有限温度格子計算における グルーオン伝播関数 と センターボーテックス

T. Saito (Kochi Univ.)

M.N. Chernodub (Univ. of Tours, Univ. of Gent, ITEP)

A. Nakamura (Hiroshima Univ.)

V.I. Zakharov (ITEP, Max Planck Institute)

Introduction

- ◆QGP
  - ◻ Strongly interacting QGP (sQGP)
- ◆Question: How to understand properties of sQGP
  - ◻ Some lattice calculations (spatial Wilson loop, magnetic gluons, instantaneous potential, etc.) show a confining behavior above Tc.
  - ◻ Are magnetic degrees of freedom important in QGP ?
  - ◻ Magnetic plasma made of monopole
    - I. Liao and Shuryak, PRC75(2007)054907; PPNP62(2009)48.
    - II. Chernodub and Zakharov, PRL98(2007)082002.
  - ◻ Recent related lattice calculations
    - I. Center vortex at finite temperature; Chernodub, Nakamura, Zakharov, PRD78,074021(2008).
    - II. EOS in the magnetic monopole and center voretex; Chernodub, et. al, PoS(LATTICE 2007)174.

Spatial Wilson loop in the QGP

- Spatial Wilson loop gives a linearly rising potential in the QGP.

$$W(R,S) \sim \exp(-\sigma_s RS)$$

$$\sqrt{\sigma_s(T)} = cg^2(T)T$$

$T > T_c$

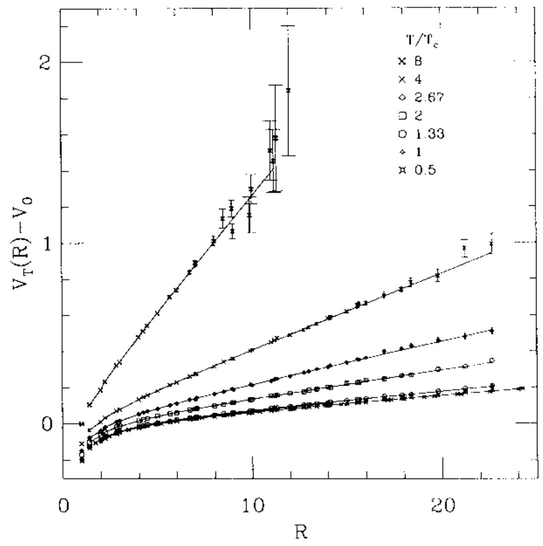
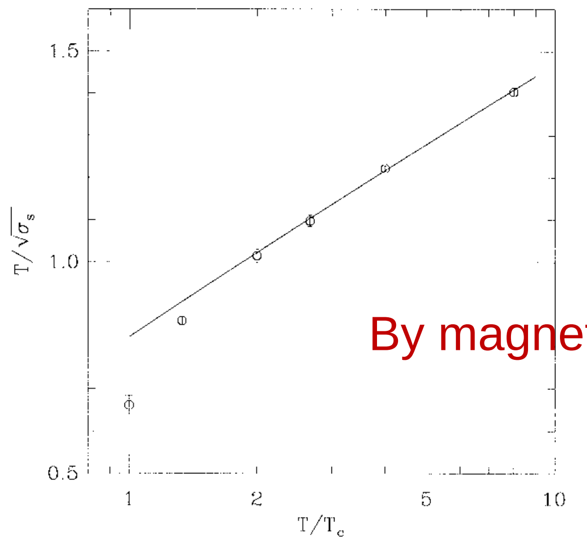


FIG. 1. The pseudopotentials $V_T(R)$ minus the (constant) self-energy contributions V_0 [Eq. (4)] on lattices of size $N_\tau \times 32^3$ for $\beta = 2.74$ as a function of the spatial separation R measured in lattice units.



By magnetic scaling

FIG. 3. The ratio of the critical temperature and square root of the spatial string tension versus temperature for $\beta = 2.74$. The line shows a fit to the data in the region $2 \le T/T_c \le 8$ using the two-loop relation for $g(T)$ given in Eq. (7).

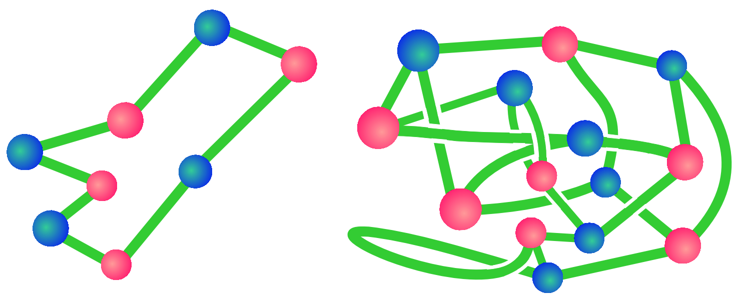
G.S. Bali, et. al, PRL71,3059(1993)

Center vortex

◆ Topological object, which influences various non-perturbative characteristics of QCD such as color confinement and chiral symmetry breaking.

◆Center vortex can be defined via center group Z(N). (originally, by t'Hooft, Mack, Cornwall)

◆ An illustration of the monopole-vortex chains and the monopole-vortex nets:



SU(2) chains SU(3) nets

From Chernodub Nakamura, Zakharov, Phys.Rev.D78:074021,2008

Maximal center projection

◆ Numerical technique

□Direct Maximal Center Projection (MCP) by Debbio, et. al, PRDv58,094501

◆ We apply the MCP to all configurations of the SU(2) gauge field

$$\text{All the Us} \Rightarrow \pm \mathrm{I} \quad \text{Maximize } R = \frac{1}{VT} \sum_{x,t} \mathrm{Tr}\left[U_\mu(x,t)\right]^2$$

$$Z_\mu(x) = \mathrm{sgn}\,\mathrm{Tr}\left[U_\mu(x)\right]$$

◆ Removing center vortex (via de Forcrand – D'Elia procedure,PRL82,4582(1999))

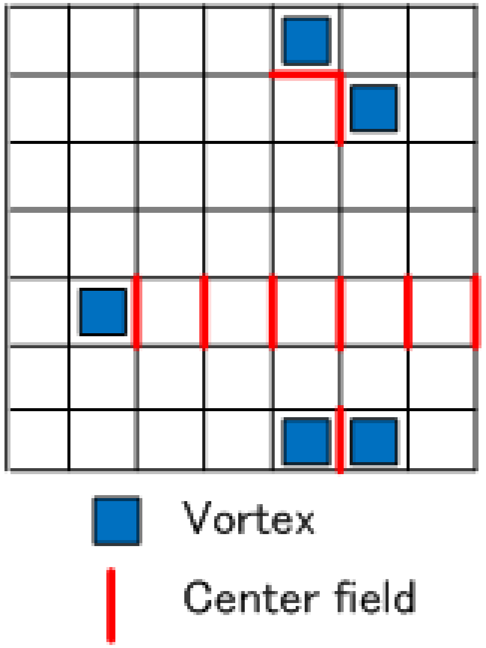
$$U_\mu(x) \to U'_\mu(x) = Z_\mu(x) U_\mu(x)$$

◆Some important results

◆Center-projected lattice are confining,

◆After vortex removal, no confining linear potential exists.

◆ Vortices carry the non-perturbative IR physics of QCD

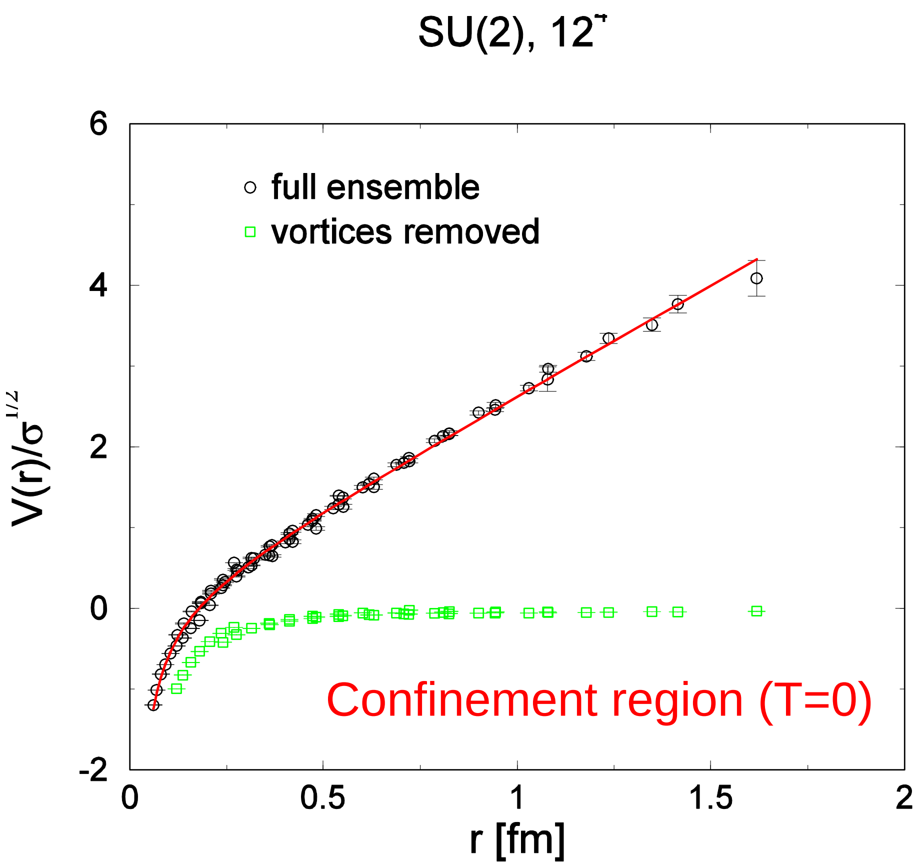


$$W \Rightarrow (-1)^n W$$

Random vortex picture

Example for center vortex removal

◆ Vortices removed configurations give us a non-confining theory.



☐This figure is from “SU(2) gluon propagators from the lattice – a preview”, hep-lat/0104003, Kurt Langfeld

The result changes drastically after vortices removal

☐Modified configurations have only perturbative propertis

☐All the non-perturbative infrared physics must be carried by {Z}.

Aim of this work

◆Aim of this work:

□Investigate relationship between gluons and topological objects (vortex) , in order to understand sQCD.

□Study of magnetic and electric gluon propagators *in the lens of the center vortex mechanism*.

□Observe gluon propagators after/before removal of center vortices.

Gluons at finite temperature

- Screened gluons
  - Gluons would have finite masses in the QGP phase.
  - Heat-bath system breaks Lorentz invariance and favors some rest frame.
- *Electric gluon*
  - Color-Debye screening:Yukawa-type potential between quarks (not linearly rising potential at long distances)
  - Perturbatively, the electric mass is calculable gauge-invariantly $m_e \sim g(T)T$
- *Magnetic gluon*
  - Magnetic screening for QCD (not exist in QED)
  - Perturbatively not calculable (depend on a gauge parameter, etc.)
  - Thermal perturbation theory spoils if the magnetic mass vanishes; therefore we hope it has a non-zero value.
  - Non-zero magnetic masses would have non-perturbative origin.
  - 3D reduction arugument $m_m \sim g^2(T)T$

Gluon propagators at finite temperature

◆Self-energy and propagators

$$\Pi^{\mu\nu} = GP_T^{\mu\nu} + FP_L^{\mu\nu} \quad D^{\mu\nu} = \frac{1}{G+k^2}P_T^{\mu\nu} + \frac{1}{F+k^2}P_L^{\mu\nu} + \frac{\rho}{k^2}\frac{k^\mu k^\nu}{k^2} \quad \rho = 0 : \text{Landau gauge}$$

◆Projection operators

$$P_T^{00} = P_T^{0i} = P_T^{i0}, \qquad P_T^{ij} = \delta^{ij} - \frac{k^i k^j}{\vec{k}^2}, \qquad P_L^{\mu\nu} = \delta^{\mu\nu} - \frac{k^\mu k^\nu}{k^2} - P_T^{\mu\nu},$$

$$(P_T)^2 = P_T,\ (P_L)^2 = P_L,\ P_T P_L = 0$$

◆Electric and magnetic gluon propagators in the momentum space

$$D_E(\vec{k}, k_0 = 0) = D^{00} = \frac{1}{F+\vec{k}^2}, \quad D_M(\vec{k}, k_0 = 0) = D^{ii} = \frac{1}{G+\vec{k}^2}$$

$$F(\vec{0},0) = m_E \sim g(T)T \qquad G(\vec{0},0) = m_M \sim g^2(T)T$$

Gluon propagators on the lattices

◆Gauge potentials and correlators

$$A_\mu^a(x,t) = \mathrm{Tr}\,\sigma^a U_\mu(x,t) \quad D_{\mu\nu}(x,t) = \left\langle A_\mu(x,t) A_\nu^*(x,t) \right\rangle$$

◆Unequal-time propagators $t(= t' - t'')$

$$D_{\mu\nu}(\vec{q},t) = \frac{1}{V(N_c^2-1)} \sum_x A_\mu^a(x,t') A_\nu^a(y,t'') e^{iq(x-y)}$$

◆Sum of t with q_0=0,

$$D_{\mu\nu}(\vec{q},q_0=0) = \frac{1}{N_t} \sum_t D_{\mu\nu}(\vec{q},t)$$

Maximal center projection

- Numerical technique
  - Direct Maximal Center Projection (MCP) by Debbio, et. al, PRDv58,094501
  - de Forcrand and D'Elia, PRL82,4582(1999)

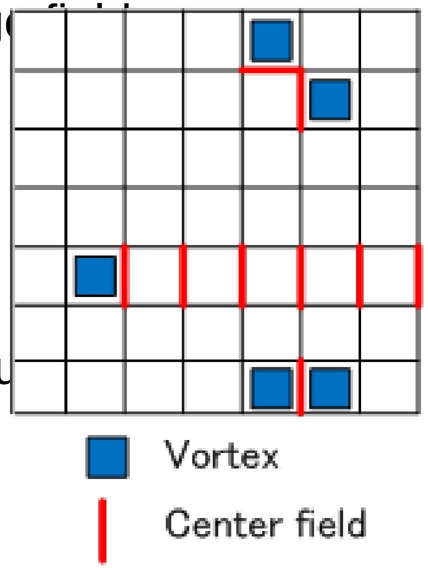
- We apply the MCP to all configurations of the SU(2) gaug

$$\text{All the Us} \Rightarrow \pm \mathrm{I} \quad \text{Maximize } R = \frac{1}{VT}\sum_{x,t} \mathrm{Tr}\left[U_\mu(x,t)\right]^2$$

$$Z_\mu(x) = \mathrm{sgn}\,\mathrm{Tr}\left[U_\mu(x)\right]$$

- Removing center vortex (via de Forcrand – D'Elia procedu

$$U_\mu(x) \to U'_\mu(x) = Z_\mu(x) U_\mu(x)$$



- Numerical procedures

Link Update → MCP → Gauge fixing → Measure gluon propagators

Numerical parameters

◆ SU(2) lattice calculation with quenched Wilson-gauge action
◆ Landau (Coulomb) gauge on the lattice in the path-integral formula satisfies the following condition:

$$\partial_\mu A_\mu(x,t) = 0 \;\Rightarrow\; \text{Maximize } R = \frac{1}{VT}\sum_{x,t} \mathrm{Re\,Tr U}_\mu(x,t)$$

$$\left|\sum_\mu \mathrm{Tr}\sigma^{\mathrm{a}}\left(U_\mu(x) - U_\mu(x-\hat{\mu})\right)\right|^2 \le 10^{-eps}$$

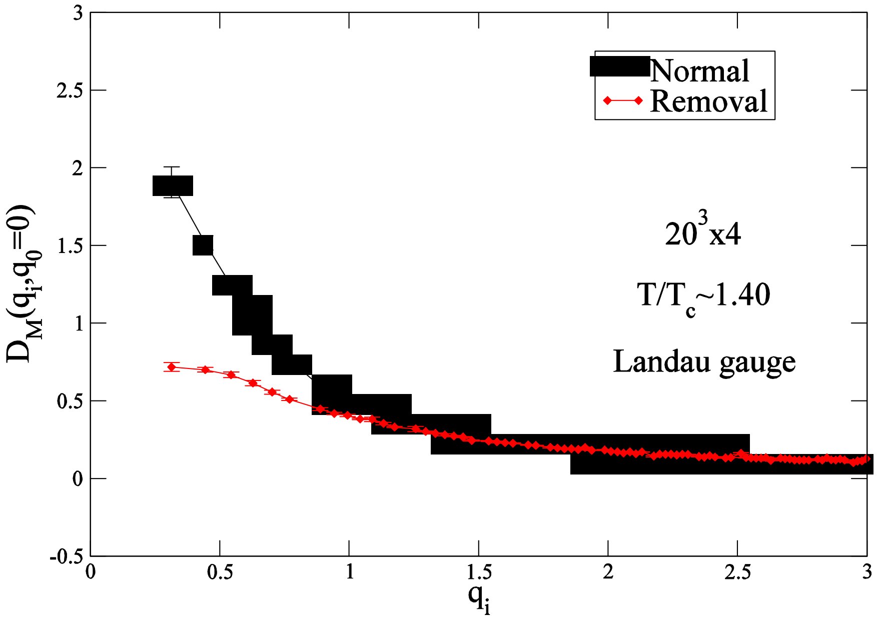
Wilson-Mandula Method (PLB185,127(1987))

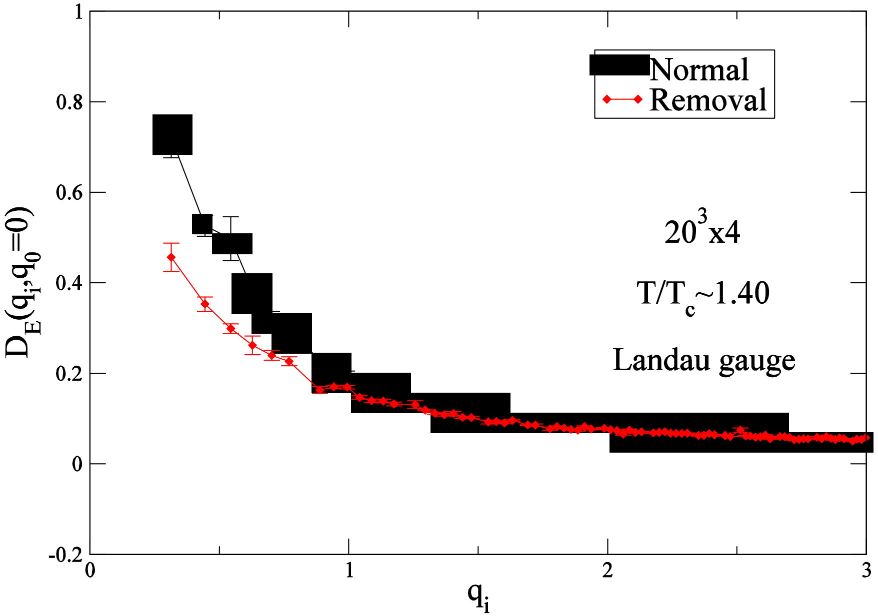
◆Parameters:

β	Temp.	Size	Eps of	Confs.
β =2.40	T/T_c~1.40	12x12x12x4	10^{-8}	30
		20x20x20x4	10^{-8}	30
		32x32x32x4	10^{-8}	30
		48x48x48x4	10^{-8}	10
β =2.88	T/T_c~6.00	32x32x32x4	10^{-8}	10

Landau-gauge propagators

$T / T_c \sim 1.40$



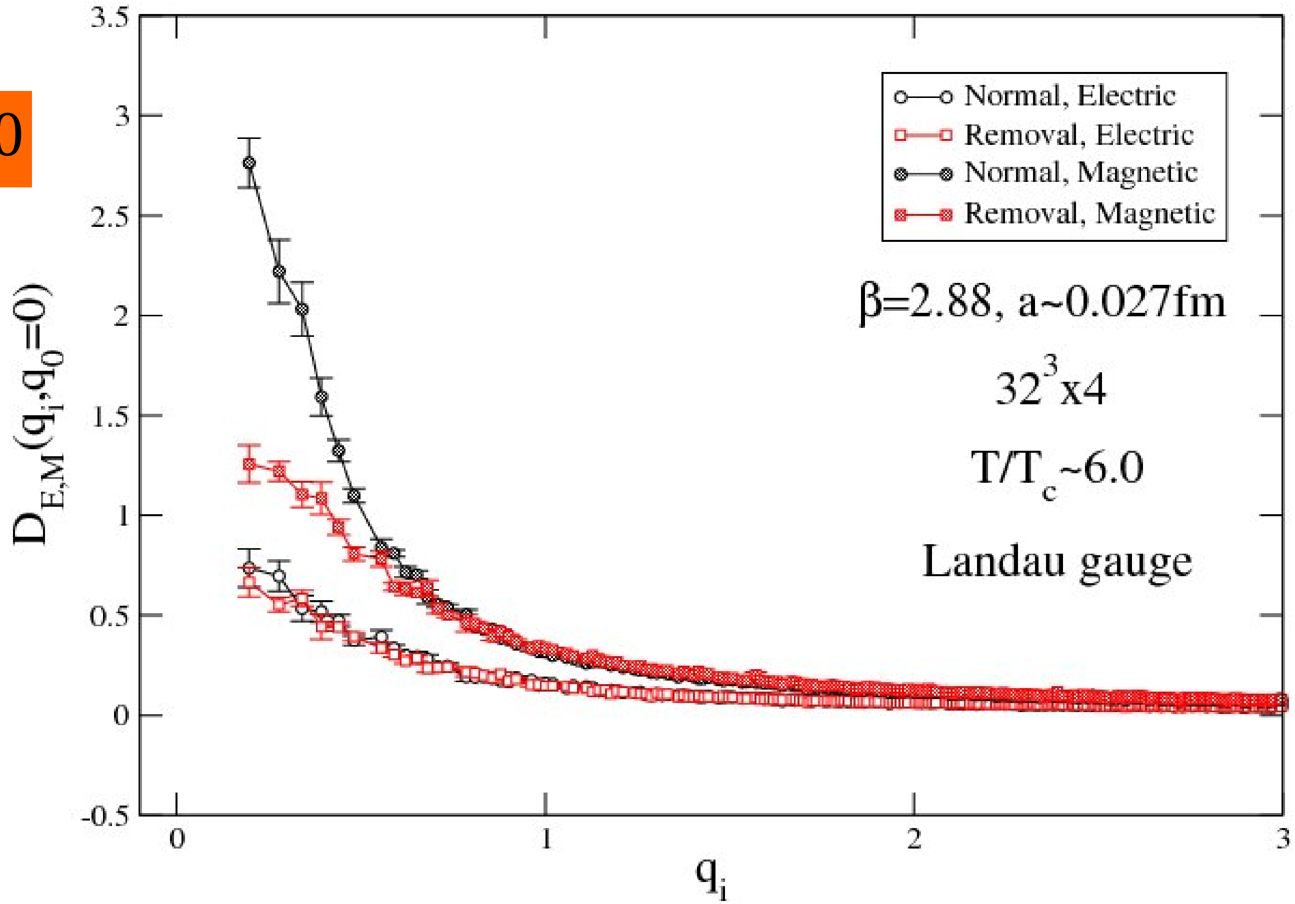


◆After center vortices were removed,

- ☐The magnetic propagator shows a suppression at low momenta.
- ☐The electric propagator at low momenta changes slightly.

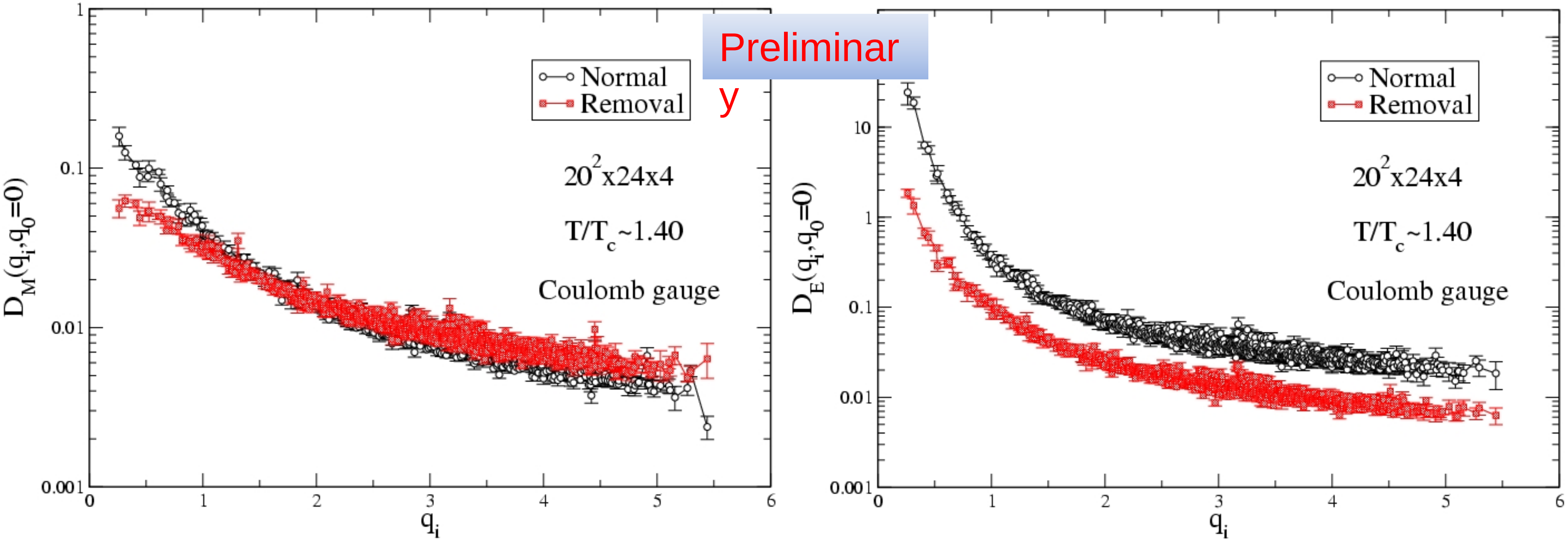
Results at high temperature

$T/T_c \sim 6.0$



◆ At high temperature (may be relevant to LHC experiment), we get the same result. (Note that the lattice size is very small compared with the simulations of T/T_c~1.40.)

Coulomb-gauge propagators

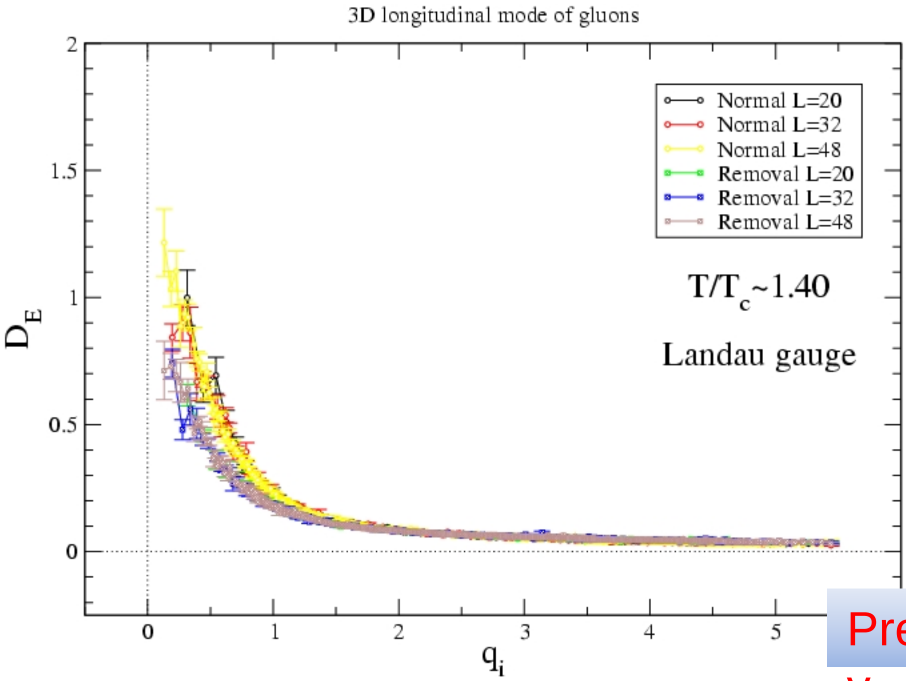


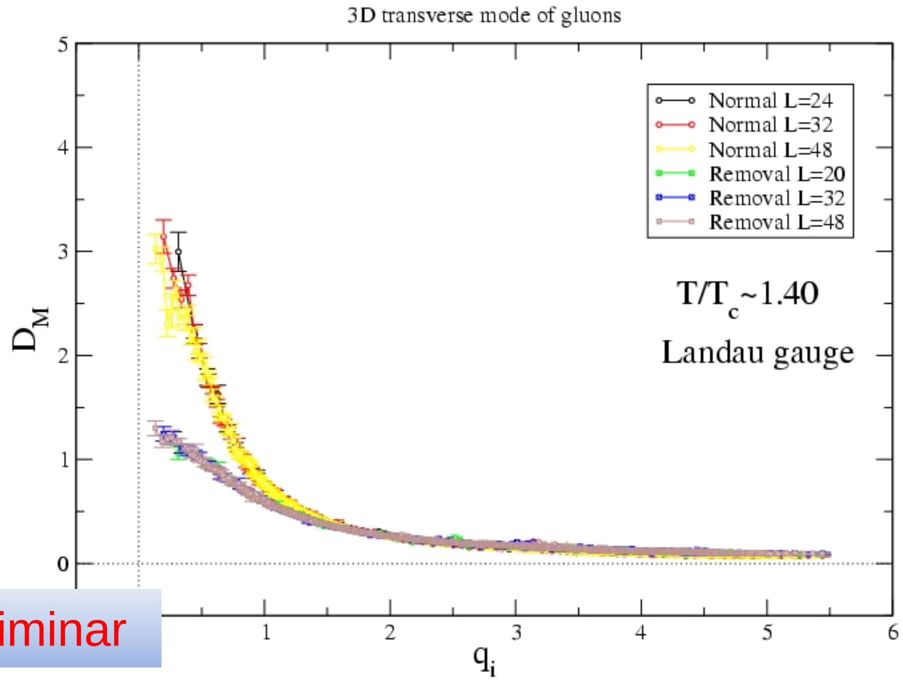
◆We have the same results as in the case of Landau-gauge.

□At the configuration with removed vortices, the magnetic gluon is affected crucially, while the electric gluon is not.

□In the later case, the removal affects the overall normalization.

Landau-gauge propagators volume dependence





Preliminary

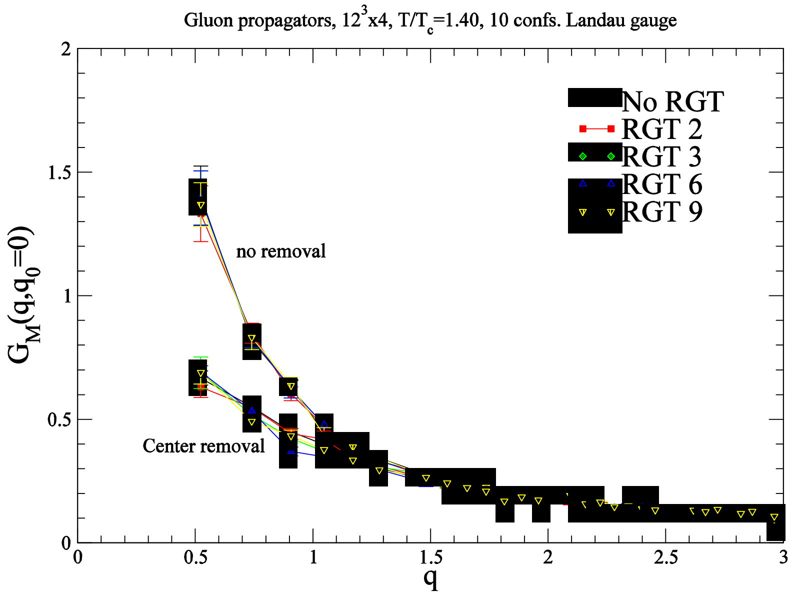
equal-time propagators

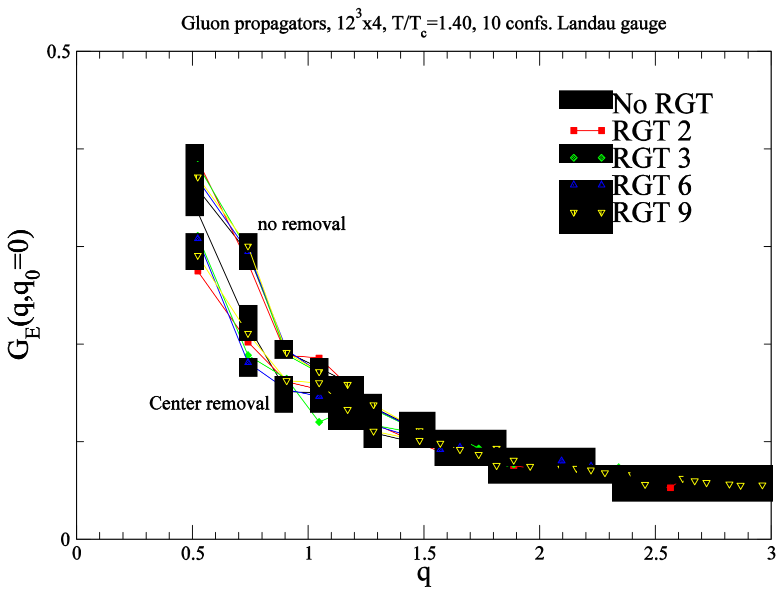
◆The volume dependence seems to be not significant.

◆If the magnetic gluons are confining, should their low-momentum propagator vanish

Effect for a numerical ambiguity of the maximal center (gauge) procedure

after some random gauge transformations





◆ The procedure "direct maximal center gauge (projection)" (Debbio, et. al, PRDv58,094501) produces a lot of gauge ambiguities (copies); but the influence to the gluon propagators is very small.

Summary of this talk

◆We studied infrared properties of gluons at finite temperature *in the lens of center vortex mechanism,* which is responsible for a non-perturbative physics.

◆ After removal of center vortices, the magnetic gluon propagators change drastically at low momenta, while the electric gluons do not vary significantly.

◆This numerical study shows the importance of magnetic degree of freedom and relationship between (magnetic) gluons and topological objects in the QGP phase.

Buck-up slides

Center vortex

◆Other examples:

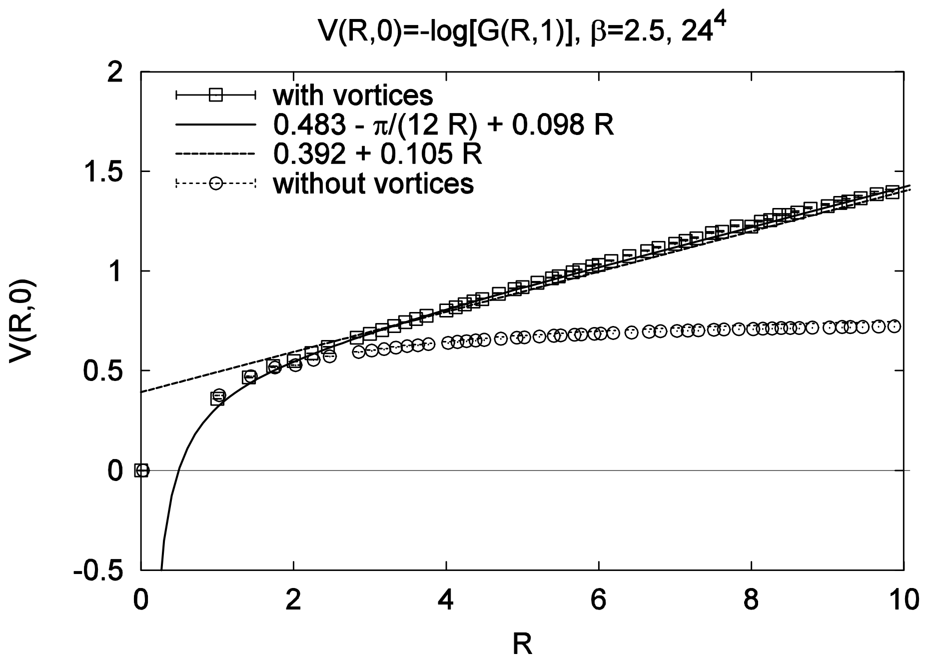
- Relation of chiral symmetry breaking; that has been extensively studied now.
  Forcrand and D'Elia, PRL82, 4582 (1999); Hollweieser, et.al, PRD78, 054508 (2008); Bowman, et. al, PRD78,054509(2008).

- Center vortices at finite temperature. Langfeld, et. al, PLB452(1999) 301.

- Gluons in the confinement regions Gattnar, et. al, PRL93(2004)061601

Example for center vortex removal

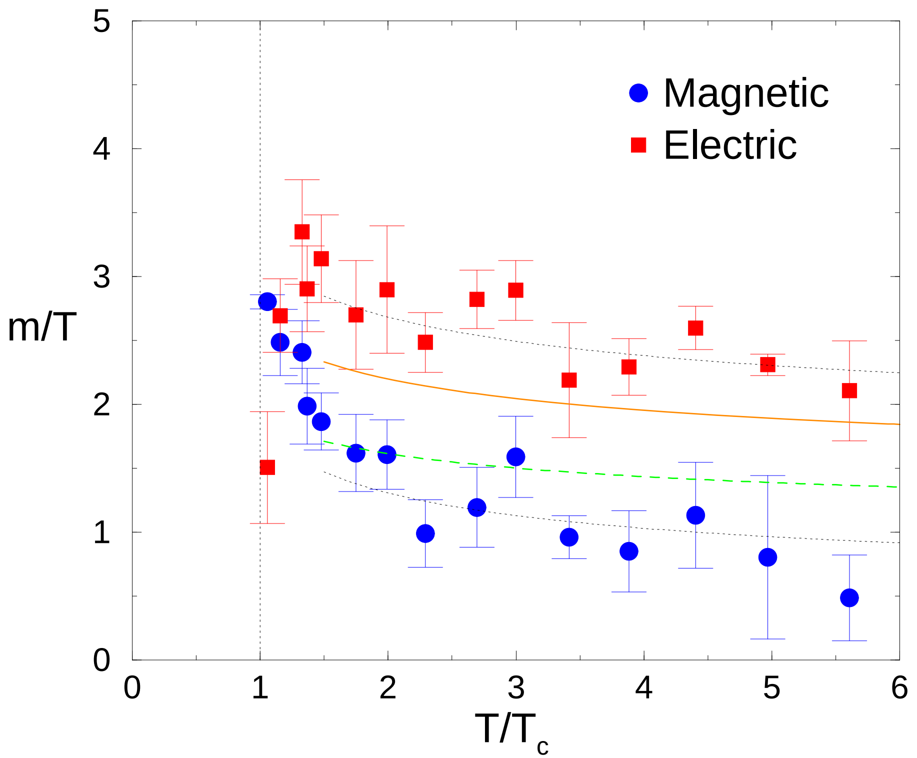
◆ In the Coulomb gauge QCD, an instantaneous interaction cause a linearly confing potential among quarks.

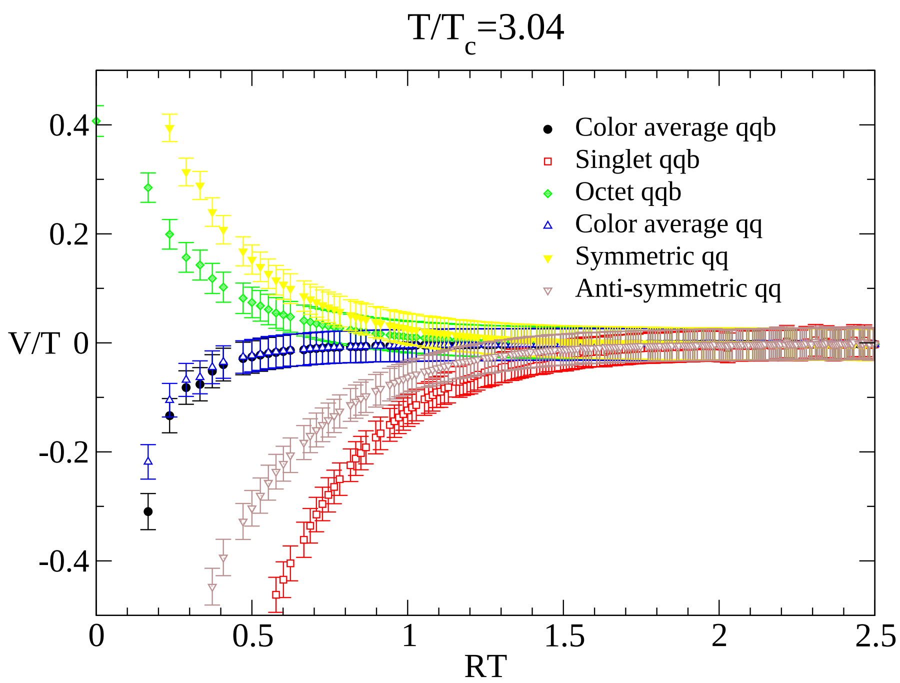


This figure is from "Coulomb enery, vortices, and confinement", PRD67,094503(2003), Jeff Greensite, Stefan Ojejnik.

The result changes drastically after vortices removal.

Screened gluons in lattice calculations





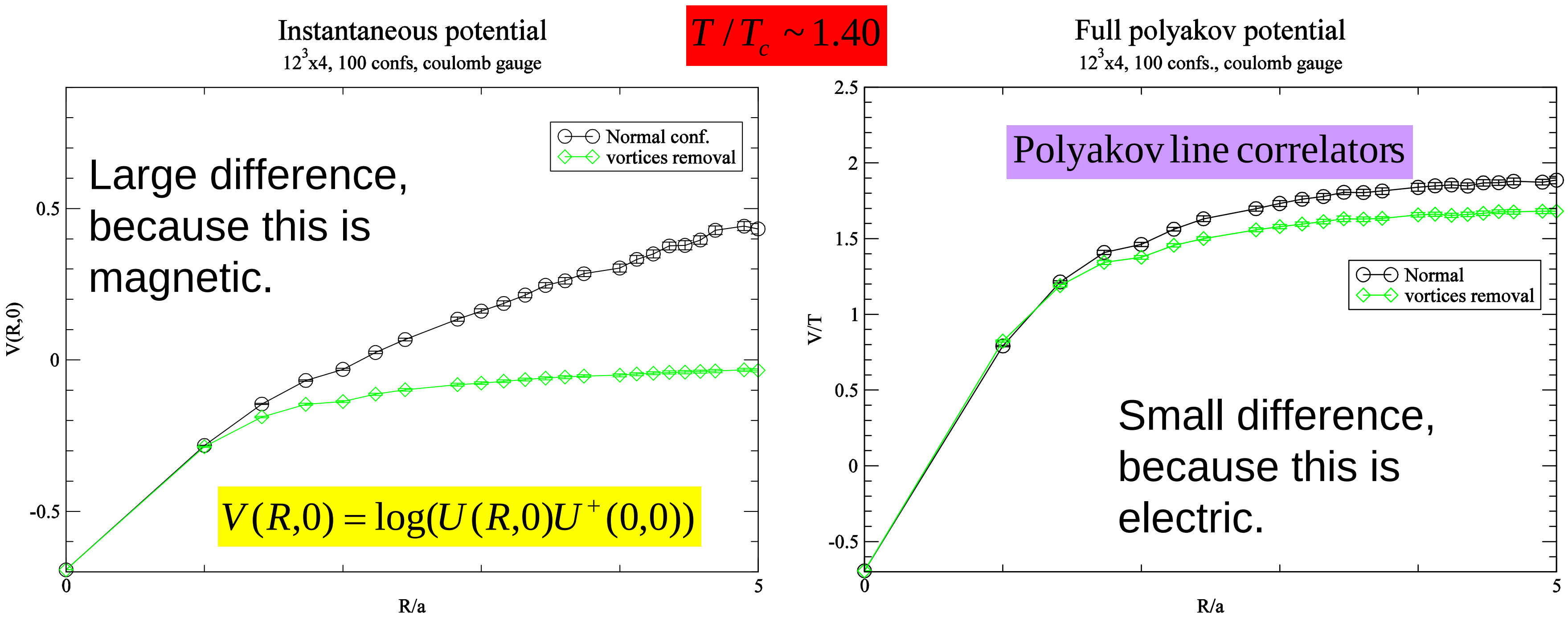
Electric and Magnetic masses vs. the temperature in the stochastic gauge fixing approach: Nakamura, Saito, Sakai, PRD69(2004)014506.

Screening potentials between two quarks in each color-channel: Nakamura, Saito PTP112(2004)183; PTP111(2004)733

Example for center vortex removal

◆ Numerical test by us; the calculation of instantaneous potentials at finite temperature.

◆The instantaneous potential being still a confining potential is also affected by the removal of vortices but the color-Debye potential is not so.



Gluon propagators at finite temperature on the lattices

◆Self-energy and propagators

$$\Pi^{\mu\nu} = GP_T^{\mu\nu} + FP_L^{\mu\nu} \quad D^{\mu\nu} = \frac{1}{G+k^2}P_T^{\mu\nu} + \frac{1}{F+k^2}P_L^{\mu\nu} + \frac{\rho}{k^2}\frac{k^\mu k^\nu}{k^2} \quad \rho = 0 : \text{Landau gauge}$$

◆Projection operators

$$P_T^{00} = P_T^{0i} = P_T^{i0}, \qquad P_T^{ij} = \delta^{ij} - \frac{k^i k^j}{\vec{k}^2}, \qquad P_L^{\mu\nu} = \delta^{\mu\nu} - \frac{k^\mu k^\nu}{k^2} - P_T^{\mu\nu},$$

$$(P_T)^2 = P_T,\ (P_L)^2 = P_L,\ P_T P_L = 0$$

◆Electric and magnetic gluon propagators in the momentum space

$$D_E(\vec{k}, k_0 = 0) = D^{00} = \frac{1}{F+\vec{k}^2}, \quad D_M(\vec{k}, k_0 = 0) = D^{ii} = \frac{1}{G+\vec{k}^2}$$

◆Electric and magnetic gluons in the coordinate space

$$D_E(k_y, z) \sim D_{tt}(k_y, z) \quad D_M(k, z) \sim D_{xx}(k_y, z) + D_{yy}(k_x, z)$$

$$D_{E,M}(k, z) \sim \exp(-E(k)z) \text{ for large z}$$

Gluon propagators on the lattices

◆Gauge potentials and correlators

$$A_\mu^a(x,t) = \mathrm{Tr}\,\sigma^a U_\mu(x,t) \quad D_{\mu\nu}(x,t) = \left\langle A_\mu(x,t) A_\nu^*(x,t) \right\rangle$$

◆Equal-time propagators

$$D_{\mu\nu}(\vec{q}) = \frac{1}{V(N_c^2 - 1)} \sum_{x,a} A_\mu^a(x,t) A^a(y,t) e^{iq(x-y)}$$

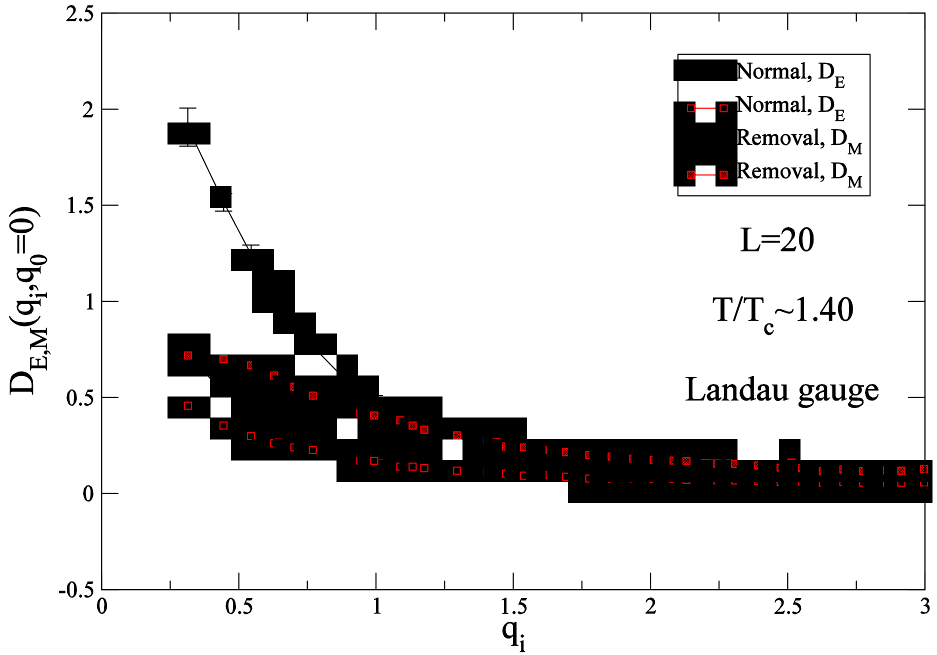
◆Unequal-time propagators $(t = t^{'} - t^{''})$

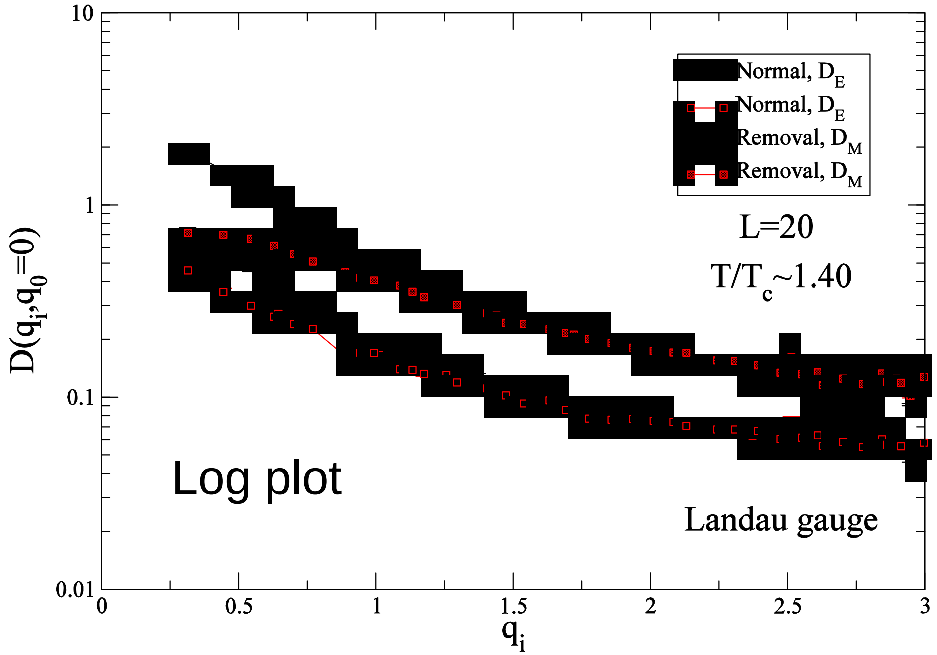
$$D_{\mu\nu}(\vec{q},t) = \frac{1}{V(N_c^2 - 1)} \sum_{x} A_\mu^a(x,t^{'}) A_\nu^a(y,t^{''}) e^{iq(x-y)}$$

◆Sum of t with q_0=0,

$$D_{\mu\nu}(\vec{q}, q_0 = 0) = \frac{1}{N_t} \sum_t D_{\mu\nu}(\vec{q},t)$$

Landau-gauge propagators (2)





◆After center vortices were removed,

- ☐The magnetic propagator display a suppression at low momenta.
- ☐The electric propagator at low momenta changes slightly.