Weakly and strongly coupled degrees of freedom in the quark-gluon plasma

'Excited QCD'
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Two (extreme) pictures of the quark-gluon plasma

- weakly coupled (QCD asymptotic freedom)
- strongly coupled (AdS/CFT)

RHIC, and LHC, suggest a strongly coupled quark-gluon plasma

A puzzling situation

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

Is initial concept wrong ?

No...

QCD asymptotic freedom works !

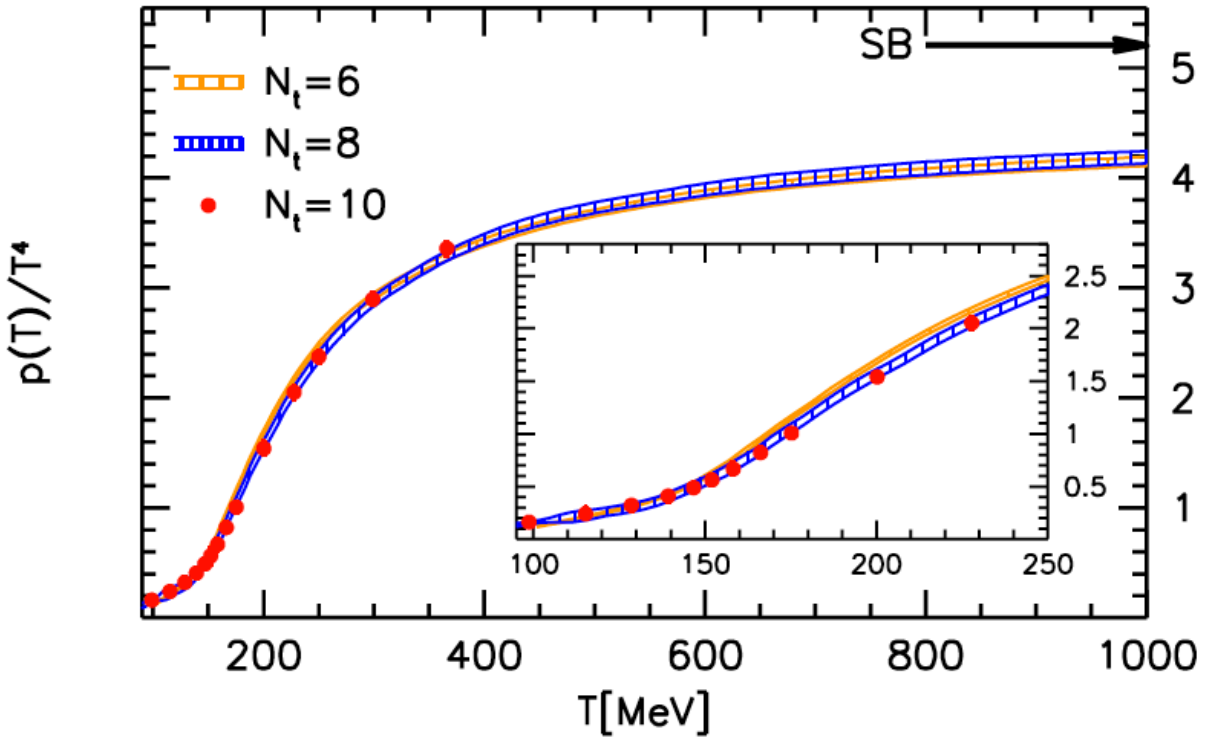
Asymptotic freedom

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

Matter is « simple » at high temperature:

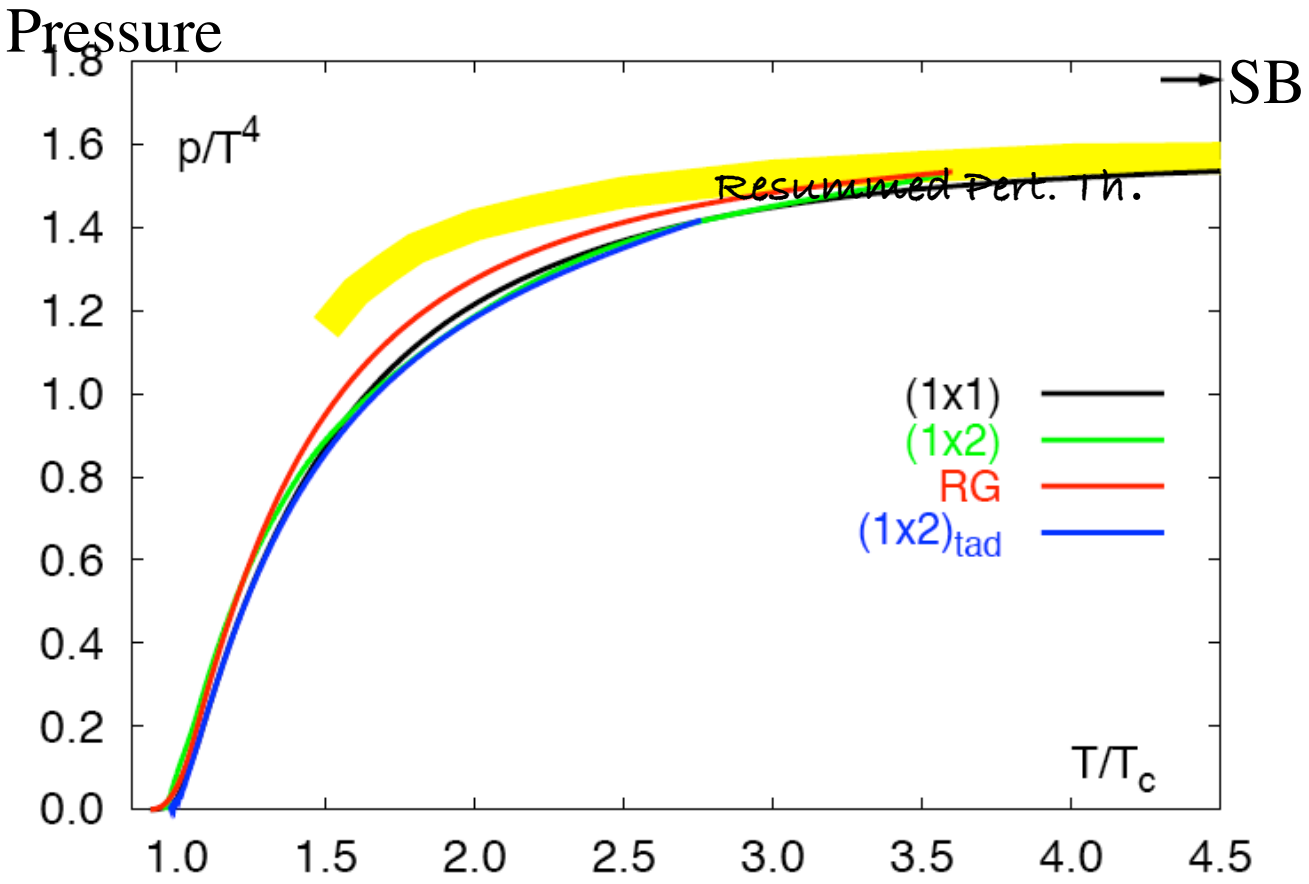
- an ideal gas of quarks and gluons
- the dominant effect of interactions is to turn (massless) quarks and gluons into weakly interacting (massive) quasiparticles.

Crossover from hadrons to quarks and gluons



(from S. Borsanyi et al, arXiv:1007.2580)

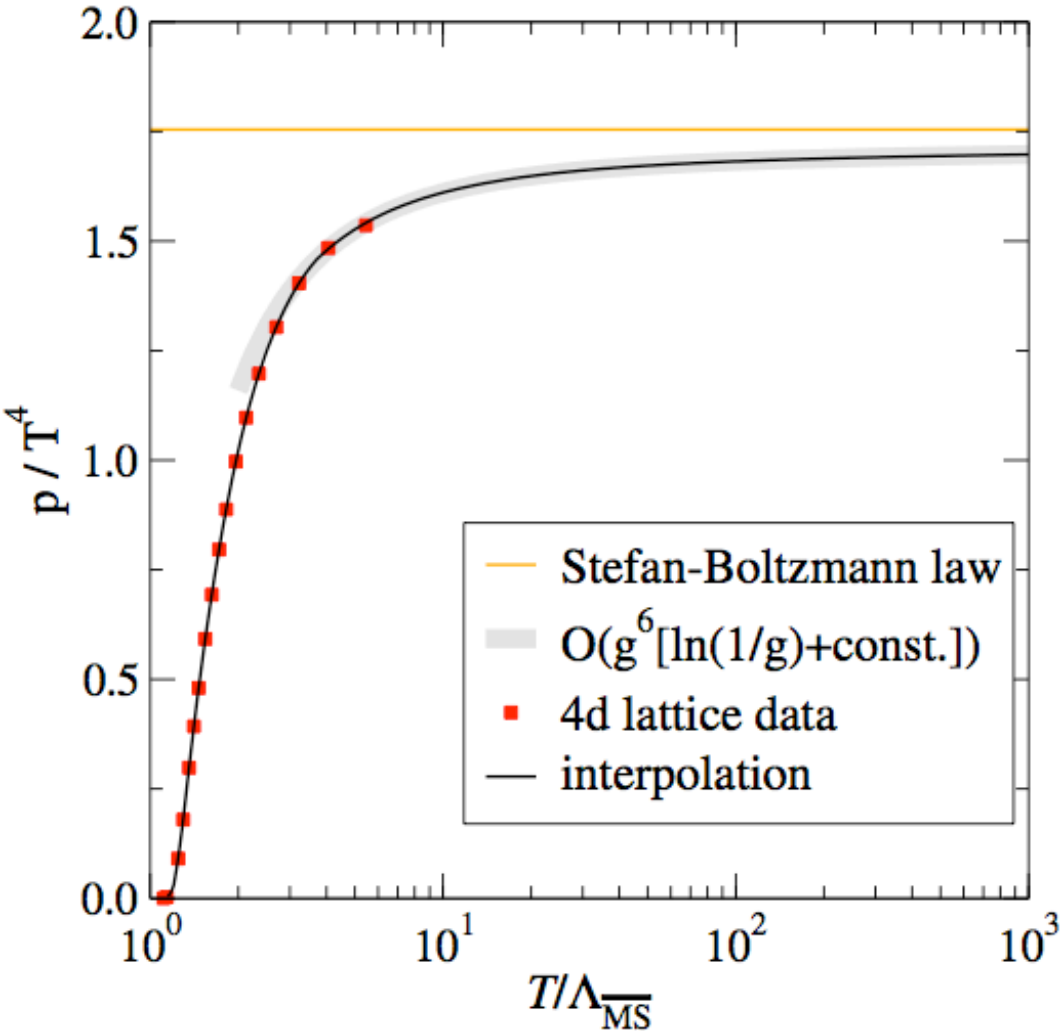
At T>3Tc Resummed Pert. Theory accounts for lattice results



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

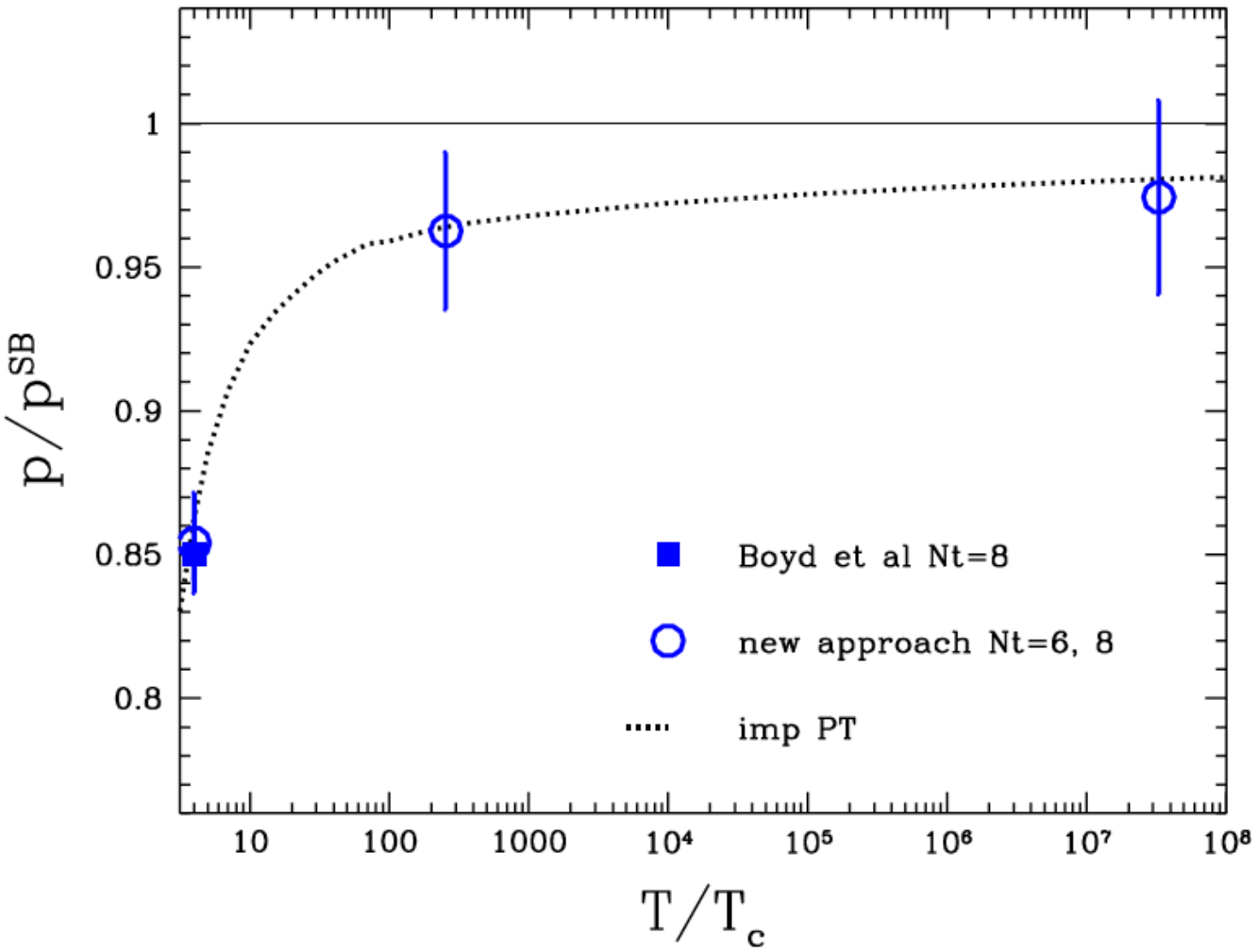
(resummed pert. th. from J.-P. B., E. Iancu, A. Rebhan: Nucl.Phys.A698:404-407,2002)

State of the art in high order perturbative calculations



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

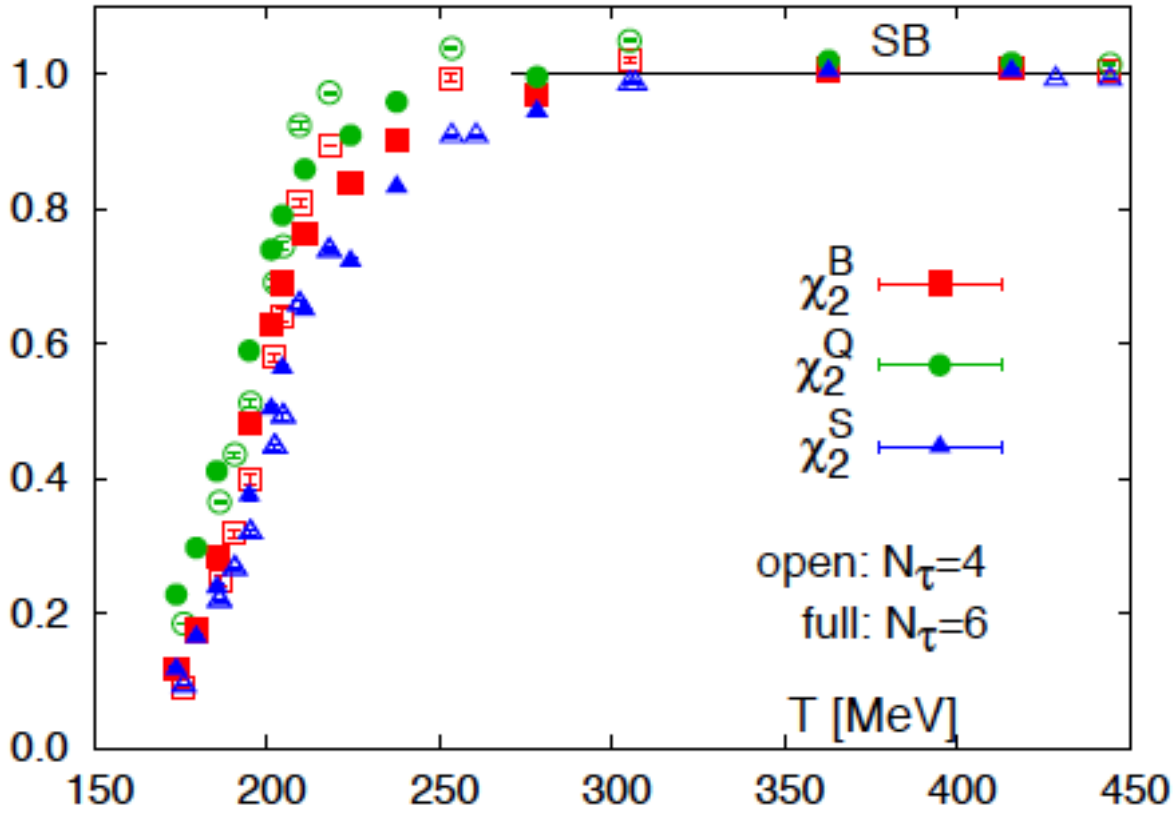
Pressure for SU(3) YM theory at (very) high temperature



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

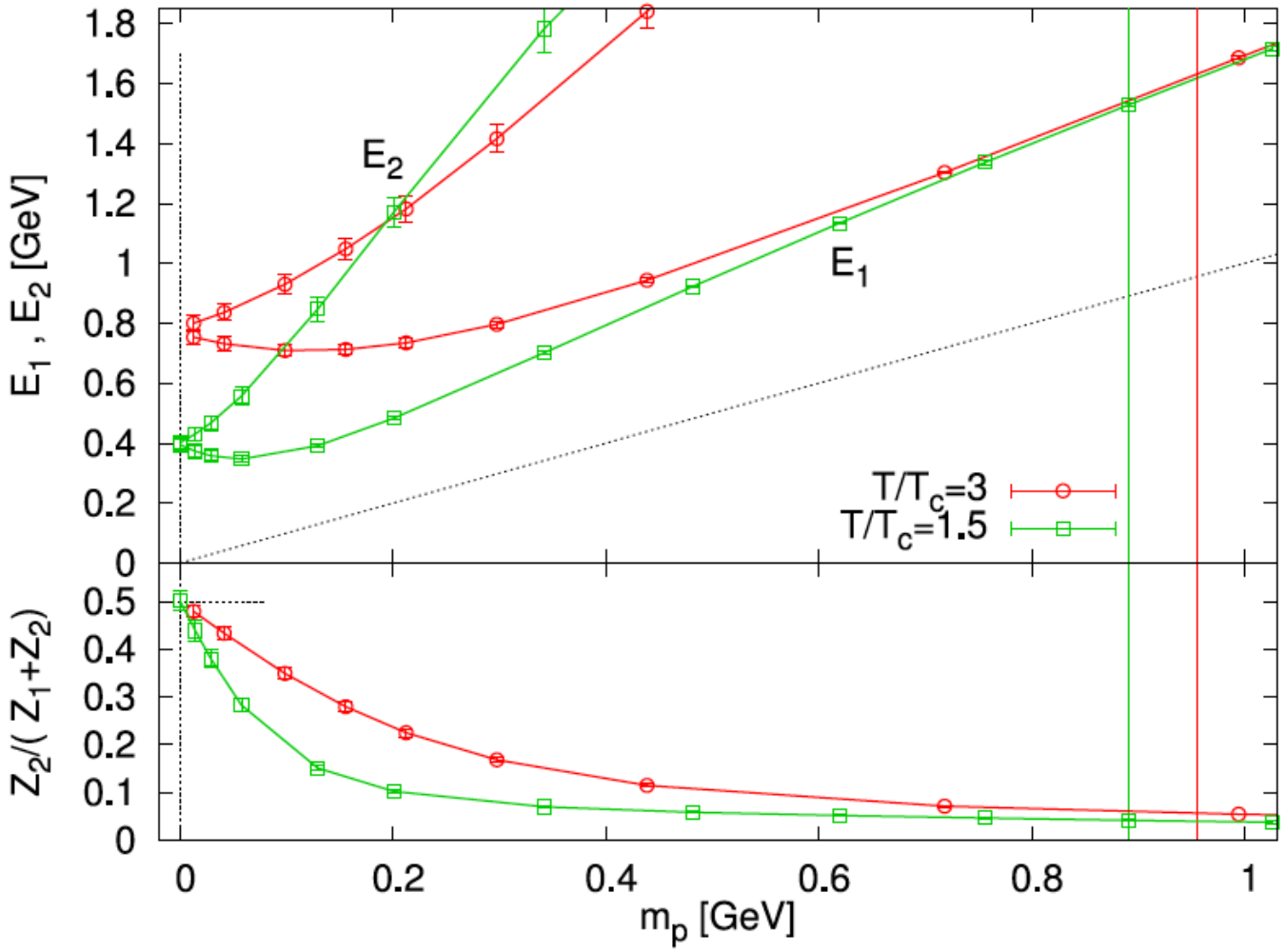
Conserved charge susceptibilities

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



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

Quark quasiparticles seen on the lattice

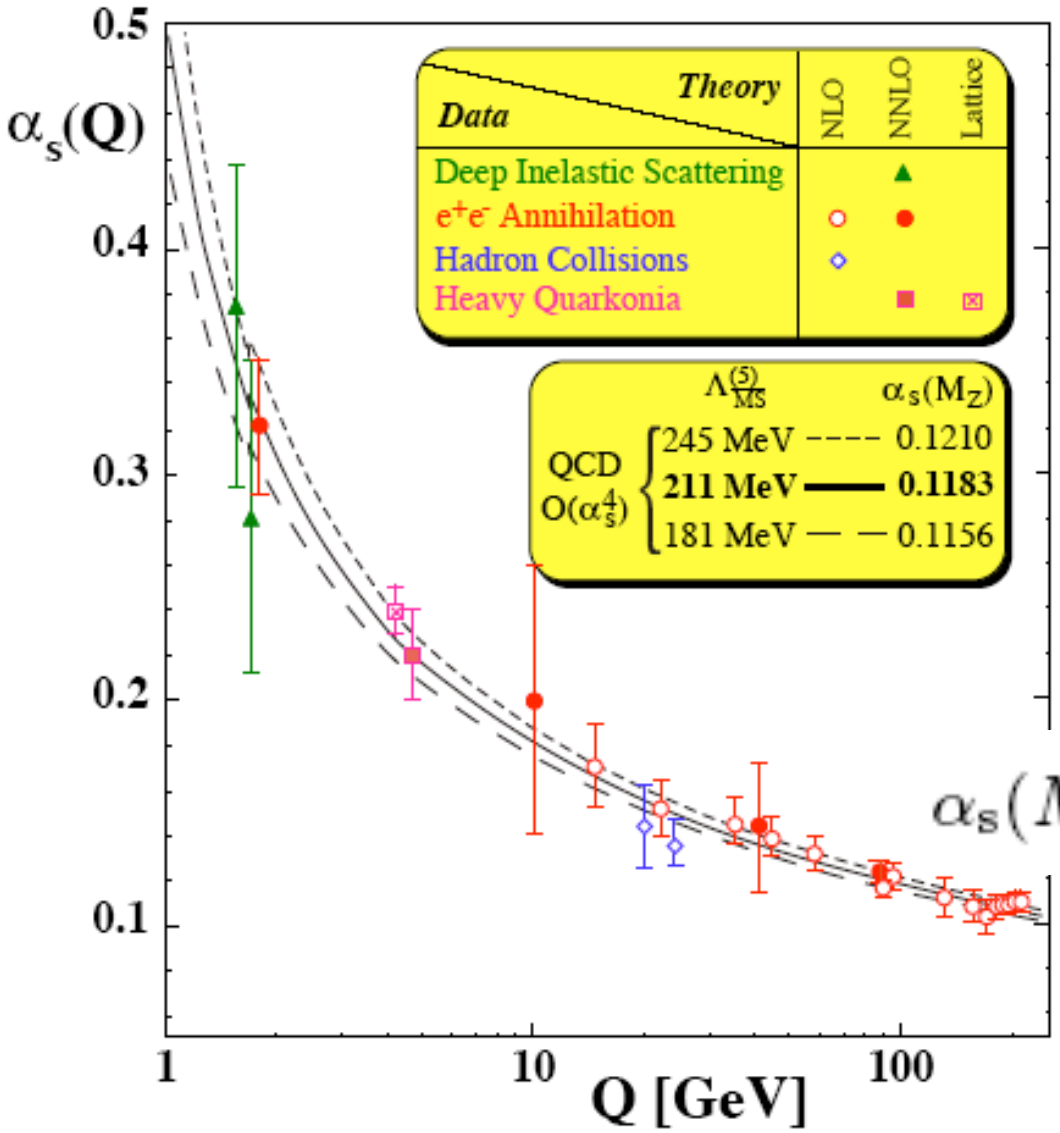


(from F. Karsch and M. Kitazawa, arXiv: 0906.3941)

Is the coupling constant large ?

Not really !

The QCD running coupling constant

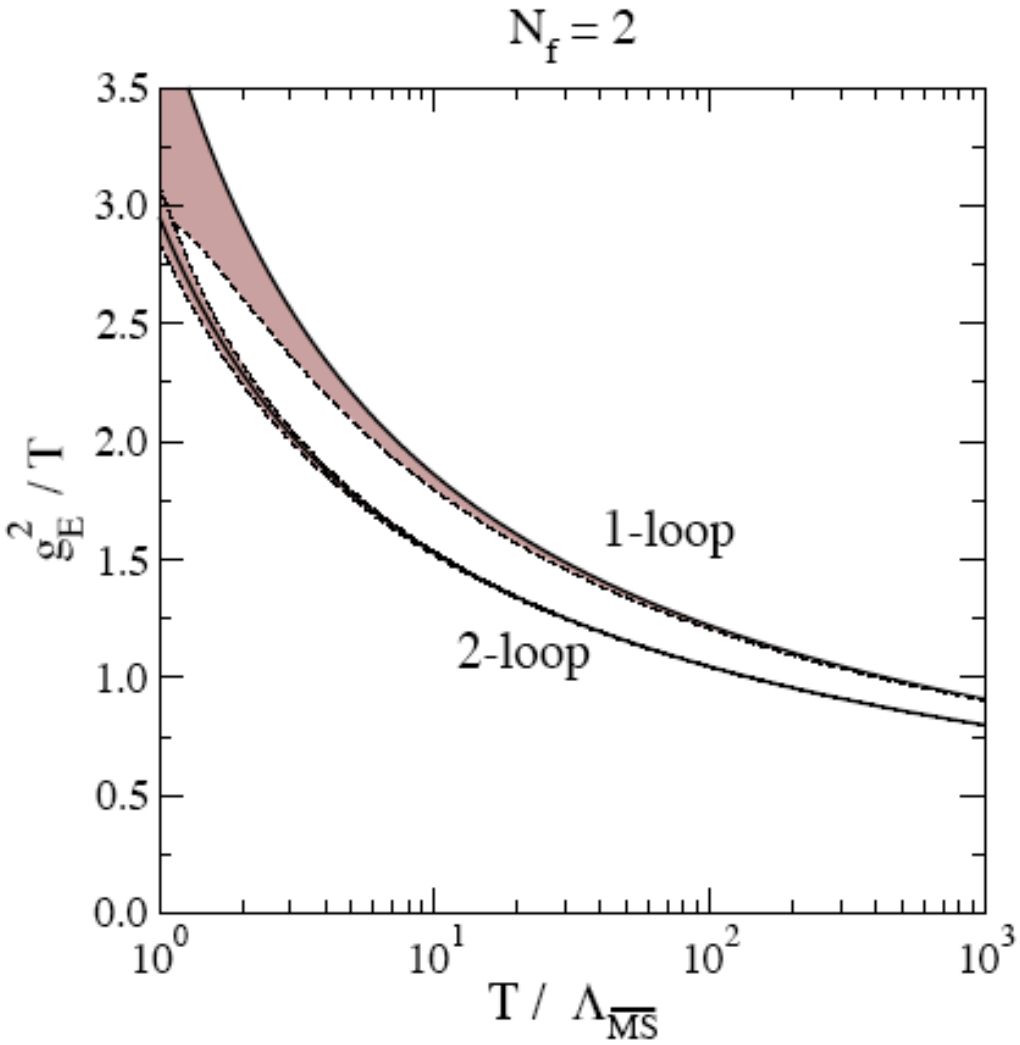


$$\alpha_s = \frac{g^2}{4\pi}$$

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

(S. Bethke, hep-ex/0211012)

The effective coupling is not huge, even close to Tc



M. Laine, Y. Schröder, hep-ph/0503061

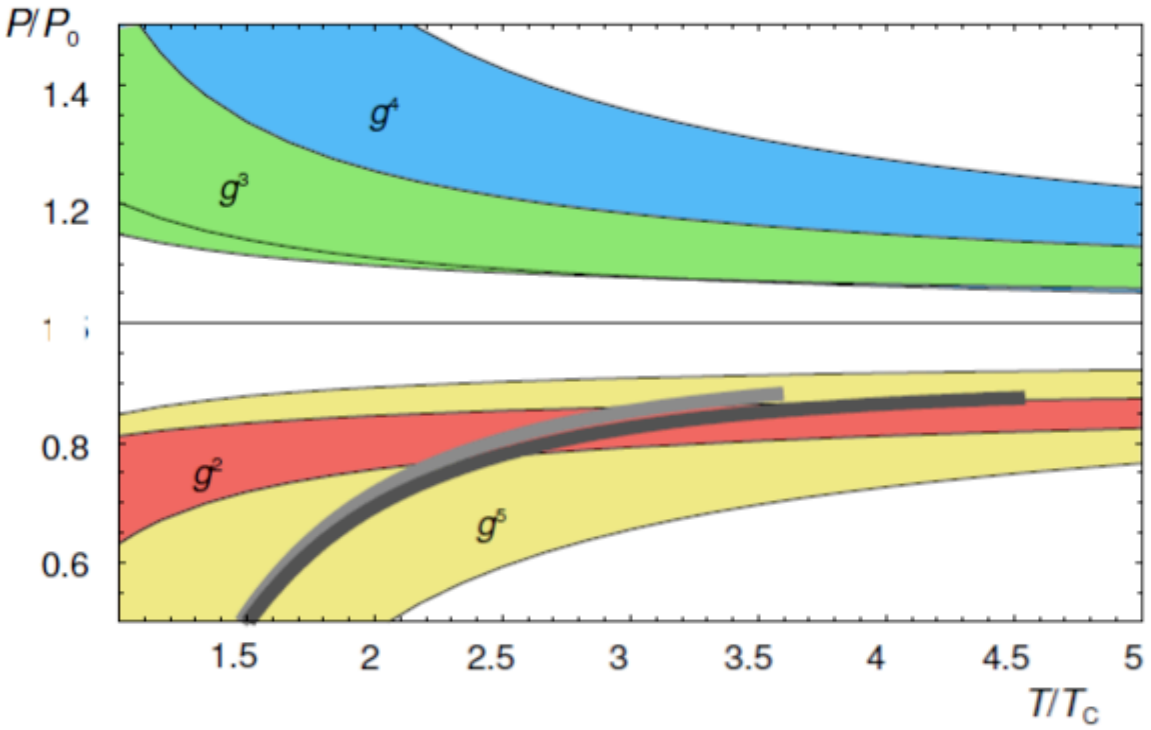
Strict perturbation theory breaks down

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

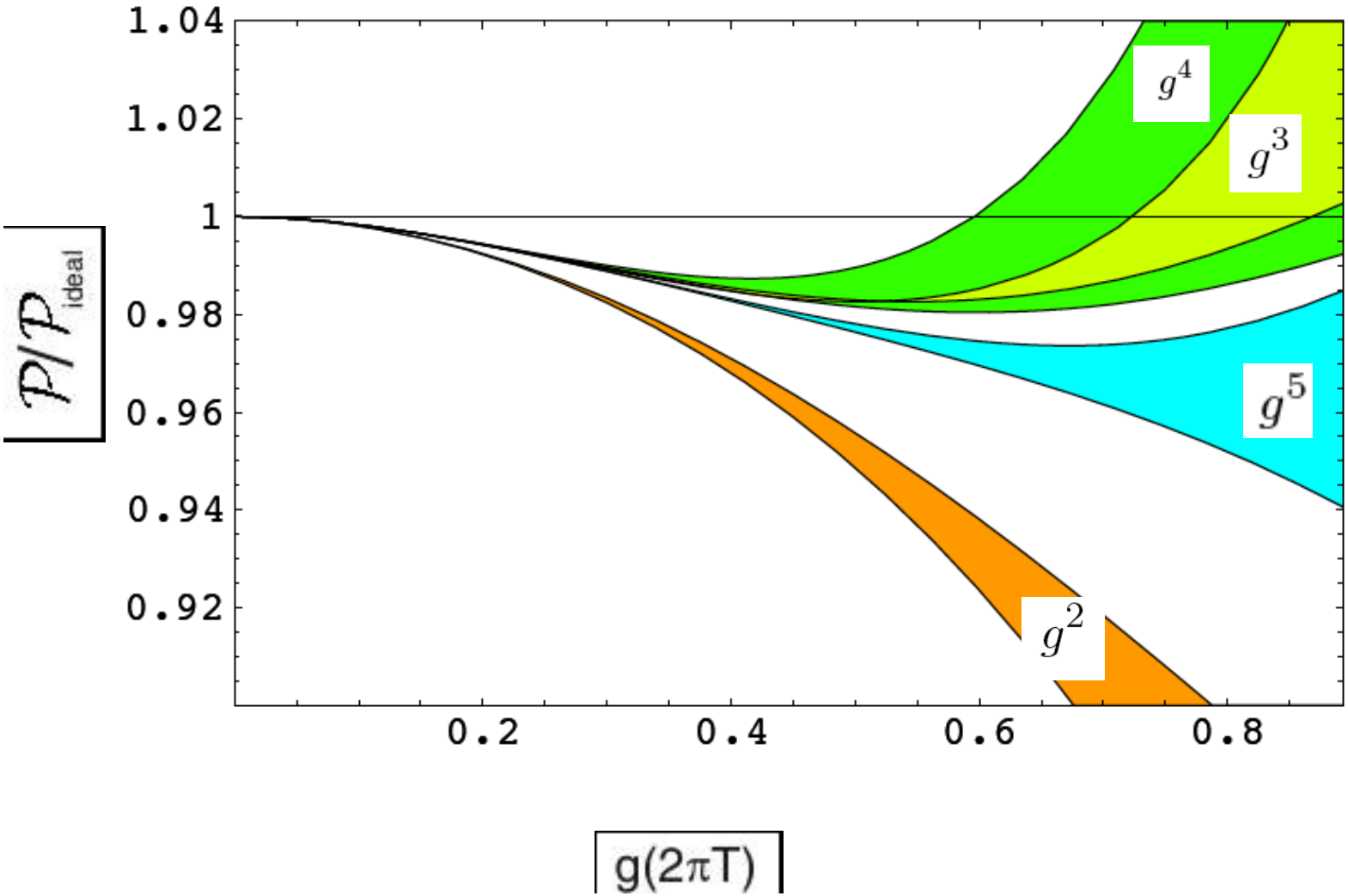


Perturbation theory:

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

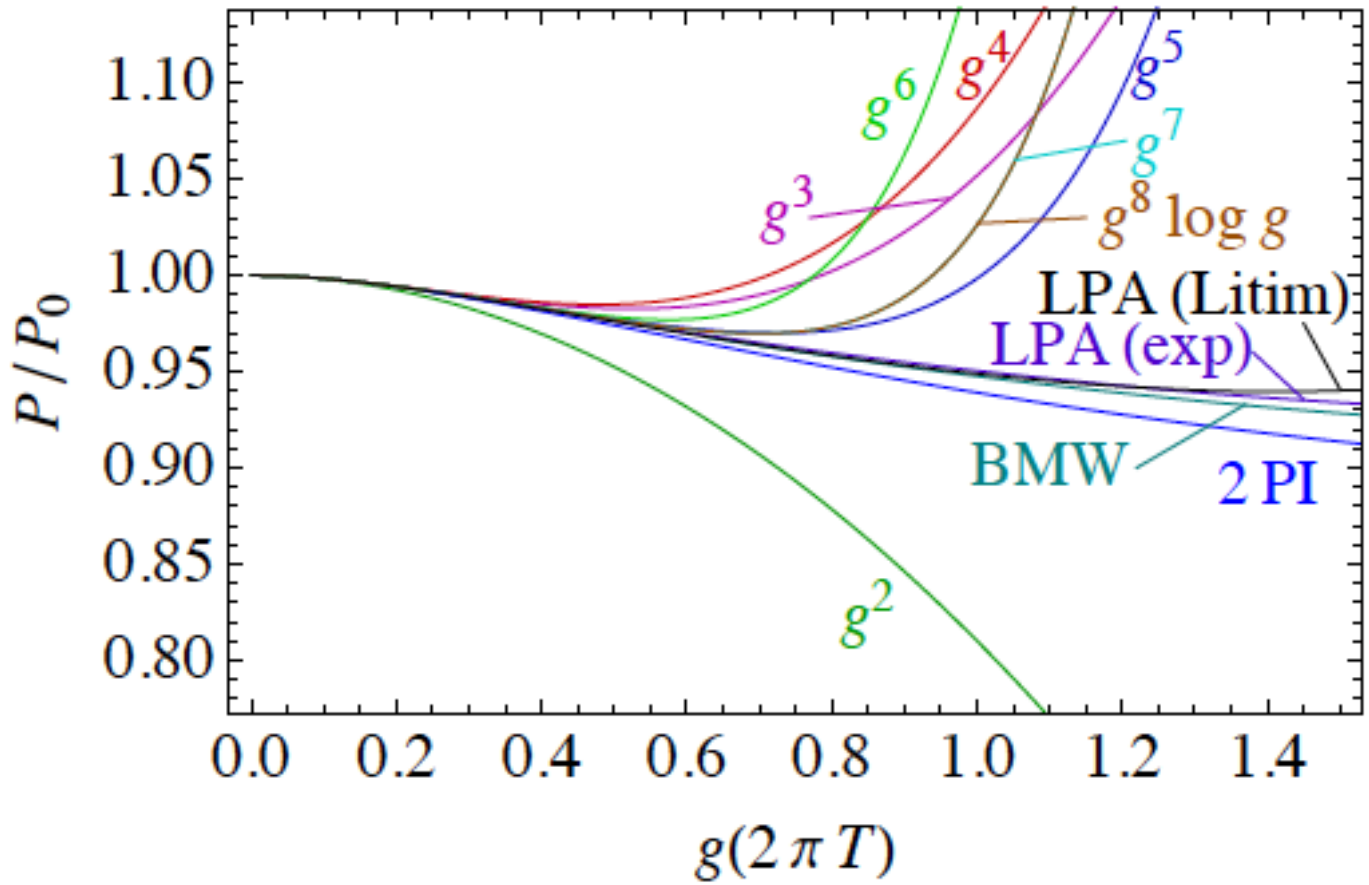
$$\kappa \sim T \qquad \gamma_\kappa \sim g^2$$

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

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

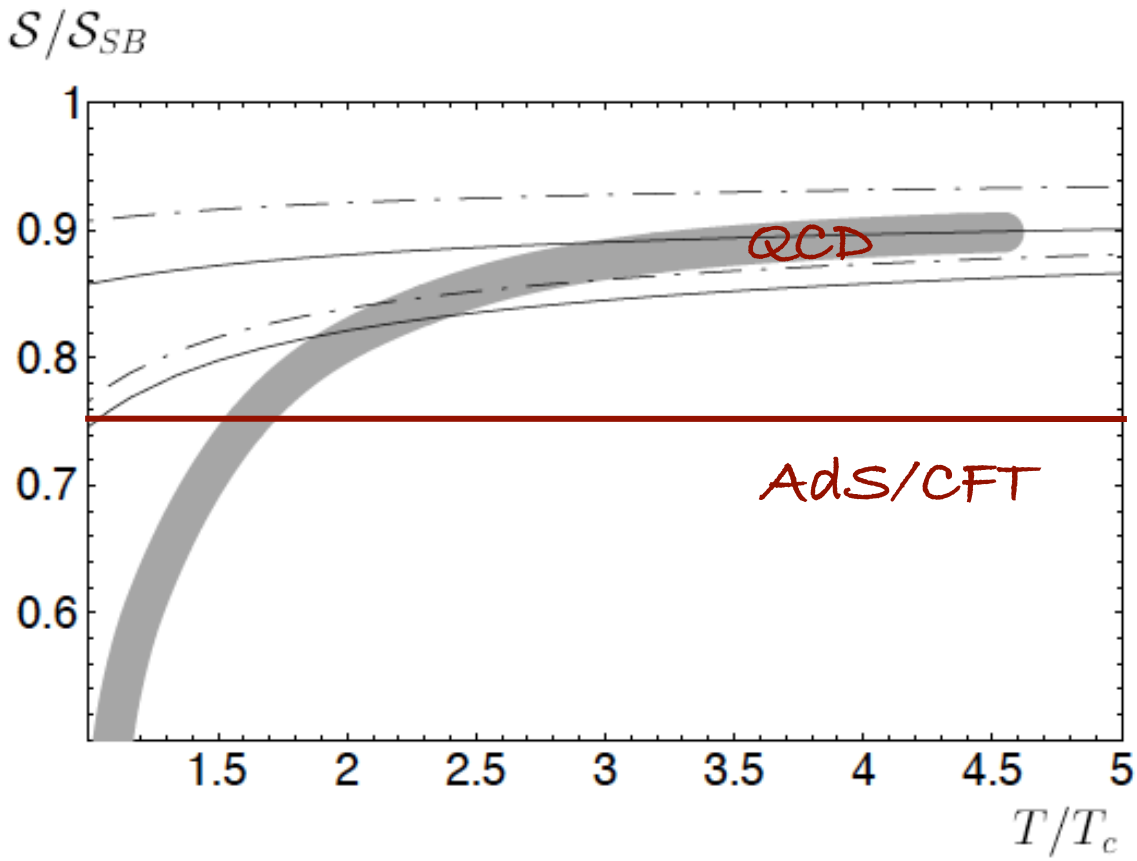
RG techniques yield smooth extrapolation to strong coupling (scalar field theory)

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



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

Entropy at weak and strong coupling



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

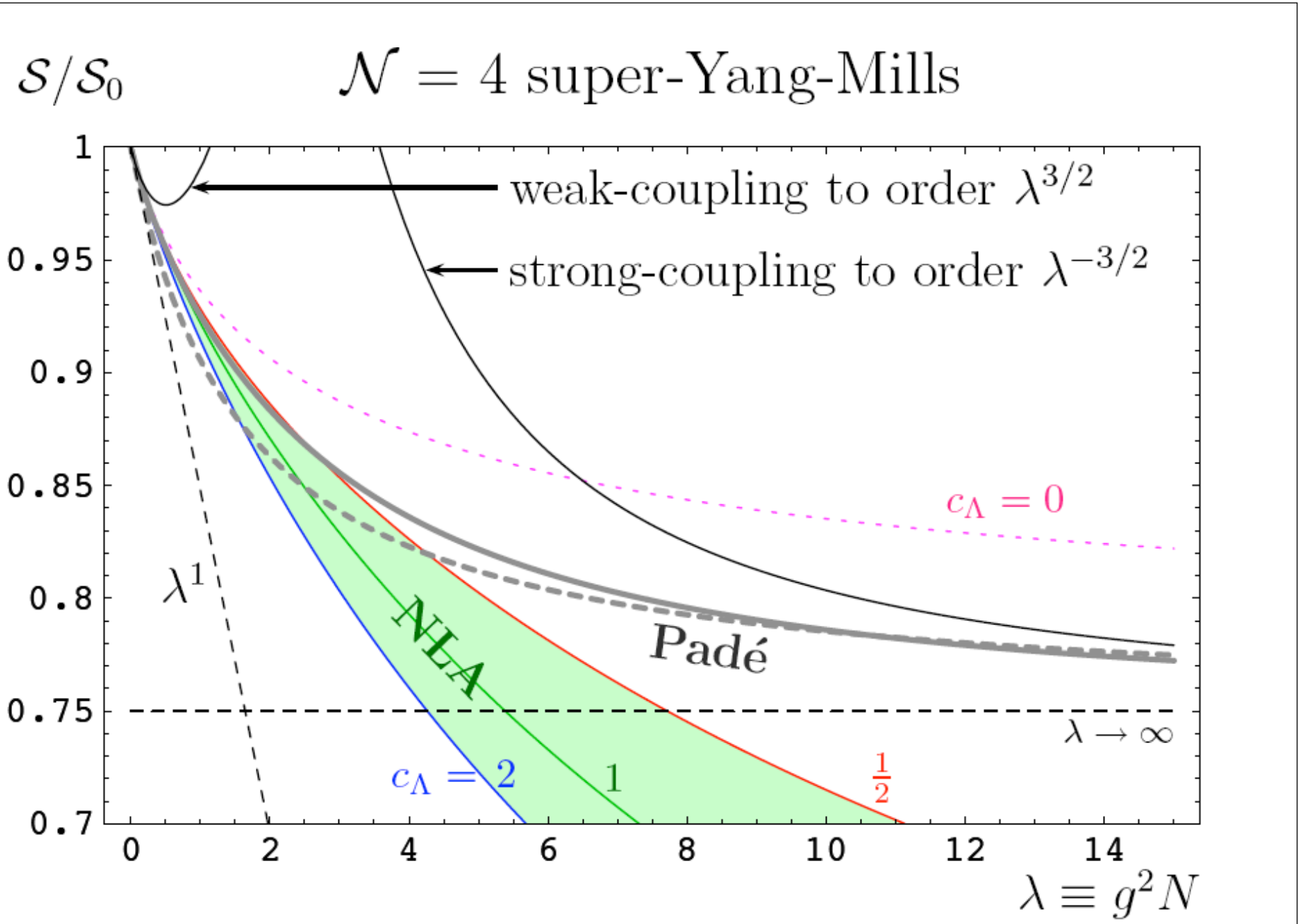
J.-P. B., E. Iancu, A. Rebhan: Phys.Rev.D63:065003,2001
G. Boyd *et al.*, Nucl. Phys. B469, 419 (1996).

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)



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

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

Not really (?)