Study of thermal monopoles in lattice QCD

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Motivation:
To study in SU(3) gluodynamics and QCD
– thermal monopole properties and their role in the quark-gluon plasma
– magnetic currents properties near the confinement-deconfinement transition

Dual superconductor - one of the most popular ideas about nature of confinement
t' Hooft '75, Mandelstam '76
Confinement in QCD is due to condensation of color-magnetic monopoles
Respective effective theory - dual Abelian Higgs model (dual superconductor)

Problem: how to determine monopoles in QCD
t' Hooft '81:
Partial gauge fixing
$SU(N) \to U(1)^{N-1}$

Very successful application of the MA gauge to define monopoles on a lattice

$$\sum_{c\neq 3,8}\left(\partial_\mu\delta_{ac}+\sum_{b=3,8} f_{abc}A_\mu^b(x)\right)A_\mu^c(x)=0\,,\quad a\neq 3,8$$

extremums (over g) of the functional $F_{\mathrm{MAG}}[A^g]$

$$F_{\mathrm{MAG}}[A]=\frac{1}{V}\int d^4x\sum_{a\neq 3,8}[A_\mu^a(x)]^2$$

Abelian projection:
$A_\mu^a(x)T^a\rightarrow A_\mu^3(x)T^3+A_\mu^8(x)T^8$

on lattice
$F(U)=\frac{1}{V}\sum_{x,\mu}\left(|U_\mu(x)^{11}|+|U_\mu(x)^{22}|+|U_\mu(x)^{33}|\right)$,
$U_\mu(x)\rightarrow u_\mu(x)\in U(1)^2$

Magnetic currents definition:

$$j_\mu^{(a)} \equiv \frac{1}{4\pi}\epsilon_{\mu\nu\rho\sigma}\partial_\nu \overline{\Theta}_{\rho\sigma}^{(a)} = -\frac{1}{2}\epsilon_{\mu\nu\rho\sigma}\partial_\nu m_{\rho\sigma}^{(a)}\,, a = 1,2,3$$

satisfy the constraint

$$\sum_a j_\mu^{(a)}(x) = 0\,,$$

on any link $\{x,\mu\}$ of the dual lattice
Magnetic currents form closed loops

Simulations details:

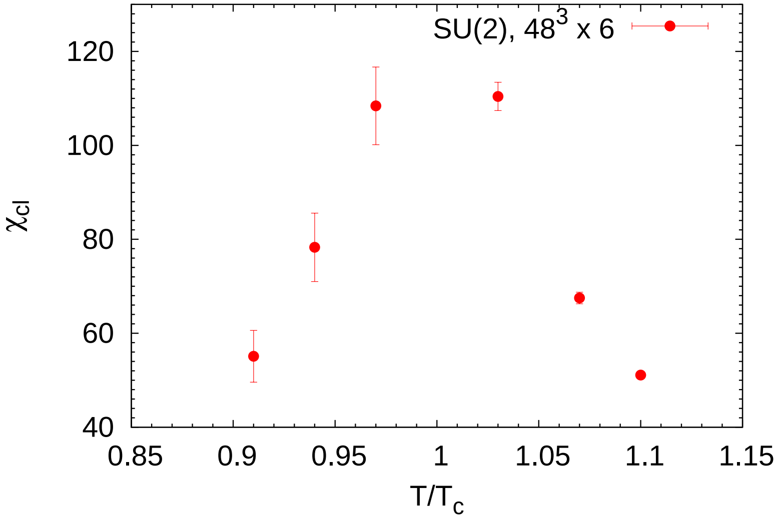
SU(3) gluodynamics, standard Wilson action, mostly 32^3x6 lattices

$N_f = 2$ lattice QCD at $T > 0$, configurations produced by DIK collaboration, 2009

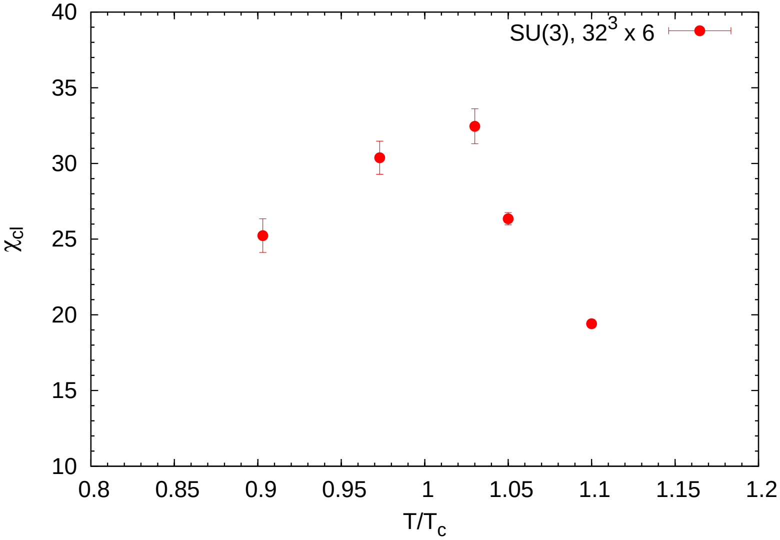
- Wilson action for the gauge field
- the non-perturbatively $O(a)$ improved Wilson fermionic action S_F:

$$S_F = S_F^{(0)} - \frac{\mathrm{i}}{2}\kappa\, g\, c_{sw} a^5 \sum_s \bar{\psi}(s)\sigma_{\mu\nu}F_{\mu\nu}(s)\psi(s)$$

- Lattice size $12 \times (32)^3$
- Crossover at $T_c = 200$ MeV, $m_\pi = 400$MeV
- Variation of temperature by variation of L_t



Nonpercolating monopole cluster average size - 'susceptibility' χ_{cl}


40
35
30
25
20
15
10
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2
χ_{cl}
T/T_c
SU(3), 32^3 x 6

Same for SU(3)

There are proposals suggesting that the color-magnetic monopoles contribution can explain strong coupling property of QGP near transition

Chernodub and Zakharov 2006, Liao and Shuryak 2006,

<u>Chernodub and Zakharov:</u>
Thermal monopoles are related to clusters of magnetic currents wrapped in T dimension

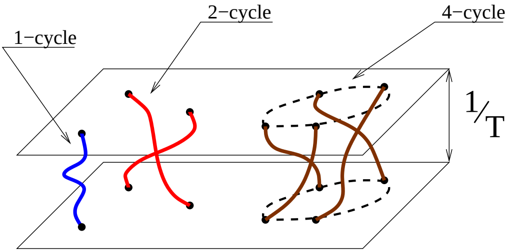


Figure from D'Alessandro, D'Elia and Shuryak, 2010

Wrapping number for given cluster:

$$N_{wr}^{a} = \frac{1}{3L_t} \sum_{j_4^a(x) \in cluster} j_4^a(x)$$

$$\rho = \frac{\langle \sum_{clusters,a} |N_{wr}^{a}| \rangle}{3L_s^3 a^3}$$

First lattice study in SU(2) by VB, Mitrjushkin, Muller-Preussker , 1992

Comprehensive lattice study in SU(2) by D'Alessandro and D'Elia 2007

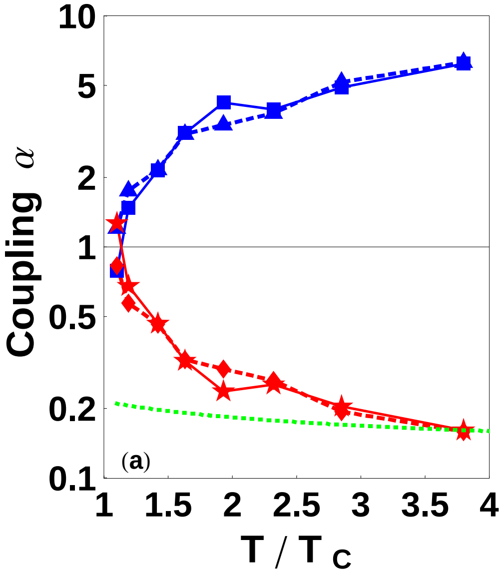
Subsequent work, also in SU(2): VB, Braguta, 2011; VB, Kononenko, 2012

First resilts for SU(3) and QCD: VB, Kononenko, Mitryushkin, presented at Confinement X, 2012

Liao and Shuryak

Magnetic scenario:
– magnetic monopoles are weakly interacting ($\alpha_M \sim 1/\alpha_E$) near T_c and are dominating fluctuations
– strongly influence QGP property, in particular reduce its viscosity

Alternative approach to study of monopoles: Classical molecular dynamics simulations for system with mixture of magnetic and electric charges
– Remarkably, good qualitative agreement with lattice results for density-density correlation functions
– Magnetic coupling α_M was computed from (lattice) correlation functions
– α_M increases with temperature

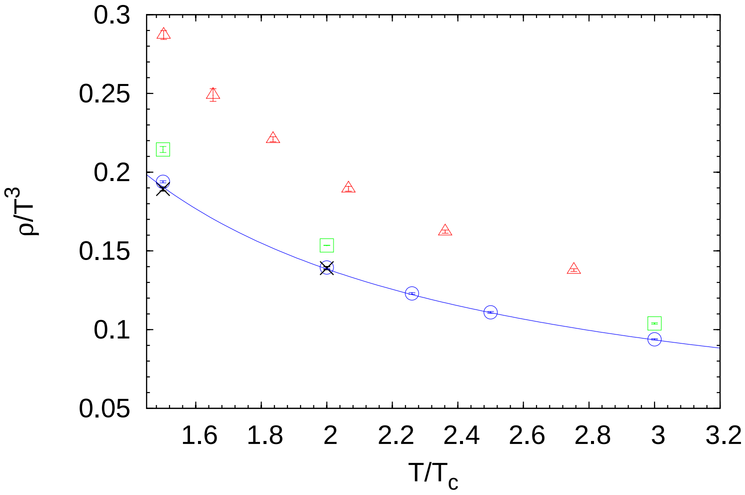


α_M (blue symbols) extracted by Shuryak and Liao from lattice data obtained by D'Alessandro and D'Elia

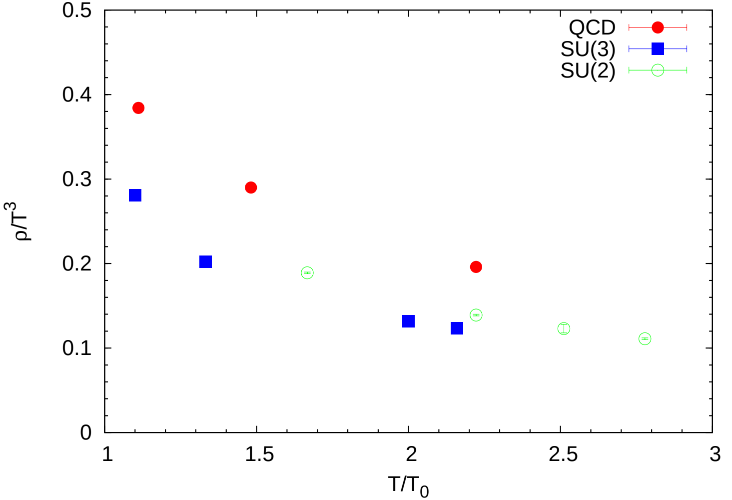
Coulomb plasma parameter

$$\Gamma = \alpha_m \left(\frac{4\pi\rho}{3T^3} \right)^{1/3}$$

– $\Gamma > 1$, i.e. strongly coupled plasma
– Γ increases up to about 5 with increasing temperature



Total thermal monopoles density in *SU*2



Total thermal monopoles density ρ vs T/T_0

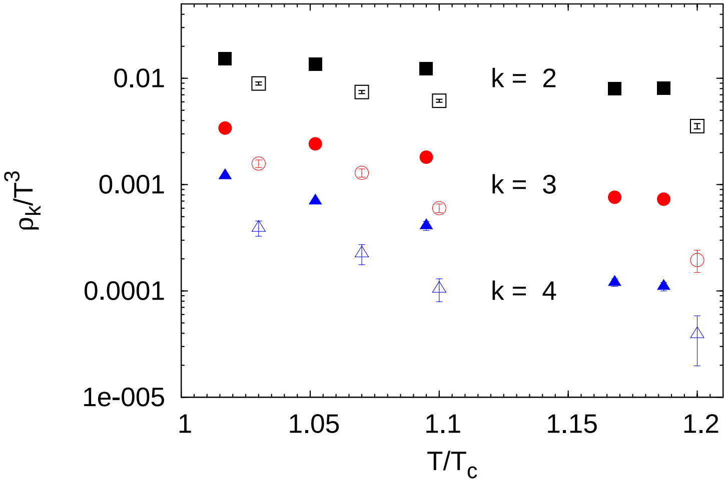
Bose-Einstein condensation of the thermal monopoles

First study in SU(2) theory by D'Alessandro, D'Elia and Shuryak, 2010

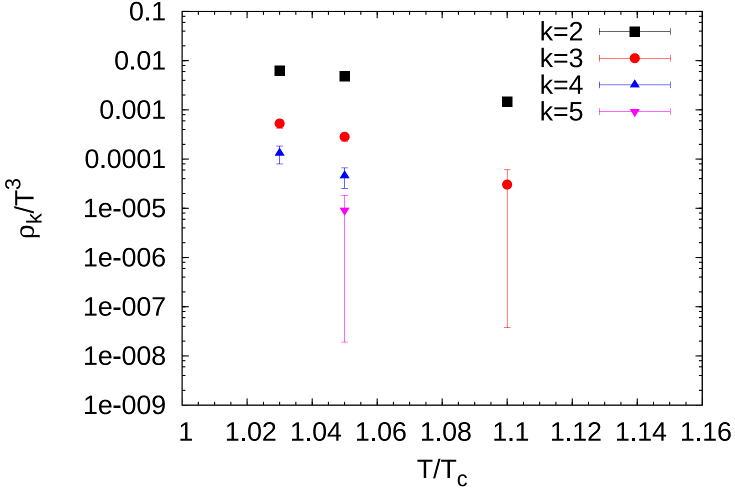
a trajectory wrapping k times in a time direction represents a set of k monopoles permutated cyclically
for non-relativistic noninteracting bosons

$$\rho_k = \frac{e^{-\hat{\mu} k}}{\lambda^3 k^{5/2}} \tag{1}$$

$\hat{\mu} \equiv -\mu/T$ is a chemical potential
λ is the De Broglie thermal wavelength
the condensation temperature T_{BEC} is determined by the vanishing of the chemical potential
$T_{BEC} \approx T_c$ D'Alessandro, D'Elia and Shuryak, 2010
confirmed in VB, Kononeko, 2012



Thermal monopoles density ρ_k vs T/T_c for $SU(2)$



Thermal monopoles density ρ_k vs T/T_c for $SU(3)$

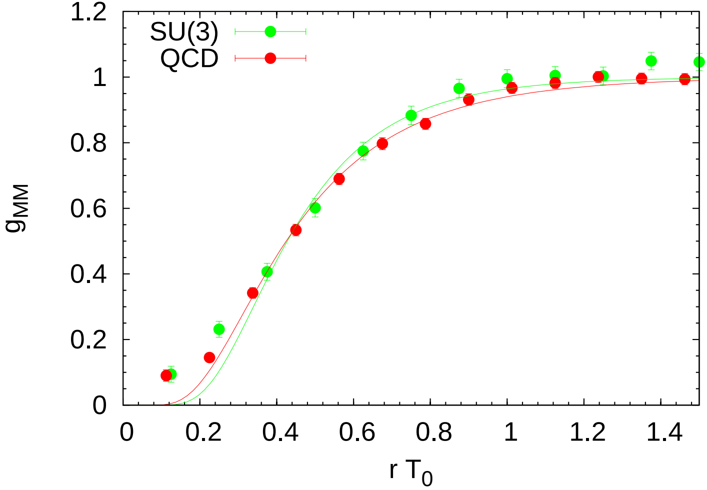
Thermal monopole interactions

$$g_{MM}(r) = \frac{\langle \rho_M^a(0)\rho_M^a(r)\rangle}{2\rho_M^b\rho_M^b} + \frac{\langle \rho_A^a(0)\rho_A^a(r)\rangle}{2\rho_A^b\rho_A^b}$$

$$g_{AM}(r) = \frac{\langle \rho_A^a(0)\rho_M^a(r)\rangle}{2\rho_A^b\rho_M^b} + \frac{\langle \rho_M^a(0)\rho_A^a(r)\rangle}{2\rho_A^b\rho_M^b}$$

$$g_{MM,AM}(r) = e^{-U(r)/T}$$

$$U(r) = \frac{\alpha_m}{r} e^{-m_D r}$$



Thermal monopoles correlation functions for $T/T_c = 2$

Table of results for $T/T_c = 2$

	α_M	m_D/T	Γ
$SU(2)$	2.61(15)	1.75(12)	1.95(16)
$SU(3)$	2.8(6)	1.8(2)	2.2(4)
QCD	1.4(2)	1.8(1)	1.4(2)

Conclusions

We present new evidence on the percolation transition at T_c in $SU(3)$ gluodynamics

Our numerical results indicate

– Density of thermal monopoles in $SU(3)$ gluodynamics is similar to that in $SU(2)$ gluodynamics

– In QCD it is substantially higher

– qualitative confirmation of the Bose-Einstein condensation in $SU(3)$ gluodynamics

– Magnetic coupling α_m and screening mass m_D/T in $SU(3)$ are close to those in $SU(2)$

– α_m in QCD is lower by factor 2, m_D/T is somewhat lower