PAC meeting, BNL, September 31, 2006

RHIC II & eRHIC: the Science of QCD Lab

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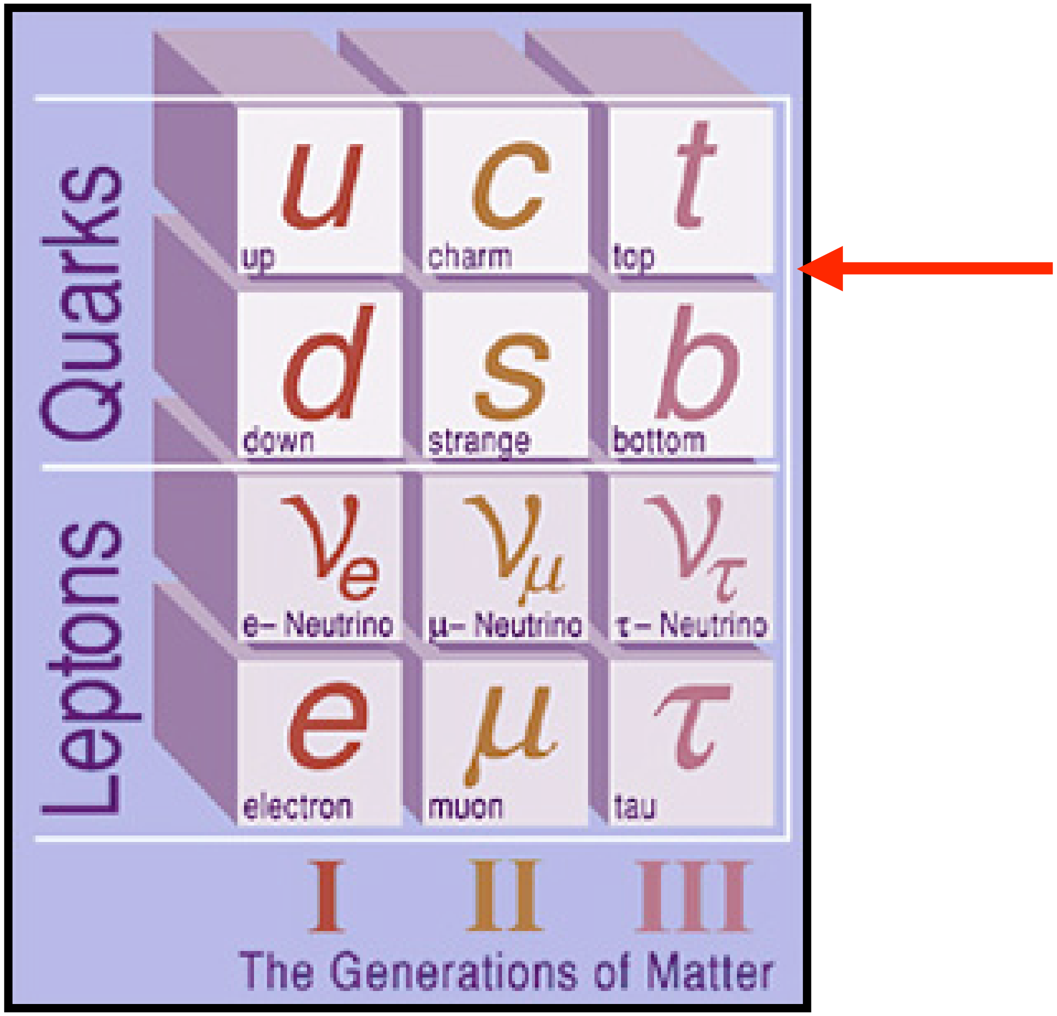
Outline

- The Big Questions
- What have we learned from RHIC in the first five years?
- Why RHIC II? Why eRHIC?

eRHIC: talks by R.Milner and R.Venugopalan
RHIC II: talk by C. Gagliardi

Quarks and the Standard Model



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

they are confined within hadrons (mechanism unknown)

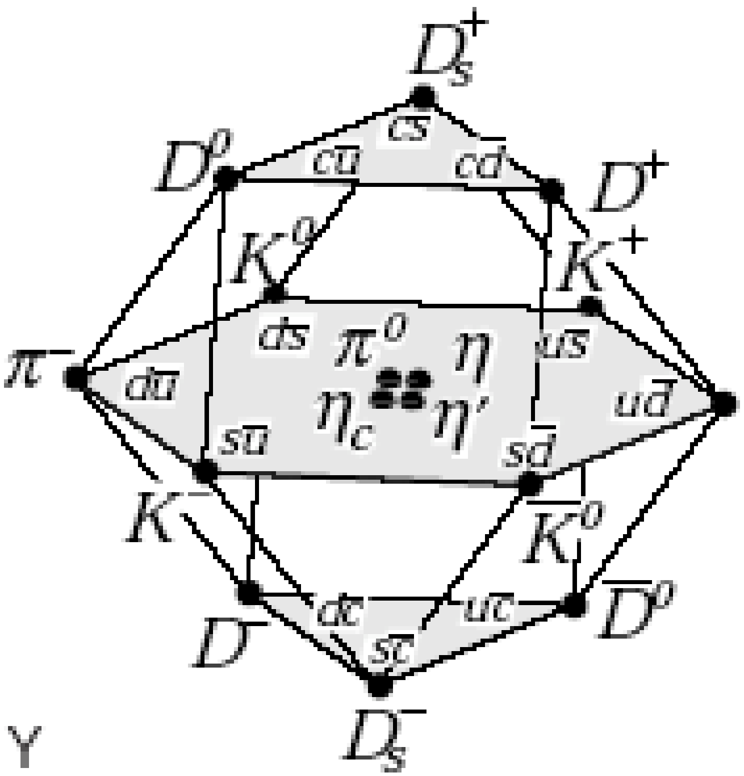
The Big Questions

1. What is the origin of fermion generations?
2. What is the origin of quark masses?
3. What is the origin of CP violation?
4. What is the origin of hadron masses (~ observable Universe)?
5. What is the mechanism of quark confinement?
6. Why is chiral symmetry broken in the Universe?
7. What are the phases of strongly interacting matter?
8. How did the Universe evolve in the first few μseconds of its existence? What are the traces of that era in the present Universe?

The Science of QCD Lab

What is QCD?

QCD = Quark Model + Gauge Invariance



local gauge transformation:

$$q(x) \to \exp\left(i\omega_a(x)T^a\right)\ q(x),$$

$$\left[T^a, T^b\right] = i f^{abc} T_c$$

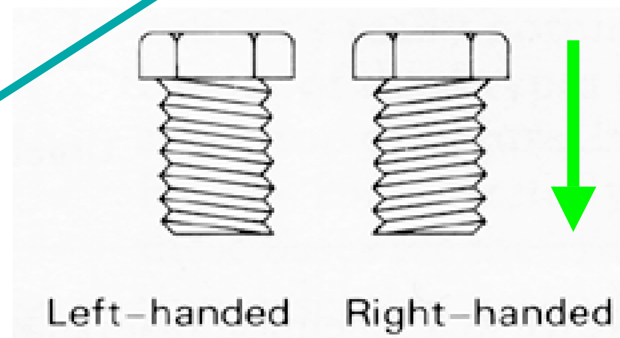
QCD and the origin of mass

$$\mathcal{L} = -\frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu} + \sum_f \bar{q}^a_f(i\gamma_\mu D_\mu - m_f)q^a_f;$$

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

gluons

quarks



Invariant under scale ($x \rightarrow \lambda x$) and chiral Left ⟷ Right

transformations in the limit of massless quarks

Experiment: u,d quarks are almost massless…

… but then… all hadrons must be massless as well!

Where does the mass of the proton come from?

QCD and quantum anomalies

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

Classical scale invariance is broken by quantum effects:

scale anomaly

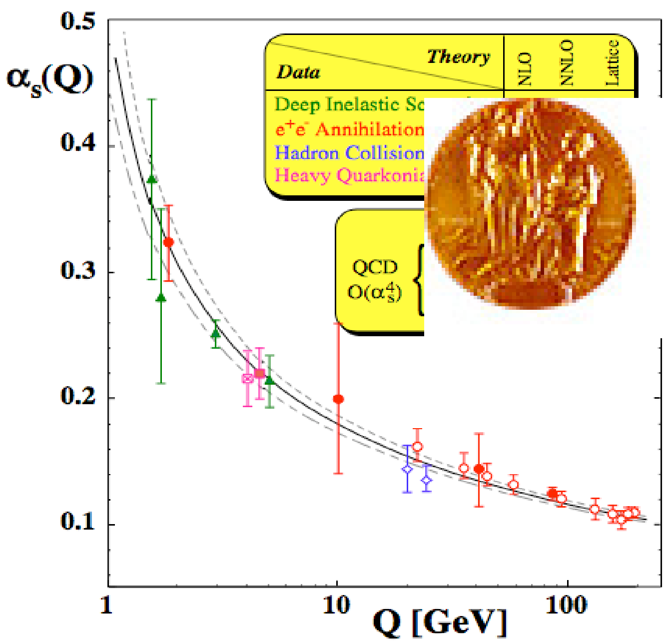
$$\theta^\mu_\mu = \frac{\beta(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_q m_q \bar{q} q$$

trace of the energy-momentum tensor

"beta-function"; describes the dependence of coupling on momentum

Hadrons get masses ⟺ coupling runs with the distance

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)

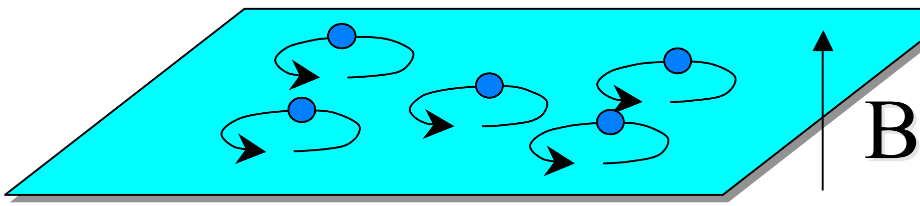
$$\alpha_s(Q) \simeq \frac{4\pi}{b \ln(Q^2/\Lambda^2)}$$

number of colors

number of flavors

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

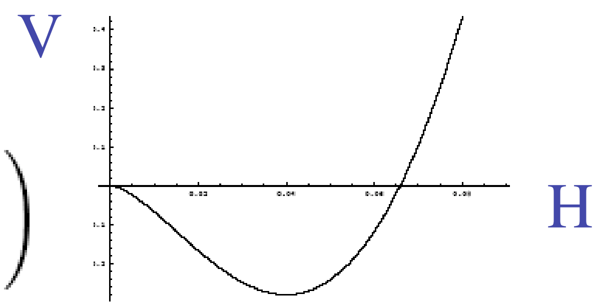
Asymptotic freedom and vacuum as a medium



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 ⟷ 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 $\hbar \rightarrow 0$)

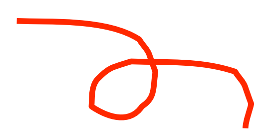
=> Need weak coupling and strong fields

$$D_\mu = \partial_\mu - igA_\mu^a t^a$$

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

weak field

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



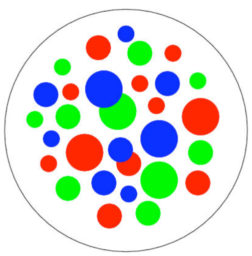
strong field

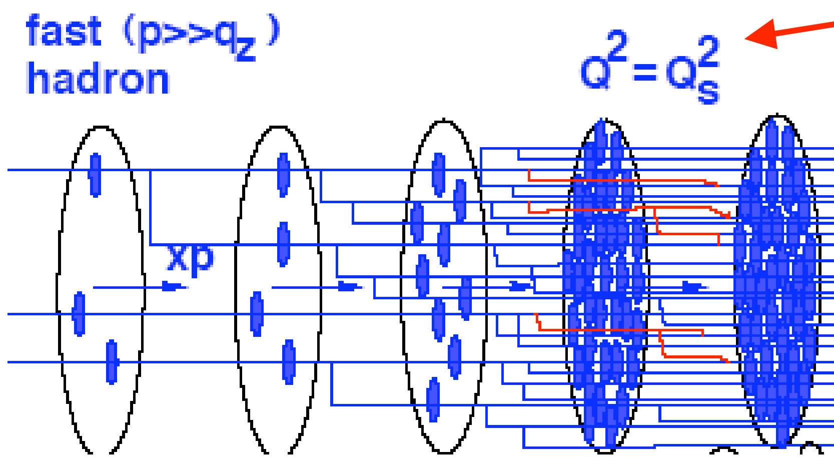
Building up strong color fields:
small x (high energy) and large A (heavy nuclei)

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

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

Large x

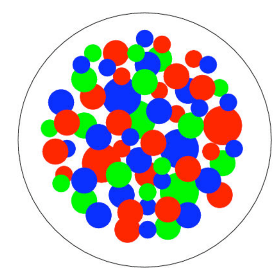




Gribov, Levin, Ryskin;
Mueller, Qiu;

McLerran, Venugopalan; …

small x

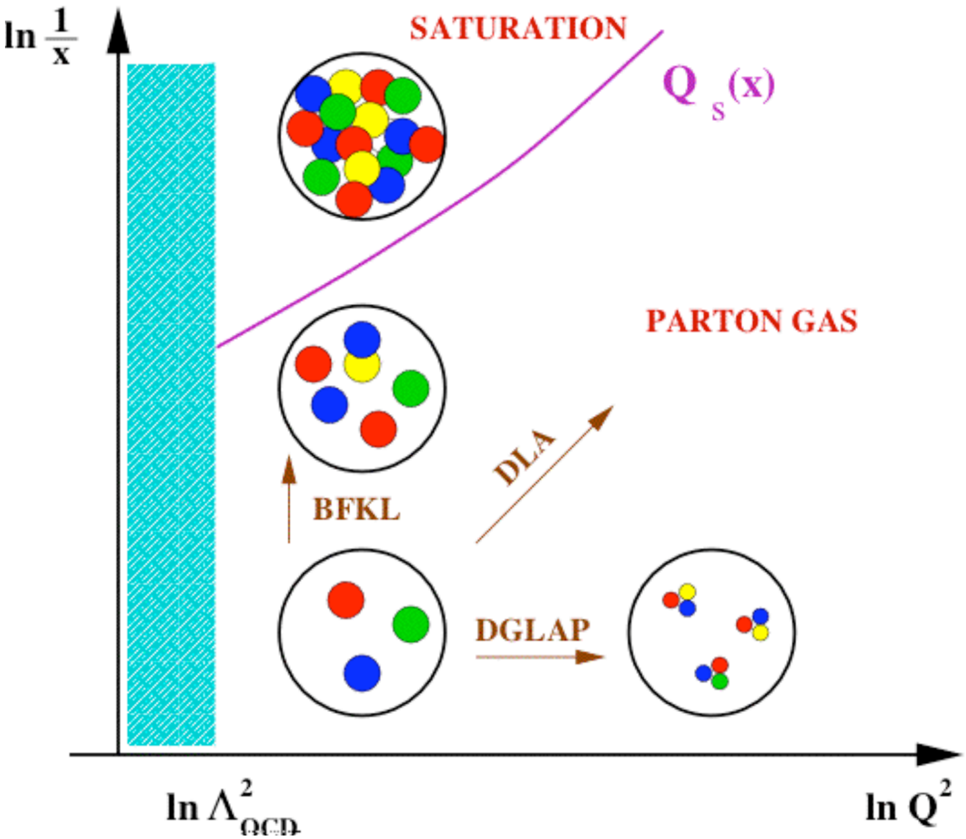


Because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$, the number of gluons at small x grows; the transverse area is limited

→ transverse density becomes large

Non-linear QCD evolution and population growth

Color glass condensate



time $t \to \ln \frac{1}{x} \equiv y$ rapidity

Linear evolution: T. Malthus (1798)

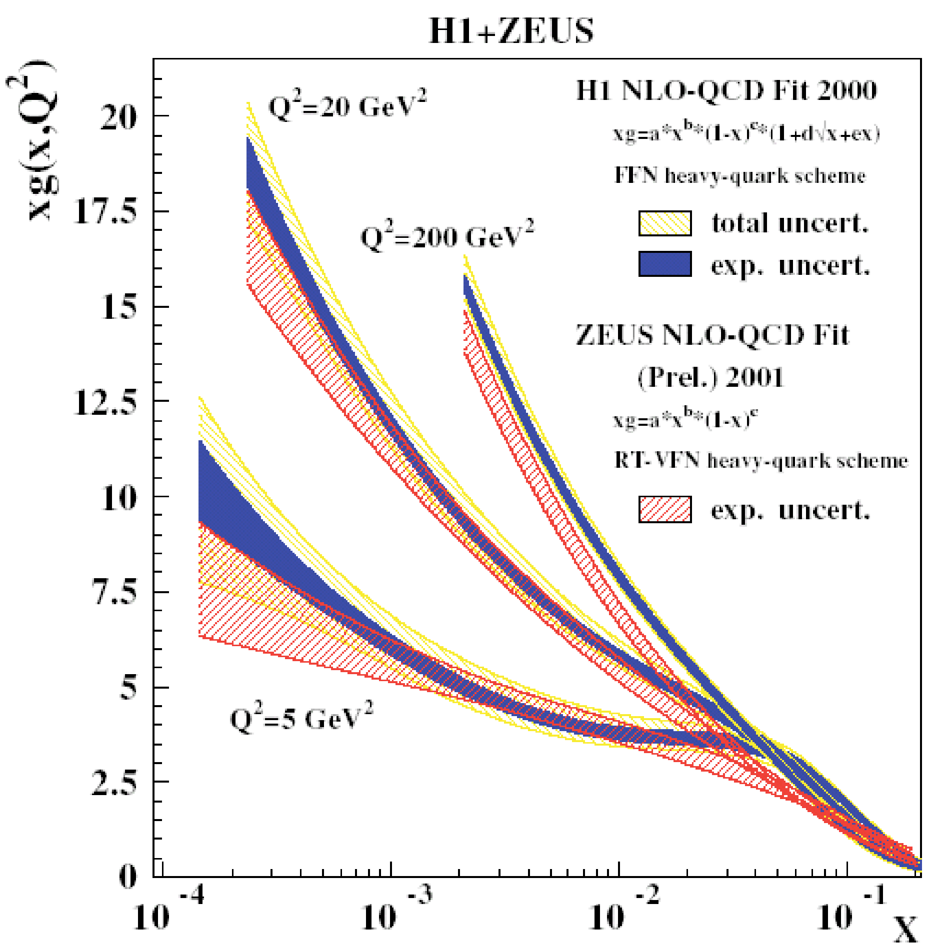
$$\frac{d}{dt} N(t) = r \; N(t)$$

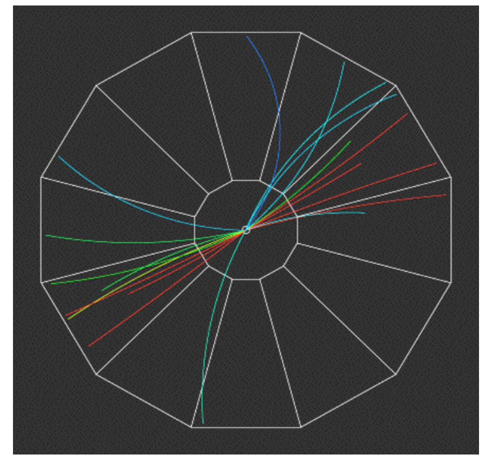
r - rate of maximum population growth

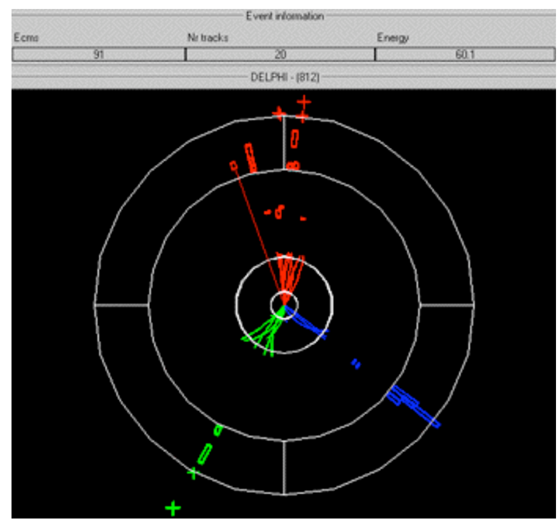
$$N(t) = N_0 \; \exp(r \; t)$$

Unlimited growth!

Resolving the gluon cloud
at small x and short distances ~ $1/Q^2$







number of gluons

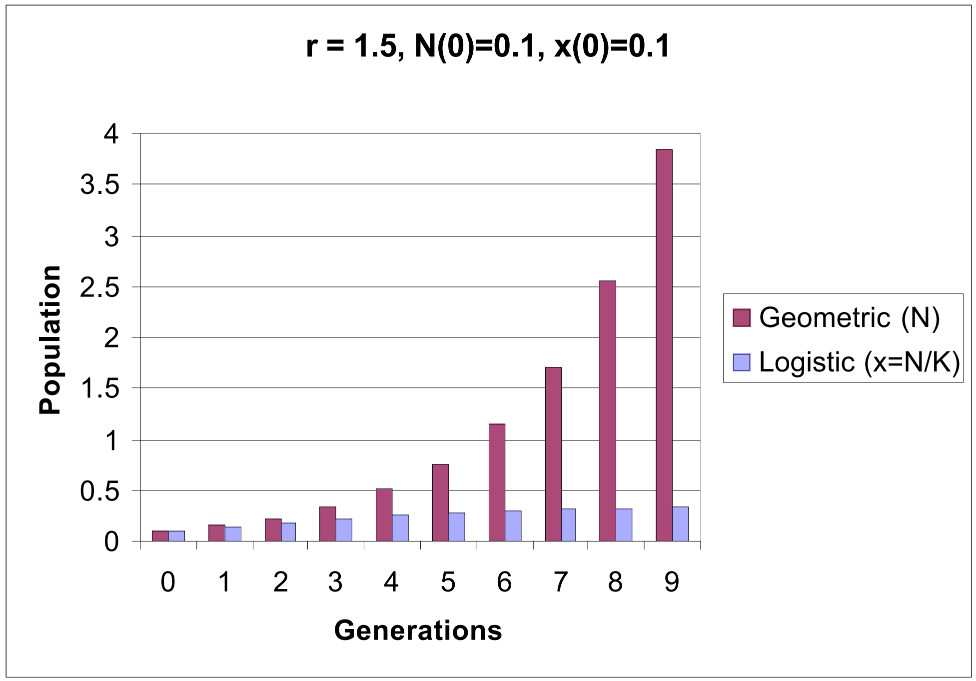
"jets": high momentum partons

Population growth in a limited environment

$$\frac{dN(t)}{dt} = \frac{rN(K-N)}{K}$$ "logistic equation"

K - maximum sustainable population; define $x = \frac{N}{K}$

Pierre Verhulst (1845)



$$\frac{dx}{dt} = rx(1-x)$$

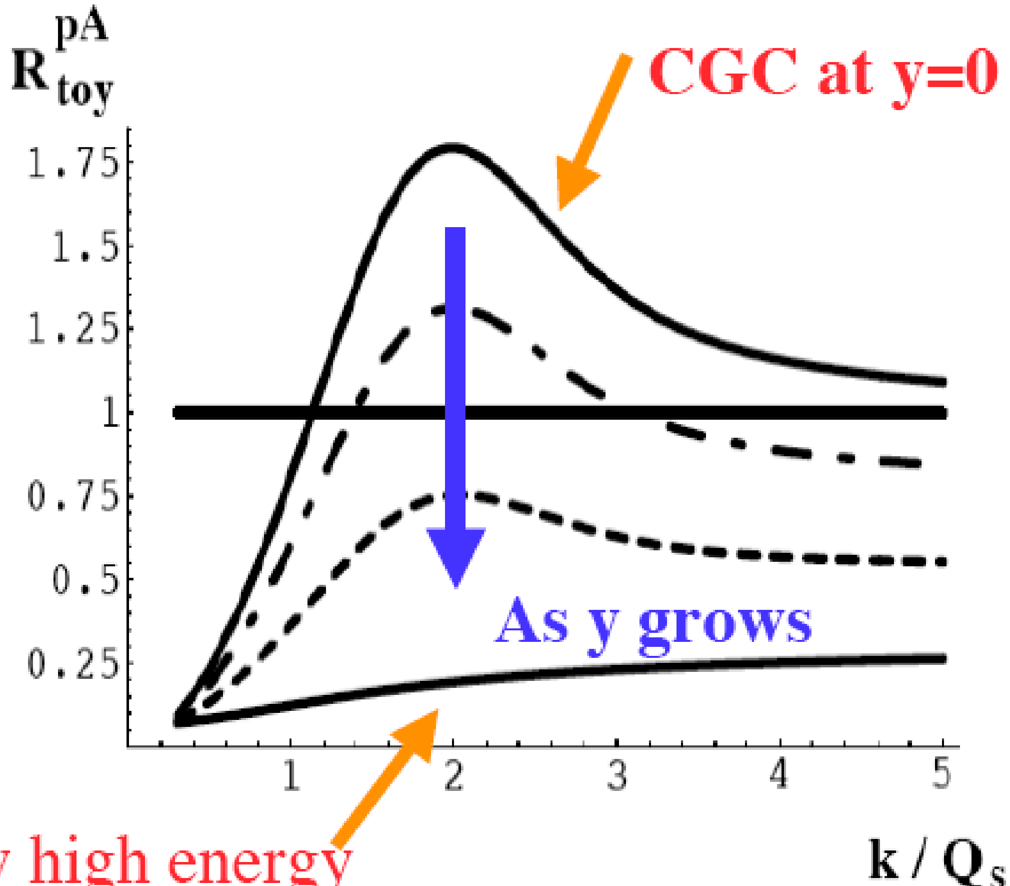
$$x(t) = \frac{1}{1 + \left(\frac{1}{x_0} - 1\right) e^{-rt}}$$

Stable population: $N(t) \rightarrow K, \quad \frac{dN}{dt} \rightarrow 0 \quad \text{as } t \rightarrow \infty$

The limit is universal (no dependence on the initial condition)

Gluon multiplication in a limited (nuclear) environment

The ratio of pA and pp cross sections



Very high energy

transverse momentum

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

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

Fundamental questions for QCD Lab

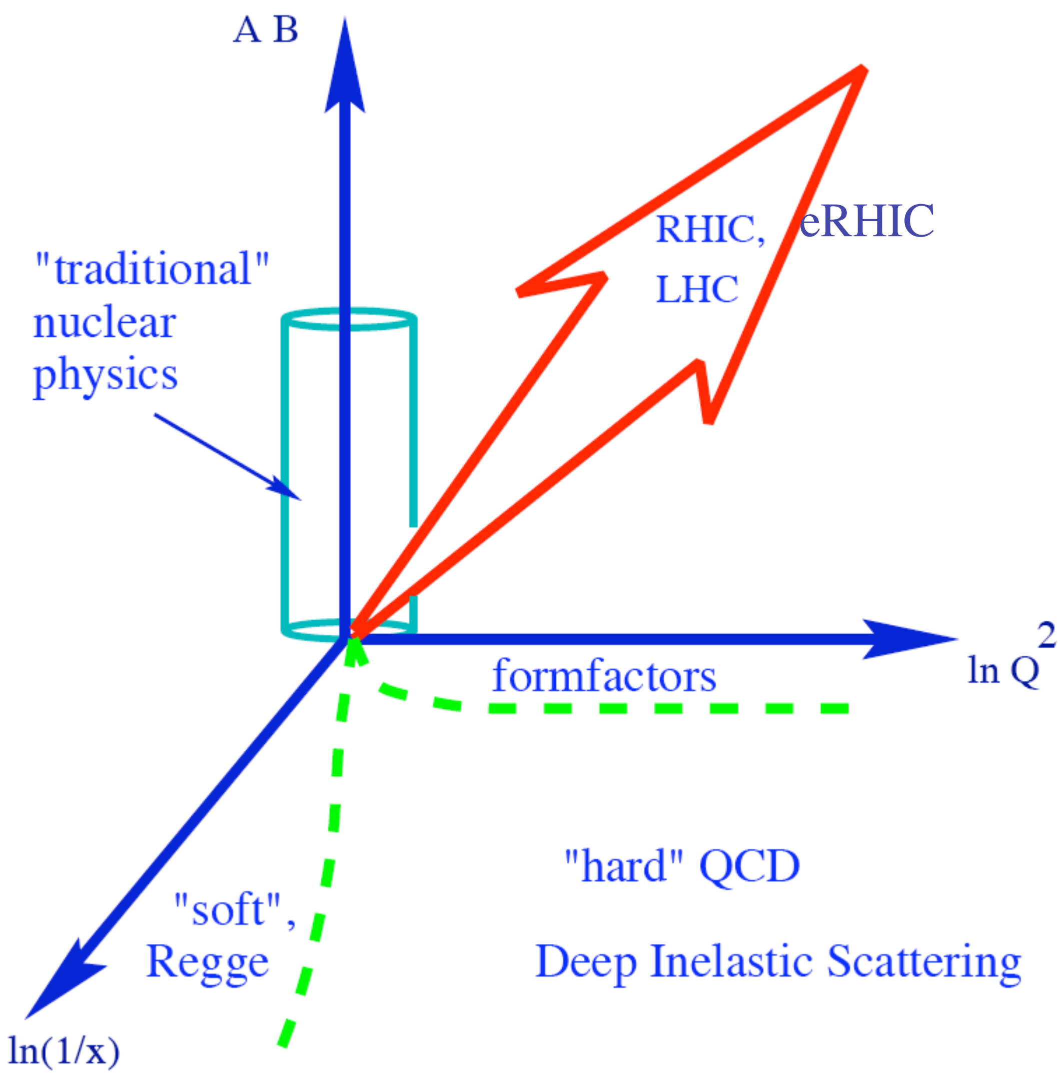
1. What are the phases of QCD matter?

2. What is the wave function of the proton?

3. What is the wave function of a heavy nucleus?

4. What is the dynamics of non-equilibrium processes in a fundamental gauge theory?

QCD and nuclei



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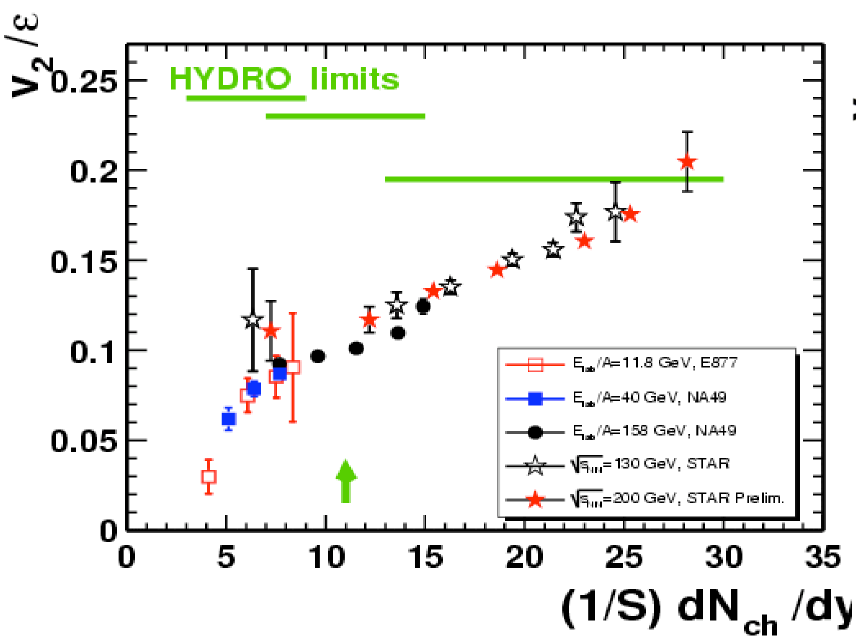
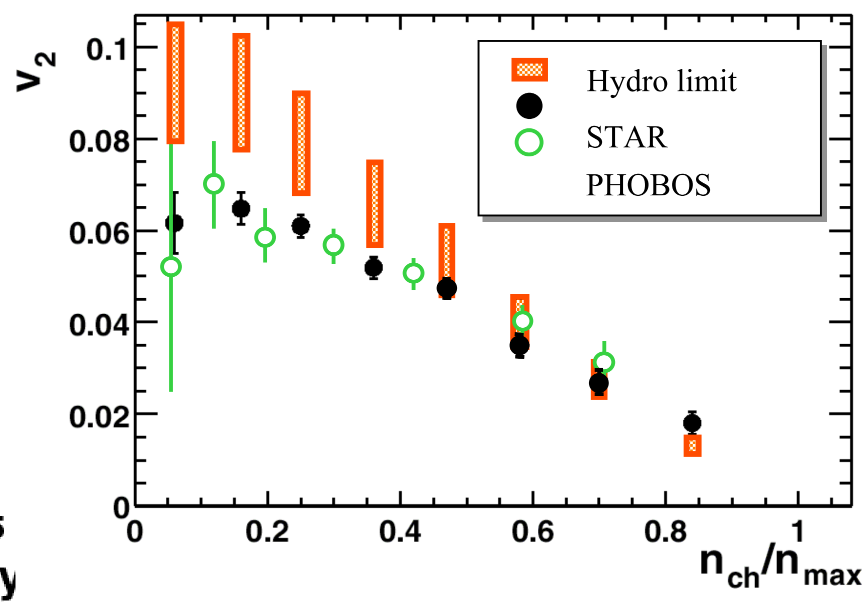
What have we learned from RHIC so far ?

I. Collective flow =>

Au-Au collisions at RHIC produce strongly interacting matter

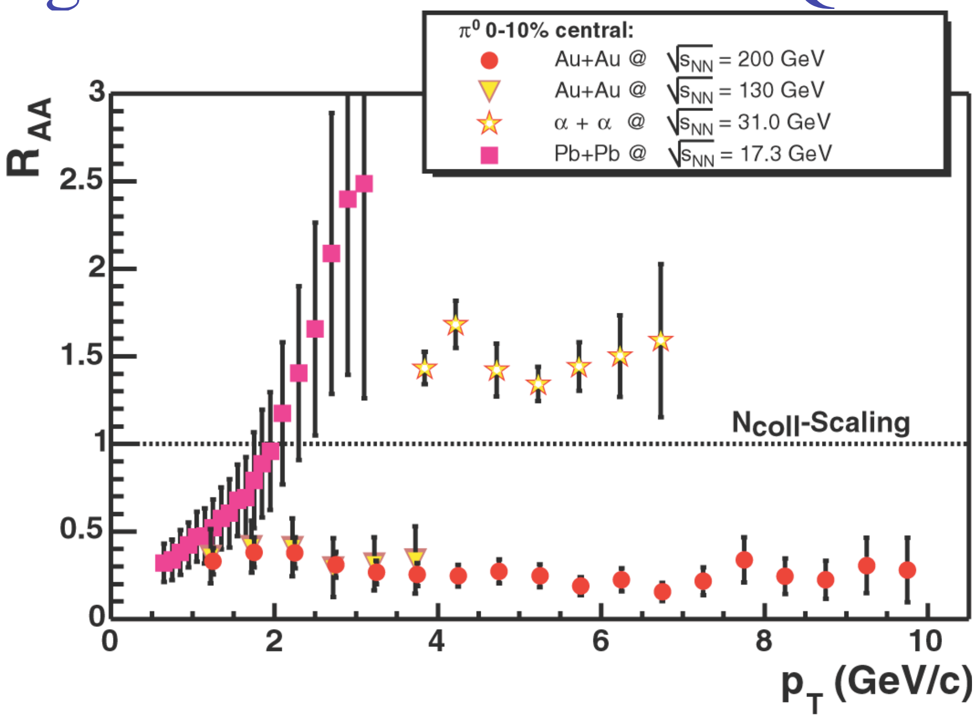
("perfect liquid"; how small is the viscosity?)

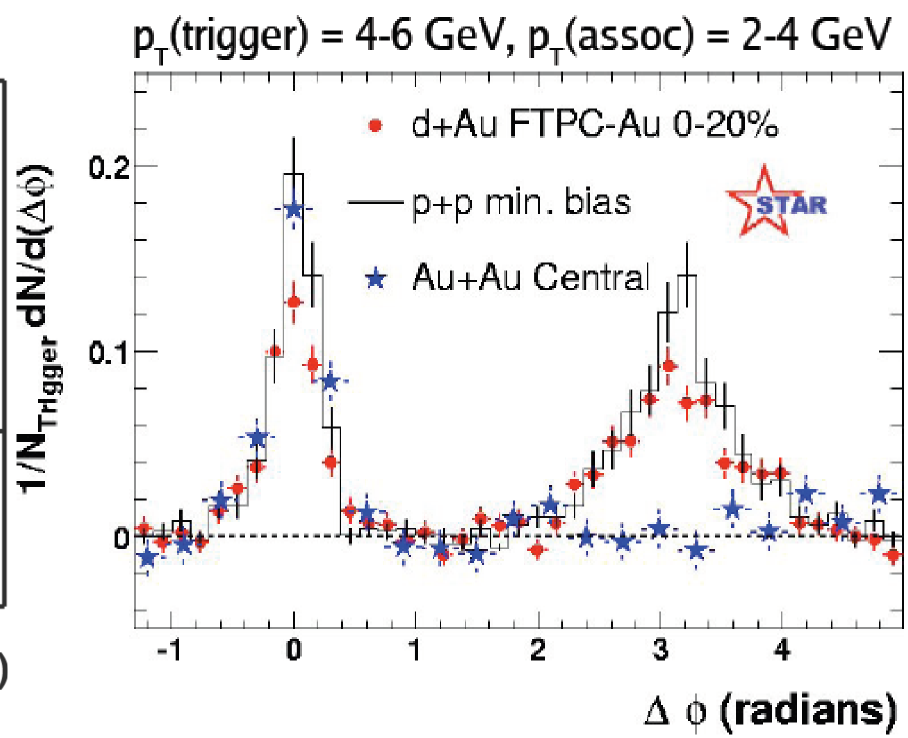




What have we learned from RHIC so far ?

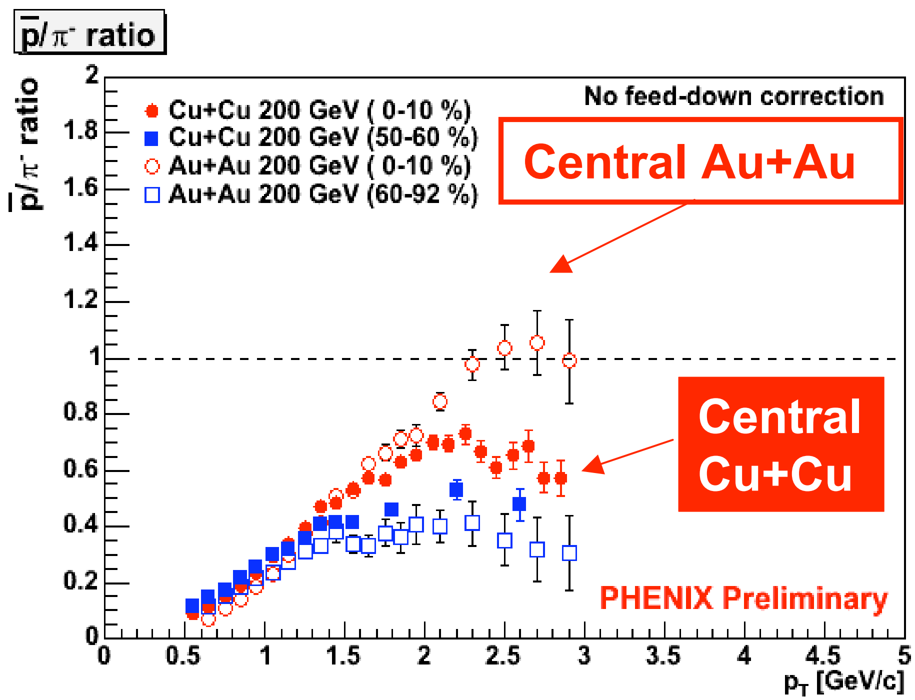
II. Suppression of high p_T particles =>
consistent with the predicted jet energy loss from induced gluon radiation in dense QCD matter (but: heavy quarks…)

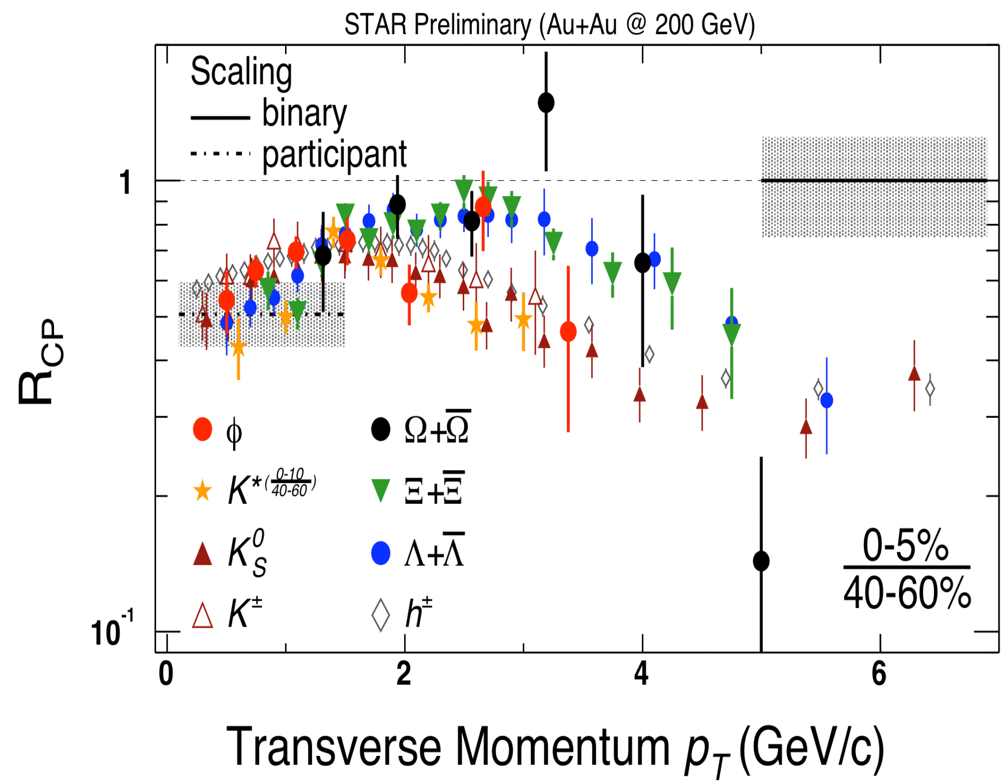




What have we learned from RHIC so far ?

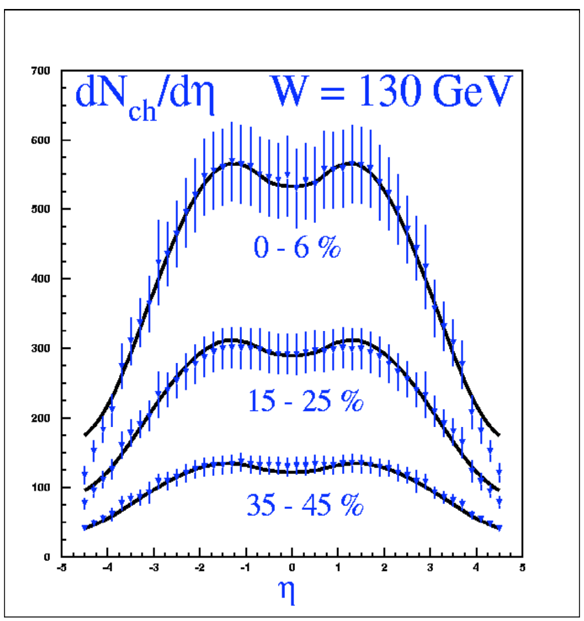
III. Baryon/meson enhancement =>
Constituent quark recombination? Baryon junctions?

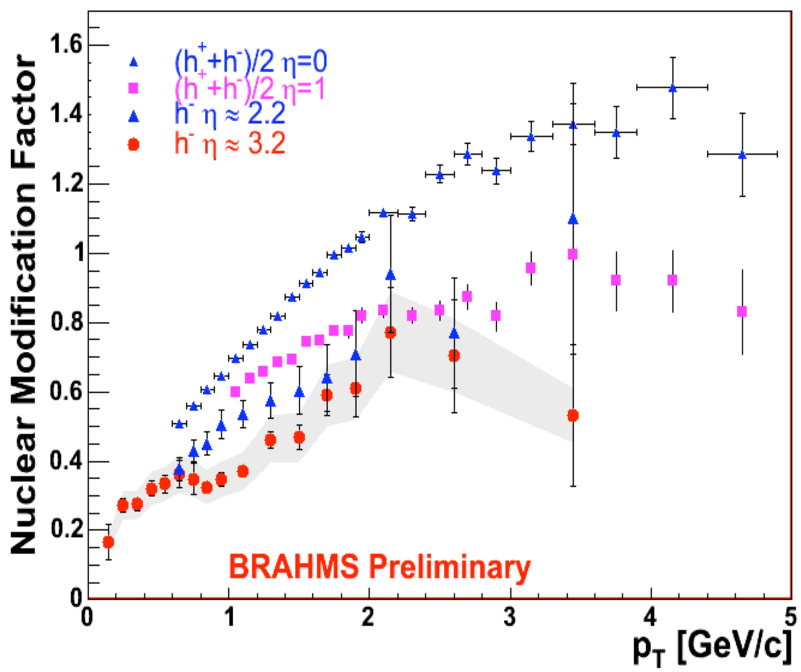




What have we learned from RHIC so far ?

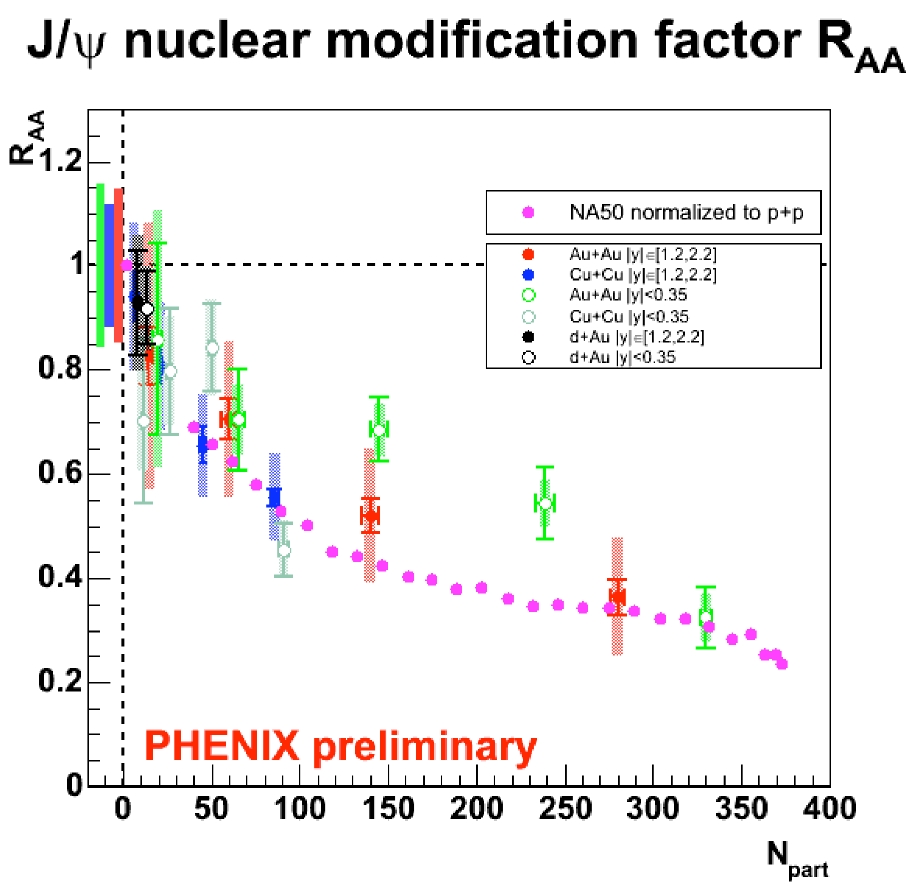
IV. “Small” hadron multiplicities +
suppression of high p_T particles at forward rapidities =>
coherent interactions in the initial state, consistent
with the presence of parton saturation/Color Glass Condensate





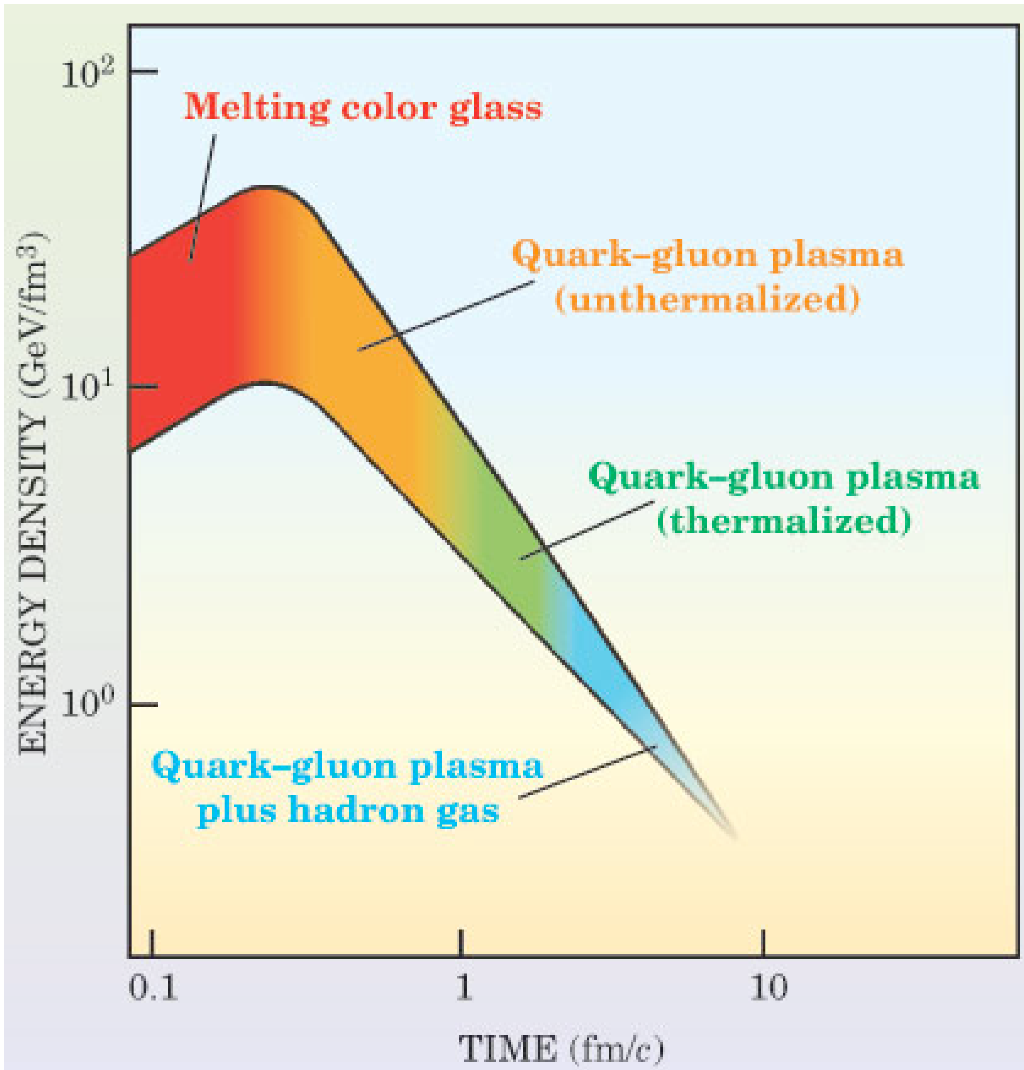
What have we learned from RHIC so far ?

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



"same as at SPS"?

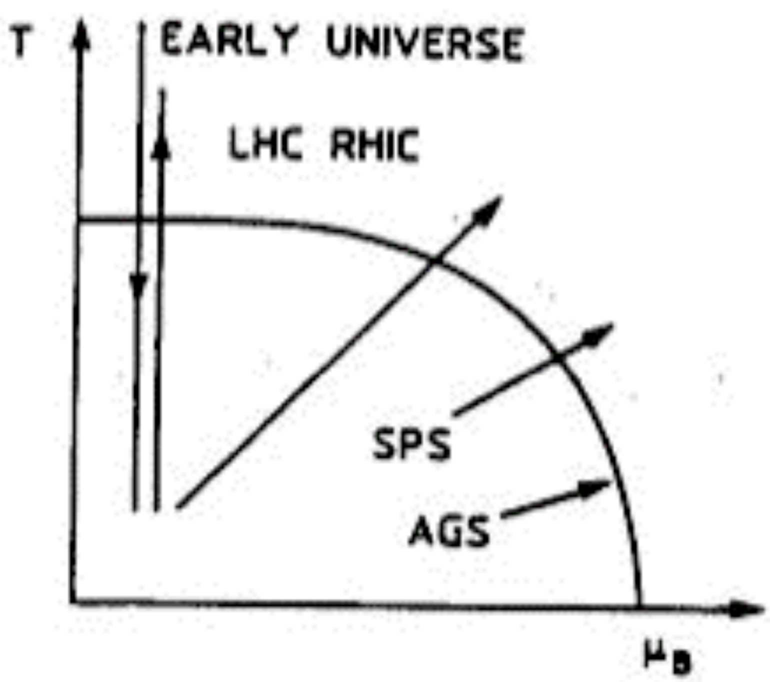
The emerging picture

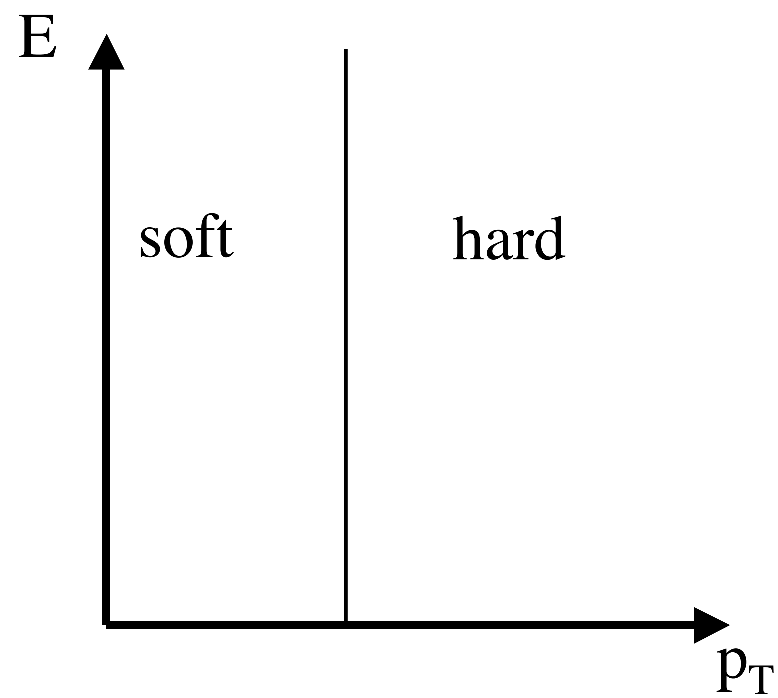


Why is thermalization so fast?

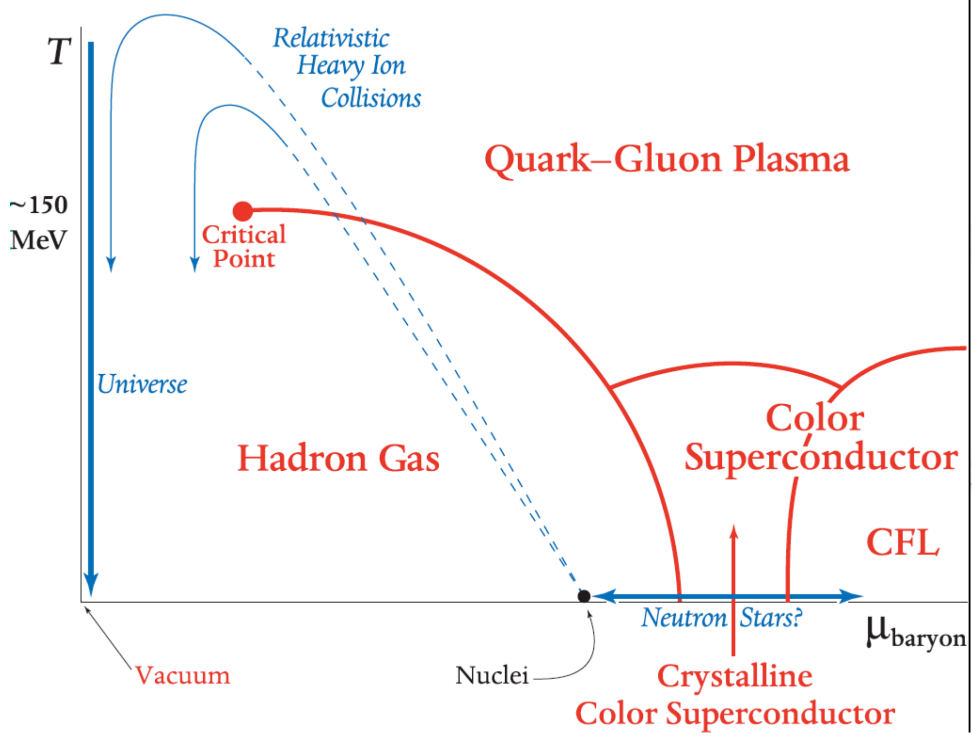
(is it, really?)

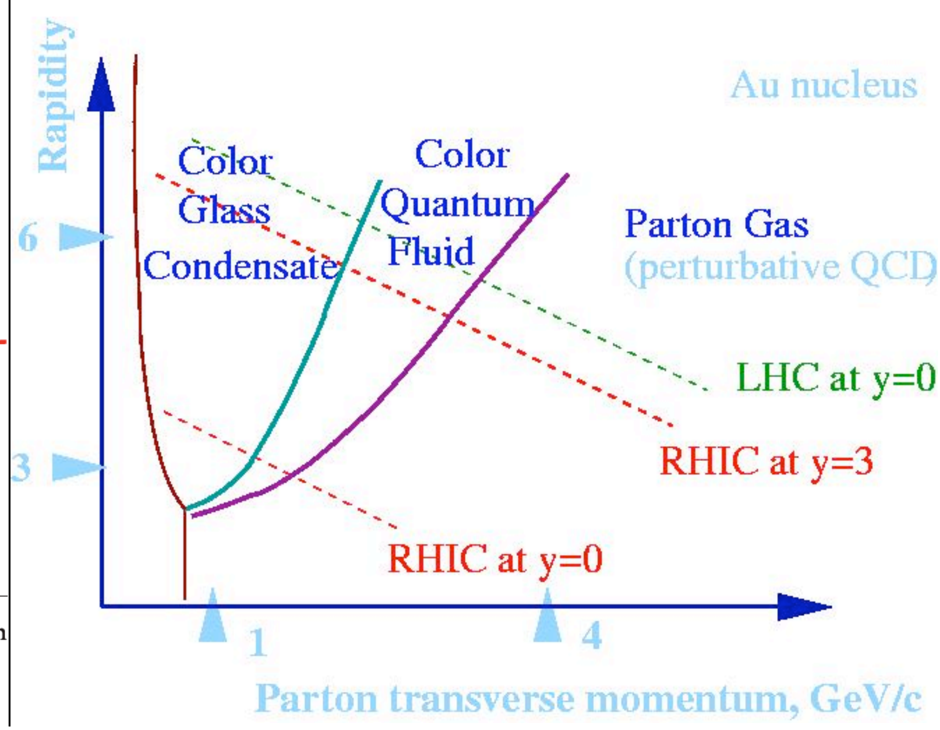
QCD diagrams, late XX century





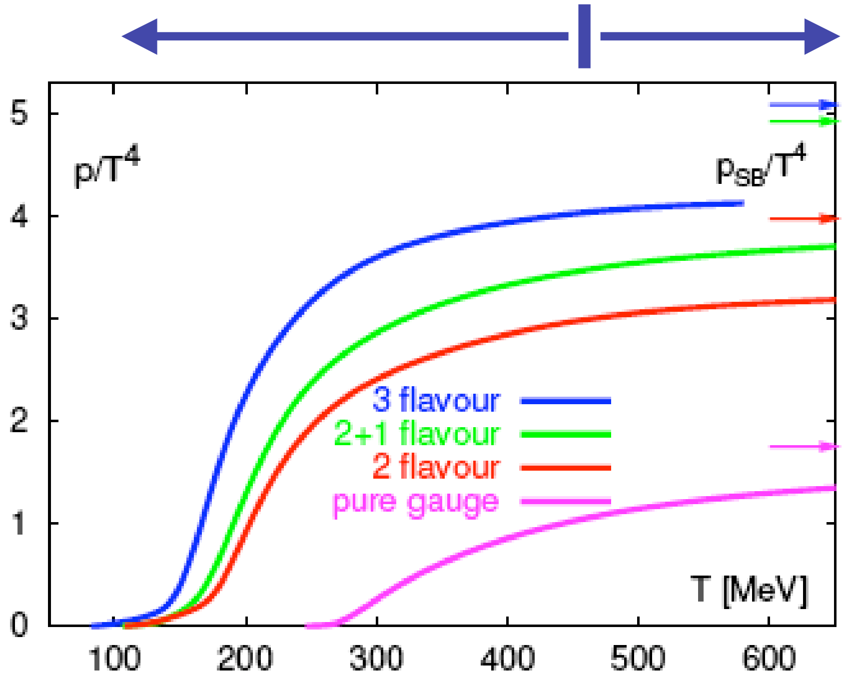
QCD diagrams, early XXI century

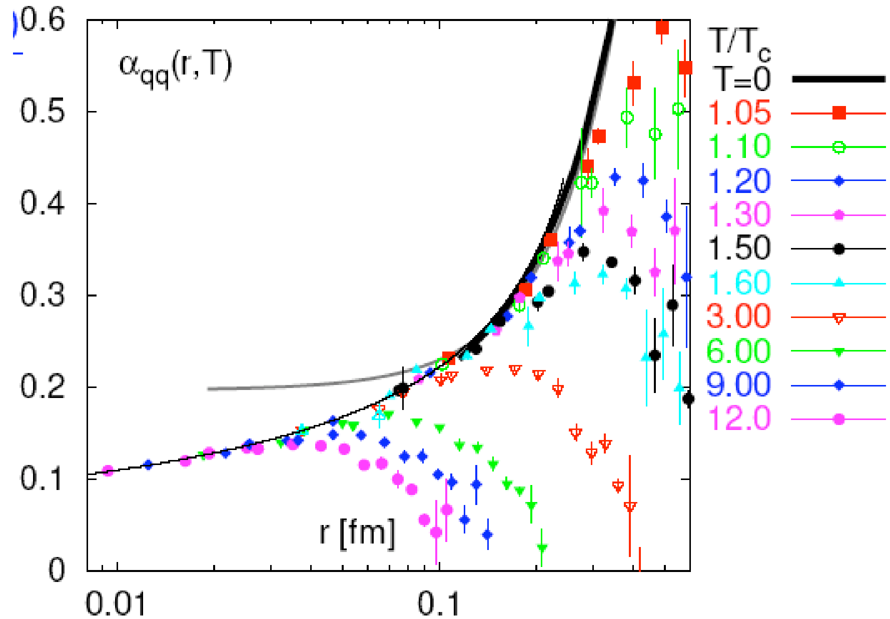




Strongly coupled QGP

RHIC LHC

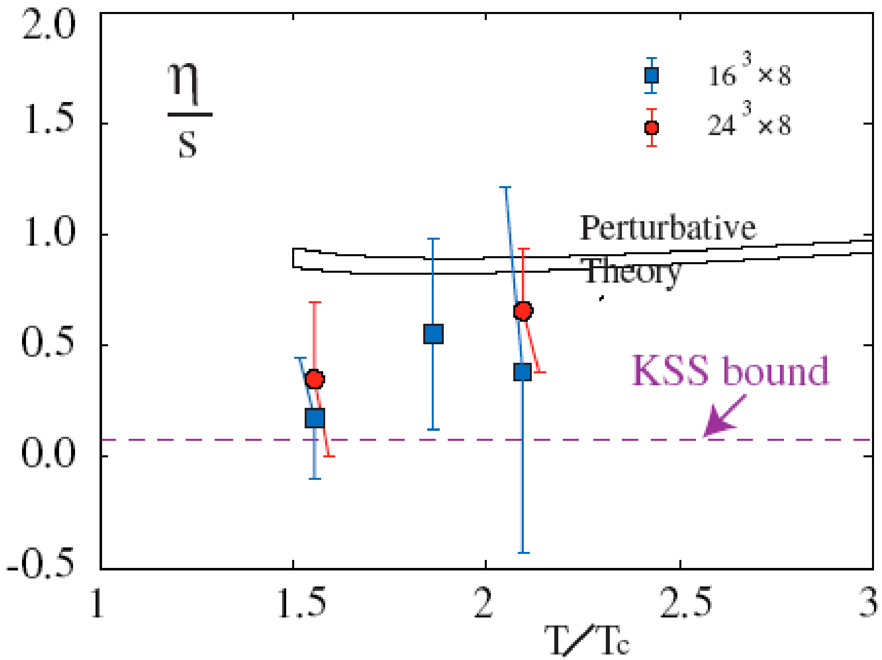




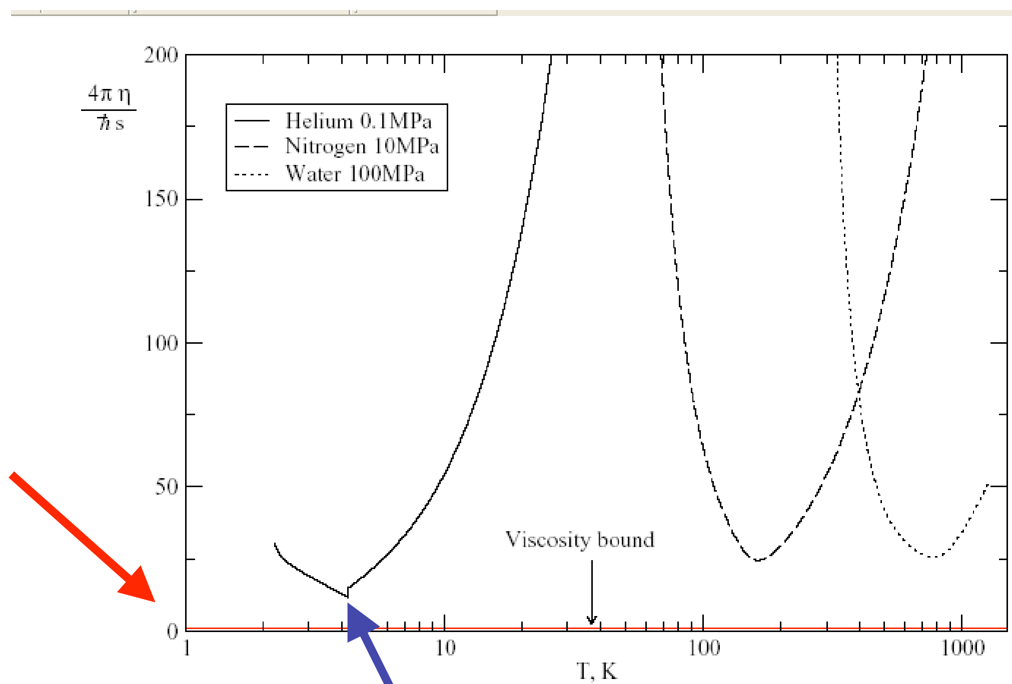
$$\epsilon \neq 3P$$

T-dependence of the running coupling develops in the NP-region at T < 3 T_c

sQGP: more fluid than water?



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



Superfluid helium

KSS bound:
strongly coupled SUSY QCD = classical supergravity

Testing new phases of QCD matter at RHIC-II

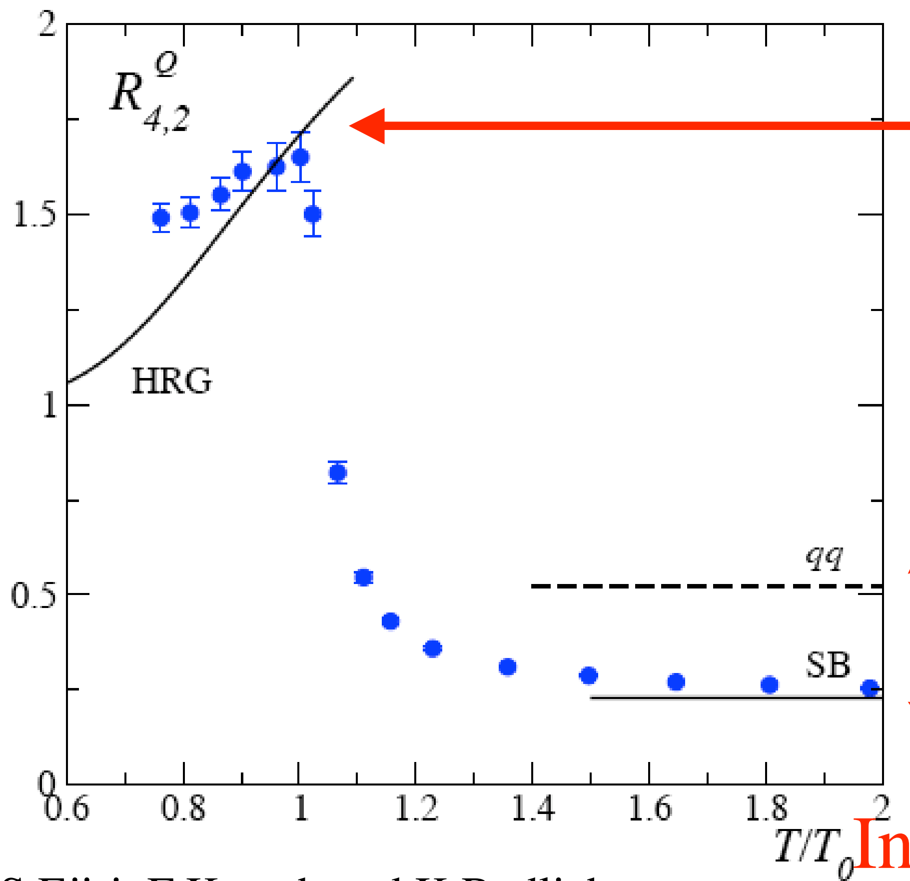
1. What are the dynamical degrees of freedom in sQGP and CGC?

2. How does the transition from CGC to sQGP occur?

3. How does the sQGP interact with the hard probes?

What are the dynamical degrees of freedom in sQGP?

Let's look at the charge fluctuations:



S.Ejiri, F.Karsch and K.Redlich

Hadron resonance gas

QQ bound states

Dynamical quarks

Influence on hadronization out of equilibrium?

How does the transition from CGC to sQGP occur?

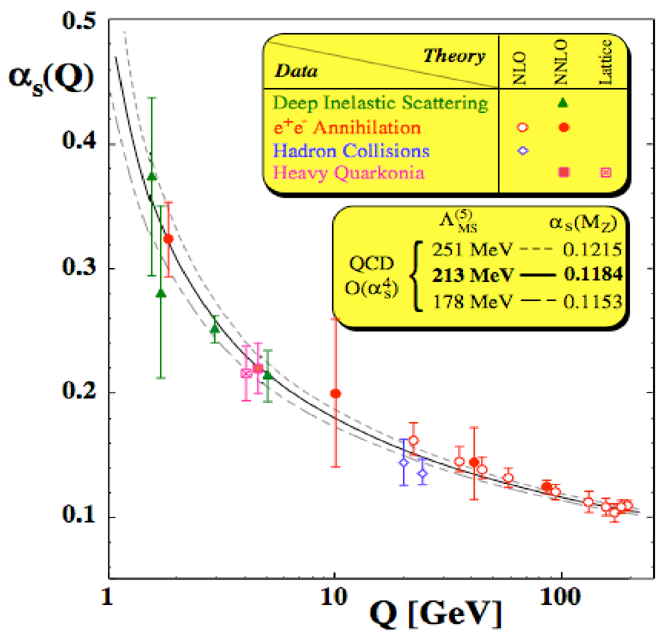
Parton re-scattering?
Instabilities of classical color fields?
NLO effects/Hawking-Unruh radiation?

Probes of thermalization dynamics:
Photons and di-leptons freely escape from the system -

Study intermediate mass (M ~ 1.5 - 3 GeV) dileptons,
direct photon spectra at intermediate (~ 1.5 - 3 GeV)
transverse momenta, “low-virtuality” photons

The physics of the first 0.1 fm/c

Hard probes of QCD matter



At short distances,
the strong force becomes weak -

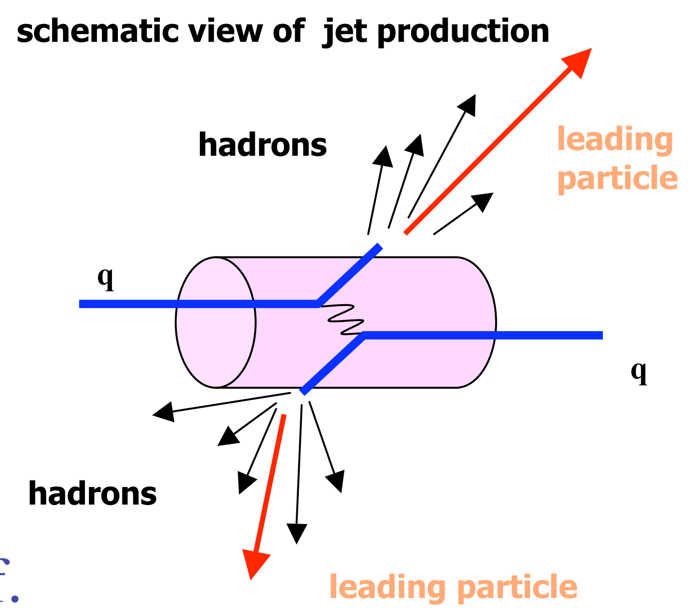
one can access the "asymptotically free" regime in hard processes

But: the harder a parton is hit,
the more intense radiation it emits;
this happens because even though
$\alpha_s << 1$, $\alpha_s \ln (Q^2 / \Lambda^2) \sim 1$
(large phase space)

=> Scaling violations, jet structure

Fast partons as a probe

In QCD vacuum, the probability of gluon radiation ~ $\alpha_s \ln (Q^2 / \Lambda^2)$;



in medium, the scale Λ is determined by the properties of matter:

In hot quark-gluon plasma

$\Lambda^2 = \hat{q}_{hot} L$ $\qquad \hat{q}_{hot}$ - transport coeff.

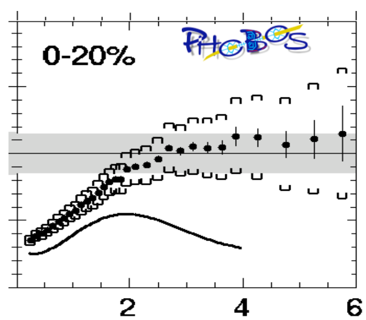
L - size of the system

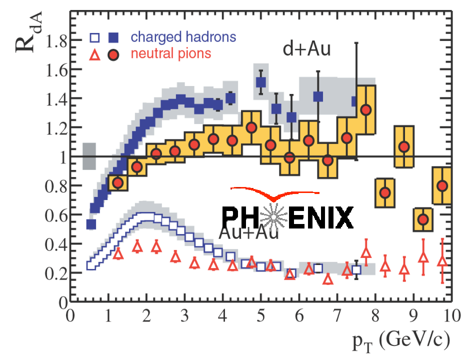
In cold nucleus at small x

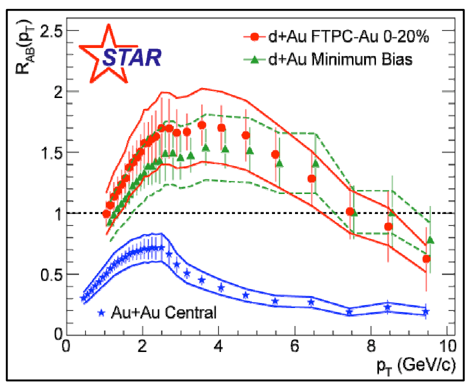
$\Lambda^2 = Q_s^2$ - the saturation scale; $Q_s^2 = \hat{q}_{cold} L$

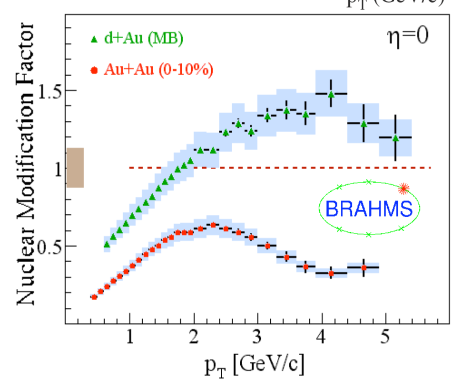
What do we still need to know?

d-Au experiments have shown that at y=0 the suppression of high p_T particles is a final-state effect:





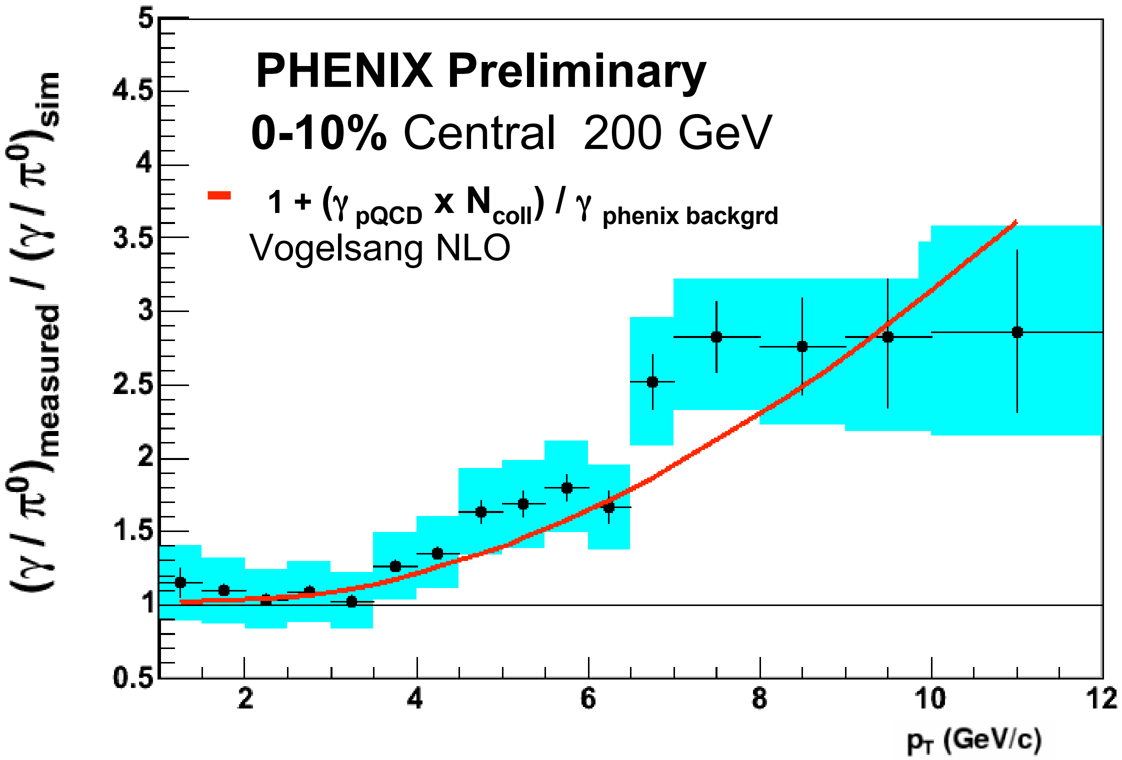




Is it due to the radiative energy loss in sQGP?

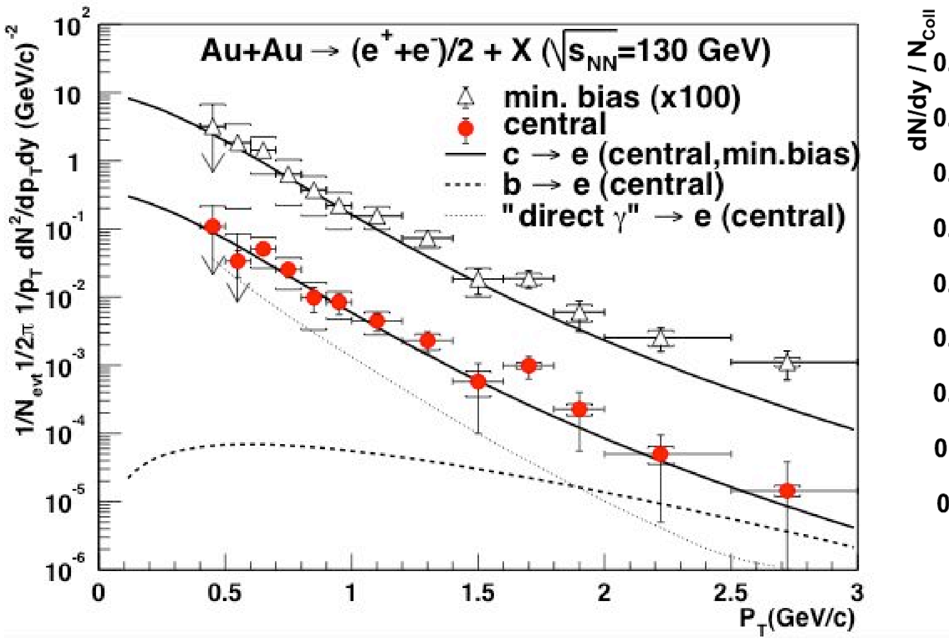
What do we still need to know?

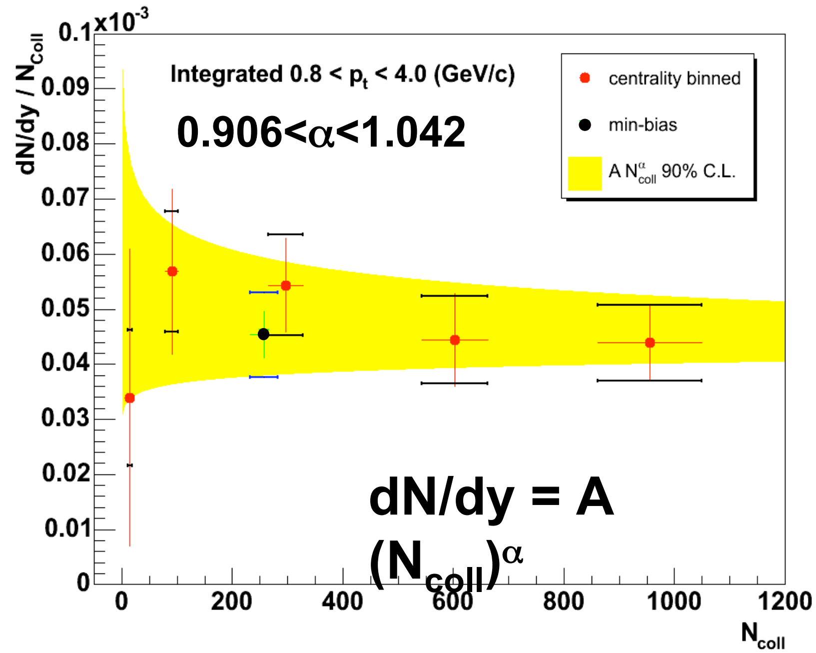
Look at the weakly coupled probes -
Direct photons are not suppressed:



another probe: heavy quarks

For heavy quarks the induced gluon radiation should be suppressed; is it?

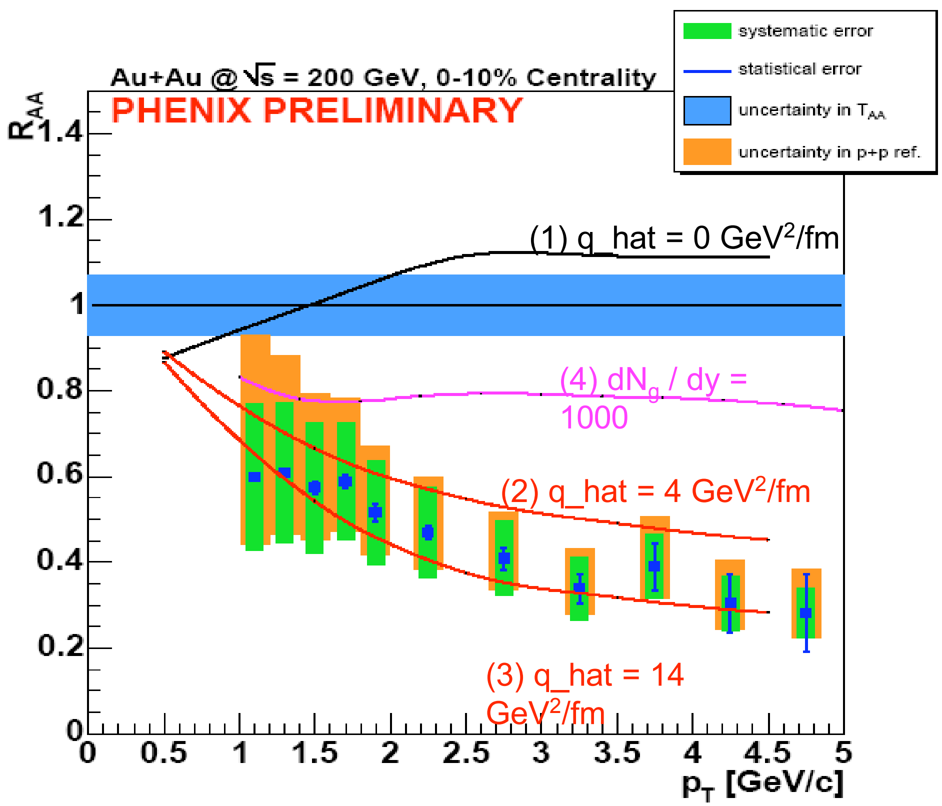


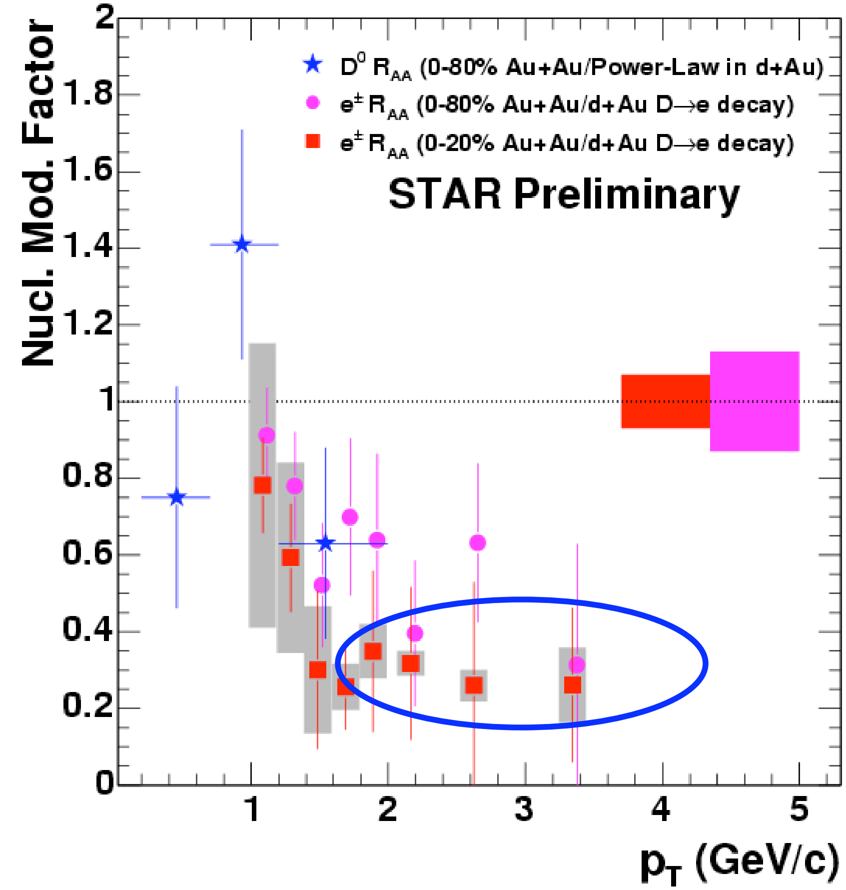


Data from PHENIX

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!?

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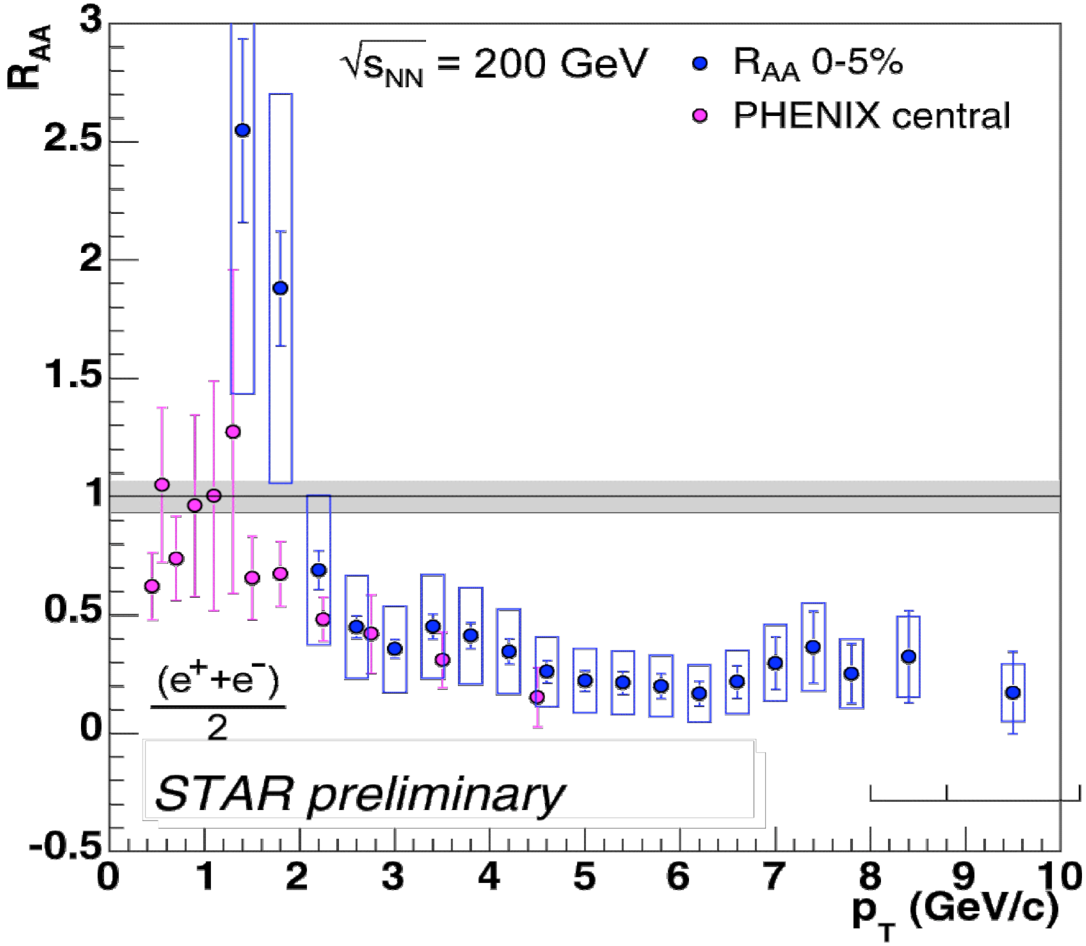
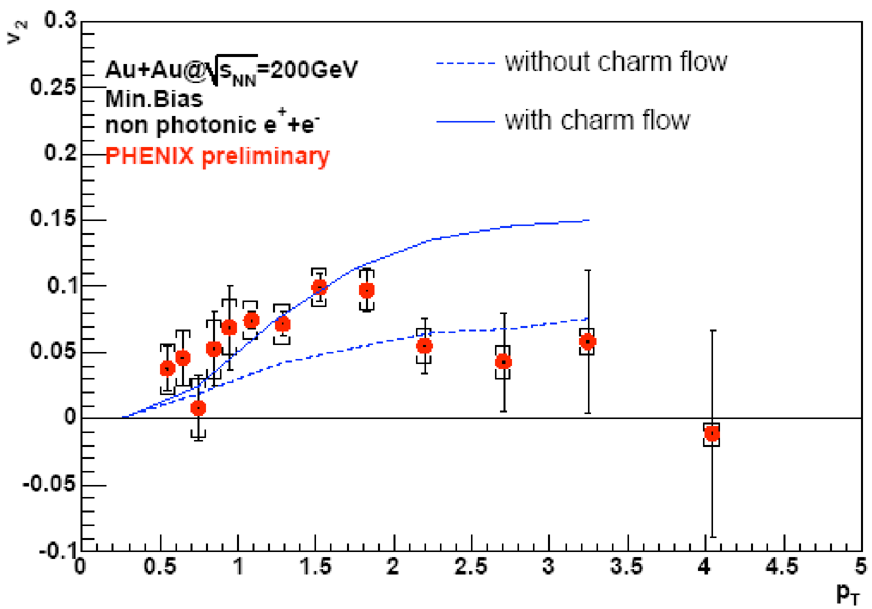


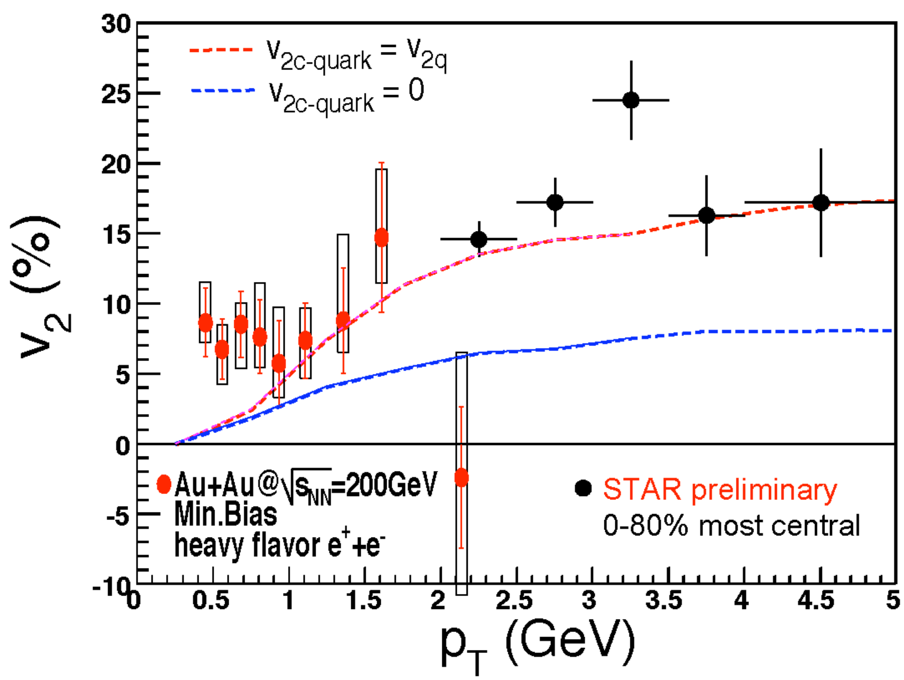
STAR Coll., Quark Matter'05

Must detect
c, b directly
=> RHIC II

AuAu collisions: charm flows!

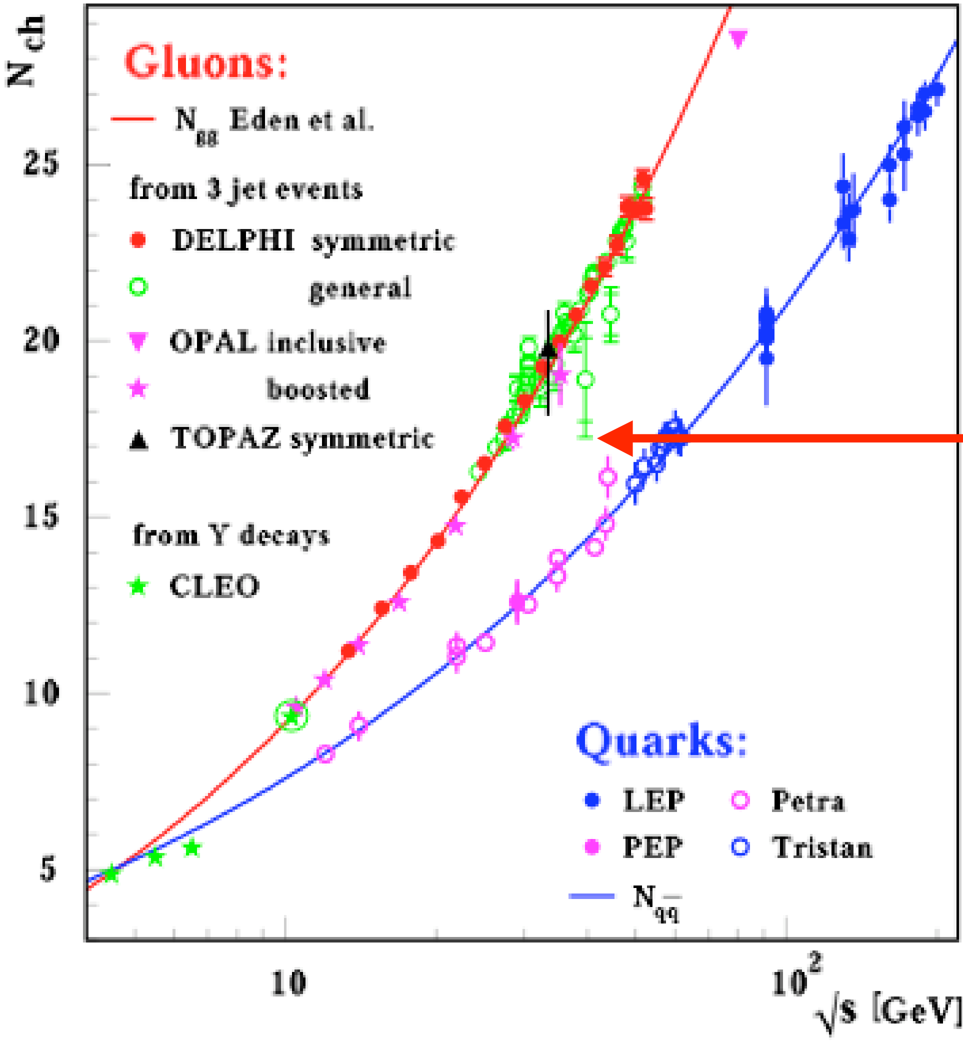
Extract the heavy quark transport coefficients?





PHENIX Coll., Quark Matter'05 STAR Coll., Quark Matter'05

Can one distinguish between the quark and gluon jets?



Flavor tagging of jets

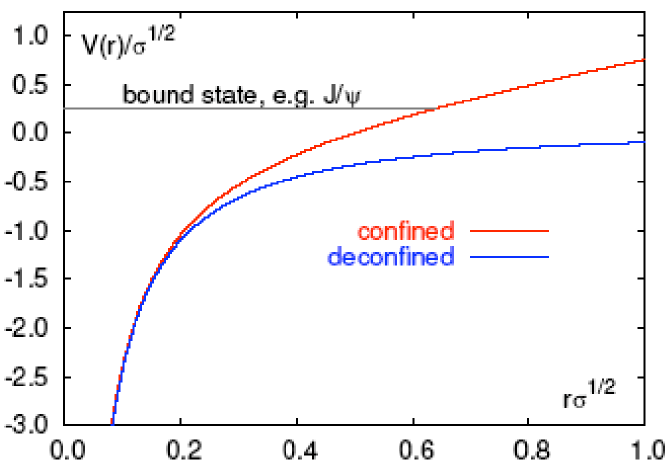
The difference in hadron multiplicities becomes visible at large momenta

Tagging gluon jets e.g. by g->ccbar ?
g-> J/ψ ?

Heavy quarkonium as a probe

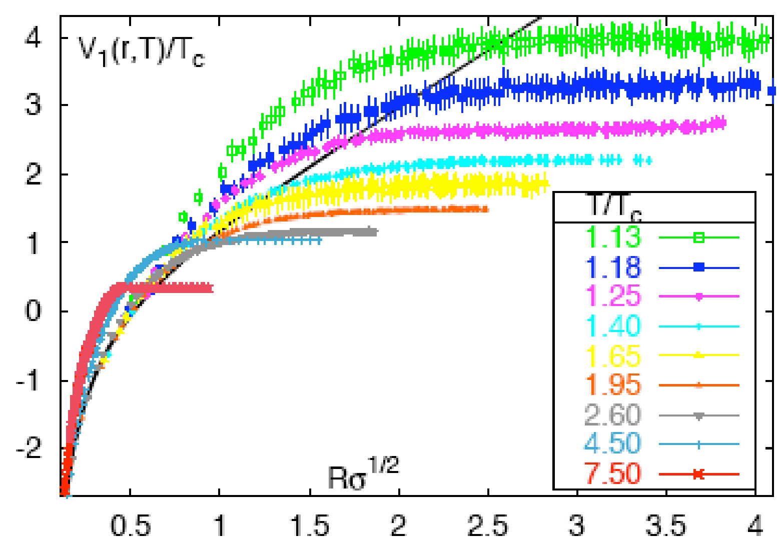
The Matsui-Satz argument:

- deconfinement $\Rightarrow$ screening
  $\Rightarrow$ no heavy quark bound states in a QGP



$V_{\bar{q}q}(r,T) \to \infty$ confinement

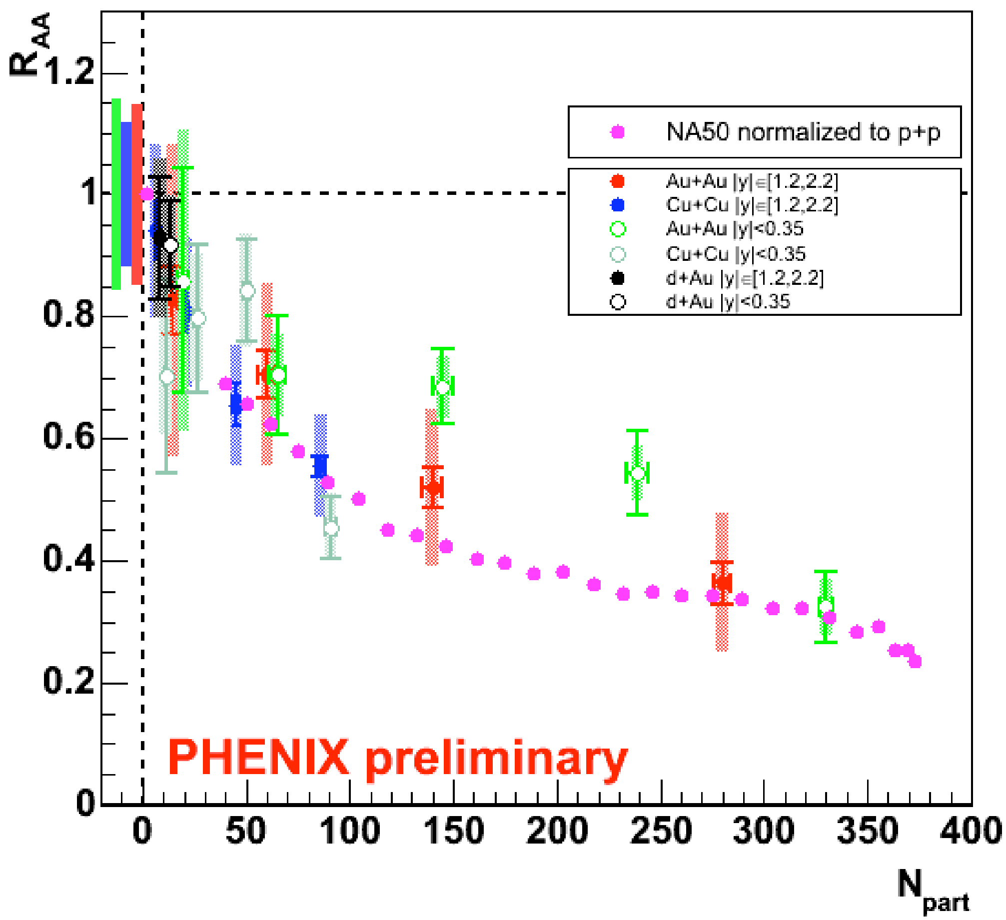
$V_{\bar{q}q}(r,T) < \infty$ deconfinement



A link between the experiment and the McLerran-Svetitsky confinement criterion

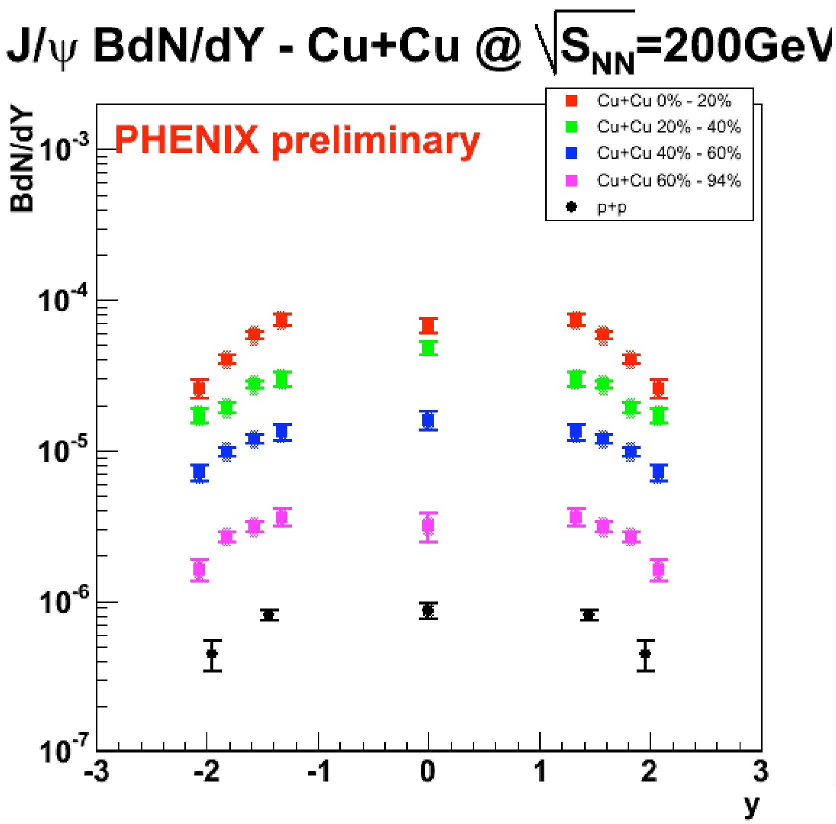
J/ψ suppression at RHIC

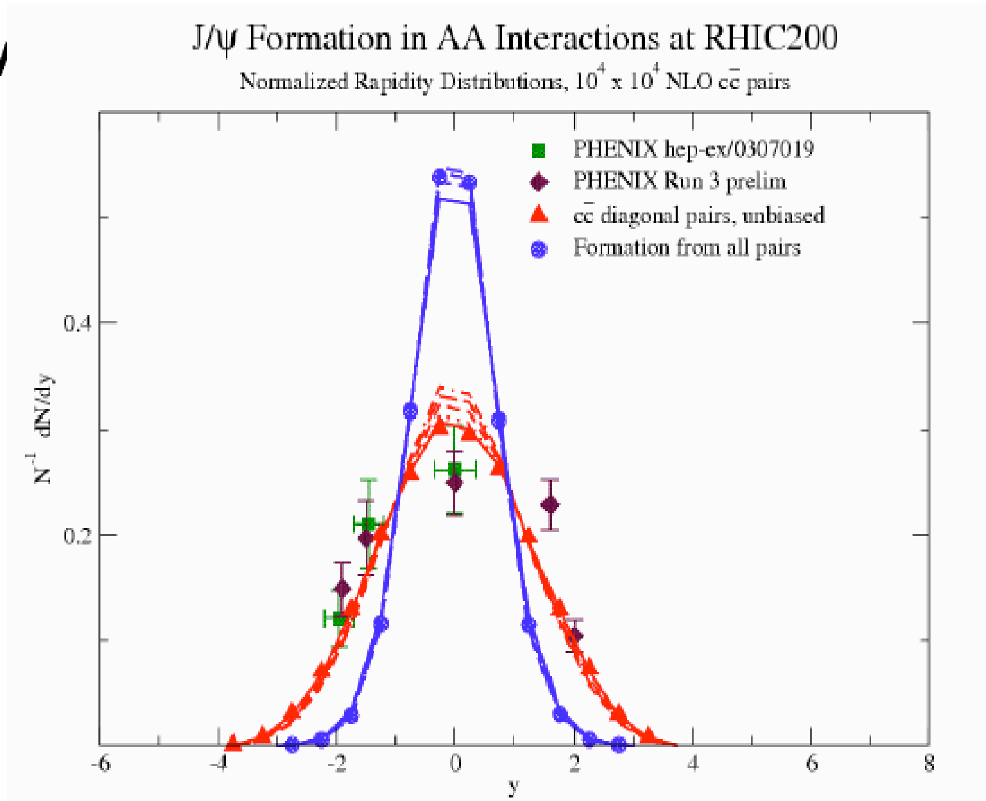
J/ψ nuclear modification factor R_{AA}



"same as at SPS"?

Recombination of charm quarks?

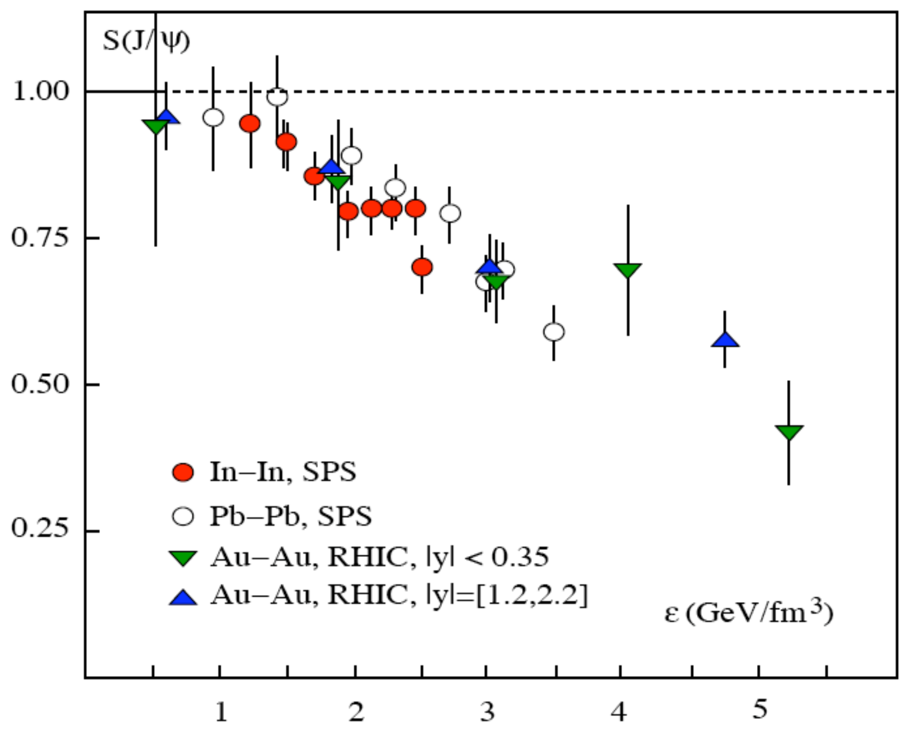


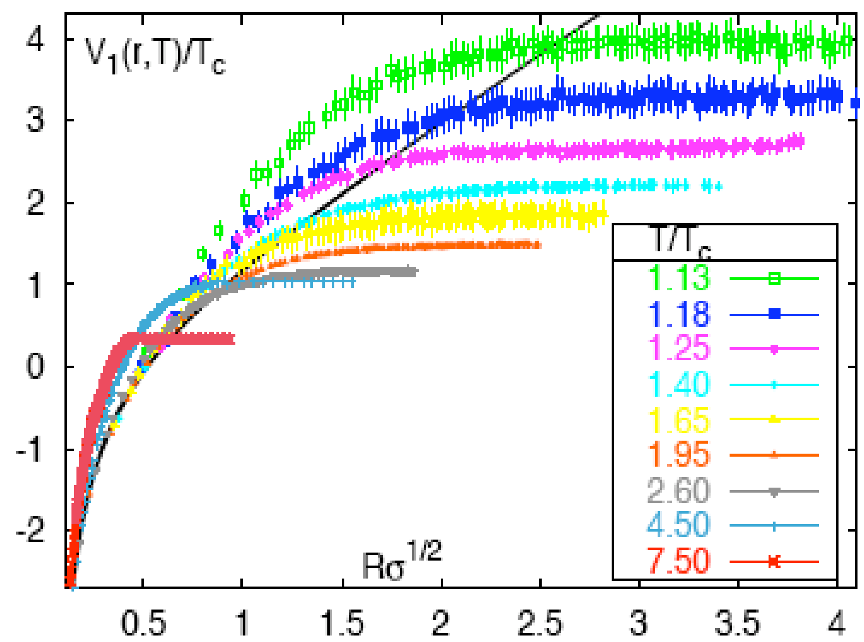


Recombination narrows the rapidity distribution; is this seen?

Are high p_t charmonia suppressed stronger than open charm?

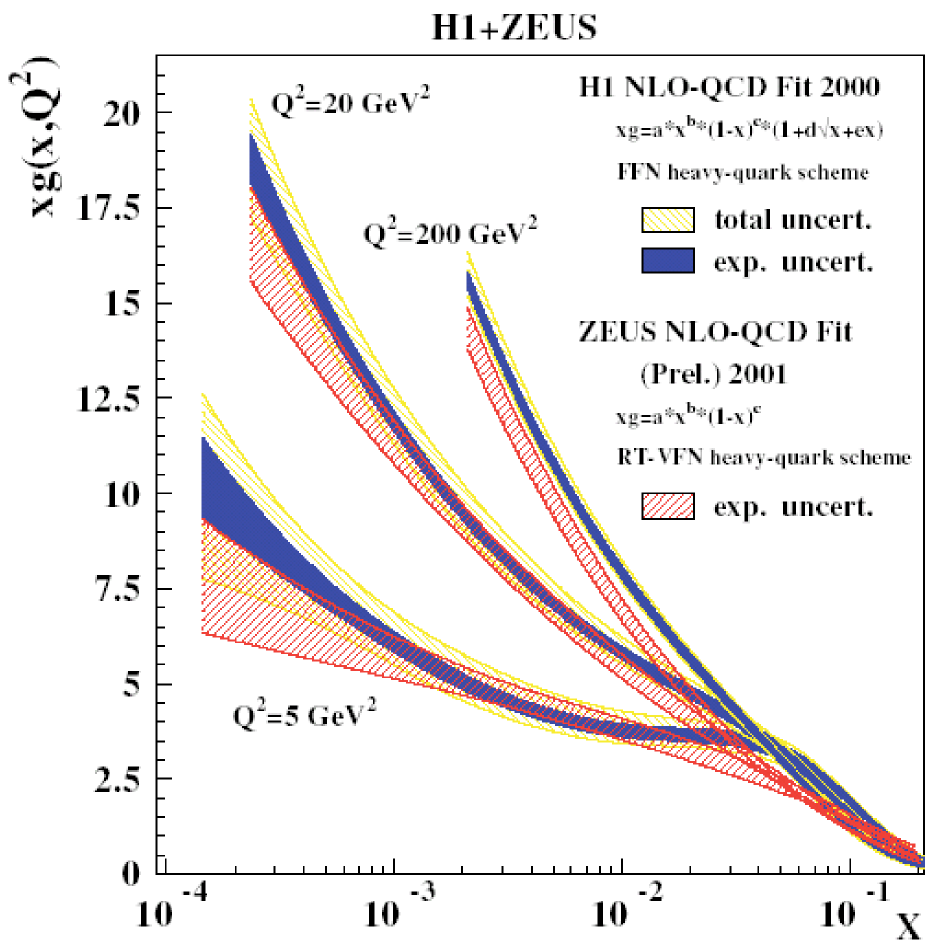
…or the survival of direct J/ψ's in the plasma?

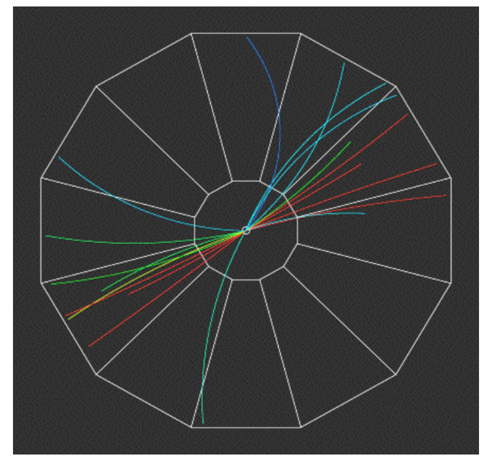


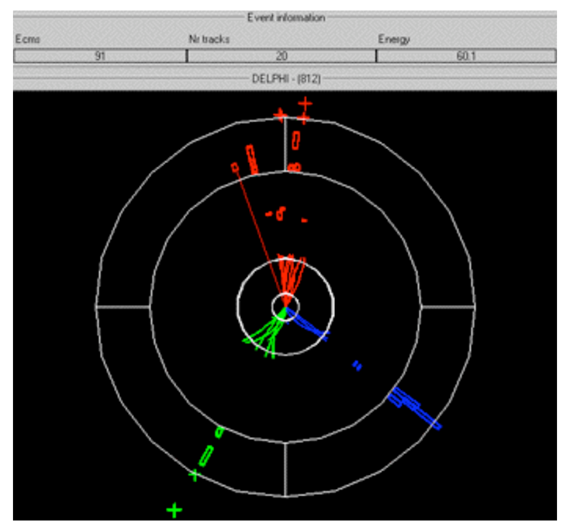


Crucial tests at RHIC-II:
excited charmonia, Υ states

What are the wave functions of the proton and of the nucleus?

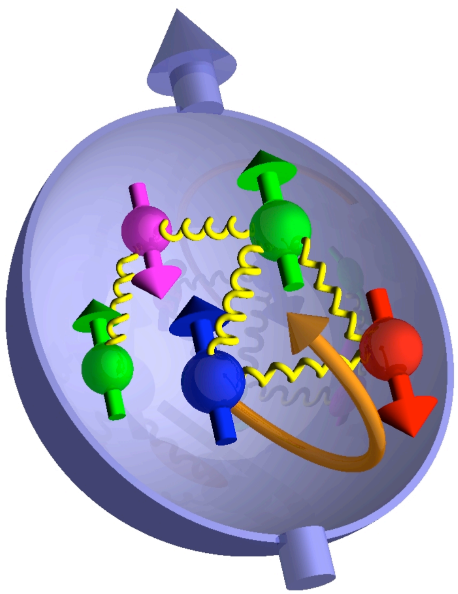






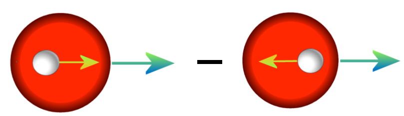
Exciting program with polarized protons underway at RHIC:

What carries the proton spin ?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Quark spins — only ≈ 20 %



Gluon spins — ??

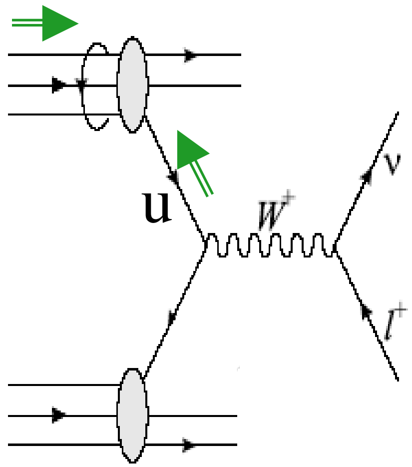
Quark and gluon orbital ang. mom. — ??

- **RHIC addresses the proton spin structure in new ways**
- **Major effort at RHIC-II & eRHIC**

Slides from W. Vogelsang

at RHIC:

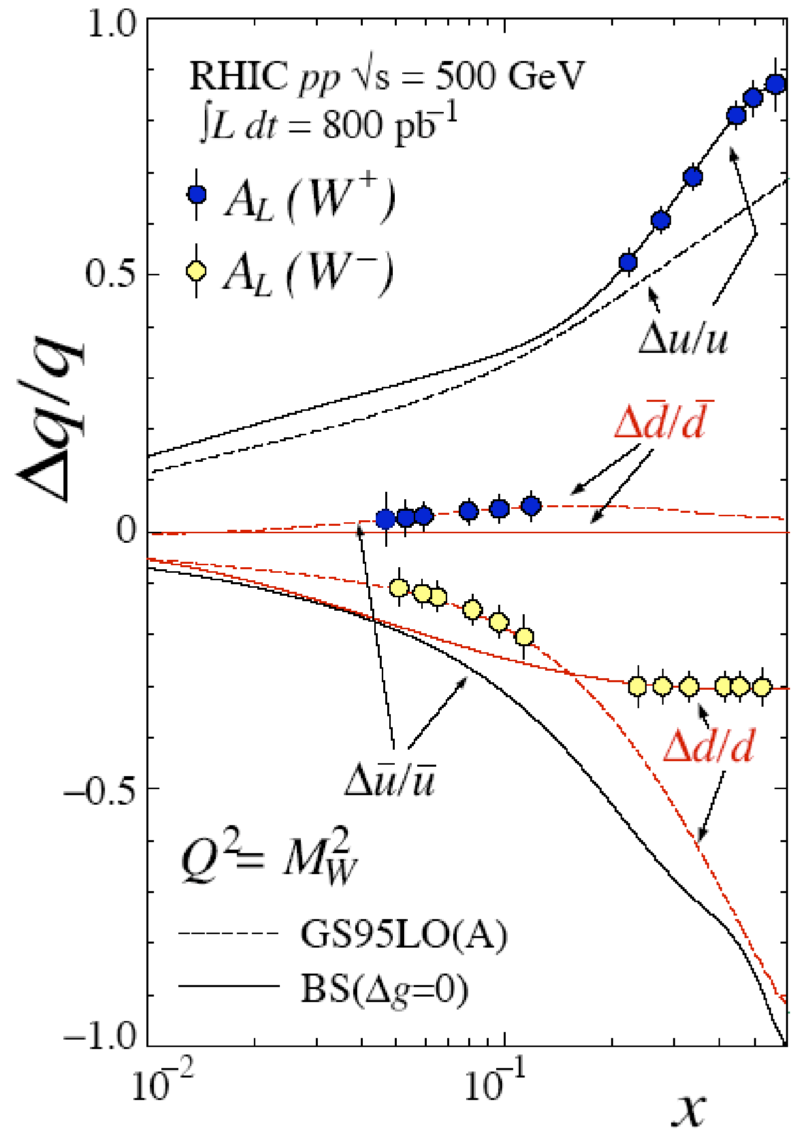
W boson production



unpol.

$$\mathbf{A_L^{PV}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

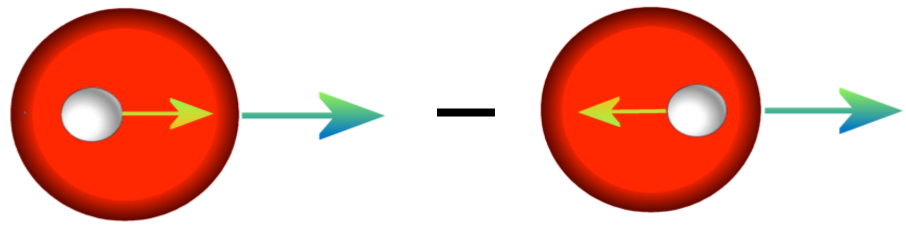
$$A_L^{W^+} \approx \frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}$$



RHIC-II: W+charm - access to strange quarks

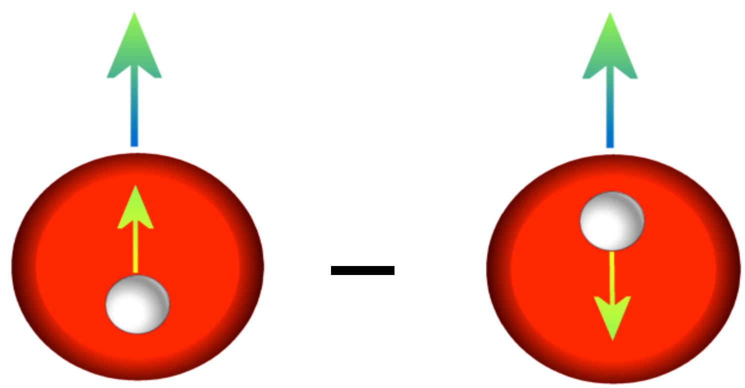
Helicity :

$$\Delta \mathbf{q}(\mathbf{x}) =$$



Transversity :

$$\delta \mathbf{q}(\mathbf{x}) =$$

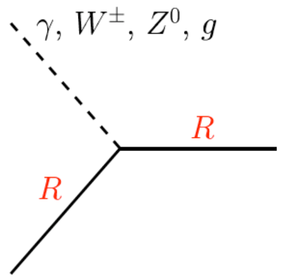


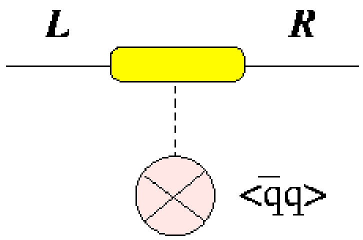
Ralston,Soper; Jaffe,Ji; …

* **difference probes relativistic / dynamical effects**

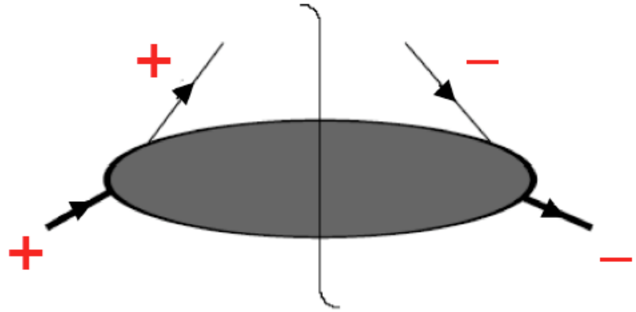
- **the physics involved:**

  - ∗ "odd chirality" $\rightarrow$ helicity-flip, χSB





  - ∗ no mixing with gluons

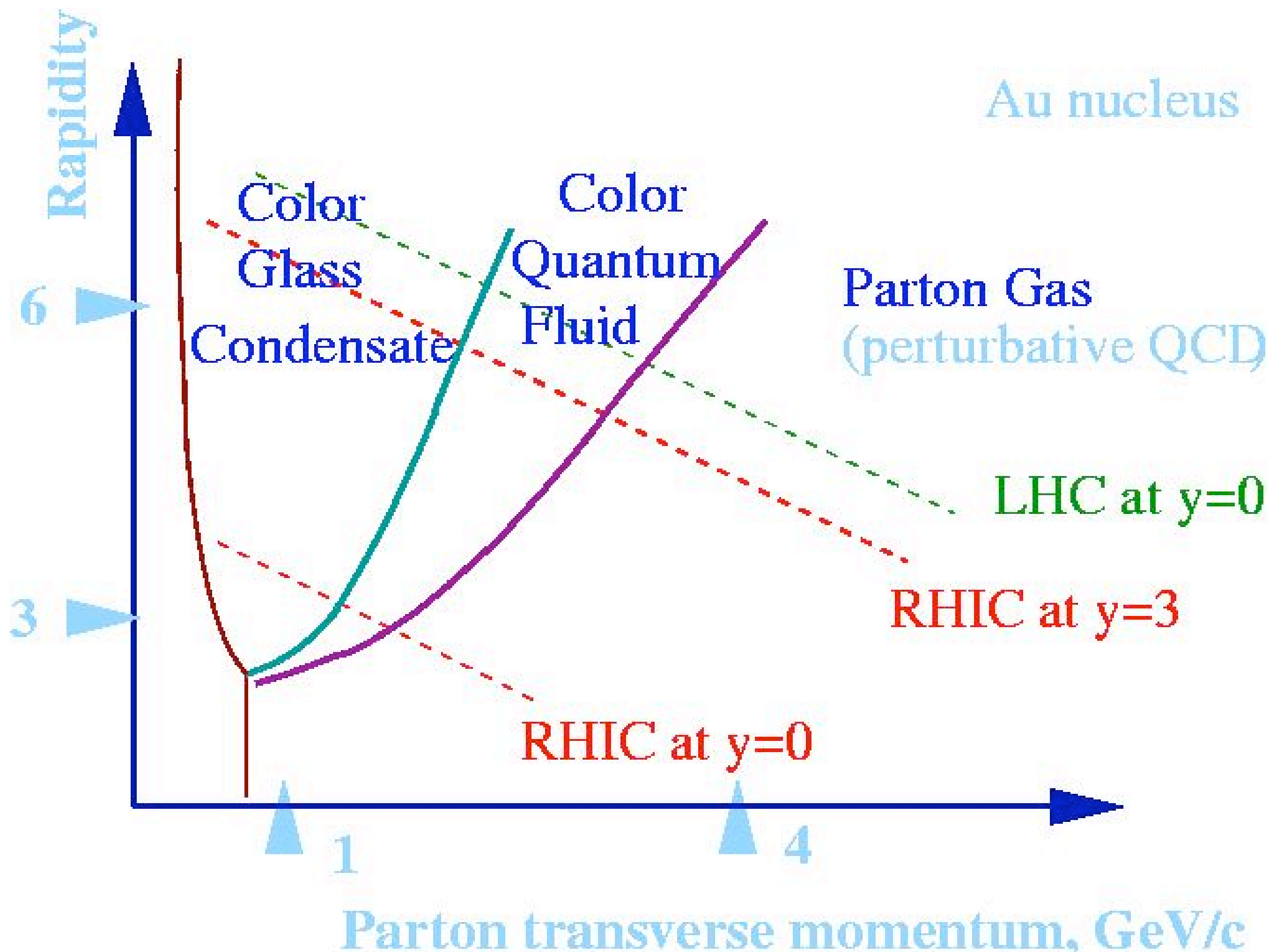


  - ∗ tensor charge

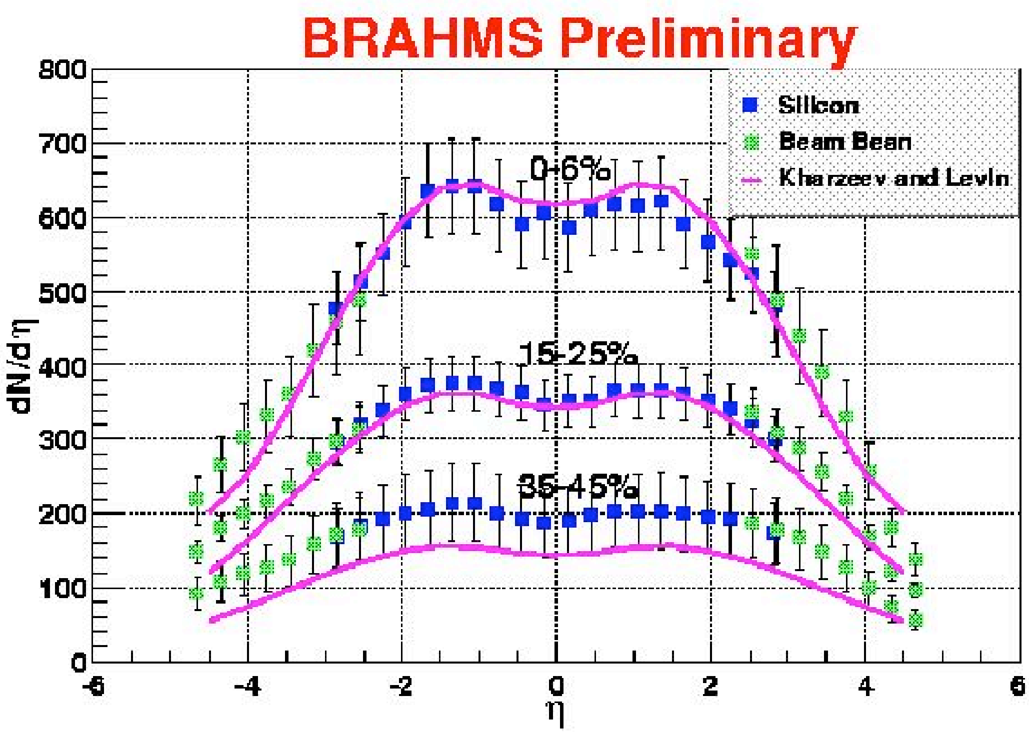
$$\langle \mathbf{P} \,|\, \bar{\mathbf{q}}\, \mathbf{i}\, \sigma^{\mu\nu} \gamma^5 \mathbf{q} \,|\, \mathbf{P} \rangle = \int_0^1 \mathbf{dx}\, [\, \delta \mathbf{q}(\mathbf{x}) - \delta \bar{\mathbf{q}}(\mathbf{x}) \,]$$

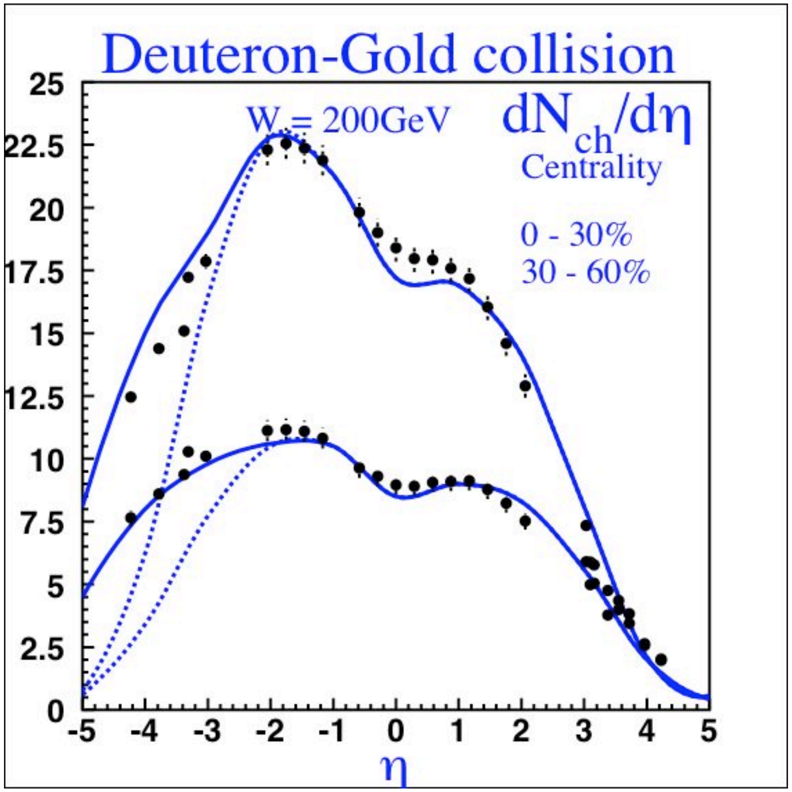
Major part of RHIC, RHICII, eRHIC programs

Phase diagram of high energy QCD and the small x wave function of the nucleus



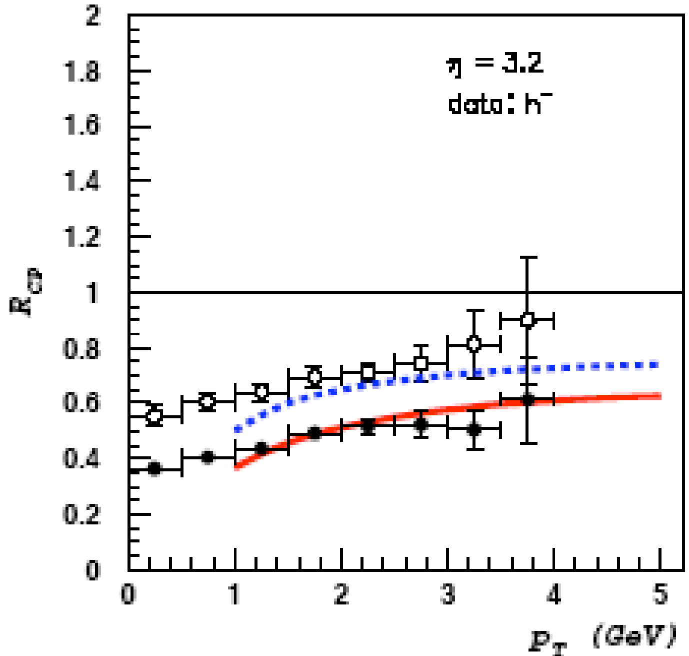
CGC and hadron multiplicities





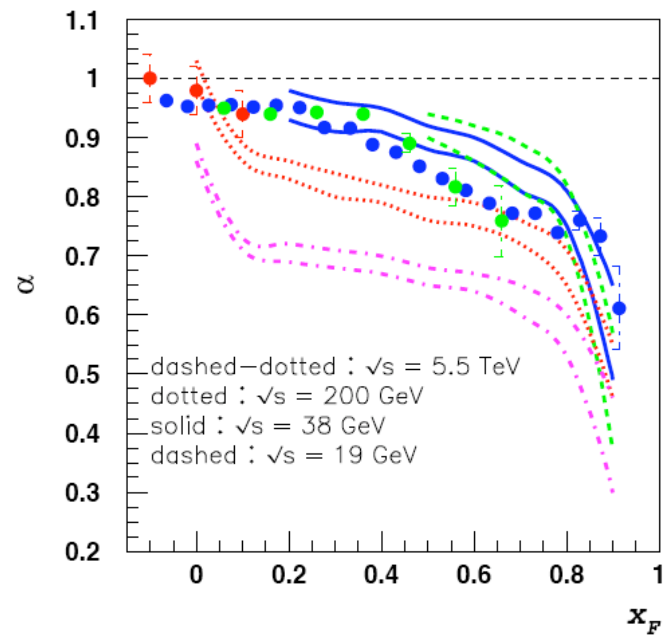
CGC confronts the data

hadrons

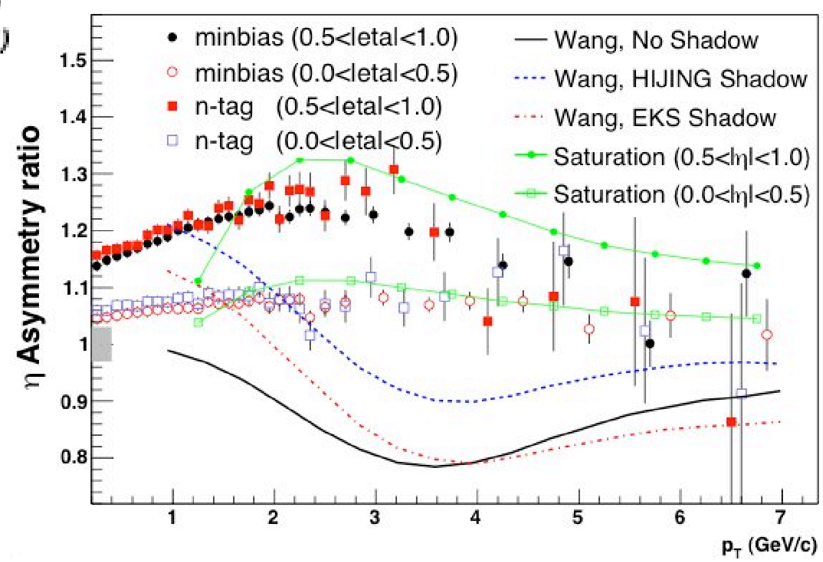


BRAHMS

charmonium



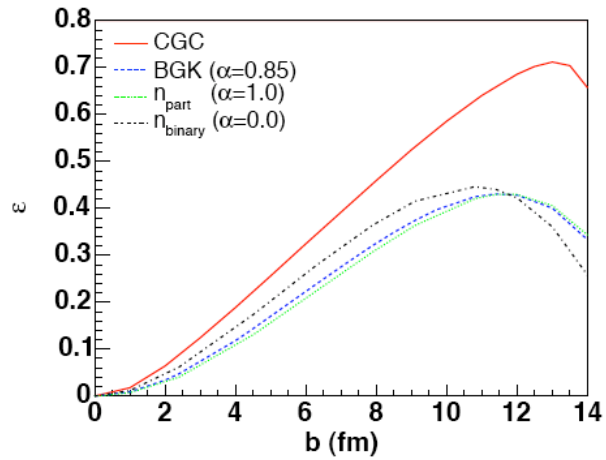
PHENIX



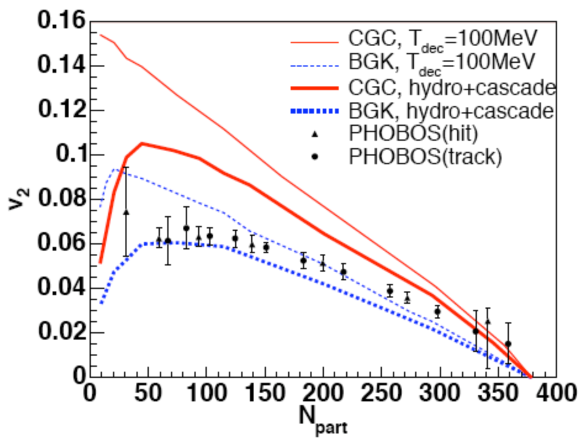
STAR

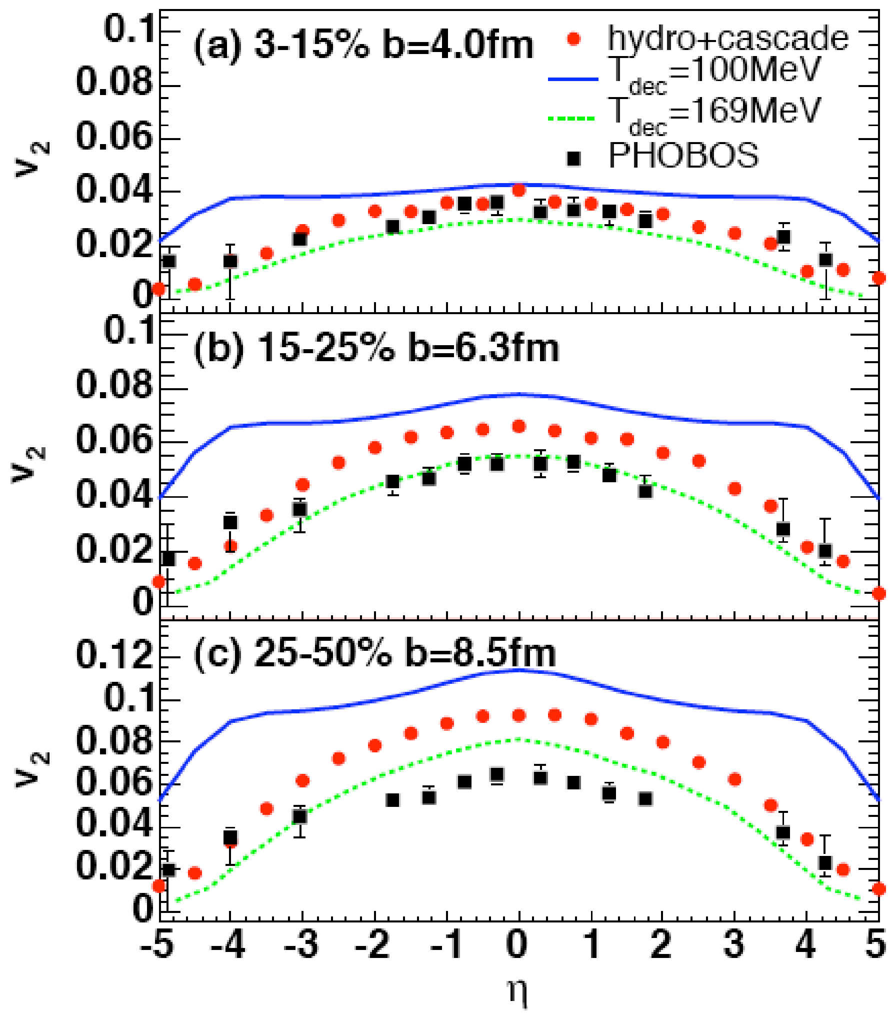
CGC & QGP: How small really is the viscosity?

CGC initial conditions lead to larger ellipticity,



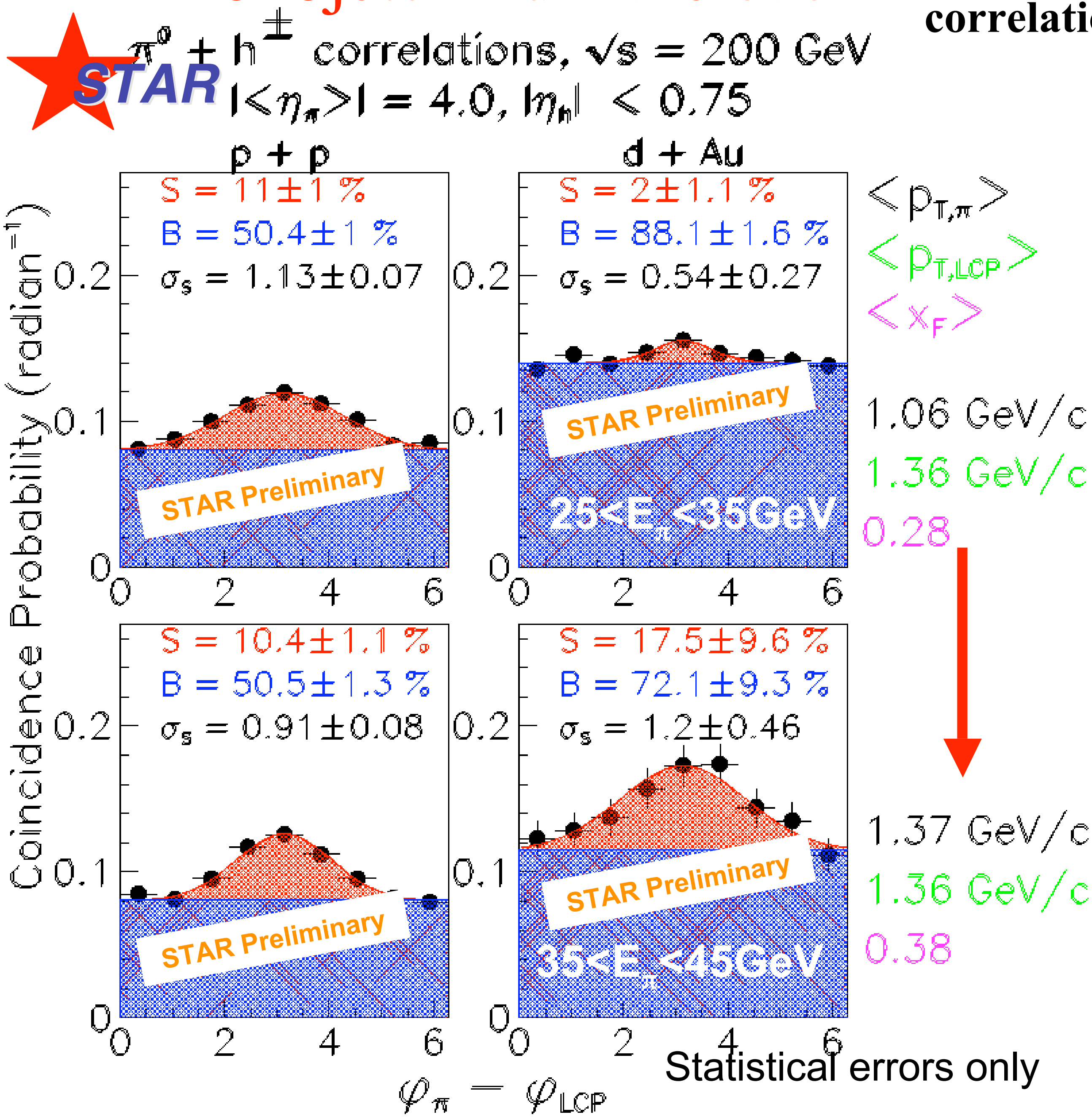
require some viscous effects:





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

Monojets in dA are back

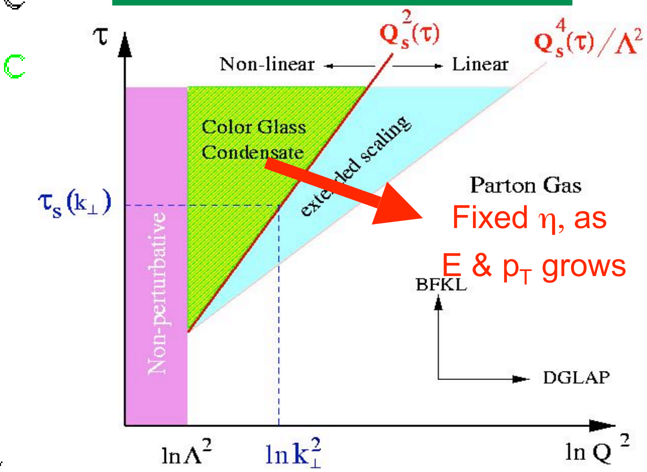


Large rapidity gap π^0+$h^{\pm}$ correlation data…

- **are suppressed in d+Au relative to p+p at small $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**

S_{pp}-S_{dAu}= (9.0 ± 1.5) %

Consistent with CGC picture



- **are consistent in d+Au and p+p at larger $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$**

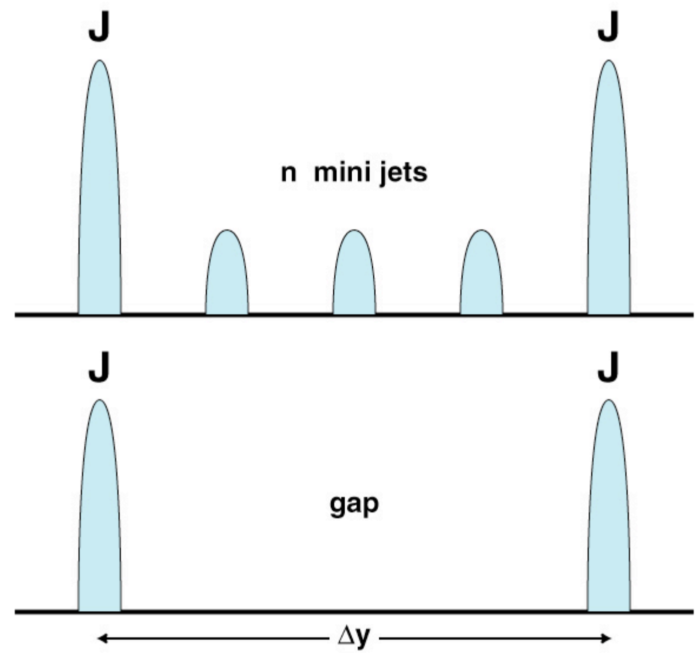
as expected by HIJING

Are the effects observed at forward rapidity due to parton saturation in the CGC?

•Back-to-back correlations for jets separated by several units of rapidity are very sensitive to the evolution effects

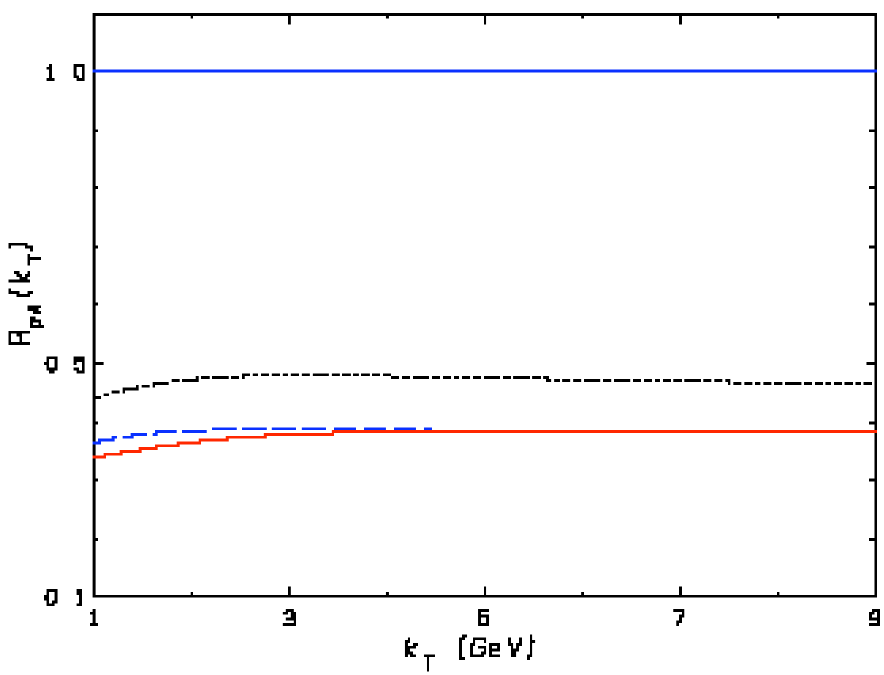
("Mueller-Navelet jets")

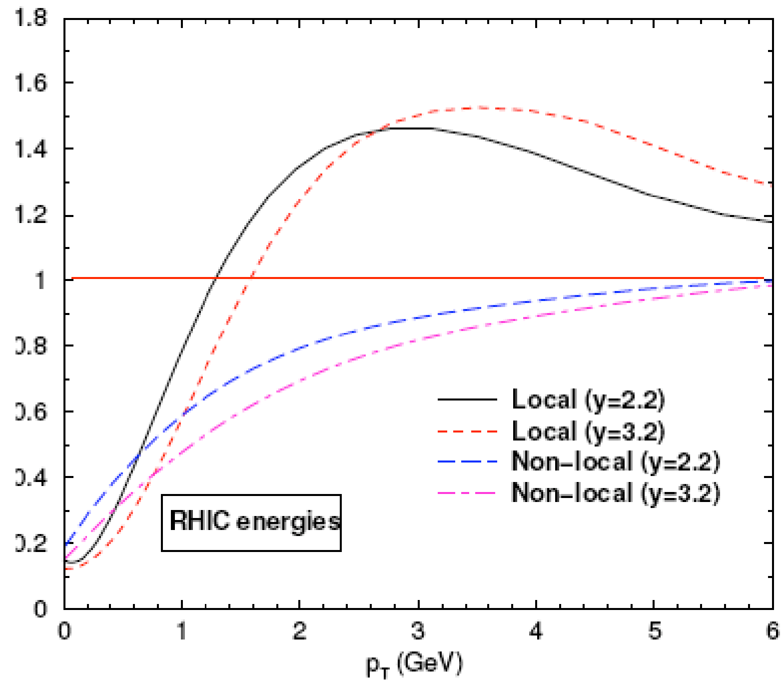
and to the presence of CGC



Forward measurements at RHIC-II and eRHIC

Dileptons from the CGC



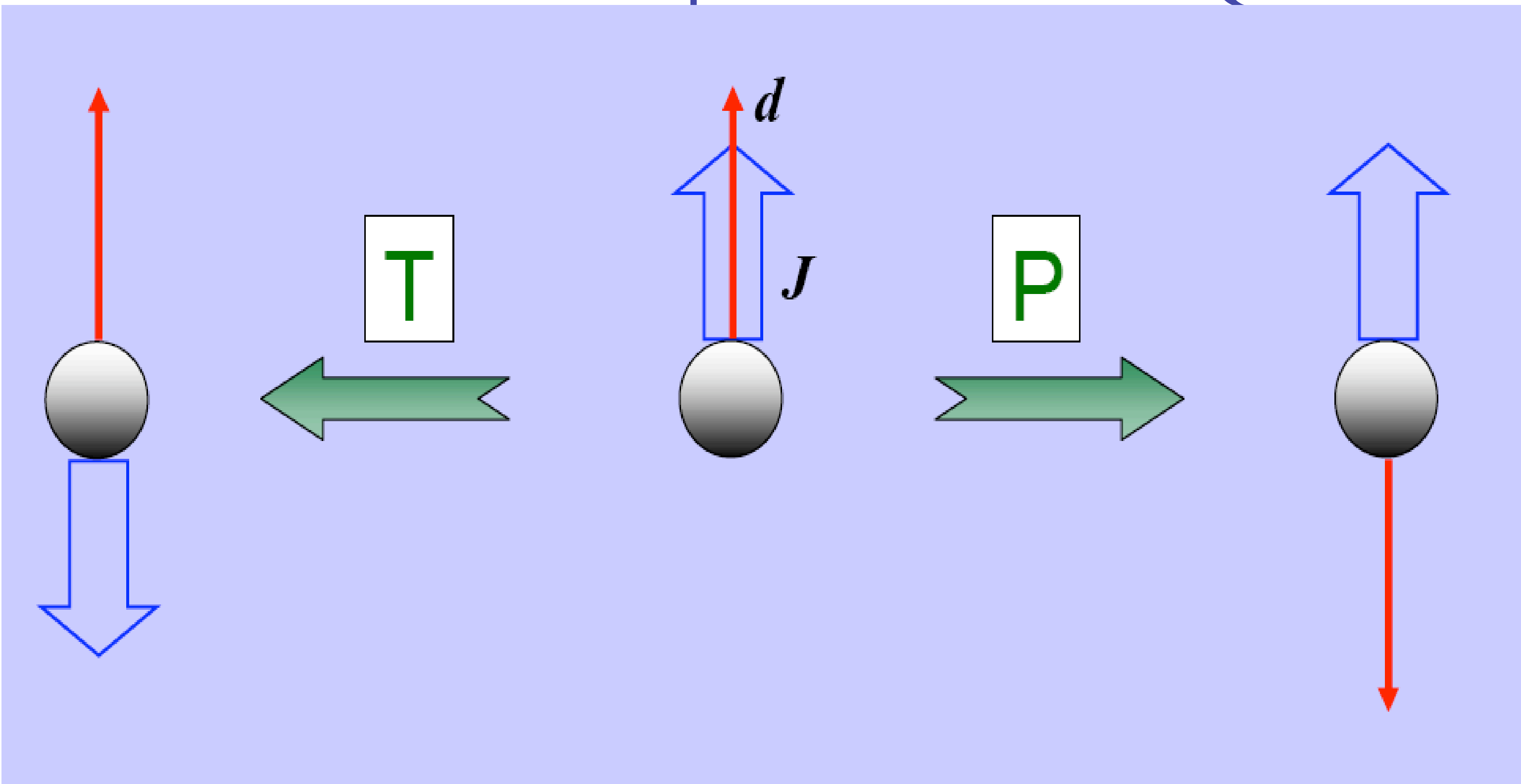


A RHIC-II measurement

Exploratory studies:

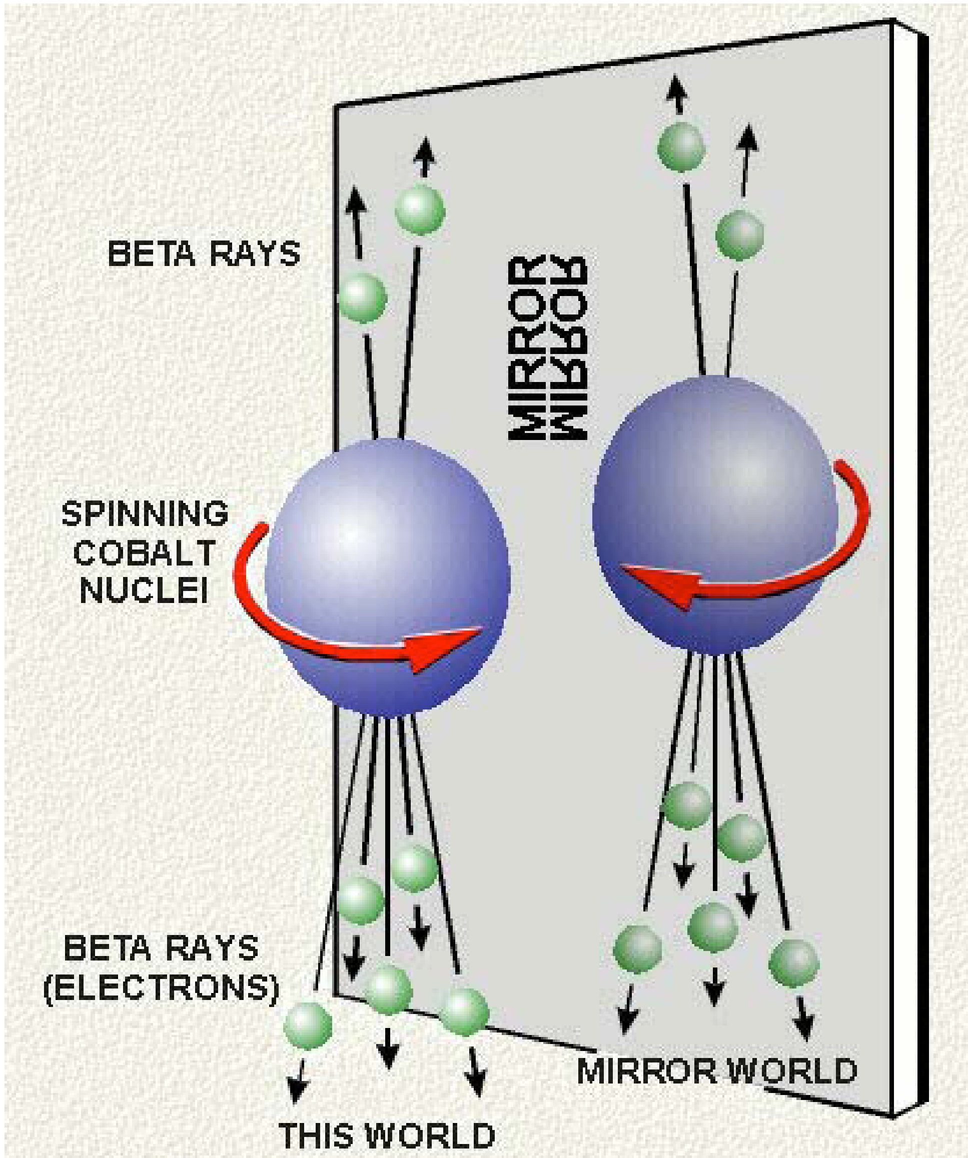
P & CP violations in deconfined QCD matter?

Measure electric dipole moment of sQGP!



A spatial asymmetry in the production of positive and negative pions w.r.t. reaction plane would signal P, T, and CP violations

Analogy to P violation in weak interactions



Strong CP violation at high T ?

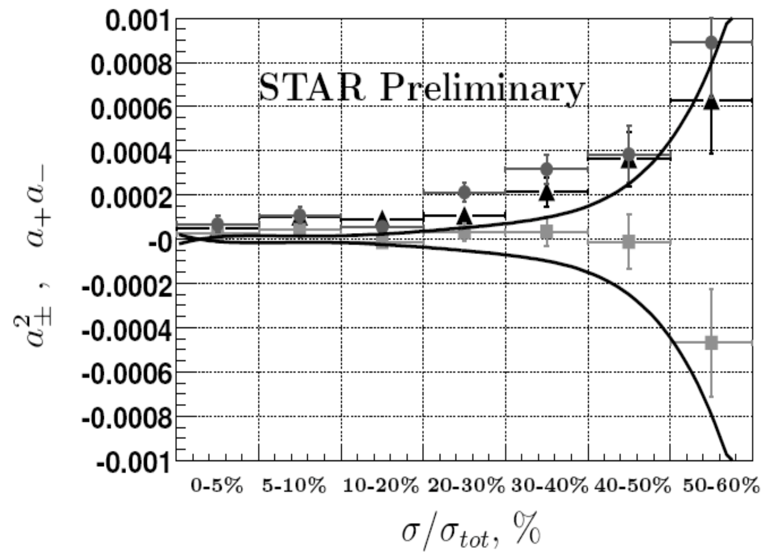


Figure 2: Charged particle asymmetry parameters as a a function of standard STAR centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are a_+a_-. Black lines are theoretical prediction [1] corresponding to the topological charge $|Q| = 1$.

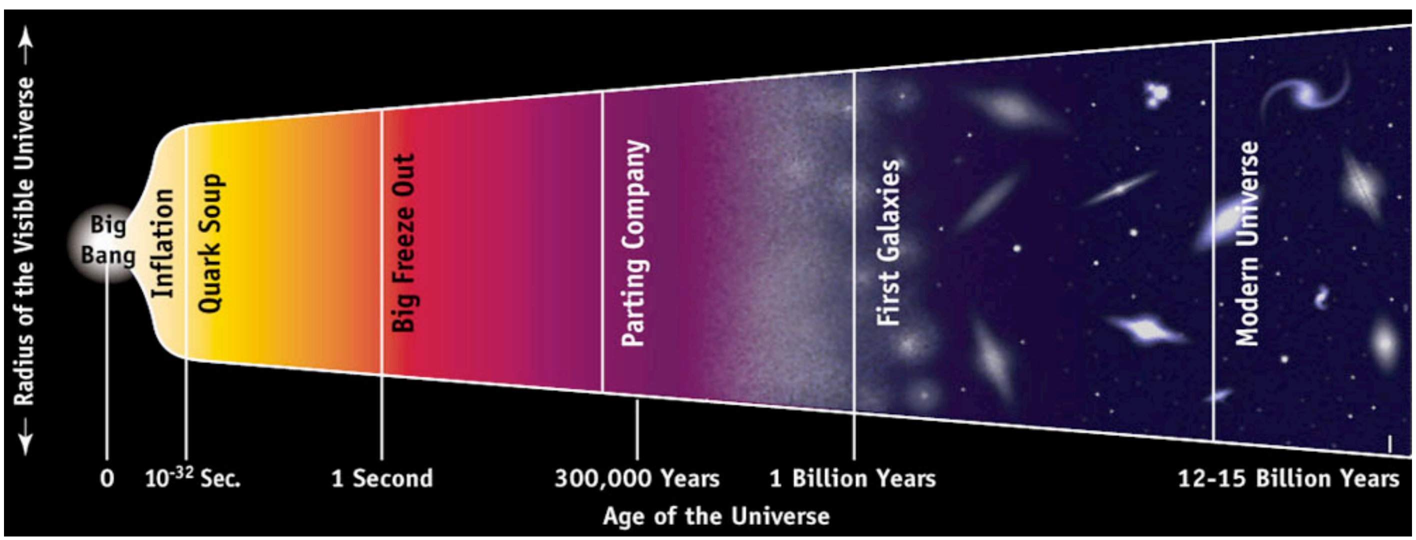
STAR Coll., nucl-ex/0510069

Need to analyze the systematics, improve statistics

Chern-Simons number generation in QCD at high temperatures?

Analogous to the baryon number generation above the electroweak phase transition;

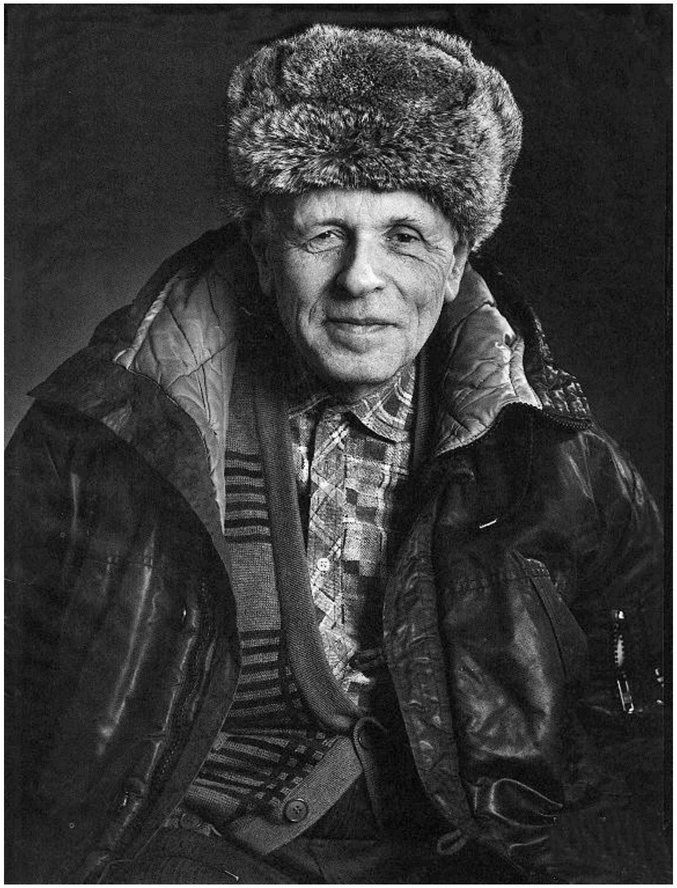
Understanding it will help to understand the origin of the Baryon asymmetry in the Universe



What is the origin of the matter-antimatter asymmetry in the Universe?

1. B violation
2. CP violation
3. Non-equilibrium dynamics

A.D. Sakharov,
JETP Lett. 5 (1967) 24



The Science of QCD Lab

We need RHIC-II and eRHIC to address the following questions:

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 dynamics of non-equilibrium processes in a fundamental gauge theory?