Heavy Ion Collisions
Puzzles and Hopes

'Physics at the LHC'
DESY, Hamburg
7-12 June 2010

Jean-Paul Blaizot, IPhT- Saclay

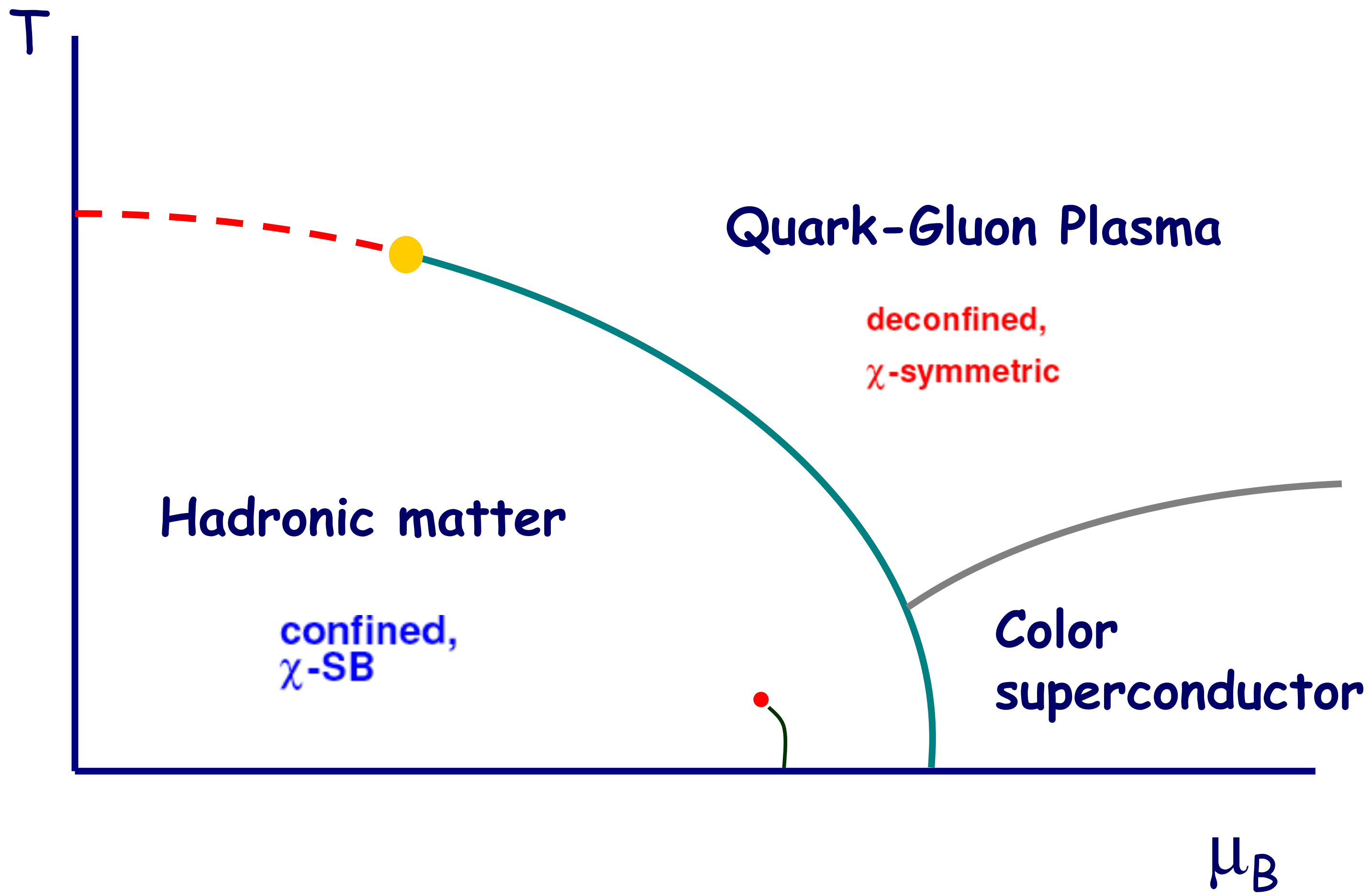
Fundamental questions

- 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 asymptotic situations

The QCD phase diagram

(« low resolution »)



The ideal baryonless Quark-Gluon Plasma

Asymptotic freedom

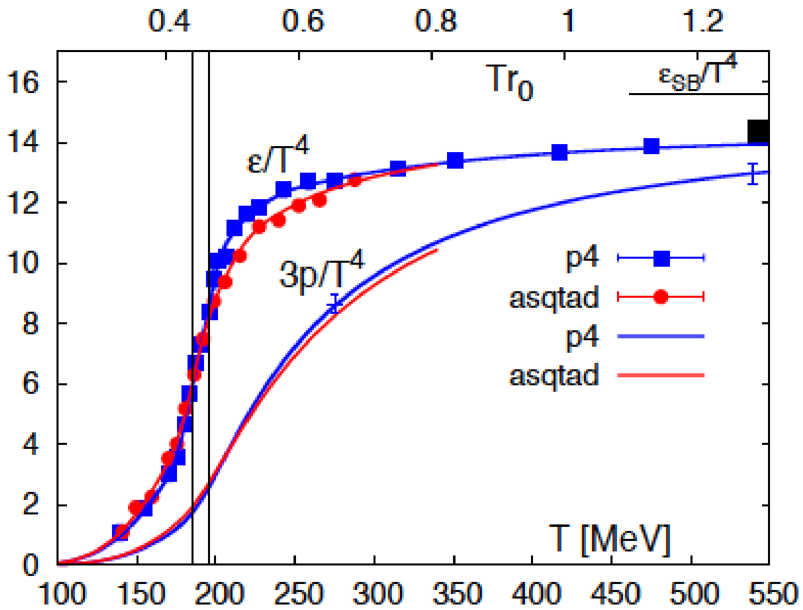
$$\alpha_s = \frac{g^2}{4\pi} \approx \frac{2\pi}{b_0 \ln\left(\mu / \Lambda_{QCD}\right)} \qquad \left(\mu \approx 2\pi T\right)$$

Matter is « simple » at high temperature:

- an ideal gas of quarks and gluons
- the dominant effect of interactions is to turn (massless) quarks and gluons into weakly interacting (massive) quasiparticles.

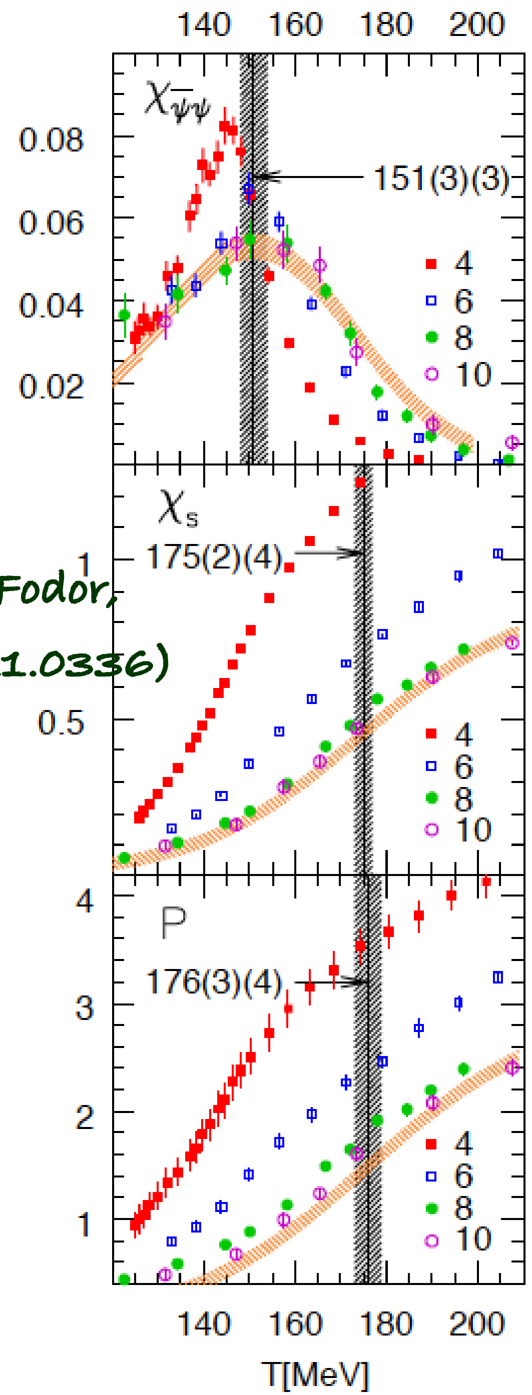
Phase transition(s)

(crossover)

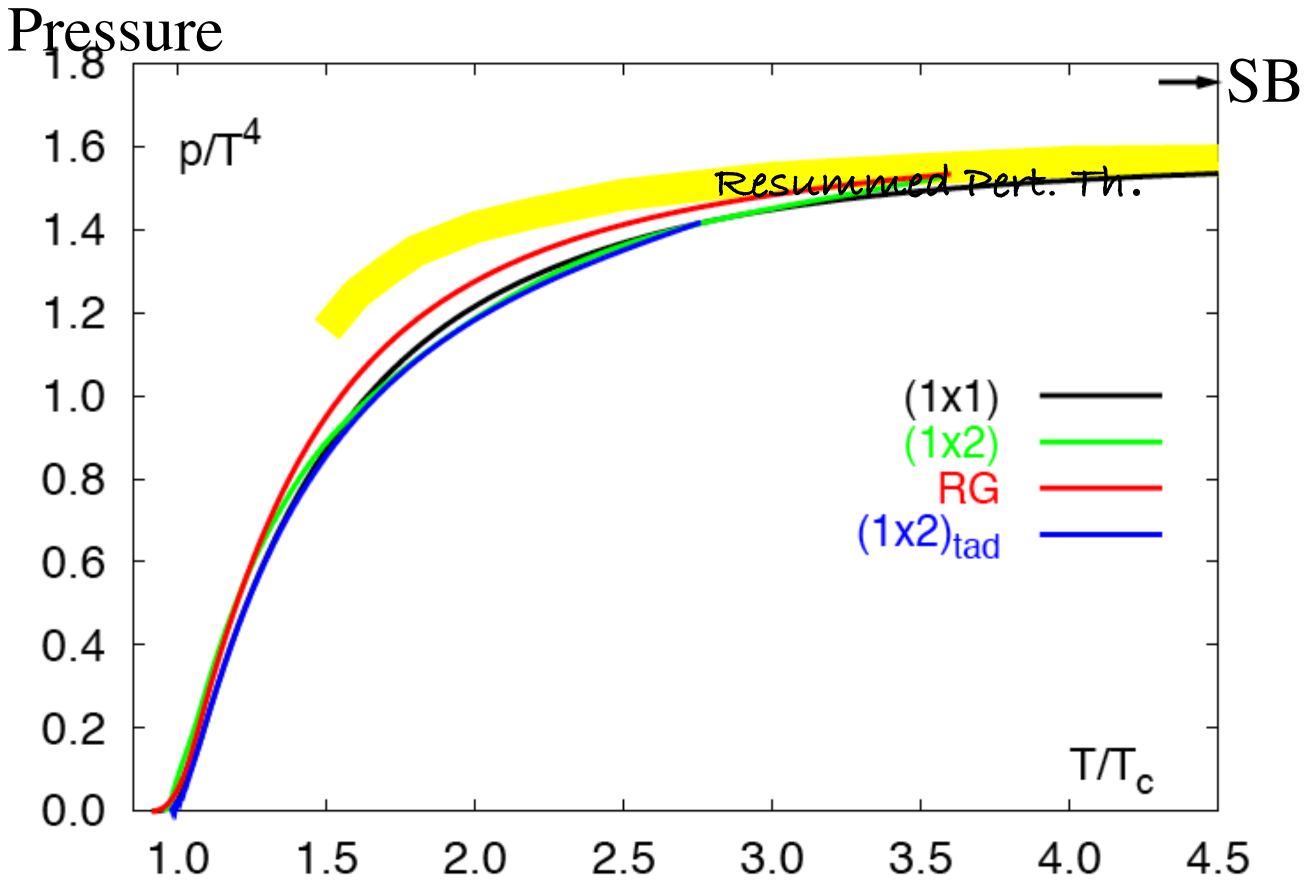


(from M. Bazavov et al, arXiv:0903.4379)

(from Z. Fodor, arXiv:0711.0336)



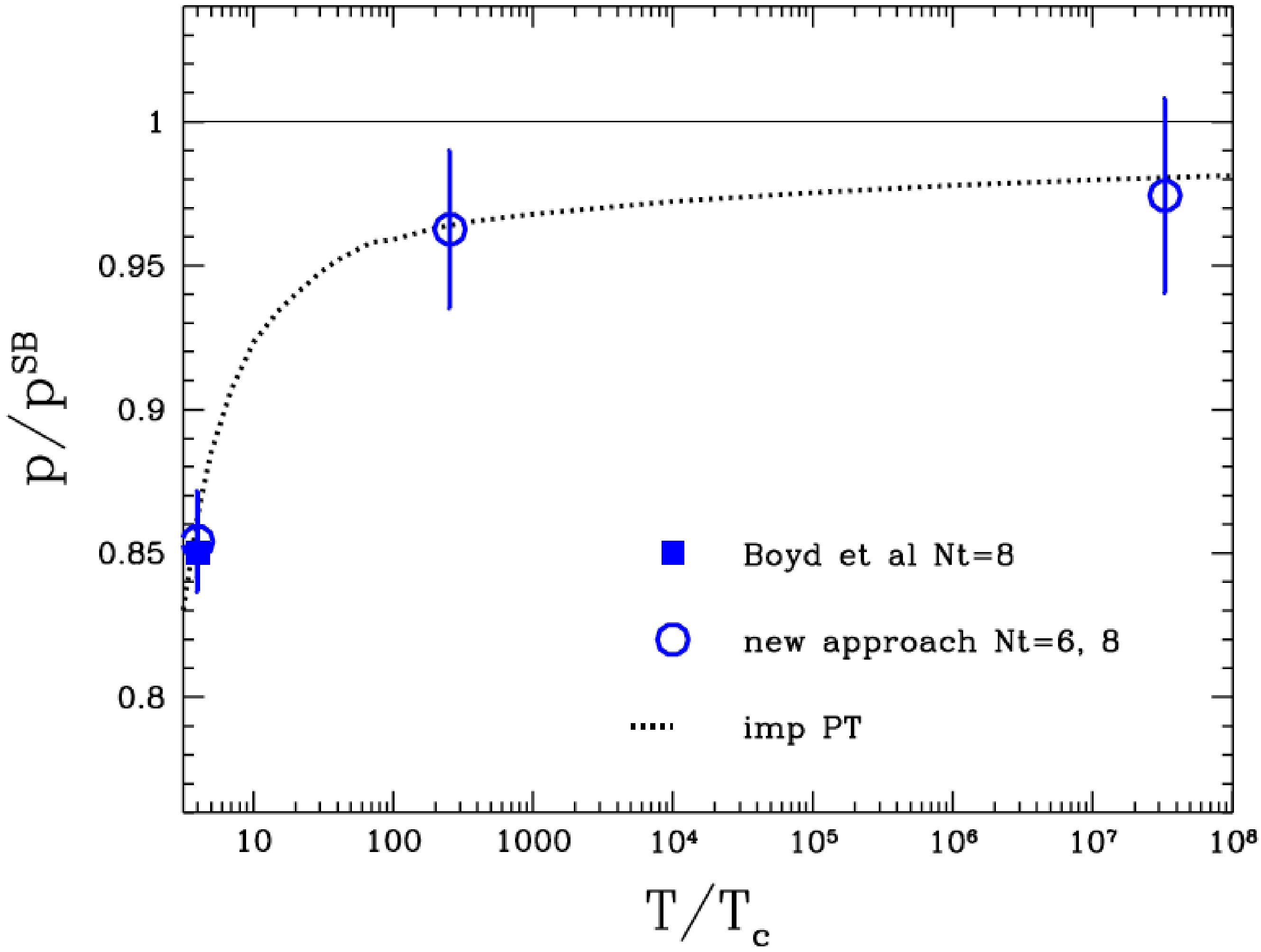
At T>3Tc Resummed Pert. Theory accounts for lattice results



(SU(3) lattice gauge calculation from Karsch et al, hep-lat/0106019)

(resummed pert. th. from J.-P. B., E. Iancu, A. Rebhan: Nucl.Phys.A698:404-407,2002)

Pressure for SU(3) YM theory at (very) high temperature

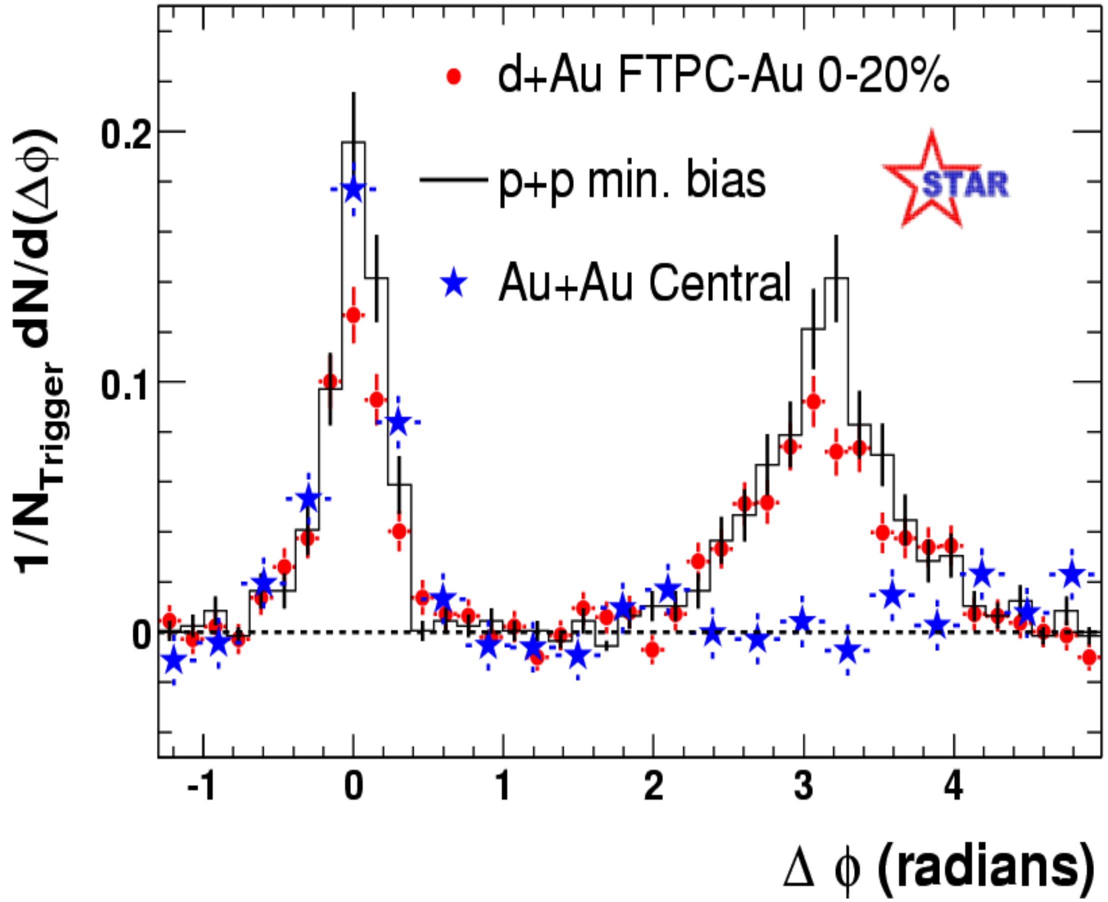


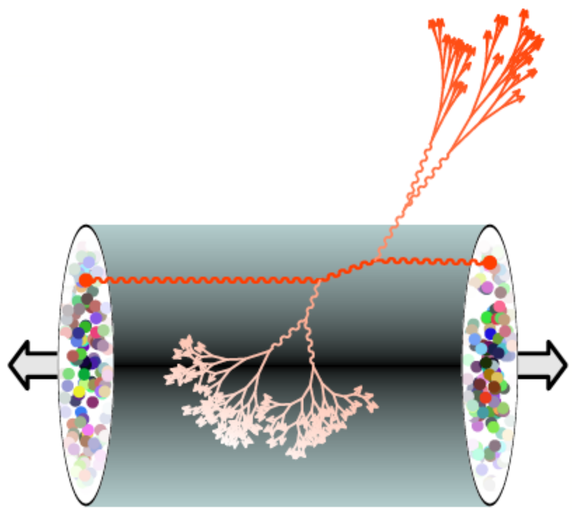
(from G. Endrodi et al, arXiv: 0710.4197)

From the « ideal gas » to the « perfect liquid »

Lessons from RHIC

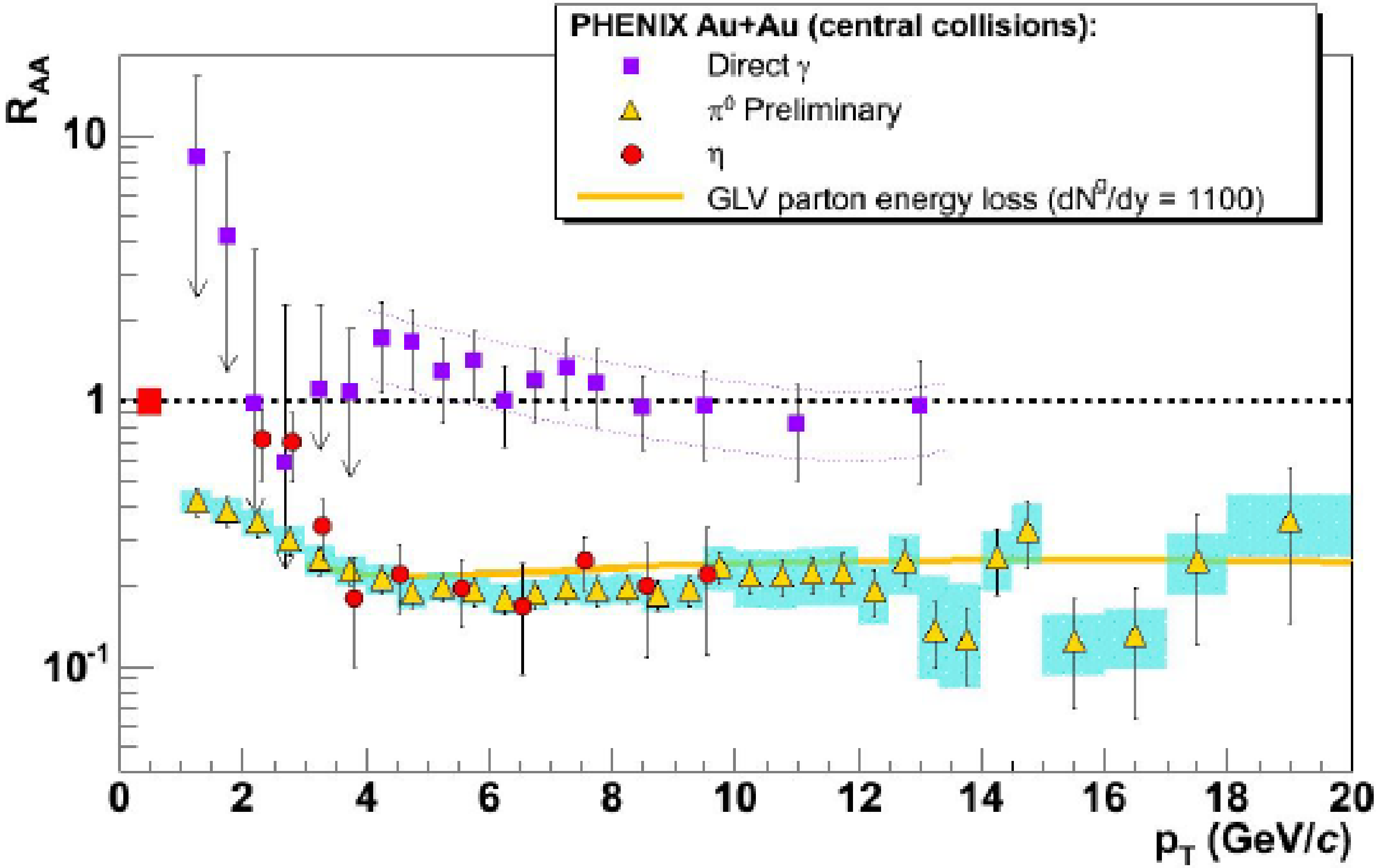
Matter is opaque to the propagation of jets



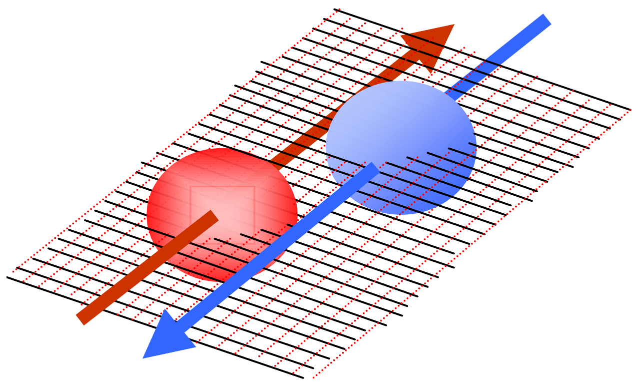


(STAR: Phys.Rev.Lett.91:072304,2003)

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

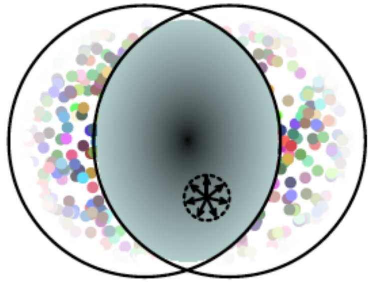


(from Akiba et al, NPA 774 (2006) 403)

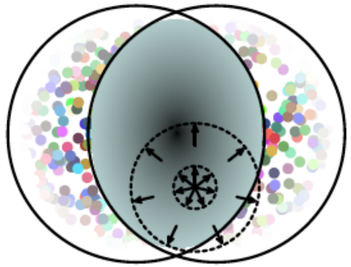


Matter flows like a fluid

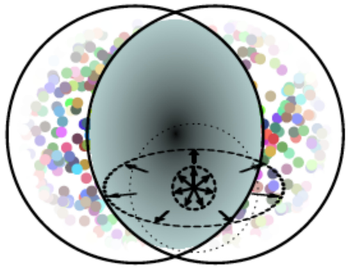
Initial momentum
distribution isotropic



Without interactions, the particles
would escape isotropically, irrespective
of the shape of the interaction zone

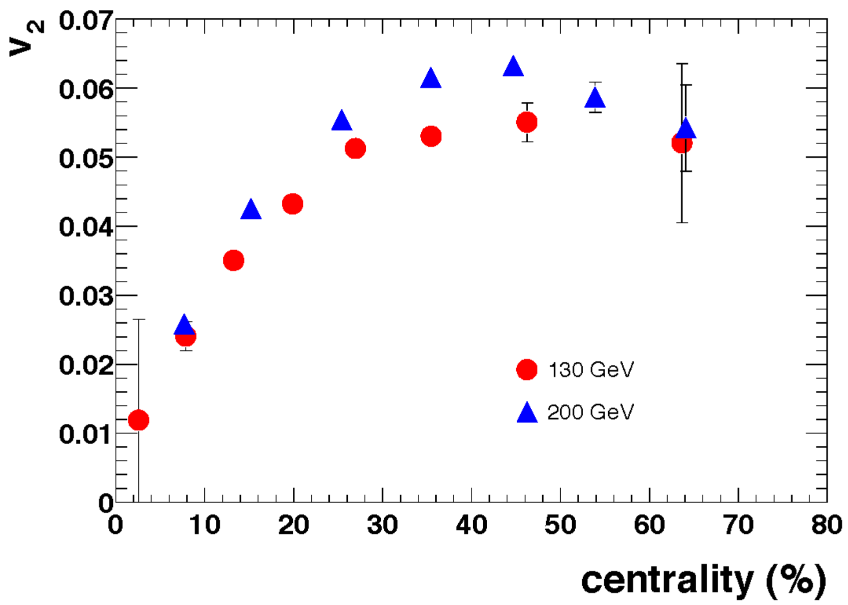


Strong interactions induce pressure gradients.
The expansion becomes anisotropic, and
the momentum distribution reflects the anisotropy
of the initial interaction region

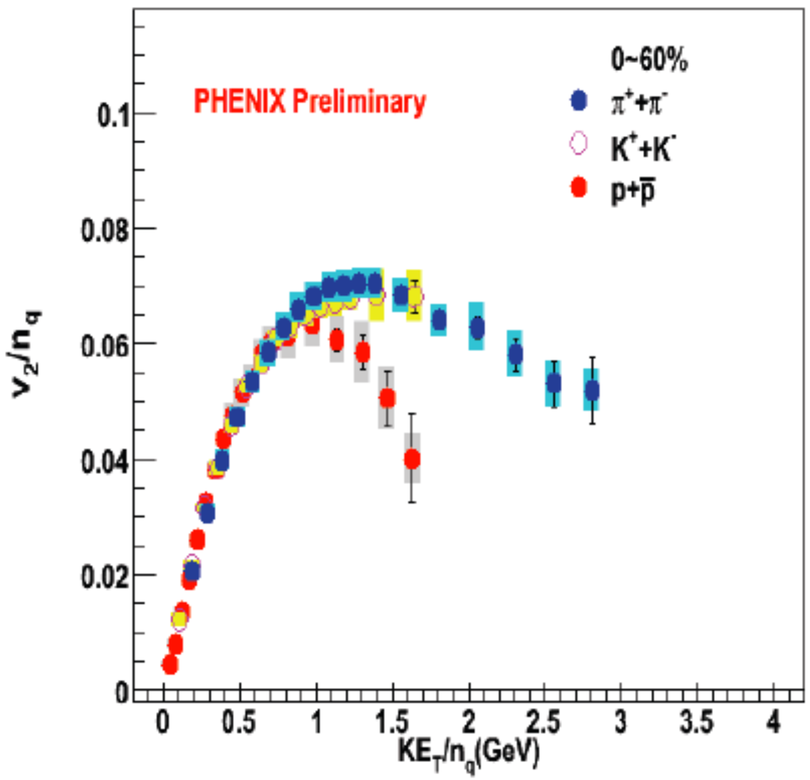


Elliptic flow

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

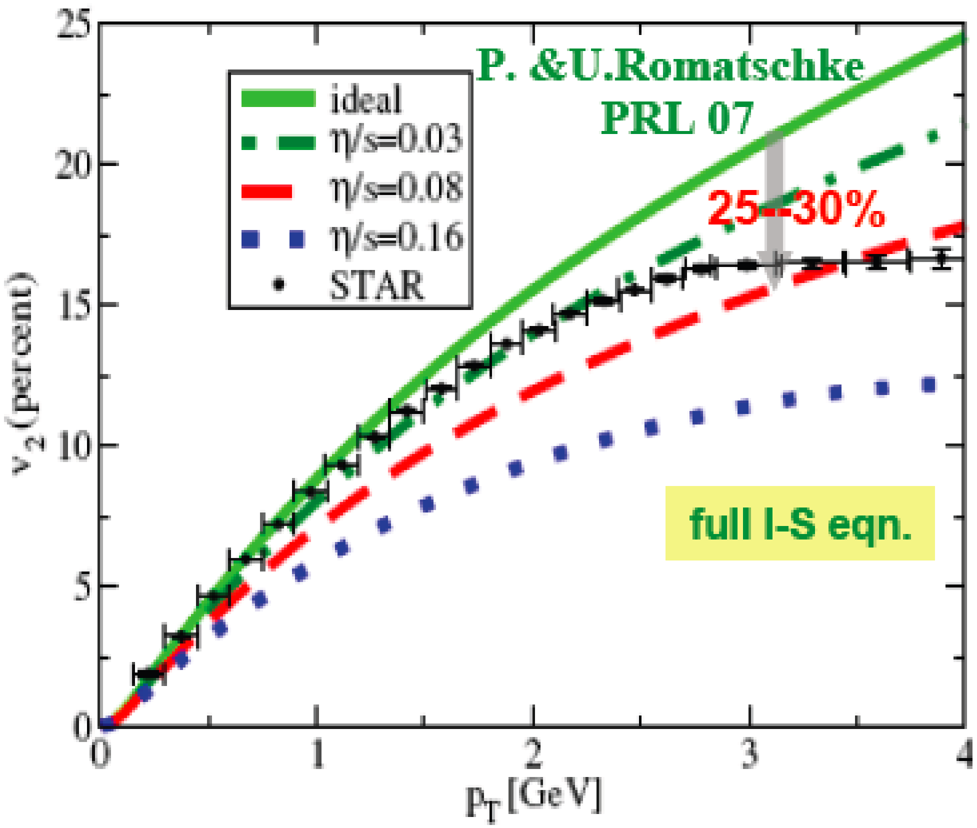


(Quark-Matter 02)



(Quark Matter 09)

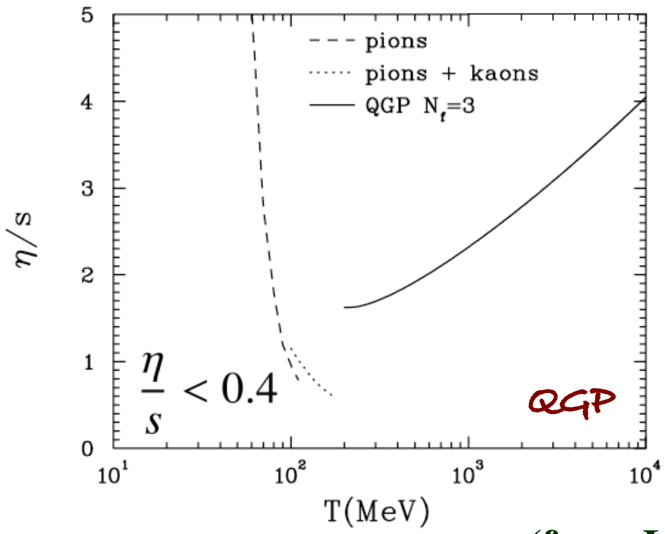
The low viscosity of the quark-gluon plasma

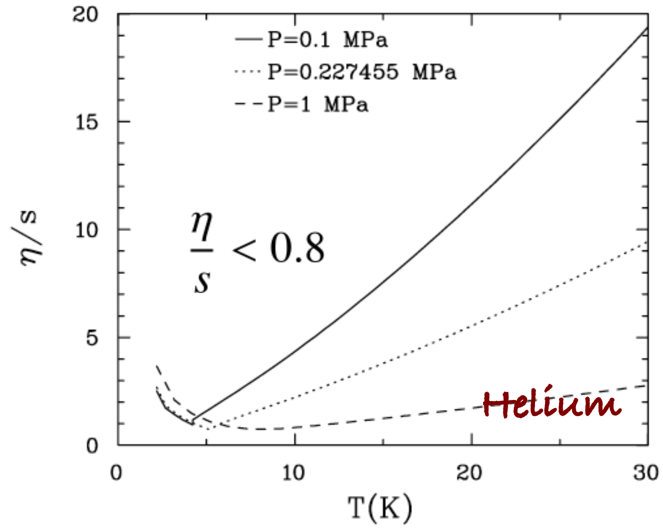


$$\frac{\eta}{s} < 5 \times \frac{1}{4\pi}$$

(M. Luzum and P. Romatschke, arXiv: 0804.4015)

Low viscosity, phase transition and strong coupling

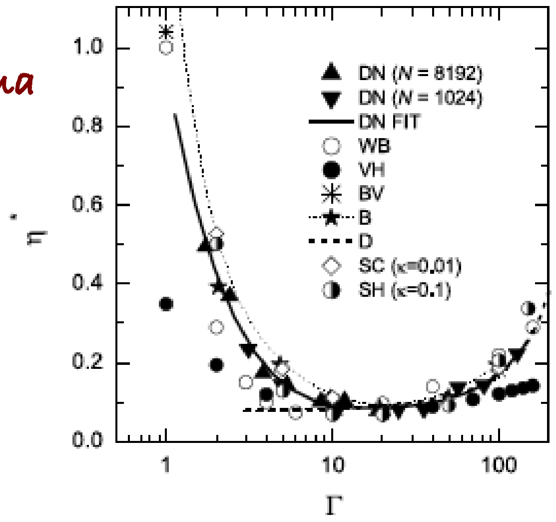




(from L. Csernai et al, nucl-th/0604032)

Strongly correlated plasma

(from Z. Donko et al, arXiv: 0710.5229)



Also, cold fermionic gas at unitarity $\frac{\eta}{s} \sim 0.5$

The ideal strongly coupled Quark-Gluon Plasma

A new 'reference' system

A theoretical breakthrough
AdS/CFT Duality

New techniques (borrowed from string theory) allow calculations in (some) strongly coupled gauge theories .

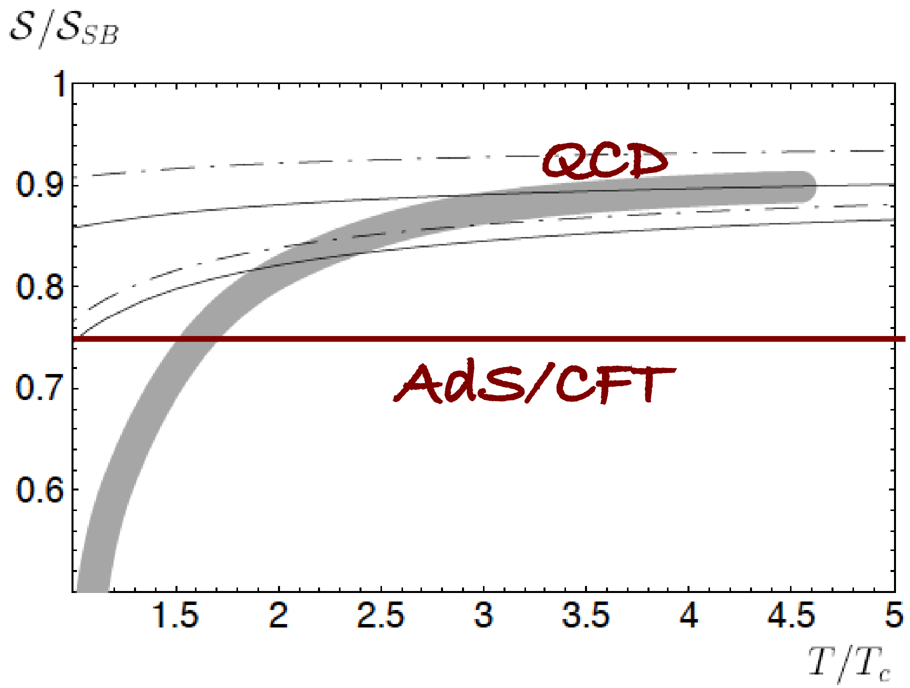
Rely on a mapping between a strongly coupled gauge theory and a weakly coupled (i.e. classical) gravity theory.

New reference state: the strongly coupled quark-gluon plasma (instead of the weakly coupled one).
New ideal system, allowing for many explicit Calculations.

Some strong coupling results

Simple limit of the entropy density at strong coupling

$$\frac{S}{S_0} = \frac{3}{4} + \frac{45}{32}\varsigma(3)\frac{1}{\lambda^{3/2}} \qquad \left(\lambda \equiv g^2 N_c\right)$$

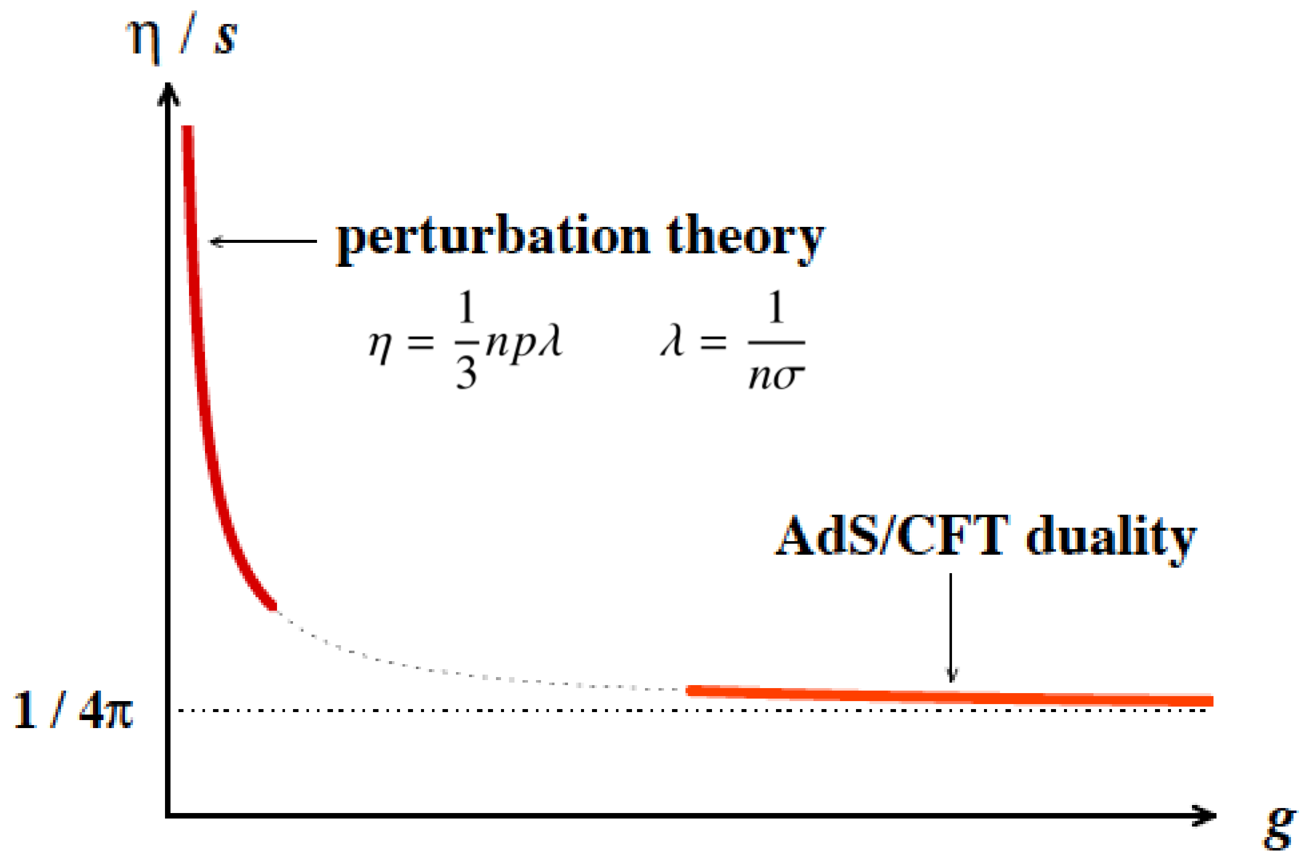


Simple result for the viscosity

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

(G. Poliacstro et al, PRL87 (2001))

Viscosity at weak and strong coupling



A puzzling situation

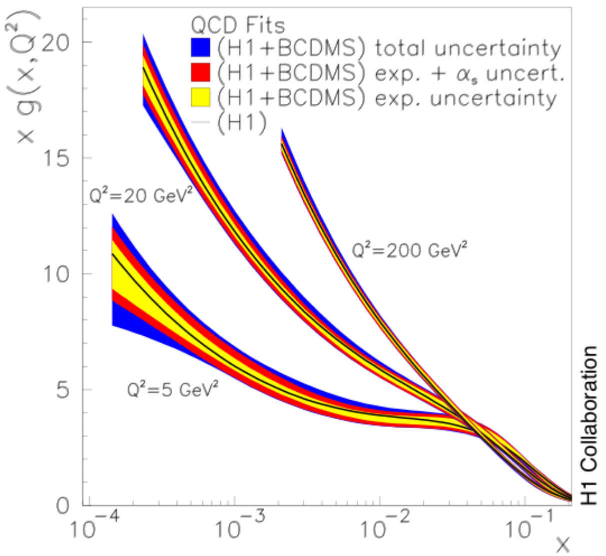
Weakly or strongly coupled ?

Weakly AND strongly coupled ...

In the qgp coexist degrees of freedom with different wavelengths. Whether these degrees of freedom are weakly or strongly coupled depends on their wavelength.

Non perturbative features arise from the cooperation of many degrees of freedom, or strong classical fields. An example: the color glass condensate.

High density partonic systems



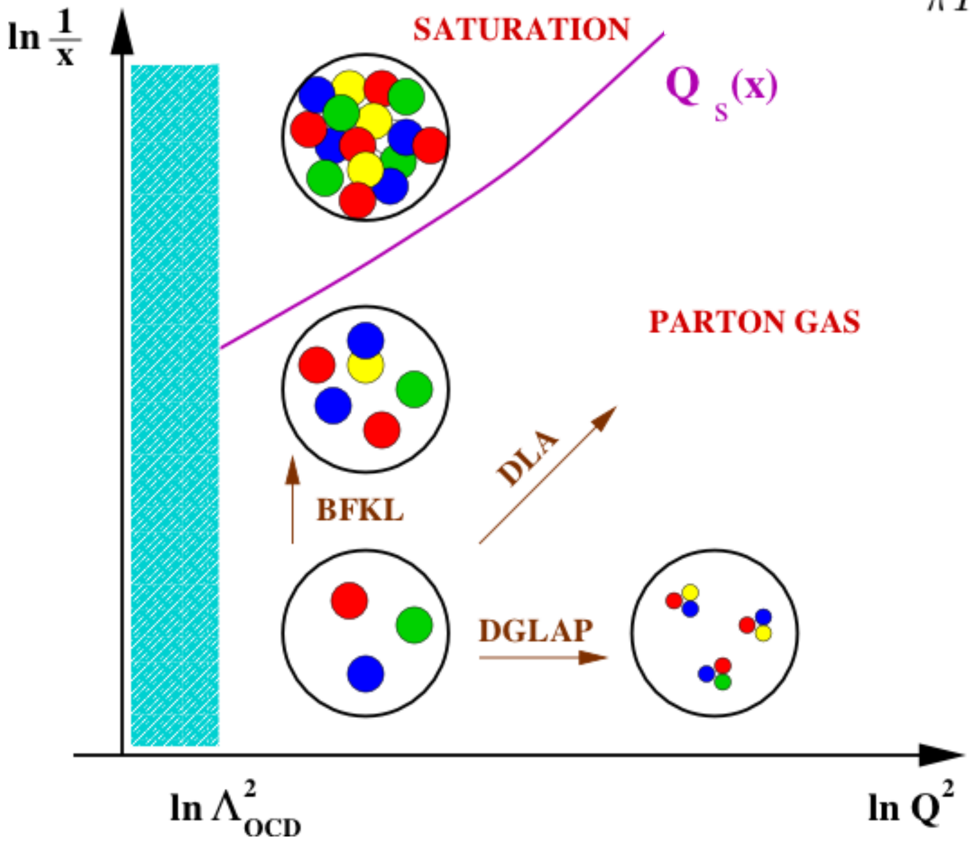
Large occupation numbers

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

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

> classical fields

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



The saturation scale from DIS

"Geometrical scaling"

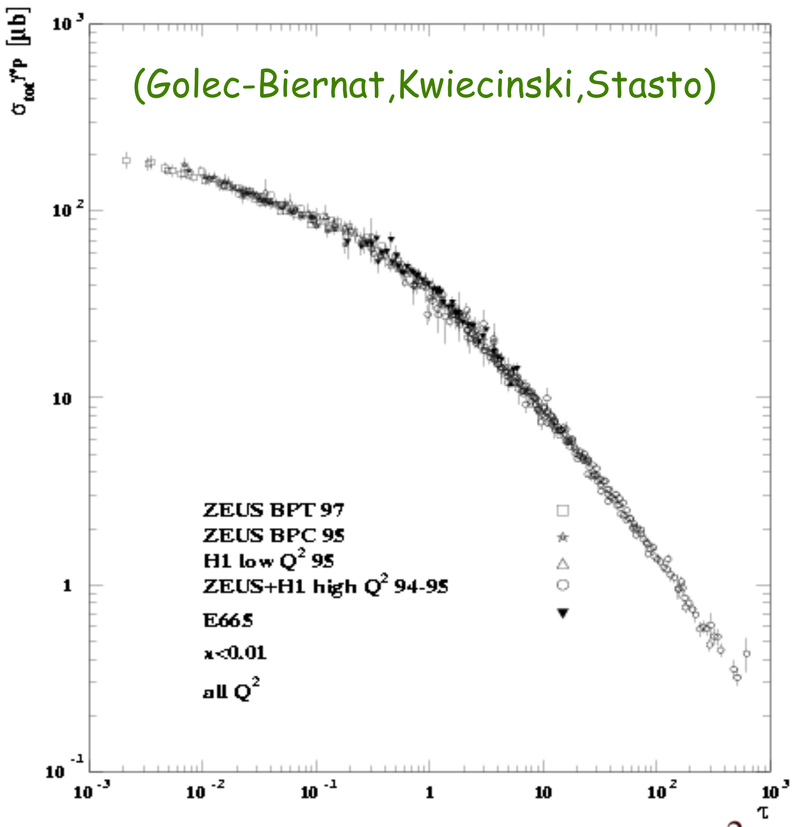
$$\sigma_{\gamma^* p}(x, Q^2) = \sigma_{\gamma^* p}(Q^2/Q_s^2(x))$$

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

$$Q_0 \approx 1Gev$$

$$x_0 \approx 3 \times 10^{-4}$$

$$\lambda \approx 0.3$$



Q^2/Q_s^2

The saturation scale in nuclei

In a nucleus : $\frac{xG_A(x,Q^2)}{\pi R^2} \sim A^{1/3}$ $\qquad Q_0^2 \to Q_0^2 A^{1/3}$

=>dependence on impact parameter $Q_s^2(b) = Q_s^2(0)\sqrt{1 - b^2/R^2}$

In a AA collision, partons are set free at (proper) time $\tau \sim Q_s^{-1}$

with typical transverse momenta $k_T \sim Q_s$

they interact with strength $\alpha_s = \alpha_s(Q_s)$

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

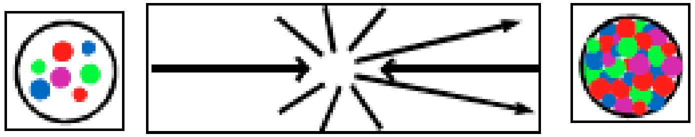
Successful phenomenology at RHIC

RBRC wks, BNL, May 2010 : http://www.bnl.gov/riken/glasma/

Di-hadron production
Azimuthal correlations at forward rapidity

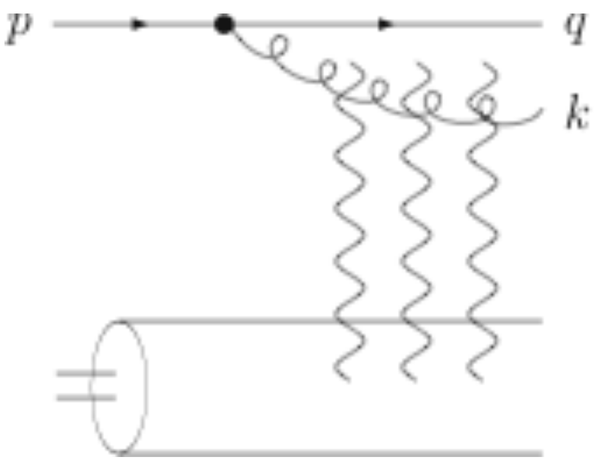
$$\mathrm{d\,Au} \to \mathrm{h_1\,h_2\,X}$$

$$x_p = \frac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}}$$



$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$

$$x_p \sim 1,\ x_A << 1$$



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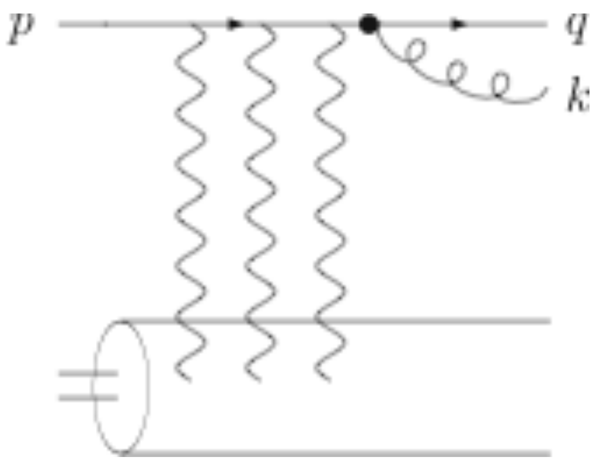
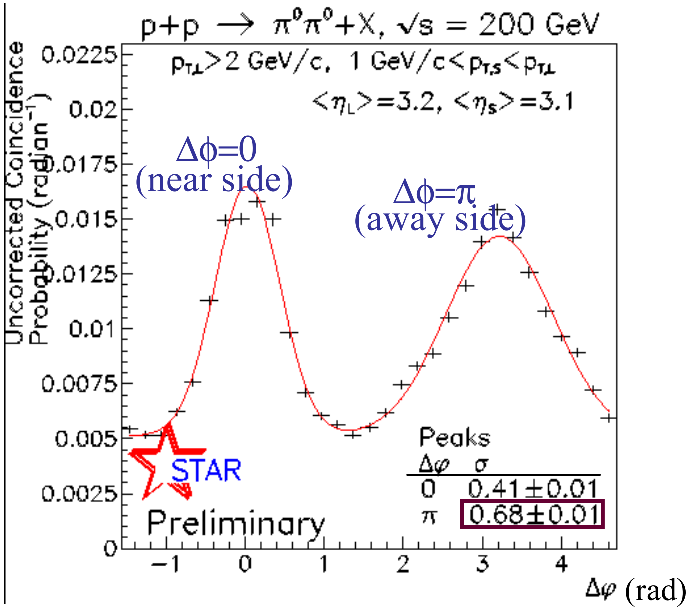
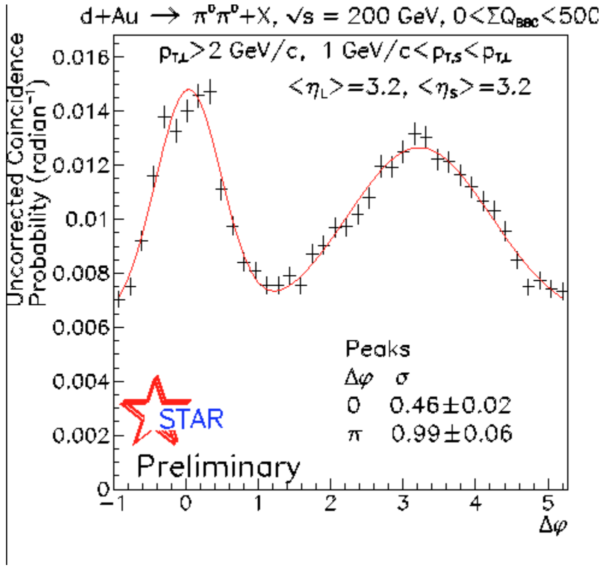


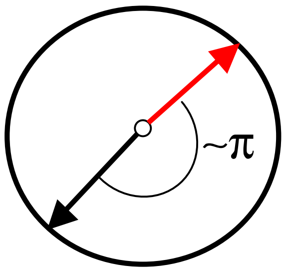
Azymuthal correlations

p+p

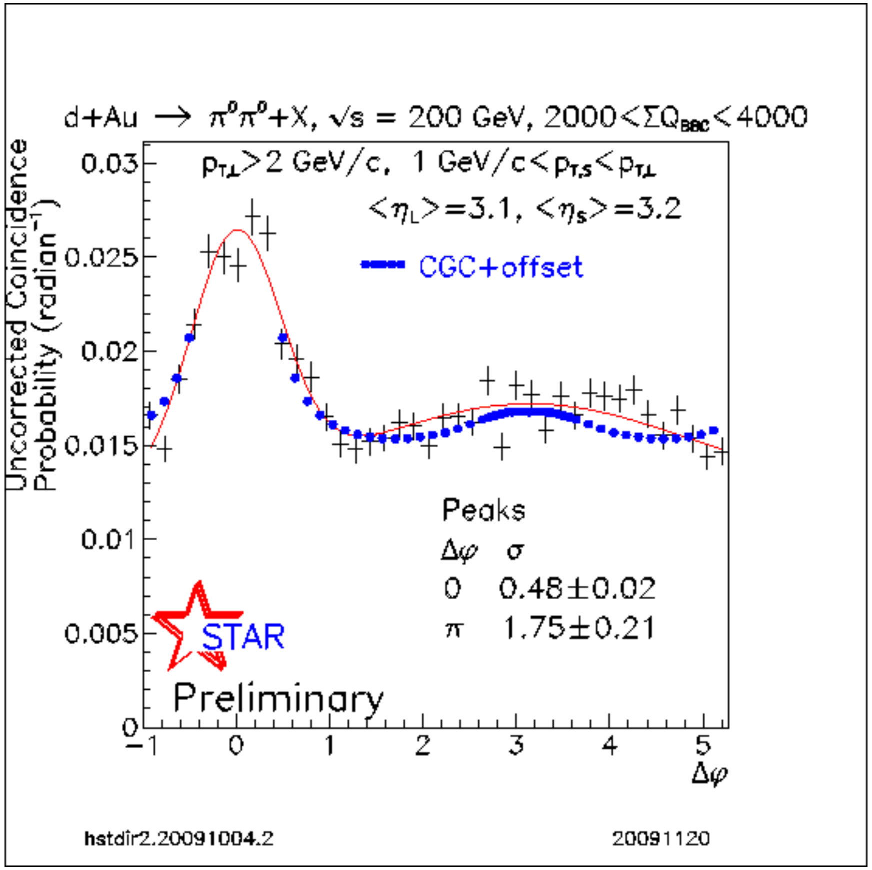


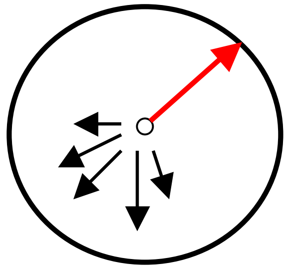
d+Au peripheral





Disappearance of away side jet in central d+Au





(Albacete & Marquet RBRC wks, May 2010)

Conclusions

- the field of ultra-relativistic heavy ion collisions is a very rich one: hot and dense QCD matter, high density partonic systems, etc.

- exciting developments in recent years, both experimentally and theoretically (RHIC; CGC, AdS/CFT, etc)

- many open questions/puzzles (weak vs strong coupling, thermalization, etc)

- some of these open questions will be clarified at the LHC (in particular, good prospect to study parton saturation at the LHC, in pp, AA and pA collisions)