The strongly coupled quark-gluon plasma and heavy ion collisions

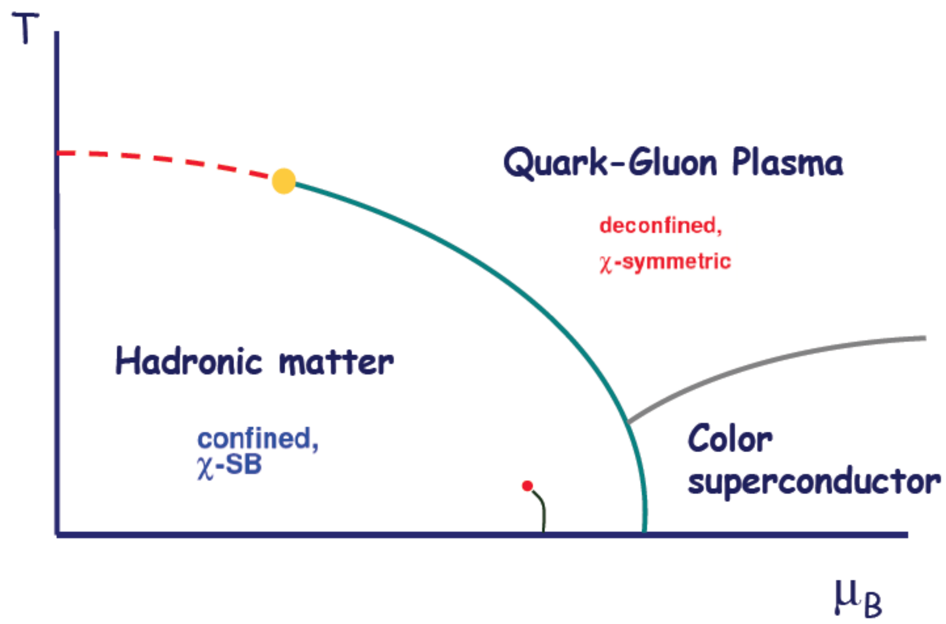
Christmas Workshop

Madrid, 15-17 December 2009

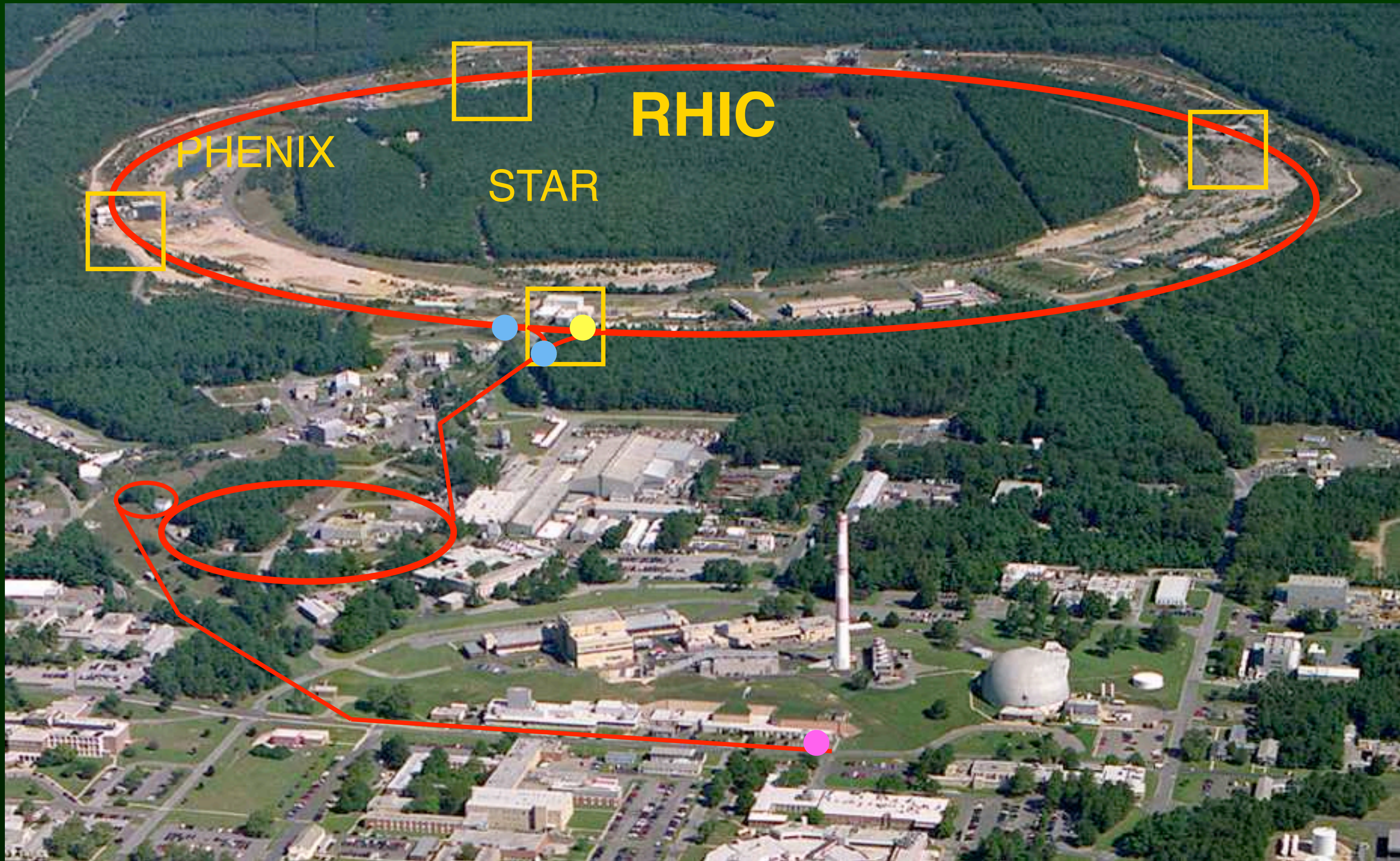
Jean-Paul Blaizot, IPhT- Saclay

Early concept - Asymptotic freedom

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



Relativistic Heavy Ion Collider RHIC @ BNL



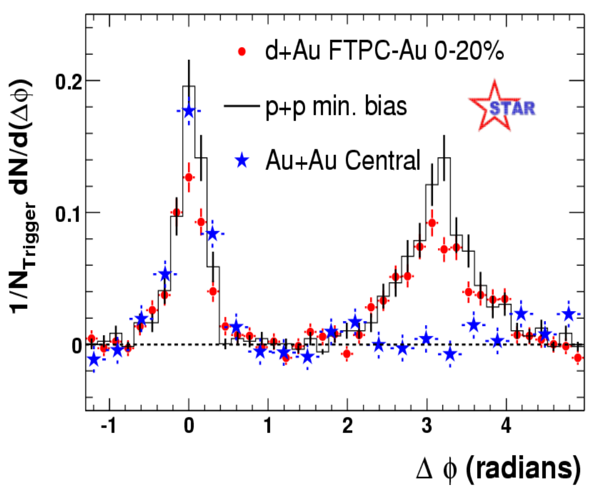
3 km ring

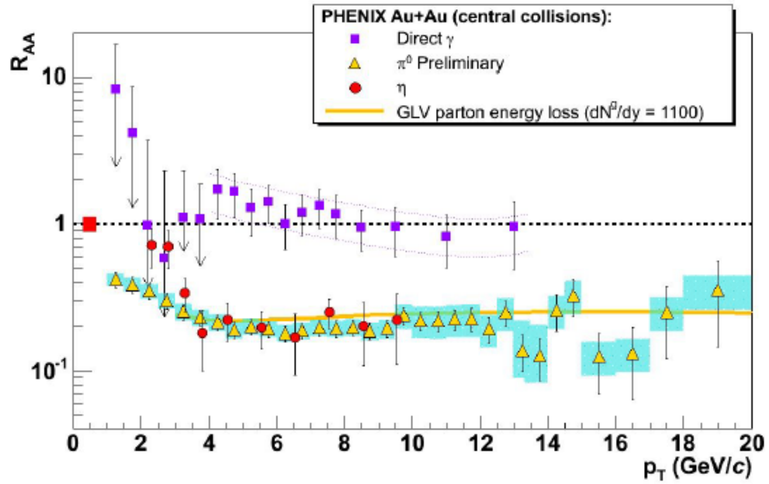
animation by Mike Lisa

major international enterprise: thousands of scientists and engineers

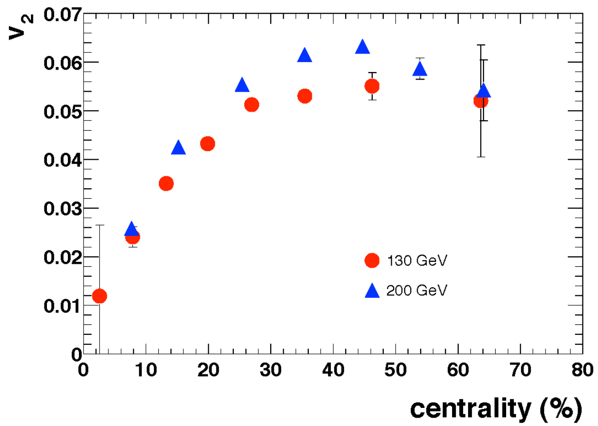
RHIC perfect liquid

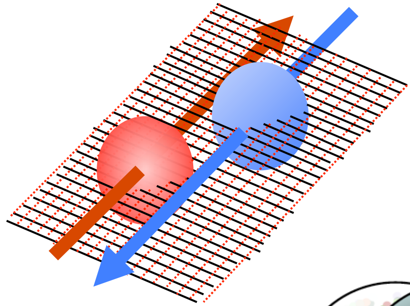
Strong opacity of matter to propagation of hard partons

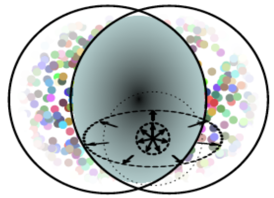




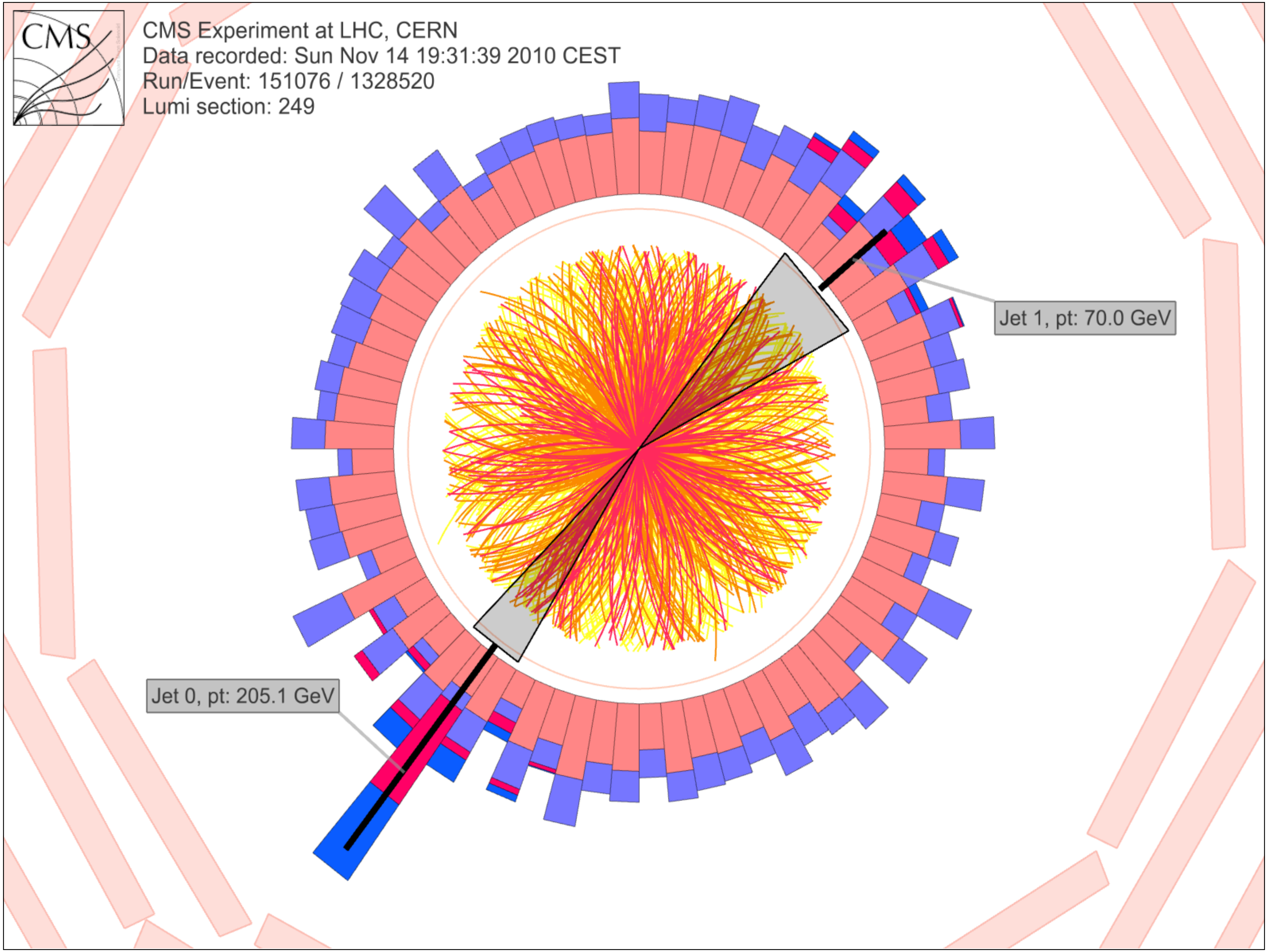
Collective (elliptic) flow of matter

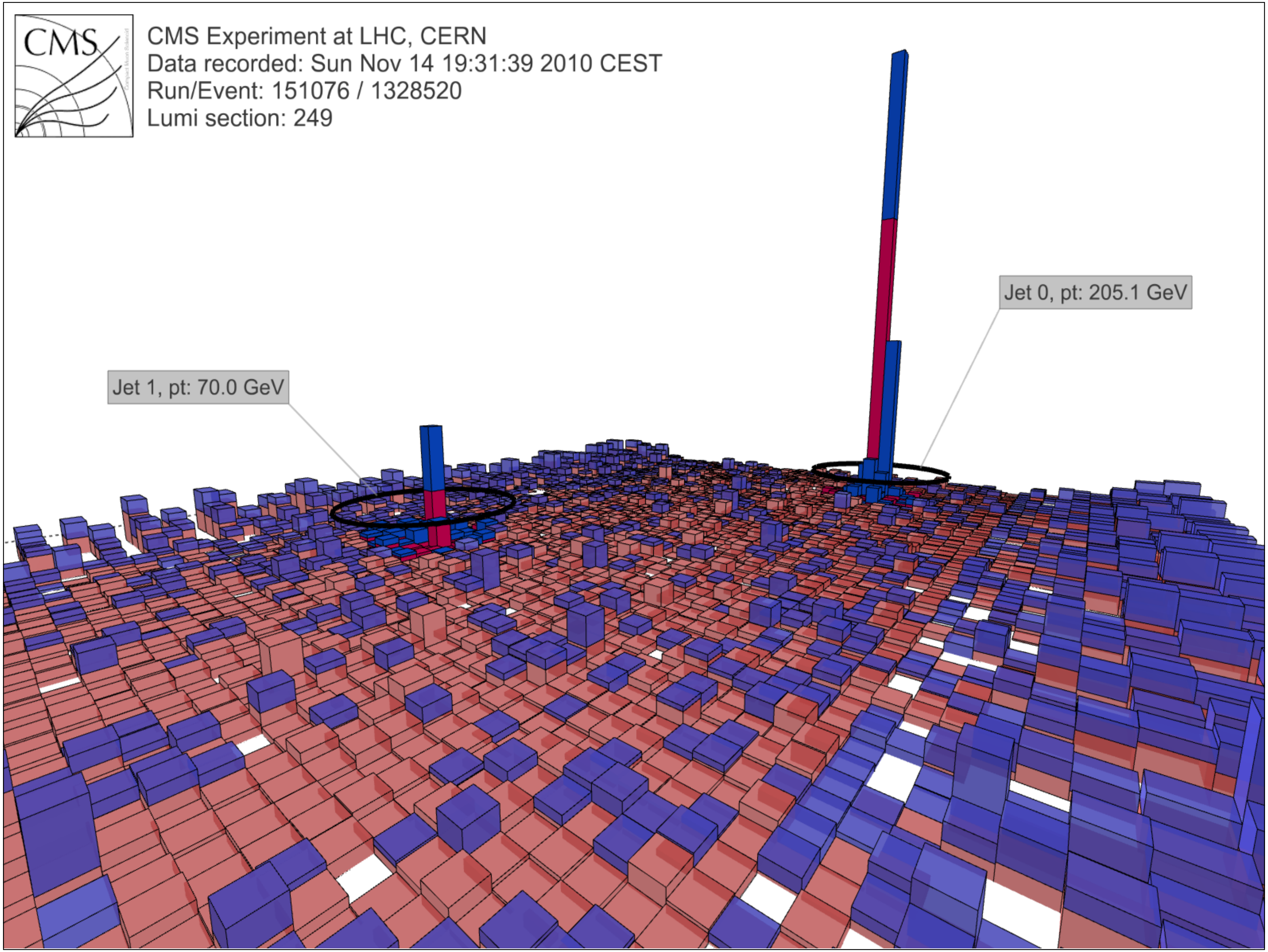


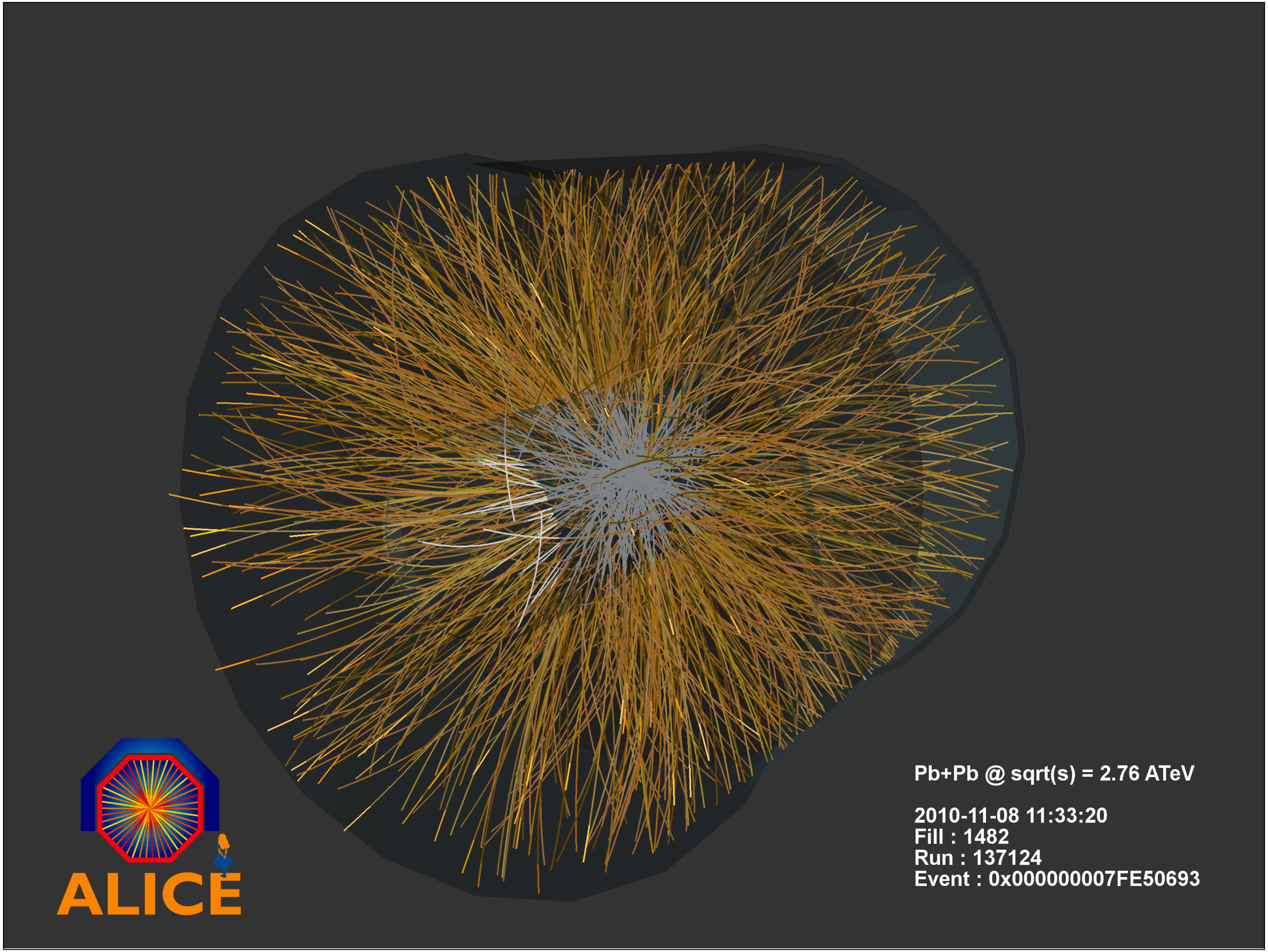




News from the Large Hadron Collider

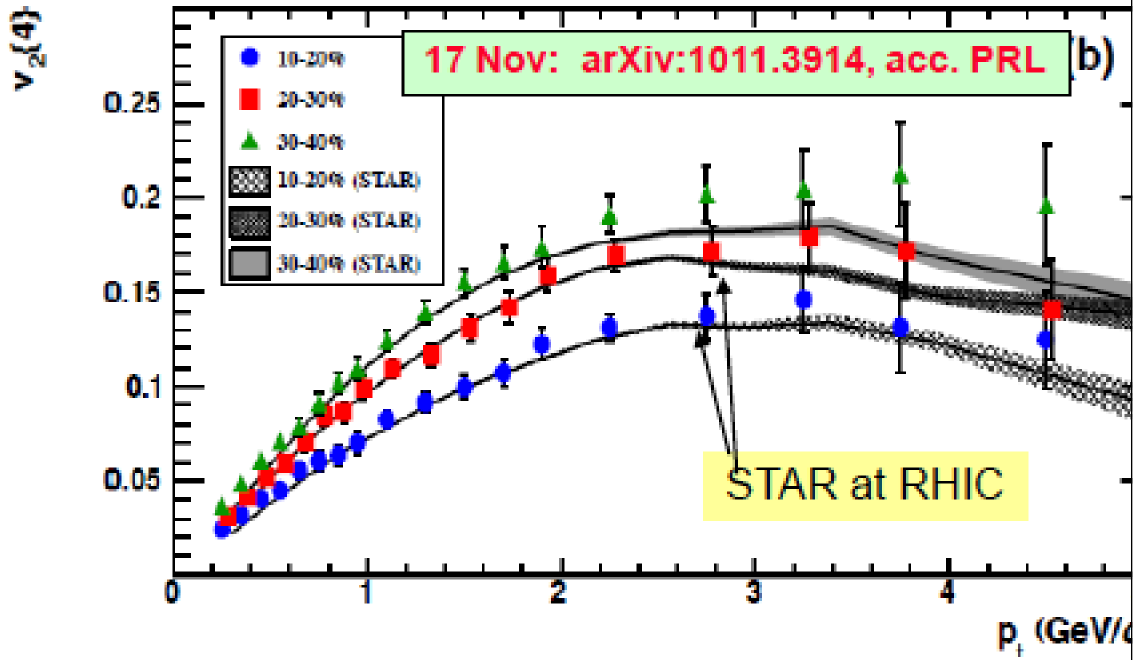

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

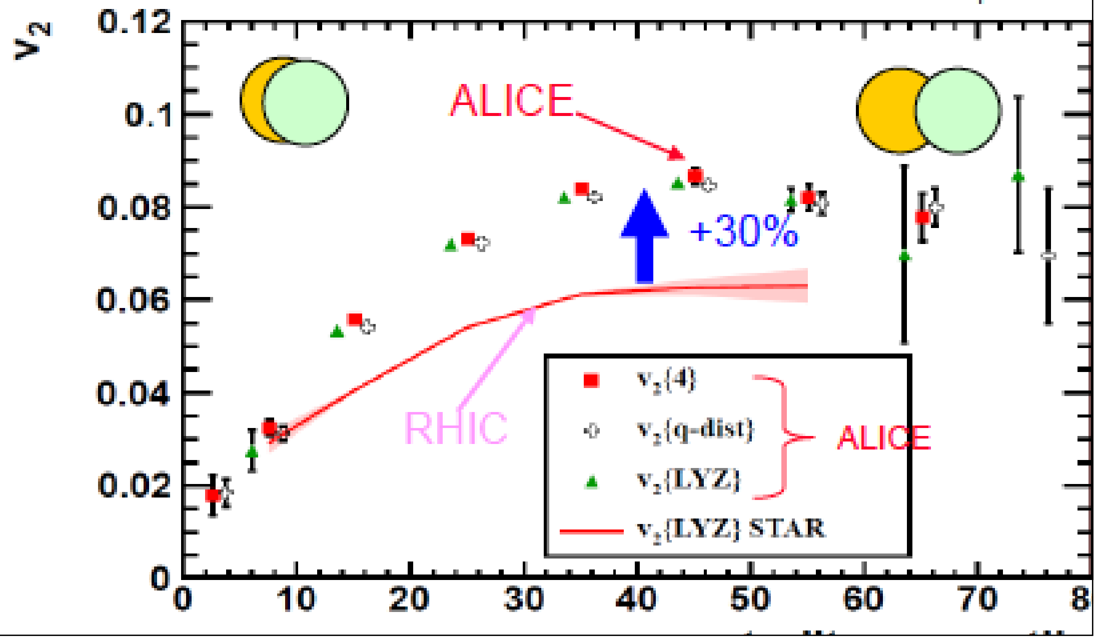

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:33:20
Fill : 1482
Run : 137124
Event : 0x000000007FE50693

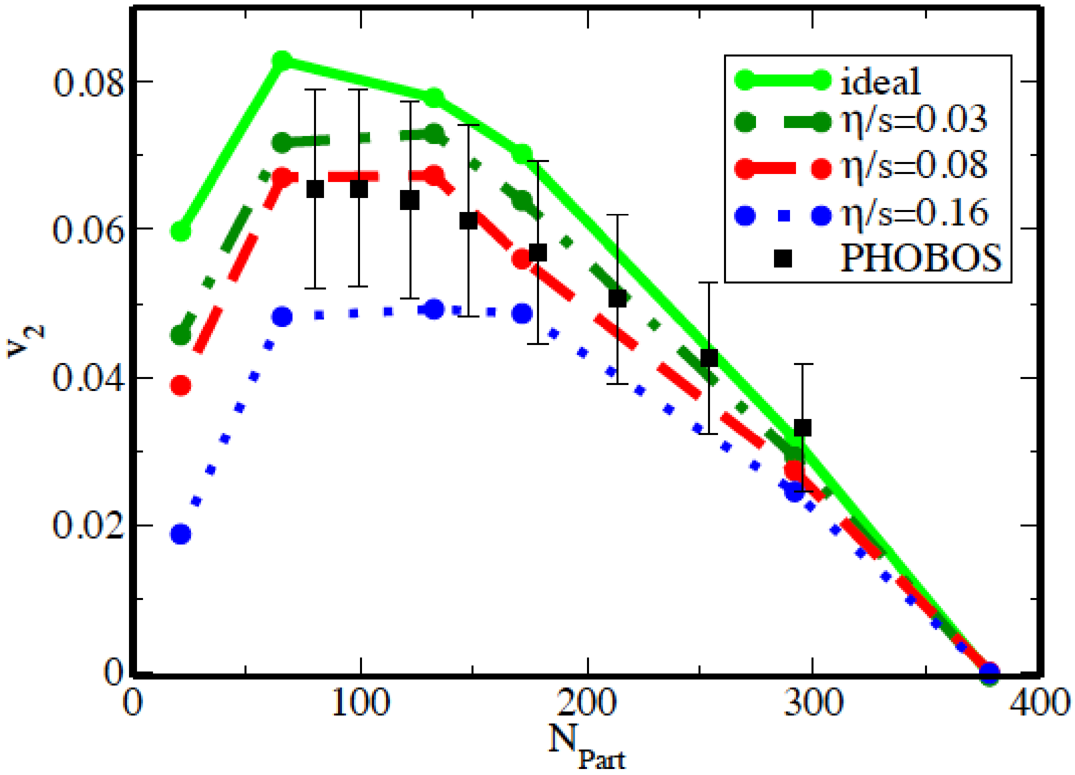
First Elliptic Flow Measurement at LHC

- v_2 as function of p_t
  - ⇨ **practically no change with energy !**
    - ✪ extends towards larger centrality/higher p_t ?
- v_2 integrated over pt
  - ⇨ **30% increase from RHIC**
  - ⇨ <p_t> increases with $\sqrt{s}$
    - ✪ pQCD powerlaw tail ?
  - ⇨ Hydro predicts increased 'radial flow'
    - ✪ very characteristic p_t and mass dependence; **to be confirmed !**





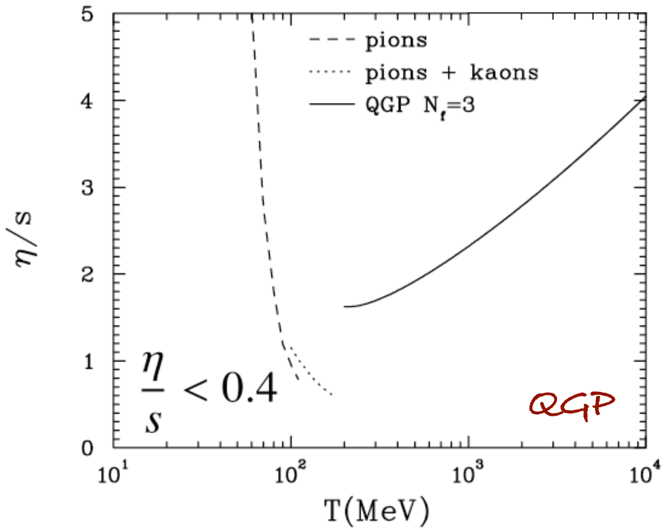
The low viscosity of the quark-gluon plasma

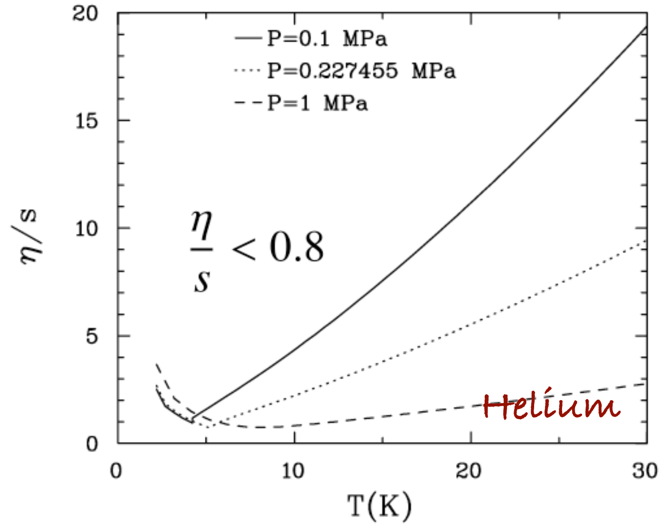


$$\frac{\eta}{s} < 5 \times \frac{1}{4\pi}$$

(Luzum, Romatschke, 2007)

Low viscosity, phase transition and strong coupling

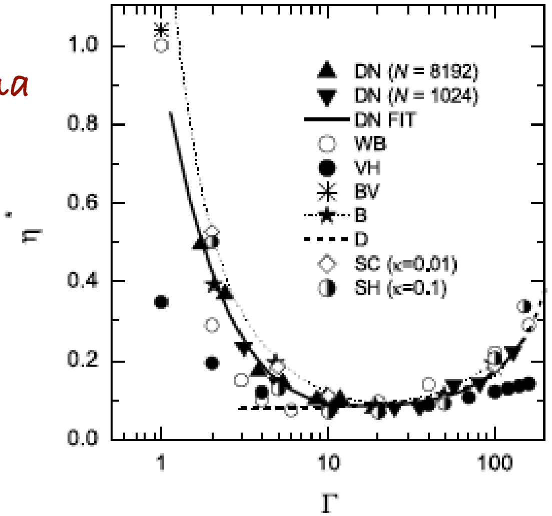




(Csernai et al, 2006)

Strongly correlated plasma

(Z. Donko et al, arXiv: 0710.5229)



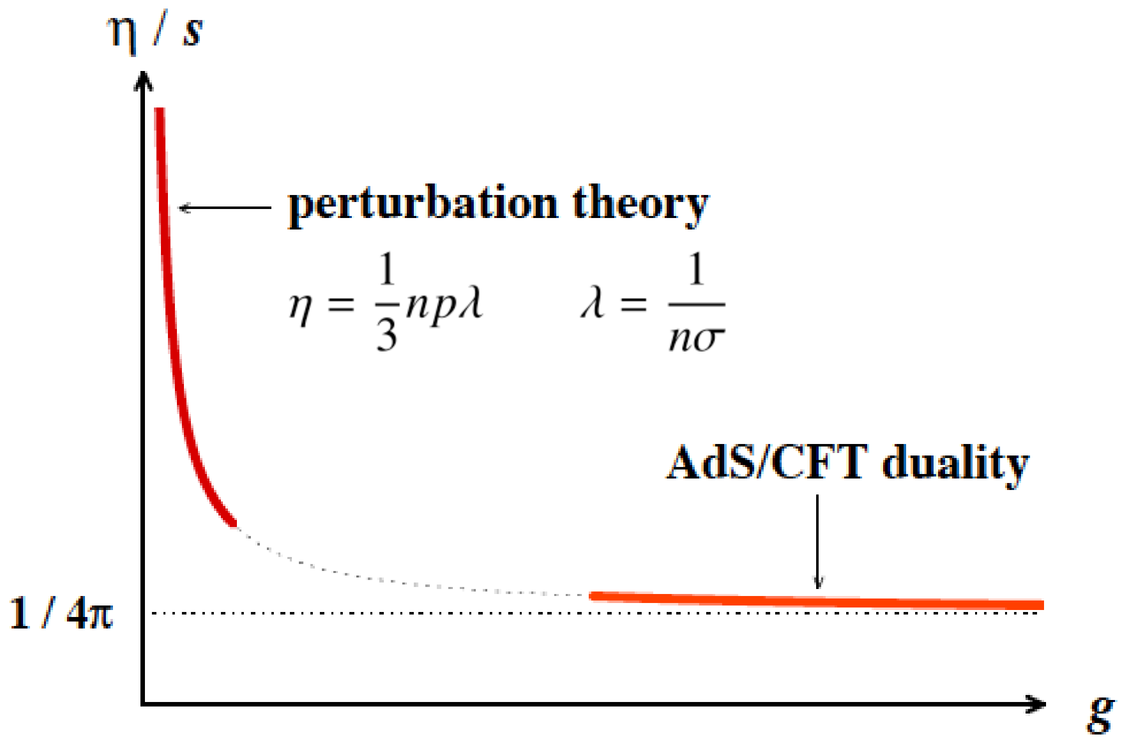
Also, cold fermionic gas at unitarity $\frac{\eta}{s} \sim 0.5$

AdS/CFT Duality

A 'natural' explanation for the small viscosity

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

(Policastro et al, 2001)



A puzzling situation

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

Is initial concept wrong ?

No...

QCD asymptotic freedom works !

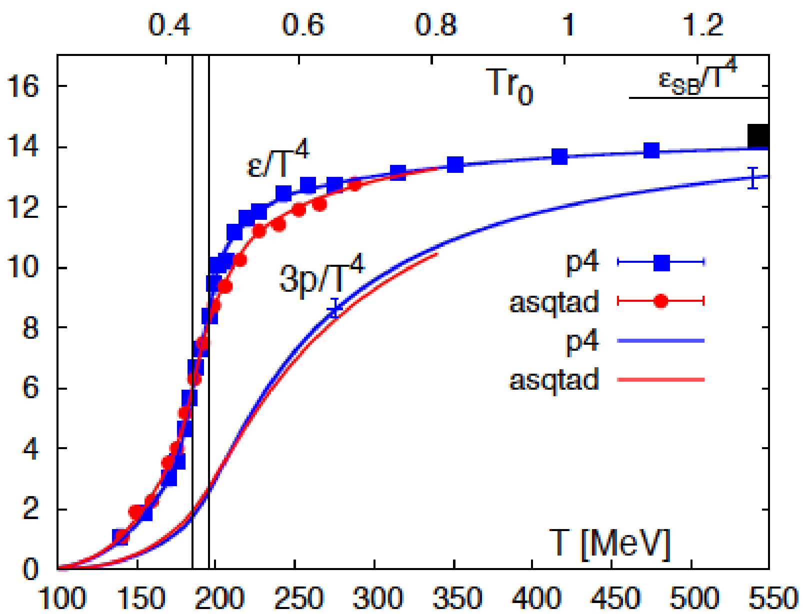
Asymptotic freedom

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

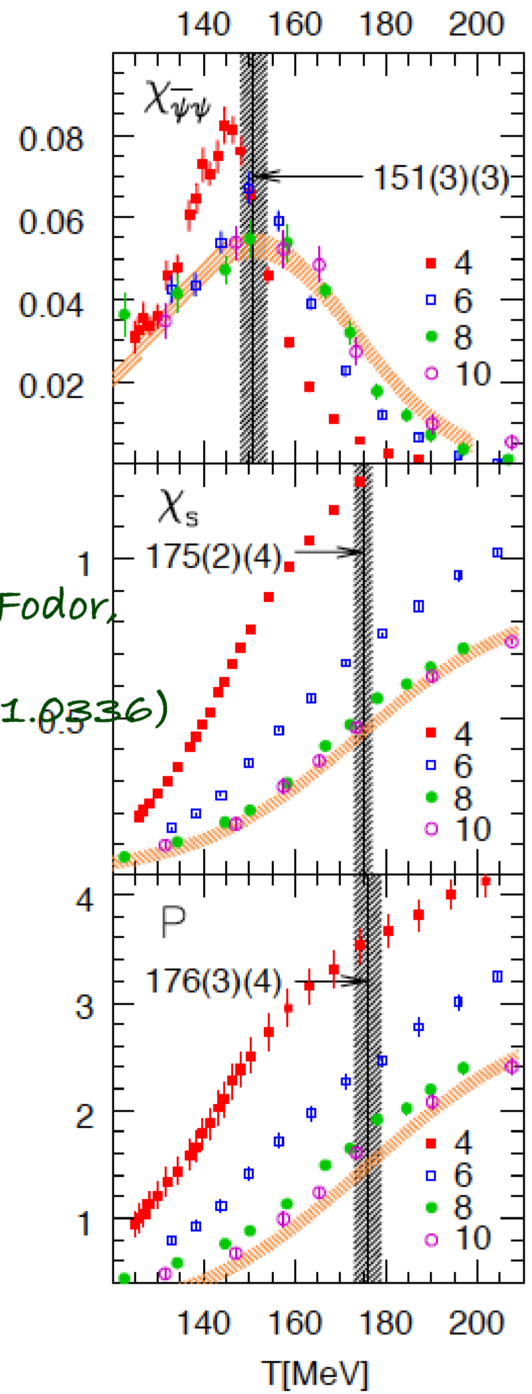
Matter is « simple » at high temperature:

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

Crossover from hadrons to quarks and gluons

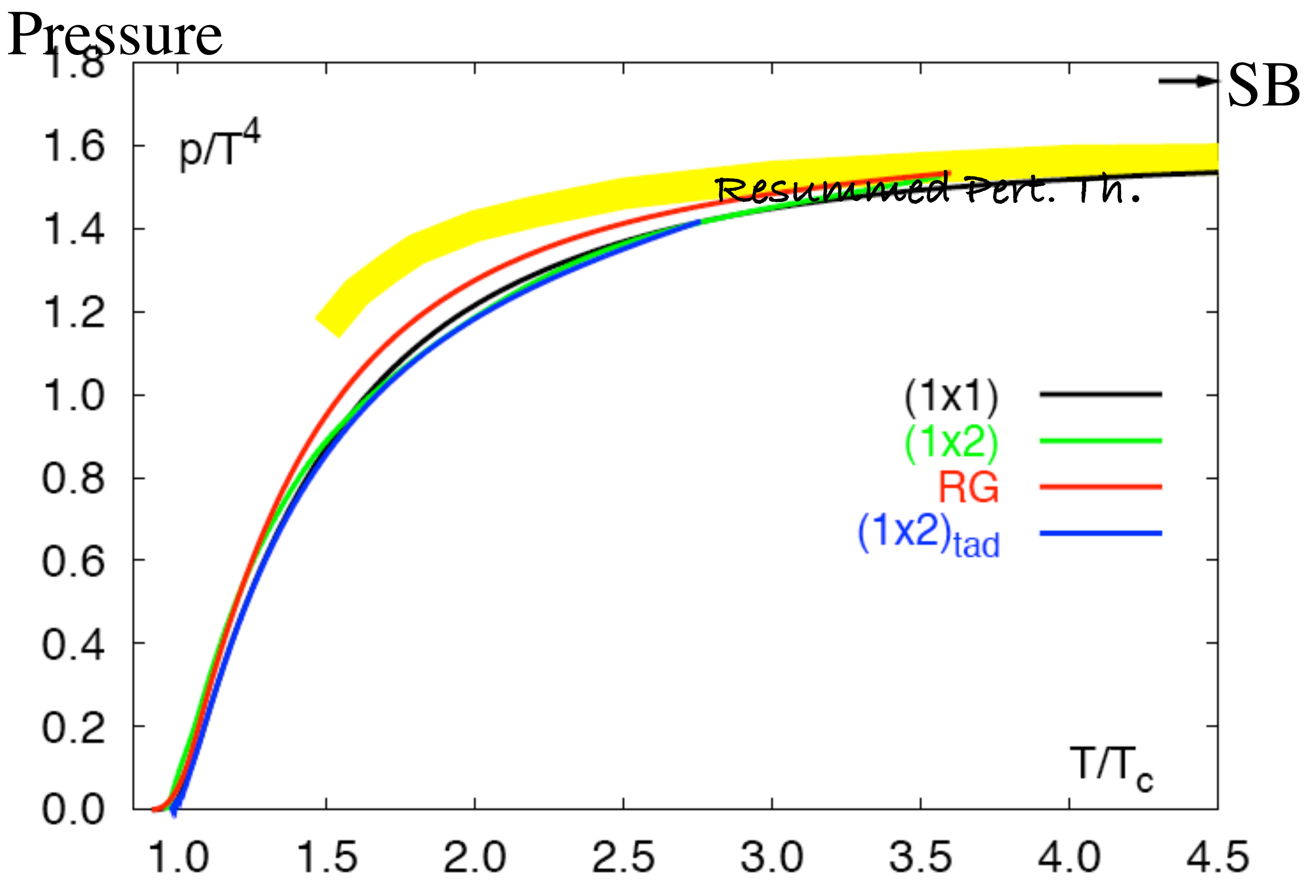


(from M. Bazavov et al, arXiv:0903.4379)



(from Z. Fodor, arXiv:0711.0336)

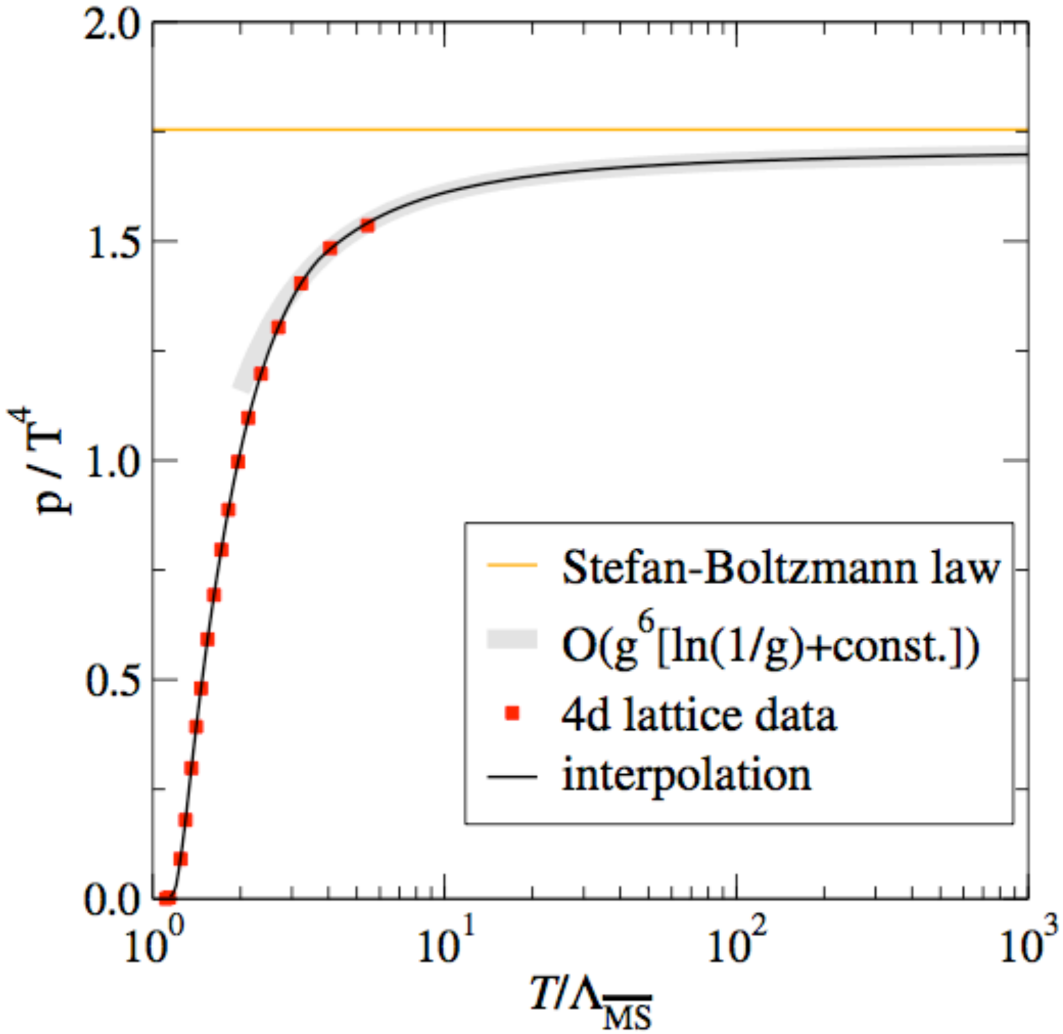
At T>3Tc Resummed Pert. Theory accounts for lattice results



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

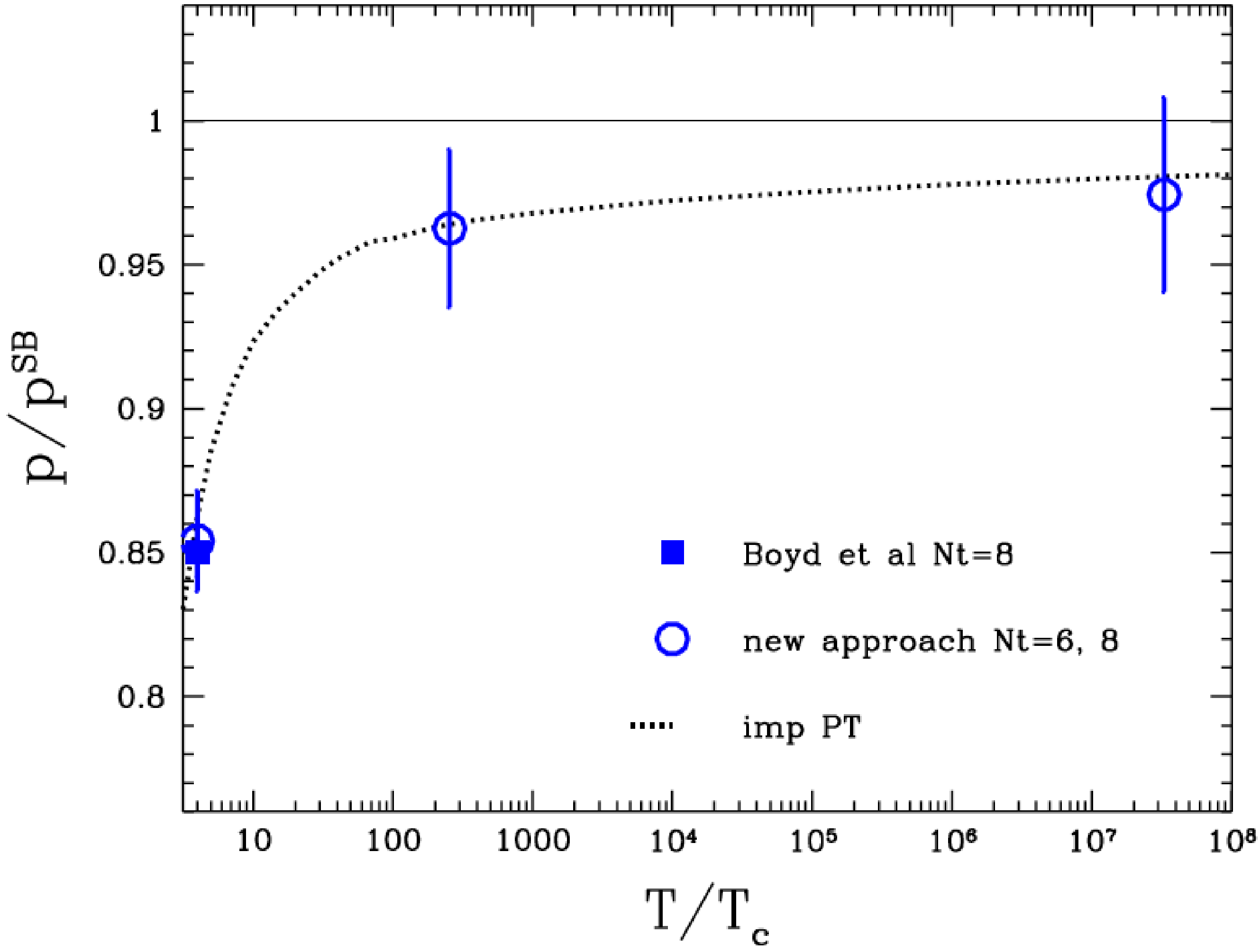
(resummed pert. th. from J.-P. B., E. Iancu, A. Rebhan: Nucl.Phys.A698:404-407,2002)

State of the art in high order perturbative calculations



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

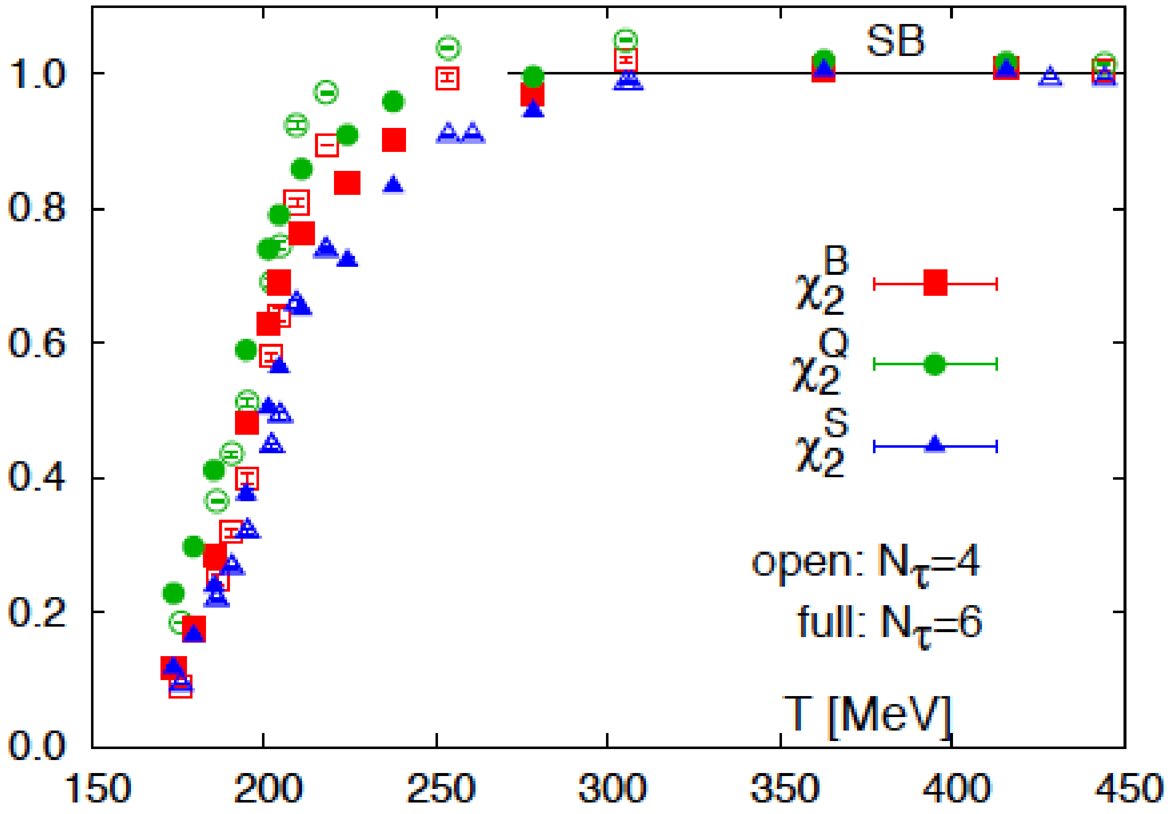
Pressure for SU(3) YM theory at (very) high temperature



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

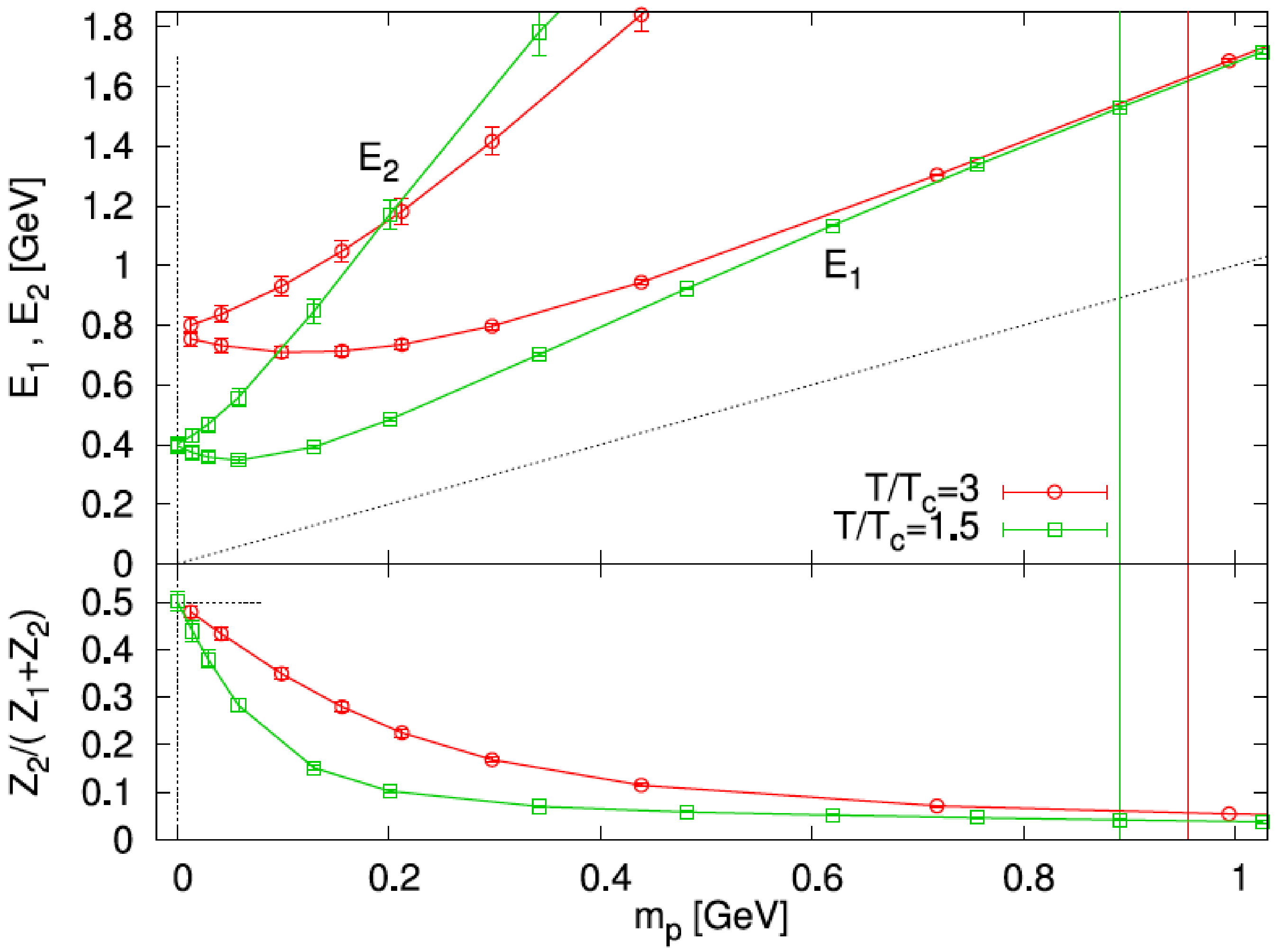
Conserved charge susceptibilities

$$\chi_C \sim < C^2 > \qquad C = B, Q, S$$



(from M. Cheng et al, arXiv: 0811.1006)

Quark quasiparticles seen on the lattice

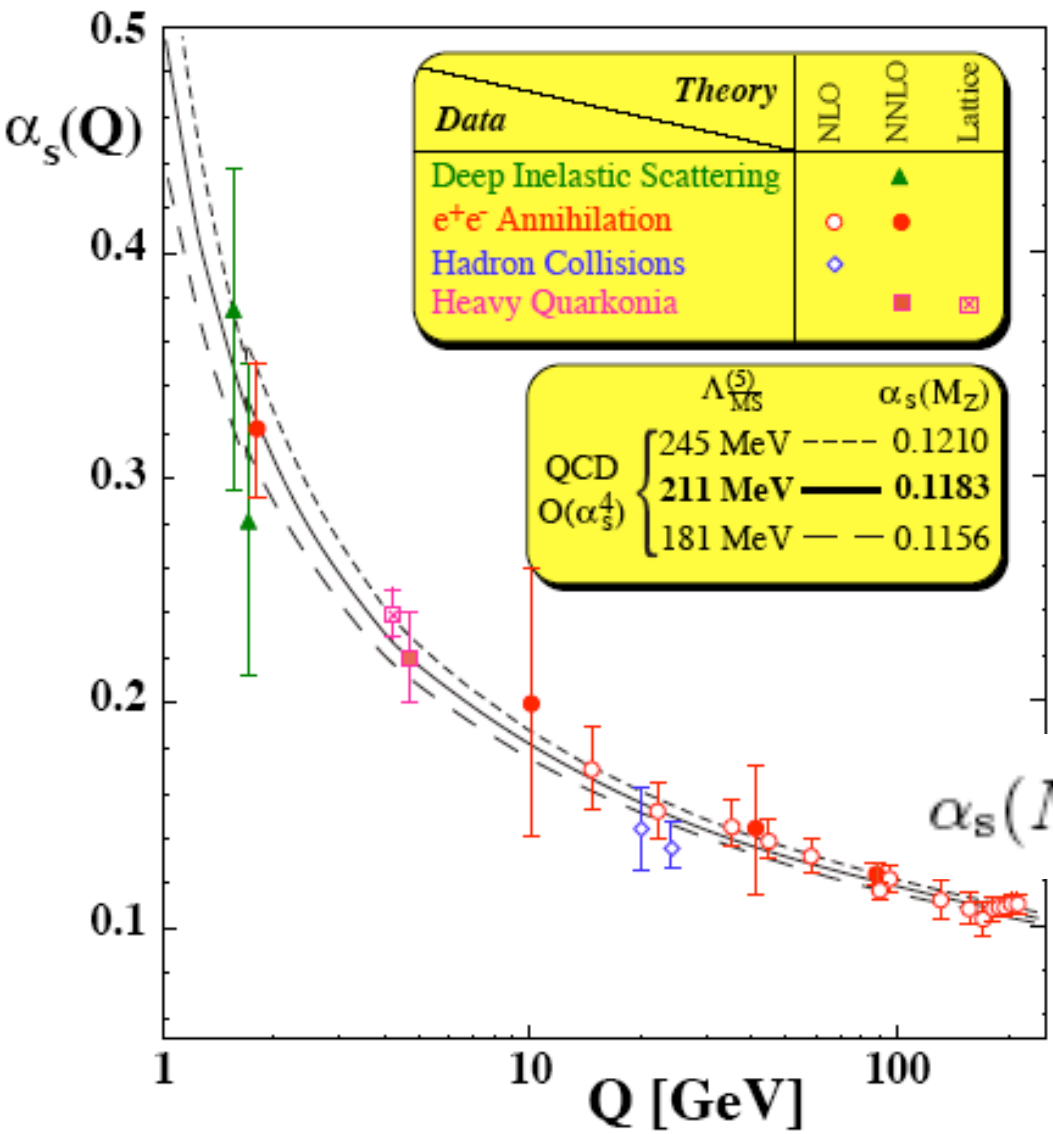


(from F. Karsch and M. Kitazawa, arXiv: 0906.3941)

Is the coupling constant large ?

Not really !

The QCD running coupling constant

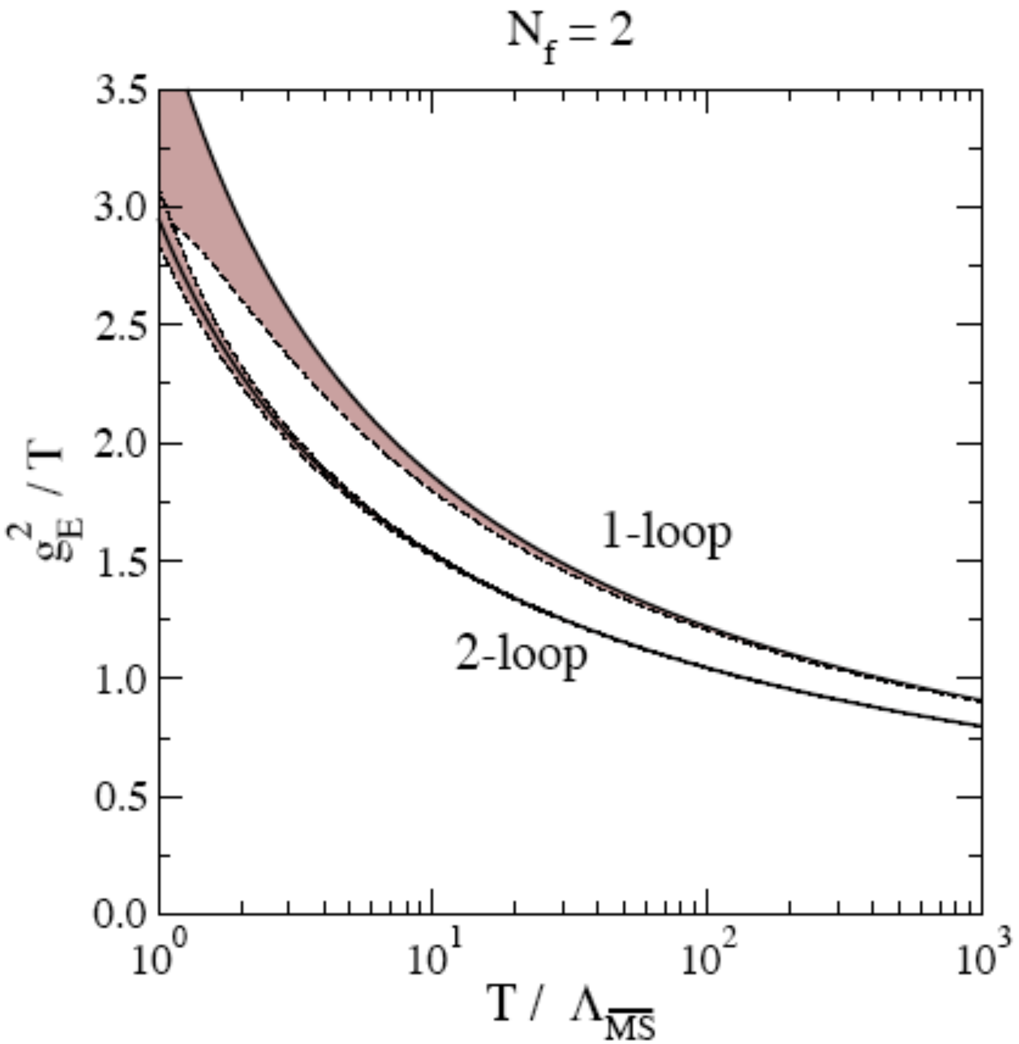


$$\alpha_s = \frac{g^2}{4\pi}$$

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

(S. Bethke, hep-ex/0211012)

The effective coupling is not huge, even close to Tc



M. Laine, Y. Schröder, hep-ph/0503061

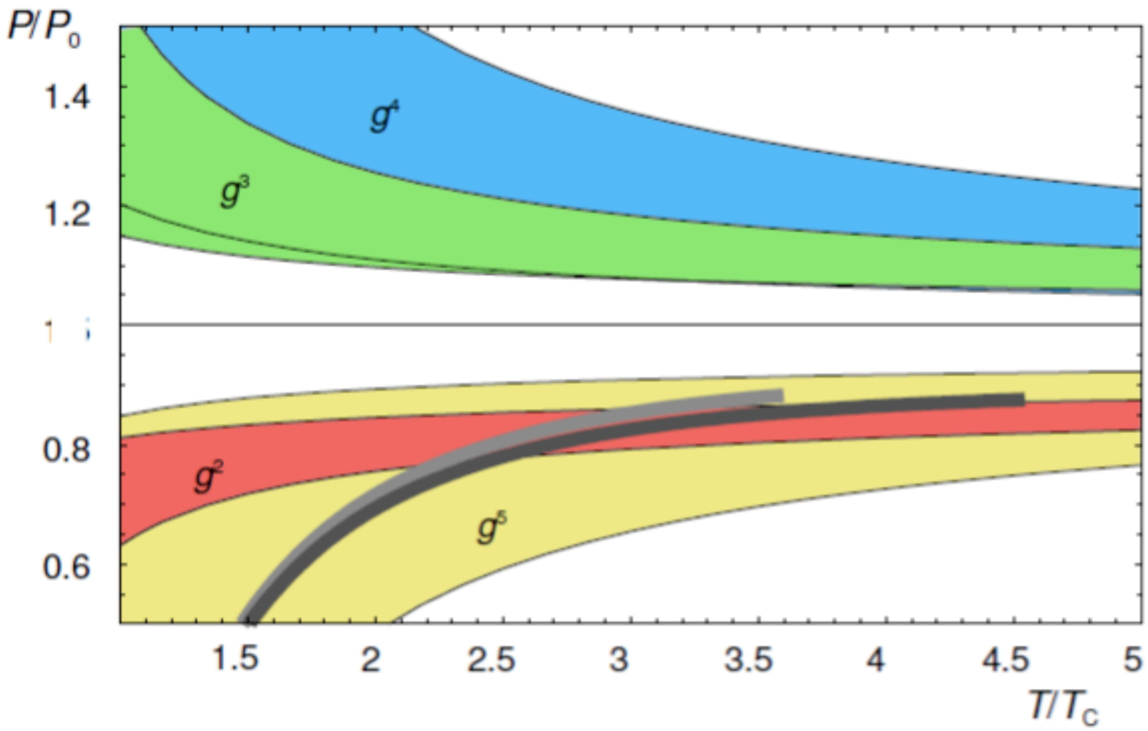
Strict perturbation theory breaks down

Often used as an argument in favor of strong coupling

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)

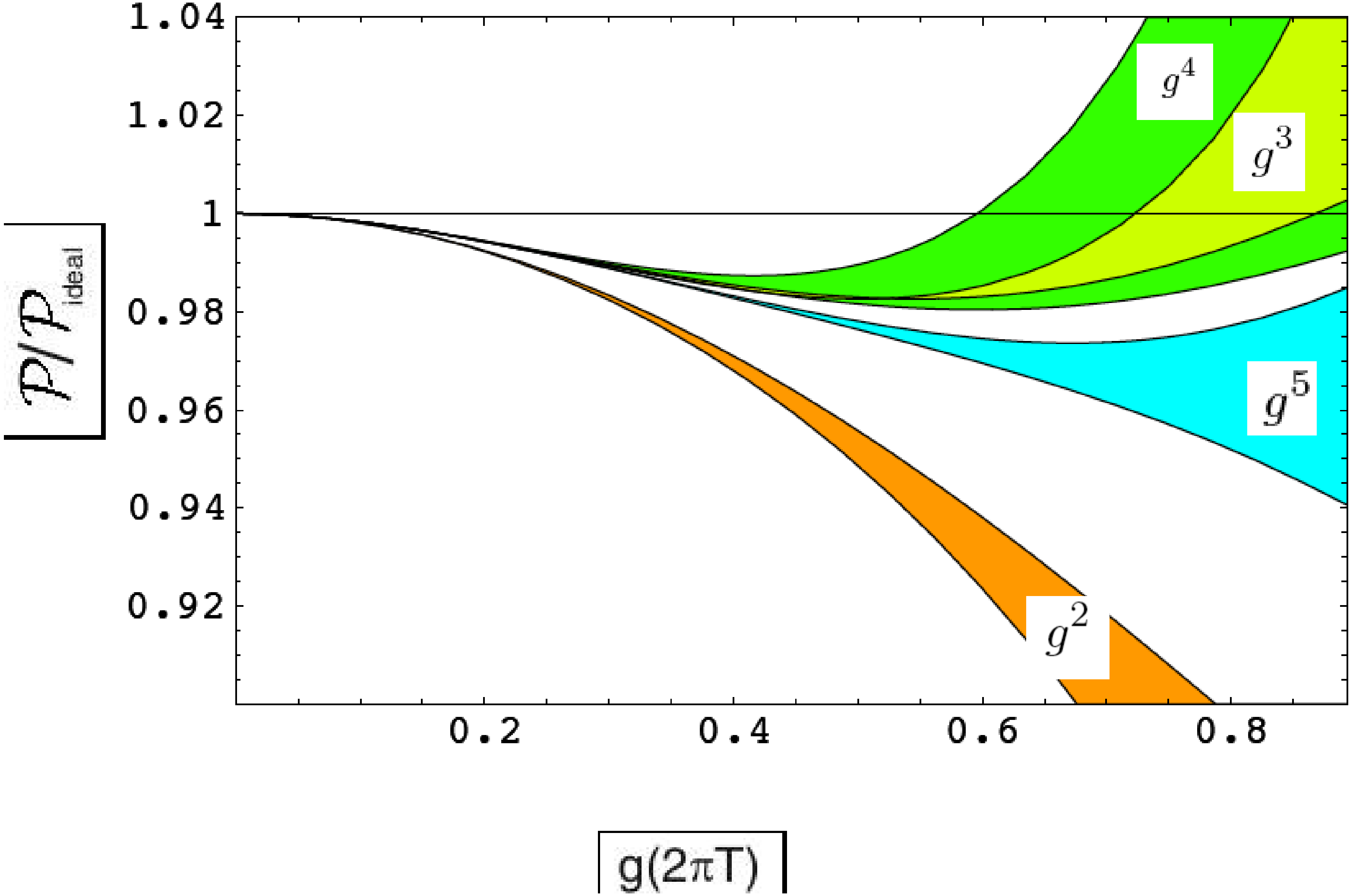
g^5 : Zhai, Kastening (1995), Braaten, Nieto (1996)

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).

Generic feature in (most) field theories,
e.g in scalar field theory



Weakly AND strongly coupled ...

Degrees of freedom with different wavelengths are differently coupled.

Expansion parameter

$$\gamma_\kappa = \frac{g^2 \langle \phi^2 \rangle}{\kappa^2} \qquad \langle \phi^2 \rangle_\kappa \sim \kappa T \quad (\kappa \lesssim T)$$

Dynamical scales

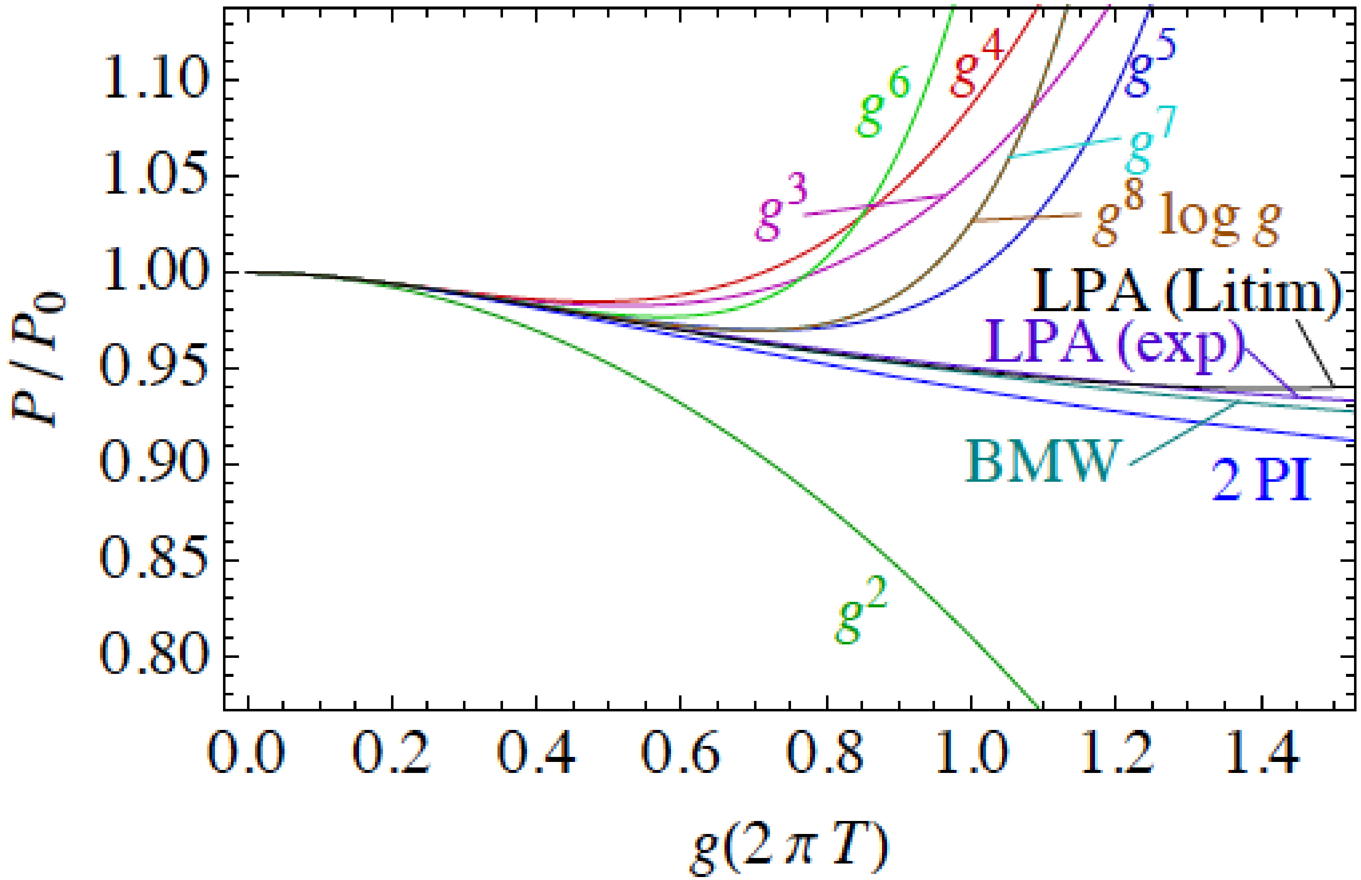
$$\kappa \sim T \qquad \gamma_\kappa \sim g^2$$

$$\kappa \sim gT \qquad \gamma_\kappa \sim g$$

$$\kappa \sim g^2 T \qquad \gamma_\kappa \sim 1$$

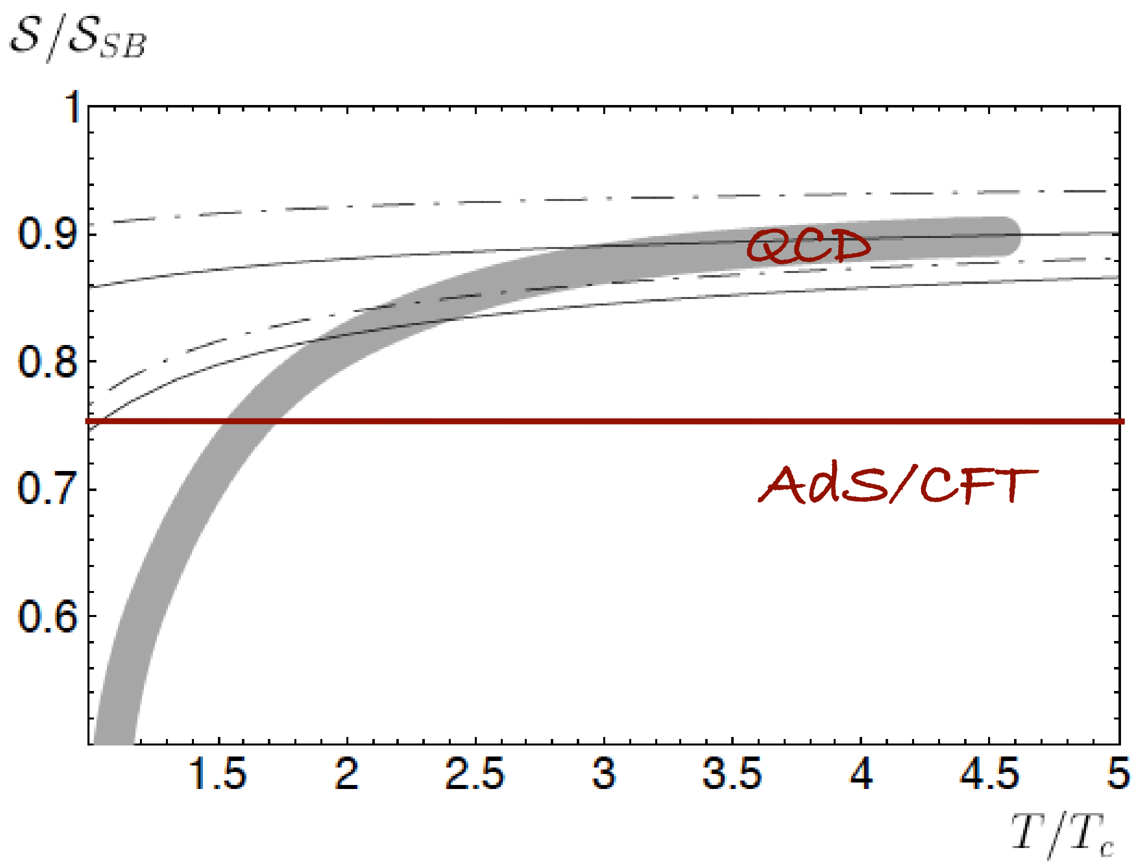
RG techniques yield smooth extrapolation to strong coupling (scalar field theory)

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



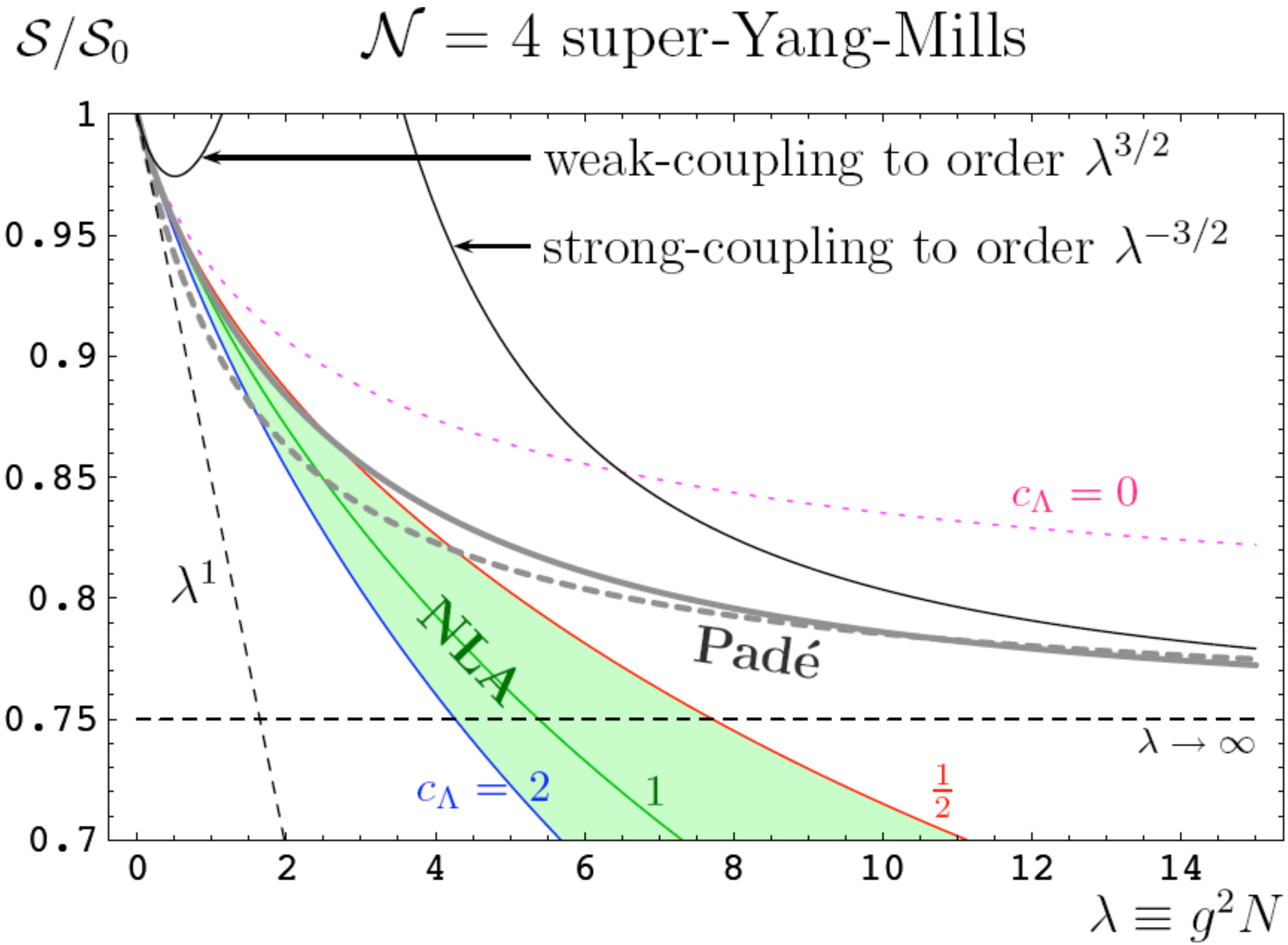
(high orders from J. O. Andersen et al, arXiv 0903.4596)

Entropy at weak and strong coupling



$$\frac{s}{s_{SB}} = \frac{3}{4}$$

J.-P. B., E. Iancu, A. Rebhan: Phys.Rev.D63:065003,2001
G. Boyd *et al.*, Nucl. Phys. B469, 419 (1996).



(JPB, Iancu, Kraemmer, Rebhan, hep-ph/0611393)

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

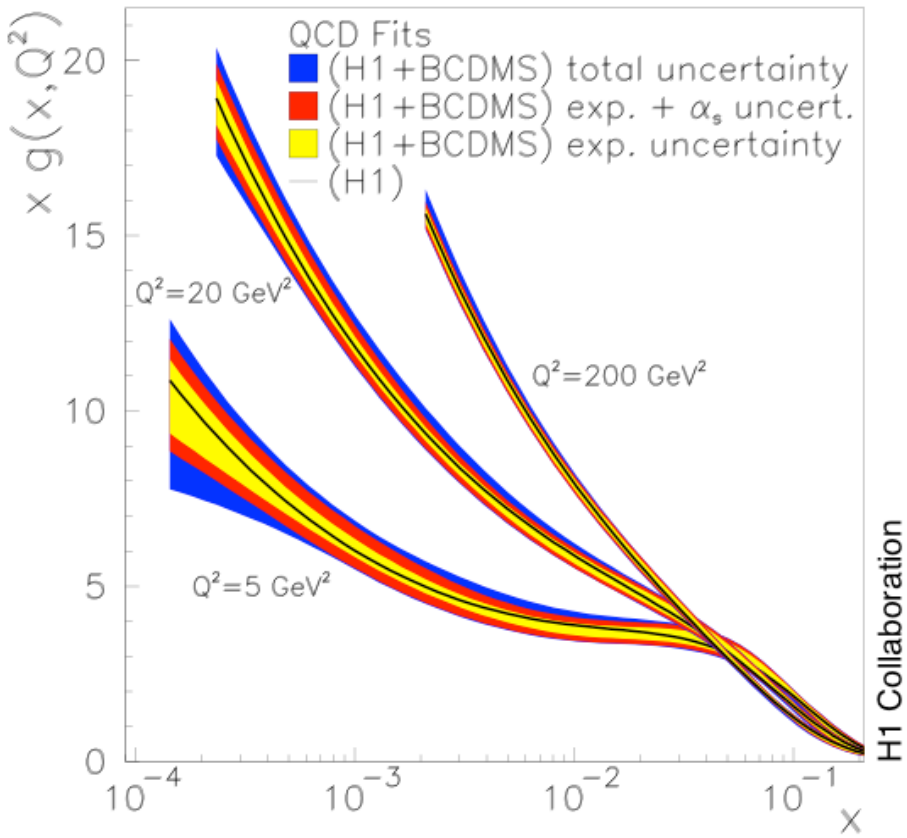
Not really (?)

Nuclear wave-functions in high energy collisions

Bulk of particle production ($p_T \lesssim 2$ GeV)

RHIC ($\sqrt{s} = 200\,\text{GeV}$) $x \sim 10^{-2}$

LHC ($\sqrt{s} = 5.5\,\text{TeV}$) $x \sim 4 \times 10^{-4}$



The growth of parton distribution at small x is tamed by QCD non linear effects (saturation)

Saturation momentum

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

In a nucleus

$$\frac{xG_A(x,Q^2)}{\pi R^2} \sim A^{1/3}$$

Most partons taking part in collision have $k_T \sim Q_s$

Successful phenomenology at RHIC

Weak coupling but non-perturbative

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

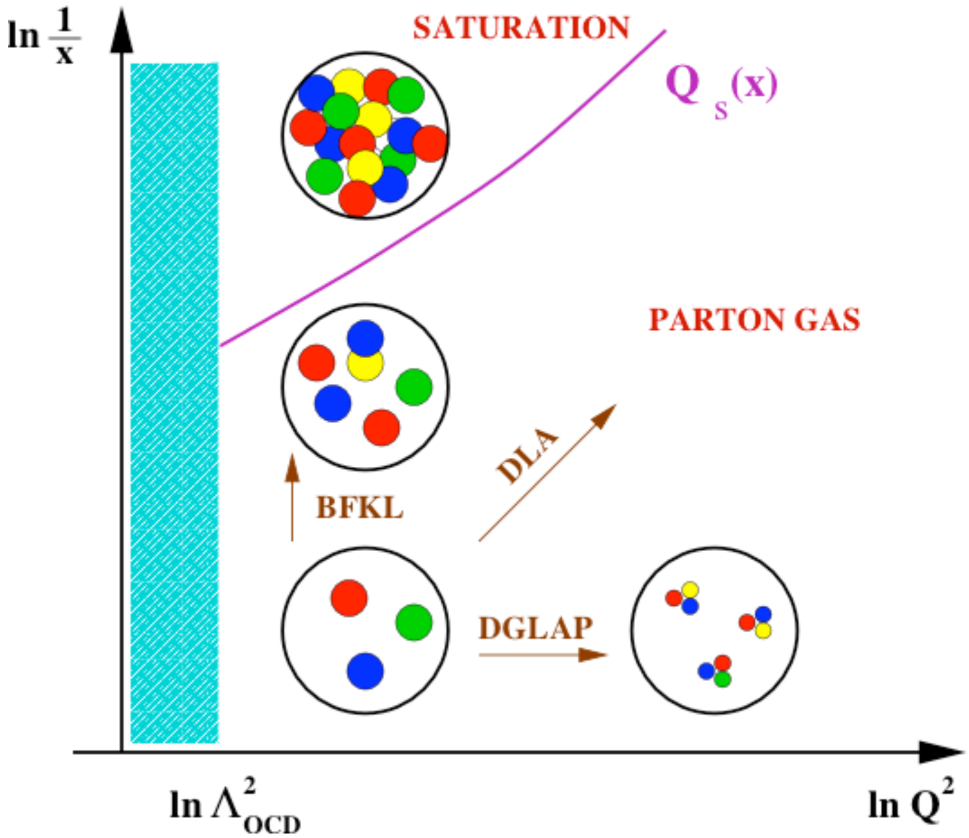
Large parton density at saturation

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

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

Suggest a description in terms of classical fields

Dense and dilute parton systems



Conclusions

- LHC confirms the strongly coupled character of the QGP

- The strongly coupled character of the quark-gluon plasma does not seem related in any obvious way to a large value of the coupling constant.

- Non perturbative features may arise from the cooperation of many degrees of freedom, or strong classical fields.

- The quark-gluon plasma is a multiscale system (no ideal plasma, neither weakly nor strongly coupled)