Color-magnetic monopoles in finite temperature lattice QCD

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Lattice QCD, Hadron Structure and Hadronic Matter
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Outline of Lecture 1:

- Motivation
- Dirac monopole
- Monopoles in compact $U(1)$ gauge theory
- Monopoles in nonabelian gauge theory (t'Hooft-Polyakov monopole)
- Dual superconductor scenario of confinement
- Abelian projection, gauge fixing
- Why Maximally Abelian gauge ?
- Some lattice results at $T = 0$
- Percolation and condensation
- IR density scaling
- Abelian dominance and monopole dominance

Outline of Lecture 2:

- Lattice results at $0 < T < T_c$
- Percolation transition
- Thermal monopoles (ThM)
- MD results of Shuryak and Liao
- Lattice results for density
- ThM interactions
- ThM B-E condensation
- Other indications of the phase transition

Computer simulations of the nonabelian gauge theories in lattice regularization is one of the most powerful nonperturbative methods which does not use uncontrolled approximations

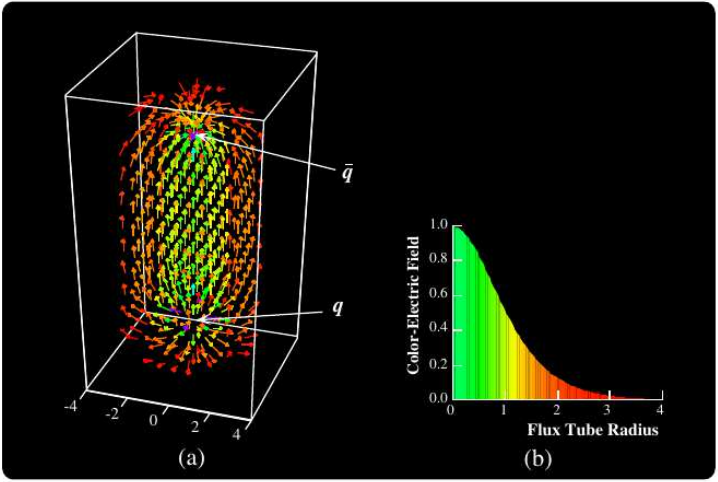
Apart from getting numerically precise results for hadronic observables the sumulations are aimed at getting information which helps us to understand the nature of the nonperturbative phenomena like confinement of quarks and chiral symmetry breaking

Dual superconductor - one of the most popular ideas about nature of confinement t' Hooft '75, Mandelstam '76

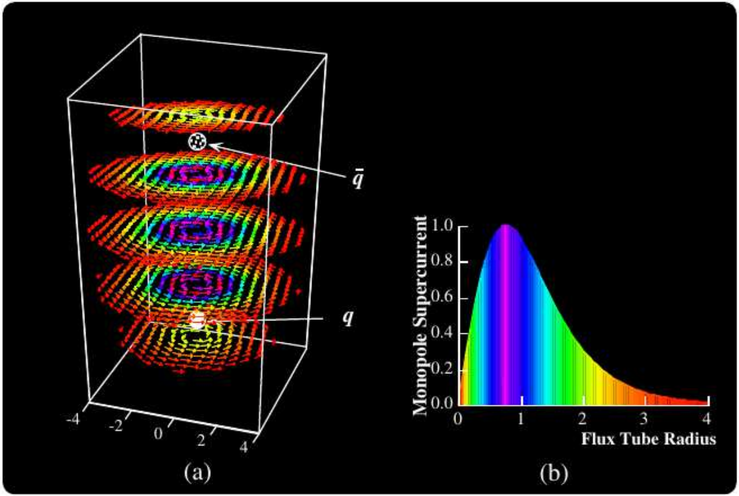
A dual superconductor is a superconductor in which the roles of the electric and magnetic fields are exchanged.

Formation of the Abrikosov string in a usual superconductor due to condensation of electric charges is dual to formation of the flux tube in QCD due to condensation of color-magnetic monopoles

Superconductor is described by Landau - Ginzburg model (Abelian Higgs model)
Dual superconductor - by dual Landau - Ginzburg model (dual Abelian Higgs model)
It is yet unsolved task to rigorously prove that infrared QCD is dual to Abelian Higgs model
But there are many lattice results supporting this conjecture



The profile of the color-electric field



The profile of the monopole currents

In heavy ion collisions experiments at RHIC and LHC signatures of the strong interactions in the quark-gluon matter were found. In particular very small viscosity to entropy ratio.
There are proposals suggesting that color-magnetic monopoles contribution can explain this rather unexpected property.
These proposals inspired an interest to studies of the properties and possible roles of these monopoles in the quark-gluon phase

Lattice simulations demonstrated that

- in the confinement phase color-magnetic monopoles are condensed
- monopoles are not condensed in the deconfinement phase and the temperature of their condensation coincides with confinement-deconfinement phase transition temperature
- Abelian and monopole dominance for the string tension and other IR relevant quantities
- monopoles are interrelated with instantons/calorons
-

At present, we have no analytic proof of the existence of the condensate of abelian magnetic monopoles in gluodynamics and in chromodynamics.
However, in all theories allowing for an analytical proof of confinement, the latter is due to the condensation of monopoles.
These analytical examples are: compact electrodynamics (Polyakov '75) , the 3D Georgi–Glashow model (Polyakov '77), and super-symmetric Yang–Mills theory (Seiberg and Witten '94).

$$\vec{A}(\vec{x}) = \frac{g_m}{4\pi}\frac{sin\theta}{r(1+cos\theta)}\vec{e}_\phi\,, \qquad \vec{e}_\phi = (-sin\phi, cos\phi, 0),$$

$$\vec{H}(\vec{x}) = \vec{\partial}\times\vec{A}(\vec{x}) + \vec{H}_{st}(\vec{x}) = \frac{g_m}{4\pi r^2}\frac{\vec{r}}{r}\,,$$

$$\vec{H}_{st}(\vec{x}) = g_m\vec{e}_z\int_{-\infty}^{0} dz'\delta\left(\vec{x}-\vec{R}(z')\right)\,, \qquad \vec{R}(z') = \{0,0,z'\}\,.$$

In general case

$$F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x) + F_{\mu\nu,st}(x)$$

To make Dirac string unoservable - Dirac quantization condition should be satisfied:

$$eg_m = 2n\pi \, .$$

Dirac monopole has divergent energy :

$$\epsilon_{mon} \sim \int d^3x \, \mathbf{H}^2 \sim \frac{1}{e^2 a}$$

Lattice definitions

$$U_\mu(s) = exp(i\theta_\mu(s)), \quad \theta_\mu(s) \in [-\pi, \pi)$$

$$\theta_{\mu\nu}(s) = \partial_\mu\theta_\nu(s) - \partial_\nu\theta_\mu(s)$$

($\partial_\nu f(s) = f(s+\hat{\nu}) - f(s)$ - lattice forward derivative
$\partial_\nu^- f(s) = f(s) - f(s+\hat{\nu})$ - lattice backward derivative)

$$\overline{\theta}_{\mu\nu}(s) = \theta_{\mu\nu}(s) + 2\pi m_{\mu\nu}(s),$$

$$-\pi \leq \overline{\theta}_{\mu\nu}(s) < \pi, \quad m_{\mu\nu} = 0, \pm 1, \pm 2$$

$\overline{\theta}_{\mu\nu}(s)$ is gauge invariant electromagnetic flux
$2\pi m_{\mu\nu}(s)$ counts number of Dirac strings through plaquette $(s, \mu\nu)$

Partition function

$$\mathcal{Z} = \int_{-\pi}^{+\pi} \mathcal{D}\theta_l \; \text{exp}\{-S(\text{d}\theta)\}$$

$\int_{-\pi}^{+\pi} \mathcal{D}\theta_l = \prod_l \int_{-\pi}^{+\pi} \text{d}\theta_l$ is the integral over all link variables

Wilson lattice action:

$$S(\text{d}\theta) = \beta \sum_{s,\mu,nu} (1 - cos(\theta_{\mu\nu}))$$

Villain form

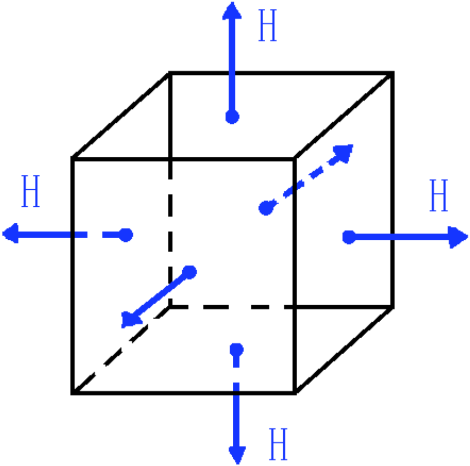
$$\mathcal{Z}^{Villain} = \int_{-\pi}^{+\pi} \mathcal{D}\theta \sum_{m(C_2)\in \mathbb{Z}} \text{exp}\left\{-||\text{d}\theta + 2\pi m||^2\right\}$$

Using duality transformation, the theory (in the Villain form) can be rewritten in the form of the (limiting case of) dual Abelian Higgs model in the Higgs phase

$$\mathcal{Z} = \mathrm{const.} \cdot \lim_{\gamma\to\infty} \lim_{\lambda\to\infty} \int\limits_{-\infty}^{+\infty} \mathcal{D}^*B \int \mathcal{D}^*\Phi \, \exp\{-S^{AH}(^*B, {}^*\Phi)\}$$

$$S^{AH}(^*B, {}^*\Phi) = \sum_P S^d(\mathrm{d}^*B) + \frac{1}{2}\sum_x \sum_{\mu=1}^{4} \left|{}^*\Phi_x - e^{i^*B_{x,\mu}}\, {}^*\Phi_{x+\hat{\mu}}\right|^2$$

$$+\lambda \sum (|{}^*\Phi_x|^2 - \gamma)^2$$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$$k_\mu(s^*) = \frac{1}{4\pi}\varepsilon_{\mu\nu\rho\sigma}\partial_\nu\overline{\theta}_{\rho\sigma}(s)$$

s^* - site on the dual lattice
sites of the dual lattice are defined by the shift $\rho = \{1/2, 1/2, 1/2, 1/2\}$

$$\sum_\mu \partial_\mu k_\mu(s^*) = 0\,.$$

$$k'_\mu(s^*) = k_\mu(s^* + \hat{\mu})\,,$$

$$\sum_\mu \partial^-_\mu k'_\mu(s^*) = 0\,,$$

i.e. magnetic currents form closed loops, loops are combined into clusters.

$$\mathcal{L} = \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \frac{1}{2} (D_\mu \phi)^a (D_\mu \phi)^a + \frac{\lambda}{4} (\phi^a \phi^a - \mu^2)^2$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + e\epsilon^{abc} A^b_\mu A^c_\nu$$

$\phi^a(x)$ - adjoint scalar field

$$(D_\mu \phi)^a = \partial_\mu \phi^a + e\epsilon^{abc} A^b_\mu \phi^c$$

monopole solution (radial gauge):

$$eA^a_k(\vec{x}) = \epsilon_{akl} \frac{\hat{x}_l}{r} (1 - F(r)) \,, \quad A^a_0 = 0$$

$$\phi^a(\vec{x}) = \hat{x}^a \mu (1 - H(r))$$

$$E_M = \frac{4\pi m_W}{e^2} C\left(\frac{m_H^2}{m_W^2}\right)$$

$C(m_H^2/m_W^2)$ - smoothly increasing function, $m_W = e\mu$, $m_H = \sqrt{2\lambda}\mu$
In the BPS limit $\lambda = 0$

$$F(r) = \frac{e\mu r}{sinh\, e\mu r}$$

$$1 - H(r) = cth\, e\mu r - \frac{1}{e\mu r}$$

$$E_M = \frac{4\pi m_W}{e^2}$$

non trivial homotopy π_2: a non trivial mapping of the sphere S^2 at spatial infinity onto $SU(2)/U(1)$

Global SU(2) is broken down to U(1) which direction is determined by scalar field direction at infinity.
U(1) gauge invariant Abelian $F_{\mu\nu}$

$$F_{\mu\nu} = \hat{\phi}^a F^a_{\mu\nu} - \frac{1}{e}\epsilon^{abc}\hat{\phi}^a D_\mu \hat{\phi}^b D_\nu \hat{\phi}^c$$

Magnetic field

$$eH_i = \frac{1}{r^2}\hat{x}_i + O(e^{-m_W r})$$

Then magnetic charge

$$g_m = \frac{4\pi}{e}$$

In the unitary gauge $\phi^1 = \phi^2 = 0$

$$e\vec{A}^3(\vec{x}) = -\frac{sin\theta}{r(1+cos\theta)}\vec{e}_\phi$$

i.e. form of Dirac monopole with charge $g_m = \frac{4\pi}{e}$

Without scalar field solution also exist.
$A_4^a(x)$ plays role of scalar field
In the unitary gauge

$$g\vec{A}^3(\vec{x}) = -\frac{sin\theta}{r(1+cos\theta)}\vec{e}_\phi$$

$$gA_4^3(\vec{x}) = \frac{H(\mu r) - 1}{r}\,, \quad A_4^1 = A_4^2 = 0$$

$$gA_k^l(\vec{x}) = -\epsilon_{lm3} R_{mk}(\theta,\phi)\frac{1 - F(\mu r)}{r}\,, \quad l = 1,2$$

where $R = e^{-i\phi T_3} e^{i\theta T_2} e^{i\phi T_3}$ is a gauge transformation from the radial to the unitary gauge
This solution satisfies MAG

$$\left(\partial_\mu \delta_{kl} + \epsilon_{k3l} A_\mu^3(x)\right) A_\mu^l(x) = 0\,, \quad k = 1,2$$

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)
According to this scenaro, color confinement is due to the spontaneous breaking of a magnetic simmetry, induced by the condensation of magnetically charged defects (magnetic monopoles), which yields a non-vanishing magnetically charged Higgs condensate.

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

t'Hooft's idea
cb

$$X(x) \to X'(x) = g(x)X(x)g^\dagger(x)\,, \quad X(x) = X_a(x)T_a$$

gauge fixing condition: $g(x)$: $X'(x)$ is diagonal
Gauge freedom is fixed up to $U(1)^{N_c-1}$ which is maximal Abelian subgroup or Cartan subgroup.
Gauge field has Abelian components $a^i_\mu(x) \equiv (\tilde{A}_\mu(x))_{ii}$

$$a^i_\mu(x) \to a^i_\mu(x) + \frac{1}{g}\partial_\mu \alpha_i$$

and off-diagonal components
$c^{ij}_\mu(x) \equiv (\tilde{A}_\mu(x))_{ij}\,, i \neq j$

$$c^{ij}_\mu(x) \to e^{i\left(\alpha_i(x)-\alpha_j(x)\right)} c^{ij}_\mu(x)$$

There is a singularity at points where two or more eigenvalues are equal.
In the vicinity of such singularity gauge field has a form of the t'Hooft - Polyakov monopole, i.e. it has a magnetic charge.

$$A^3_{sing} T_3 = -\frac{1}{g} \vec{e}_\phi \frac{1 + cos\theta}{r sin\theta} T_3$$

$g_m = -\frac{4\pi}{g} T_3$

Examples of $X(x)$: $F_{12}(x); L(x)$
Thus QCD becomes equivalent to theory with color magnetic monopoles, 'photons', and charged matter fields: off-diagonal gluons and quarks.

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

MA gauge condition:

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

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

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

Abelian projection:

$A^a_\mu(x)T^a \to A^3_\mu(x)T^3+A^8_\mu(x)T^8$

MAG is a proper Abelian gauge to find gauge invariant monopoles since tHooft- Polyakov monopoles can be identified in this gauge by the Abelian flux, but this is not possible in other Abelian gauges
Thus monopoles are indeed gauge invariant, but the method used to detect them works only for MAG
Bonati, DElia and Di Giacomo, '13

on lattice

gauge fixing functional:

$$F_{\mathrm{MAG}}[U] = \frac{1}{V} \sum_{x,\mu} \left(|U_\mu(x)^{11}|^2 + |U_\mu(x)^{22}|^2 + |U_\mu(x)^{33}|^2 \right)$$

Abelian projection:

$$U_\mu(x) \to u_\mu(x) \in U(1)^2$$

Abelian dominance hypothesis

Ezawa,Iwazaki '82

Physical observables, related to the infrared properties of the theory, can be computed with the help of the Abelian variables i.e.

$$< \mathcal{O} >= \frac{1}{\mathcal{Z}} \int e^{-S} \mathcal{O}(U_\mu) \mathcal{D} U_\mu(s)$$

and

$$< \mathcal{O} >^{Ab}= \frac{1}{\mathcal{Z}} \int e^{-S} \mathcal{O}(u_\mu) \mathcal{D} U_\mu(s)$$

give approximately equal values of the infrared physical quantities. Example: static potential $V(r) = \alpha / r + \sigma r$. Good approximation for σ but not for α

Nonperturbative gauge fixing

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int DU \, e^{-S(U)} \mathcal{O}(U^{g^*})$$

U^{g^*} solves $f(U) = 0$.

$$Z = \int DA \, e^{-S(A)} \, I^{-1}(A) \int Dg \, e^{-\lambda F(A^g)}$$

$$I(A) = \int Dg \, e^{-\lambda F(A^g)}$$

λ - gauge parameter

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int DA \, e^{-S(A)} \, I^{-1}(A) \int Dg \, e^{-\lambda F(A^g)} \mathcal{O}(A^g)$$

$\lambda \to \infty$

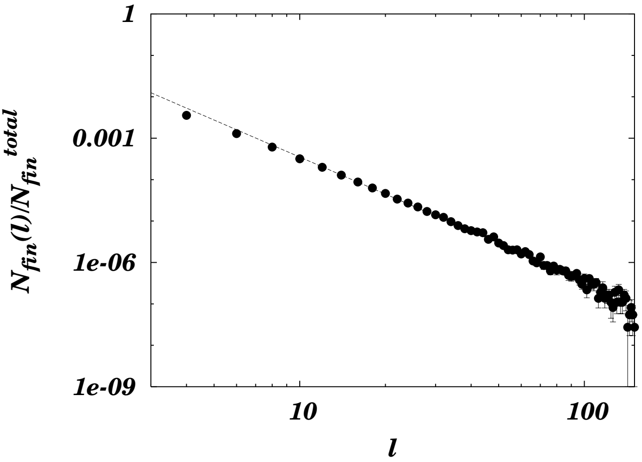
$$\int Dg \to \sum_{\text{global minima}} F(A^g)$$

The trajectories of the Abelian monopoles form three different types of clusters

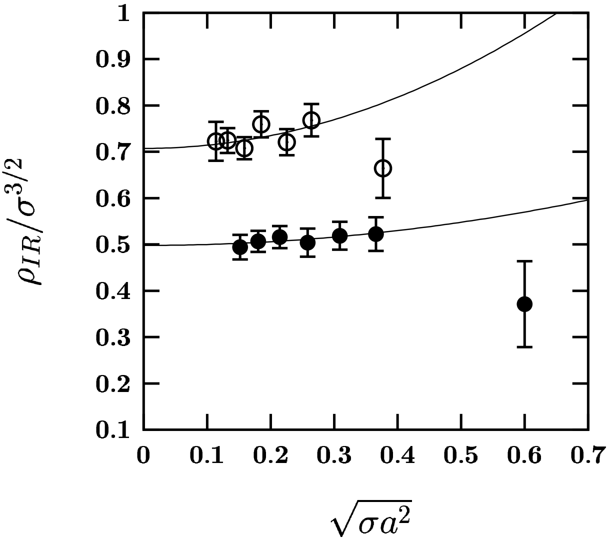
- Large cluster (one per configuration percolating cluster, of infinite size on the infinite lattice)
magnetic currents from this cluster are called IR monopoles

- Finite size clusters with distribution of length $N(L) = C/L^3$
This is in accordance with percolation theory prediction and also was derived within the polymer approach to the field theory of free or Coulomblike interacting scalar particles   Chernodub and Zakharov, ’03

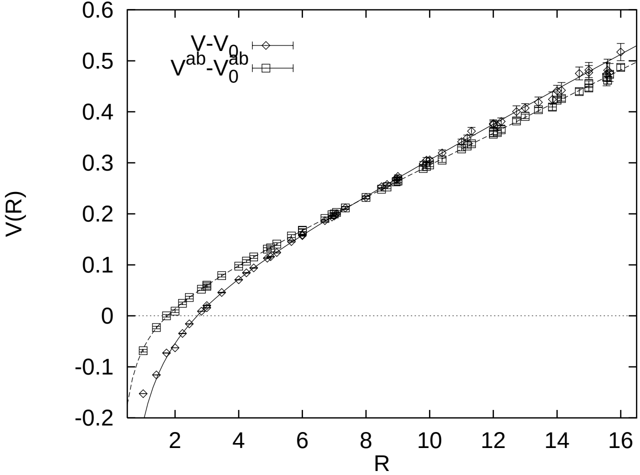
- Small clusters with length $L = O(a)$. These are UV monopoles



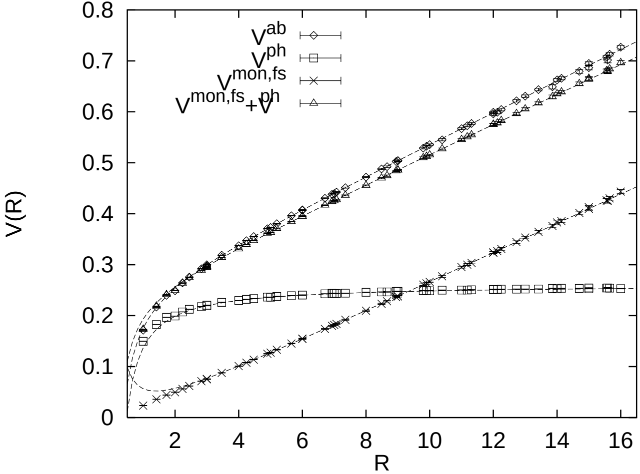
The length distribution of finite clusters. $\beta = 2.4$, lattice 32^4 .
From VB, Boyko, Polikarpov, Zakharov, '03


$\rho_{IR}/\sigma^{3/2}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$\sqrt{\sigma a^2}$

Abelian and monopole dominance in lattice gauge theory



Abelian and nonabelian static potentials. Bali, VB, Mueller-Preussker, Schilling, 1996



Abelian static potential in comparison with 'monopole' and 'photon' static potentials

Results in $SU(2)$:

$$\sigma^{ab}/\sigma = 0.92(4)$$

$$\sigma^{mon}/\sigma^{ab} = 0.95(2)$$

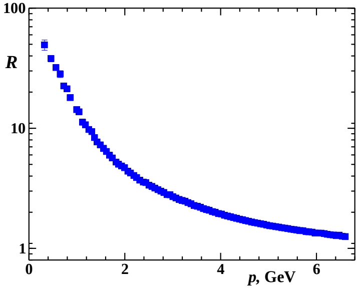
$$\sigma^{ab,2}/\sigma^{ab} = 2.23(5)$$

σ^{ab}/σ was computed in the limit of infinite cutoff

σ^{ab}/σ was computed for improved lattice action and universality of the Abelian dominance had been demonstrated

For the gluon field propagator dominance of the diagonal gluon propagator in IR had been found

$$\frac{D_{diag}(p_{min})}{D_{offdiag}(p_{min})} = 50(5), \quad p_{min} = 325 \text{ GeV}$$



Ratio of diagonal to offdiagonal transverse propagators

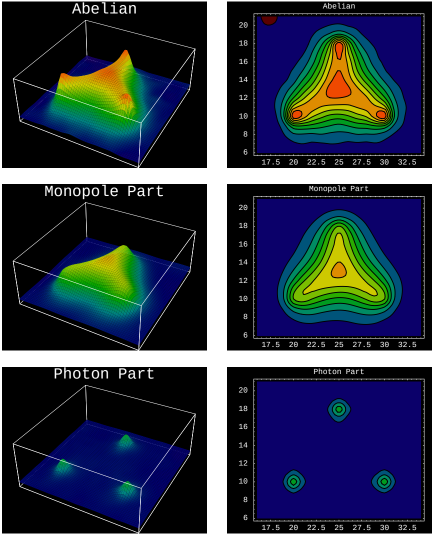
VB, Morozov, Polikarpov, 2002

Properties of superconductors are often described in terms of a penetration depth and a correlation length , which are equal to the inverse vector and Higgs masses.
They were computed on the lattice from the Abelian flux tube properties.

Abelian and monopole dominance in lattice SU(3) gluodynamics and lattice QCD

Generalization of the approach to $SU(3)$ case
DIK (DESY-ITEP-Kanazawa) collaboration, 2001 :
Most careful study of the subject in $SU(3)$ gluodynamics
First study in lattice QCD ($N_f = 2$)
First study of the hadron string internal structure in Abelian projection
Results:

m_π/m_ρ	$\sigma_{\rm ab}/\sigma$	$\sigma_{\rm mon}/\sigma_{\rm ab}$	δ, ??	λ, ??
0.60(1)	0.89(4)	0.80(4)	0.29(1)	0.15
-	0.83(3)	0.84(3)	0.29(1)	0.17



Abelian action density in three-quark system (static baryon) in lattice QCD

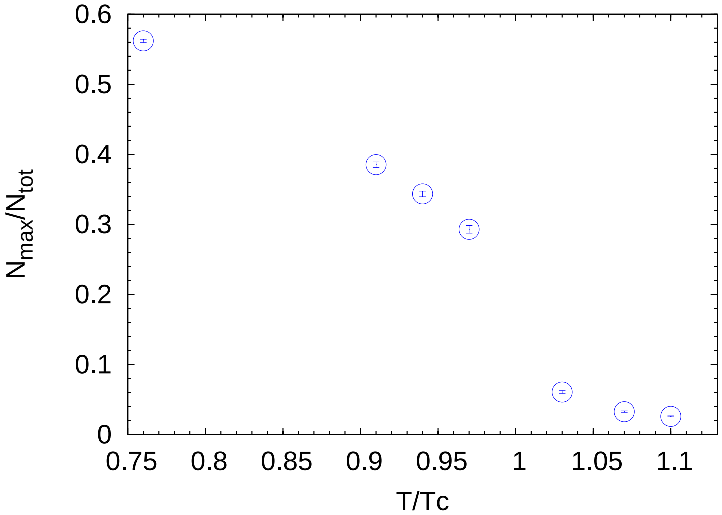
DIK collaboration

- $N_f = 2$ lattice QCD at $T > 0$

- Lattice action:
- Wilson action for gauge field
- Improved Wilson action for quarks

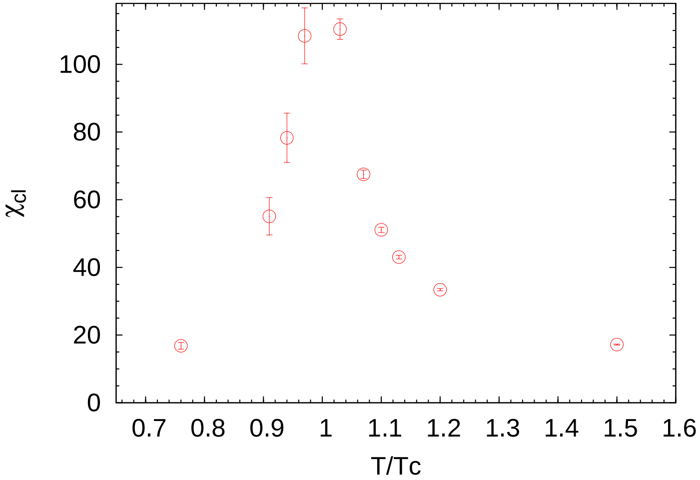
$$S_F = S_F^{(0)} - \frac{i}{2}\kappa\, g\, c_{sw} a^5 \sum_s \bar{\psi}(s)\sigma_{\mu\nu}F_{\mu\nu}(s)\psi(s)$$

- Lattice size $12 \times (32)^3$



Percolation order parameter N_{max}/N_{tot}

$SU(2)$, $48^3 \times 6$, lattice



Average size of the nonpercolating monopole clusters - cluster susceptibility

χ_{cl}

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,

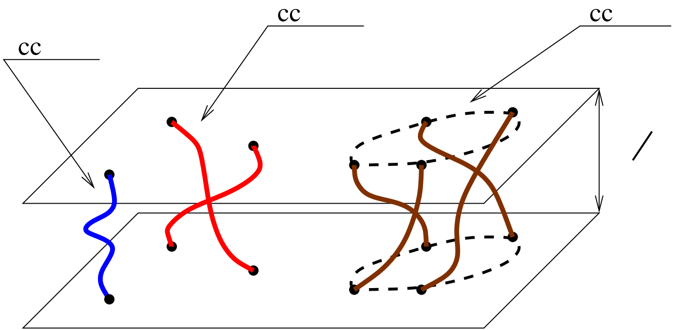
Chernodub and Zakharov:
Clusters of magnetic currents wrapped in T dimension corresponds to particles in thermal equilibrium at temperature T - thermal monopoles

Wrapping number for given cluster:

$$N^a_{wr} = \frac{1}{L_t} \sum_{k^a_4(x) \in cluster} k^a_4(x) \; = 1, 2, 3 etc.$$

density of thermal monopoles

$$\rho = \frac{\langle \sum_{clusters,a} |N^a_{wr}| \rangle}{3 L_s^3 a^3}$$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First lattice study in $SU(2)$ by VB, Mitrjushkin, Muller-Preussker , '92

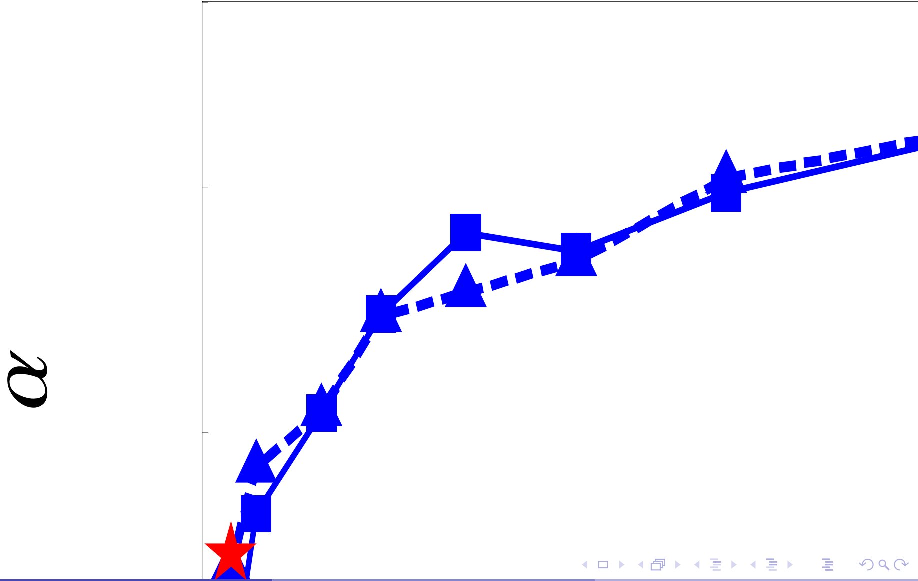
Comprehensive lattice study in $SU(2)$ by D'Alessandro and D'Elia '07

Subsequent work, also in $SU(2)$: VB, Braguta, '11; VB, Kononenko, '12 in $SU(3)$ VB, Kononenko, Mitrjushkin, '13; Bonati, D'Elia '13

Liao and Shuryak

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

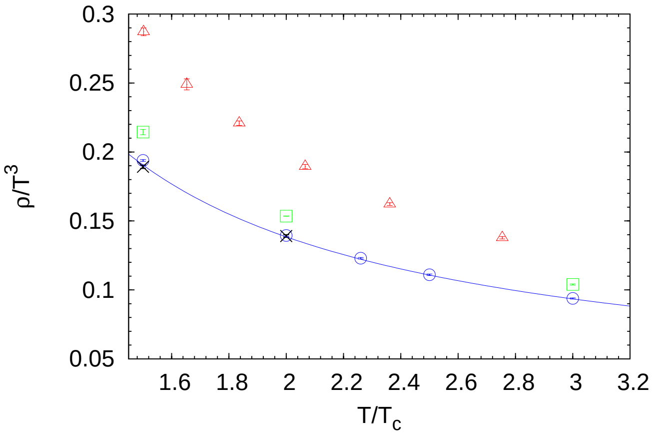
They used alternative approach to study thermal monopoles:
Classical molecular dynamics simulations for system with mixture of magnetic and electric charges
– Remarkably, good qualitative agreement with lattice results for density-density correlation functions
– Magnetic coupling α_M was computed from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


α

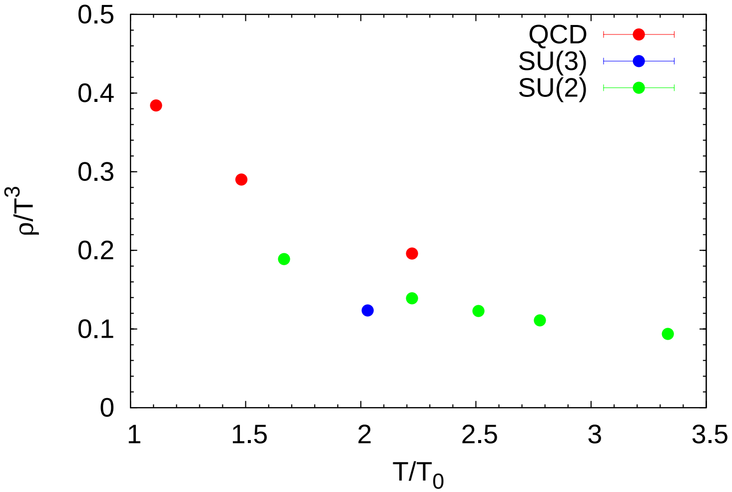
Coulomb plasma parameter

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

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



Thermal monopole density in SU2.
Results by D'Alessandro and D'Elia '07 (triangles), by VB and Braguta '11(squares) and by VB and Kononenko '12 (circles and crosses).



Thermal monopoles density in $SU(2)$, $SU(3)$ and QCD

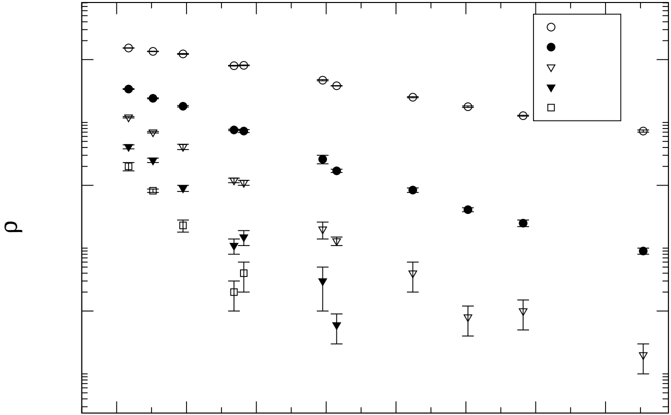
Bose-Einstein condensation of the thermal monopoles

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

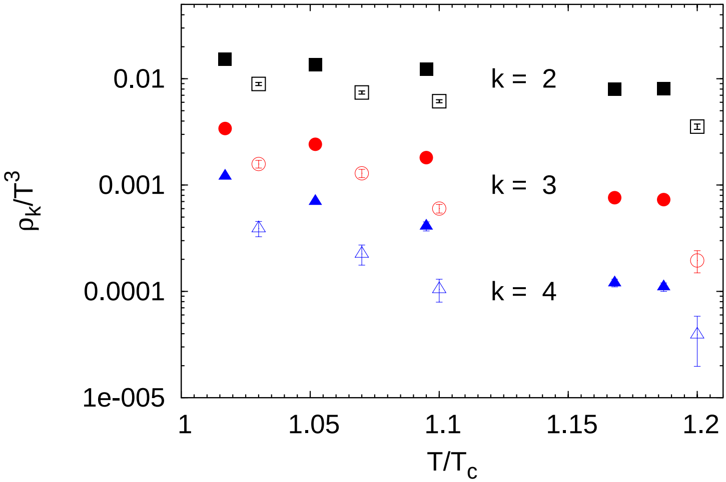
A trajectory wrapping *k* times in a time direction represents a set of *k* monopoles permutated cyclically
For non-relativistic noninteracting bosons

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

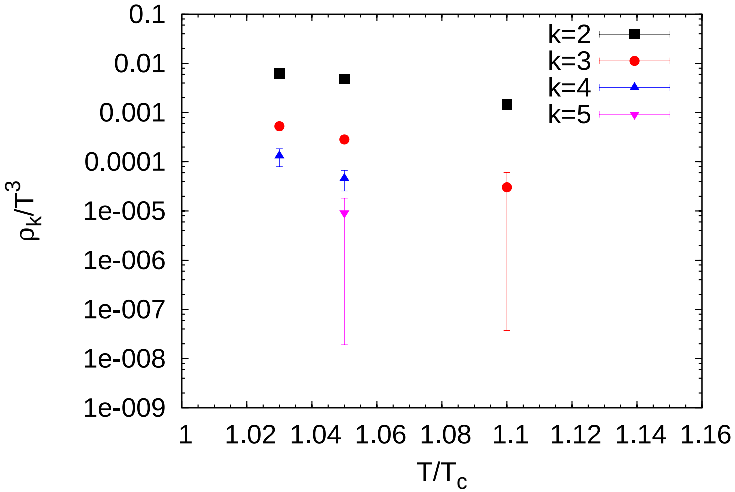
$\hat{\mu} \equiv -\mu/T$ is a chemical potential
λ is the De Broglie thermal wavelength
the condensation temperature T_{BEC} is determined by the vanishing of the chemical potential
$T_{BEC} \approx T_c$ D'Alessandro, D'Elia and Shuryak, 2010
confirmed in VB, Kononeko, 2012



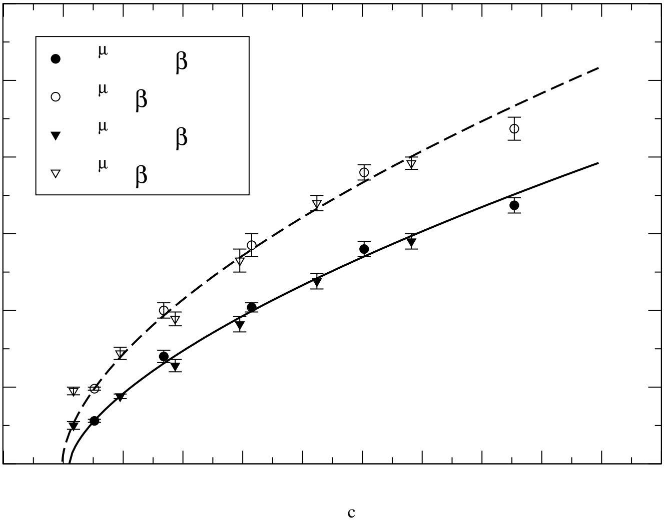
Thermal monopoles density as function of number of wrappings k.
D'Alessandro and D'Elia and Shuryak '09



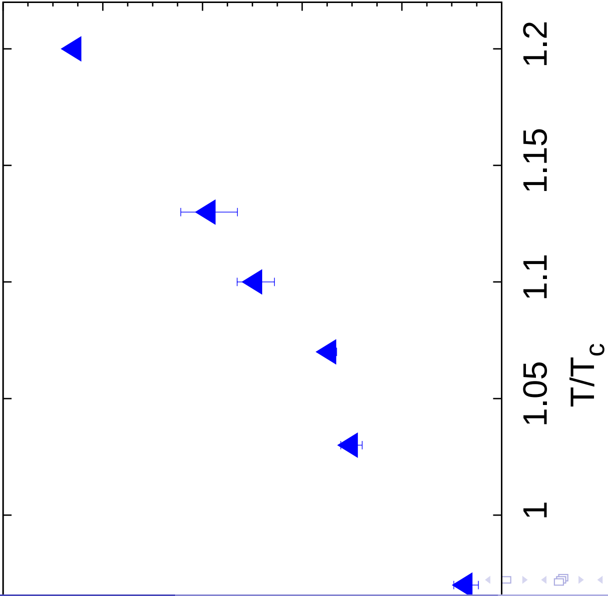
Thermal monopoles density ρ_k vs T/T_c for $SU(2)$



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



Thermal monopoles chemical potential. D'Alessandro and D'Elia and Shuryak '09

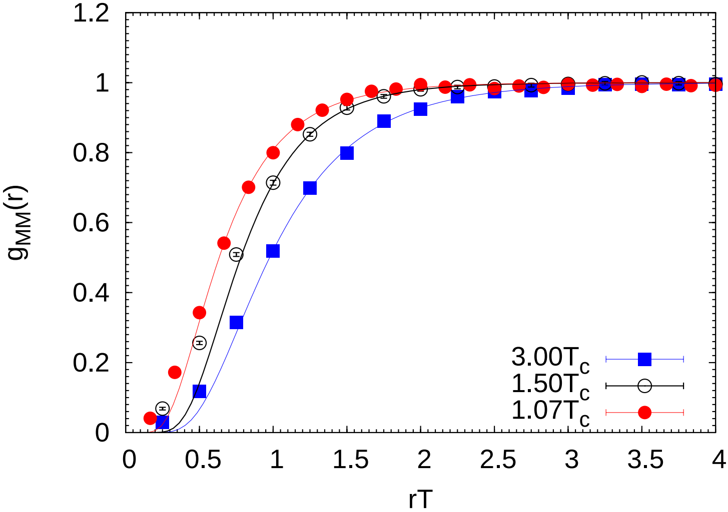

1.2
1.15
1.1
1.05
1
T/Tc

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

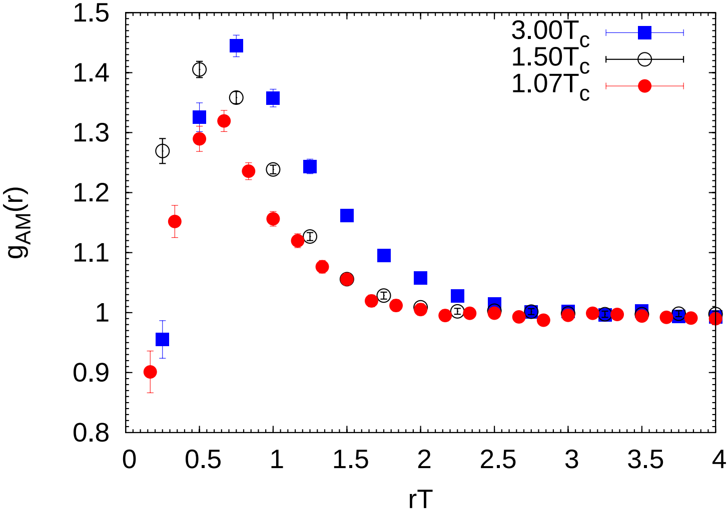
$$g_{AM}(r) = \frac{\langle \rho_A^a(0)\rho_M^a(r)\rangle}{2\rho_A^b\rho_M^b} + \frac{\langle \rho_M^a(0)\rho_A^a(r)\rangle}{2\rho_A^b\rho_M^b}$$

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

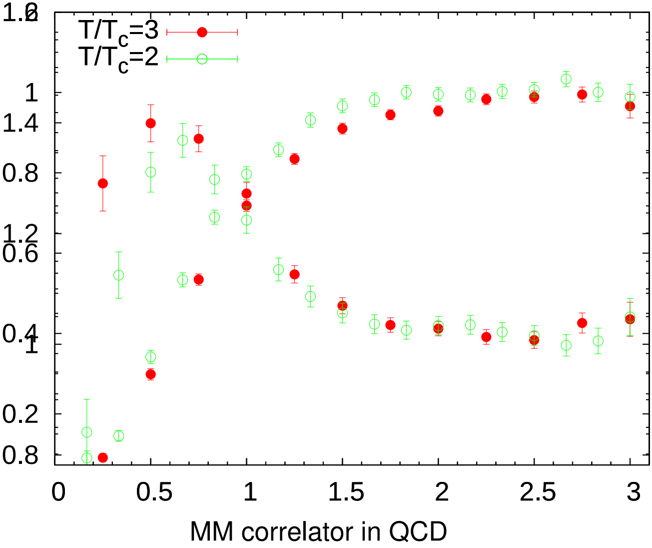
$$U(r) = \frac{\alpha_m}{r} e^{-m_D r}$$

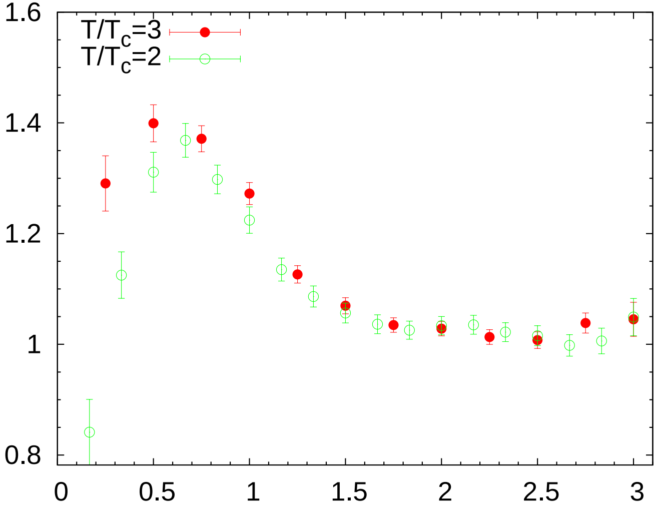


MM correlator in SU(2)

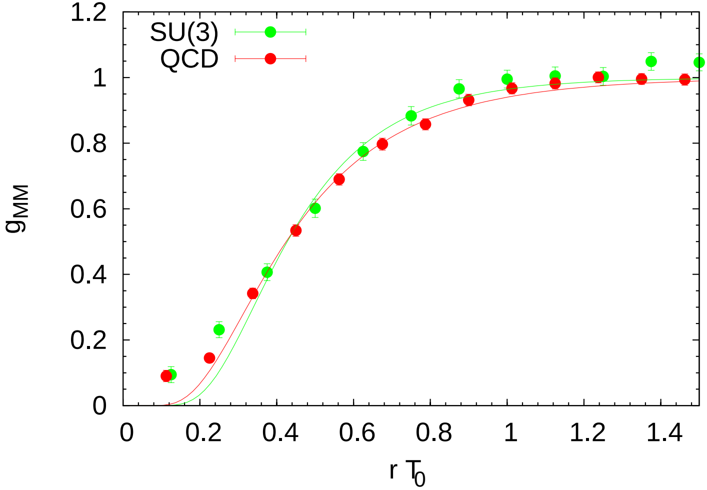


MA correlator in SU(2)


1.6
1.2
1
1.4
0.8
1.2
0.6
0.4
1
0.2
0.8
T/T$_c$=3
T/T$_c$=2
0
0.5
1
1.5
2
2.5
3
MM correlator in QCD



MA correlator in QCD



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

Table of results for $T/T_c = 2$

q

	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

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

– 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

– $\Gamma > 1$ for all three theories