“Particle physics at the verge of discovery”,
Aspen, February 12-18, 2006

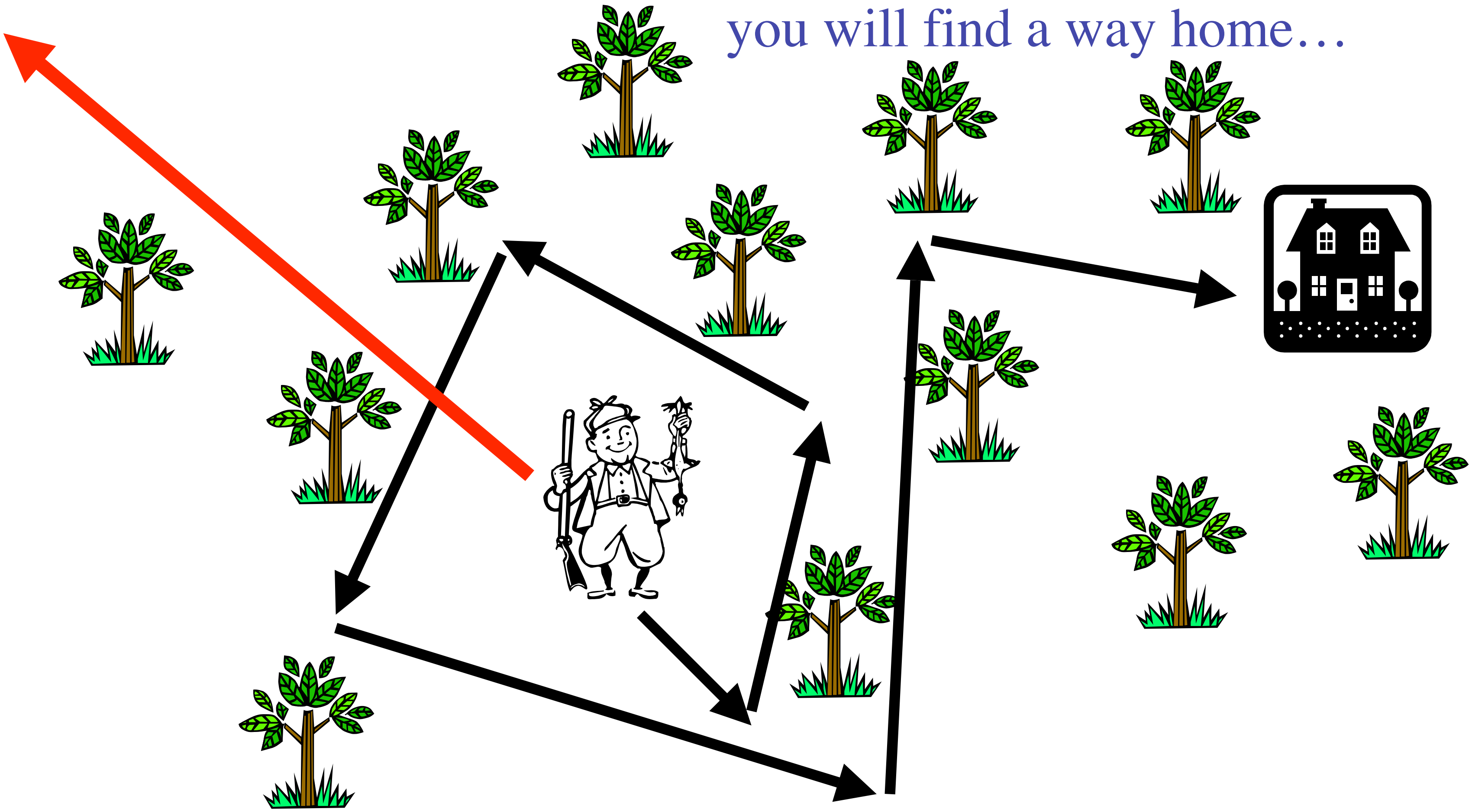
# The physics of RHIC: a theorist’s view

D. Kharzeev
BNL

BROOKHAVEN NATIONAL LABORATORY

# An "infinite forest" theorem, or the role of theory in physics

If you are lost in an infinite forest, sooner or later you will find a way home…



…unless you <u>think</u> you know where your home is !

# Outline

- What physics questions are we trying to answer?
- What have we learned from RHIC in the first five years?
- Why does it matter?
- What do we still want to know?

Partial, biased, personal view

# Four questions which drive the RHIC program

1. What are the phases of QCD matter?

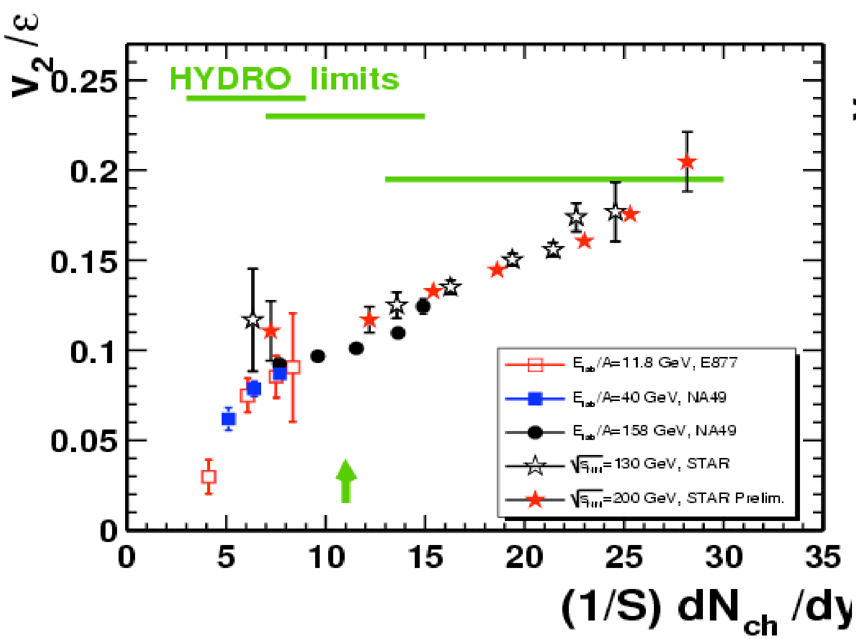
2. What is the wave function of the proton?

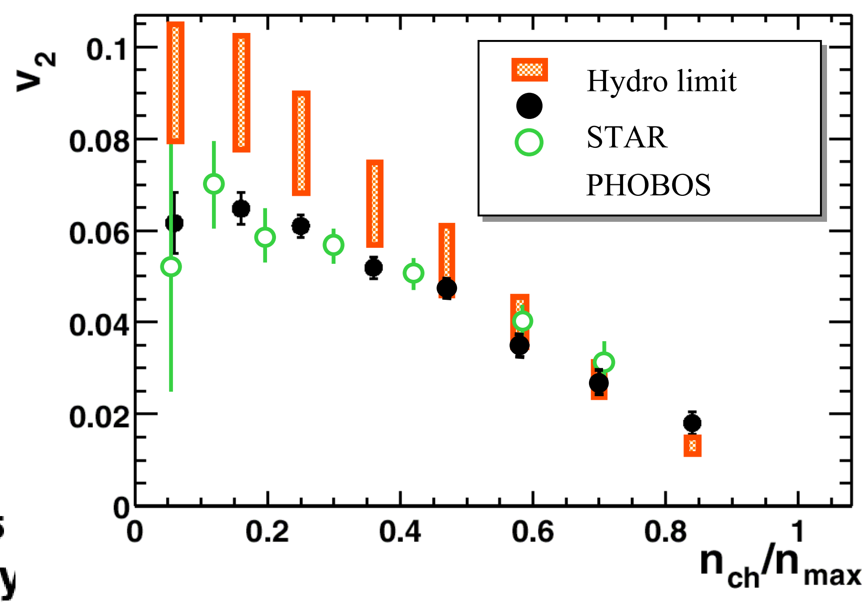
3. What is the wave function of a heavy nucleus?

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

# What have we learned from RHIC so far ?

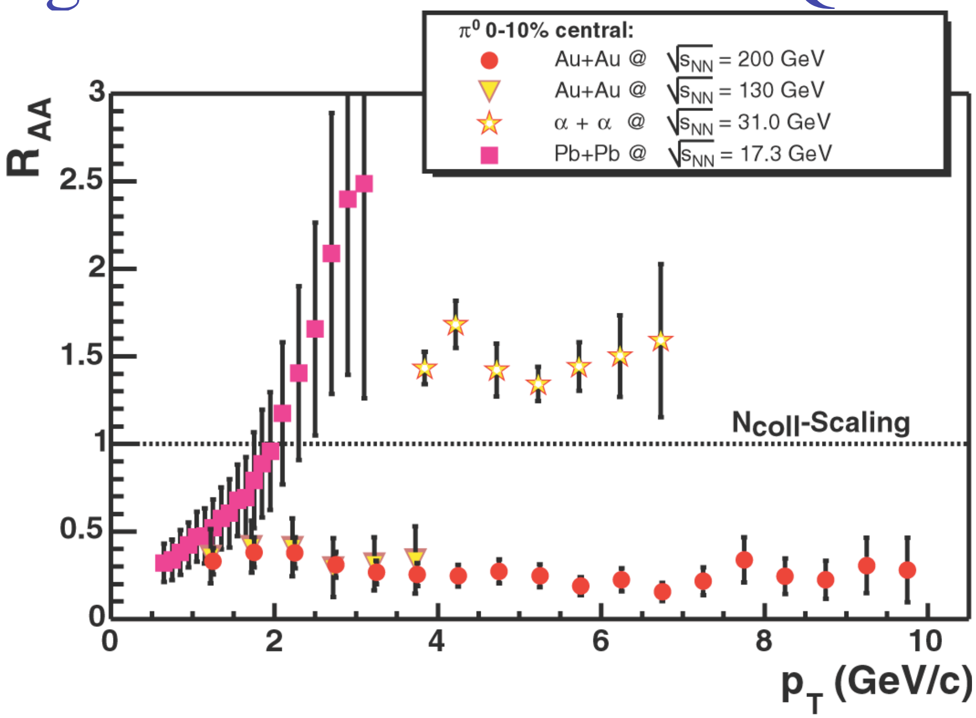
I. Collective flow =>
Au-Au collisions at RHIC produce strongly interacting matter

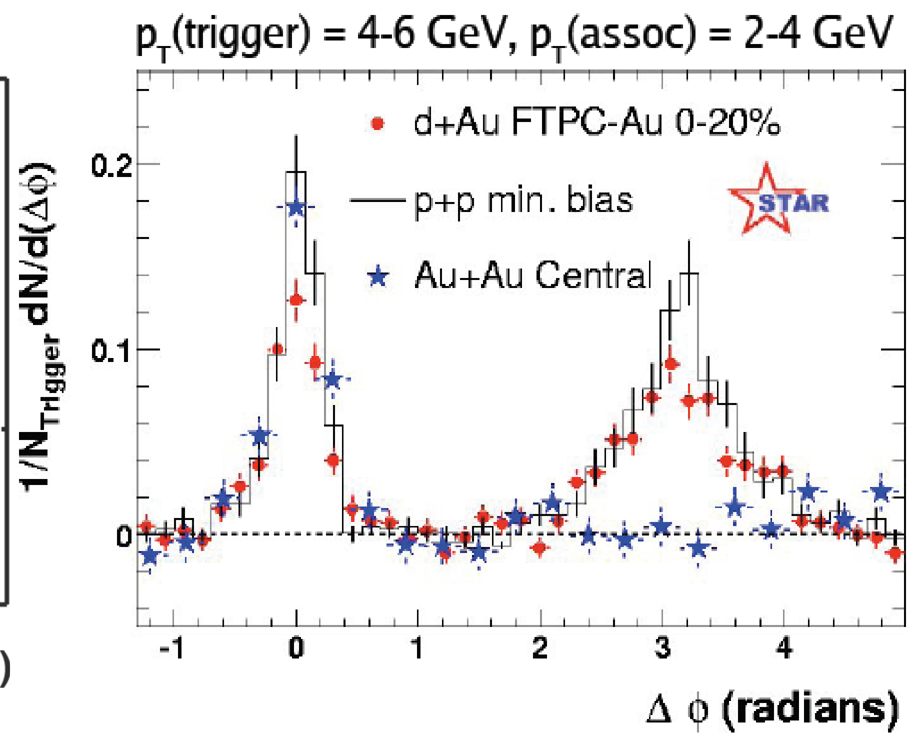


# What have we learned from RHIC so far ?

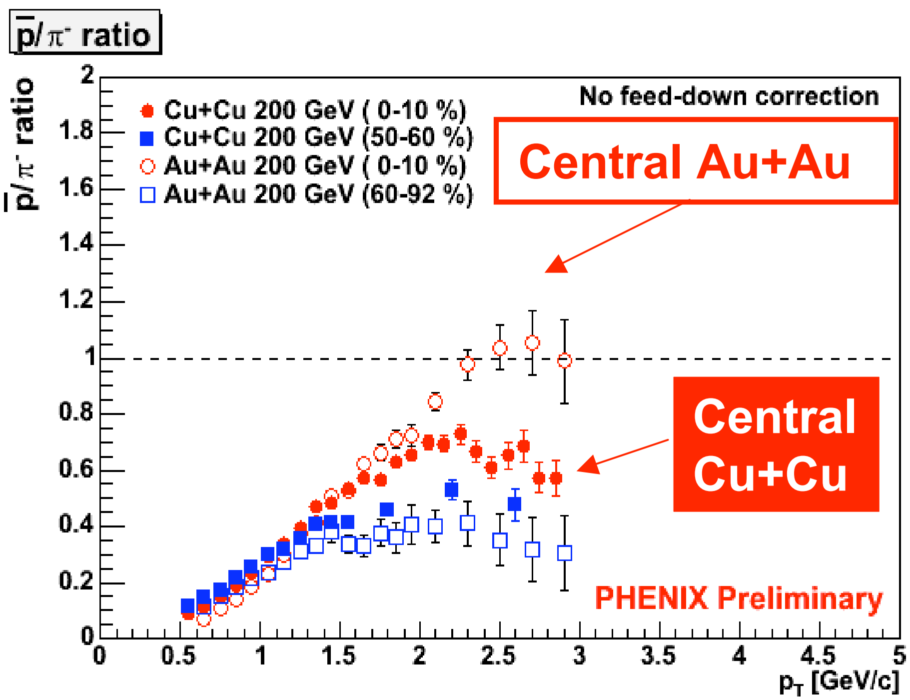
II. Suppression of high $p_T$ particles =>
consistent with the predicted jet energy loss from induced gluon radiation in dense QCD matter

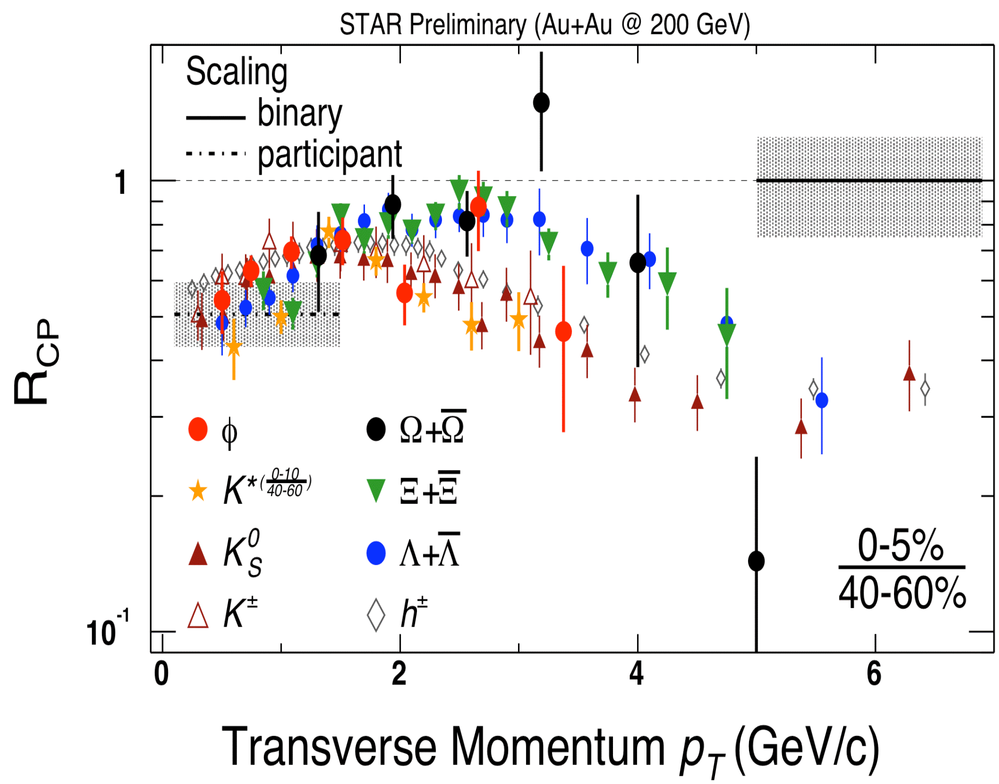


# What have we learned from RHIC so far ?

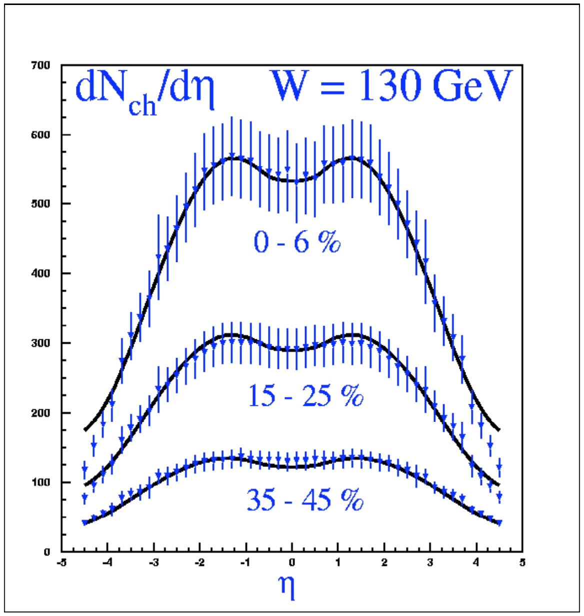
III. Baryon/meson enhancement =>
Constituent quark recombination? Baryon junctions?

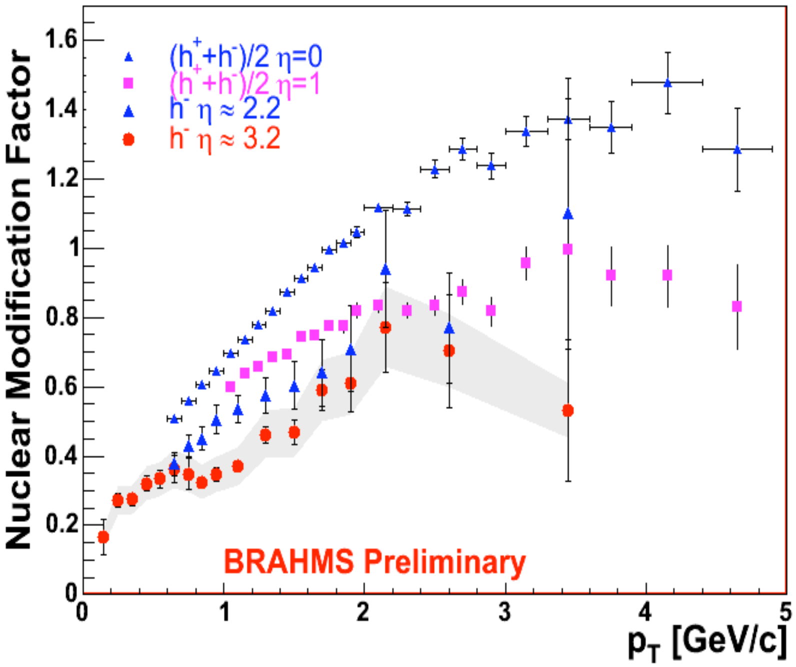


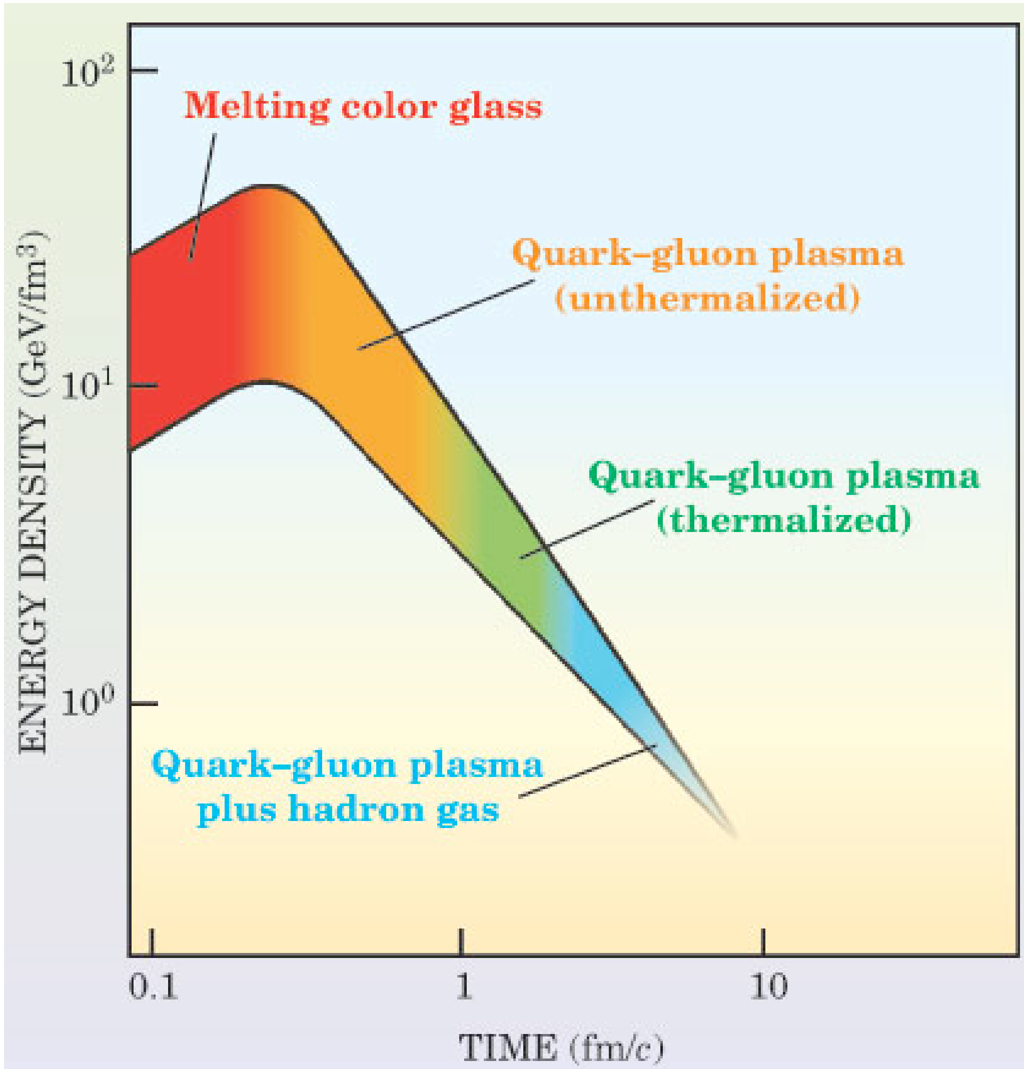
# What have we learned from RHIC so far ?

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



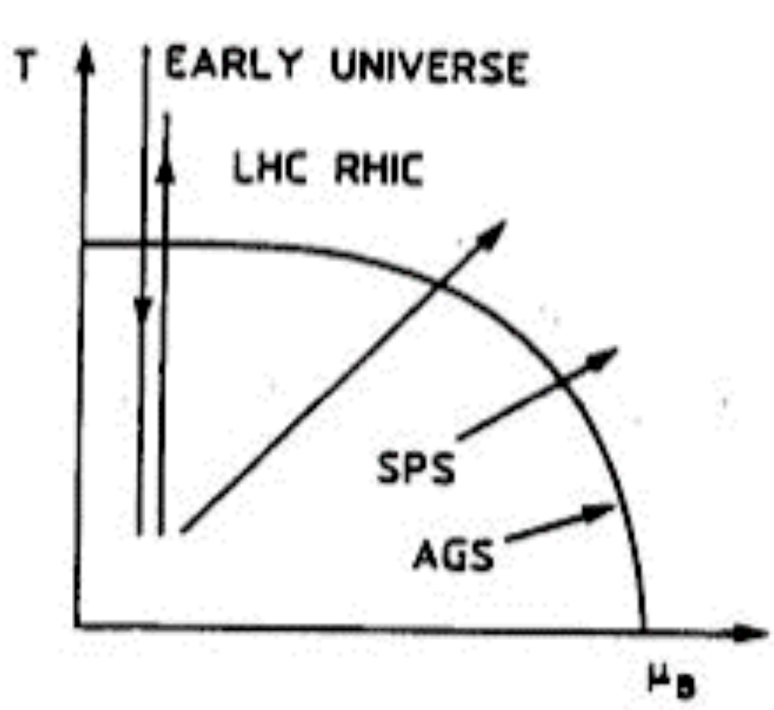
# The emerging picture

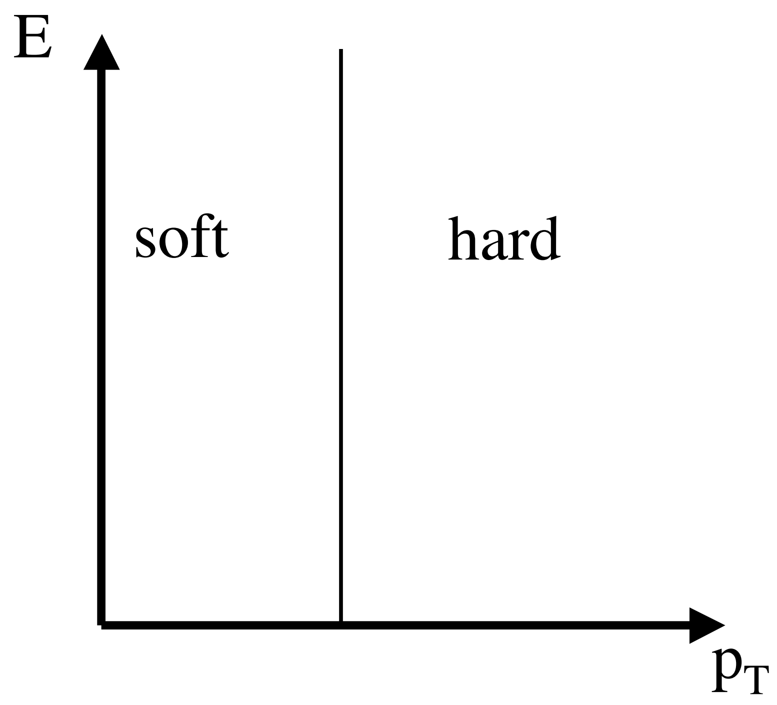



Why is thermalization so fast?

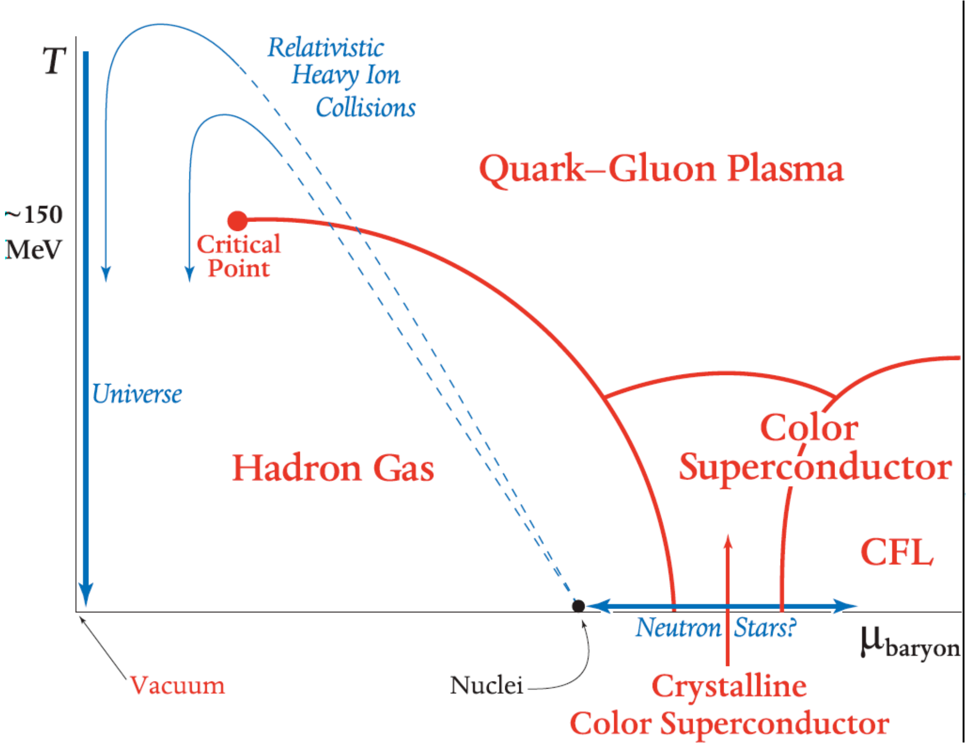
T. Ludlam,
L. McLerran,
Physics Today
October 2003

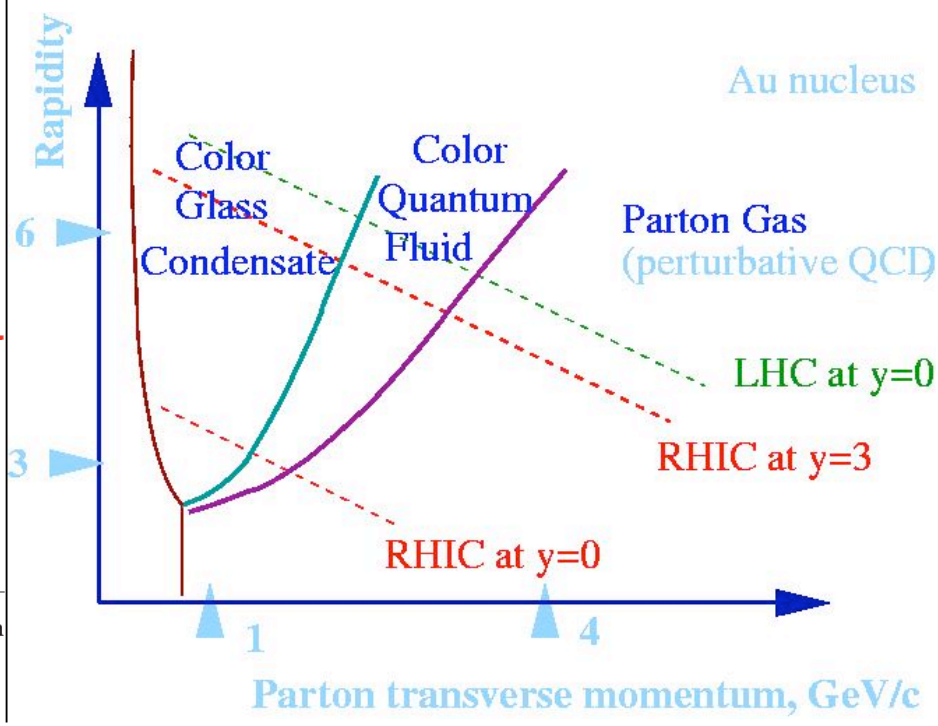
# QCD diagrams, late XX century



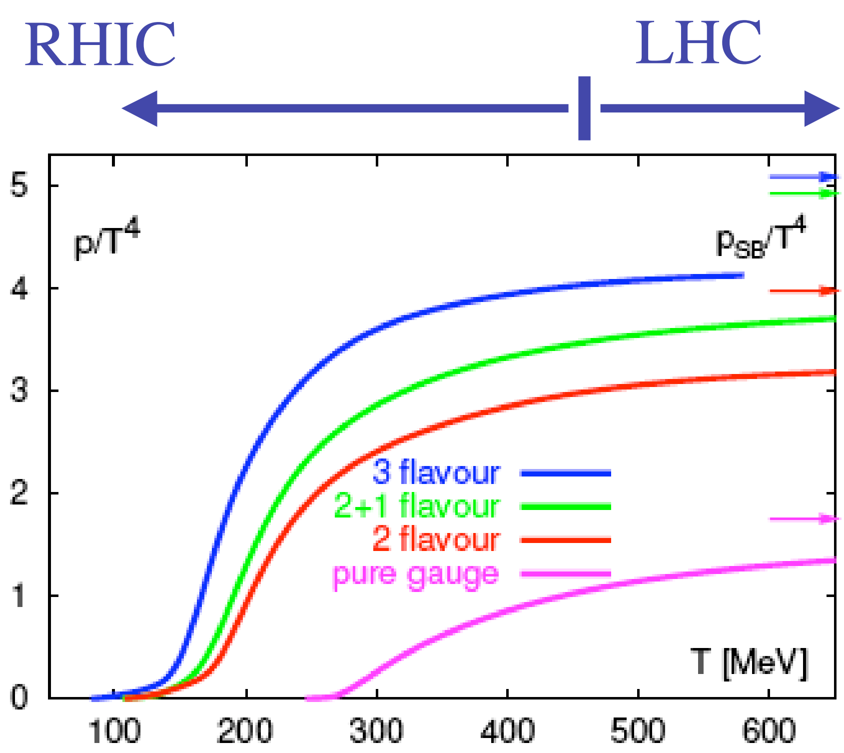
# QCD diagrams, early XXI century

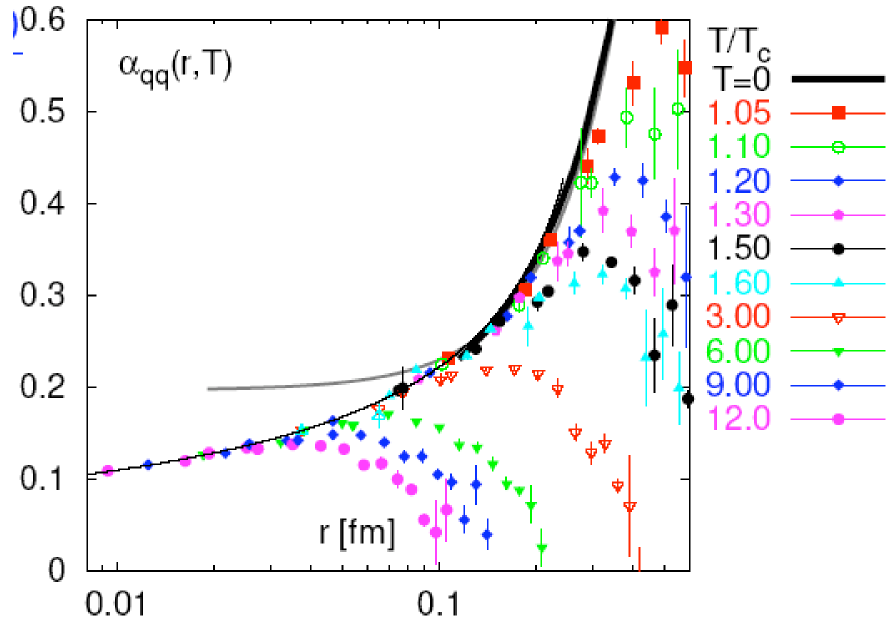



K.Rajagopal, F.Wilczek

# Strongly coupled QGP



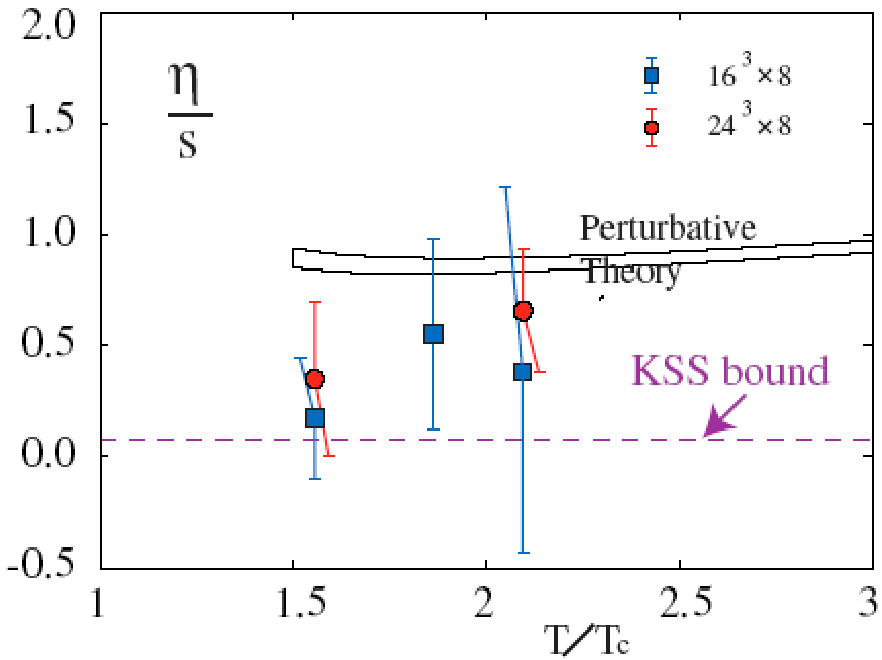




$$\epsilon \neq 3P$$

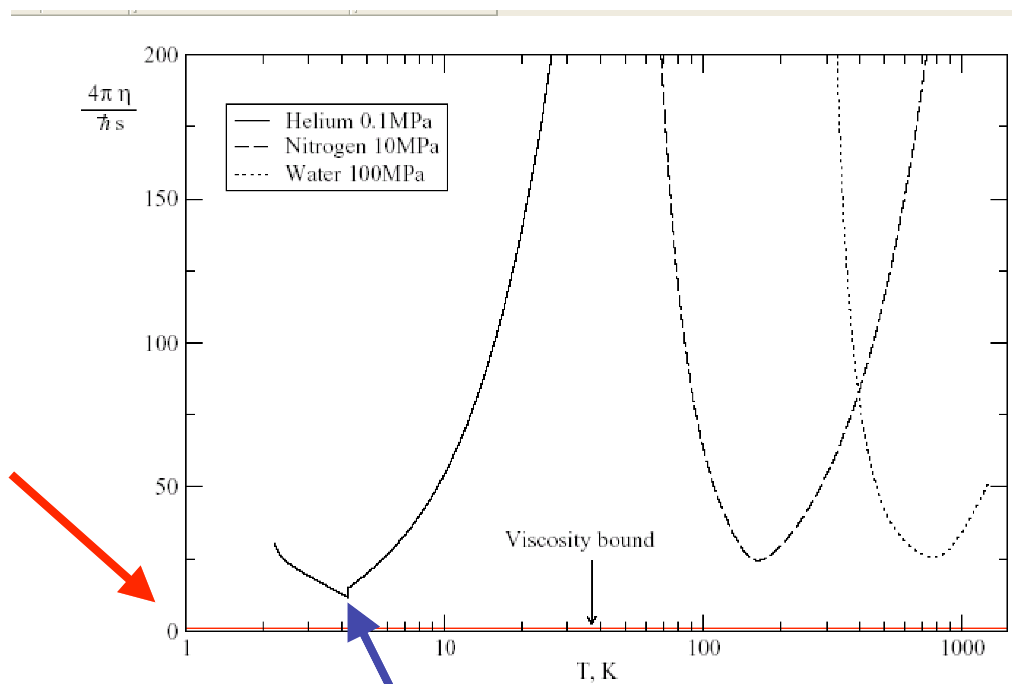
F. Karsch et al

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

# What do we still need to know?

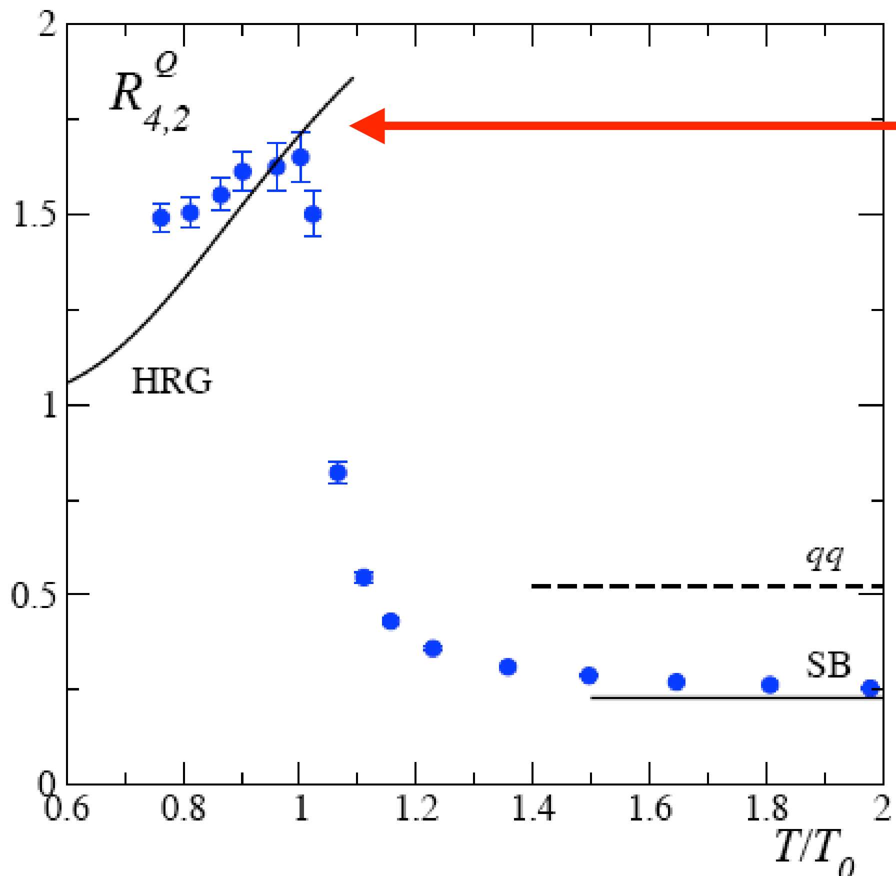
1. What are the dynamical degrees of freedom in sQGP and CGC?

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

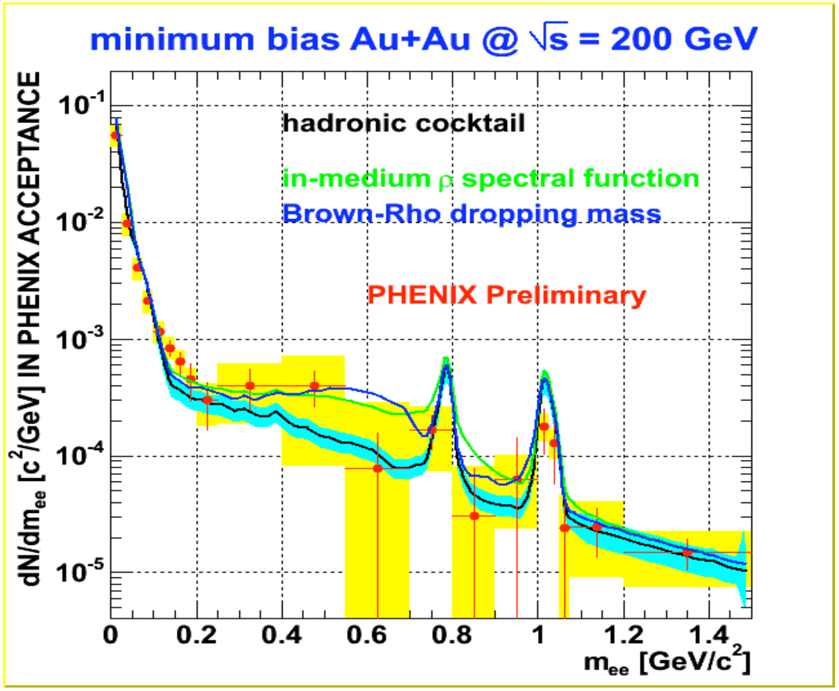
QQ bound states

Dynamical quarks

Influence on hadronization?

# What are the dynamical degrees of freedom in sQGP?

## What is the fate of the chiral symmetry in dense QCD matter?




Spontaneous chiral symmetry breaking mixes left-and right-handed quarks and generates their masses (analogous to Cooper pair condensate in a superconductor)

At high temperature, the condensate can be destroyed - Measure the mass spectra of vector and axial-vector quark-antiquark current through low-mass dileptons and $\gamma\pi$

# How does the transition from CGC to sQGP occur?

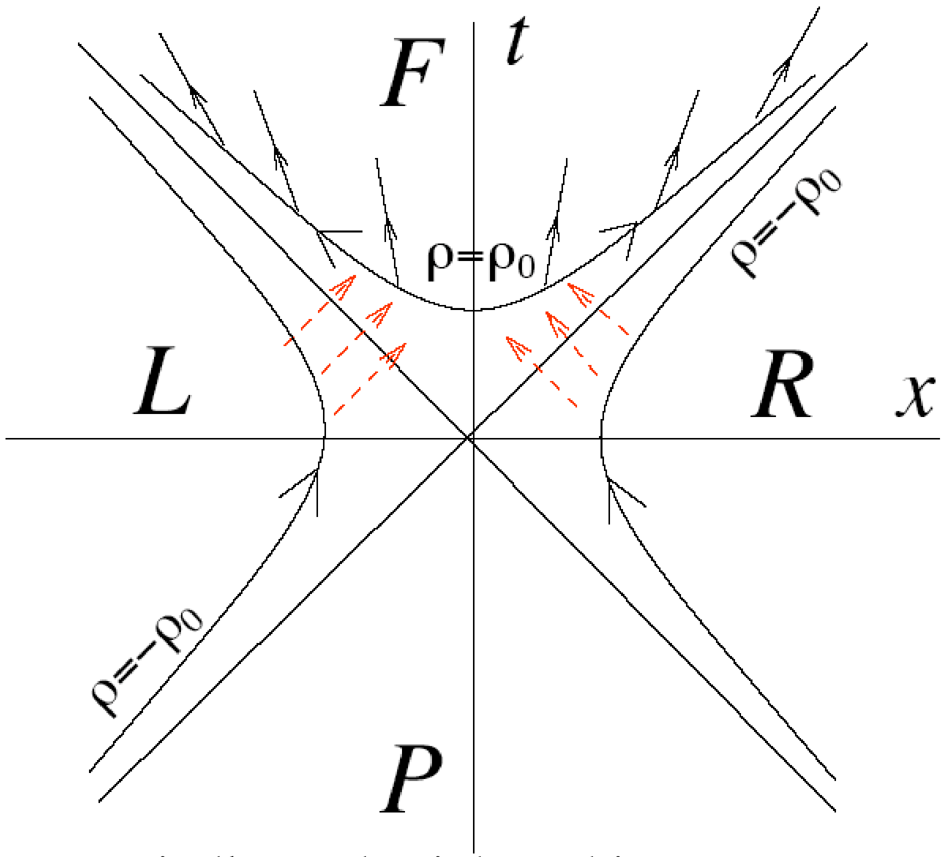
Parton re-scattering?

Instabilities of classical color fields?

Hawking-Unruh radiation?

# Quantum thermal radiation at RHIC?

$$T = \frac{a}{2\pi} \simeq \frac{Q_s}{2\pi}$$



Rindler and Minkowski spaces

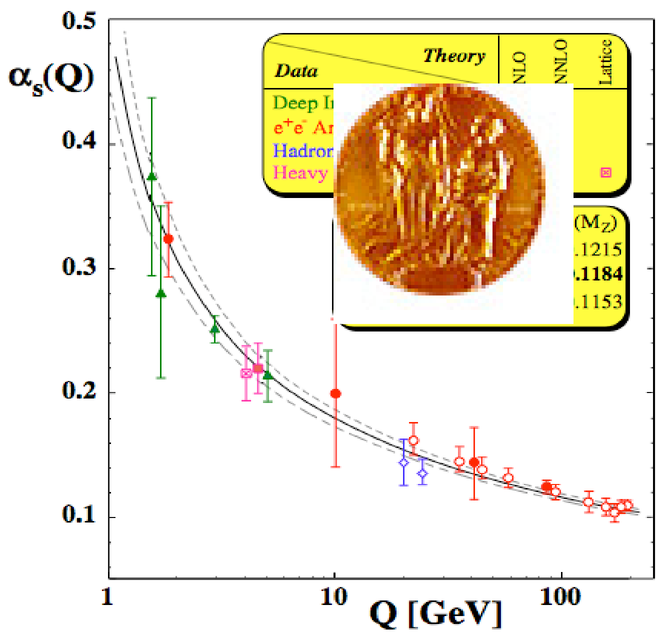
The event horizon emerges due to the fast decceleration $a \simeq Q_s$ of the colliding nuclei in strong color fields;

Tunneling through the event horizon leads to the thermal spectrum

DK, K.Tuchin,hep-ph/012345;

DK,E.Levin,K.Tuchin,hep-ph/0602063

# Hard probes of QCD matter




At short distances,
the strong force becomes weak -

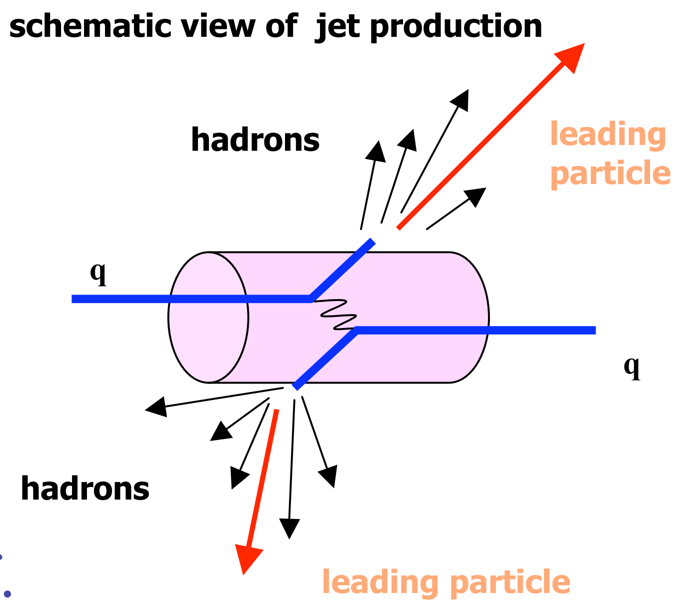
one can access the "asymptotically free" regime in hard processes

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 $\Lambda$ is determined by the properties of matter:

In hot quark-gluon plasma

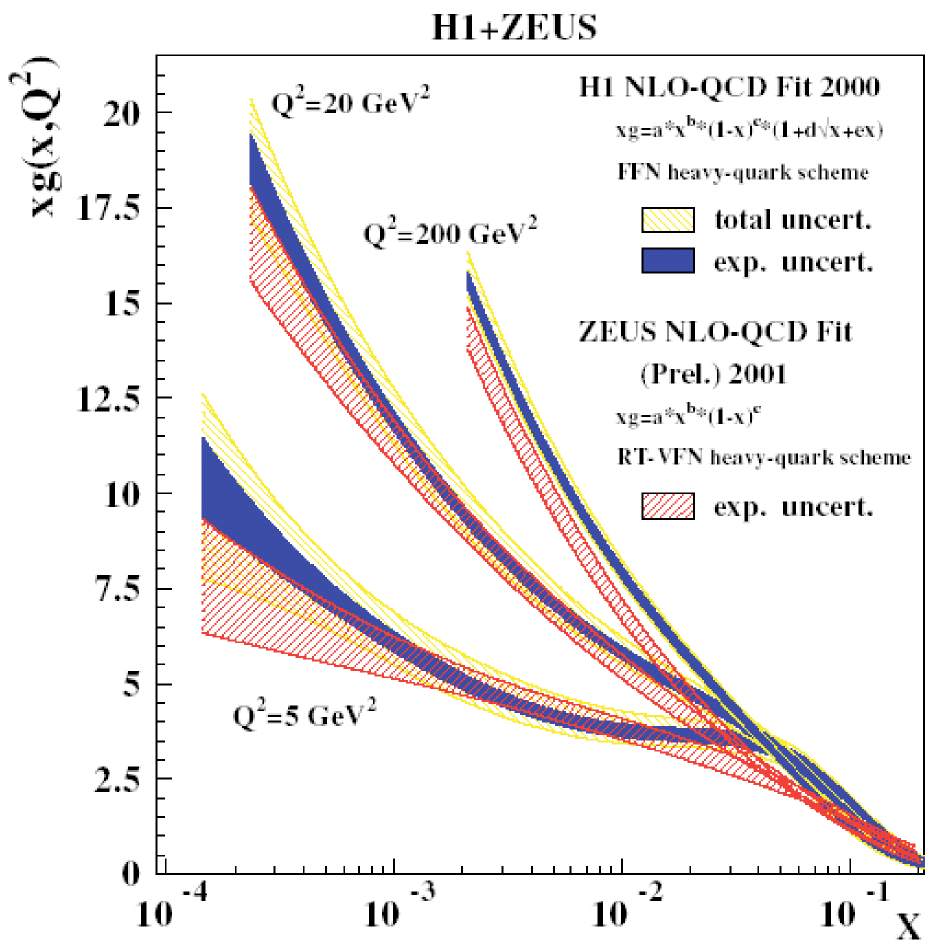
$\Lambda^2 = \hat{q}_{hot} L$ $\quad \hat{q}_{hot}$ - transport coeff.

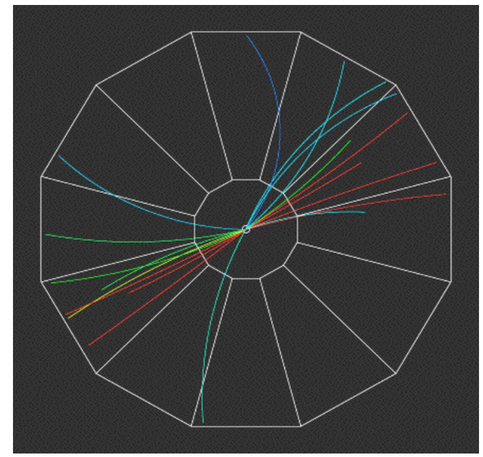
$L$ - size of the system

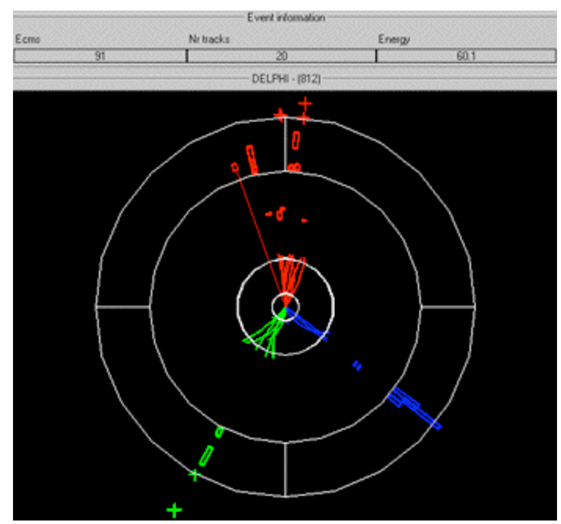
In cold nucleus at small x

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

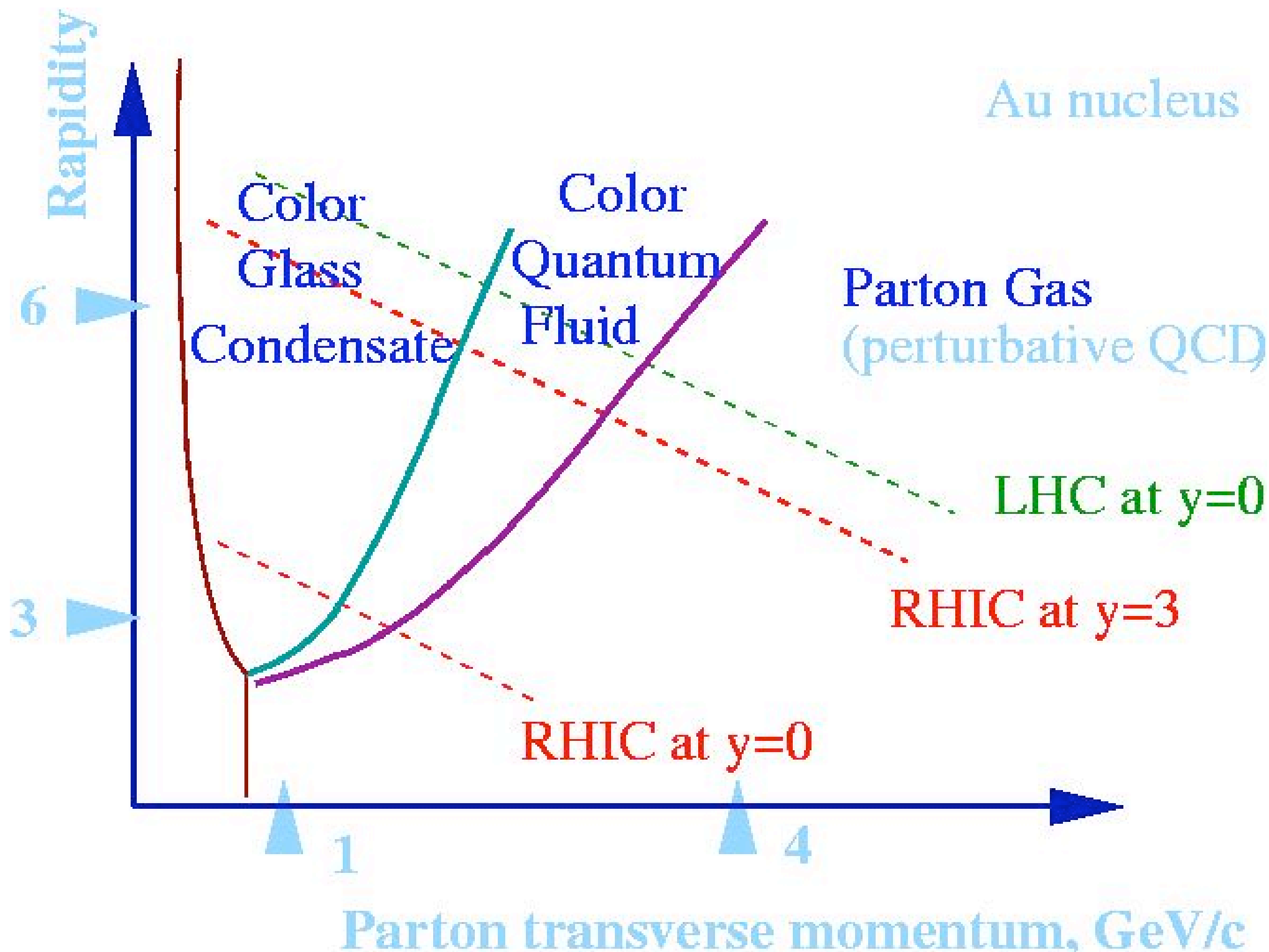
# What are the wave functions of the proton and of the nucleus?



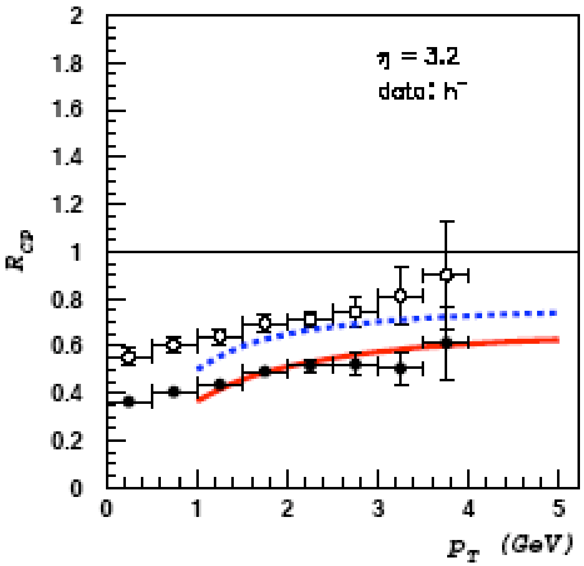


# Phase diagram of high energy QCD

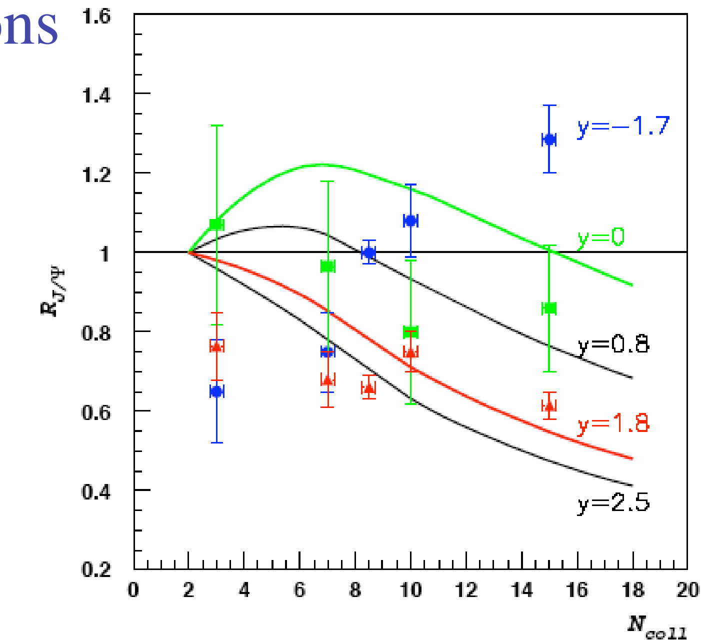


# CGC confronts the data

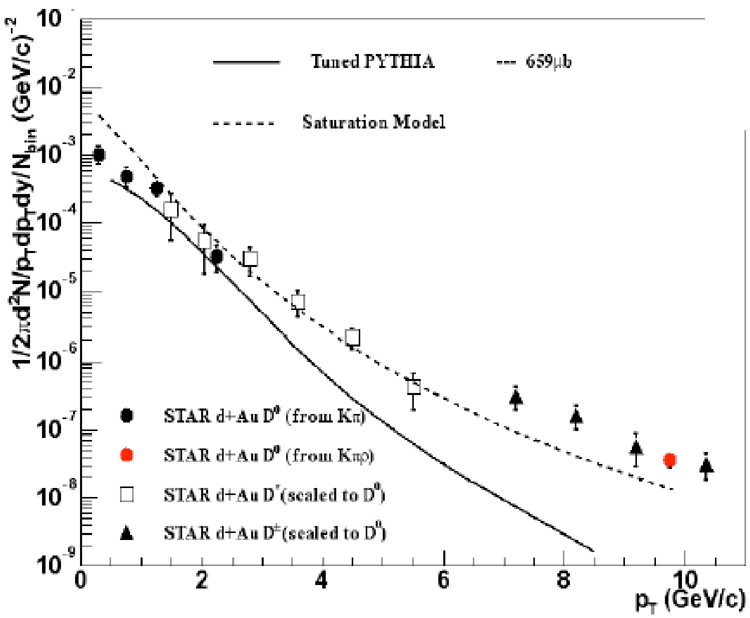
hadrons

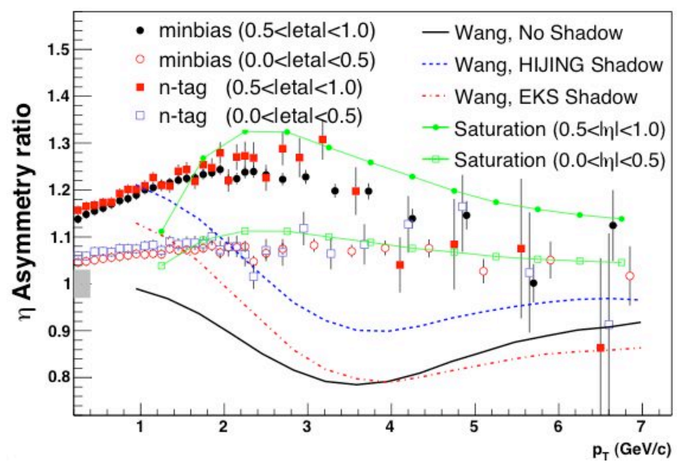



charmonium

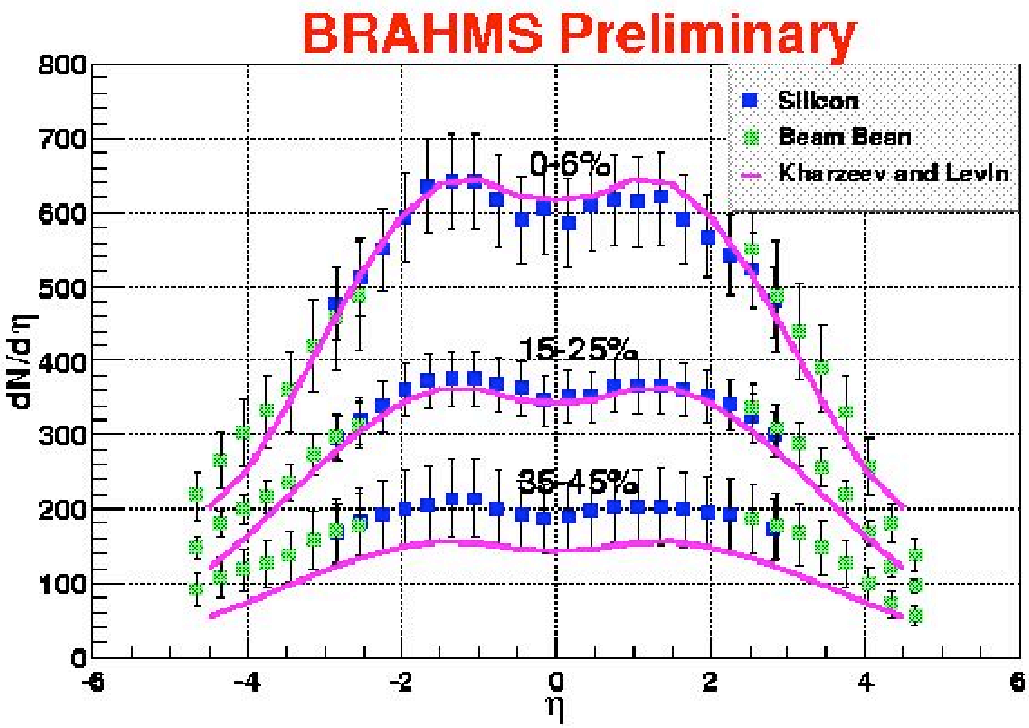


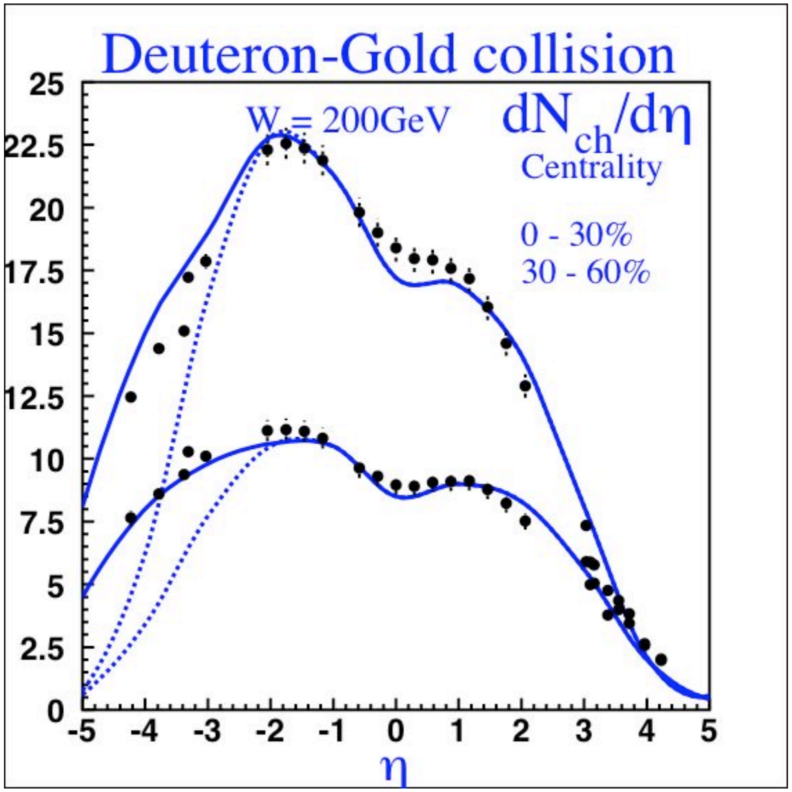

charm



# CGC and hadron multiplicities



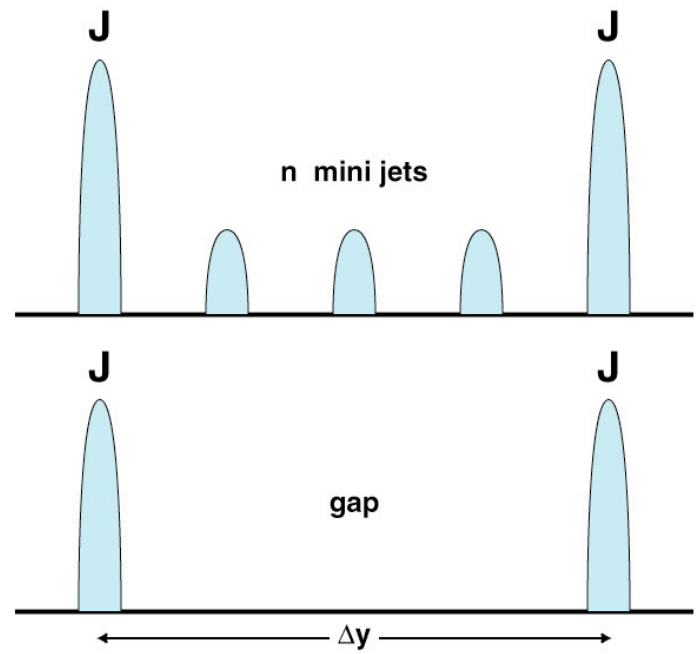



# Are the effects observed at forward rapidity due to parton saturation in the CGC?

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

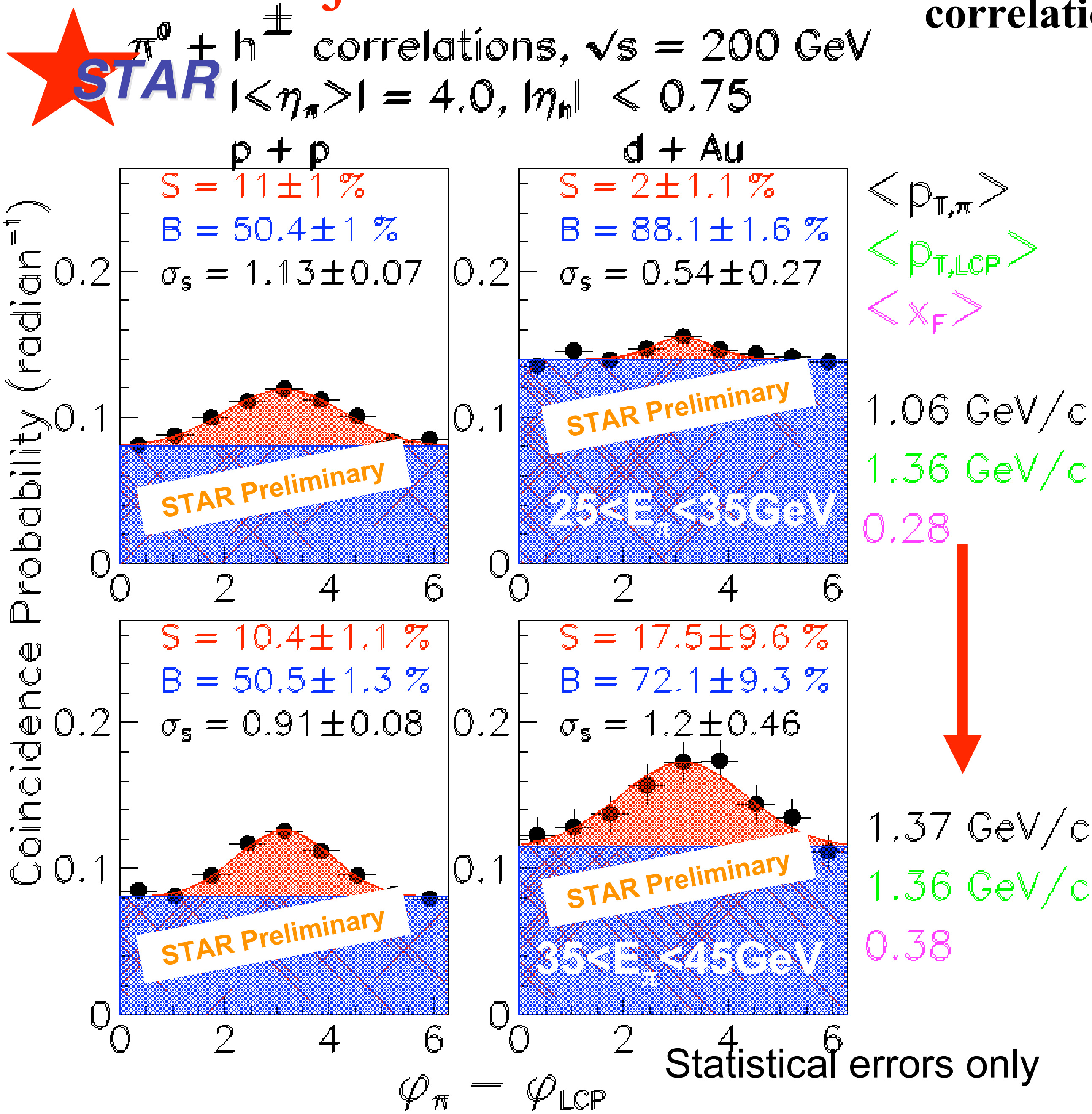
(“Mueller-Navelet jets”)

and to the presence of CGC




Forward measurements at RHIC-II

# Monojets in dA are back

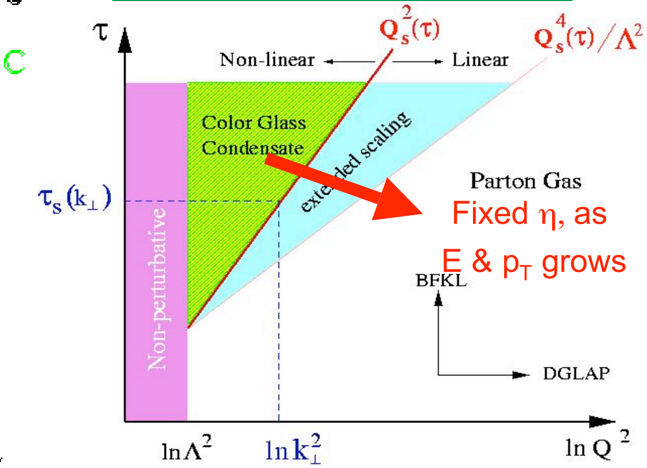



**Large rapidity gap $\pi^0$+$h^{\pm}$ correlation data…**

- **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) %**

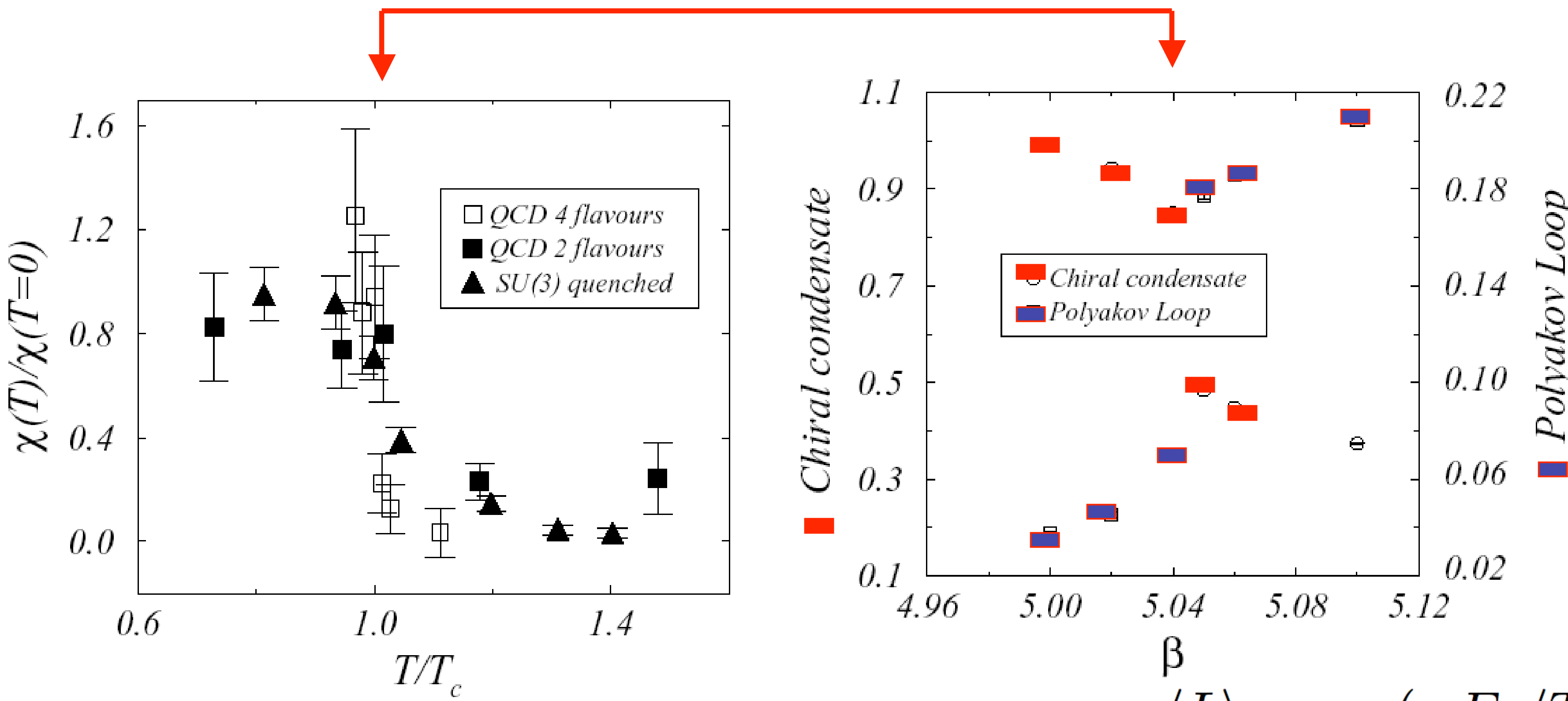
**Consistent with CGC picture**




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

**as expected by HIJING**

# Exploratory studies: can P and CP be broken in the deconfined phase of QCD ?

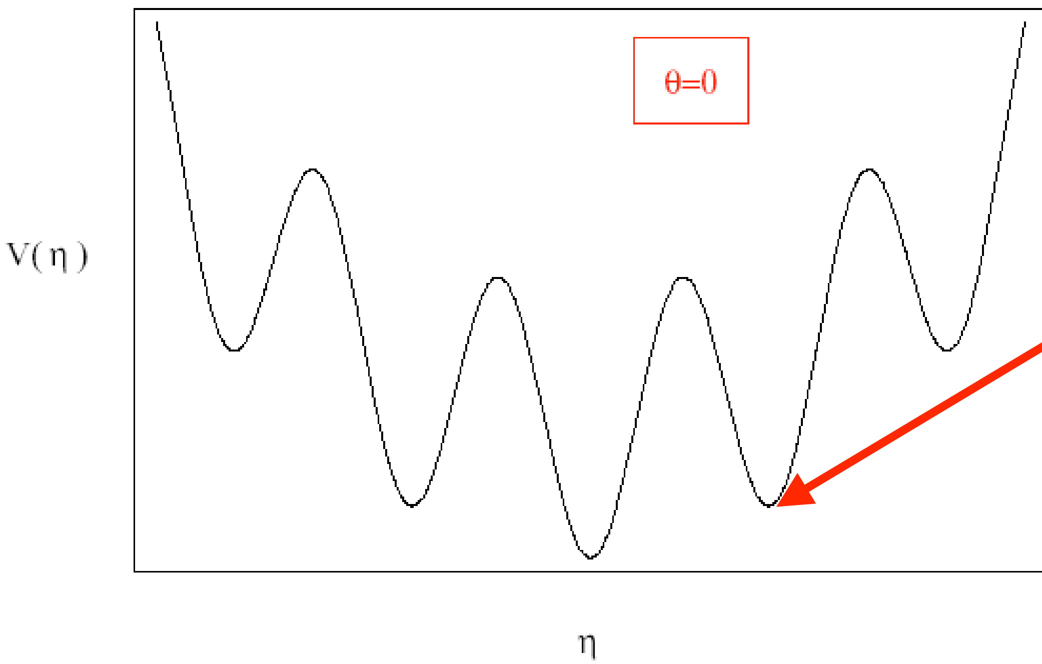



$$\langle L \rangle \sim exp(-E_q/T)$$

Rapid decrease of susceptibility at the deconfinement phase transition

B.Alles, M.D'Elia and A.DiGiacomo, hep-lat/0004020

# θ–vacuum in the presence of light quarks: chiral description



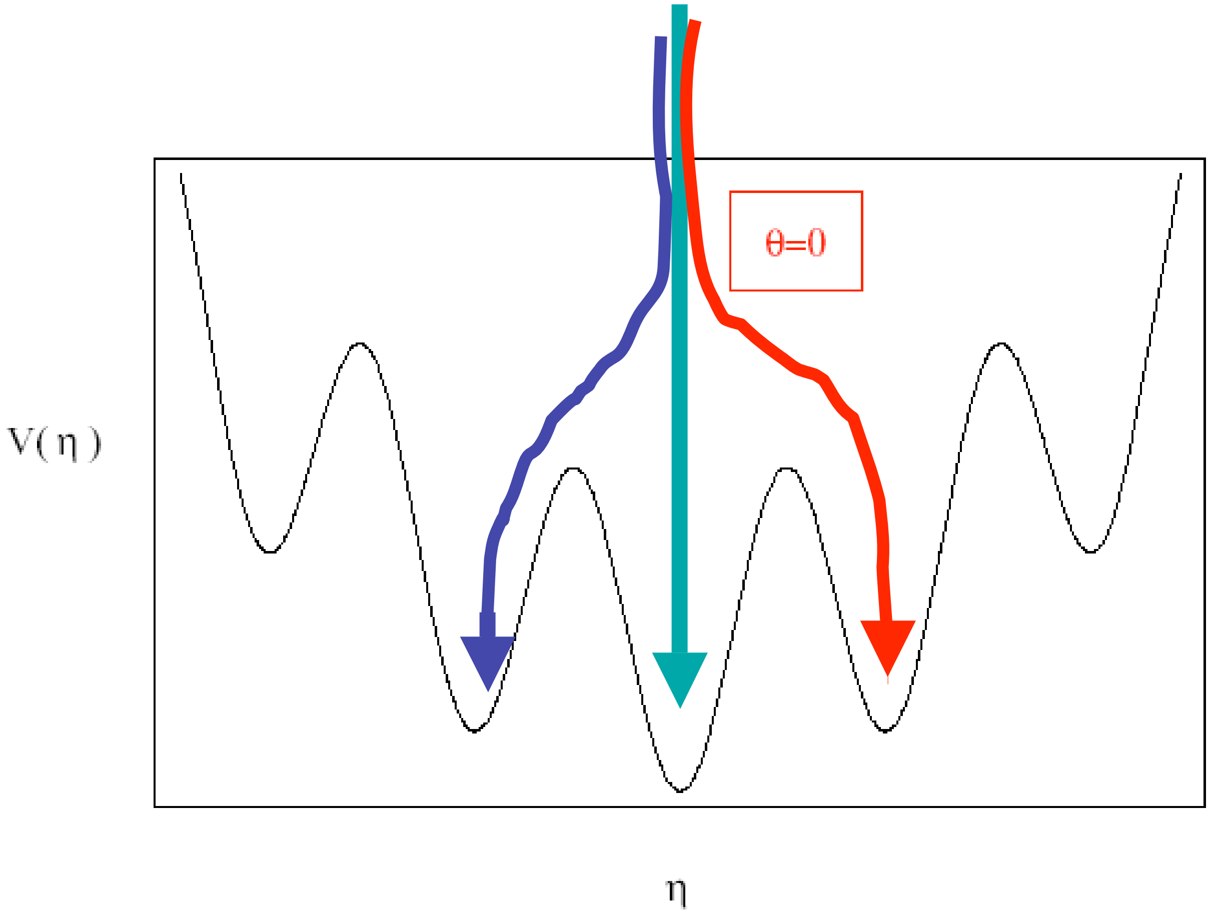

Decrease of $\chi$ results in the appearance of metastable CP-odd domains

$$\mathcal{V} = -\sum_{i=u,d,s} m_i \Sigma \cos\frac{\phi_i}{f_\pi} + \frac{\chi}{2}\left(\theta - \sum_{i=u,d,s} \phi_i / f_\pi\right)^2$$

v.e.v. of the η field is equivalent to non-zero θ

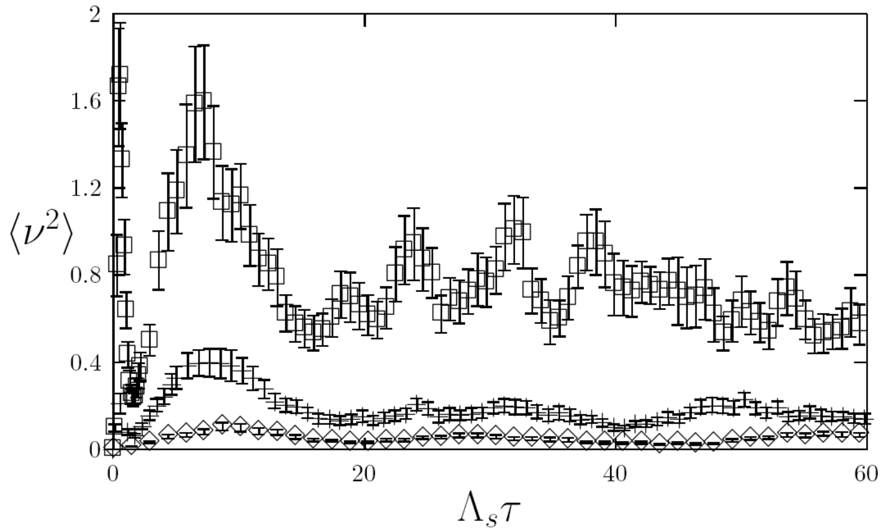
DK, R.Pisarski, M.Tytgat ‘98

# CP-odd domains in heavy ion collisions: how to look for them?

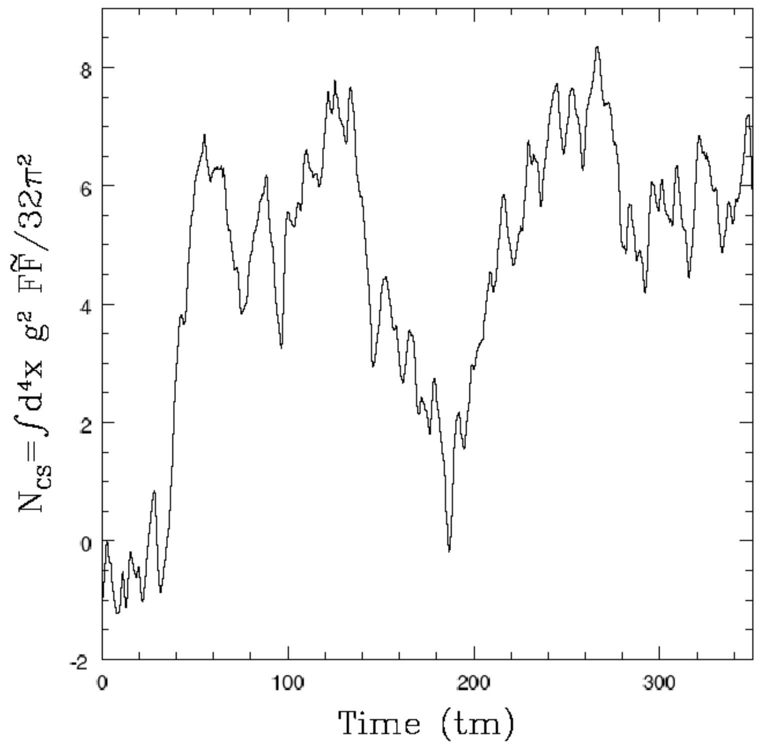



v.e.v. of the η field is equivalent to non-zero θ

# Diffusion of Chern-Simons number in QCD: real time lattice simulations

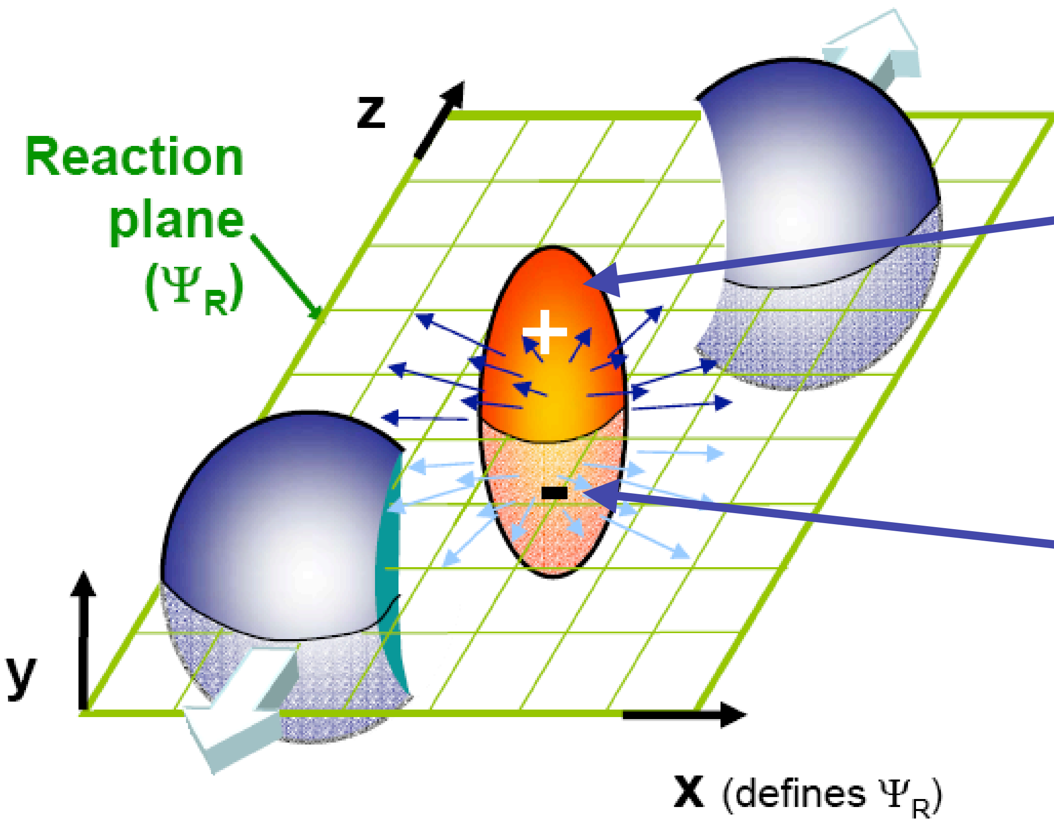



DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002




P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

# Charge asymmetry w.r.t. reaction plane as a signature of strong CP violation



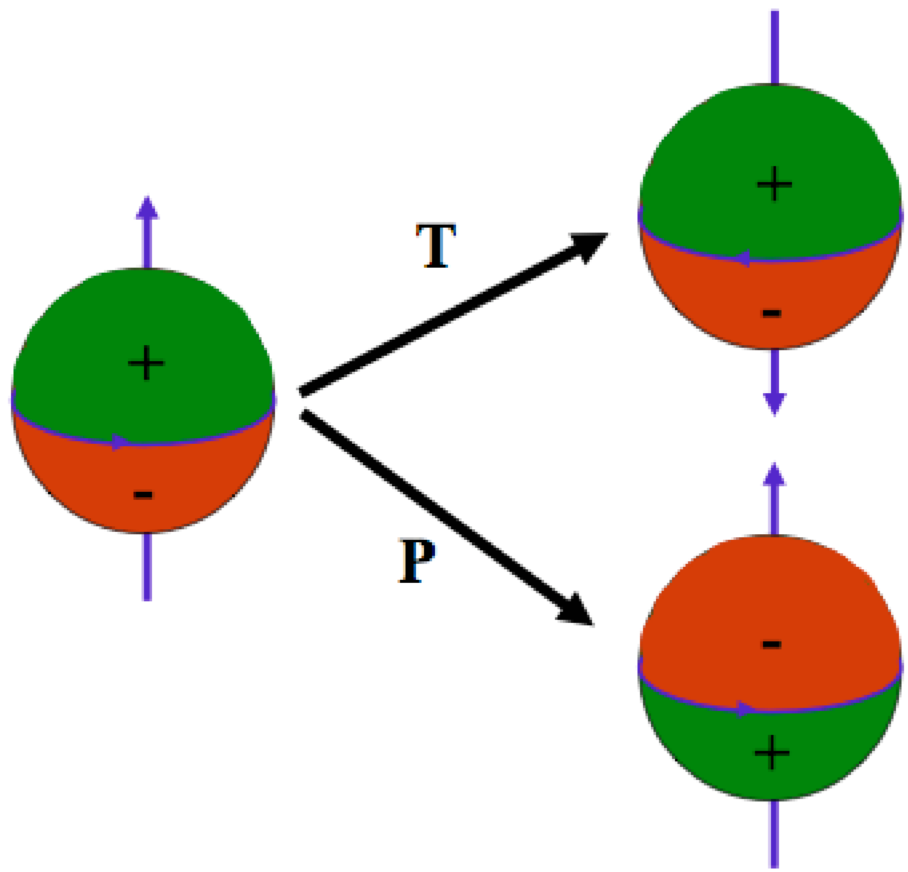

excess of positive charge

excess of negative charge

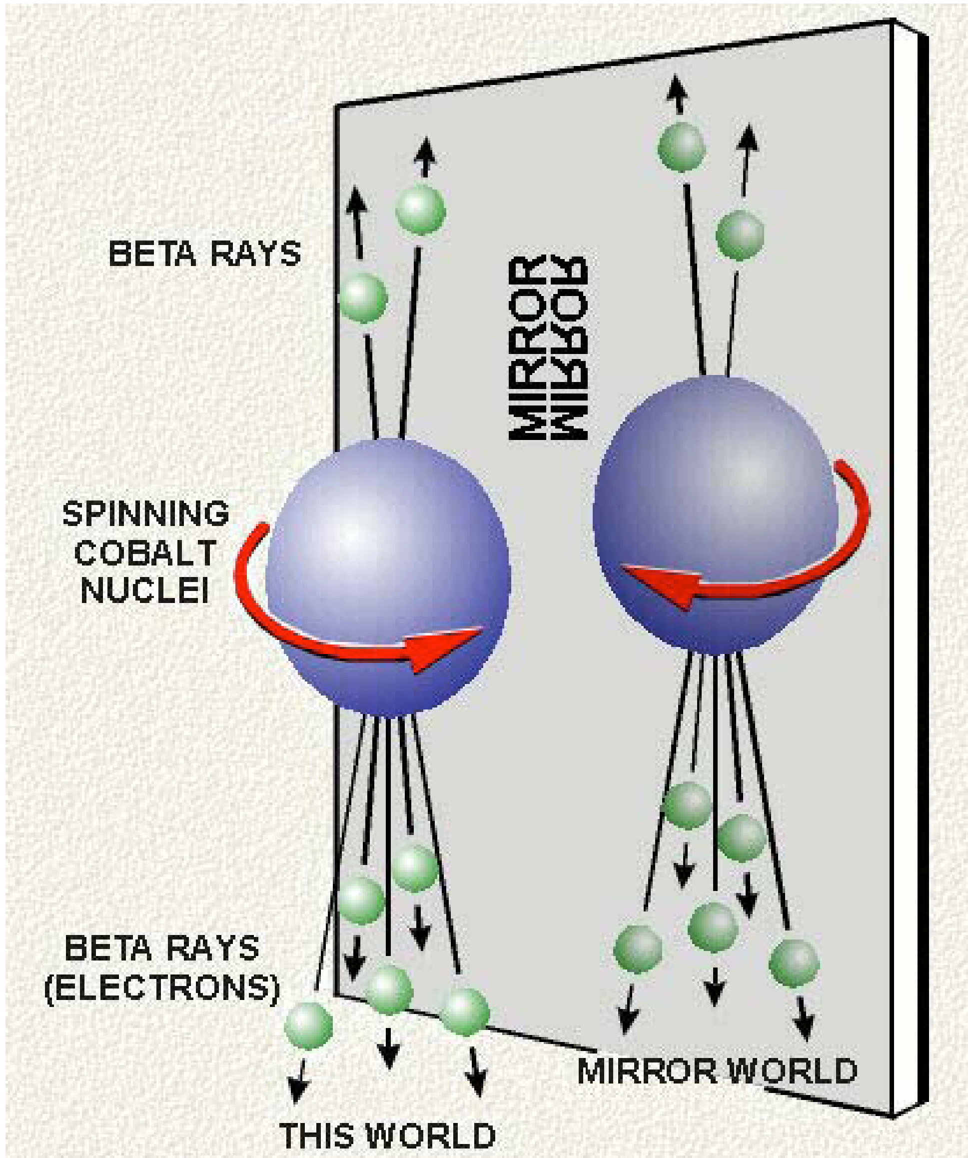
Electric dipole moment of QCD matter!

DK, hep-ph/0406125

Charge asymmetry w. r.t. reaction plane violates T, P, and (by CPT theorem) CP:



# Analogy to P violation in weak interactions



# Strong CP violation at high T ?

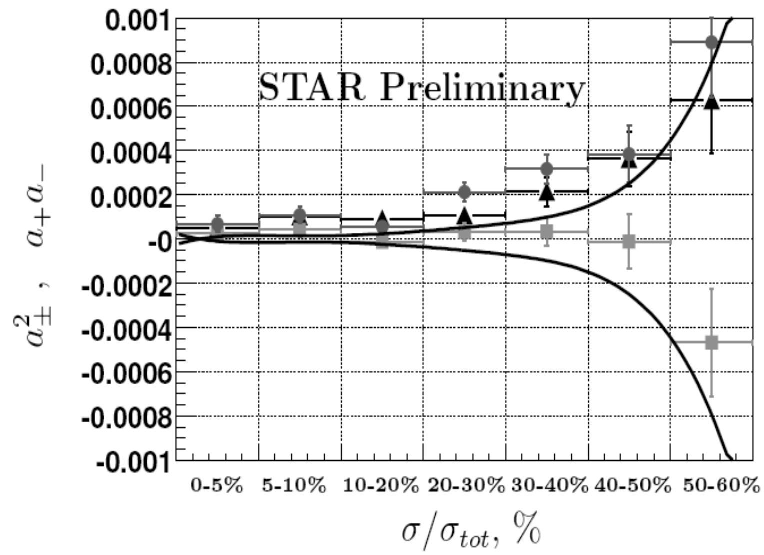
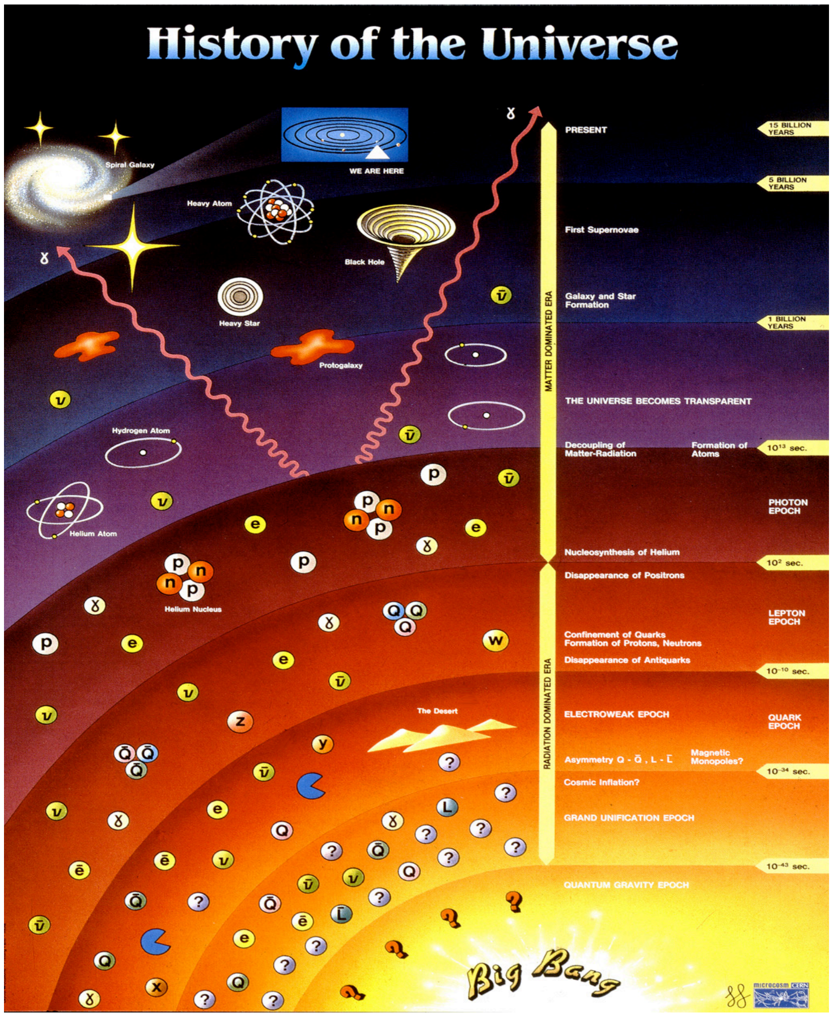


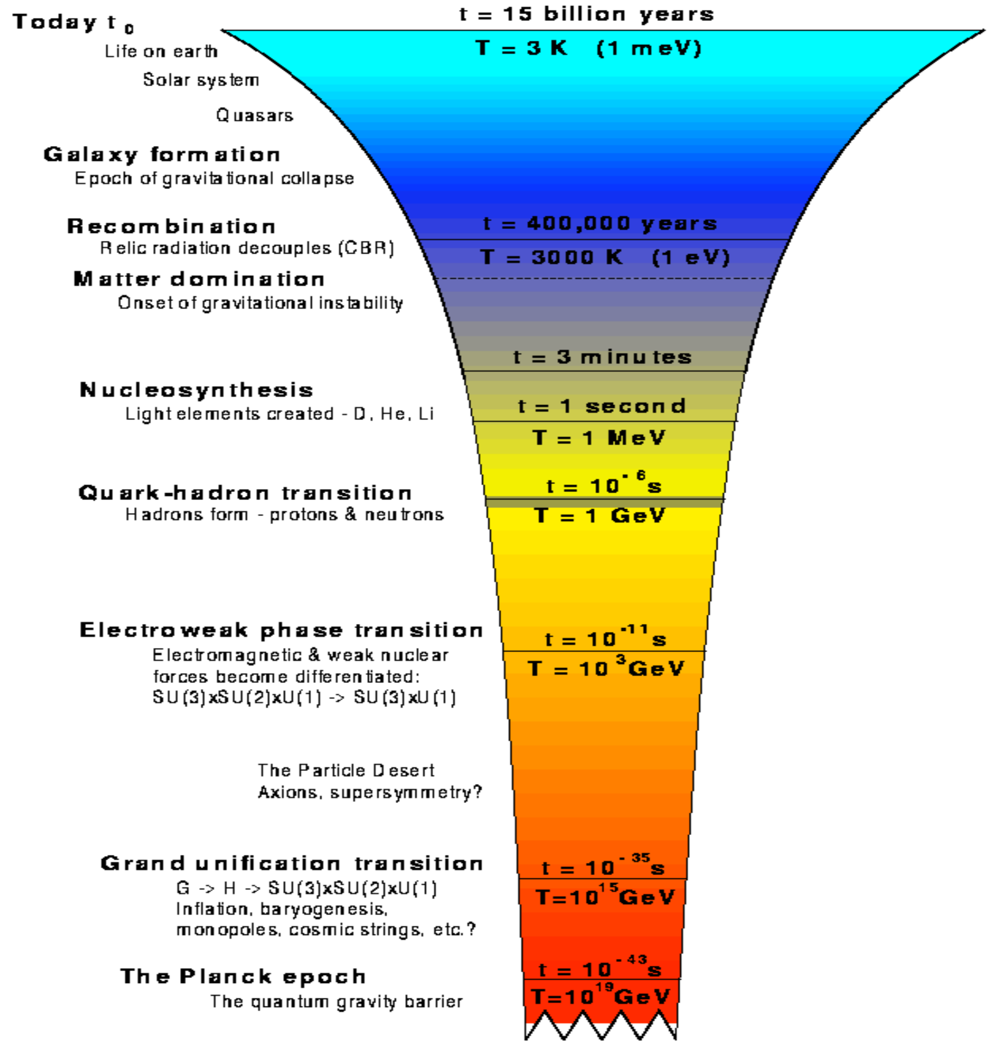

Figure 2: Charged particle asymmetry parameters as a a function of standard STAR centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are $a_+^2$, triangles are $a_-^2$ and squares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

STAR Coll., nucl-ex/0510069; October 25, 2005

Need to analyze the systematics, improve statistics

# What are the implications for the Early Universe?

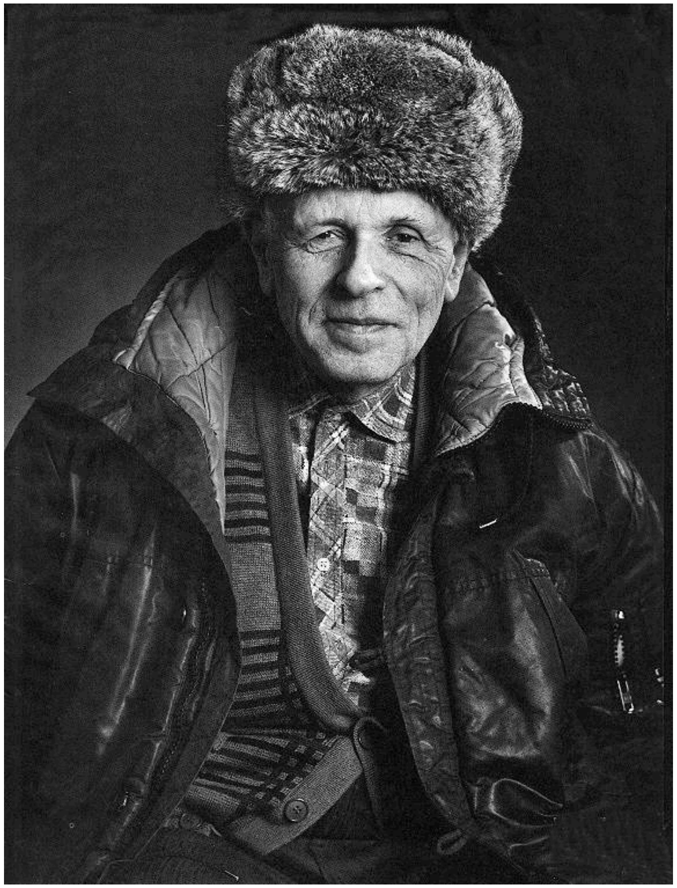


# What is the origin of the matter-antimatter asymmetry in the Universe?

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

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



# Baryon asymmetry in the Universe and strong CP violation

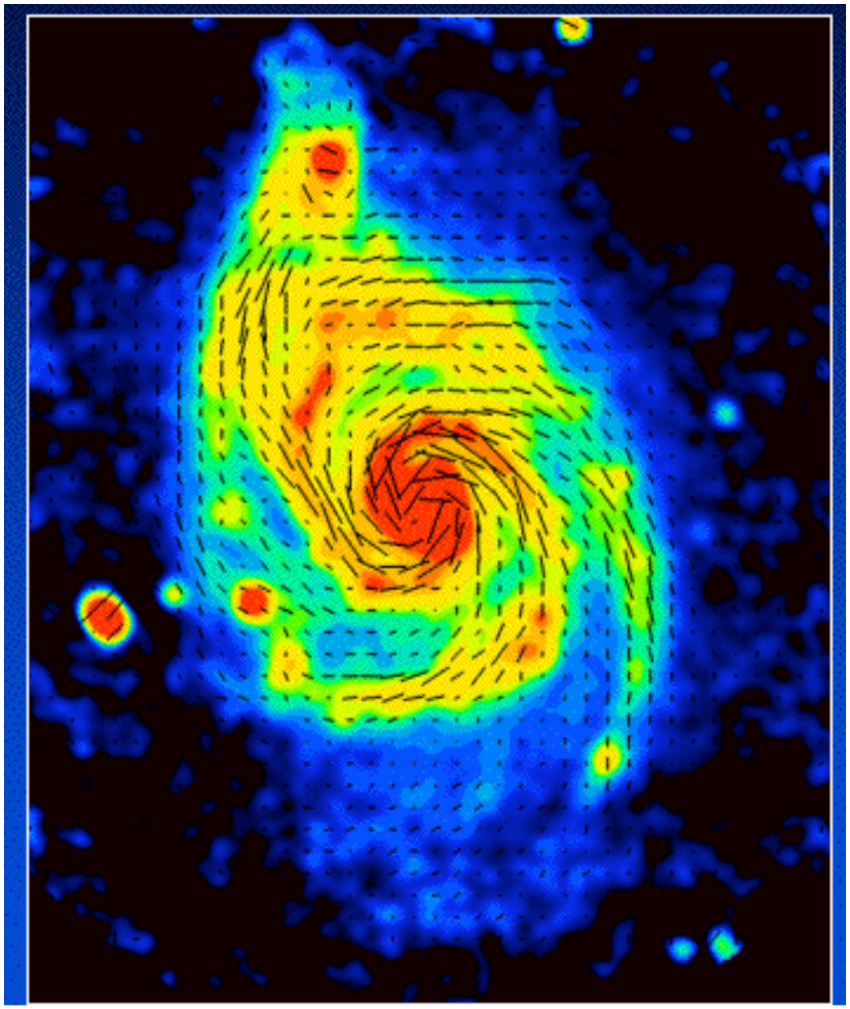
1. Generation of Chern-Simons number at the QCD phase transition is analogous to baryon number generation in the electroweak phase transition

e.g. V.Kuzmin, V.Rubakov and M.Shaposhnikov, Phys.Lett.B155(1985)36

2. Strong CP violation can lead to the separation of matter and antimatter in the Universe at the QCD phase transition

e.g. R.Brandenberger, I.Halperin and A.Zhitnitsky, hep-ph/9903318

# What is the origin of cosmic magnetic fields?



Domain walls in the QCD vacuum?

Through the quark loops

$$\vec{E}^a \cdot \vec{B}^a$$

couples to

$$\vec{E} \cdot \vec{B}$$

May create primordial field; how to make it ordered over galactic scales?

# Summary

1. RHIC program aims at understanding the phase structure of QCD, the bulk non-equilibrium dynamics of gauge theories, and the spin structure of the nucleon (not covered in this talk)

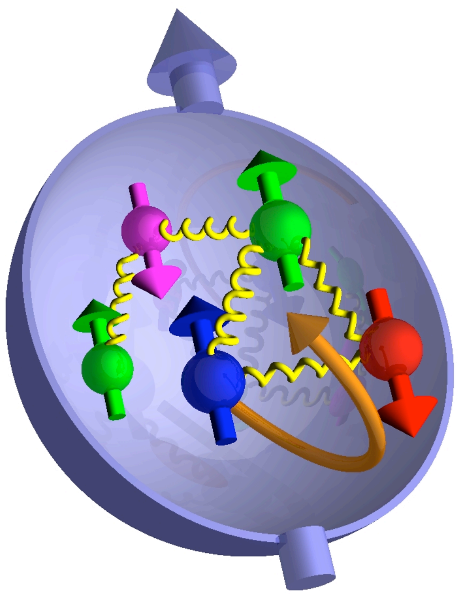
2. A very significant experimental and theoretical progress has been made in the first five years of RHIC operation, and much more is expected

3. RHIC physics appears very rich and is tied to a number of different fields: condensed matter, astrophysics, cosmology, quantum optics, …

# Additional slides

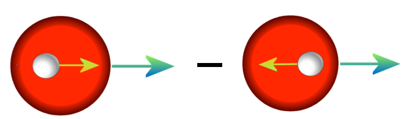
## Exciting program with polarized protons underway at RHIC:

# 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**

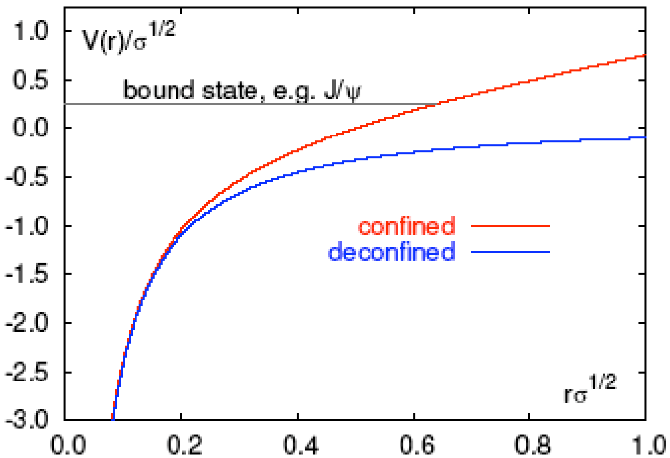
W. Vogelsang

# Heavy quarkonium as a probe

The Matsui-Satz argument:

- deconfinement $\Rightarrow$ screening

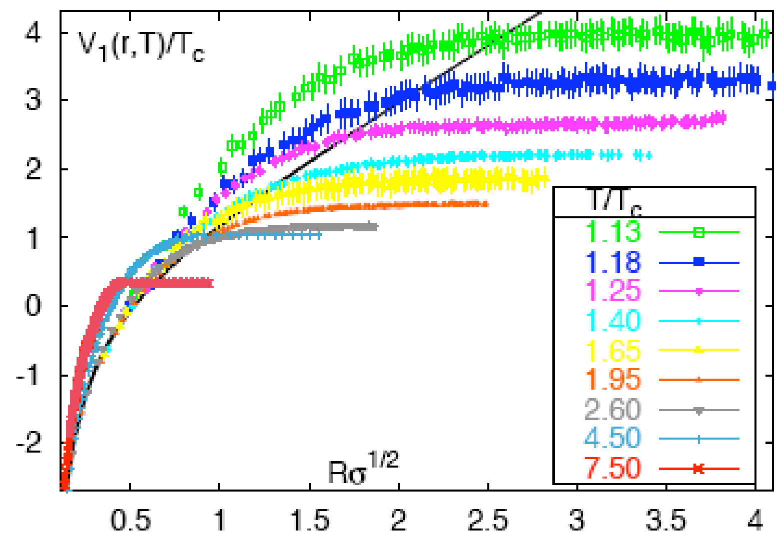
  $\Rightarrow$ no heavy quark bound states in a QGP



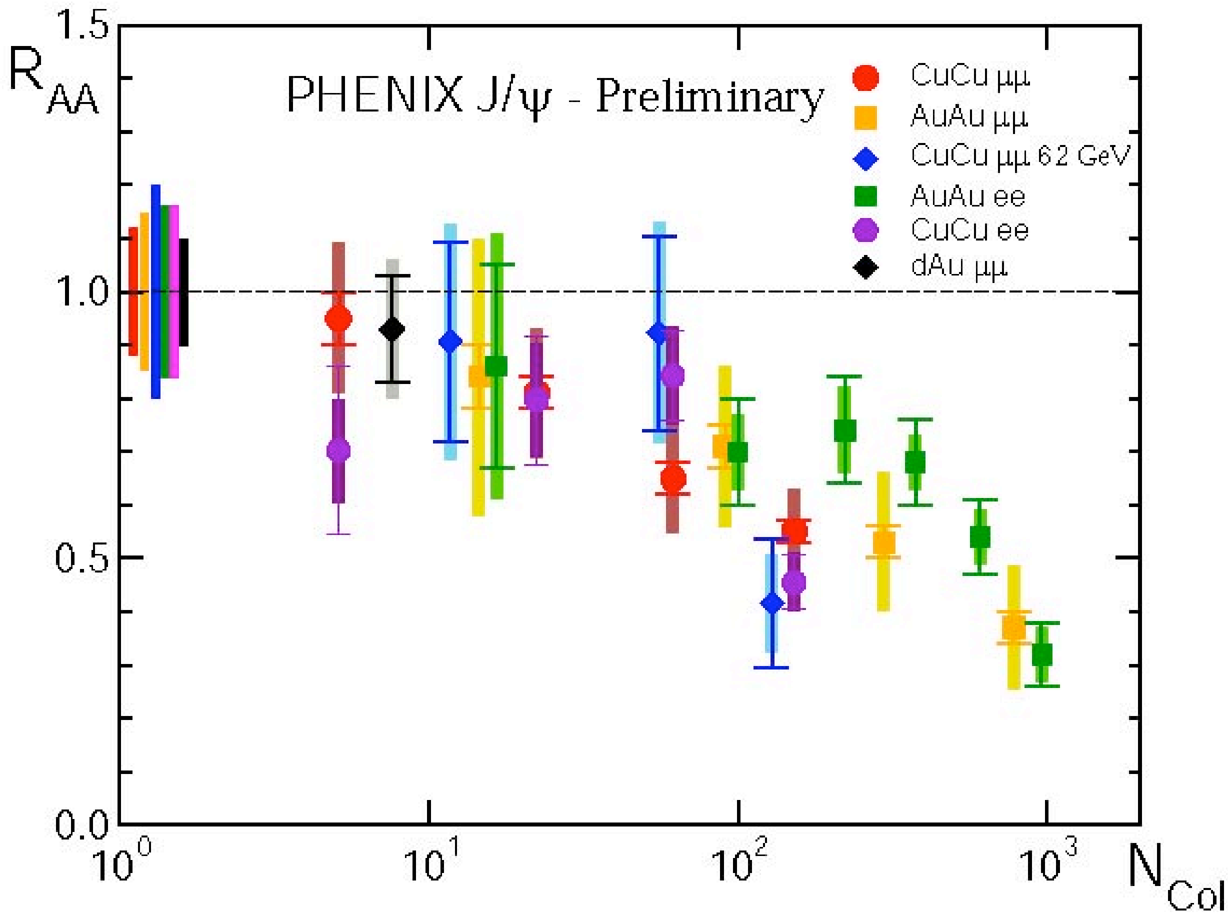

$V_{\bar{q}q}(r,T) \to \infty$ confinement

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

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

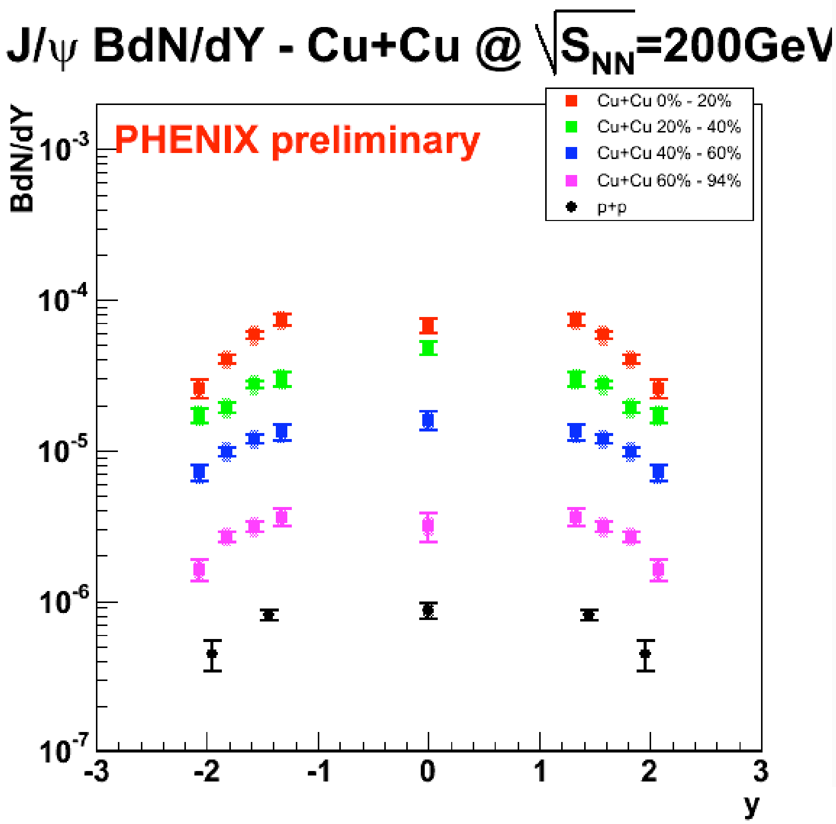


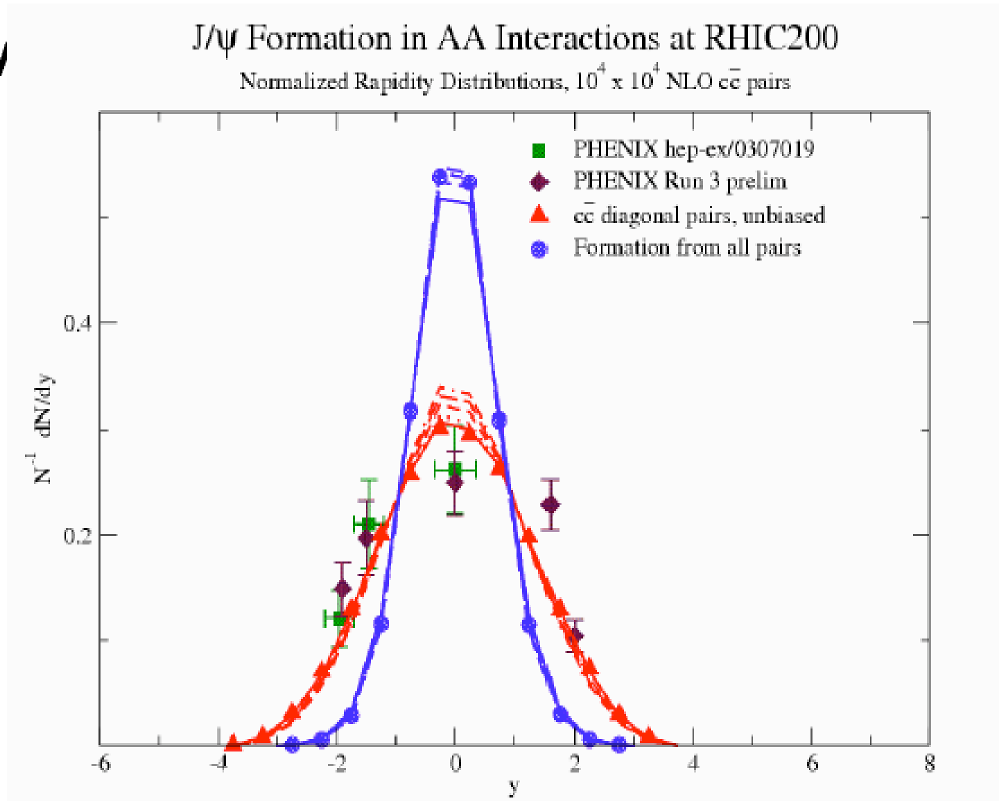
# J/ψ suppression at RHIC




"same as at SPS"?

# Recombination of charm quarks?

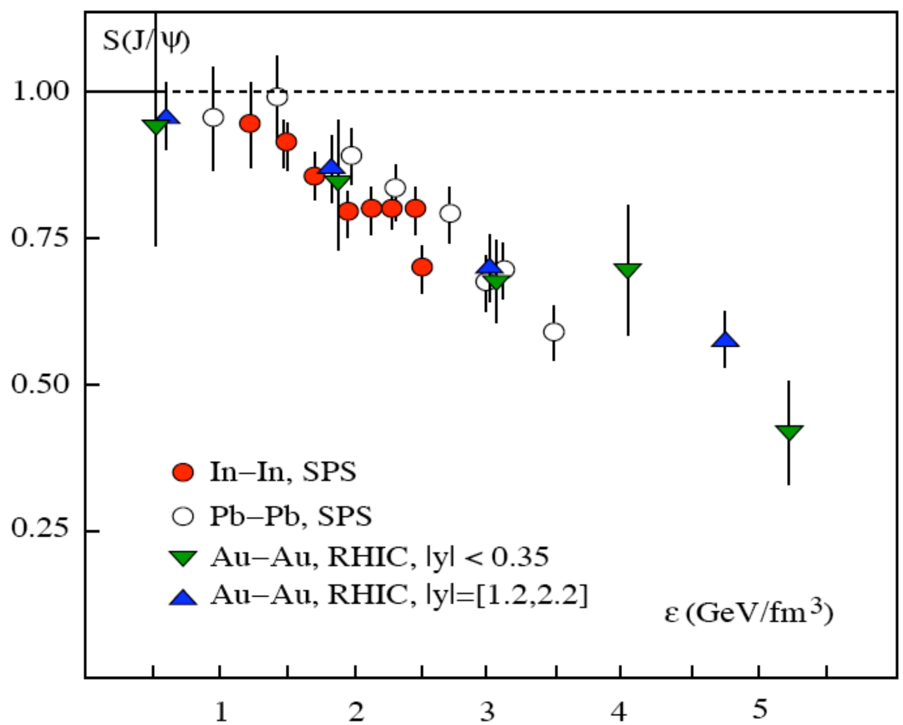


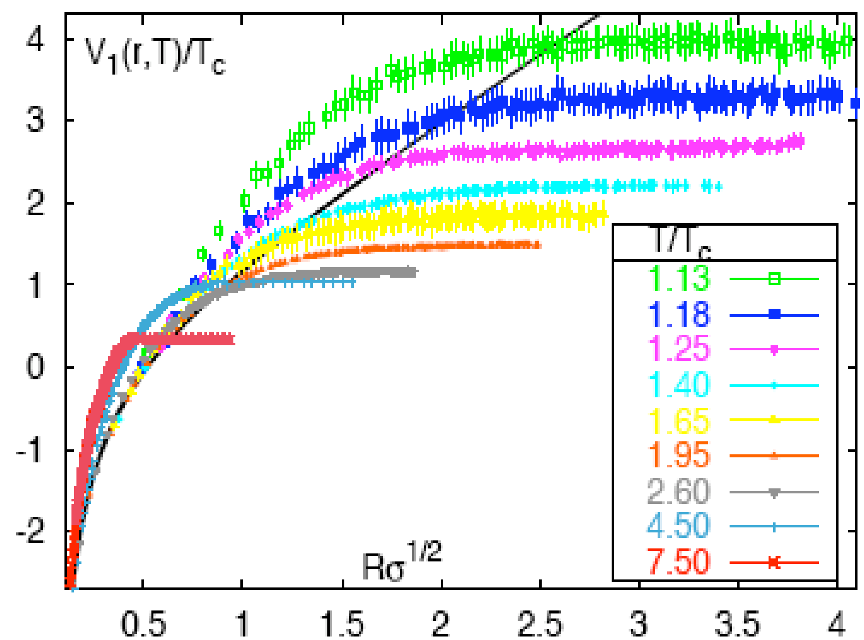




Recombination narrows the rapidity distribution; is this seen?

Are high p_t charmonia suppressed stronger than open charm?

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

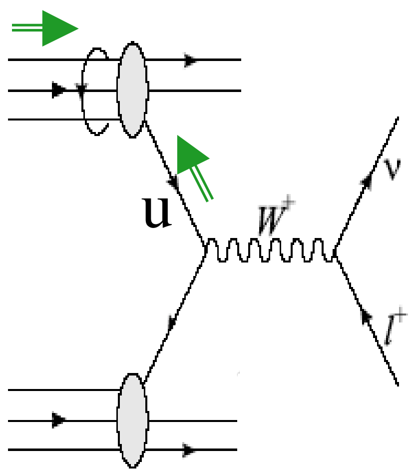



Crucial tests at RHIC-II:
excited charmonia, Y states

at RHIC:

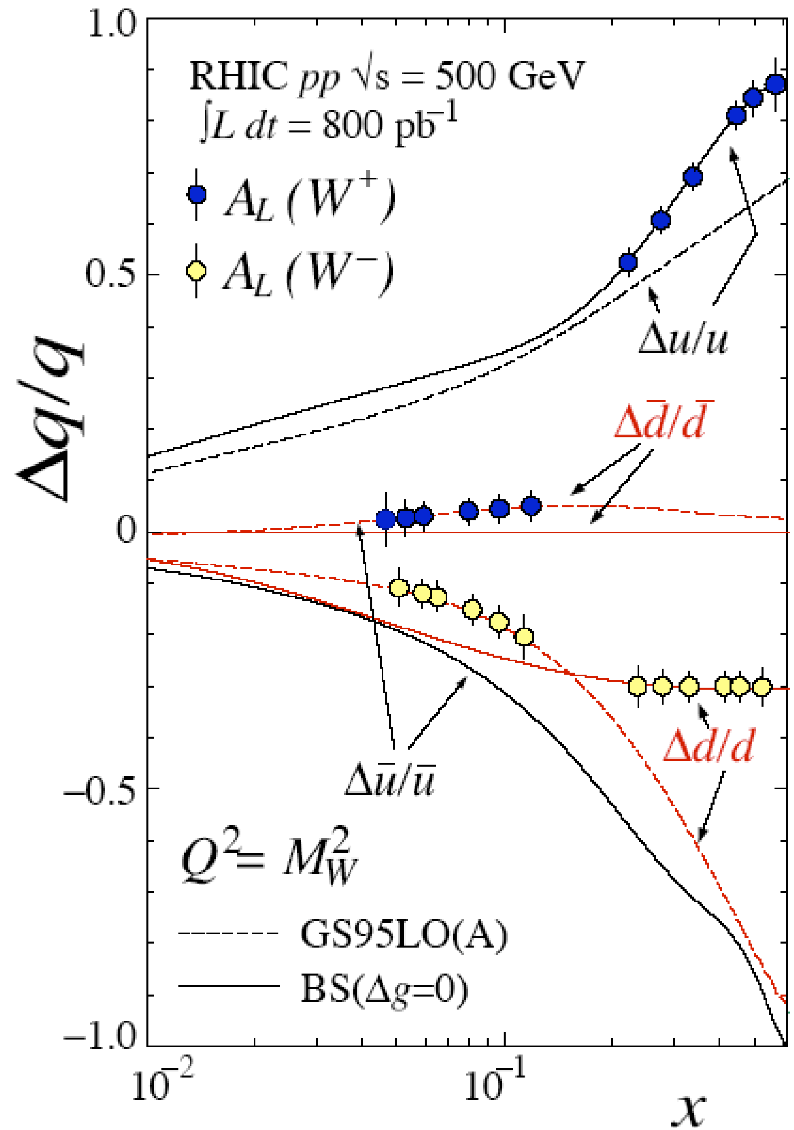
W boson production




unpol.

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

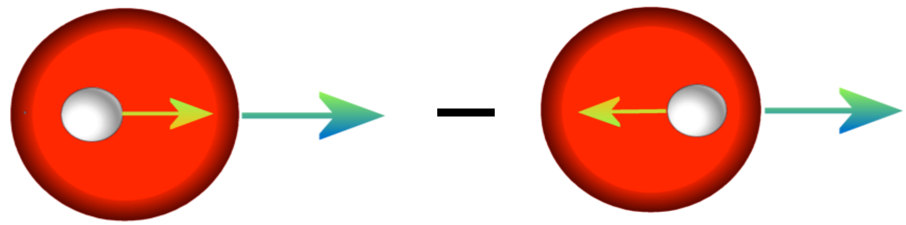
$$A_L^{W^+} \approx \frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}$$




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

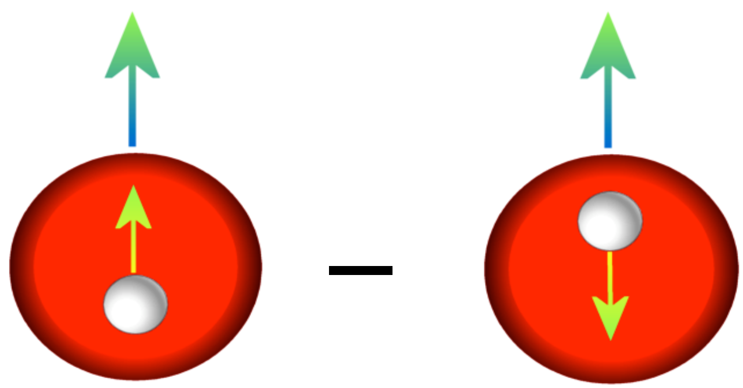
**Helicity :**

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



**Transversity :**

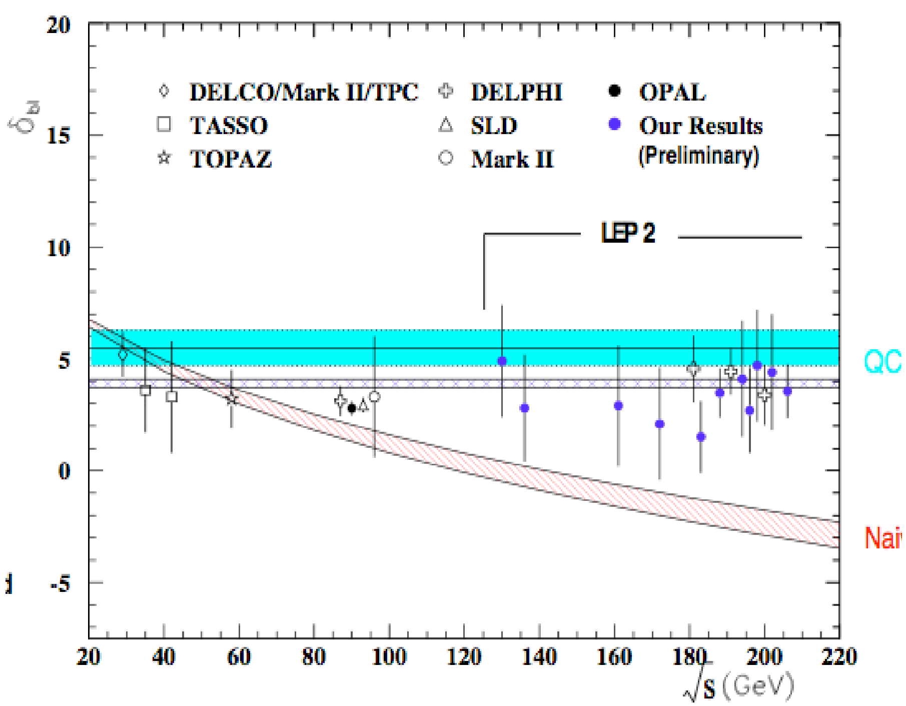
$$\delta \mathbf{q(x)} =$$



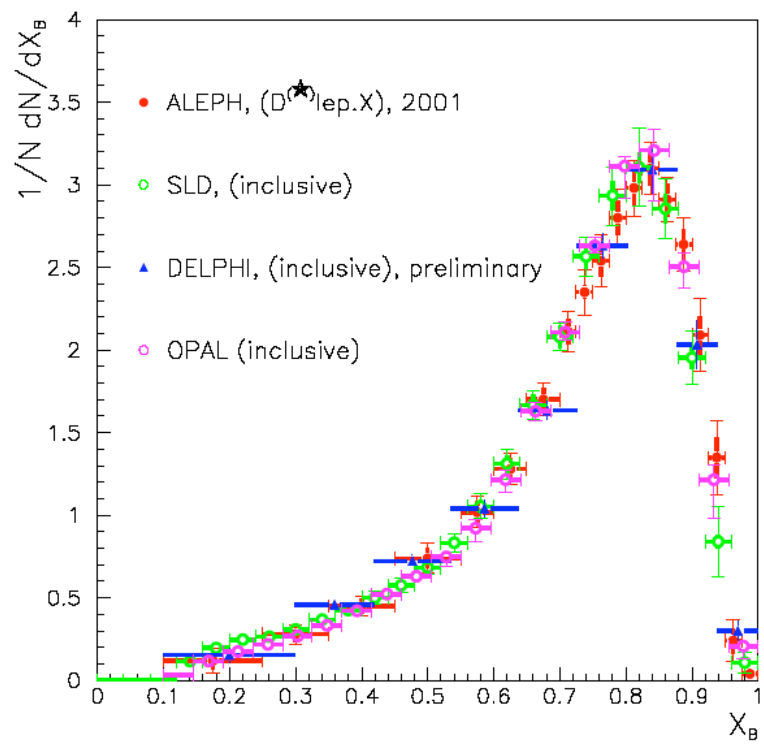
Ralston,Soper; Jaffe,Ji; …

* **difference probes relativistic / dynamical effects**

# Heavy quarks fragment differently



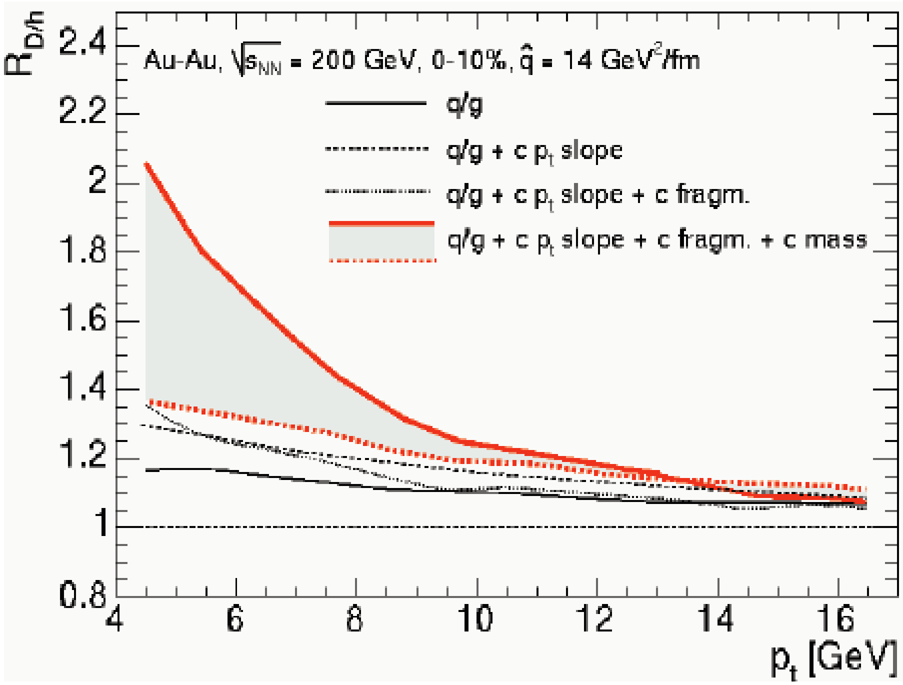

OPAL Collaboration




Heavy quarks produce a larger number of particles

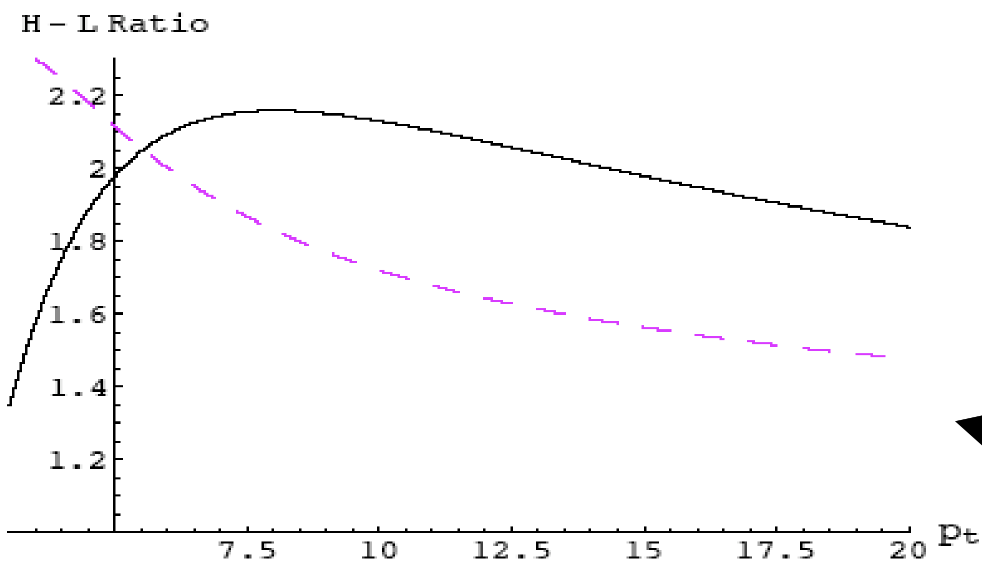
and carry a larger fraction of jet momentum

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




Yu.L.Dokshitzer and DK,
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