Confinement/deconfinement phase transition in SU(3) Yang-Mills theory and Non-Abelian dual Meissner effect

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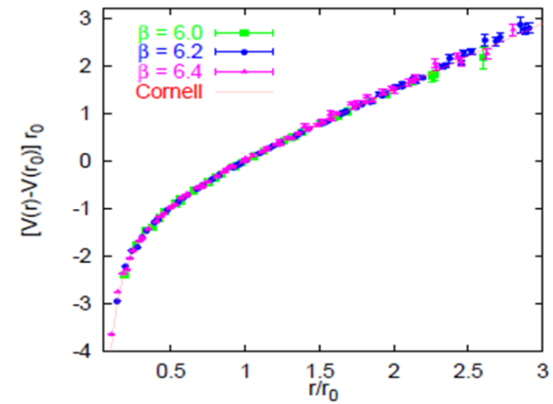
Introduction(1)

G.S. Bali Phys. Rept. **343, 1–136 (2001)**



- Quark confinement follows from the area law of the Wilson loop average [Wilson,1974]
- **Dual superconductivity** is promising mechanism. [Y.Nambu (1974). G.'t Hooft, (1975). S.Mandelstam(1976), A.M. Polyakov (1975)]

- To establish this picture, we must show evidences of the dual version of the superconductivity in various situations.

- ➢ Quark confinement in the fundamental representation (our preceding works)
- ➢ Quark confinement in the higher representation (Matsudo, May 31 NFQCD)
- ➢ Confinemet/deconfinement phase transition at finite temperature (this talk)

Dual superconductivity

Superconductor (condensed matter)

- Condensation of electric charges (Cooper pairs)
- Meissner effect: Abrikosov string (magnetic flux tube) connecting monopole and anti-monopole
- Linear potential between monopoles

Dual superconductor (QCD)

- Condensation of magnetic monopoles
- Dual Meissner effect: formation of a hadron string (chromo-electric flux tube) connecting quark and antiquark
- Linear potential between quark and anti-quark

Extracting relevant mode for confinement

Abelian projection method	**Decomposition method**
Extracting the relevant mode as the diagonal (Abelian) part in the maximal Abelian (MA) gauge. $U=XV$ – SU(2) → U(1) – SU(3) → U(1)XU(1) Problems: ✓ The results of Abelian projection method depends on the gauge fixing of the Yang-Mills theory. ✓ The gauge fixing breaks (global) color symmetry.	**[a new formulation on a lattice]** Extracting the relevant mode V for quark confinement by solving the defining equation in the gauge independent way (gauge-invariant way). ➔ The Abelian projection method can be reformulated by using the decomposition method in the gauge invariant way.

A new formulation of Yang-Mills theory (on a lattice)

[Phys.Rept. 579 (2015) 1-226]

Decomposition of SU(N) gauge links For SU(N) YM gauge link, there are sever al possible options of decomposition *discriminated by its stability groups*:

- SU(2) Yang-Mills link variables: unique $U(1) \subset SU(2)$
- SU(3) Yang-Mills link variables: **Two options**

minimal option : $U(2) \cong SU(2) \times U(1) \subset SU(3)$

Minimal case is derived for the Wilson loop, defined for quark in the fundamental representation, which follows from the non-Abelian Stokes' theorem

maximal option : $U(1) \times U(1) \subset SU(3)$

Maximal case is a gauge invariant version of Abelian projection in the maximal Abelian (MA) gauge. (the maximal torus group)

Dual Superconductivity in SU(3) Yang-Mills

Abelian Dual superconductivity

□Abelian projection in MA gauge ::
SU(3) ➔ U(1)xU(1) (Maximal torus)

•Perfect Abelian dominance in string tension[Sakumichi-Suganuma]

□Decomposition method

•**Maximal option** of a new formulation [ours]

Cho-Faddev-Niemi-Shavanov decomposition [N Cundy, Y.M. Cho et.al]

Non-Abelian Dual superconductivity

□Decomposition method

•**Minimal option: (**non-Abelian dual superconductivity) based on the U(2) stability sub-group.

we have showed in the series works

✓V-field dominance, non-Abalian magnetic monopole dominance in string tension

✓ chromo-flux tube and dual Meissner effect,

✓confinement/deconfinement phase transition in terms of dual Meissner effect at finite temperature

Dual Superconductivity in SU(3) Yang-Mills (II)

- In the series of workshop, we have studied the minimal option.

Because the non-Abelain Stokes theorem shows that *Wilson loop of Yang-Mills field in the fundamental representation can be rewritten by using the restricted field V which is decomposed as new variables (U = XV)*

- Ordinary, Abelian picture (maximal option) has been studied.
- Both can derive dual superconductivity picture such as V-field or "Abelian" dominance in string tension.

- **Therefore, we investigate the dual superconductor picture in both options**

minimal option: The decomposition of SU(3) link variable

$$W_C[U] := \mathrm{Tr}\left[P \prod_{\langle x, x+\mu \rangle \in C} U_{x,\mu} \right] / \mathrm{Tr}(\mathbf{1})$$

$$U_{x,\mu} = X_{x,\mu} V_{x,\mu}$$

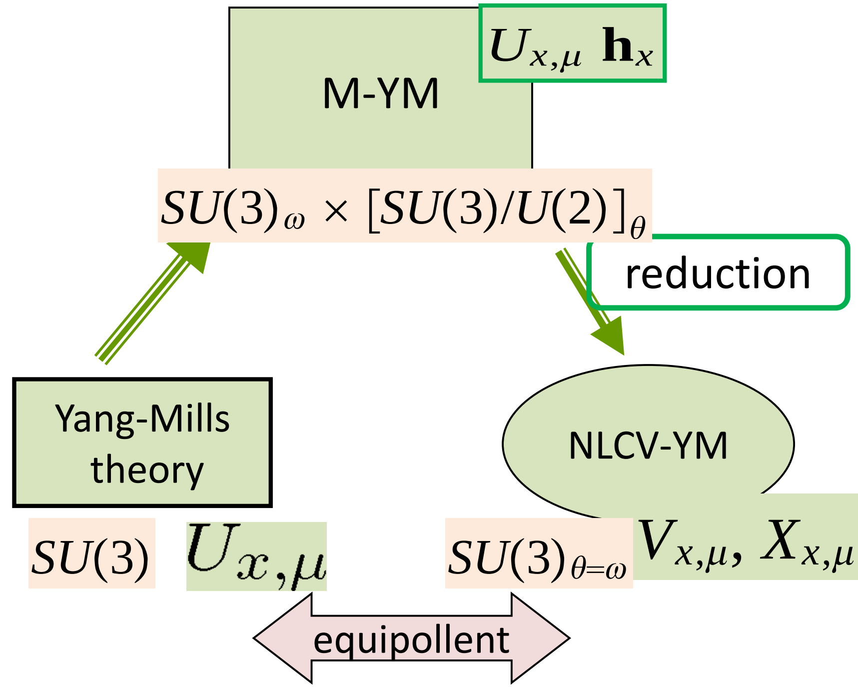
$$U_{x,\mu} \to U'_{x,\mu} = \Omega_x U_{x,\mu} \Omega^{\dagger}_{x+\mu}$$

$$V_{x,\mu} \to V'_{x,\mu} = \Omega_x V_{x,\mu} \Omega^{\dagger}_{x+\mu}$$

$$X_{x,\mu} \to X'_{x,\mu} = \Omega_x X_{x,\mu} \Omega^{\dagger}_{x}$$

$$\Omega_x \in G = SU(N)$$

$$W_C[V] := \mathrm{Tr}\left[P \prod_{\langle x, x+\mu \rangle \in C} V_{x,\mu} \right] / \mathrm{Tr}(\mathbf{1})$$



$$W_C[U] = \mathrm{const.} W_C[V] \quad !!$$

Minimal option: Defining equation for the decomposition

Introducing a color field $\mathbf{h}_x = \xi(\lambda^8/2)\xi^\dagger \in SU(3)/U(2)$ with $\xi \in SU(3)$, a set of the defining equation of decomposition $U_{x,\mu} = X_{x,\mu}V_{x,\mu}$ is given by

$$D^\epsilon_\mu[V]\mathbf{h}_x = \frac{1}{\epsilon}(V_{x,\mu}\mathbf{h}_{x+\mu} - \mathbf{h}_x V_{x,\mu}) = 0,$$

$$g_x = e^{-2\pi q_x/N}\exp(-a_x^{(0)}\mathbf{h}_x - i\sum_{i=1}^{3} a_x^{(l)} u_x^{(i)}) = 1,$$

which correspond to the continuum version of the decomposition, $\mathcal{A}_\mu(x) = \mathcal{V}_\mu(x) + \mathcal{X}_\mu(x)$,

$$D_\mu[\mathcal{V}_\mu(x)]\mathbf{h}(x) = 0, \qquad \mathrm{tr}(\mathcal{X}_\mu(x)\mathbf{h}(x)) = 0.$$

Exact solution (N=3)

$$X_{x,\mu} = \hat{L}^\dagger_{x,\mu}(\det \hat{L}_{x,\mu})^{1/N} g_x^{-1} \quad V_{x,\mu} = X^\dagger_{x,\mu}U_{x,} = g_x \hat{L}_{x,\mu}U_{x,}(\det \hat{L}_{x,\mu})^{-1/N}$$

$$\hat{L}_{x,\mu} = \left(\sqrt{L_{x,\mu}L^\dagger_{x,\mu}}\right)^{-1} L_{x,\mu}$$

$$L_{x,\mu} = \frac{N^2 - 2N + 2}{N}\mathbf{1} + (N-2)\sqrt{\frac{2(N-2)}{N}}(\mathbf{h}_x + U_{x,\mu}\mathbf{h}_{x+\mu}U^{-1}_{x,\mu}) + 4(N-1)\mathbf{h}_x U_{x,\mu}\mathbf{h}_{x+\mu}U^{-1}_{x,\mu}$$

continuum limit

$$\mathbf{V}_\mu(x) = \mathbf{A}_\mu(x) - \frac{2(N-1)}{N}[\mathbf{h}(x),[\mathbf{h}(x),\mathbf{A}_\mu(x)]] - ig^{-1}\frac{2(N-1)}{N}[\partial_\mu \mathbf{h}(x),\mathbf{h}(x)],$$

$$\mathbf{X}_\mu(x) = \frac{2(N-1)}{N}[\mathbf{h}(x),[\mathbf{h}(x),\mathbf{A}_\mu(x)]] + ig^{-1}\frac{2(N-1)}{N}[\partial_\mu \mathbf{h}(x),\mathbf{h}(x)].$$

Minimal option: Non-Abelian magnetic monopole

For Wilson loop in the fundamental representation

From the non-Abelian Stokes theorem and the Hodge decomposition, the magnetic monopole is derived without using the Abelian projection

$$W_C[\mathcal{A}] = \int [d\mu(\xi)]_\Sigma \exp\left(-ig\int_{S:C=\partial\Sigma} dS^{\mu\nu}\sqrt{\frac{N-1}{2N}}\,\mathrm{tr}(2\mathbf{h}(x)\mathcal{F}_{\mu\nu}[\mathcal{V}](x))\right)$$

$$= \int [d\mu(\xi)]_\Sigma \exp\left(ig\sqrt{\frac{N-1}{2N}}(k,\Xi_\Sigma) + ig\sqrt{\frac{N-1}{2N}}(j,N_\Sigma)\right)$$

magnetic current $k := \delta^* F = {}^*dF, \quad \Xi_\Sigma := \delta^*\Theta_\Sigma\Delta^{-1}$

electric current $j := \delta F, \quad N_\Sigma := \delta\Theta_\Sigma\Delta^{-1}$

$\Delta = d\delta + \delta d, \quad \Theta_\Sigma := \int_\Sigma d^2S^{\mu\nu}(\sigma(x))\delta^D(x - x(\sigma))$

k and j are gauge invariant and conserved currents; $\delta k = \delta j = 0$.

K.-I. Kondo PRD77 085929(2008)

Note that field strength $F[V]$ is described by V-field in the minimal option.

The lattice version of magnetic monopole current is defined by using plaquette:

$$\Theta^8_{\mu\nu} := -\arg\,\mathrm{Tr}\left[\left(\frac{1}{3}\mathbf{1} - \frac{2}{\sqrt{3}}\mathbf{h}_x\right)V_{x,\mu}V_{x+\mu,\mu}V^\dagger_{x+\nu,\mu}V^\dagger_{x,\nu}\right],$$

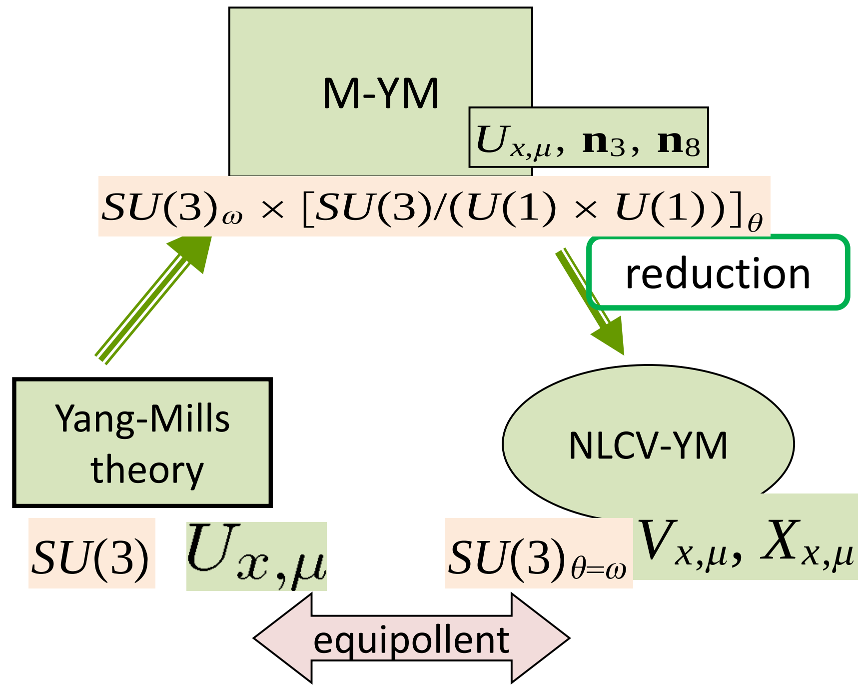
$$k_\mu = 2\pi n_\mu := \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}\partial_\nu\Theta^8_{\alpha\beta},$$

maximal option: The decomposition of SU(3) link variable

$$U_{x,\mu} = X_{x,\mu} V_{x,\mu}$$

$$U_{x,\mu} \rightarrow U'_{x,\mu} = \Omega_x U_{x,\mu} \Omega^{\dagger}_{x+\mu}$$
$$V_{x,\mu} \rightarrow V'_{x,\mu} = \Omega_x V_{x,\mu} \Omega^{\dagger}_{x+\mu}$$
$$X_{x,\mu} \rightarrow X'_{x,\mu} = \Omega_x X_{x,\mu} \Omega^{\dagger}_{x}$$

$$\Omega_x \in G = SU(N)$$



Gauge invariant construction of the Abelian projection to maximal torus group U(1) x U(1) in MA gauge.

maximal option: Defining equation for the decomposition

By introducing color fields $\mathbf{n}_x^{(3)} = \Theta_x(\lambda^3/2)\Theta^\dagger$, $\mathbf{n}_x^{(8)} = \Theta_x(\lambda^8/2)\Theta^\dagger$ $\in SU(3)_\omega \times [SU(3)/(U(1)\times U(1))]_\theta$, a set of the defining equation for the decomposition $U_{x,\mu} = X_{x,\mu}V_{x,\mu}$ is given by

$$D_\mu^\varepsilon[V]n_x^{(k)} = \frac{1}{\varepsilon}(V_{x,\mu}n_{x+\mu}^{(k)} - n_x^{(k)}V_{x,\mu}) = 0, \ (k = 3,8)$$

$$g_x = \exp(2\pi i n/N)\exp(i\sum_{j=3,8} a^{(j)}n_x^{(j)}) = 1$$

Coressponding to the continuum version of the dexomposition $\mathcal{A}_\mu(x) = \mathcal{V}_\mu(x) + \mathcal{X}_\mu(x)$

$$D_\mu[\mathcal{V}_\mu]\mathbf{n}^{(k)}(x) = 0, \quad tr(\mathbf{n}^{(k)}(x)\mathcal{X}_\mu(x)) = 0, \ (k = 3,8)$$

$$X_{x,\mu} = \hat{K}_{x,\mu}^\dagger \det(K_{x,\mu})^{1/3} g_x^{-1}, \quad V_{x,\mu} = g_x \hat{K}_{x,\mu} \det(K_{x,\mu})^{-1/3}$$

where

$$\hat{K}_{x,\mu} := \left(\sqrt{K_{x,\mu}K_{x,\mu}^\dagger}\right)^{-1} K_{x,\mu}, \quad \hat{K}_{x,\mu}^\dagger = K_{x,\mu}^\dagger \left(\sqrt{K_{x,\mu}K_{x,\mu}^\dagger}\right)^{-1}$$

$$K_{x,\mu} = 1 + 6\mathbf{n}_x^{(3)}U_{x,\mu}\mathbf{n}_{x+\mu}^{(3)}U_{x,\mu}^\dagger + 6\mathbf{n}_x^{(8)}U_{x,\mu}\mathbf{n}_{x+\mu}^{(8)}U_{x,\mu}^\dagger$$

Reduction condition

- The reduction condition is introduced such that the theory in terms of new variables is <u>equipollent to the original Yang-Mills theory</u>

- We here introduce the reduction condition which is the kinetic term of adjoint gauge-Higgs system.

➔ gauge-Higgs system as effective theory in view of the new variables V,X,**n**

Minimal option:

$$SU(3)_\omega \times [SU(3)/U(2)]_\theta \to SU(3)_{\omega-\theta}$$

Determining $\mathbf{h}_x$ to minimize the reduction function for given $U_{x,\mu}$

$$F_{\rm red}[\mathbf{h}_x, U_{x,\mu}] = \sum_{x,\mu} \mathrm{tr}\left\{ (D_\mu^\epsilon[U_{x,\mu}]\mathbf{h}_x)^\dagger (D_\mu^\epsilon[U_{x,\mu}]\mathbf{h}_x) \right\}$$

Maximal option:

$$SU(3)_\omega \times [SU(3)/(U(1)\times U(1))]_\theta \to SU(3)_{\omega=\theta}$$

Determine $\mathbf{n}^{(3)}$ and $\mathbf{n}^{(8)}$ to minimize the following functional

$$F_{\max}[\mathbf{n}^{(3)}, \mathbf{n}^{(8)}; U_{x,\mu}] = \sum_{x,\mu} tr\left(\left\| D_\mu[U]\mathbf{n}_x^{(3)} \right\|^2 \right) + \sum_{x,\mu} tr\left(\left\| D_\mu[U]\mathbf{n}_x^{(8)} \right\|^2 \right)$$

$$\mathbf{n}_x^{(3)} = \Theta_x(\lambda^3/2)\Theta_x^\dagger, \quad \mathbf{n}_x^{(8)} = \Theta_x(\lambda^8/2)\Theta_x^\dagger$$

Reduction condition for maximal option is rewritten into the gauge fixing of maximal Abelian gauge (next slide)

Maximal option

□ magnetic monopole

We have two kind of magnetic monopoles in the maximal option

□ Decomposition in the MA gauge

Decomposition formula is rewritten into Abelian projection in Maximal Abelian gauge

➔ Abelian projection in in the MA gage

$$k_\mu^{(j)} := \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}\partial_\nu \Theta_{\alpha\beta}^{(j)}$$

$$\Theta_{\alpha\beta}^{(1)} = \arg\left[\left(\frac{1}{3}\mathbf{1} + \mathbf{n}_x + \frac{1}{\sqrt{3}}\mathbf{m}_x\right) V_{x,\alpha} V_{x+\alpha,\beta} V_{x+\beta,\alpha}^\dagger V_{x,\beta}^\dagger\right]$$

$$\Theta_{\alpha\beta}^{(2)} = \arg\left[\left(\frac{1}{3}\mathbf{1} - \frac{2}{\sqrt{3}}\mathbf{m}_x\right) V_{x,\alpha} V_{x+\alpha,\beta} V_{x+\beta,\alpha}^\dagger V_{x,\beta}^\dagger\right]$$

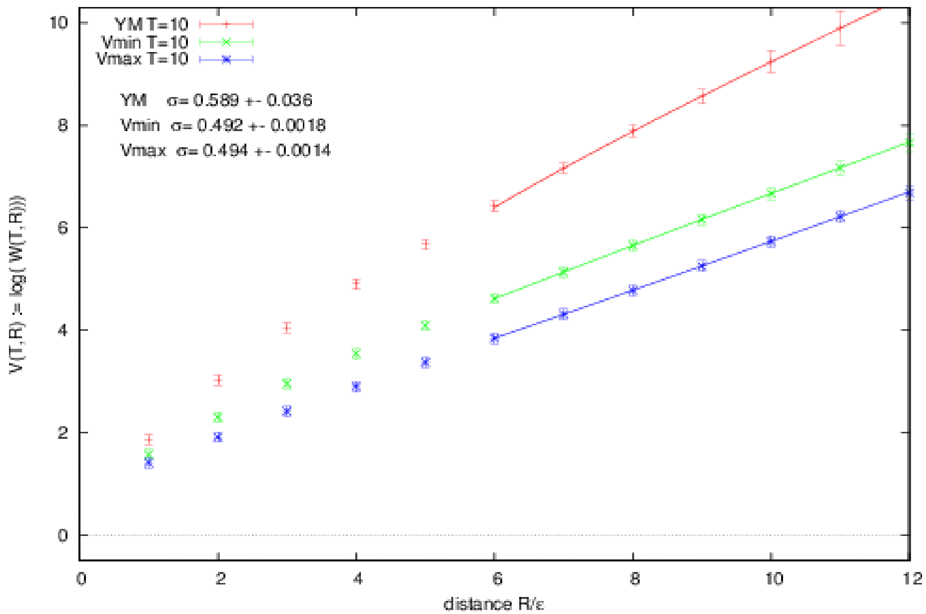
$$\mathbf{n}_x^{(3)} = \Theta_x(\lambda^3/2)\Theta_x^\dagger, \quad \mathbf{n}_x^{(8)} = \Theta_x(\lambda^8/2)\Theta_x^\dagger \quad , {}^{\Theta}U_{x,\mu} = \Theta_x^\dagger U_{x,\mu}\Theta_{x+\mu}$$

$$\begin{aligned} K_{x,\mu} &= \left(U_{x,\mu} + 6\mathbf{n}_x^{(3)} U_{x,\mu}\mathbf{n}_{x+\mu}^{(3)} + 6\mathbf{n}_x^{(8)} U_{x,\mu}\mathbf{n}_{x+\mu}^{(8)}\right) U_{x,\mu}^\dagger \\ &= \Theta_x\left[{}^{\Theta}U_{x,\mu}^\dagger + 6\frac{\lambda^3}{2}{}^{\Theta}U_{x,\mu}^\dagger\frac{\lambda^3}{2} + 6\frac{\lambda^8}{2}{}^{\Theta}U_{x,\mu}^\dagger\frac{\lambda^8}{2}\right]\Theta_{x+\mu}^\dagger\, U_{x,\mu}^\dagger \\ &= 3\Theta_x \begin{bmatrix} {}^{\Theta}u_{x,\mu}^{11} & 0 & 0 \\ 0 & {}^{\Theta}u_{x,\mu}^{22} & 0 \\ 0 & 0 & {}^{\Theta}u_{x,\mu}^{33} \end{bmatrix} \Theta_{x+\mu}^\dagger\, U_{x,\mu}^\dagger \end{aligned}$$

$$V = diag\left(\frac{{}^{\Theta}u_{x,\mu}^{11}}{|{}^{\Theta}u_{x,\mu}^{11}|}, \frac{{}^{\Theta}u_{x,\mu}^{22}}{|{}^{\Theta}u_{x,\mu}^{22}|}, \frac{{}^{\Theta}u_{x,\mu}^{33}}{|{}^{\Theta}u_{x,\mu}^{33}|}\right)$$

DUAL SUPERCONDUCTIVITY AT ZERO TEMPERATUER

String tension: zero temperature



Static potential from Wilson loop average of YM-field and two V-fields in minimal and maximal options

log <W[T=10,R]> vs R

- We obtain the restricted field ("Abelian") dominance (86%) in the string tension for both the minimal option and the maximal option.
- The string tension is almost same with the both options and YM field

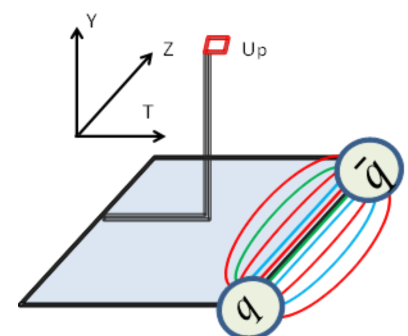
Measurement of chromo flux:

$$\rho_W = \frac{\langle \mathrm{tr}(WLU_pL^\dagger) \rangle}{\langle \mathrm{tr}(W) \rangle} - \frac{1}{N}\frac{\langle \mathrm{tr}(W)\mathrm{tr}(U_p) \rangle}{\langle \mathrm{tr}(W) \rangle}$$

Proposed by Adriano Di Giacomo et.al.
[Phys.Lett.B236:199,1990]
[Nucl.Phys.B347:441-460,1990]

The field strength by quark and antiquark can be defined as

$$F_{\mu\nu}(x) = \sqrt{\frac{\beta}{2N}}\,\rho_W(x)$$

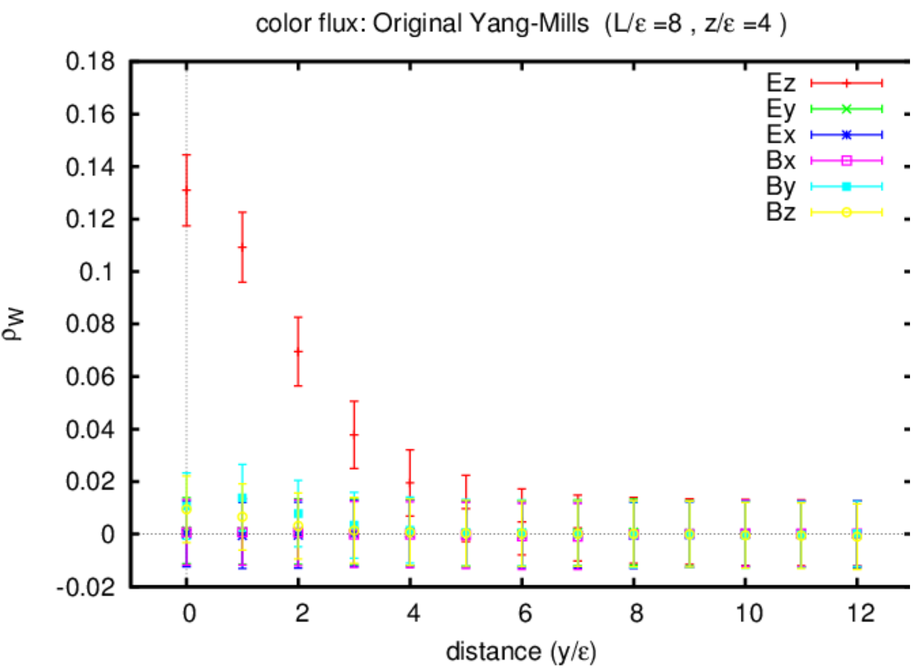


To know the difference between the decomposition, we measure the three types of probes and compare them.

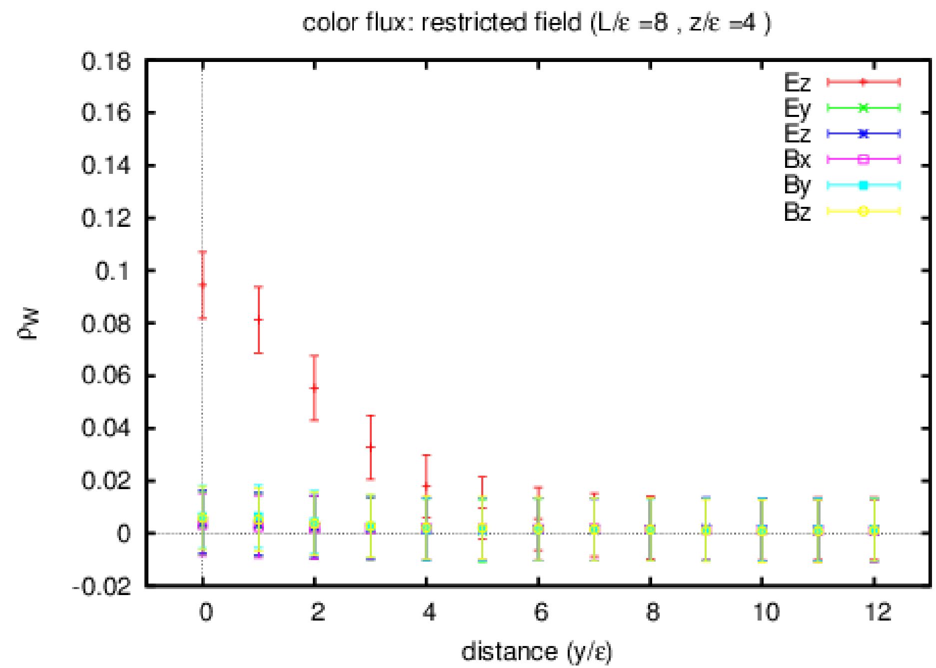
$$O^{[YM]} = L[U]U_pL[U]^{-1} \quad :: \text{ original YM}$$
$$O^{[\mathrm{nin}]} = L[V^{[\mathrm{min}]}]V_p^{[\mathrm{min}]}L[V^{[\mathrm{min}]}]^{-1} \quad :: \text{ V field in minimal option}$$
$$O^{[\mathrm{max}]} = L[V^{[\mathrm{max}]}]V_p^{[\mathrm{max}]}L[V^{[\mathrm{max}]}]^{-1} \quad :: \text{ V field in maximal option}$$

chromo flux

Full Yang-Mills field

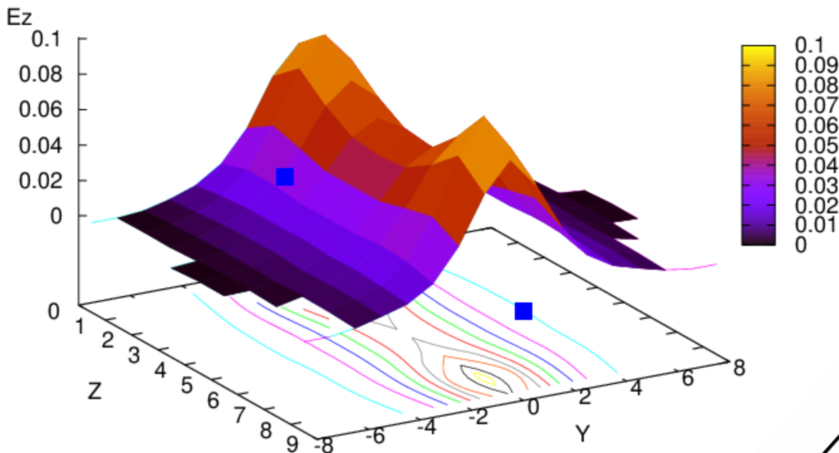


Ristriced field in minimal option

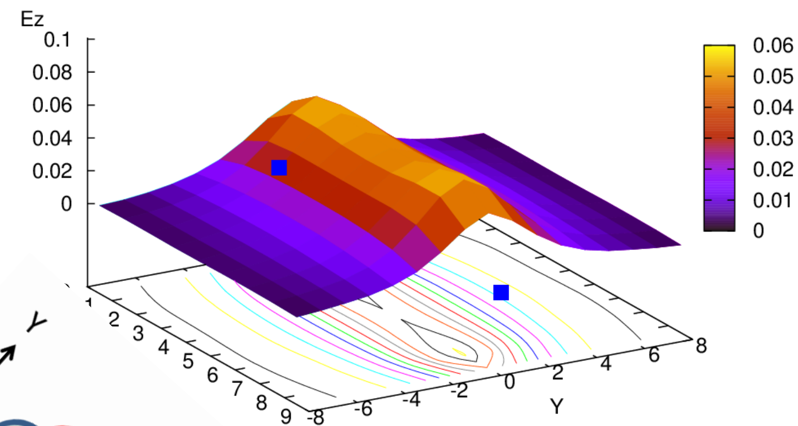


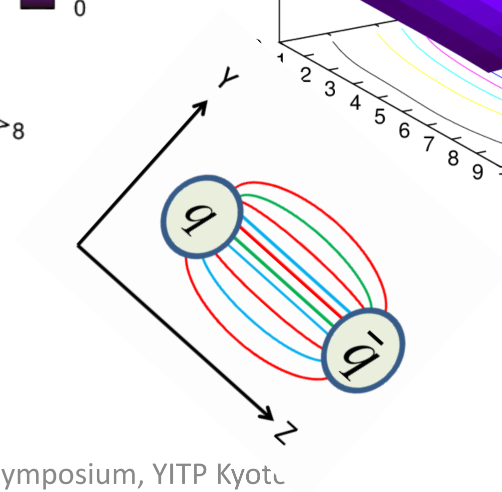
Chromoelectric flux tubes in QCD

Full Yang-Mills



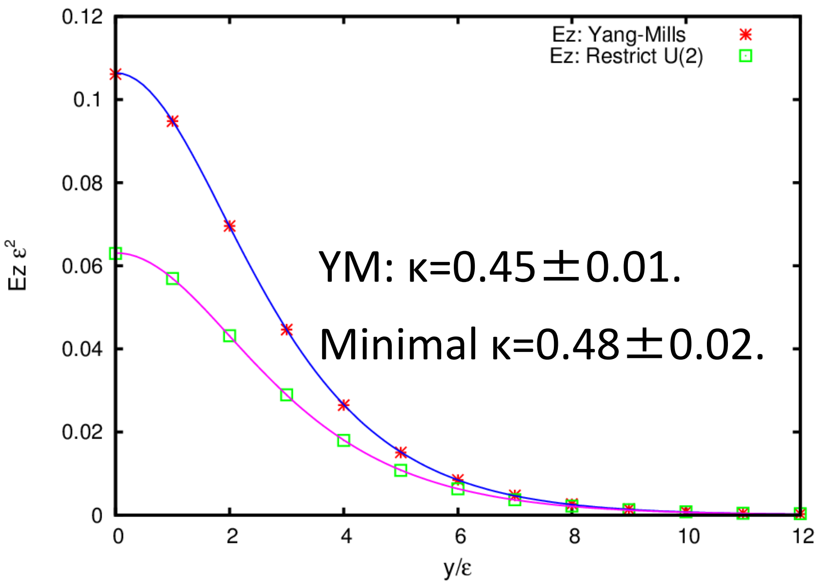
Restricted field V in minimal option





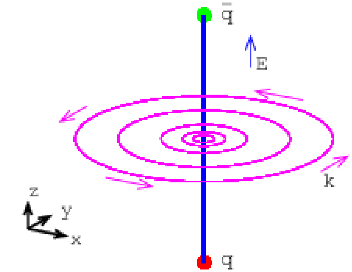
Dual Meissner effect and type of vacuum

Clem’s method

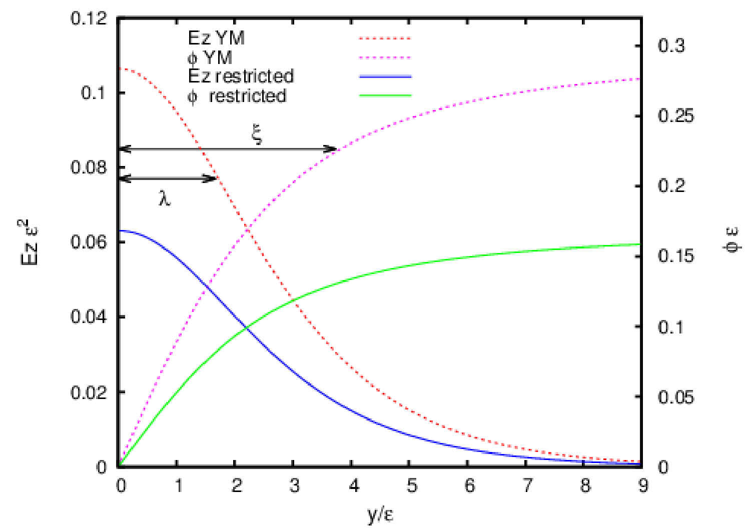


Using U(1) model and Ansatz for scalar field.

GL parameter

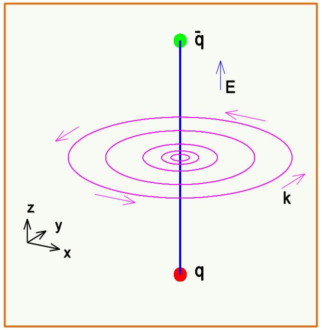


$$\kappa = \sqrt{2}\,\frac{\lambda}{\zeta}\sqrt{1 - K_0^2(\zeta/\lambda)/K_1^2(\zeta/\lambda)}$$



Nishino’s talk (June 13) for improved method.

Induced magnetic current (monopole)



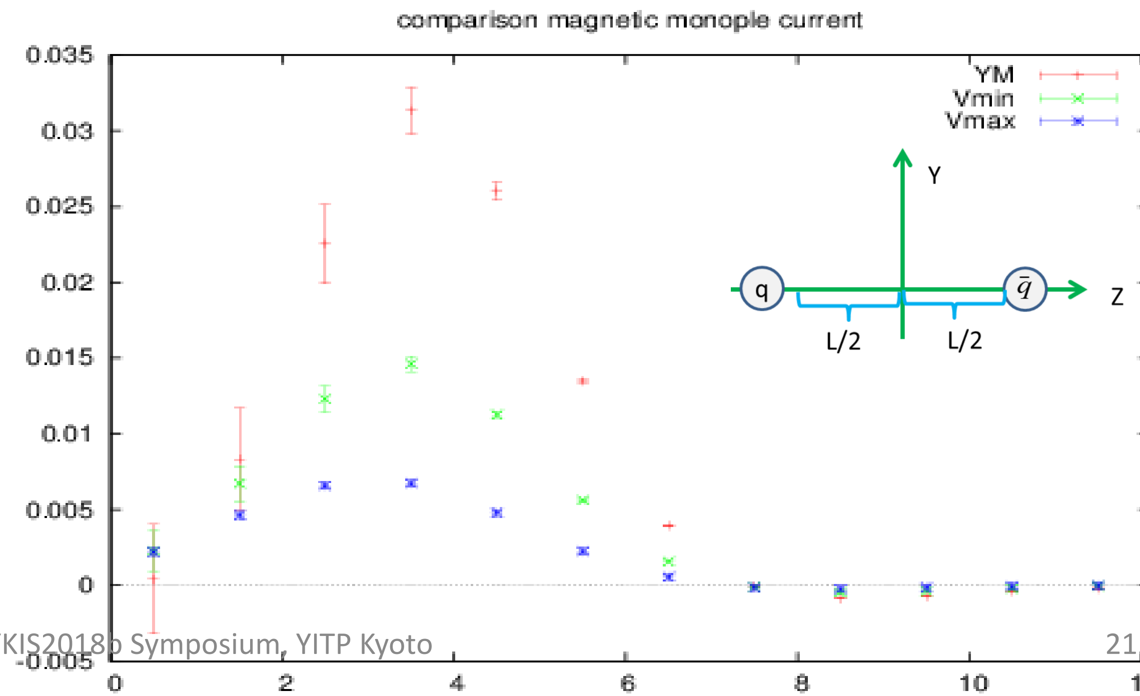
The magnetic current *k must* be *zero* for regular function F due Bianchi Identity.

Non zero k suggests the monopole condensation

Yang–Mills equation (Maxell equation) fo rrestricted field V_μ, the magnetic current (monopole) can be calculated as

$$k = \delta^* F[V] = {}^* dF[V],$$

where $F[V]$ is the field strength of V, d exterior derivative, $*$ the Hodge dual and δ the coderivative $\delta := {}^* d^*$, respectively.



DUAL SUPERCONDUCTIVITY AT FINITE TEMPERATURE

- Plyakov loops and ristriced field at finite temperature
  - Distribution of Plyakov loop values
  - Plyakov loop average and center symmetry breaking/restoration
- Static potential of quark and antiquark
  - correlation function of Plyakov loops
  - Wilson loop average
- dual Meissner effect and confiment/deconfinement phase transition
  - Appearance/disappearance of chromoelectric flux tube
  - Induced magnetic current (monopole)

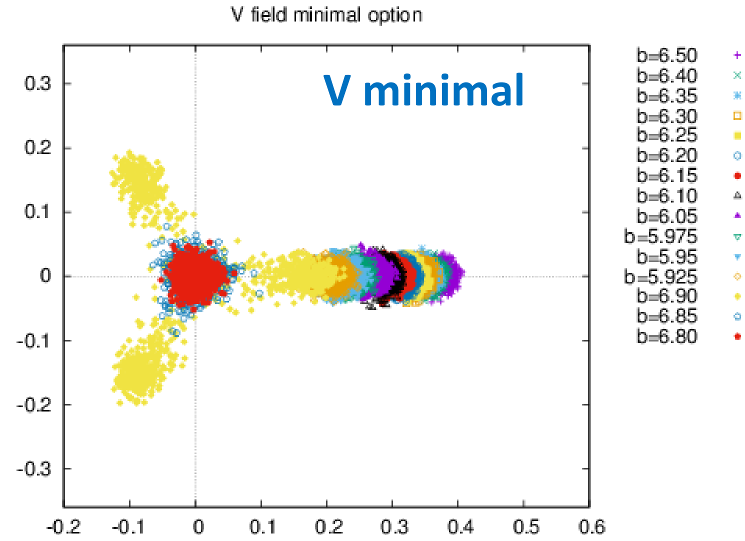
Polyakov loop

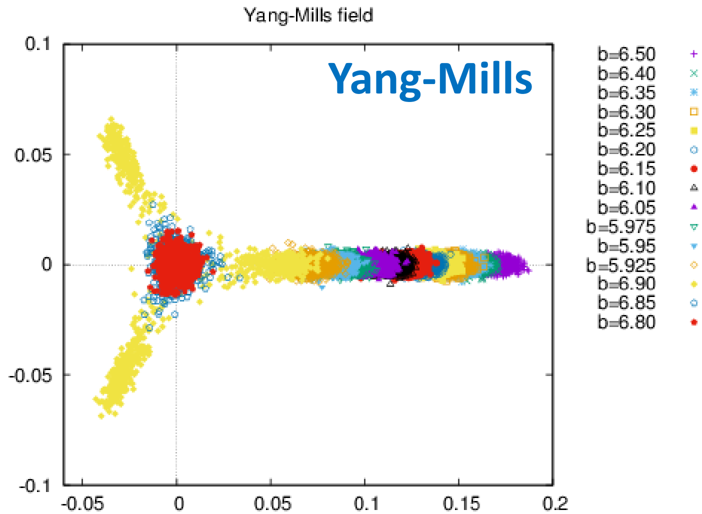
$$P_U(x) = \mathrm{tr}\left(\prod_{t=1}^{Nt} U_{(x,t),4}\right) \text{ for original Yang–Mills filed}$$

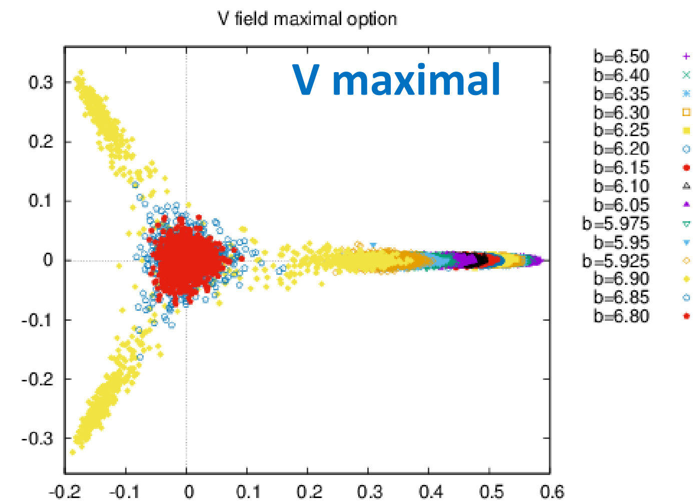
$$P_V(x) = \mathrm{tr}\left(\prod_{t=1}^{Nt} V_{(x,t),4}\right) \text{ for restricted field}$$

- Distribution of Plyakov loop values
- Plyakov loop average and center symmetry breaking/restoration

Distribution of Polyakov loop values

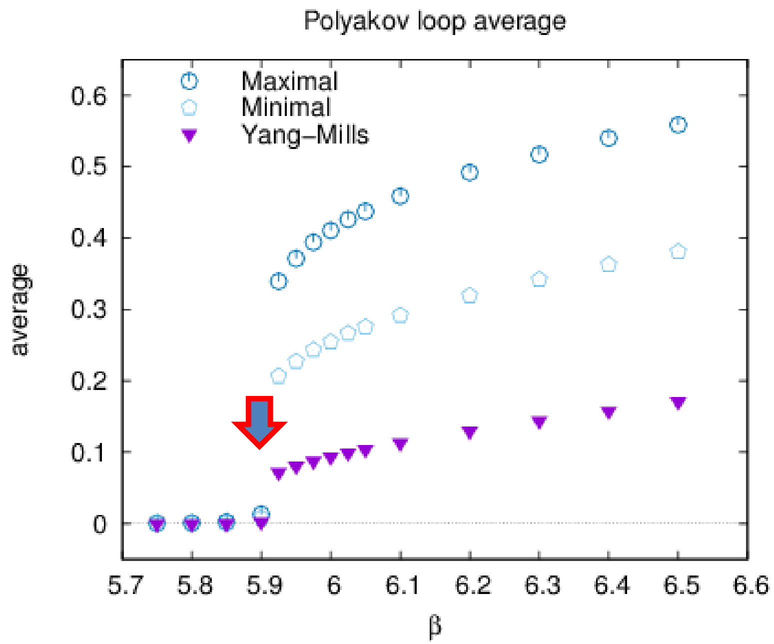




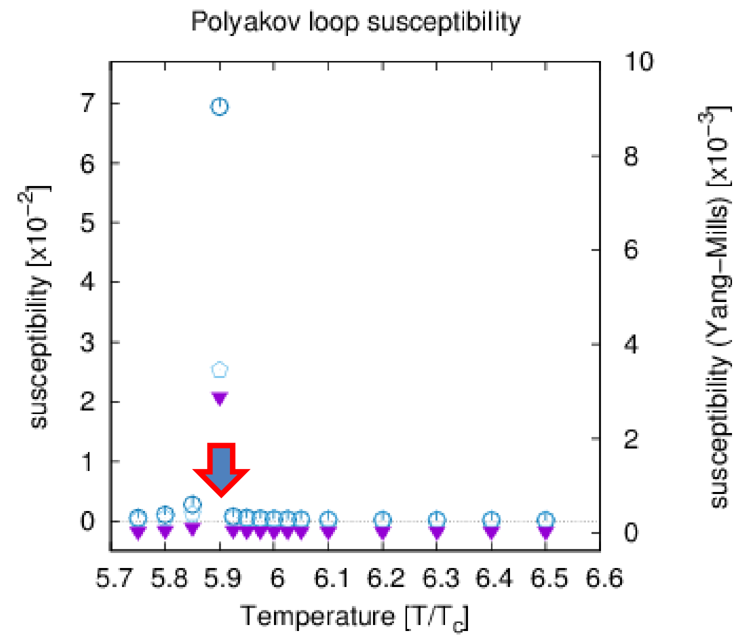


Polyakov loop average and center symmetry

Polyakov loop average



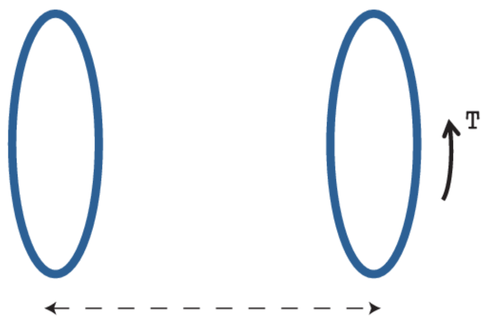
Polyakov loop susceptibility



Magnitude of Polyakov-loop average is different, but gives the same phase transition temperature (β).

Static potential of quark and antiquark

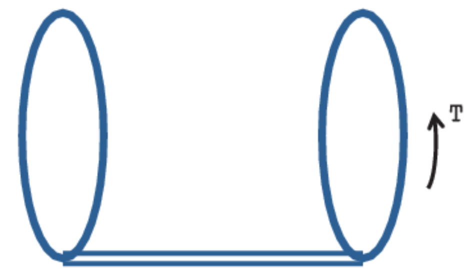
Correlation function of Plyakov loop



$$\tilde{V}(R;U) \coloneqq -T\log\langle P_U(\vec{x})P^*_U(\vec{y})\rangle,$$
$$\tilde{V}(R;V) \coloneqq -T\log\langle P_V(\vec{x})P^*_V(\vec{y})\rangle,$$

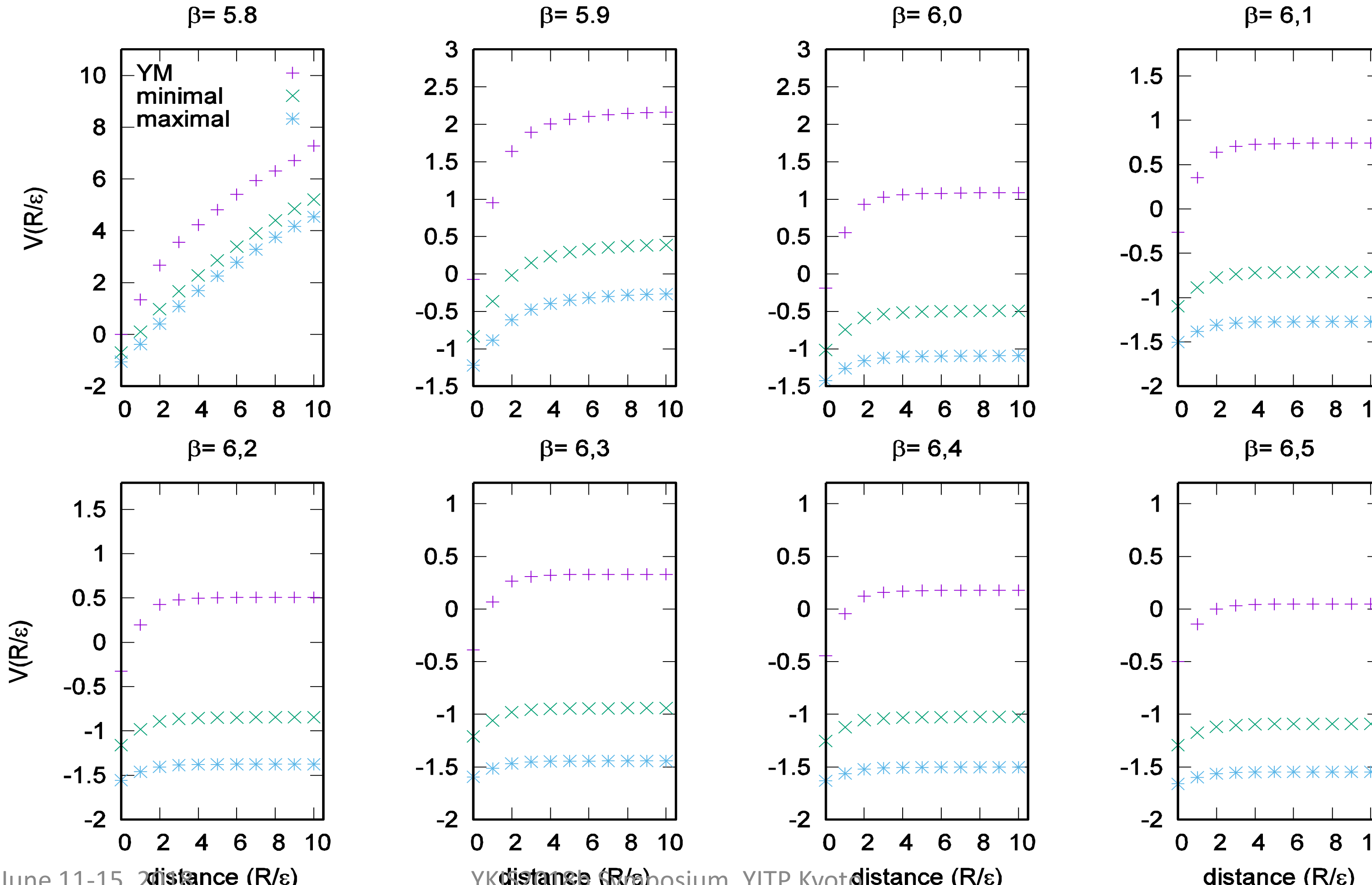
$$\langle P_U(\vec{x})P^*_U(\vec{y})\rangle$$
$$\simeq e^{-F_{q\bar{q}}/T} = \frac{1}{N_c^2}e^{-F^{(S)}/T} + \frac{N_c^2-1}{N_c^2}e^{-F^{(A)}/T}$$

Wilson loop

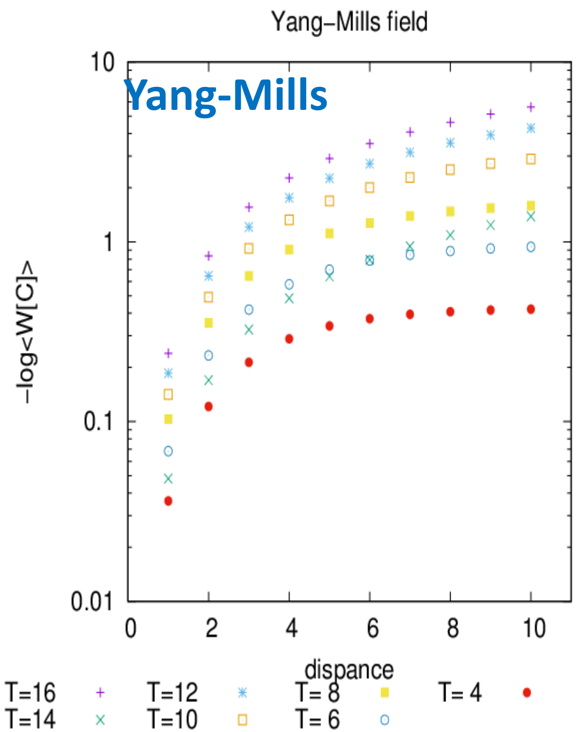


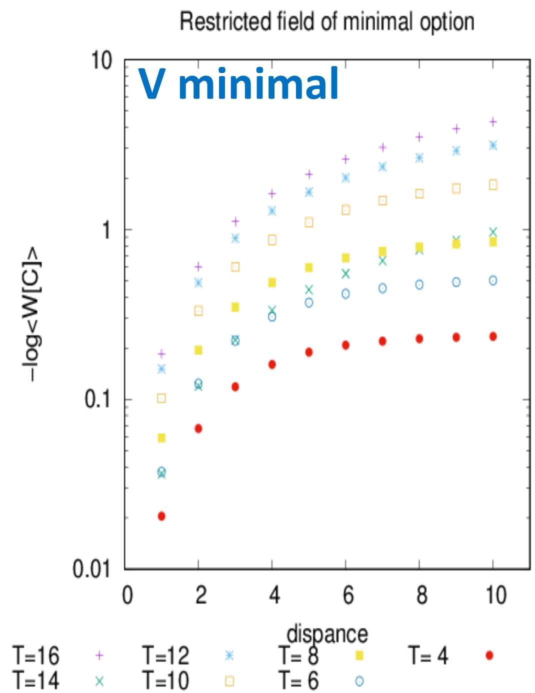
$$V(R;U) \coloneqq -T\log\langle W_U\rangle,$$
$$V(R;V) \coloneqq -T\log\langle W_V\rangle$$

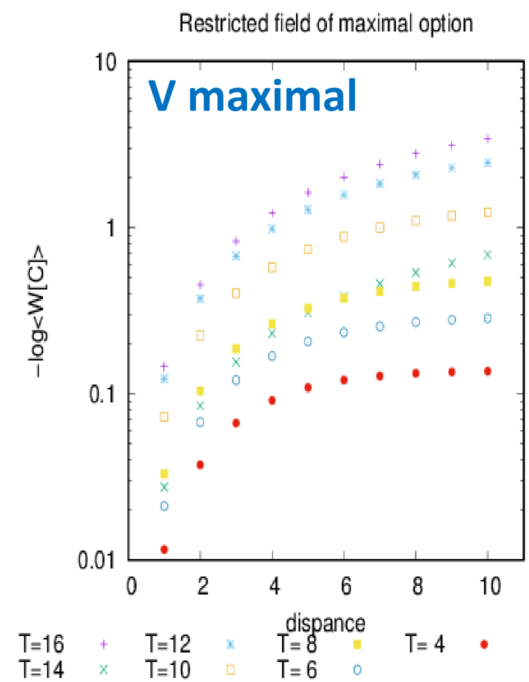
static potential (correlation function of Plyakov loops)



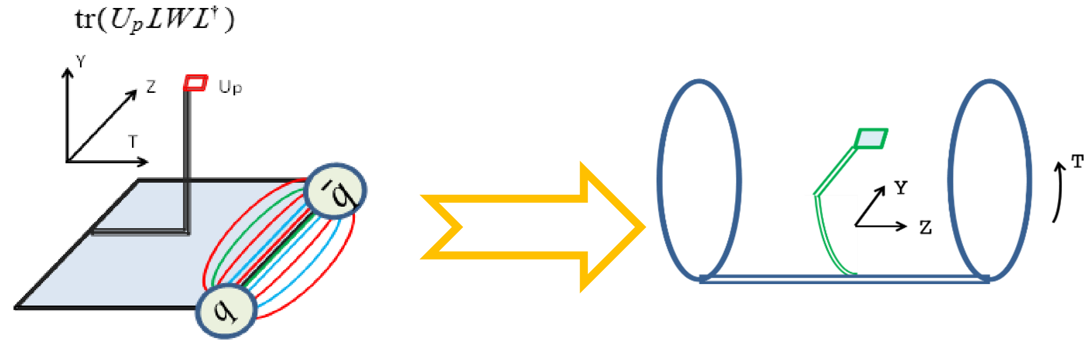
Static potential by Wilson loop







Measurement of chromo flux at finite temperature



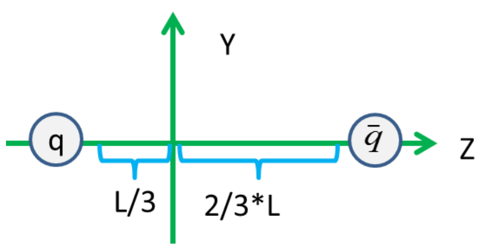
$$\rho_W = \frac{\langle \mathrm{tr}(W L U_p L^\dagger) \rangle}{\langle \mathrm{tr}(W) \rangle} - \frac{1}{N} \frac{\langle \mathrm{tr}(W) \mathrm{tr}(U_p) \rangle}{\langle \mathrm{tr}(W) \rangle}$$

$$F_{\mu\nu}(x) = \sqrt{\frac{\beta}{2N}} \rho_W(x)$$

- Using the same operator with that of zero temperature.
- Size of Wilson loop T-direction = Nt

➔The source of quark and antiquark are given by **Plyakov loops** connecting by Wilson line.

- The three types of probes and compare them.

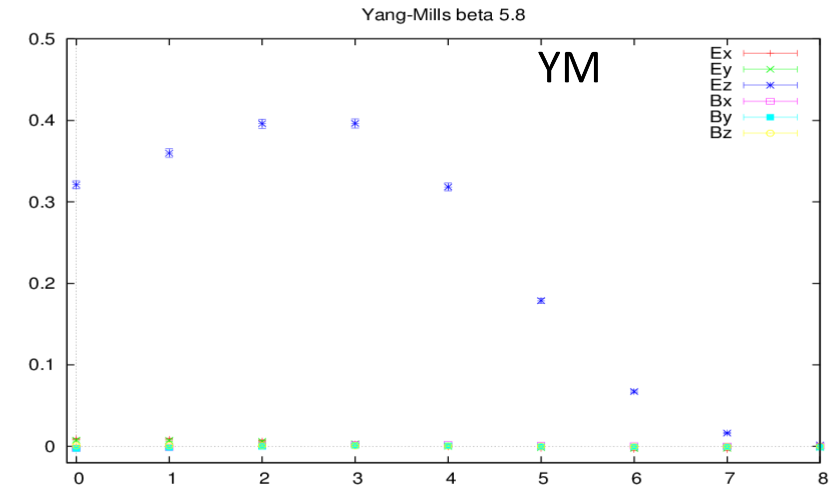


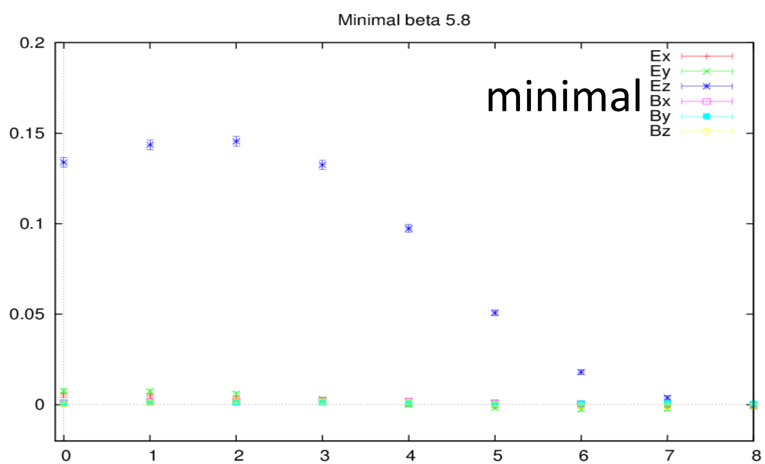
$$O^{[YM]} = L[U] U_p L[U]^{-1} \quad \text{:: original YM}$$

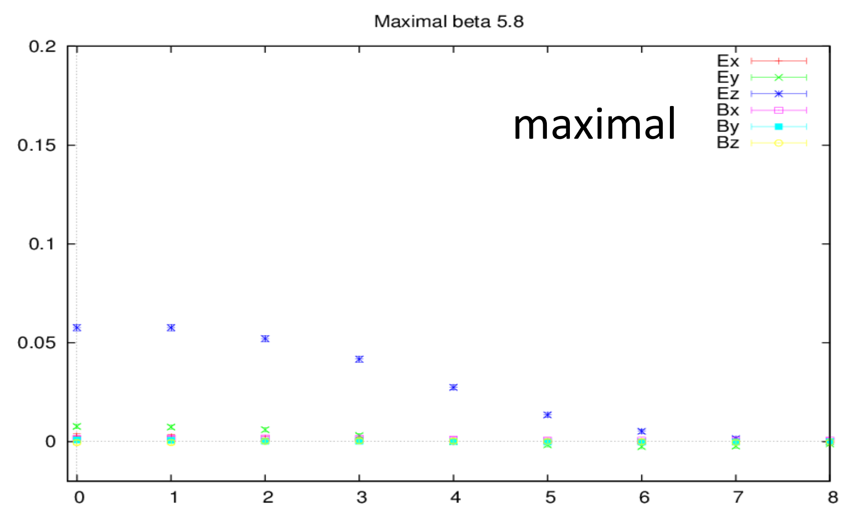
$$O^{[\min]} = L[V^{[\min]}] V_p^{[\min]} L[V^{[\min]}]^{-1} \quad \text{:: V field in minimal option}$$

$$O^{[\max]} = L[V^{[\max]}] V_p^{[\max]} L[V^{[\max]}]^{-1} \quad \text{:: V field in maximal option}$$

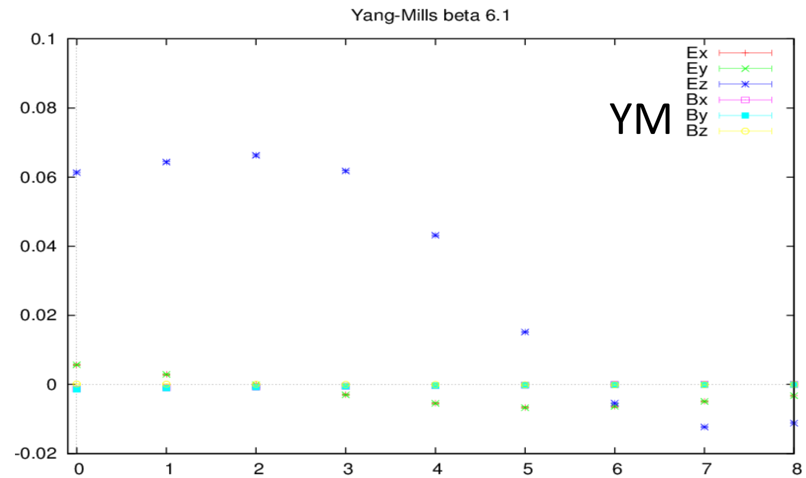
Chromo flux in confining phase

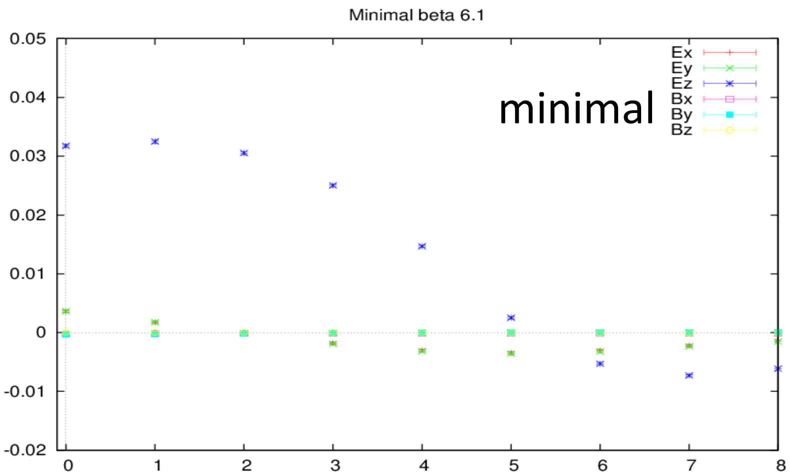


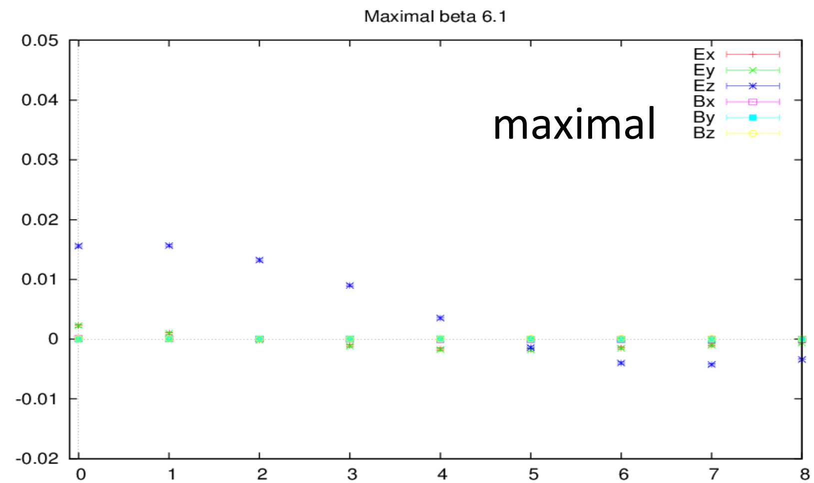




Chromo flux
in deconfining phase





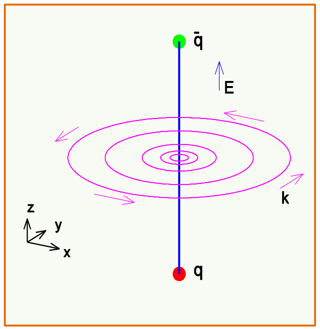


Induced magnetic current (monopole) at finite temperature

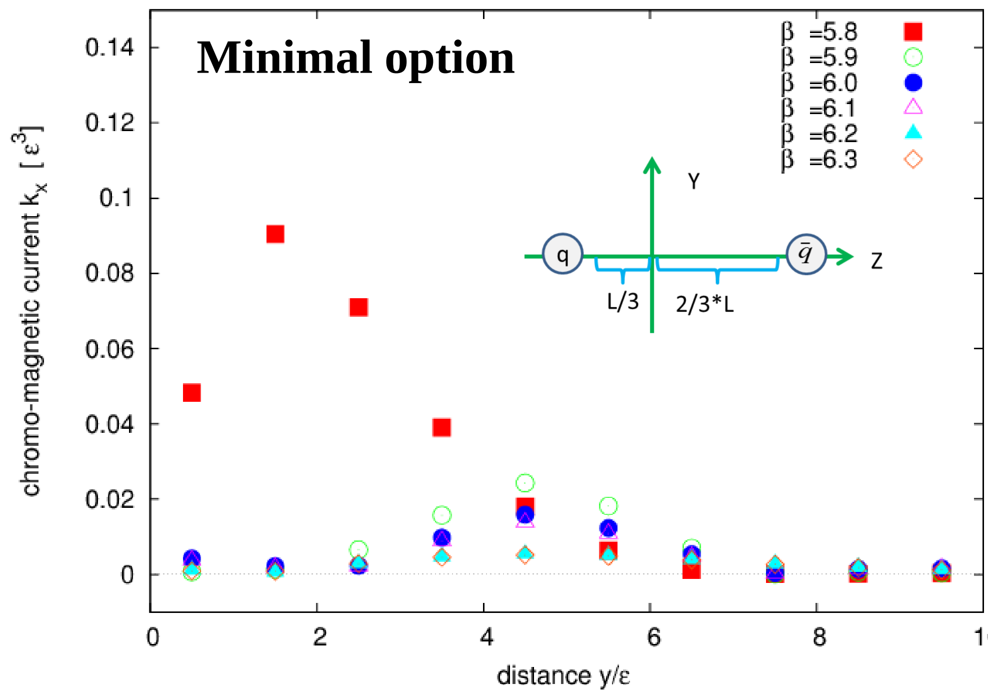
Yang–Mills equation (Maxell equation) fo rrestricted field V_μ, the magnetic current (monopole) can be calculated as

$$k = \delta^* F[V] = {}^* dF[V],$$

where $F[V]$ is the field strength of V, d exterior derivative, * the Hodge dual and δ the coderivative $\delta := {}^*d^*$, respectively.



Induced magnetic current (monopole) k can be a order parameter of the dual Meissner effect.



Summary

- We investigate dual superconductivity applying our new formulation of Yang-Mills theory on the lattice, i.e., in the minimal and maximal options as well as Yang-Mills field at finite temperature.

- In both options we have found that
  - The Polyakov loop averages, the conventional order parameter, gives the same critical temperature of confinement/deconfinement phase transition with both options and the YM field
  - the restricted field (V-field) dominance in the string tension, and the string tension is almost same.

Summary(cont')

- Confinement/deconfinement phase transition
- In confining phase
  - we observe the dual Meissner effect.
  - The induced magnetic (monopole) currents appear around chromo-electro flux tube between a pair of quark and antiquark.
- In deconfining phase
  - we find no more the dual Meissner effect
  - i.e., the induced magnetic (monopole) currents disappear or becomes very small

THANK YOU FOR YOUR ATTENTION