The strongly coupled quark-gluon plasma

EMMI workshop
"Strongly Coupled Systems"
GSI
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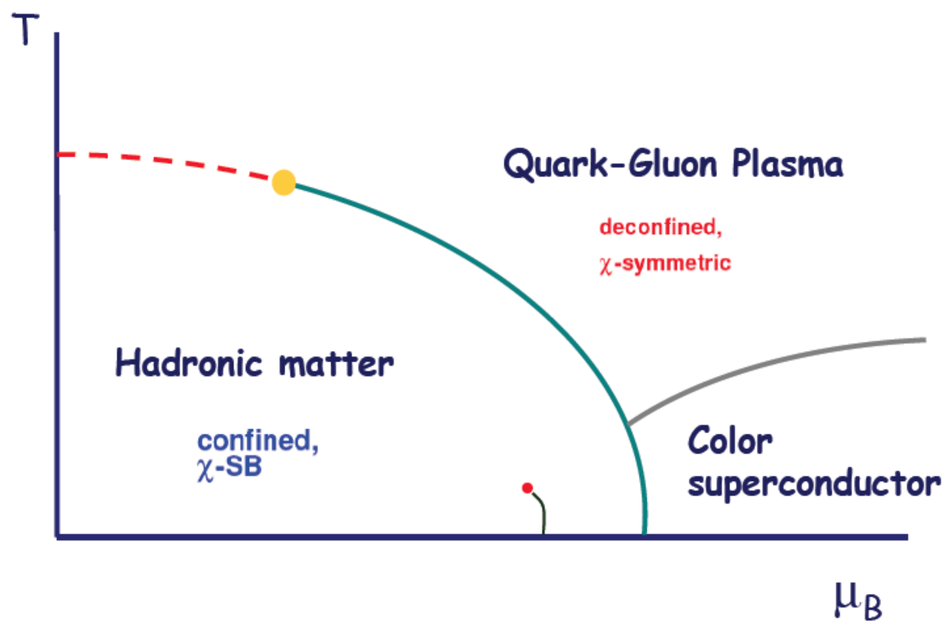
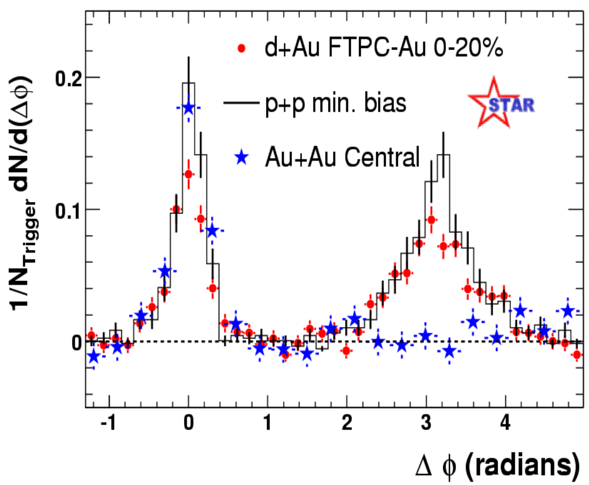
Early concept - Asymptotic freedom

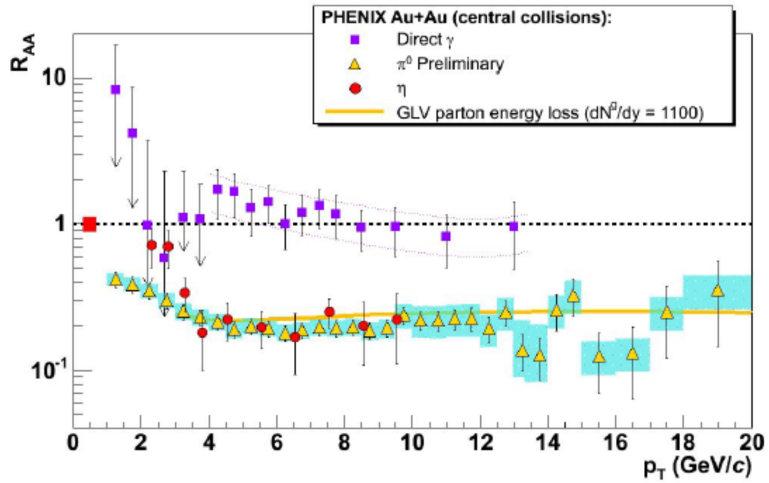
$$\alpha_s = \frac{g^2}{4\pi} \approx \frac{2\pi}{b_0 \ln\left(\mu / \Lambda_{QCD}\right)}$$



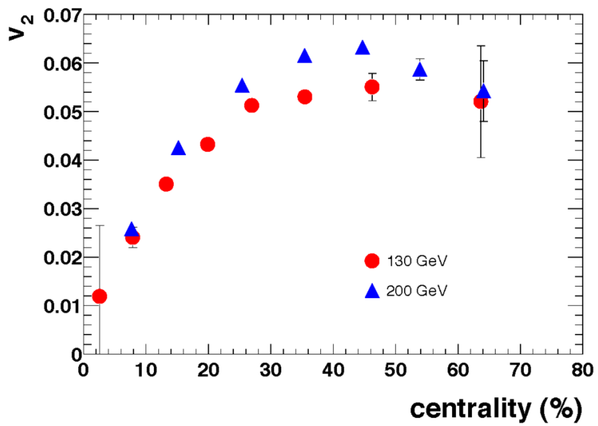
RHIC perfect liquid

Strong opacity of matter to propagation of hard partons

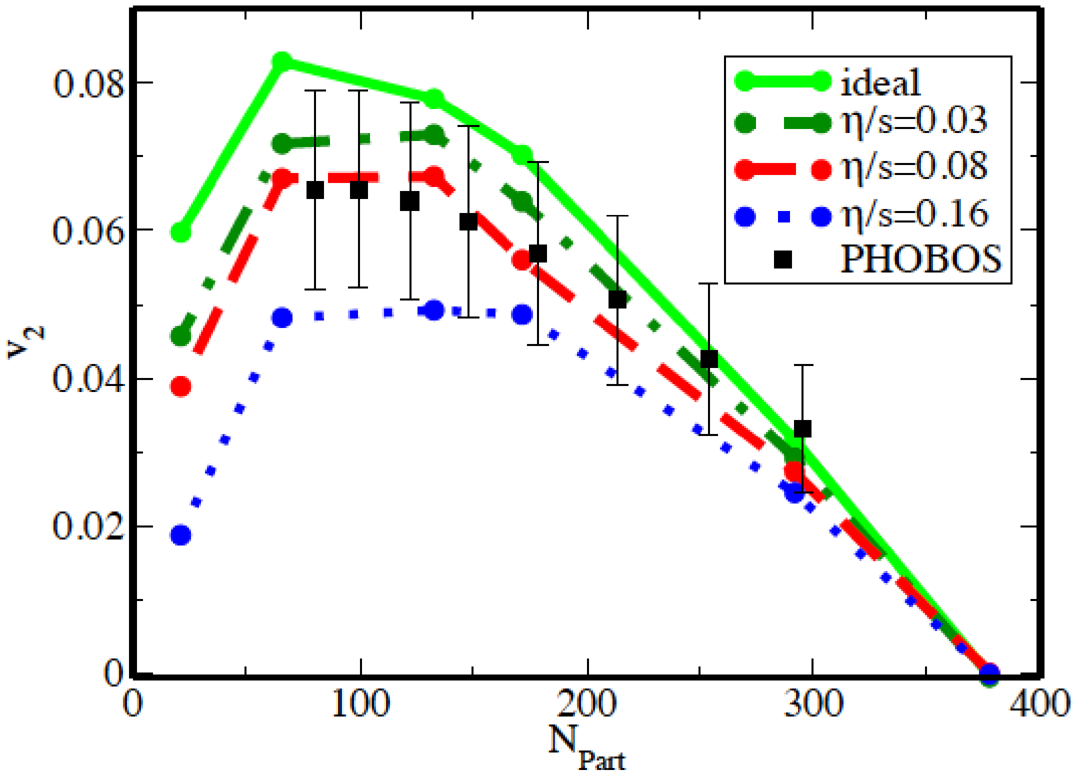




Collective (elliptic) flow of matter



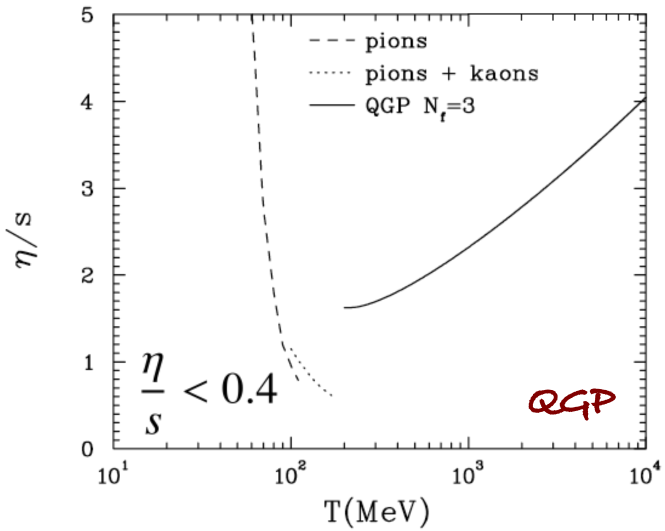
The low viscosity of the quark-gluon plasma

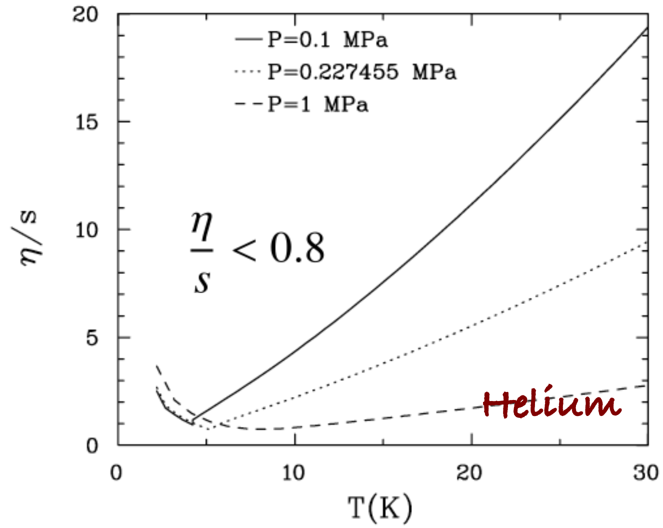


$$\frac{\eta}{s} < 5 \times \frac{1}{4\pi}$$

(Luzum, Romatschke, 2007)

Low viscosity, phase transition and strong coupling

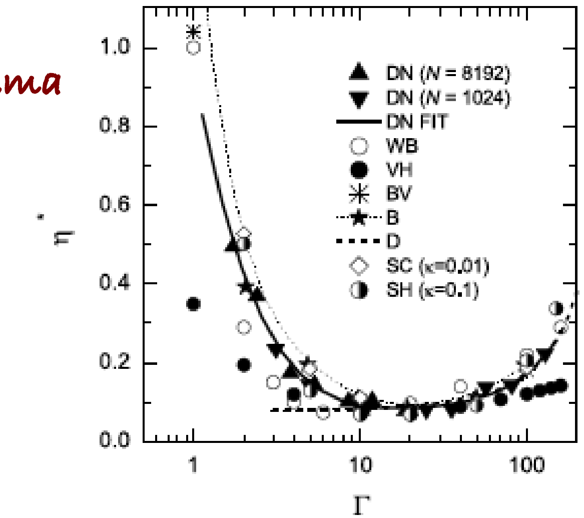




(Csernai et al, 2006)

Strongly correlated plasma

(Z. Donko et al, arXiv: 0710.5229)



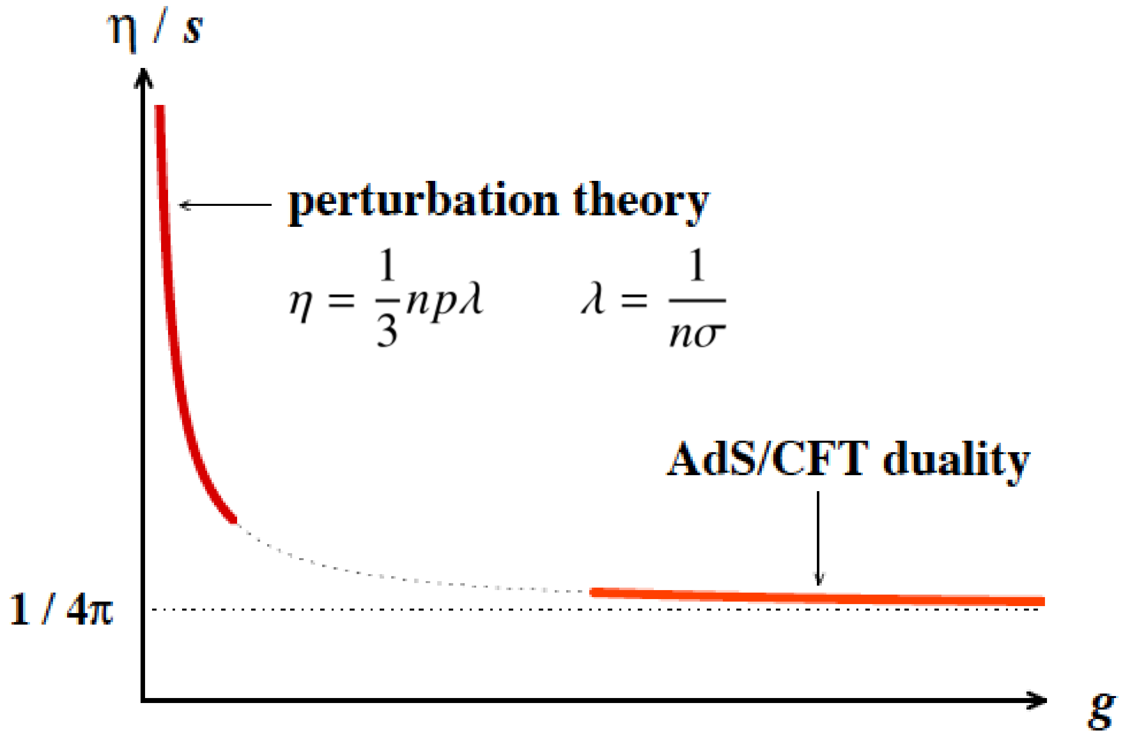
Also, cold fermionic gas at unitarity $\frac{\eta}{s} \sim 0.5$

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 !

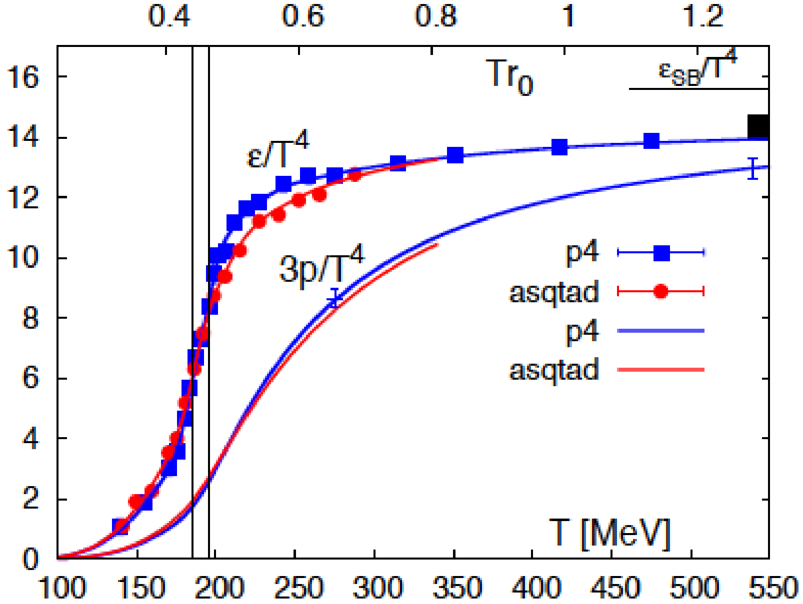
Asymptotic freedom

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

Matter is « simple » at high temperature:

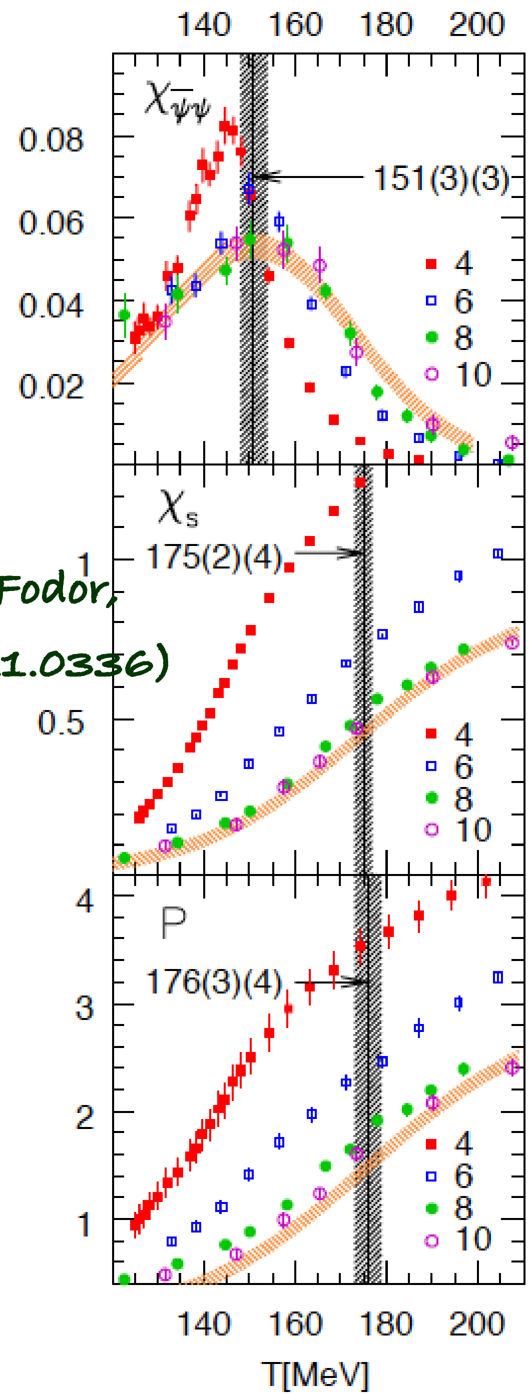
- an ideal gas of quarks and gluons
- the dominant effect of interactions is to turn (massless) quarks and gluons into weakly interacting (massive) quasiparticles.

Crossover from hadrons to quarks and gluons

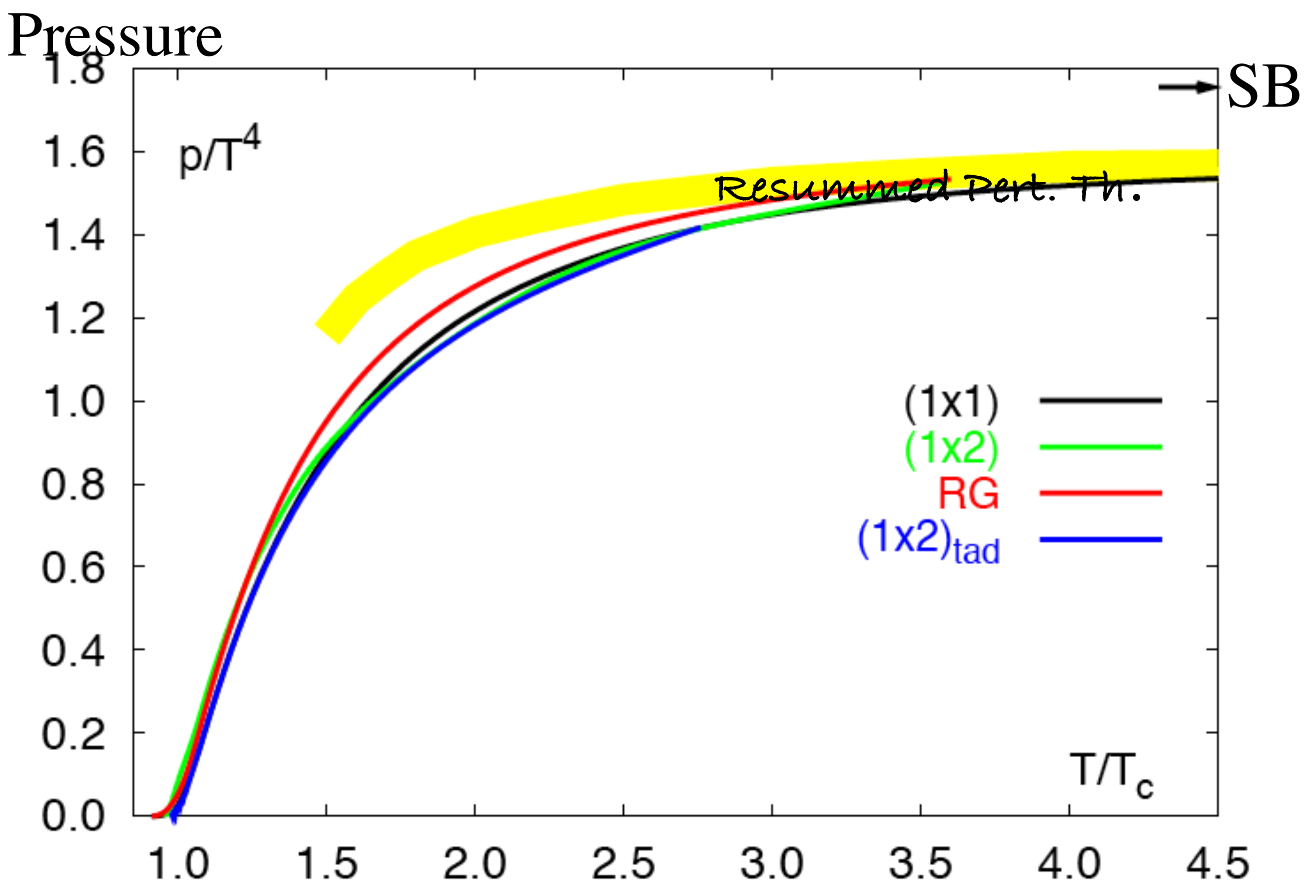


(from M. Bazavov et al, arXiv:0903.4379)

(from Z. Fodor, arXiv:0711.0336)



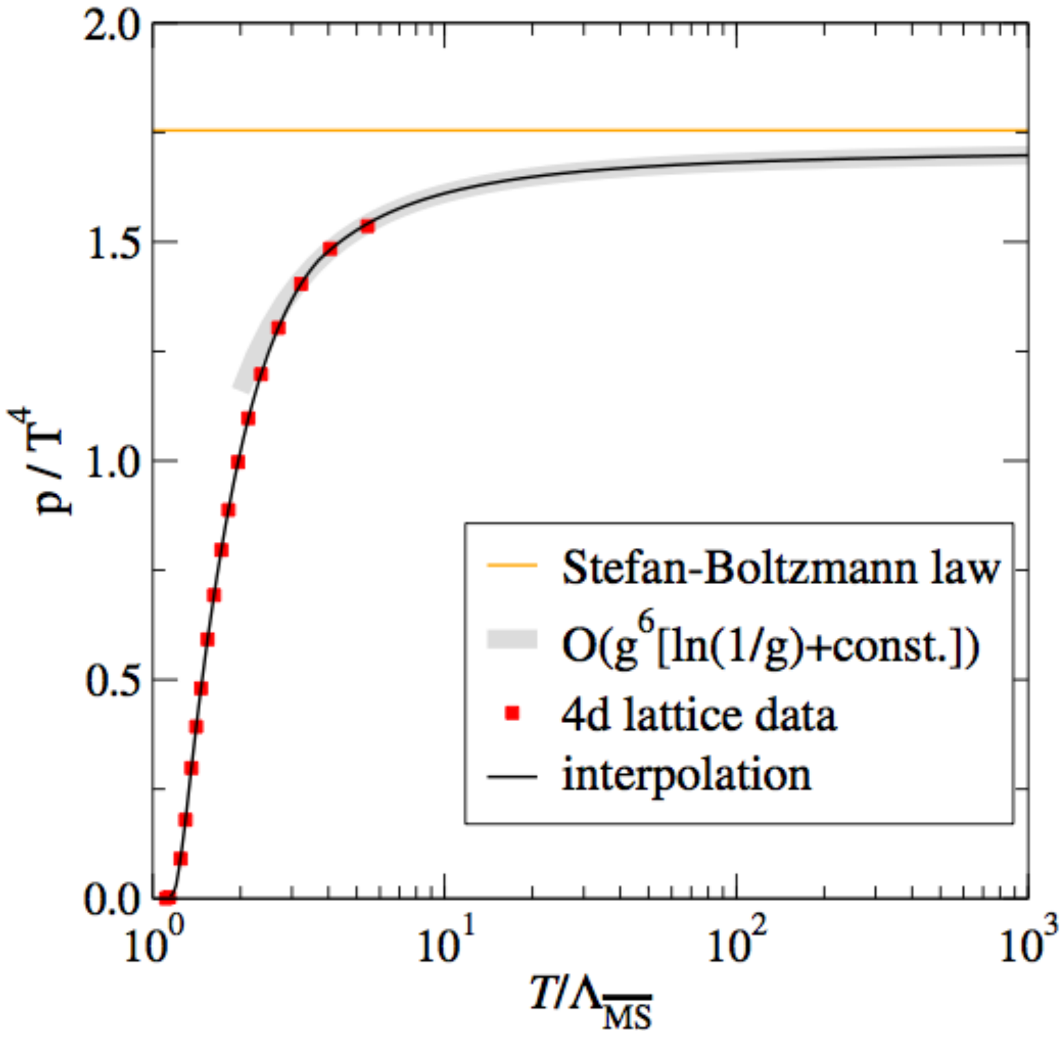
At T>3Tc Resummed Pert. Theory accounts for lattice results



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

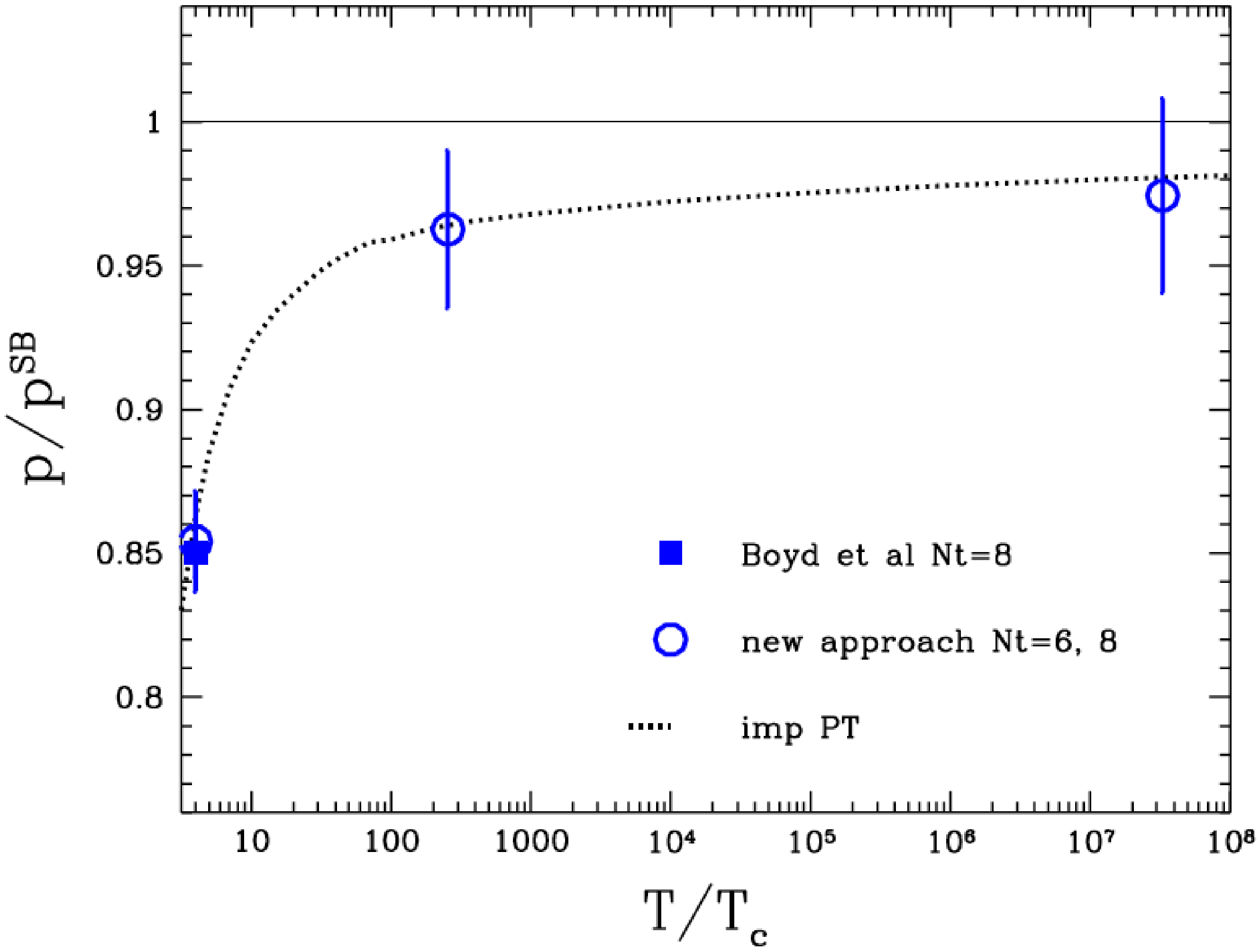
(resummed pert. th. from J.-P. B., E. Iancu, A. Rebhan: Nucl.Phys.A698:404-407,2002)

State of the art in high order perturbative calculations



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

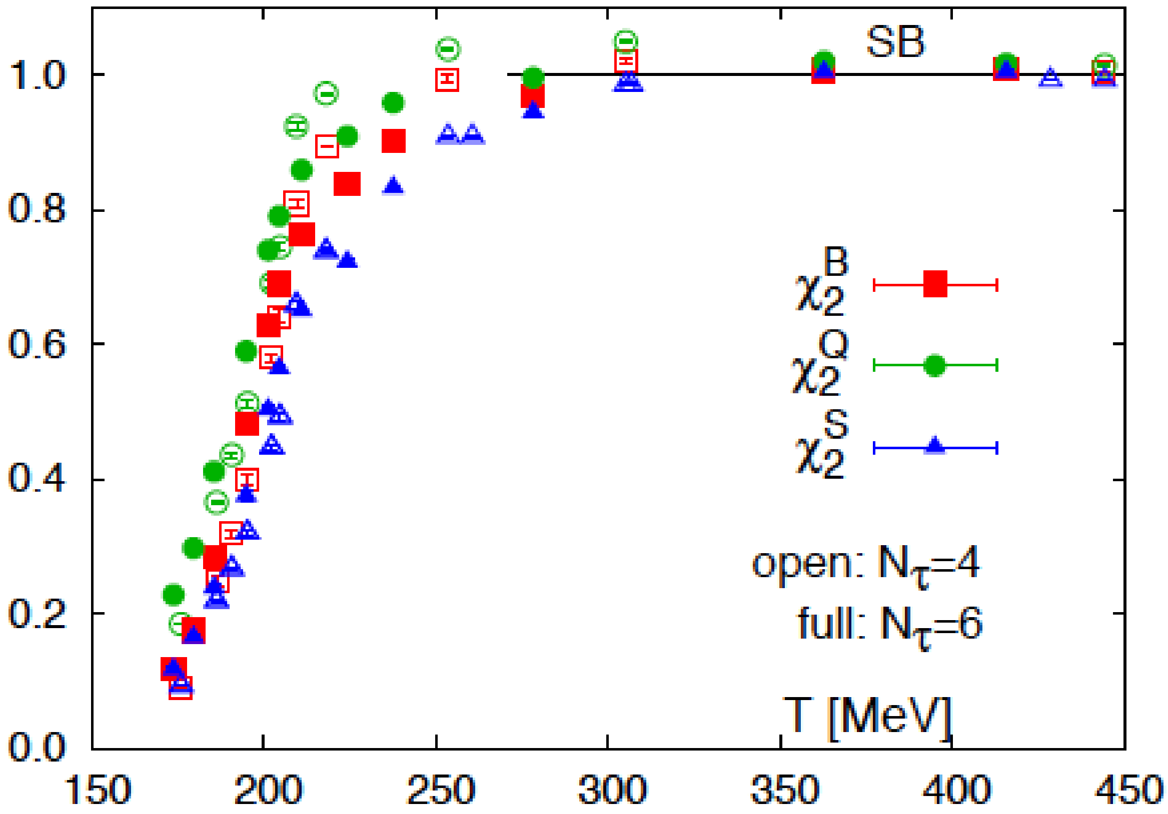
Pressure for SU(3) YM theory at (very) high temperature



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

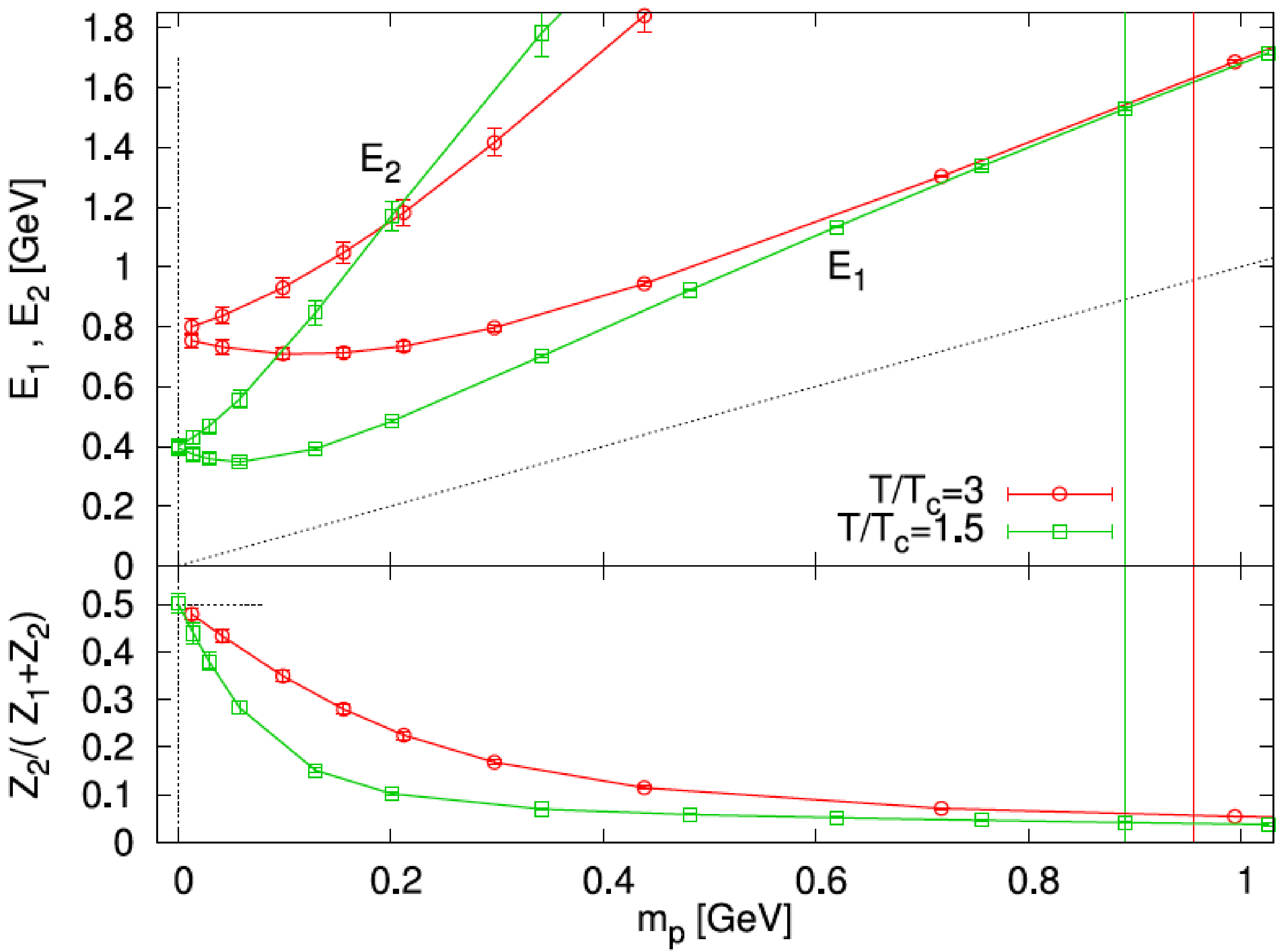
Conserved charge susceptibilities

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



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

Quark quasiparticles seen on the lattice

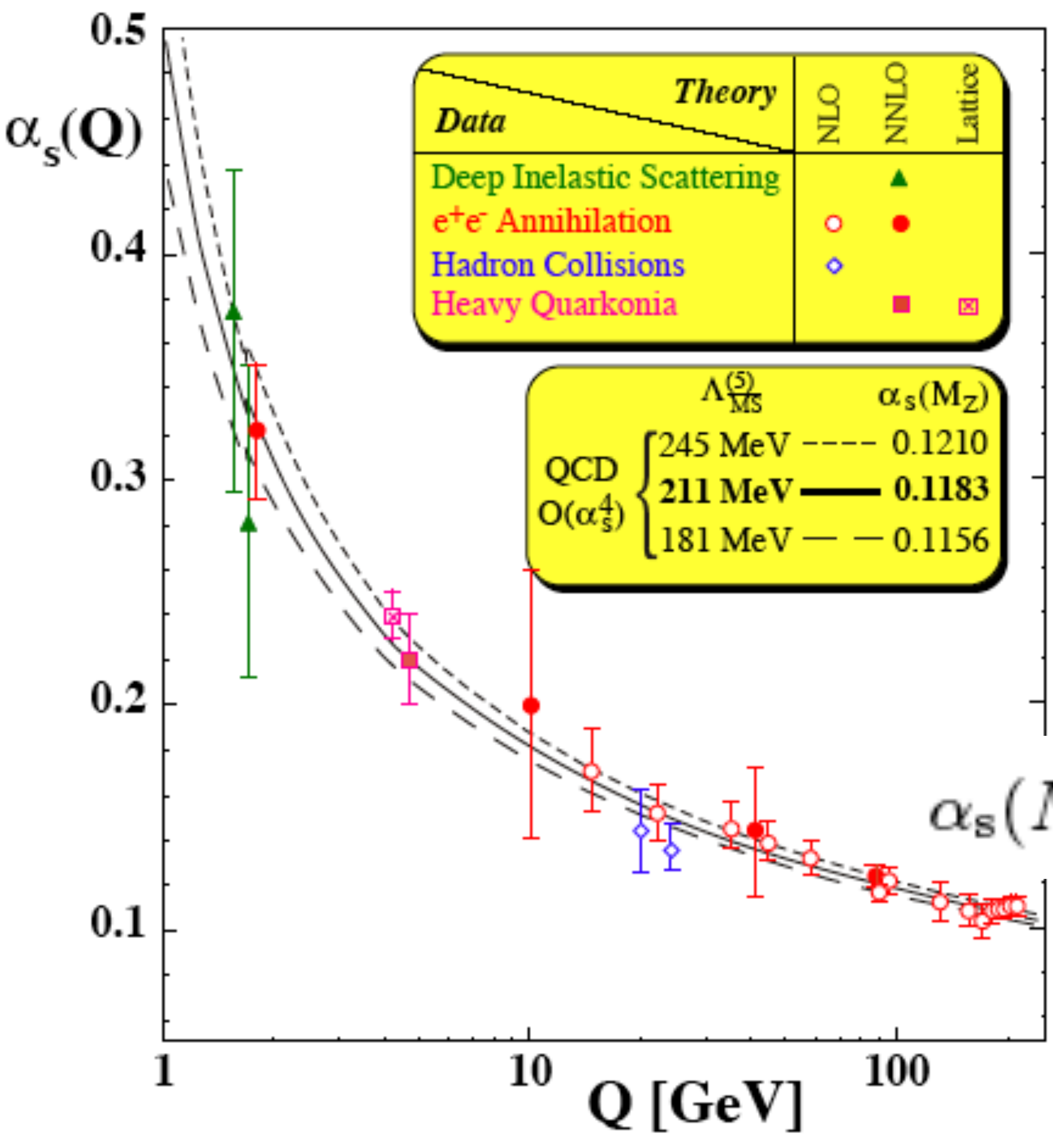


(from F. Karsch and M. Kitazawa, arXiv: 0906.3941)

Is the coupling constant large ?

Not really !

The QCD running coupling constant

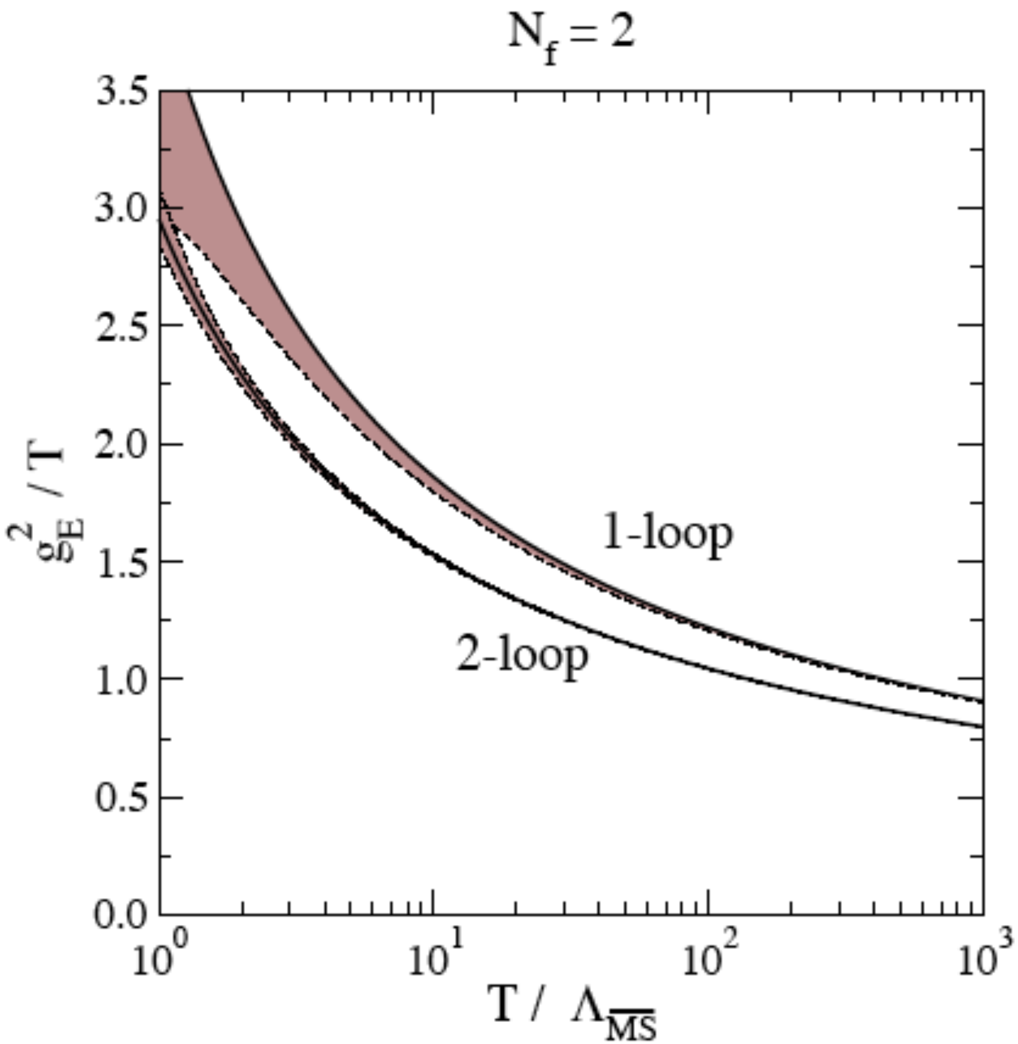


$$\alpha_s = \frac{g^2}{4\pi}$$

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

(S. Bethke, hep-ex/0211012)

The effective coupling is not huge, even close to Tc



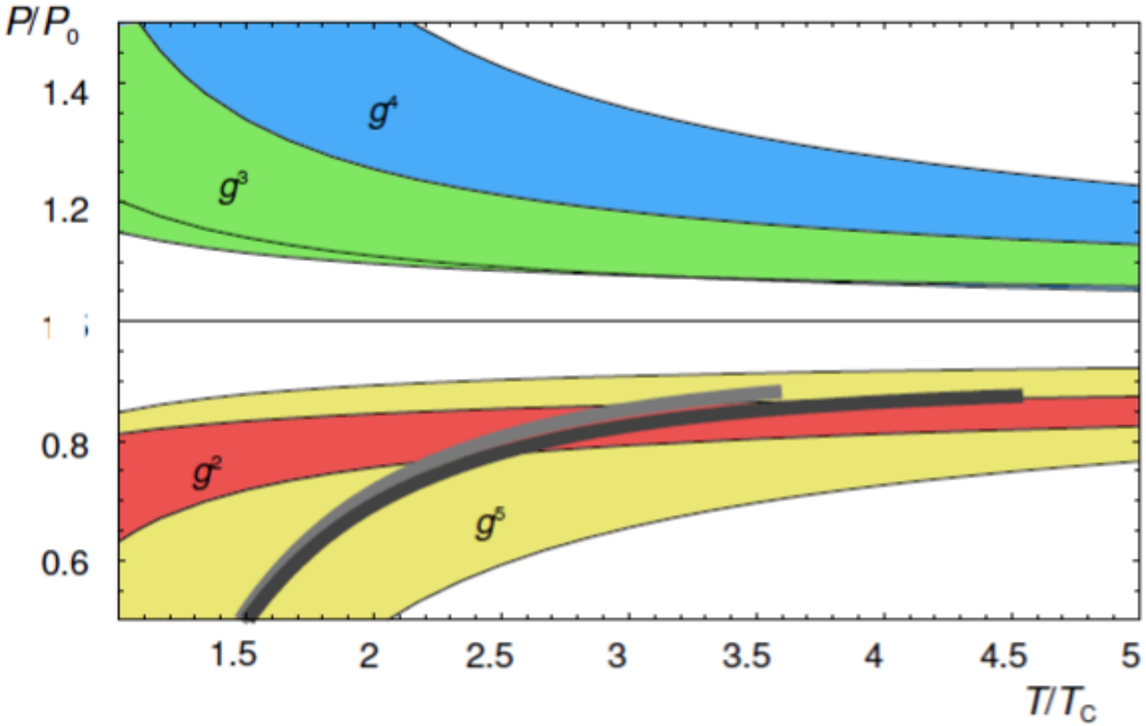
M. Laine, Y. Schröder, hep-ph/0503061

Strict perturbation theory breaks down

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 ...

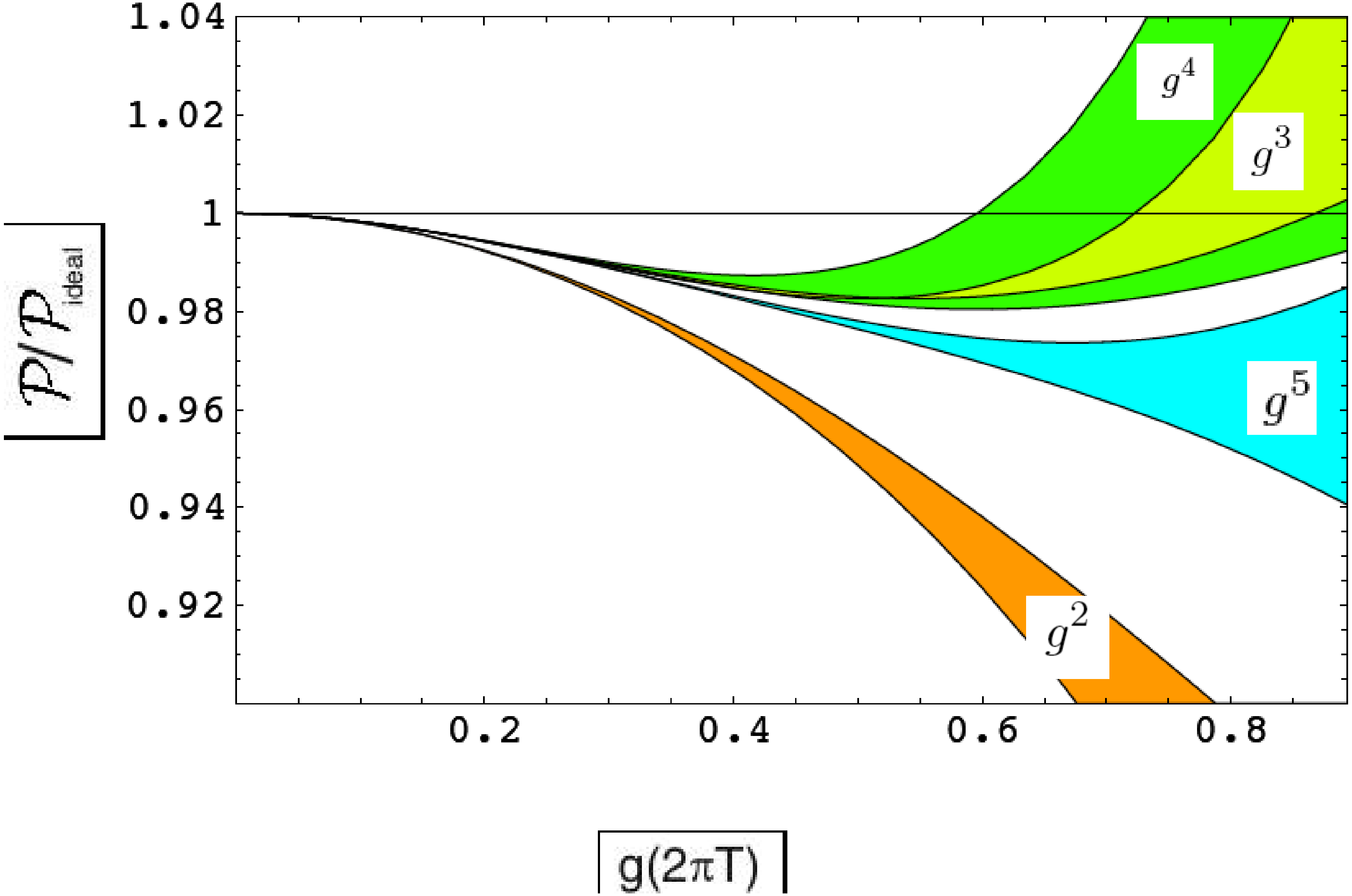
The QGP is a multiscale system

Degrees of freedom with different wavelengths are differently coupled.

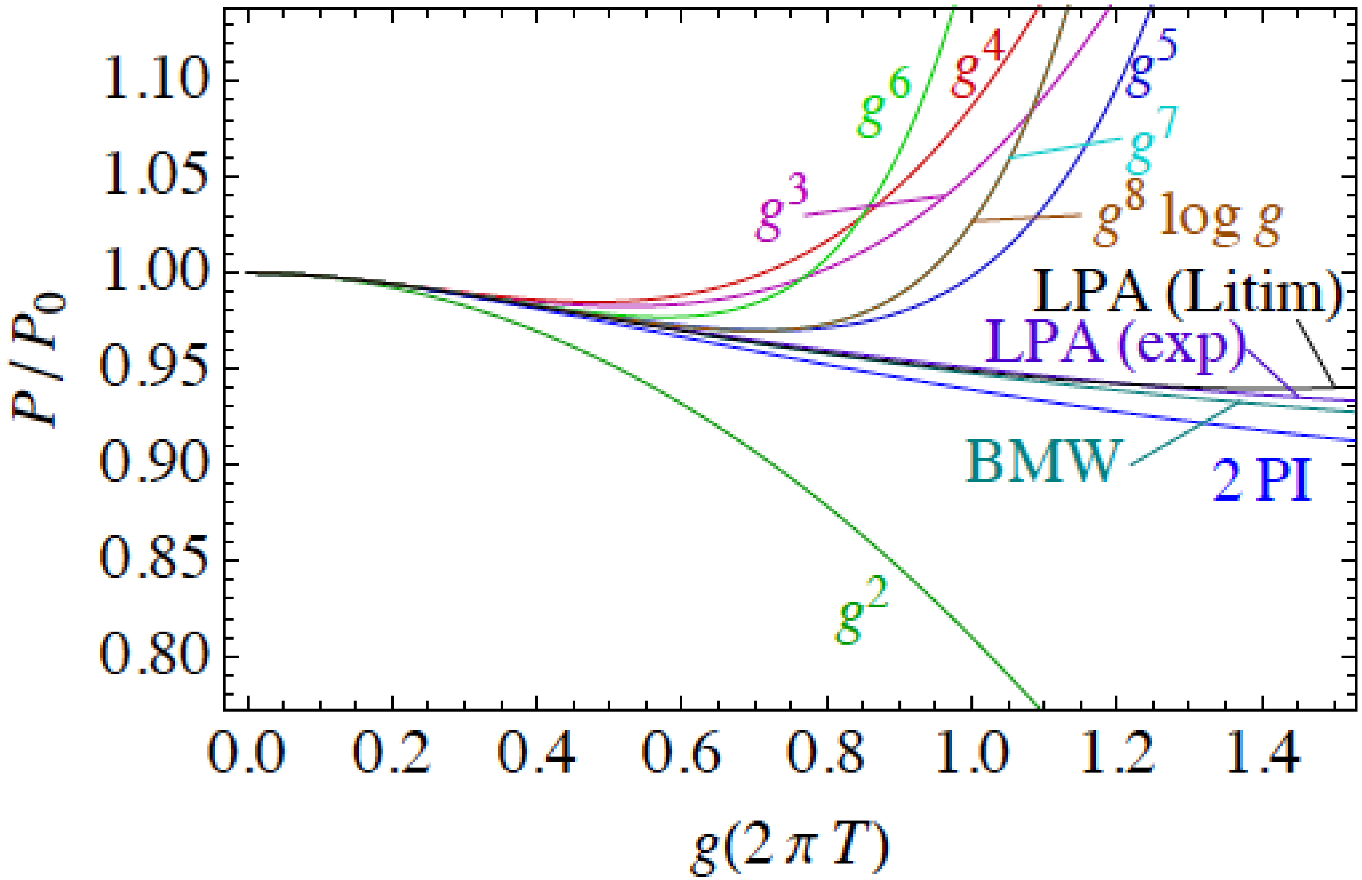
Expansion parameter depends on magnitude of thermal fluctuations and on their wavelengths

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

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



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?

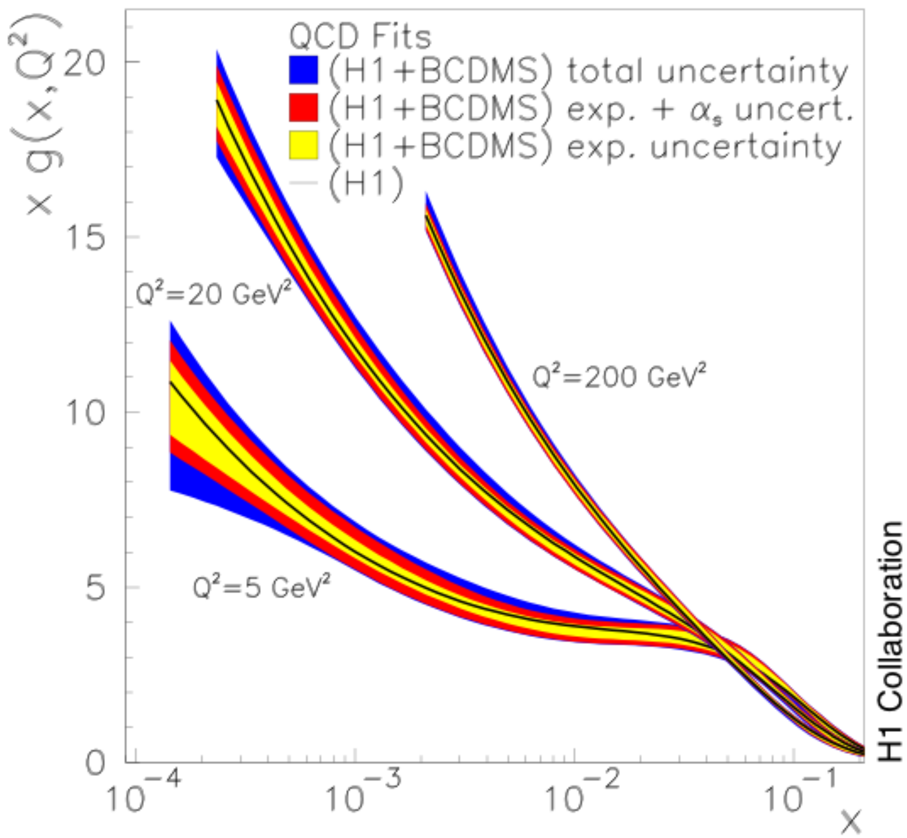
Not really (?)

Nuclear wave-functions in high energy collisions

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

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

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



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

Saturation momentum

$$Q_s^2 \sim \alpha_s \langle A^2 \rangle_{Q_s^2} \sim \frac{xG(x, Q^2)}{\pi R^2}$$

Large occupation factor

$$\frac{xG(x, Q_s^2)}{\pi R^2 \, Q_s^2} \approx \frac{1}{\alpha_s}$$

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

Successful phenomenology at RHIC

Conclusions

- 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)