Heavy quark free and internal energies in 2-flavor QCD

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Motivation - Heavy quark bound states above deconfinement

Quarkonium suppression as a probe for thermal properties of hot and dense matter [Matsui and Satz]

- heavy quark potential gets screened
- screening radius related to parton density

$$r_D \sim \frac{1}{g\sqrt{n/T}}$$

- at high T screening radius smaller than size of a quarkonium state

Typical length scales of heavy quark bound states: $1/\Lambda_{QCD} \sim 1$ fm

- screening has to be strong enough to modify short distance behaviour
- detailed analysis of ”heavy quark potentials”
  - temperature and r dependence
  - screening properties above deconfinement
  - What is the correct effective potential at finite temperature ?

$$F_1(r,T) = U_1(r,T) - T\,S_1(r,T)$$

Heavy quark bound states above deconfinement

Strong interactions in the deconfined phase $T \gtrsim T_c$

Possibility of heavy quark bound states?

Charmonium ($\chi_c, J/\psi$) as thermometer above T_c

Suppression patterns of charmonium/bottomonium

$\Longrightarrow$ Potential models

$\rightarrow$ heavy quark potential (T=0)

$$V_1(r) = -\frac{4}{3}\frac{\alpha(r)}{r} + \sigma\, r$$

$\rightarrow$ heavy quark free energies ($T > T_c$)

$$F_1(r,T) \simeq -\frac{4}{3}\frac{\alpha(r,T)}{r}\, e^{-m(T)r}$$

$\rightarrow$ heavy quark internal energies ($T \neq$0)

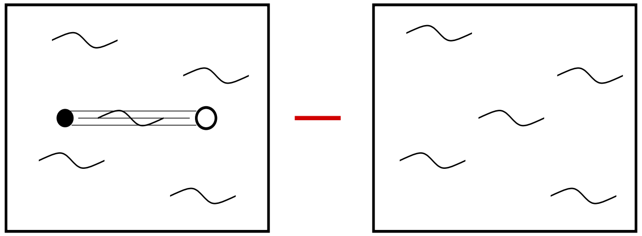
$$F_1(r,T) = U_1(r,T) - T\, S_1(r,T)$$

$\Longrightarrow$ Charmonium correlation functions/spectral functions

Polyakov loop correlation function and free energy:

L. McLerran, B. Svetitsky (1981)

$$\frac{\mathcal{Z}_{\mathbf{Q\bar{Q}}}}{\mathcal{Z}(\mathbf{T})} \simeq \frac{1}{\mathcal{Z}(\mathbf{T})}\int \mathcal{D}\mathbf{A}\ldots\,\mathbf{L}(\mathbf{x})\,\mathbf{L}^{\dagger}(\mathbf{y})\,\exp\left(-\int_{\mathbf{0}}^{\mathbf{1/T}}\mathbf{dt}\int \mathbf{d^3x}\mathcal{L}[\mathbf{A},\ldots]\right)$$



$$= -\frac{\mathbf{F_{Q\bar{Q}}(r,T)}}{\mathbf{T}}$$

$$\mathbf{Q\bar{Q}} = \mathbf{1},\ \mathbf{8},\ \mathbf{av}$$

O. Philipsen (2002)
O. Jahn, O. Philipsen (2004)

Lattice data used in our analysis:

$N_f = 0$:
$32^3 \times 4, 8, 16$-lattices
(*Symanzik*)

O. Kaczmarek,
F. Karsch,
P. Petreczky,
F.Z. (2002, 2004)

$N_f = 2$:
$16^3 \times 4$-lattices
(*Symanzik, p4-stagg.*)

$m_\pi/m_\rho \simeq 0.7$ $(m/T = 0.4)$

O. Kaczmarek, F.Z. (2005),
O. Kaczmarek et al. (2003)

$N_f = 3$:
$16^3 \times 4$-lattices

$m_\pi/m_\rho \simeq 0.4$

P. Petreczky,
K. Petrov (2004)

$N_f = 2$ with $m/T = 0.4$ ($m_\pi/m_\rho \approx 0.7$ at T_c)

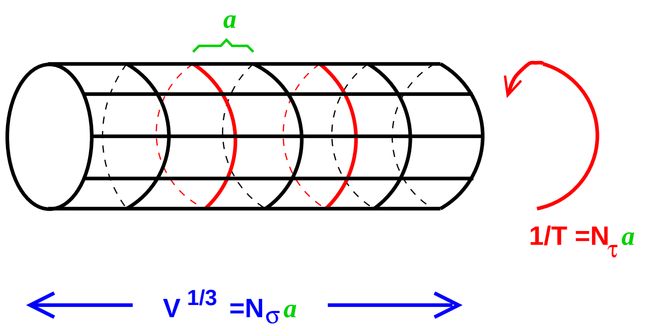
Lattice size: $16^3 \times 4$, $T_c \approx 170$MeV
(generated by the Bielefeld-Swansea collaboration)

Symanzik improved gauge action and
p4-improved staggered fermion action

Physical scale is determined by string tension

T=0 potential obtained from Wilson loops
[F. Karsch, E. Laermann and A. Peikert, Nucl. Phys . B 605 (2001) 579]

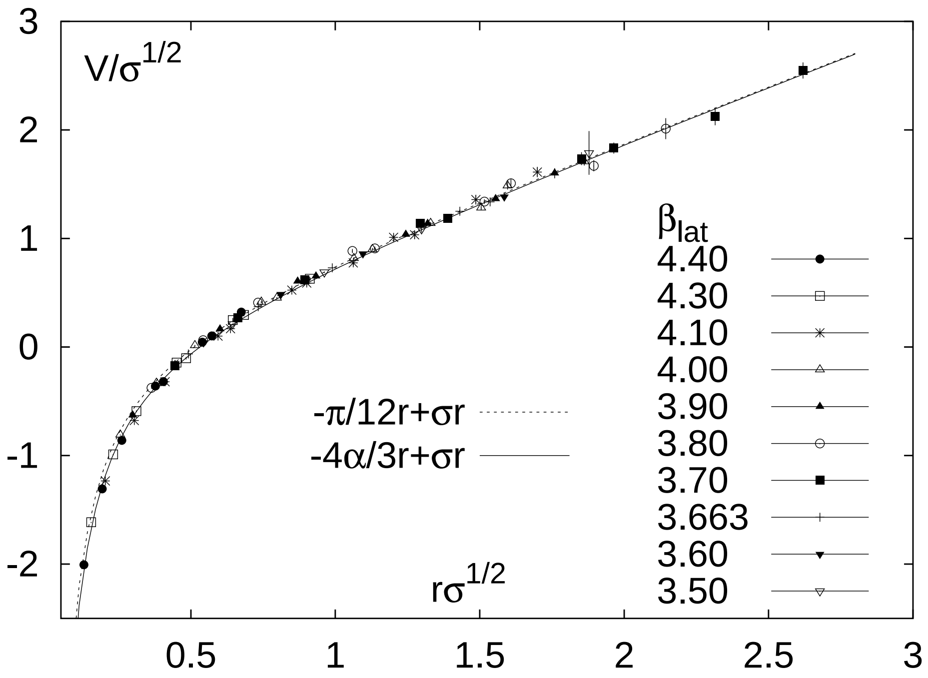
Coulomb gauge fixing [O. Philipsen, Phys. Lett. B535 (2002) 138]



$$-\ln\left(\langle \tilde{\mathrm{Tr}} L(\mathbf{x}) \tilde{\mathrm{Tr}} L^\dagger(\mathbf{y})\rangle\right) = \frac{F_{\bar{q}q}(r,T)}{T}$$

$$-\ln\left(\langle \tilde{\mathrm{Tr}} L(\mathbf{x}) L^\dagger(\mathbf{y})\rangle\right)\Big|_{GF} = \frac{F_1(r,T)}{T}$$

$$-\ln\left(\frac{9}{8}\langle \tilde{\mathrm{Tr}} L(\mathbf{x}) \tilde{\mathrm{Tr}} L^\dagger(\mathbf{y})\rangle - \frac{1}{8}\langle \tilde{\mathrm{Tr}} L(\mathbf{x}) L^\dagger(\mathbf{y})\rangle\Big|_{GF}\right) = \frac{F_8(r,T)}{T}$$



Large distance behaviour

consistent with string model prediction:

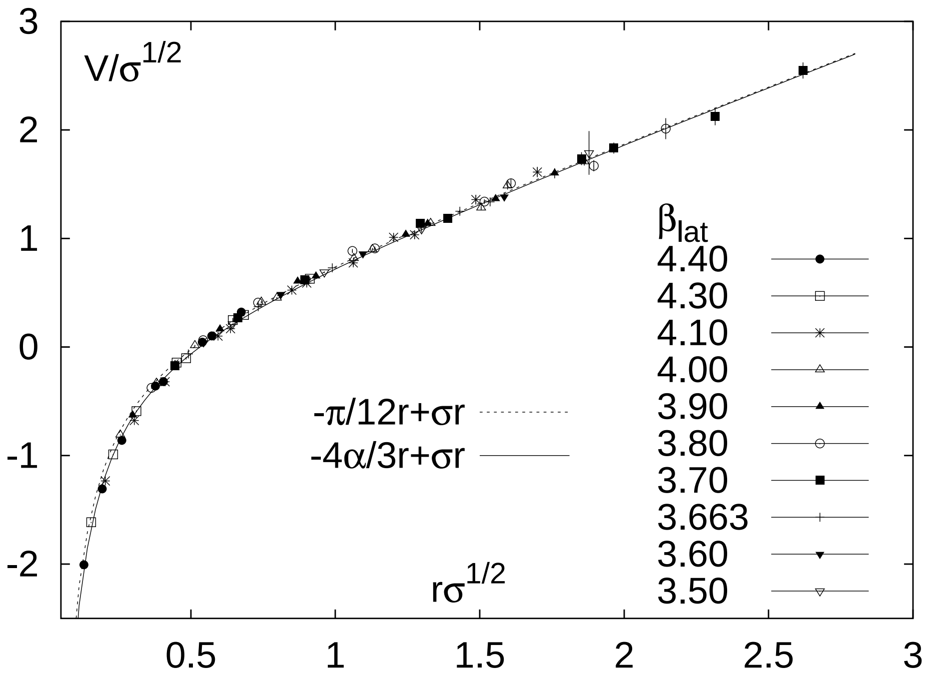
$$V(r) = -\frac{\pi}{12r} + \sigma r \quad , \text{ for large } r$$

consistent with quenched potential for $r \gtrsim 0.4$ fm

no string breaking observed

due to the used operator

$r_{\mathrm{str}} \approx 1.3$fm



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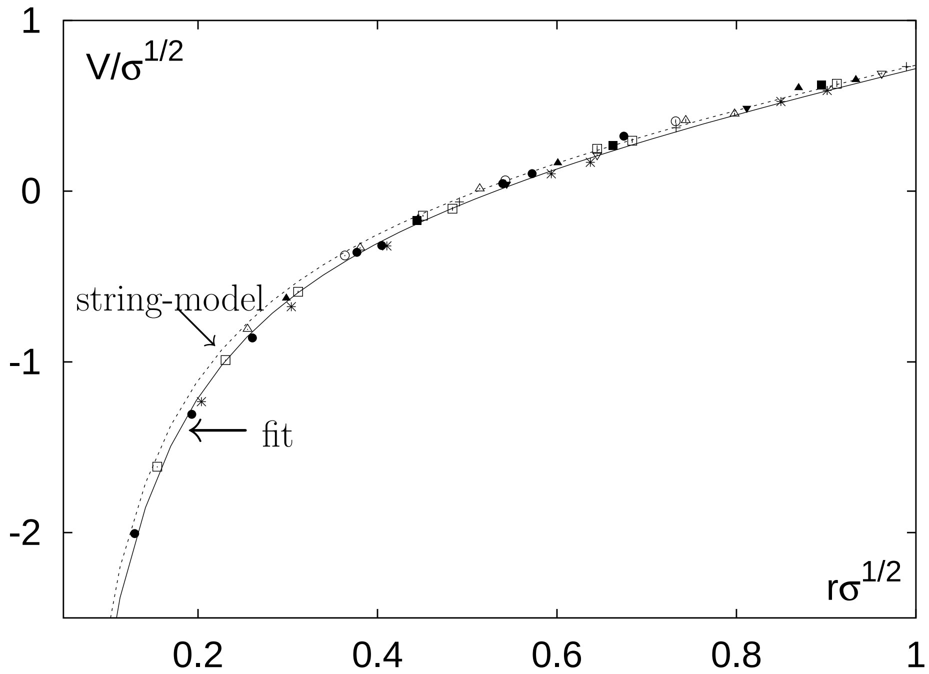
Short distance behaviour

deviations at small r

enhancement of the running coupling

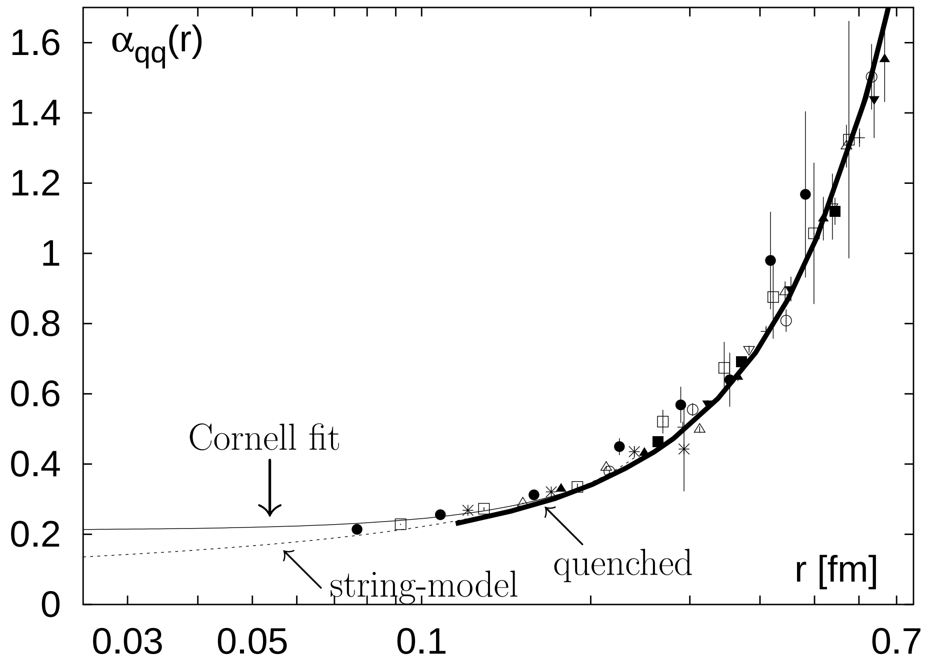
fit: $V(r) = -0.2822(28)/r + \sigma\, r$

r-dependent running coupling $\alpha(r)$



QCD running coupling in the qq-scheme

$$\alpha_{qq}(r) = \frac{3}{4} r^2 \frac{dV(r)}{dr}$$



Large distance behavior

non-perturbative confining part for $r \gtrsim 0.4$ fm

$$\alpha_{qq}(r) \simeq 3/4 r^2 \sigma$$

consistent with quenched potential

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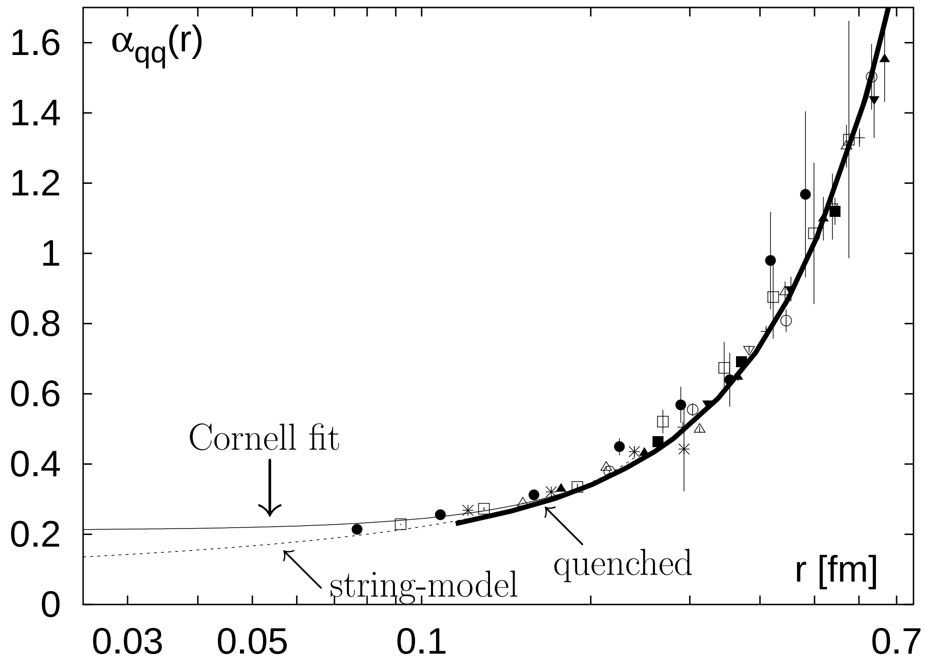

leading order perturbation theory:

$$\alpha(r) \simeq \frac{1}{8\pi} \frac{1}{\beta_0 \log(1/(r\Lambda_{\mathrm{QCD}}))}$$

Large distance behavior

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$$\alpha_{qq}(r) \simeq 3/4 r^2 \sigma$$

consistent with quenched potential

consistent with string model prediction

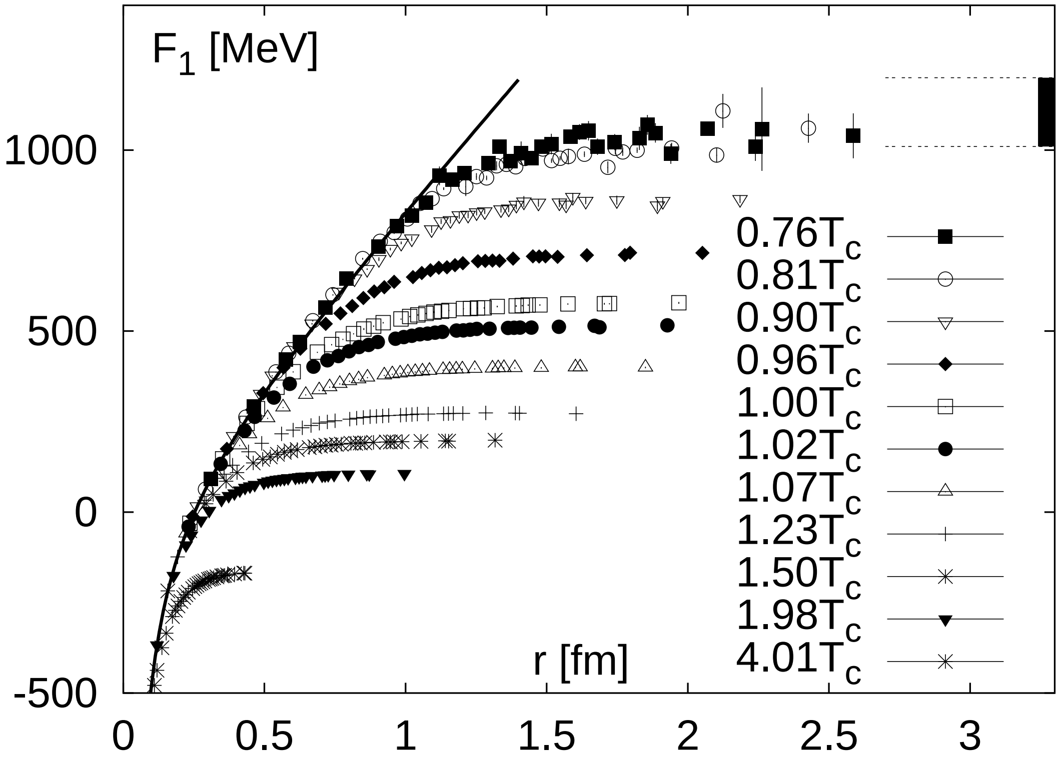
Short distance behavior

logarithmic weakening, i.e. $\alpha_{\mathrm{qcd}} = \alpha_{\mathrm{qcd}}(r)$

flavor and quark mass dependence

$$\beta_0 = \frac{33 - 2N_f}{48\pi^2}$$

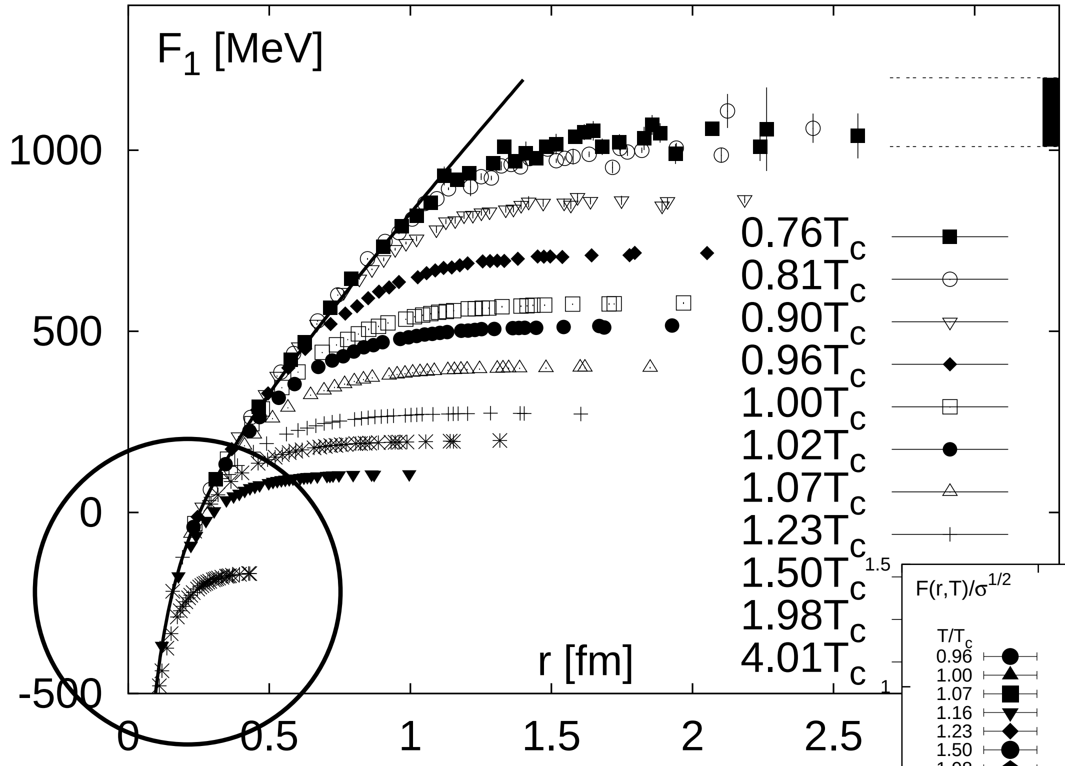
Heavy quark free energy



Renormalization of $F(r,T)$
by
matching with T=0 potential

$$e^{-F_1(r,T)/T} = \left(Z_r(g^2)\right)^{2N_\tau} \langle \mathrm{Tr}\ (L_x L_y^\dagger) \rangle$$

Heavy quark free energy



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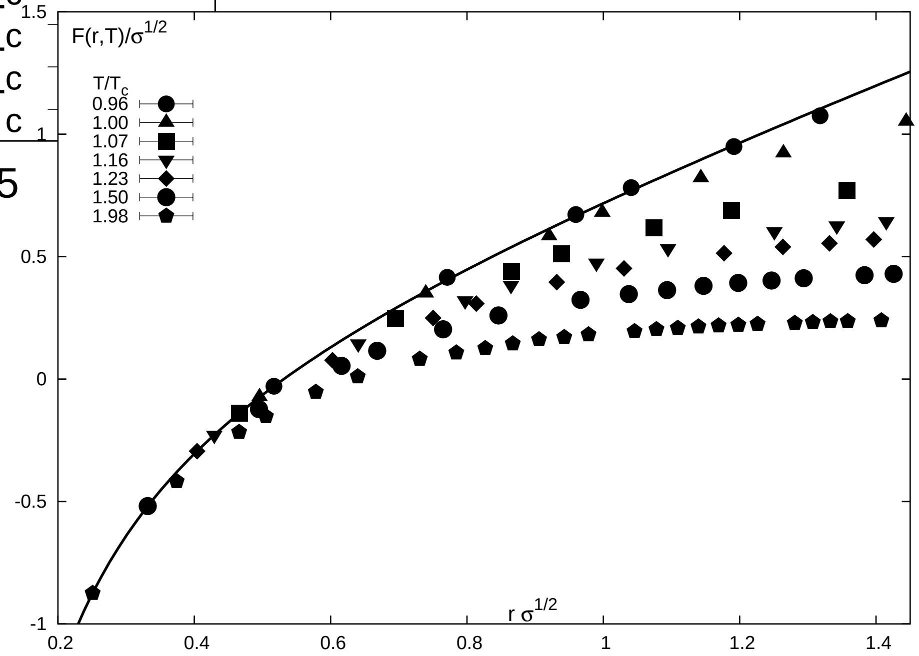
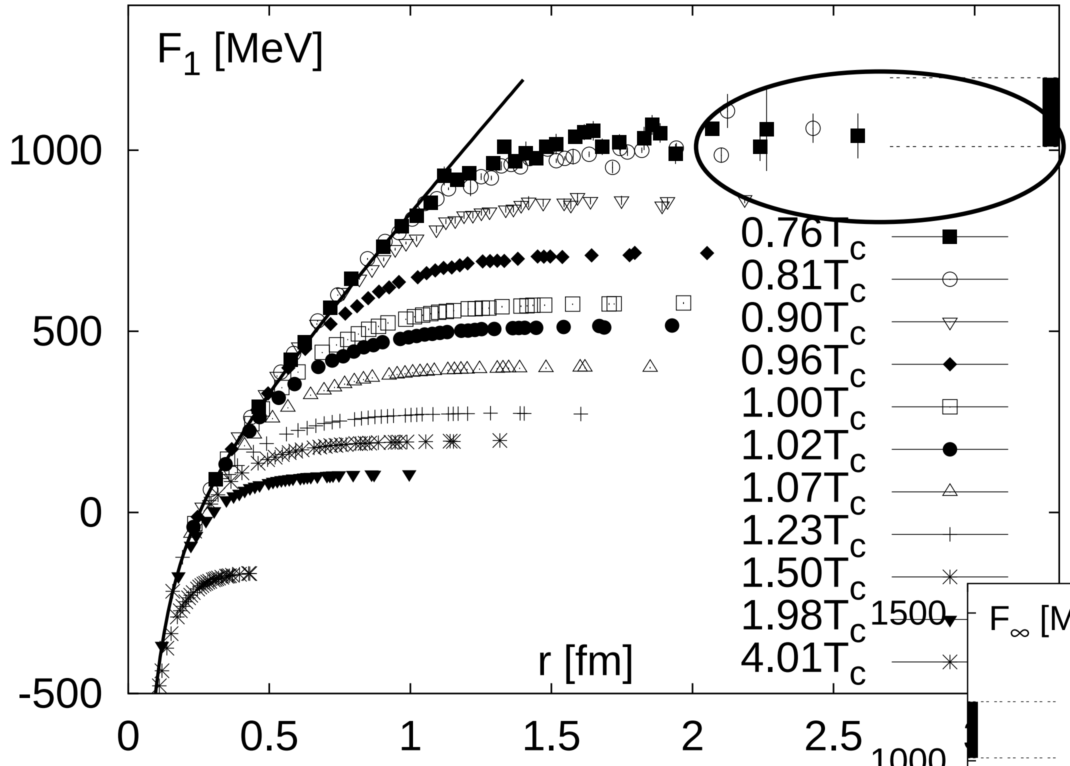


T-independent

$r \ll 1/\sqrt{\sigma}$

$F(r,T) \sim g^2(r)/r$

Heavy quark free energy



String breaking

$T < T_c$

$F(r\sqrt{\sigma} \gg 1, T) < \infty$

T-**independent**

$r \ll 1/\sqrt{\sigma}$

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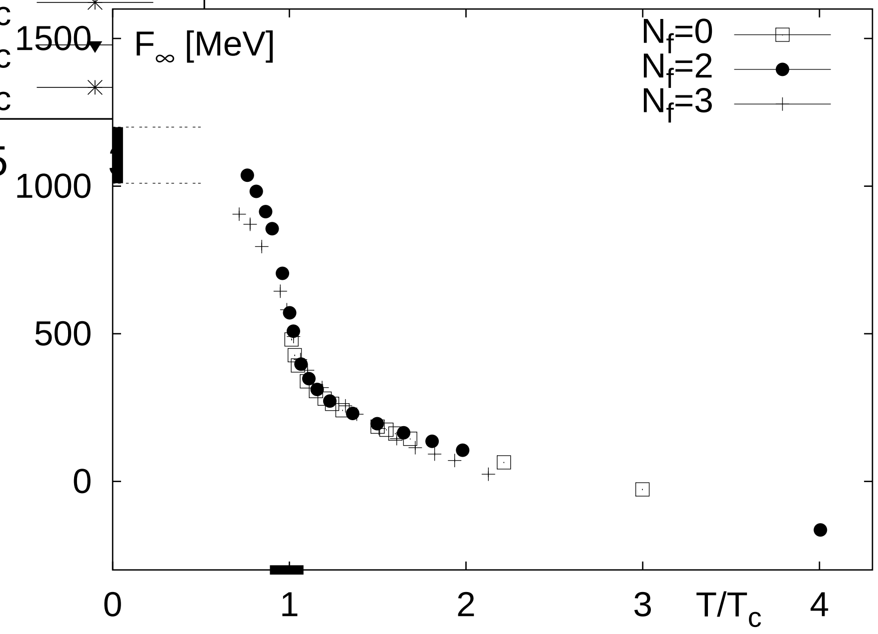

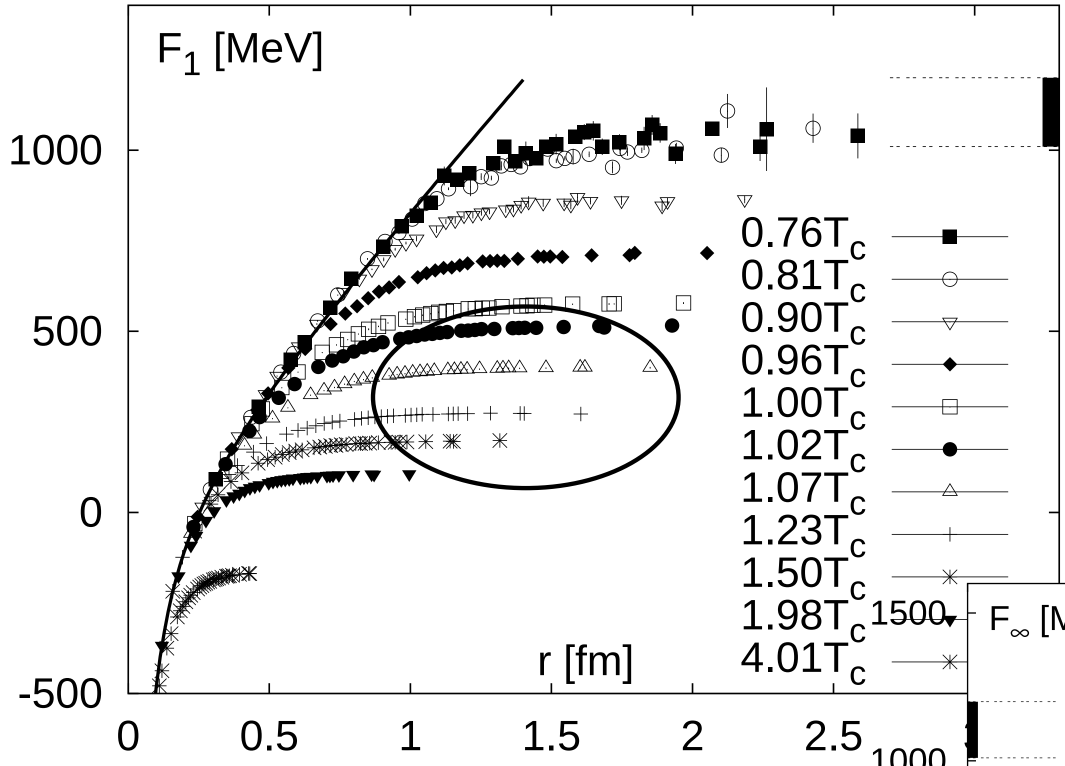

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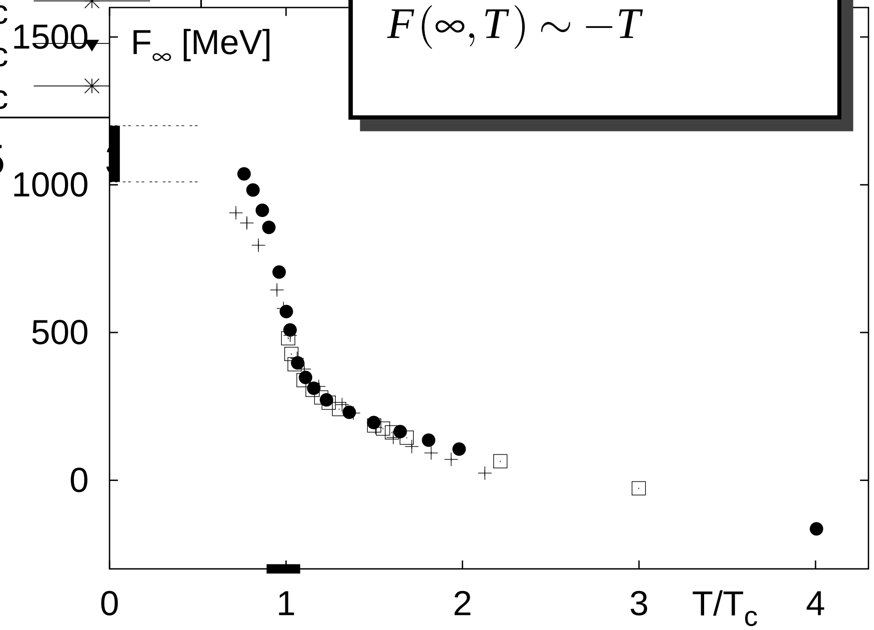
$F(r\sqrt{\sigma} \gg 1, T) < \infty$

high-T physics

$rT \gg 1$; screening

$\mu(T) \sim g(T)T$

$F(\infty, T) \sim -T$



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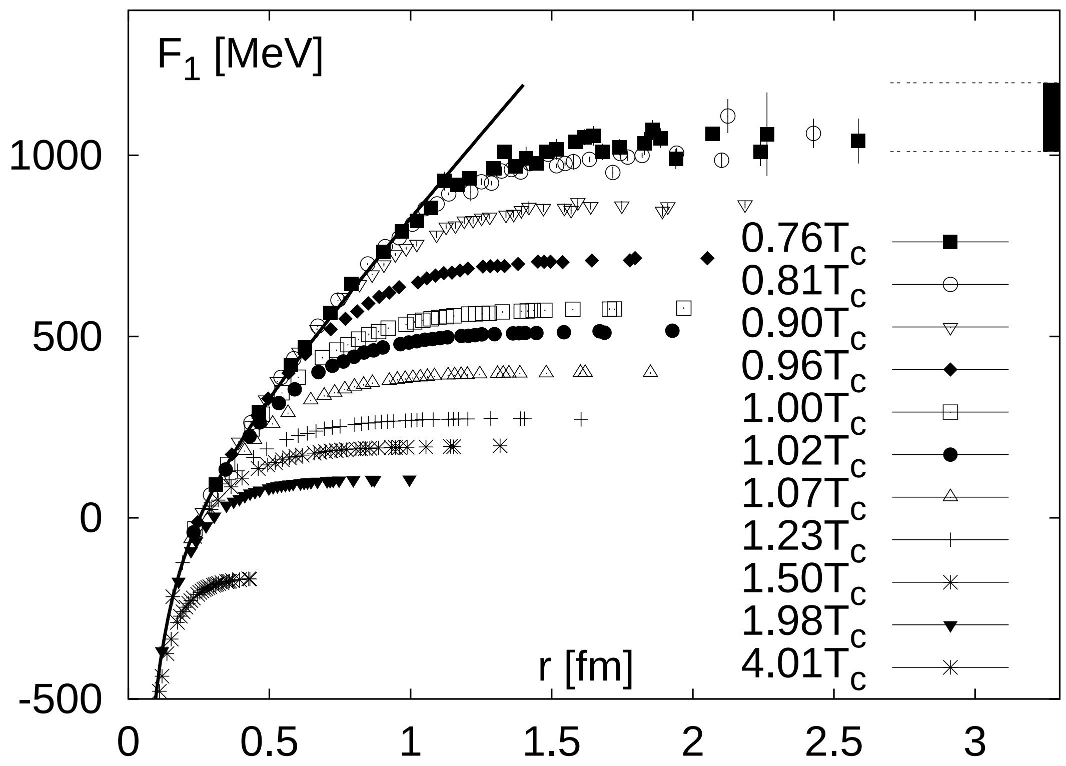

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T-independent

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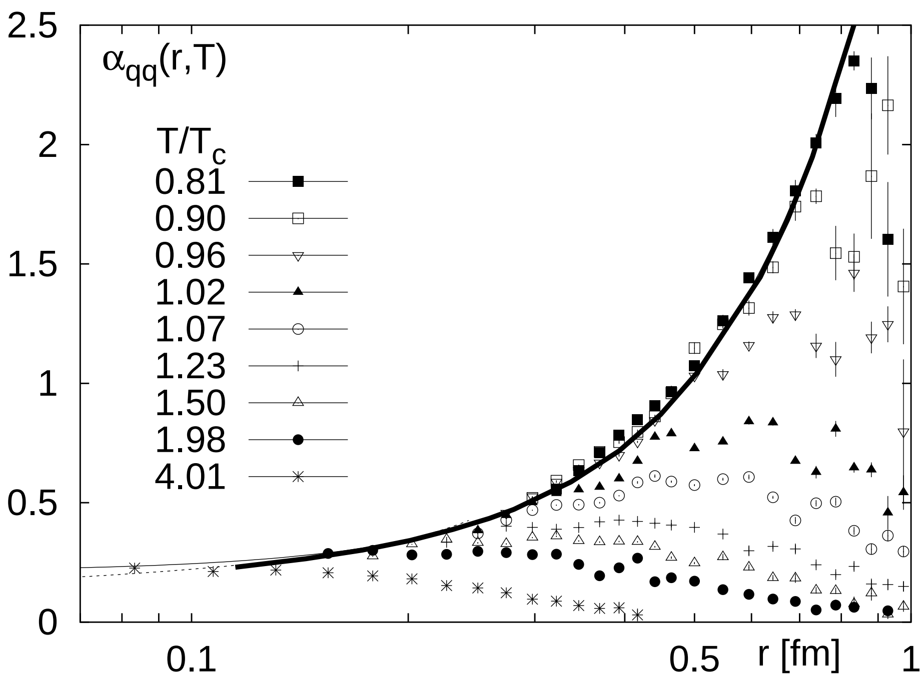
Complex r and T dependence

Small vs. large distance behavior

Running coupling vs. screening

Where do temperature effects set in?

Temperature depending running coupling



Free energy in perturbation theory:

$$F_1(r,T) \equiv V(r) \simeq -\frac{4}{3}\frac{\alpha(r)}{r} \quad \text{for} \quad r\Lambda_{\text{QCD}} \ll 1$$

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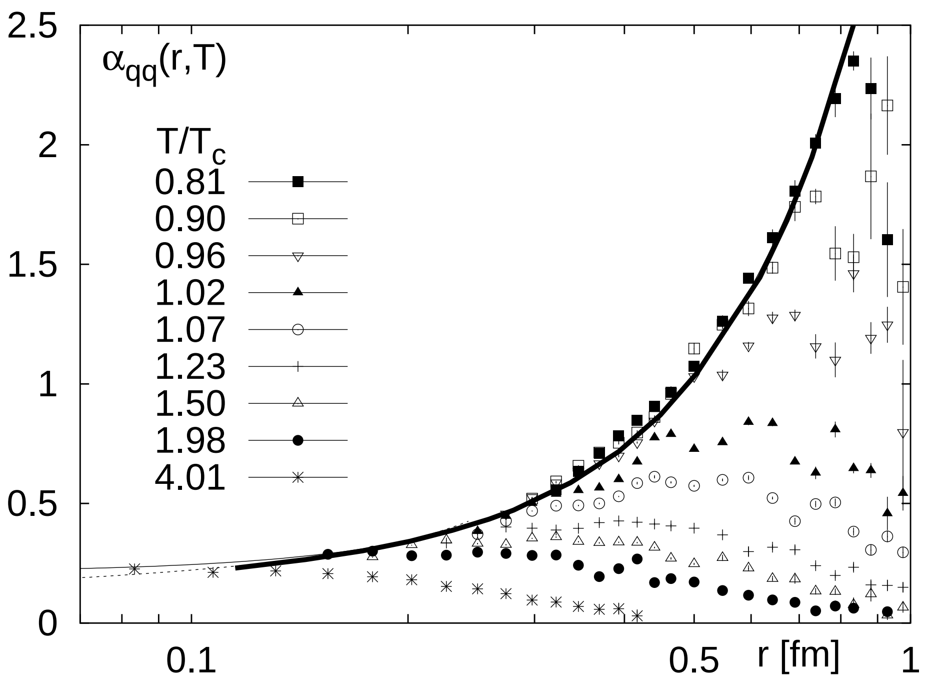

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non-perturbative confining part for $r \gtrsim 0.4$ fm

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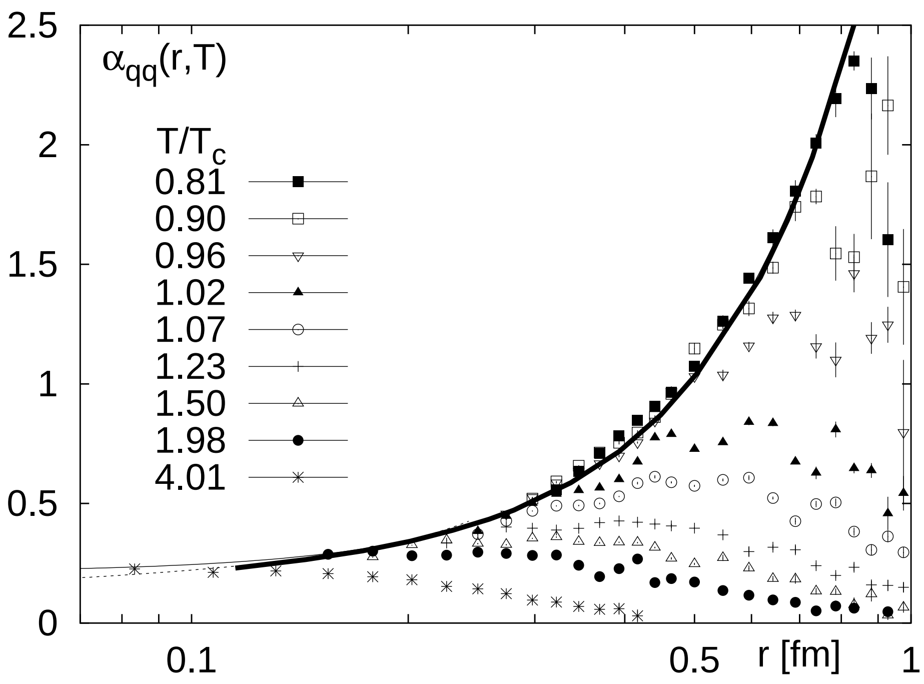
present below and just above T_c

temperature effects set in at smaller r with increasing T

maximum due to screening

Temperature depending running coupling



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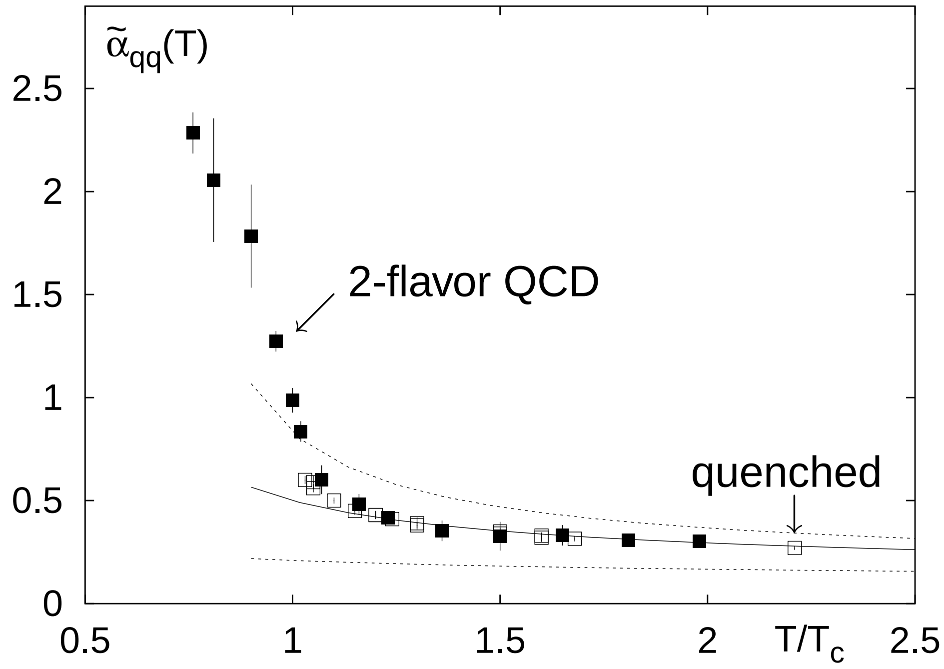
$\Longrightarrow$ At which distance do T-effects set in ?

$\Longrightarrow$ definition of the screening radius/mass

$\Longrightarrow$ definition of the T-dependent coupling

Temperature depending running coupling



define $\tilde{\alpha}_{qq}(T)$ by maximum of $\alpha_{qq}(r,T)$:

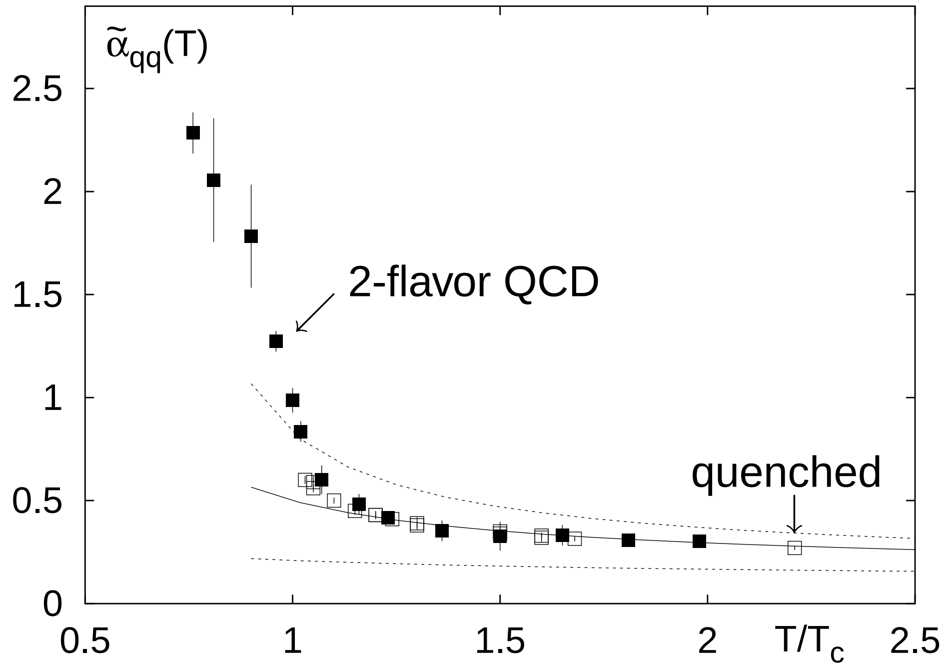
$$\tilde{\alpha}_{qq}(T) \equiv \alpha_{qq}(r_{max},T)$$

perturbative behaviour at high T:

$$g^{-2}_{\text{2-loop}}(T) = 2\beta_0 \ln\left(\frac{\mu T}{\Lambda_{\overline{MS}}}\right) + \frac{\beta_1}{\beta_0} \ln\left(2\ln\left(\frac{\mu T}{\Lambda_{\overline{MS}}}\right)\right),$$

Using $T_c/\Lambda_{\overline{MS}} = 0.77(21)$ we find $\mu = 1.14(2)\pi$

Temperature depending running coupling



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non-perturbative large values near T_c

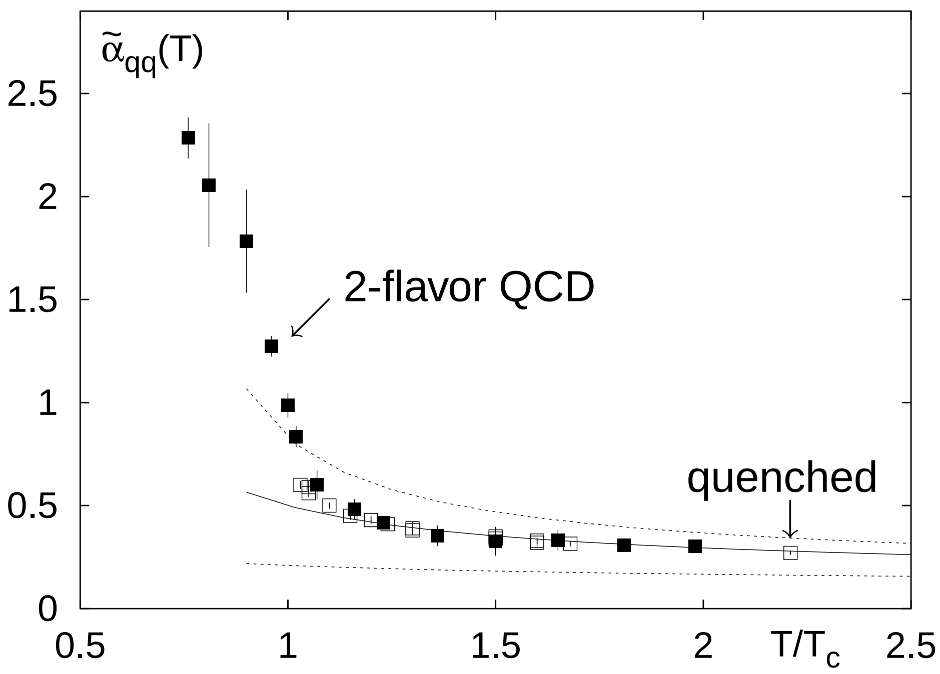
not a large Coulombic coupling

remnants of confinement at $T \gtrsim T_c$

string breaking and screening difficult to separate

slope at high T well described by perturbation theory

Temperature depending running coupling



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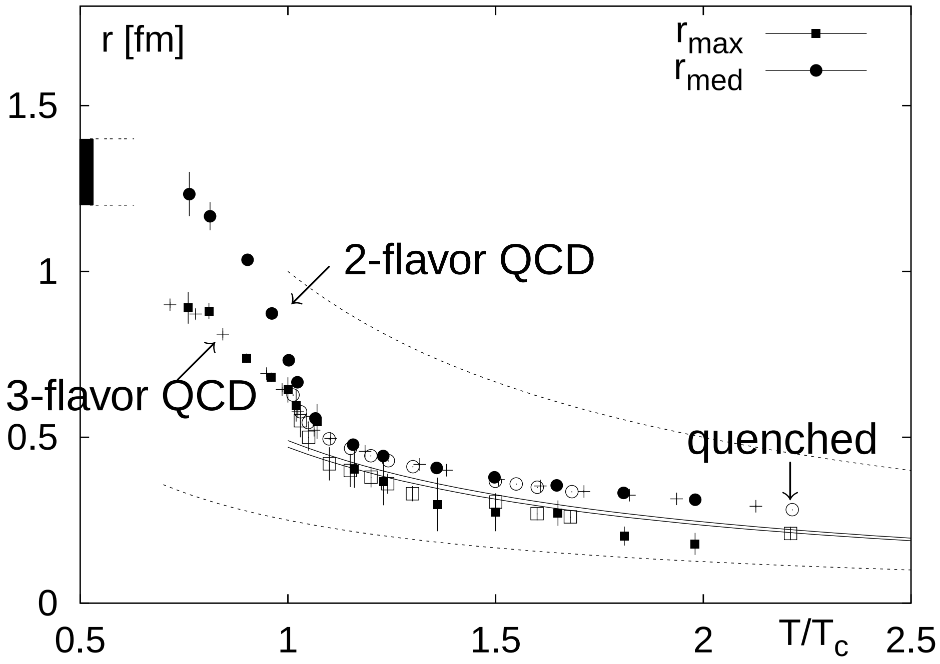
$\Longrightarrow$ definition of the screening radius/mass

Screening/String breaking radius



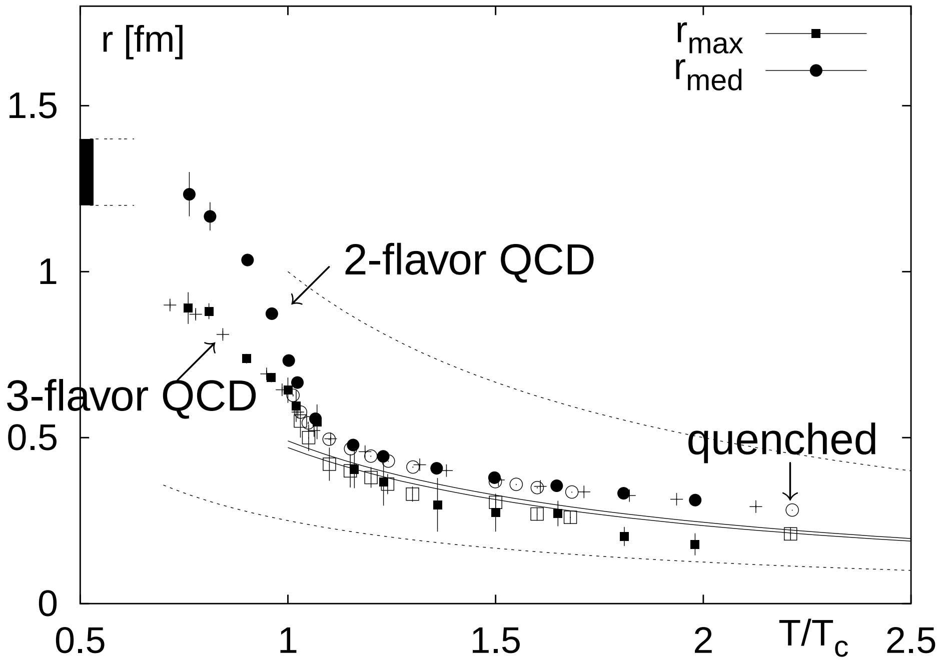
At which distances do medium effects set in?

Definitions of the screening radius:

$$\tilde{\alpha}(T) \equiv \alpha_{qq}(r_{max}, T)$$

$$V(r_{med}) \equiv F_\infty(T)$$

Both define similar scales, but $r_{max} \lesssim r_{med}$



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Above T_c:

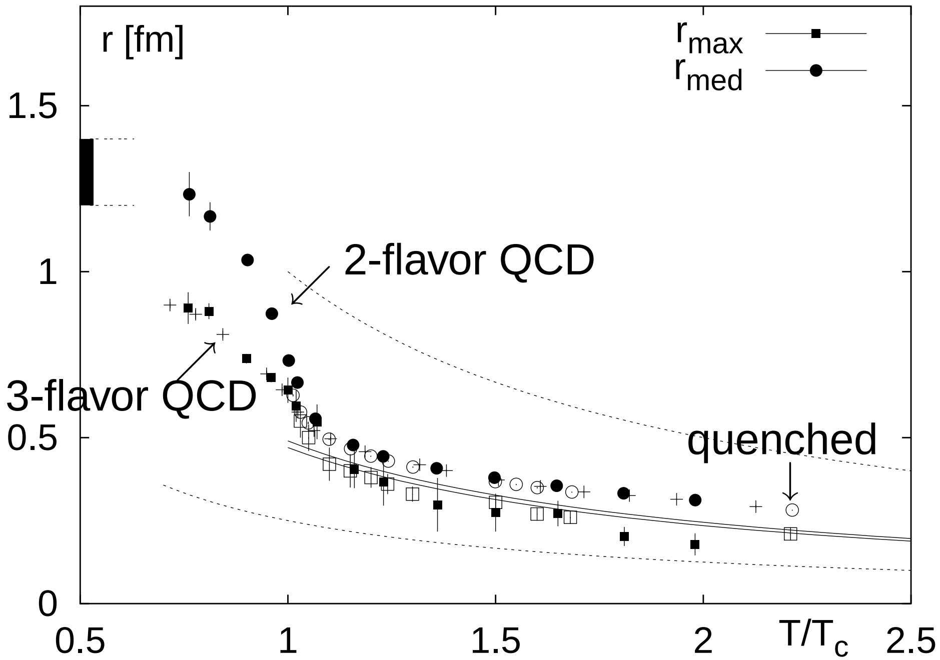
Only small flavor/quark mass effects

Both scales allmost coincide

Change in r_{max} from 0.6 fm (T_c) to 0.25 fm $(2\,T_c)$

$r_{max} = 0.48(1)\text{fm} \cdot T_c/T$

Screening/String breaking radius



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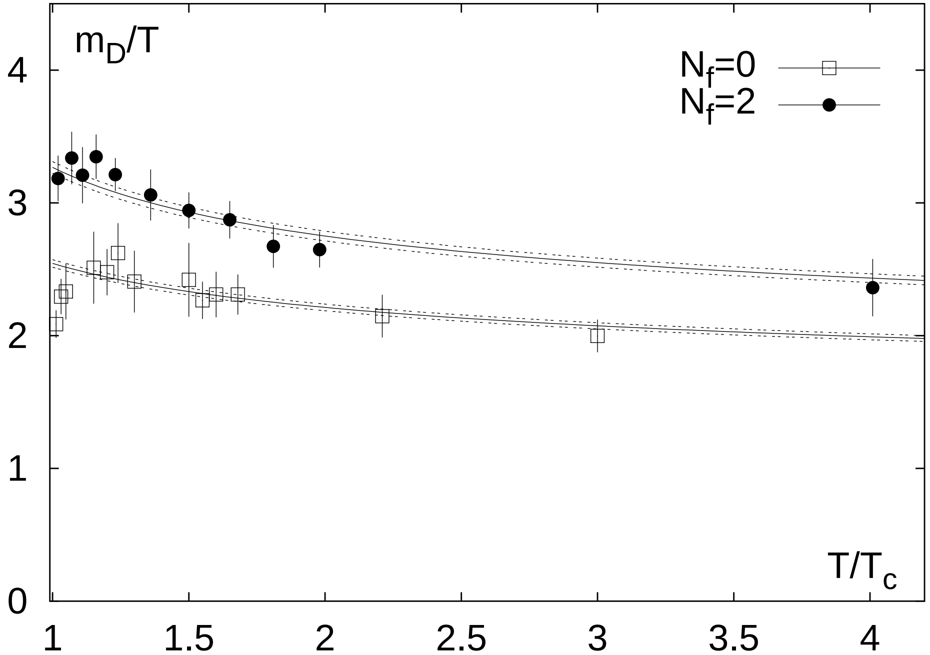
Below T_c:

Large flavor/quark mass effects

Both scales fall apart

Rapid increase to values expected at T=0

Screening mass



Screening masses obtained from fits to:

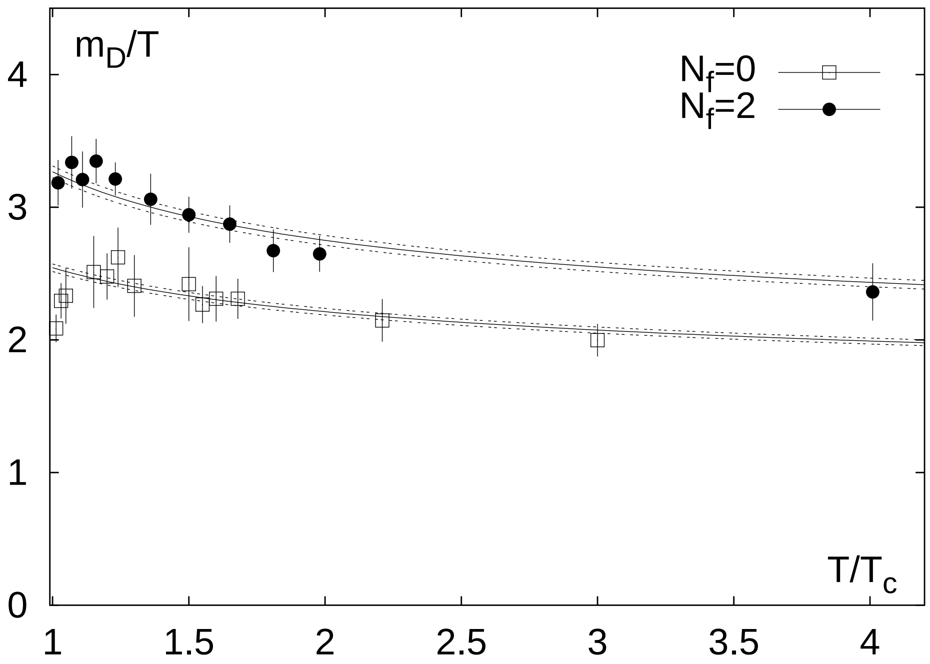
$$F_1(r,T) - F_1(r=\infty,T) = -\frac{4\alpha(T)}{3r} e^{-m_D(T)r}$$

at large distances $rT \gtrsim 1$

leading order perturbation theory:

$$\frac{m_D(T)}{T} = A\left(1 + \frac{N_f}{6}\right)^{1/2} g(T)$$

Screening mass



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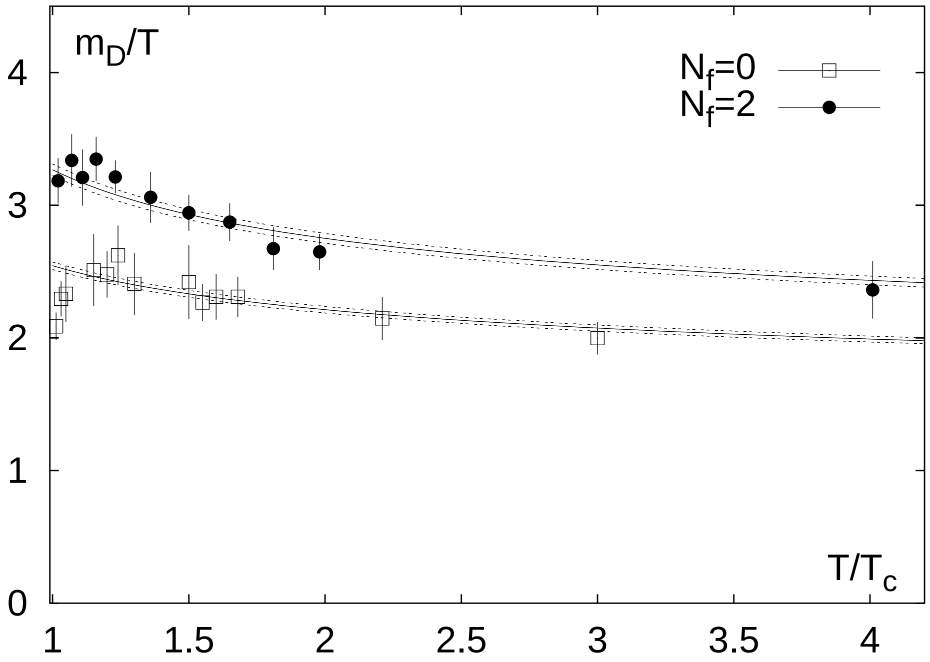
T depencence qualitatively described by perturbation theory

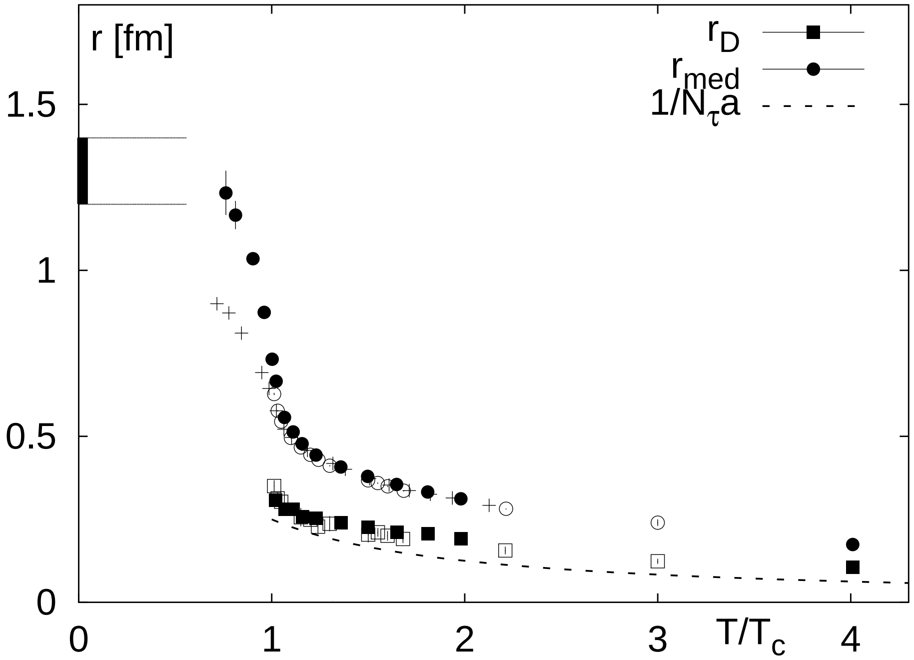
But $A \approx 1.4$ - $1.5 \quad \Longrightarrow \quad$ non-perturbative effects

$A \rightarrow 1$ in the (very) high temperature limit

Difference between $N_f = 0, 2$ disappears when converting to physical units

Screening mass





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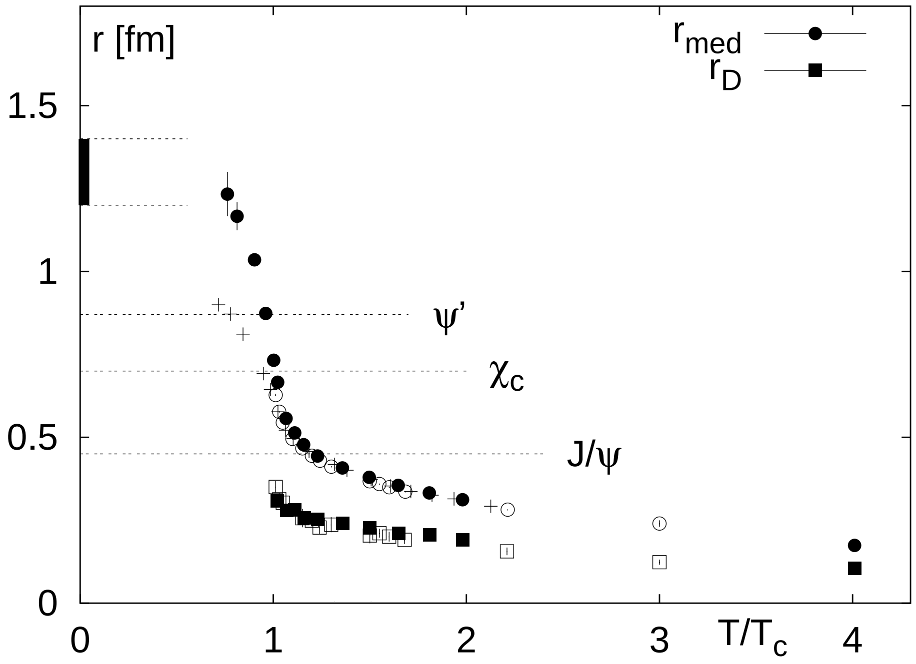
Debye screening radius $r_D = 1/m_D$

of the order of smallest attainable distance

r_{med} about twice as large

r_{med} indicates where medium effects become relavan

Heavy quark bound states above T_c?



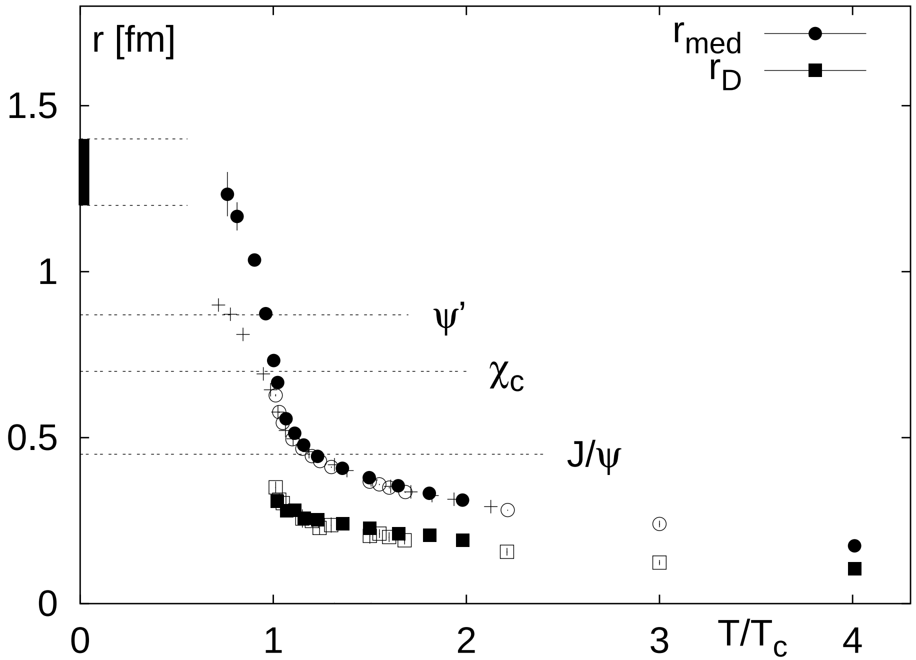
bound states above deconfinement?

first estimate:

mean charge radii of charmonium states compared to r_{med}

thermal modifications on ψ' and χ_c already at T_c

J/ψ may survive above deconfinement



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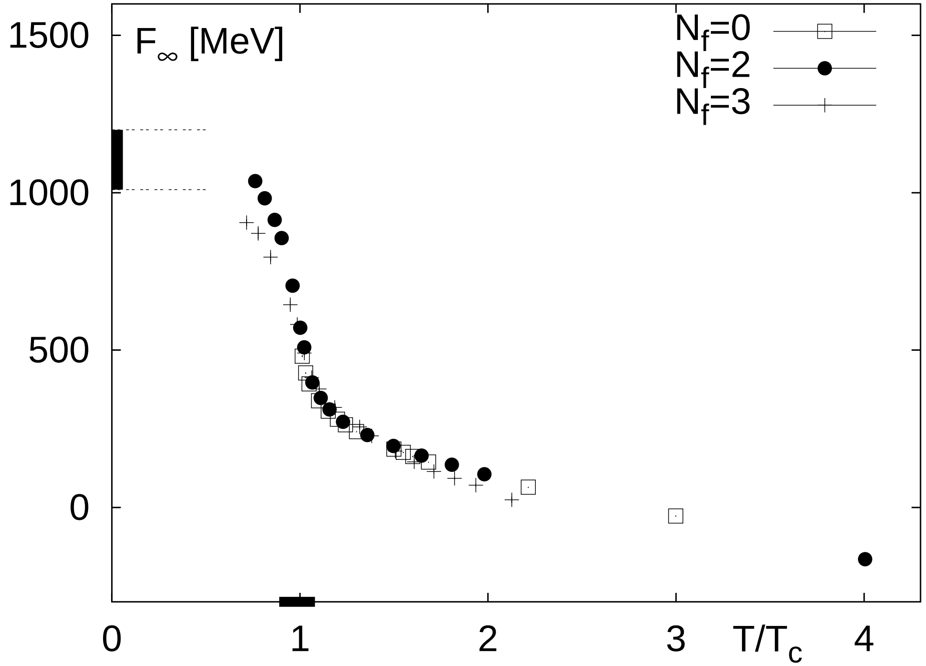
Better estimate:

effective potentials in Schrödinger Equation

Potential models, effective potential $V_{eff}(r,T)$

But: Free energies vs. internal energies $F(r,T) = U(r,T) - TS(r,T)$

Free energy vs. Entropy for $r \to \infty$



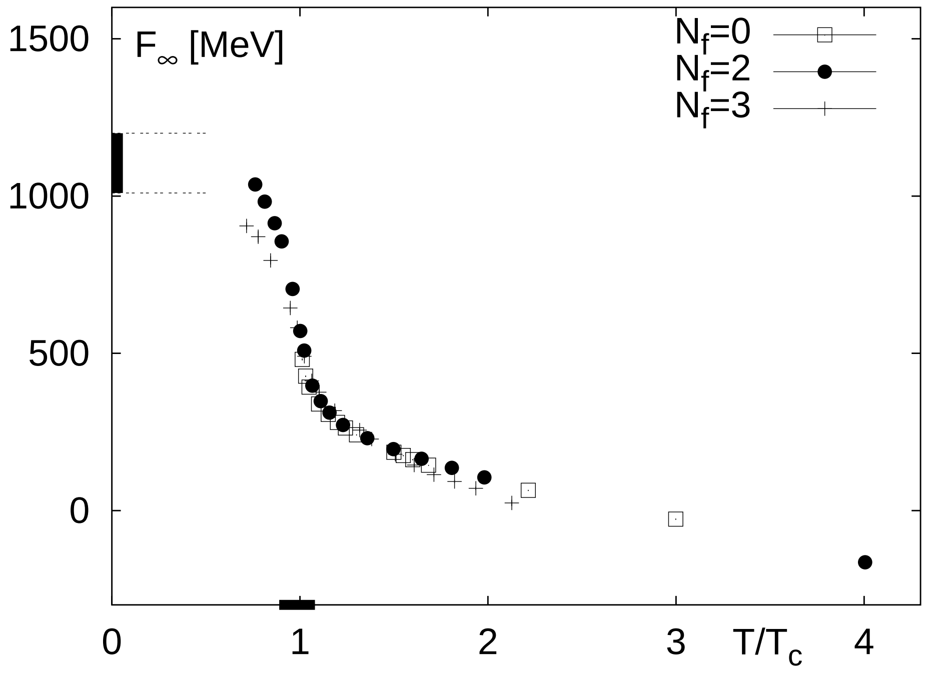
Free energies not only determined by potential energy

$$F_\infty = U_\infty - T S_\infty$$

Entropy contributions play a role at finite T

$$S_\infty = -\frac{\partial F_\infty}{\partial T}$$

Free energy vs. Entropy for $r \to \infty$



Free energies not only determined by potential energy

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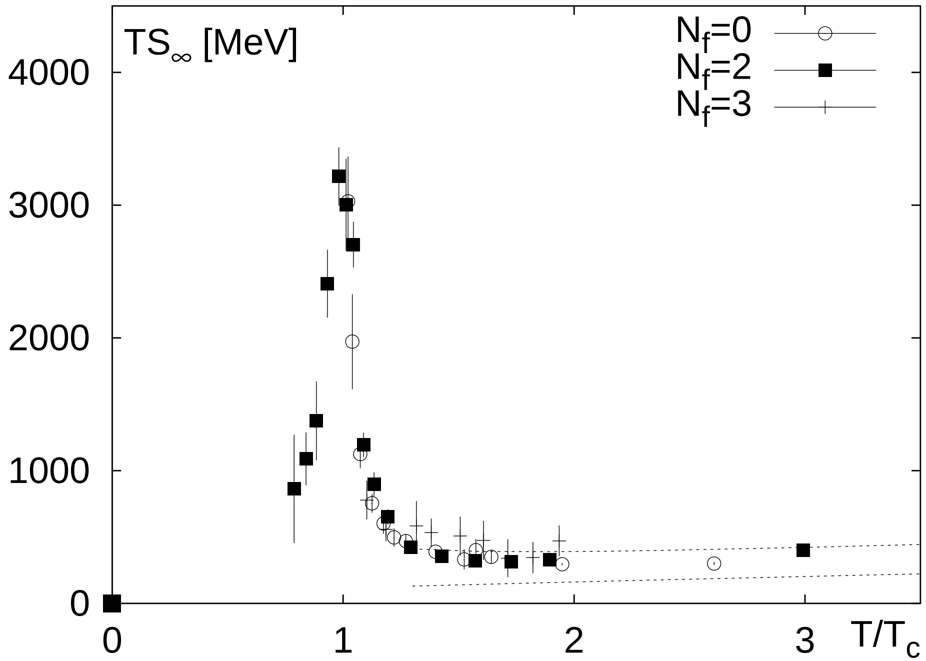

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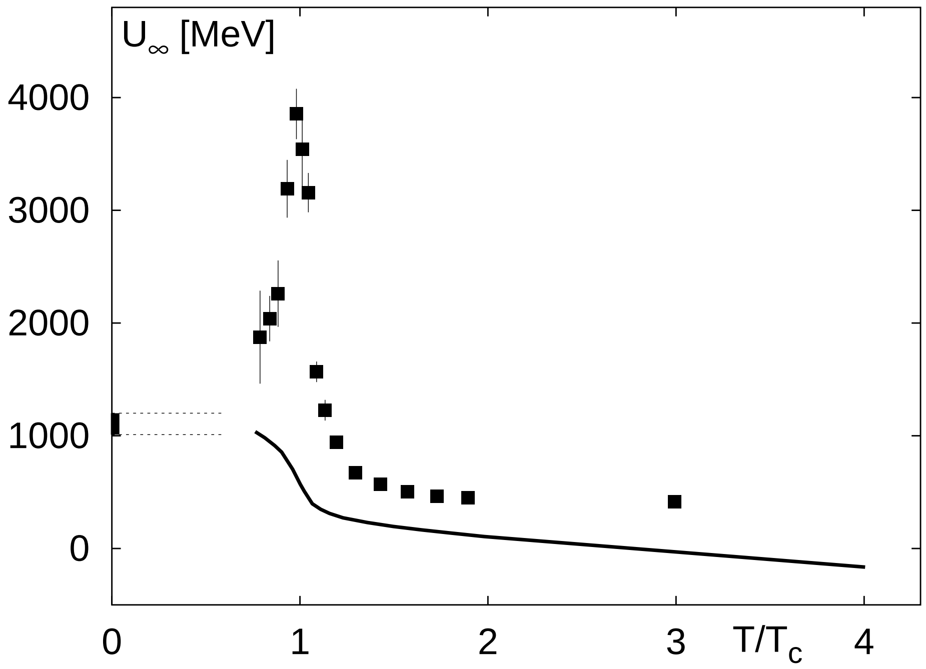

Free energies not only determined by potential energy

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Entropy contributions play a role at finite T

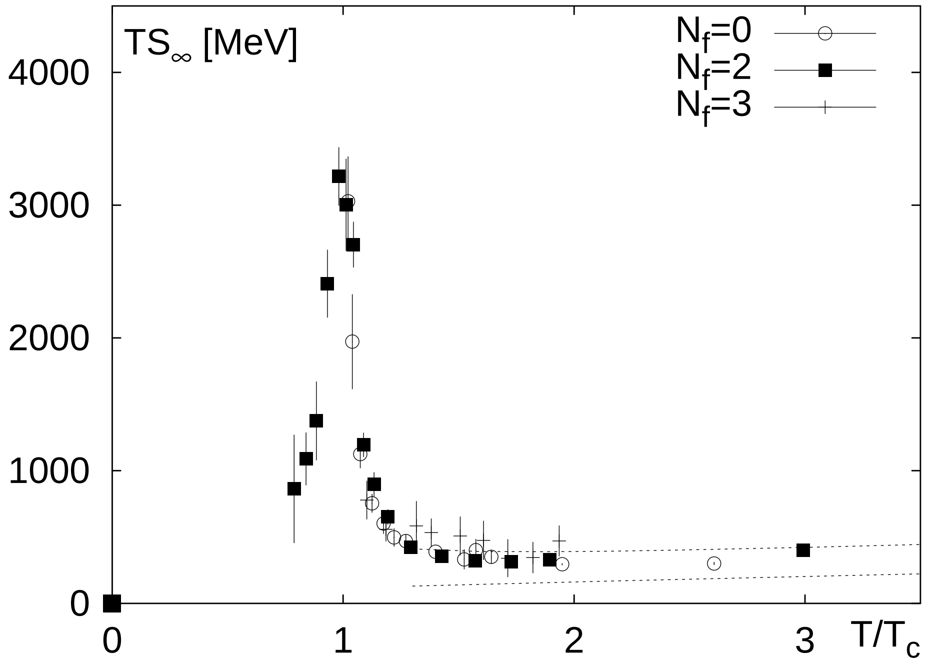
$$S_\infty = -\frac{\partial F_\infty}{\partial T}$$

Internal energy:

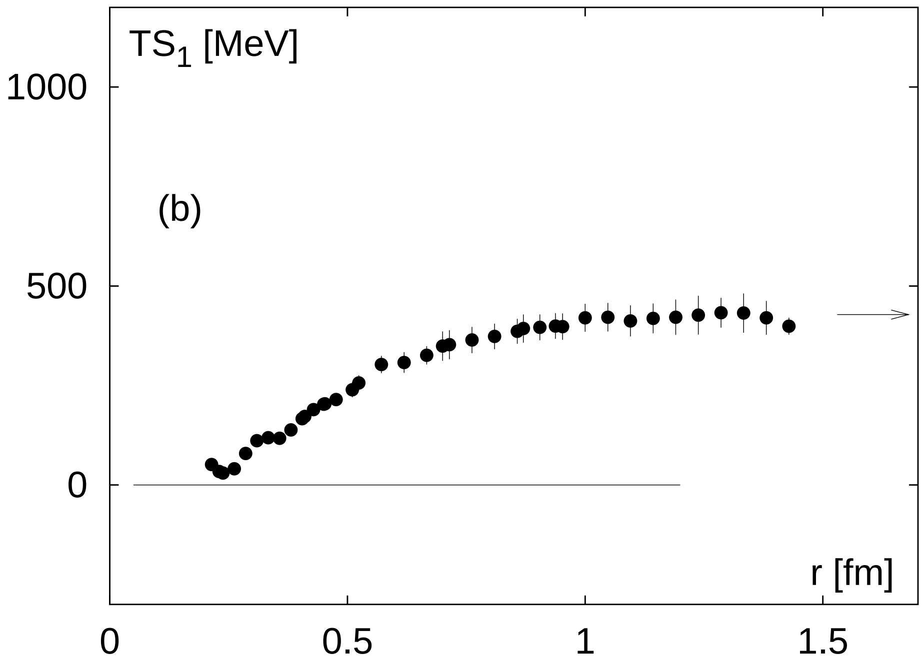
$$U_\infty = -T^2 \frac{\partial F_\infty / T}{\partial T}$$

enhancement compared to free energies

strongest enhancement around T_c



r-dependence of internal energies



$$F_1(r,T) = U_1(r,T) - TS_1(r,T)$$

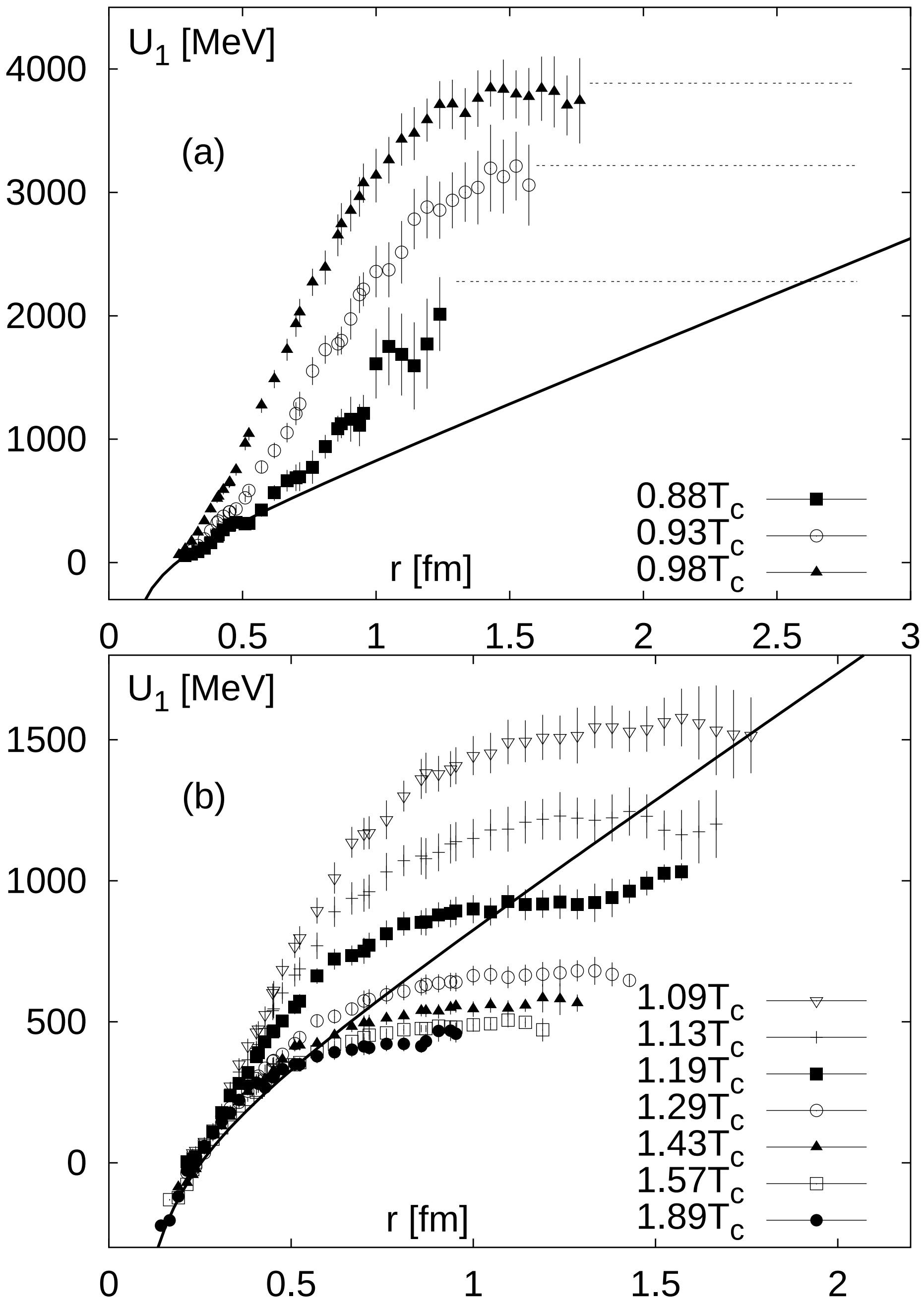
$$S_1(r,T) = \frac{\partial F_1(r,T)}{\partial T}$$

$$U_1(r,T) = -T^2 \frac{\partial F_1(r,T)/T}{\partial T}$$

Entropy contributions vanish in the limit $r \to 0$

$$F_1(r \ll 1, T) = U_1(r \ll 1, T) \equiv V_1(r)$$

important at intermediate/large distances



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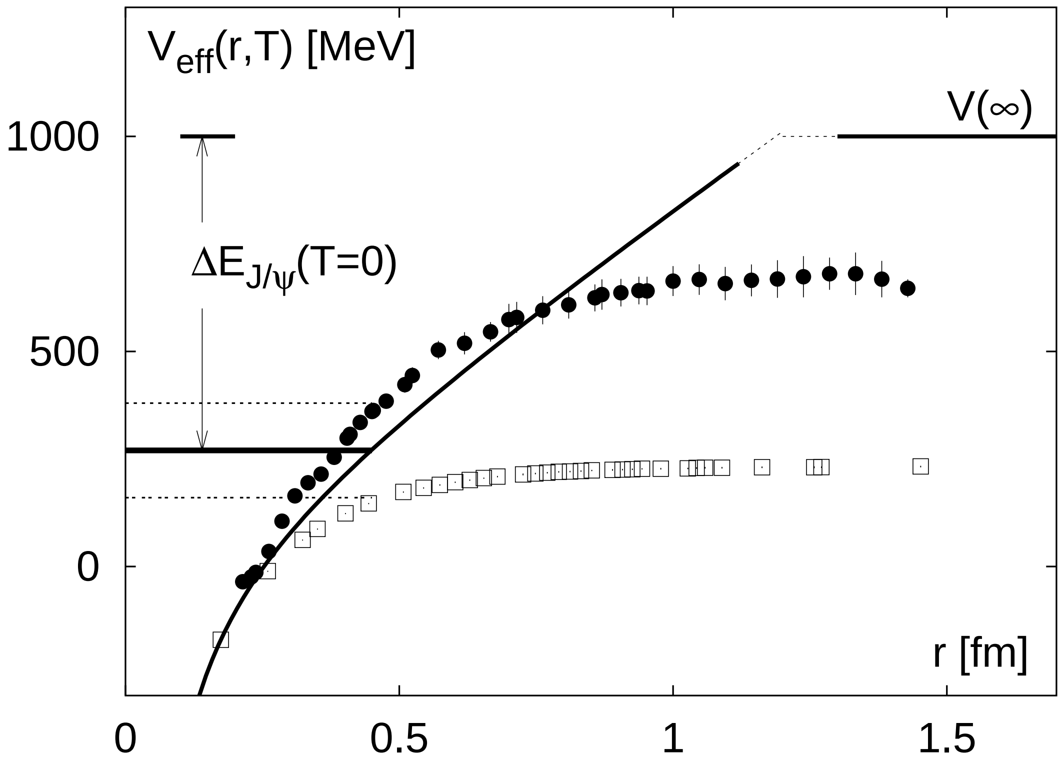
important at intermediate/large distances

$\Longrightarrow$ Implications on heavy quark bound states?

$\Longrightarrow$ What is the correct $V_{eff}(r,T)$?

Heavy quark bound states



steeper slope of $V_{eff}(r,T) = U_1(r,T)$

$\Longrightarrow$ J/ψ stronger bound using $V_{eff} = U_1(r,T)$

$\Longrightarrow$ dissociation at higher temperatures compared to $V_{eff}(r,T) = F_1(r,T)$

Schrödinger equation for heavy quarks:

$$\left[2m_f + \frac{1}{m_f}\Delta^2 + V_{eff}(r,T)\right]\Phi_i^f = E_i^f(T)\Phi_i^f \quad , \quad f = \text{charm, bottom}$$

T-dependent color singlet heavy quark potential mimics in-medium modifications of $q\bar{q}$ interaction

reduction to 2-particle interaction clearly too simple, in particular close to T_c

recent analysis:

using $V_{eff} = F_1$: S.Digal, P.Petreczky, H.Satz, Phys. Lett. B514 (2001)57
using $V_{eff} = V_1$: C.-Y. Wong, hep-ph/0408020
using $V_{eff} = V_1$: W.M. Alberico, A. Beraudo, A. De Pace, A. Molinari, hep-ph/0507084

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
$E_s^i[GeV]$	0.64	0.20	0.005	1.10	0.67	0.54	0.31	0.20
T_d/T_c	1.1	0.74	0.1-0.2	2.31	1.13	1.1	0.83	0.74
T_d/T_c	~ 2.1	~ 1.2	~ 1.2	~ 5.0	~ 1.95	~ 1.65	-	-
T_d/T_c	1.75-1.95	1.13-1.15	1.10-1.11	4.4-4.7	1.5-1.6	1.4-1.5	~ 1.2	~ 1.2

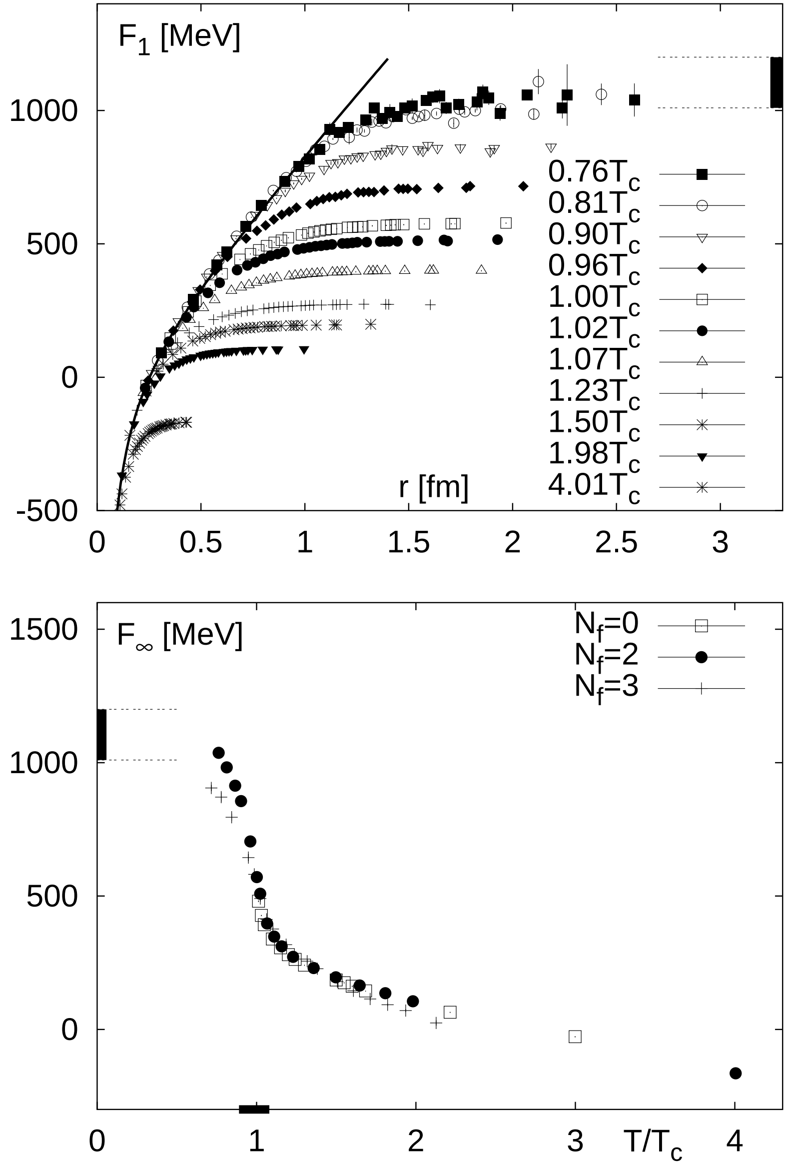
Renormalized Polyakov loop

$$L_{ren} = \exp\left(-\frac{F(r=\infty,T)}{2T}\right)$$

Defined by long distance behaviour of $F(r,T)$.

Renormalized by renormalization of $F(r,T)$ at small distances.

$$L_{ren} = \left(Z_R(g^2)\right)^{N_t} L_{lattice}$$



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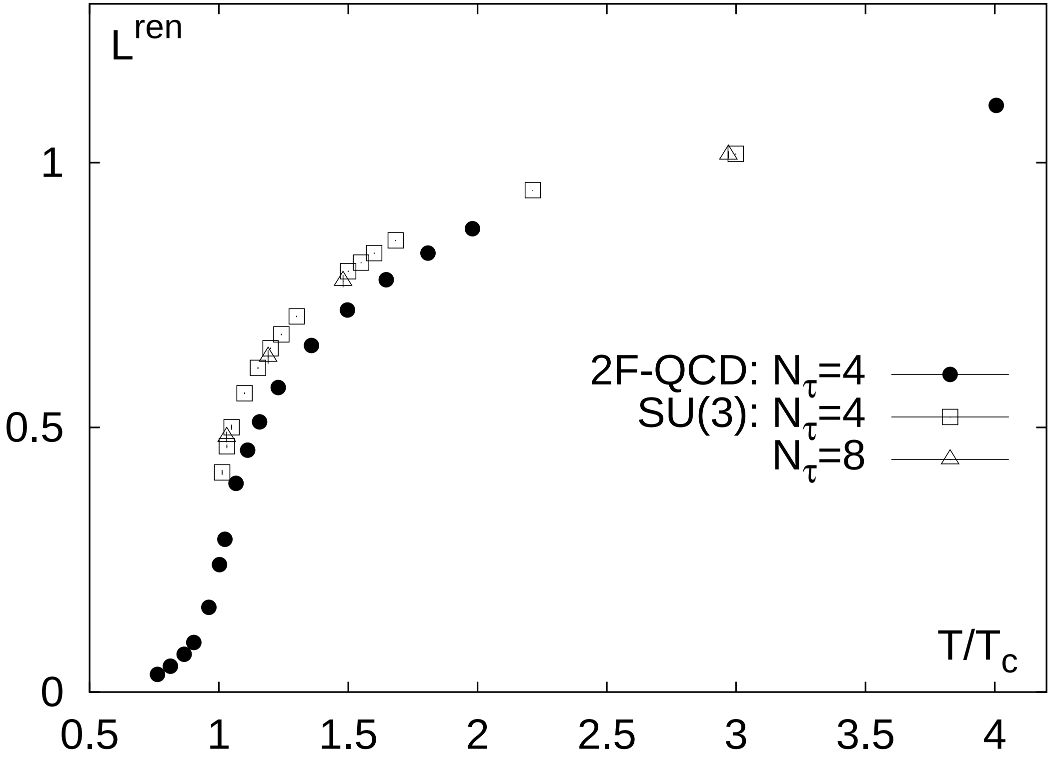

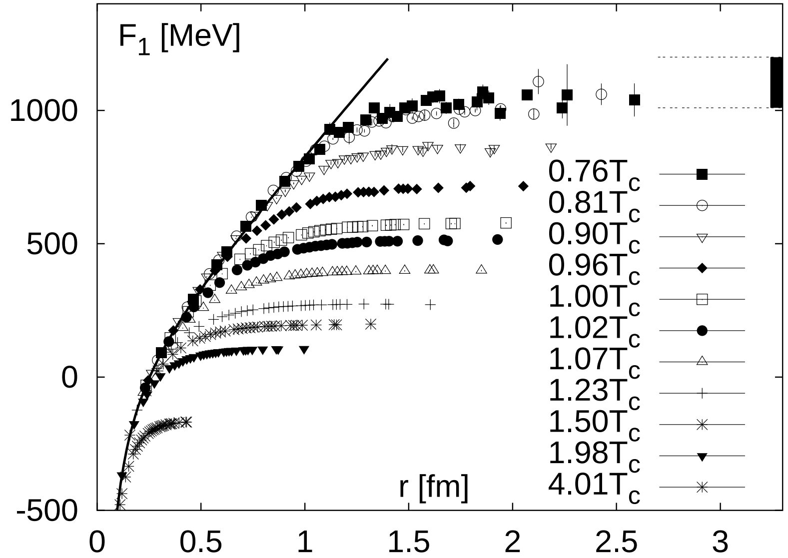

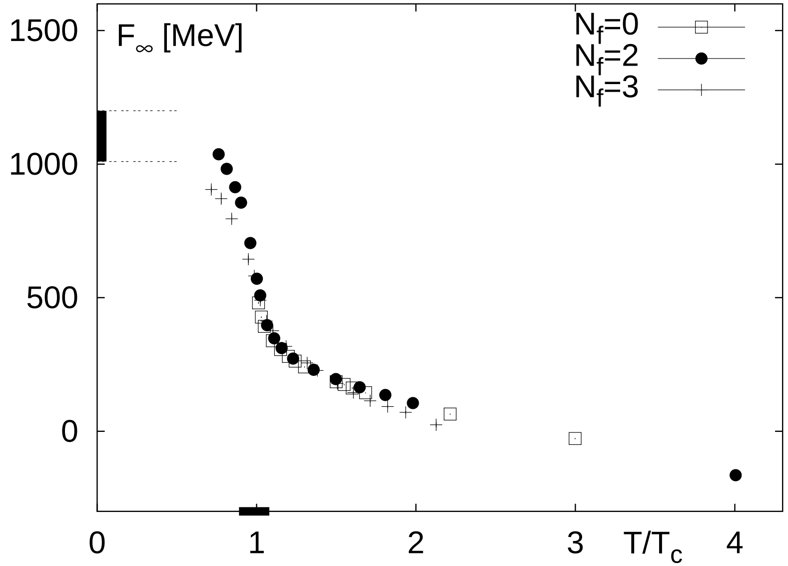

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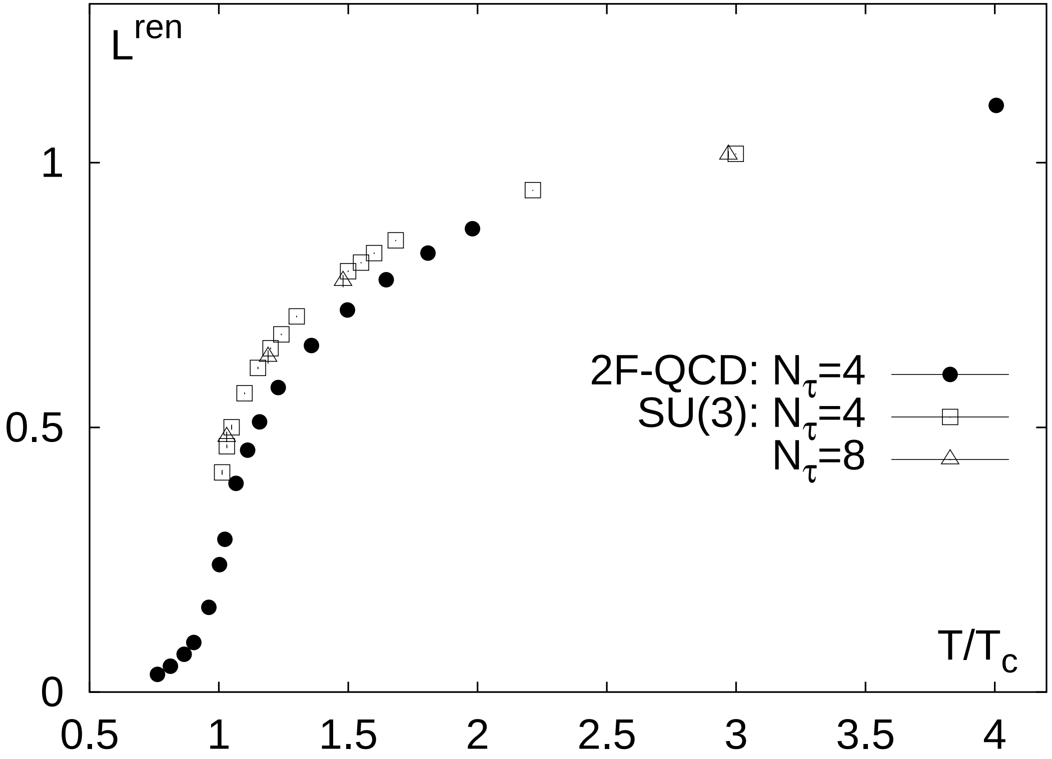

Quenched QCD:

$L_{ren} = 0$ for $T < T_c$.

Finite gap at T_c

Full QCD:

L_{ren} finite for all T.

Strong increase near T_c.

Renormalized Polyakov loop

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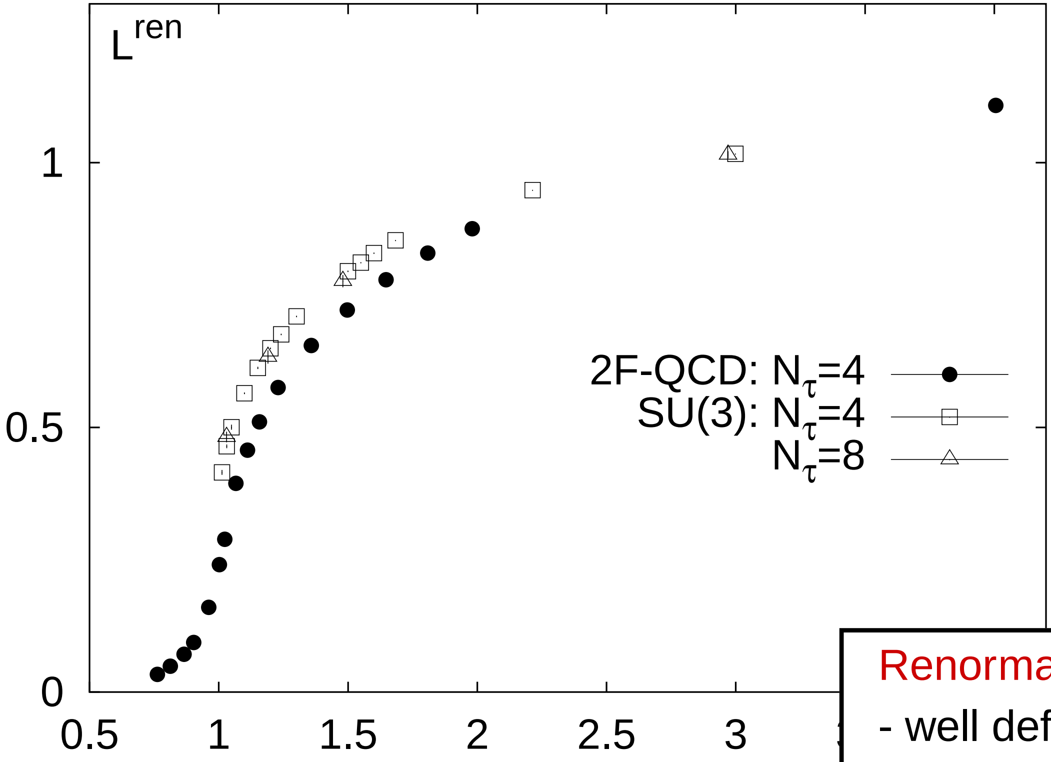

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Full QCD:

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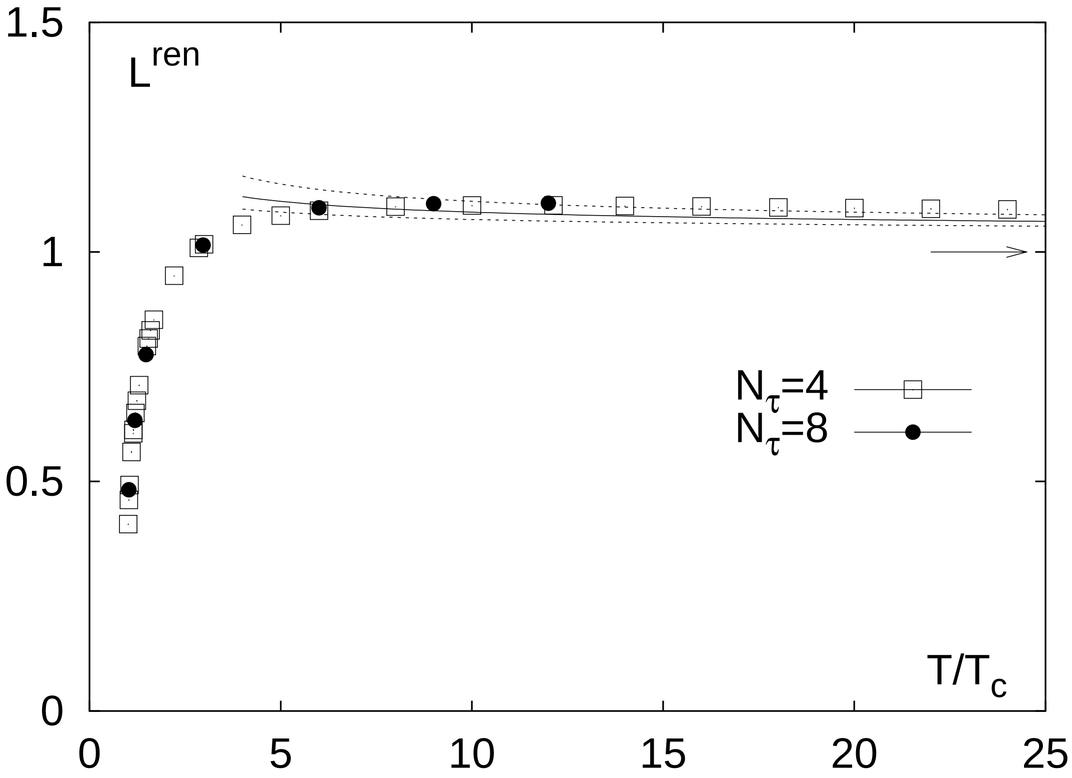
Strong increase near T_c.

Renormalized Polyakov loop

- well defined in quenched and full QCD
- non-zero for finite quark mass
- strong increase near T_c

Renormalized Polyakov loop

$$L_{ren} = \exp\left(-\frac{F(r=\infty, T)}{2T}\right)$$



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$L_{ren} = 0$ for $T < T_c$.

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Full QCD:

L_{ren} finite for all T.

Strong increase near T_c.

Conclusions

Heavy quark free and internal energies

- Complex r and T dependence
- Running coupling shows remnants of confinenement above T_c
- Entropy contributions play a role at finite T
- Separation of entropy and internal energy contributions possible
- Potential energy larger than free energy

Charmonium in the quark gluon plasma

- First estimates from potential models
- Higher dissociation temperature using V_1
- (directly produced) J/ψ exist well above T_c

Outlook

Heavy quark free and internal energies

- Smaller quark masses
- Smaller lattice spacing to analyze small r dependence
- Better understanding of the different contributions

Charmonium in the quark gluon plasma

- What is the correct V_{eff} in potential models
- Full QCD calculations of correlation/spectral functions
- Relevant processes for charmonium production/dissociation ?

Density dependence of heavy quark free energies

$\longrightarrow$ poster by M. Döring

Extension to qq and qqq free energies