

Finite temperature gluon propagator in the center-symmetric Landau gauge

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Outline

- 1 Introduction and Motivation
 - QCD Phase Diagram
 - Center-symmetric Landau gauge
- 2 Results
 - Features of center-symmetric Landau gauge
 - Gluon propagator - preliminary results
- 3 Conclusions and Outlook

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QCD phase diagram

- study of the phase diagram of QCD relevant e.g. for heavy ion experiments
- QCD has phase transition where quarks and gluons become deconfined for sufficiently high T
- Polyakov loop
 - order parameter for the confinement-deconfinement phase transition
 - $L = \langle L(\vec{x}) \rangle \propto e^{-F_q/T}$
 - Definition on the lattice:

$$L(\vec{x}) = \text{Tr} \prod_{t=0}^{N_t-1} \mathcal{U}_4(\vec{x}, t)$$

- $T < T_c : L = 0$ (center symmetry)
- $T > T_c : L \neq 0$ (spontaneous breaking of center symmetry)

Center symmetry

- Wilson gauge action is invariant under a center transformation
- temporal links on a hyperplane $x_4 = \text{const}$ multiplied by

$$z \in Z_3 = \{e^{-i2\pi/3}, 1, e^{i2\pi/3}\}$$

- Polyakov loop $L(\vec{x}) \rightarrow zL(\vec{x})$
- $T < T_c$
 - local P_L phase equally distributed among the three sectors

$$L = \langle L(\vec{x}) \rangle \approx 0$$

- $T > T_c$
 - Z_3 sectors not equally populated: $L \neq 0$

G. Endrödi, C. Gattringer, H.-P. Schadler, arXiv:1401.7228

C. Gattringer, A. Schmidt, JHEP **01**, 051 (2011)

C. Gattringer, Phys. Lett. **B 690**, 179 (2010)

F. M. Stokes, W. Kamleh, D. B. Leinweber, arXiv:1312.0991

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Center-symmetric Landau gauge in the continuum

- Center-symmetric Landau gauge is defined by

$$D_\mu[\bar{A}_c](A_\mu - \bar{A}_{c,\mu}) = 0$$

- center symmetric background configuration:

$$\bar{A}_{c,\mu} = \frac{T}{g} \bar{r}_j t_j \delta_{\mu 0}$$

- for $SU(2)$ we consider $j = 3$, with $\bar{r} = \pi$ and $t_3 = \sigma_3/2$
- for $SU(3)$ we have $j = 3$, with $\bar{r} = 4\pi/3$ and $t_3 = \lambda_3/2$
- background covariant derivative:

$$D_\mu[\bar{A}] = \partial_\mu - ig [\bar{A}_{c,\mu}, \dots]$$

Lattice formulation

- Gauge fixing functional

$$F = \sum_{x,\mu} \text{Re Tr} \left[g_c^\dagger(\mu) g_0(x) U_\mu(x) g_0^\dagger(x + \hat{\mu}) \right]$$

where $g_c^\dagger(\mu) = g_c^\dagger(x + \mu) g_c(x)$

- $g_c^\dagger(\mu)$ can be written as

$$g_c^\dagger(\mu) = e^{iaT \bar{r}_j t_j \delta_{\mu 3}} = e^{iag \bar{A}_{c,\mu} \delta_{\mu 3}}$$

- $aT = 1/L_t$, where L_t is the number of points in the temporal direction.
- maximization of F works in a very similar way to standard Landau gauge

Center invariance

- F is invariant under the particular center transformation (CT)

$$g(n) = e^{i\pi\frac{\lambda_4}{2}} e^{i\pi\frac{\lambda_1}{2}} e^{-i\frac{n_4}{L_4}\pi\left(\lambda_3 + \frac{\lambda_8}{\sqrt{3}}\right)}$$

- it is periodic modulo a center element

$$g(n + L_4\hat{4}) = e^{i\frac{2\pi}{3}} g(n)$$

- F is invariant, and U^g still maximizes F
- note that the Polyakov loop changes: $P_L \rightarrow e^{\mp i\frac{2\pi}{3}} P_L$

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Predictions for the symmetric phase

- in the continuum: $\beta \langle gA_4^3(x) \rangle = \frac{4\pi}{3}$ that becomes $\langle agA_4^3(x) \rangle = \frac{4\pi}{3L_t}$ on the lattice

van Egmond, Reinosa, Phys.Rev.D 109 (2024) 3, 036002

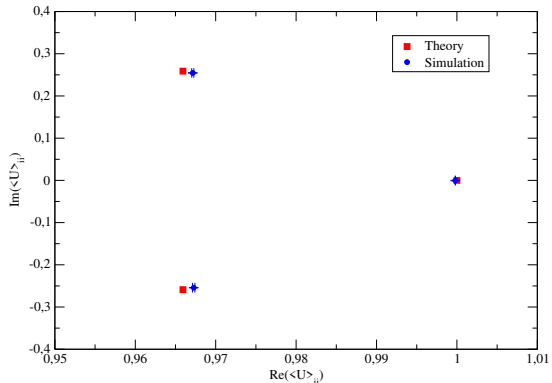
van Egmond, Reinosa, Phys.Rev.D 106 (2022) 7, 074005

- on the lattice: $\langle agA_4^3(x) \rangle = \frac{4\pi}{3L_t}$
- this can also be studied through the link average:

$$\frac{\langle U_4(x) \rangle}{(\det \langle U_4(x) \rangle)^{1/3}} = e^{-\frac{i}{L_4} \frac{4\pi}{3} \frac{\lambda^3}{2}}$$

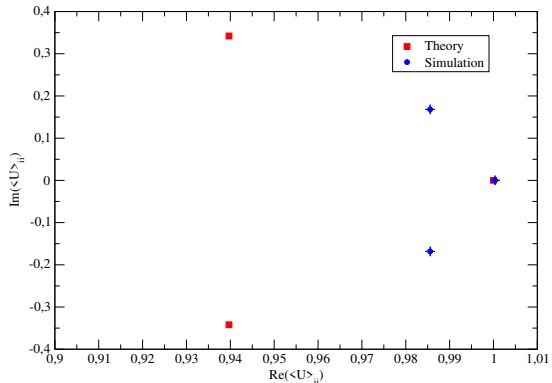
Link average - below T_c

- $64^3 \times 8$,
 $\beta = 6.0$,
 $T = 243 \text{ MeV}$
- non-diagonal elements are zero within errors.



Link average - above T_c

- $64^3 \times 6$,
 $\beta = 6.0$,
 $T=324$ MeV
- non-diagonal elements are zero within errors.



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Gluon propagator

- for color indices 3 and 8, the propagator decomposition becomes the same as in the standard Landau gauge

$$D_{\mu\nu}^{ab}(\hat{q}) = \delta^{ab} \left(P_{\mu\nu}^T D_T(q_4, \vec{q}) + P_{\mu\nu}^L D_L(q_4, \vec{q}) \right)$$

- special care for zero momentum due to disconnected parts

$$D_{ii}^{aa}(q) = \frac{2}{V} \left\langle \text{Tr} \left[A_i(\hat{q}) A_i^\dagger(\hat{q}) \right] \right\rangle = \delta^{aa} \left(P_{ii}^T D^T + P_{ii}^L D^L \right)$$

$$D_{44}^{aa}(q) = \frac{2}{V} \left\langle \text{Tr} \left[A_4(\hat{q}) A_4^\dagger(\hat{q}) \right] \right\rangle = \delta^{aa} \left(P_{44}^T D^T + P_{44}^L D^L \right)$$

- theoretical prediction: $D^{33} = D^{88}$ in the symmetric phase

Lattice setup

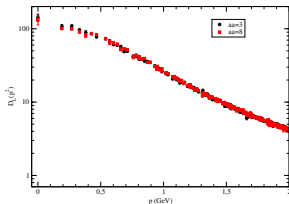
- Wilson gauge action, $\beta = 6.0$
- Lattice volumes $64^3 \times L_t$

$$L_t = 16, 10, 8, 6$$

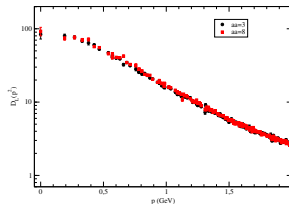
- Lattice spacing $a \sim 0.10\text{fm}$

Bare Longitudinal gluon propagator — 0 CTs

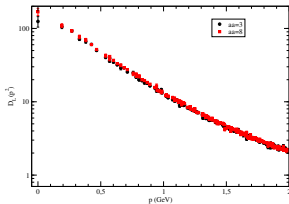
$T = 121 \text{ MeV}$



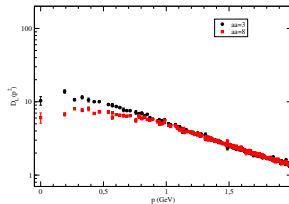
$T = 194 \text{ MeV}$



$T = 243 \text{ MeV}$

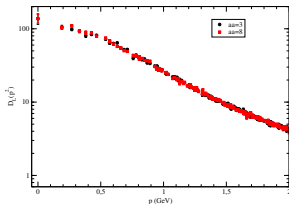


$T = 324 \text{ MeV}$

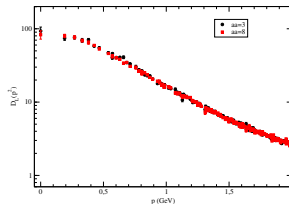


Bare Longitudinal gluon propagator — 1 CTs

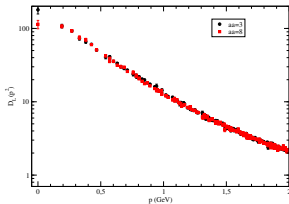
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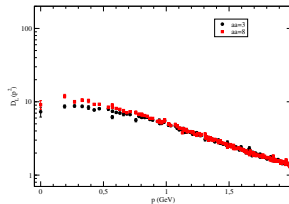
$T = 194 \text{ MeV}$



$T = 243 \text{ MeV}$

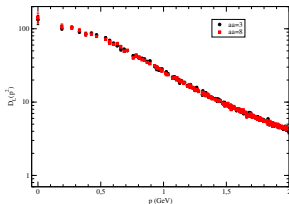


$T = 324 \text{ MeV}$

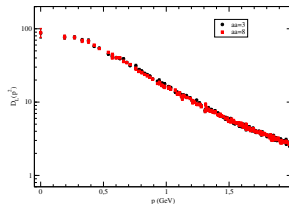


Bare Longitudinal gluon propagator — 2 CTs

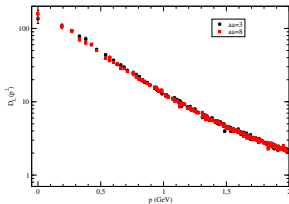
$T = 121 \text{ MeV}$



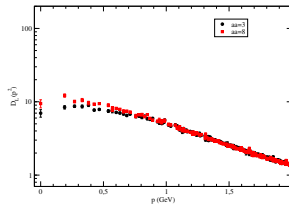
$T = 194 \text{ MeV}$



$T = 243 \text{ MeV}$

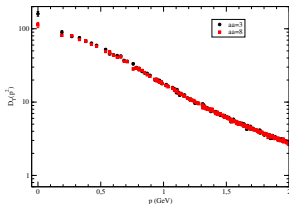


$T = 324 \text{ MeV}$

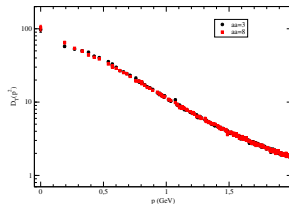


Bare Transverse gluon propagator — 0 CTs

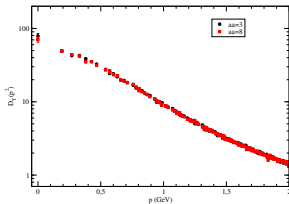
$T = 121 \text{ MeV}$



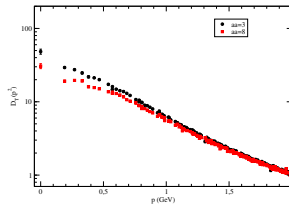
$T = 194 \text{ MeV}$



$T = 243 \text{ MeV}$

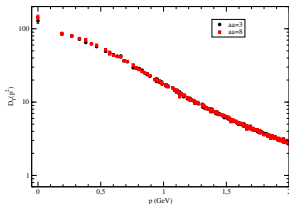


$T = 324 \text{ MeV}$

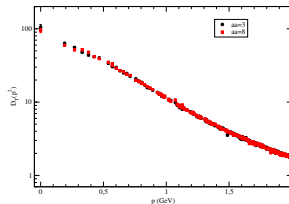


Bare Transverse gluon propagator — 1 CTs

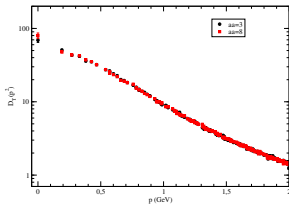
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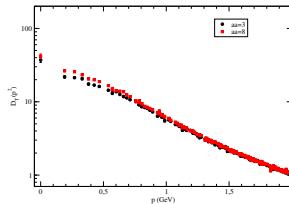
$T = 194 \text{ MeV}$



$T = 243 \text{ MeV}$

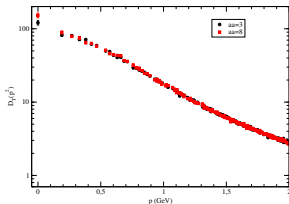


$T = 324 \text{ MeV}$

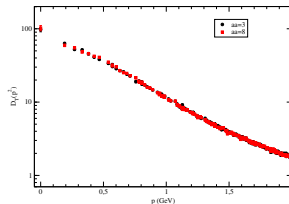


Bare Transverse gluon propagator — 2 CTs

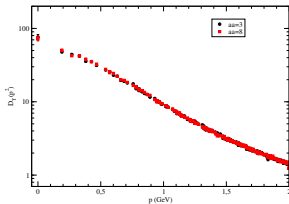
$T = 121 \text{ MeV}$



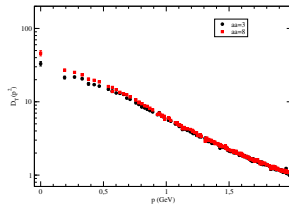
$T = 194 \text{ MeV}$



$T = 243 \text{ MeV}$



$T = 324 \text{ MeV}$



Conclusions and Outlook

- Lattice implementation of the Center-symmetric Landau gauge

Phys. Rev. D112 (2025) 014512, arXiv:2412.07930 [hep-lat]

- Main continuum properties seem to hold on the lattice
 - Link average
 - $D^{33} = D^{88}$ in the symmetric phase
- Outlook:
 - other temperatures
 - ghost propagator
 - higher-order correlation functions
 - SU(2)
 - dynamical configurations

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