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

CONFINEMENT

implies

- a non–perturbative RG invariant confinement scale

$$\Lambda = \mu \exp\left(-\int^g \frac{dg'}{\beta(g')}\right) \overset{g\to 0}{\to} \mu \exp\left(-\frac{1}{2\beta_0 g^2}\right)$$

- infrared singularities $\Longleftrightarrow$ continuum approach

Motivation

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Covariant Gauge Theory and BRST Quartets

Gauge theory in covariant gauges: Unphysical degrees of freedom!

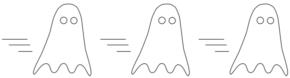
QED: Physical states obey Lorentz condition.

$$\partial_\mu A^\mu |\Psi\rangle = 0 \quad (\mathrm{Gupta-Bleuler}).$$

$\Rightarrow$ Two physical massless photons.

Time-like photon (i.e. negative norm state!) cancels longitudinal photon in physical states!

Faddeev-Popov Quantization & BRST in QCD:



Selfinteraction of gluons $\Rightarrow$
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!

$$\delta_B A^a_\mu = D^{ab}_\mu c^b \lambda\,, \qquad \delta_B q = -igt^a c^a q \lambda\,,$$

$$\delta_B c^a = -\frac{g}{2} f^{abc} c^b c^c \lambda\,, \qquad \delta_B \bar{c}^a = \frac{1}{\xi}\partial_\mu A^a_\mu \lambda\,,$$

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

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)

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Kugo–Ojima confinement criterion

$\Rightarrow$ Hypothesis: Physical states are BRST singlets!

(BRST cohomology: Hilbert space $\mathcal{H} = \frac{\mathrm{Ker}\, Q_{BRST}}{\mathrm{Im}\, Q_{BRST}}$.)

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!**

($\Rightarrow$ **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 $$Q^a = G^a \quad + \quad N^a.$$

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, ...)

Kugo–Ojima confinement criterion

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

$$Q^a = N^a = \{Q_B, \int d^3x\, D_0^{ab}\bar{c}^b\}$$

With $D_\mu^{ab}\bar{c}^b(x) \stackrel{x^0\to\pm\infty}{\longrightarrow} (\delta^{ab} + u^{ab})\partial_\mu\bar{\gamma}^b + \dots$

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

where

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

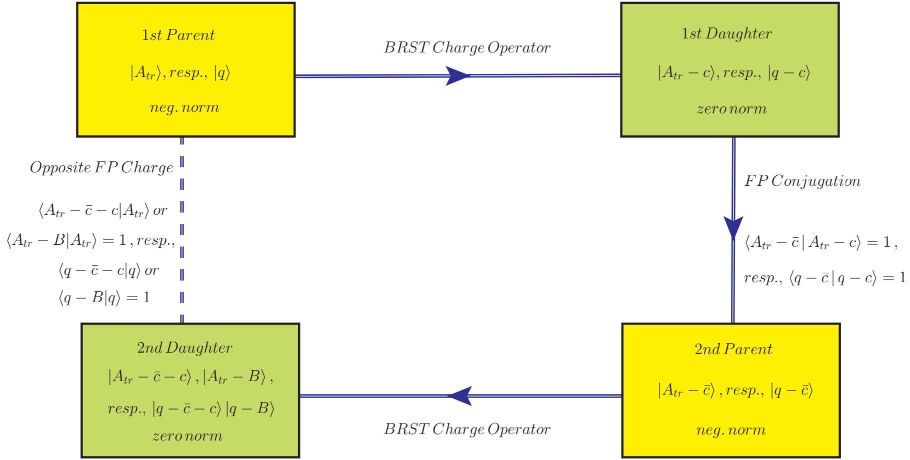
Sufficient condition in Landau gauge:

Ghost propagator more sing. than simple pole!

If fulfilled: **Physical States $\equiv$ BRST singlets $\equiv$ color singlets!**

Kugo–Ojima confinement criterion

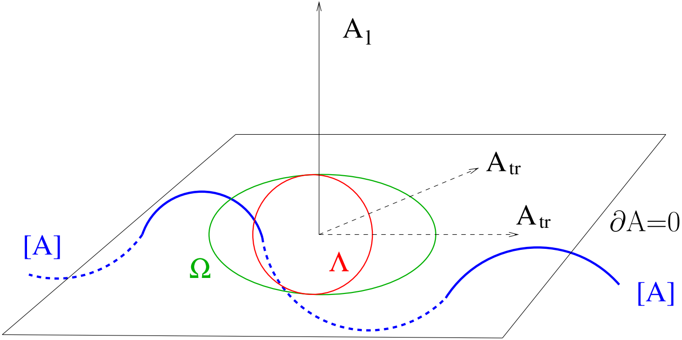
Non-perturbative BRST quartets of transverse gluons, resp., quarks:



N. Alkofer and R.A., Phys. Lett. B **702** (2011) 158 [arXiv:1102.2753 [hep-th]];
PoS **QCD-TNT-II** (2011) 002 [arXiv:1112.4483 [hep-th]].

Gribov horizon & Zwanziger condition

Gauge fixing in YM theories never completely unique:



Λ topologically non-trivial as complete config. space also is!

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

Minimal Landau gauge: $\Omega = \{A : ||A||^2 \textit{ minimal}\}$

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

Fundam. Modular Region: $\Lambda = \{A : \textit{global extrema}\}$

NO GRIBOV COPIES

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NO GRIBOV COPIES

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.

$$\lim_{k^2 \to 0} \left(k^2 D_{\text{Ghost}}(k^2)\right)^{-1} = 0.$$

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$$\lim_{k^2 \to 0} \left(k^2 D_{\rm Ghost}(k^2)\right)^{-1} = 0.$$

Kugo-Ojima vs. Gribov-Zwanziger

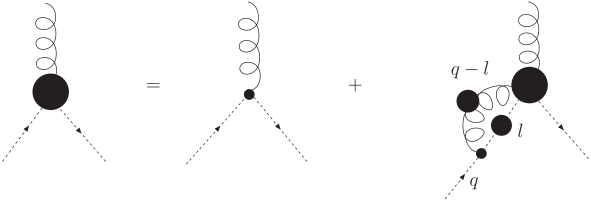
- In Landau gauge: Kugo-Ojima and Gribov-Zwanziger lead to practically same infrared constraints.
- Results in positivity violation for transverse gluons: non-pert. realization of Oehme–Zimmermann superconvergence relation (antiscreening contradicts positivity of gluon spectral density).
  R. Oehme and W. Zimmermann, Phys. Rev. **D21** (1980) 471.

- 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 Λ is compact and convex),
  but *e.g.* not to Maximally Abelian gauge
  (where Gribov region is unbounded).

- Recently: generalized ("refined") Gribov-Zwanziger scheme which results in infrared finite Landau gauge Green functions,
  D. Dudal, S. Sorella, N. Vandersickel, *et al.* .

Infrared Structure of Landau gauge Yang-Mills theory

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



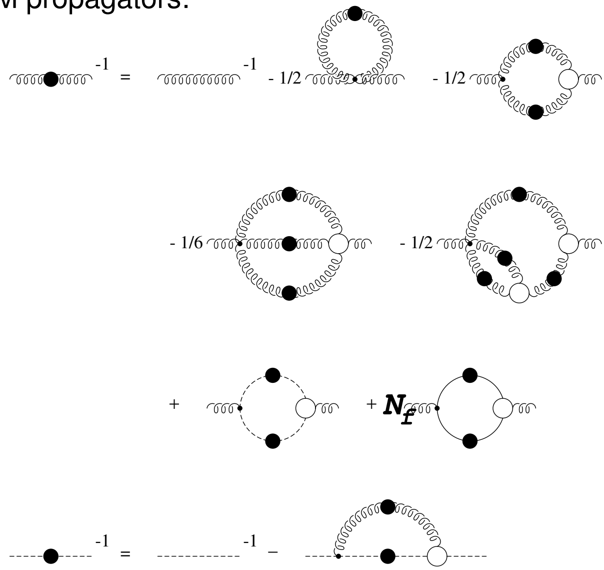
  - Transversality of gluon $l_\mu D_{\mu\nu}(l-q) = q_\mu D_{\mu\nu}(l-q) \Rightarrow$ Bare Vertex for $q_\mu \to 0$
  - No anomalous dimensions in the IR

J.C. Taylor, Nucl. Phys. B **33** (1971) 436;
C. Lerche, L. v. Smekal, PRD **65** (2002) 125006.

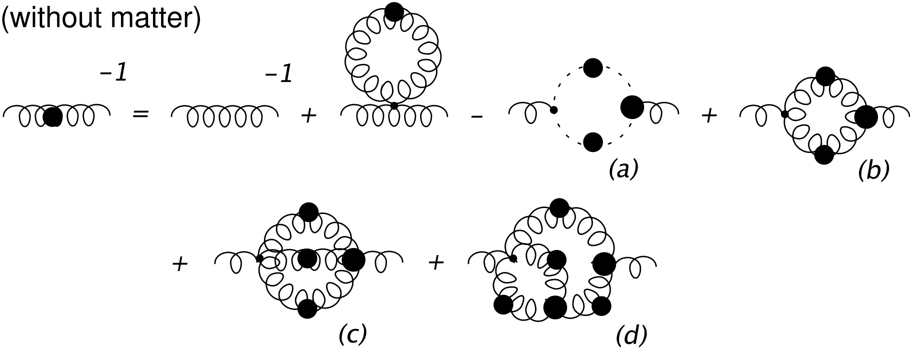
Recently:
Solution of DSEs for YM propagators *and* ghost-gluon vertex!
Poster of M. Q. Huber; M. Q. Huber, L. v. Smekal, arXiv:1211.6092.

Infrared Structure of Landau gauge Yang-Mills theory

DSEs for YM propagators:



Gluon propagator DSE:
(without matter)

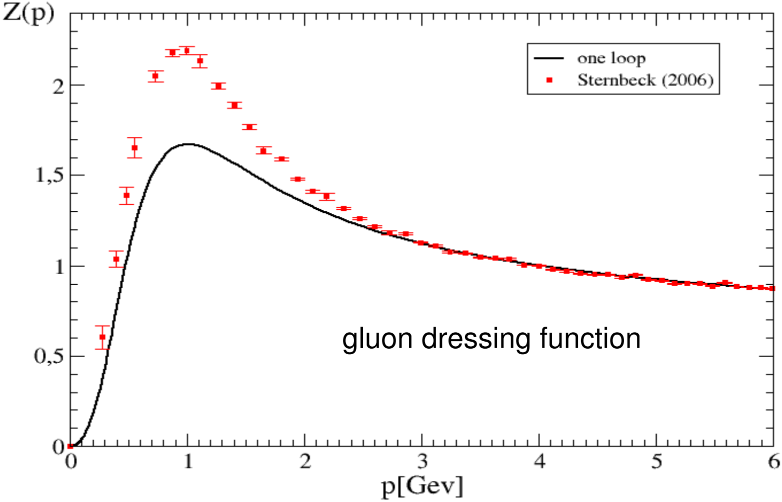


IR leading: ghost loop (a)
UV leading: ghost loop (a) + gluon loop (b)
$\Rightarrow$ 2-loop terms, sunset (c) and squint (d), qualitatively unimportant

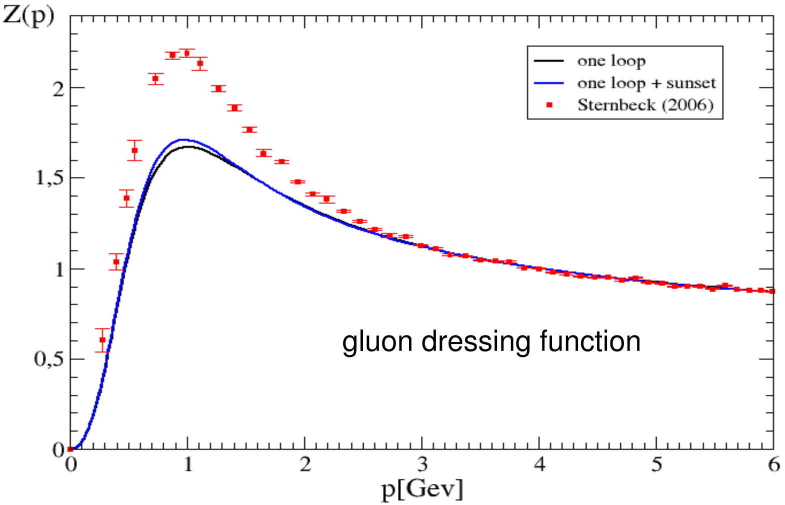
Quantitatively?

Sunset diagram:

- Overlapping divergence!
- non-perturbative renormalization?
  RA, M.Q.Huber, V.Mader, A.Windisch, PoS **QCD-TNT-II** (2011) 003 [1112.6173];
  V. Mader, A. Windisch and RA, in preparation.
- $\widetilde{\mathrm{MOM}}$ (verified by BPHZ)


Z(p)
one loop
Sternbeck (2006)
gluon dressing function
0
0,5
1
1,5
2
0
1
2
3
4
5
6
p[Gev]

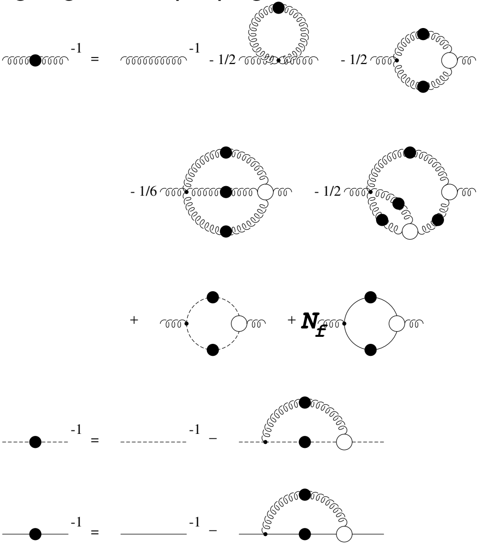
Infrared Structure of Landau gauge Yang-Mills theory



- Include squint diagram (in progress):
  - also quantitatively unimportant?
  - qualitatively: cancelation of spurious divergencies!?!
- Mismatch to lattice data at intermediate p^2
  - resolved in ERG
    C.S. Fischer, A. Maas, J.M. Pawlowski, Ann. Phys. **324** (2009) 2408.
  - in DSEs:
    zero crossing of 3-gluon vertex function
    Poster of M. Q. Huber; M. Q. Huber, L. v. Smekal, arXiv:1211.6092.

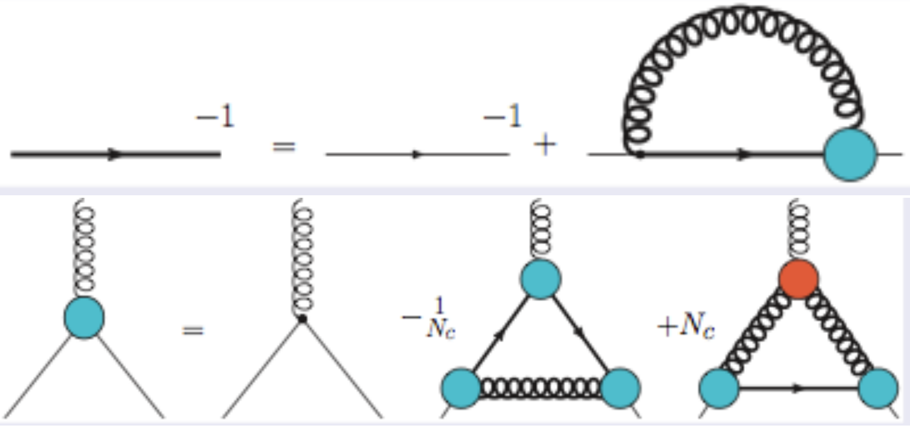
Coupling matter to gluons

DSEs for Landau gauge QCD propagators:



Coupling matter to gluons

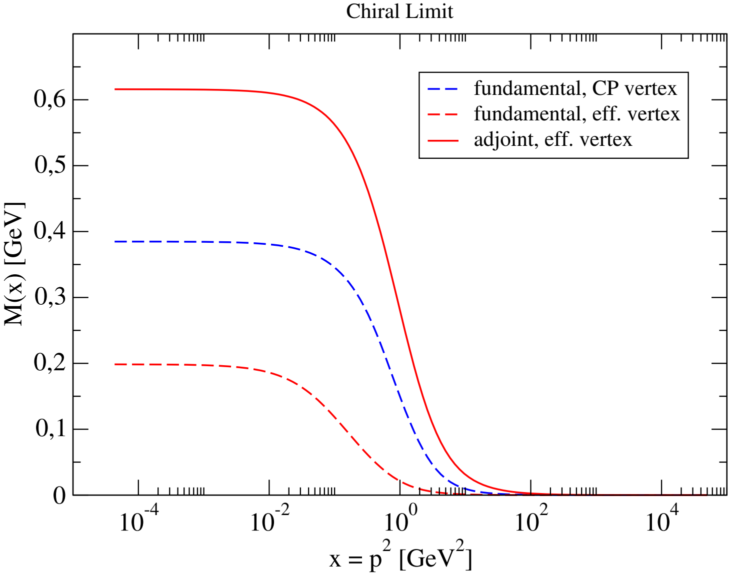
DSEs for quark propagator and quark-gluon vertex:



cf. poster of M. Hopfer

Coupling matter to gluons

Quark mass function with models for QGV:



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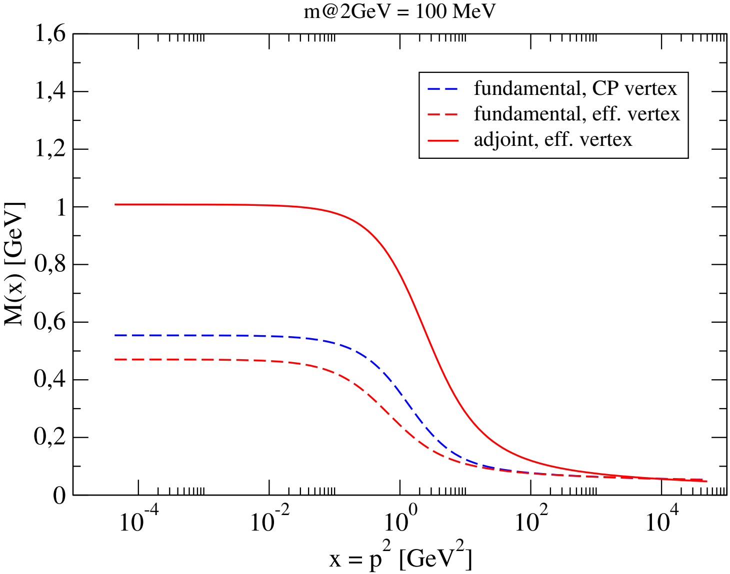
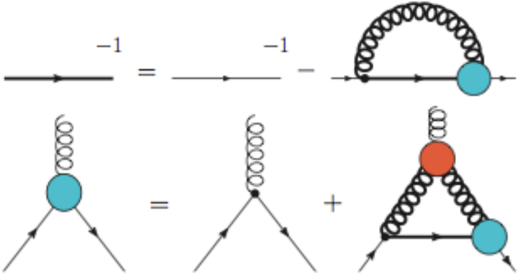


Coupling matter to gluons

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

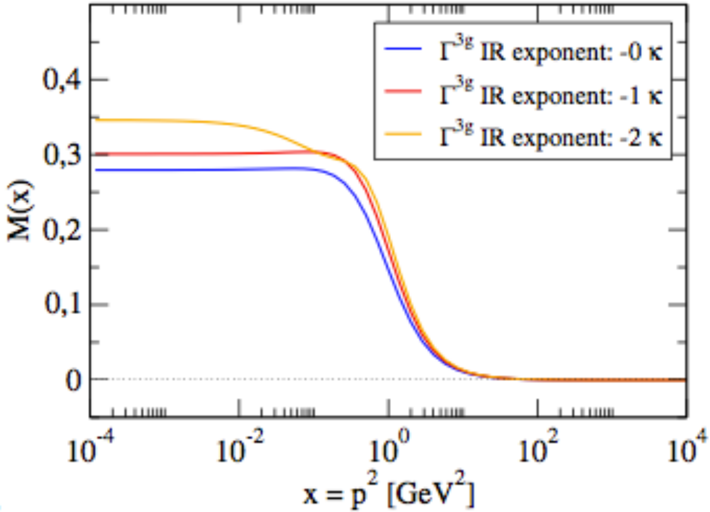


cf. poster of M. Hopfer

- scaling-type gluon propagator
- model for three-gluon vertex (*cf.* MQ Huber)

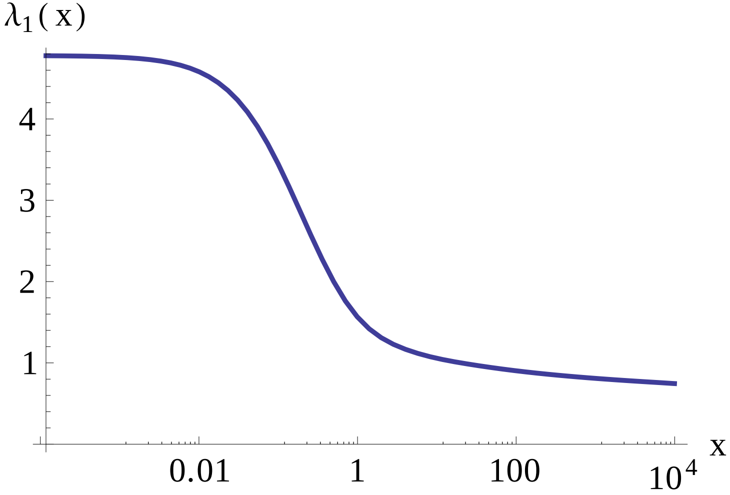
Coupling matter to gluons

Quark mass function with calculated QGV:

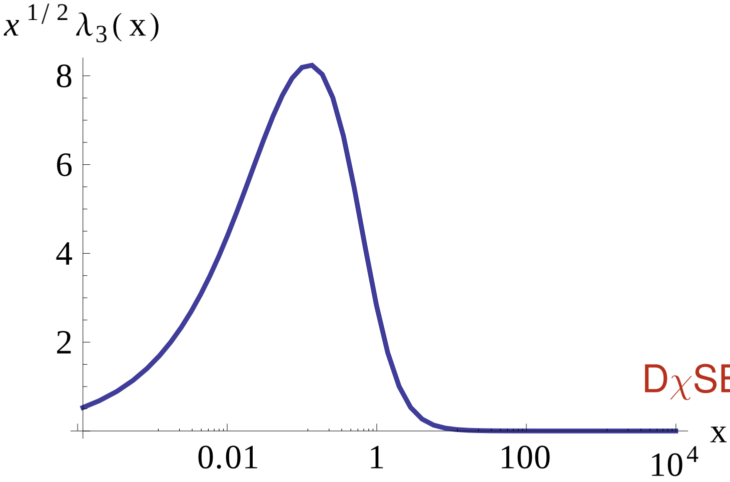


Coupling matter to gluons

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



Subleading DχSB tensor structure, calculated QGV:



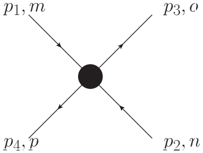
DχSB in QGV!!!

Assuming an IR divergent 4-point function

M. Mitter, RA, in preparation

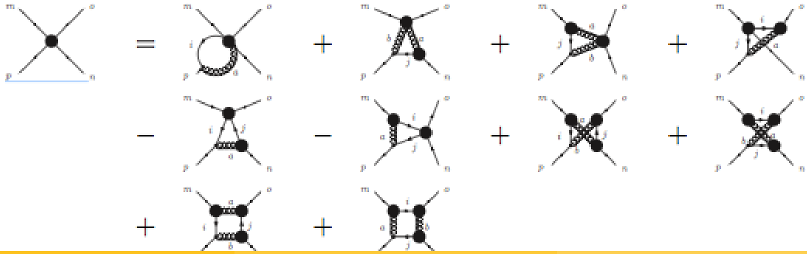
How is Confinement described by Green's functions?

- Assume quark 4-point function to be maximally IR singular, *i.e.*, $\propto \mathbf{1/k^4}$:



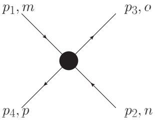
$$\stackrel{p_1 \to p_3}{\propto} \left. \frac{1}{(p_1 - p_3)^4} \right|_{reg.}$$

- 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 $1/k^4 \Longrightarrow$ matter-gluon vertex less singular $\Longrightarrow$ **colour structure**



$$\overset{p_1 \to p_3}{\propto} \left. \frac{\delta_{mo}\delta_{np}}{(p_1 - p_3)^4} \right|_{reg.}$$

  - ☺ 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!?!

Consequences an IR divergent 4-point function

- 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

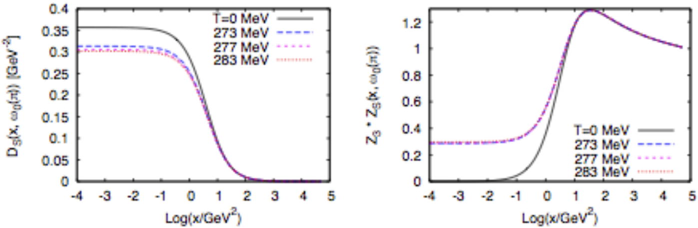
M. Mitter, M. Hopfer, BJ Schaefer, RA, in preparation

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

Propagator of fund. scalar:

- gluon propagator from lattice data
  C.S. Fischer, A. Maas, J.A. Mueller, Eur. Phys. J. **C 68** (2010) 165 [1003.1960].
- vacuum vertex model

Anti-periodic boundary conditions:



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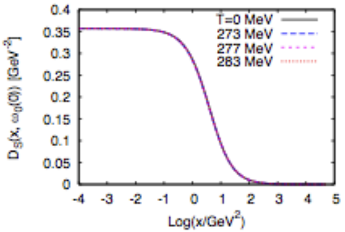
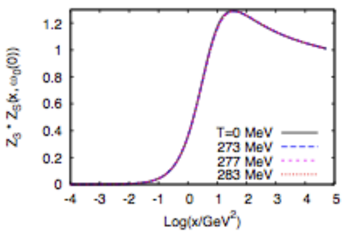
Periodic boundary conditions:





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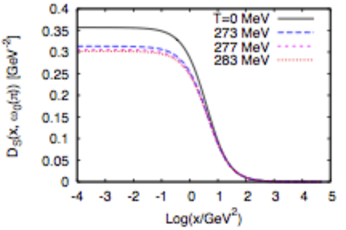
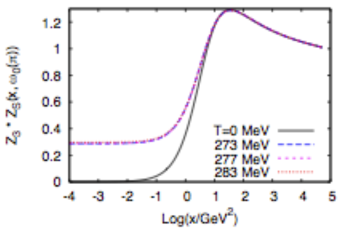


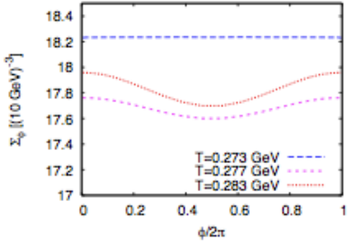


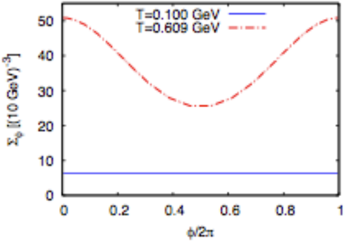
Dual order parameter for scalar QCD:

$$\Sigma_\phi = T \sum_{\omega_n(\phi)} D^2_{S,\phi}(\vec{0}, \omega_n(\phi)) \xrightarrow{z} T \sum_{\omega_n(\phi)} D^2_{S,\phi+\arg(z)}(\vec{0}, \omega_n(\phi))$$

$$= T \sum_{\omega_n(\phi+\arg(z))} D^2_{S,\phi+\arg(z)}(\vec{0}, \omega_n(\phi+\arg(z))) = \Sigma_{\phi+\arg(z)}$$

$$\Sigma_{\phi+2\pi} = \Sigma_\phi$$

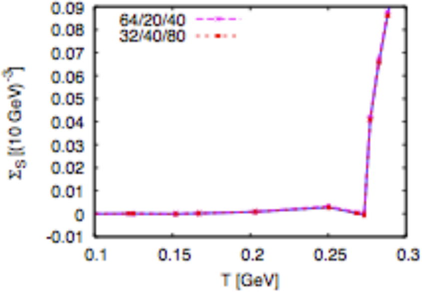


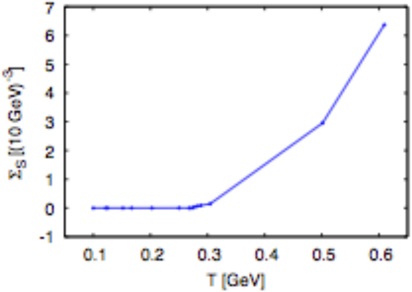


Center symmetry phase transition

Center transition in scalar QCD:

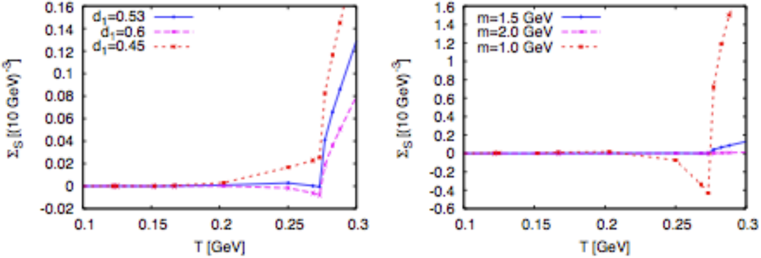
$$\Sigma_S = \int_0^{2\pi} \frac{d\phi}{2\pi} e^{-i\phi} \Sigma_\phi \, , \qquad \Sigma_\phi = T \sum_{\omega_n(\phi)} D^2_{S,\phi}(\vec{0}, \omega_n(\phi))$$





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

$$A(x,y,z) = \tilde{Z}_3 \frac{D_S^{-1}(x) - D_S^{-1}(y)}{x-y} d_1 \left\{ \left(\frac{\Lambda^2}{\Lambda^2 + k^2} \right) + \frac{k^2}{\Lambda^2 + k^2} \left(\frac{\beta_0 \alpha(\mu) \ln \left[k^2/\Lambda^2 + 1 \right]}{4\pi} \right)^{2\delta} \right\}$$

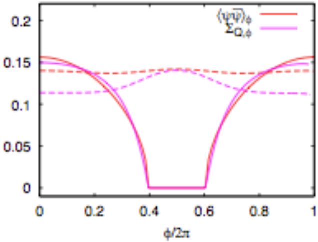


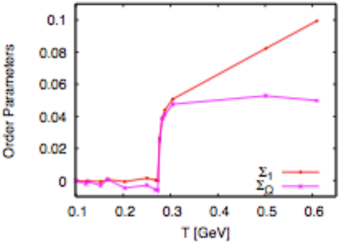
Center symmetry phase transition

Alternative order paramater in QCD (with quarks):

$$\Sigma_Q = \int_0^{2\pi} \frac{d\phi}{2\pi} e^{-i\phi} \Sigma_{Q,\phi} \,, \qquad \Sigma_{Q,\phi} = T \sum_{\omega_n(\phi)} \frac{1}{4i} \mathrm{tr} \left[S_{Q,\phi}(\vec{0}, \omega_n(\phi)) \right]^2$$

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





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Landau gauge QCD Green functions:

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- ☺ Coupled system of quark propagator and quark-gluon vertex DSEs under investigation.
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  - quark/matter confinement, DχSB, $U_A(1)$
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