Hong-Jo Park, Chang-Hwan Lee & G.E.B.

Role of the Color Coulomb Interaction based on the Bielefeld LGS by

O. Kaczmarek, F. Karsch, P. Petreczky and F. Zantow (who are not responsible for our *model-dependent* arguments).

(KKPZ)

1. Lattice calculations have shown that m_q, $\bar{m}_q$ (thermal masses) > 1 GeV above T_c ∴ quarks (and gluons) are *not* the thermodynamical variables.

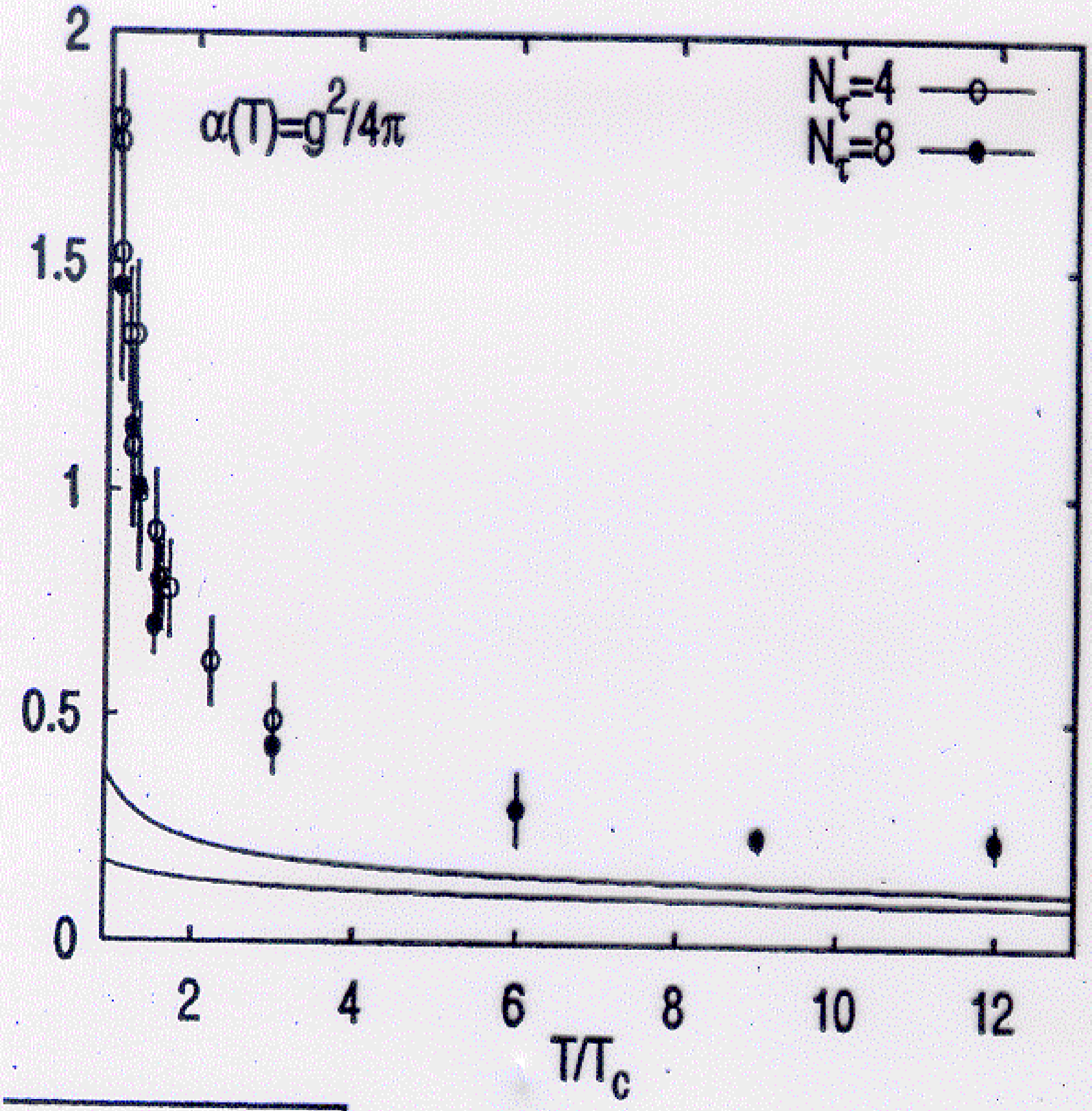
2. Assume baryon free.* (LGS are) Then m_π & m_σ should go through T_c from below to above with zero (in the chiral limit) mass.

3. Mesons: π, σ, ρ, A_1 (32 d.o.f.) are the thermodynamic variables $T \gtrsim T_c$.

4. Equilibration is down to $T = T_c + \epsilon$ at which point mesons are set loose.

Earlier papers: Brown, Lee, Rho, Shuryak (hep-ph/0312175); Brown, Lee, Rho (hep-ph/0405114) both to be publ.

Large distance behavior of $\alpha(T)$ from the Polyakov lines.



F. Zantow (private communication)
Bielefeld thesis
Quenched Calculations $T_c \sim 260$ MeV

$\Lambda_{\chi sb} \to 0$ at T_c; if massless mesons are the true variables, then move back far to the Infra red.

Static quark-anti-quark free energy and the running coupling at finite temperature

O. Kaczmarek, F. Karsch & F. Zantow
& P. Petreczky

hep-lat/0406036

Results are pure gauge SU(3), but similar studies in full 2-flavor QCD already exist & differ (only) by rescaling; i.e. $(T_c)_{\text{quenched}} \to (T_c)_{\text{full QCD}}$.

"Our analysis of the running coupling shows that up to a certain distance scale confining features* of the heavy quark potential indeed survive in the plasma phase..."

*e.g. string tension.

Our Coulomb bound states at T_c have rms radius 0.12 fm & are

Once the nucleons clear out in collisions at central rapidity, have essentially a 2nd order phase transition, so

$$m_\pi = m_\sigma = 0 \quad \text{(chiral limit)}$$

as T goes <u>through</u> T_c. (Anyway LGS are baryon free.)

But $T \gtrsim T_c$, $m_q = m_{\bar q} \sim 1$ GeV, so color singlet (Coulomb) interactions must give ~ 2 GeV binding energy. (m_q, $m_{\bar q}$ are thermal masses – 4th components of 4-vectors; so is the Coulomb int.)

LGS (Bielefeld Grp) gives us the heavy quark (as in charmonium) Coulomb potential

$$-\alpha_s / r$$

where α_s scales with r, since gauge theory.

Add light quark effects:

Total: $V = -\frac{\alpha_s}{r}\left(1 - \underset{\sim}{\alpha}_1 \cdot \underset{\sim}{\alpha}_2\right)$

G.E.B. 1952 tested for K-electrons in heavy atoms

mesons, quarks massless at T_c.

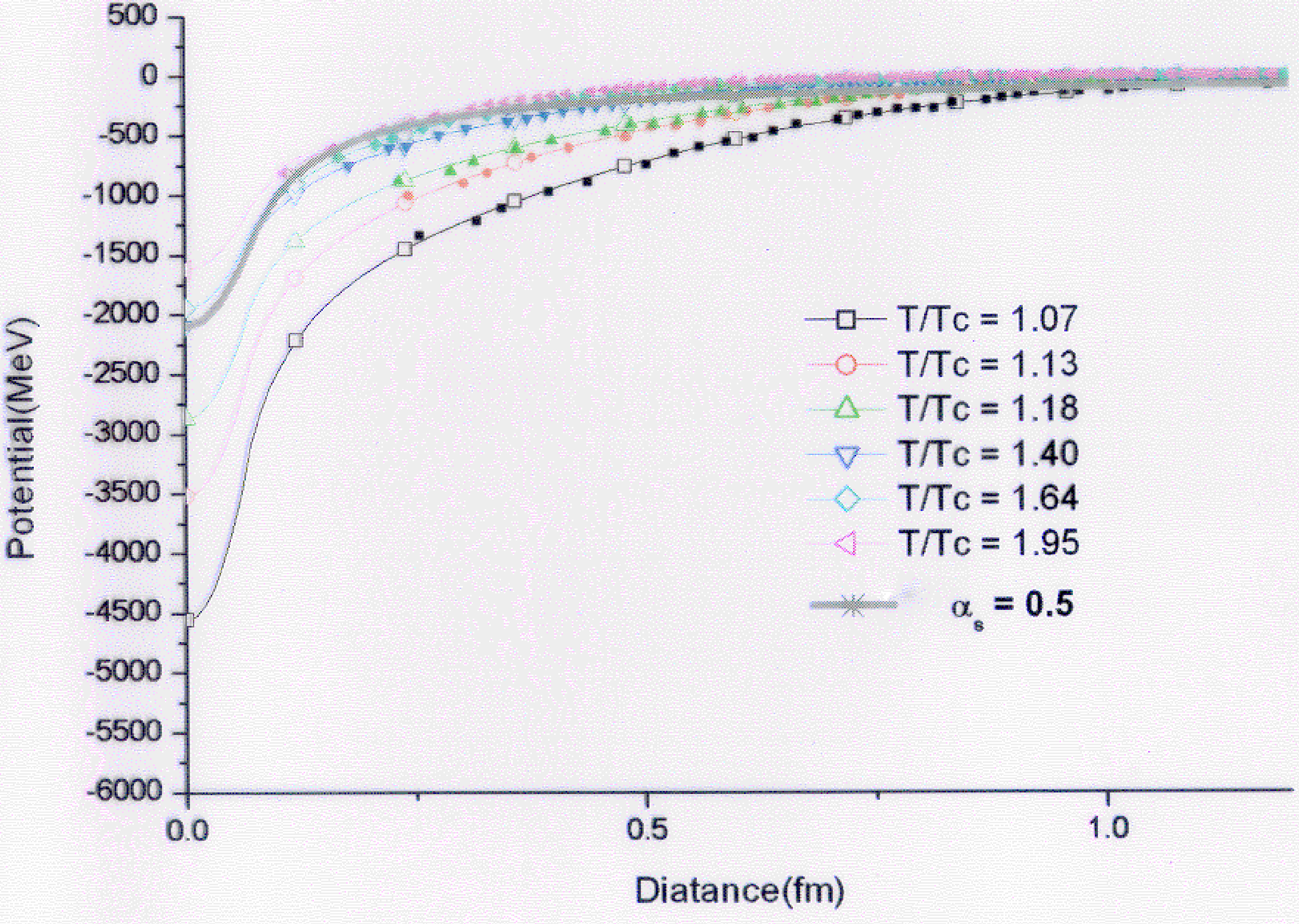
Local Summary

At T_c the magnetic (Ampére's law) interaction doubles the Coulomb interaction if the quark and antiquark rotate in opposite directions,

and if they rotate in the same direction it kills the Coulomb interaction off! leaving the excitations at high energy of $2m_q$.

32 degrees of freedom are tightly bound states

the other 32 d.o.f. remain at energy $2m_q$ & are irrelevant at T_c.


Potential(MeV)
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
-5500
-6000
0.0
0.5
1.0
Diatance(fm)
T/Tc = 1.07
T/Tc = 1.13
T/Tc = 1.18
T/Tc = 1.40
T/Tc = 1.64
T/Tc = 1.95
α_s = 0.5

With double (for the magnetic interaction) the heavy quark Bielefeld LGS potential we obtain for
$m_q = 1$ GeV (uncertain).

T/T_c	Binding Energy
1.18	1.12 GeV
1.13	1.33 GeV
1.07	1.55 GeV
1.00	1.8 GeV extrapolated.

extrapolated to ~ 1.8 GeV at $T = T_c$. (an additional ~ 0.1 GeV from instanton molecule interaction).

So the Coulomb + magnetic binding energies compensate the $2m_q$!

$$\langle r^2 \rangle^{1/2} = 0.12 \text{ fm}.$$

(too small for the instanton effects to be important)

No isospin dependence above T_c and spin-dependence was shown by BLRS to be negligible above T_c.

So π, σ, ρ, A_1 all have zero

Quark Masses and Meson Binding

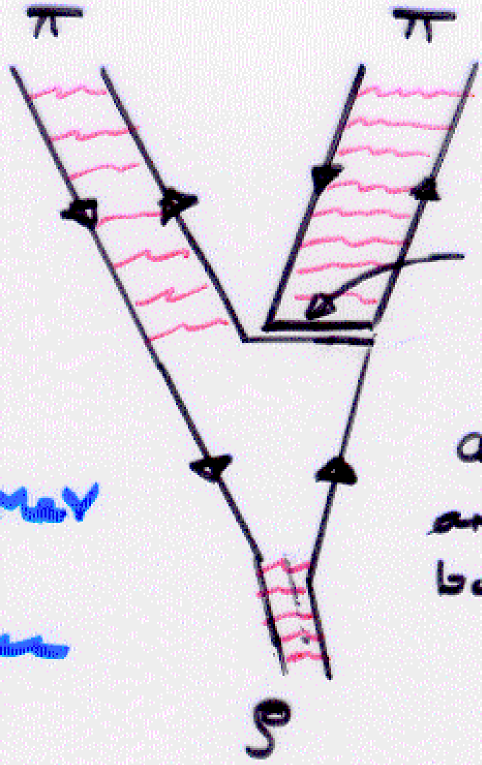
all in GeV

near T_c

T/T_c	$m_q = 1.0$		$m_q = 1.8$
	LGS	LGS + V.V	
1.07	0.77	1.55	0.96
1.13	0.56	1.33	0.61
1.18	0.37	1.18	0.41
1.40	0.12		0.15

Instanton molecule interaction gives a small contribution ~ 0.1 GeV at T_c, but ~ 0.6 GeV at $1.4\,T_c$.

So the masses of the π, σ, ρ, A_1 are brought to zero at T_c. In the chirally restored region above T_c, good chirality: therefore σ & π, ρ and A_1 equivalent.



All mesons are Coulomb bound states.

So the only interspecies interaction is $\rho \to 2\pi$.

BLR: $\Gamma_\rho \sim 380$ MeV

Equilibration comes from $\rho \to 2\pi \to \rho$ every 0.5 fm/c.

There will be lots of ρ's with "masses" 0 - 380 MeV, so lots of dileptons. But they will come at this energy interval where the "cocktail" (background) has its peak.

8 [redacted]

We see the vibrations in LGS.

also Wetzorke et al. (Bielefeld).

As shown in Sec.2, this is necessary for reliable MEM analysis.

In Fig. 4, we show the results at $N_\tau = 40$, i.e., $T \simeq 1.9T_c$. There is an apparent
around $\omega = 0$. A possible explanation of the peak is the effect of Landau dampi
However, this peak is, at the moment, not statistically significant yet. The peaks a
$\omega \simeq 4.5$ GeV are significantly broader than those around 2 GeV at $T \simeq 1.9T_c$.

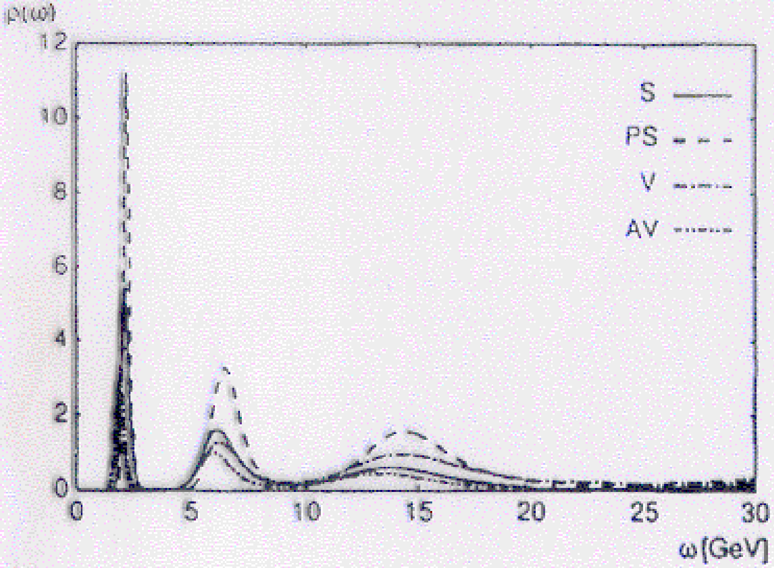


Figure 3. Spectral Functions for $N_\tau = 54$ $(T \simeq 1.4T_c)$

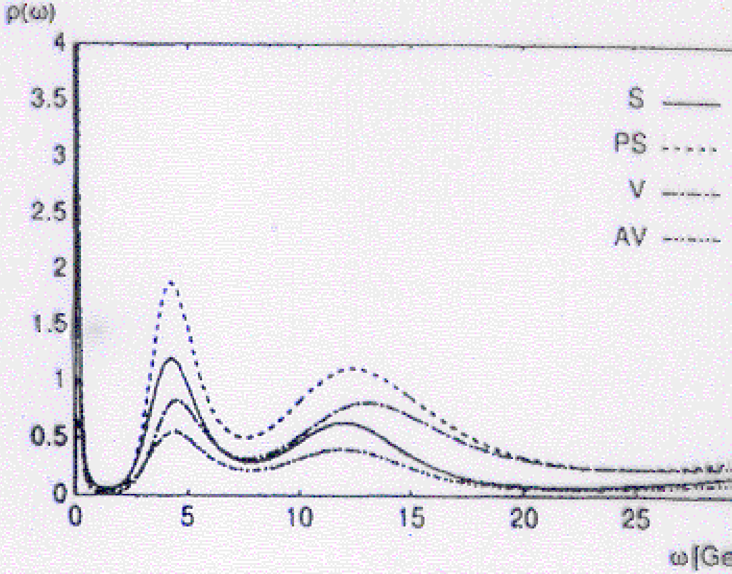


Figure 4. Spectral Functions for N_τ $(T \simeq 1.9T_c)$

KKPZ: In the entire regime of distances for which at zero temperature the heavy quark potential is considered to be described well by QCD perturbation theory, ($r \lesssim 0.1$ fm) the QCD coupling remains unaffected by temperature effects up to $T \simeq 3T_c$.

For the purpose of defining a running coupling at finite temperature the singlet free energy is most appropriate

$$F_1(r, T) = \begin{cases} -\dfrac{g^2(r)}{3\pi r} & rT_c << 1. \\ -\dfrac{g^2(T)}{3\pi r}\, e^{-g(T)\, rT} \,* & rT >> 1,\ T >> T_c \end{cases}$$

(~ one gluon exchange)

"even at high temperature the short distance part of the color averaged free energy is dominated by the singlet contribution and $F(r, T) \sim F_1(r, t)$ holds at short distances."

* Distances so small that no

Summary

1. Quark masses m_q and gluon masses m_g are large ~ 1 GeV above T_c. So quarks and gluons are not the thermodynamic variables.

2. The color Coulomb interaction, largely by left over (from the vacuum) confinement (string tension) dynamically confines these quarks at T_c into mesons: π, σ, ρ, A_1 with mass zero in the chiral limit.

3. This gives 32 degrees of freedom at T_c, massless in the chiral limit.

4. Equilibration is achieved by $\rho \to 2\pi \longrightarrow \rho$ above T_c with ρ-width $\Gamma_\rho \sim 380$ MeV. Affects ρ^0/π^- ratio.

5. Going up to T_c from below, the Harada & Yamawaki RG has $m_\rho^* \longrightarrow 0$ as $T \to T_c$, as in B/R scaling. So the meson masses are continuous across T_c, as dictated by chiral invariance for the π & σ.