熱場の量子論とその応用　2022年 9月20日～22日

クォーク閉じ込め・非閉じ込め相転移と双対超伝導描像

柴田章博　(KEK, 計算科学センター)
共同研究：近藤慶一（千葉大），加藤清考（小山高専）

Based on
• arXiv 1911.00898 [hep-lat], KEK Preprint 2019-2. CHIBA-EP-226
•results in recent development

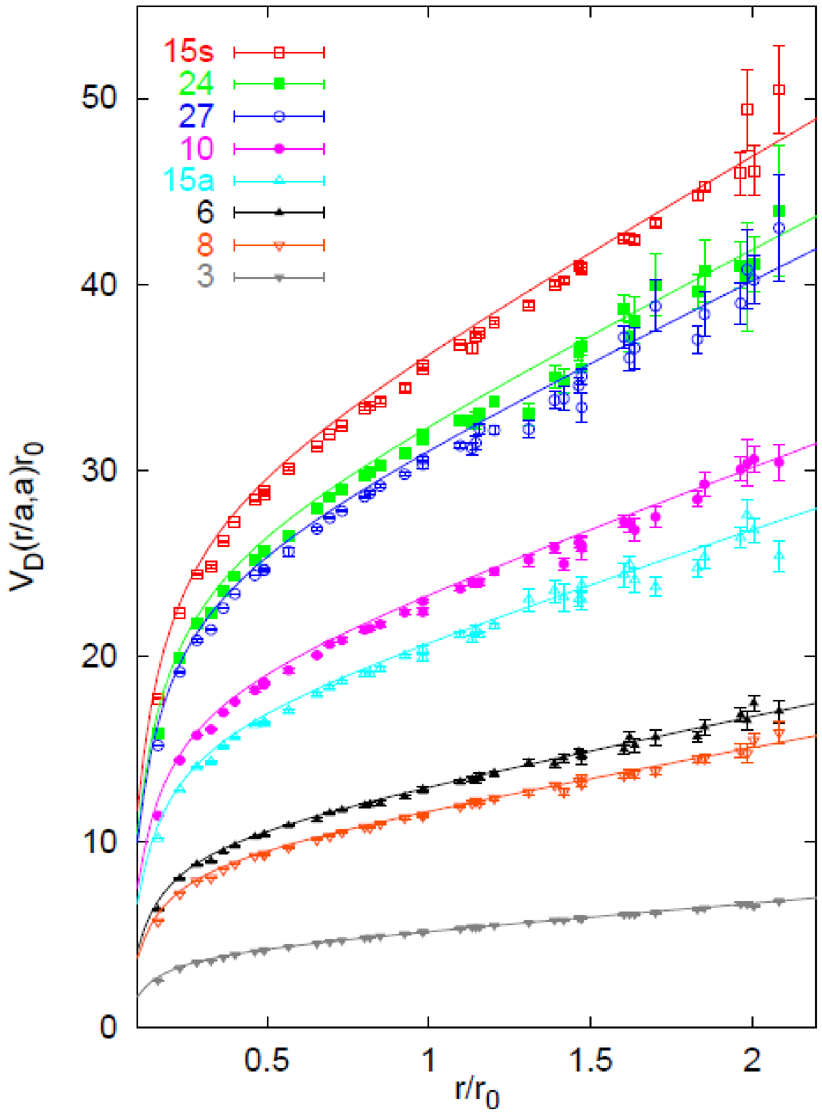
Intoroduction

- 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
  - For Wilson loops in the various representations
  - confinement/deconfinement phase transition at finite temperature

In $SU(3)$ Source: Bali(2000)



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

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.

✓Only for Wilson loop in the fundamental representation.

Decomposition method

[a new formulation on a lattice]

Extracting the relevant mode *V* for quark confinement in the gauge independent way (gauge-invariant way) by solving the gauge-covariant defining equation

➔The Abelian projection method can be reformulated by using the decomposition method in the gauge invariant way.

➔ For Wilson loops in arbitrary representations [PRD 100, 014505 (2019)]

Gauge-covariant Decomposition (fundamental representations)

[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)⊂SU(2)
- SU(3) Yang-Mills link variables: Two options

minimal option : U(2)≅SU(2)×U(1)⊂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)×U(1)⊂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 theory

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

Gauge-covariant decomposition (minimal option)

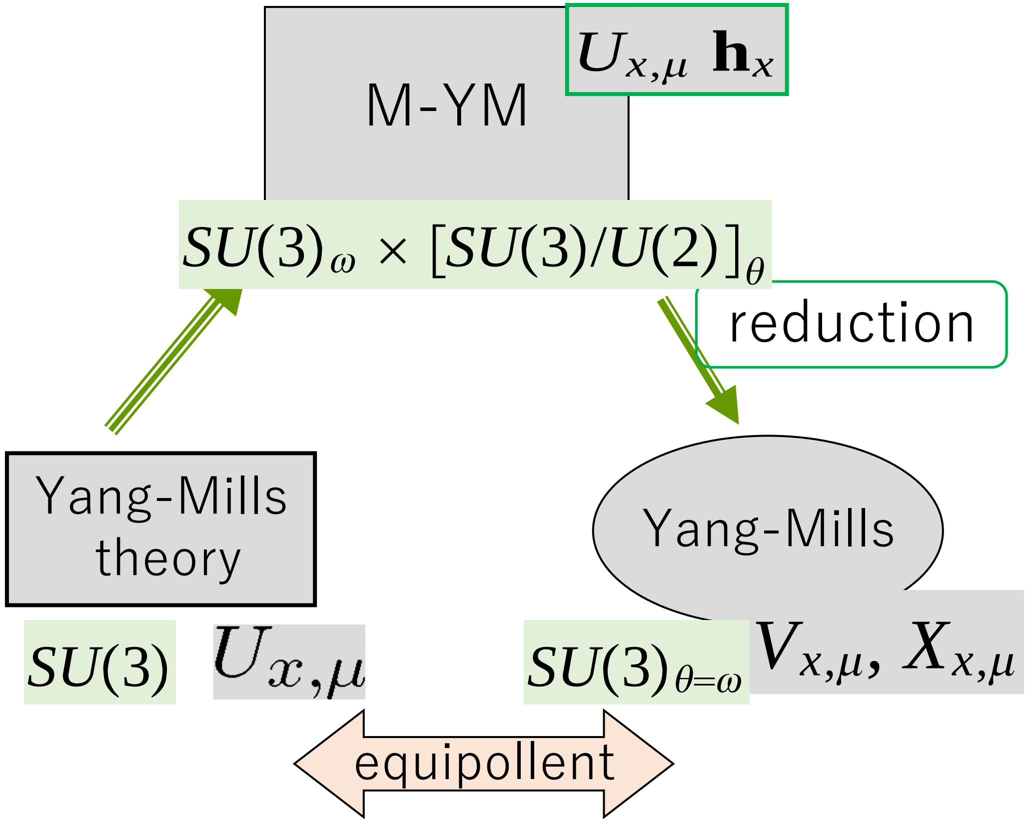
$$W_C[U] := \mathrm{Tr}\left[P \prod_{\langle x, x+\mu \rangle \in C} U_{x,\mu} \right] / \mathrm{Tr}(\mathbf{1})$$

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

$$\begin{aligned} U_{x,\mu} &\to U'_{x,\mu} = \Omega_x U_{x,\mu} \Omega^\dagger_{x+\mu} \\ V_{x,\mu} &\to V'_{x,\mu} = \Omega_x V_{x,\mu} \Omega^\dagger_{x+\mu} \\ X_{x,\mu} &\to X'_{x,\mu} = \Omega_x X_{x,\mu} \Omega^\dagger_x \end{aligned}$$

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

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



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

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

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

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:

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

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

Gauge-covariant decomposition (maximal option)

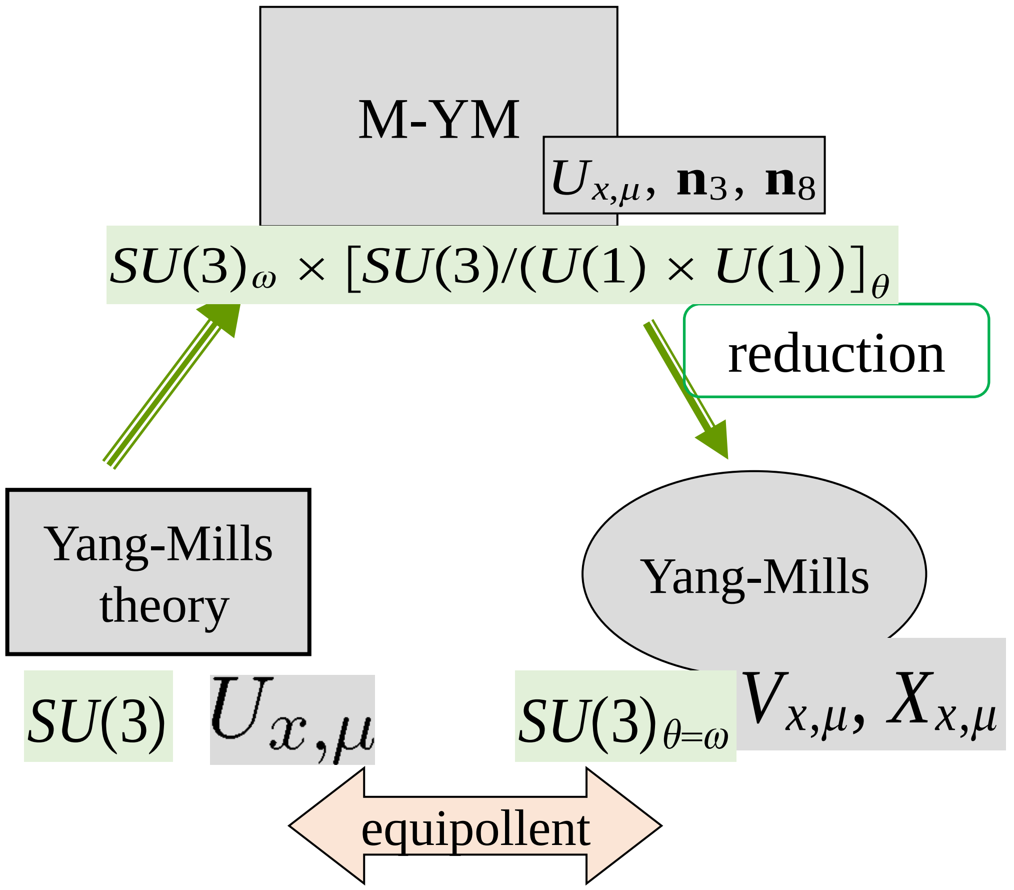
$$U_{x,\mu} = X_{x,\mu} V_{x,\mu}$$

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

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

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

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



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 $\mathcal{A}_\mu(x) = V_\mu(x) + \mathcal{X}_\mu(x)$

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

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

where

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

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

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

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

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

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

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

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

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

Reduction Condition:

- The decomposition is uniquely determined for a given set of link variables $U_{x,\mu}$ and color fields which is given by minimizing the reduction condition.
- The reduction condition is introduced such that the theory in terms of new variables is equipollent to the original Yang-Mills theory, i.e., defining an effective gauge-scalar model whose kinetic term is given by the reduction condition

for given $U_{x,\mu}$

$$F[\Theta; U] = \begin{cases} \sum_{x,\mu} \mathrm{tr}\left[\sum_{j=3,8} (D^{\epsilon}_{\mu}[U]\mathbf{n}^{(j)})^{\dagger} (D^{\epsilon}_{\mu}[U]\mathbf{n}^{(j)})\right] & \text{represented MA} \\ \sum_{x,\mu} \mathrm{tr}\left[\sum_{j} (D^{\epsilon}_{\mu}[U]\mathbf{n}^{(8)})^{\dagger} (D^{\epsilon}_{\mu}[U]\mathbf{n}^{(8)})\right] & \text{representied n8} \\ \sum_{x,\mu} \mathrm{tr}\left[\sum_{j} (D^{\epsilon}_{\mu}[U]\mathbf{n}^{(3)})^{\dagger} (D^{\epsilon}_{\mu}[U]\mathbf{n}^{(3)})\right] & \text{represented n3} \end{cases}$$

$\mathbf{n}^{(3)}$where $\mathbf{n}_j := \Theta^{\dagger} H_j \Theta$, H_j Cartan generators, and $D^{\epsilon}_{\mu}[U]\mathbf{n}^{(j)} := U_{x,\mu}\mathbf{n}^{(j)}_{x+\mu} - \mathbf{n}^{(j)}_{x} U_{x,\mu}$

Wilson loop operator in the representation R=[m_1,m_2] for SU(3) case

PRD 100, 014505 (2019)

Written by using decomposed gauge field *V* (for fundamental representation)

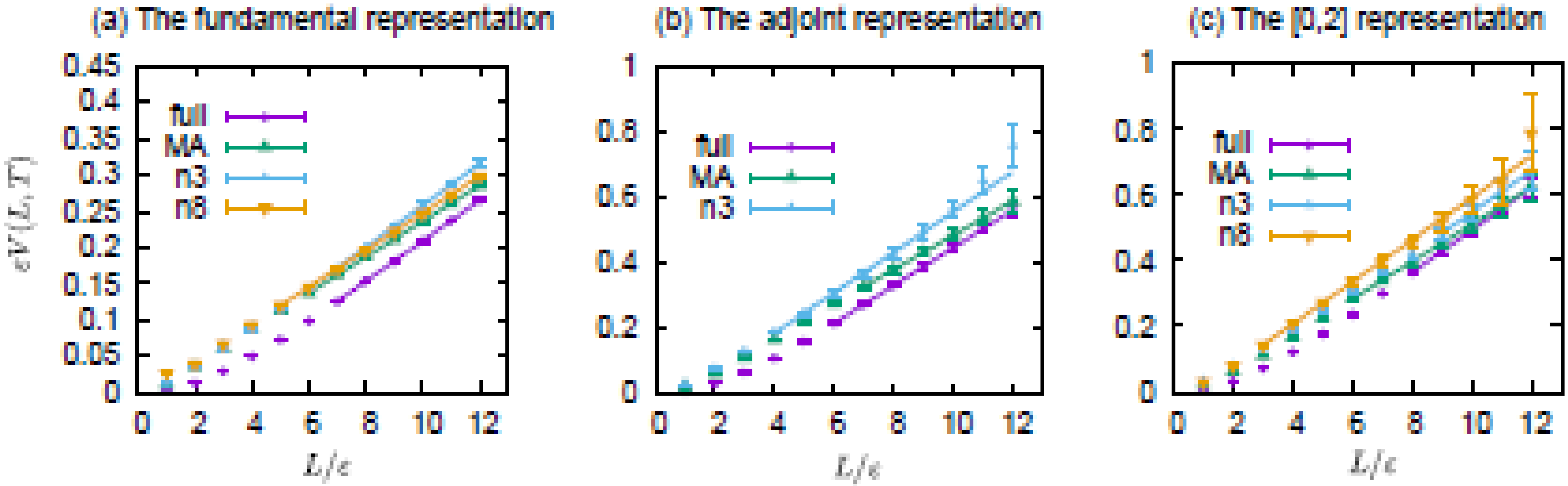
$$W_{(m_1,m_2)}[V](C) = \frac{1}{6}\left(\mathrm{tr}(V_c^{m_1})\mathrm{tr}(V_c^{\dagger m_2}) - \mathrm{tr}(V_c^{m_1} V_c^{\dagger m_2})\right)$$

$$V_c \; := \prod_{<x.\mu>\in C} V_{x,\mu}$$

Dual superconductivity at zero temperature

Static Potential at zero temperature

PRD 100, 014505 (2019)



The ristricted field (V-field) dominance for (left) fundamental [0,1] (middle) adjoint [1,1] (right) [0,2] representations.

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 average at the confinement/deconfinement transition

$$P_U(\vec{x}) := \frac{1}{3}\mathrm{tr}\left(P\prod_{t=1}^{N_T} U_{(\vec{x},t),4}\right),$$

$$P_{V^{\min}}(\vec{x}) := \frac{1}{3}\mathrm{tr}\left(P\prod_{t=1}^{N_T} V^{\min}_{(\vec{x},t),4}\right),$$

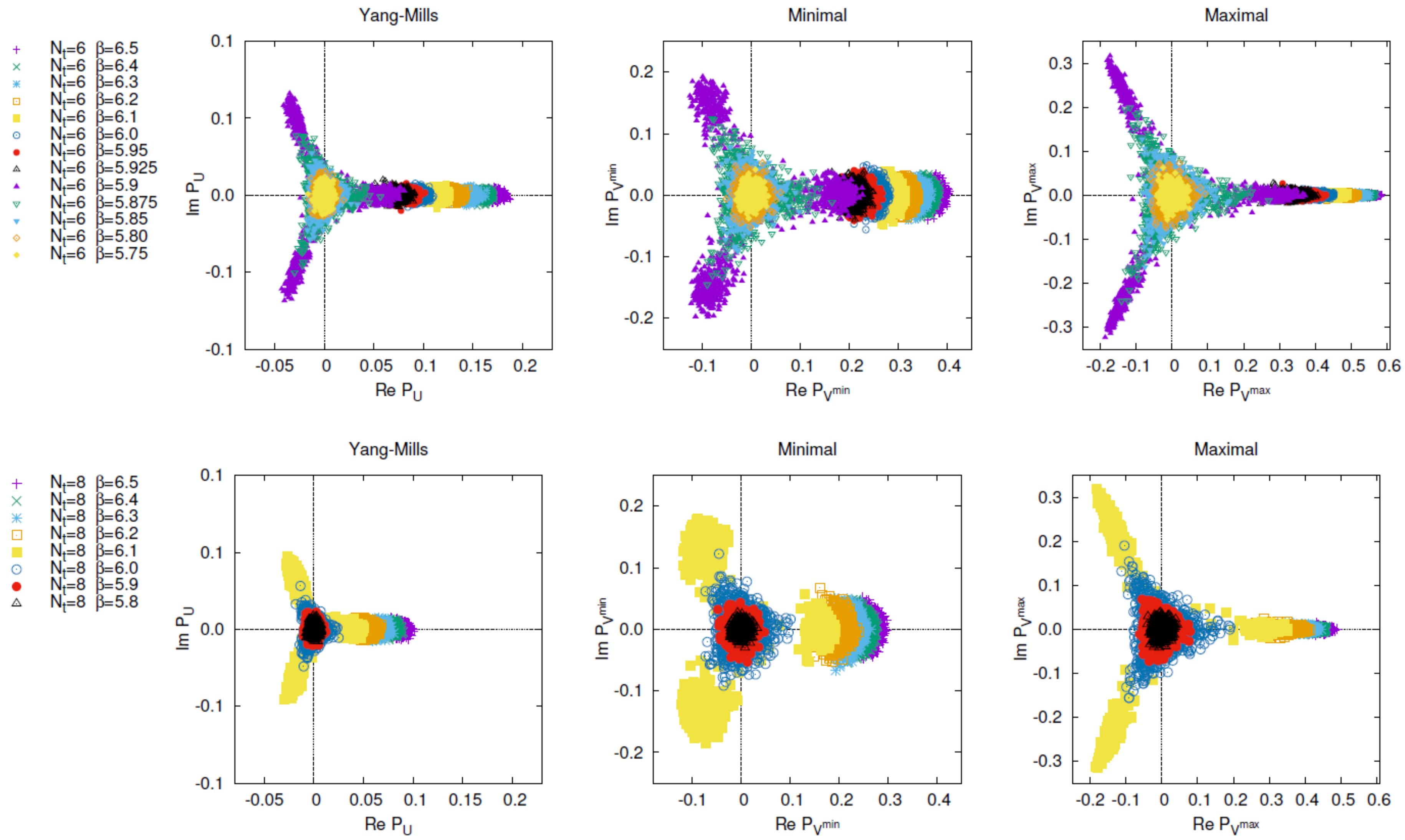
$$P_{V^{\max}}(\vec{x}) := \frac{1}{3}\mathrm{tr}\left(P\prod_{t=1}^{N_T} V^{\max}_{(\vec{x},t),4}\right),$$

$$P_U = \frac{1}{L^3}\sum_{\vec{x}} P_U(\vec{x}),$$

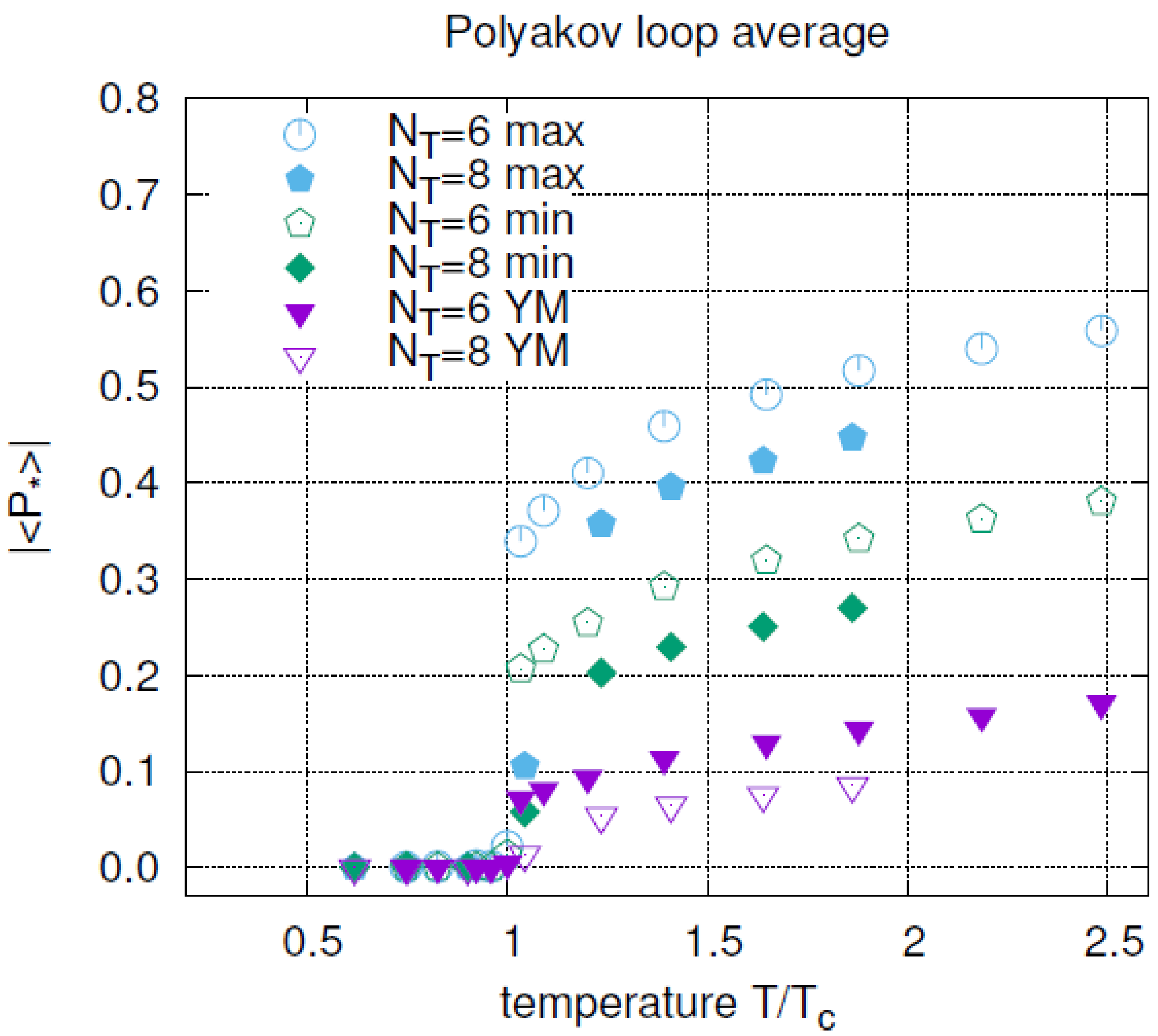
$$P_{V^{\min}} = \frac{1}{L^3}\sum_{\vec{x}} P_{V^{\min}}(\vec{x}),$$

$$P_{V^{\max}} = \frac{1}{L^3}\sum_{\vec{x}} P_{V^{\max}}(\vec{x}),$$

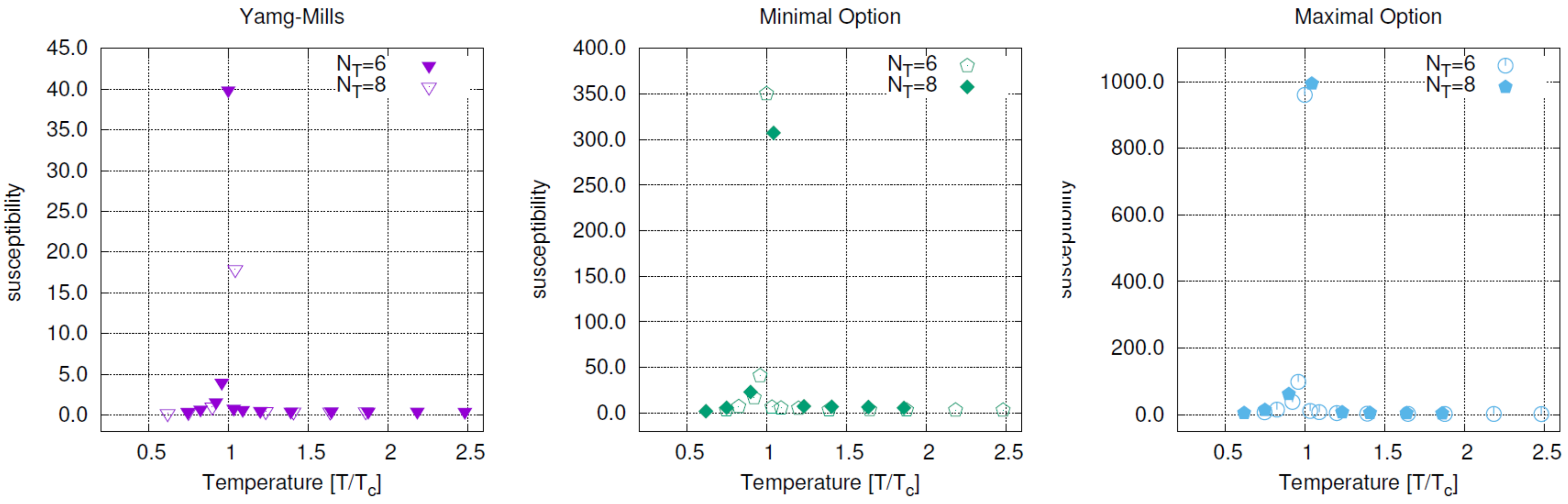
Distribution of space averaged Polyakov loops (R=[0,1])



Polyakov loop average (R=[0,1])

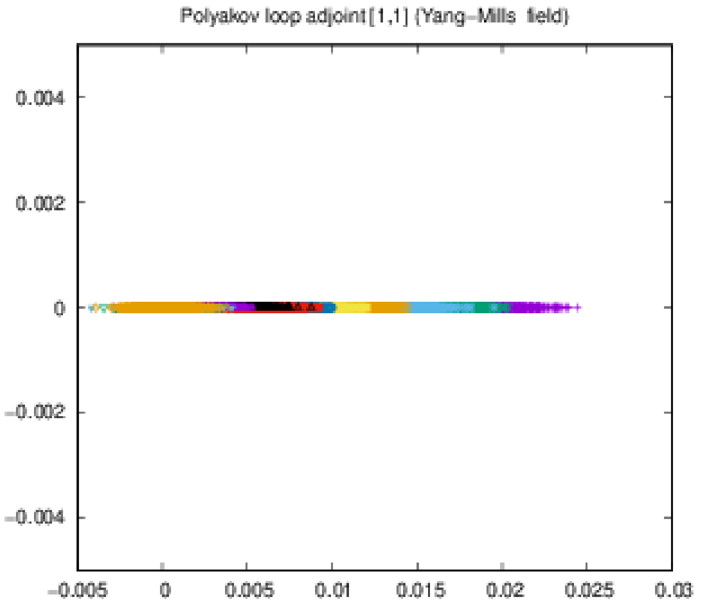


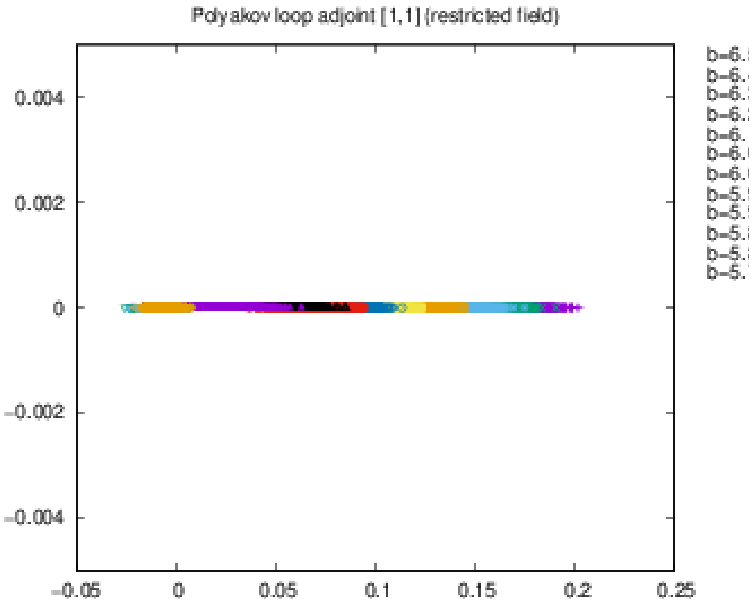
Polyakov loop susceptibility

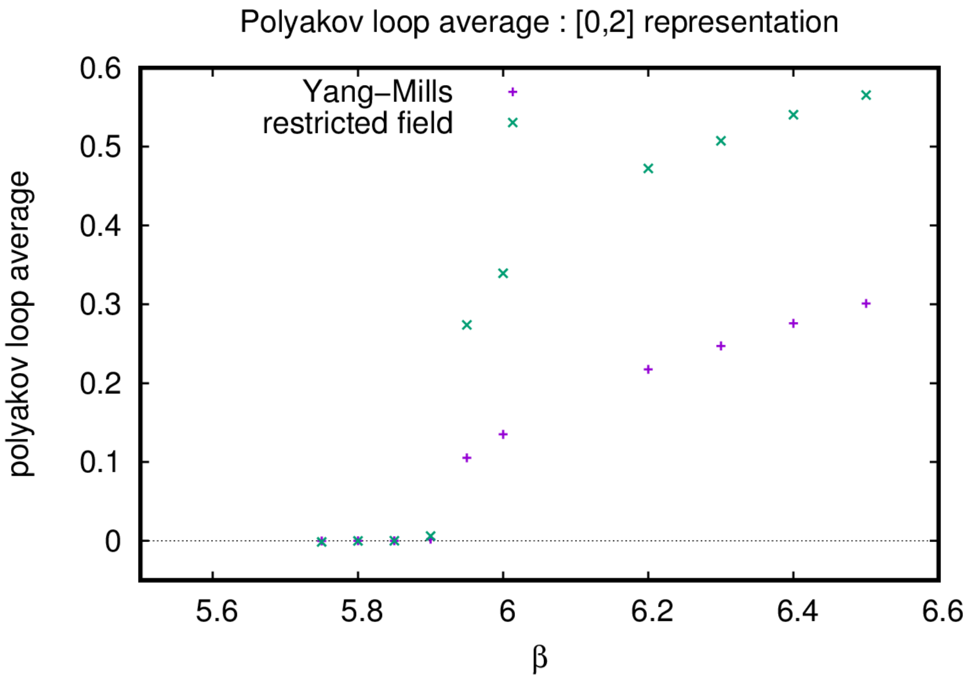


Distribution of space averaged Polyakov loops and averages (R=[1,1])

preliminary

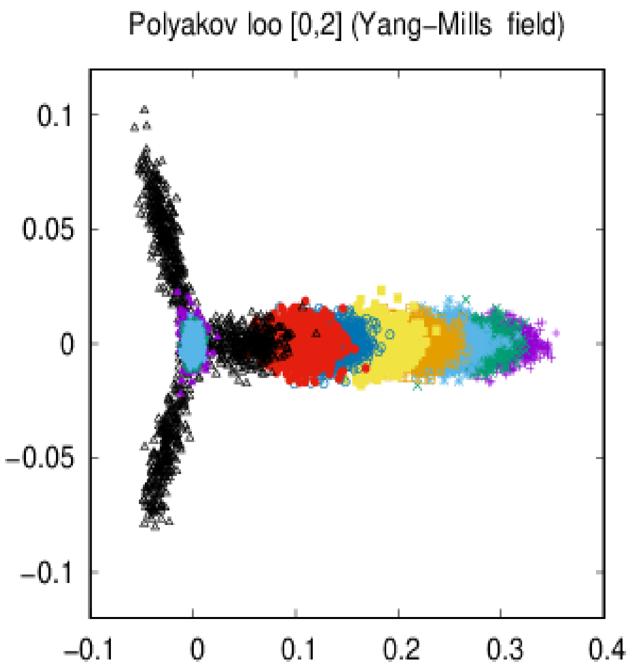


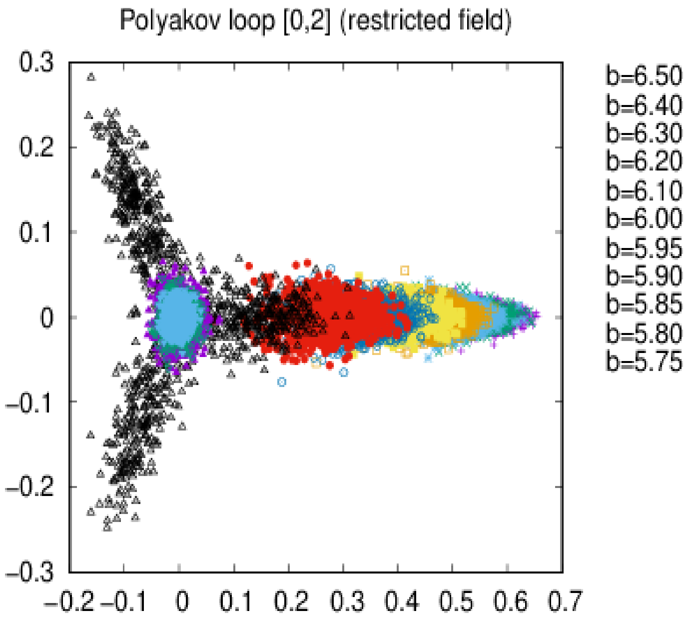


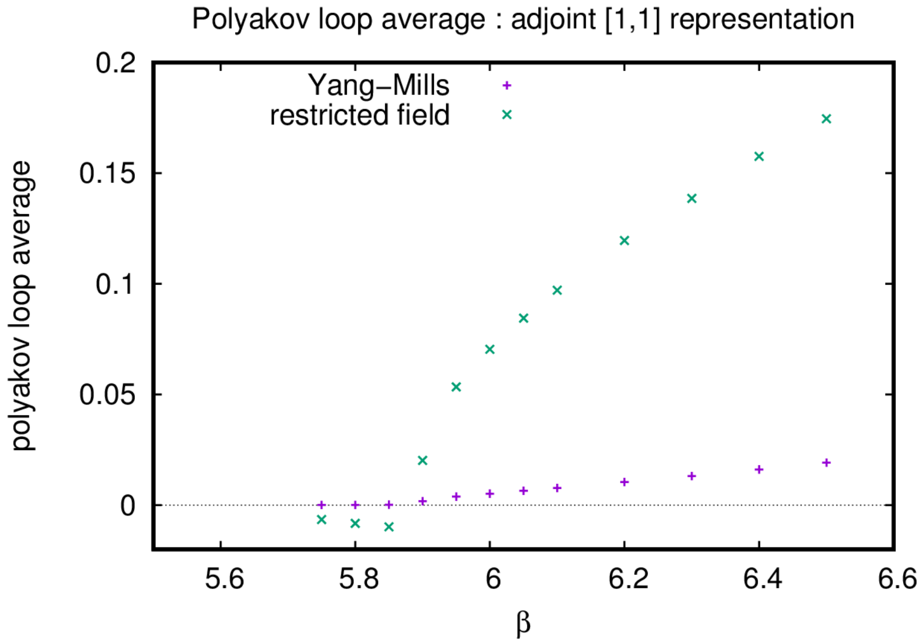


Distribution of space averaged Polyakov loops and averages (R=[0,2])

preliminary

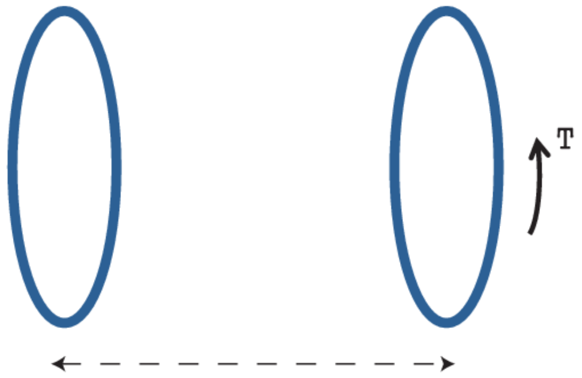






Static potential of quark and antiquark

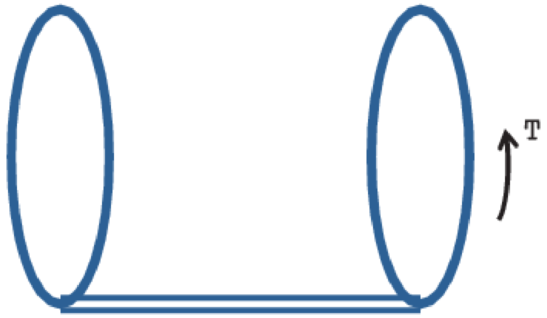
Correlation function of Plyakov loop



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

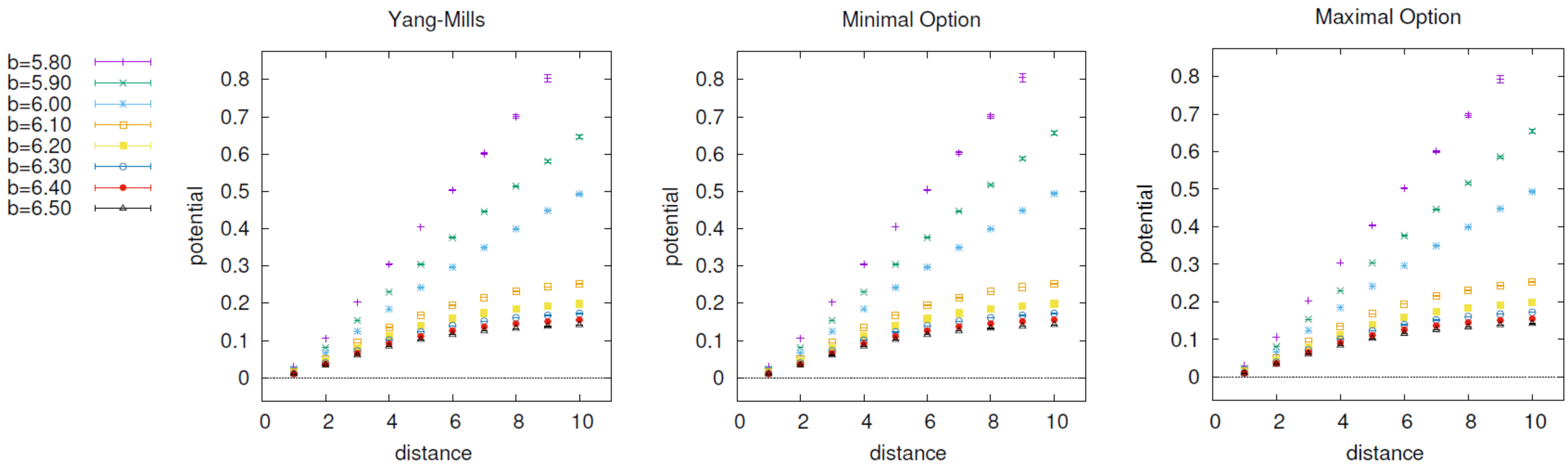
$$\langle P_U(\vec{x})P_U^*(\vec{y})\rangle$$
$$\simeq e^{-F_{q\bar{q}}/T} = \frac{1}{N_c^2}e^{-F^{(S)}/T} + \frac{N_c^2-1}{N_c^2}e^{-F^{(A)}/T}$$

Wilson loop



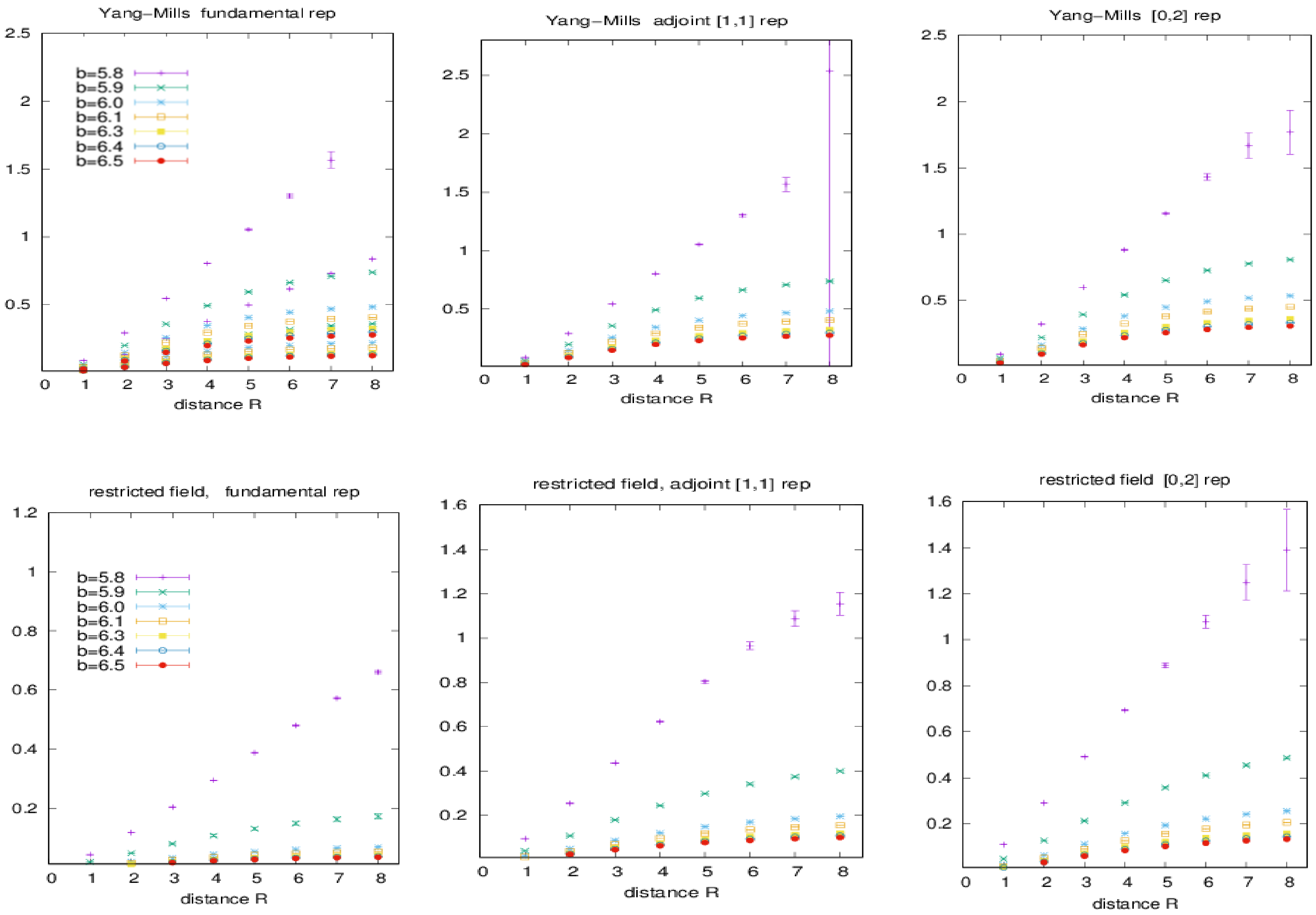
$$V(R;U) := -T\log\langle W_U\rangle,$$
$$V(R;V) := -T\log\langle W_V\rangle$$

Static quark-antiquark potential from maximally extended Wilson loops (fundamental representation)

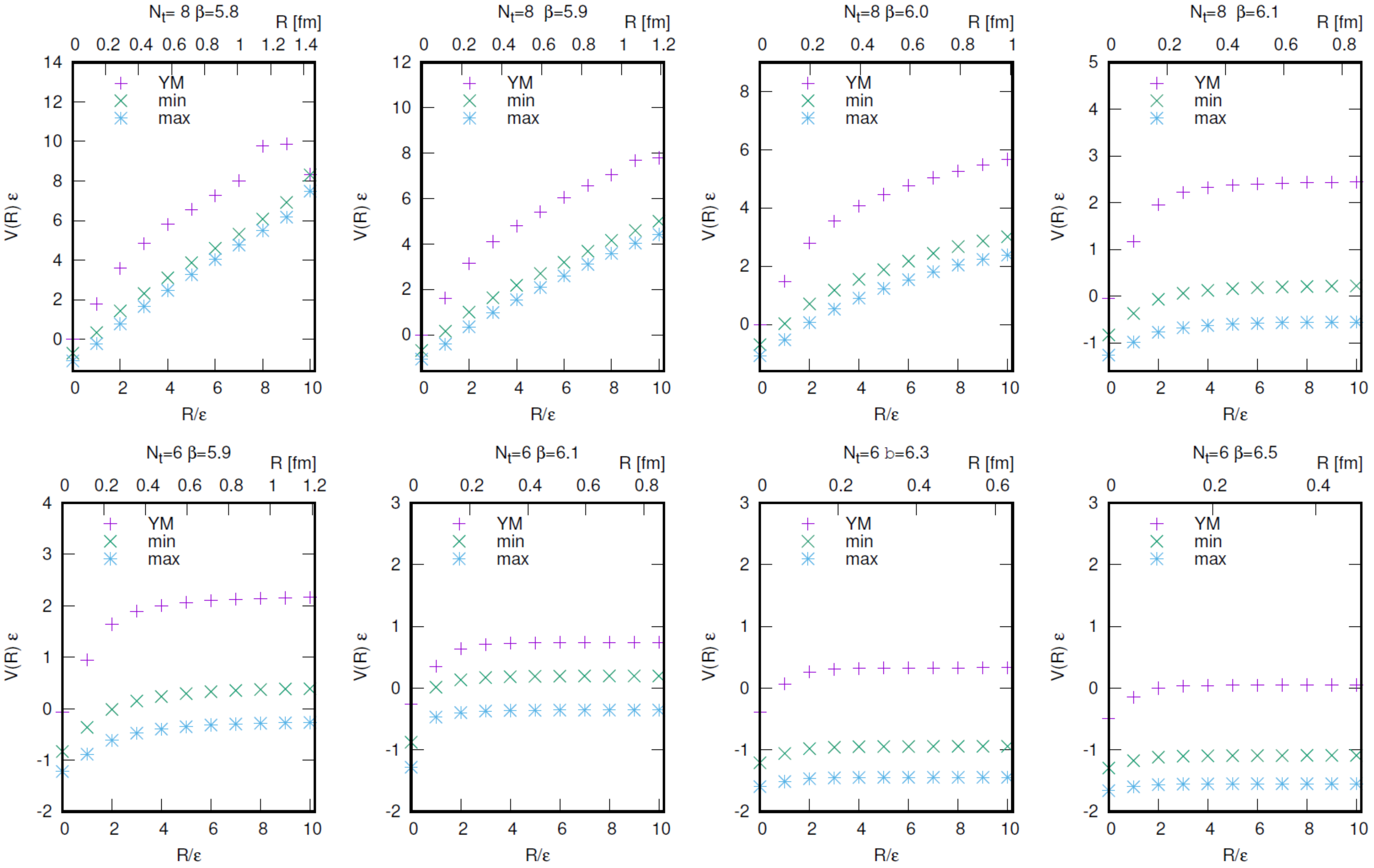


Static potential for various temperatures and for various representations

preliminary



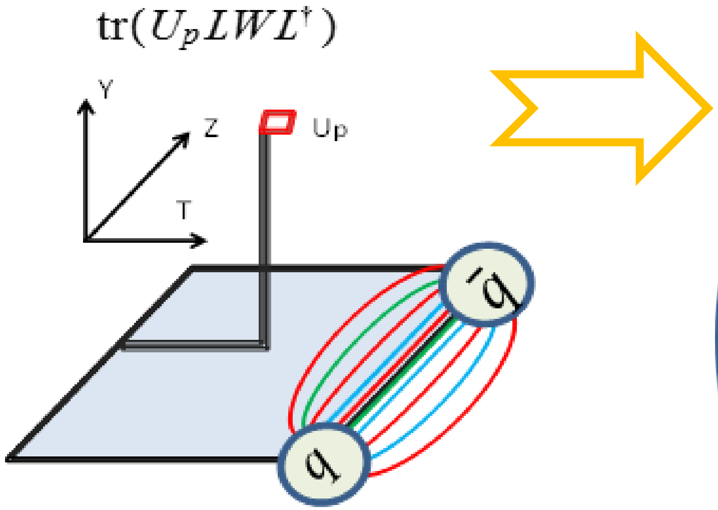
Static potential from Polyakov loop (fundamental rep.)

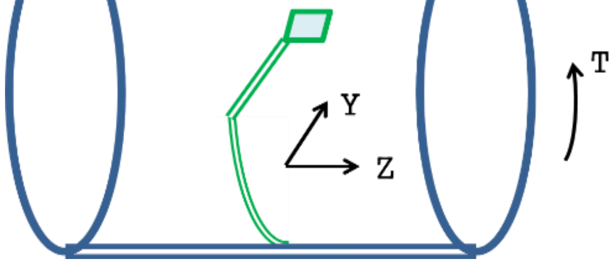


Measurement of chromo flux at finite temperature

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

$$\rho_W := \frac{\langle \mathrm{tr}(W O_{[*]})\rangle}{\langle \mathrm{tr}(W)\rangle} - \frac{1}{N}\frac{\langle \mathrm{tr}(W)\rangle\langle \mathrm{tr}(O_{[*]})\rangle}{\langle \mathrm{tr}(W)\rangle}$$





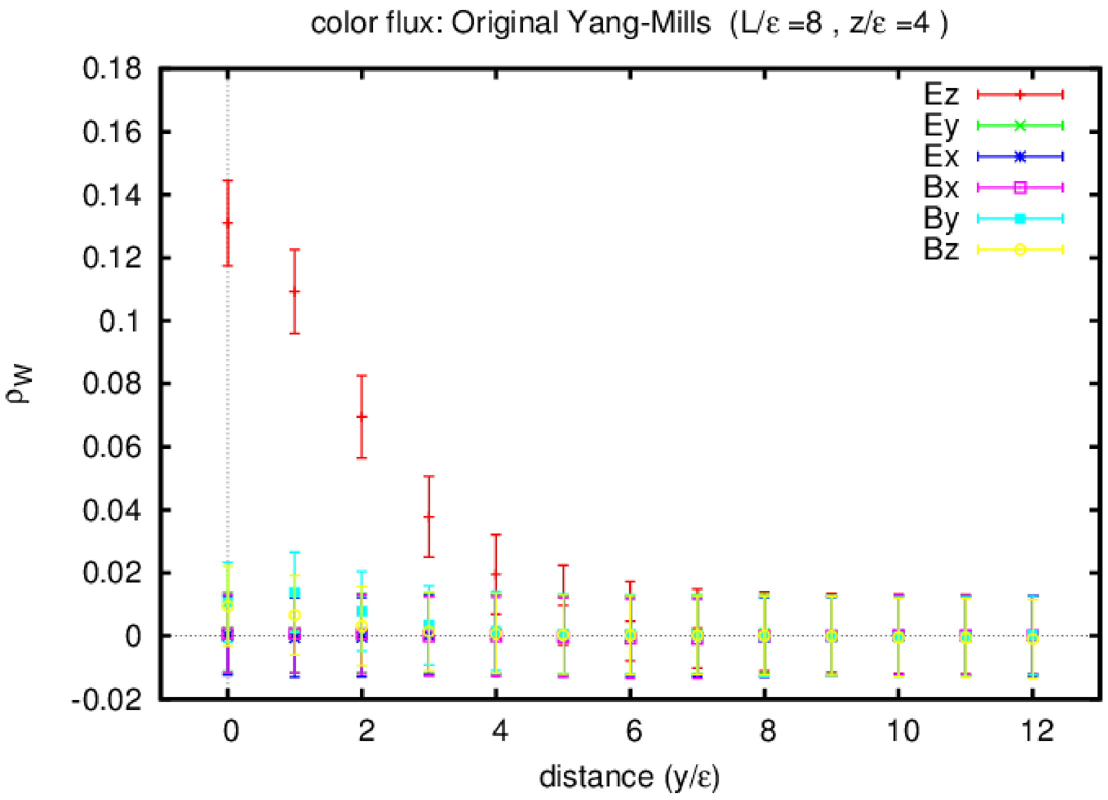
$$O^{[YM]} = L[U]U_pL[U]^{-1} \quad \text{:: original YM}$$

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

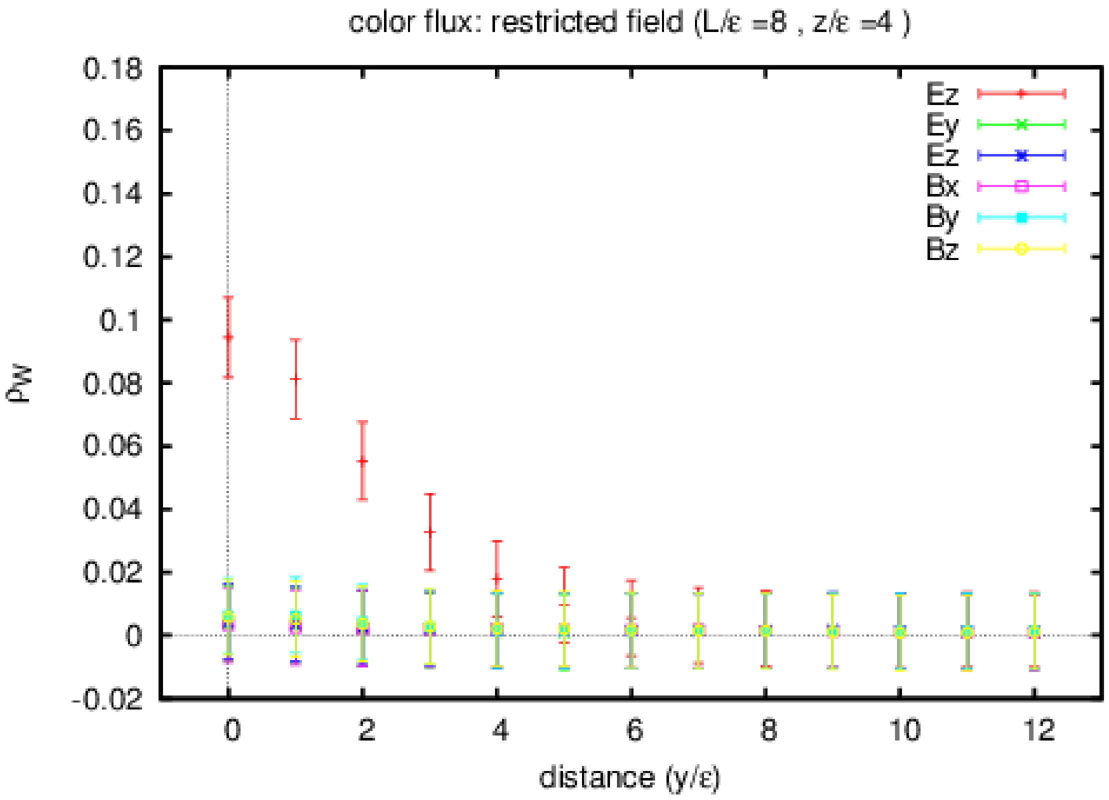
$$O^{[\mathrm{max}]} = L[V^{[\mathrm{max}]}]V_p^{[\mathrm{max}]}L[V^{[\mathrm{max}]}]^{-1} \quad \text{:: V field in maximal option}$$

chromo flux (zero temperature)

Full Yang-Mills field



minimal option



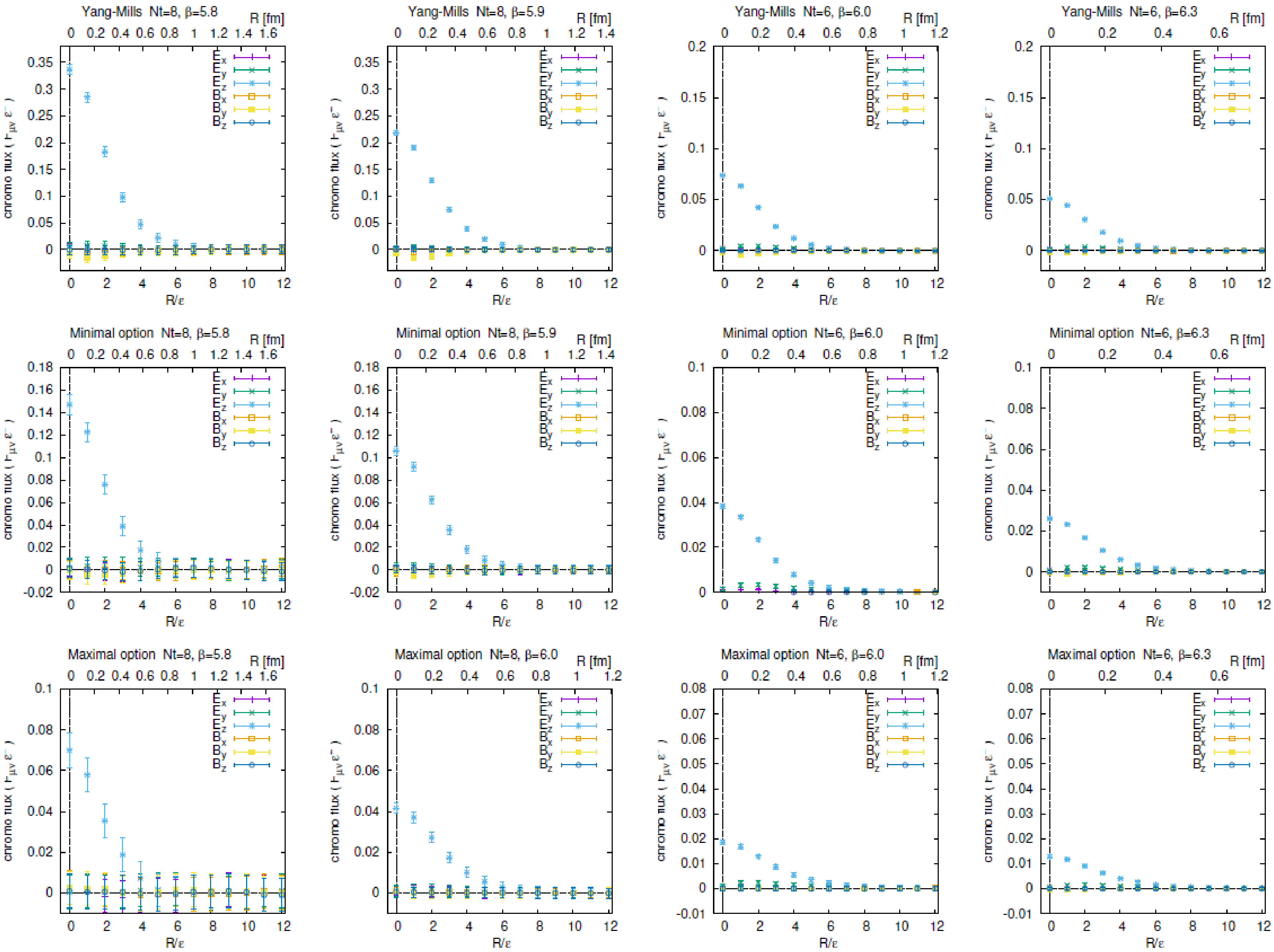
Low Temp.

High Temp.

Yang-Mills

Minimal option

maximal option

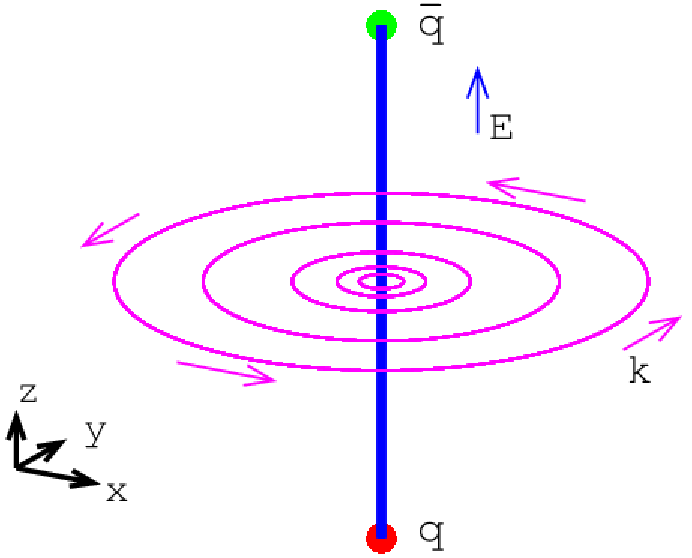


Induced magnetic (monopole) current

$$k_\mu^{\mathrm{YM}}(x) = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}\left(F_{\alpha\beta}^{YM}(x+\hat{\nu}) - F_{\alpha\beta}^{YM}(x)\right),$$

$$k_\mu^{\min}(x) = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}\left(F_{\alpha\beta}^{\min}(x+\hat{\nu}) - F_{\alpha\beta}^{\min}(x)\right),$$

$$k_\mu^{\max}(x) = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}\left(F_{\alpha\beta}^{\max}(x+\hat{\nu}) - F_{\alpha\beta}^{\max}(x)\right),$$

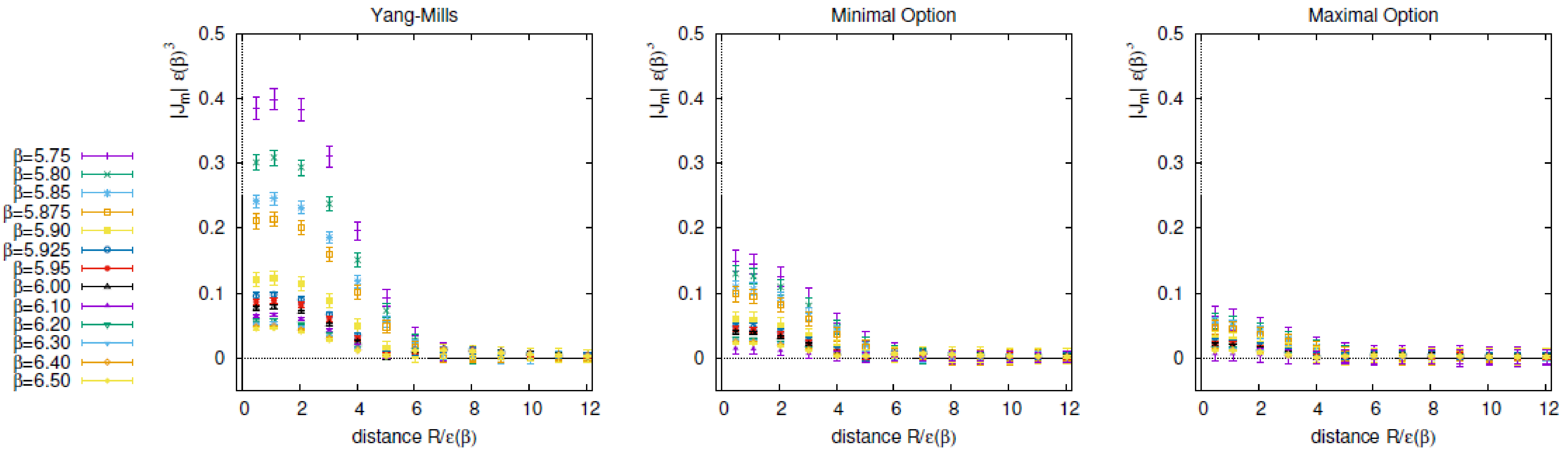


Yang–Mills equation (Maxell equation) fo rrestricted field V_μ, the magnetic current (monopole) can be calculated as

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

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

The magnitude of the induced magnetic currents |k2| around the flux tube.



Summary

- We have investigated dual superconductivity picture at finite temperature by applying the decomposition method for SU(3) Yang-Mills theory on the lattice, i.e.,
  - The Wilson loop and Polyakov loop in the fundamental representation for the minimal and maximal option as well as Yang-Mills field.
  - The Wilson loop and Polyakov loop in the 6-dimension and adjoint representations.
- We have succeeded even at finite temperature to extract the restricted field (V-field) variable from the original Yang-Mills field variable as the dominant mode for confining quarks, so called the restricted field dominance at finite temperature.
  - Wer have found the Polyakov loop average of the restricted field V gives the same critical temperature Tc as that detected by the Polyakov loop average of the original gauge field U:
  - We have found the restricted field (V -field) dominance in the string tension at finite temperature. The string tension calculated from the restrict fields reproduce the string tension calculated from the original Yang-Mills field.

Summary(cont′)

- Note that the Polyakov loop average cannot be the direct signal of the dual Meissner effect or magnetic monopole condensation. Therefore, it is important to find an order parameter which enables one to detect the dual Meissner effect directly.

➔ we have measured the chromo-electric and chromo-magnetic flux for both the original field and the restricted fields in the two options.

  - In the low–temperature confined phase T < Tc, the squeezing of the chromo-electric flux tube created by a quark-antiquark pair and the associated magnetic–monopole current induced around the flux tube.
  - In the high–temperature deconfined phase T > Tc, the disappearance of the dual Meissner effect, namely, no more squeezing of he chromo-electric flux tube detected by non-vanishing component in the chromo-electric flux and the vanishing of the magnetic-monopole current associated with the chromo-flux tube.