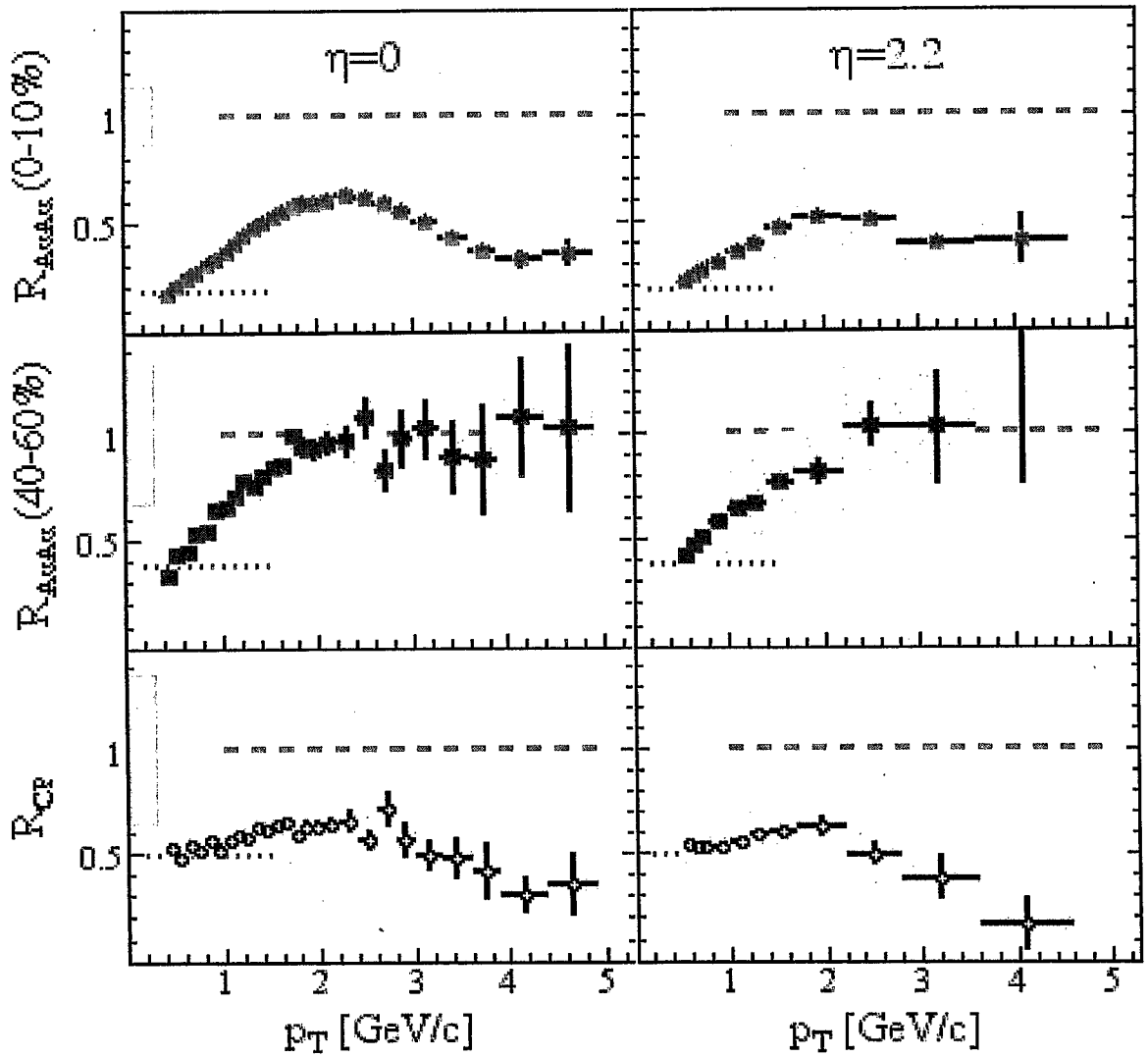
And, in BRAHMS, we only "see" this much…



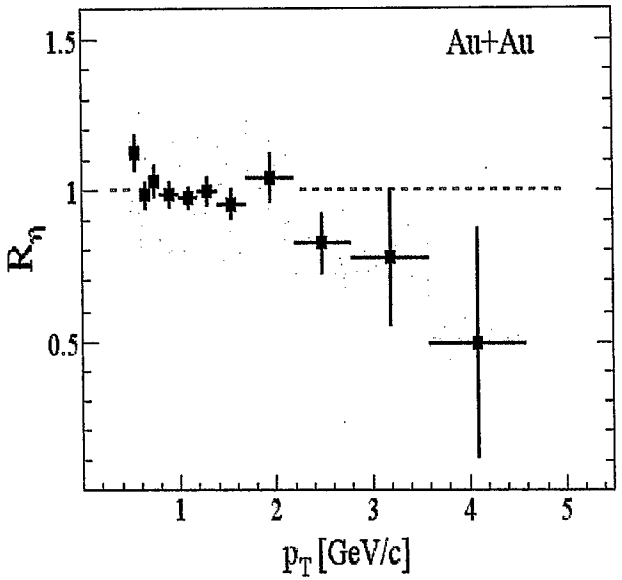
Au+Au →???
(STAR@RHIC)

Characterize "high" p_T by single particle spectra



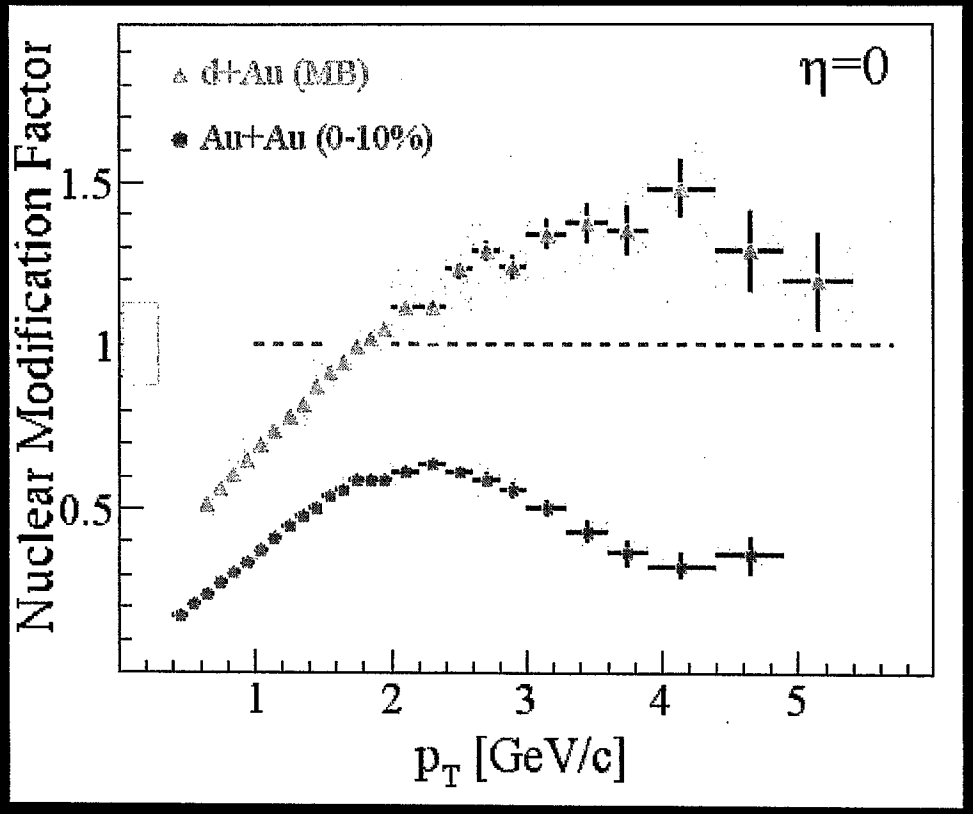


To look at 'only' data, form ratio $R_\eta = R_{cp}(\eta=2.2)/R_{cp}(\eta=0)$



Arsene et al. PRL2003

d+Au Nuclear Modification η =0

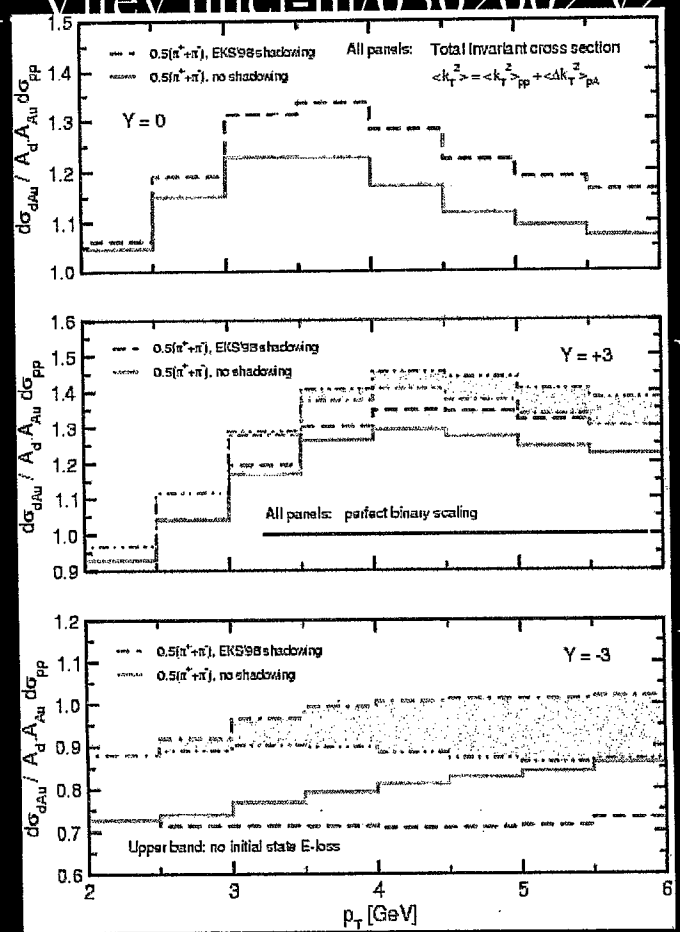


High p_T enhancement observed in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV.

Comparing Au+Au to d+Au
⇒ strong effect of dense medium

Predictions from theory

I. Vitev nucl-th/0302002 v2

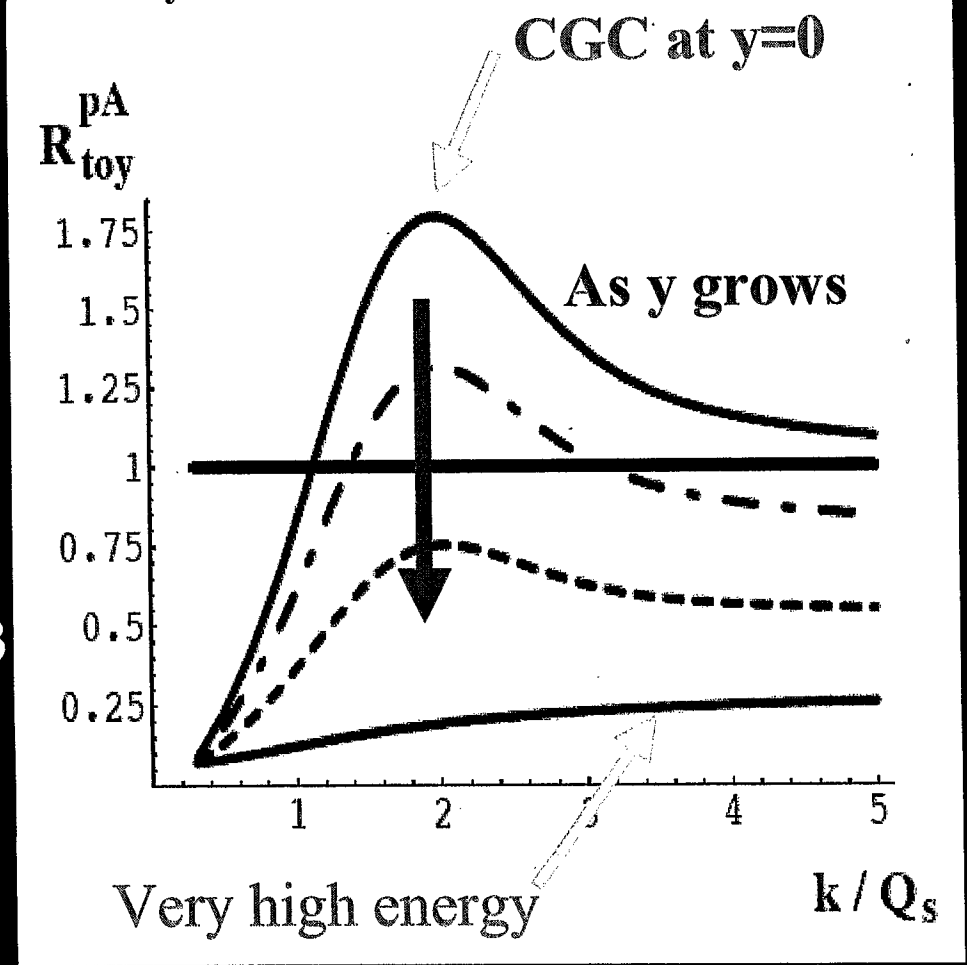


Y=3

Y=-3

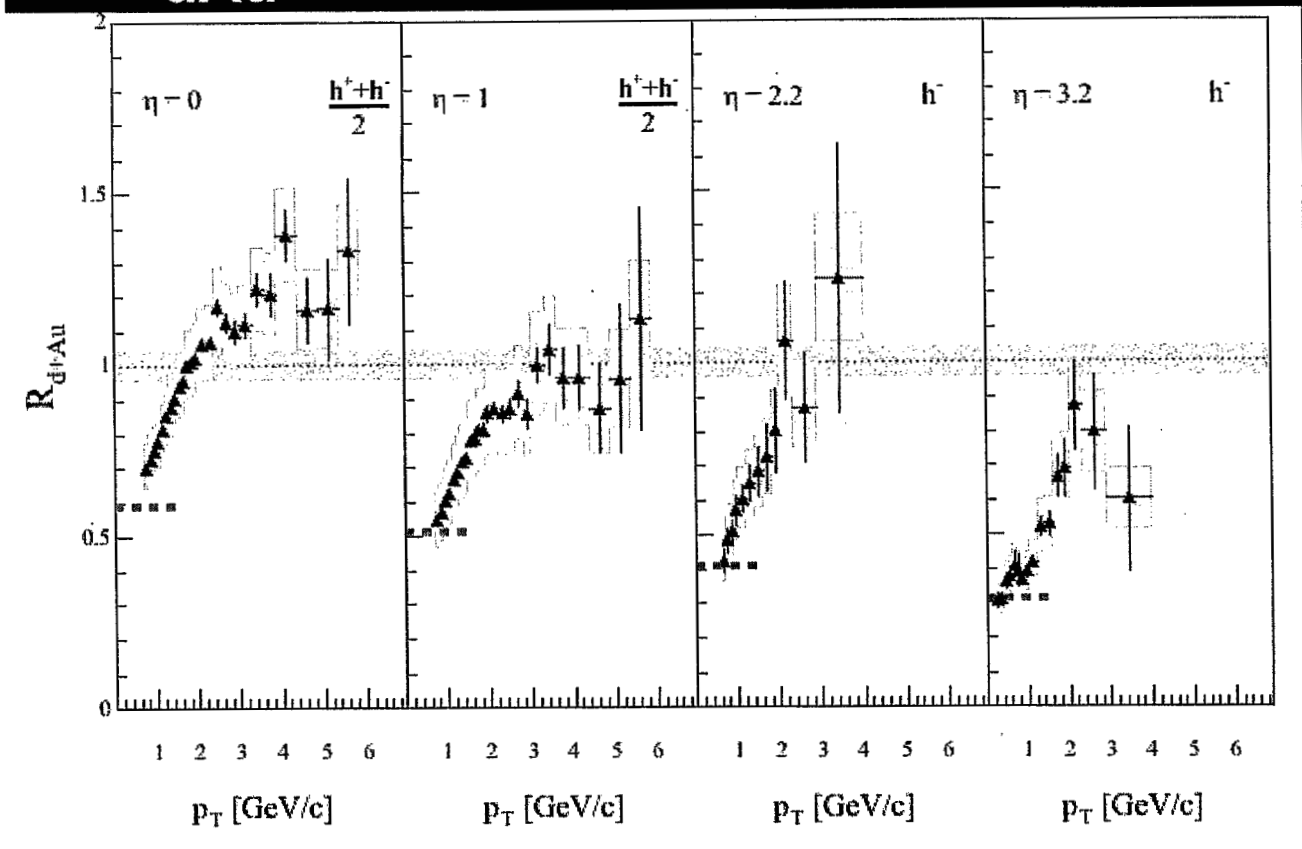
D. Kharzeev et al.

Phys.Rev.D68:094013,2003



R_{dAu}

BRAHMS



$$R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{dAu}/dp_T d\eta}{d^2N^{pp}_{inel}/dp_T d\eta}$$

where $\langle N_{coll} \rangle = 7.2 \pm 0.3$

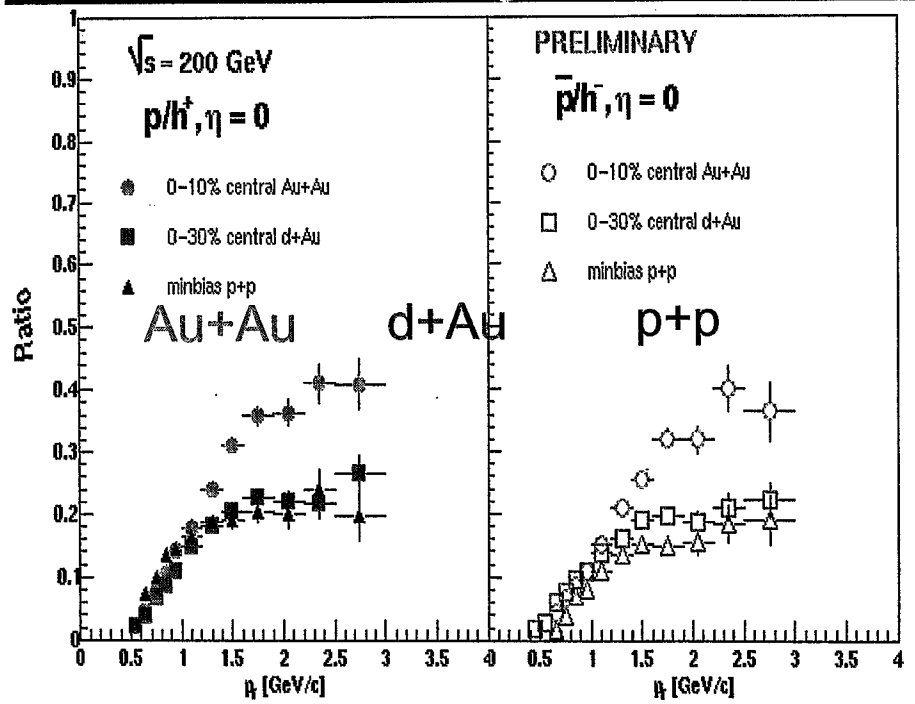
Cronin like enhancement at η=0.

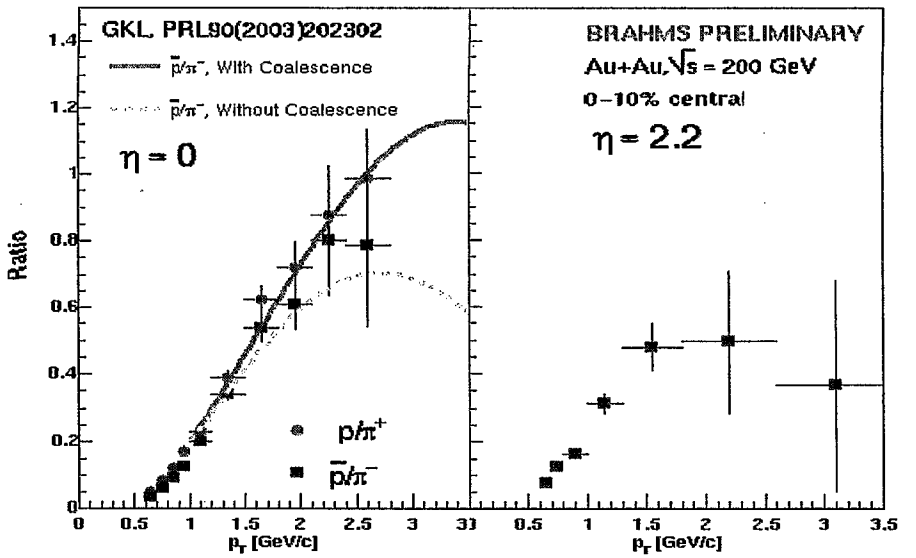
Clear suppression as η changes up to 3.2

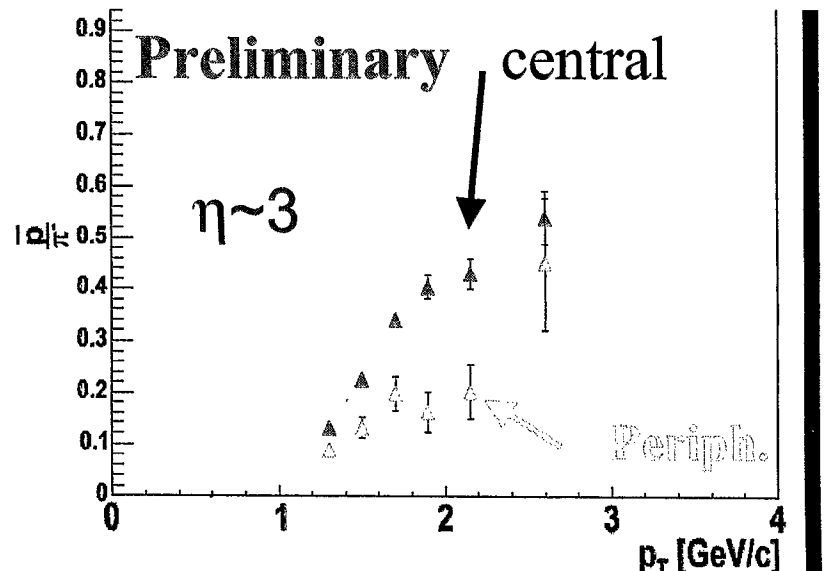
Same ratio made with dn/dη follows the low p_T R_{dAu}

pbar/π^- ratio probes extent of new medium in y

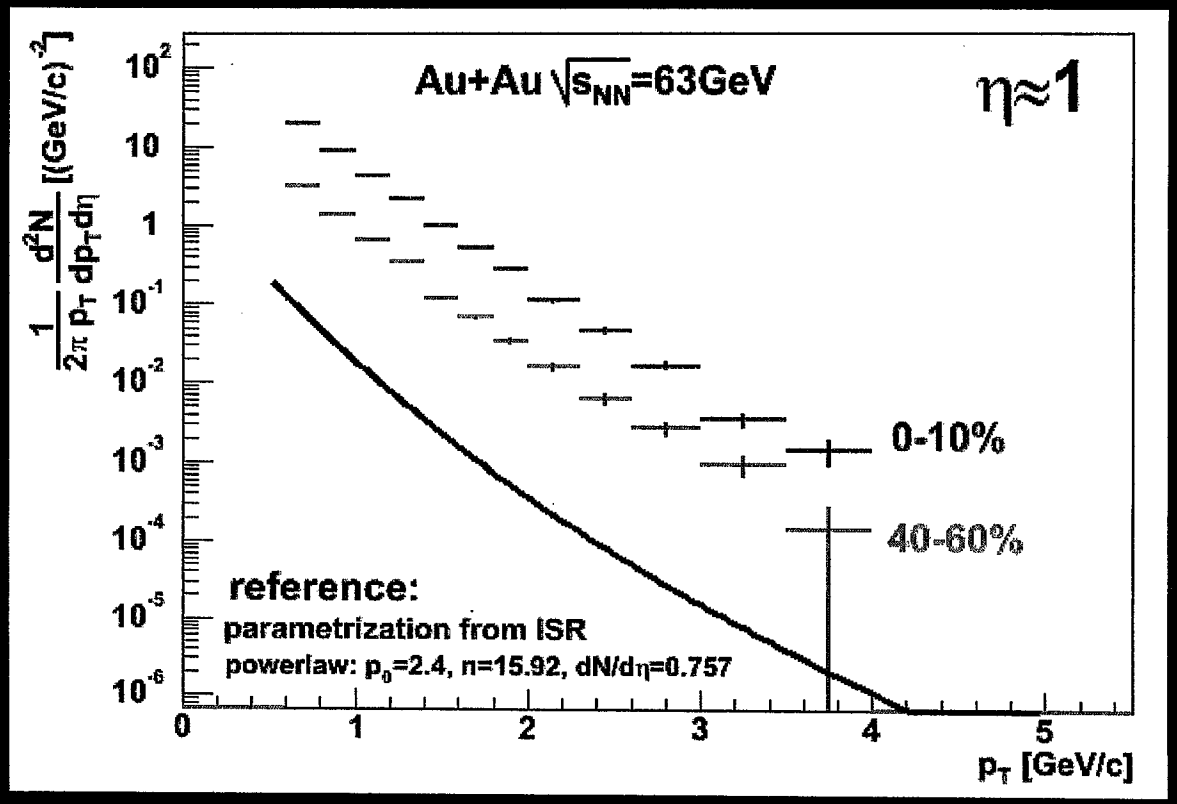
BRAHMS

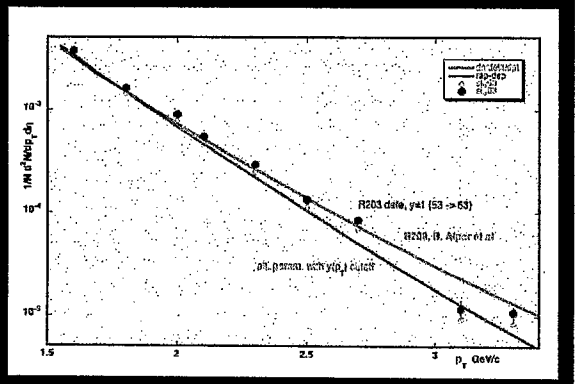




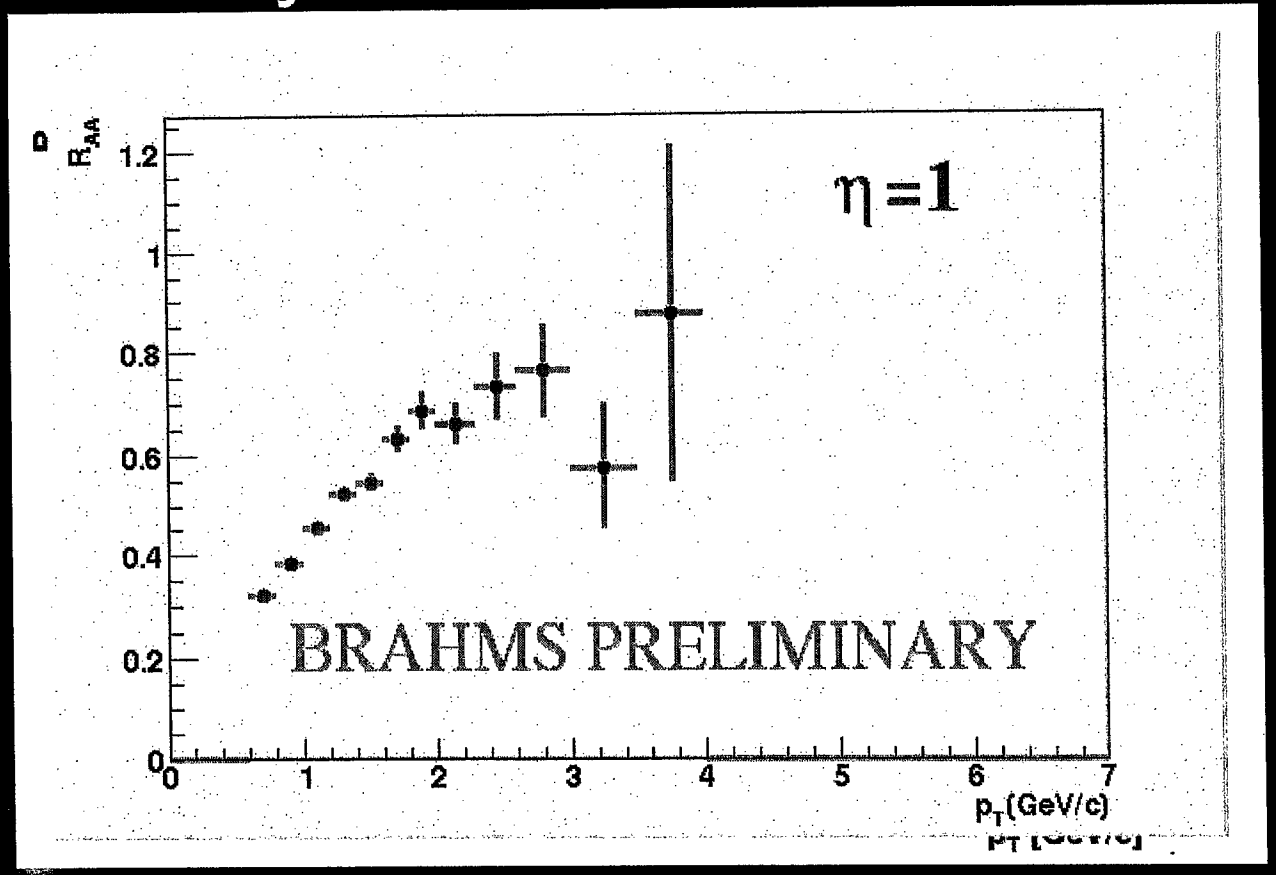


Preliminary results from 63GeV





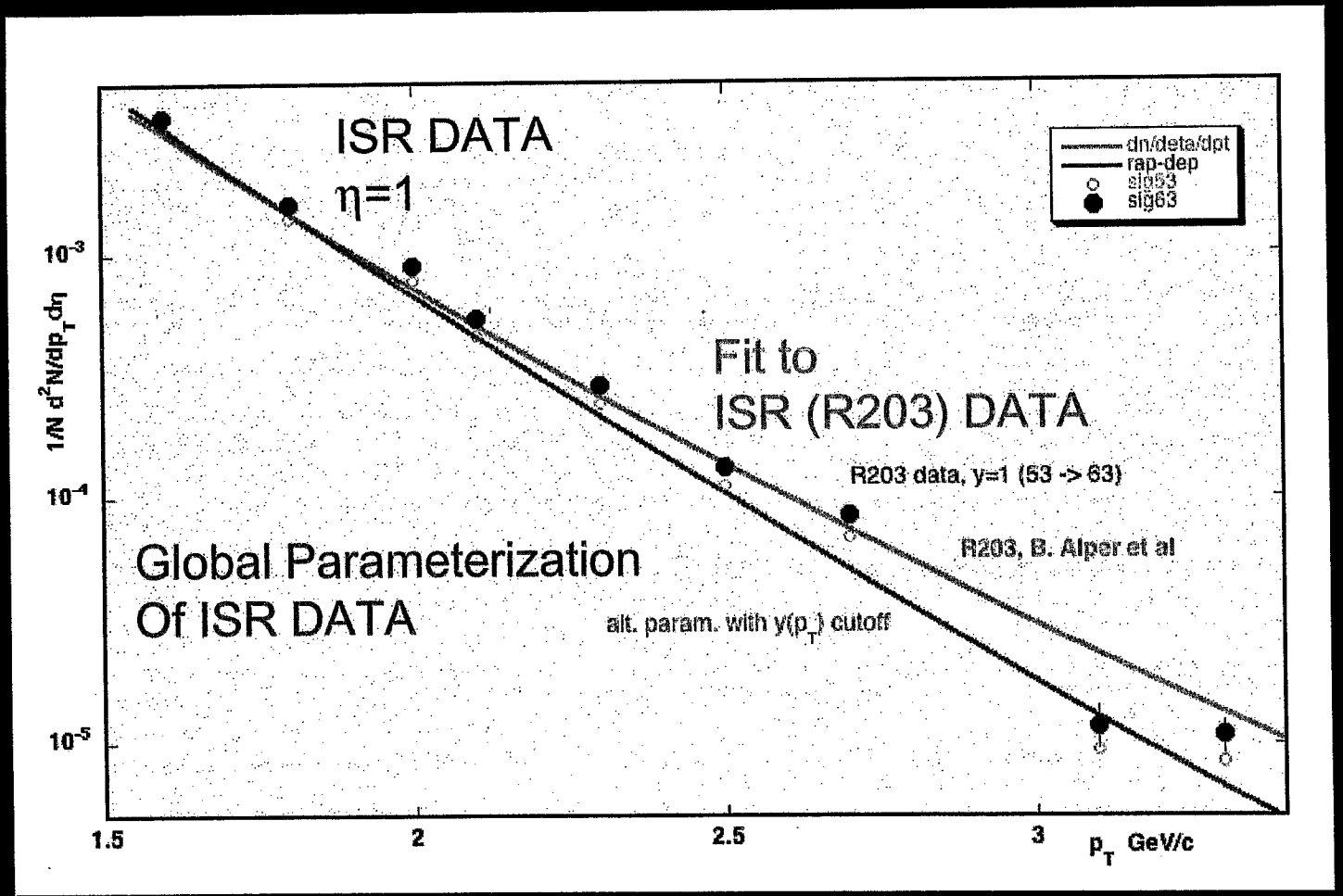
Preliminary results from 63GeV



Conclusions

- High energy density
- Gluon saturation describes data, though not uniquely
- 70% of energy available for particle production
- Source (nearly) same over >1 unit rapidity
- High p_T suppression persists to high y in Au+Au
- Grows vs y in d+Au
- Lots left to do…

Reference Spectrum



PHENIX

PHENIX Highlights and Discoveries

W.A. Zajc
for the PHENIX Collaboration

(this talk available at http://www.phenix.bnl.gov/phenix/WWW/publish/zajc/sp/presentations/RBRC/)

15-May-04

PHENIX

Subject

- A talk on

  "on the progress made during the first three years in the search for the QGP at RHIC, and on important open questions."

- which is ~ same as

  a report on
  our ongoing White Paper process
  and
  the current status of our discussions

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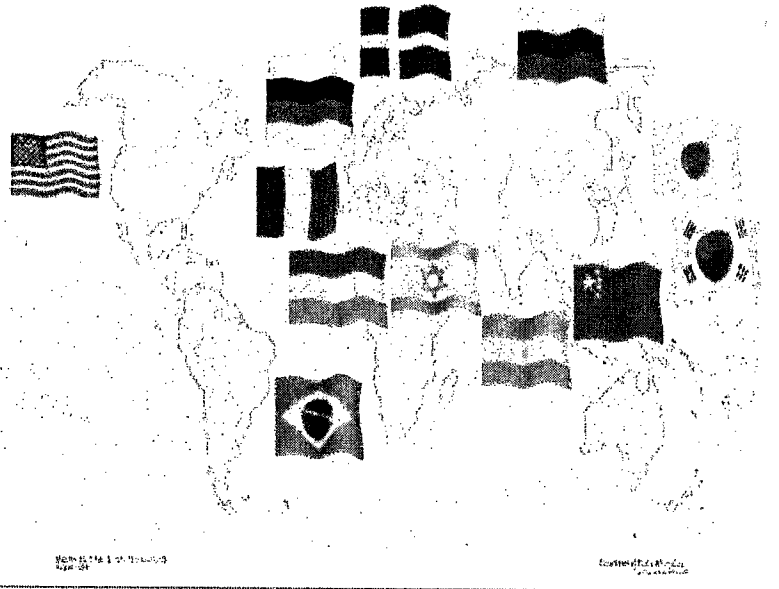
Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	University of Tokyo, Bunkyo-ku, Tokyo
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund



12 Countries; 57 Institutions; 460 Participants*

USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, Urbana-Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

*as of July 2002

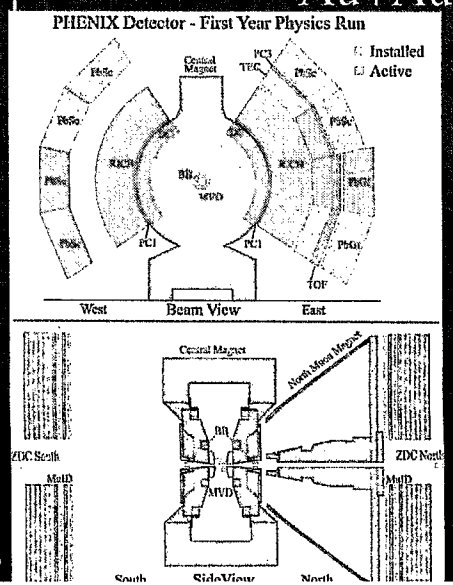
White Paper Writing Group

- Charged with assessing the current PHENIX (and RHIC) data set and its implications for the discovery of a new state of matter.
- Members:
  - Y. Akiba (chair)
  - S. Bathe (scientific secretary)
  - B. Cole
  - S. Esumi
  - B. Jacak
  - J. Nagle
  - C. Ogilvie
  - R. Seto
  - P. Stankus
  - M. Tannenbaum
  - I. Tserruya
- *In this short talk, I will not do justice to their detailed and ongoing efforts.*

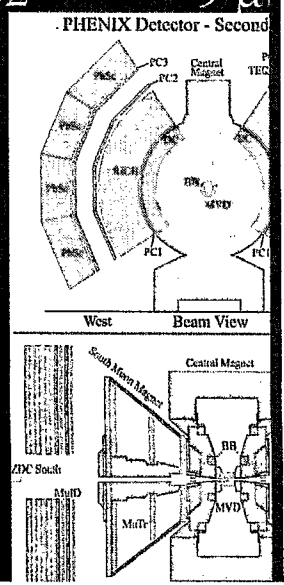
Run-1 to Run-4 Capsule History

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μ			
		Au+Au	62	9 μ			

Run-1



Run-2



PHENIX Successes (to date) based on ability to deliver physics at ~all scales:

barn : Multiplicity (Entropy)

millibarn: Flavor yields (temperature)

microbarn: Charm (transport)

nanobarn: Jets (density)

picobarn: J/Psi (deconfinement ?)

15-May-04

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Run-1 Publications

- "Centrality dependence of charged particle multiplicity in Au-Au collisions at $\sqrt{s_{NN}}$ = 130 GeV", PRL 86 (2001) 3500
- "Measurement of the midrapidity transverse energy distribution from $\sqrt{s_{NN}}$ = 130 GeV Au-Au collisions at RHIC", PRL 87 (2001) 052301
- "Suppression of hadrons with large transverse momentum in central Au-Au collisions at $\sqrt{s_{NN}}$ = 130 GeV", PRL 88, 022301 (2002).
- "Centrality dependence of $\pi^{+/-}$, $K^{+/-}$, p and pbar production at RHIC," PRL 88, 242301 (2002).
- "Transverse mass dependence of the two-pion correlation for Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV", PRL 88, 192302 (2002)
- "Measurement of single electrons and implications for charm production in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV", PRL 88, 192303 (2002)
- "Net Charge Fluctuations in Au+Au Interactions at $\sqrt{s_{NN}}$ = 130 GeV," PRL 89, 082301 (2002)
- "Event-by event fluctuations in Mean p_T and mean e_T in sqrt(s_NN) = 130GeV Au+Au Collisions" Phys. Rev. C66, 024901 (2002)
- "Flow Measurements via Two-particle Azimuthal Correlations in Au + Au Collisions at $\sqrt{s_{NN}}$ = 130 GeV", PRL 89, 212301 (2002)
- "Measurement of the lambda and lambda^bar particles in Au+Au Collisions at $\sqrt{s_{NN}}$ =130 GeV", PRL 89, 092302 (2002)
- "Centrality Dependence of the High pT Charged Hadron Suppression in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV", Phys. Lett. B561, 82 (2003)
- "Single Identified Hadron Spectra from $\sqrt{s_{NN}}$ = 130 GeV Au+Au Collisions", to appear in Physical Review C, nucl-ex/0307010

15-May-04

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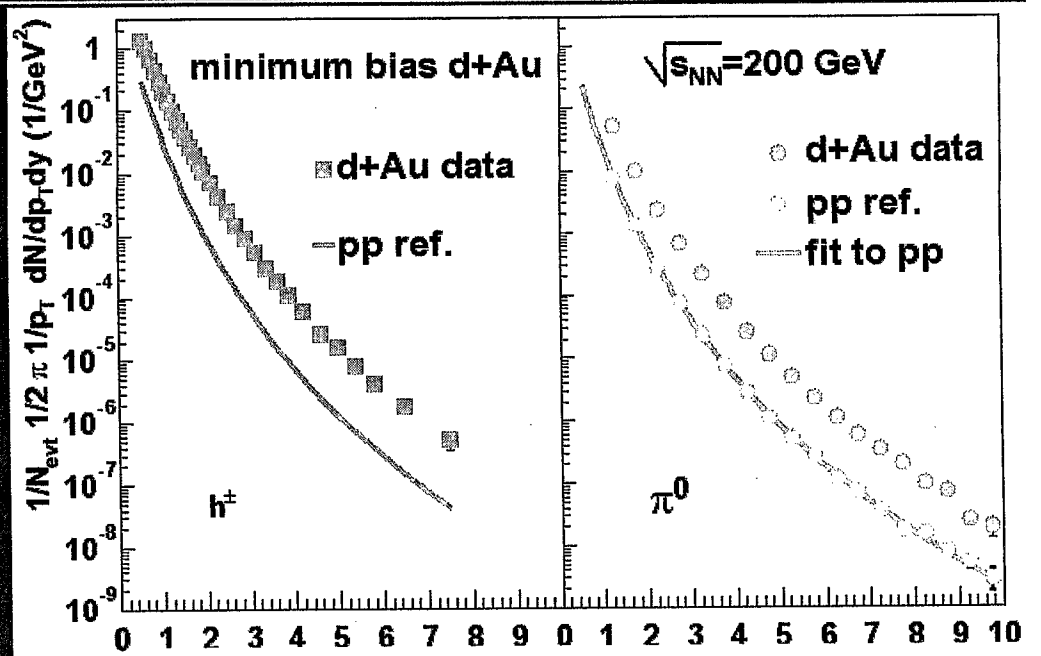
Run-2 Publications

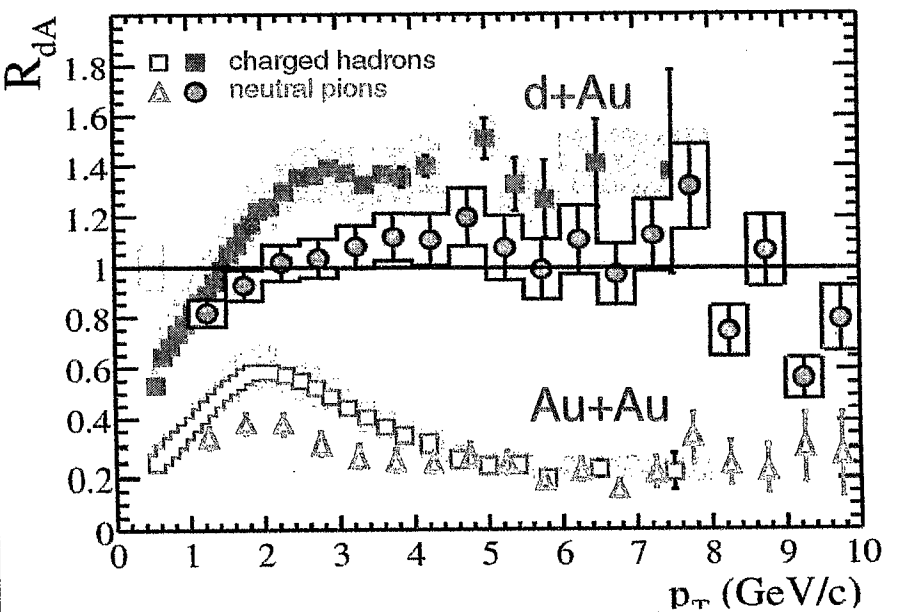
- "Suppressed π^0 Production at Large Transverse Momentum in Central Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV" , PRL 91, 072301 (2003)
- "Scaling Properties of Proton and Anti-proton Production in $\sqrt{s_{NN}}$ = 200 GeV Au+Au Collisions", accepted for publication in PRL 21 August 2003, nucl-ex/0305036
- "J/Psi Production in Au-Au Collisions at $\sqrt{s_{NN}}$ =200 GeV at the Relativistic Heavy Ion Collider", accepted for publication in Phys. Rev. C on 6 September 2003, nucl-ex/0305030
- "Elliptic Flow of Identified Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV" , accepted for publication in PRL 9 September 2003, nucl-ex/0305013
- "Midrapidity Neutral Pion Production in Proton-Proton Collisions at $\sqrt{s}$ = 200 GeV", accepted for publication in PRL on 19 September 2003, hep-ex/0304038
- "Identified Charged Particle Spectra and Yields in Au-Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV", Phys. Rev. C 69, 034909 (2004)
- "J/psi production from proton-proton collisions at $\sqrt{s}$ = 200 GeV", submitted to PRL July 8 2003, hep-ex/0307019
- "High-pt Charged Hadron Suppression in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 Gev", submitted to Physical Review C on 11 August 2003, nucl-ex/0308006
- "Bose-Einstein Correlations of Charged Pion Pairs in Au+Au Collisions at $\sqrt{s_{NN}}$ =200 GeV" Submitted to PRL, Jan. 05, 2004, nucl-ex/0401003

Run-3 Publications

- "Absence of Suppression in Particle Production at Large Transverse Momentum in $\sqrt{s_{NN}}$ = 200 GeV d+Au Collisions", PRL 91, 072303 (2003)



- PID-ed particles (π^0's) out to the highest p_T's PHENIX's unique contribution to the June "press event"



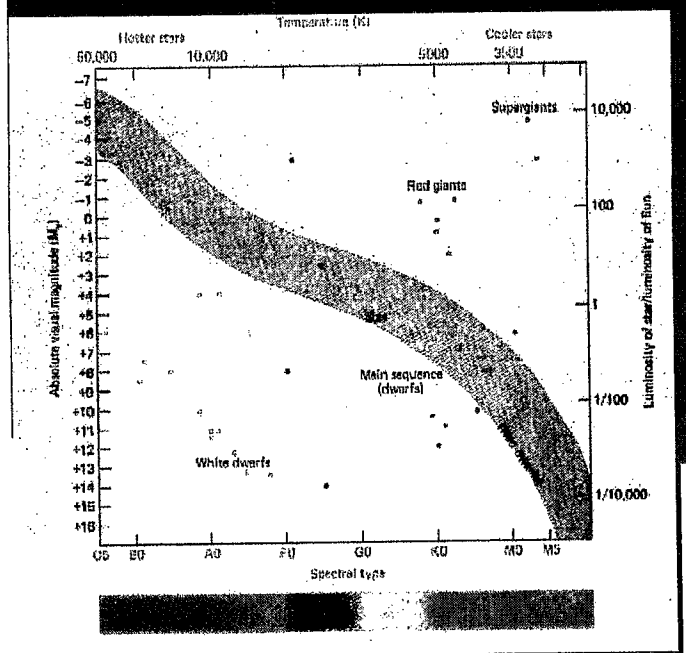
PHENIX

Accomplishments and Discoveries

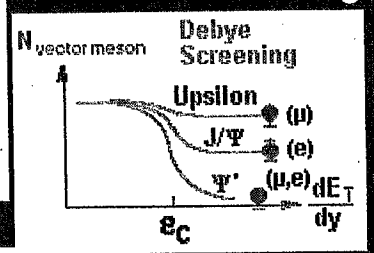
- First measurement of the dependence of the charged particle pseudo-rapidity density and the transverse energy on the number of participants in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV.
- Discovery of high p_T suppression in π^0 and charged particle production in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV and a systematic study of the scaling properties of the suppression; extension of these results to much higher transverse momenta in Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV
- (Co)-Discovery of absence of high p_T suppression in d+Au collisions at s_{NN} =200~GeV.
- Discovery of the anomalously large proton and anti-proton yields at high transverse momentum in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV through the systematic study of $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ spectra; measurement of Λ and anti-Λ in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV ; study of the scaling properties of the proton and anti-proton yields in Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV.
- Measurement of HBT correlations in $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs in Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV , establishing the ``HBT puzzle" of $R_{OUT} \sim R_{SIDE}$ extends to high pair momentum; extension of these results to $\sqrt{s_{NN}}$ = 200 GeV
- First measurement of single electron spectra in Au+Au collisions at $\sqrt{s_{NN}}$ =130~GeV, suggesting that charm production scales with the number of binary collisions.
- Sensitive measures of charge fluctuations and fluctuations in mean p_T and transverse energy per particle in Au+Au collisions at at $\sqrt{s_{NN}}$ =130~GeV.
- Measurements of elliptic flow for charged particles from Au+Au collisions at $\sqrt{s_{NN}}$ =130~GeV and identified charged hadrons from Au+Au collisions at $\sqrt{s_{NN}}$ =200~GeV.
- Extensive study of hydrodynamic flow, particle yields, ratios and spectra from Au+Au collisions at $\sqrt{s_{NN}}$ =130 GeV and 200 GeV.
- First observation of J/Ψ production in Au+Au collisions at $\sqrt{s_{NN}}$ =200~GeV.
- Measurement of crucial baseline data on π^0 spectra and J/Ψ production in p+p collisions at $\sqrt{s_{NN}}$ =200~GeV.

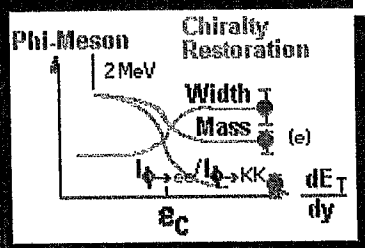
15-May-04

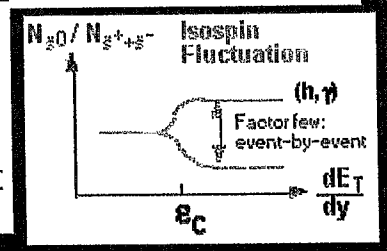
Pre-History of Pre-Discoveries

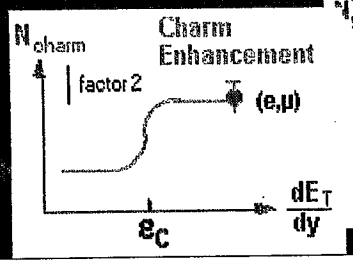


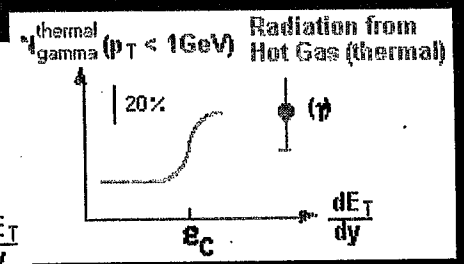
- T.D. Lee, circa 1984:
  - Explicit analogy with Hertzsprung-Russell diagram
- PHENIX, circa 1994:
  - A comprehensive detector devoted to study of hadronic and leptonic observables
  - Explicit consideration given to characterization of all data versus some global control parameter











15-May-04

PHENIX, circa 2004

- 24 papers, > 1000 citations
- Comprehensive study of hadronic and leptonic observables (consistent with available luminosity)
- Essentially all results studied as function of control parameters
  - N_{part} and/or N_{coll} extracted via
  - 'Glauber modeling'

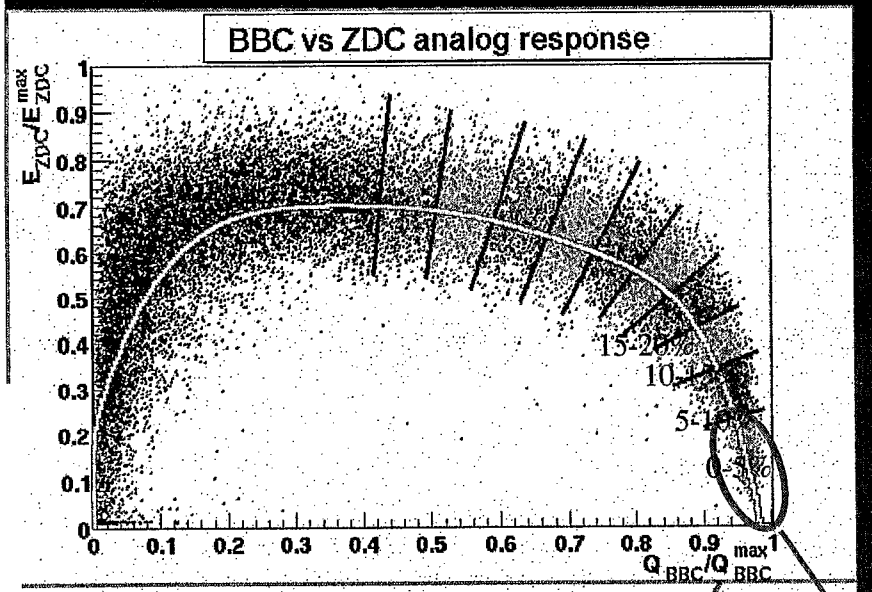
    see, for example,

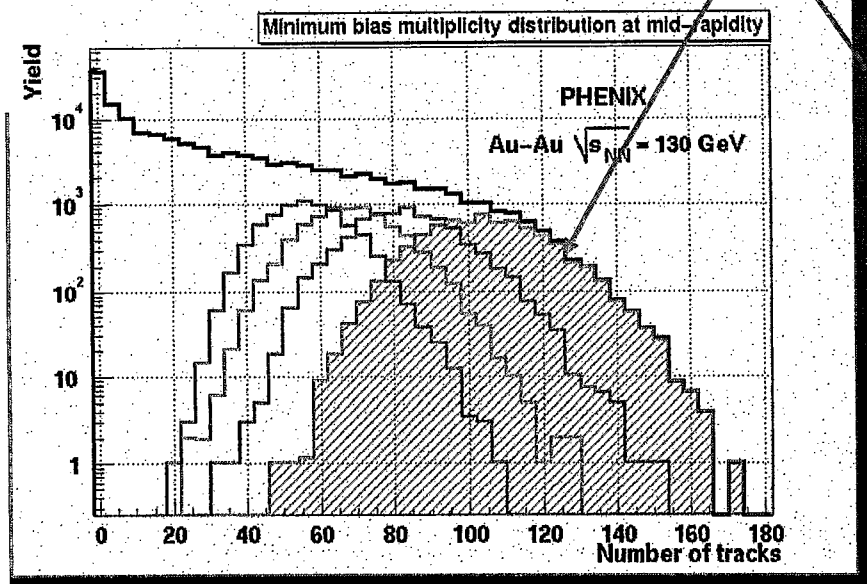
    D. Kharzeev and J. Raufeisen, PASI proceedings,

    P. Kolb *et al.*, Nucl.Phys.A696, 197, (2001)
- The first "discovery" at RHIC was the development of a technology that permits experimental extraction of these crucial parameters.

15-May-04

Determining N_{part} and N_{coll}





Use combination of

- Zero Degree Calorimeters
- Beam-Beam Counters

to define centrality classes which are then used together with 'Glauber modeling' to extract N_{part} and Ncoll

(~ essentially uniform definitions between 4 experiments)

determines Multiplicity vs. Centrality

i.e

$dN_{ch}/d\eta$ vs. N_{part}

which is presented as

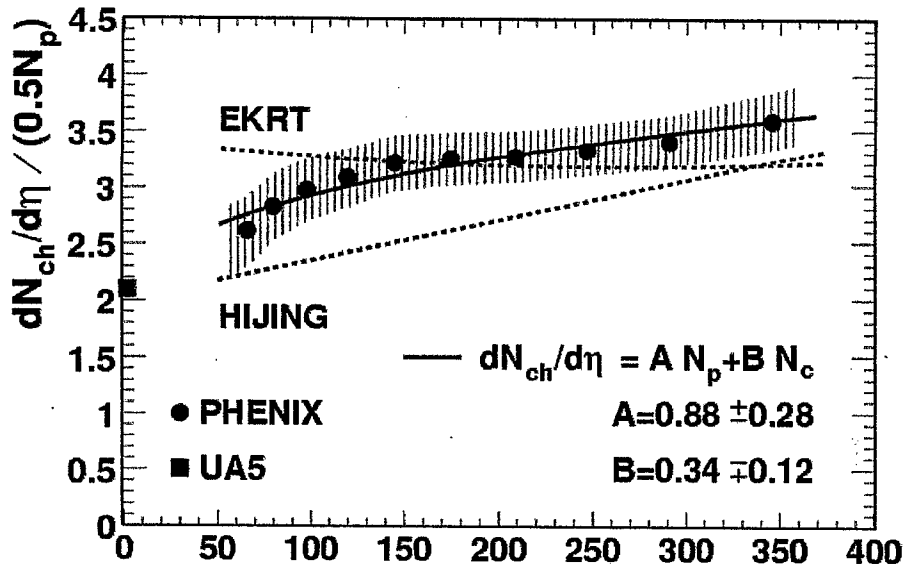
"specific particle production"

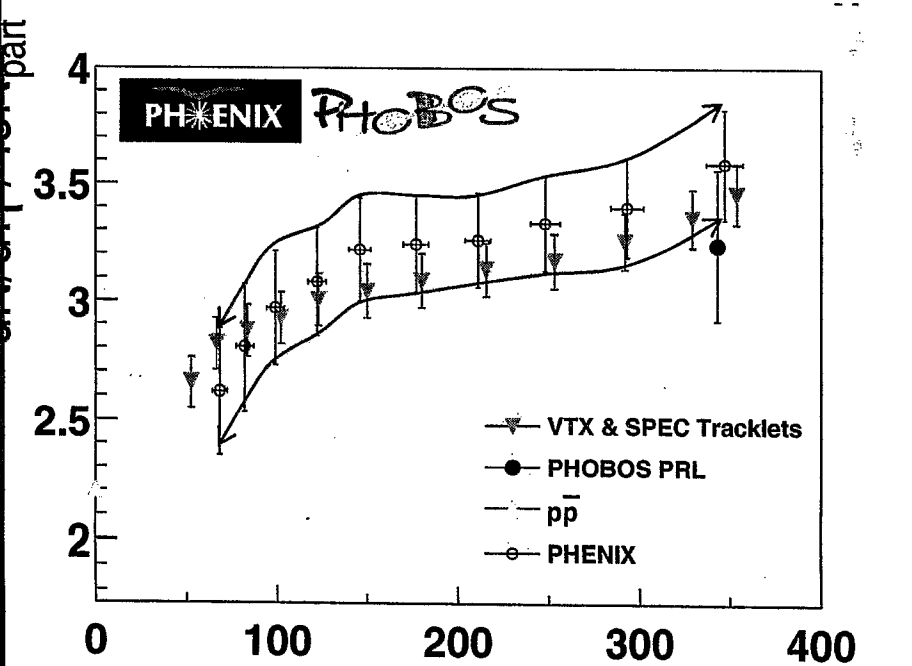
multiplicity *per N-N collision*

$(dN_{ch}/d\eta) \;/\; (N_{part}/2)$

First PHENIX Paper

- "Centrality dependence of charged particle multiplicity in Au-Au collisions at $\sqrt{s_{NN}}$ = 130 GeV", PRL 86 (2001) 3500
- Systematic study of multiplicity dependence on N_{part} and N_{coll}
- Subsequent interpretation as strong evidence for role of CGC in determining final multiplicity (next slide)



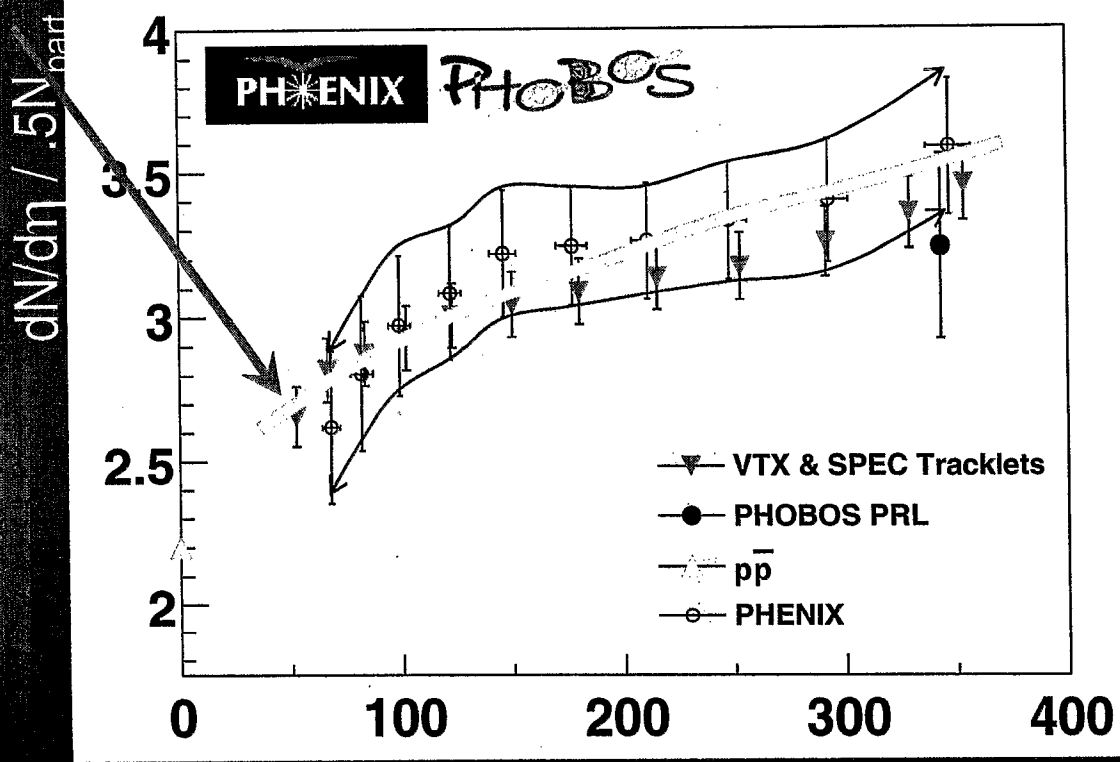


Saturation in Multiplicity

- Large nucleus (A) at low momentum fraction x
  → gluon distribution saturates ~ $1/\alpha_s(Q_s^2)$ with $Q_s^2 \sim A^{1/3}$
- A collision* puts these gluons 'on-shell' $\rho \sim A\, xg(x,Q^2) / \pi R^2$
- Parton-hadron duality maps gluons directly to charged hadrons

$$\Rightarrow \frac{N_{ch}}{A} \sim \frac{1}{\alpha_s(Q_s^2)} \sim \ln\left(\frac{Q_s^2}{\Lambda^2}\right)$$

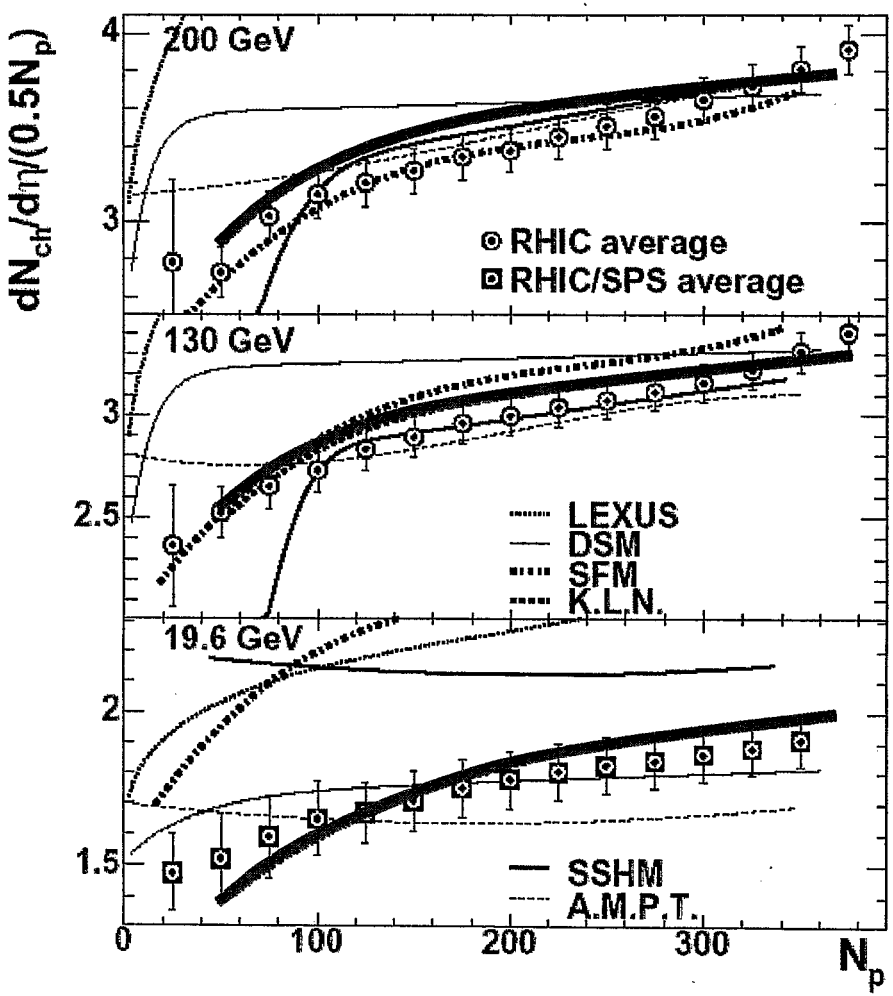
- Each collision varies the *effective* A, i.e, the number of participants N_{PART}



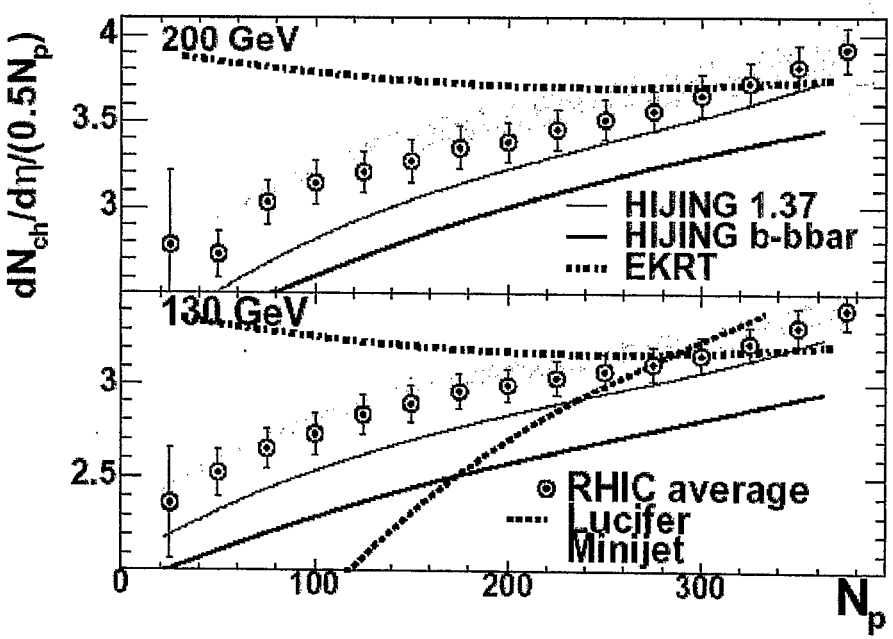
❁ Shattering the 'Color Glass Condensate')

Further developments

- Data now available from 200 and 19 GeV
- Only CGC (Kharzeev, Nardi, Levin) provides consistent description (?!?)

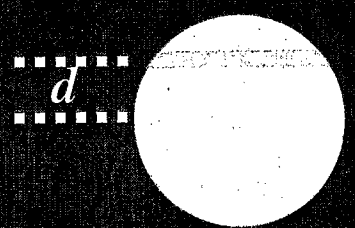


☞ **This important question should be answered crisply so that we have a common basis for understanding this most basic phenomenon!**



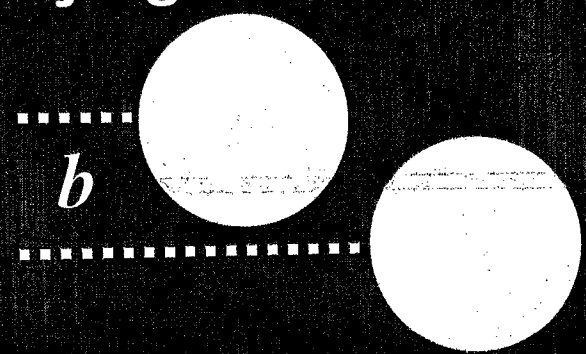
"N_{coll} Scaling"

- Particle production via *rare processes* should scale with N_{coll}, the number of underlying binary nucleon-nucleon collisions



$$T_A(d) = \int \rho(d,z)dz$$

Thickness Function



$$T_{AB}(b) = \int T_A(\vec{s} + \frac{\vec{b}}{2}) T_B(\vec{s} - \frac{\vec{b}}{2}) d\vec{s}$$

Overlap Function

If Nucleus "A" has A constituents and Nucleus "B" has B constituents which interact with cross section σ_{INT} the TOTAL cross section σ_{AB} is then

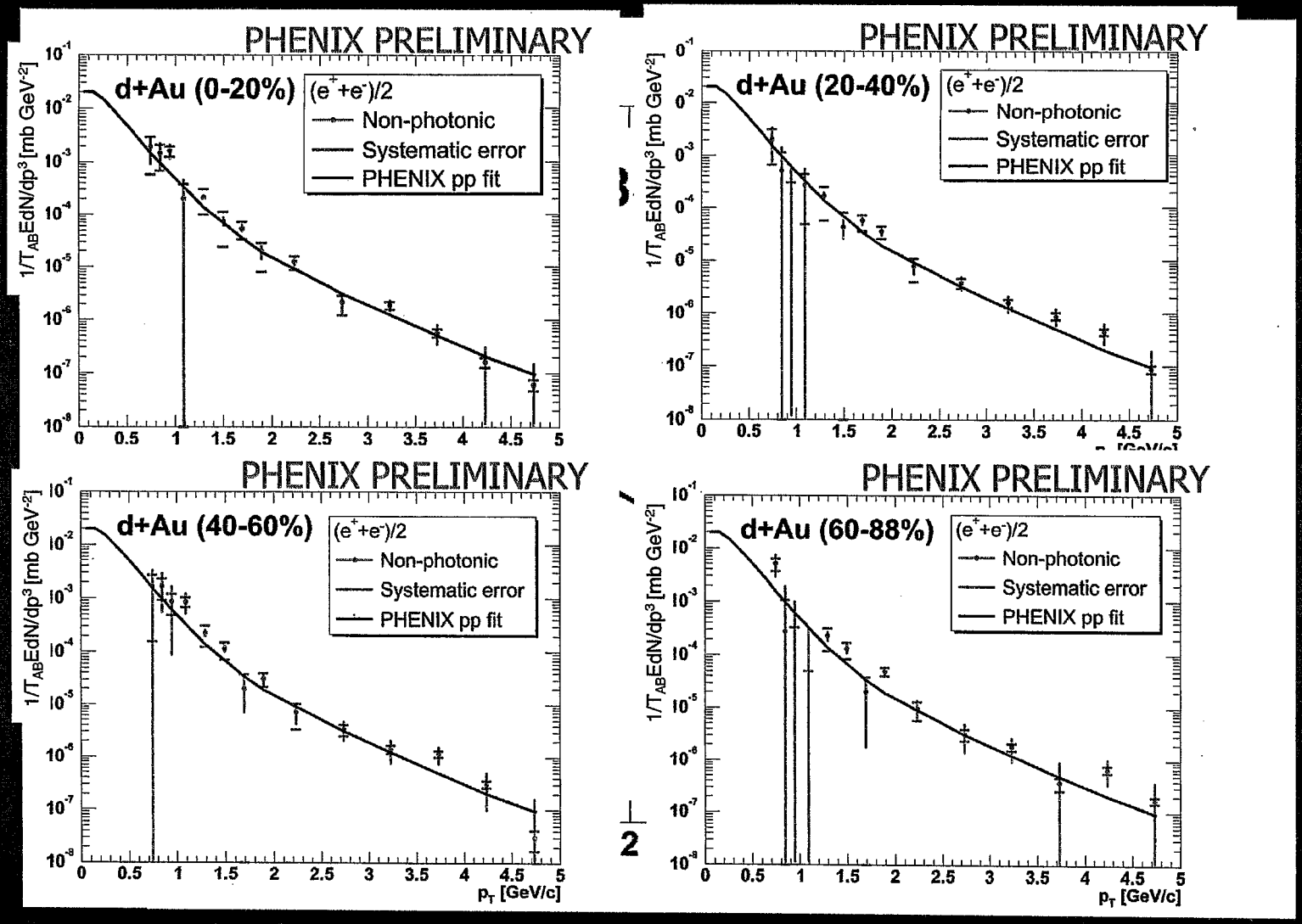
$$\sigma_{AB} = \int d^2b \left[1 - e^{-\sigma_{INT} T_{AB}(b)}\right]$$

$$\rightarrow \approx A \cdot B \times \sigma_{INT} \text{ for "small" } \sigma_{INT}$$

→ Assuming no "collective" effects

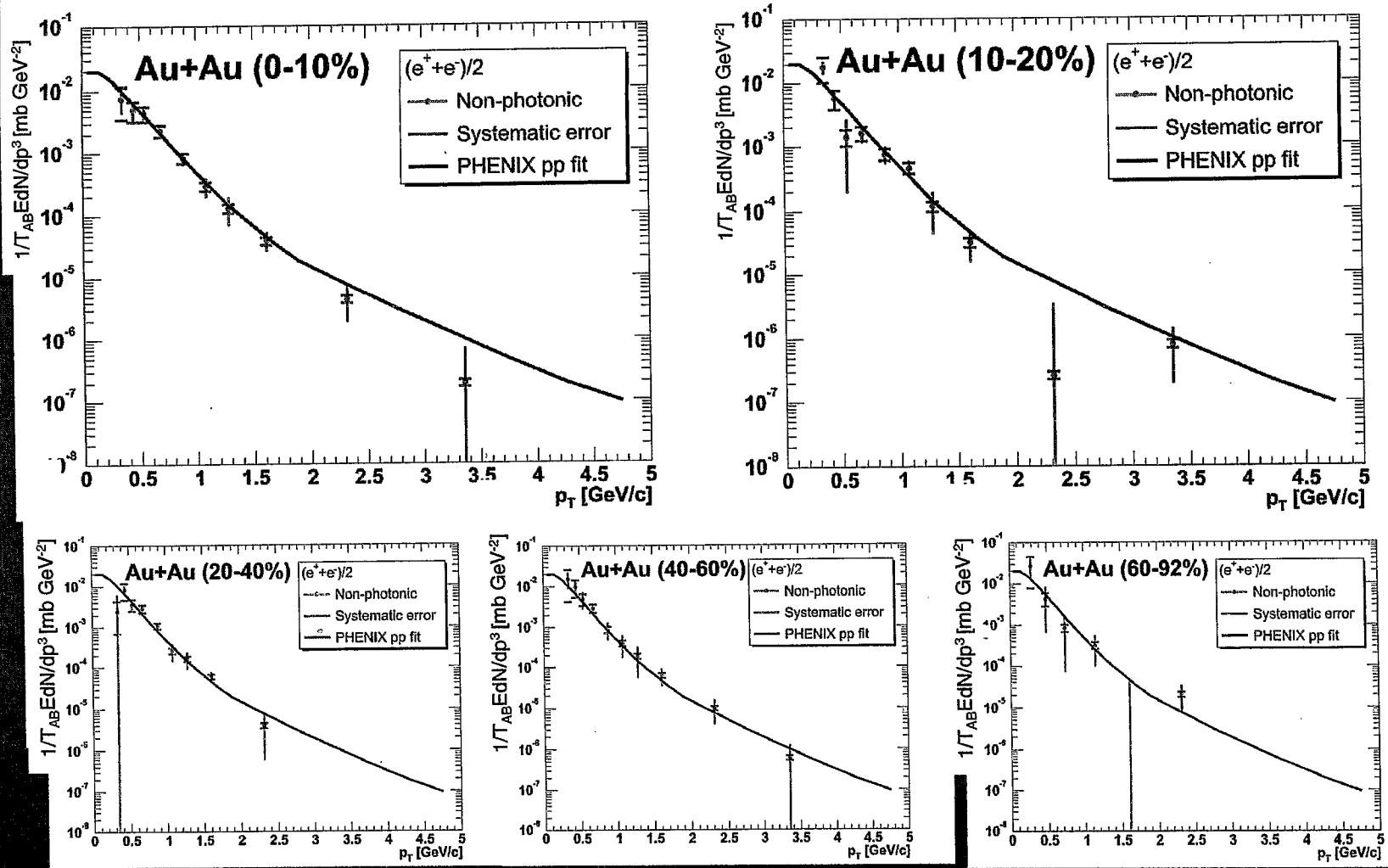
- Test this on various rare processes

N_{coll} Scaling in d+Au



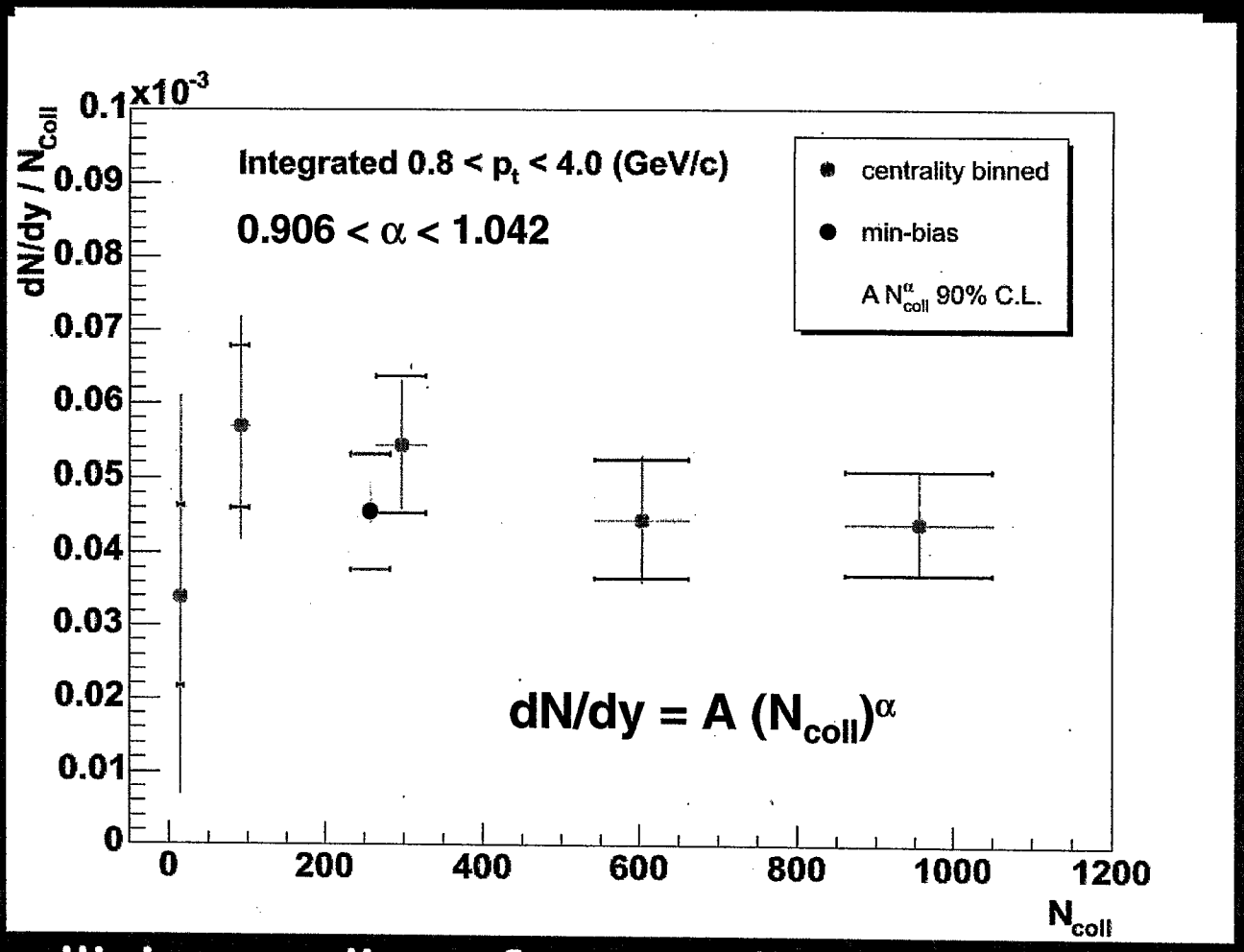
- single electrons from non-photonic sources agree well with pp fit and binary scaling

N_{coll} Scaling in Au+Au



- Again, good agreement of electrons from charm with N_{coll}

N_{coll} Scaling for Charm

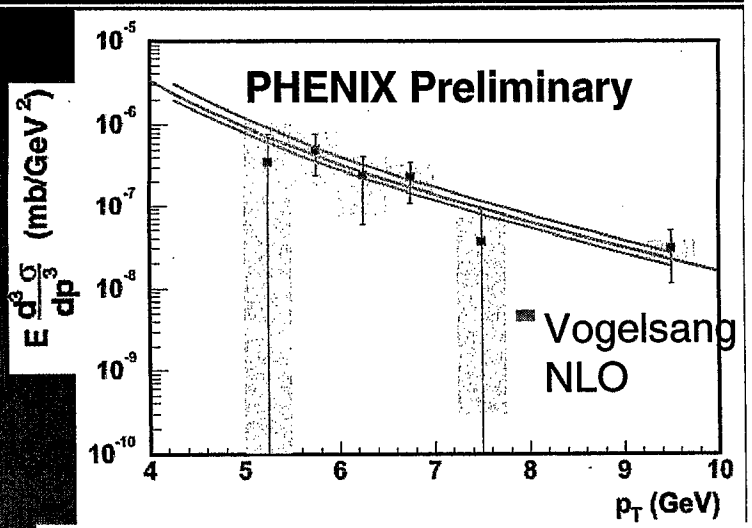


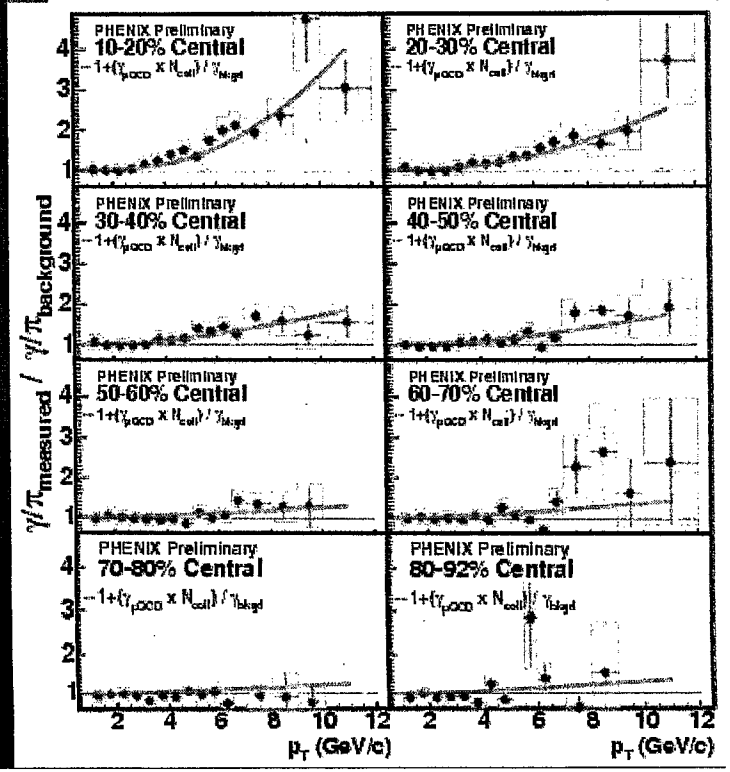
- binary collision scaling of pp result works VERY WELL for non-photonic electrons in d+Au, Au+Au open charm is a good CONTROL, similar to direct photons

N_{coll} Scaling for Direct Photons

- N_{coll} scaling works to describe the direct photon yield in Au+Au, starting from NLO description of measured p+p yields

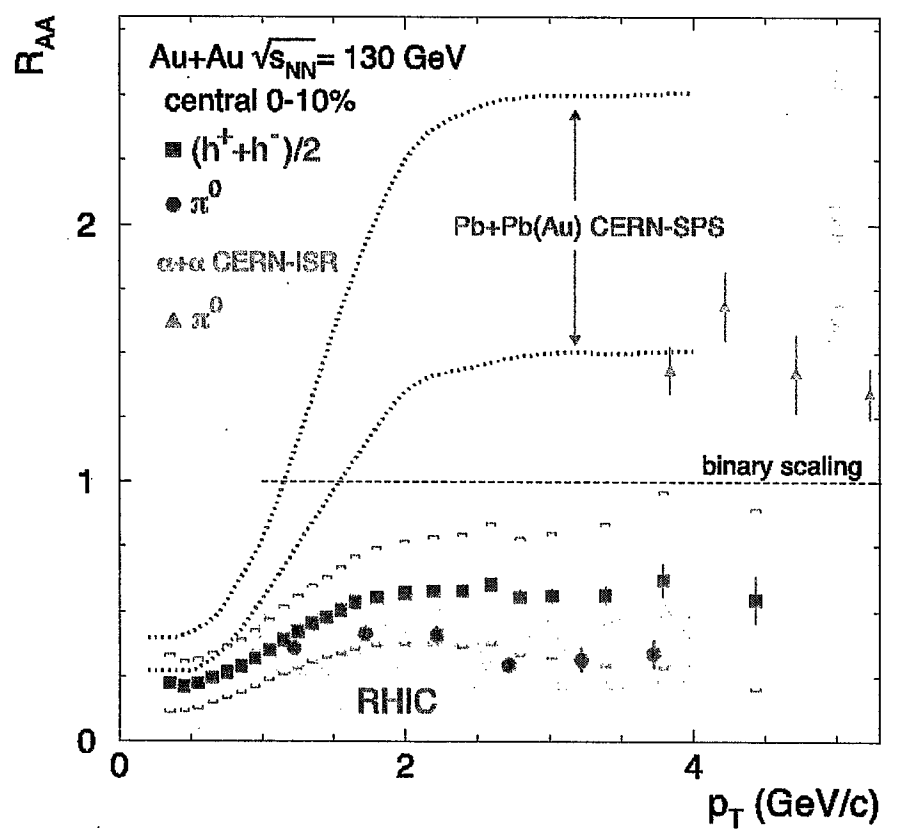
- N.B. This method of analysis (double ratio of γ/π^0) shows N_{coll} scaling after accounting for observed suppression of π^0 yields in Au+Au collisions (to be discussed next)





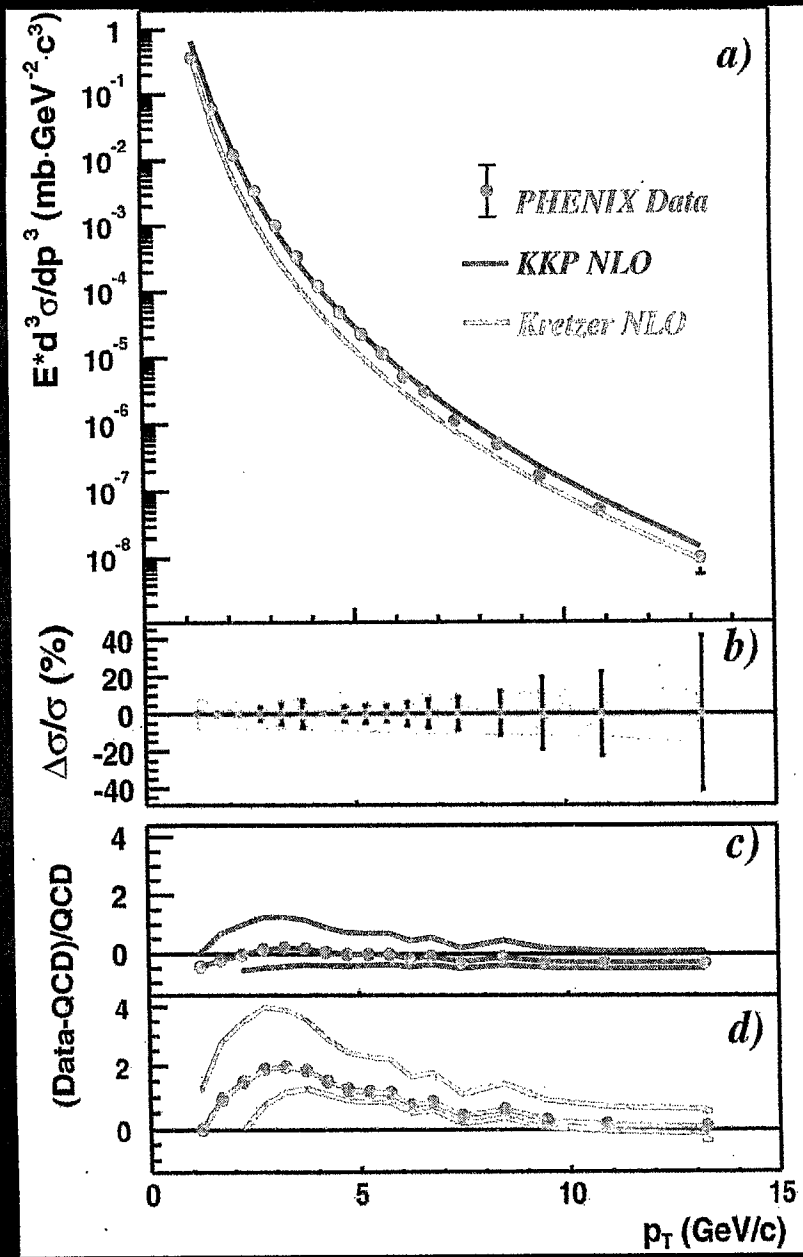
Discovery of Suppression

- That is, suppression of yields calculated relative to (established) N_{coll} scaling
- Described in "Suppression of hadrons with large transverse momentum in central Au-Au collisions at $\sqrt{s_{NN}}$ = 130 GeV", PRL 88, 022301 (2002).



The All-Important p+p Reference

- "Midrapidity Neutral Pion Production in Proton-Proton Collisions at $\sqrt{s}$ = 200 GeV", Phys. Rev. Lett. 91, 241803 (2003)
  - *Important confirmation of theoretical foundations for spin program*
    - Results consistent with pQCD calculation
    - Favors a larger gluon-to-pion FF (KKP)
    - *Provides confidence for proceeding with spin measurements via hadronic channels*
- For our purposes today: demonstrate crucial importance of timely *in situ* measurements of reference data set



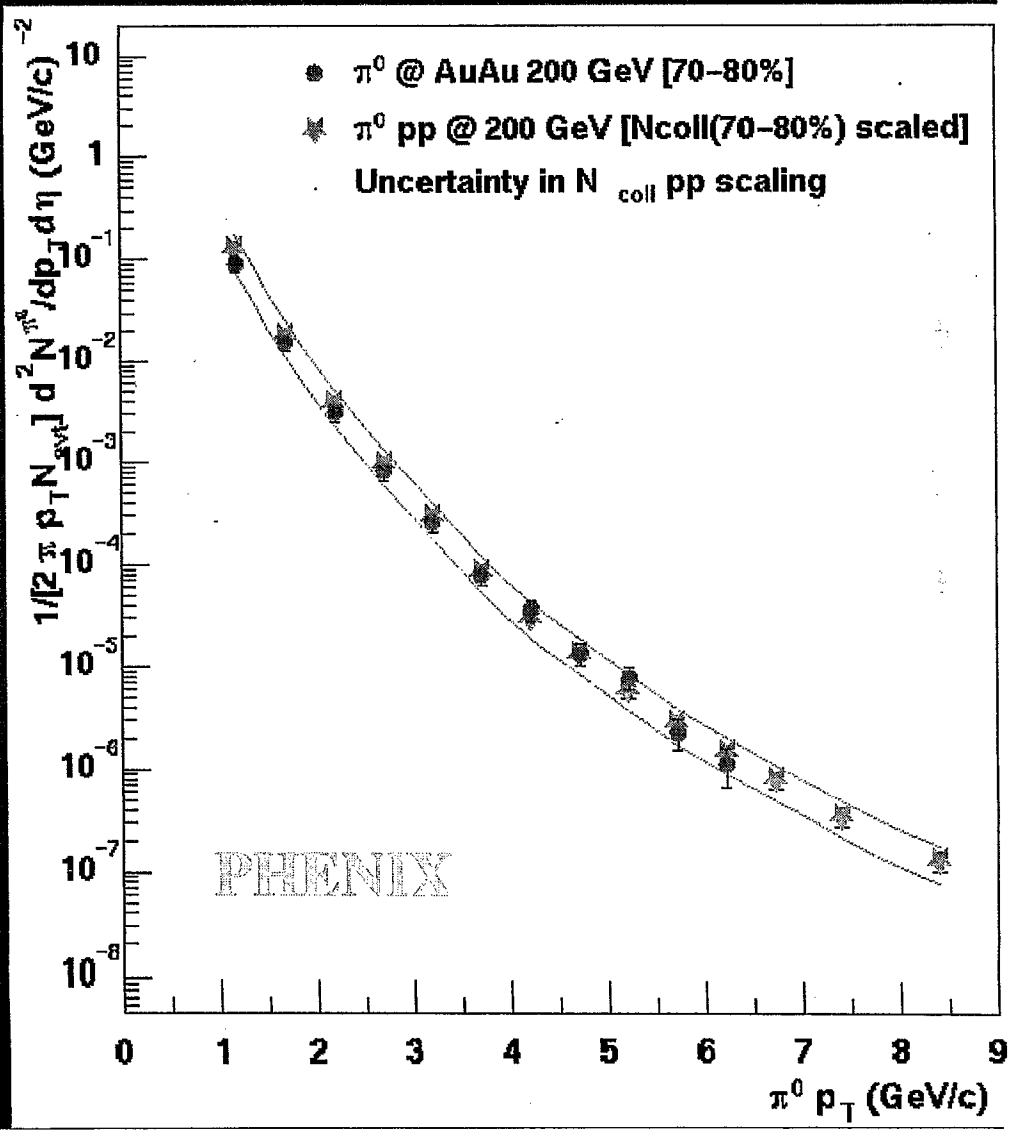
Another Example of N_{coll} Scaling

- PHENIX (Run-2) data on π^0 production in peripheral collisions:
- Excellent agreement between PHENIX measured π^0's in p+p

  and

  PHENIX measured π^0's in Au-Au *peripheral* collisions scaled by the number of collisions

  over ~ 5 decades



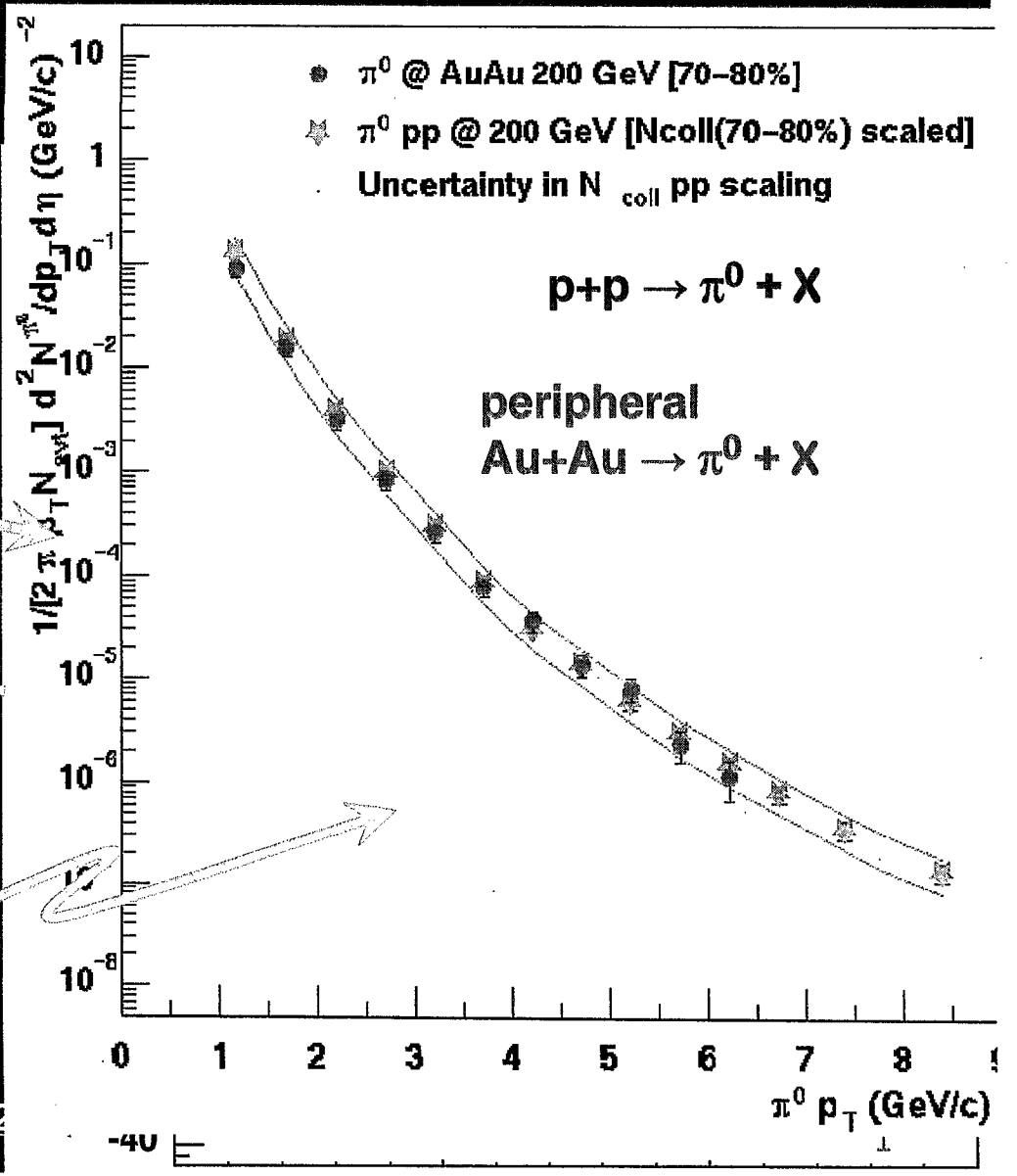
Probing the Density

Q. How to probe (very high?) initial state densities?

A. Using probes that are

- Auto-generated (initial hard scatterings)
- Calculable (in pQCD)
- Calibrated (measured in p+p)
- Have known scaling properties (~ A*B "binary collisions)

"Suppressed π^0 Production at Large Transverse Momentum in Central Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV" , PRL 91, 072301 (2



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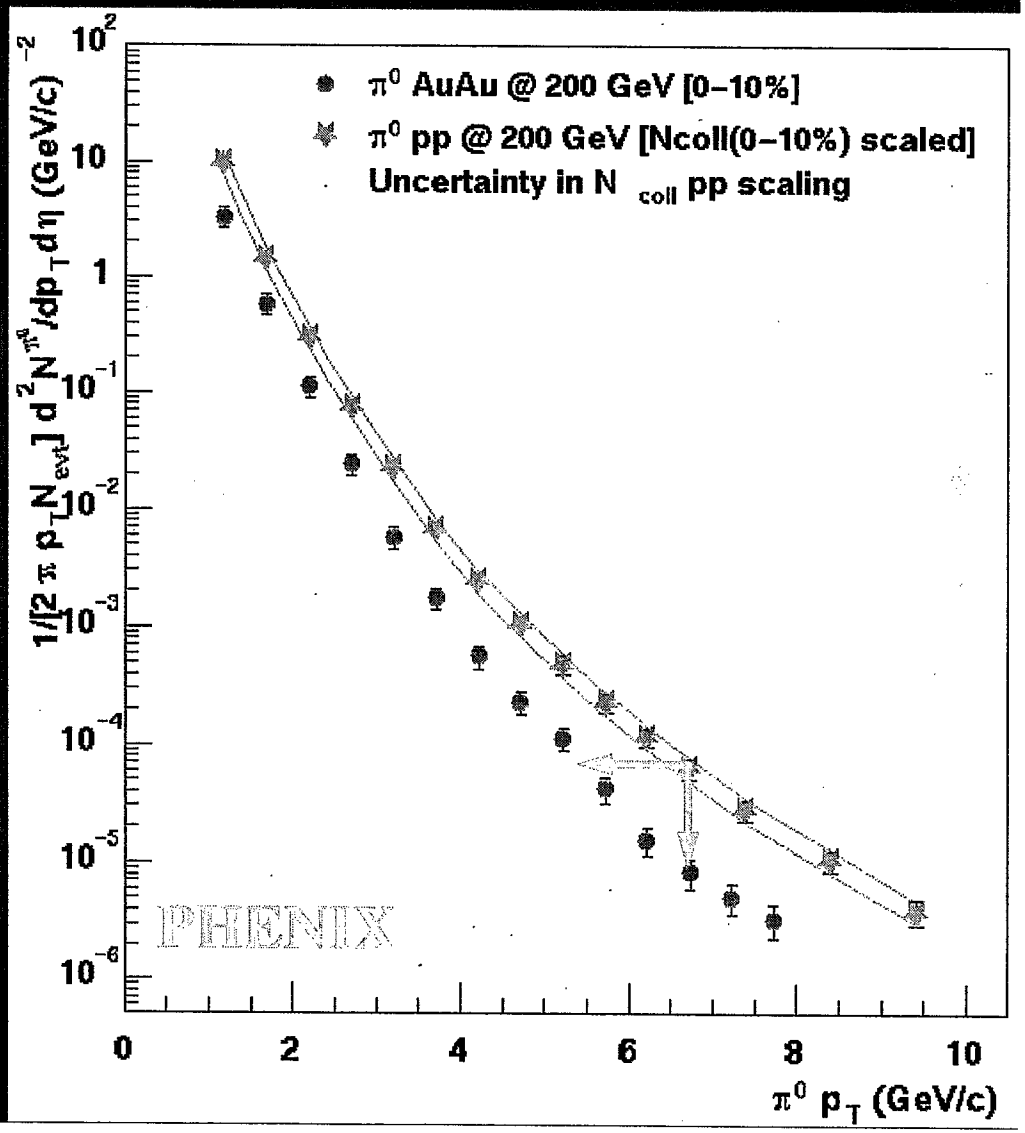
Central Collisions Are *Profoundly Different*

Q: Do all processes that *should* scale like A*B do just that?

A: No!

→ Central collisions are *different*. (Huge deficit at high p_T)

- This is a *clear* discovery of *new* behavior at RHIC
  - ☐ Suppression of low-x gluons in the initial *state*?
  - ☑ Energy loss in a new state of *matter*?



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Exceedingly High Densities?

Both

- Au+Au suppression (I. Vitev and M. Gyulassy, hep-ph/0208108)
- d+Au enhancement (I. Vitev, nucl-th/0302002)

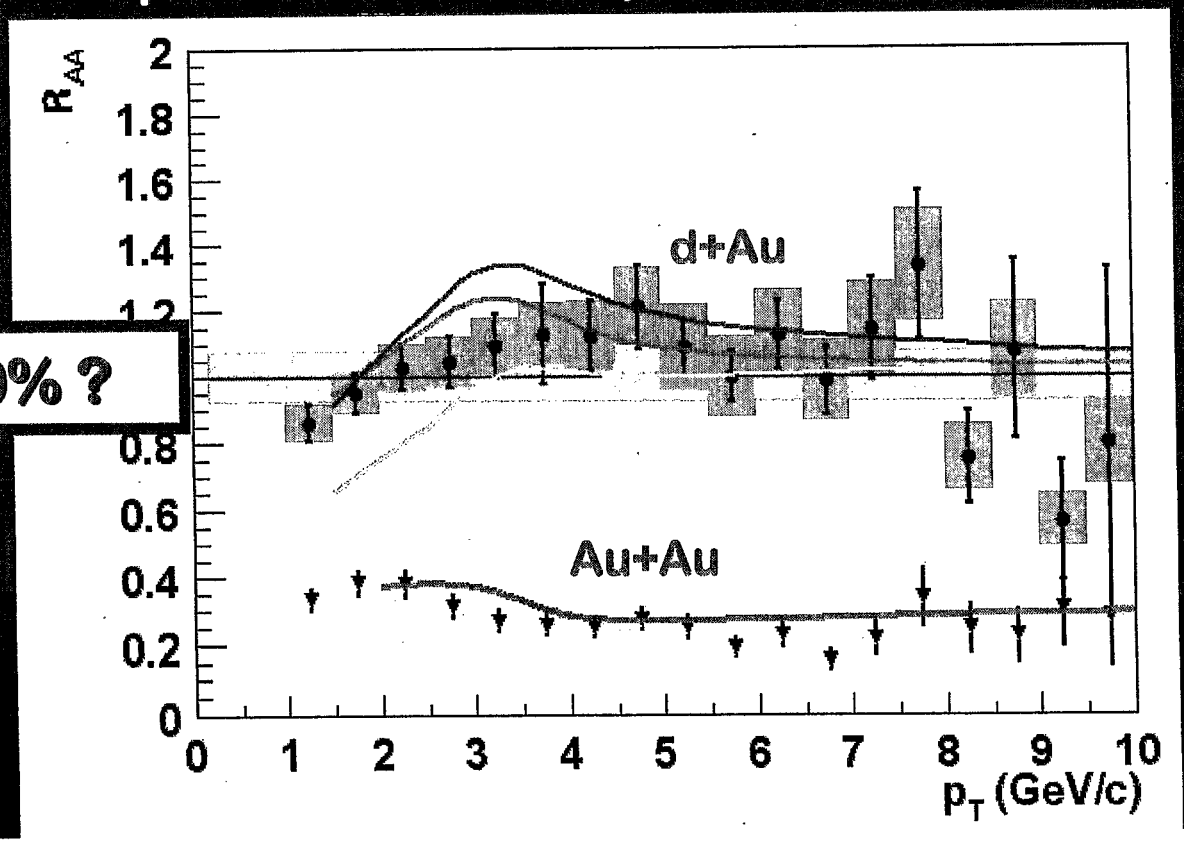
understood in an approach that combines multiple scattering with absorption in *a dense partonic medium*

➡ Our high p_T probes have been calibrated

±50% ?

$dN_g/dy \sim 1100$

$\varepsilon > 100\ \varepsilon_0$ (!)



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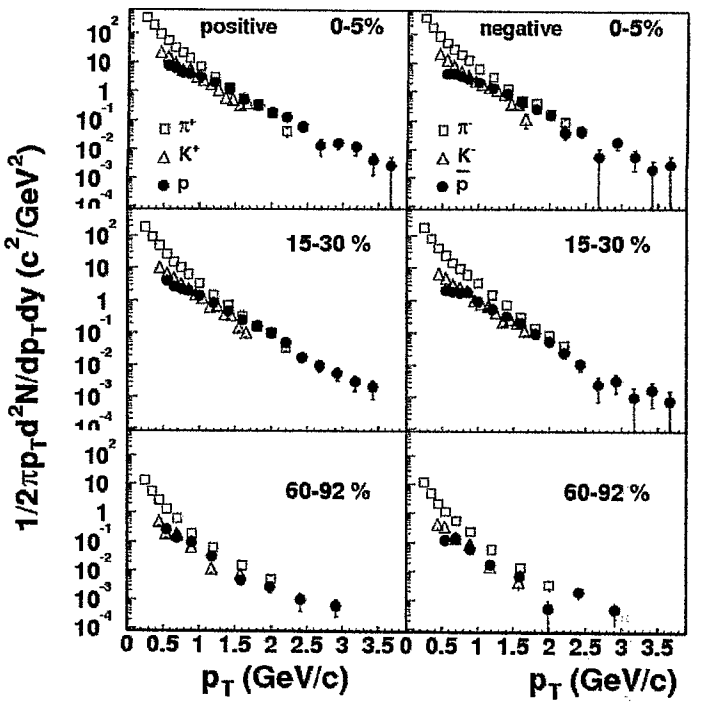
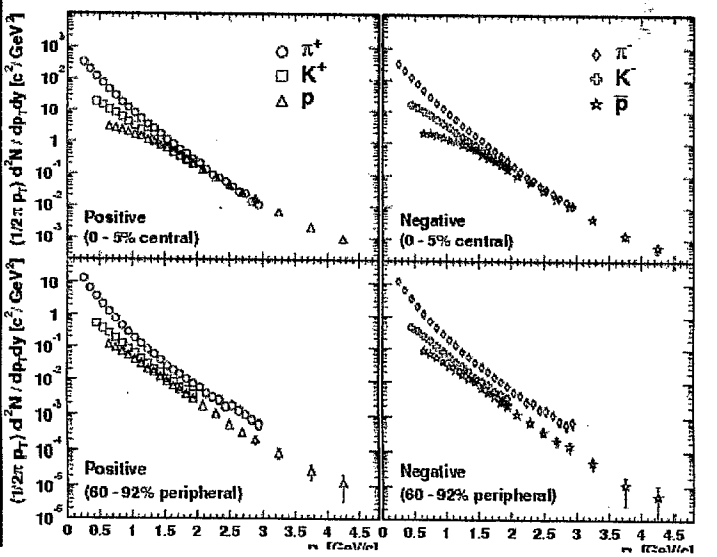
Identified Hadrons

- PHENIX goal of providing quality particle identification for hadrons
  - ❑ realized in Run-1:
    "Centrality dependence of $\pi^{+/-}$, $K^{+/-}$, p and pbar production at RHIC," PRL 88, 242301 (2002).
  - ❑ Extended in Run-2:
    "Identified Charged Particle Spectra and Yields in Au-Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV", Phys. Rev. C 69, 034909 (2004)





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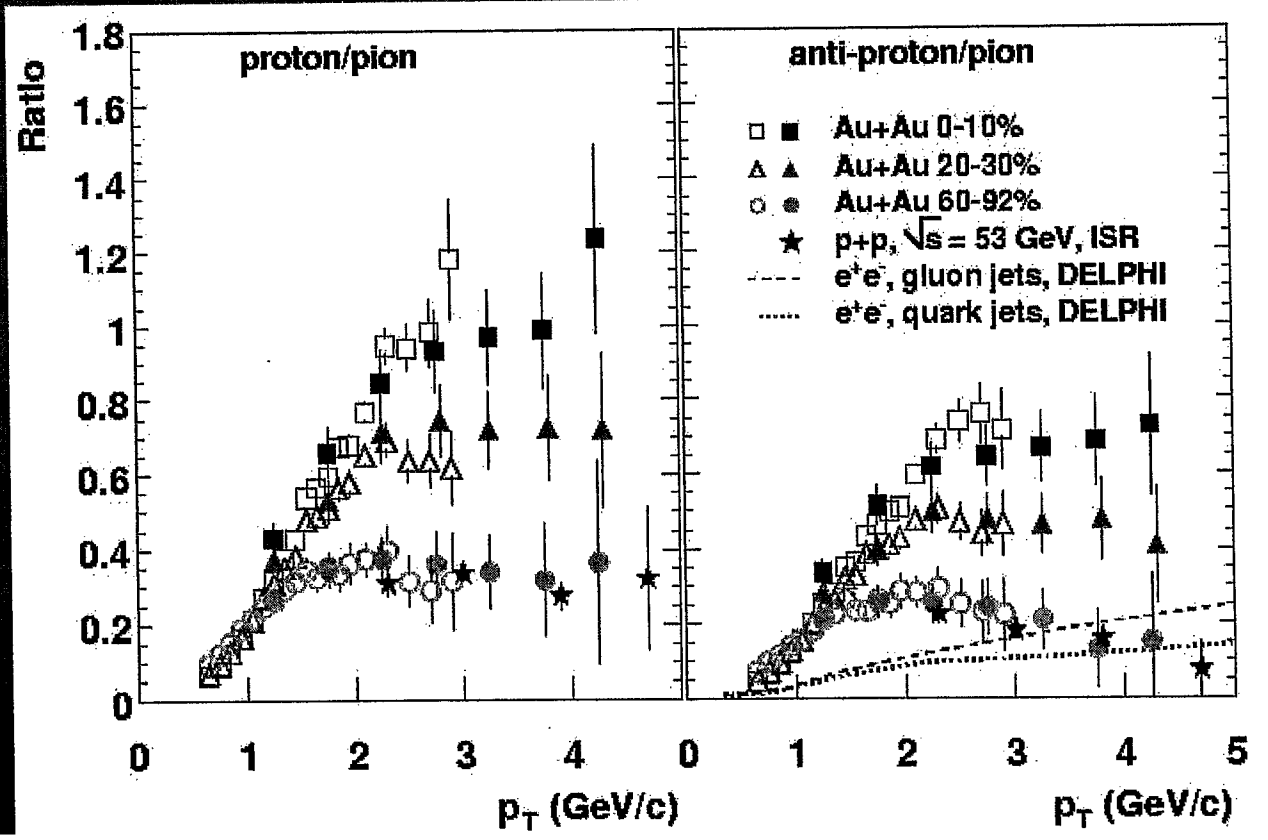
On the p/π Yields

- There is a vast set of results from these hadron measurements on freeze-out temperature, radial expansion, etc. that will not be presented here.
- Instead, concentrate on the discovery of anomalous p/π ratios at intermediate transverse momenta:



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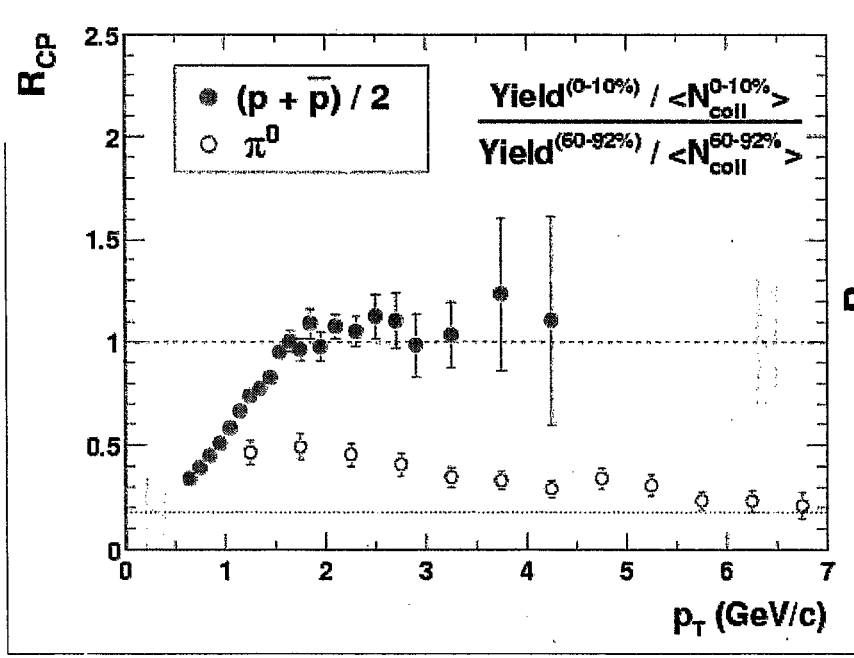
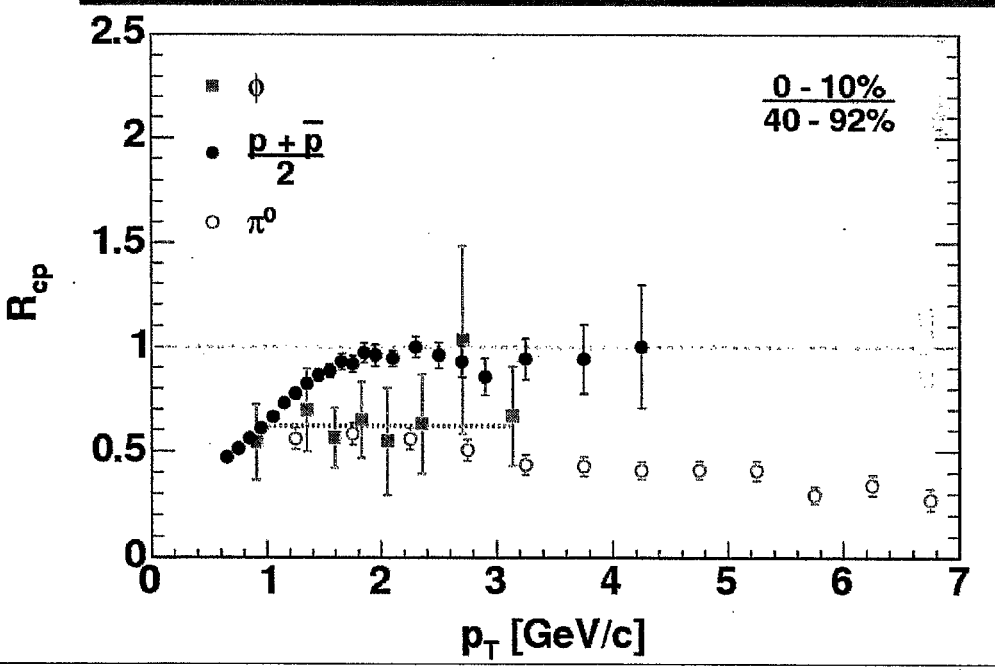
Baryons Are Different

- Results from
  - PHENIX (protons and anti-protons)
  - (also STAR lambda's and lambda-bars)

  indicate little or no suppression of *baryons* in the range ~2 < p_T < ~5 GeV/c
- One explanation: quark recombination (next slide)



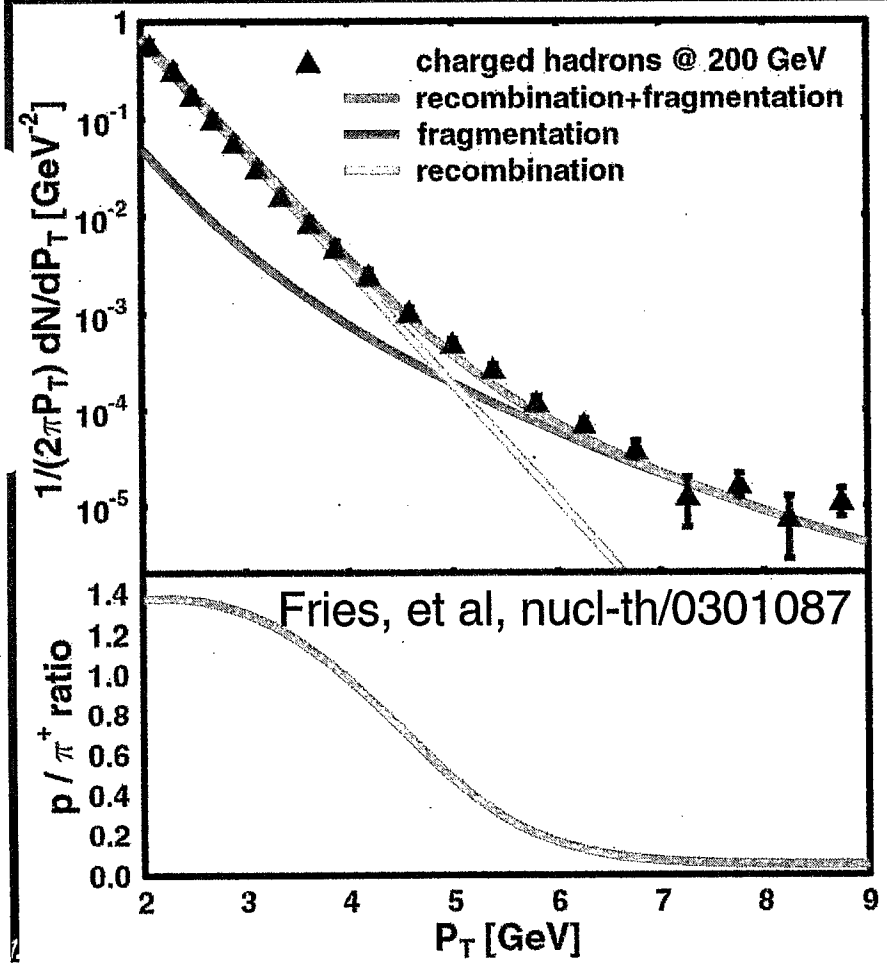


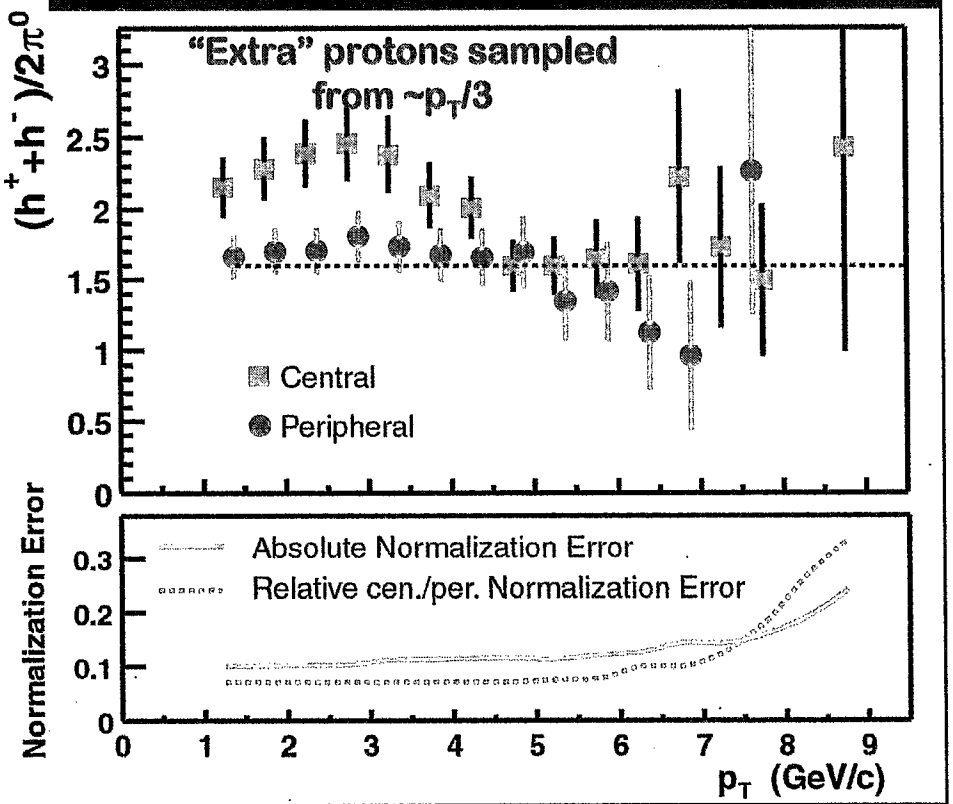
Recombination Meets Data

- Provides a "natural" explanation of
  - Spectrum of charged hadrons
  - Enhancements seen in p/π
  - Momentum scale for same

...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma

Fries *et al.*, nucl-th/0301087





Recombination Extended

The *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

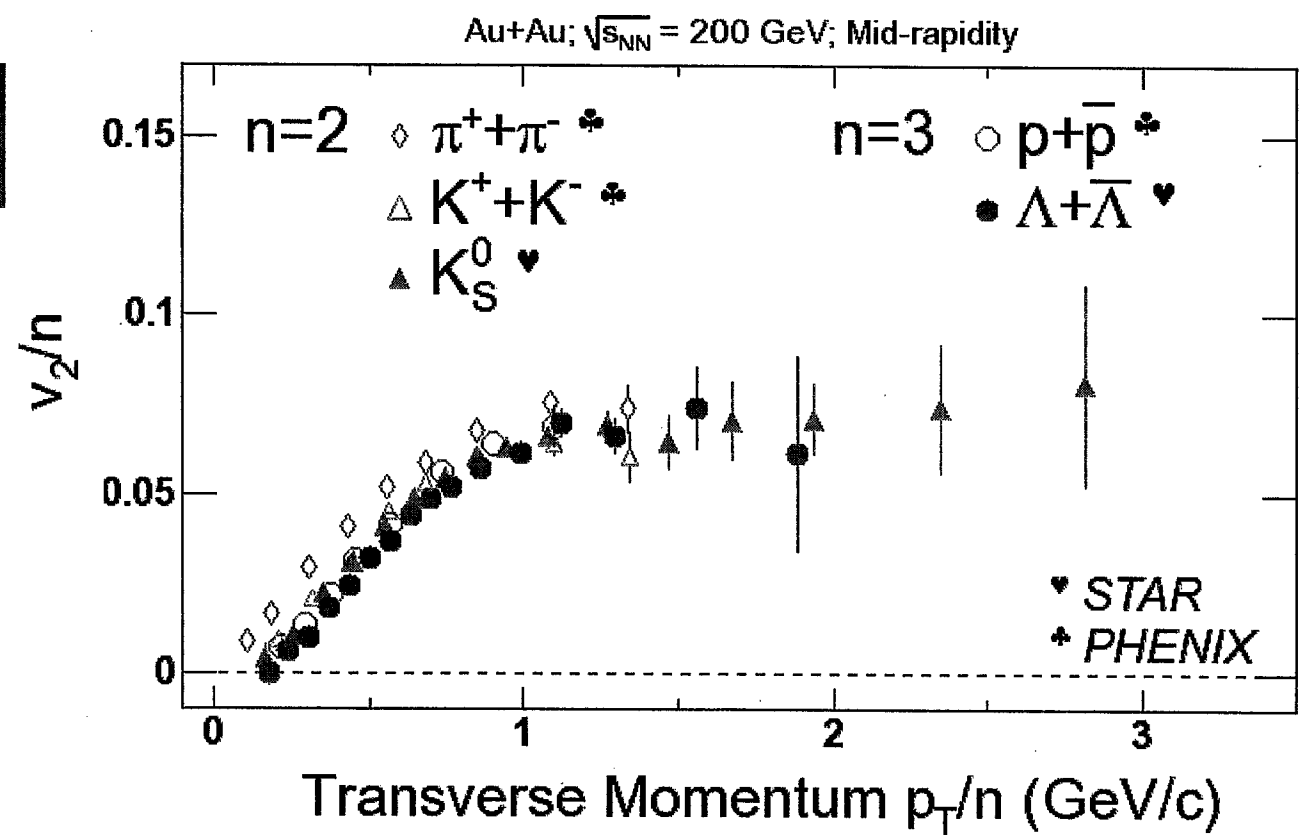
$$d^2n/dp_T d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$$

is predicted to be *simple* at the quark level under

$$p_T \to p_T/n,\ v_2 \to v_2/n,\ n = (2, 3) \text{ for (meson, baryon)}$$

if the flow pattern is established at the quark level

Compilation courtesy of H. Huang



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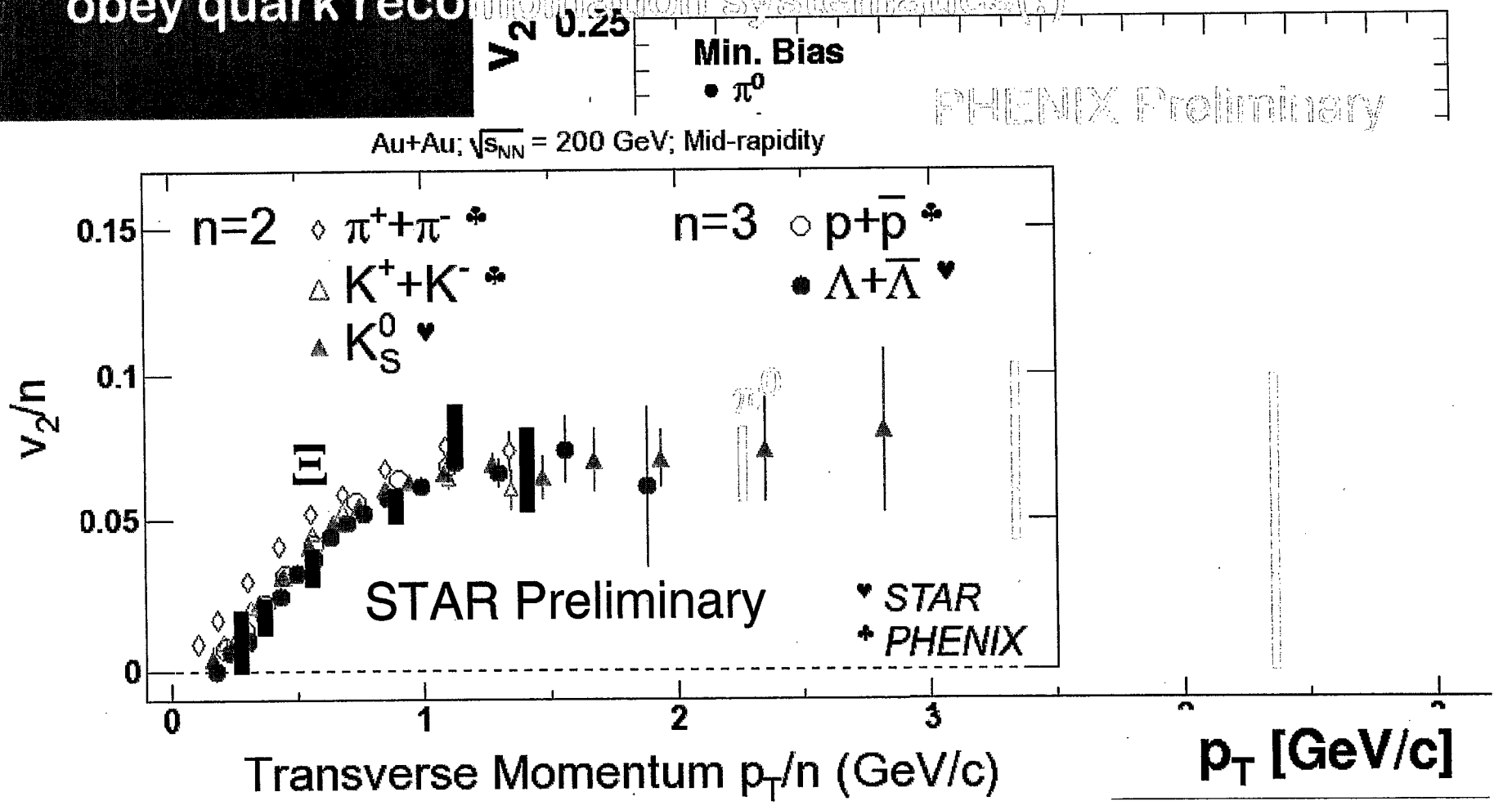
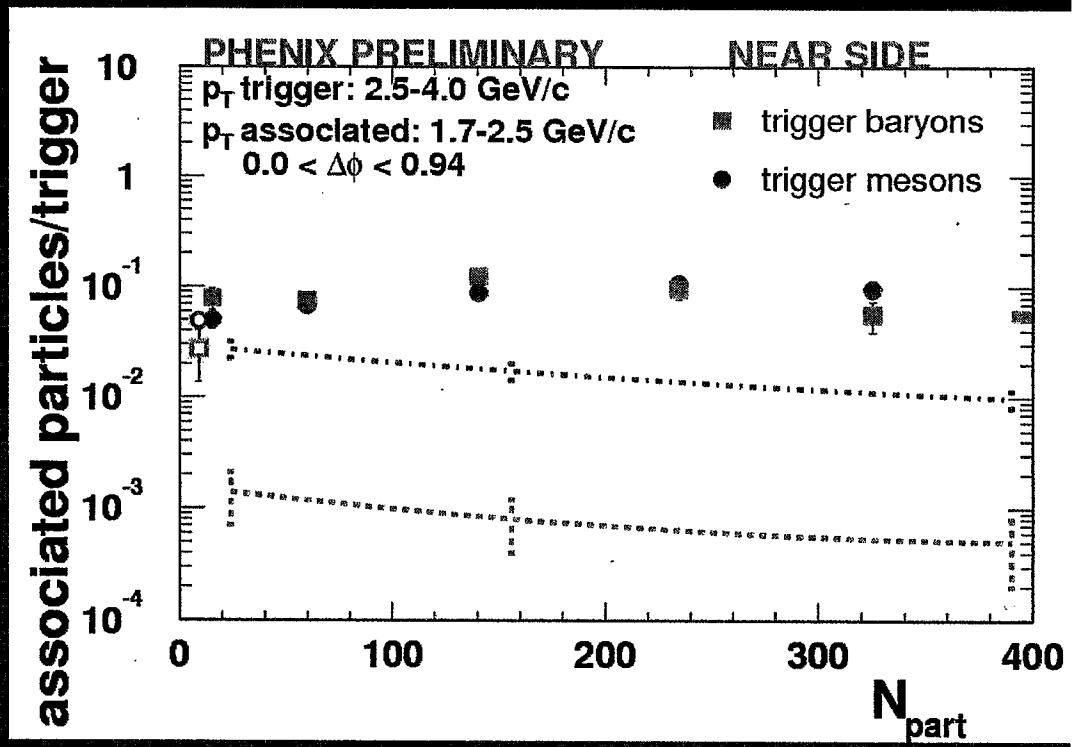
PHENIX *Further* Extending Recombination

- New PHENIX Run-2 result on v2 of π^0's:
- New STAR Run-2 result on v2 for Ξ's:
- ALL (non-pion) hadrons measured to date obey quark recombination systematics(!)



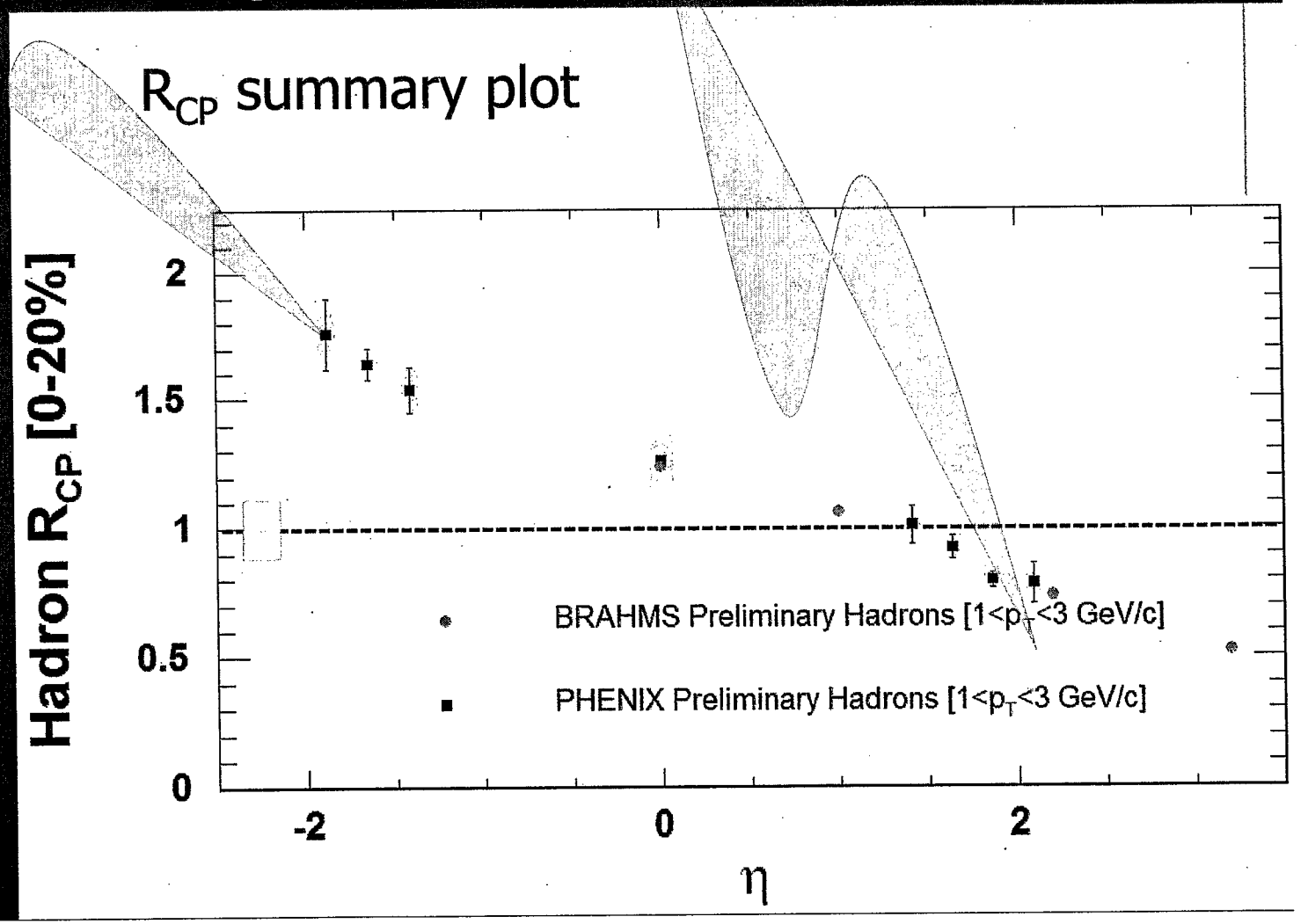
Recombination Challenged

- Successes:
  - Accounts for p_T dependence of baryon/meson yields
  - Unifies description of $v_2(p_T)$ for baryons and mesons
- Challenged by
  - "Associated emission" at high p_T
  - Can the simple appeal of Thermal-Thermal correlations survive extension to Jet-Thermal ?



CGC Challenged (?)

- Can it account for both
  - suppression in deuteron-going direction
  - enhancement in Au-going direction



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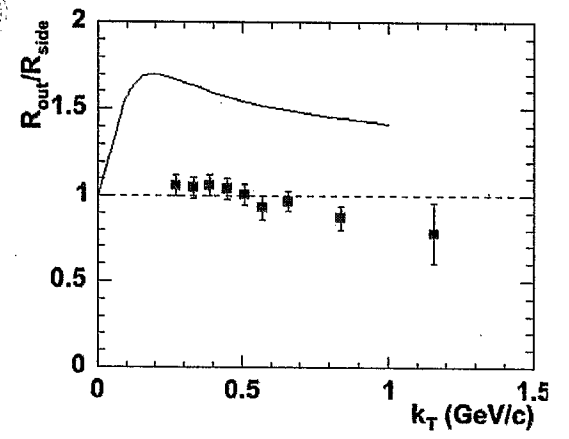
Summary

- Evidence for bulk behavior (flow, thermalization): *unequivocal*
- Evidence for high densities (high p_T suppression): *unequivocal*
  (Control measurement of d+Au essential supporting piece of evidence)
- Empirical
  - scaling of v_2 based on quark content
  - p_T dependence of meson/baryon ratios

  strongly suggestive of recombination at work
  - Jet correlations may prove critical test of the model

- What remains?
  - (Much) more robust *quantitative* understanding
  - Quantitative understanding of "failures" (e.g., HBT)
  - Direct evidence for deconfiment(?)
  - Contrary to some opinions:

more data is good for you!



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It's a Hard Problem

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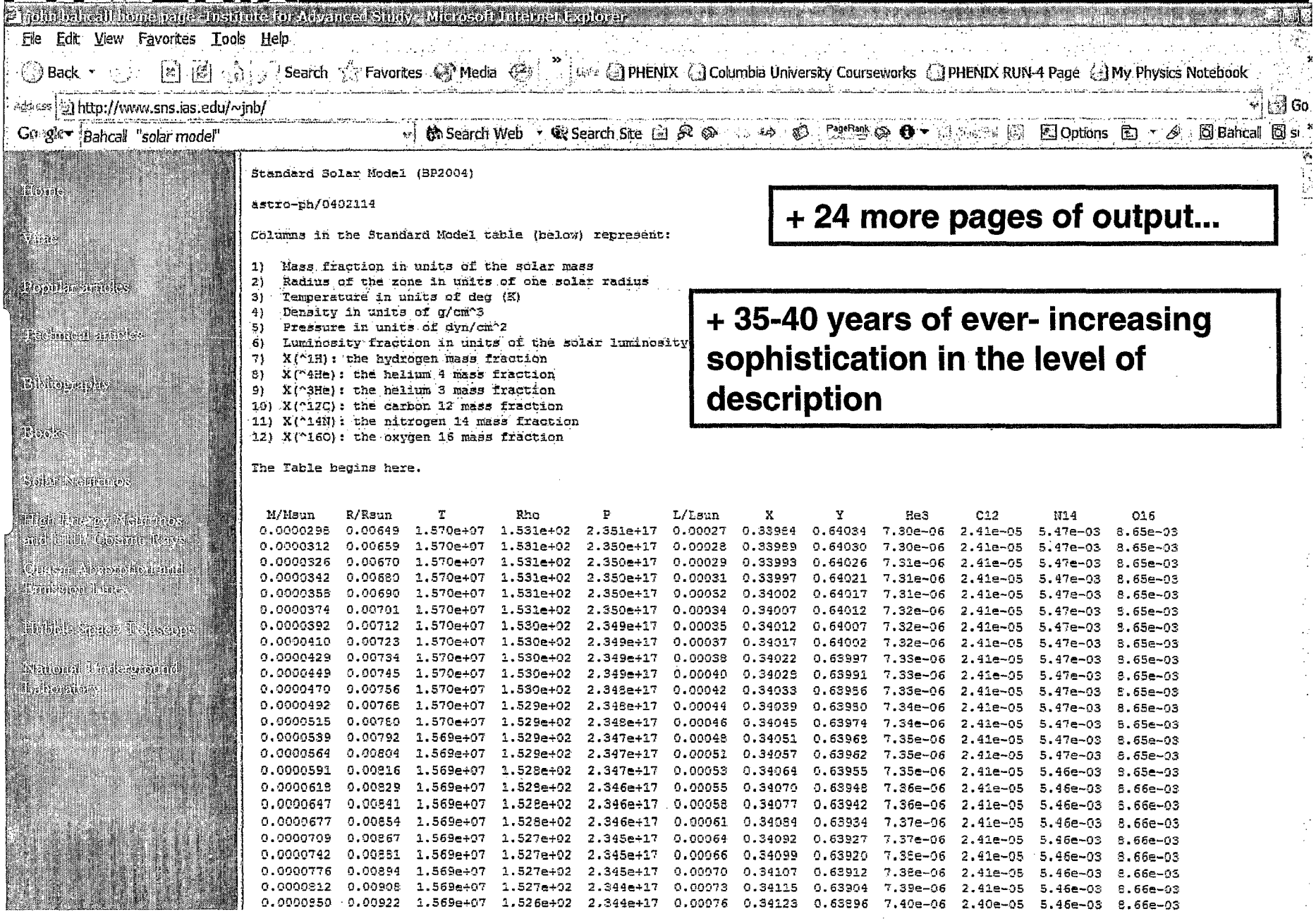


Standard Solar Model (BP2004)

astro-ph/0402114

Columns in the Standard Model table (below) represent:

1) Mass fraction in units of the solar mass
2) Radius of the zone in units of one solar radius
3) Temperature in units of deg (K)
4) Density in units of g/cm^3
5) Pressure in units of dyn/cm^2
6) Luminosity fraction in units of the solar luminosity
7) X(^1H): the hydrogen mass fraction
8) X(^4He): the helium 4 mass fraction
9) X(^3He): the helium 3 mass fraction
10) X(^12C): the carbon 12 mass fraction
11) X(^14N): the nitrogen 14 mass fraction
12) X(^16O): the oxygen 16 mass fraction

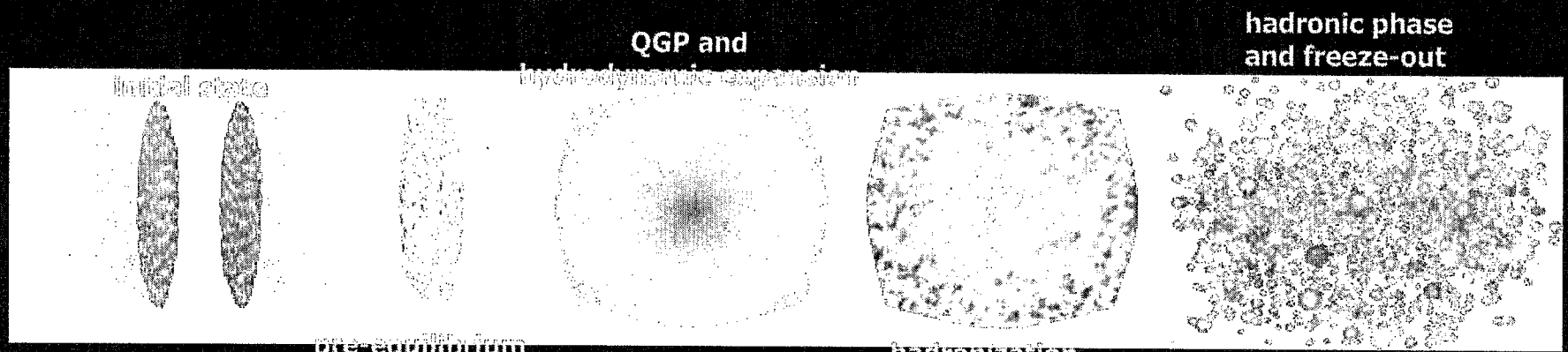
The Table begins here.

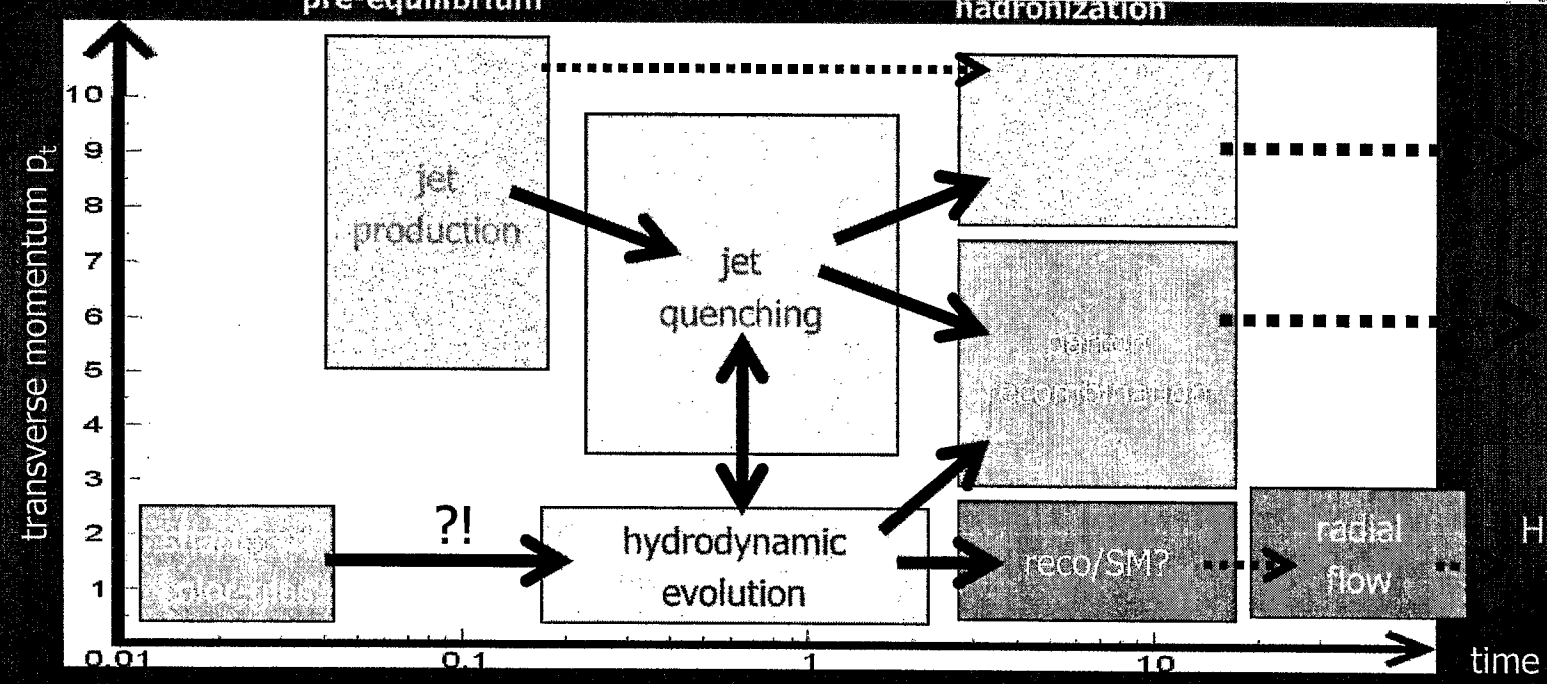
M/Msun	R/Rsun	T	Rho	P	L/Lsun	X	Y	He3	C12	N14	O16
0.0000298	0.00649	1.570e+07	1.531e+02	2.351e+17	0.00027	0.33984	0.64034	7.30e-06	2.41e-05	5.47e-03	8.65e-03
0.0000312	0.00659	1.570e+07	1.531e+02	2.350e+17	0.00028	0.33989	0.64030	7.30e-06	2.41e-05	5.47e-03	8.65e-03
0.0000326	0.00670	1.570e+07	1.531e+02	2.350e+17	0.00029	0.33993	0.64026	7.31e-06	2.41e-05	5.47e-03	8.65e-03
0.0000342	0.00680	1.570e+07	1.531e+02	2.350e+17	0.00031	0.33997	0.64021	7.31e-06	2.41e-05	5.47e-03	8.65e-03
0.0000358	0.00690	1.570e+07	1.531e+02	2.350e+17	0.00032	0.34002	0.64017	7.31e-06	2.41e-05	5.47e-03	8.65e-03
0.0000374	0.00701	1.570e+07	1.531e+02	2.350e+17	0.00034	0.34007	0.64012	7.32e-06	2.41e-05	5.47e-03	8.65e-03
0.0000392	0.00712	1.570e+07	1.530e+02	2.349e+17	0.00035	0.34012	0.64007	7.32e-06	2.41e-05	5.47e-03	8.65e-03
0.0000410	0.00723	1.570e+07	1.530e+02	2.349e+17	0.00037	0.34017	0.64002	7.32e-06	2.41e-05	5.47e-03	8.65e-03
0.0000429	0.00734	1.570e+07	1.530e+02	2.349e+17	0.00038	0.34022	0.63997	7.33e-06	2.41e-05	5.47e-03	8.65e-03
0.0000449	0.00745	1.570e+07	1.530e+02	2.349e+17	0.00040	0.34028	0.63991	7.33e-06	2.41e-05	5.47e-03	8.65e-03
0.0000470	0.00756	1.570e+07	1.530e+02	2.348e+17	0.00042	0.34033	0.63986	7.33e-06	2.41e-05	5.47e-03	8.65e-03
0.0000492	0.00768	1.570e+07	1.529e+02	2.348e+17	0.00044	0.34039	0.63980	7.34e-06	2.41e-05	5.47e-03	8.65e-03
0.0000515	0.00780	1.570e+07	1.529e+02	2.348e+17	0.00046	0.34045	0.63974	7.34e-06	2.41e-05	5.47e-03	8.65e-03
0.0000539	0.00792	1.569e+07	1.529e+02	2.347e+17	0.00048	0.34051	0.63968	7.35e-06	2.41e-05	5.47e-03	8.65e-03
0.0000564	0.00804	1.569e+07	1.529e+02	2.347e+17	0.00051	0.34057	0.63962	7.35e-06	2.41e-05	5.47e-03	8.65e-03
0.0000591	0.00816	1.569e+07	1.528e+02	2.347e+17	0.00053	0.34064	0.63955	7.35e-06	2.41e-05	5.46e-03	8.65e-03
0.0000618	0.00829	1.569e+07	1.528e+02	2.346e+17	0.00055	0.34070	0.63948	7.36e-06	2.41e-05	5.46e-03	8.66e-03
0.0000647	0.00841	1.569e+07	1.528e+02	2.346e+17	0.00058	0.34077	0.63942	7.36e-06	2.41e-05	5.46e-03	8.66e-03
0.0000677	0.00854	1.569e+07	1.528e+02	2.346e+17	0.00061	0.34084	0.63934	7.37e-06	2.41e-05	5.46e-03	8.66e-03
0.0000709	0.00867	1.569e+07	1.527e+02	2.345e+17	0.00064	0.34092	0.63927	7.37e-06	2.41e-05	5.46e-03	8.66e-03
0.0000742	0.00881	1.569e+07	1.527e+02	2.345e+17	0.00066	0.34099	0.63920	7.38e-06	2.41e-05	5.46e-03	8.66e-03
0.0000776	0.00894	1.569e+07	1.527e+02	2.345e+17	0.00070	0.34107	0.63912	7.38e-06	2.41e-05	5.46e-03	8.66e-03
0.0000812	0.00908	1.569e+07	1.527e+02	2.344e+17	0.00073	0.34115	0.63904	7.39e-06	2.41e-05	5.46e-03	8.66e-03
0.0000850	0.00922	1.569e+07	1.526e+02	2.344e+17	0.00076	0.34123	0.63896	7.40e-06	2.40e-05	5.46e-03	8.66e-03

+ 24 more pages of output...

+ 35-40 years of ever- increasing sophistication in the level of description

PHENIX (Slide Courtesy of S. Bass)



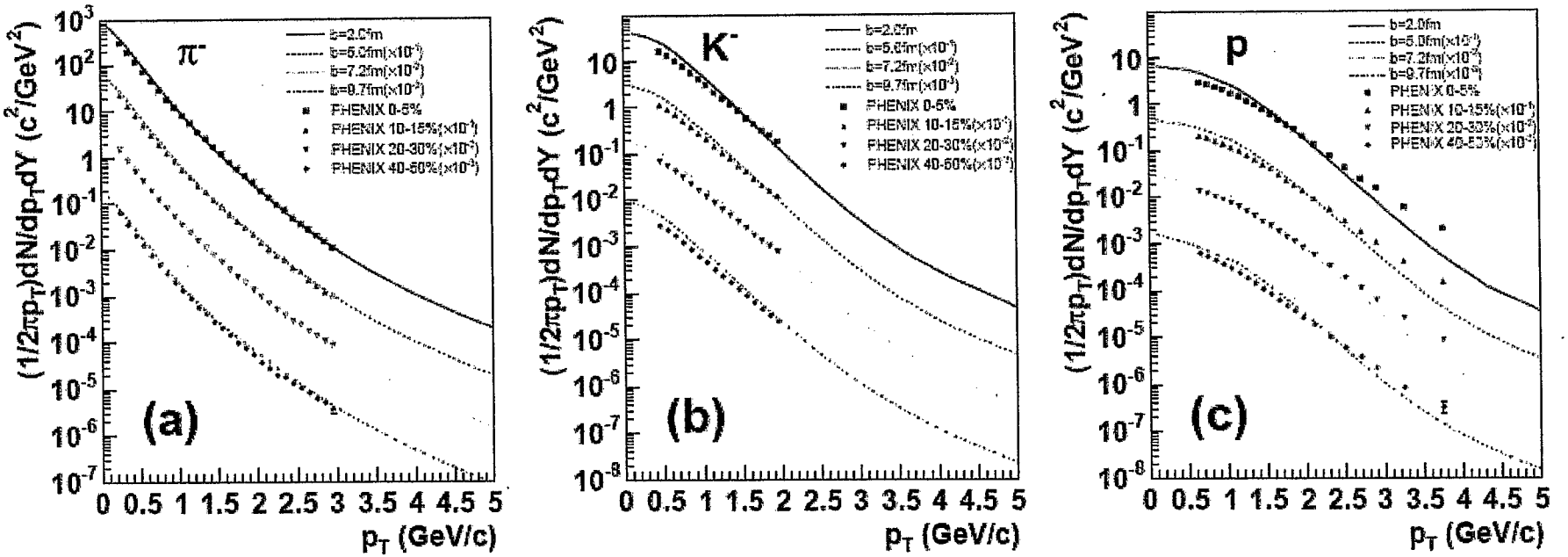


"Consistent in the sense of being disjoint"

15-May-04

CGC + Hydro + Jets

- T. Hirano and Y. Nara, nucl-th/0404039:
  3D hydro with CGC initial conditions and parton energy loss (!)



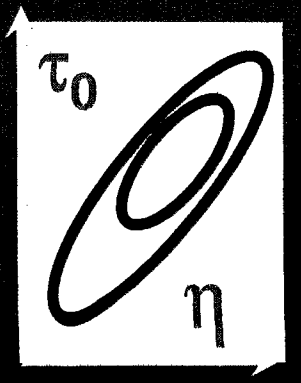
(Soup ingredients to) Soup to Nuts description

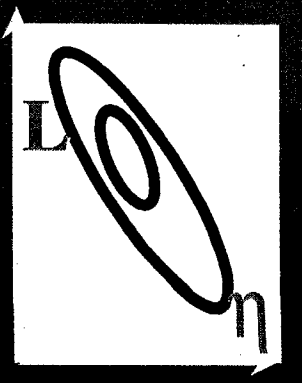
On Estimating Errors

- ~All of data analysis effort is expended on understanding systematic errors:
  - Example taken from (required) Analysis Note prior to release of even Preliminary Data

	p_T indep.	2 GeV	6 GeV	type
peak extraction	5.0%(5.0%)			A
geometric acc.		3.0%(3.0%)	2.0%(2.0%)	B
π^0 reconstr. eff.		5.0%(5.0%)	5.0%(5.0%)	B
energy scale		4.0%(4.0%)	9.0%(9.0%)	B
Conversion corr.	3.0%(3.0%)			C
Total error		9.1%(9.1%)	12%(12%)	

- Would like to see this (and more) from those theory analyses dedicated to extraction of physical parameters

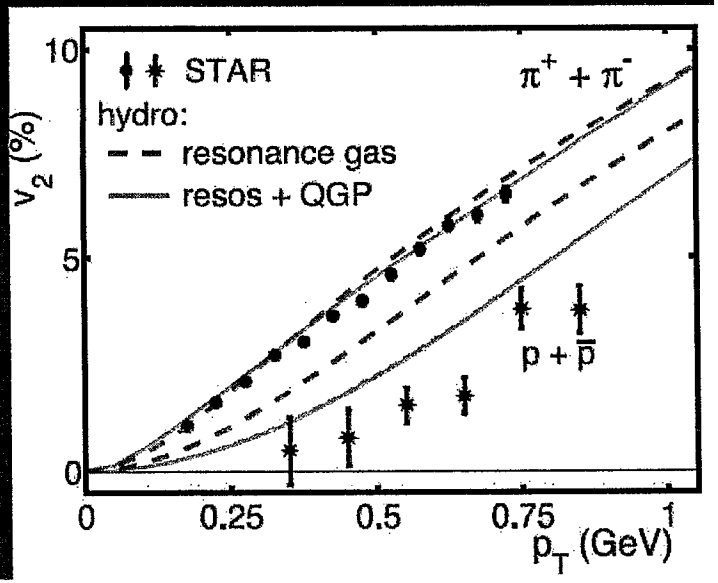


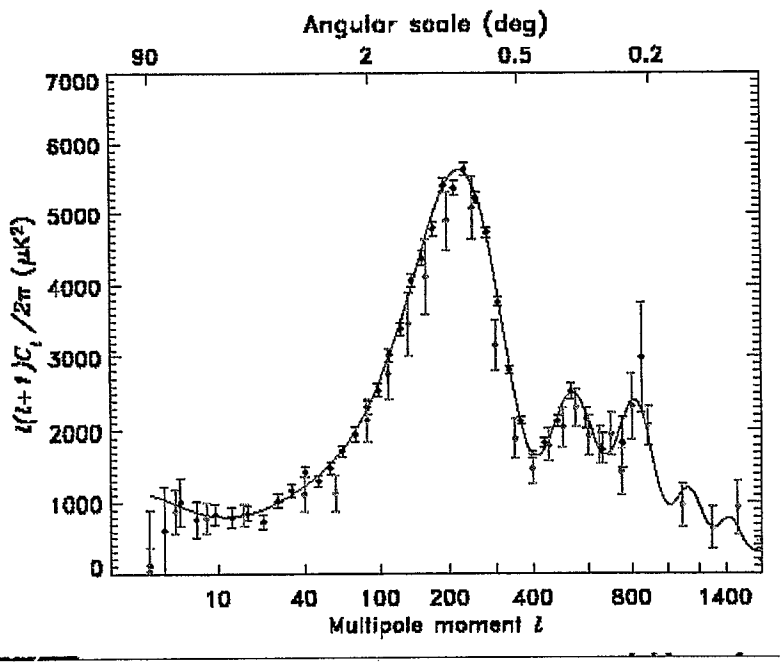


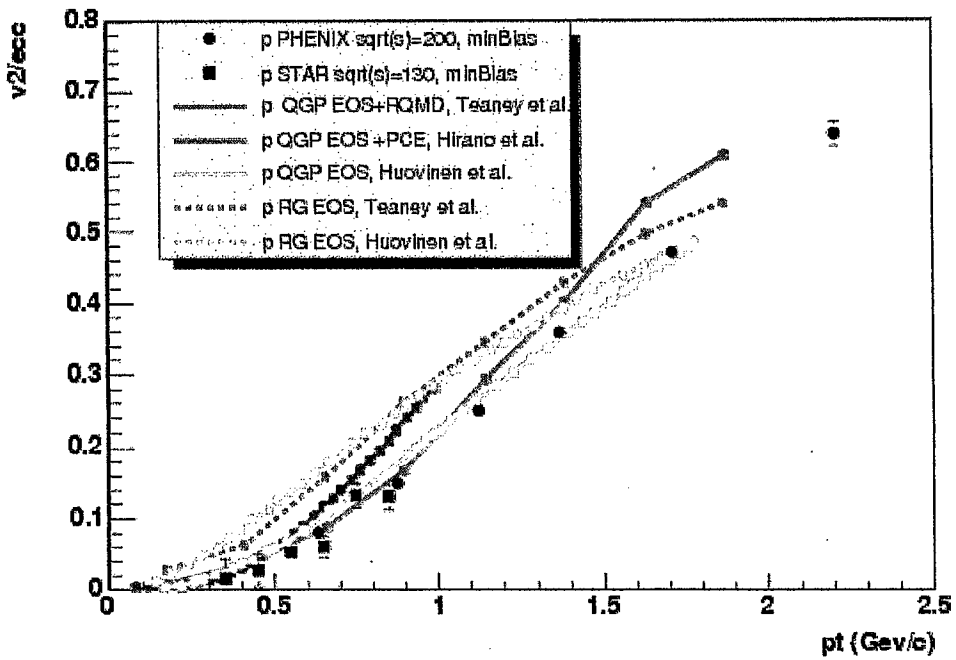
Current "Error" Status

- The evidence cited (in these examples) for
  - QGP equation of state
  - Very low viscosity

  may be
  - "Fingerprints", but they're rather smudged...
  - "Fine structure", but it's somewhat coarse...
- Compare to







PHENIX (Slide from R. Ellis, Caltech)

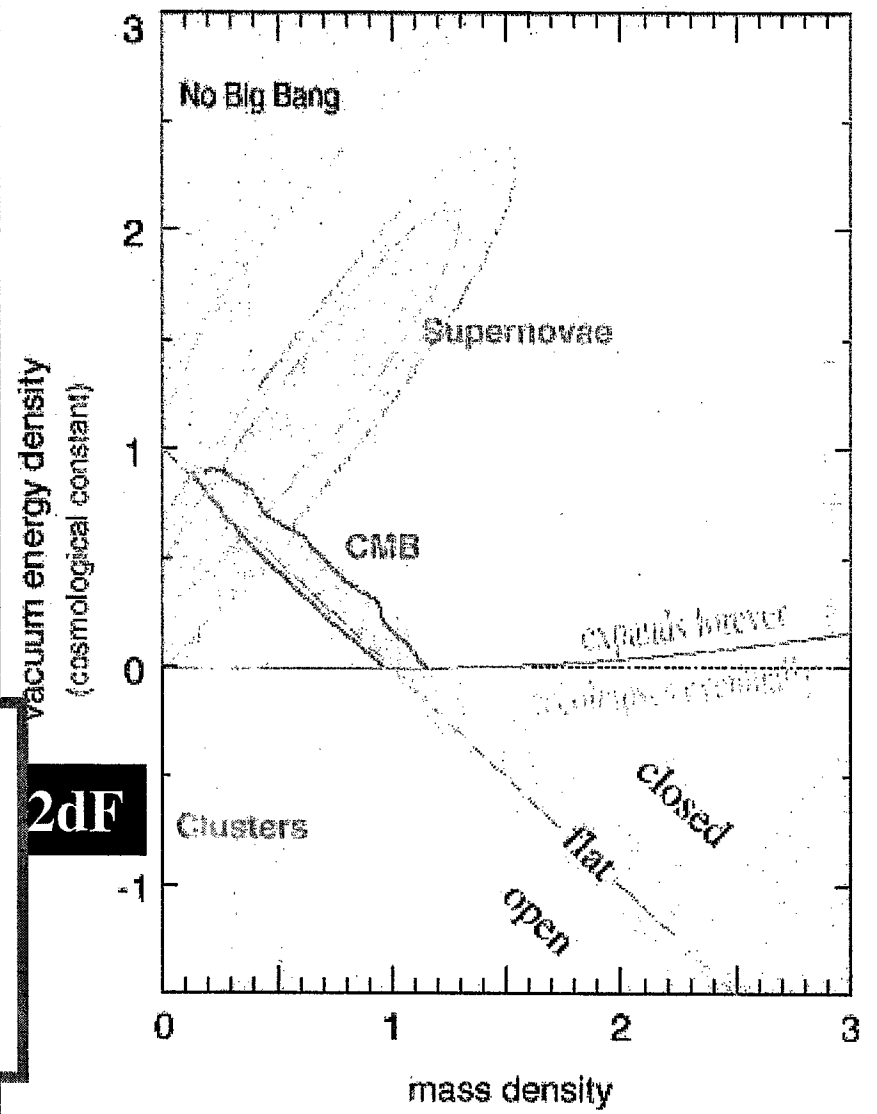
Concordance is worrying:

- $\Omega_{DM} \approx 0.27 \pm 0.04$ (dark matter)
- $\Omega_B \approx 0.044 \pm 0.004$ (baryons)
- $\Omega_\Lambda \approx 0.73 \pm 0.04$ (dark energy)

(Bennett et al 2003)

All 3 ingredients comparable in magnitude but only one component physically understood!

We would really like to have these kind of worries about contours and concordance!!



2dF

15-May-04

PHENIX

Is This Your Parents' QGP?

- Recently, much interest in the "strongly interacting" (i.e., non-ideal) behavior of the matter produced at RHIC
- This property has been known long enough to be forgotten several times:
  - 1982: Gordon Baym, proceedings of Quark Matter '82:
    - A hint of trouble can be seem from the first order result for the entropy density ($N_f = 3$)

$$s(T) = \frac{19\pi^2}{9}\{\ 1 - \frac{54}{19\pi}\alpha_s(T)\ +\ldots\ \}\ T^4$$

which turns negative for $\alpha_s > 1.1$

  - 1992: Berndt Mueller, Proc. of NATO Advanced Study Institute
    - For plasma conditions realistically obtainable in the nuclear collisions ($T \sim 250$ MeV, $g = \sqrt{(4\pi\alpha_s)} = 2$) the effective gluon mass $m_g^* \sim 300$ MeV. We must conclude, therefore, that the notion of almost free gluons (and quarks) in the high temperature phase of QCD is quite far from the truth. Certainly one has $m_g^* \ll T$ when $g \ll 1$, but this condition is never really satisfied in QCD, because $g \sim 1/2$ even at the Planck scale (10^{19} GeV), and $g<1$ only at energies above 100 GeV.
  - 2002: Ulrich Heinz, Proceedings of PANIC conference:
    - Perturbative mechanisms seem unable to explain the phenomenologically required very short thermalization time scale, pointing to strong non-perturbative dynamics in the QGP even at or above 2Tc.... The quark-hadron phase transition is arguably the most strongly coupled regime of QCD.
  - Atomic plasmas:
    - Strongly coupled $\Rightarrow \Gamma \equiv$ <Coulomb>/<Kinetic> > 1

$$\Gamma = \langle \alpha_S(T)/r \rangle / 3T \sim \alpha_S(T) n^{1/3}/3T \sim \alpha_S(T)[\,5T^3\,]^{1/3}/3T = 0.6\alpha_S(T) \sim 1$$

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Future Directions

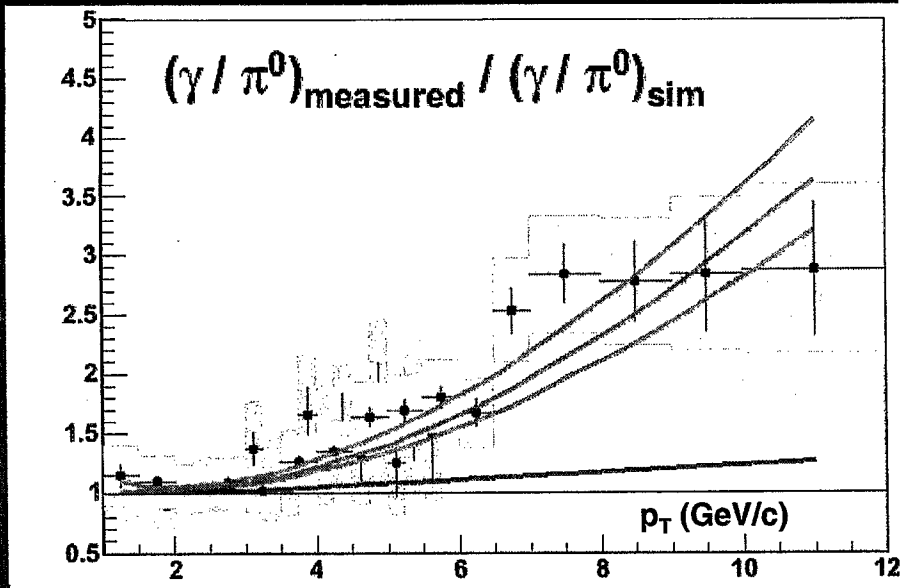
- **Again, quote U. Heinz from PANIC-2002:**

"But much more is to come: only now, with RHIC finally running at full energy and luminosity (and, hopefully, for the full promised time per year) it is possible to address such hallmark measurements as thermal dilepton and direct photon emission and heavy quarkonium production, all of which play crucial roles in the early diagnostics of the QGP which we are apparently mass-producing at RHIC. While trying to solve the HBT puzzle and to quantitatively understand jet quenching, we are looking forward to these high-luminosity measurements and any surprises they may bring."

The Shape of Things to Come

- Suppression pattern of J/Ψ's
  - ➡ Sensitive to Debye screening in the deconfined state?
- Direct photons
  - ➡ Seeing the QGP in its own light
- Separate charm and beauty yields
  - ➡ To understand existing indications of no charm energy loss in RHIC matter (consistent with pre-dictions for heavy quarks in a deconfined medium)
- Measure meson modifications
  - ➡ To identify the quasi-particles in the new state
- Measurement of γ+jet correlations
  - ➡ the "tagged photons" of heavy ion physics

➡ All aimed at improving our ability to characterize the new state of matter formed at RHIC



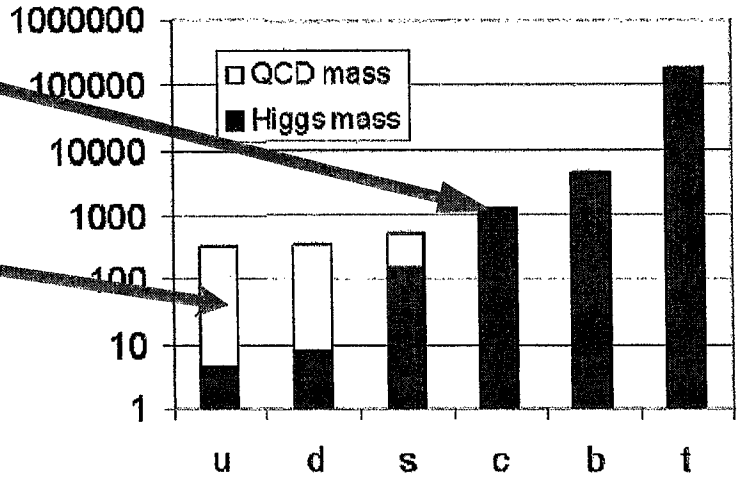


FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking

15-May-04

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On the Road to Discovery

- *An experimentalist does something that everybody believes except himself.*
  A theorist does something that nobody believes except himself.
  - *A. Einstein*

- *Details that could throw doubt on your interpretation must be given, if you know them. You must do the best you can--if you know anything at all wrong, or possibly wrong--to explain it. If you make a theory, for example, and advertise it, or put it out, then you must also put down all the facts that disagree with it, as well as those that agree with it....*

  In summary, the idea is to give all of the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another.
  - *R.P. Feynman*

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Final Remarks

- The production of
  - reliable data,
  - with good inter-experiment consistency,
  - and with careful treatment of systematic errors,

  has been the *hallmark* of the experimental discoveries made to date.

⇨ *This has been recognized in the external community as a new and welcome way of doing business in heavy ion physics.*

- Let's agree to treat our discovery *announcements* with the same precision and care.
- The White Paper process in the experiments, and discussions such as this workshop, are crucial elements in that process.

15-May-04

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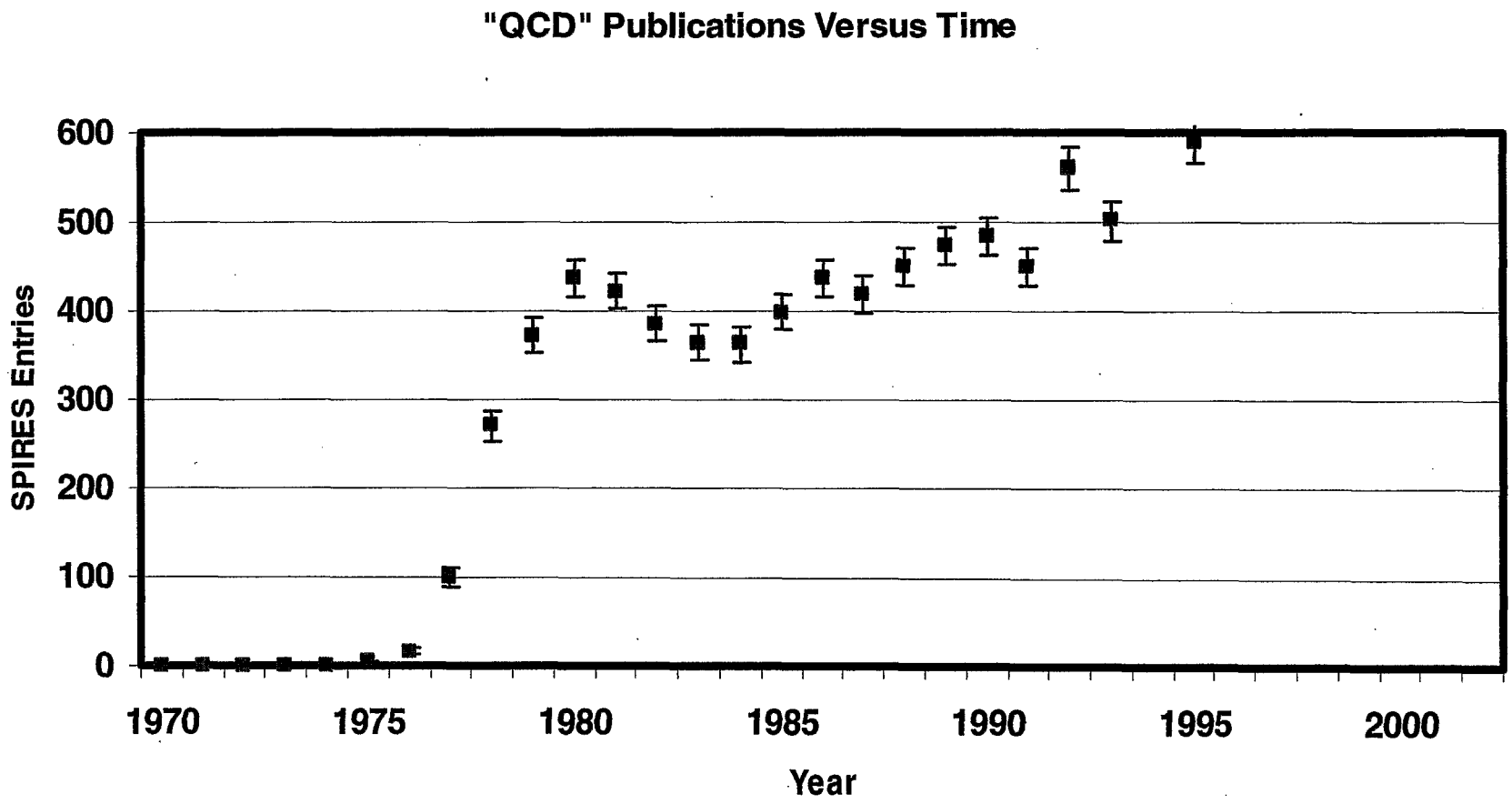
- With the most sincere thanks to the more than 400 PHENIX collaborators who
  - Have worked so hard to produce these accomplishments

and

  - Are working to insure that the future successes will exceed even the impressive accomplishments of the initial years at RHIC

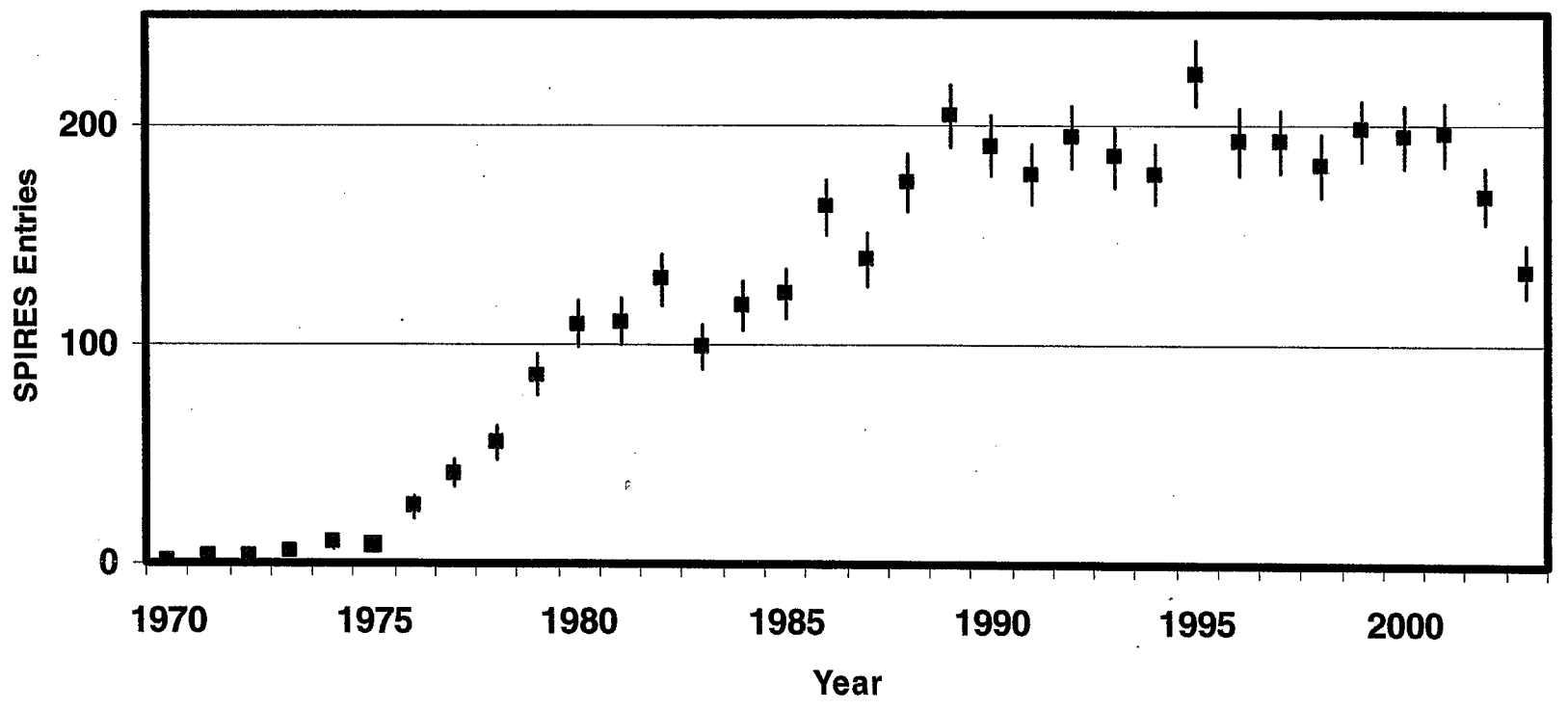
Paradigm Shifts (1)

- Rapid when
  - Theory is clear (and sastisifies Occam's razor)
  - Experimental evidence is clear



Paradigm Shifts (2)

- Not quite as rapid when
  - Theory case remains clear, but
  - Experimental evidence is less direct:



RBRC Workshop

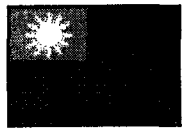
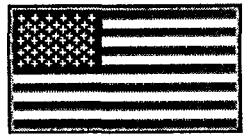
14/15 May 2004

PHOBOS Discoveries at RHIC

Wit Busza

on behalf of the PHOBOS Collaboration

PHOBOS Collaboration (May 2004)

Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Abigail Bickley, Richard Bindel, Wit Busza (Spokesperson), Alan Carroll, Zhengwei Chai, Patrick Decowski, Edmundo García, Tomasz Gburek, Nigel George, Kristjan Gulbrandsen, Clive Halliwell, Joshua Hamblen, Adam Harrington, Michael Hauer, Conor Henderson, David Hofman, Richard Hollis, Roman Holynski, Burt Holzman, Aneta Iordanova, Jay Kane, Nazim Khan, Piotr Kulinich, Chia Ming Kuo, Willis Lin, Steven Manly, Alice Mignerey, Gerrit van Nieuwenhuizen, Rachid Nouicer, Andrzej Olszewski, Robert Pak, Inkyu Park, Heinz Pernegger, Corey Reed, Christof Roland, Gunther Roland, Joe Sagerer, Helen Seals, Iouri Sedykh, Wojtek Skulski, Chadd Smith, Maciej Stankiewicz, Peter Steinberg, George Stephans, Andrei Sukhanov, Marguerite Belt Tonjes, Adam Trzupek, Carla Vale, Sergei Vaurynovich, Robin Verdier, Gábor Veres, Peter Walters, Edward Wenger, Frank Wolfs, Barbara Wosiek, Krzysztof Wozniak, Alan Wuosmaa, Bolek Wyslouch

ARGONNE NATIONAL LABORATORY
INSTITUTE OF NUCLEAR PHYSICS PAN, KRAKOW
NATIONAL CENTRAL UNIVERSITY, TAIWAN
UNIVERSITY OF MARYLAND
BROOKHAVEN NATIONAL LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF ILLINOIS AT CHICAGO
UNIVERSITY OF ROCHESTER

• To date, in Heavy Ion Collisions, *there is no evidence* for the weakly interacting QGP, as naively imagined by a large segment of the community before RHIC turn-on,...

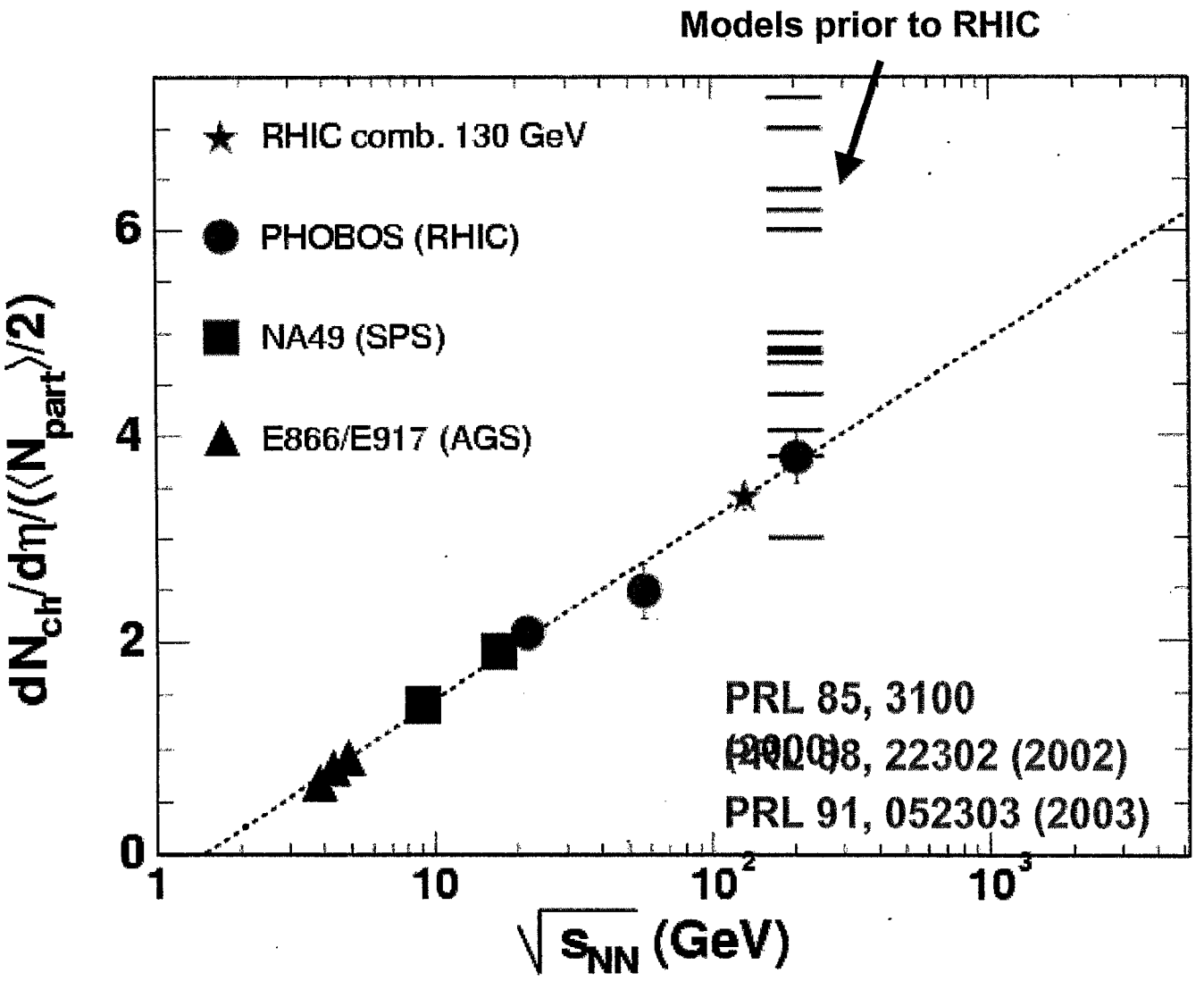
...however,

• We have *discovered* a strongly interacting medium with extremely *high energy density* whose description in terms of simple *hadronic* degrees of freedom makes no sense;

• Furthermore, we have *discovered* that much of the data can be expressed in terms of *simple scaling rules* which suggest the existence of strong global *constraints*.

...Key early PHOBOS observation...

Particle Density near Mid-Rapidity



In Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV

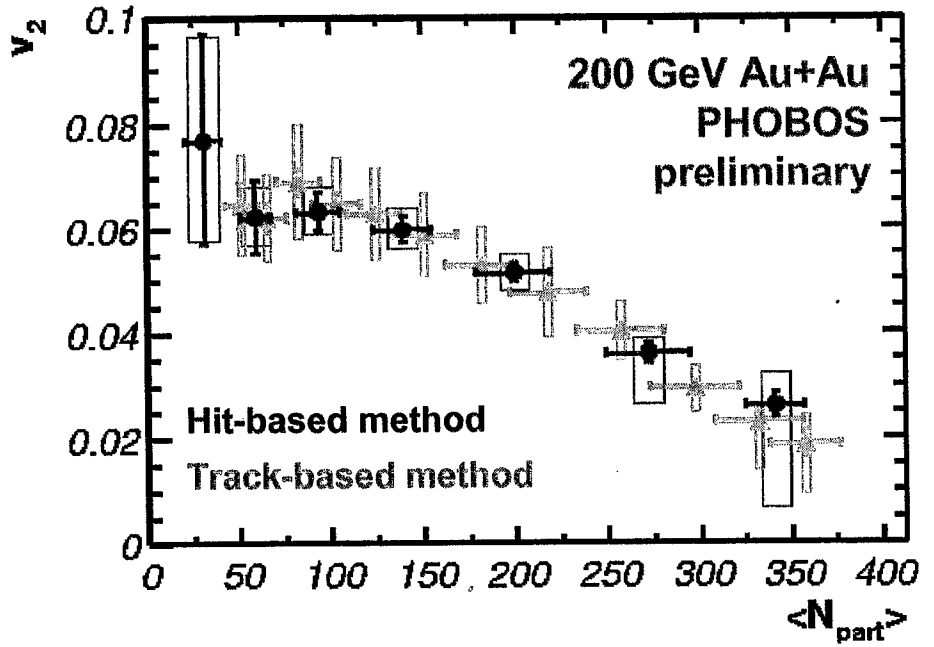
- **Maximum released energy is at mid-rapidity**
- **In a system at rest with the center of mass**

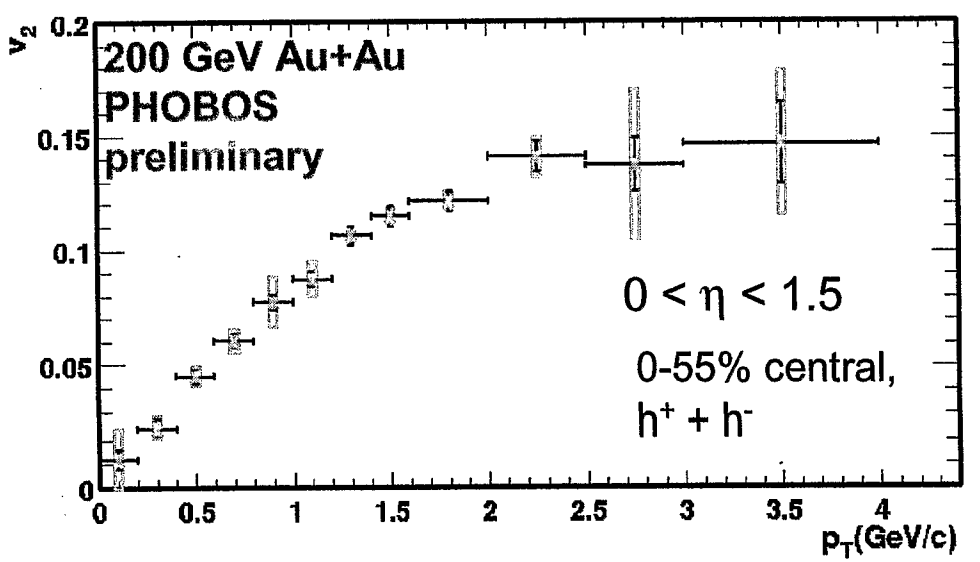
  Energy/volume > 5 GeV/fm^3

→ **It makes *no sense* to describe it in terms of *simple hadronic degrees of freedom***

...The high energy system is strongly interacting...

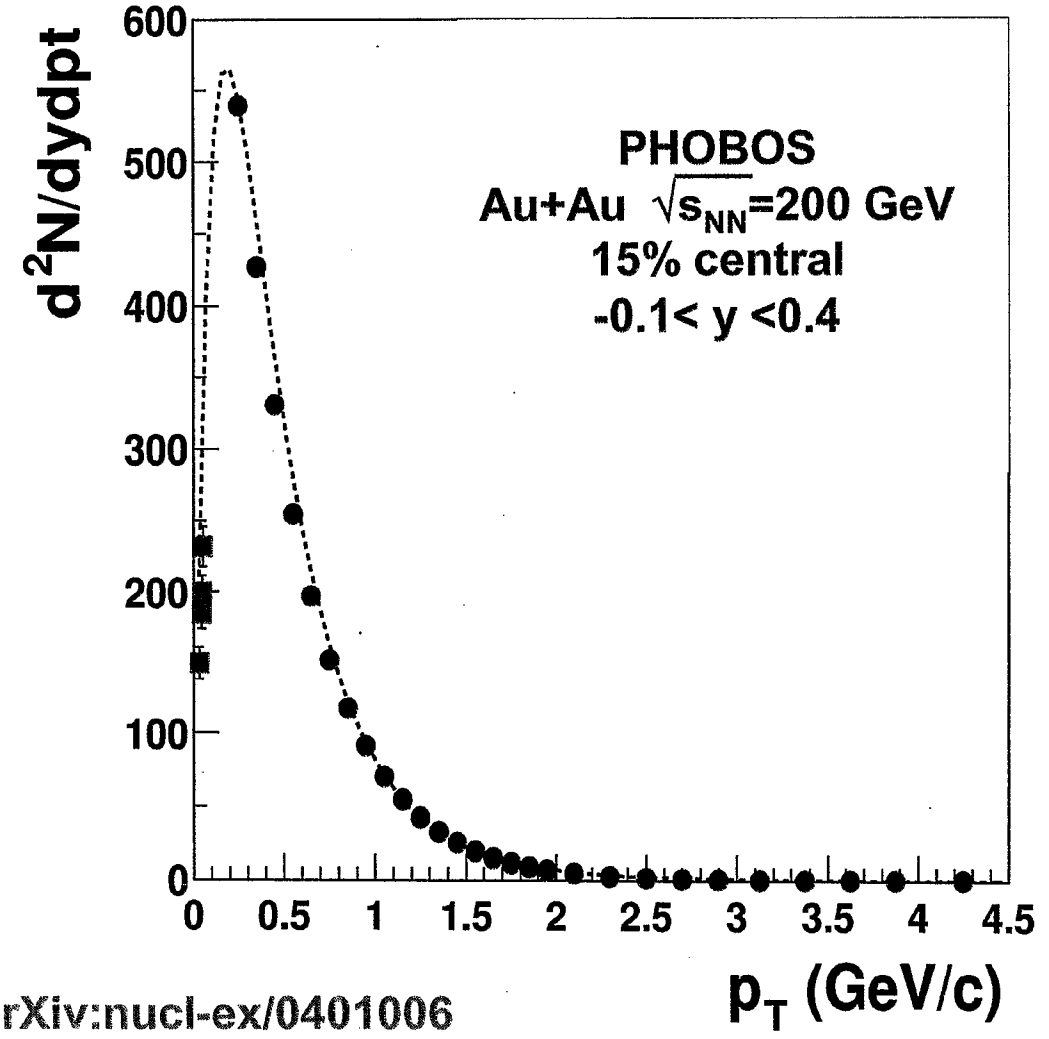
Evidence from flow:





Nucl. Phys. A715 (2003) 611-614

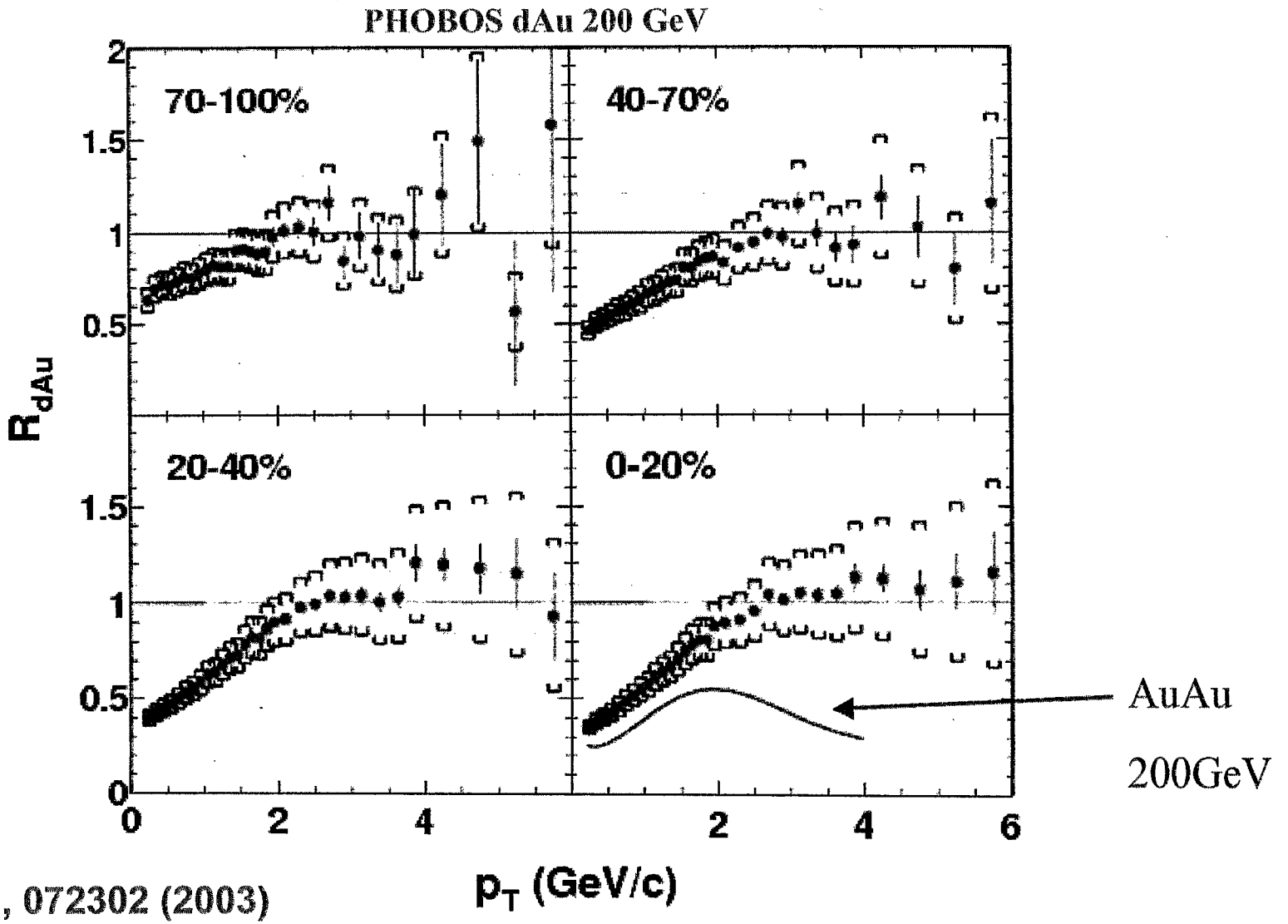
Evidence from the small number of particles produced with very low p_T:



arXiv:nucl-ex/0401006

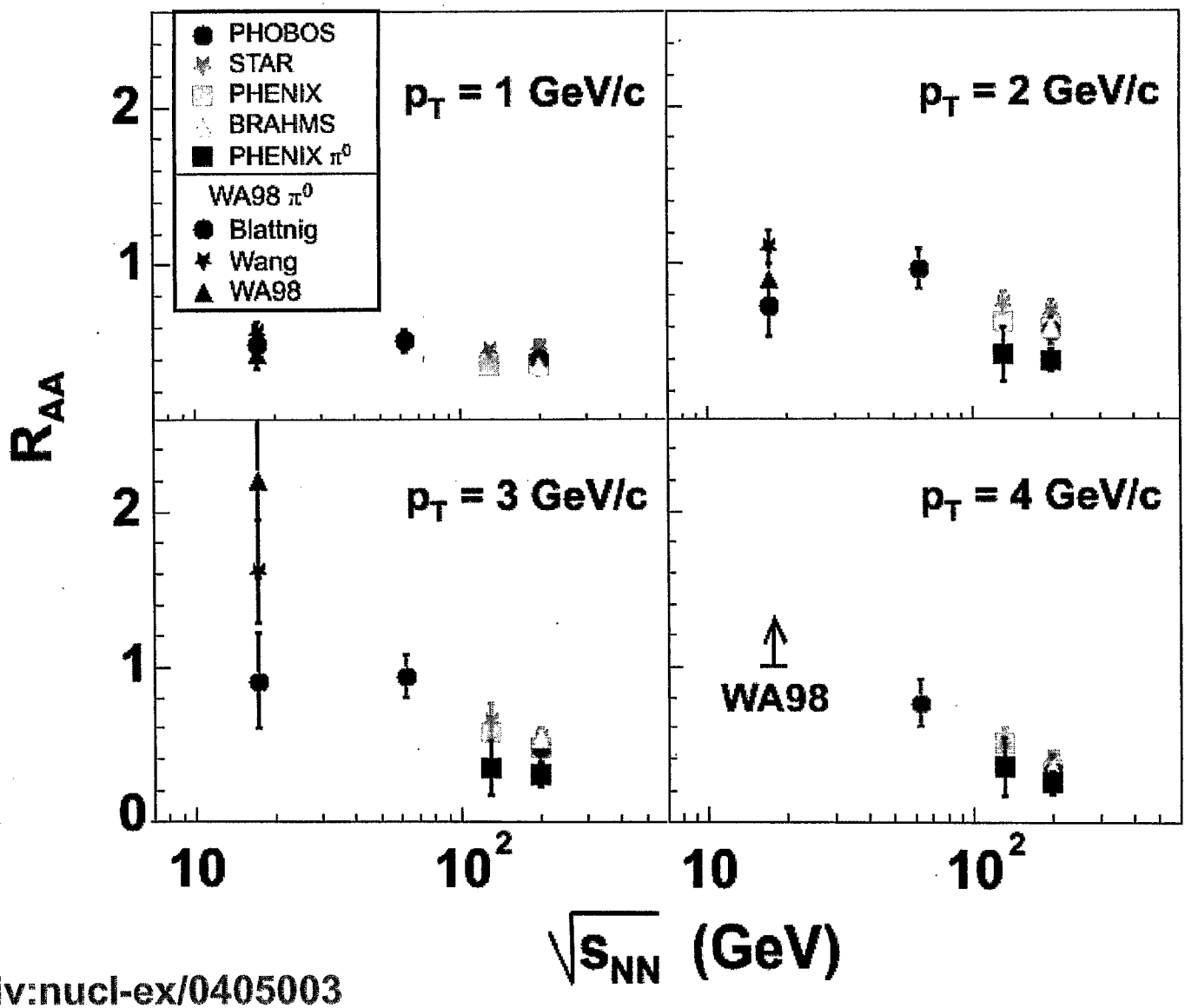
In a large volume weakly interacting system you could expect the development of particles with long wavelength

Evidence from the suppression of high-p_T particles:



PRL 91, 072302 (2003)

R_{AA} as a function of $\sqrt{s_{NN}}$



arXiv:nucl-ex/0405003

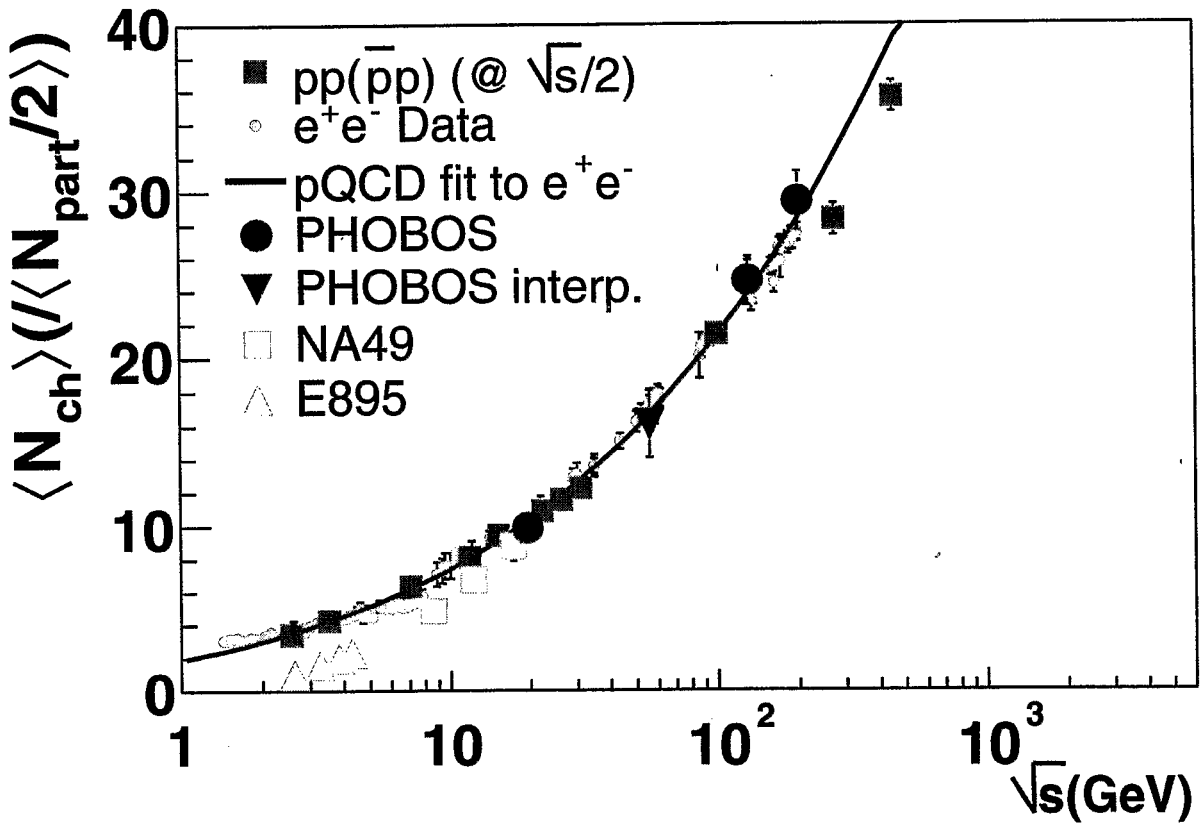
Discovery of simple <u>scaling rules</u>…

…in other words,

discovery of <u>global constraints</u>

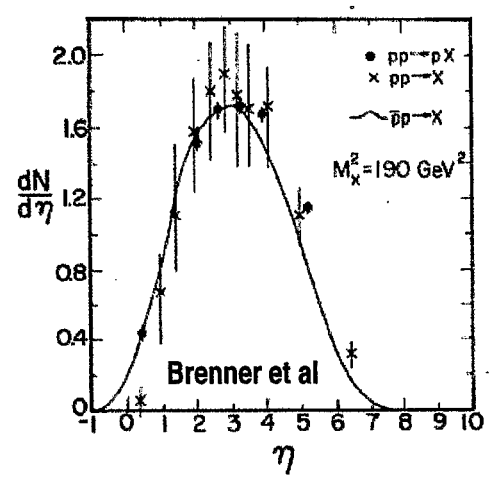
Energy dependence of particle production

1. Universality of total multiplicity
2. Limiting fragmentation



arXiv:nucl-ex/0301017

Note: In pp collisions, on average, approximately half the energy goes into the leading baryon



$pp \to pX \equiv pp \to X$

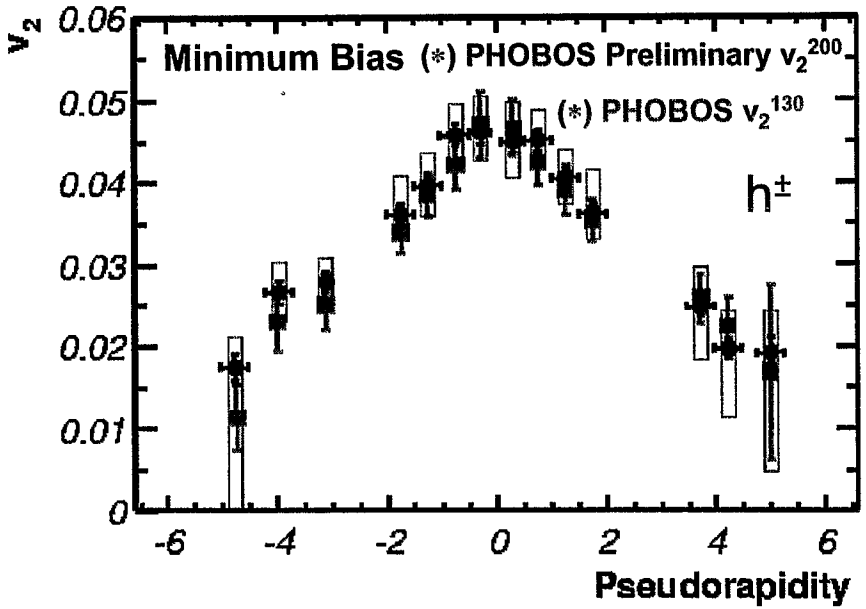
provided M_x^2 is the same

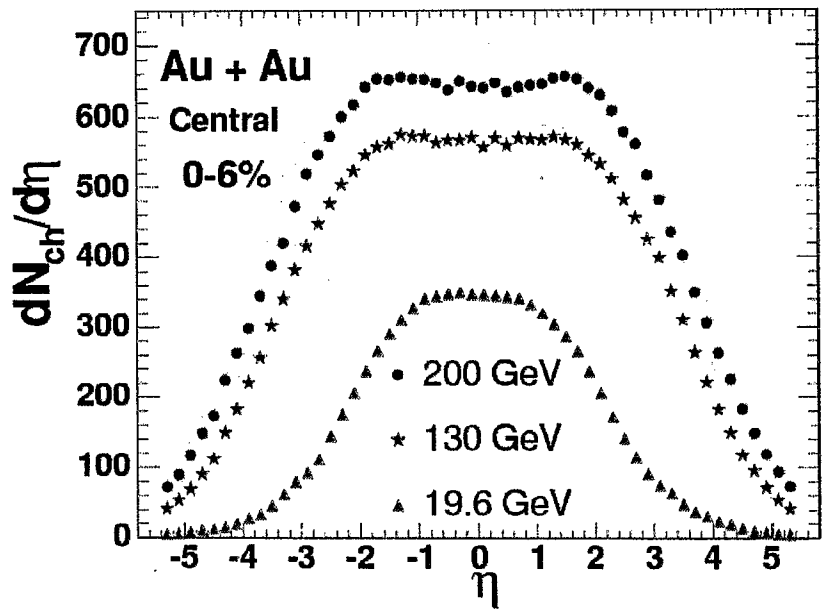
A.Brenner et a., Phys.Rev.D26 (1982) 1497l

Energy dependence of particle production

1. Universality of total multiplicity
2. Limiting fragmentation

No boost invariant central plateau seen in v_2 or dN/dy

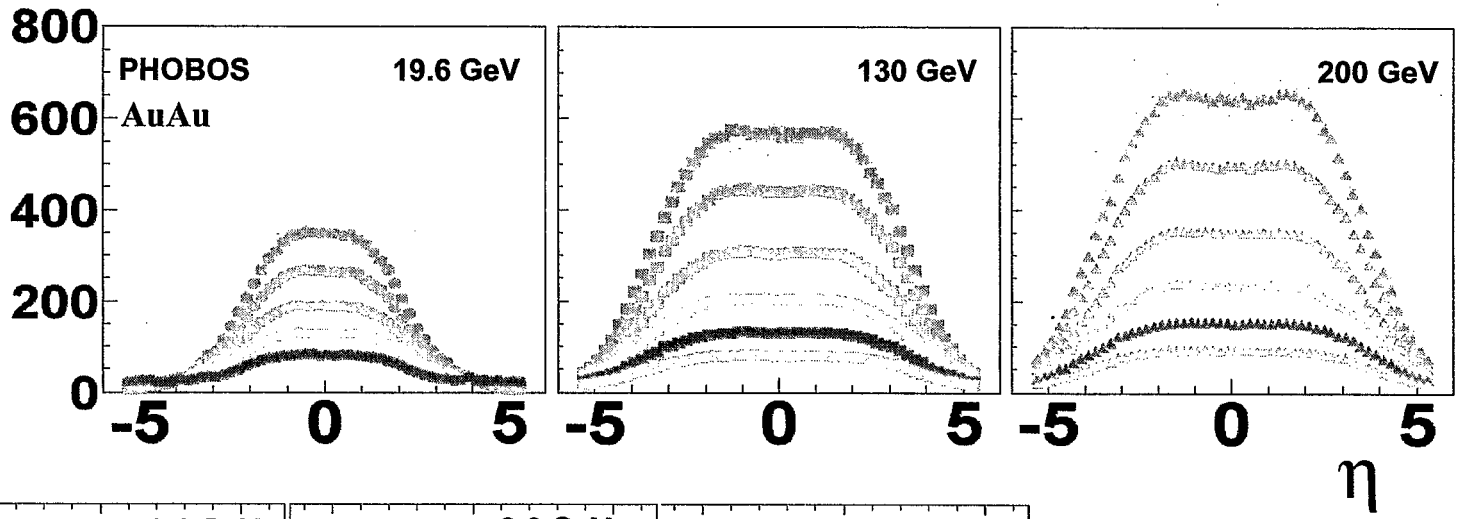




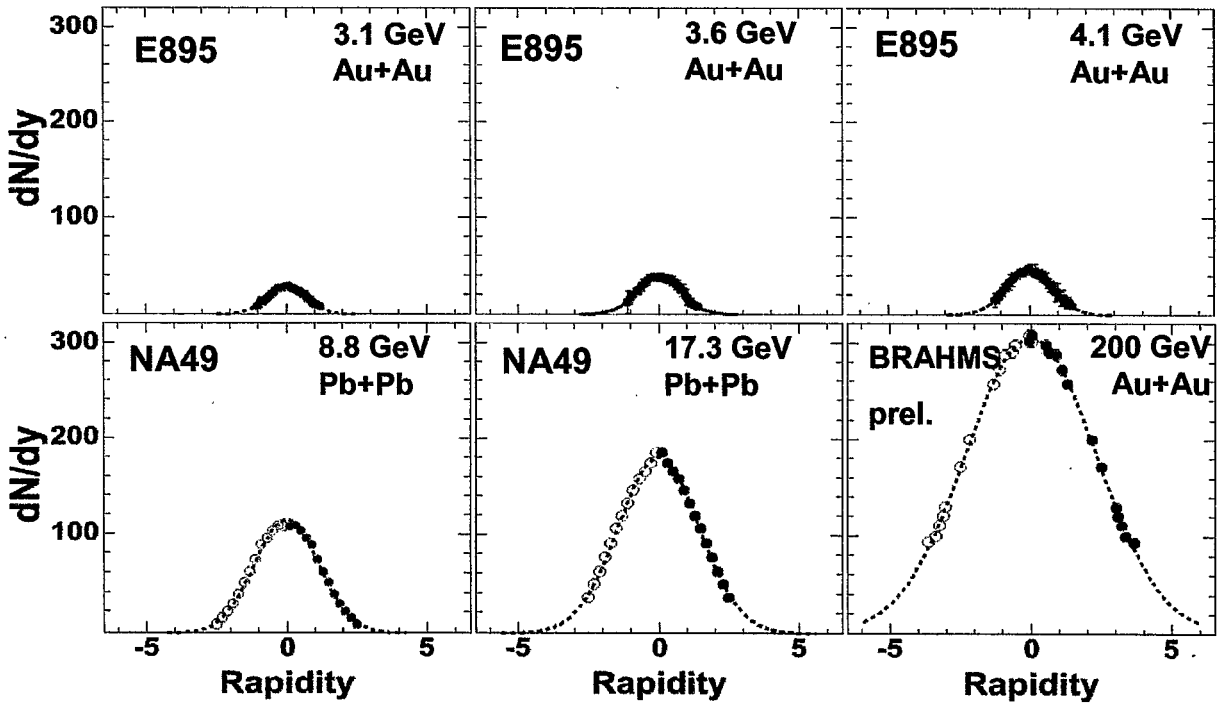
(*) Nucl. Phys. A715 (2003) 611-614
(*) PRL 89, 222301 (2002)

PRL 91, 052303 (2003)

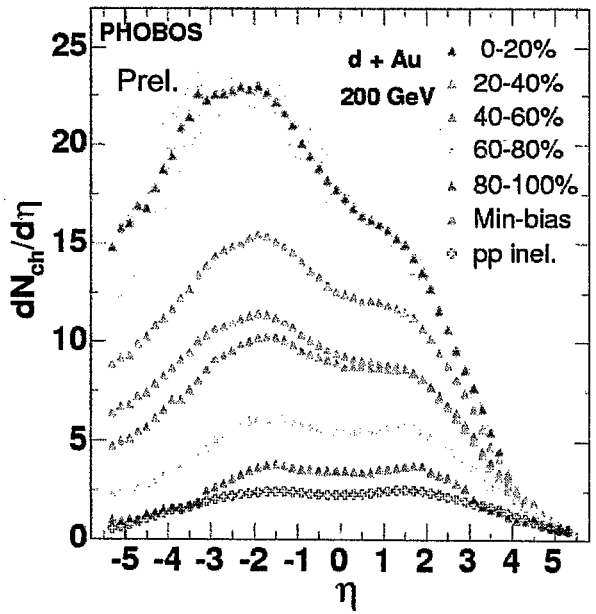
No boost invariant central plateau seen in dN/dy



PRL 91, 052303 (2003)



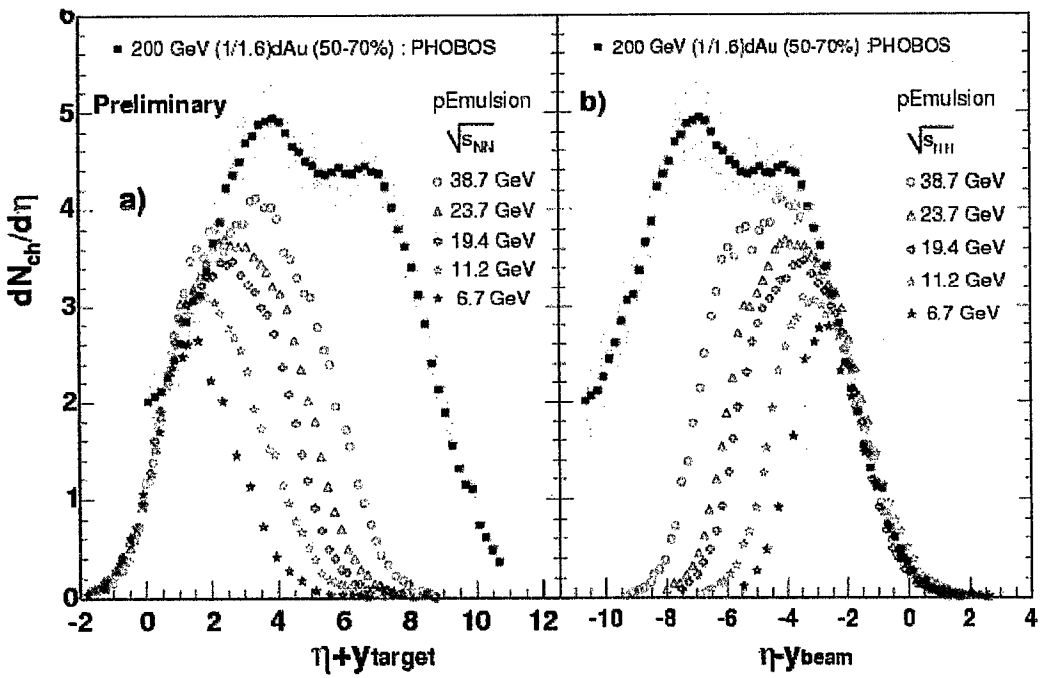
G.Roland, QM2004

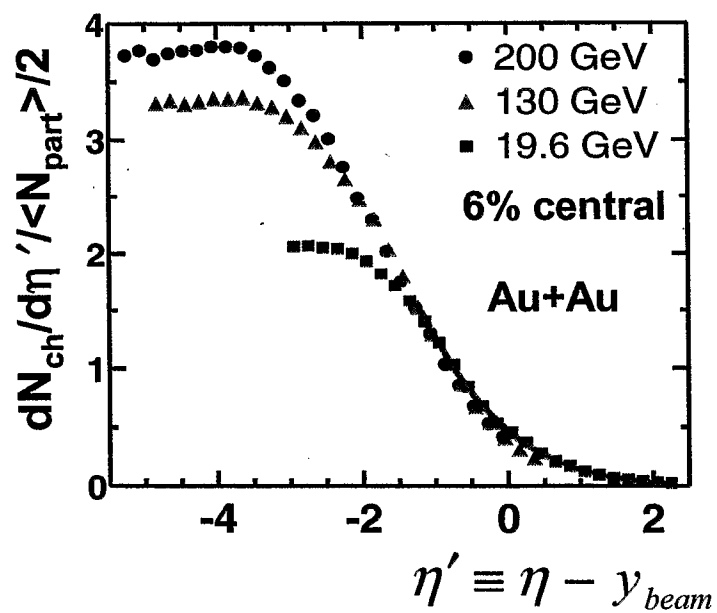


arXiv:nucl-ex/0403033

Universal limiting fragmentation

In rest frame of one of the incident particles:



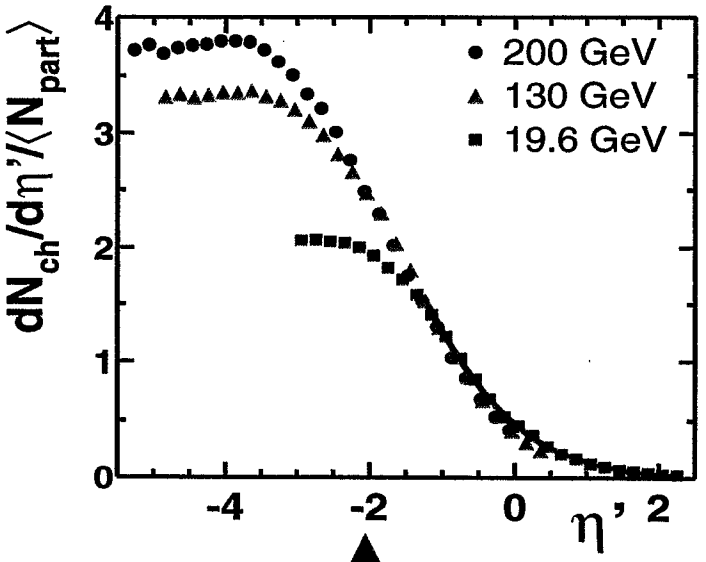


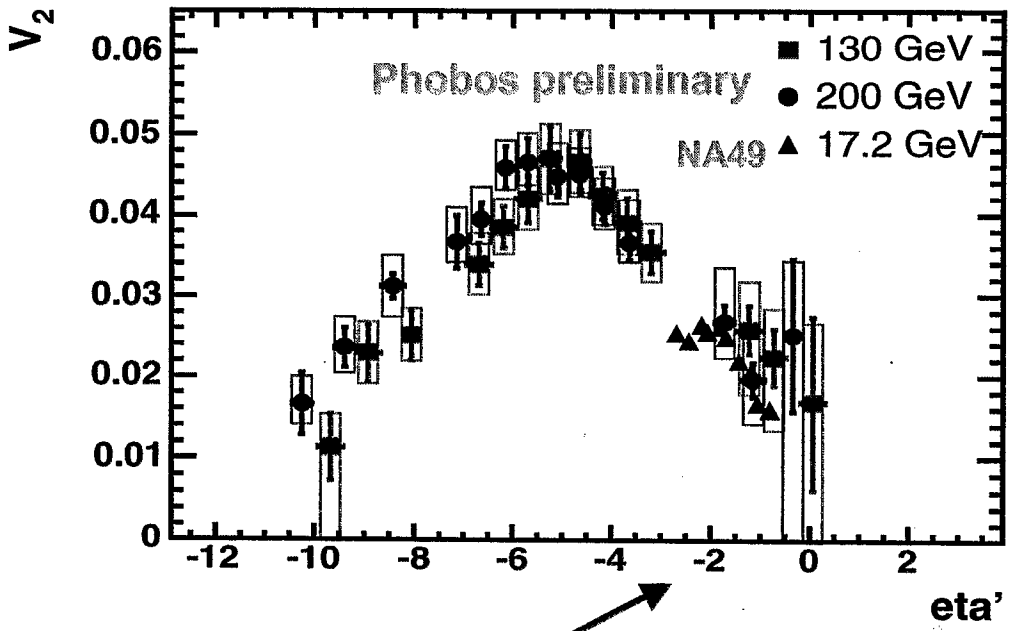
arXiv:nucl-ex/0403033

PRL 91, 052303 (2003)

Elliptic flow:

PRL 91, 052303 (2003)





To see the limiting behavior, imagine that RHIC collided beams with asymmetric energy, with $\eta' = -2$ corresponding to $y = 0$.

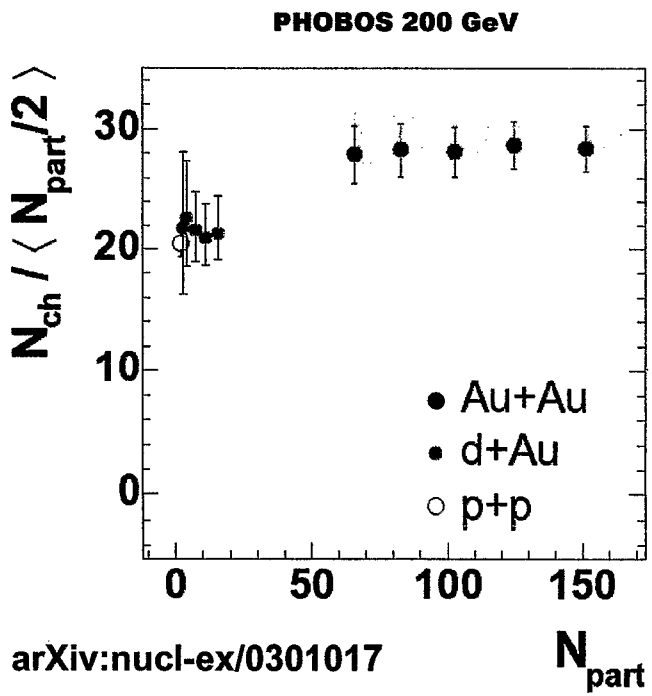
Centrality dependence

N_{part} scaling for:

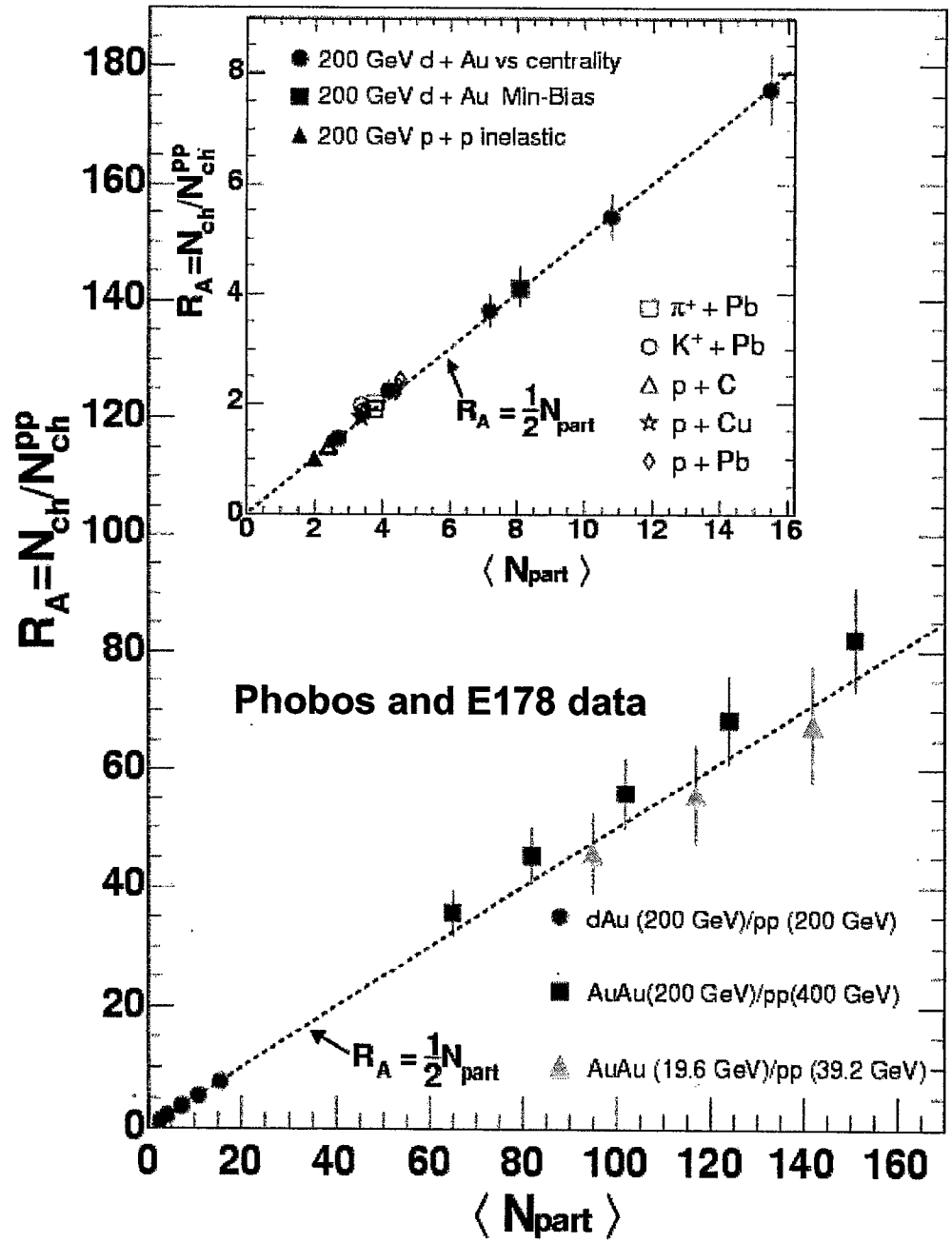
πA, KA, pA, dA, AA

10 GeV to 200 GeV

N_{part} from 2 to 344

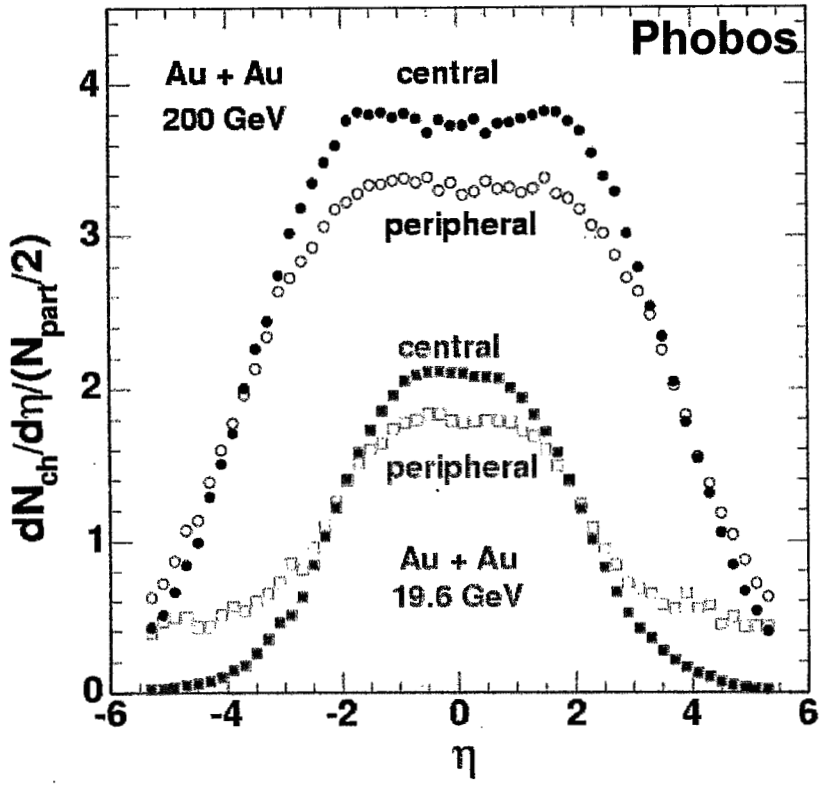


arXiv:nucl-ex/0301017



E178: J.E.Elias et al., Phys.Rev.D22(1980) 13 arXiv:nucl-ex/0403033

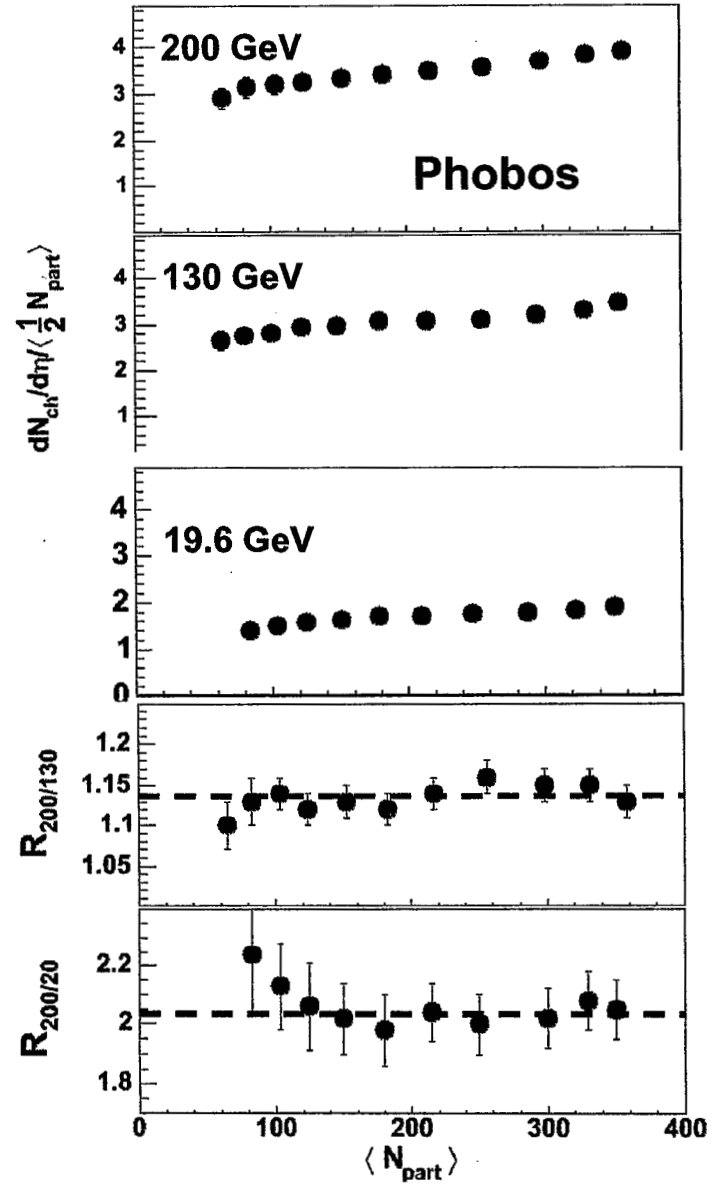
N_{part} scaling for symmetric collisions:



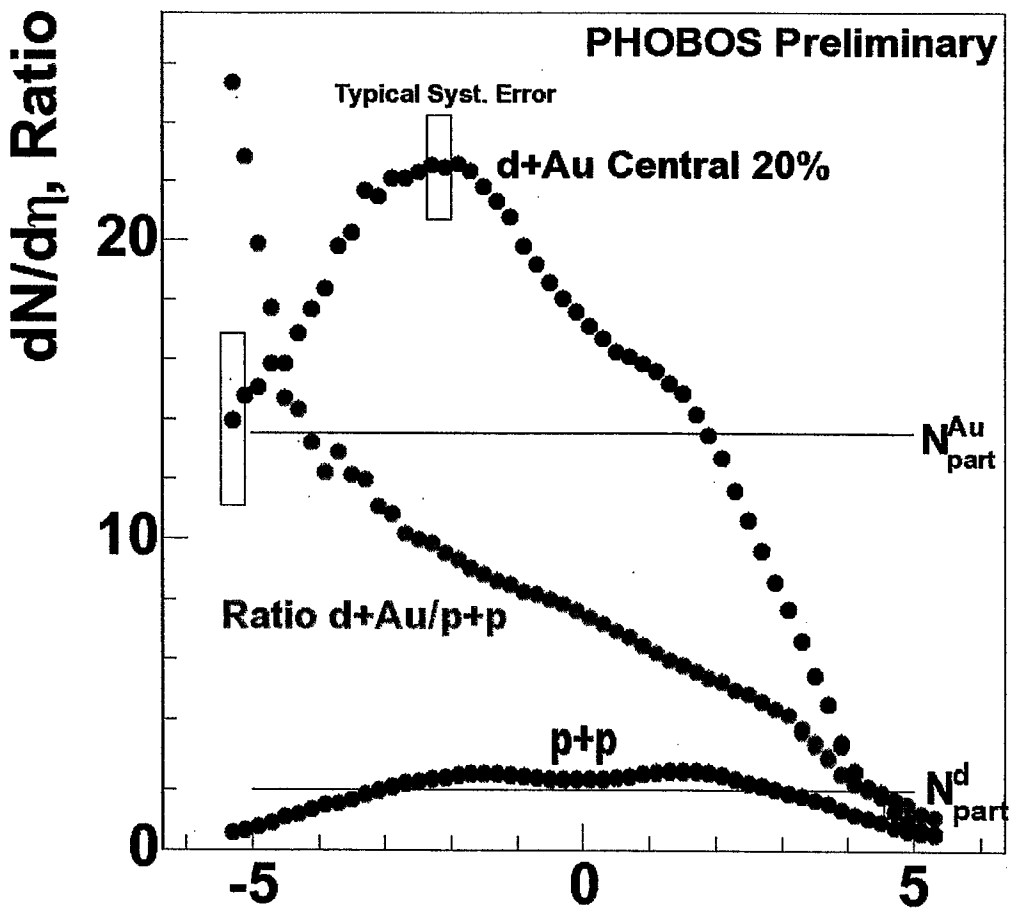
PRL 91, 052303 (2003)

Nucl.Phys. A715 (2003) 65-74

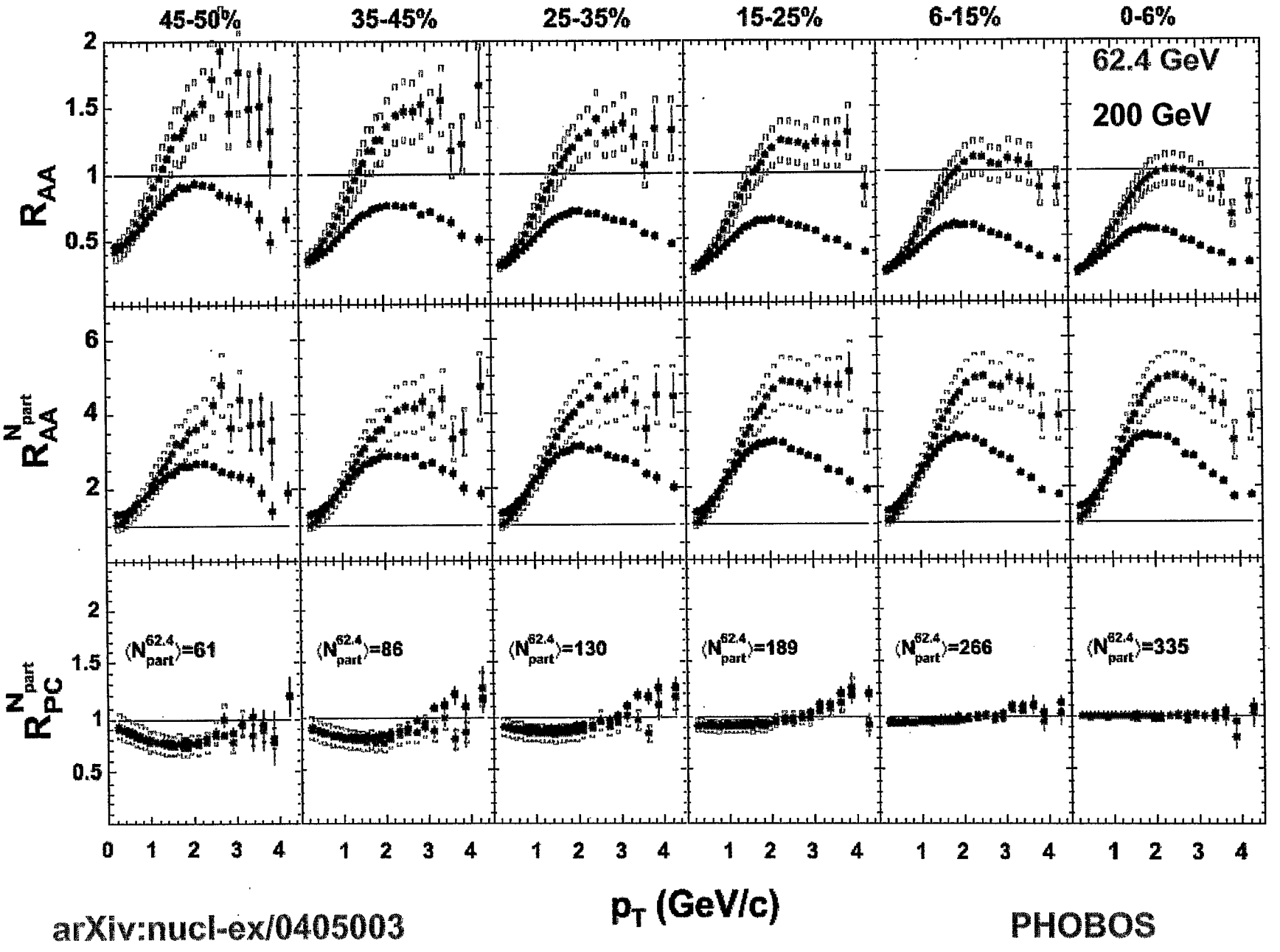
Centrality Dependence at $|\eta| < 1$



N_{part} scaling for asymmetric collisions:



arXiv:nucl-ex/0403033



arXiv:nucl-ex/0405003

PHOBOS

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A critical assessment of evidence obtained in the first three years of RHIC running for QGP formation

Raimond Snellings

For the STAR Collaboration

Introduction

- The main goal of RHIC is to search for QGP formation in the laboratory and study the properties of this state of matter
- We are in the process of assessing what the overall quality of evidence is for the formation of a QGP, based on the data obtained in three successful years of RHIC running (while being close to the end of run 4, the most successful run to date where an *order of magnitude more* data became available)
  - Time scale: collaboration discussion June 12th , available to the public mid-June
- The outline of this talk:
  - Present some of the striking measurements obtained at RHIC so far
  - In our ongoing effort to interpret these striking observation; present questions to the (theory) community which we would like to see discussed in more detail. This will allow us to do a better assessment of the implications of these measurements for the write-up of our whitepaper

The STAR Collaboration: 51 Institutions, ~ 500 People

U.S. Labs:
Argonne, Lawrence Berkeley, and Brookhaven National Labs

U.S. Universities:
UC Berkeley, UC Davis, UCLA, Caltech, Carnegie Mellon, Creighton, Indiana, Kent State, MIT, MSU, CCNY, Ohio State, Penn State, Purdue, Rice, Texas A&M, UT Austin, Washington, Wayne State, Valparaiso, Yale

Brazil:
Universidade de Sao Paolo

China:
IHEP - Beijing, IPP - Wuhan, USTC, Tsinghua, SINR, IMP Lanzhou

Croatia:
Zagreb University

Czech Republic:
Nuclear Physics Institute

England:
University of Birmingham

France:
Institut de Recherches Subatomiques Strasbourg, SUBATECH - Nantes

Germany:
Max Planck Institute – Munich
University of Frankfurt

India:
Bhubaneswar, Jammu, IIT-Mumbai, Panjab, Rajasthan, VECC

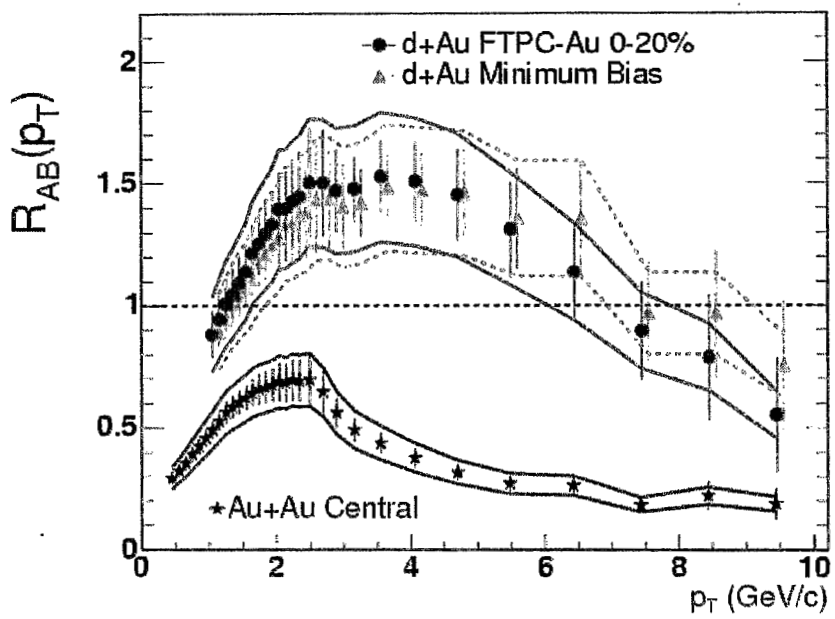
Netherlands:
NIKHEF

Poland:
Warsaw University of Technology

Russia:
MEPHI – Moscow, LPP/LHE JINR – Dubna, IHEP – Protvino

Switzerland:
University of Bern

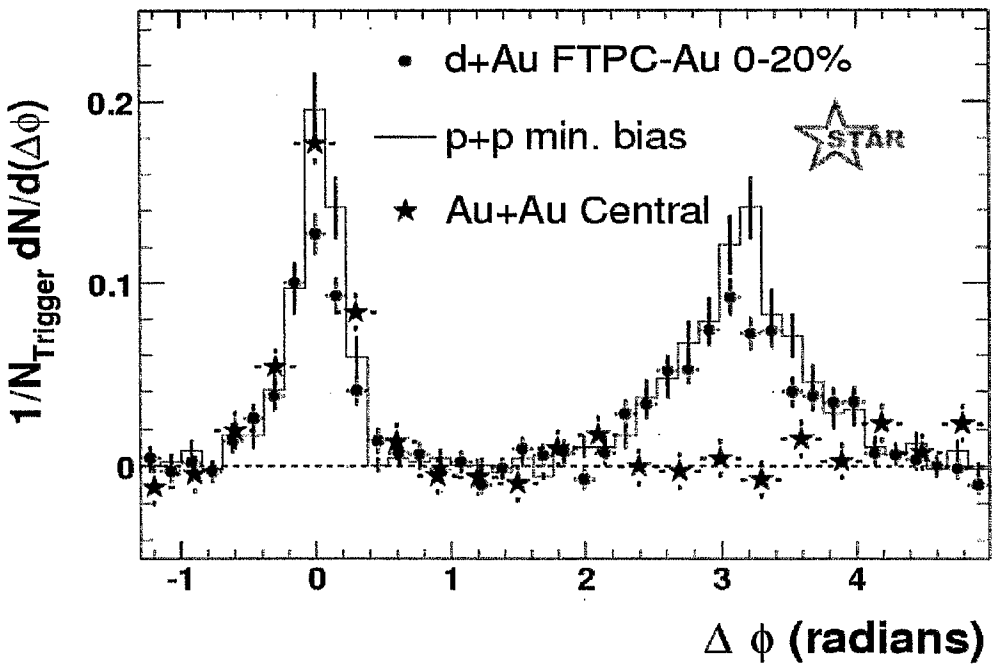
Suppression of the particle yield at high transverse momenta



- Suppression of particle yield is a final state effect!
- Consistent with expectations from parton energy loss in a dense medium!

Strong suppression of the back to back correlation in central Au+Au

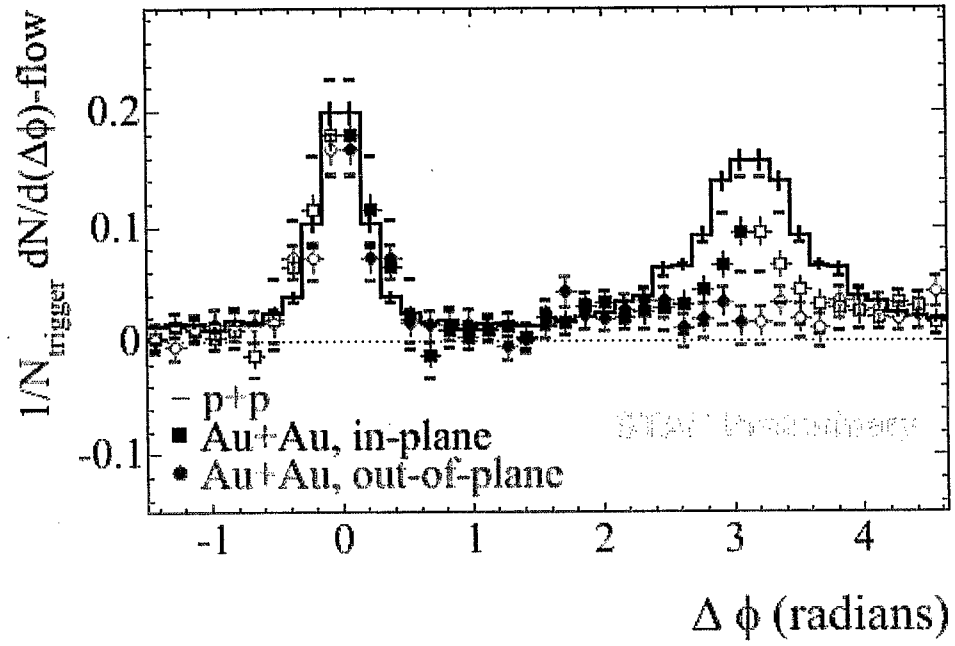
- Back to back supression is a final state effect
- Consistent with expectations of parton energy loss in a dense medium



Trigger particle range 4-6 GeV/c, associated range > 2 GeV/c

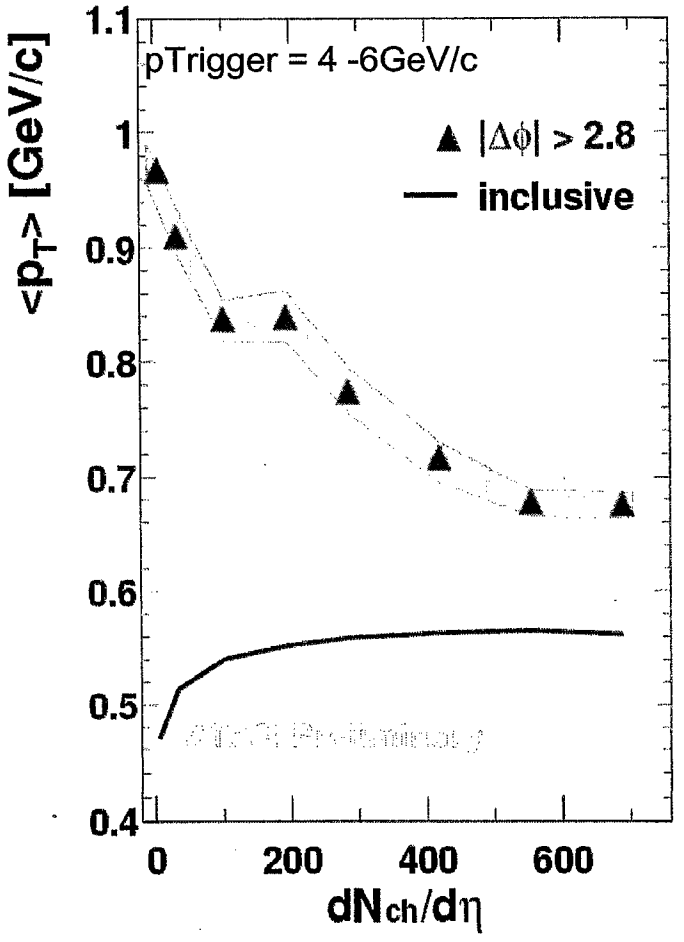
Back to back correlations versus the reaction plane

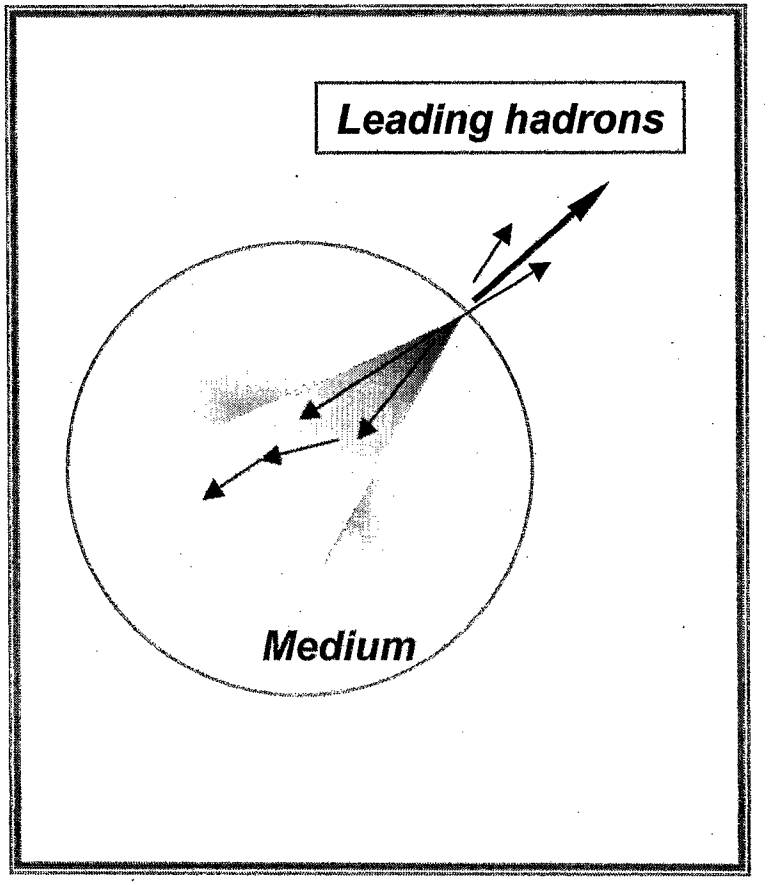
Au+Au centrality:
20-60%



- The back to back correlation depends on the average distance traveled through the medium!

Where does the energy go?



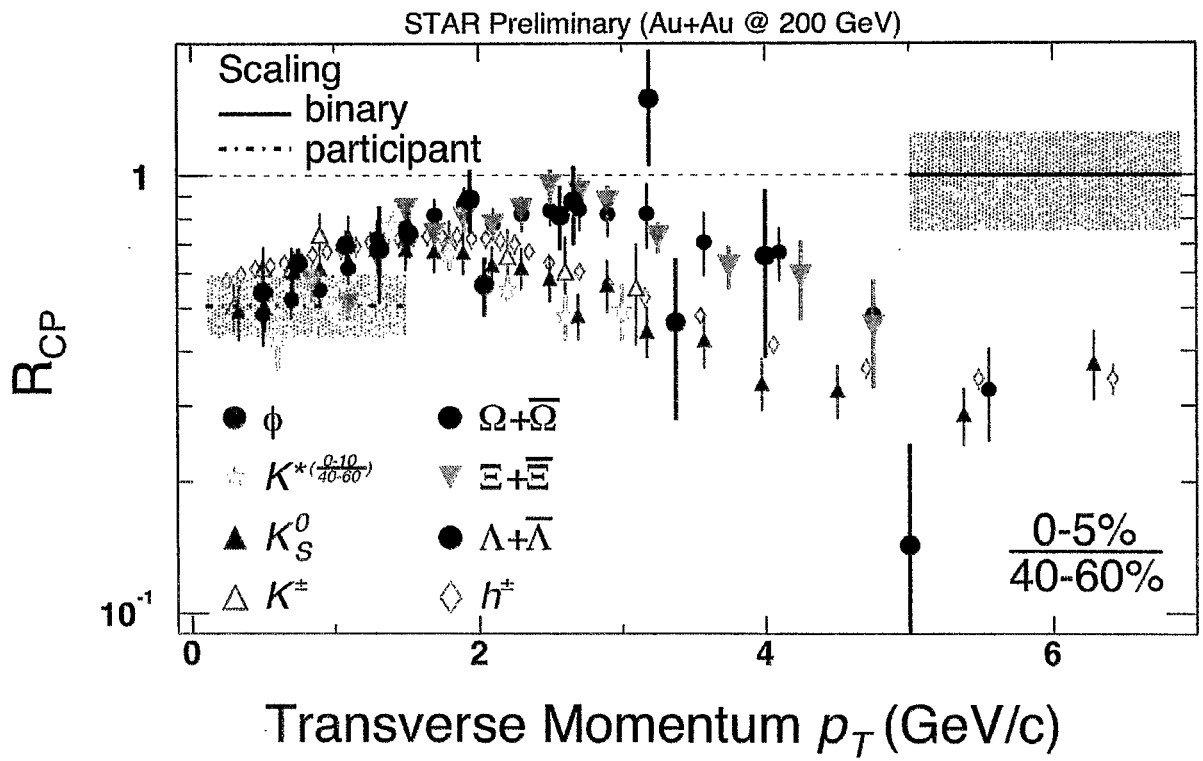


Discovery of the suppression phenomena at RHIC

- The observed strong suppression can be described efficiently by parton energy loss in matter starting with large energy and gluon densities

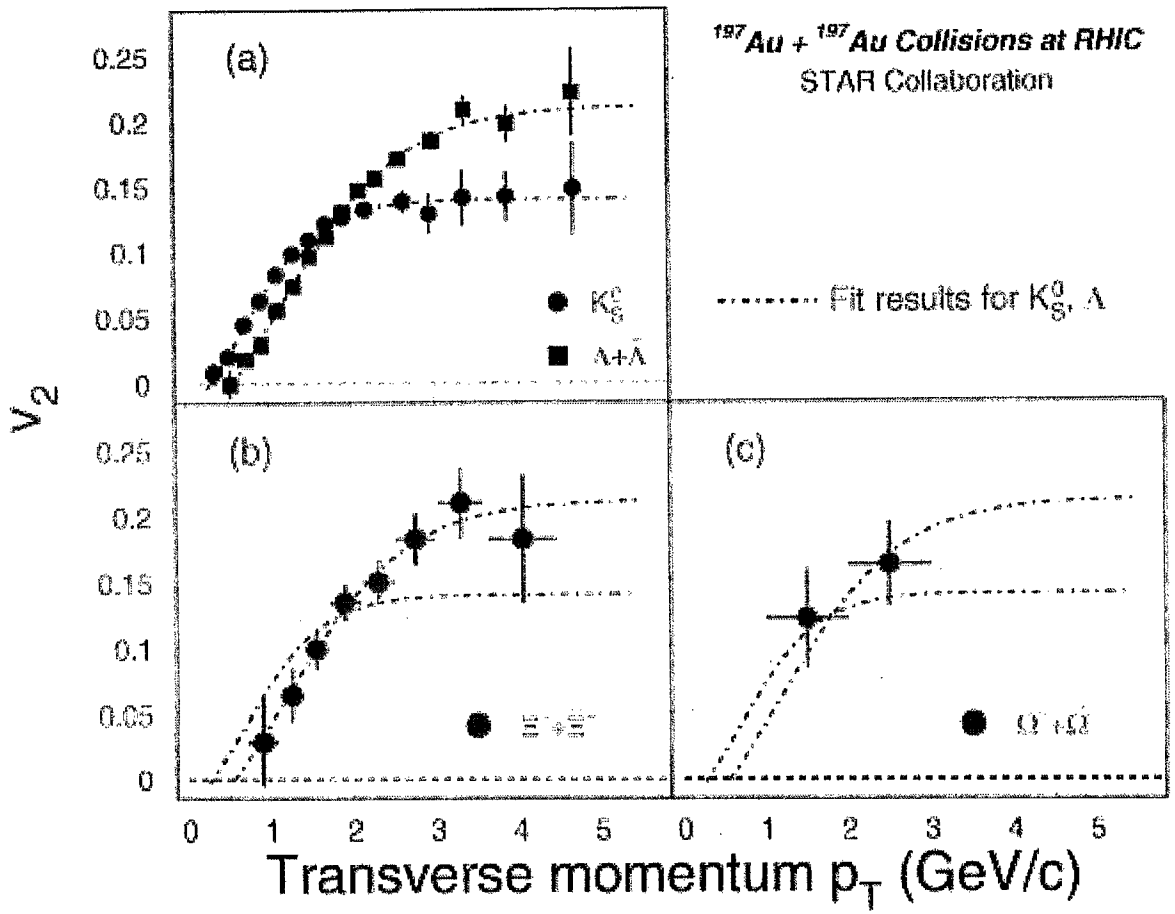
- Does the magnitude of parton energy loss inferred from these observations ***demand*** an explanation in terms of traversal through deconfined matter?
  - What are the uncertainties due to factorization in-medium, in-medium fragmentation versus vacuum fragmentation?
  - How are possible uncertainties amplified due to the longitudinal (and also transverse) expansion of the system?
- Can we ***prove*** from the inferred densities that deconfined matter has been created?

Identified particles at intermediate to high-p_t



- Two groups, baryons and mesons
- At ~5 GeV/c baryons and mesons seem to approach each other
- Suggesting relevance of constituent quarks for hadron production
- Coalescence/recombination provides a description between ~1.5-5 GeV/c

Elliptic flow at intermediate to high-p_t



- Two groups, baryons and mesons
- Suggesting relevance of constituent quarks for hadron production
- Coalescence/recombination provides a description between 1.5-5 GeV/c

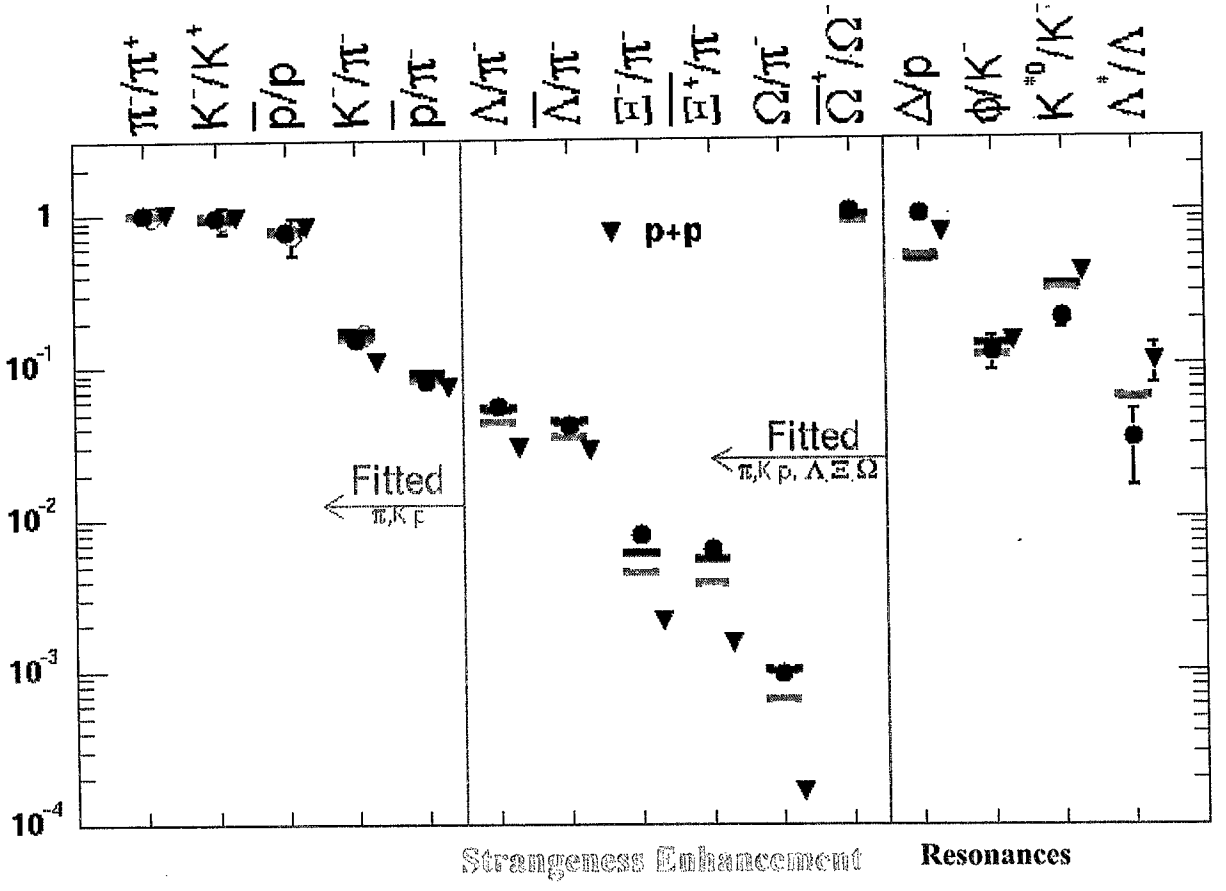
Identified particles at intermediate to high-p_t

- Baryons and mesons scaling is suggestive of importance of constituent quark degree of freedom in hadronization and suggestive of collective flow at the constituent quark level
- This scaling is compactly described in a coalescence/recombination model

- Aside from providing an organizing principle, what predictive power do these models have? Can they predict the correct centrality-dependence of these ratios, or meson vs. baryon correlations (angular or otherwise) at moderate p_t? Does it also still work when applied on models with a more complete space-time evolution?

Particle yields

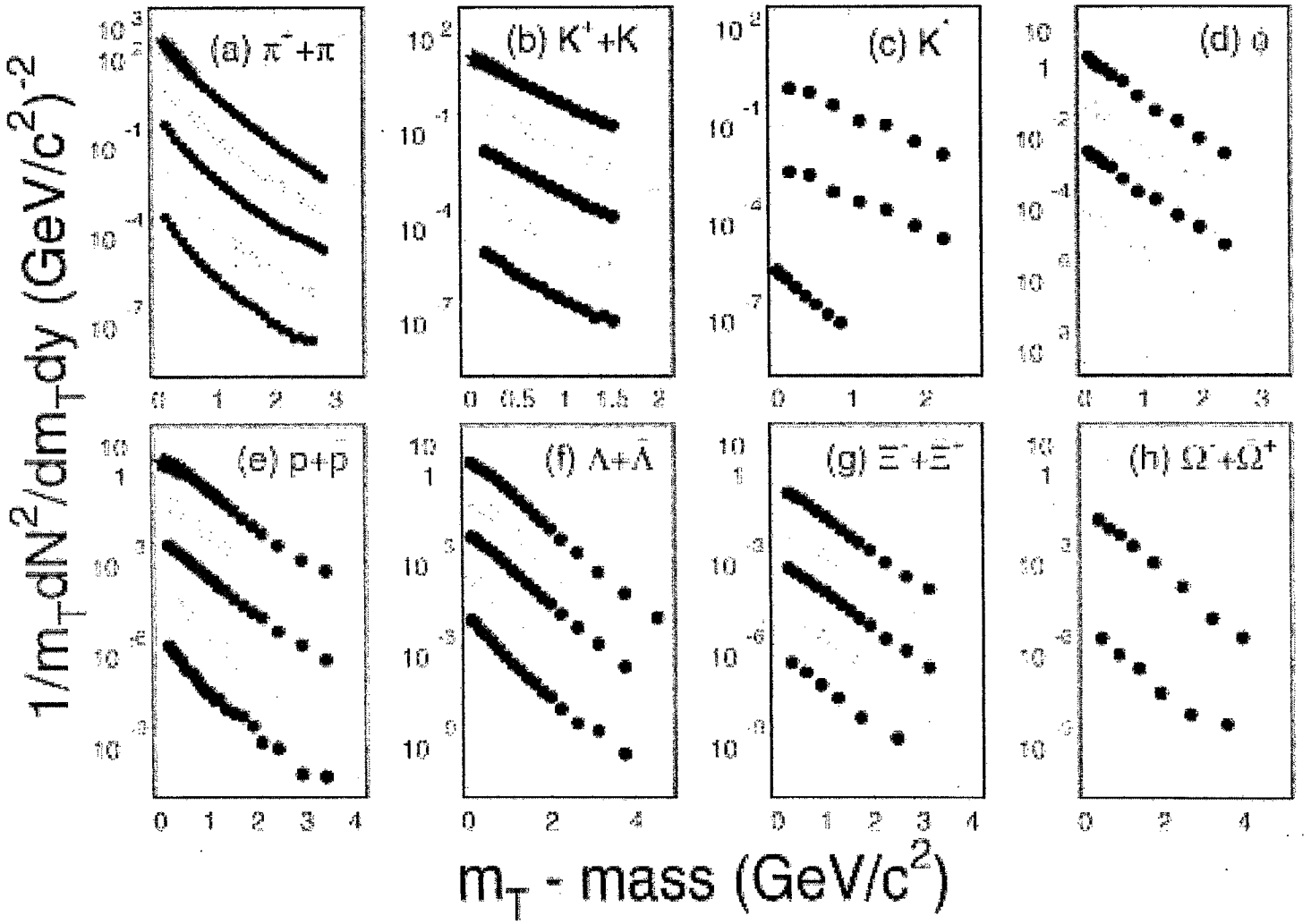
STAR
O PHENIX



- Chemical freeze-out 160 +/- 10 MeV, close to expected critical temperature, particle ratios similar in pp for most abundant species
- Deviations of the resonance yields compared to thermal model predictions indicative of hadronic phase after chemical freeze-out

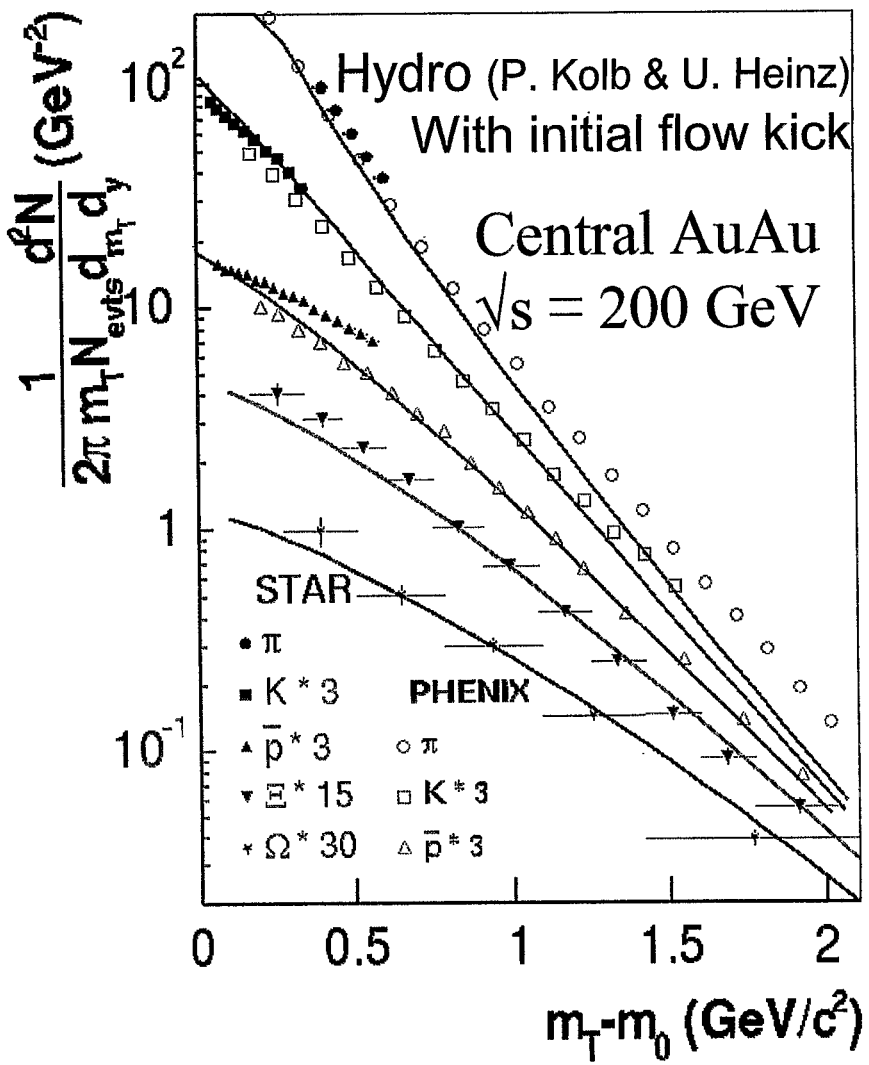
Identified particle spectra

STAR and PHENIX data



PHENIX Phys. Rev. C 69, 034909 (2004)

Identified particle spectra

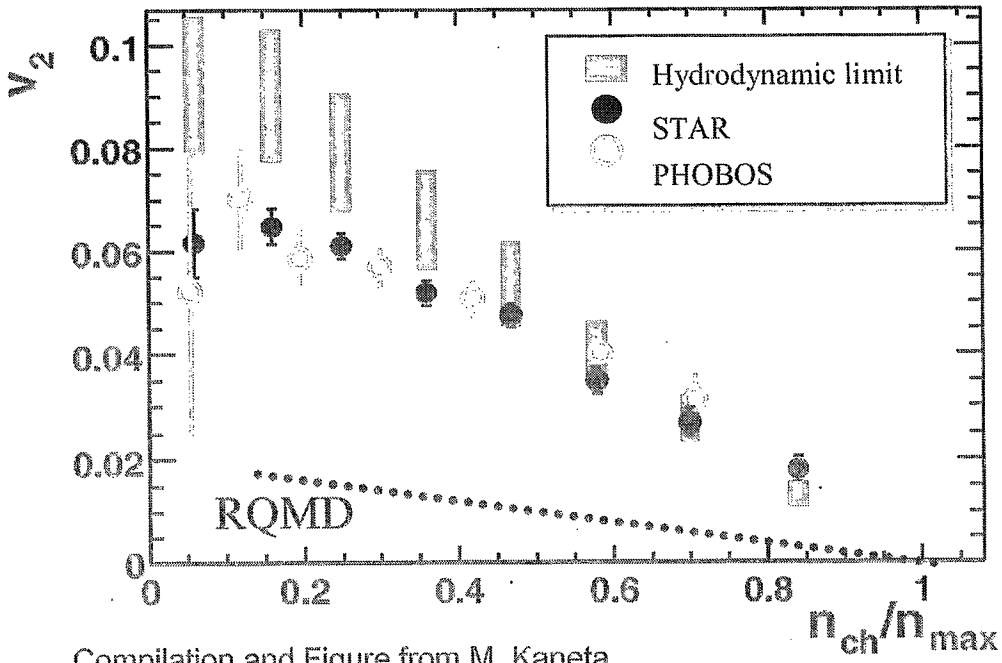


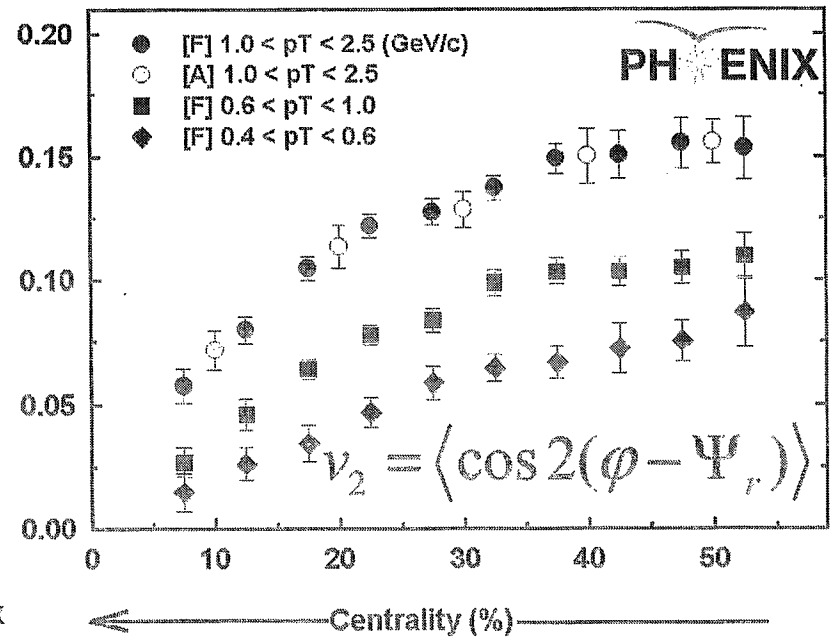
- Mass dependence of particle spectra described reasonably well by ideal hydrodynamics

Charged hadron elliptic flow

PHOBOS: Phys. Rev. Lett. **89**, 222301 (2002)
STAR: Phys. Rev. Lett. **86**, 402 (2001)

PHENIX: Phys. Rev. Lett. 89, 212301 (2002)



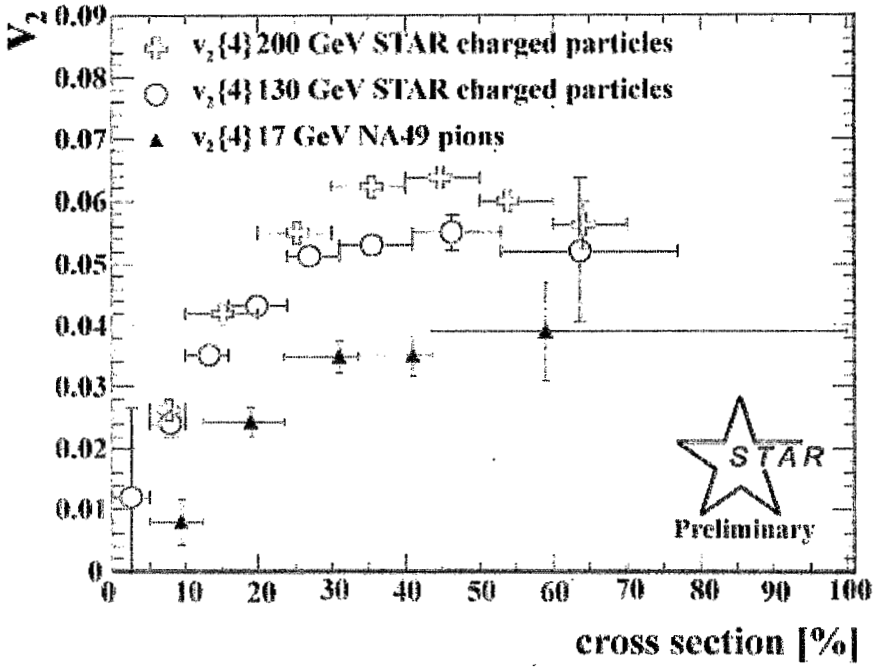


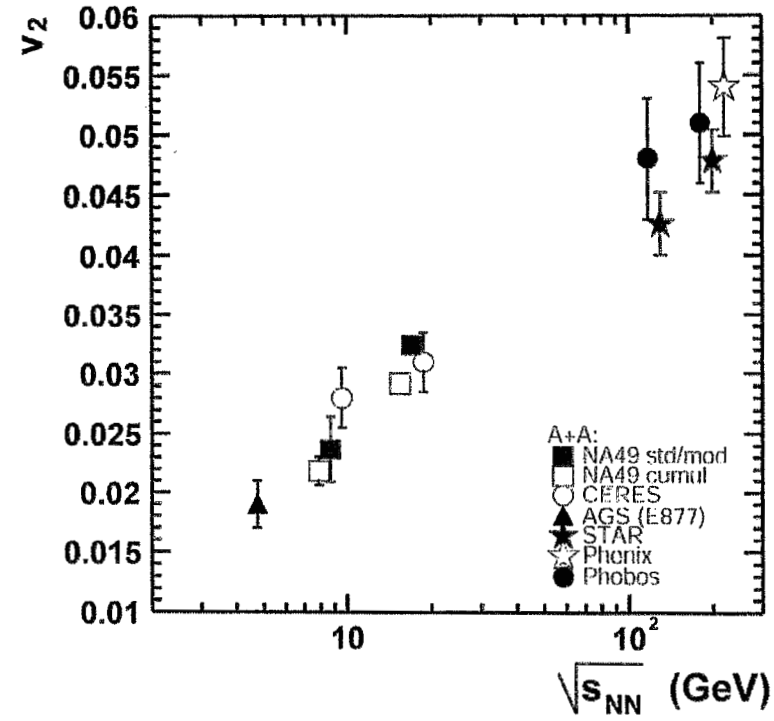
Compilation and Figure from M. Kaneta

p_t is in agreement with ideal hydrodynamic model predictions for v_2 up to mid-central collisions

Energy dependence of v_2

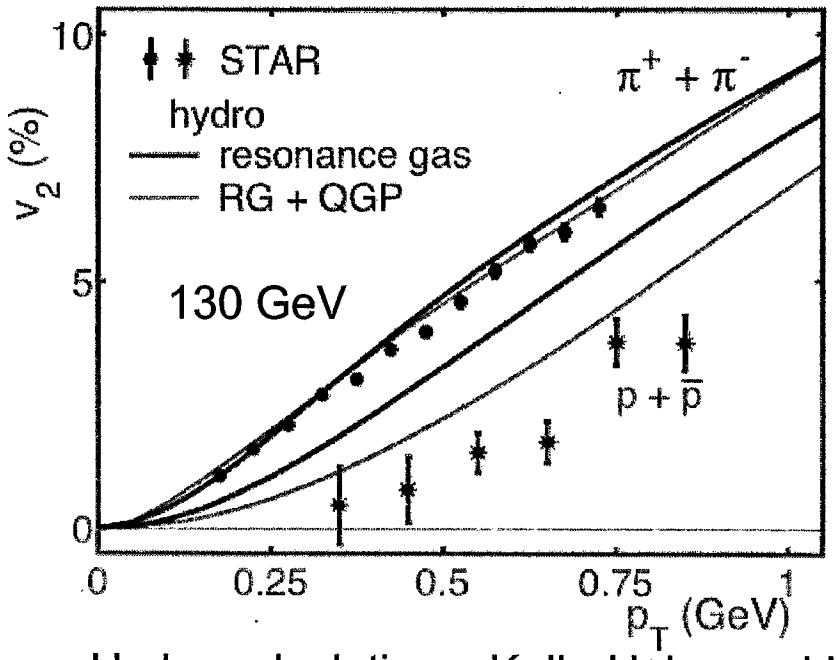
NA49 Phys.Rev. C68 (2003) 034903

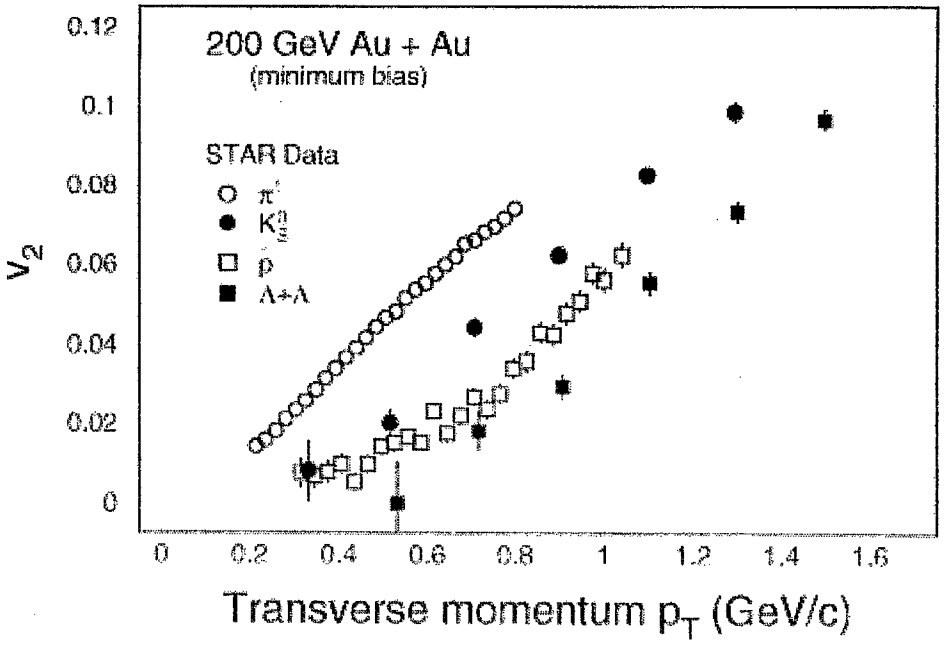




- See: Peter F. Kolb and Ulrich Heinz, review for 'Quark Gluon Plasma 3', nucl-th/0305084. Pasi Huovinen, review for 'Quark Gluon Plasma 3', nucl-th/0305064. D. Teany, J. Lauret and E. V. Shuryak, nucl-th/0110037; Phys. Rev. Lett 86, 4783 (2001)
- Rather smooth dependence versus beam energy

$v_2(m,p_t)$





Hydro calculations: Kolb, Heinz and Huovinen

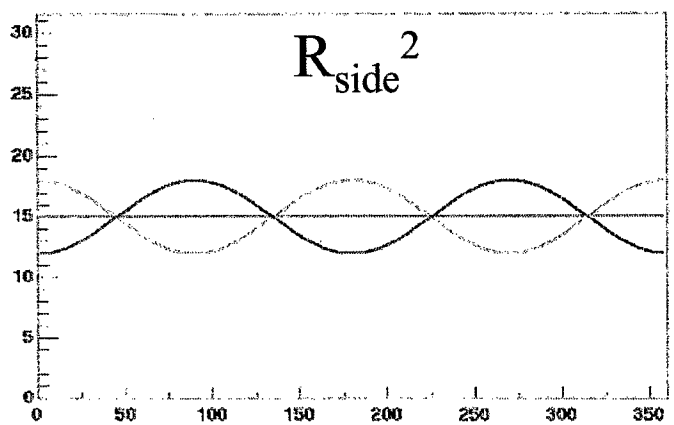
- Clear mass dependence; signature of collective flow (not only in hydro)
- Hydrodynamics gives reasonable description of various mass particles at low transverse momenta
- Hydro calculation constrained by particle spectra

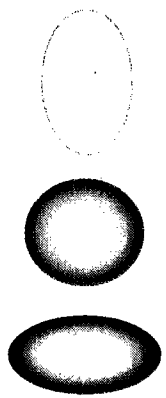
Is the system in approximate local thermal equilibrium?

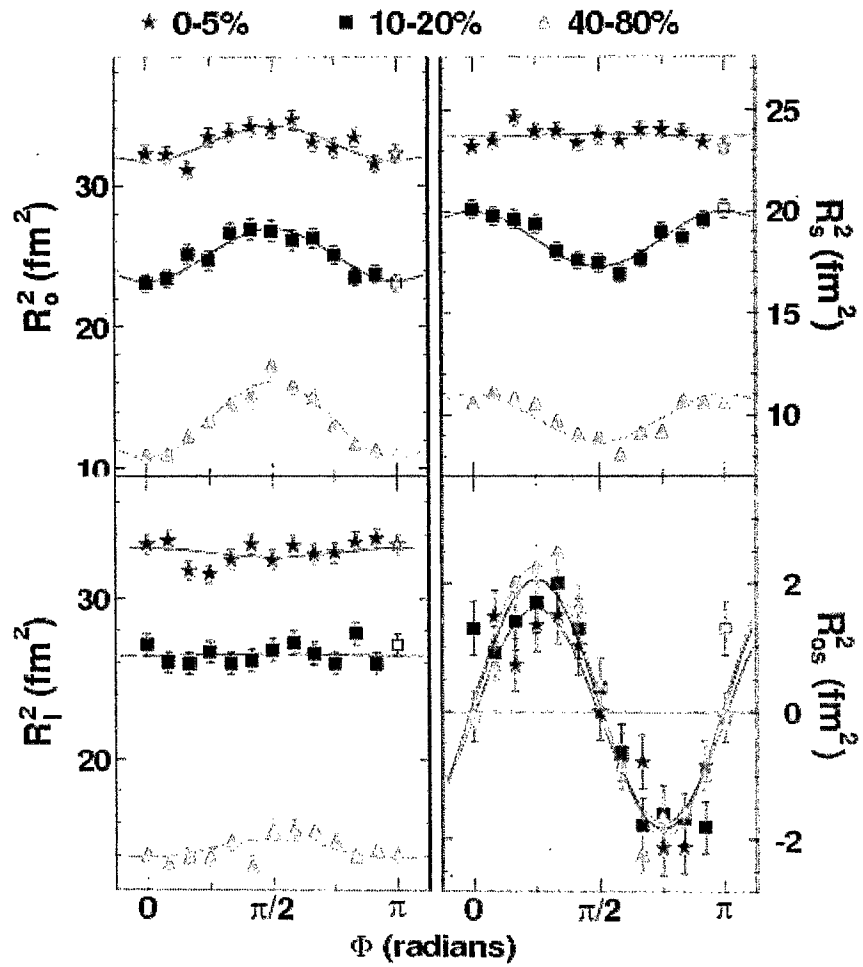
- The unprecedented success of hydrodynamics calculations assuming ideal relativistic fluid behavior in accounting for RHIC elliptic flow results has been interpreted as evidence for both early attainment of local thermal equilibrium and softening of the equation of state, characteristic of the predicted phase transition.

- How do we know that the observed elliptic flow can not result alternatively from a harder EOS coupled with incomplete thermalization? (D. Teaney, J. Lauret, E.V. Shuryak; Phys. Rev. Lett 86, 4783 (2001))

Space-time information

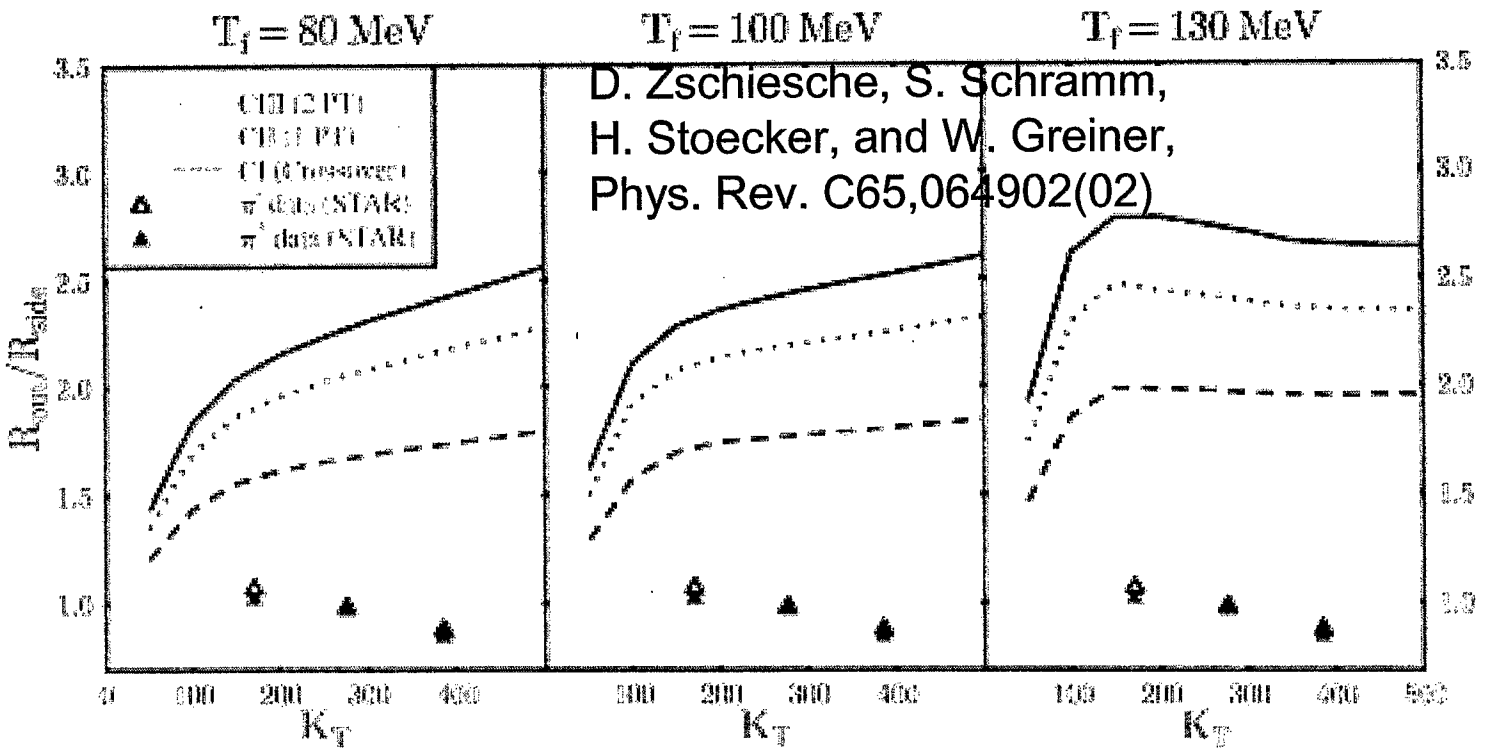






- HBT "radii" show an azimuthal dependence; qualitative centrality dependence fits into picture obtained from v_2 and spectra

Space-time information



- Dynamical models which describe the relatively well the spectra and elliptic flow give a rather poor description of the HBT "radii"
- Key observables like the elliptic flow compared to hydro depend on the time evolution of the system, which seems not completely under control

HBT, spectra and v_2; the soft sector

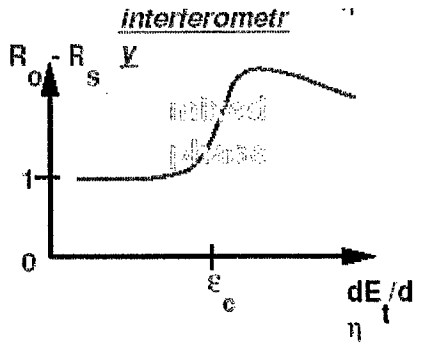
- The indirect evidence for a phase transition in the elliptic flow results comes primarily from the sensitivity in hydrodynamic calculations of the magnitude and hadron mass-dependence of v_2 to the EOS

- How does the level of this EOS sensitivity compare quantitatively to that of uncertainties in the calculations, based the range of adjustable parameters and the failure to describe the spectra, elliptic flow and HBT at the same time?

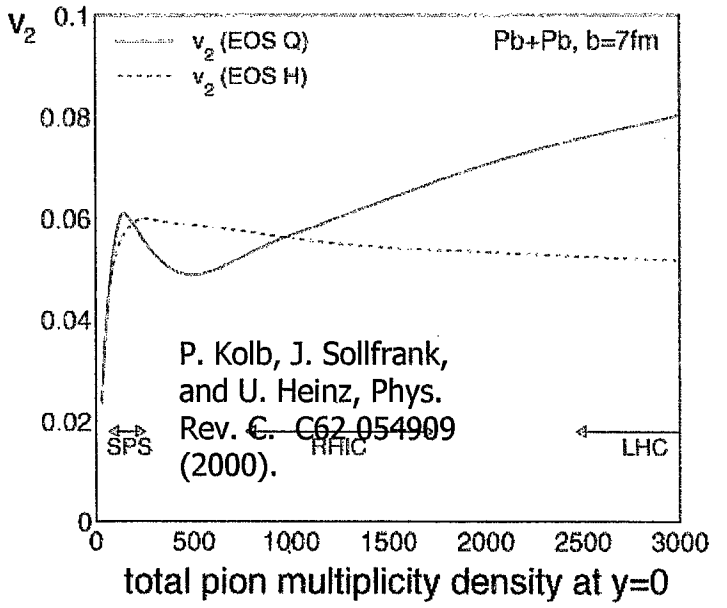
Initial conditions (CGC)

- If there is a truly universal gluon density saturation scale, determined already from HERA *e*-p deep inelastic scattering measurements, why has it been necessary to refit parameters of the saturation scale to RHIC A+A particle multiplicities? Is not the A-dependence of the gluon densities at the relevant Bjorken x-ranges predicted in gluon saturation treatments

Going back in history… (actually even not so long ago)



Harris & Mueller
AnnRevNuclPartSci '96



P. Kolb, J. Sollfrank, and U. Heinz, Phys. Rev. C. C62 054909 (2000).

Critical behavior?

- Is it naïve to expect non-monotonic behavior?
- Can we make a convincing QGP discovery claim without a rapid change in an observable characteristic of a phase transition?
  - Where is the smoking gun?
- Can we predict, based on what we now know from SPS and RHIC, at what energies or under what conditions we produce matter below the critical temperature and which observables from those collisions will show a non-monotonic behavior?

Experimental observations/discoveries

- At RHIC we showed that Au+Au collisions create a medium that is dense, dissipative and exhibits strong collective behavior
  - We observe suppression phenomena in single particle observables and very importantly also in the correlations (large acceptance)
  - We observed baryon meson scaling in v_2 and R_{cp} at ~ 2-5 GeV/c
  - We observe strong collective behavior, manifest in all observables

OBSERVATIONS

Nicholas P. Samios

These are indeed exciting, productive and historic times. RHIC was conceived as a machine with a huge discovery potential and it is meeting all expectations. The underlying theory for the physics of RHIC is Quantum Chromodynamics (QCD). This involves both perturbative and non-perturbative aspects of QCD. This is analogous to Condensed Matter Physics where Quantum Electrodynamics (QED) is the underlying theory. In both cases there are complex phenomena involving collective effects and phase changes. This implies close interaction between theory and experiment. This workshop is a major step in fostering such an interaction between theorists and experimentalists towards understanding the physics emanating from RHIC.

This is also a time for some celebration in light of some major accomplishments. With regard to the RHIC accelerator complex it is clear that it is a well conceived and constructed machine. In its first years of operation it has achieved its design goals and has shown its versatility by running various modes. These have included Gold on Gold (Au x Au) at a variety of energies including full energy (100 GeV/A x 100 GeV/A): Deuteron on Gold at full energy, and polarized protons polarized protons at 100 GeV x 100 GeV with 50% polarization--quite an accomplishment. On the detector domain, the concept of four complementary detectors, two large, two small with some kinematic overlap has bee a great success. The excellent performance of the four detectors coupled with the extraordinary capability in data accumulation and analysis have produced a plethora of new information and insight into heavy ion collisions. Particle multiplicities, transverse energy distributions, radial and azimuthal flow, nuclear modification factor for Gold Gold Collisions (RAA) and for deuteron Gold Collisions (RdA) as well as nuclear sizes via Hanbury-Brown Twiss (HBT) measurement have been made. The results are overwhelming. The lattice gauge theorists had predicted a phase change at RHIC energies, where all the nucleons would melt into quarks and gluons. The canonical thinking was that this new phase would consist of a gas of weakly interacting quarks and gluons and that one could calculate such a state of matter in perturbative QCD. Alas that is not what has been found. In fact it would have been dull if indeed this standard quark gluon gas were observed. Instead one has found a highly

dense, strongly interacting quark gluon plasma, sQGP! – Something new and completely unexpected. As a bonus our theoretical colleagues conjecture that another phenomena, the color glass condensate CGC or saturation of gluons at low momentum may have also been observed. We may be saturated with riches. Everyone should receive an accolade for this discovery of sQGP and we salute you all

Are there lessons to be learned from the recent past, experiences in the evolution of physics that may be relevant for RHIC physics? Several examples come to mind.

1) Observations of jets in hadron-hadron collisions.

The first attempts to see jets at the Fermilab fix target facility at a proton lab energy of 400 GeV (27 GeV center of mass energy) were rather unsuccessful. When the energy was raised to greater than 40 GeV in the center of mass the evidence for jets became obvious via the so-called lego plots. This was due to both the increase in the cross section for the prediction of jets as well as favorable kinematics of the jet opening angle versus their separation. After the jets were clearly observed at the higher energies, the data from the lower energy were reexamined and with hindsight one could find evidence for the existence of jets. The lesson to be derived is that being at the right energy is important.

2) Low Temperature Superconductivity.

The phenomenon that some materials exhibit zero resistance at low temperatures was observed in the year 1911, low temperature superconductivity. The understanding of this amazing effect occurred in 1957, 46 years later. This demonstrates the experimental discovery is separate from its explanation. More recently, in 1987, high temperature superconductors have been discovered. It is now 2004, 17 years later and there is still no understanding of this new phenomenon. There is an interesting aside to this story in that Professor Krumhamsl of Cornell who was also President of the American Physics Society argued in 1989 that one should delay construction of the SSC accelerator because one could build it more cheaply with these new superconducting materials. Of course this was not so, you can't even do it now, and as a result of his and other peoples' lack of vision, the SSC was lost as well as $600 M per year in the DOE high energy budget. The lesson to be learned is that the theoretical understanding of a new phenomenon sometime follows many years after its discovery.

3) Elementary Particles.

Investigation of particles and resonances began in the late 40's, with intense activities in the '50's, '60's and early 70's. It is amusing to note that in the very early stages, when mostly the numerous decay modes of what became the K meson were being studied, $K\mu_2$, $K\mu_3$, Ke_3, τ, $K\pi_2$, etc. Even in the early days when resonances began to proliferate, Fermi was quoted as saying: If I had to remember all these names I would have become a botanist. SU(3) came in 1964 as well as quarks a little later with deeply inelastic scattering in 1969. This set the stage for the development of Quantum Chromodynamics in 1974. The lesson in this case is that the timescale for the development of theoretical understanding is relatively short, of the order of 15 years.

4) Successful Accelerators.

The Brookhaven AGS must be considered one of the very successful high energy machines constructed to date. It is amazing that the proposal for this accelerator consisted of a six-page letter written by the Director of BNL to the AEC. The construction of the AGS was proposed in 1954 based on the new principle of strong focusing and built in the period of 1956-1960. The ostensible physics justification was the increase in energy 30 GeV versus the Bevatron 7 GeV, and interesting features in the pion-nucleon interactions. The major findings were different: Two neutrons '62, CP violation and Ω^- in 1964, the J particle in '74 g-2 in 2003, etc. The other attributes leading to the success of the AGS was the constant improvements in its intensity from 10^{10} ppp at inception to 7×10^{13} ppp today. As such the famous CP experiment of '64 with several hundred hours of machine time was reproduced in the '80's at the AGS in one pulse! The lesson to be learned is again to be at the right energy regime where new phenomena occur and constantly upgrade where possible.

The other area of concern that I would like to briefly address is that of errors, mistakes, bad decisions. Physics is replete with incorrect publications. Among the more noteworthy are (1) Finding of free, fractionally charged quarks. With more particular attention applied to the systematics of cloud and bubble chambers this claim was negated. (2) A published report that there were eight reasons why the Sigma Lambda parity was odd. All wrong! (3) Measurements of the electron spectrum from muon decay were characterized by a parameter ρ and experimental values ranged from zero and slowly went to 0.75 over a

number of years. The fascinating property was that each measurement agreed with the one preceding and following; yet the value settled down only after theory made a firm prediction. (4) Cold Fusion—The fusion of two deuterium nuclei in a palladium medium at room temperature. Great if it were real but unfortunately sloppy experimental technique contributed to this false report. (5) Super heavy elements—looking for a needle in a haystack and finding it. This allegation was pure fraud. Lesson, one has to check on one's collaborators; and (6) Splitting of the A_2, meson, which had the consequences of negating the systematics observed in meson spectroscopy which led to SU(3) symmetry and the existence of quarks. This involved a powerful new experimental technique, the missing mass spectrometer which vastly increased data taking capability and in principle mass resolution. With huge amounts of data one must be very careful of biases and systematics. Although the statistical validity of the split of the A_2 was overwhelming, more than five standard deviation, it turned out to be wrong. I have been quoted as saying, give me a huge amount of data and five cuts and I will get you any result you want. What are the lessons to be learned from all these examples? You have to be honest, use good experimental technique, be critical of results, have redundancy and distinguish between discovery and understanding of new phenomena.

A few comments on accelerators. As noted earlier the AGS is situated in an energy, intensity domain that allows it to be a very productive machine even 40 years after its completion. This of course has not been true of all accelerators, some have been more successful than others. The SPEAR electron positron collider at SLAC has also been a most successful machine. It also benefited by being at the right energy and luminosity, at the right time. Several succeeding electron positron colliders have not been as fortunate. PEP, DORISB and TRISTAN were all built to find the top quark, naively expected to be at ~15 GeV, and all failed. The top was found at 175 GeV. This provided a valuable lesson, namely one should utilize hadron-hadron collisions to explore a broad energy range and then exploit any particular energy with an electron-positron collider. It's bad to build a machine that is below threshold for the phenomena in question. And this is the tragedy of the cancellation of the SSC, a 20 TEV x 20 TEV proton proton collider, which would have mapped out the physics of the several TEV region. This termination occurred in 1994 and we won't have the backup LHC 7 TEX x 7 TEV until 2007-2008. And as a result the Next

Linear Collider, NLC, will probably not start construction until 2010 or later. Not a pleasant story for high energy physics.

But what does all this say about RHIC? The early evidence indicates that RHIC is in the correct energy range 40-200 GeV/Amu. One is seeing the effects of sQGP and possibly CGC. The luminosity is adequate and the flexibility and versatility built into RHIC have proven to be valuable assets. This is not an accident. One of the original designs for the superconducting magnet system was in two in one design, invented at BNL, and now being utilized in LHC. The present design of one on one magnets was adopted because of the requirements of a large energy scans as well as a wide species capability, including PA which proved to be invaluable. The energy choice, as noted earlier, was also appropriate. It was chosen to be one hundred times higher than the Bevatron and ten times larger than the anticipated SPS capability. The detector situation was more complex. As you may recall all thirteen initial proposals for detector experiments at RHIC were rejected. After resubmission four were approved, two large, two small detectors, complementary to each other with different strengths and overlapping capability. As has become evident with all four experiments, they have had the ability to verify nearly all the important findings to date.

It is now clear that we have the proper accelerator. We need to run it as much as possible in a variety of energies and species to extract the exciting physics. We need to upgrade RHIC by increasing the luminosity by at least an order of magnitude and then add an electron capability, eRHIC. It is also clear that we have the proper initial complement of detectors. These need to be upgraded to cover more of the interesting kinematical regions as well as coping with the increased luminosity. It is also clear that we have the talented people to accomplish the analysis, theory, data handling, calculations, etc. I would conclude by stating that we are all indeed fortunate to be here at BNL at RHIC and have been given the opportunity to partake in the rich and exciting physics to emerge from this facility, now and over the next many years. To paraphrase and old New York saying, let us not misuse this golden opportunity. On behalf of RBRC, T.D. Lee and myself, I want to thank all of you for coming and participating in this important and historic workshop.

New Discoveries at RHIC
May 14-15, 2004
A RIKEN BNL Research Center Workshop

LIST OF REGISTERED PARTICIPANTS

NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Alberto Accardi	Columbia University	aaccardi@nt3.phys.columbia.edu
Yasuyuki Akiba	RIKEN Japan / RBRC	akiba@bnl.gov
Sam Aronson	Brookhaven National Laboratory	aronsons@bnl.gov
Ralf Averbeck	SUNY Stony Brook	Ralf.Averbeck@stonybrook.edu
Terry Awes	Oak Ridge National Laboratory	awes@mail.phy.ornl.gov
Mark D. Baker	Brookhaven National Laboratory	Mark.Baker@bnl.gov
Anthony Baltz	RBRC / BNL	baltz@bnl.gov
Kenneth Barish	University of California Riverside	Kenneth.Barish@ucr.edu
Peter Barnes	Los Alamos National Laboratory	pdbarnes@lanl.gov
Ian Bearden	Niels Bohr Institute	ianbearden@mac.com
Russell Betts	Univ. of Illinois @ Chicago	betts@uic.edu
Jean-Paul Blaizot	Centre de Recherches Nucleaires	blaizot@spht.saclay.cea.fr
Peter Bond	Brookhaven National Laboratory	bond@bnl.gov
Gerald Brown	SUNY Stony Brook	gbrown@insti.physics.sunysb.edu
Gerry Bunce	RBRC / BNL	bunce@bnl.gov
Wit Busza	Massachusetts Institute of Tech.	busza@mit.edu
Manuel Calderon de la Barca Sanchez	Brookhaven National Laboratory	mc@bnl.gov
Jorge Casalderrey Solana	SUNY Stony Brook	casalder@grad.physics.sunysb.edu
Zhengwei Chai	Brookhaven National Laboratory	zwchai@bnl.gov
Chelis Chasman	Brookhaven National Laboratory	chasman@bnl.gov
Praveen Chaudhari	Brookhaven National Laboratory	chaudhari@bnl.gov
William Christie	Brookhaven National Laboratory	christie@bnl.gov
Brian Cole	Columbia University	cole@nevis.columbia.edu
Sidney A. Coon	U. S. Department of Energy	Sidney.A.Coon@science.doe.gov
Kushal Das	Florida State University	dask@nucmar.physics.fsu.edu
David d'Enterria	Columbia University	denterri@bnl.gov
Abhay Deshpande	SUNY Stony Brook/RBRC	abhay@skipper@physics.sunysb.edu
Takumi Doi	RIKEN BNL Research Center	doi@quark.phy.bnl.gov
Axel Drees	Brookhaven National Laboratory	drees@bnl.gov
Hideto En'yo	RIKEN Japan / RBRC	enyo@riken.go.jp
Patricia Fachini	Brookhaven National Laboratory	pfachini@bnl.gov
Kirill Filimonov	Lawrence Berkeley National Lab	KVFilimonov@lbl.gov
Anthony Frawley	Florida State University	frawley@fsuhip.physics.fsu.edu
Yoshinori Fukao	Kyoto University / RBRC	fukao@bnl.gov
David Gabor	Brookhaven National Laboratory	david@bnl.gov
Irakli Garishvili	University of Tennessee	igarishv@utk.edu
Michel Gonin	Centre National de la Recherche Scientifique (CNRS)	mgonin@in2p3.fr
Elena Gonzalez Ferreiro	Univ. of Santiago de Compostela	Elena@fpaxp1.usc.es
Yuji Goto	RIKEN Japan / RBRC	goto@bnl.gov
Oleg Grachov	Wayne State University	grachov@physics.wayne.edu
Victoria Greene	Vanderbilt University	senta.v.greene@vanderbilt.edu
Wlodek Guryn	Brookhaven National Laboratory	guryn@bnl.gov
Miklos Gyulassy	Columbia University	gyulassy@nt3.phys.columbia.edu
John Haggerty	Brookhaven National Laboratory	haggerty@bnl.gov
Tim Hallman	Brookhaven National Laboratory	hallman@bnl.gov
John Harris	Yale University	john.harris@yale.edu

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LIST OF REGISTERED PARTICIPANTS

NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Koichi Hashimoto	RIKEN BNL Research Center	koichi@quark.phy.bnl.gov
Eva Haslum	Lund University	eva.haslum@hep.lu.se
Yoshitaka Hatta	RIKEN BNL Research Center	hatta@bnl.gov
Ping He	Brookhaven National Laboratory	phe@bnl.gov
Xiaochun He	Georgia State University	xhe@gsu.edu
Ulrich Heinz	Ohio State University	heinz@mps.ohio-state.edu
Tom Hemmick	SUNY Stony Brook	hemmick@skipper.physics.sunysb.edu
Hiro Hiejima	University of Illinois	hhiejima@yahoo.com
Tetsufumi Hirano	RIKEN BNL Research Center	hirano@quark.phy.bnl.gov
Takuma Horaguchi	RIKEN BNL Research Center	horaguchi@bnl.gov
Donald Hornback	University of Tennessee	dhornbac@utk.edu
Huan Huang	University of California @ LA	huang@physics.ucla.edu
Takashi Ichihara	RIKEN Japan	ichihara@riken.jp
Kei Iida	RIKEN Japan / RBRC	keiiida@riken.jp
Barbara Jacak	SUNY Stony Brook	jacak@skipper.physics.sunysb.edu
Jiangyong Jia	Columbia University	jjia@skipper.physics.sunysb.edu
Jiamin Jin	Columbia University	jiamin@phys.columbia.edu
Brant Johnson	Brookhaven National Laboratory	brant@bnl.gov
Sonia Kabana	CERN	sonja.kabana@cern.ch
Fukutaro Kajihara	Tokyo University	kajihara@bnl.gov
Masashi Kaneta	RIKEN BNL Research Center	kaneta@bnl.gov
Dmitri Kharzeev	Brookhaven National Laboratory	kharzeev@bnl.gov
Tom Kirk	Brookhaven National Laboratory	tkirk@bnl.gov
Edouard Kistenev	Brookhaven National Laboratory	kistenev@bnl.gov
Yuji Koike	Niigata University / BNL	koike@quark.phy.bnl.gov
Martin Kramer	City University of New York	mkramer@bnl.gov
Chia Ming Kuo	National Central University Taiwan	ncukcm@bnl.gov
John Lajoie	Iowa State University	lajoie@iastate.edu
Frank Laue	Brookhaven National Laboratory	laue@bnl.gov
Tsung-Dao Lee	Columbia University / RBRC	tdl@cuphyb.phys.columbia.edu
Thomas Ludlam	Brookhaven National Laboratory	ludlam@bnl.gov
Richard Majka	Yale University	majka@hepmail.physics.yale.edu
Larry McLerran	Brookhaven National Laboratory	mclerran@bnl.gov
Alice Mignerey	University of Maryland	mignerey@umd.edu
Denes Molnar	Ohio State University	molnard@mps.ohio-state.edu
Berndt Mueller	Duke University	muller@phy.duke.edu
Michael Murray	University of Kansas	mjmurray@ku.edu
Jamie Nagle	Columbia University	jamie.nagle@colorado.edu
Jun Nakamura	RIKEN BNL Research Center	jnakamura@bnl.gov
Chiho Nonaka	Duke University	nonaka@phy.duke.edu
Rachid Nouicer	UIC / BNL	rachid.nouicer@bnl.gov
Ed O'Brien	Brookhaven National Laboratory	eobrien@bnl.gov
Helmut Oeschler	Darmstadt University	h.oeschler@gsi.de
Shigemi Ohta	KEK / RBRC	shigemi.ohta@kek.jp
Kensuke Okada	RIKEN BNL Research Center	okada@bnl.gov
Vitaly Okorokov	Moscow Engineering Physics Institute (State University)	okorokov@bnl.gov
Markus Oldenburg	Lawrence Berkeley National Lab	mdoldenburg@lbl.gov

New Discoveries at RHIC
May 14-15, 2004
A RIKEN BNL Research Center Workshop

LIST OF REGISTERED PARTICIPANTS

NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Anders Oskarsson	Lund University	anders.oskarsson@hep.lu.se
Satoshi Ozaki	Brookhaven National Laboratory	ozaki@bnl.gov
Robert Pak	Brookhaven National Laboratory	pak@bnl.gov
Sergey Panitkin	Brookhaven National Laboratory	panitkin@bnl.gov
Hua Pei	Iowa State University	hpei@iastate.edu
Peter Petreczky	Brookhaven National Laboratory	petreczk@bnl.gov
Michal Praszalowicz	Jagiellonian University	michal@quark.phy.bnl.gov
Krishna Rajagopal	MIT	krishna@ctp.mit.edu
Jan Rak	Iowa State University	janrak@bnl.gov
Corey Reed	MIT	cjreed@mit.edu
Thorsten Renk	Duke University	trenk@phy.duke.edu
Marzia Rosati	Iowa State University	mrosati@iastate.edu
Vladimir Rykov	RIKEN Japan / RBRC	rykov@bnl.gov
Takao Sakaguchi	University Tokyo	takao@phenix.cns.s.u-tokyo.ac.jp
Shingo Sakai	Tsukuba University	shingo@bnl.gov
Sevil Salur	Yale University	sevil.salur@yale.edu
Nicholas Samios	BNL / RBRC	samios@bnl.gov
Jack Sandweiss	Yale University	sandweiss@hepmail.physics.yale.edu
Jurgen Schukraft	CERN	schukraft@cern.ch
Richard Seto	University of California Riverside	richard.seto@ucr.edu
Kenta Shigaki	Hiroshima University	shigaki@hiroshima-u.ac.jp
Maya Shimomura	Tsukuba University	mayap@bnl.gov
Edward Shuryak	SUNY Stony Brook	shuryak@tonic.physics.sunysb.edu
David Silvermyr	Oak Ridge National Laboratory	silvermy@ornl.gov
Raimond Snellings	NIKHEF	Raimond.Snellings@nikhef.nl
Paul Stankus	Oak Ridge National Laboratory	stankus@mail.phy.ornl.gov
Peter Steinberg	Brookhaven National Laboratory	peter.steinberg@bnl.gov
Misha Stephanov	UIC / RBRC	misha@uic.edu
George Stephans	MIT	gsfs@mit.edu
Horst Stocker	University of Frankfurt	stoecker@uni-frankfurt.de
Taka Sugihara	RIKEN BNL Research Center	sugihara@bnl.gov
Bernd Surrow	MIT	surrow@lns.mit.edu
James Symons	Lawrence Berkeley National Lab	tjsymons@lbl.gov
Janos Sziklai	Hungarian Academy of Sciences	sziklai@rmki.kfki.hu
Jacek Szmigielski	University of Saskatchewan	szmigiel@math.usask.ca
Tsuguchika Tabaru	RIKEN BNL Research Center	tsugu@bnl.gov
Hiroshi Takahashi	Brookhaven National Laboratory	takahash@bnl.gov
Michael Tannenbaum	Brookhaven National Laboratory	mjt@bnl.gov
Marguerite Belt Tonjes	University of Maryland	belt@bnl.gov
Vasile Topor Pop	McGill University	toporpop@physics.mcgill.ca
Thomas Trainor	University of Washington	trainor@hausdorf.npl.washington.edu
Yuji Tsuchimoto	Hiroshima University	tsuchimoto@bnl.gov
Marco van Leeuwen	Lawrence Berkeley National Lab	mvanleeuwen@lbl.gov
Julia Velkovska	Vanderbilt University	julia.velkovska@vanderbilt.edu
Raju Venugopalan	Brookhaven National Laboratory	raju@quark.phy.bnl.gov
Ivan Vitev	Iowa State University	ivitev@iastate.edu
Werner Vogelsang	RIKEN BNL Research Center	wvogelsang@bnl.gov
Sergei Voloshin	Wayne State University	voloshin@wayne.edu

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NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Fuqiang Wang	Purdue University	fwang@purdue.edu
Xiaorang Wang	NMSU	xrwang@gsu.edu
Xin-Nian Wang	Lawrence Berkeley National Lab	xnwang@lbl.gov
Bill Willis	Columbia University	willis@nevis.columbia.edu
David Winter	Columbia University	winter@nevis.columbia.edu
C. Y. Wong	Oak Ridge National Laboratory	wongc@ornl.gov
Craig Woody	Brookhaven National Laboratory	woody@bnl.gov
Bolek Wyslouch	MIT	wyslouch@mit.edu
Wei Xie	RIKEN BNL Research Center	xiewei@bnl.gov
Nu Xu	Lawrence Berkeley National Lab	nxu@lbl.gov
Zhangbu Xu	Brookhaven National Laboratory	xzb@bnl.gov
Glenn Young	Oak Ridge National Laboratory	younggr@ornl.gov
Ismail Zahed	SUNY Stony Brook	zahed@zahed.physics.sunysb.edu
W. A. Zajc	Columbia University	zajc@nevis.columbia.edu
Chun Zhang	Columbia University	zhangc@phys.columbia.edu

First Meeting of the RHIC Round Table Discussion Group
Friday, May 14, 2004

We want to clarify the rationale for the way the First Meeting of the RHIC Round Table Discussion Group was organized. This meeting will take place in the South Room of the Brookhaven Center from 1-4:30 pm, Friday, May 14. It is sponsored by the RIKEN Brookhaven Research Center and is associated with the RBRC Workshop, New Discoveries at RHIC: The Current Case for the Strongly Interactive Quark Gluon Plasma, which will be held on Saturday, May 15.

In order to have a reasonably coherent round table discussion, the number of participants in this discussion had to be limited. This limitation has been communicated to the leaders of the various experiments. The meeting is informal and will be entirely focused on the scientific issues, as such, we encouraged a minimal participation from lab management and representatives of DOE. Interested members of the experimental and theoretical community are most welcome to listen in to the discussion, subject to space limitation. At the end of the meeting, we will allow time for a general participation from the audience (a minimum time of ½ hour).

RIKEN BNL Research Center Workshop

New Discoveries at RHIC

Saturday, May 15, 2004

Physics Dept., Brookhaven National Laboratory

*******AGENDA*******

All talks to be held in the Large Seminar Room, first floor, Physics Bldg. 510

Saturday, May 15

Morning Session

8:30 AM - Registration & Coffee
9:00 AM - Overview: The Strongly Interacting Quark Gluon Plasma, T. D. Lee (20+5)
9:25 AM - Early Days at RHIC: T. Ludlam (20+5)
9:50 AM - New Forms of QCD Matter Discovered at RHIC, M. Gyulassy (and L. McLerran, 30+5)
10:25 AM - What RHIC Experiments and Theory tell us about Properties of the Quark Gluon Plasma, Edward Shuryak (20+5)

Break 10:50 - 11:15

11:15 AM - The Color Glass Condensate, J. P. Blaizot (and F. Gelis, 20+5)
11:40 AM - Hadronic Signals of Deconfinement at RHIC, Berndt Muller (20+5)
12:05 PM - Discovery of Jet Quenching and Beyond, X. N. Wang (20+5)
12:30 PM - Collective Flow Signals the Quark Gluon Plasma, H. Stocker (20+5)

Lunch 12:55 - 2:00

Afternoon Session – Presentations

2:00 PM - BRAHMS (20+10)
2:30 PM - PHENIX (30+10)

Break 3:10-3:30

3:30 PM - PHOBOS (20+10)
4:00 PM - STAR (30+10)
4:40 PM - Obervations, Nick Samios (20)

Additional RIKEN BNL Research Center Proceedings:

Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL-
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-
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
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

Additional RIKEN BNL Research Center Proceedings:

Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634
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. Tammy Heinz
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

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

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

RIKEN BNL RESEARCH CENTER

New Discoveries at RHIC

May 14-15, 2004

Li Keran

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

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Speakers:

I. Bearden	J. P. Blaizot	W. Busza	M. Gyulassy
T. D. Lee	T. Ludlam	B. Muller	N. Samios
E. Shuryak	R. Snellings	H. Stocker	X. N. Wang
B. Zajc			

Organizers: W. Busza, M. Gyulassy, L. McLerran