The search for the Quark-Gluon Plasma
Theoretical and experimental status

Galileo Galilei Institute
Inaugural Conference

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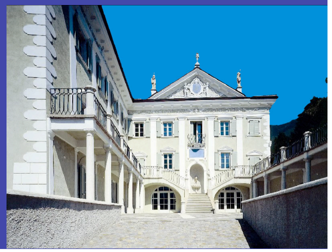


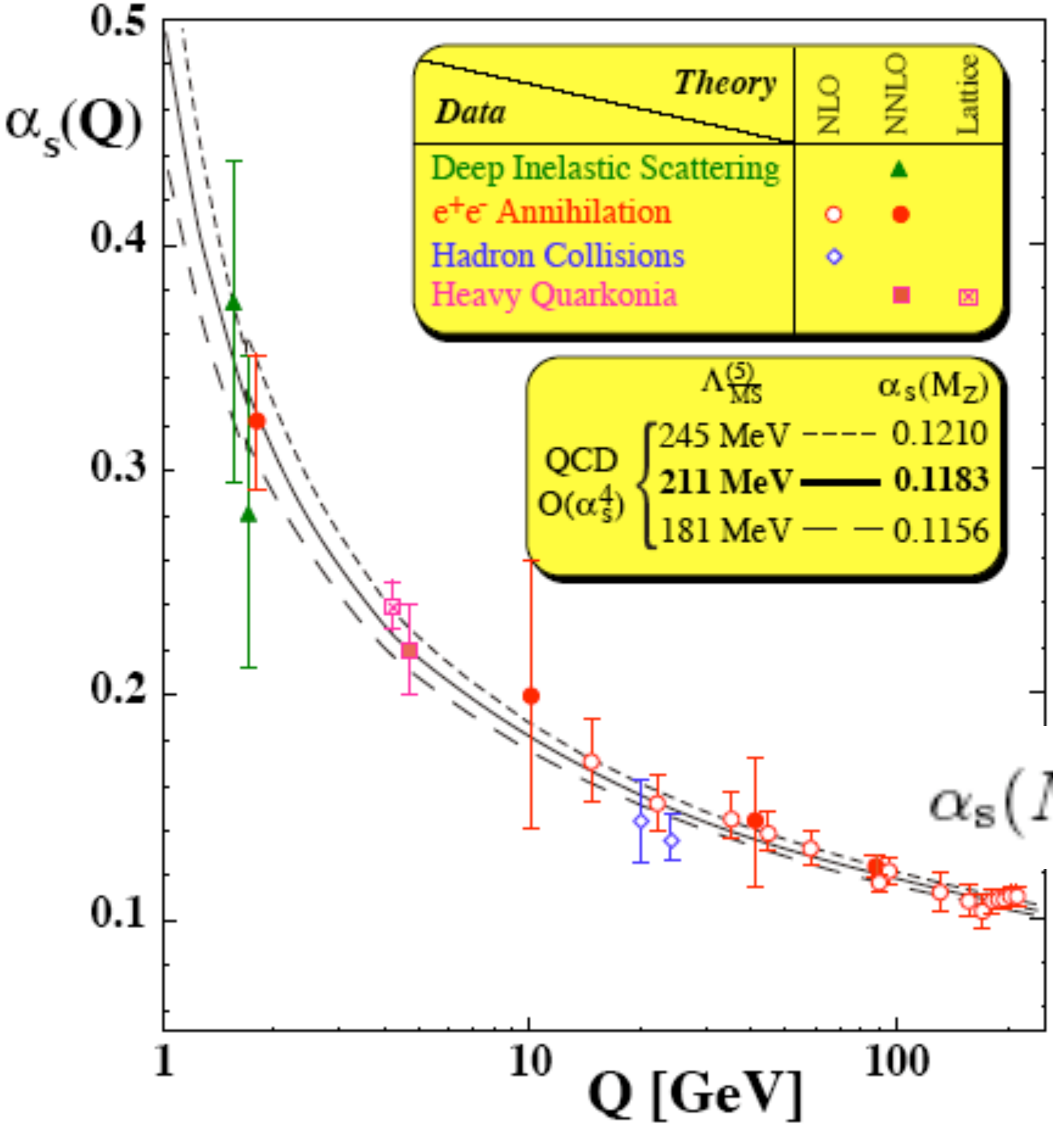
Fundamental questions

- What is the form of matter at « extreme » temperature or density?
- What is the wave function of a hadron, a nucleus, at asymptotically high energy?

SIMPLICITY emerges in extreme (asymptotic) situations

At high temperature
and/or high density
matter is « simple »

QCD Interactions Weaken at High Energy

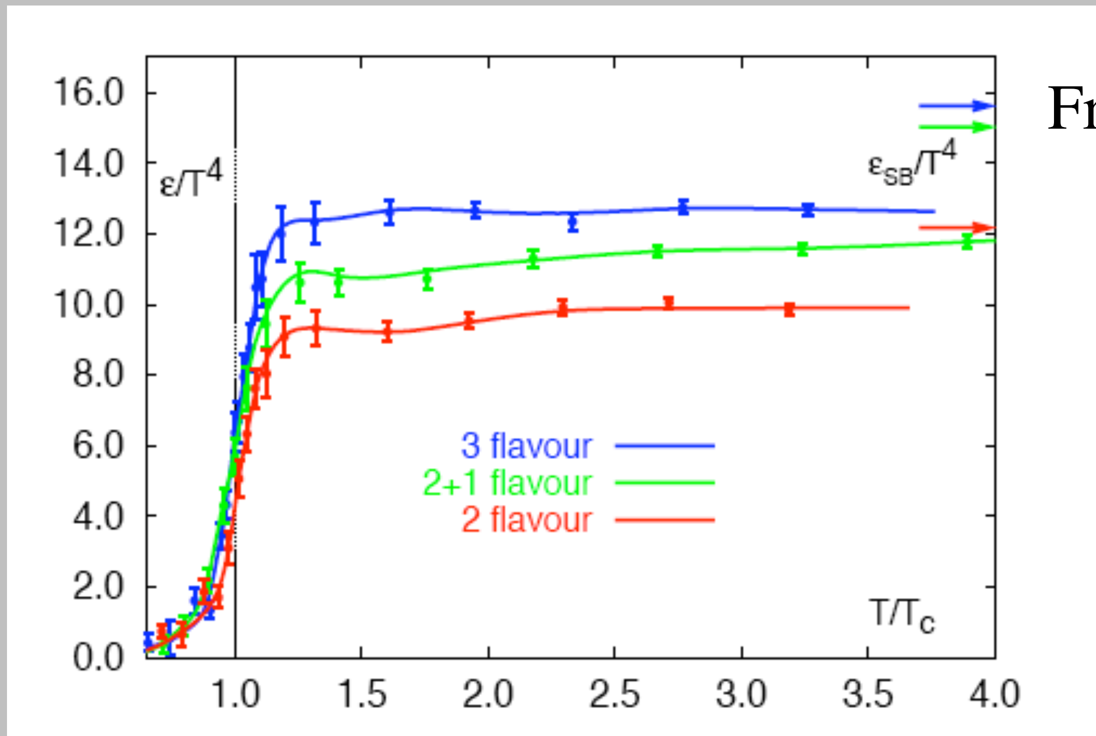


$$\alpha_s(M_Z) = 0.1183 \pm 0.0027$$

(S. Bethke, hep-ex/0211012)

The quark-gluon plasma

Energy density



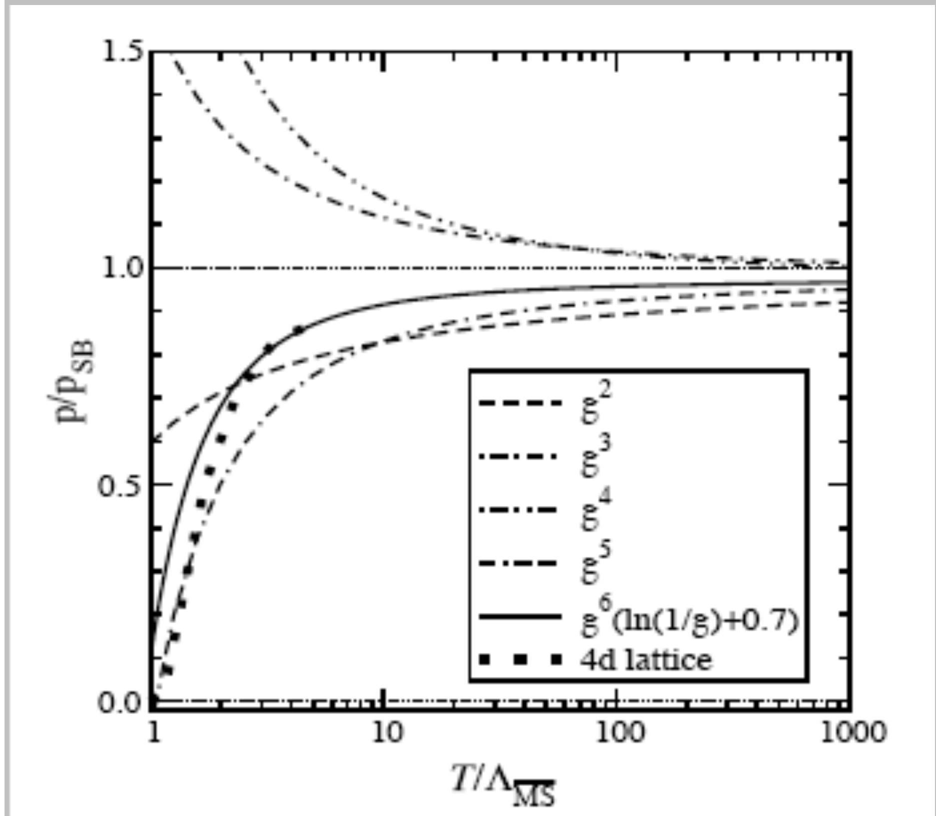
Free gas limit

Temperature

(from F. Karsch, hep-lat/0106019)

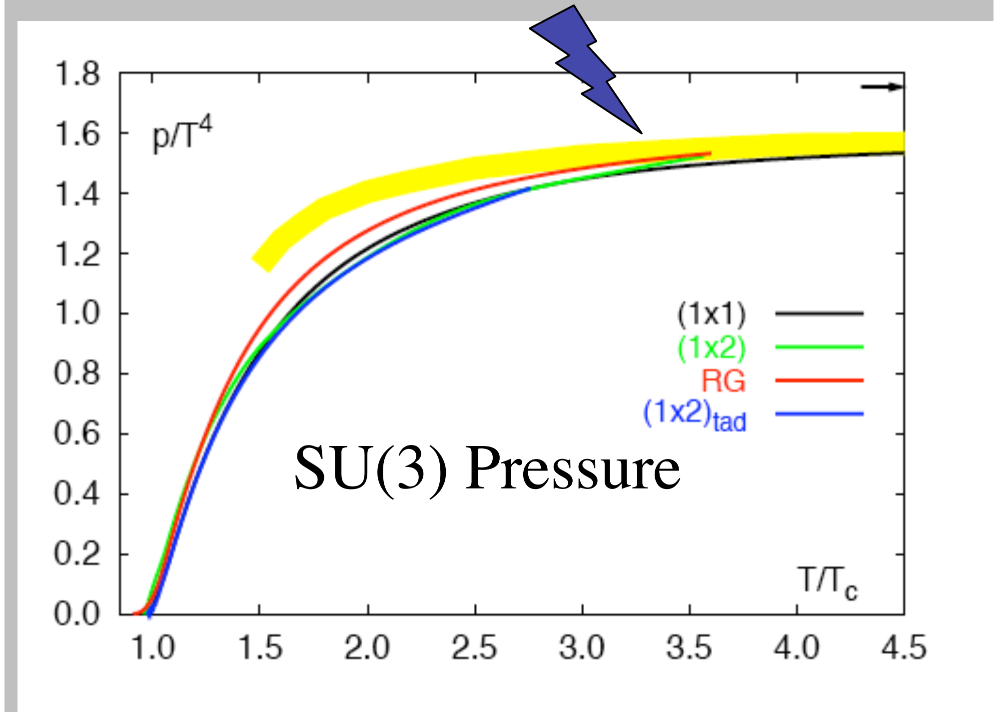
Weak coupling calculations provide adequate description Of the thermodynamics at high temperature $(T \geq 3T_c)$

Dimensional reduction



(from F. Kajantie et al, PRL86, PRD67)

Weakly interacting quasiparticles

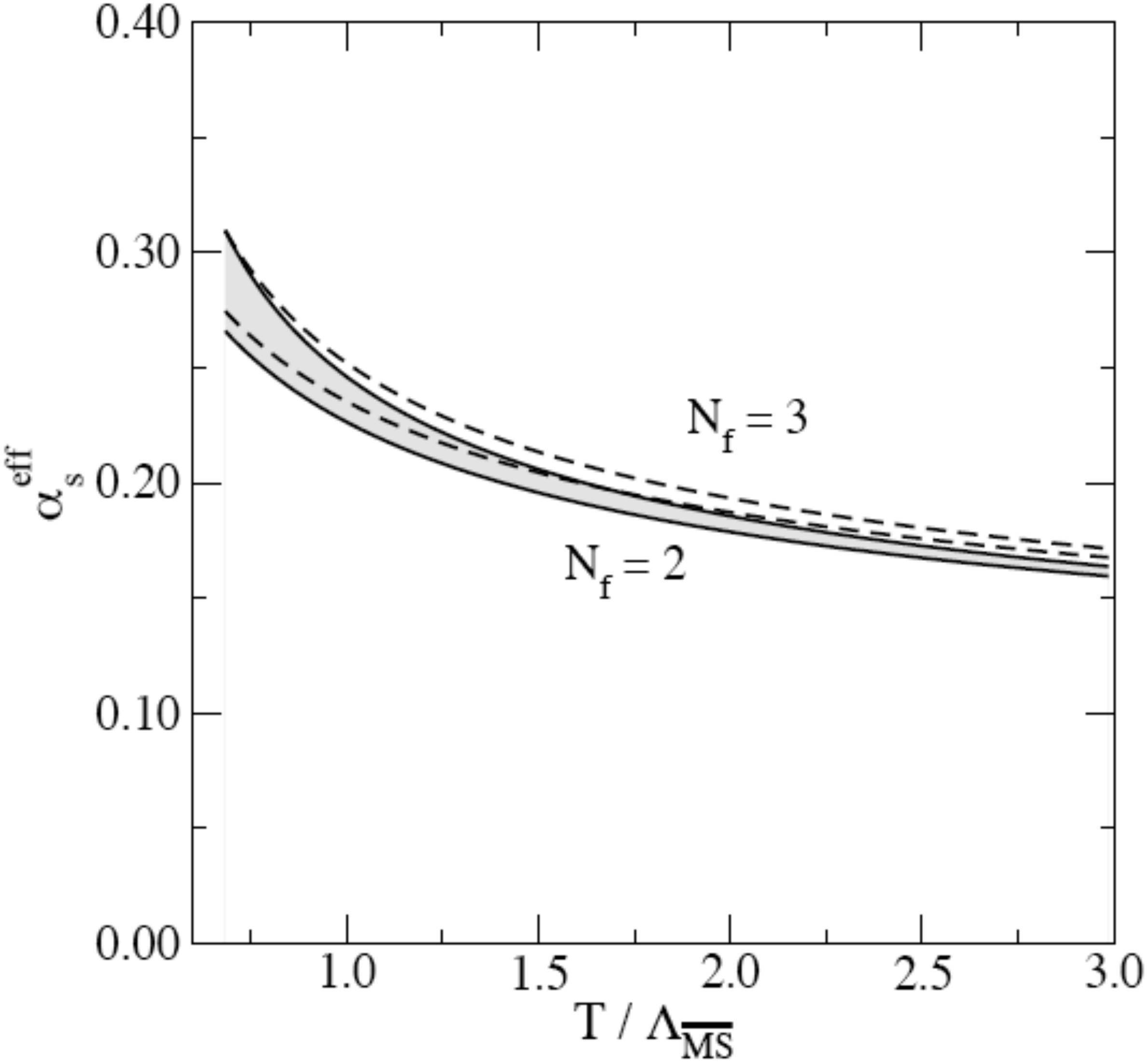


(from F. Karsch, hep-lat/0106019)

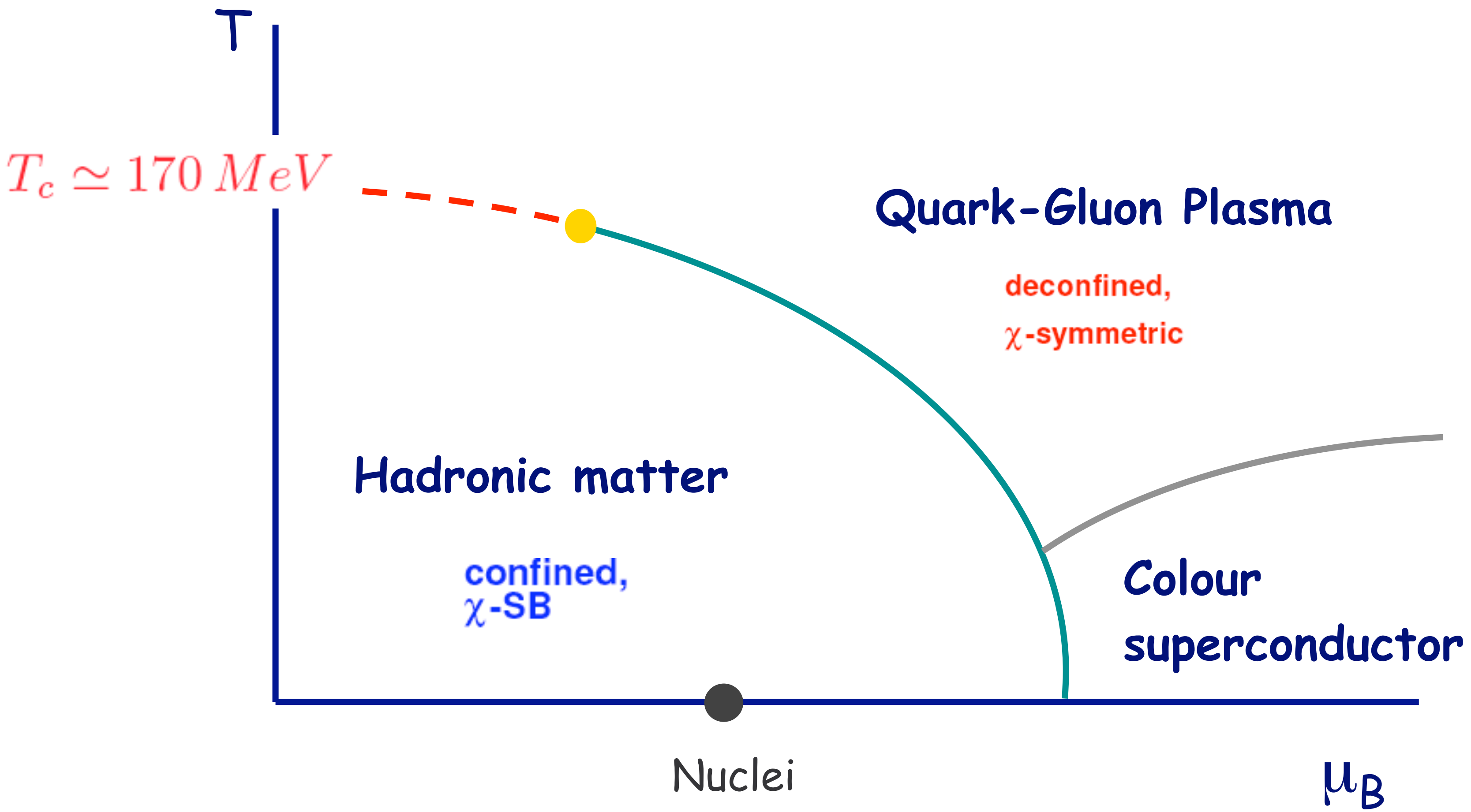

J.-P. Blaizot, E. Iancu and A. Rebhan, Phys. Lett. B470, 181 (1999)

Effective coupling in 3d reduced theory
(relevant scale is $2\pi T$)

[Laine, Schröder, hep-ph/0503061]



The QCD phase diagram



Theory near Tc is difficult

Degrees of freedom?

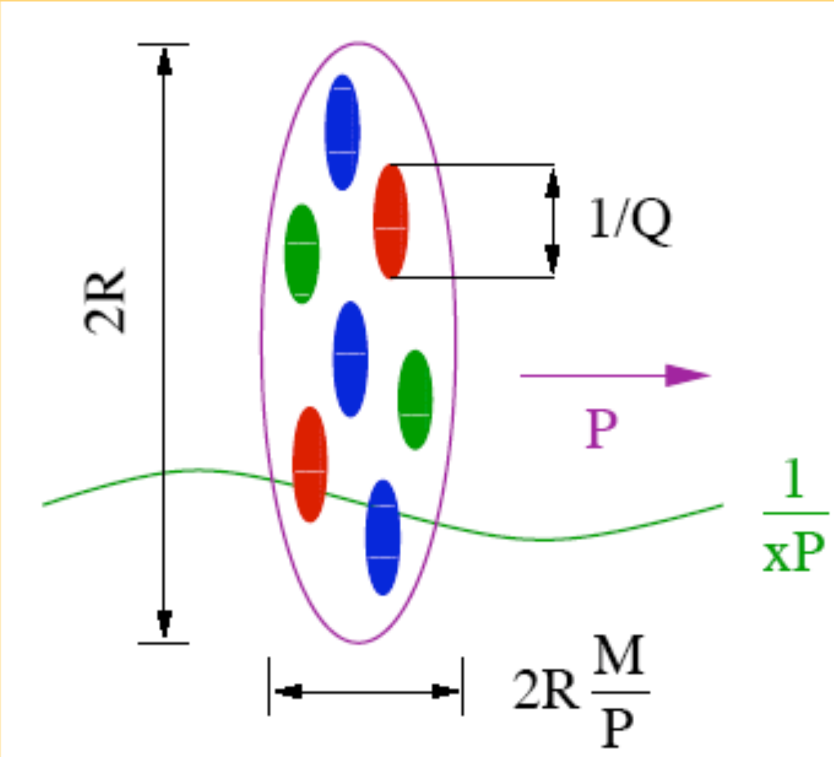
Strong coupling?

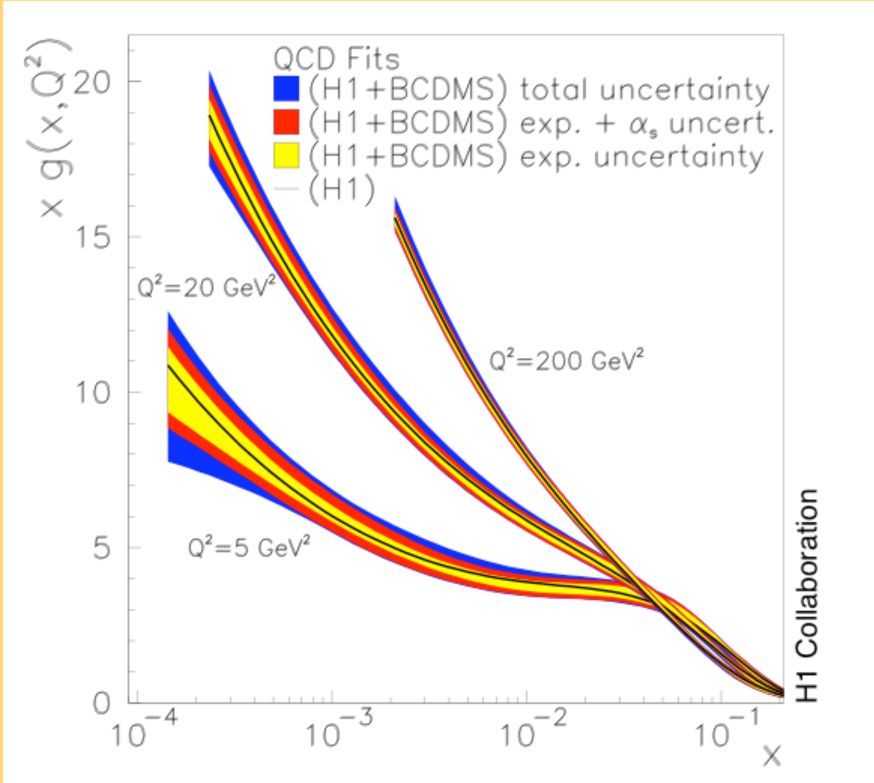
Bound states?

... and present experiments may be Probing this region...

How does the wavefunction of a nucleus look like at asymptotically high energy ?

High density partonic systems





Parton density grows as x decreases

Relevant in the very early stages of nucleus-nucleus collisions

Physics of dense systems of quarks and gluons

Weak coupling but many active degrees of freedom

Non linear QCD effects become important when

$$\left\langle (\partial A)^2 \right\rangle \approx g^2 \left\langle A^4 \right\rangle \approx g^2 \left\langle A^2 \right\rangle^2$$

Gluon saturation

(Gribov, Levin, Ryskin 83)

Large gluon densites at small x

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

Non linear effects important when $$\langle (\partial A)^2 \rangle \approx g^2 \langle A^2 \rangle^2$$

i.e. at a characterisitic scale $$Q^2 \approx g^2 \langle A^2 \rangle$$

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

$k_T \le Q_s$ (saturated regime) $k_T \ge Q_s$ (dilute regime)

The saturation scale

From fit to DIS (HERA)

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

$Q_0 = 1\text{GeV} \qquad x_0 = 3 \times 10^{-4}$

$\lambda \approx 0.3$

In a nucleus

$$Q_0^2 \rightarrow Q_0^2 A^{1/3}$$

$x = 10^{-2} \rightarrow Q_s^2 \approx 2\text{GeV}^2 \qquad (\text{for}\, A = 200)$

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

At the LHC $\quad \sqrt{s} = 5.5\text{TeV} \qquad x \sim 5 \times 10^{-4} - 10^{-5} \qquad Q_s^2 \sim 5 - 14\text{GeV}^2$

At RHIC, smaller x can be reached in the forward rapidity region

Early stages of a nucleus-nucleus collision

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

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

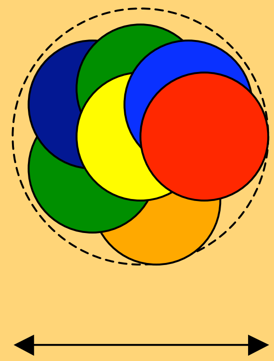
At that time

$$\frac{dN}{dy} \approx 2AxG(x,Q_s) \qquad \frac{dE_T}{dy} \approx 2Q_s AxG(x,Q_s)$$

Phenomenology based on such arguments (refined) is reasonably successful at RHIC

High density partonic systems

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



$2/Q_s$

Large occupation numbers

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

Classical fields

McLerran-Venugopalan, etc.

Non linear evolution equations

Balitsky-Kovchegov equation

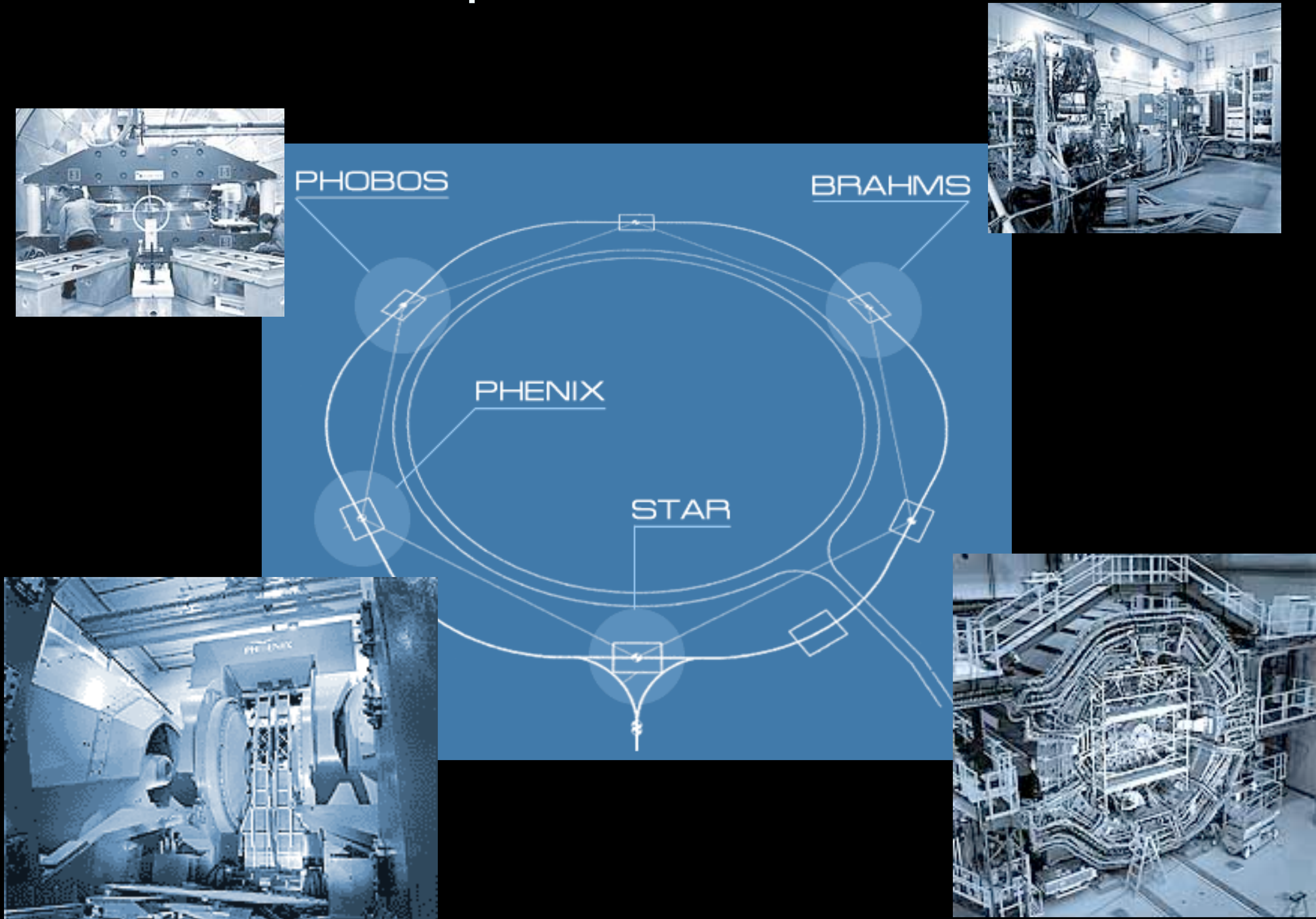
COLOR GLASS CONDENSATE and JIMWLK(*) equation

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

Hot and dense matter is produced in ultra-relativistic heavy ion collisions

AGS/BNL	$\sqrt{s} \approx 5 \cdot A \cdot GeV$
SPS/CERN	$\sqrt{s} \approx 20 \cdot A \cdot GeV$
RHIC/BNL	$\sqrt{s} \approx 200 \cdot A \cdot Gev$
LHC/CERN	$\sqrt{s} \approx 5000 \cdot A \cdot Gev$

RHIC experiments



Some important results from RHIC

Large energy density achieved

Collective behaviour observed

Jet quenching and strong « final state » interactions

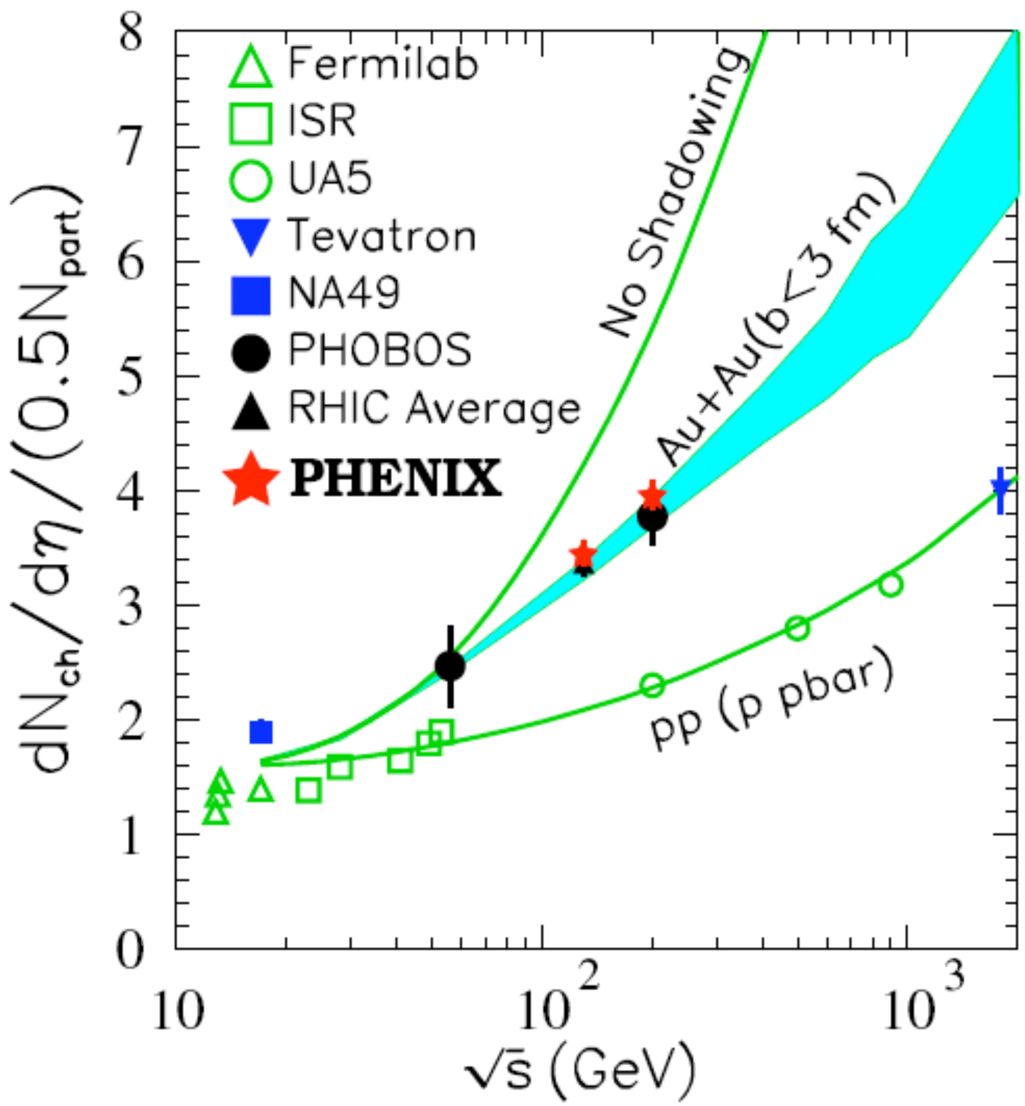
Hints of gluon saturation

And much, much, more!...

(Focus on observables sensitive to initial state)

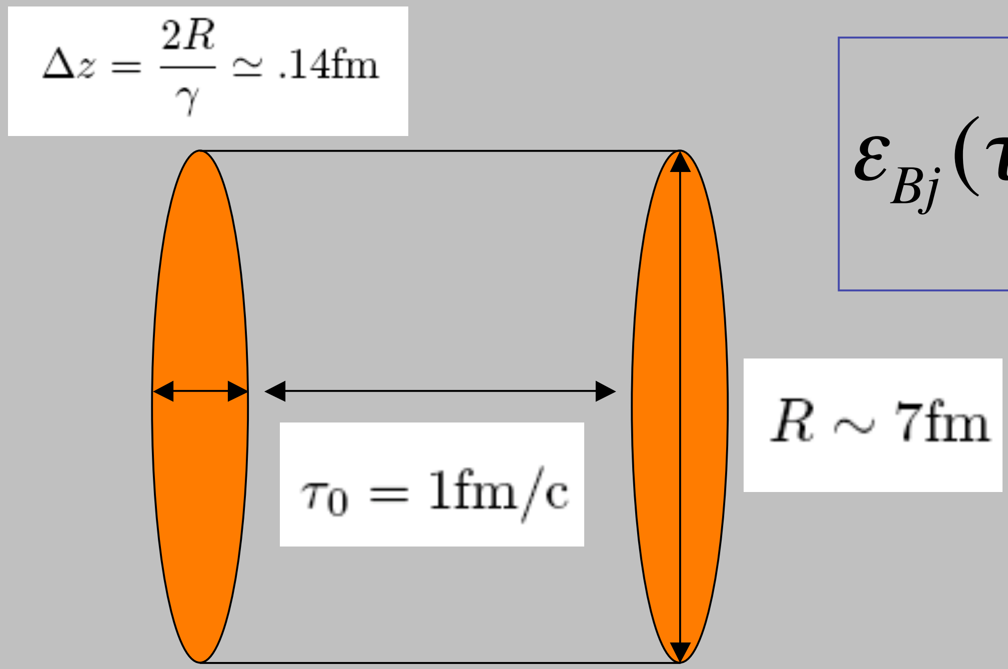
Large energy density

Moderate increase of multiplicity with beam energy



From Phenix
White paper

Bjorken energy density



$$\varepsilon_{Bj}(\tau_0) = \frac{1}{\pi R^2 \tau_0} \frac{dE_T}{dy}$$

$$\varepsilon_{Bj}(1 fm/c) \approx 5.5 GeV/fm^3$$

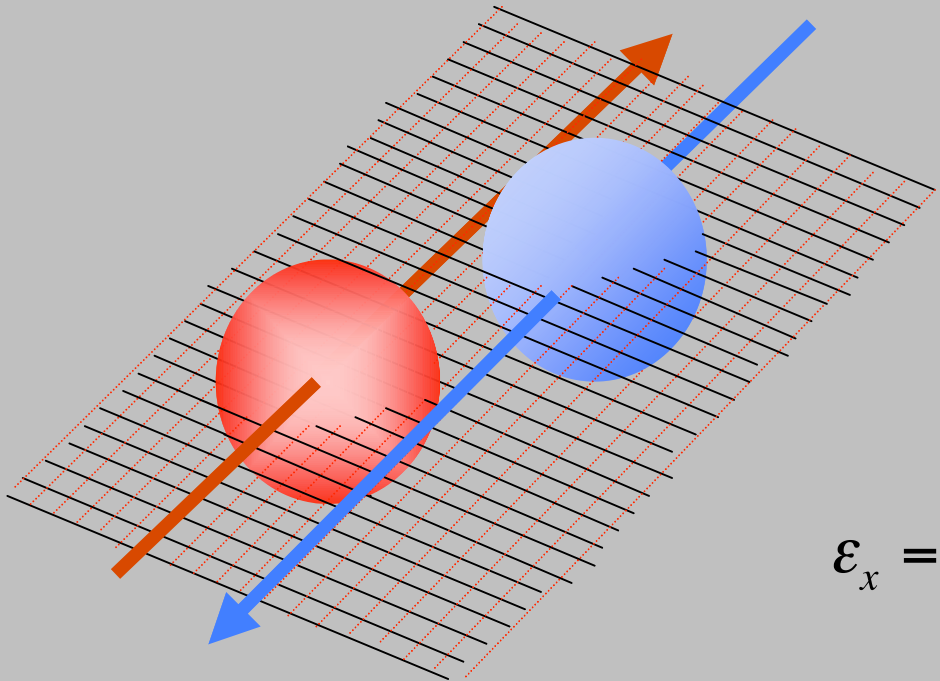
$$\varepsilon_{Bj}(0.35 fm/c) \approx 16 GeV/fm^3 \quad (\tau_0 \approx 1/m_T)$$

$$\varepsilon_{Bj}(0.14 fm/c) \approx 40 GeV/fm^3 \quad (\tau_0 \approx 1/Q_s)$$

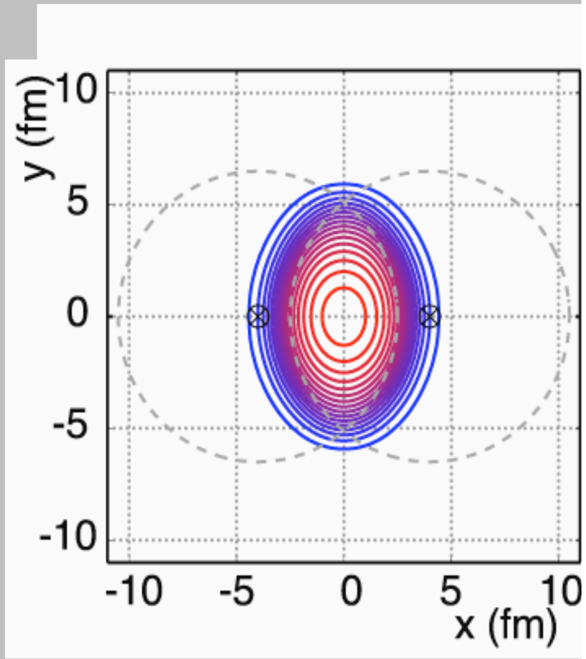
Elliptic flow

Produced particles flow preferentially in the reaction plane

(J.-Y. Ollitrault, 1992)



$$\varepsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



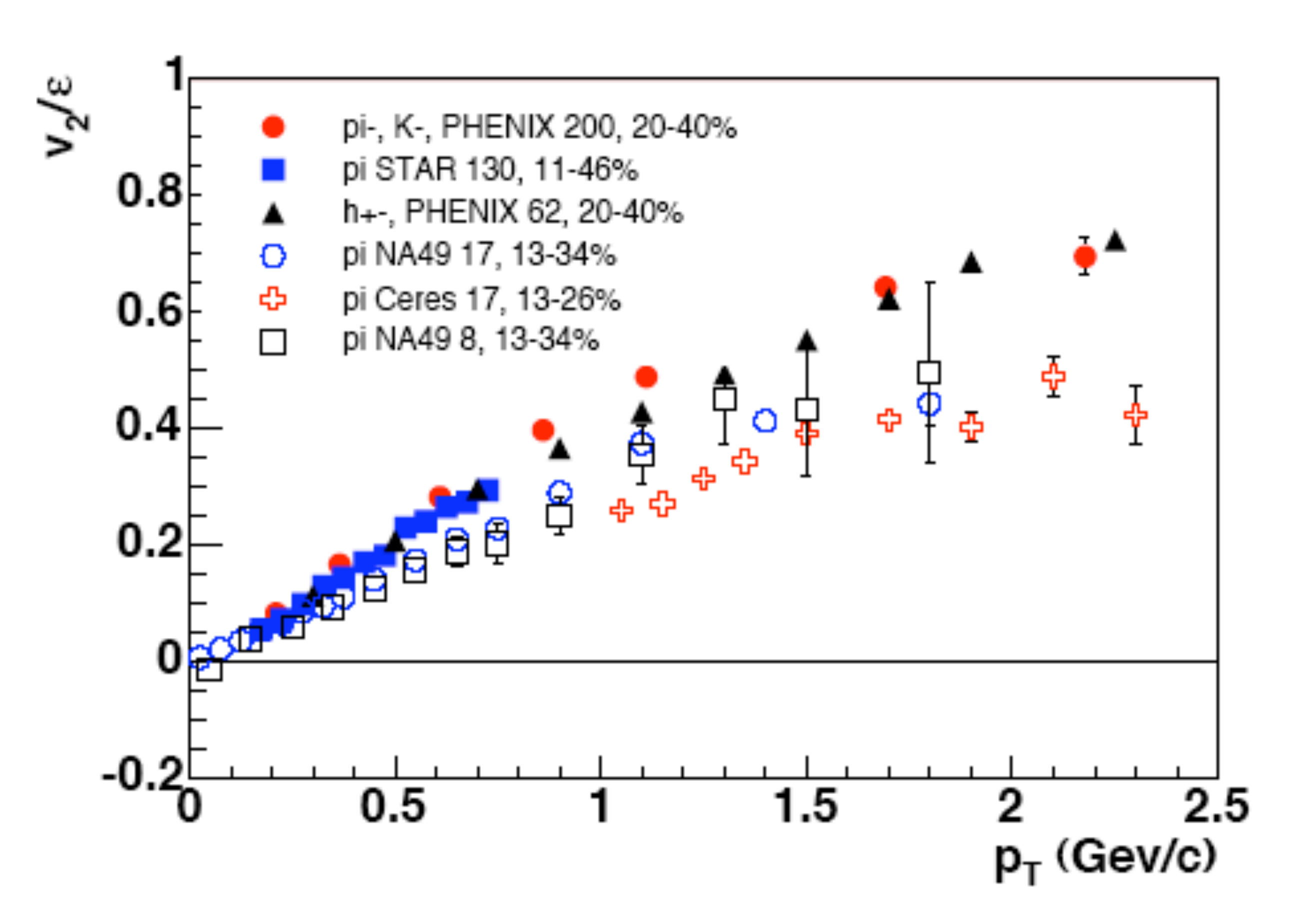
$$V_2 = \langle \cos(2\varphi) \rangle$$

(S. Voloshin and Y. Zhang, 1994)

(P.F. Kolb, J. Sollfrank and U. Heinz, PRC 62 (2000) 054909)

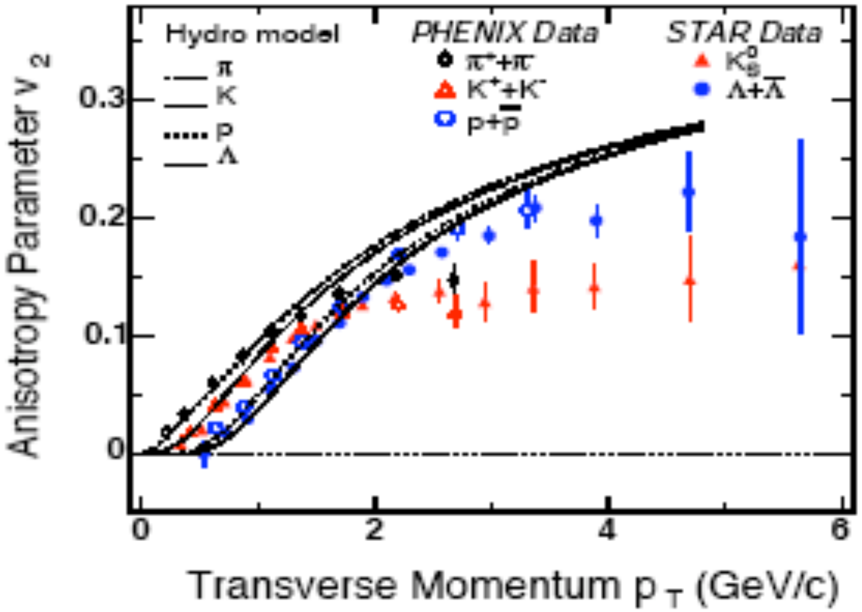
Elliptic flow

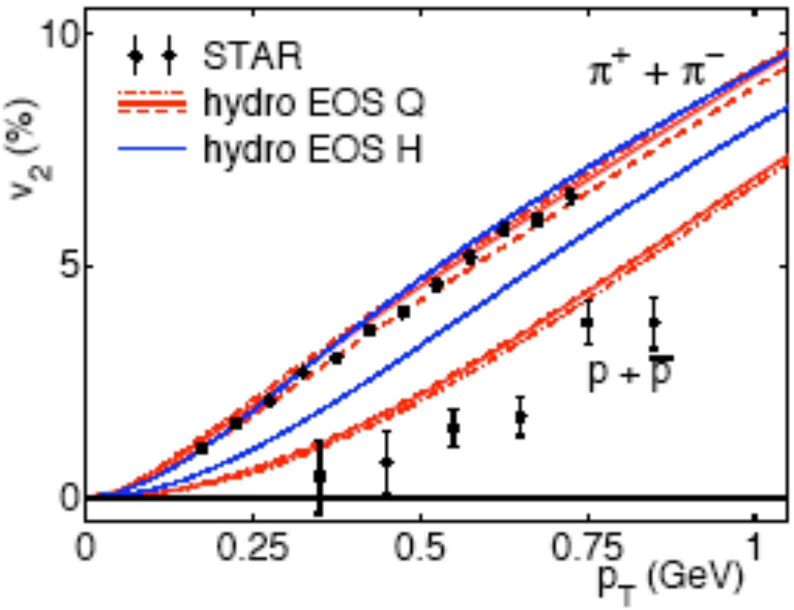
$$v_2 = \langle \cos(2\phi) \rangle$$



(Phenix white paper)

Comparison with hydrodynamics





(From U. Heinz, nucl-th/0412094)

Strong conclusions drawn from comparison with hydrodynamical calculations:

- early thermalisation time
- sensitivity to equation of state
- low viscosity

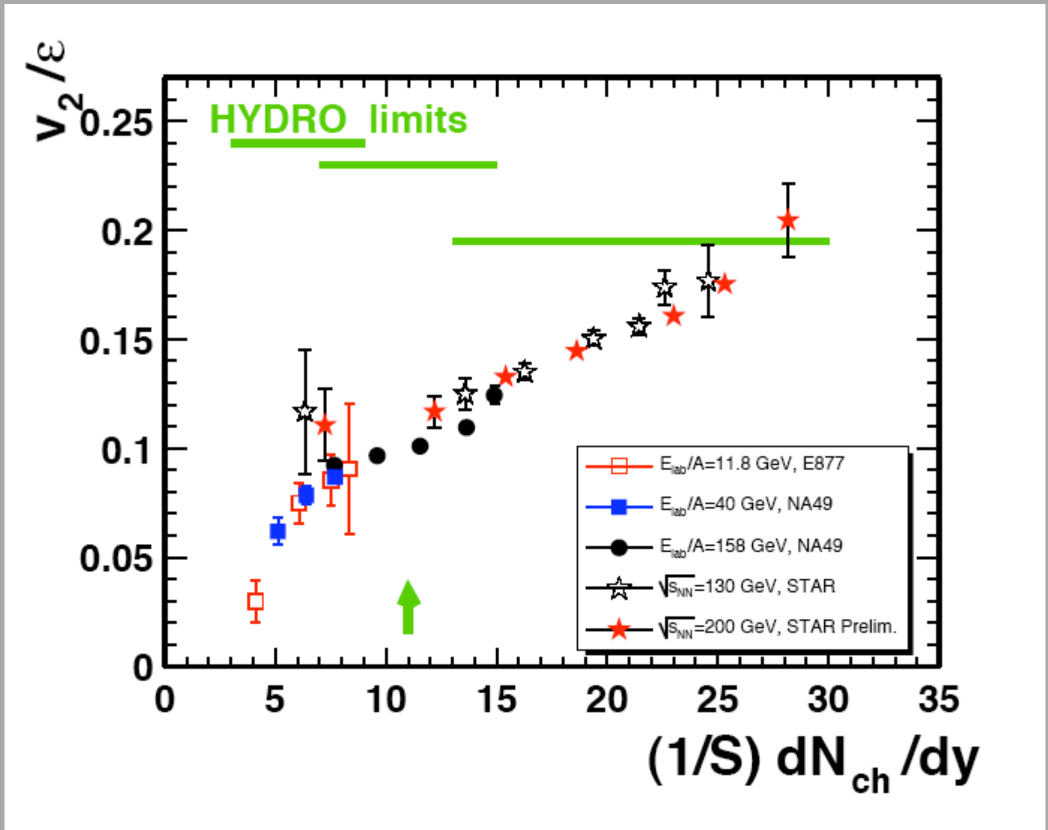
R.S. Bhalerao, J.-P. B, N. Borghini, J.-Y. Ollitrault, nucl-th/0508009

Good control parameter ?

-initial energy density (no)

-average number of collisions during the build up of elliptic flow (?)

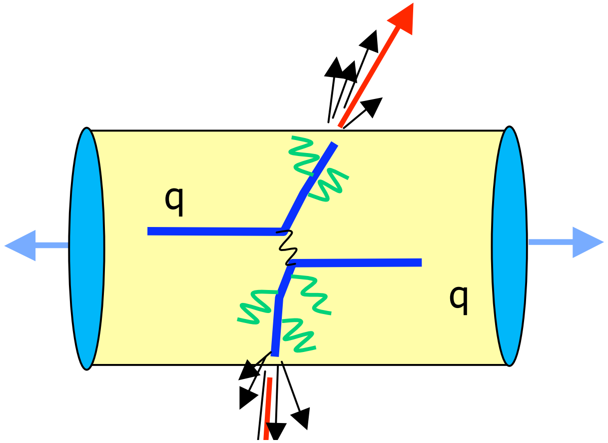
$$\left(\frac{R}{\lambda} \approx \frac{c_s}{c}\frac{\sigma}{S}\frac{dN}{dy}\right)$$

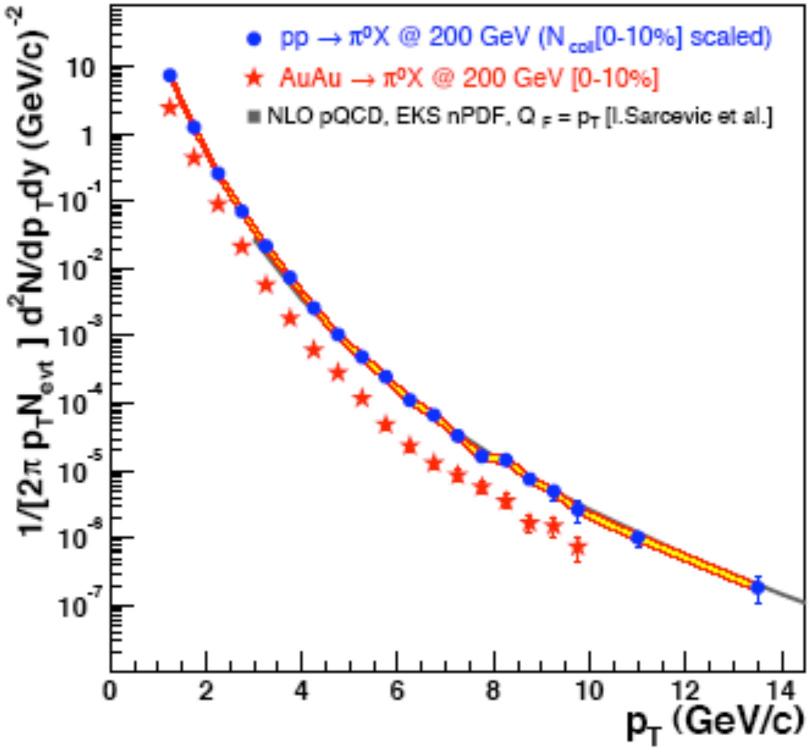


(From NA49, nucl-ex/0303001)

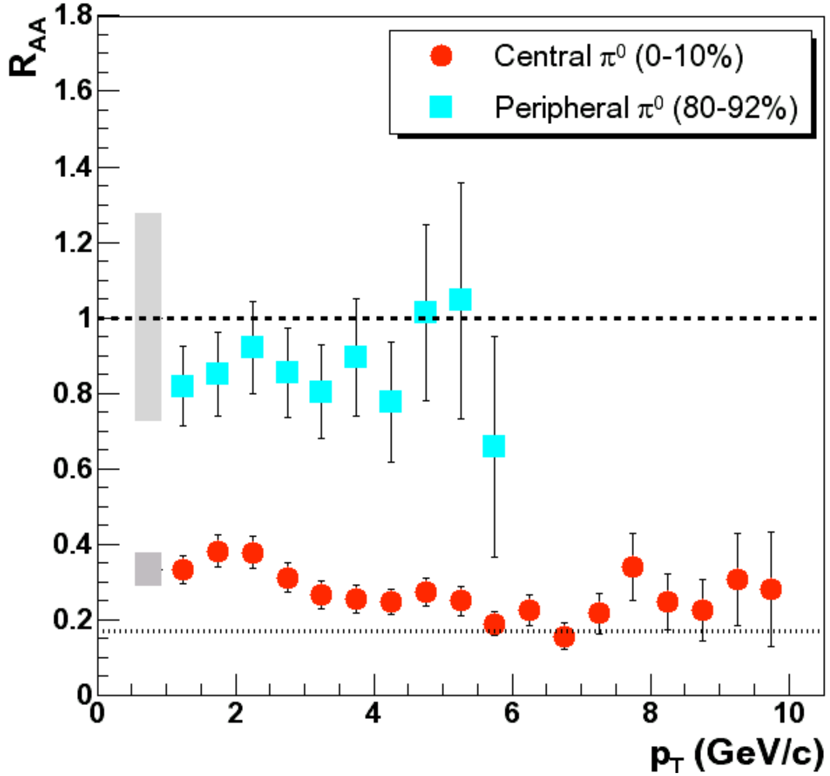
Jet quenching and strong « final state » interactions

Jet production in matter



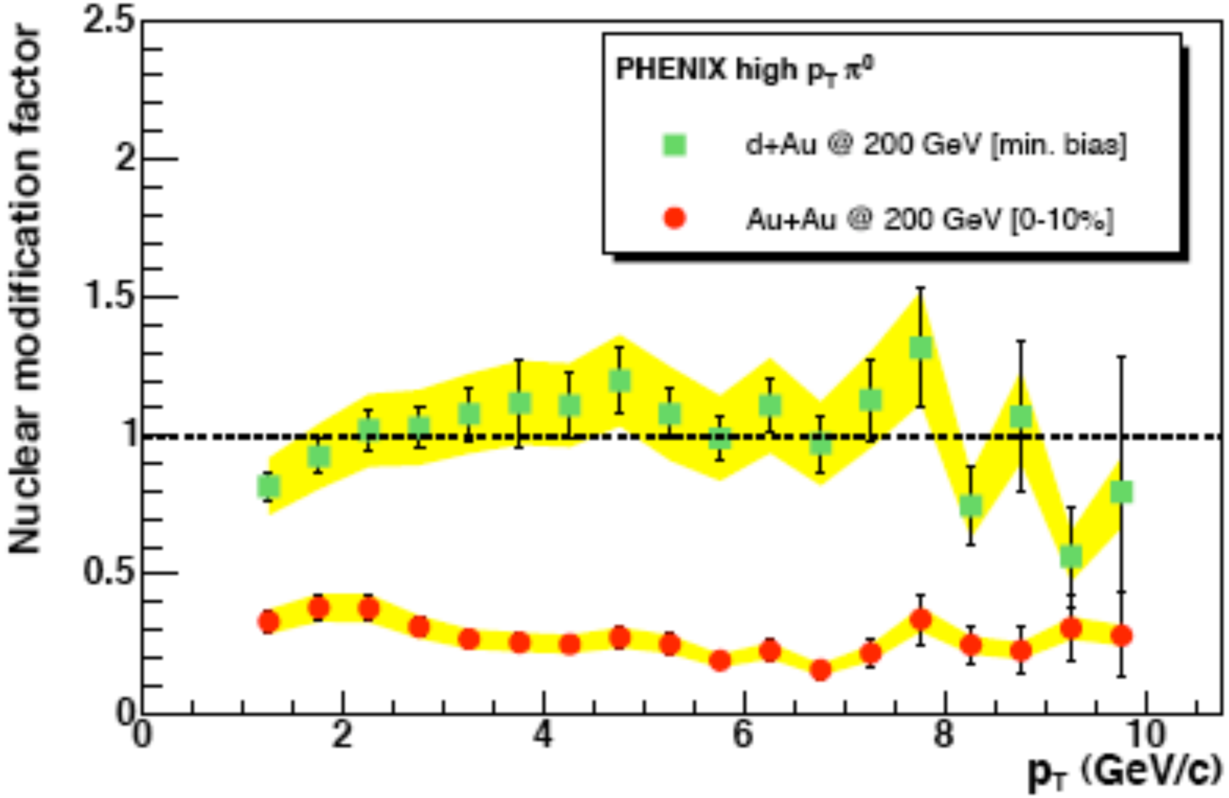


Au-Au nucl-ex/0304022

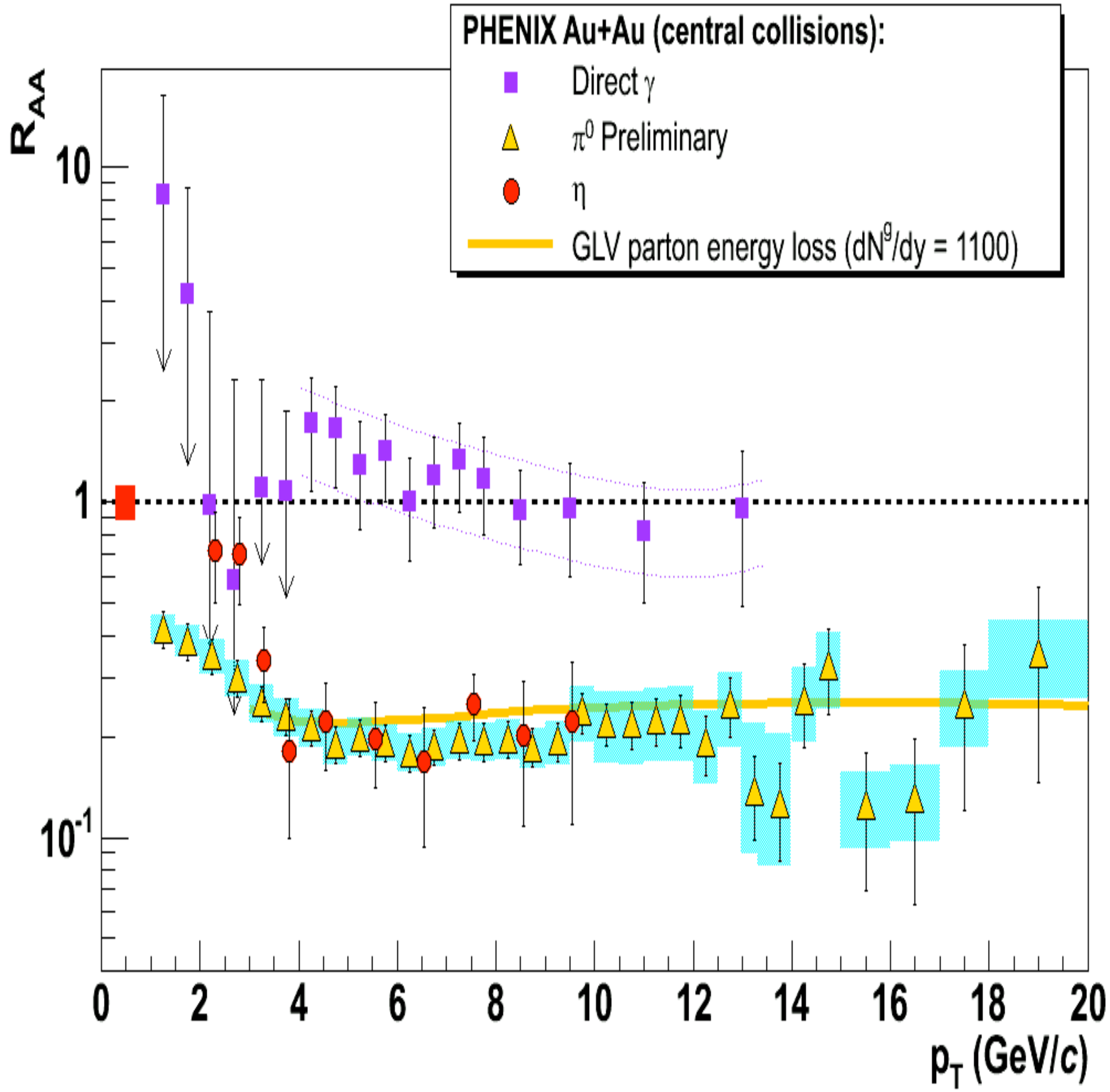


$$R_{AA} = \frac{\mathrm{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\mathrm{Yield}_{pp}}$$

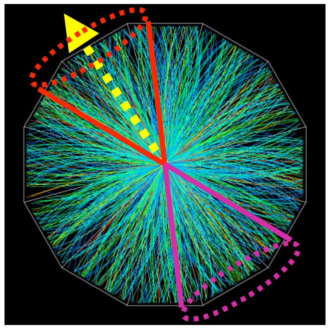
Control experiment: d-AU

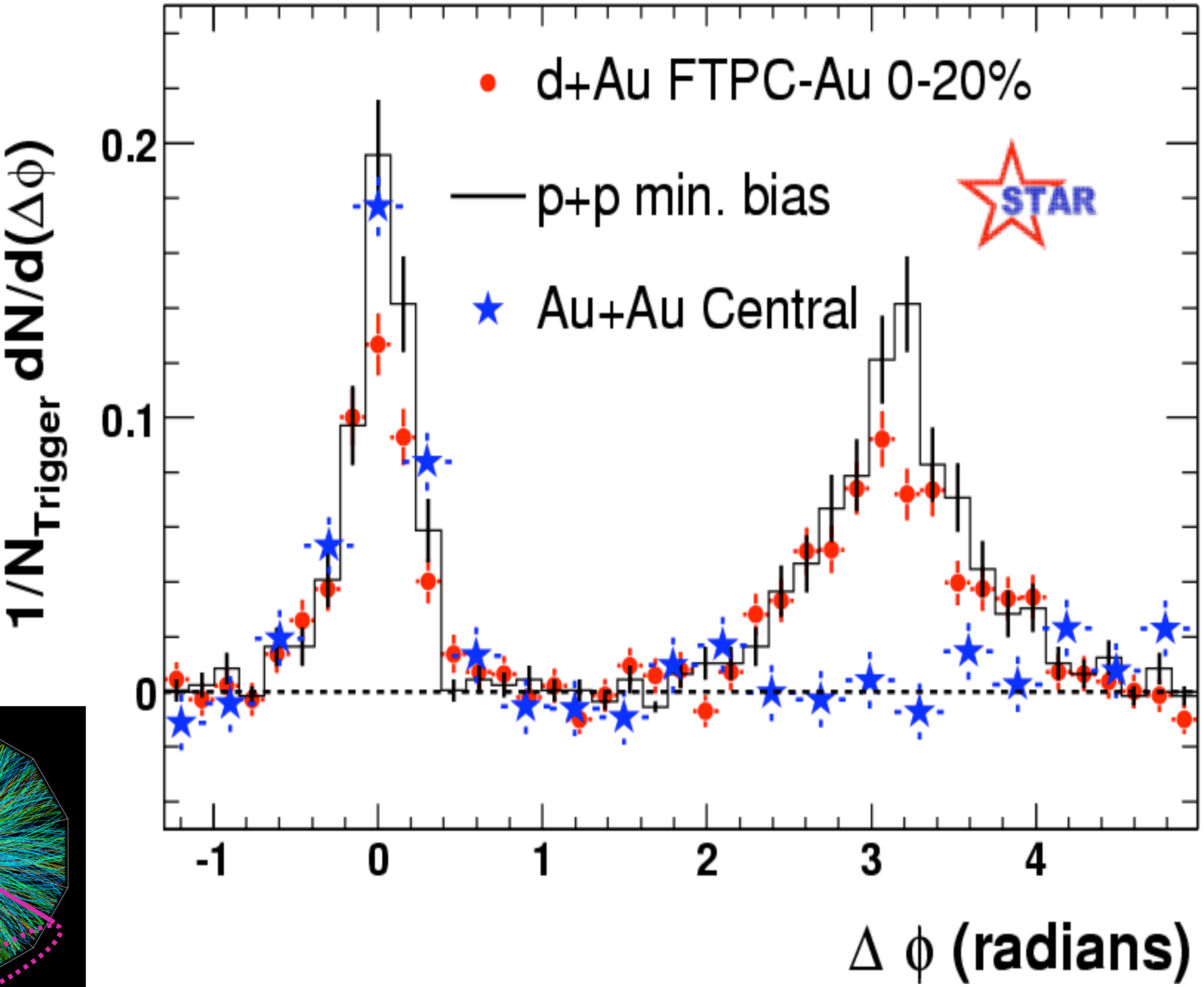


(PHENIX, nucl-ex/0401001)


PHENIX Au+Au (central collisions):
Direct γ
π0 Preliminary
η
GLV parton energy loss (dNg/dy = 1100)
RAA
10
1
10-1
0
2
4
6
8
10
12
14
16
18
20
pT (GeV/c)

QM'05



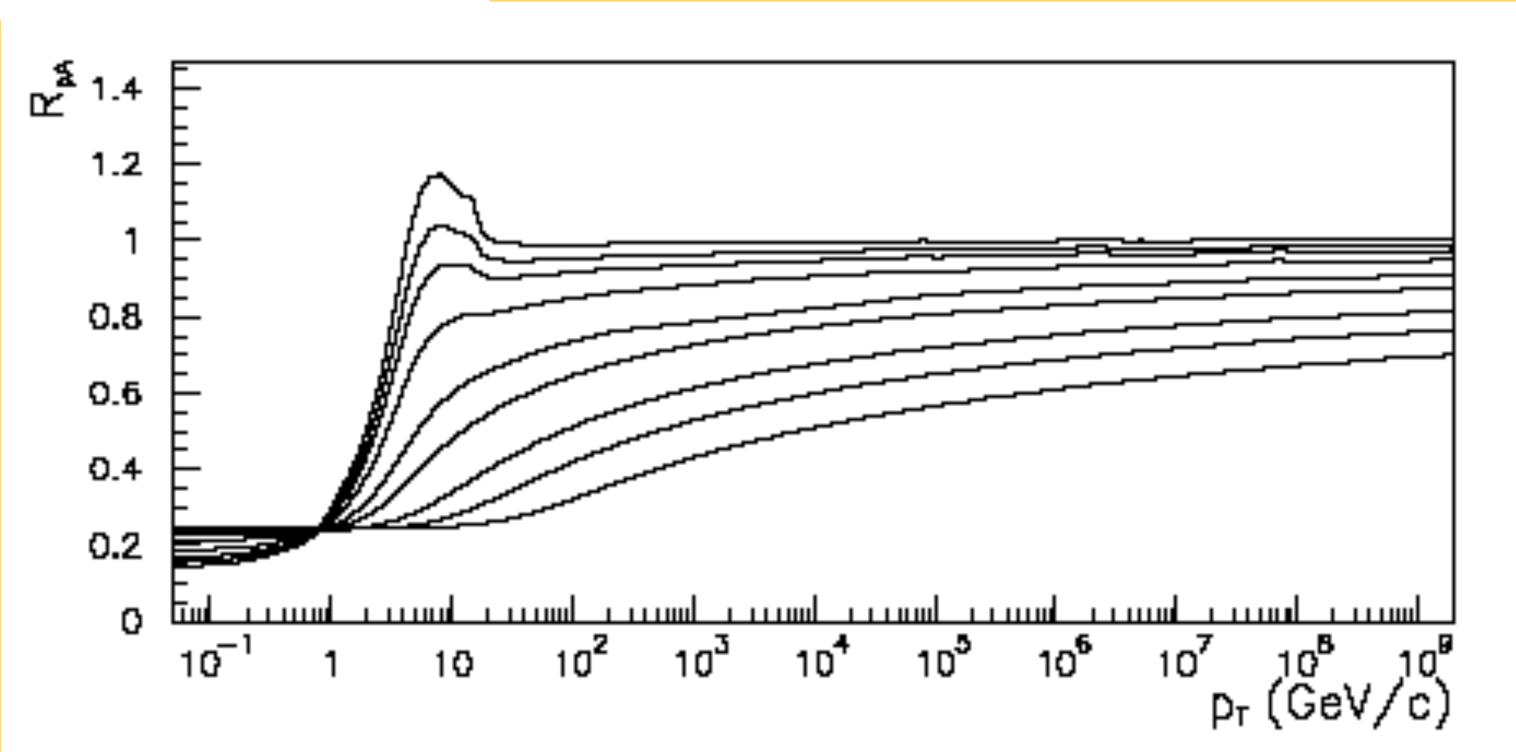


STAR: Phys.Rev.Lett.91:072304,2003

Hints of gluon saturation

Suppression can also be due to initial state effects (nuclear wave function probed at small x; color glass condensate)

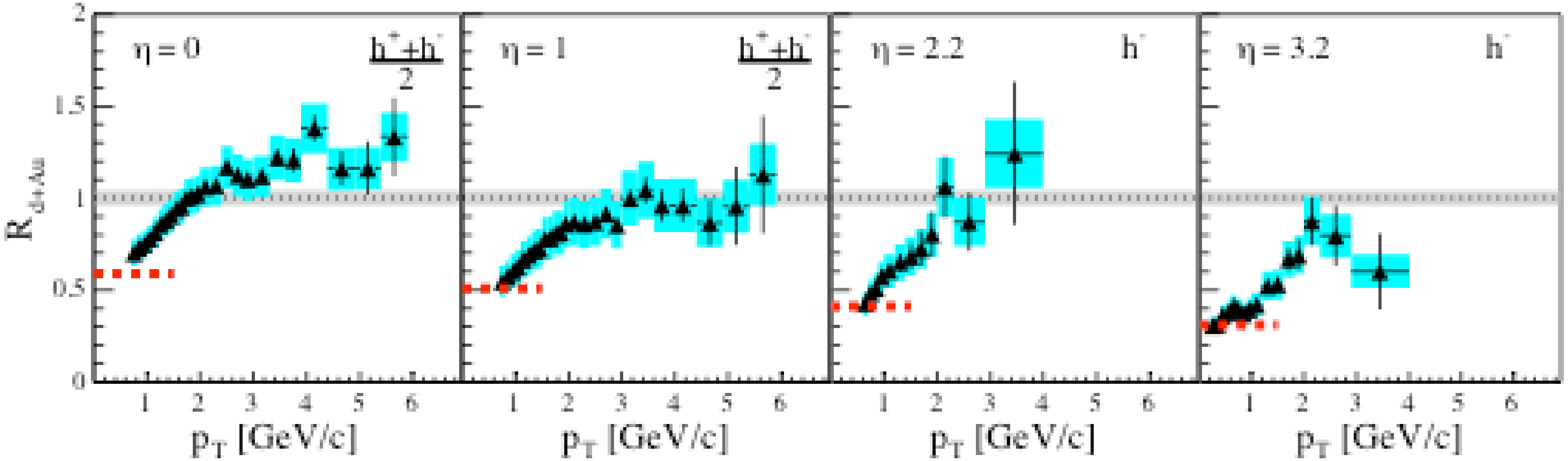
$$R_{pA} = \frac{\frac{dN_{pA}}{dy\,d^2p\,d^2b}}{A^{1/3}\frac{dN_{pp}}{dy\,d^2p\,d^2b}}$$



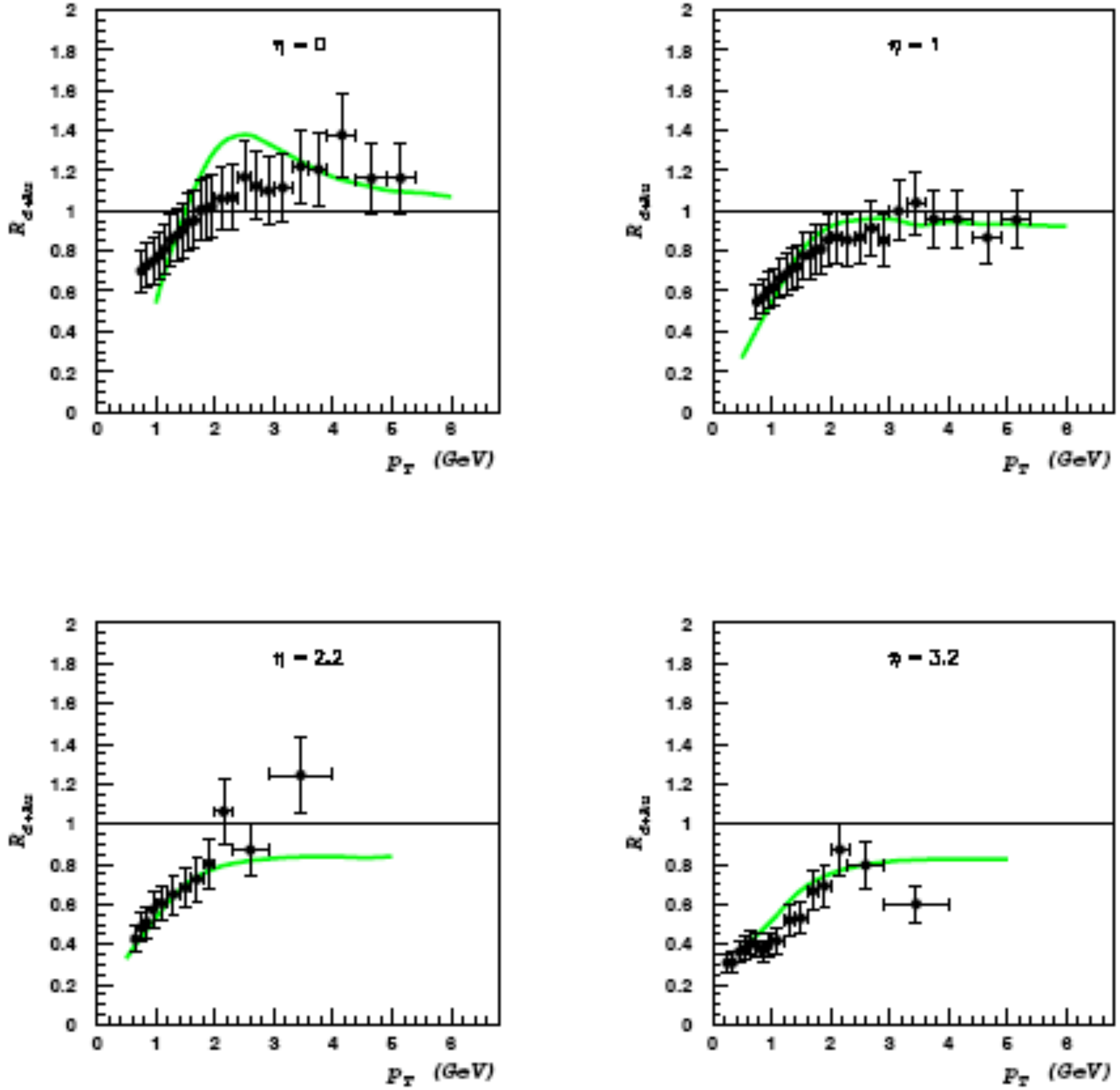
Solution of the BK equation, Albacete et al, hep-ph/0307179

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

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



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



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

SUMMARY

-Strongly interacting matter is produced in high energy nucleus-nucleus collisions. Large « initial » energy density. Collective behaviour.

- Many (indirect) evidences that partonic degrees of freedom play an important role in the collision dynamics at RHIC

- Early stages of the collisions, and hence « initial state effects » are important at RHIC (and will be more so at LHC).

- Hints of saturation (color glass condensate) may be already present at RHIC. Phenomenology based on saturation ideas is reasonably successful at RHIC