Properties of QGP: A lattice perspective

- Introduction:

  T, gT, g^2T,...

- Bulk thermodynamics

  the equation of state: QCD and SU(3)

- Heavy quark free energies

  running coupling and heavy-light bound states

- Hadronic fluctuations

  quark number and charge fluctuations

- Conclusions

Thermal scales in QCD

- the hard scale: $p \sim T$
  thermal modes, bulk thermodynamics, eg. pressure

$$\frac{p}{T^4} = a_{SB} f_p(g(T))$$

- the soft scale: $p \sim gT$
  static color-electric modes, eg. Debye screening

$$\frac{m_D(T)}{g(T)T} = \sqrt{\frac{N_c}{3} + \frac{n_f}{6} + \frac{n_f}{2\pi^2}\left(\frac{\mu_q}{T}\right)^2} \cdot f_E(g(T))$$

- the ultra-soft scale: $p \sim g^2 T$
  static color-magnetic modes, eg. spatial string tension

$$\frac{\sqrt{\sigma_s}}{g^2(T)T} = c_M f_M(g(T))$$

Non-thermal scales in thermal QCD

- even harder scales: $p \gg T$, $r^{-1} \gg T$, $M \gg T$

  short distance physics, eg. quarkonium

  $$g^2(r, T)$$

- quantitative questions, eg.

  When does T become the dominant scale?

.

- Perturbation theory provides a hierachy of length scales

  $T \gg gT \gg g^2T$...$\Rightarrow$ guiding principle for effective theories,

  resummation, dimensional reduction...

- Early lattice results show that $g^2(T) > 1$ even at $T \sim 5T_c$

  G. Boyd et al, NP B469 (1996) 419: SU(3) thermodynamics..

  ...one has to conclude that the temperature dependent running coupling has to be large, $g^2(T) \simeq 2$ even at $T \simeq 5T_c$

- the Debye screening mass is large close to T_c
- the spatial string tension does not vanish above T_c

  $\sqrt{\sigma_s} \neq 0 \Rightarrow$ the QGP is "non-perturbative" up to very high T

The spatial string tension

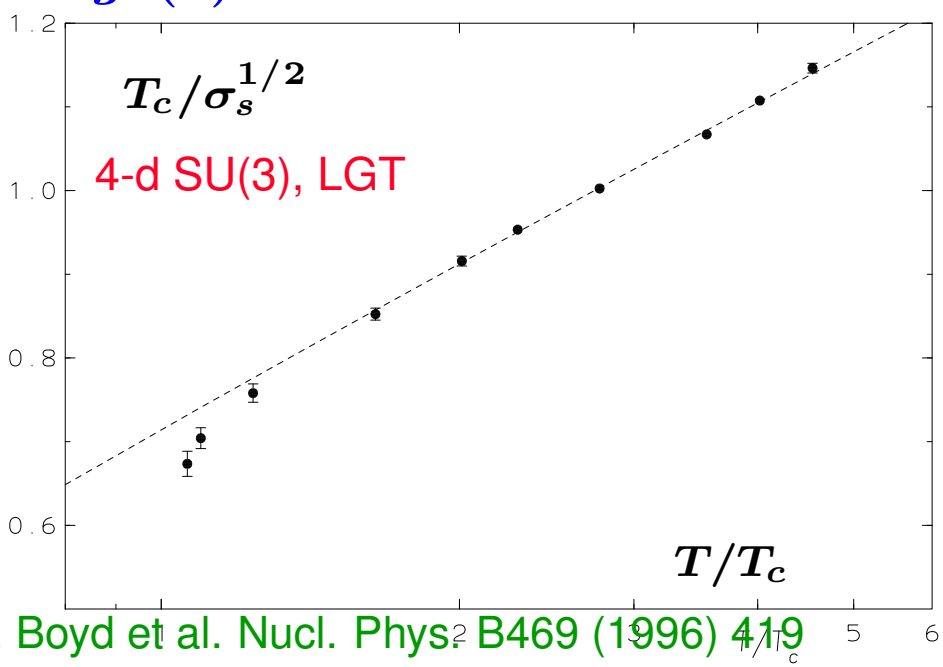
- Non-perturbative, vanishes in high-T perturbation theory:

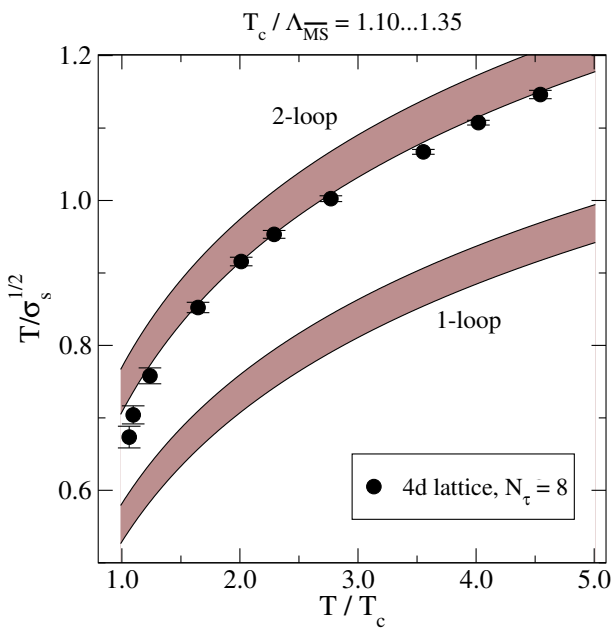
$$\sqrt{\sigma_s} = -\lim_{R_x, R_y \to \infty} \ln \frac{W(R_x, R_y)}{R_x R_y}$$

- $$\frac{\sqrt{\sigma_s}}{g^2(2)T} = c_M f_M(g(T)) \ , \ c_M = 0.553(1)$$

c_M : 3-d SU(3), LGT

$g_M \equiv g^2 f_M$: dim. red. pert. th.





G. Boyd et al. Nucl. Phys. B469 (1996) 419

M. Laine, Y. Schröder, JHEP 0503 (2005) 067

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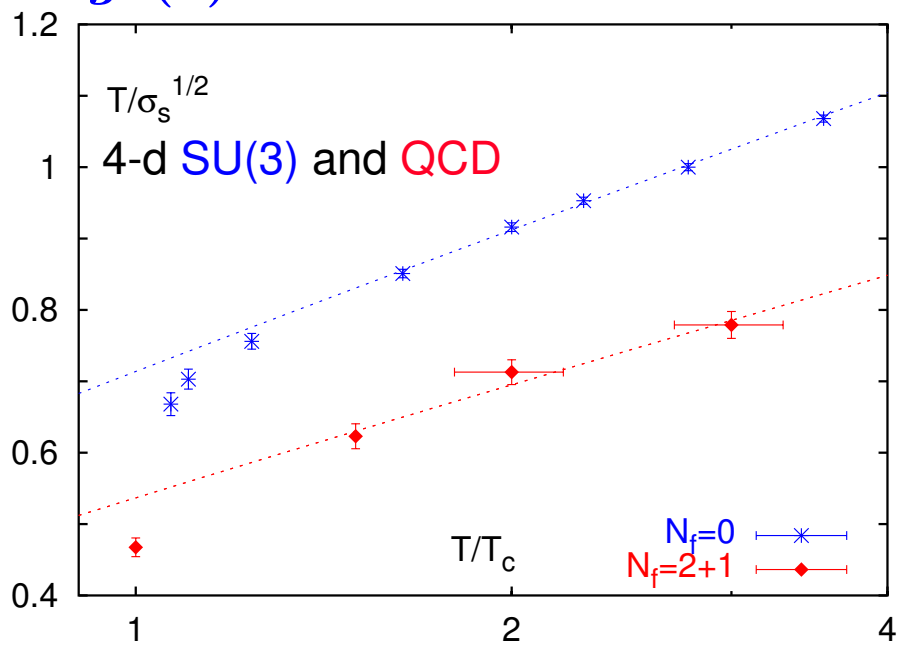


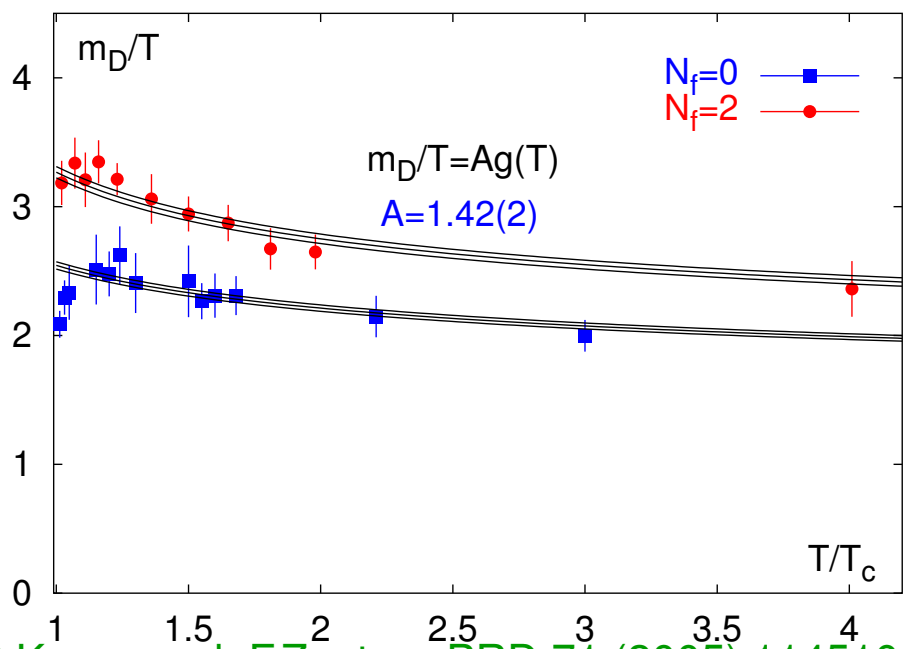
dimensional reduction works for $T \gtrsim 2T_c$

- c_M (almost) flavor independent
- $g^2(T)$ shows 2-loop running

RBC-Bielefeld, preliminary

Non-perturbative Debye screening

- leading order perturbation theory: $m_D = g(T)T\sqrt{1+\frac{n_f}{6}}$
- $T_c < T \lesssim 10T_c$: non-perturbative effects are well represented by an "A-factor": $m_D \equiv Ag(T)T,\ A \simeq 1.5$
- perturbative limit is reached very slowly (logarithms at work!!)



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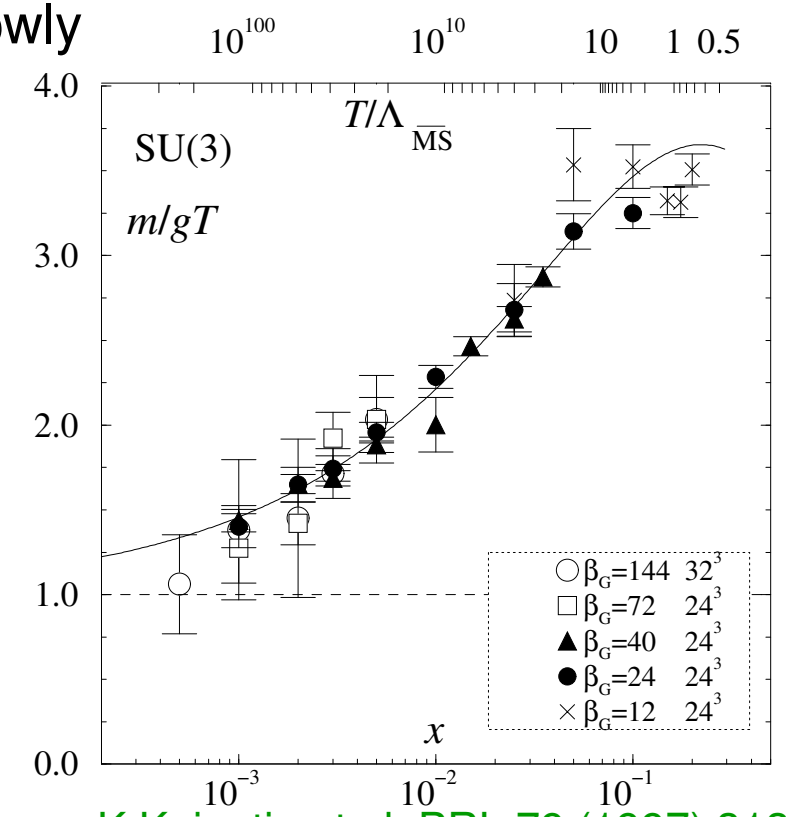

K.Kajantie et al, PRL 79 (1997) 3130

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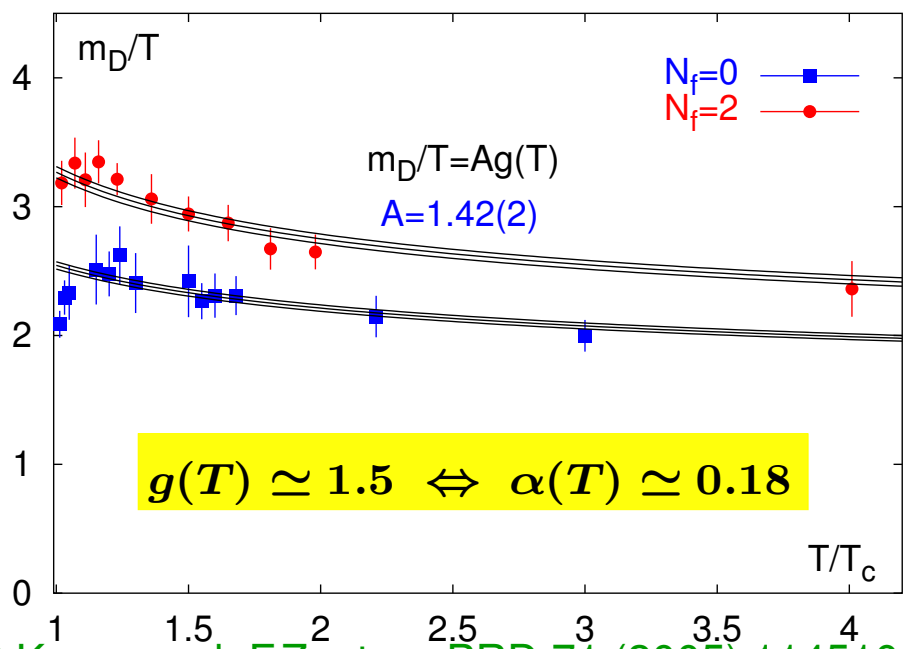

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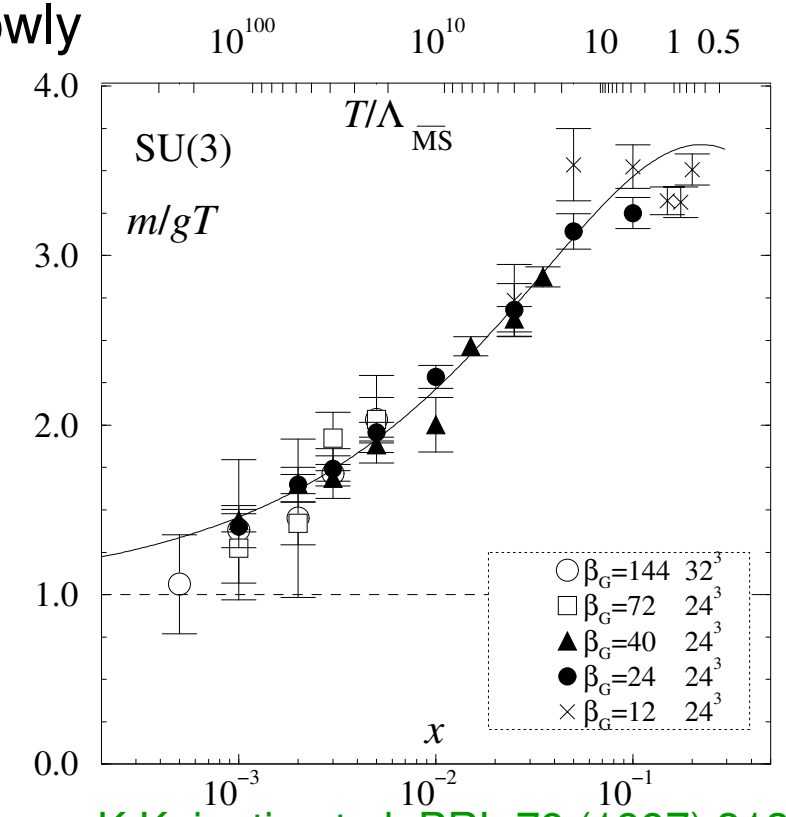

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Non-perturbative Debye screening
μ_q-dependence

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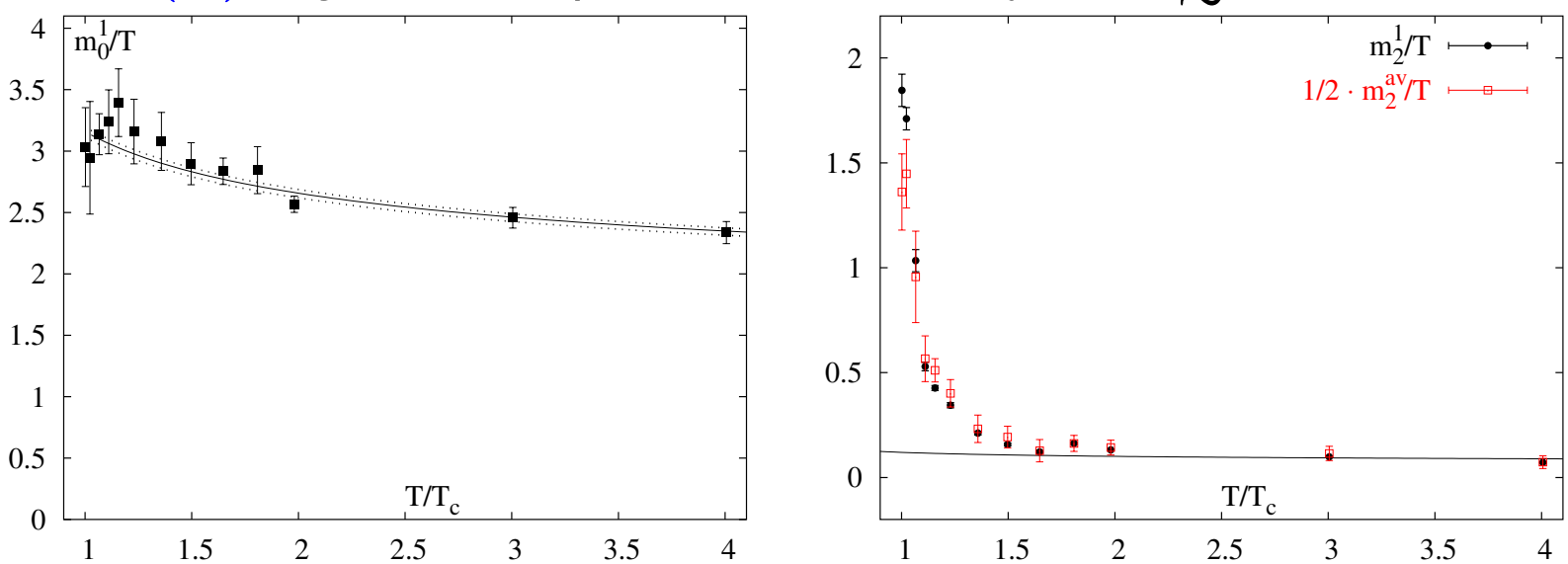
$$m_D = g(T)T\sqrt{1 + \frac{n_f}{6} + \frac{n_f}{2\pi^2}\left(\frac{\mu_q}{T}\right)^2}$$

- Taylor expansion, 2-flavor QCD:

$$m_D(T) = m_0(T) + m_2(T)\left(\frac{\mu_q}{T}\right)^2 + \mathcal{O}(\mu_q^4)$$

$m_2(T)$: agrees with perturbation theory for $T \gtrsim 1.5T_c$



M. Döring et al., Eur. Phys. J. C46 (2006) 179

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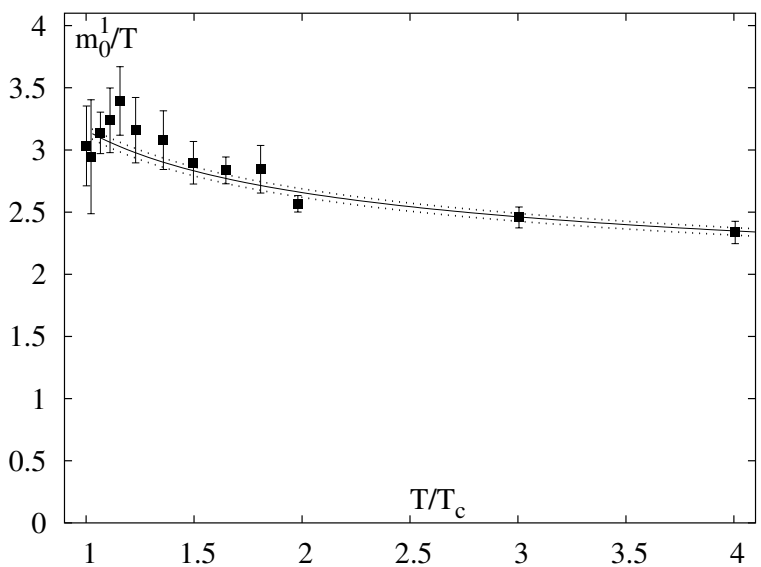
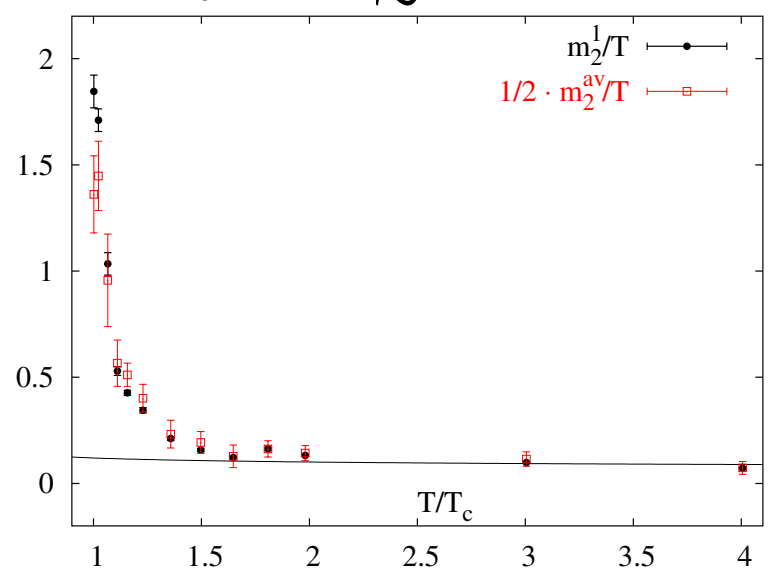
non-perturbative effects are in the glue

quark sector "perturbative" above $T \gtrsim 1.5T_c$?

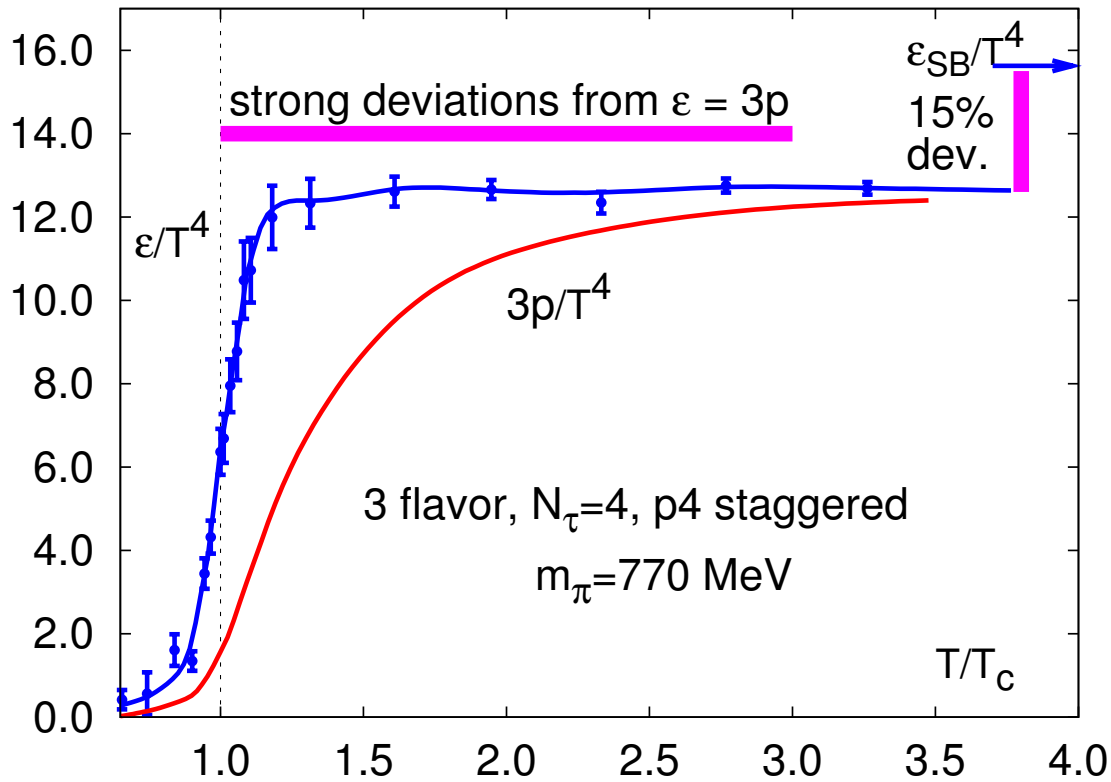




M. Döring et al., Eur. Phys. J. C46 (2006) 179

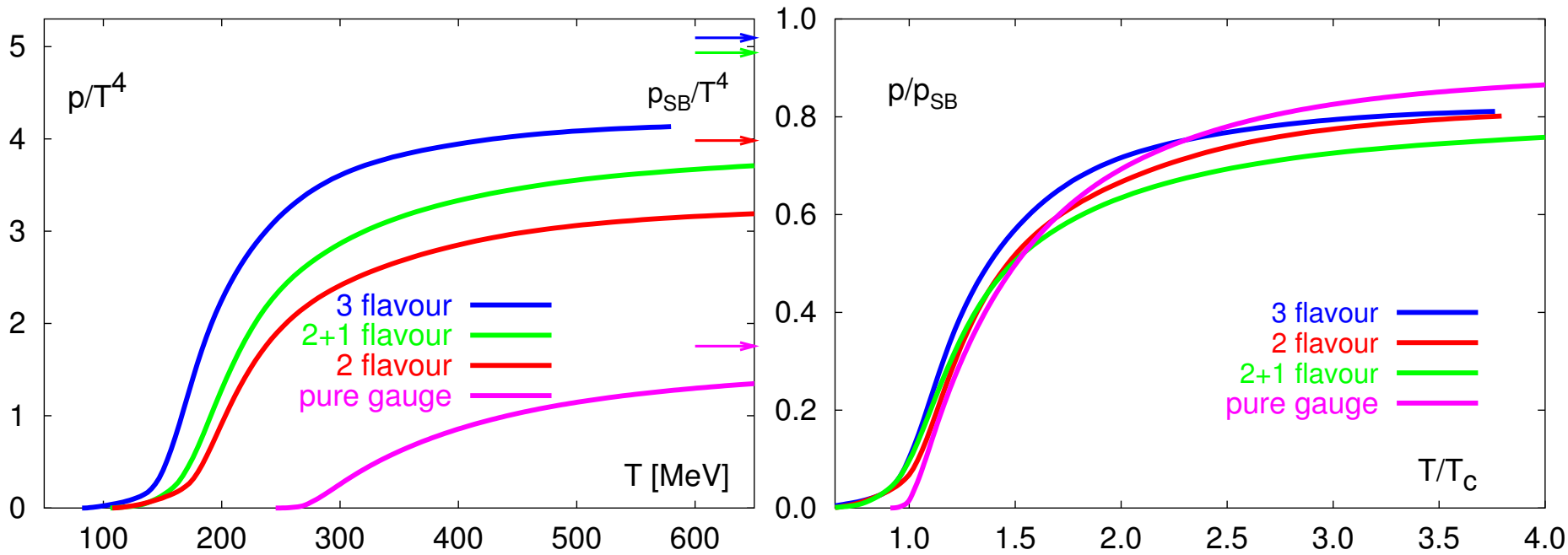
QCD equation of state

- two features of EoS are central in the ongoing discussion of the non-perturbative structure of QCD at high temperature
  - strong deviations from ideal gas behavior ($\epsilon = 3p$) for $T_c \leq T \sim 3T_c$
  - deviations from Stefan-Boltzmann limit persist even at high T



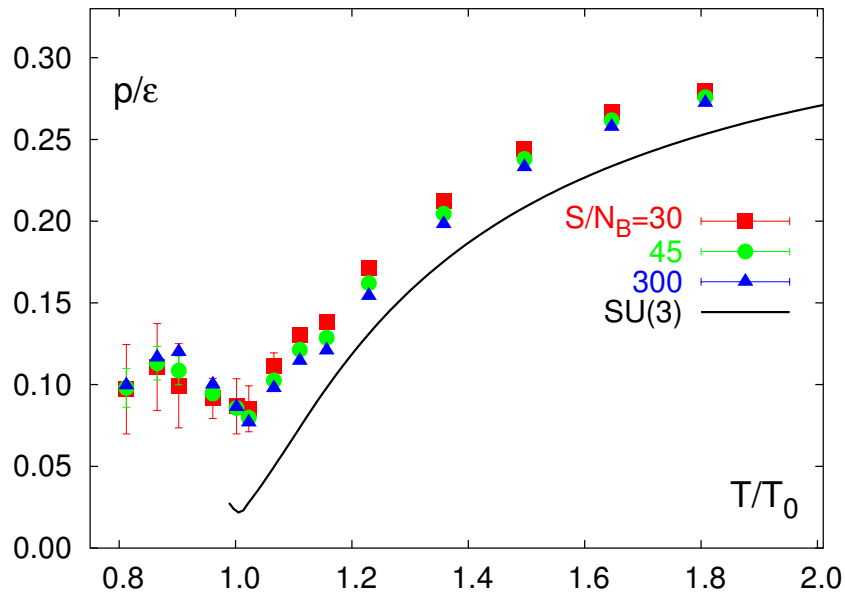
The pressure revisited

- $T \gtrsim (2\text{-}3) T_c$: deviations from ideal gas understood in terms of HTL-resummed perturbation theory
- $T \lesssim 2T_c$: strong deviations from ideal gas
- deviations from p_{SB} almost flavor independent



FK, E. Laermann and A. Peikert, Phys. Lett. B478 (2000) 447

Isentropic Equation of State: p/ϵ



EoS for 2-flavor QCD at fixed S/N_B and EoS for SU(3) gauge theory

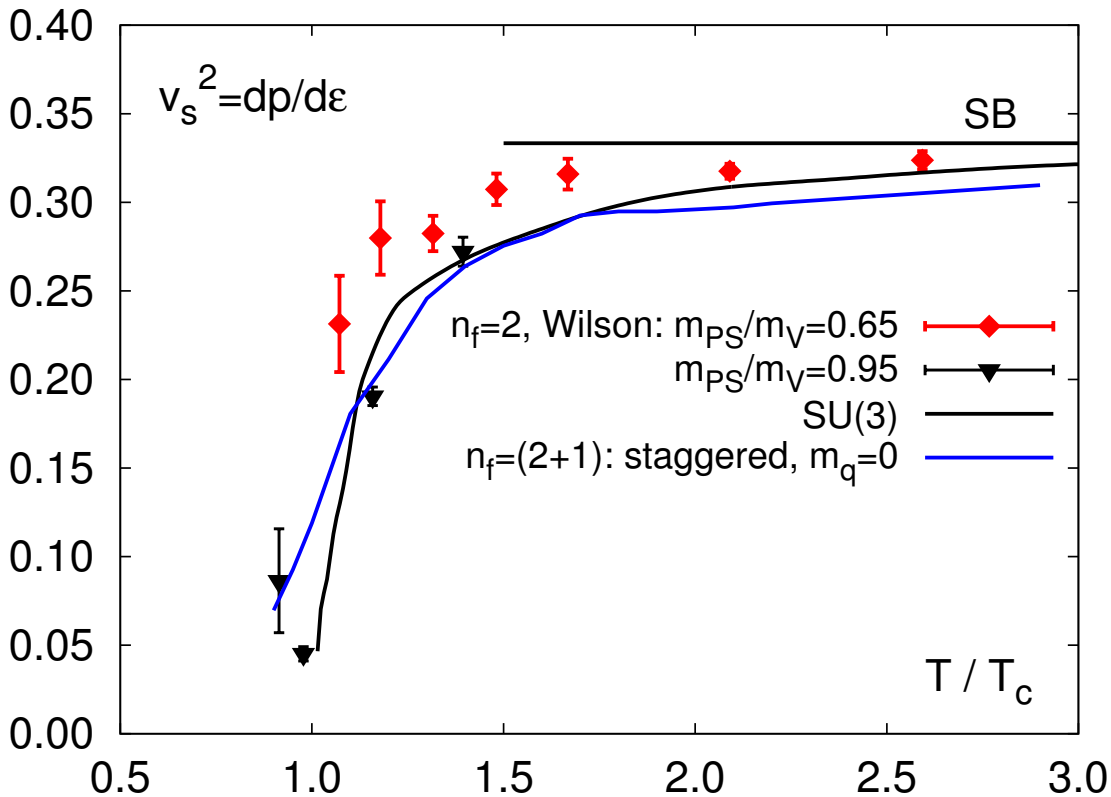
S. Ejiri et al., PRD 73 (2006) 054506

- p/ϵ vs. ϵ shows almost no dependence on S/N_B, *i.e.* μ_q/T
- p/ϵ has only weak dependence on n_f (cut-off effects??)
- phenomenological EoS for $T_0 \lesssim T \lesssim 2T_0$

$$\frac{p}{\epsilon} = \frac{1}{3}\left(1 - \frac{1.2}{1+0.5\epsilon}\right) \ , \ \left(\frac{p}{\epsilon}\right)_{min} \simeq 0.075$$

Velocity of sound

- steep EoS:
  rapid change of energy density; slow change of pressure
  $\Rightarrow$ reduced velocity of sound $\Rightarrow$ more time for equilibration



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$n_f = (2+1)$:
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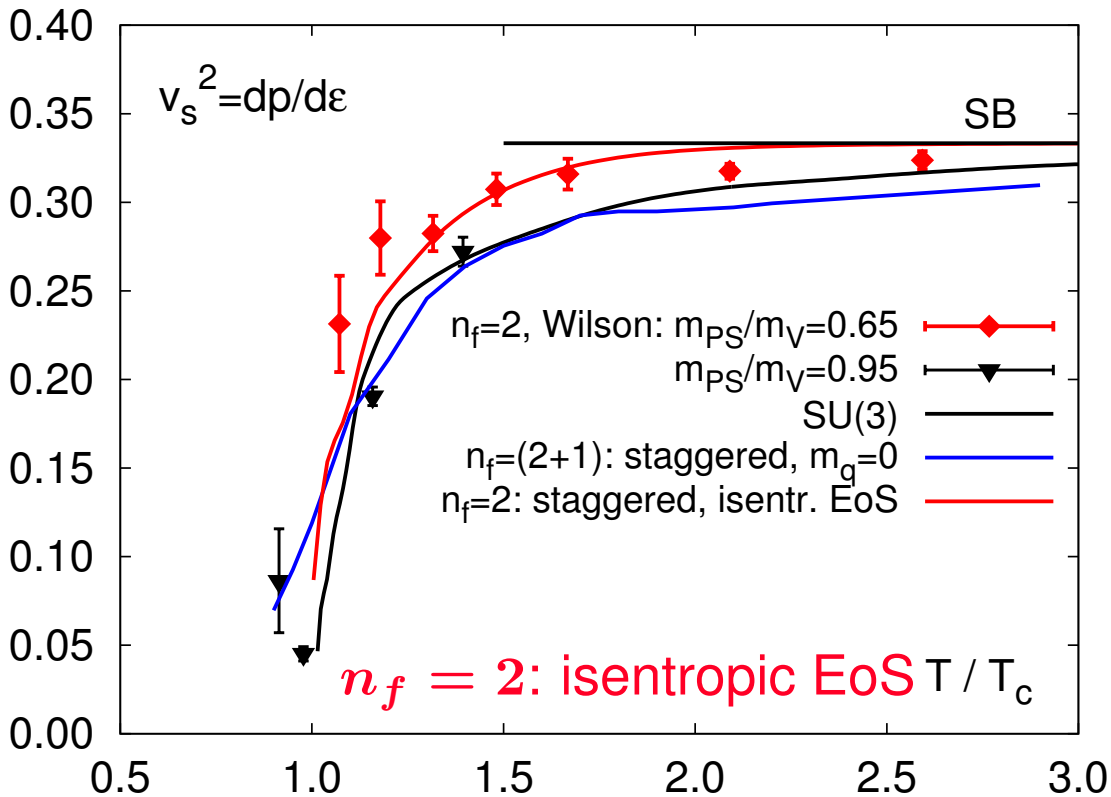

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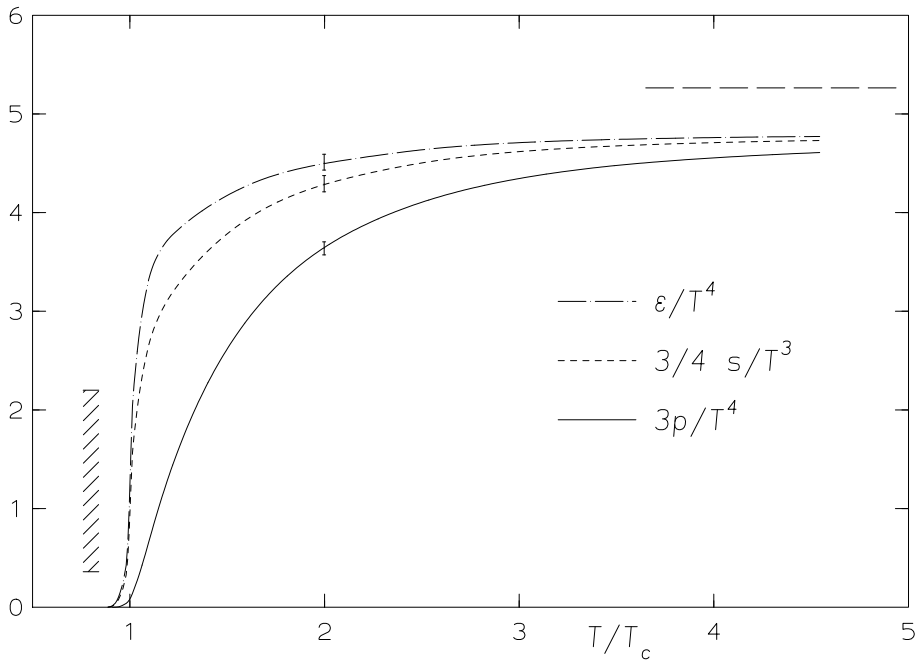
SU(3) Thermodynamics - revisited

- SU(3) EoS deviates from ideal gas by about 15% at $4T_c$
- slow approach to the high temperature limit consistent with logarithmic running of the coupling ((2+1)-d: $g_3^2 \sim g^2/T$)

$(3+1)$-d QCD: $g^2(T) \sim 1/\ln(T/\Lambda)$



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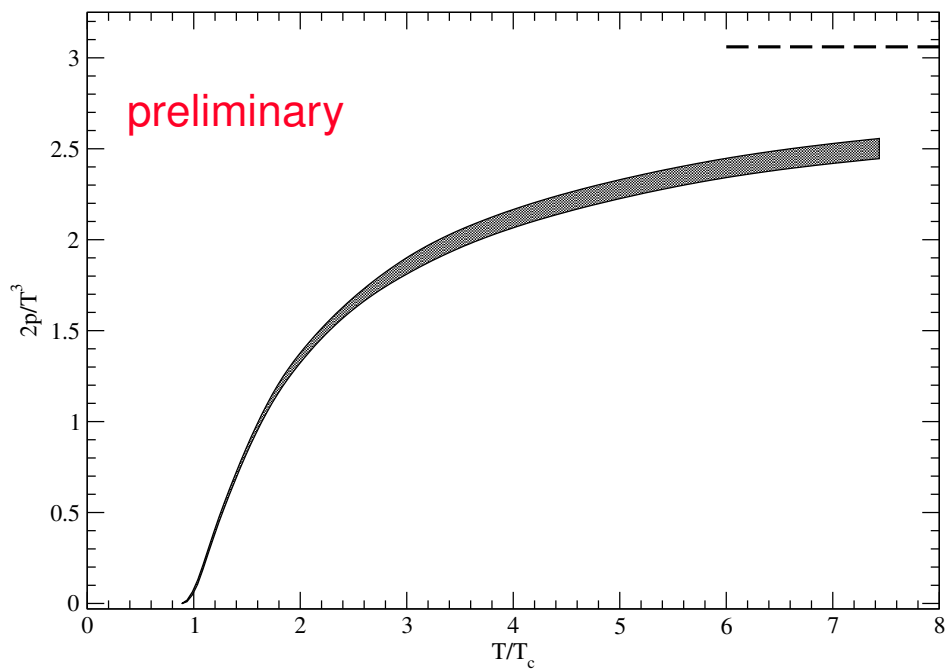

P. Bialas, L. Daniel, A. Morel, B. Petersson, in preparation

SU(3) Thermodynamics - revisited: EoS

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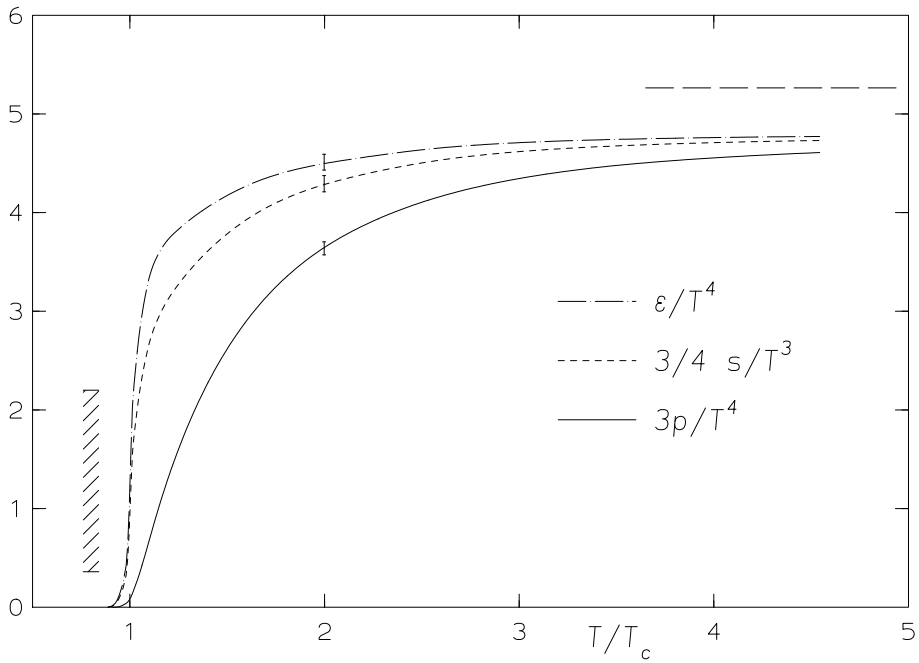
- consistent with logarithmic running of the coupling (cf. 4d vs. 3d)



$\sim$ 15% deviations from ideal gas

NOTE: p, ϵ, s normalized to be zero at $T = 0$;

non-pertubative vacuum properties show up at high-T

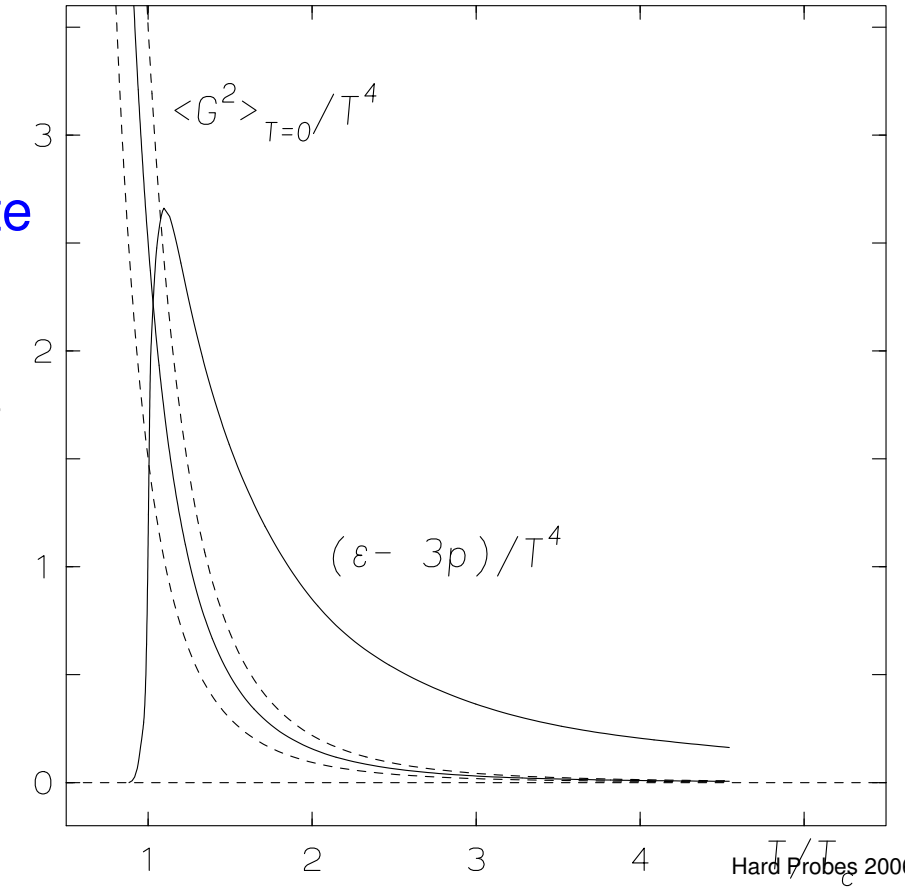
SU(3) Thermodynamics - revisited: $\langle G^2 \rangle_T$

- SU(3) EoS deviates from ideal gas by about 15% at $4T_c$
- slow approach to the high temperature limit
- consistent with logarithmic running of the coupling (cf. 4d vs. 3d)

$T = 0$: non-vanishing gluon condensate

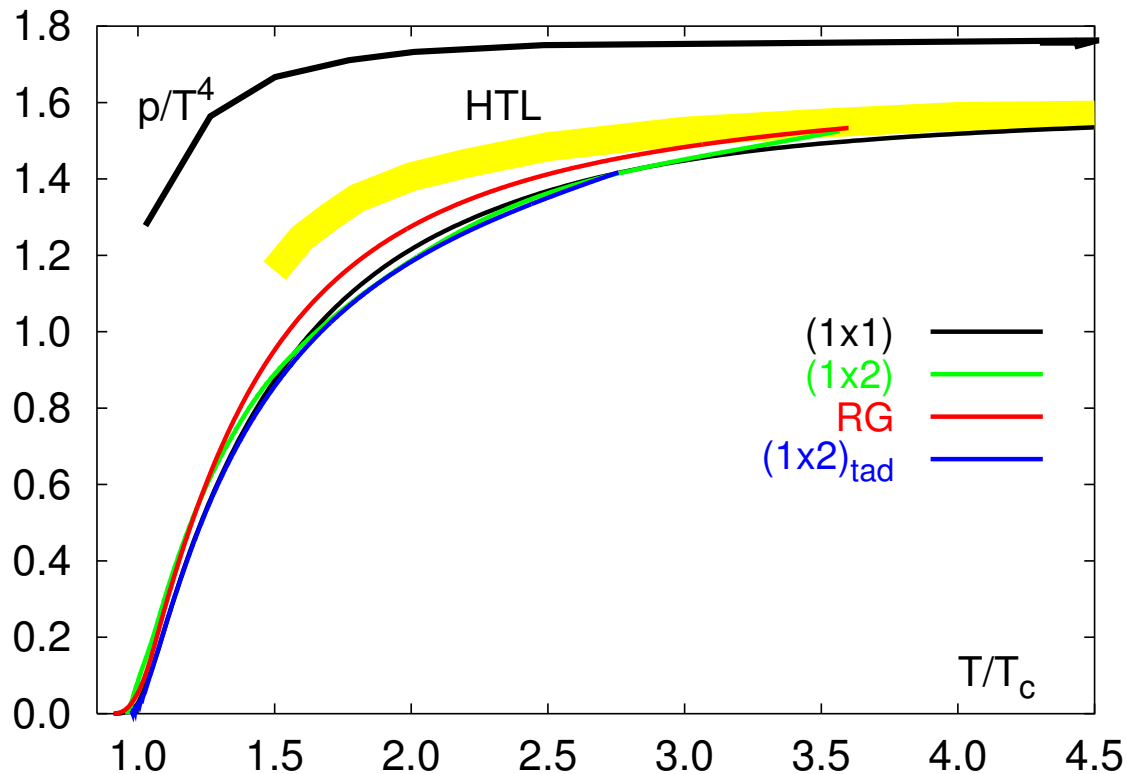
$$\epsilon - 3p = \langle G^2 \rangle_{T=0} - \langle G^2 \rangle_T$$

non-pertubative vacuum properties show up at high-T



SU(3) Equation of State pressure: LGT vs. HTL

high T part of the pressure calculated on the lattice is in good agreement with HTL-resummed perturbation theory for $T \gtrsim 3T_c$



bag pressure: $\simeq 0.5(T_c/T)^4$

HTL: J.P. Blaizot, E. Iancu, A. Rebhan, PL B470 (99) 181

bag pressure negligible for $T > 2T_c$, however 30% contribution at T_c!!

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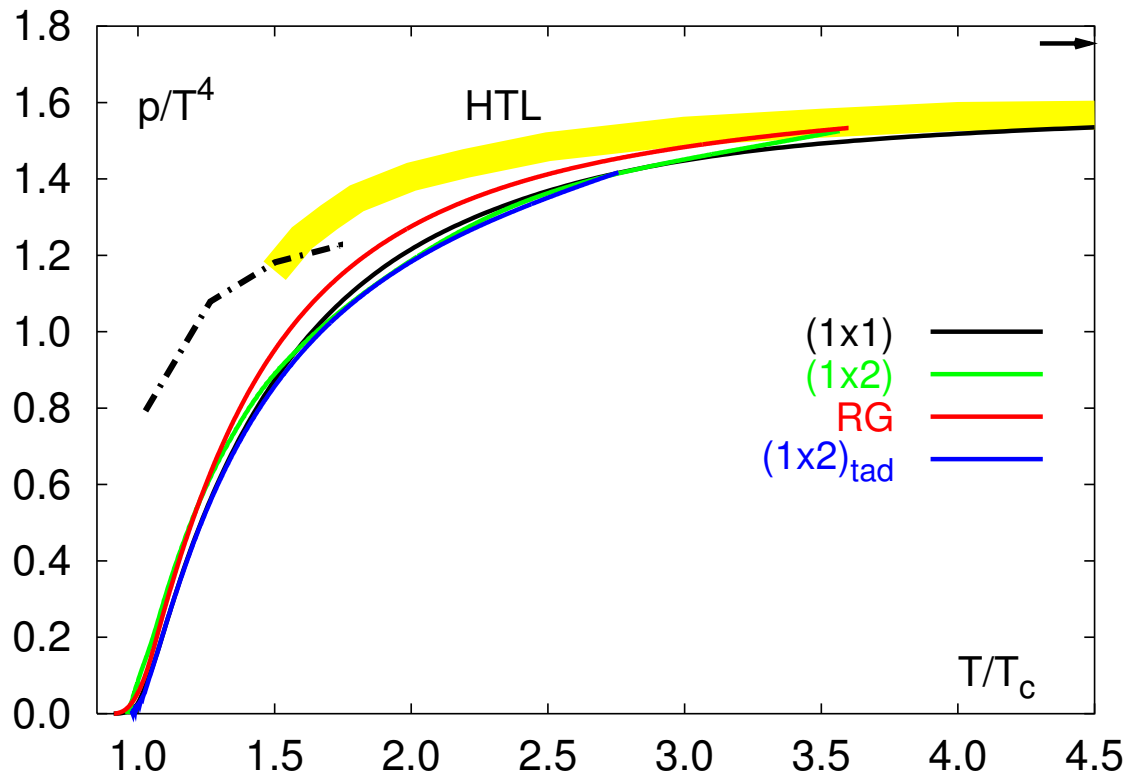

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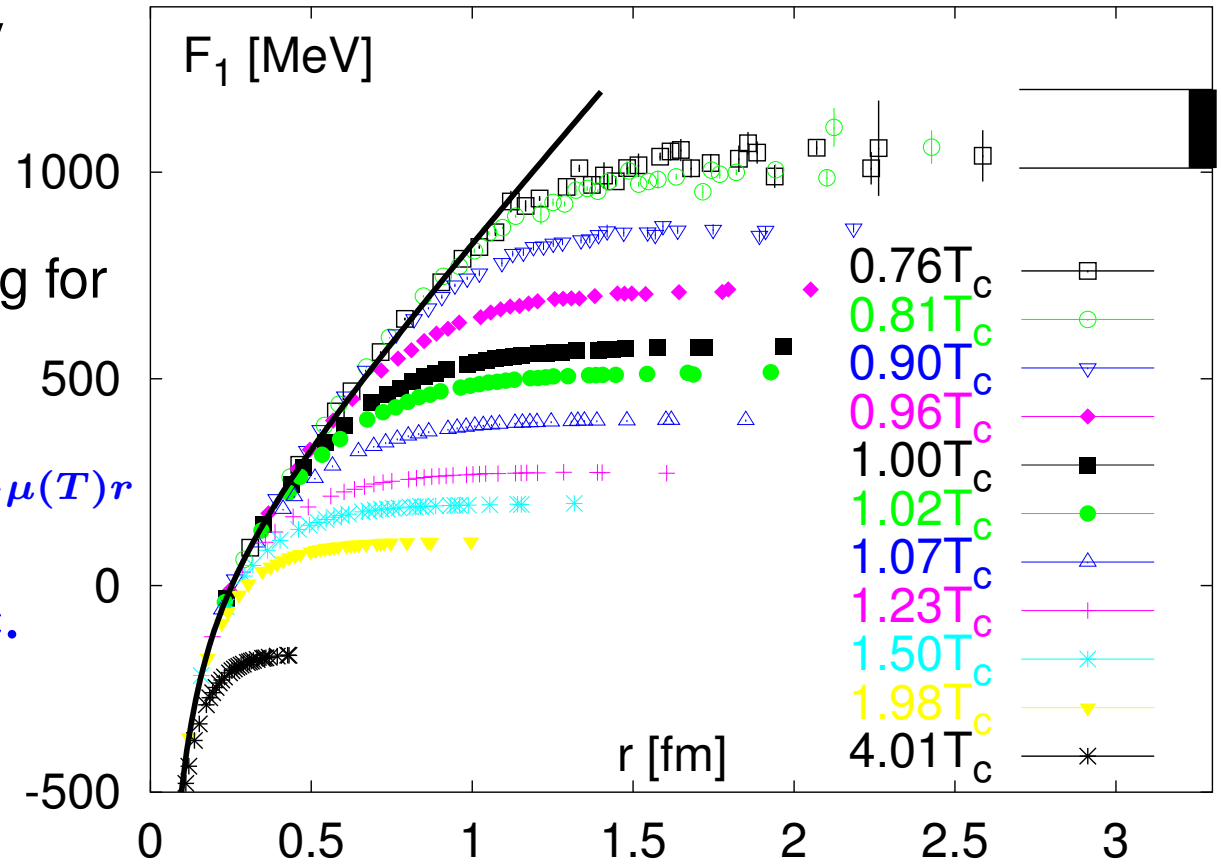
Screening of heavy quark free energies
– remnant of confinement above T_c –

pure gauge: O.Kaczmarek, FK, P. Petreczky, F. Zantow, PRD70 (2005) 074505
2-flavor QCD: O.Kaczmarek, F. Zantow, Phys. Rev. D71 (2005) 114510

- singlet free energy



- $T \simeq T_c$: screening for $r \gtrsim 0.5$fm

$$F_1(r,T) \sim \frac{\alpha(T)}{r} e^{-\mu(T) r} + const.$$

- $F_1(r,T)$ follows linear rise of $V_{\bar{q}q}(r,T=0) = -\frac{4\alpha(r,T=0)}{3r} + \sigma r$ for $T \lesssim 1.5 T_c$, $r \lesssim 0.3$ fm

Singlet free energy and asymptotic freedom

pure gauge: O.Kaczmarek, FK, P. Petreczky, F. Zantow, PRD70 (2005) 074505
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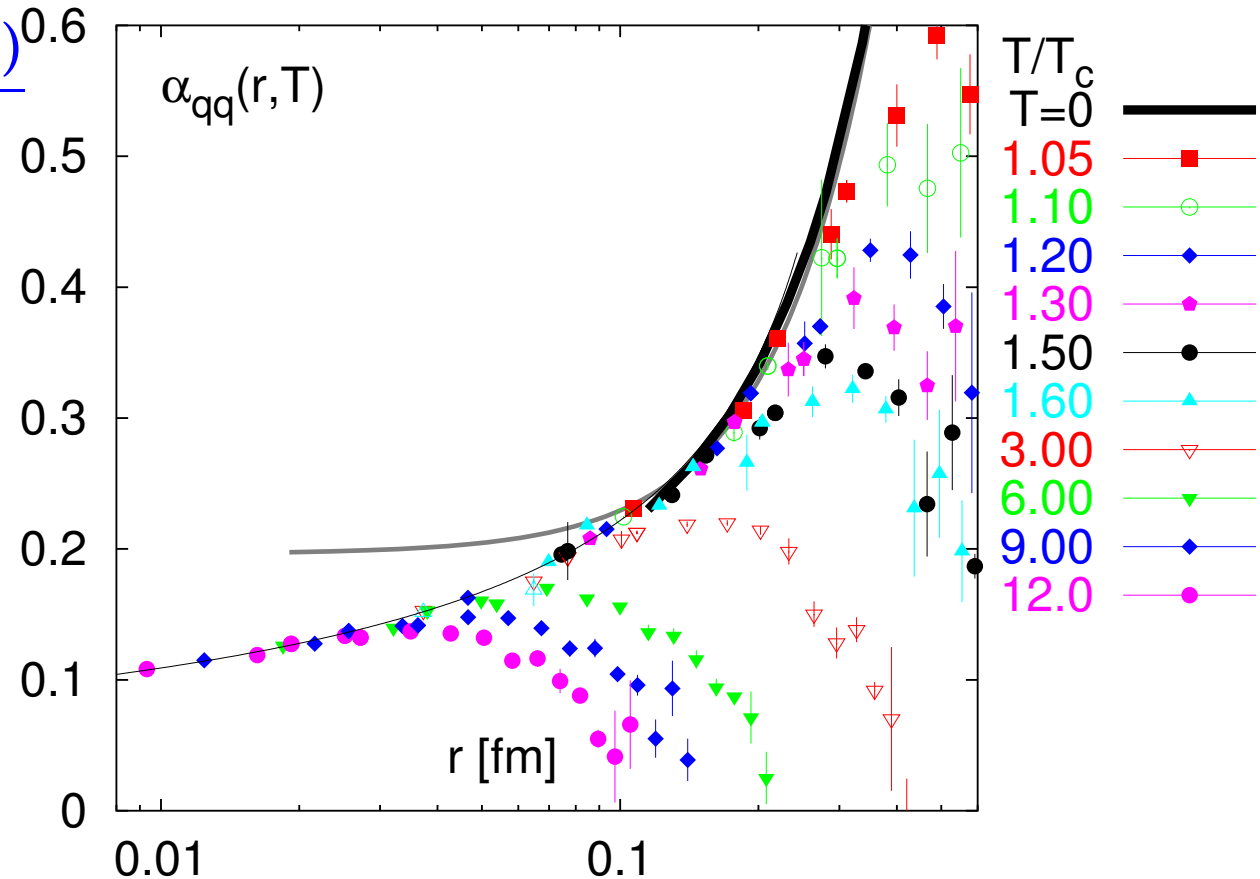
- singlet free energy defines a running coupling:

$$\alpha_{\rm eff} = \frac{3r^2}{4}\frac{{\rm d}F_1(r,T)}{{\rm d}r}$$



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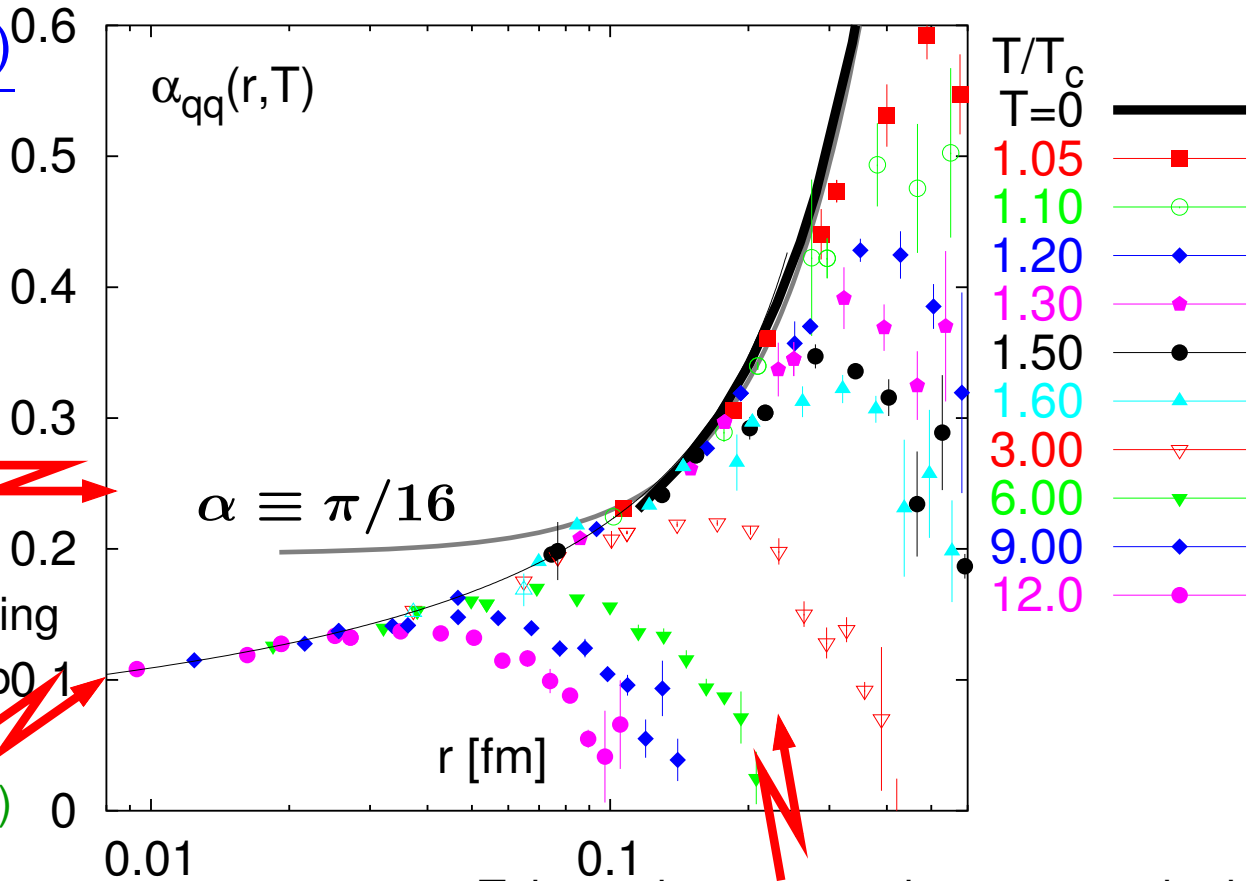

large distance: constant Coulomb term (string model)

short distance: running coupling $\alpha(r)$ from $(T=0)$, 3-loop (S. Necco, R. Sommer, Nucl. Phys. B622 (2002) 328)

T-dependence starts in non-perturbative regime for $T \lesssim 3\ T_c$

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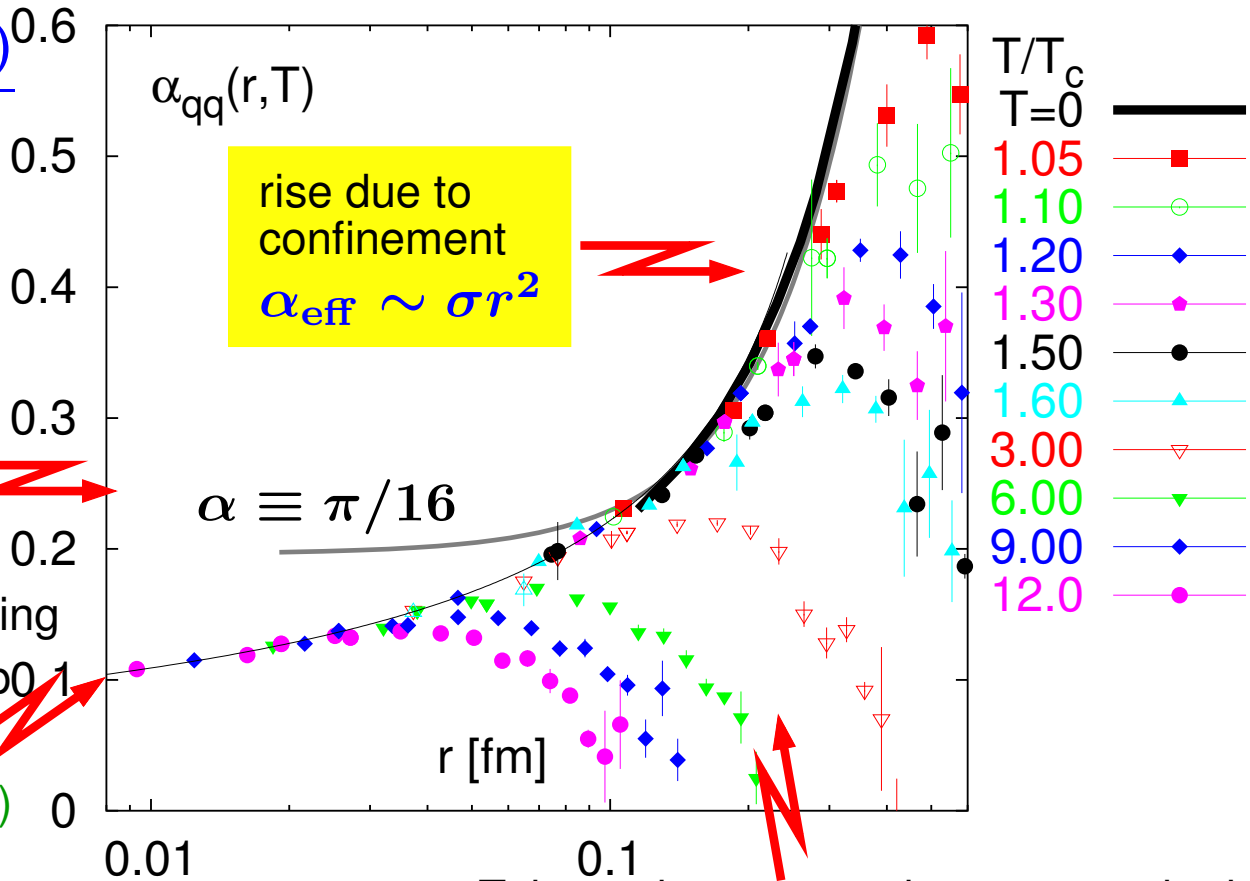

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String breaking and screening
Does a heavy quark bind a light (anti) quark?

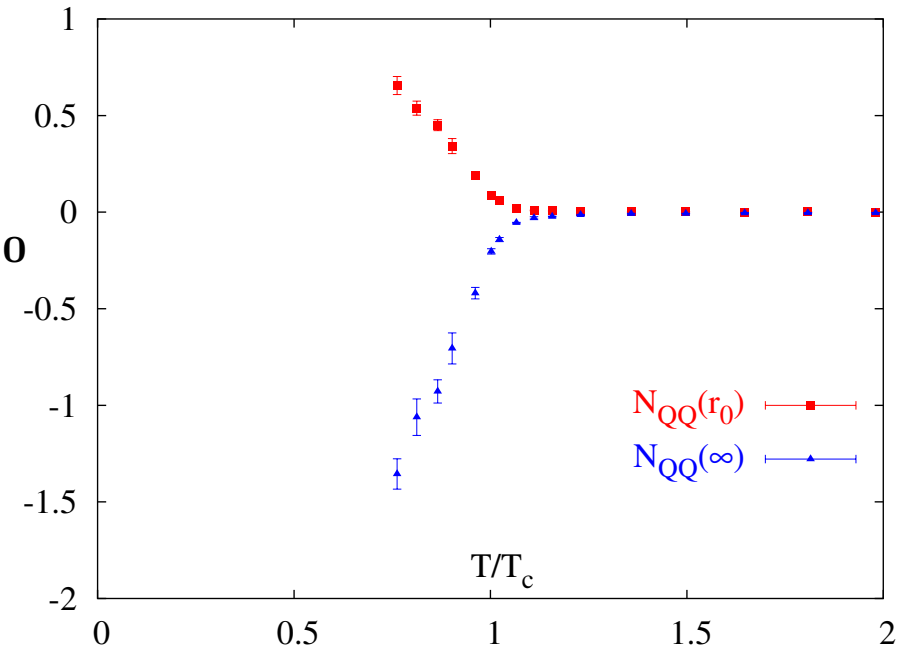
- Static quark-quark source in a thermal heat bath

  triality = 0: medium provides additional quark or 2 anti-quarks

- average quark number in the presence of two static quark sources

$$Z_{QQ}(T,\mu,r) = \int \mathrm{d}U \; \mathrm{Tr}L_0 \mathrm{Tr}L_r \; \mathrm{detD}(m_q,\mu) \; \mathrm{e}^{-\beta S_G}$$

$$N_{QQ}(T,r) = \left.\frac{\partial \ln Z_{qq}(T,\mu,r)}{\partial \mu/T}\right|_{\mu=0}$$



M. Döring, PhD thesis, in preparation

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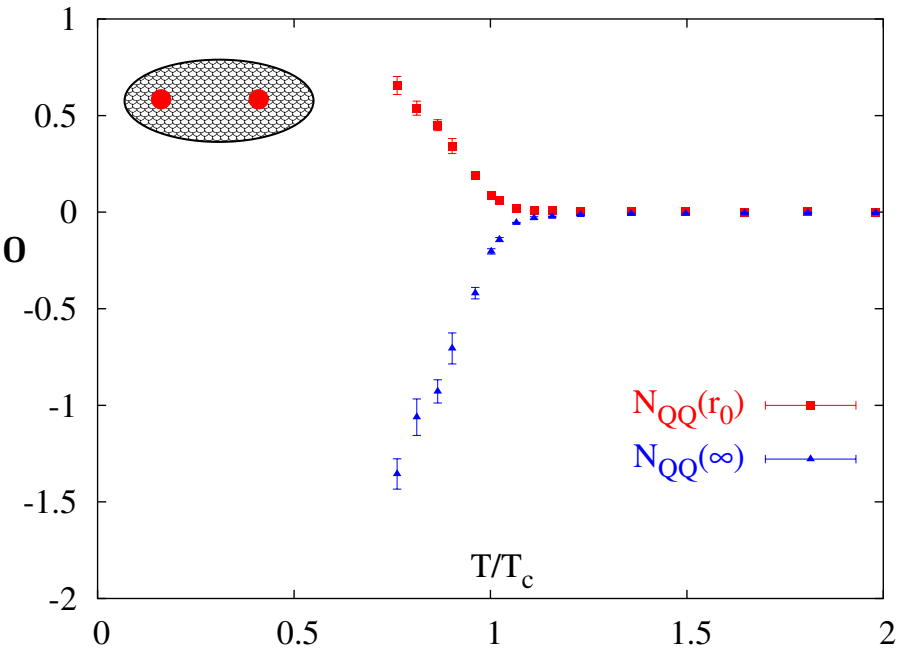

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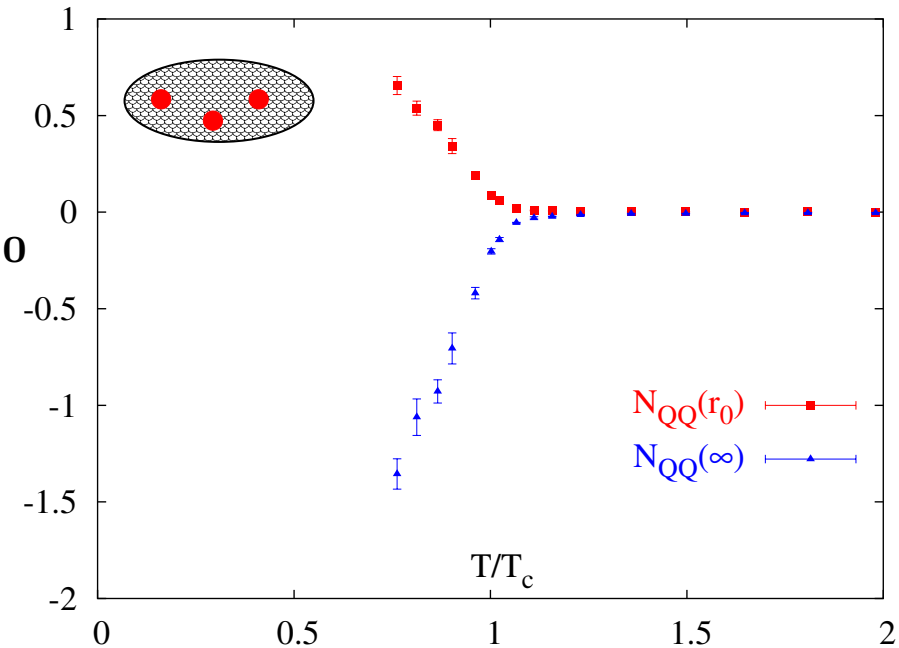

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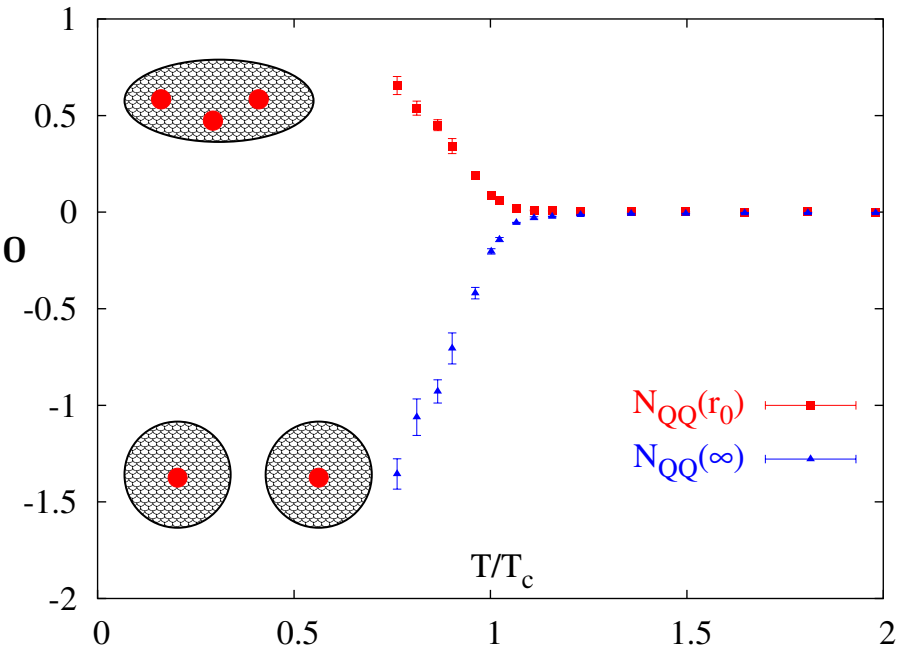

M. Döring, PhD thesis, in preparation

String breaking and screening
Does a heavy quark bind a light (anti) quark?

- Static quark-quark source in a thermal heat bath

  triality = 0: medium provides additional quark or 2 anti-quarks

- average quark number in the presence of two static quark sources

$$Z_{QQ}(T,\mu,r) = \int \mathrm{d}U \; \mathrm{Tr}L_0 \mathrm{Tr}L_r \; \mathrm{det}D(m_q,\mu) \; \mathrm{e}^{-\beta S_G}$$

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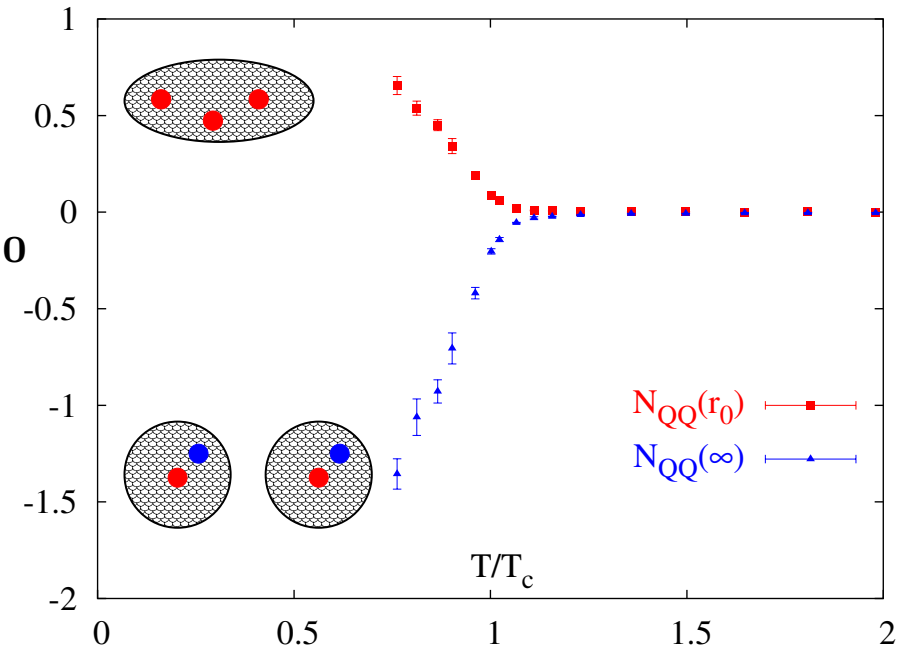
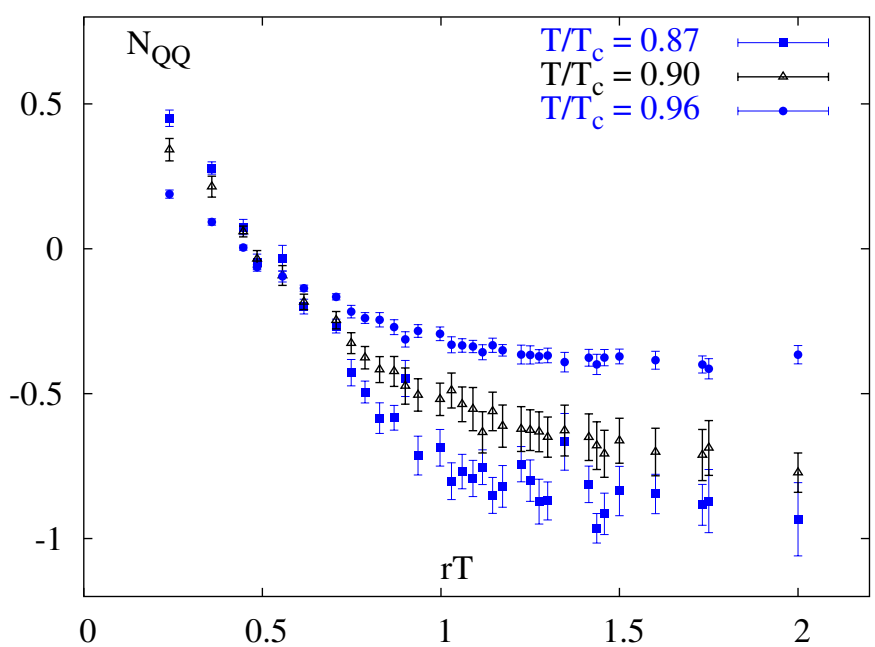
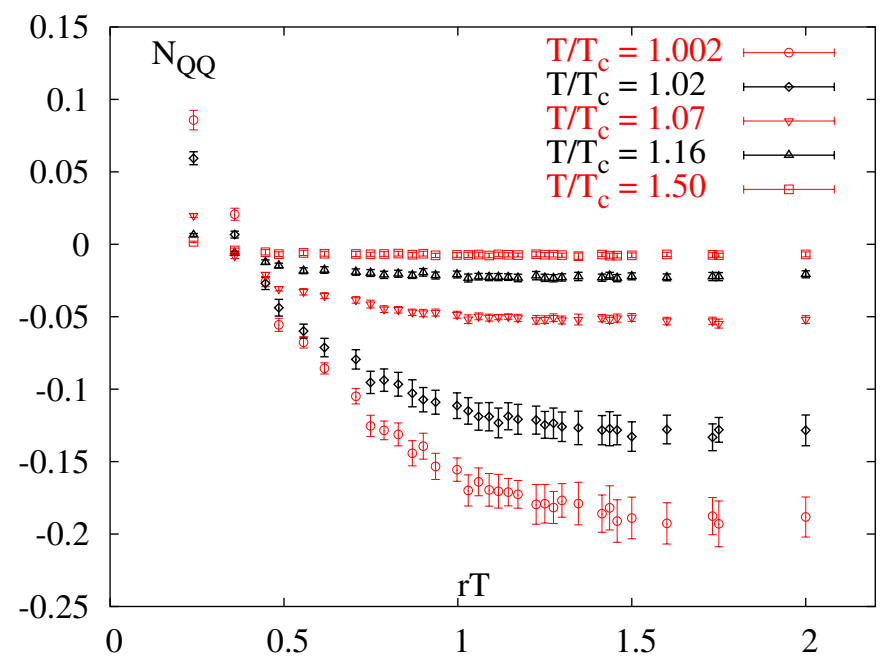


M. Döring, PhD thesis, in preparation

String breaking and screening
Does a heavy quark bind a light (anti) quark?

- $N_{QQ}(r,T)$ depends on separation between static quark-quark source
- $r = r_{b/s} \simeq 0.5/T$:
  screening changes from q-dominated to $\bar{q}\bar{q}$-dominated
- $T \gtrsim 1.1 T_c$: presence of q or $\bar{q}\bar{q}$ not important for screening

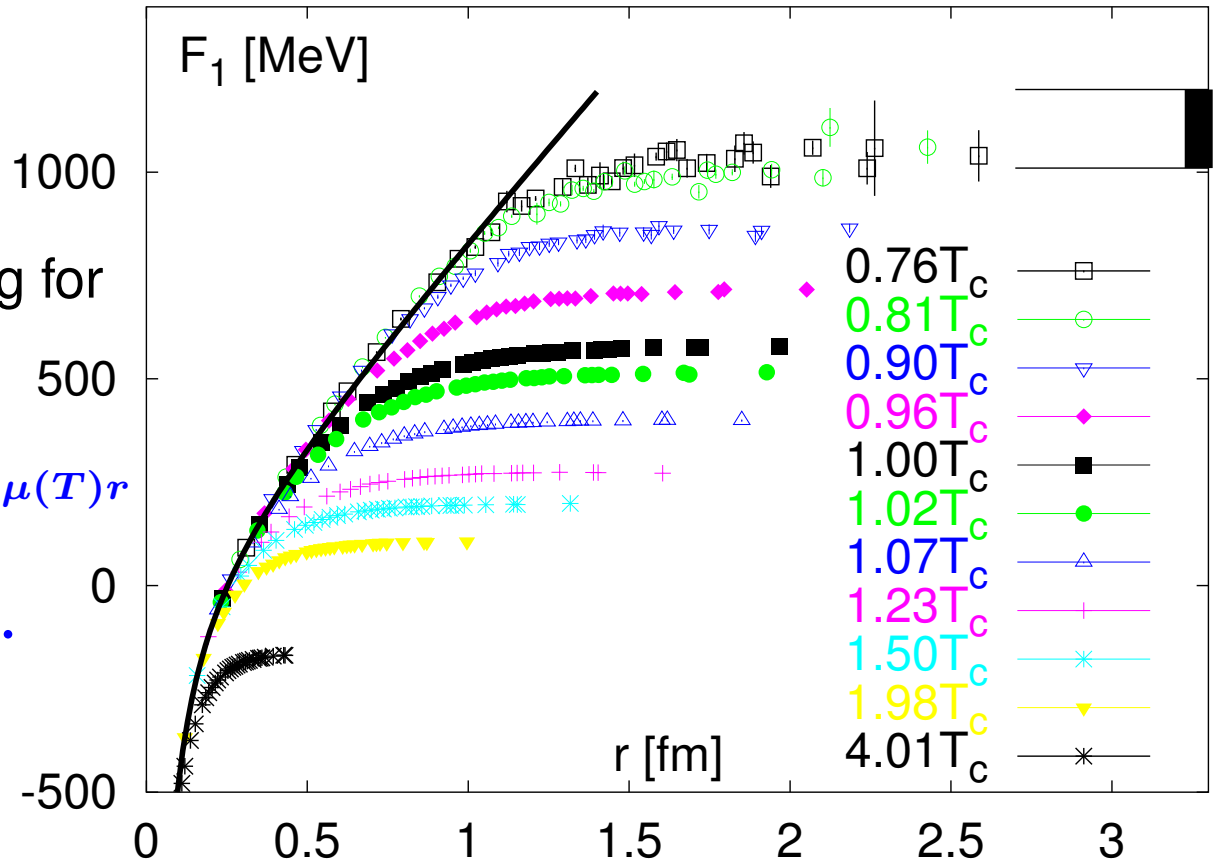




Screening of heavy quark free energies
– remnant of confinement above T_c –

pure gauge: O.Kaczmarek, FK, P. Petreczky, F. Zantow, PRD70 (2005) 074505
2-flavor QCD: O.Kaczmarek, F. Zantow, Phys. Rev. D71 (2005) 114510

- singlet free energy

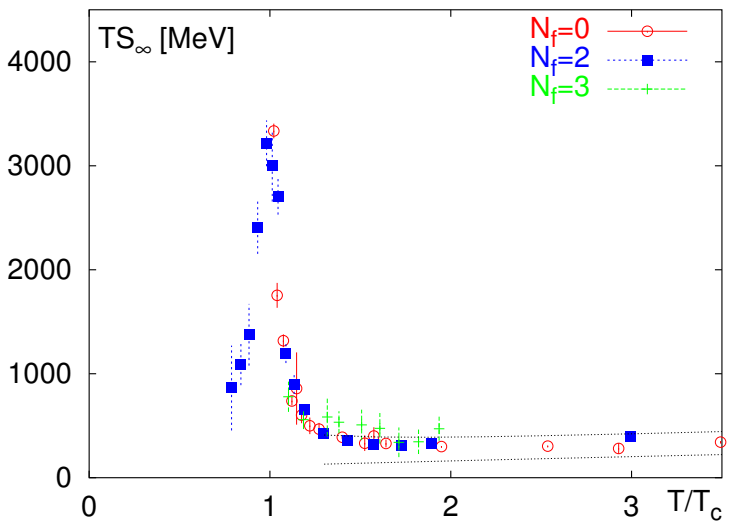


- $T \simeq T_c$: screening for $r \gtrsim 0.5$fm

$$F_1(r,T) \sim \frac{\alpha(T)}{r} e^{-\mu(T) r} + const.$$

- $F_1(r,T)$ follows linear rise of $V_{\bar{q}q}(r,T=0) = -\frac{4\alpha(r,T=0)}{3r} + \sigma r$ for $T \lesssim 1.5 T_c$, $r \lesssim 0.3$ fm

Screening of heavy quark free energies at large distance

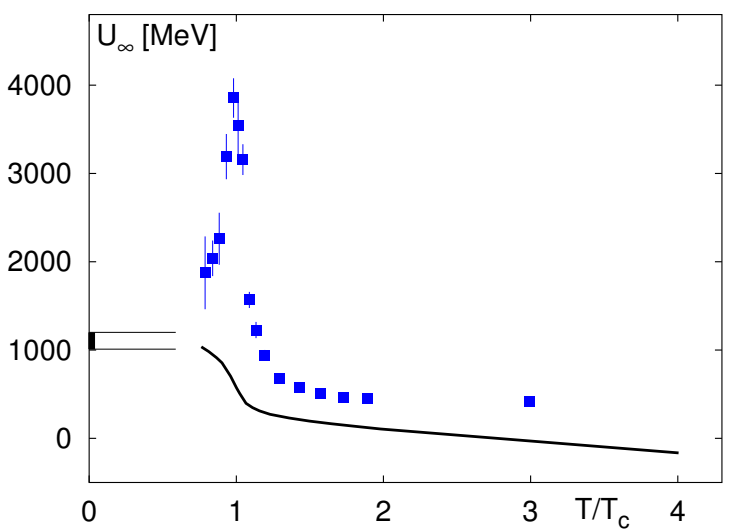


Excess entropy at $r \longrightarrow \infty$

It's all in the glue:

$$T \lesssim T_c: \; S_{\bar{q}q}^{nf=2}(\infty, T) \simeq S_{\bar{q}q}^{nf=0}(\infty, T)$$

Δ(Entropy)/Quark $\sim$ 15



Energy needed to screen 2 quarks

Large increase of energy close to T_c

Why not simply create another $\bar{q}q$ pair?

large entropy in the glue rearrangement

compensates for higher energy!!

Hadronic fluctuations at $\mu_q = 0$ from Taylor expansion coefficients for $\mu_q > 0$

V. Koch, A. Majumder, J. Randrup, PRL 95 (2005) 182301
S. Ejiri, FK, K.Redlich, PLB633 (2006) 275

- quark number and isospin chemical potentials:

$$\mu_q = \frac{1}{2}(\mu_u + \mu_d), \quad \mu_I = \frac{1}{2}(\mu_u - \mu_d)$$

- expansion coefficients evaluated at $\mu_{q,I} = 0$ are related to hadronic fluctuations at $\mu = 0$:

$\Uparrow$ baryon number, isospin, charge

event-by-event fluctuations at RHIC and LHC

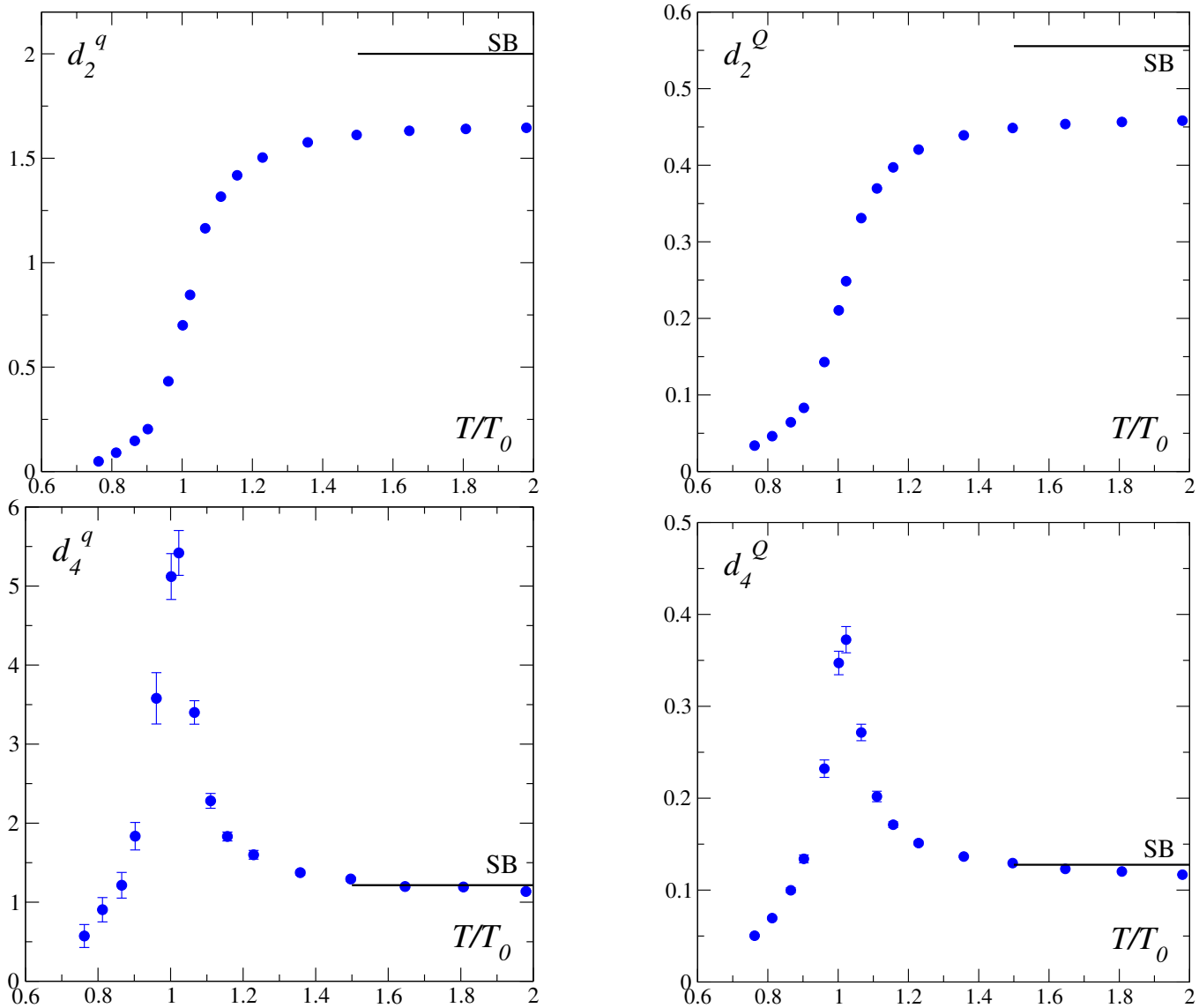
$$d_2^x = \frac{\partial^2 \ln \mathcal{Z}}{\partial(\mu_x/T)^2} = \frac{1}{VT^3}\langle(\delta N_x)^2\rangle_{\mu=0} = \frac{1}{VT^3}\langle N_x^2\rangle_{\mu=0}$$

$$d_4^x = \frac{\partial^4 \ln \mathcal{Z}}{\partial(\mu_x/T)^4} = \frac{1}{VT^3}\left(\langle(\delta N_x)^4\rangle - 3\langle(\delta N_x)^2\rangle\right)_{\mu=0} = \frac{1}{VT^3}\left(\langle N_x^4\rangle - 3\langle N_x^2\rangle\right)_{\mu=0}$$

$$\text{with} \quad , \quad x = q, I, Q \quad \text{and} \quad \partial_Q \equiv \frac{2}{3}\frac{\partial}{\partial\mu_u/T} - \frac{1}{3}\frac{\partial}{\partial\mu_d/T}$$

Quark number and charge fluctuations at $\mu_B = 0$; 2-flavor QCD ($m_\pi \simeq 770\ MeV$)

C. Allton et al. (Bielefeld-Swansea), PRD71 (2005) 054508



monotonic increase; close to ideal gas value for $T \gtrsim 1.5 T_c$

develops cusp at T_c

reaches ideal gas value for $T \gtrsim 1.5 T_c$

Hadronic fluctuations and chiral symmetry restoration

- expect 2nd order transition in 3-d, O(4) symmetry class;

  scaling field: $t = \left|\frac{T - T_c}{T_c}\right| + A\left(\frac{\mu_q}{T_c}\right)^2$, $\mu_{crit} = 0$

  singular part: $f_s(T, \mu_u, \mu_d) = b^{-1} f_s(t b^{1/(2-\alpha)}) \sim t^{2-\alpha}$

$$\frac{\partial^2 \ln \mathcal{Z}}{\partial \mu_q^2} \sim t^{1-\alpha} \quad , \quad \frac{\partial^4 \ln \mathcal{Z}}{\partial \mu_q^4} \sim t^{-\alpha} \qquad (\mu = 0)$$

- O(4)/O(2): $\alpha < 0$, small $\Rightarrow$

  $\langle(\delta N_q)^2\rangle$ dominated by T-dependence of regular part

  $\langle(\delta N_q)^4\rangle$ develops a cusp

Quark number in Boltzmann approximation

$$
\begin{aligned}
p_m/T^4 &= F(T,m,V)\cosh(B\mu_q/T) \\
d_2^q &\equiv \frac{\partial^2 p_m/T^4}{\partial(\mu_q/T)^2} = B^2 F(T,m,V)\cosh(B) \\
d_4^q &\equiv \frac{\partial^4 p_m/T^4}{\partial(\mu_q/T)^4} = B^4 F(T,m,V)\cosh(B)
\end{aligned}
$$

ratio of fourth (d_4^q) and second (d_2^q) cumulant of quark number fluctuation gives "unit of charge" carried by the particle with mass "m":

$$
m \gg T \quad \Rightarrow \quad R_{4,2}^q \equiv \frac{d_4^q}{d_2^q} = B^2
$$

Charge fluctuations in Boltzmann approximation

- hadronic resonance gas: contributions from isosinglet ($G^{(1)}$: $\eta, \ldots$) and isotriplet ($G^{(3)}$: $\pi, \ldots$) mesons as well as isodoublet ($F^{(2)}$: $p, n, \ldots$) and isoquartet ($F^{(4)}$: $\Delta, \ldots$) baryons

$$\frac{p(T,\mu_q,\mu_I)}{T^4} \simeq G^{(1)}(T) + G^{(3)}(T)\frac{1}{3}\left(2\cosh\left(\frac{2\mu_I}{T}\right)+1\right) + F^{(2)}(T)\cosh\left(\frac{3\mu_q}{T}\right)\cosh\left(\frac{\mu_I}{T}\right) + F^{(4)}(T)\frac{1}{2}\cosh\left(\frac{3\mu_q}{T}\right)\left[\cosh\left(\frac{\mu_I}{T}\right)+\cosh\left(\frac{3\mu_I}{T}\right)\right]$$

- charge fluctuations at $\mu_q = \mu_I = 0$;
  isospin quartet $F^{(4)}$ contains baryons carrying charge 2

$$R^Q_{4,2} \equiv \frac{d^Q_4}{d^Q_2} = \frac{4G^{(3)} + 3F^{(2)} + 27F^{(4)}}{4G^{(3)} + 3F^{(2)} + 9F^{(4)}} \longrightarrow 1 \text{ for } T \longrightarrow 0$$

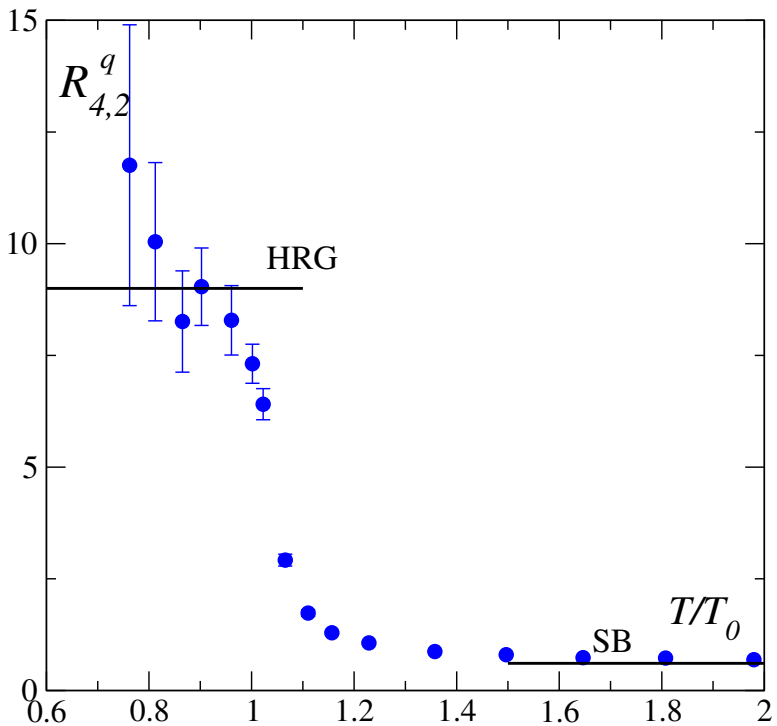
  contribution of doubly charged baryons increases quartic relative to quadratic fluctuations

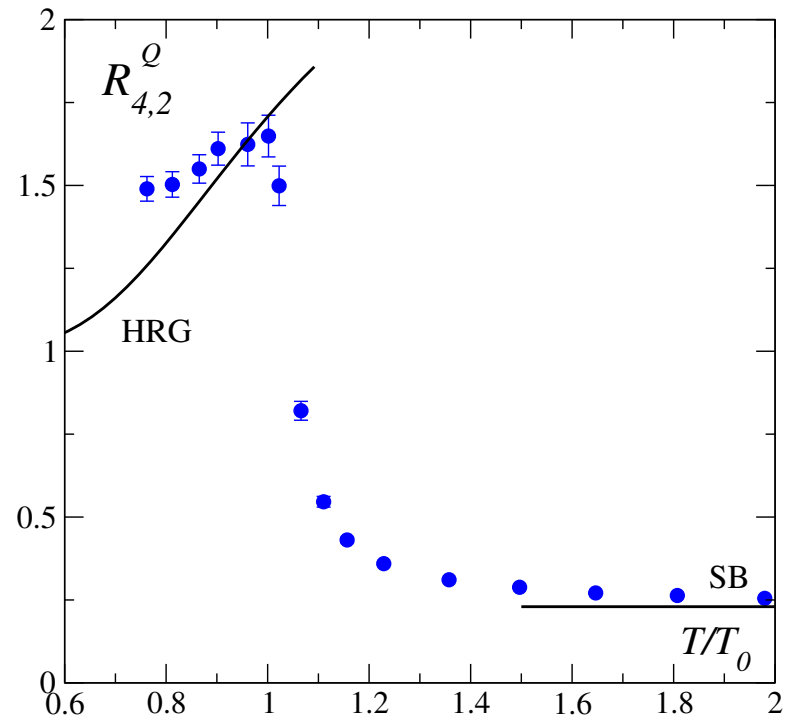
Cumulant ratios

- ratios of cumulants reflect carriers of baryon number and charge

$$R^x_{4,2} = d^x_4 / d^x_2 \quad , \quad x = q,\ Q$$

$$R^q_{4,2} = \begin{cases} 9 & , \mathrm{HRG} \\ \dfrac{6}{\pi^2} + \mathcal{O}(g^3) & , \mathrm{high} - T \end{cases} \qquad R^Q_{4,2} = \begin{cases} 1 & , \mathrm{HRG}, T \to 0 \\ \dfrac{34}{15\pi^2} + \mathcal{O}(g^3) & , \mathrm{high} - T \end{cases}$$

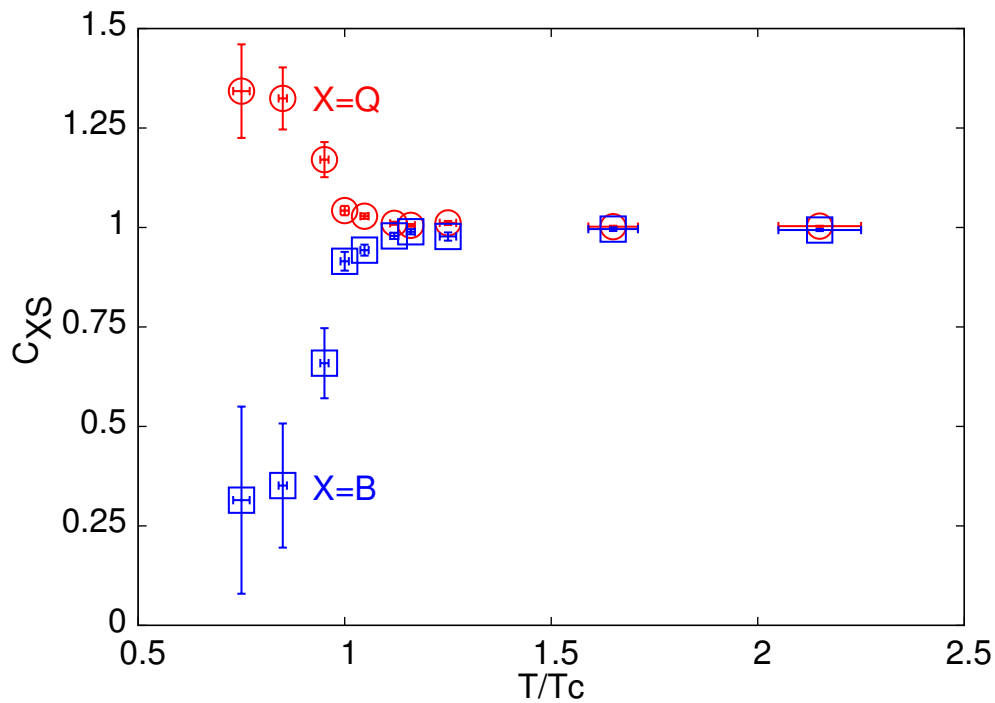




Off-diagonal correlations

- similar: correlations between eg. strangeness and baryon number sensitive to "carriers of quantum numbers"

$$\chi_{XS} \equiv \langle XS \rangle - \langle X \rangle \langle S \rangle \quad , \quad X = B,\, Q$$



R.V. Gavai, S. Gupta, PRD 73 (2006) 014004

inspired by: V. Koch, A. Majumder, J. Randrup, PRL 95 (2005) 182301

Conclusions

- glue sticks

  the interesting non-perturbative physics in QCD happens in the gluon sector

- quarks add flavor

  quarks add to the picture by 'modifying prefactors' (in accord with dimensional reduction approach)

- no glue $\Rightarrow$ no binding

  'glue-free' observables show early onset of perturbative behaviour

Conclusions

- non-perturbative QCD-EoS $\sim$ pure gauge theory EoS

  the interesting non-perturbative physics in QCD happens in the gluon sector

- nothing qualitatively new in QCD with light quarks

  quarks add to the picture by 'modifying prefactors' (in accord with dimensional reduction approach) except close to T_c!!

- quantum numbers are carried by "quarks" already close to T_c

  'glue-free' observables show early onset of perturbative behaviour

Finally...

YES,

- the regime $T_c \leq T \lesssim (1.5 - 2.0) T_c$ differs from the regime $T \gtrsim (1.5 - 2.0) T_c$

  It is more difficult (impossible?) to describe it quantitatively in terms of conventional theoretical high-T concepts: perturbation theory, resummation, dimensional reduction

Finally...

YES,

- the regime $T_c \leq T \lesssim (1.5 - 2.0) T_c$ differs from the regime $T \gtrsim (1.5 - 2.0) T_c$

  It is more difficult (impossible?) to describe it quantitatively in terms of conventional theoretical high-T concepts: perturbation theory, resummation, dimensional reduction

HOWEVER:

- Do we see new physics? $\Rightarrow$ QGL
- or, remnants of old physics? $\Rightarrow$ confinement