RBRC Symposium: RHIC and the Standard Model, 2006

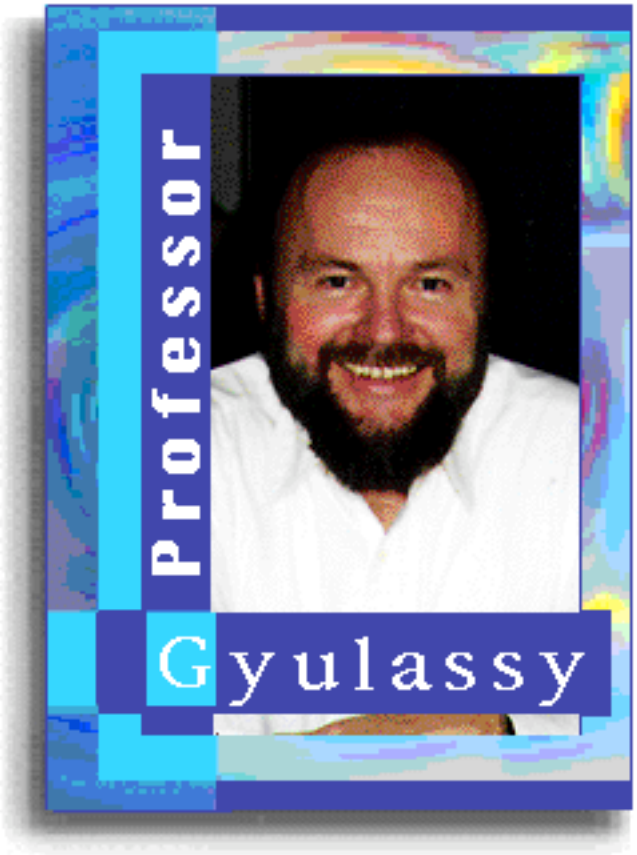
RHIC Heavy Ion Theory: Quantum Chromo-Dynamics at the high energy/density frontier

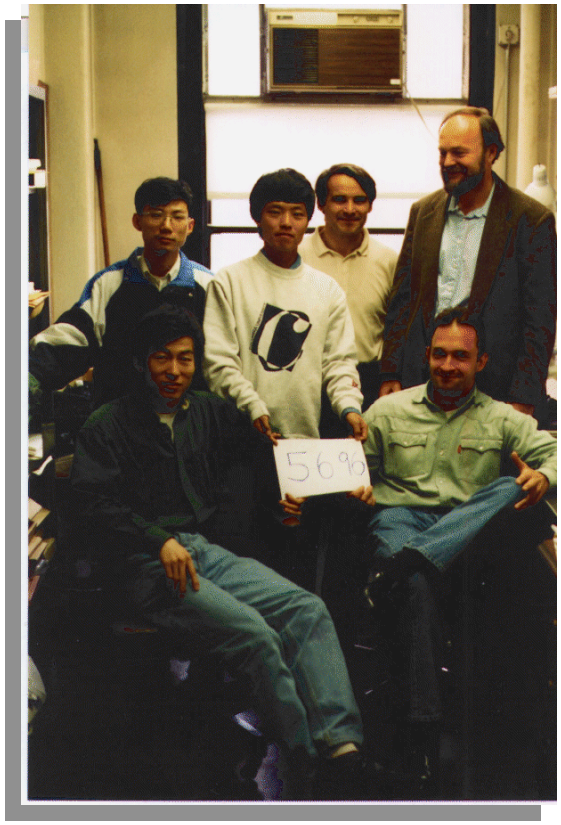
D. Kharzeev

RIKEN-BNL Fellow, 8/1997-3/2000

BROOKHAVEN NATIONAL LABORATORY

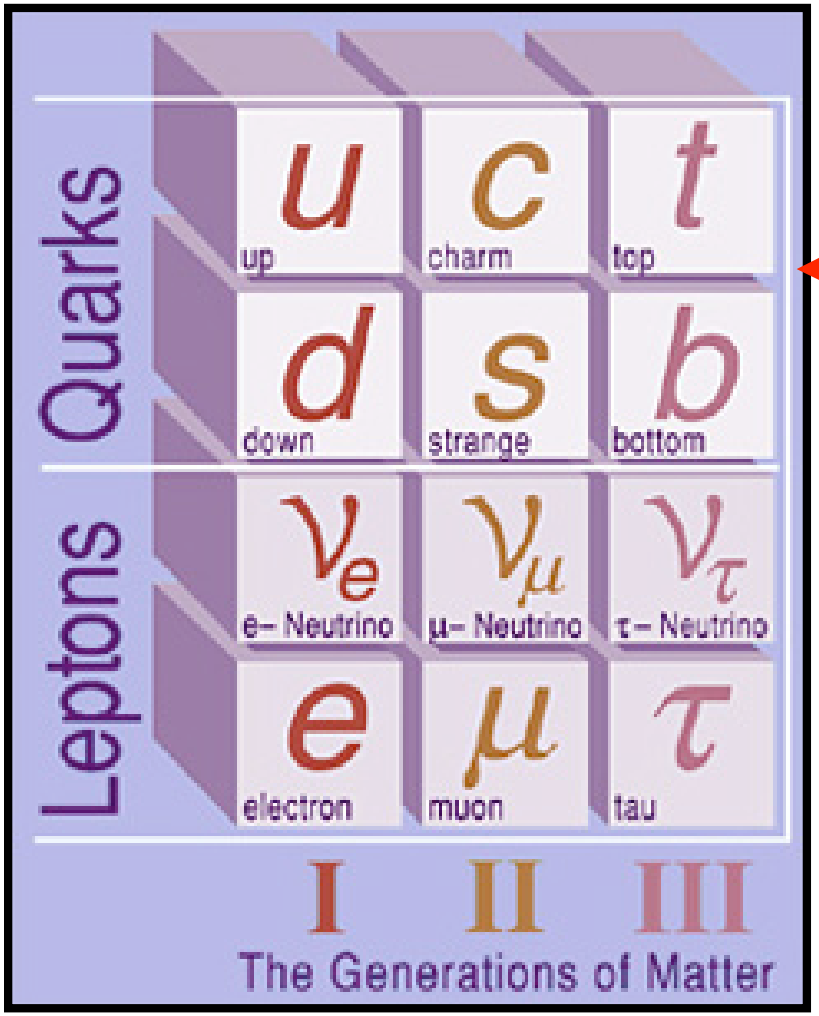
This talk had to be given by Miklos Gyulassy





Get well soon, Miklos! and thank you, Dirk and John

Quarks and the Standard Model



1/2 of all "elementary" particles of the Standard Model are not observable;

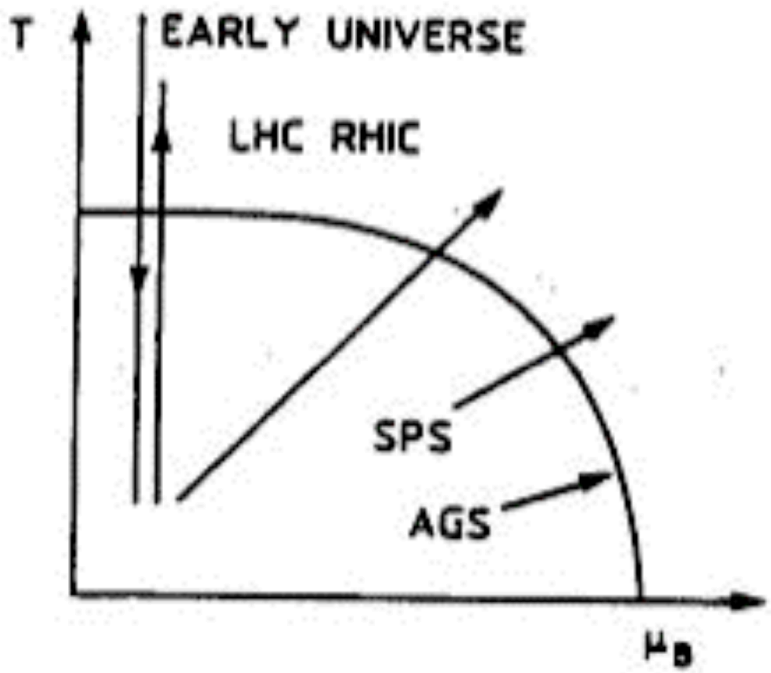
they are confined within hadrons by "color" interactions

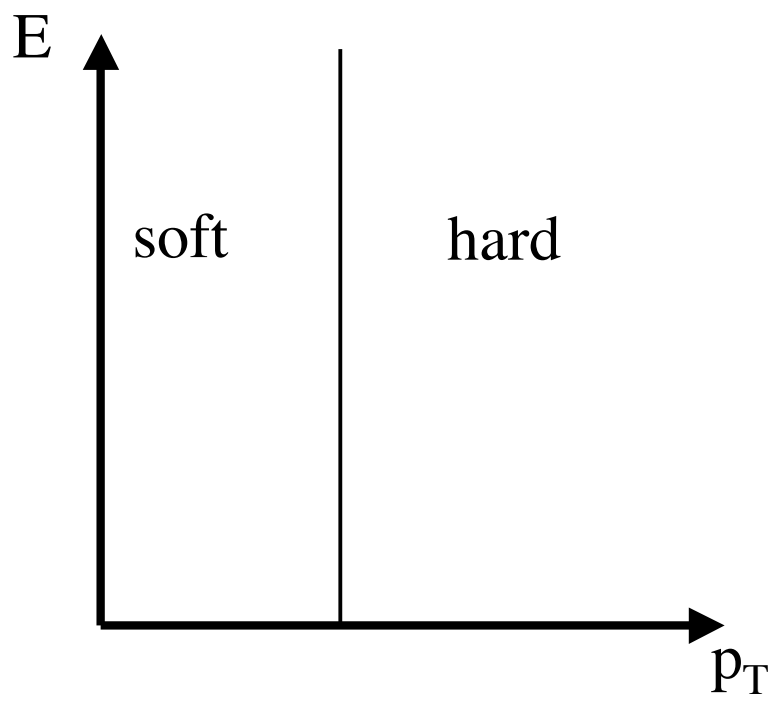
Fundamental questions

addressed at RHIC

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

QCD diagrams, late XX century
(pre-RHIC, pre-RBRC…)





QCD diagrams, early XXI century

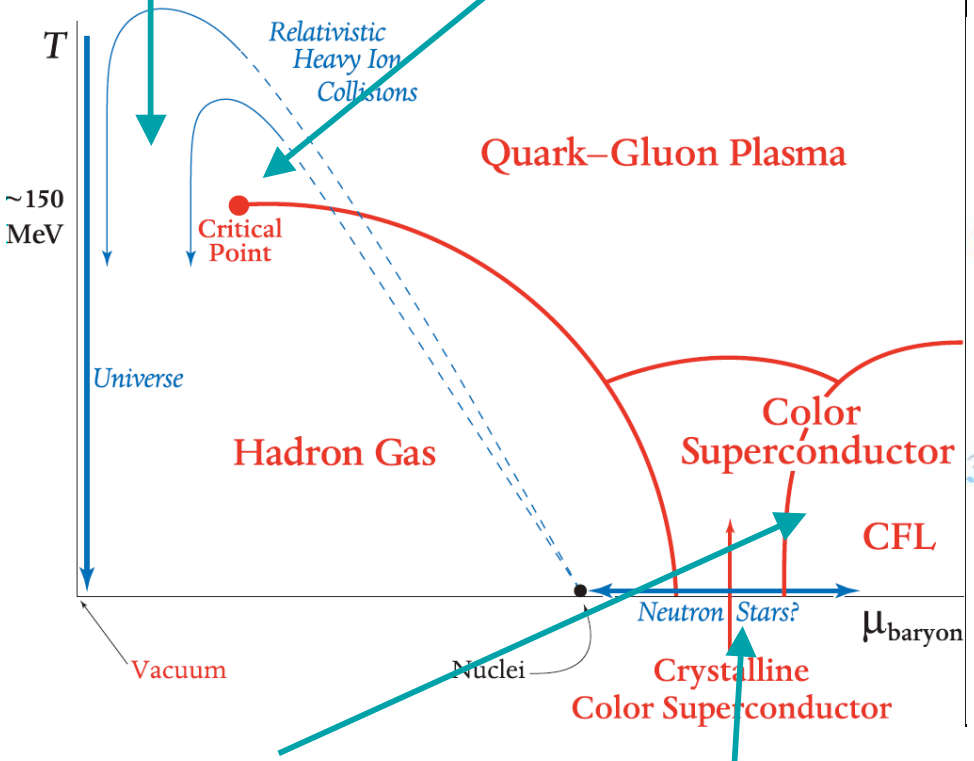
Lattice: P.Petreczky, S.Aoki,…(and RBRC alumni)
T.Hirano, Y.Nara;
D.Bodeker; S.Jeon;
S.Bass; T.Wettig;
A.Mocsy;…

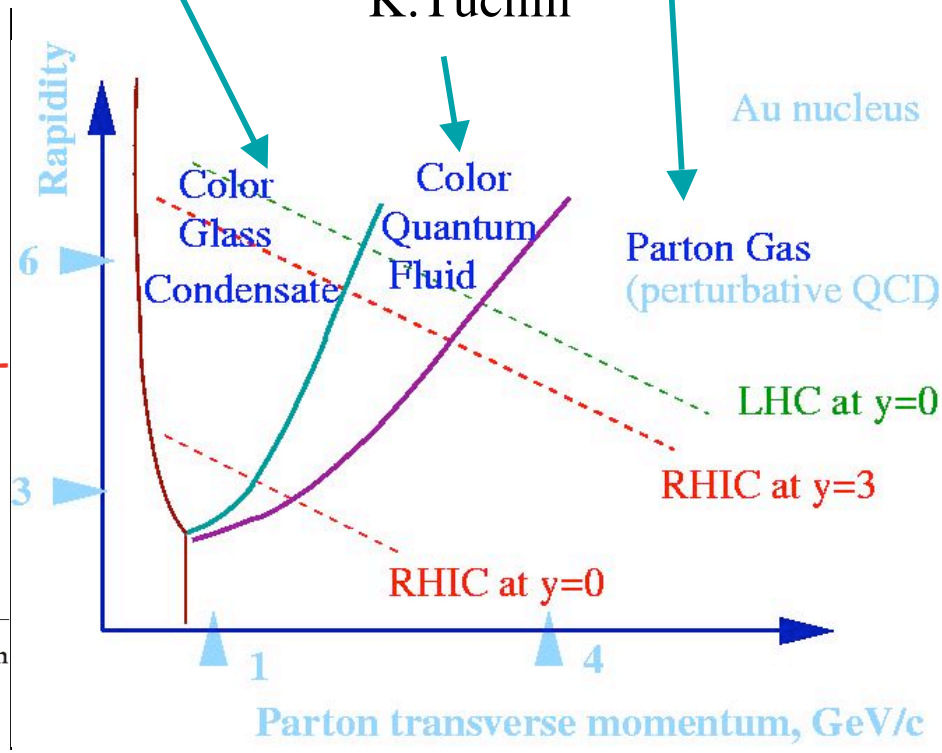
M.Stephanov

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

K.Itakura,
K.Tuchin

W.Vogelsang;
D.Boer;
S.Kretzer;…



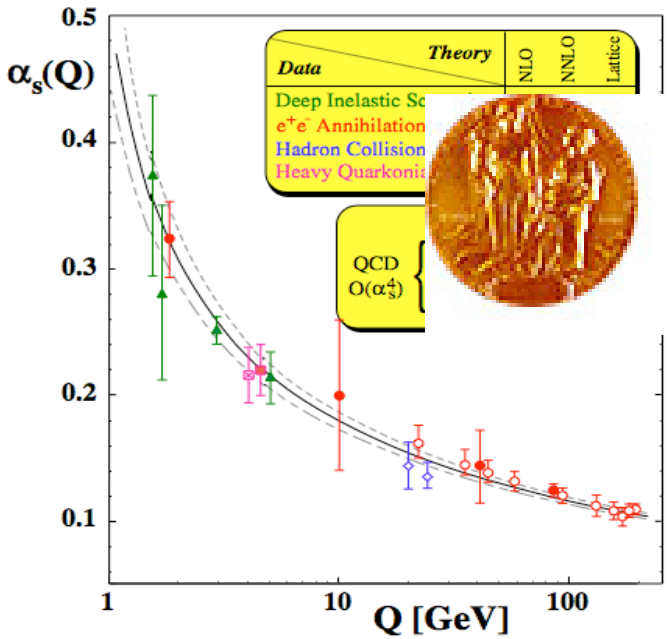


R.Pisarski, D.Rischke;

D.Son; T.Schaefer;

J.Schaffner-Bielich

Asymptotic Freedom



At short distances,
the strong force becomes weak
(anti-screening) -
one can access the "asymptotically free" regime in hard processes

and in super-dense matter
(inter-particle distances ~ 1/T)

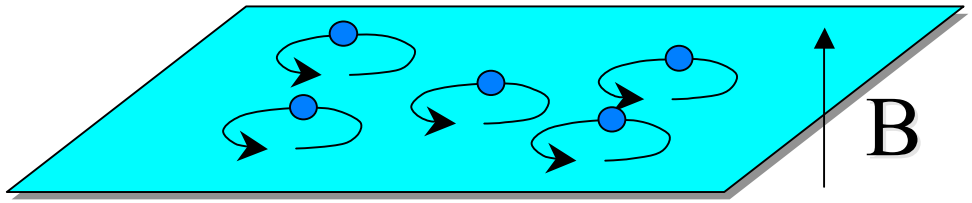
$$\alpha_s(Q) \simeq \frac{4\pi}{b \ln(Q^2/\Lambda^2)}$$

number of colors

number of flavors

$$b = (11N_c - 2N_f)/3$$

Asymptotic freedom and Landau levels of 2D parton gas

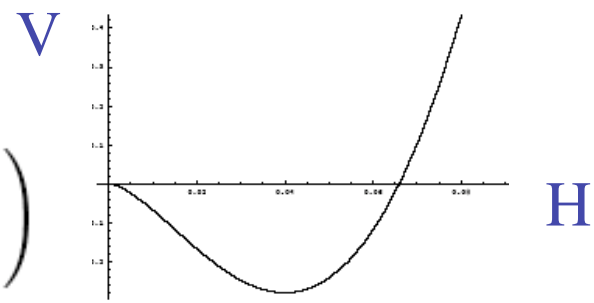


The effective potential: sum over 2D Landau levels

$$V_{\rm pert}(H) = \frac{g\,H}{4\,\pi^2}\int dp_z \sum_{n=0}^{\infty}\sum_{s_z=\pm 1}\sqrt{2\,g\,H\,(n+1/2-s_z)+p_z^2}.$$

Paramagnetic response of the vacuum:

$$\mathrm{Re}\,V_{\rm pert}(H) = \frac{1}{2}H^2 + (g\,H)^2\,\frac{b}{32\,\pi^2}\left(\ln\frac{g\,H}{\mu^2}-\frac{1}{2}\right)$$



1. The lowest level n=0 of radius $\sim (gH)^{-1/2}$ is unstable!

2. Strong fields $\longleftrightarrow$ Short distances

QCD and the classical limit

Classical dynamics applies when the action $S = \int d^4x \;\; \mathcal{L}(x)$ is large in units of the Planck constant (Bohr-Sommerfeld quantization)

$$\frac{S_{QCD}}{\hbar} \sim \frac{1}{g^2\hbar} \int d^4x \; \mathrm{tr}\; G^{\mu\nu}(x) G_{\mu\nu}(x) \gg 1$$

(equivalent to setting $\hbar \to 0$)

=> Need weak coupling and strong fields

$$A^2 \ll \frac{p^2}{g^2}$$

weak field

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

$$A^2 \sim \frac{p^2}{g^2}$$

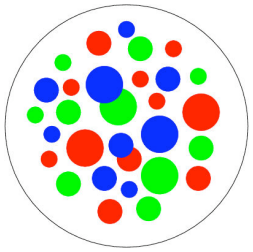
strong field

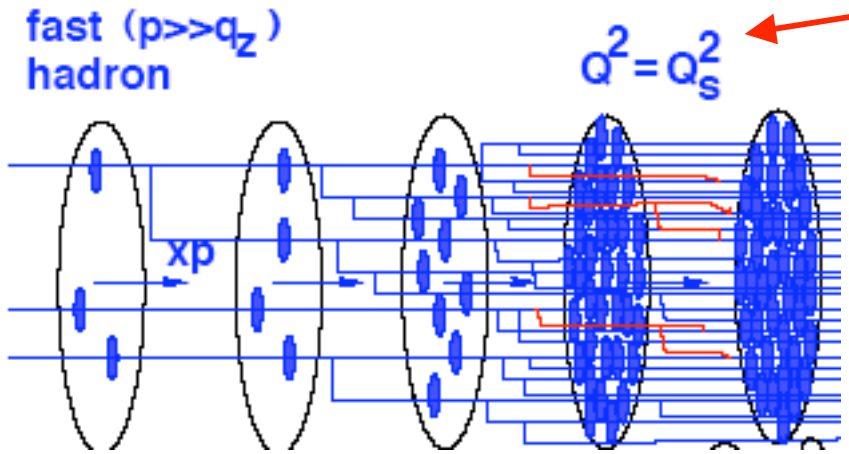
Building up strong color fields: small x (high energy) and large A (heavy nuclei)

Bjorken x : the fraction of hadron's momentum carried by a parton; high energies s open access to small $x = Q^2/s$

Talk by K.Itakura

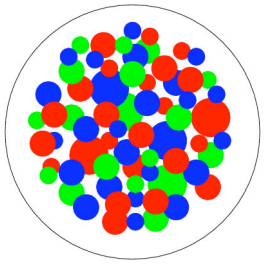
Large x





the boundary of non-linear regime: partons of size $1/Q > 1/Q_s$ overlap

small x

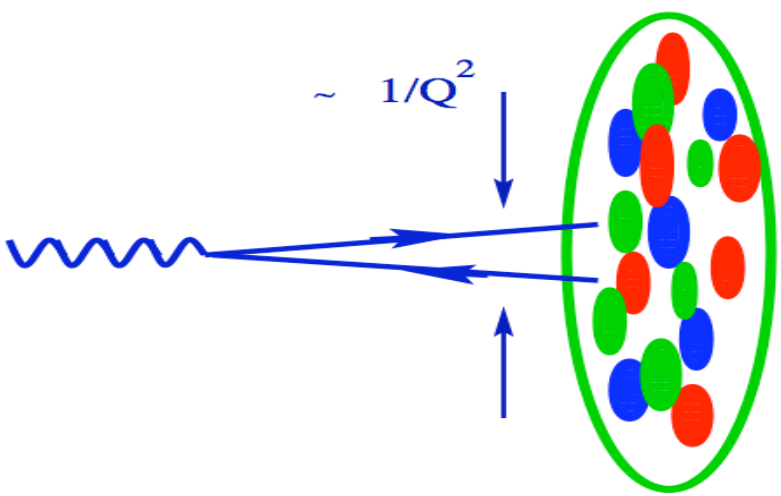


Because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$, the number of gluons at small x grows; the transverse area is limited

→ transverse density becomes large

Strong color fields in heavy nuclei

At small Bjorken x, hard processes develop over large longitudinal distances $l_c \sim \frac{2\nu}{Q^2} = \frac{1}{mx}$



Density of partons in the transverse plane as a new dimensionful parameter Q_s ("saturation scale")

Gribov, Levin, Ryskin

All partons contribute coherently => at sufficiently small x and/or large A strong fields, weak coupling!

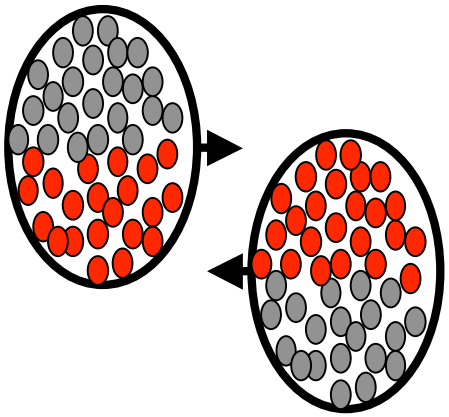
McLerran, Venugopalan

Semi-classical QCD and total multiplicities in heavy ion collisions

Expect very simple dependence of multiplicity on atomic number A / N_{part}:

$$n \sim \frac{S_A Q_s^2}{\alpha_s(Q_s^2)} \sim N_{part} \ \ln N_{part}$$

N_{part}:



Almost the wounded nucleon model!

…but wait

How dense is the produced matter?

The initial energy density achieved:

$$\epsilon_{initial} \simeq \frac{< k_t >}{\tau_0} \frac{d^2N}{d^2b\, d\eta} \simeq Q_s^2 \frac{d^2N}{d^2b\, d\eta} \simeq 18 \text{ GeV/fm}^3$$

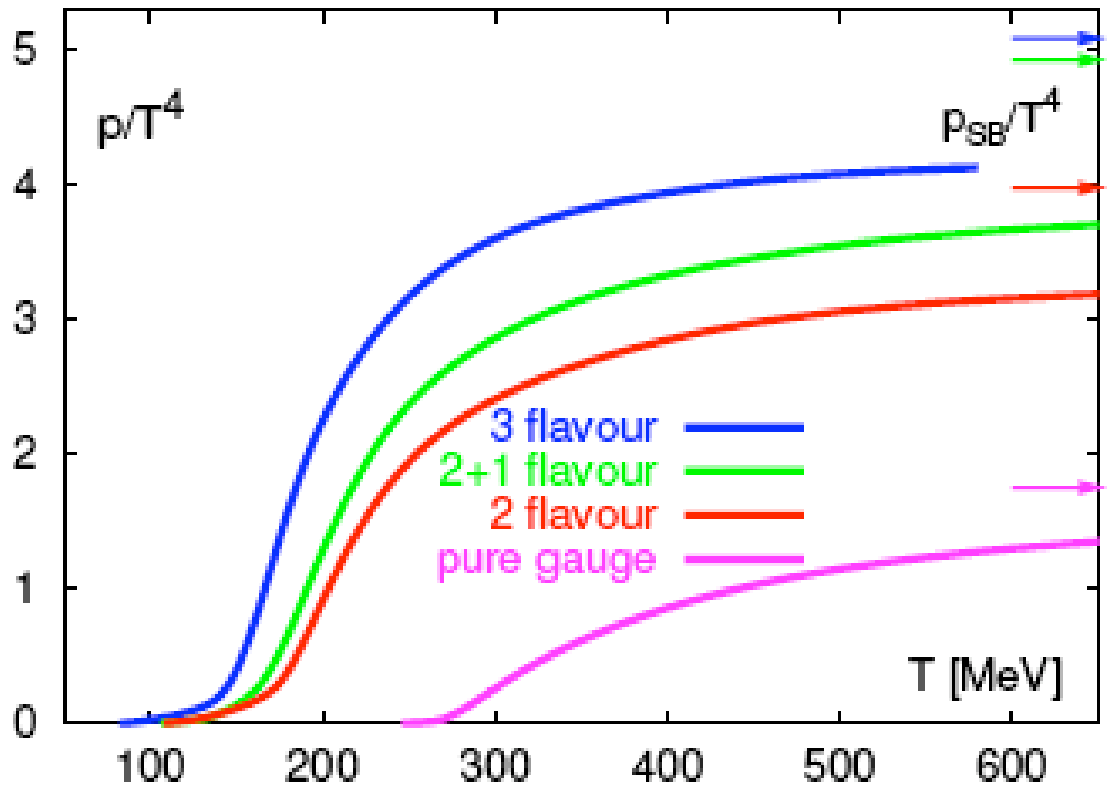
mean transverse momentum of produced gluons

gluon formation time

the density of the gluons in the transverse plane and in rapidity

about 100 times nuclear density !

What happens at such energy densities?

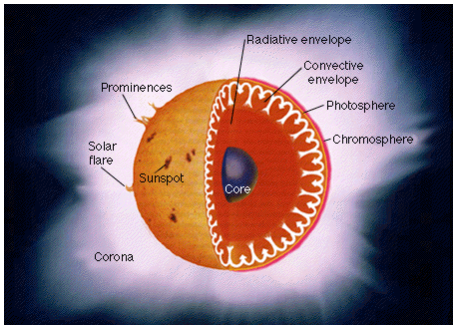


Phase transitions:

deconfinement

Chiral symmetry restoration

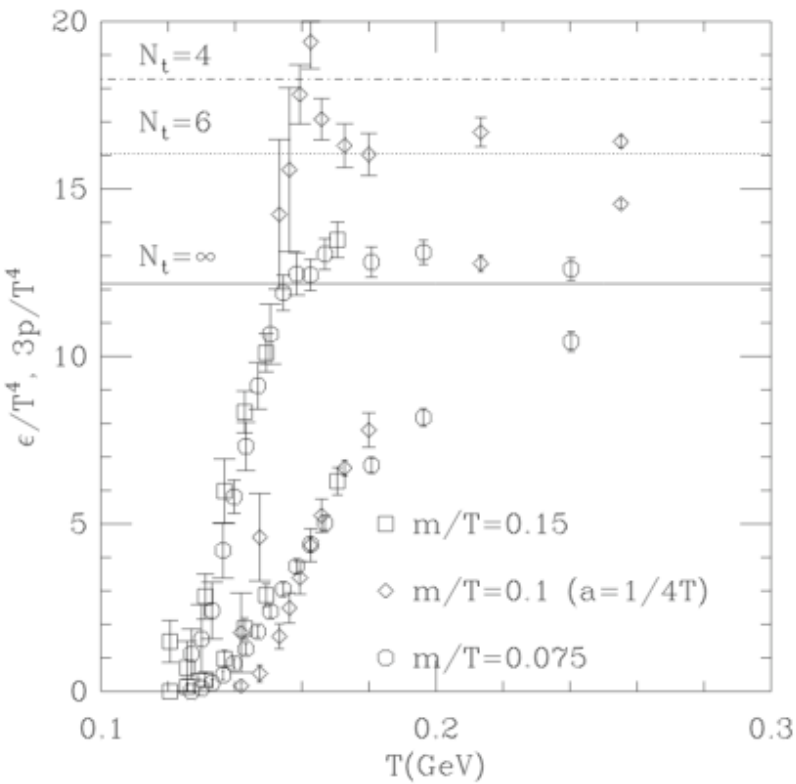
$U_A(1)$ restoration



Data from lattice QCD simulations
Bielefeld-BNL

critical temperature ~ 10^{12} K; cf temperature inside the Sun ~ 10^{7} K

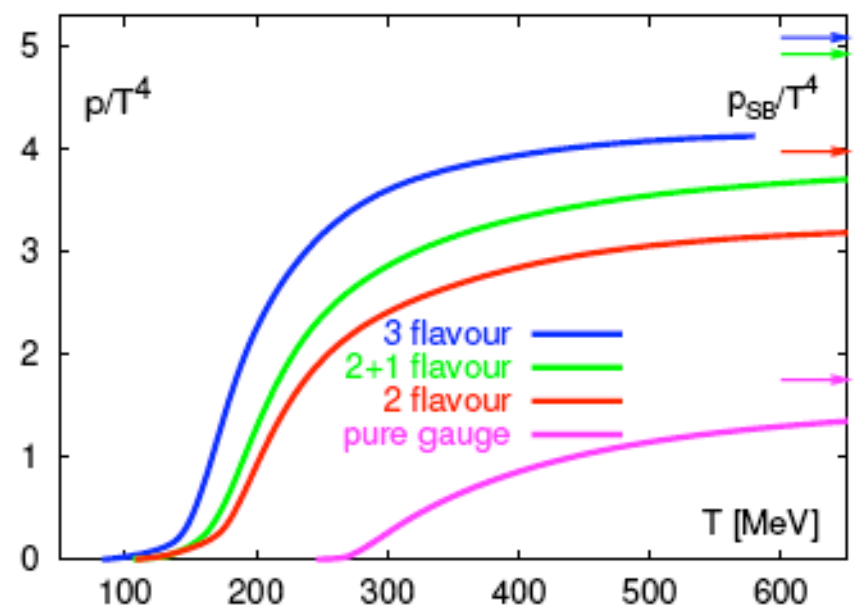
Strongly correlated QCD plasma



MILC

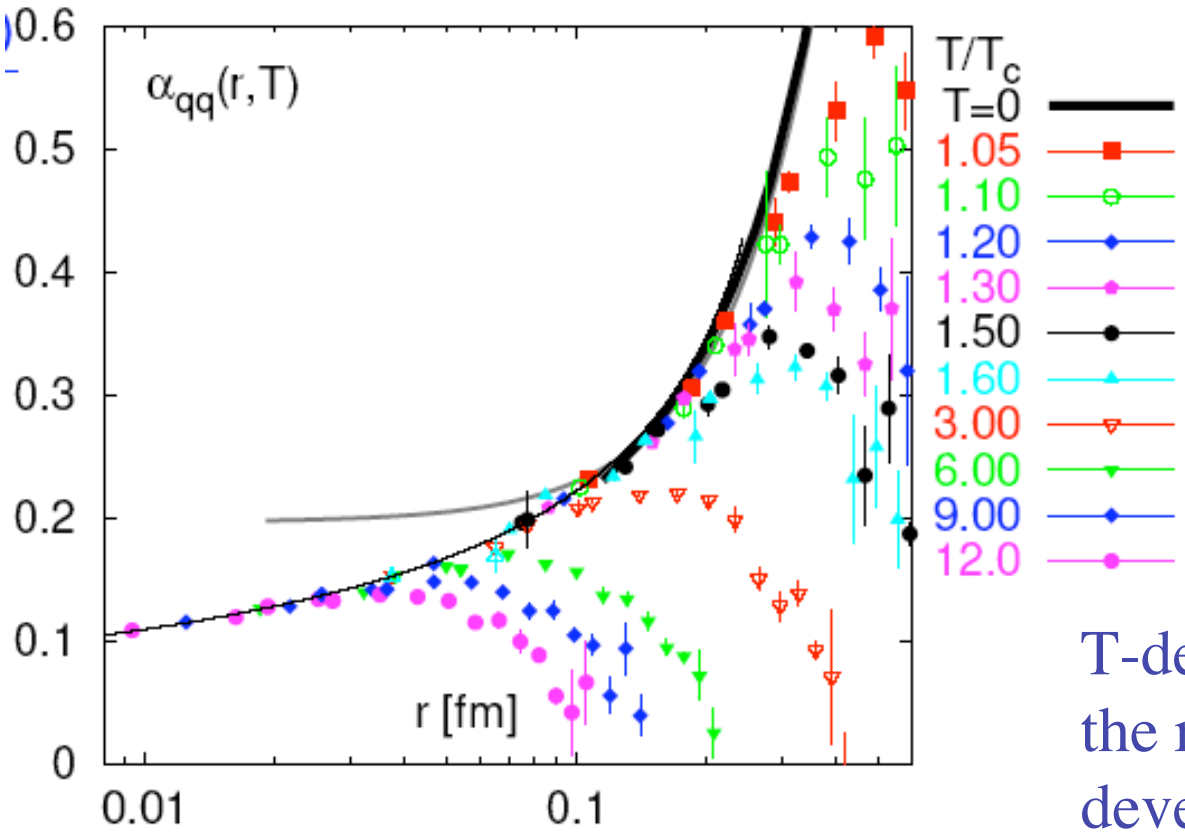
$$\langle \theta^\mu_\mu \rangle = \epsilon - 3P \neq 0$$

Interactions are important!
(strongly coupled
Quark-Gluon Plasma)



Bielefeld-BNL

Screening in QGP

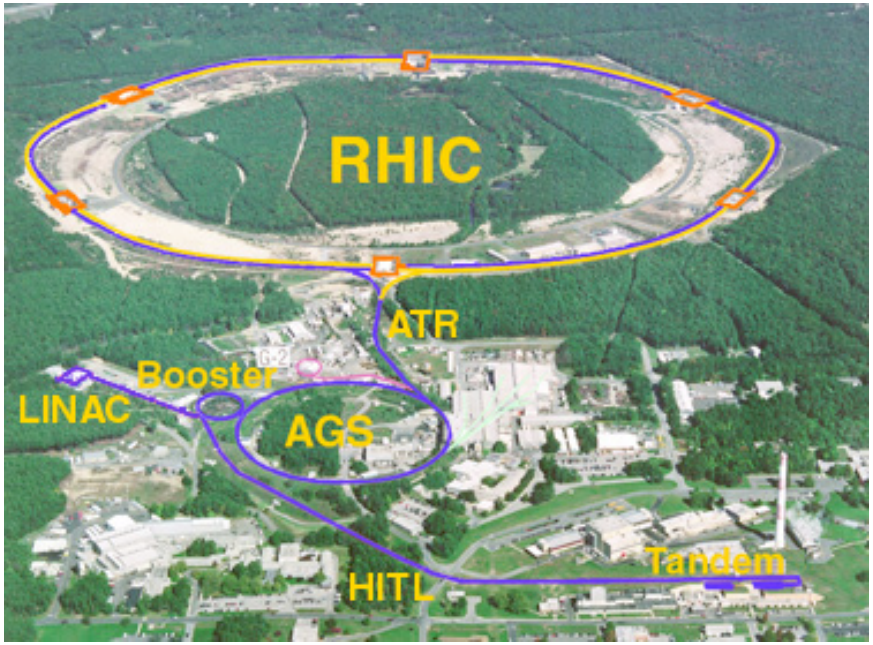


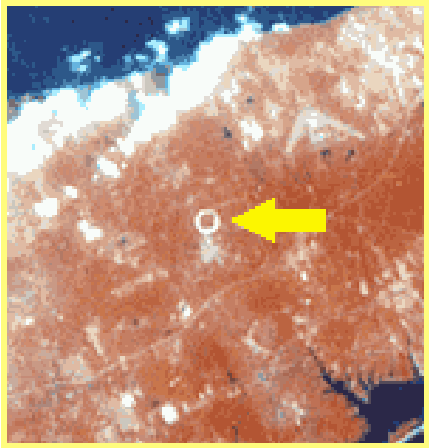
Strong force is screened by the presence of thermal gluons and quarks

T-dependence of the running coupling develops in the non-perturbative region at $T < 3\ T_c$; $\Delta E/T > 1$ - "cold" plasma

F.Karsch et al

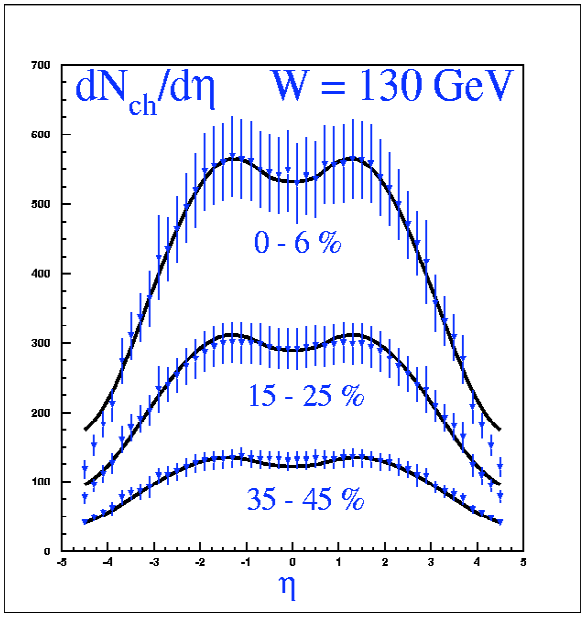
RHIC: theory meets reality…

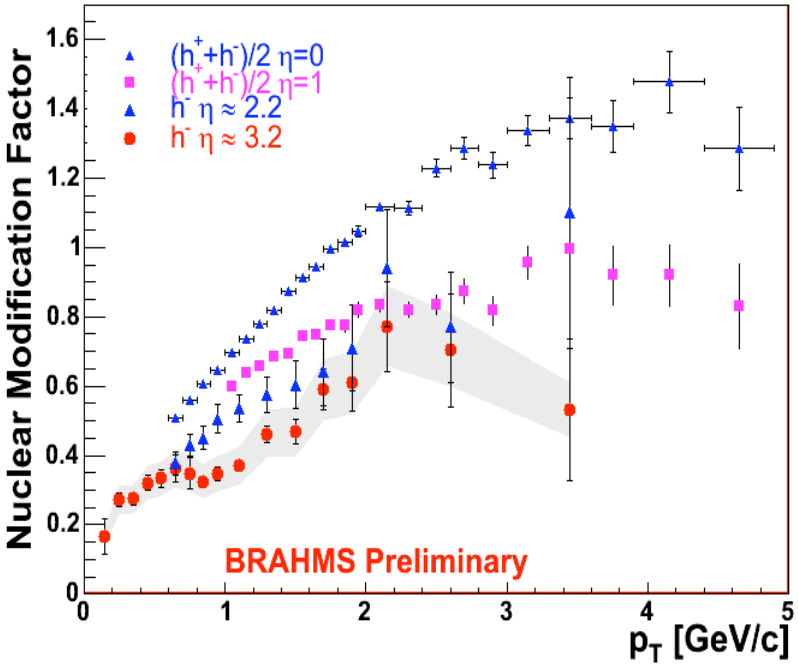




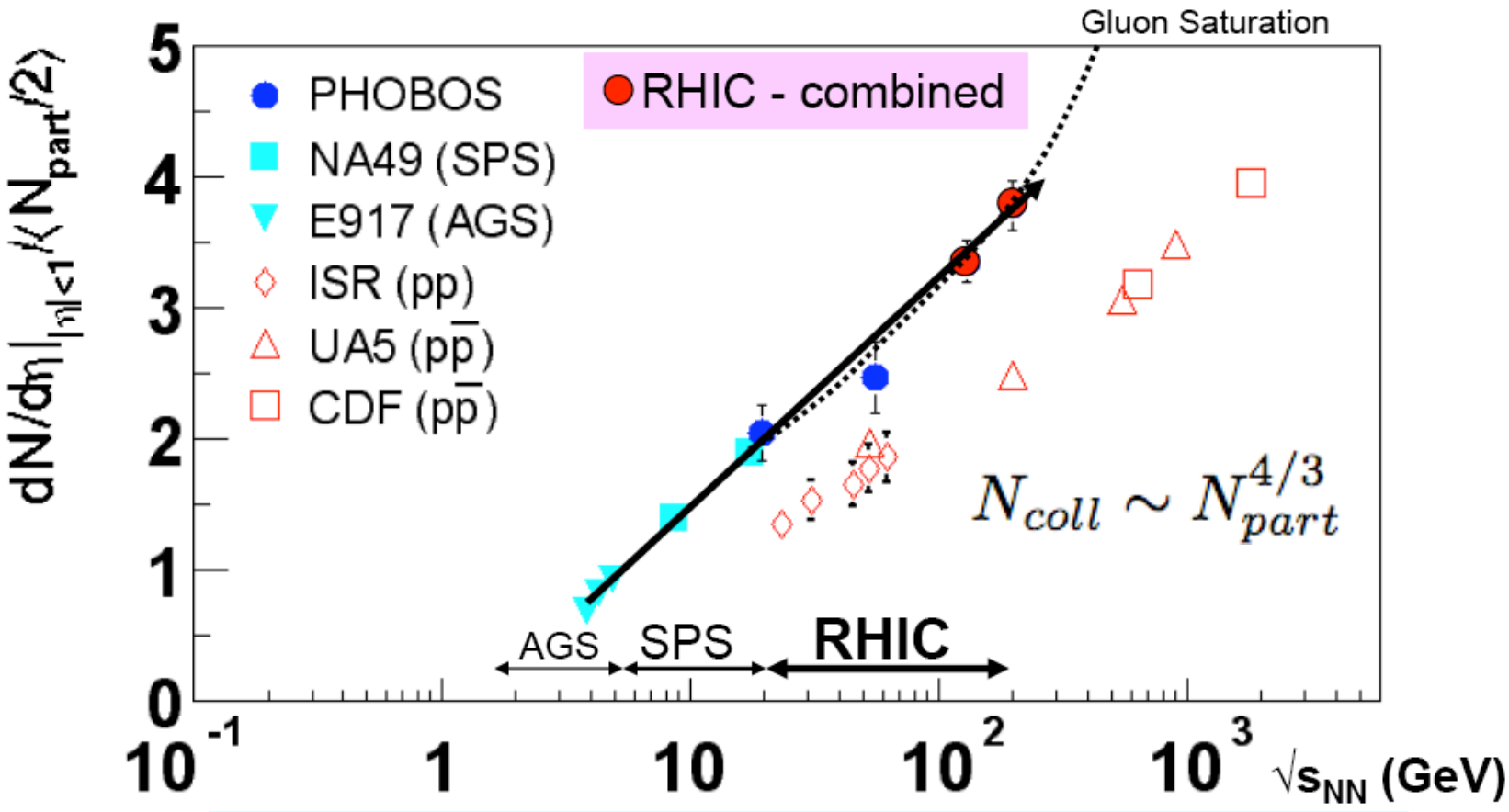
What have we learned from RHIC so far ?

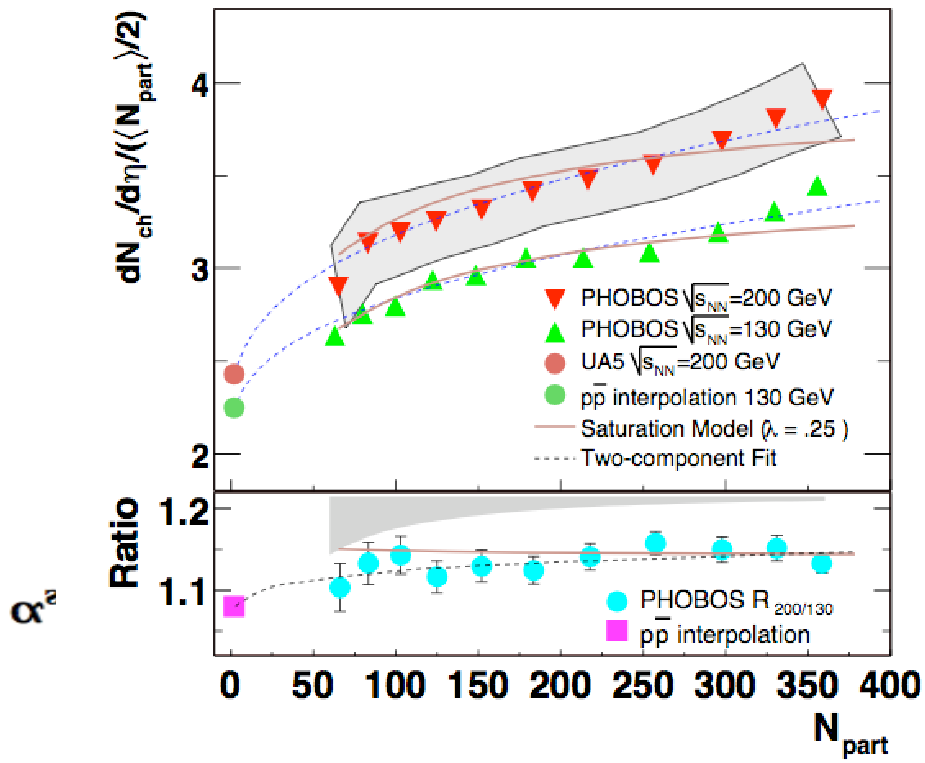
I. "Small" hadron multiplicities +
suppression of high p_T particles at forward rapidities =>
coherent interactions in the initial state, consistent
with the presence of parton saturation/Color Glass Condensate





Hadron multiplicities: the effect of parton coherence

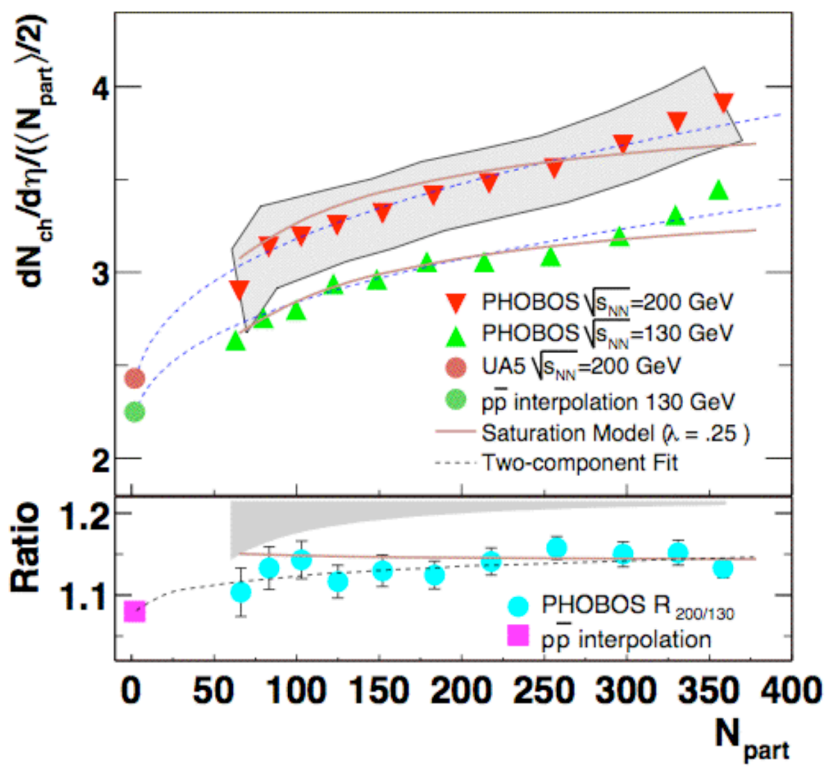


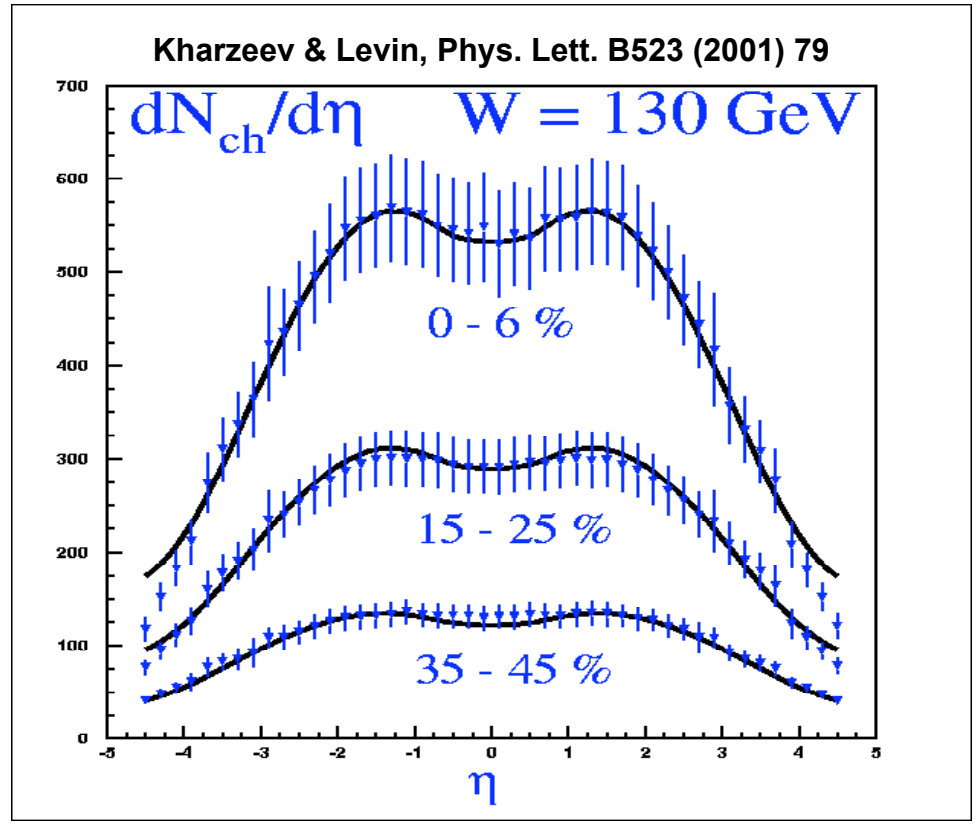


$$\frac{1}{N_{part}}\frac{dN}{d\eta} \sim \frac{1}{\alpha_s(Q_s^2)}$$

Classical QCD dynamics in action

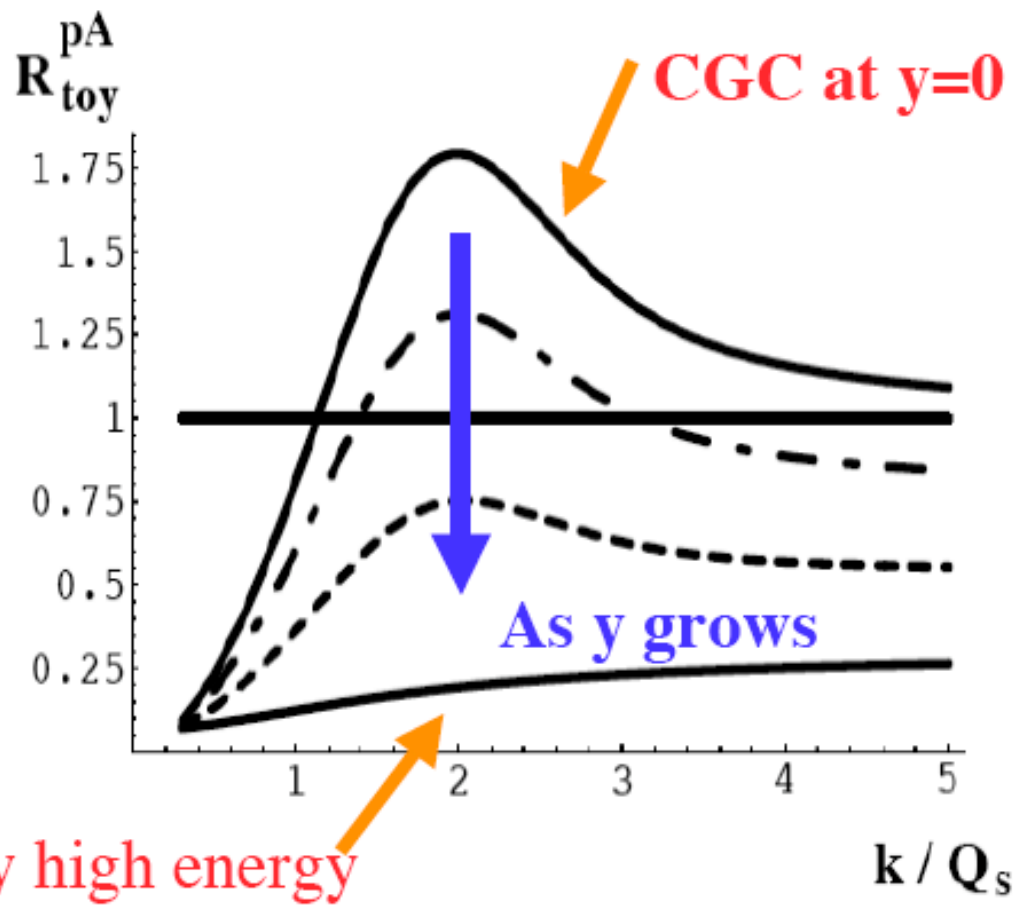
The data on hadron multiplicities in Au-Au and d-Au collisions support the quasi-classical picture





Gluon multiplication in a limited (nuclear) environment

The ratio of pA and pp cross sections

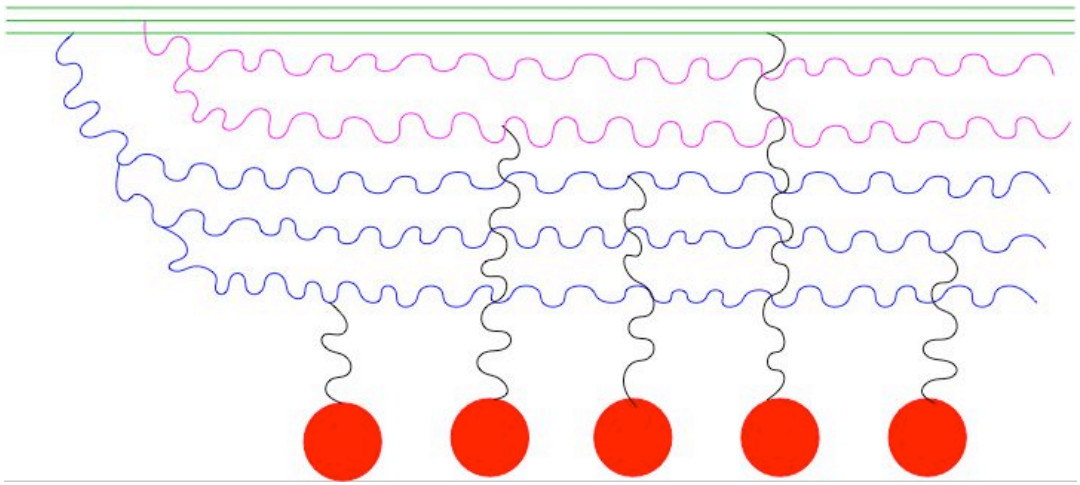


transverse momentum

DK, Levin,McLerran;
DK,Kovchegov,Tuchin
Albacete et al

At large rapidity y (small angle) expect suppression of hard particles!

Quantum regime at short distances: the effect of the classical background



1) Small x evolution leads to anomalous dimension

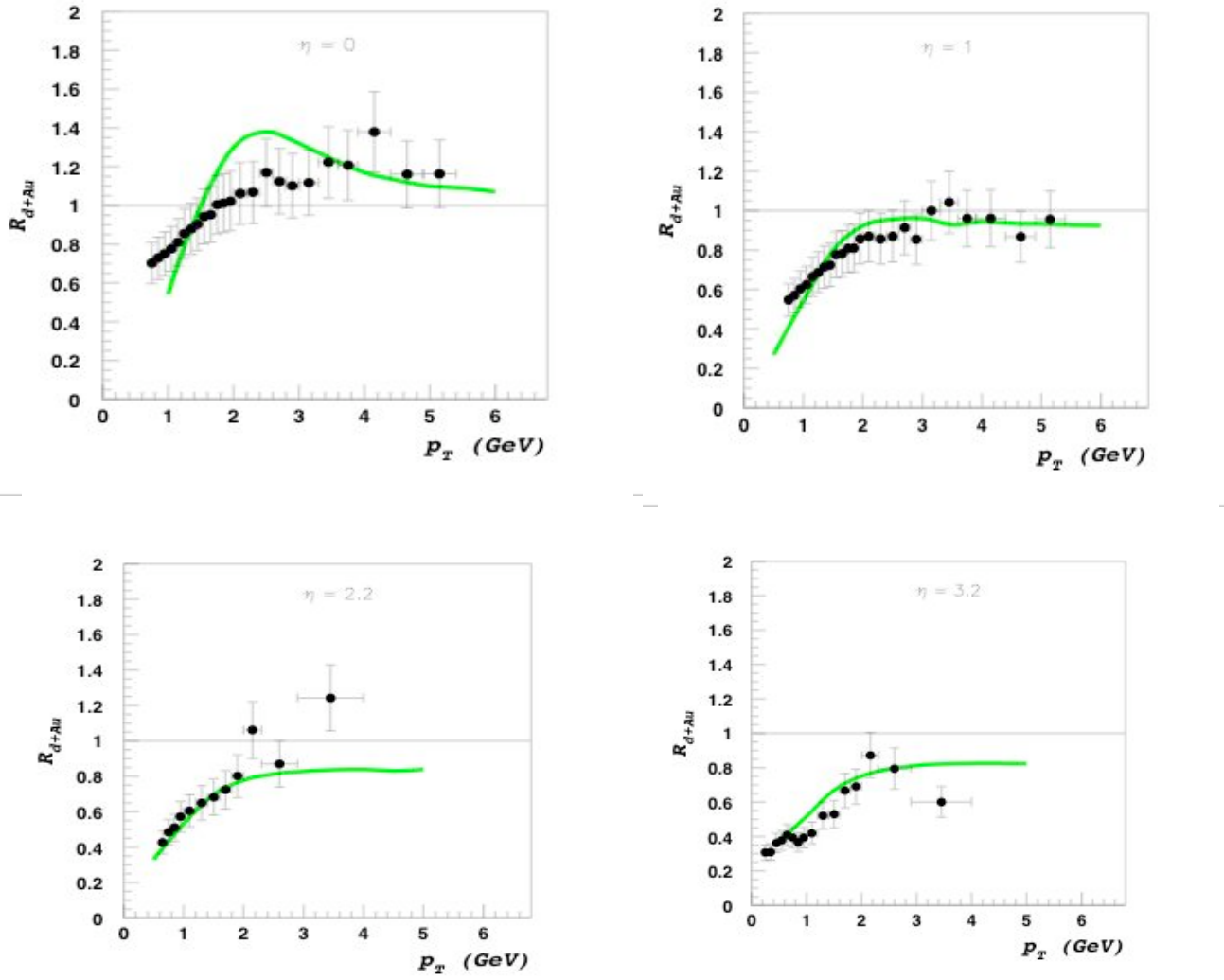
$$\frac{1}{Q^2} \to \left(\frac{1}{Q^2}\right)^{\gamma} \qquad \gamma \simeq 1/2$$

2) Q_s is the only relevant dimensionful parameter in the CGC; thus everything scales in the ratio Q_s^2/Q^2

3) Since $Q_s^2 \sim A^{1/3}$ the A-dependence is changed

→ Expect high p_T suppression at sufficiently small x

Color Glass Condensate: confronting the data

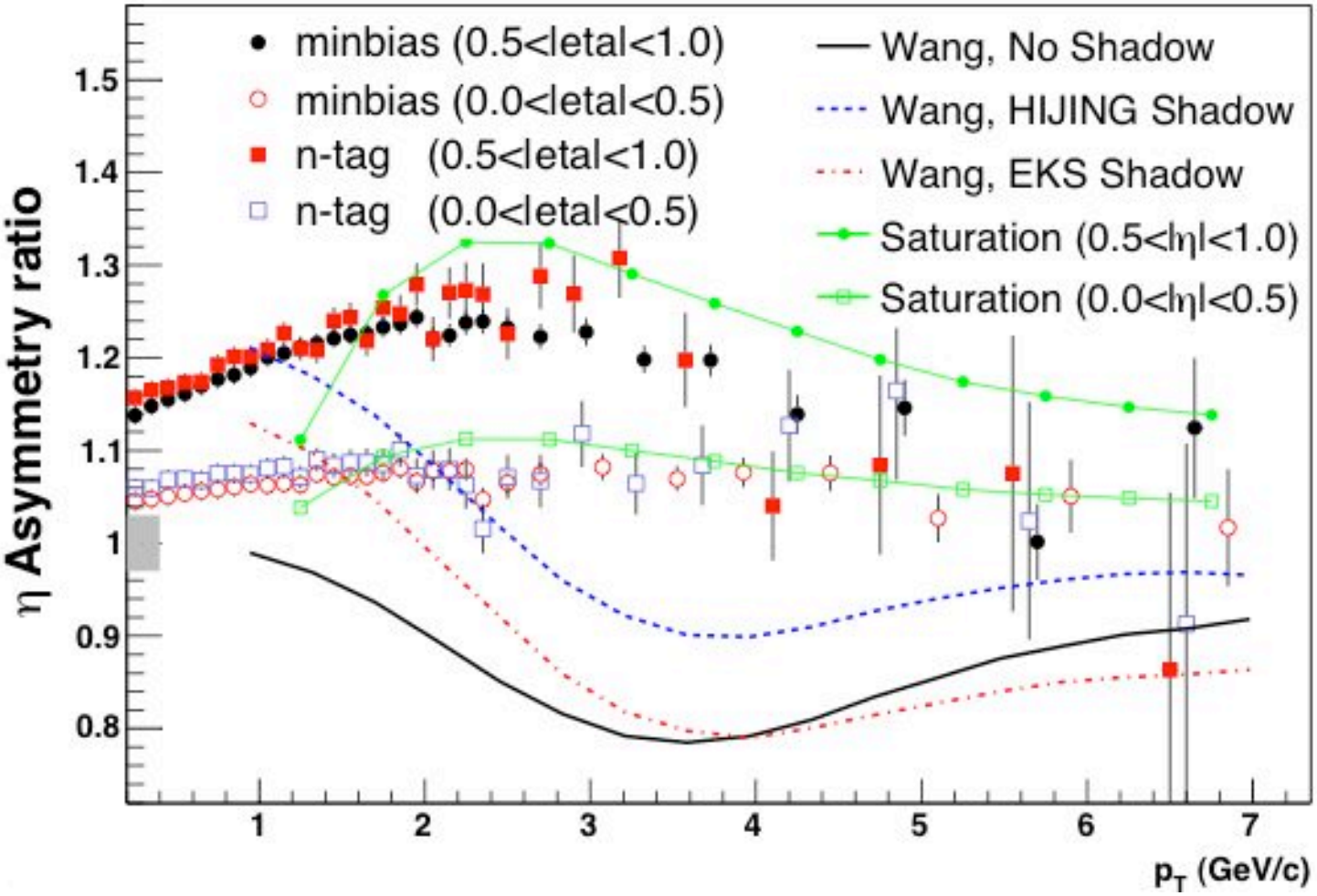


BRAHMS data, η= 0, 1, 2.2, 3.2

DK, Yu. Kovchegov, K. Tuchin, hep-ph/0405045

Confronting the RHIC data

STAR Collaboration



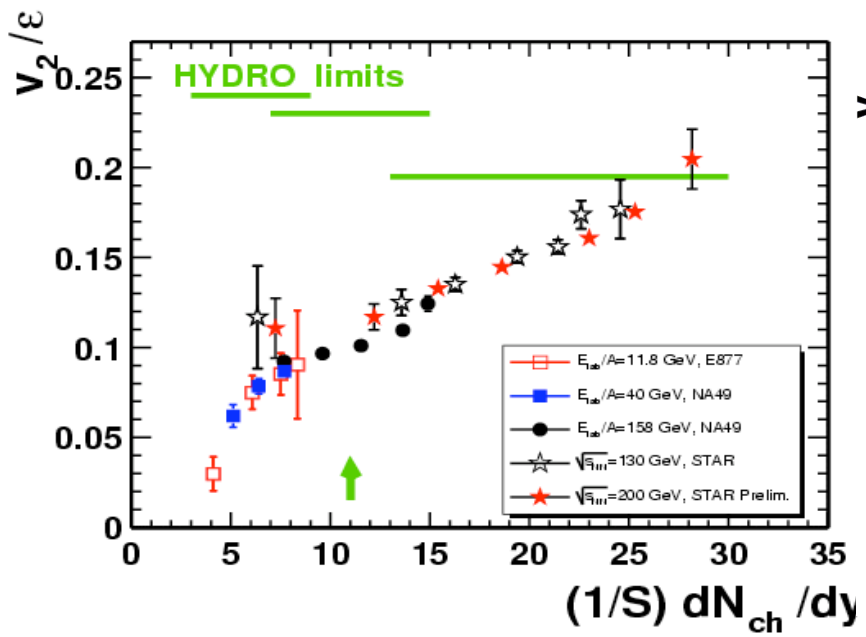
Do we see the QCD matter at RHIC ?

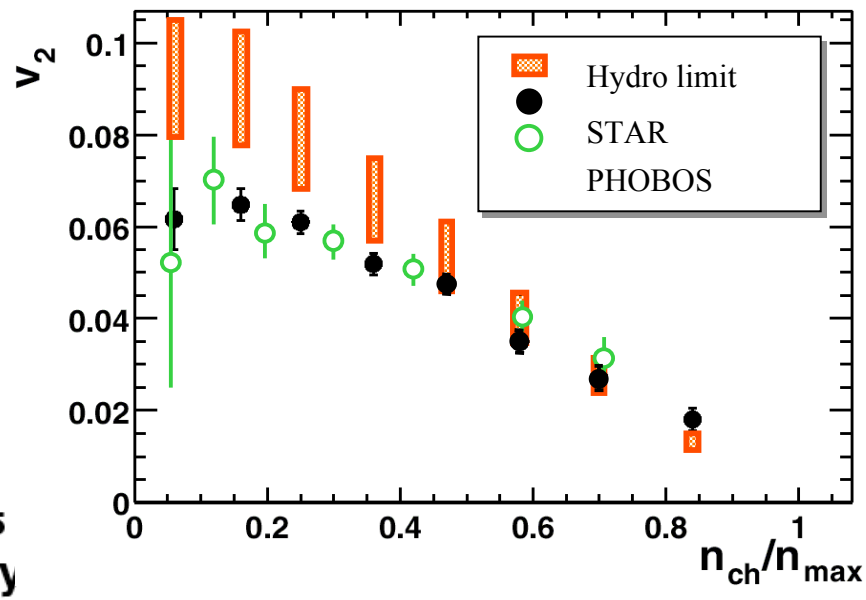
II. Collective flow =>

Au-Au collisions at RHIC produce strongly interacting matter

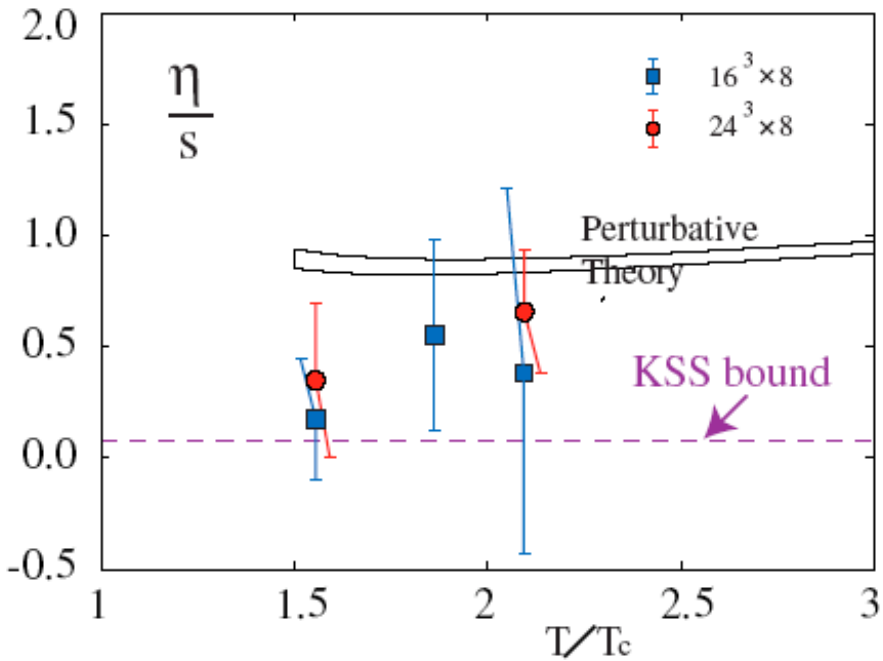
shear viscosity - to - entropy ratio

hydrodynamics: QCD liquid is more fluid than water

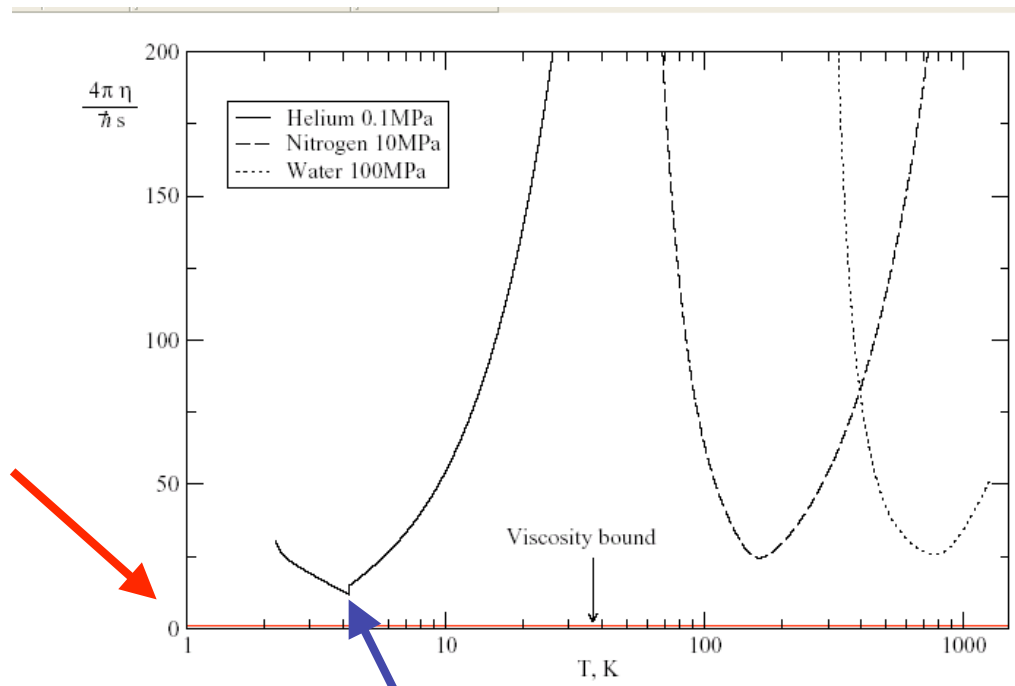




Quark-gluon plasma: more fluid than water?



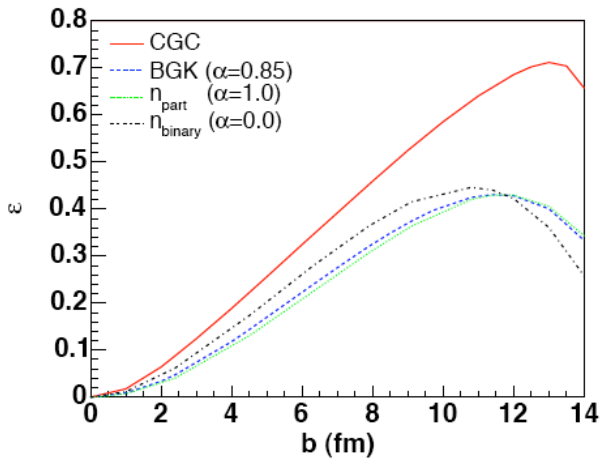
A.Nakamura and S.Sakai, hep-lat/0406009



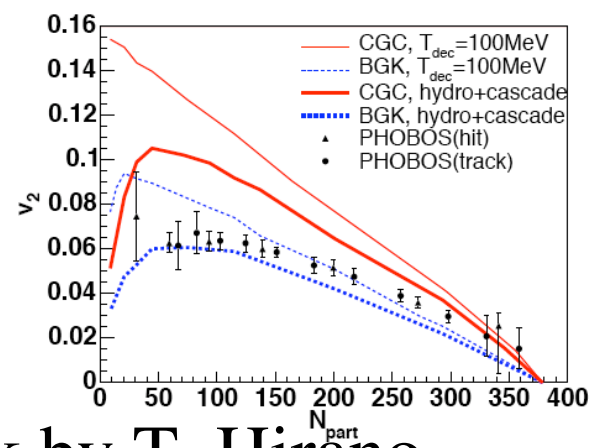
Superfluid helium

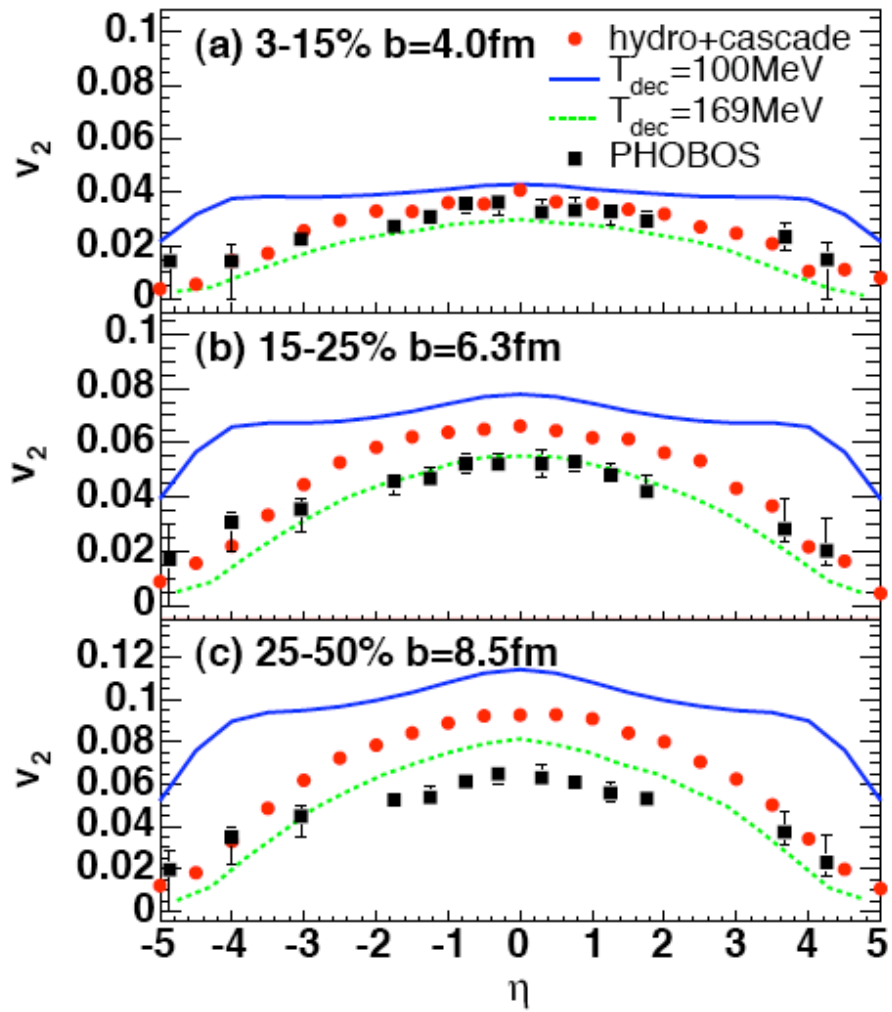
How small really is the viscosity?

CGC initial conditions lead to larger ellipticity,



require some viscous effects:





Talk by T. Hirano

T.Hirano, U.Heinz, DK, R.Lacey, Y. Nara, hep-ph/0511046

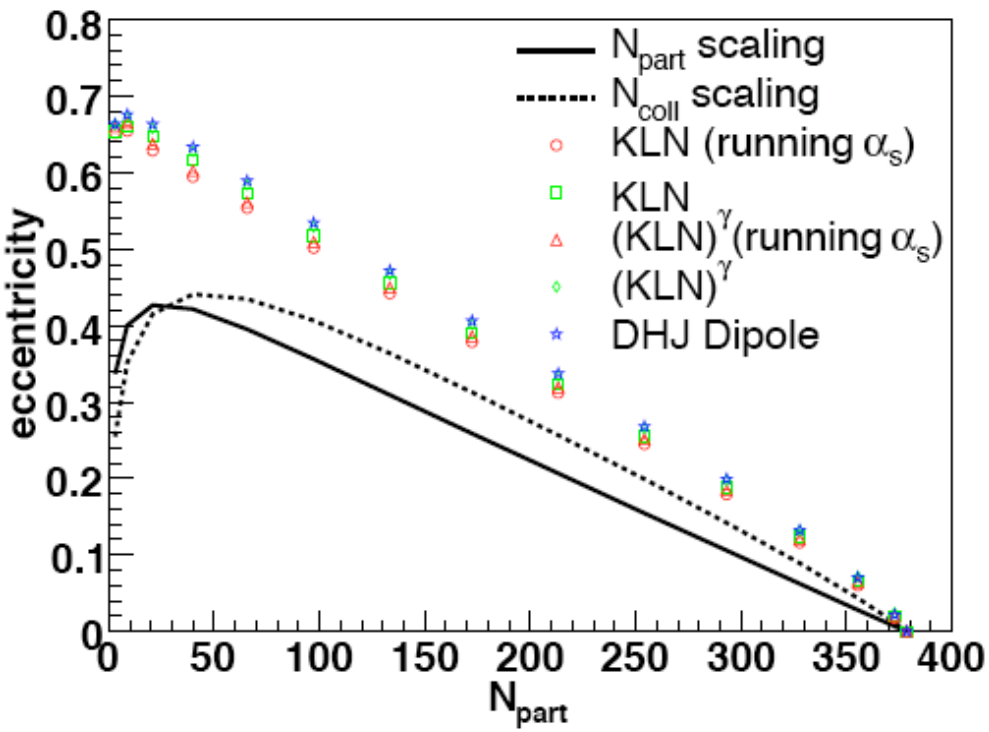
How small really is the viscosity?

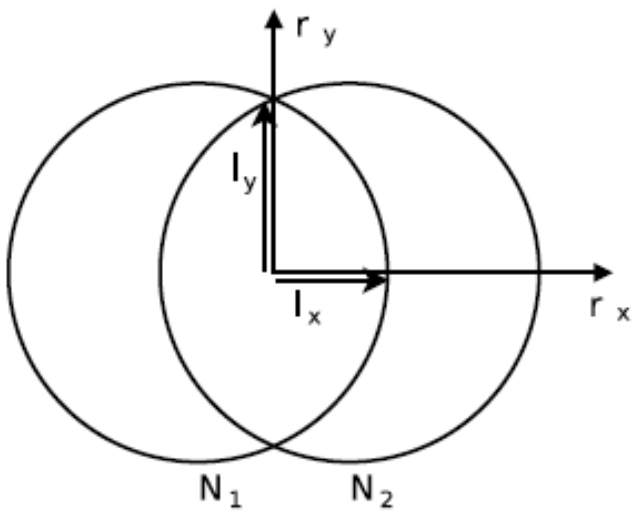
KLN initial conditions lead to larger ellipticity,

T.Hirano, U.Heinz, DK, R.Lacey, Y. Nara, hep-ph/0511046

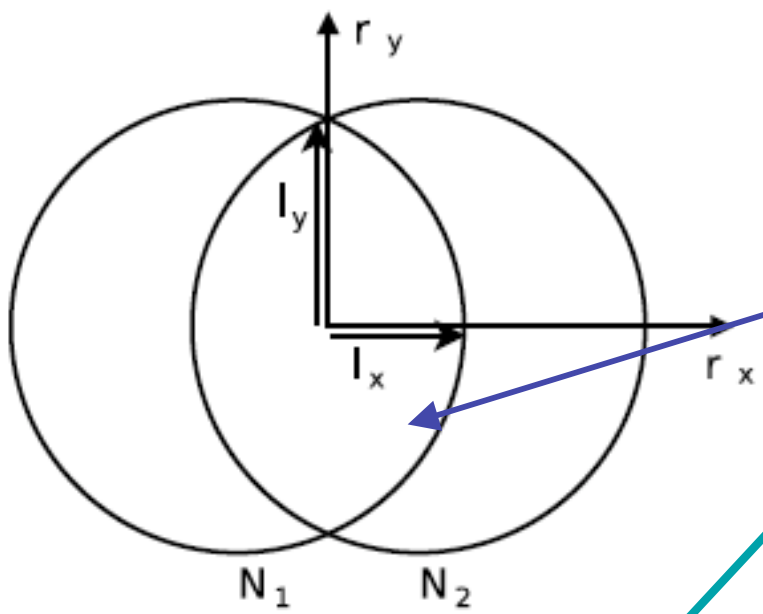
this is not an artifact of a particular model for the gluon distribution, but a generic feature of saturation

H.Drescher, A.Dumitru,A.Hayashigaki,Y.Nara, nucl-th/0605012





How small really is the viscosity?



The density of produced partons is equal to

KLN:

$$\sim Q^2_{s,min} \times \left(1 + \ln\left(\frac{Q_{s,max}}{Q_{s,min}}\right)\right)$$

Glauber model:

$$\sim Q^2_{s,min} + Q^2_{s,max}$$

(participant scaling)

$$\sim Q^2_{s,min} \times Q^2_{s,max}$$

(collisional scaling)

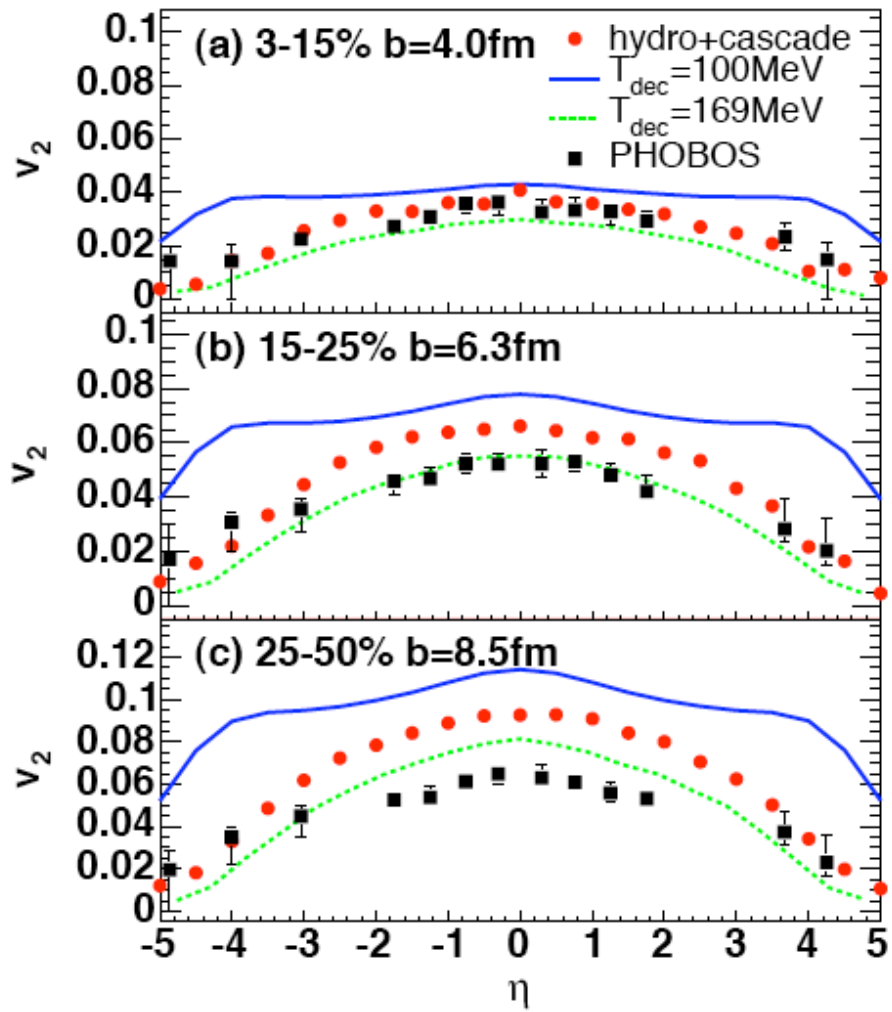
Sensitive mainly to
the smaller saturation scale
=> Steeper fall-off!

(Small dipoles cannot be resolved by large dipoles)

How small really is the viscosity?

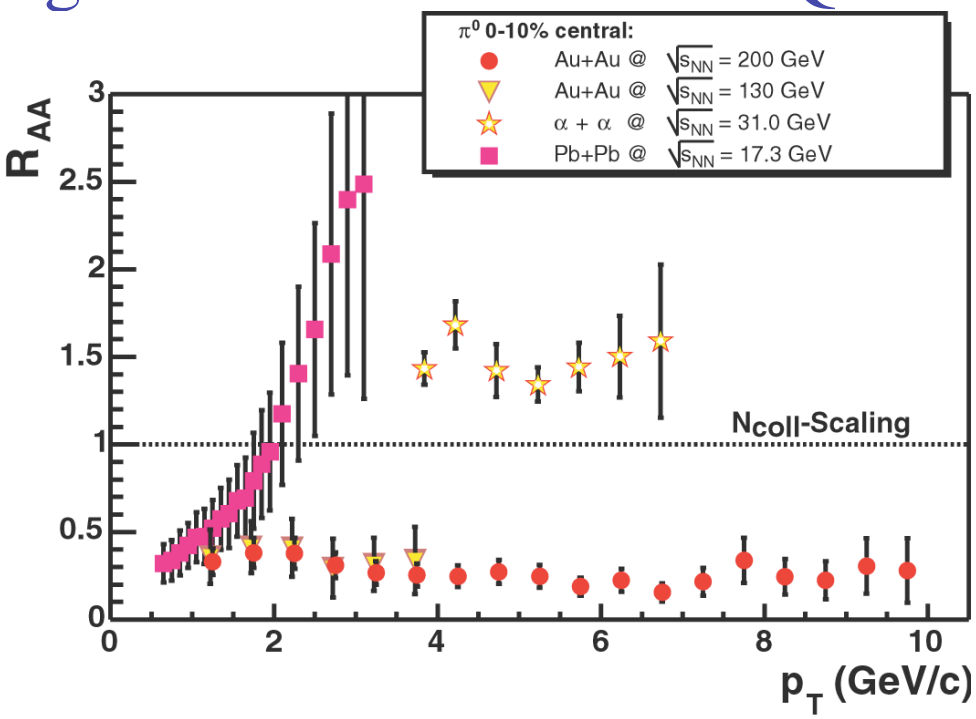
Important question:
given the CGC initial
conditions, how large
can be the viscosity
of the quark-gluon plasma?
How long can be
thermalization time?

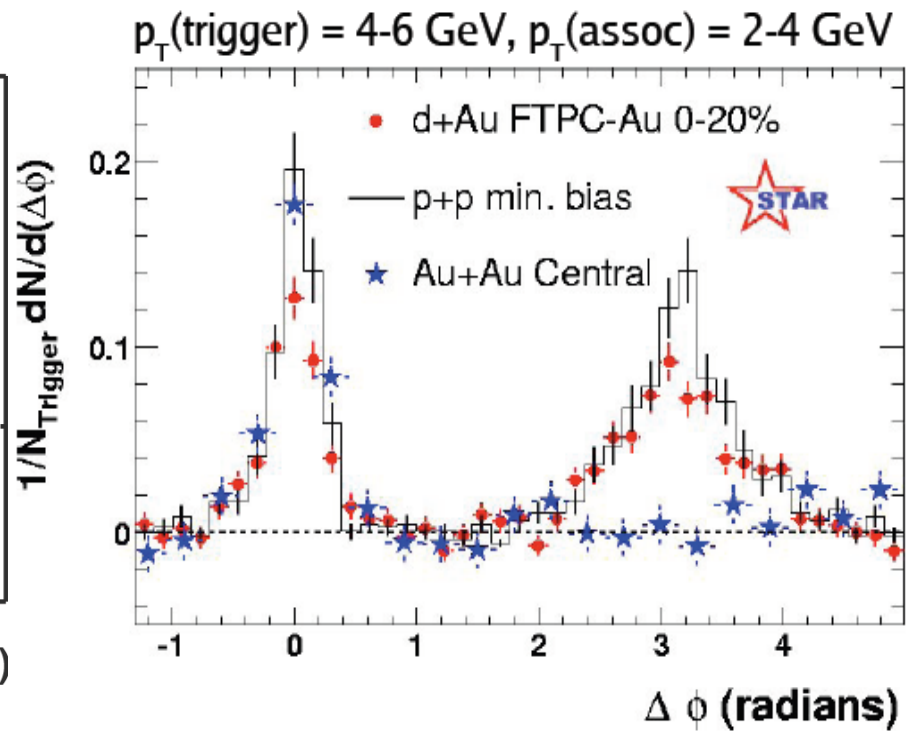
Talks by T. Hirano
Y. Nara



What have we learned from RHIC so far ?

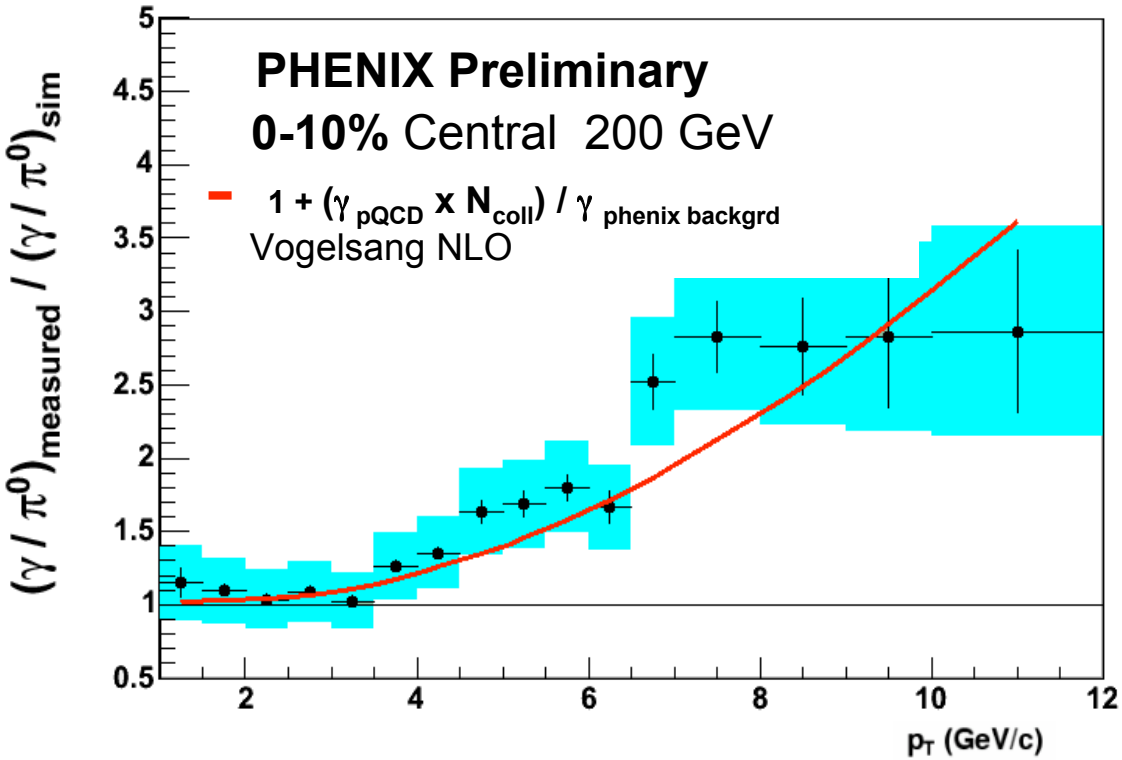
III. Suppression of high p_T particles =>
consistent with the predicted jet energy loss from induced gluon radiation in dense QCD matter (but: heavy quarks?)





What do we still need to know?

Look at the weakly coupled probes -
Direct photons are not suppressed:



Theory by
W.Vogelsang

another probe: heavy quarks

Heavy quark colorimetry of QCD matter

col·or·im·e·try *noun*
col·or·im·e·ter *noun* **:**
an instrument or device for determining and specifying colors; *specifically* **:** one used for chemical analysis by comparison of a liquid's color with standard colors

Merriam-Webster Dictionary

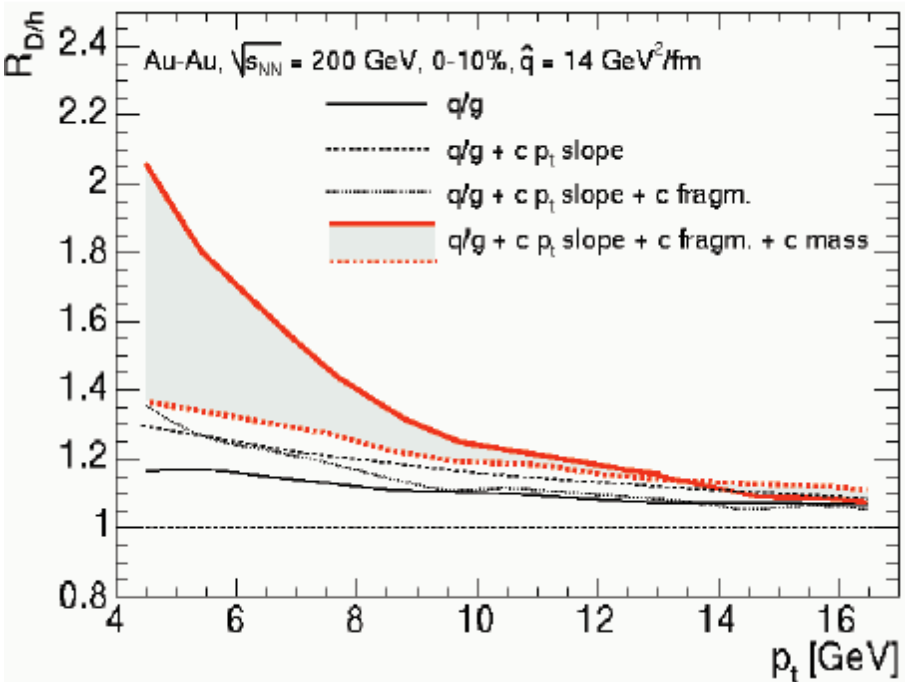
The propagation of heavy quarks in QCD matter is strongly affected by the interplay of the "dead cone" and quantum interference effects (LPM) at energies up to

$$E \leq M\sqrt{\hat{q}L^3}$$

(a consequence of quantum mechanics & causality)

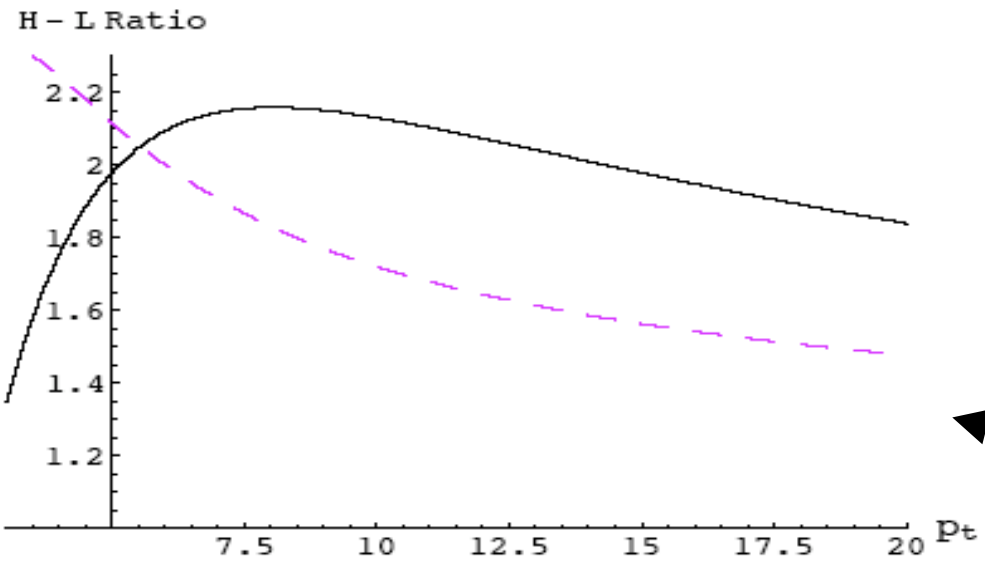
Yu.Dokshitzer, DK
hep-ph/0106202

Armesto, Dainese, Salgado, Wiedemann, in preparation



N.Armesto,
M. Djordjevic,
M. Gyulassy,
C.Salgado,
U. Wiedemann,
X.N. Wang, …

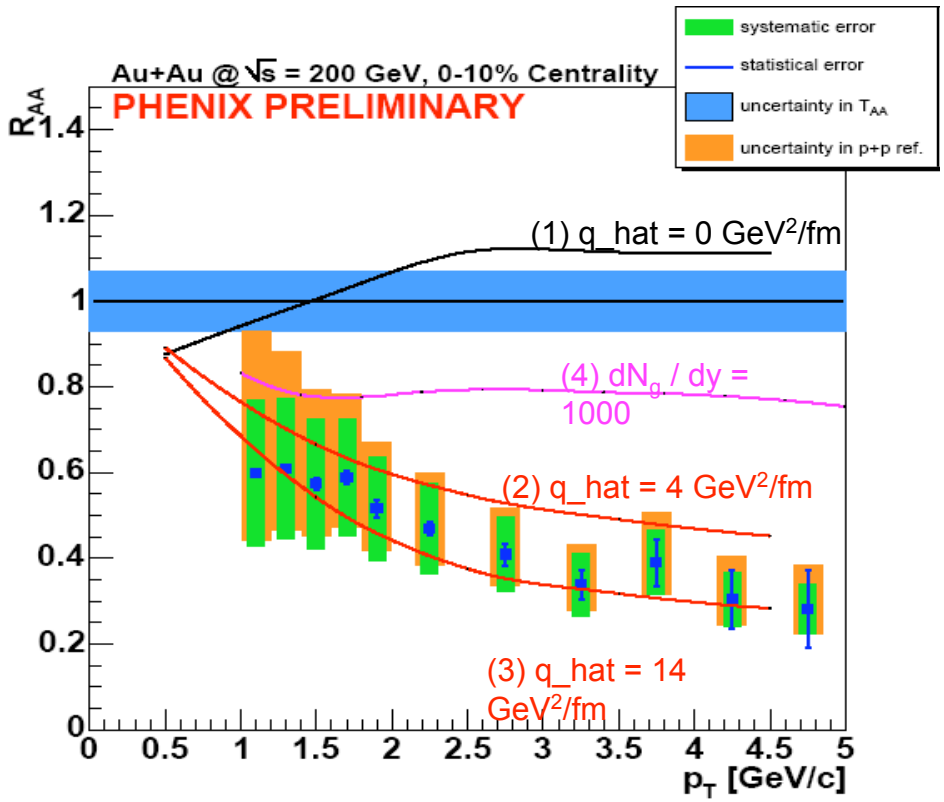
Enhancement of
the D/h ratio as
a signature of the radiative
energy loss in the QGP:
Heavy quarks lose less

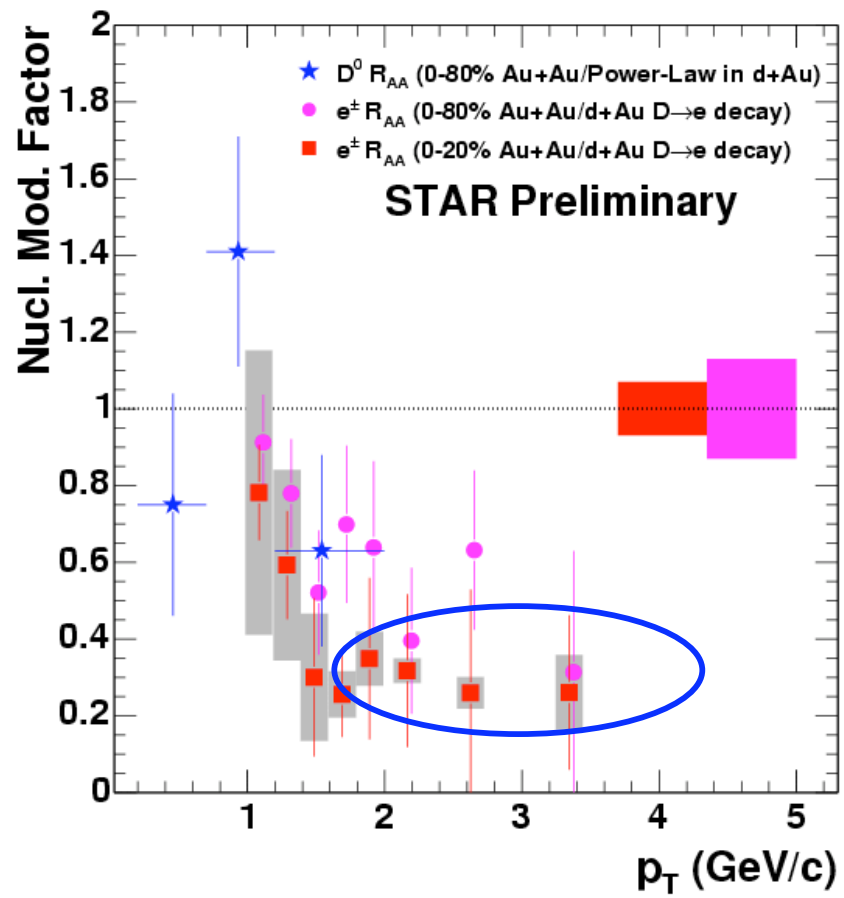


Yu.L.Dokshitzer and DK,
Phys.Lett.B519 (2001) 199

AuAu collisions: charm is quenched!?

a serious problem for the naïve radiative energy loss scenario?



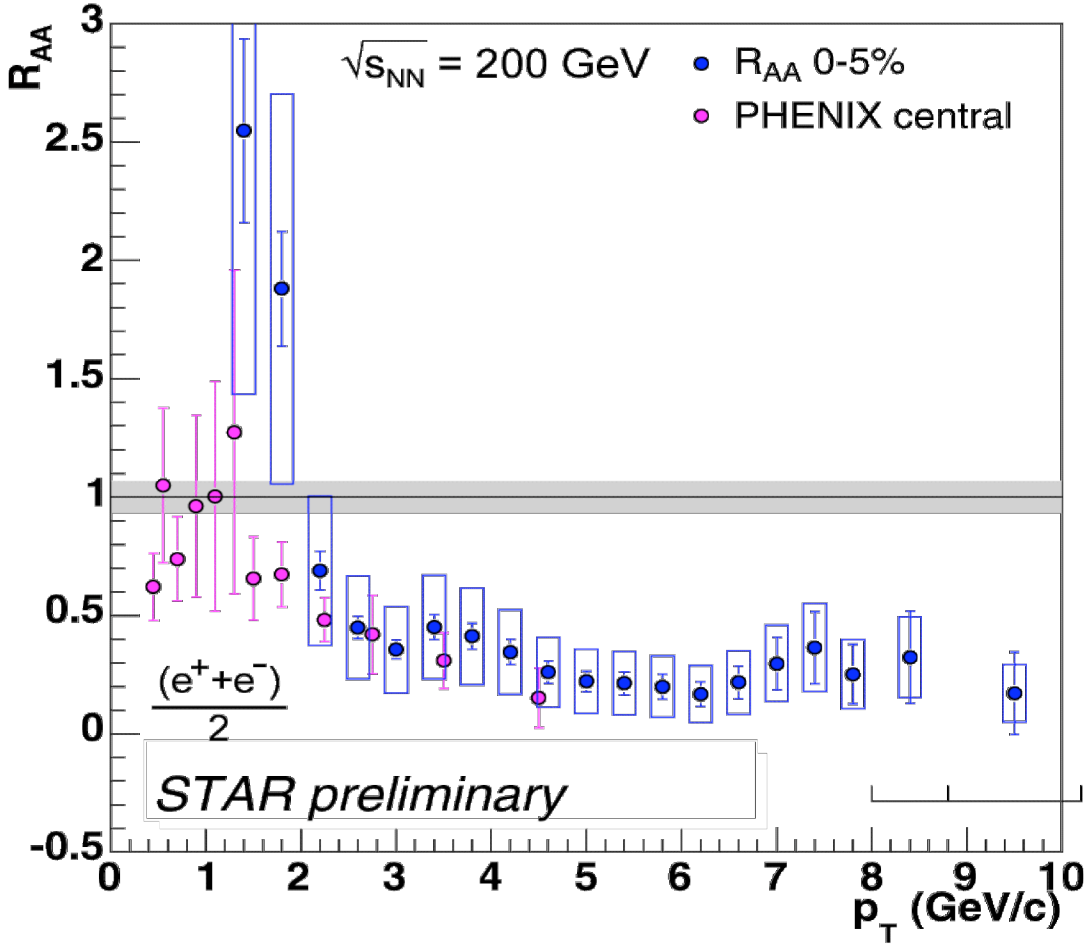


PHENIX Coll., Quark Matter'05

STAR Coll., Quark Matter'05

AuAu collisions: charm is quenched!?

a serious problem for the naïve radiative energy loss scenario?



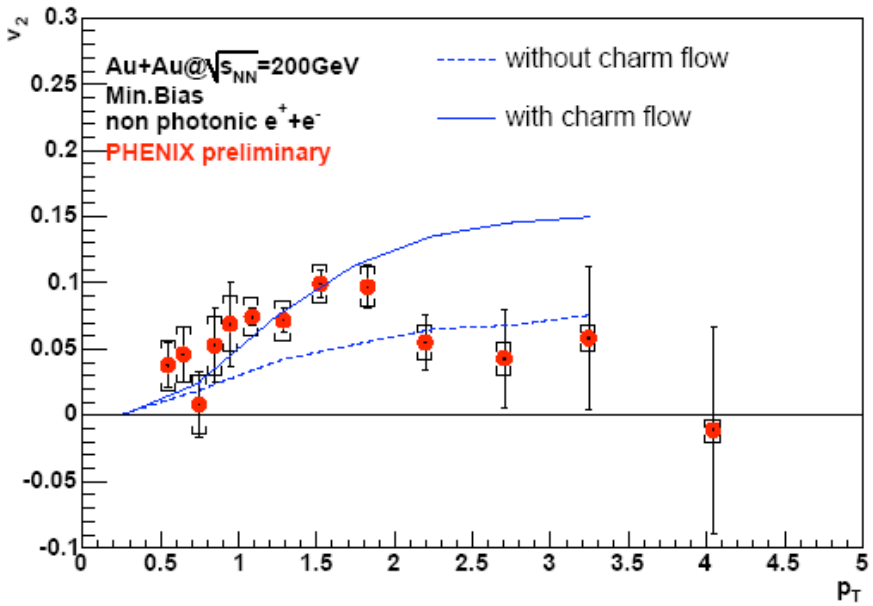
…and where is the beauty?

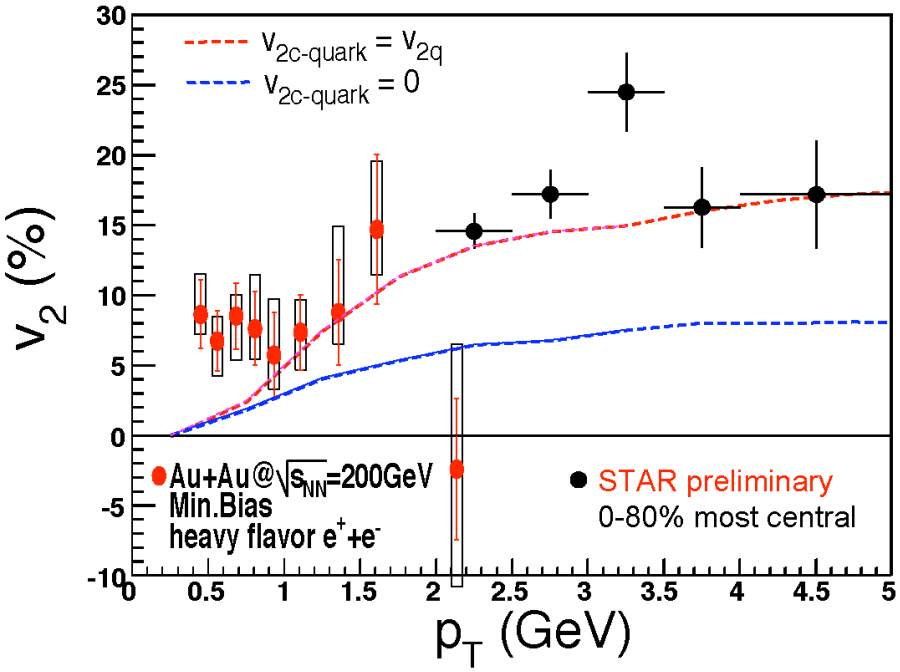
STAR Coll., Quark Matter'05

AuAu collisions: charm flows!

Extract the heavy quark transport coefficients?

P.Petreczky, D.Teaney, hep-ph/0507318



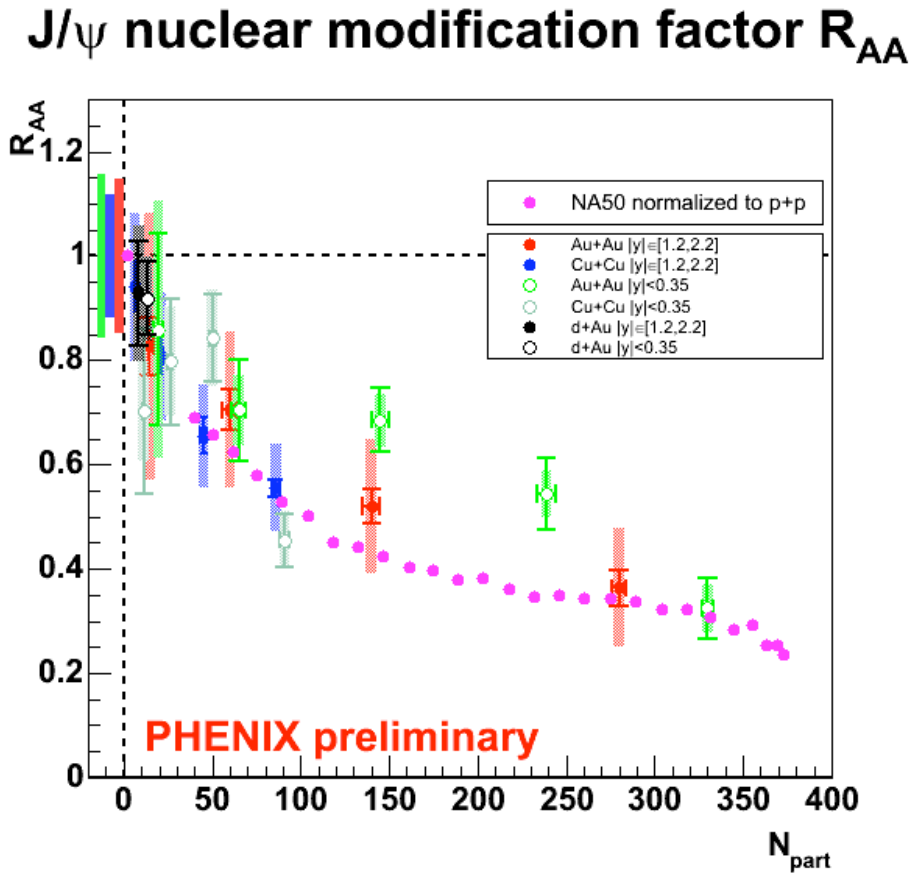


PHENIX Coll., Quark Matter'05

STAR Coll., Quark Matter'05

What have we learned from RHIC so far ?

IV. (Lack of) suppression of heavy quarkonia =>
remnants of confinement? heavy quark recombination?



"same as at SPS"?

J/Ψ as a probe:

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

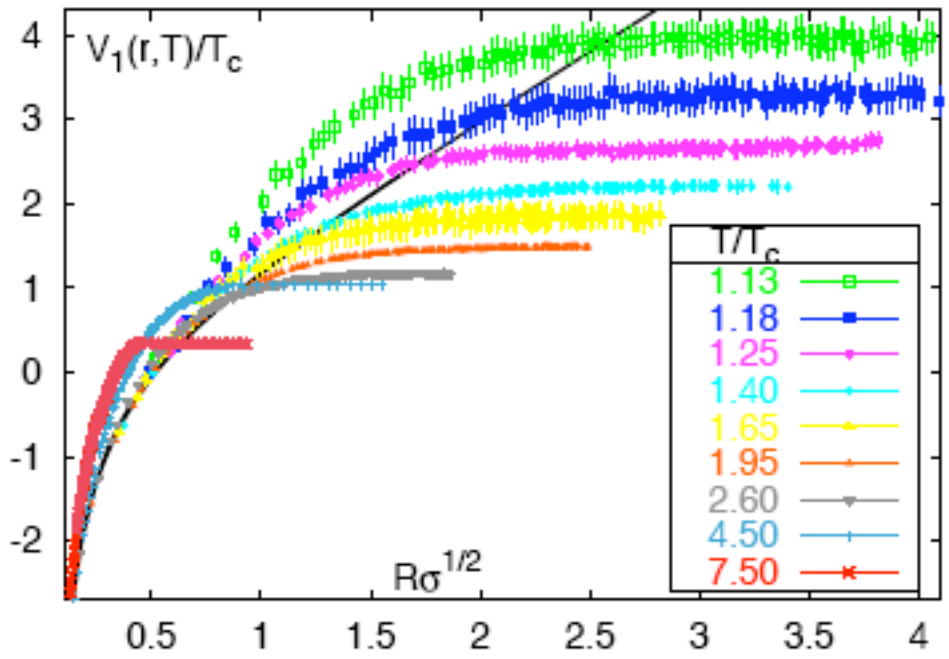
and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

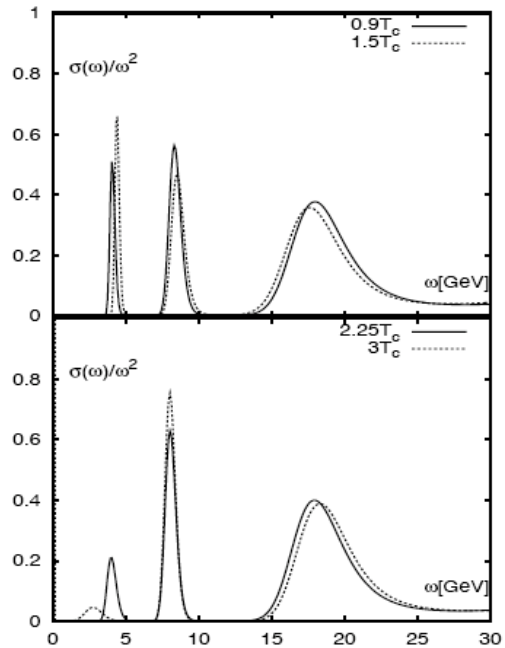
If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Heavy quark internal energy above T

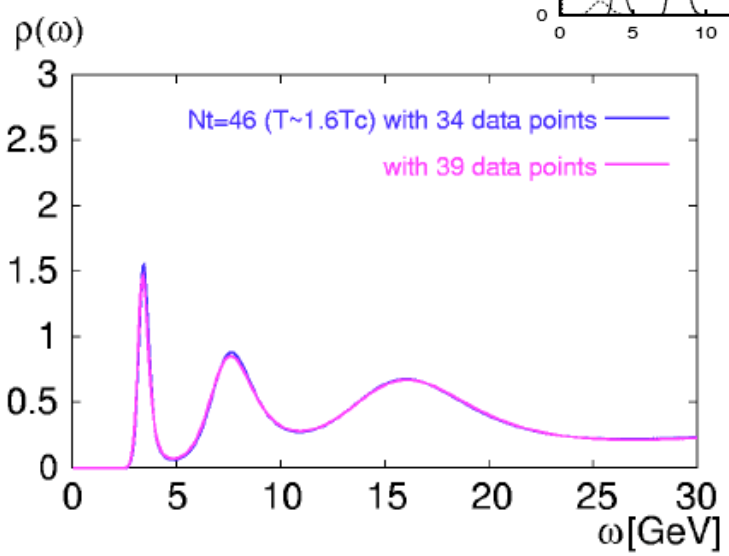


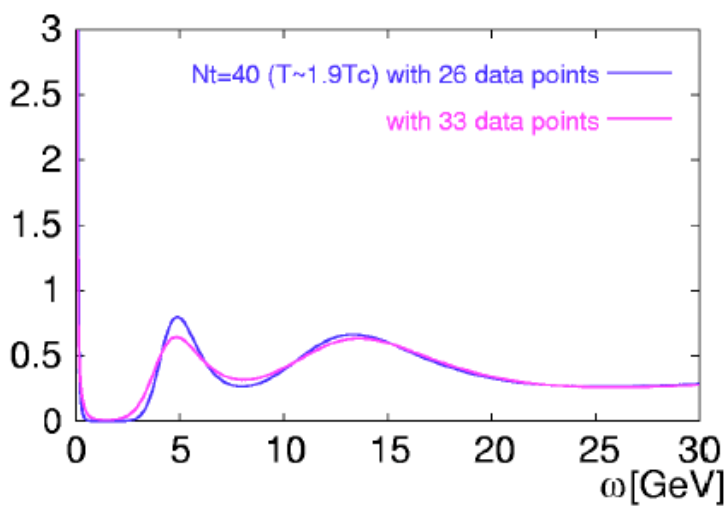
O.Kaczmarek, F. Karsch, P.Petreczky,
F. Zantow, hep-lat/0309121

J/Ψ above T_c: alive and well?



S.Datta,
F.Karsch,
P.Petreczky,
I.Wetzorke





M.Asakawa,
T.Hatsuda

Difficulties of the potential model

Potential model is based on the assumption that the interaction is instantaneous, or at least much faster than the typical revolution time of heavy quarks in quarkonium, $\tau \sim 1/\varepsilon$.

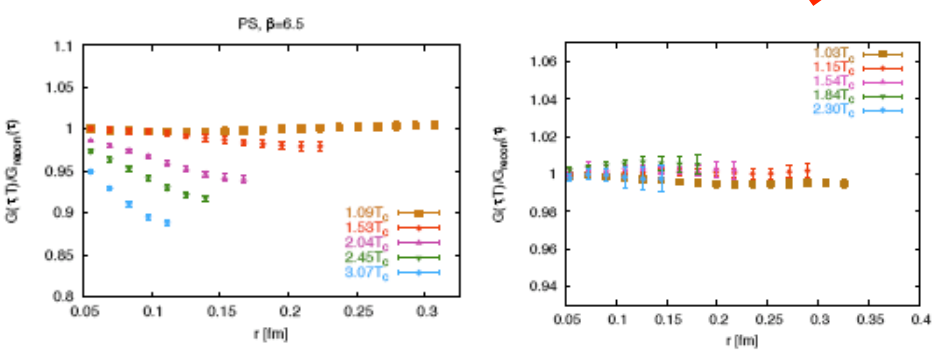
OK for the Coulomb potential;

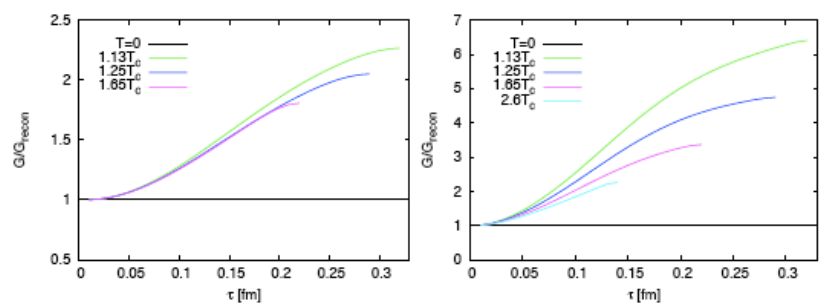
Fails for soft vacuum fields;

A.Mocsy,P.Petreczky
hep-ph/0606053

Probably fails for the screened gluon exchange as well

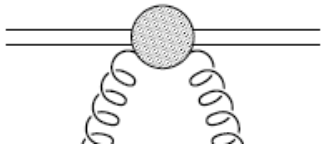
Lattice ⟷ Potential





Quarkonium in the hadron gas

Talk by H.Fujii



Quarkonium-hadron scattering amplitude

$$\mathcal{M}^{kl}(P',p';P,p) = -\bar{d}_2 \frac{a_0^2}{\epsilon_0} \langle \pi^k(p') | \frac{1}{2} g^2 \mathbf{E}^{a2}(0) | \pi^l(p) \rangle$$

can be expressed through the matrix element of the trace of the energy-momentum tensor:

$$\langle \pi^k(p') | \frac{1}{2} g^2 \mathbf{E}^{a2}(0) | \pi^l(p) \rangle = \frac{4\pi^2}{b} \langle \pi^k(p') | \theta^\mu_\mu(0) | \pi^l(p) \rangle$$

Therefore, the coupling of heavy quarkonium to hadrons at low energy is analogous to the coupling of the Higgs boson -

$$\Theta^\alpha_\alpha = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l$$

it is proportional to the hadron mass (squared); decoupling of pions!

$$\langle h | \Theta^\alpha_\alpha | h \rangle = 2M_h^2$$

DK, nucl-th/9601029
H.Fujii,DK, hep-ph/9903495

Quarkonium in hadron gas: recent lattice results

K.Yokokawa, S.Sasaki,
T.Hatsuda,A.Hayashigaki,
hep-lat/0605009

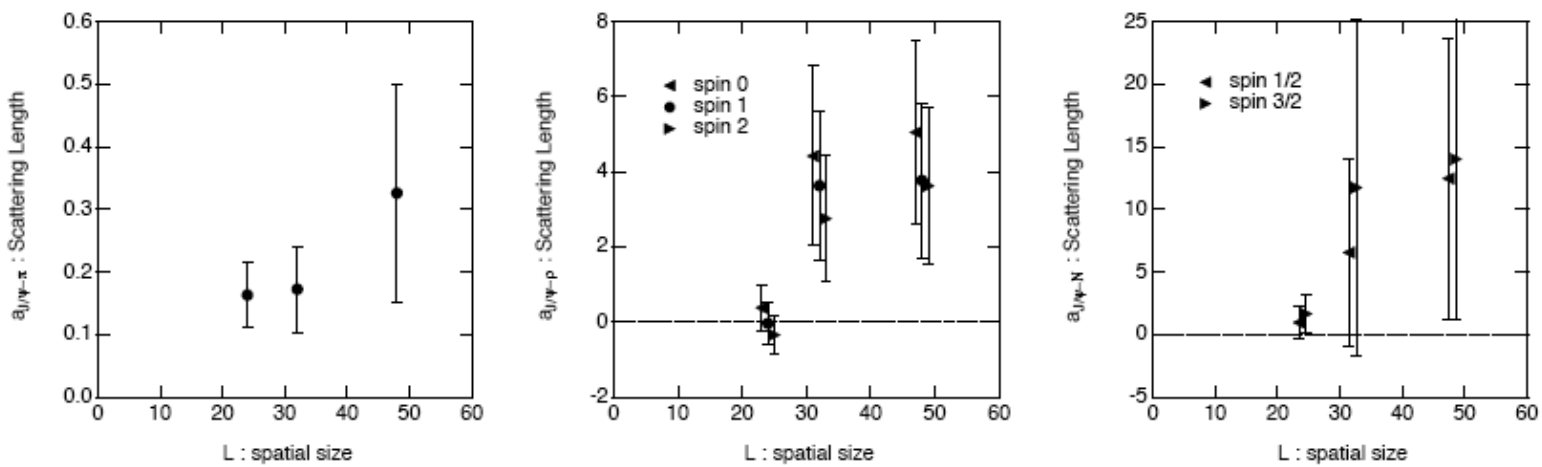


FIG. 4: The scattering lengths as a function of the spatial size L in lattice units for physical pion mass ($M_\pi = 140$ MeV). Left (middle, right) panel is for the J/ψ-π (J/ψ-ρ, J/ψ-N) channel.

$$a_{\psi\pi} : a_{\psi\rho} : a_{\psi N} \simeq 0.3 \pm 0.15 : 4 \pm 1.5 : 15 \pm 10 \sim m_\pi^2 : m_\rho^2 : m_N^2 \simeq 0.3 : 9 : 13$$

Pion “decoupling” seen in the data! J/ψ is safe in the pion gas

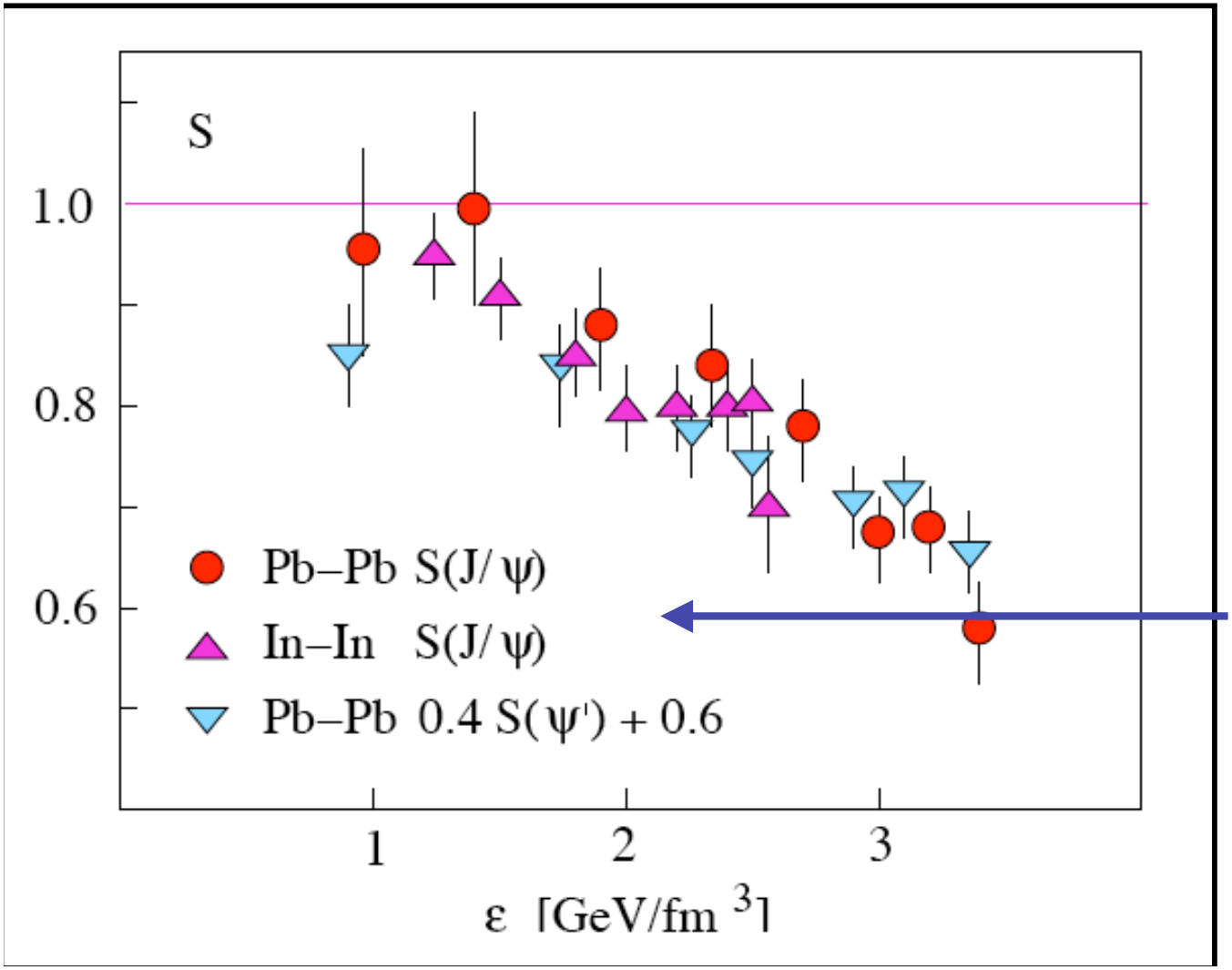
Sequential charmonium dissociation?

Both the absence of J/ψ suppression up to ~ 2 T_c in the lattice QCD data and the apparent similarity of the magnitude of suppression at RHIC and SPS are puzzling;

However, the two puzzles may be consistent with each other

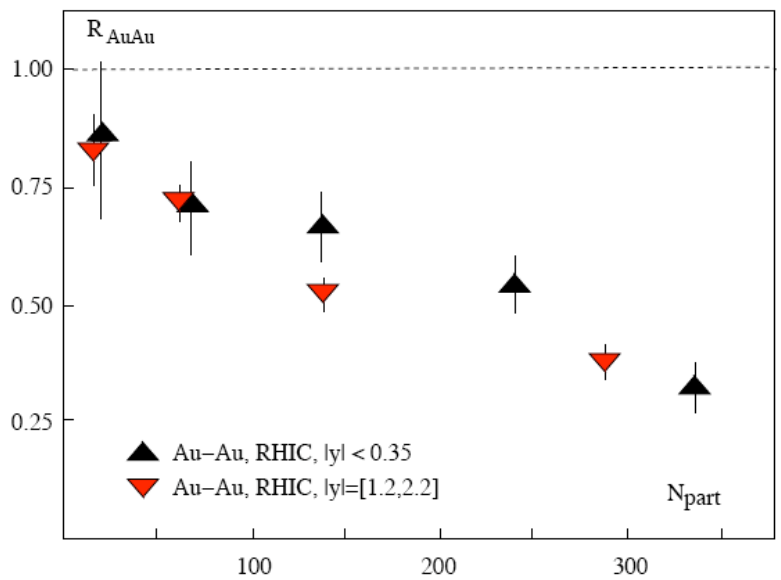
F.Karsch, DK, H.Satz,
hep-ph/0512239

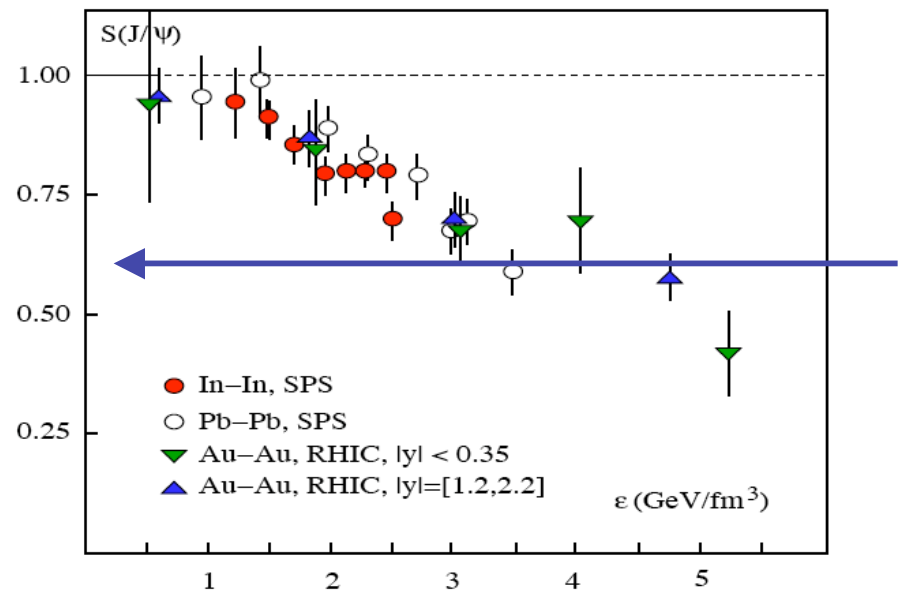
Is there a "direct" J/ψ suppression at SPS?



~ 40%
of observed
J/ψ 's
originate
from χ and ψ
decays;
they should
be gone above T_c

Is there a "direct" J/ψ suppression at RHIC?

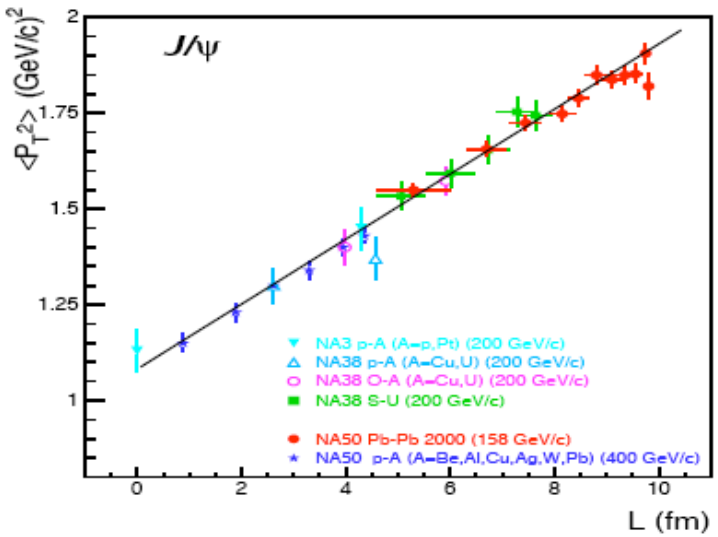


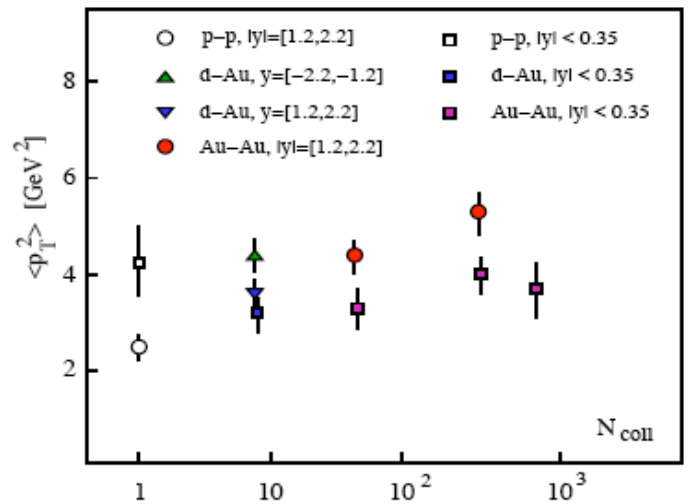


Data: PHENIX, NA50, NA60

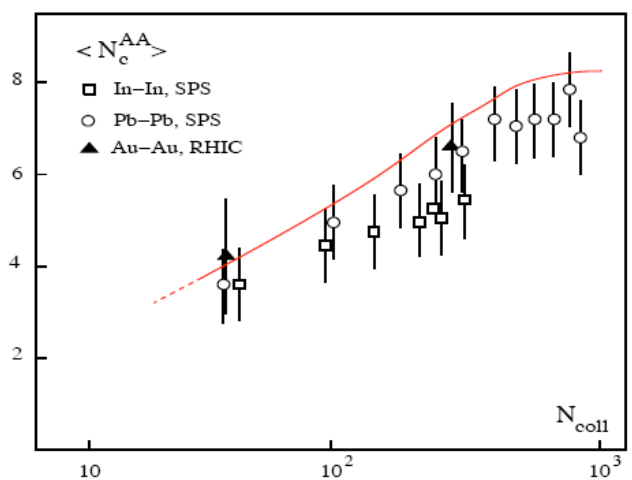
Energy density at the time J/ψ is formed - assumed τ = 1 fm/c

Transverse momentum distributions



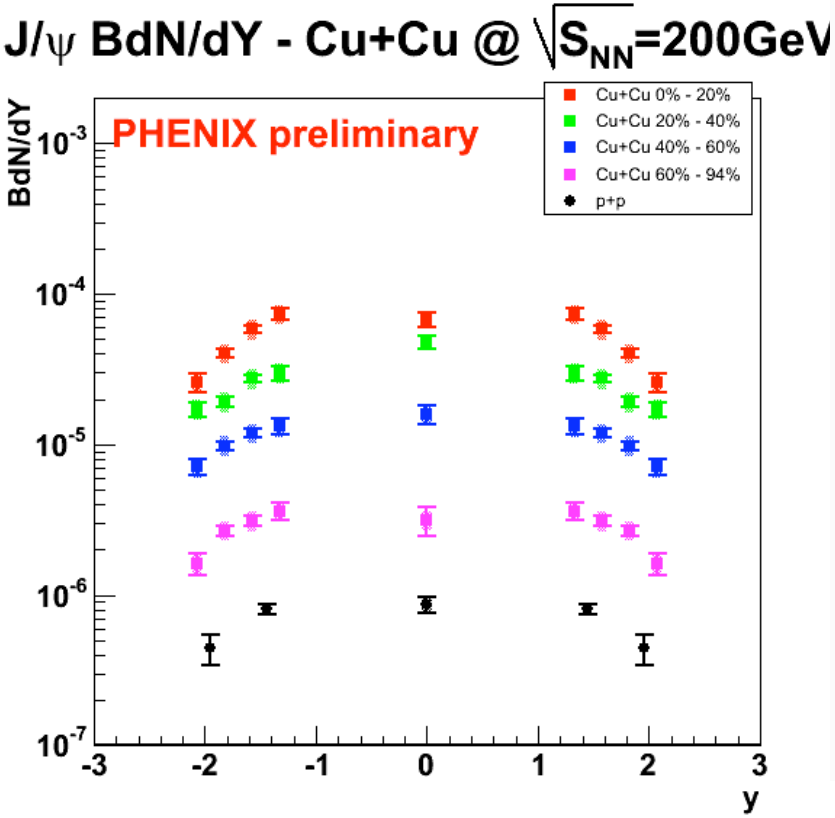


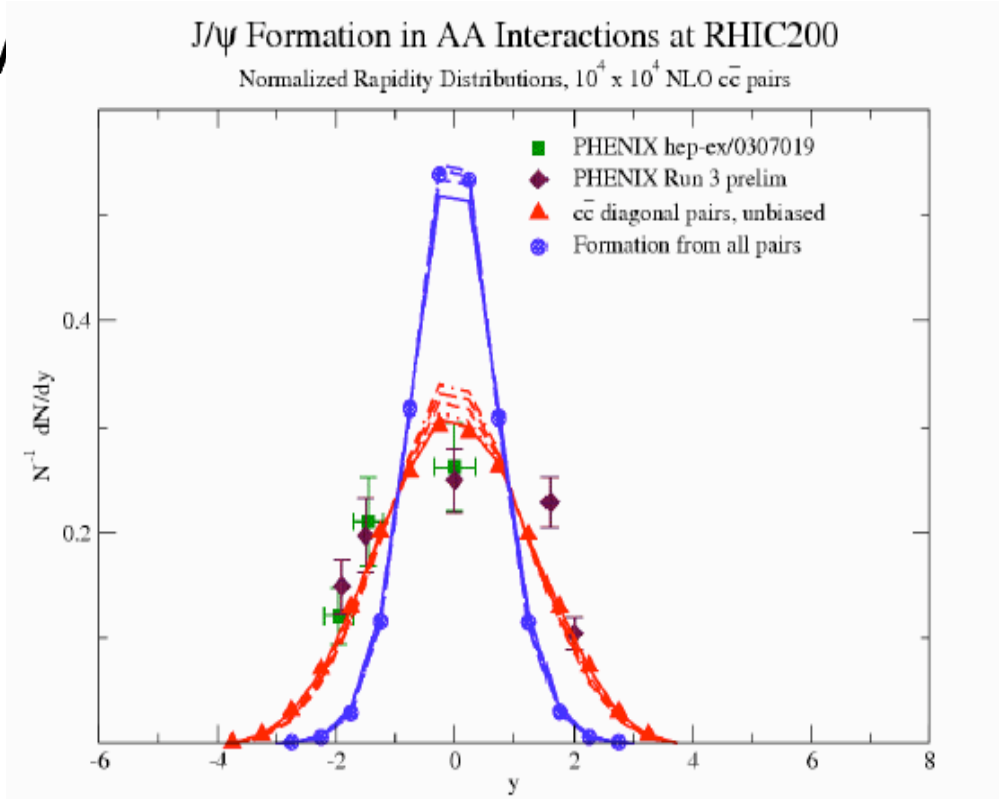
"Secondary" J/ψ's have softer p_T distributions + Cronin effect => suppression mostly at small p_T



Glauber model analysis

Recombination of charm quarks?



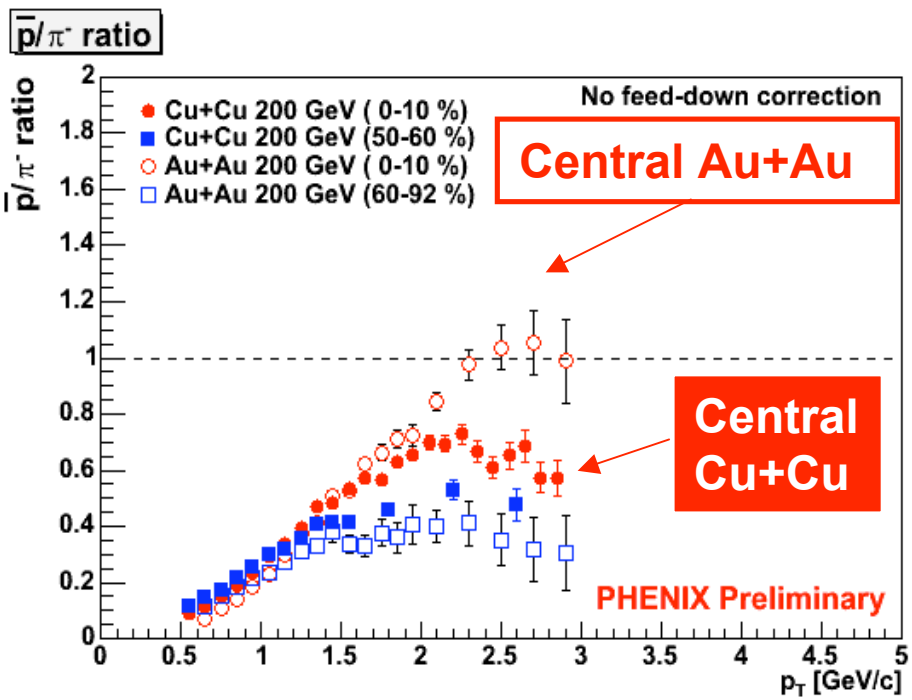


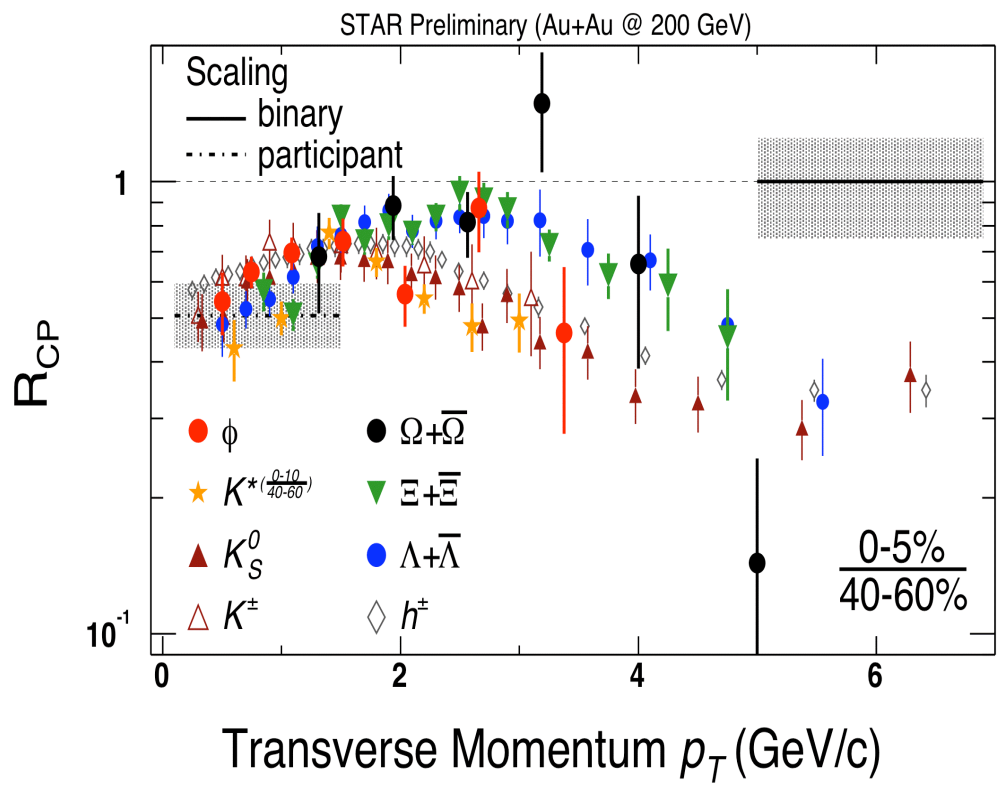
R.Thews

Recombination narrows the rapidity distribution; is this seen?
Are high p_t charmonia suppressed stronger than open charm?

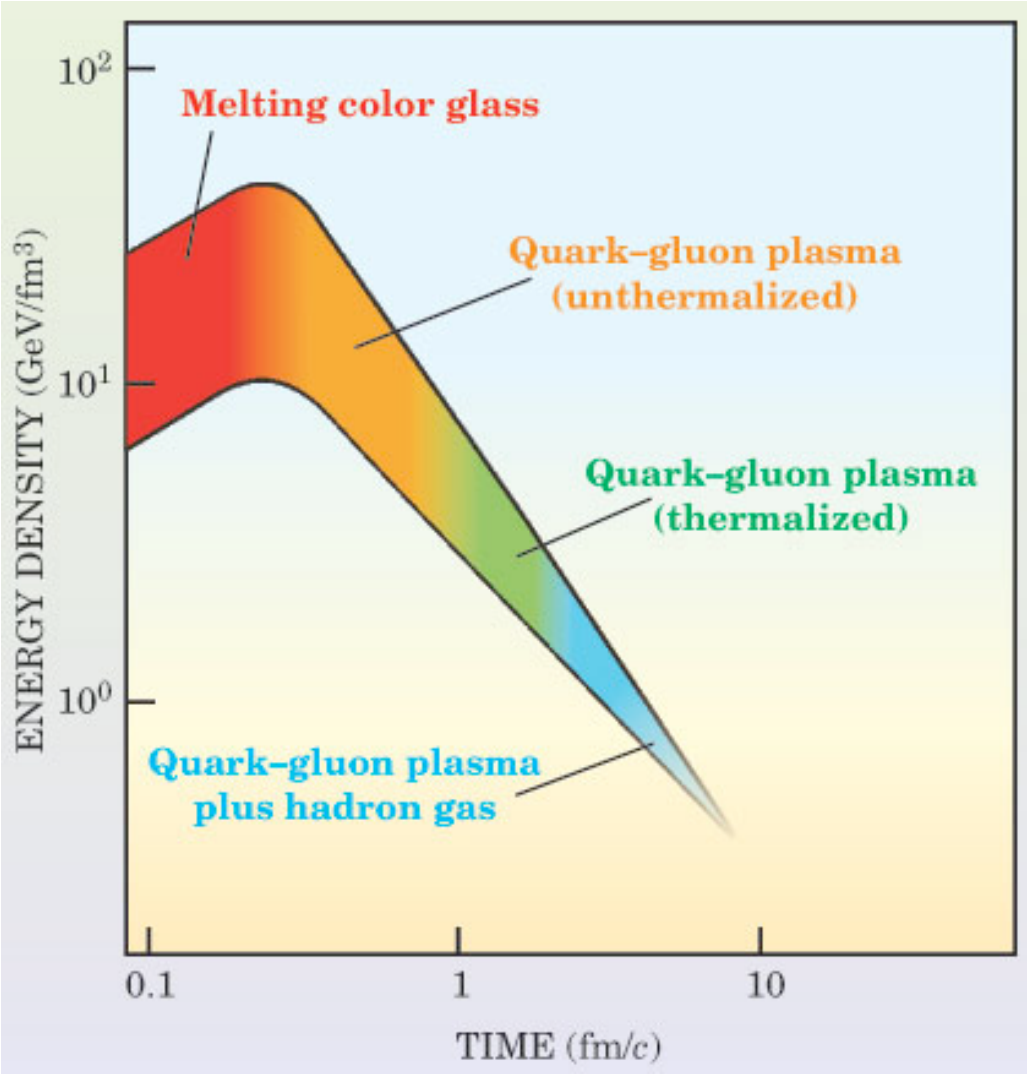
What have we learned from RHIC so far ?

V. Baryon/meson enhancement =>
Constituent quark recombination? Baryon junctions?





The emerging picture



A BIG question:
Why is thermalization so fast?

Talk by Y.Nara;
+Work by
R.Venugopalan,
K.Tuchin,…

T. Ludlam,
L. McLerran,
Physics Today
October 2003

Summary

1. Quantum Chromo-Dynamics is
an established and consistent field theory
of strong interactions
but it's properties are far from being understood

2. High energy nuclear collisions test the predictions
of strong field QCD and probe
the properties of super-dense matter

Many surprises; a lot more needs to be done

⇒Keep up the good work, RBRC -
you are making a difference!