Heavy Ion Collisions
Puzzles and Hopes

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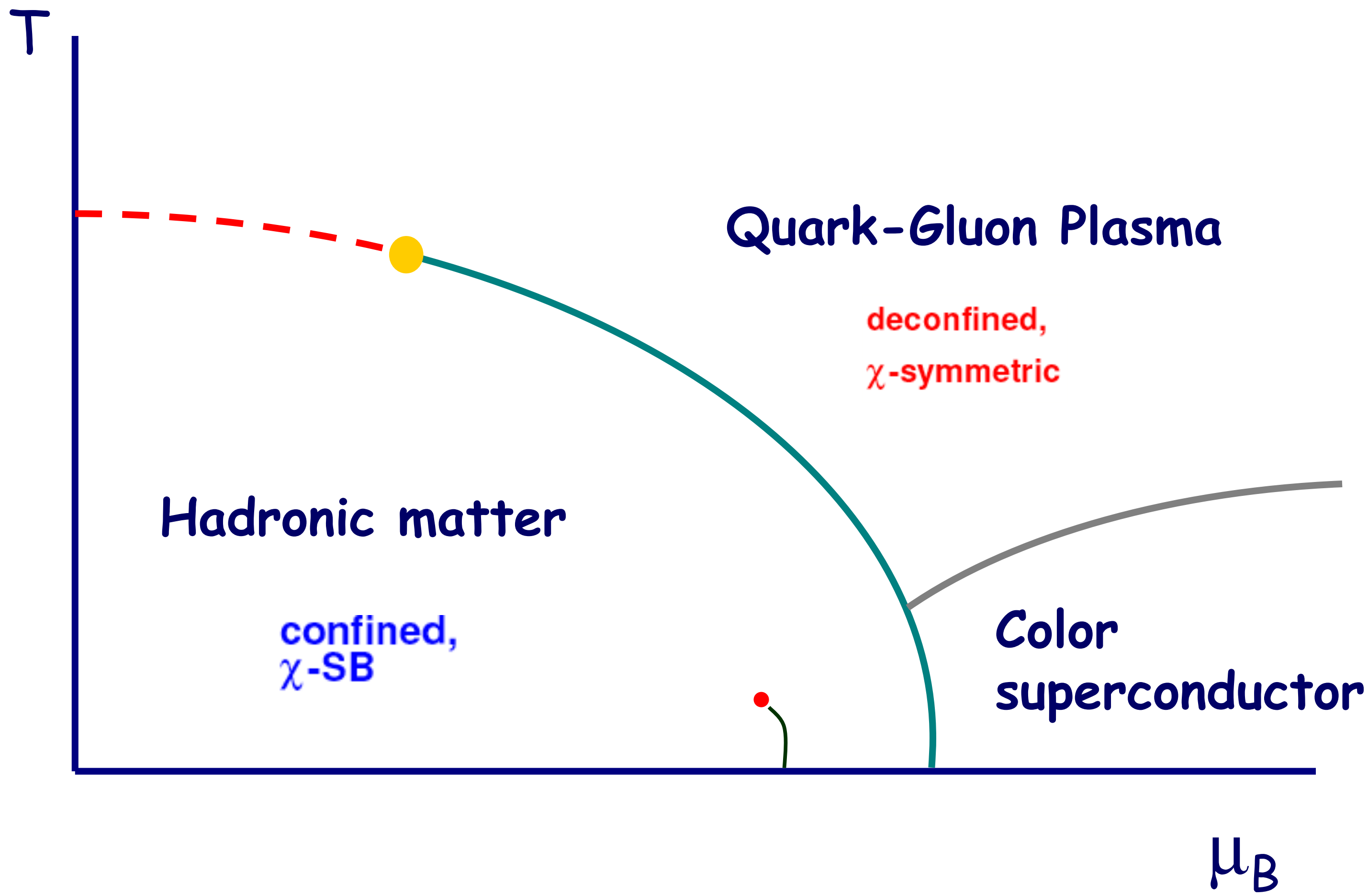
Fundamental questions

- 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?

The QCD phase diagram

(« low resolution »)



Road map

From the 'old' to the 'new' paradigm (sQGP)

Why is the present situation puzzling?

- Where Is the strongly coupled character of the QGP coming from ?
- Is it compatible with our present understanding of particle production in nucleus-nucleus collisions

Initial wave-functions, gluon saturation, etc

The Ideal baryonless Quark-Gluon Plasma

looking at the old paradigm

Asymptotic freedom

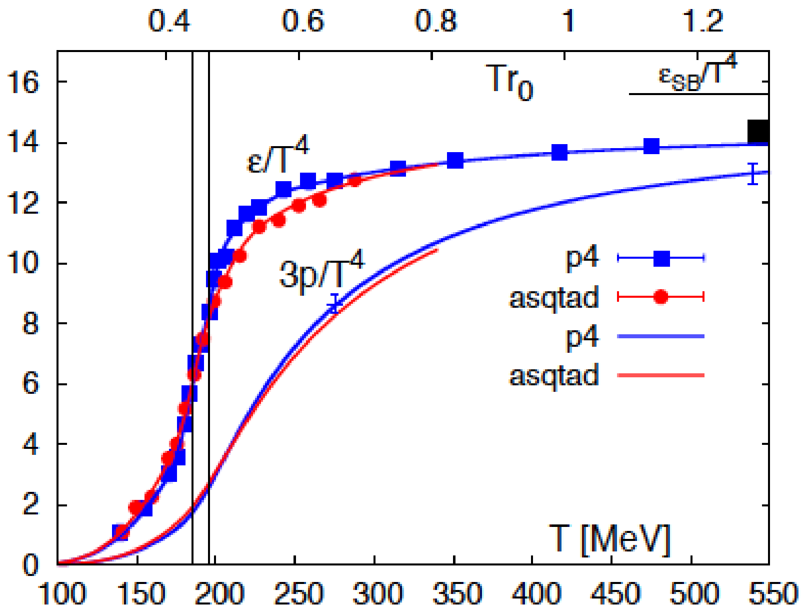
$$\alpha_s = \frac{g^2}{4\pi} \approx \frac{2\pi}{b_0 \ln\left(\mu / \Lambda_{QCD}\right)} \qquad \left(\mu \approx 2\pi T\right)$$

Matter is « simple » at high temperature:

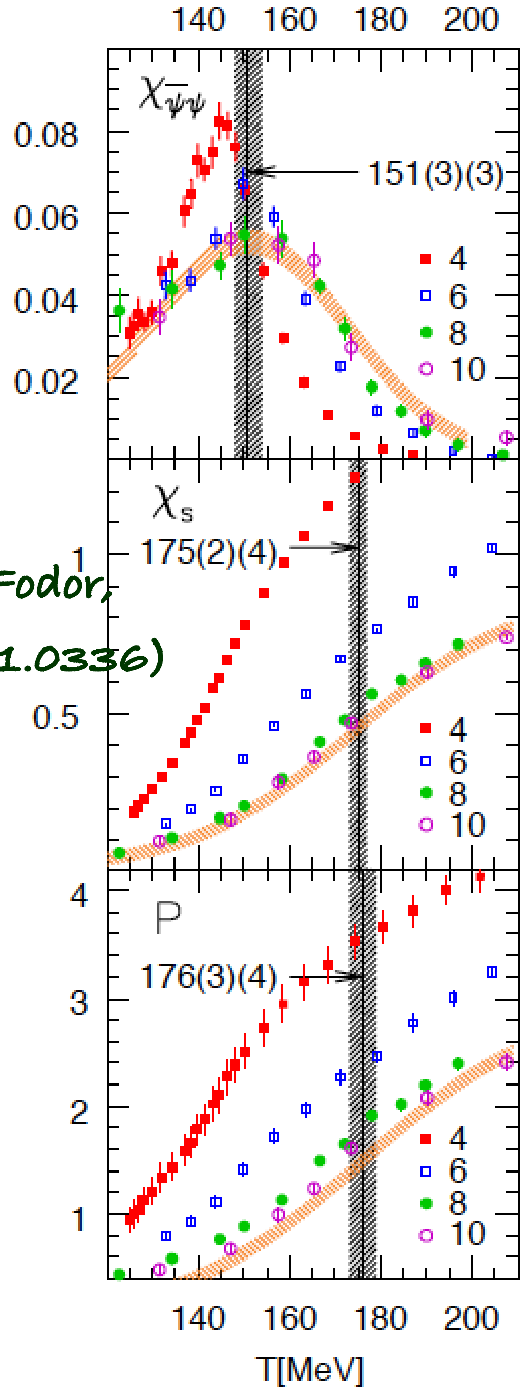
- an ideal gas of quarks and gluons
- the dominant effect of interactions is to turn (massless) quarks and gluons into weakly interacting (massive) quasiparticles.

Phase transition(s)

(crossover)

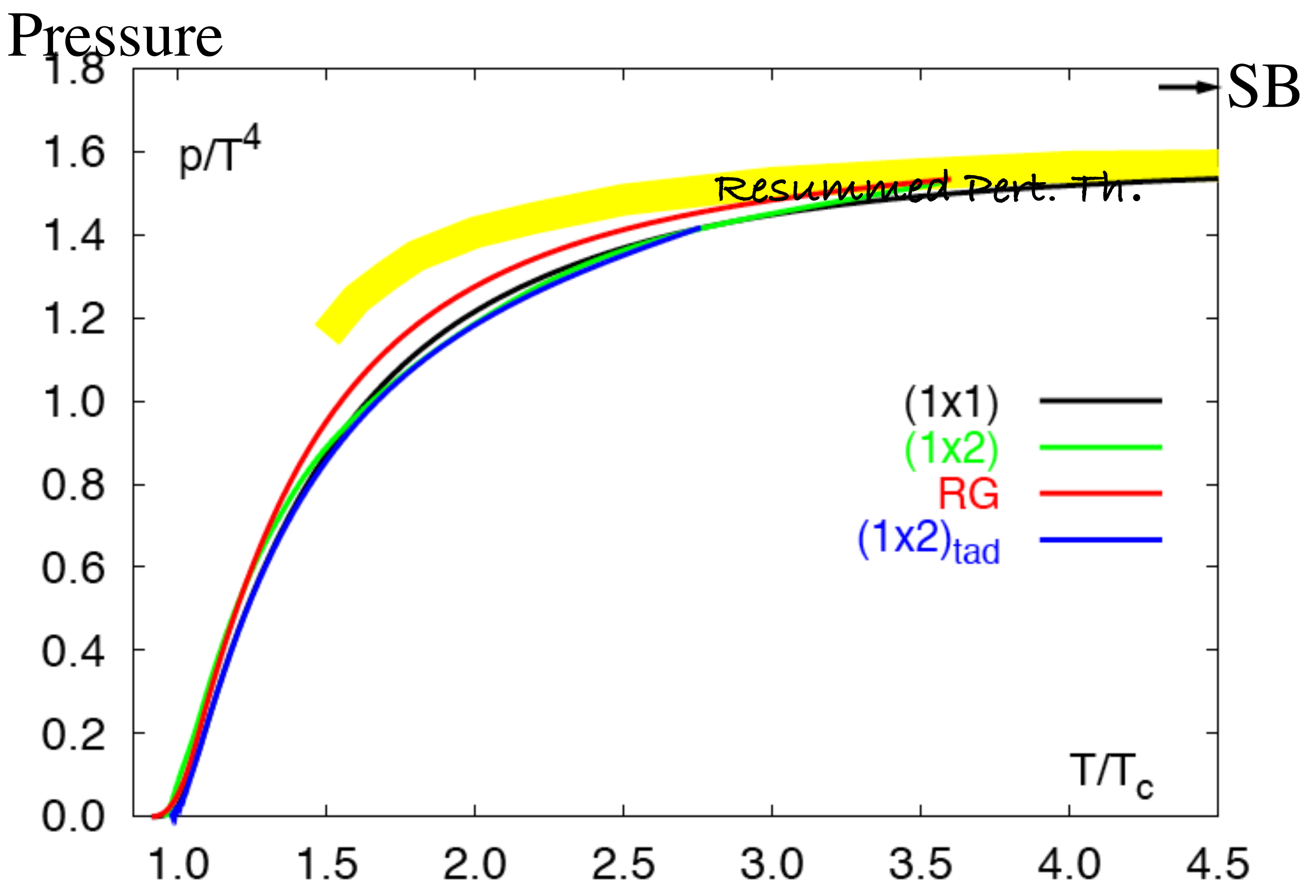


(from M. Bazavov et al, arXiv:0903.4379)



(from Z. Fodor, arXiv:0711.0336)

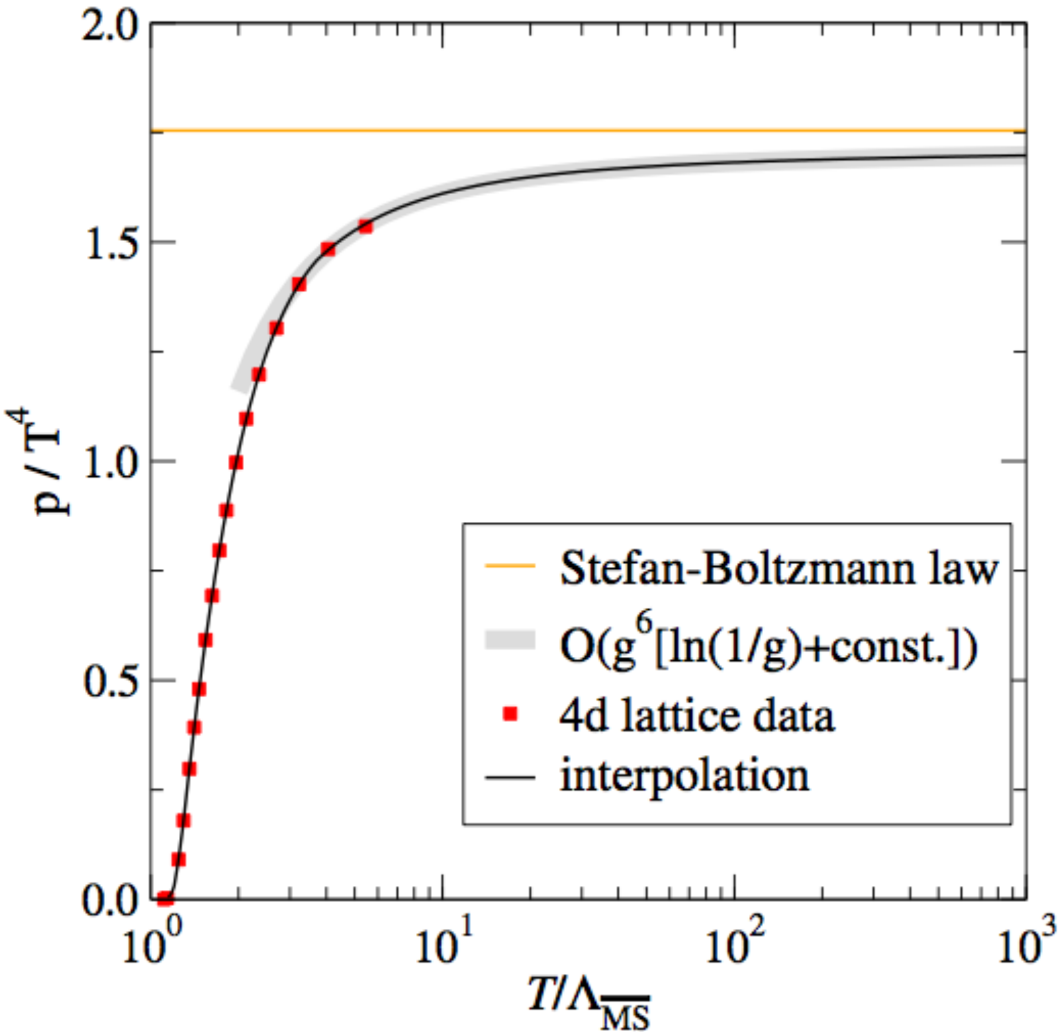
At T>3Tc Resummed Pert. Theory accounts for lattice results



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

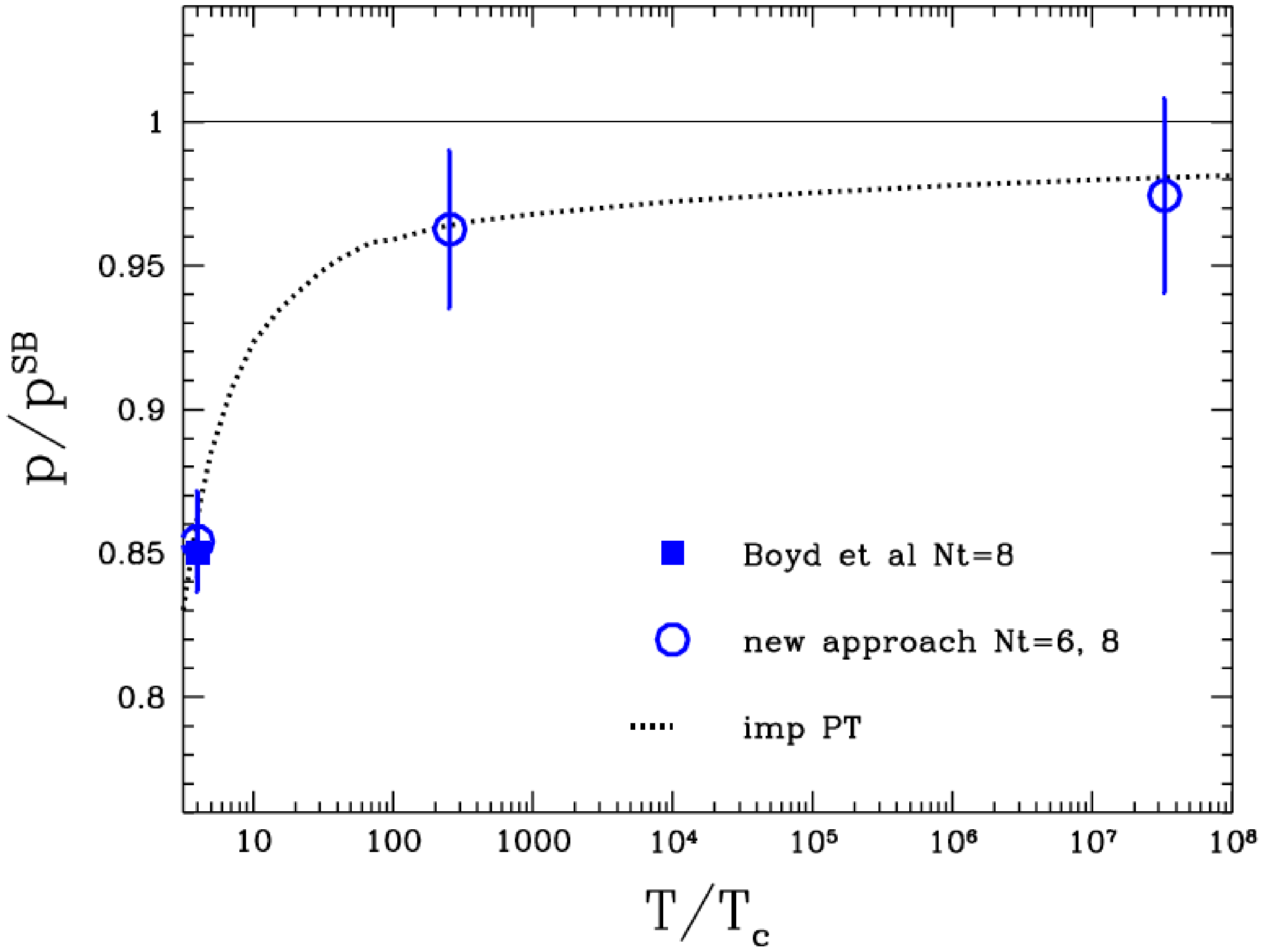
(resummed pert. th. from J.-P. B., E. Iancu, A. Rebhan: Nucl.Phys.A698:404-407,2002)

State of the art in high order perturbative calculations



(from M. Laine, Y Schroeder, hep-ph/0603048)

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

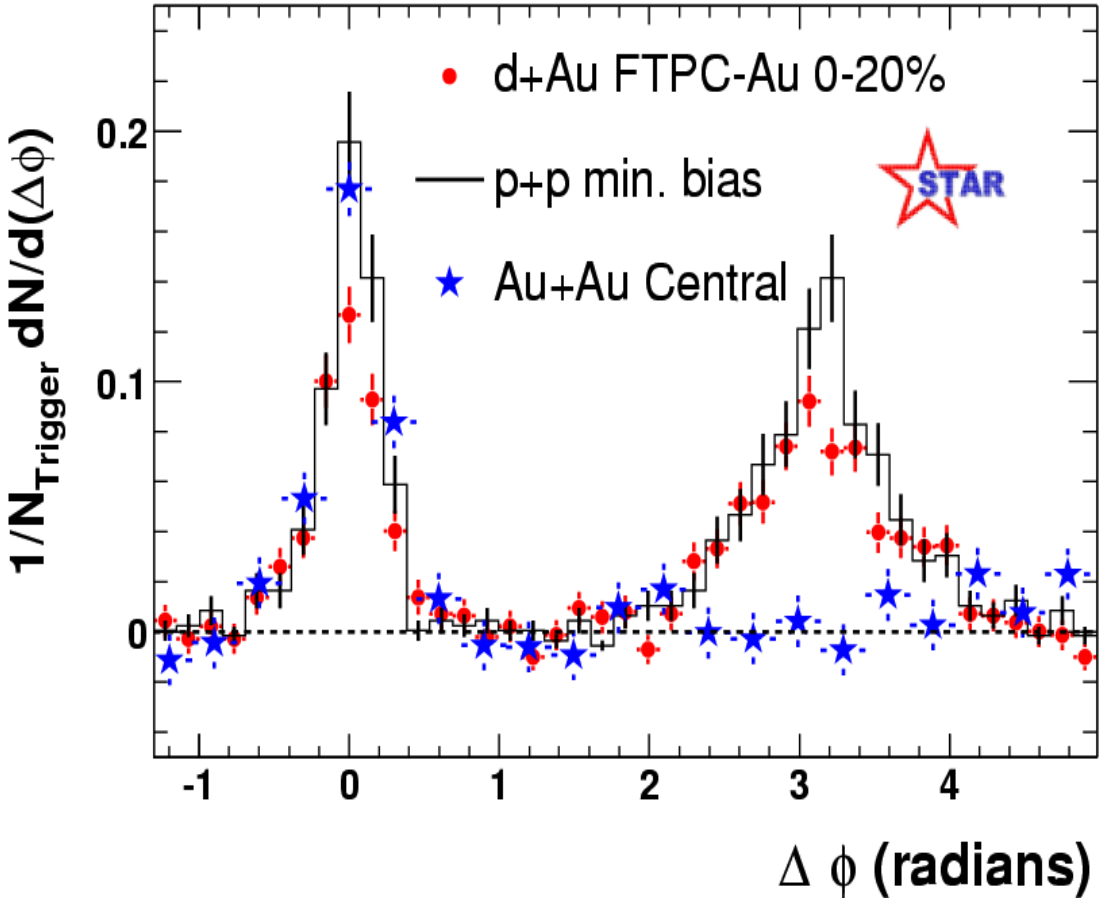


(from G. Endrodi et al, arXiv: 0710.4197)

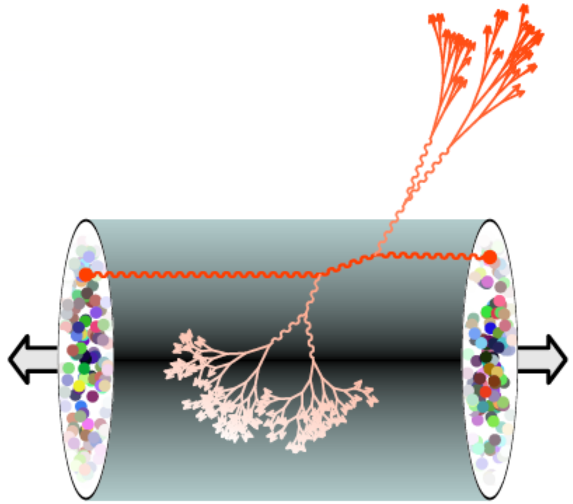
From the « ideal gas » to the « perfect liquid »

Lessons from RHIC

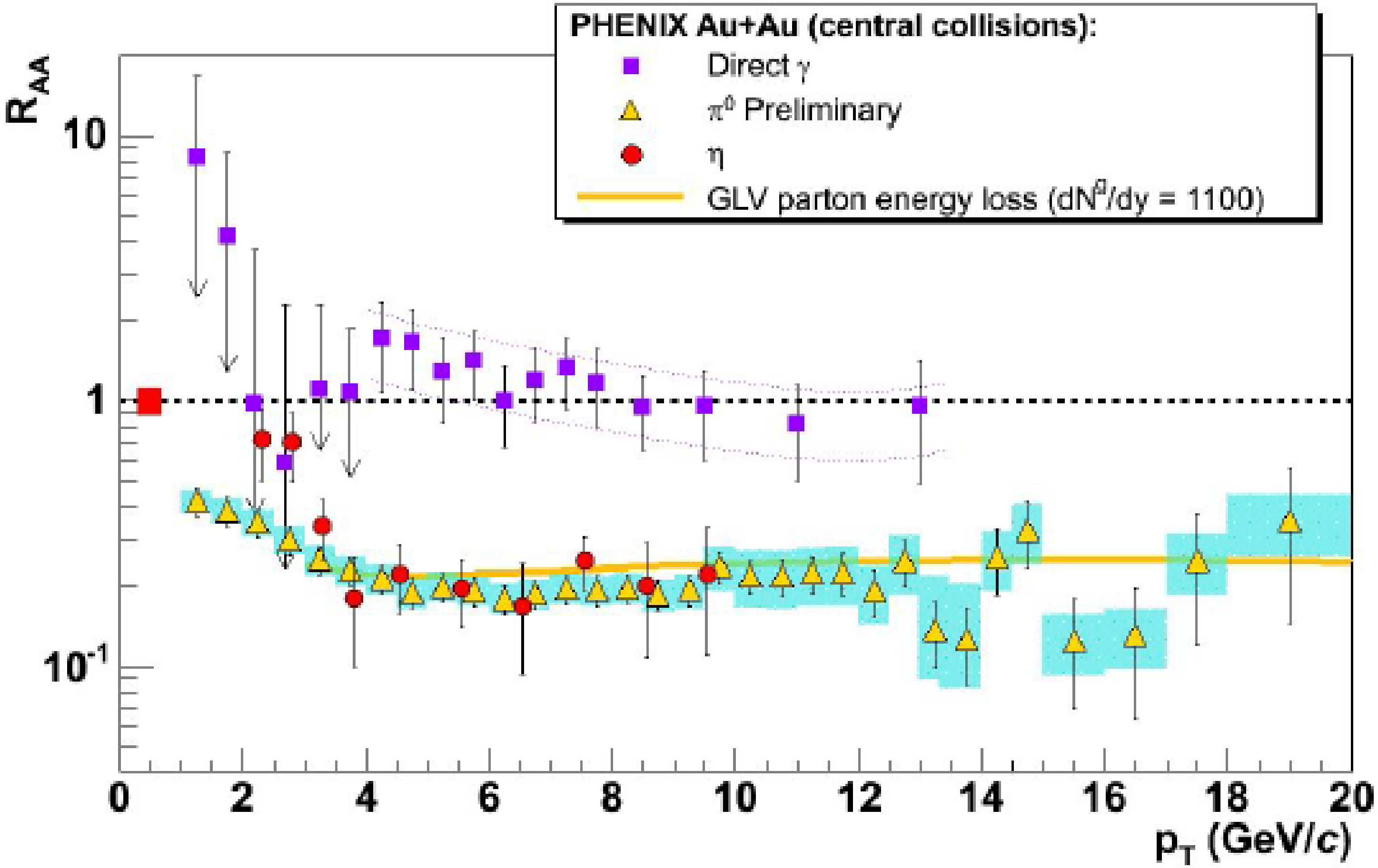
Matter is opaque to the propagation of jets



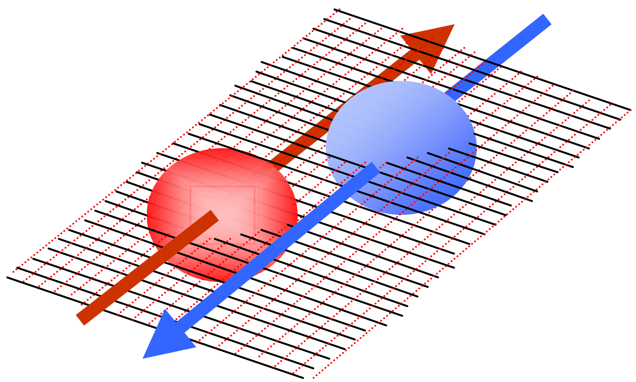
(STAR: Phys.Rev.Lett.91:072304,2003)



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

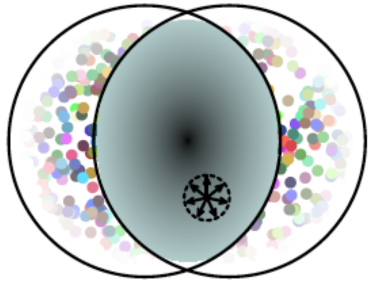


(from Akiba et al, NPA 774 (2006) 403)

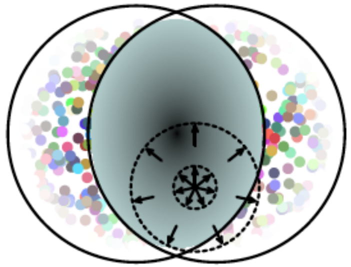


Matter flows like a fluid

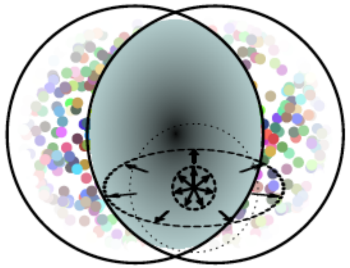
Initial momentum distribution isotropic



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

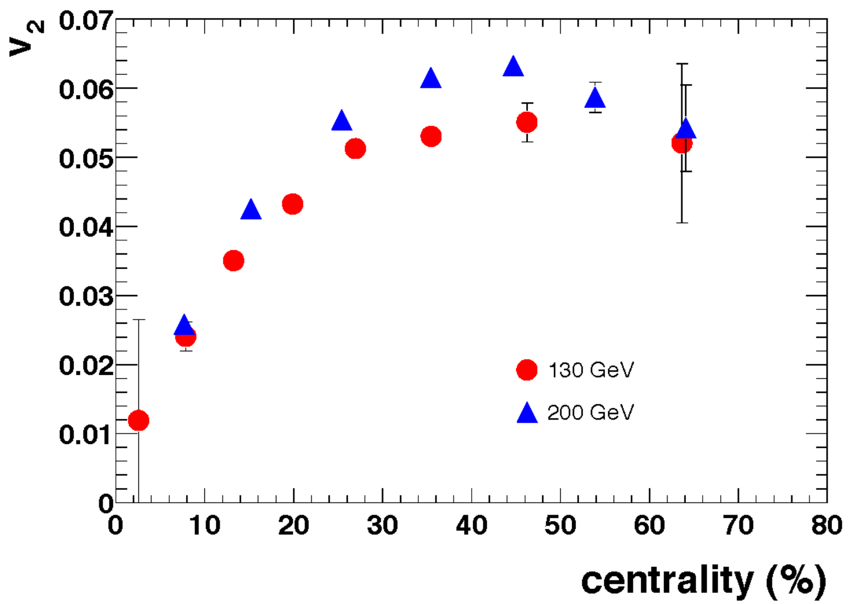


Strong interactions induce pressure gradients. The expansion becomes anisotropic, and the momentum distribution reflects the anisotropy of the initial interaction region

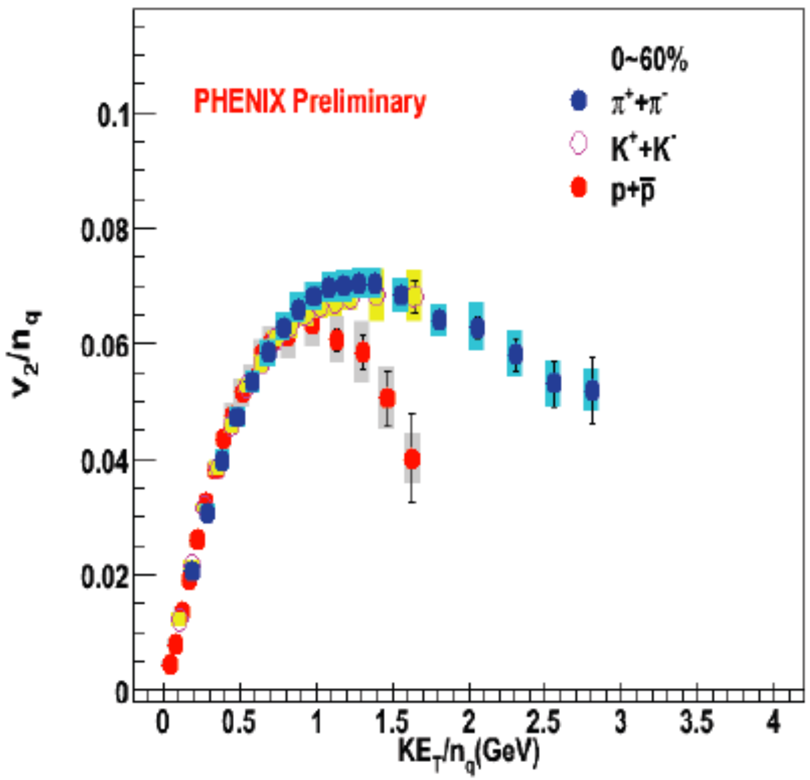


Elliptic flow

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

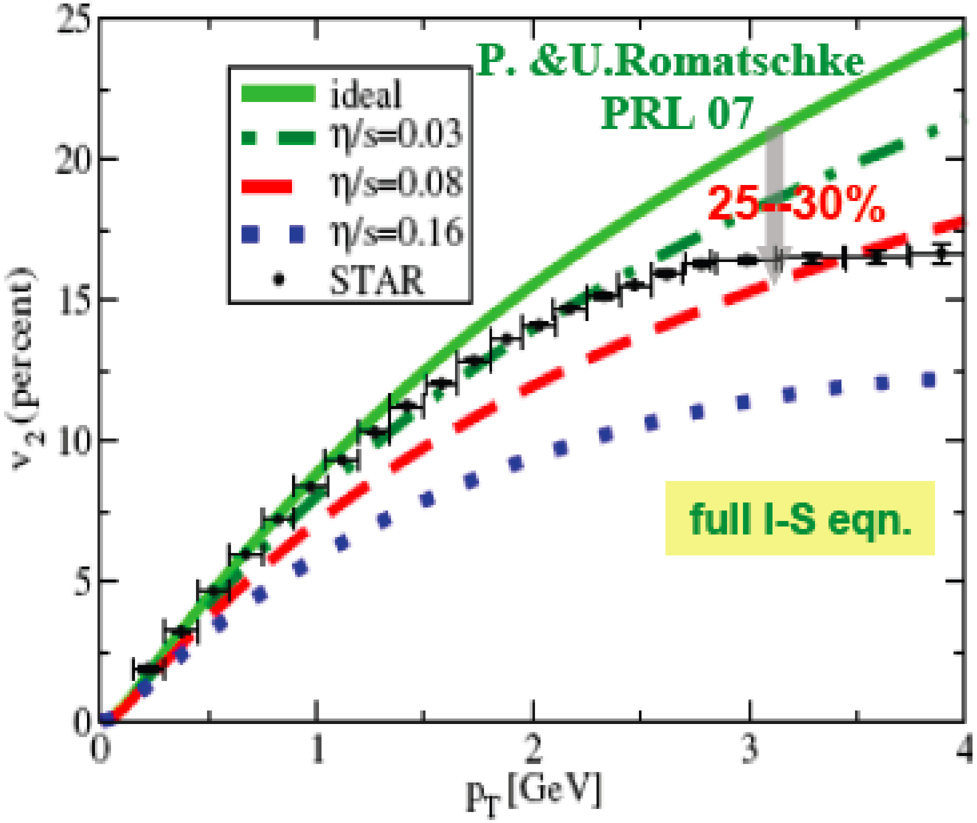


(Quark-Matter 02)



(Quark Matter 09)

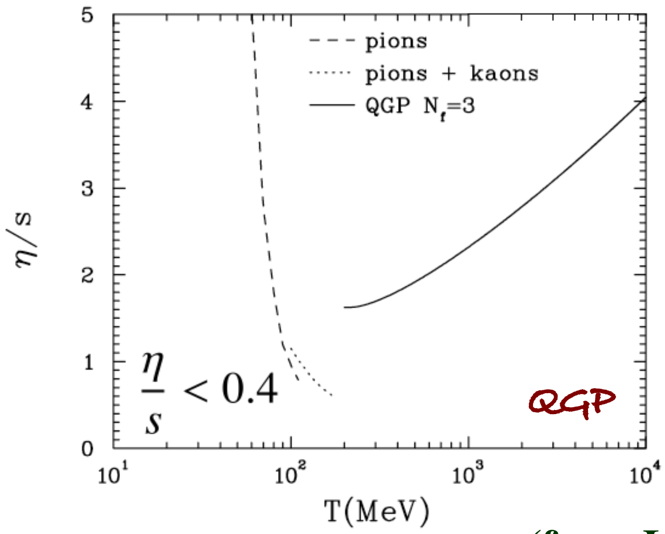
The low viscosity of the quark-gluon plasma

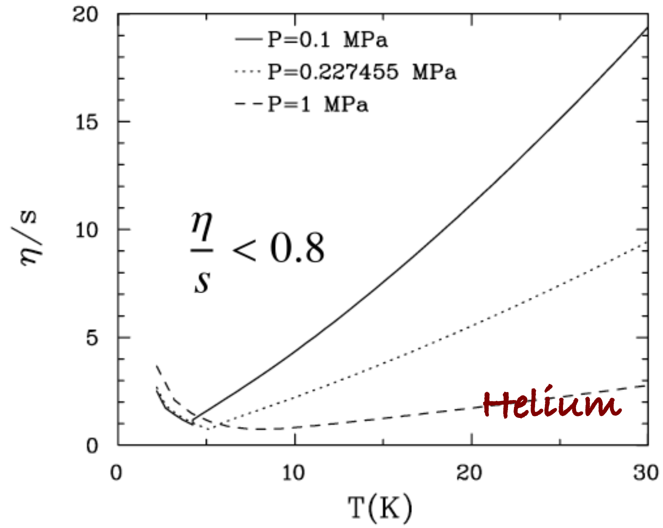


$$\frac{\eta}{s} < 5 \times \frac{1}{4\pi}$$

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

Low viscosity, phase transition and strong coupling

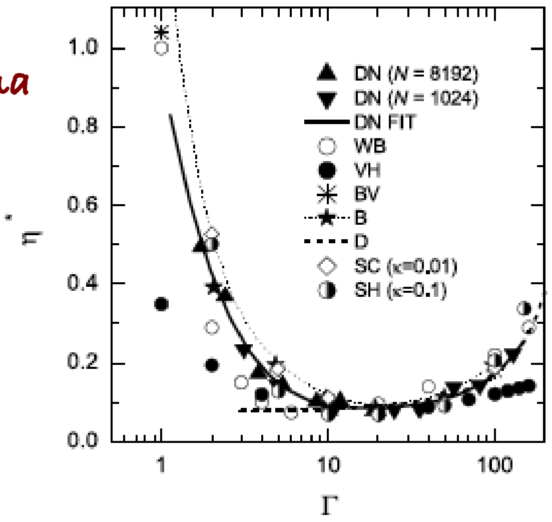




(from L. Csernai et al, nucl-th/0604032)

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 .

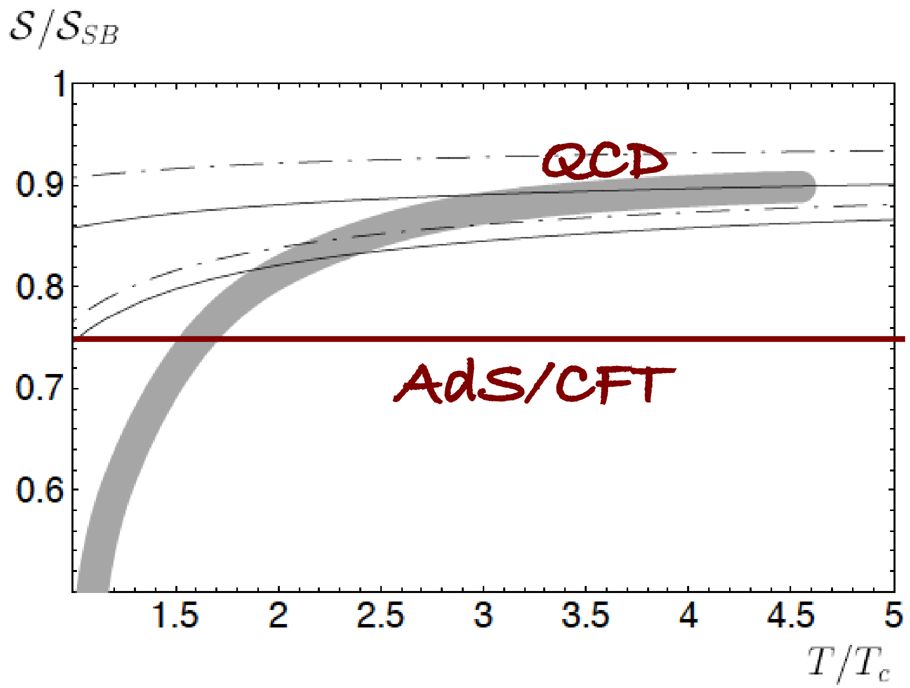
Rely on a mapping between a strongly coupled gauge theory and a weakly coupled (i.e. classical) gravity theory.

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

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

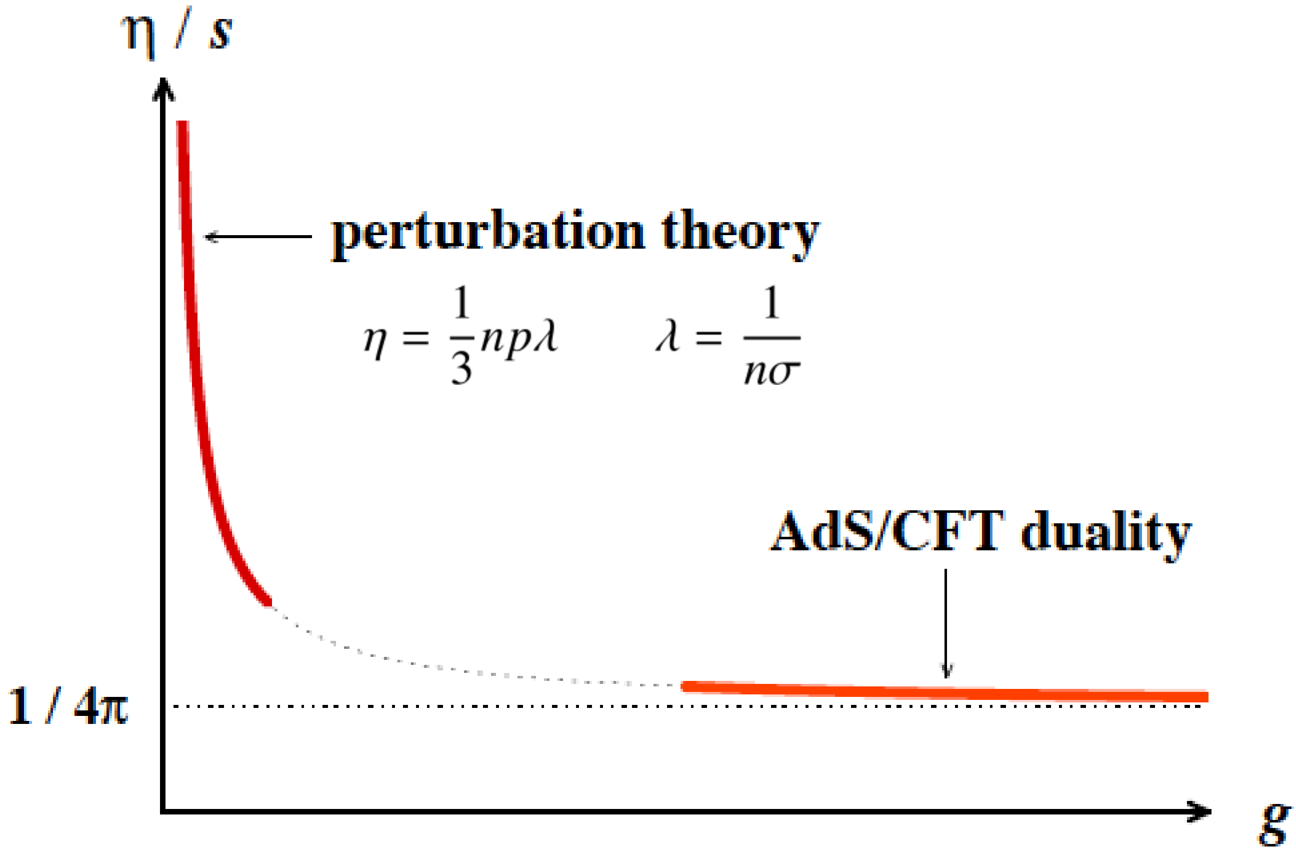


Simple result for the viscosity

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

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

Viscosity at weak and strong coupling



A puzzling situation

Where is the apparent strongly coupled character of the QGP coming from ?

Is initial concept wrong ?

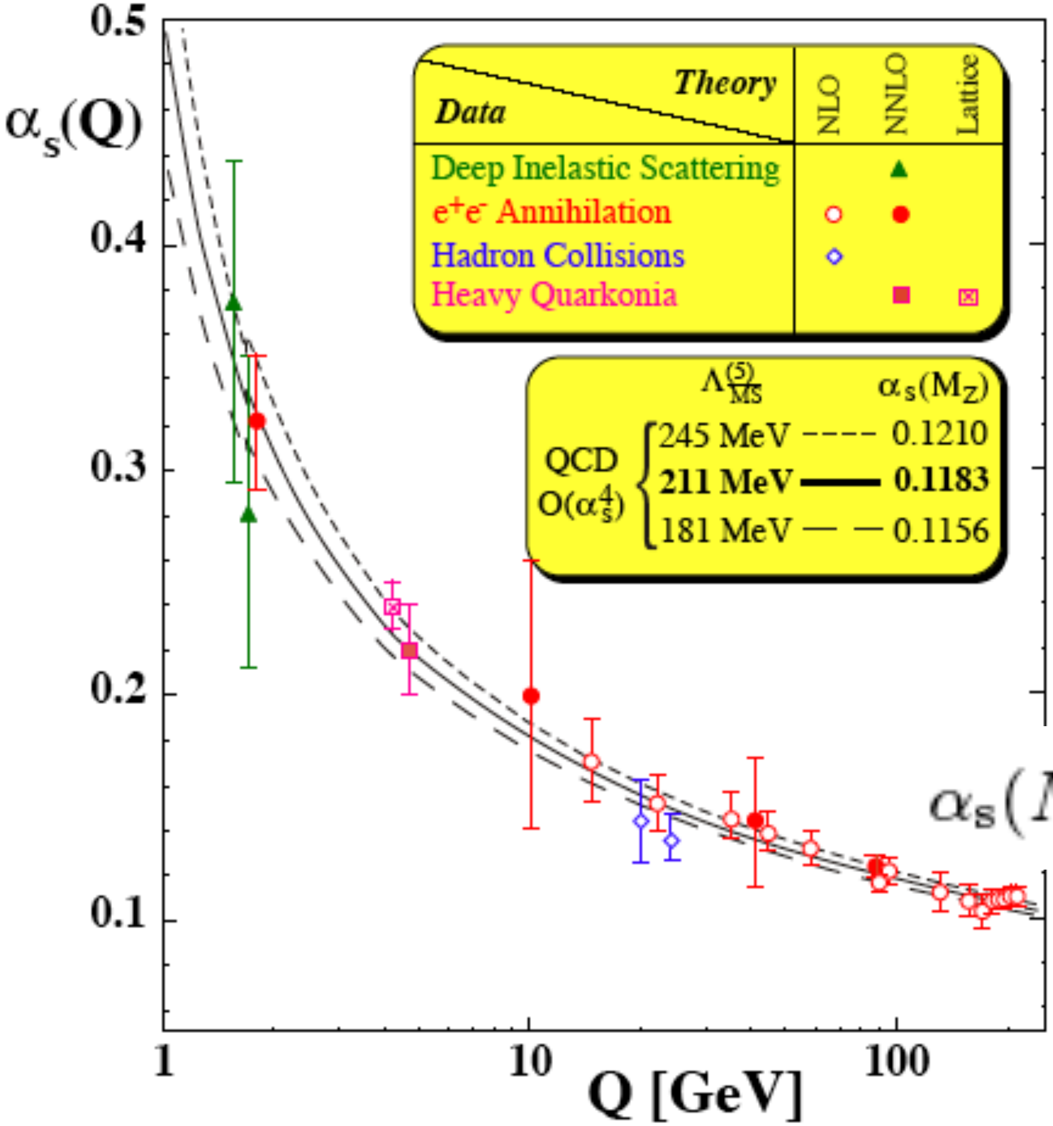
No…

QCD asymptotic freedom works !

Is the coupling constant large ?

Not really !

The QCD running coupling constant

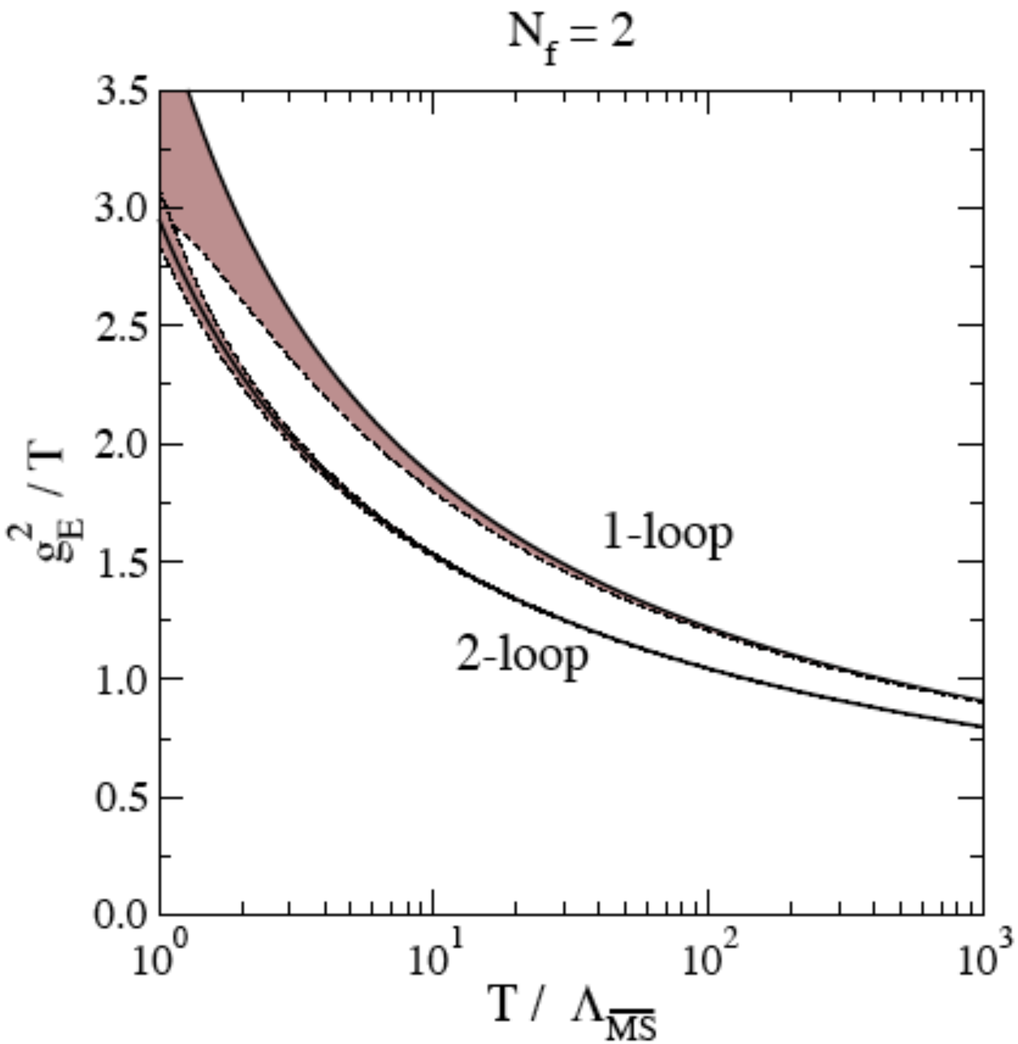


$$\alpha_s = \frac{g^2}{4\pi}$$

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

(S. Bethke, hep-ex/0211012)

The effective coupling is not huge, even close to Tc



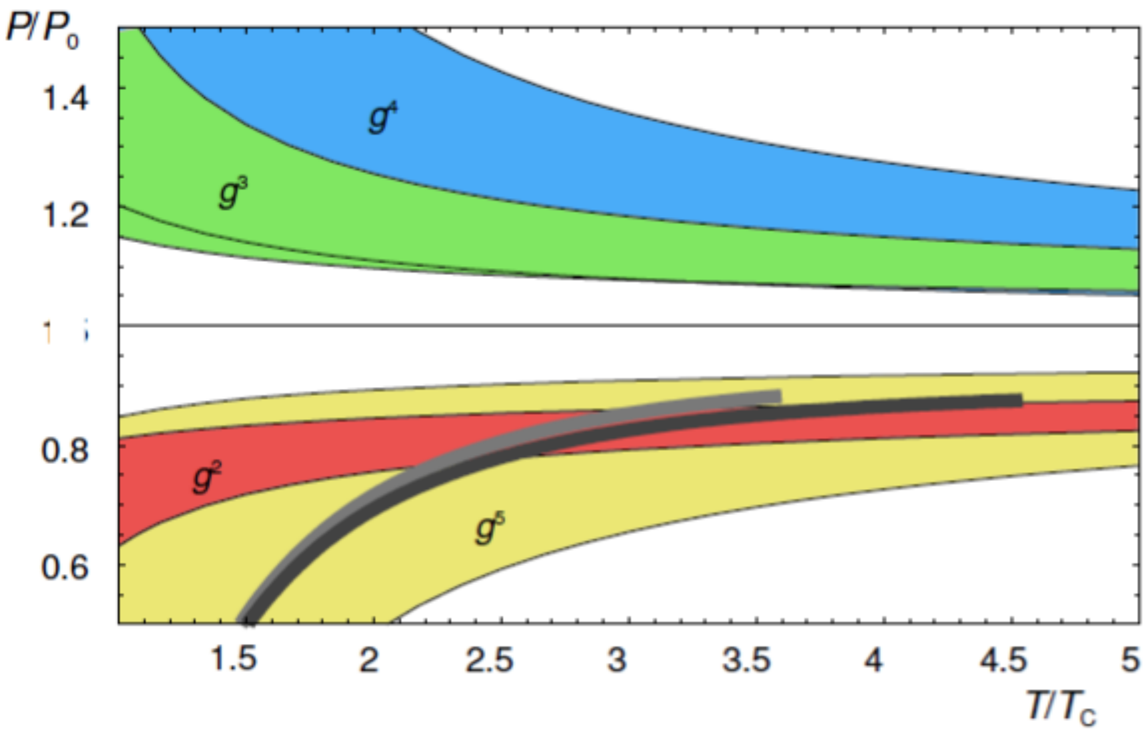
M. Laine, Y. Schröder, hep-ph/0503061

Strict perturbation theory breaks down

But

-this has (almost) nothing to do with QCD
-Pb can be handled with a variety of techniques (resummations, exact RG, etc)

Perturbation theory is ill behaved at finite temperature



Perturbation theory:

g^2: Shuryak; Chin (1978)

g^3: Kapusta (1979)

g^4 ln g: Toimela (1983)

g^4 : Arnold, Zhai (1994)

g^5 : Zhai, Kastening (1995), Braaten, Nieto (1996)

g^6 ln g: Kajantie, Laine, Rummukainen, Schröder (2002)

g^6 (partly): Di Renzo, Laine, Miccio, Schröder, Torrero (2006)

Lattice data: G. Boyd et al. (1996); M. Okamoto et al. (1999).

Weakly AND strongly coupled ...

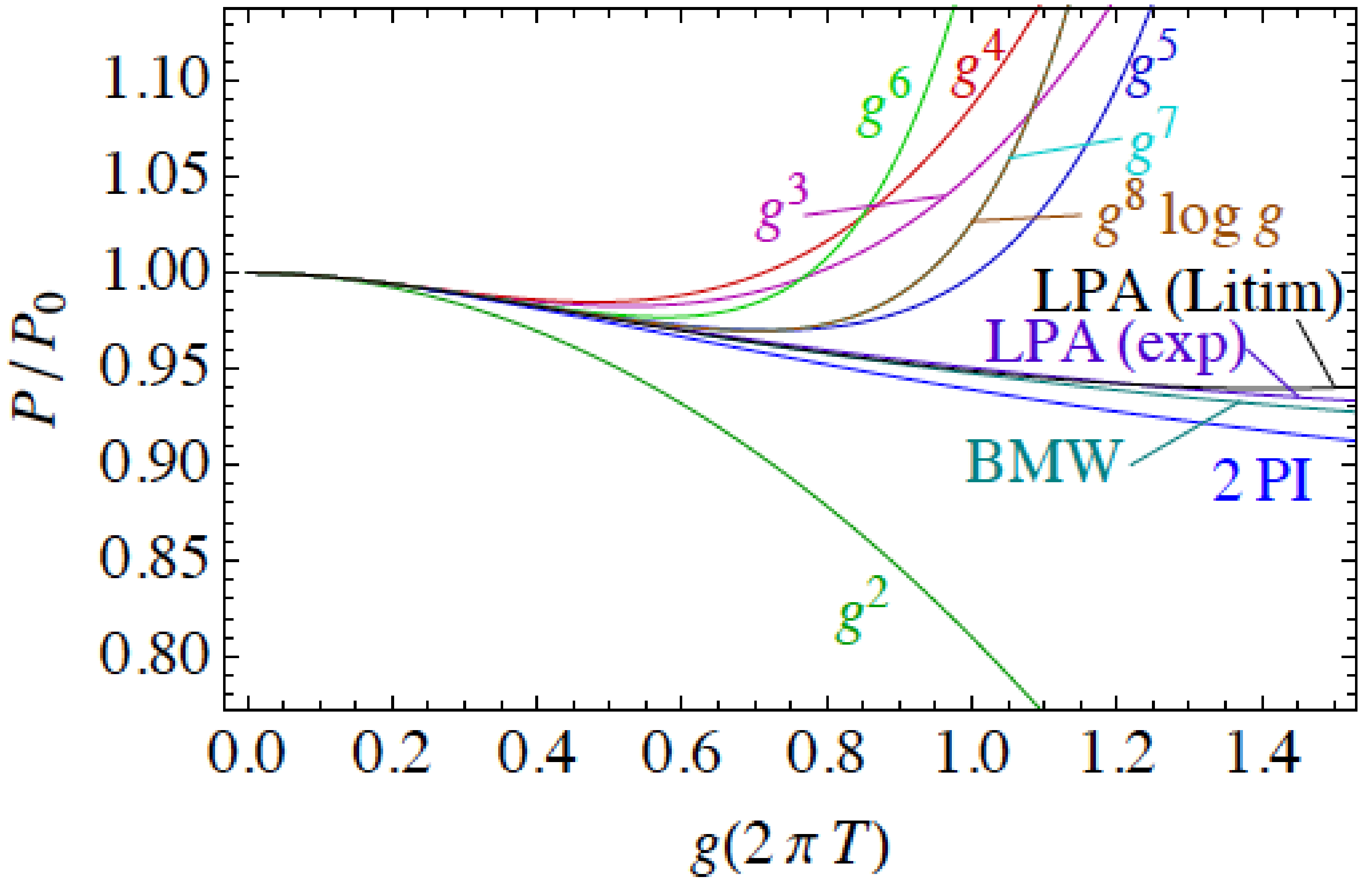
The QGP is a multiscale system

Degrees of freedom with different wavelengths are differently coupled.

Expansion parameter depends on magnitude of thermal fluctuations and on their wavelengths

$$\gamma_\kappa = \frac{g^2 \langle A^2 \rangle_\kappa}{\kappa^2}$$

RG techniques yield smooth extrapolation to strong coupling (scalar field theory)

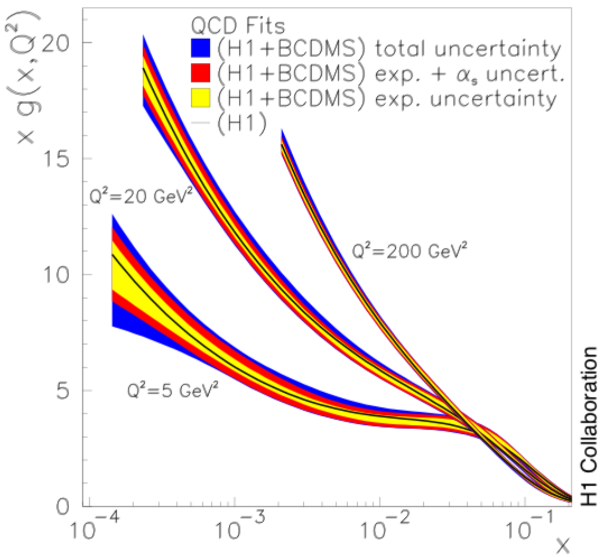


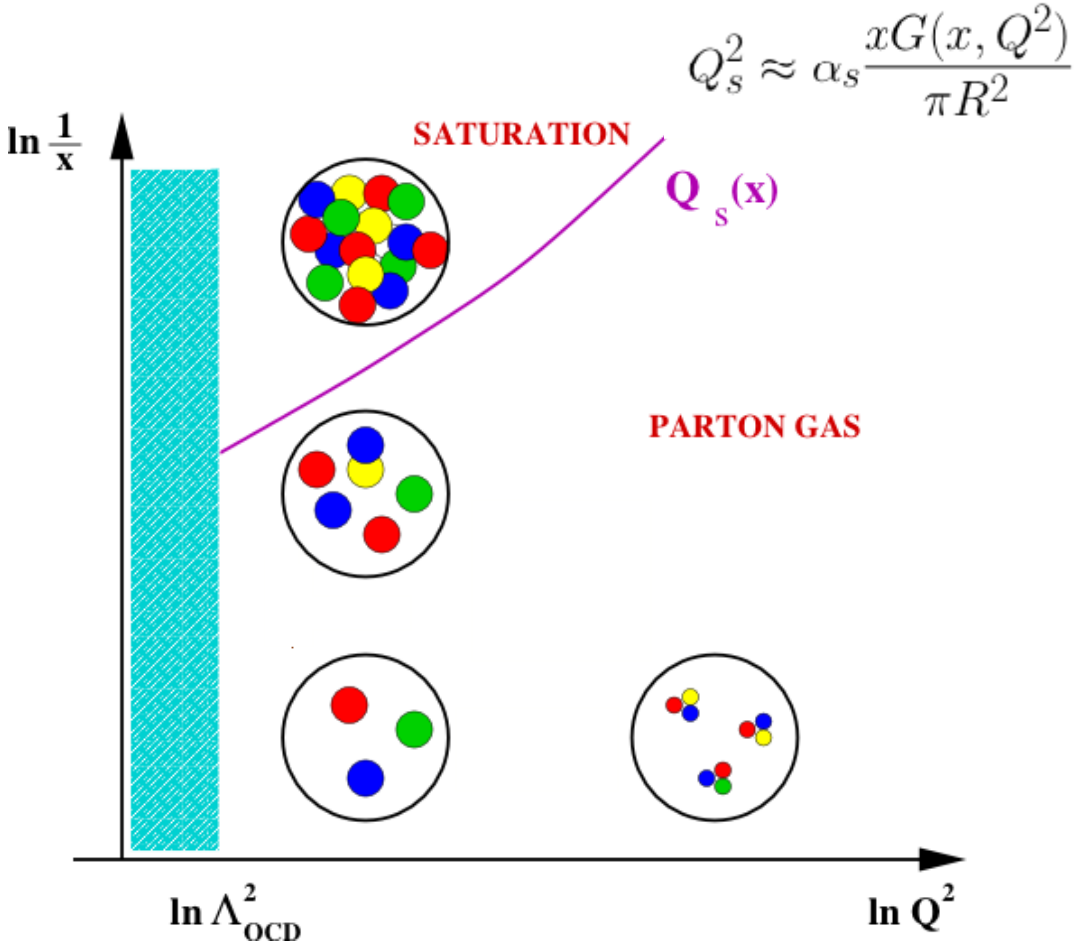
(JPB, A. Ipp, N. Wschebor, 2010)

Is production of matter in
heavy ion collisions
compatible with strong coupling?

Not really (?)

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

The saturation scale from DIS

"Geometrical scaling"

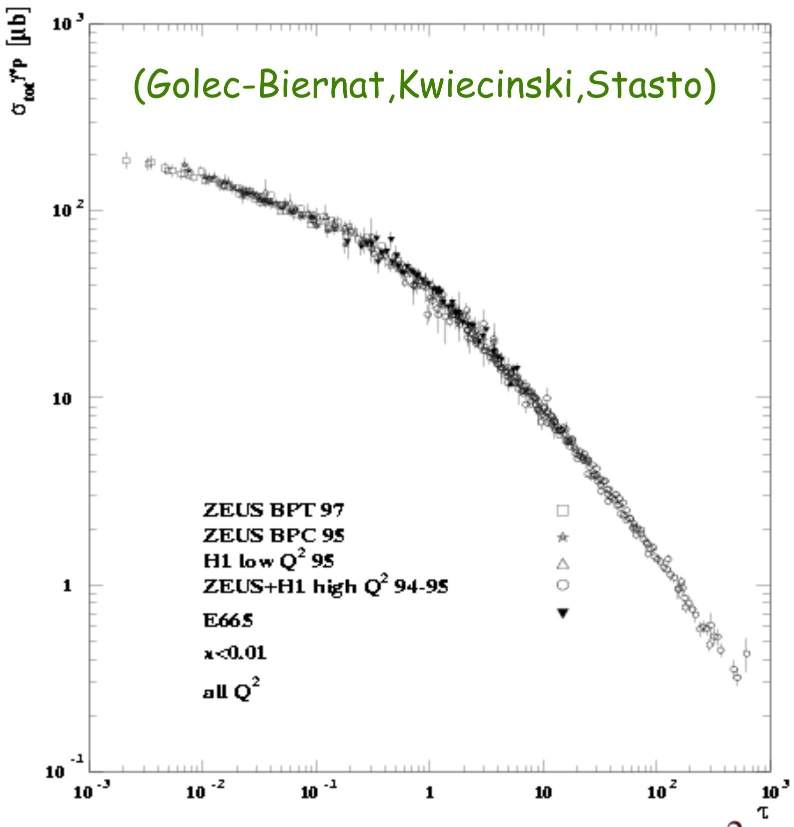
$$\sigma_{\gamma^* p}(x, Q^2) = \sigma_{\gamma^* p}(Q^2/Q_s^2(x))$$

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

$$Q_0 \approx 1Gev$$

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

$$\lambda \approx 0.3$$



Q^2/Q_s^2

The saturation scale in nuclei

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

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

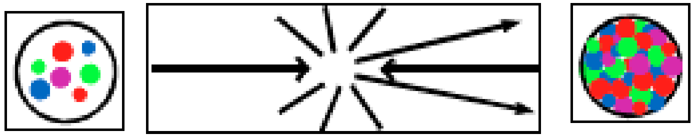
Successful phenomenology at RHIC

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

Di-hadron production
Azimuthal correlations at forward rapidity

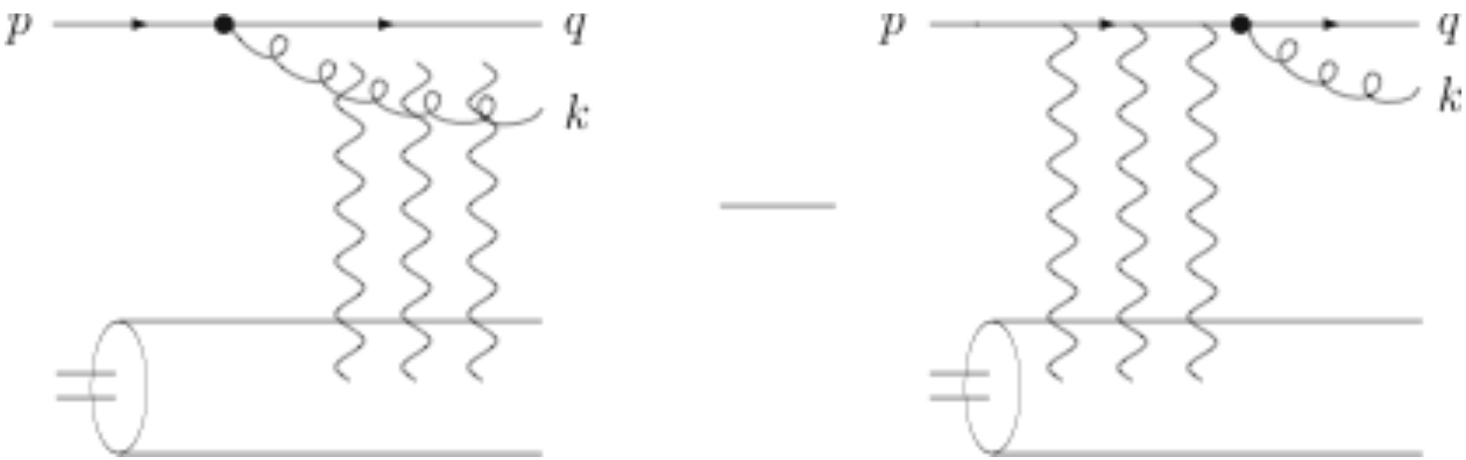
$$\mathrm{d\,Au} \rightarrow \mathrm{h_1\,h_2\,X}$$

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



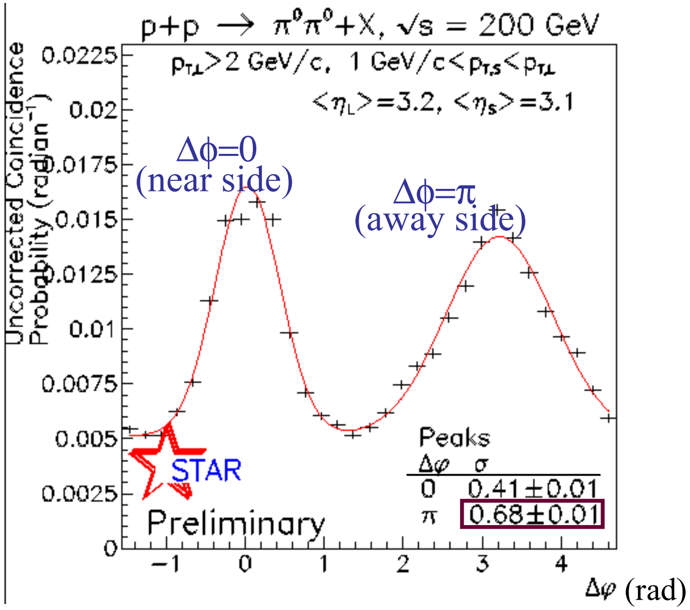
$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$

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

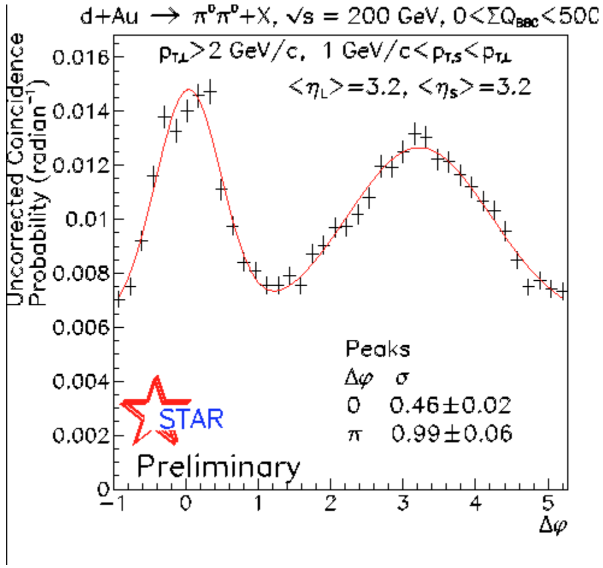


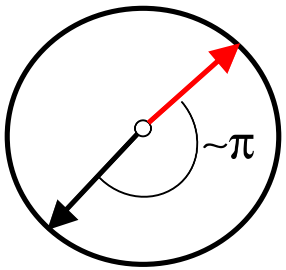
Azymuthal correlations

p+p

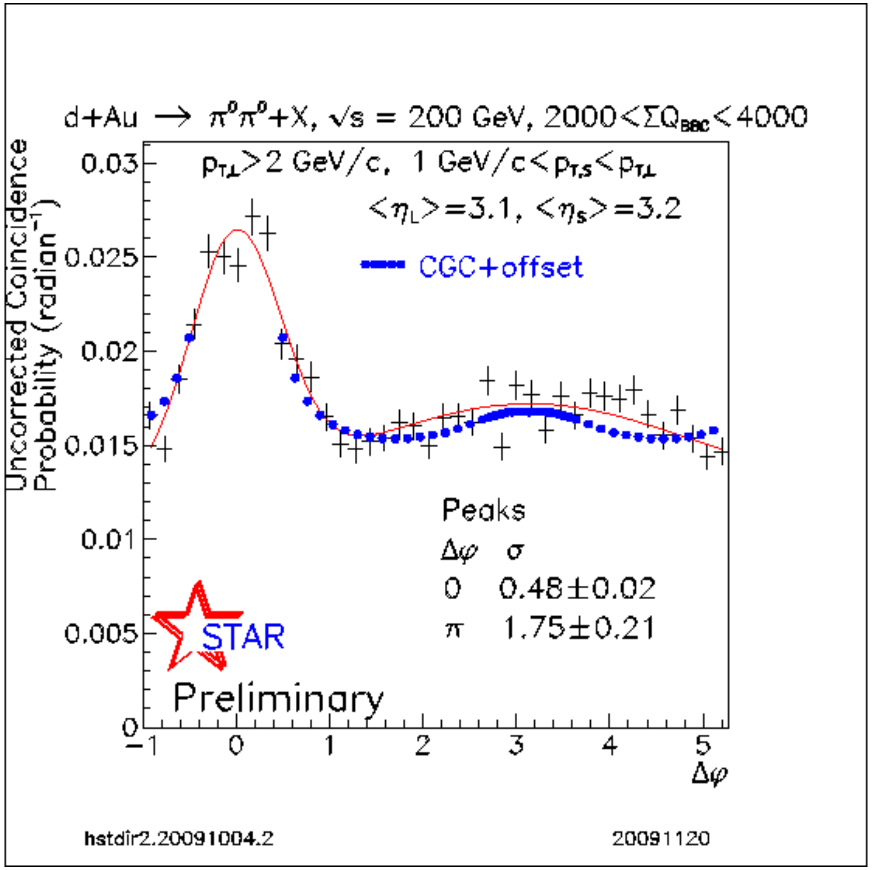


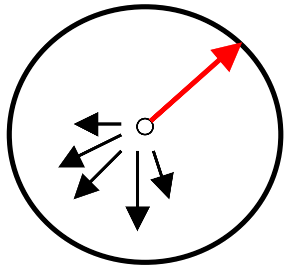
d+Au peripheral





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)