Aspects of confinement and the center symmetry phase transition from QCD correlation functions

On the status of studies of Landau gauge QCD Green functions within functional continuum methods

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Outline

1. Fundamental Concepts
   - BRST quartets & Kugo–Ojima confinement criterion
   - Gribov horizon & Zwanziger condition

2. Infrared Structure of Landau gauge Yang-Mills theory
   - Infrared Behavior of Gluons and Ghosts
   - Two-loop terms in the gluon propagator DSE

3. Coupling matter to gluons
   - Quark propagator and quark-gluon vertex
   - The effect of an IR divergent quark-antiquark interaction kernel

4. Center symmetry phase transition

5. Conclusions and Outlook
Motivation

CONFINEMENT

implies

- a non-perturbative RG invariant confinement scale

\[ \Lambda = \mu \exp \left( - \int \frac{d g'}{\beta(g')} \right) \xrightarrow{g \to 0} \mu \exp \left( - \frac{1}{2\beta_0 g^2} \right) \]

- infrared singularities \iff continuum approach
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• infrared singularities \(\iff\) continuum approach
Gauge theory in covariant gauges: **Unphysical degrees of freedom!**

**QED:** Physical states obey Lorentz condition.

\[ \partial_\mu A^\mu |\Psi\rangle = 0 \quad (\text{Gupta – Bleuler}). \]

⇒ Two physical massless photons.

Time-like photon (i.e. negative norm state!) cancels longitudinal photon in physical states!
Covariant Gauge Theory and BRST Quartets

Faddeev-Popov Quantization & BRST in QCD:

Selfinteraction of gluons ⇒
cancelation between four fields:
forward & backward pol. gluons,
ghost & antighosts,
the elementary BRST quartet!

Global ghost field as ‘gauge parameter‘:

BRST symmetry of the gauge-fixed action!

\[
\begin{align*}
\delta_B A^a_\mu &= D^a_\mu c^b \lambda, \\
\delta_B q &= -igt^a c^a q \lambda, \\
\delta_B c^a &= -\frac{g}{2} f^{abc} c^b c^c \lambda, \\
\delta_B \bar{c}^a &= \frac{1}{\xi} \partial_\mu A^a_\mu \lambda,
\end{align*}
\]

Becchi–Rouet–Stora & Tyutin (BRST), 1975
Covariant Gauge Theory and BRST Quartets

BRST symmetry of the gauge-fixed generating functional:

- Via Noether theorem: BRST charge operator $Q_B$
- generates ghost # graded algebra $\delta_B \Phi = \{iQ_B, \Phi\}$
- $\mathcal{L}_{GF} = \delta_B \left( \bar{c} \left( \partial_\mu A^\mu + \frac{\alpha}{2} B \right) \right)$ is BRST exact.

BRST algebra: $Q_B^2 = 0, [iQ_c, Q_B] = Q_B$

BRST cohomology:

Positive definite subspace $\mathcal{V}_{pos} = \text{Ker}(Q_B)$ contains $\text{Im}Q_B$.

Hilbert space: cohomology $\mathcal{H} = \frac{\text{Ker}Q_B}{\text{Im}Q_B} \sim \mathcal{V}_s$ space of BRST singlets

forw. & backw. gluons, ghosts & antighosts: elementary BRST quartet
(c.f. Gupta–Bleuler mechanism in QED)
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Hilbert space: cohomology $\mathcal{H} = \frac{\text{Ker}Q_B}{\text{Im}Q_B} \simeq \mathcal{V}_S$ space of BRST singlets forw. & backw. gluons, ghosts & antighosts: elementary BRST quartet (c.f. Gupta–Bleuler mechanism in QED)
Hypothesis: Physical states are BRST singlets!

\[ \mathcal{H} = \frac{\text{Ker } Q_{\text{BRST}}}{\text{Im } Q_{\text{BRST}}} \]

Time-like and longitudinal gluons (in elementary BRST quartet) removed from asymptotic states as in QED, but:

Transverse gluons and quarks also members of BRST quartets, i.e. kinematically confined, if ghost propagator is highly infrared singular!

(\Rightarrow \text{ Kugo–Ojima confinement criterion})
Kugo–Ojima confinement criterion

Realization of KO scenario depends on **global gauge structure**: Globally conserved current \((\partial^\mu J^a_\mu = 0)\)

\[
J^a_\mu = \partial^\nu F^a_{\mu\nu} + \{Q_B, D^{ab}_\mu \bar{c}^b\}
\]

with charge

\[
Q^a = G^a + N^a.
\]

**QED:** MASSLESS PHOTON states in both terms. Two different combinations yield:

- **unbroken global charge** \(\tilde{Q}^a = G^a + \xi N^a\).
- **spont. broken displacements** (photons as Goldstone bosons).

**No massless** gauge bosons in \(\partial^\nu F^a_{\mu\nu} : G^a \equiv 0\).

(QCD, e.w. Higgs phase, ...)

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Kugo–Ojima confinement criterion

**QCD:** Well-defined (in \( \mathcal{V} \)) unbroken global charge

\[
Q^a = N^a = \{ Q_B, \int d^3 x \, D^a_{0 \bar{c}} \bar{c}^b \}
\]

With \( D^a_{\mu \bar{c}}(x)^{x^0 \rightarrow \pm \infty} (\delta^{ab} + u^{ab}) \partial_{\mu} \bar{\gamma}^b + \ldots \)

\[\Rightarrow \text{Kugo-Ojima Confinement Criterion:} \quad u^{ab}(0) = -\delta^{ab}\]

where

\[
\int dx e^{ip(x-y)} \langle 0 | T D^{a}_{\mu} c^{a}(x) g(A_{\nu} \times \bar{c})^{b}(y) | 0 \rangle =: (g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) u^{ab}(p^2),
\]

**Sufficient condition in Landau gauge:**

Ghost propagator more sing. than simple pole!

If fulfilled: **Physical States \( \equiv \) BRST singlets \( \equiv \) color singlets!**
Kugo–Ojima confinement criterion

Non-perturbative BRST quartets of transverse gluons, resp., quarks:

1st Parent

$|A_{tr}\rangle$, resp., $|q\rangle$

neg. norm

Opposite FP Charge

$\langle A_{tr} - \bar{c} - c | A_{tr}\rangle$ or

$\langle A_{tr} - B | A_{tr}\rangle = 1$, resp.,

$\langle q - \bar{c} - c | q\rangle$ or

$\langle q - B | q\rangle = 1$

2nd Daughter

$|A_{tr} - \bar{c} - c\rangle$, $|A_{tr} - B\rangle$, resp., $|q - \bar{c} - c\rangle |q - B\rangle$

zero norm

1st Daughter

$|A_{tr} - c\rangle$, resp., $|q - c\rangle$

zero norm

FP Conjugation

$\langle A_{tr} - \bar{c} | A_{tr} - c\rangle = 1$, resp.,

$\langle q - \bar{c} | q - c\rangle = 1$

2nd Parent

$|A_{tr} - \bar{c}\rangle$, resp., $|q - \bar{c}\rangle$

neg. norm

BRST Charge Operator

BRST Charge Operator

Gribov horizon & Zwanziger condition

Gauge fixing in YM theories never completely unique:

\[ \partial A = 0 \]

\[ \Lambda \] topologically non-trivial as complete config. space also is!

Landau gauge: \( \Gamma = \{ A : \partial \cdot A = 0 \} \)

Minimal Landau gauge: \( \Omega = \{ A : \| A \|^2 \text{ minimal} \} \)

First Gribov region: \( \Omega = \{ A : \partial \cdot A = 0, \partial \cdot D(A) \geq 0 \} \)

Fundam. Modular Region: \( \Lambda = \{ A : \text{global extrema} \} \)

NO GRIBOV COPIES
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Relevant configuration space: \[ \Lambda / SU(N_c) \]

Gribov: Cut off integral at boundary \( \partial \Omega \)

Zwanziger: Ambiguities resolved due to additional IR boundary condition on ghost prop.

\[ \lim_{k^2 \to 0} (k^2 D_{\text{Ghost}}(k^2))^{-1} = 0. \]
Gribov horizon & Zwanziger condition

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\[
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\]
Kugo-Ojima vs. Gribov-Zwanziger

- In Landau gauge: Kugo-Ojima and Gribov-Zwanziger lead to practically same infrared constraints.
- Results in positivity violation for transverse gluons: non-pert. realization of Oehme–Zimmermann superconvergence relation (antiscreening contradicts positivity of gluon spectral density).

- Kugo-Ojima requires Lorentz-covariant gauge, but fails e.g. also in the Lorentz-cov. Maximally Abelian gauge.
- Gribov-Zwanziger applies to Landau and Coulomb gauge (where $\Lambda$ is compact and convex), but e.g. not to Maximally Abelian gauge (where Gribov region is unbounded).

Infrared Structure of Landau gauge Yang-Mills theory

- Starting point in gauges with transverse gluon propagator: Ghost-Gluon-Vertex fulfills Dyson-Schwinger equation

\[ q - l = + \]

- Transversality of gluon \( l_\mu D_{\mu\nu}(l - q) = q_\mu D_{\mu\nu}(l - q) \Rightarrow \) Bare Vertex for \( q_\mu \to 0 \)

- No anomalous dimensions in the IR


Recently:
Solution of DSEs for YM propagators and ghost-gluon vertex!
DSEs for YM propagators:
Infrared Structure of Landau gauge Yang-Mills theory

Gluon propagator DSE:
(without matter)

\[-1 = \text{ghost loop (a)} + \text{UV leading: ghost loop (a) + gluon loop (b)}
\]

⇒ 2-loop terms, sunset (c) and squint (d), qualitatively unimportant

Quantitatively?
Infrared Structure of Landau gauge Yang-Mills theory

Sunset diagram:

- Overlapping divergence!
- non-perturbative renormalization?
- \( \overline{\text{MOM}} \) (verified by BPHZ)
Infrared Structure of Landau gauge Yang-Mills theory

$Z(p)$

$0 \leq p \leq 6$ (GeV)

Gluon dressing function

- One loop
- Sternbeck (2006)

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Infrared Structure of Landau gauge Yang-Mills theory

Z(p)

- black: one loop
- blue: one loop + sunset
- red: Sternbeck (2006)

gluon dressing function
Include squint diagram (in progress):
  - also quantitatively unimportant?
  - qualitatively: cancelation of spurious divergencies!??
Mismatch to lattice data at intermediate $p^2$
  - resolved in ERG
  - in DSEs:
    zero crossing of 3-gluon vertex function
Coupling matter to gluons

DSEs for Landau gauge QCD propagators:

\[ -1 = -1 - \frac{1}{2} - \frac{1}{2} \]

\[ - \frac{1}{6} - \frac{1}{2} \]

\[ + N_f \]

\[ -1 = -1 \]

\[ -1 = -1 - \frac{1}{2} - \frac{1}{2} \]

\[ -1 = -1 \]

\[ -1 = -1 - \frac{1}{2} - \frac{1}{2} \]

\[ -1 = -1 \]
Coupling matter to gluons

DSEs for quark propagator and quark-gluon vertex:

\[ -1 = -1 + \]

\[ -1 = -\frac{1}{N_c} + N_c \]

*cf.* poster of M. Hopfer
Coupling matter to gluons

Quark mass function with models for QGV:

Chiral Limit

\[ M(x) \text{ [GeV]} \]

- fundamental, CP vertex
- fundamental, eff. vertex
- adjoint, eff. vertex

\[ x = p^2 \text{ [GeV}^2] \]
Coupling matter to gluons

Quark mass function with models for QGV:

\[ m_{@2\text{GeV}} = 100 \text{ MeV} \]

- **fundamental, CP vertex**
- **fundamental, eff. vertex**
- **adjoint, eff. vertex**
Coupling matter to gluons

Solving for the quark-gluon vertex:
Preliminary results for a simplified system

- self-consistent solution of the quark-gluon vertex DSE
  in a truncation including all 12 tensor structures

$-1 = -1$

$= +$

cf. poster of M. Hopfer
- scaling-type gluon propagator
- model for three-gluon vertex (cf. MQ Huber)
Coupling matter to gluons

Quark mass function with calculated QGV:

\[ M(x) \]

\[ x = p^2 [\text{GeV}^2] \]
Coupling matter to gluons

Leading tensor structure, calculated QGV, symm. momenta \( x = p_1^2 = p_2^2 = p_3^2 \): Significant IR enhancement!

\[ \lambda_1(x) \]
Coupling matter to gluons

Subleading $D\chi_{SB}$ tensor structure, calculated QGV:

$$x^{1/2} \lambda_3(x)$$

$D\chi_{SB}$ in QGV!!!
Assuming an IR divergent 4-point function

M. Mitter, RA, in preparation

How is Confinement described by Green’s functions?

- Assume quark 4-point function to be maximally IR singular, \( i.e., \propto \frac{1}{k^4} \):

\[
\begin{align*}
p_1 \rightarrow p_3 & \propto \frac{1}{(p_1 - p_3)^4} \bigg|_{\text{reg.}}
\end{align*}
\]

- Put e.g. DSE for 4-quark function:
Consequences an IR divergent 4-point function

- For simplicity: Analysis first for fundamentally charged scalar!
- Consistency requirements:

  - Boundedness of higher $n$-point functions to $1/k^4 \implies$ matter-gluon vertex less singular $\implies$ colour structure

  - One-gluon exchange fails to reproduce this colour structure!

  - All 4-point functions (4-gluon, ghost-gluon, matter-gluon, matter-ghost) inherit the $1/k^4$ singularity in specific colour channels.

  - Higher $n$-point functions contain contributions $\propto 1/k^4$ with $k$ being the momentum transfer between two coloured clusters.

  - Propagators and 3-point functions protected by cancellations.

- Decoupling theorem circumvented by IR singularities: One heavy fundamental charge induce changes in the IR behaviour of YM Green’s functions!??
Assumption of confining IR singularity in matter-matter scattering kernel leads to several wanted features.

Especially Casimir scaling!

No decoupling of infinitely heavy charges?

Further to be clarified:

- Absence of van-der-Waals forces?
- $N$-ality?
- Relation to dynamical chiral symmetry breaking / restoration?
- ...
Center symmetry phase transition


Investigate QCD correlation functions at $T \neq 0$:
Exploit dependence on boundary conditions!

Propagator of fund. scalar:

- gluon propagator from lattice data
- vacuum vertex model

Anti-periodic boundary conditions:
Center symmetry phase transition


Investigate QCD correlation functions at $T \neq 0$: Exploit dependence on boundary conditions!

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- vacuum vertex model

Periodic boundary conditions:
Investigate QCD correlation functions at \( T \neq 0 \):
Exploit dependence on boundary conditions!

Propagator of fund. scalar:
- gluon propagator from lattice data
- vacuum vertex model

Anti-periodic boundary conditions:
Center symmetry phase transition

Dual order parameter for scalar QCD:

\[
\Sigma_\phi = T \sum_{\omega_n(\phi)} D_{S,\phi}^2(\bar{0}, \omega_n(\phi)) \xrightarrow{z} T \sum_{\omega_n(\phi)} D_{S,\phi + \text{arg}(z)}^2(\bar{0}, \omega_n(\phi)) \\
= T \sum_{\omega_n(\phi + \text{arg}(z))} D_{S,\phi + \text{arg}(z)}^2(\bar{0}, \omega_n(\phi + \text{arg}(z))) = \Sigma_{\phi + \text{arg}(z)} \\
\Sigma_{\phi + 2\pi} = \Sigma_\phi
\]
Center symmetry phase transition

Center transition in scalar QCD:

\[ \Sigma_s = \int_0^{2\pi} \frac{d\phi}{2\pi} e^{-i\phi} \Sigma_\phi, \quad \Sigma_\phi = T \sum_{\omega_n(\phi)} D^2_{\Sigma,\phi}(\bar{0}, \omega_n(\phi)) \]
Center symmetry phase transition

Vertex model / mass dep. of center transition in scalar QCD:

\[
A(x, y, z) = \frac{D^{-1}_S(x) - D^{-1}_S(y)}{x - y} d_1 \left\{ \left( \frac{\Lambda^2}{\Lambda^2 + k^2} \right) + \frac{k^2}{\Lambda^2 + k^2} \left( \frac{\beta_0 \alpha(\mu) \ln \left[ \frac{k^2}{\Lambda^2 + 1} \right]}{4\pi} \right)^{2\delta} \right\}
\]
Center symmetry phase transition

Alternative order parameter in QCD (with quarks):

\[ \Sigma_Q = \int_0^{2\pi} \frac{d\phi}{2\pi} e^{-i\phi} \Sigma_{Q,\phi}, \quad \Sigma_{Q,\phi} = T \sum_{\omega_n(\phi)} \frac{1}{4i} \text{tr} \left[ S_{Q,\phi}(\bar{\phi}, \omega_n(\phi)) \right]^2 \]

- no regularization necessary for bare quark mass \( m_0 \neq 0 \)
- different definitions of crossover in unquenched QCD possible

![Graphs showing order parameters vs. \( \phi/2\pi \) and \( T \) [GeV]]
Conclusions and Outlook

Landau gauge QCD Green functions:

- Progress in the understanding of IR behaviour.
- Two-loop terms in gluon propagator DSE quant. unimportant.
- Coupled system of quark propagator and quark-gluon vertex DSEs under investigation.
- Chiral symmetry dynamically broken! In 2- and 3-point function!
- Quark/matter confinement: Analysis of IR divergencies! Color structure, Casimir scaling, no decoupling of heavy d.o.f., ...
- Center symmetry phase transition: sensitivity to quark-gluon vertex, dual order parameter, ...
- Quark/matter-gluon vertex ($T = 0$):
  - quark/matter confinement, $D_\chi$SB, $U_A(1)$
  - phase transition at $T \neq 0$
  - finite density, color-superconducting phase(s)
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