Results for Yang-Mills vacuum correlation functions in the Landau gauge from equations of motion

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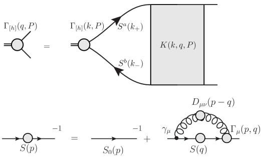
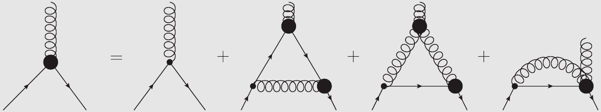
Motivation: Where Yang-Mills theory is important in QCD

Widely used truncation: Rainbow + ladder + variant of Maris-Tandy interaction



How to reduce model dependence

- Improve kernel K
- Use explicit gluon propagator + quark-gluon vertex



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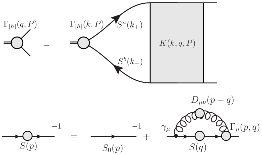

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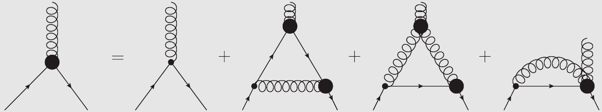

⟶ We need full control over the gluonic sector for self-contained calculations.

- Gluon propagator
- Three-gluon vertex
- . . . ?
- Glueballs

Overview

- Some details on Dyson-Schwinger equations:
  - Renormalization
  - Resummed perturbation theory
- Testing truncations:
  - Hierarchy of diagrams (testing in 3 dimensions)
  - Extensions of truncations in 4 dimensions:

    $\rightarrow$ Two-loop terms

    $\rightarrow$ Non-primitively divergent correlation functions

Landau gauge QCD

$$\mathcal{L} = \bar{q}(-\not{D} + m)q + \frac{1}{2}F^2 + \mathcal{L}_{gf} + \mathcal{L}_{gh}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + i\,g\,[A_\mu, A_\nu]$$

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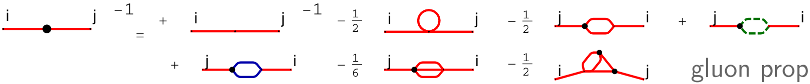
S $D^{A\bar{q}q}$ Z D^{AAA} D^{AAAA}

Landau gauge

- simplest one for functional equations
- $\partial_\mu A_\mu = 0$: $\mathcal{L}_{gf} = \frac{1}{2\xi}(\partial_\mu A_\mu)^2, \quad \xi \to 0$
- requires ghost fields: $\mathcal{L}_{gh} = \bar{c}\,(-\Box + g\,A\,\times)\,c$

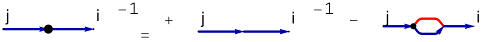
G $D^{A\bar{c}c}$

The tower of DSEs



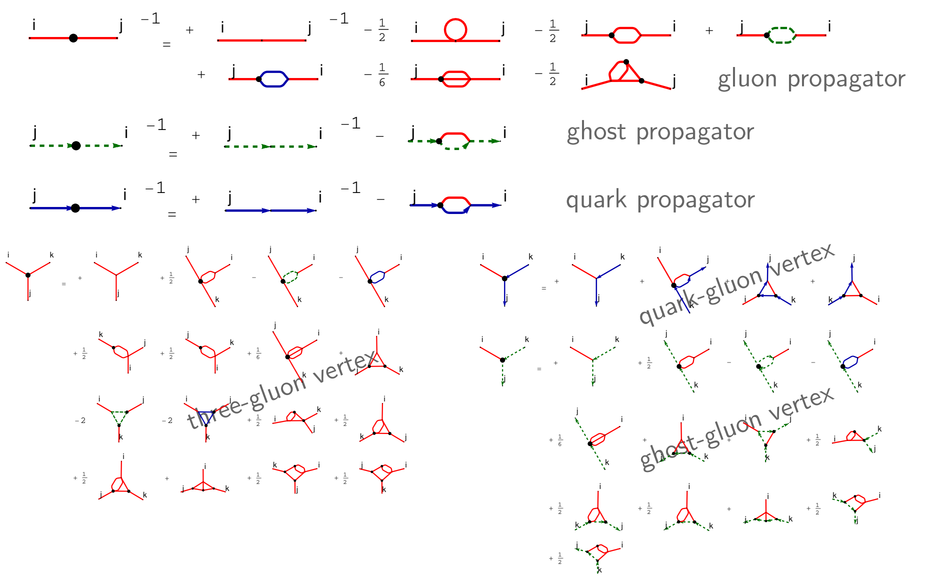
gluon propagator

ghost propagator



quark propagator

The tower of DSEs



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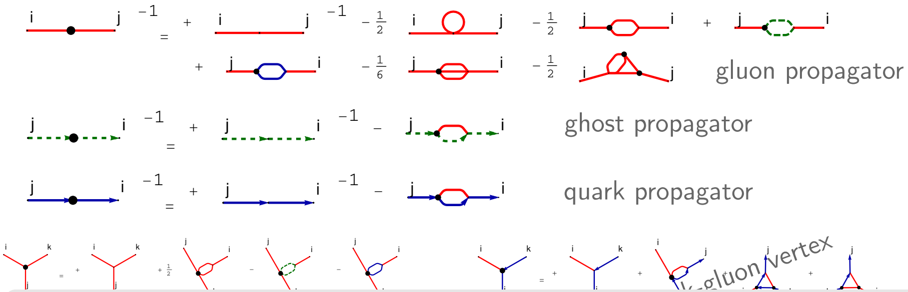
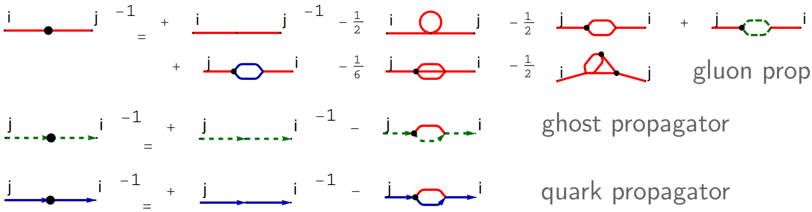


Infinitely many equations. In QCD, every n-point function depends on $(n+1)$- and possibly $(n+2)$-point functions.

The tower of DSEs



gluon propagator

ghost propagator

quark propagator

Infinitely many equations. In QCD, every n-point function depends on $(n+1)$- and possibly $(n+2)$-point functions.

Is it possible to find and solve a truncation with all relevant contributions?

Questions about truncations

- Influence of higher correlation functions?

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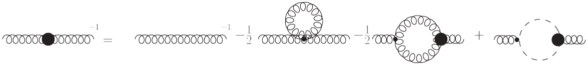
- How to realize resummation?
- Equivalence between different functional methods?

UV behavior of the gluon propagator

Resummed one-loop order: anomalous dimension $\gamma = -13/22$
One-loop truncation:



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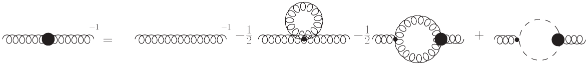

Self-consistent solution puts constraints on UV behavior of vertices [von Smekal, Hauck, Alkofer '97]:

- Ghost-gluon vertex: $\sim$ *const.* $\rightarrow \checkmark$

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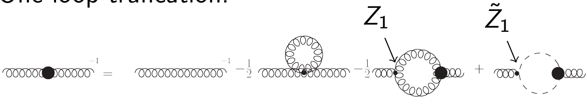


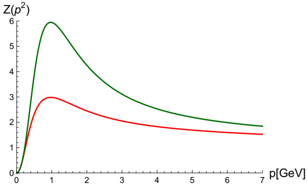
Self-consistent solution puts constraints on UV behavior of vertices [von Smekal, Hauck, Alkofer '97]:

- Ghost-gluon vertex: $\sim$ *const.* $\rightarrow$ ✓
- Three-gluon vertex: $\propto (\log p)^{17/22}$
  Anomalous dimension $\gamma_{3g} = 17/44 \rightarrow$ ☹
  Solutions: $Z_1 \rightarrow Z_1(p^2) \leftrightarrow$ modified three-gluon vertex model [von Smekal, Hauck, Alkofer '97; Fischer, Alkofer '02]

  Truncation artifact!

Resummed behavior

- Resolving the UV behavior within this truncation leads to an additional parameter dependence $\rightarrow$ part of the model
  Extreme example:



- Study of such effects for three-gluon vertex:
  [Eichmann, Williams, Alkofer, Vujinovic '14]
- However, correct UV behavior is required for self-consistency.

$\rightarrow$ How to get resummed one-loop behavior?

One-loop resummation

One-loop anomalous dimension

Origin in resummation of higher order diagrams.

$$\left(1 + \frac{\alpha(s) 11 N_c}{12\pi} \ln \frac{p^2}{s}\right)^{\gamma}$$

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Origin in resummation of higher order diagrams.

$$\left(1+\frac{\alpha(s)11N_c}{12\pi}\ln\frac{p^2}{s}\right)^{\gamma}=1+c_1\,g^2\ln p^2+c_2\,g^4\ln^2 p^2+\mathcal{O}(g^6)$$

- $\mathcal{O}(g^2)$: One-loop diagrams
- $\mathcal{O}(g^4)$: Iterated one-loop diagrams, squint (*not* sunset)

Resummed behavior

Minimal requirements to obtain one-loop resummed behavior:

- Squint diagram
- Correct anomalous dimensions of three-point functions
- Correct renormalization (constants)

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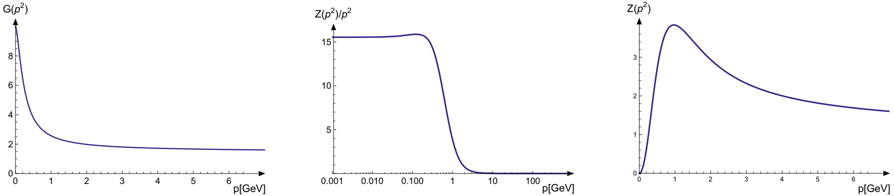
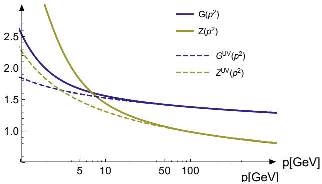


[propagator+ghost-gluon eqs. full, 3-gluon vertex model, bare 4-gluon vertex]

- Resummed behavior is recovered

  [MQH, EPJC (2017)].



Renormalization of gluon propagator (d=4)

1. 'Physics': Logarithmic divergences handled by subtraction at p_0.
2. Breaking of gauge covariance by cutoff regularization (also in perturbation theory):
   Quadratic divergences subtracted, coefficient C_{sub}.

$$Z(p^2)^{-1} := \; Z_\Lambda(p^2)^{-1} \; - C_{\text{sub}}(\Lambda)\left(\frac{1}{p^2} - \frac{1}{p_0^2}\right)$$

↑

hand side

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One-loop diagrams with model vertices: C_{sub} can be calculated analytically, since it is purely perturbative [MQH, von Smekal '14].

Dynamic vertices? Two-loop diagrams?

ht-hand side

Renormalization of gluon propagator (d=3)

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   ~~Quadratic~~ Linear and logarithmic divergences subtracted.

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Calculation of C_{sub} in $d = 4$

Example: Ghost loop

$$I_{gh}^{spur}(p^2) \propto \frac{1}{p^2} \int_{p_0^2}^{\Lambda^2} dq^2\, G_{UV}^2(q^2)$$

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What about the finite part [MQH, von Smekal '14]?

- Perturbatively: no mass term generated?
- Independent of UV parametrization.
- Dim. reg. calculation yields the same finite part.

Calculation of C_{sub} in $d = 3$

Example: Ghost loop

Note: $[g] = [mass]^{\frac{1}{2}}$

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Form of spurious divergences (analytic):

$$C_{sub} = a\,\Lambda + b \ln \Lambda$$

Dynamic vertices? Two-loop diagrams?

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Dynamic vertices? Two-loop diagrams?
$\rightarrow$ Fit possible, since the functional form is the same [MQH '16].

Testing truncations in $d = 3$:
Vary equations and systems of equations.

$d = 3$ Yang-Mills theory as testing ground

Advantages:

- UV finite: no renormalization, no anomalous running
- Spurious divergences easier to handle
- UV behavior 'easier': $\propto \frac{g^2}{p}$ instead of resummed logarithm

→ Many complications from $d = 4$ absent.
→ Disentanglement of UV easier.
⇒ 'Cleaner' system → Focus on truncation effects.

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Historically interesting because cheaper on the lattice → easier to reach the IR.

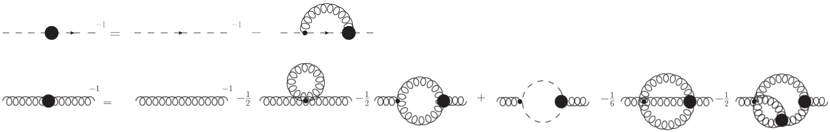
Numerically not cheaper for functional equations of 2- and 3-point functions.

Continuum results:

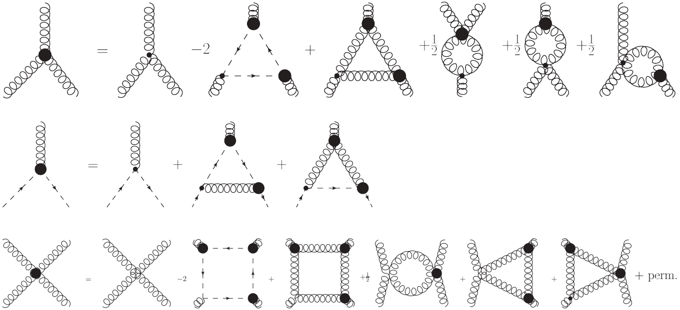
- Coupled propagator DSEs: [Maas, Wambach, Grüter, Alkofer '04]
- (R)GZ: [Dudal, Gracey, Sorella, Vandersickel, Verschelde '08]
- DSEs of PT-BFM: [Aguilar, Binosi, Papavassiliou '10]
- YM + mass term: [Tissier, Wschebor '10, '11]

Dyson-Schwinger equations: Truncation

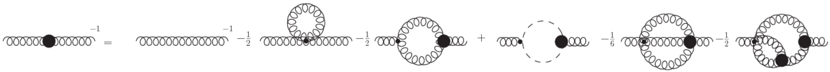
Untruncated propagators:

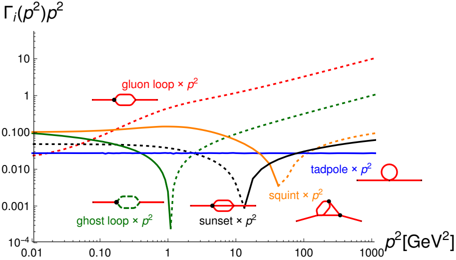


Truncated vertices:



Gluon propagator: Single diagrams



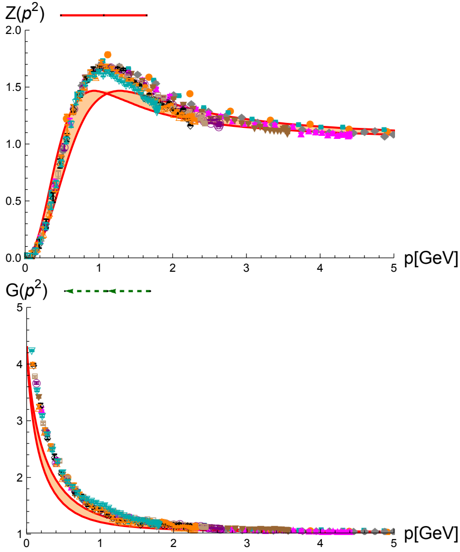


[MQH '16]

Clear hierarchies identified:

- UV: as expected perturbatively
- non-perturbative: squint important, sunset small
  (d=4: [Mader, Alkofer '13; Meyers, Swanson '14])

Results: Propagators

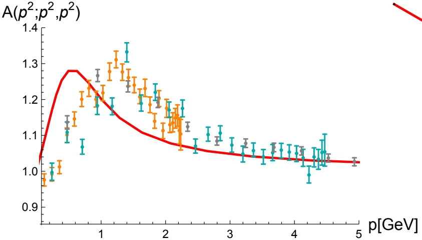


Bands from uncertainty in setting the physical scale.

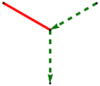
[MQH '16; lattice: Maas '14]

Comparison of three-point functions with lattice results

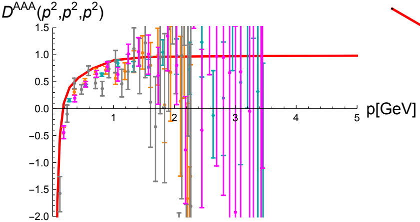
Dressings:



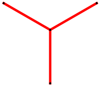
[MQH '16; lattice: Maas, unpublished]



- Deviation from tree-level in midmomentum 'small'
- Maximum position shifted.
- Bump height ok.



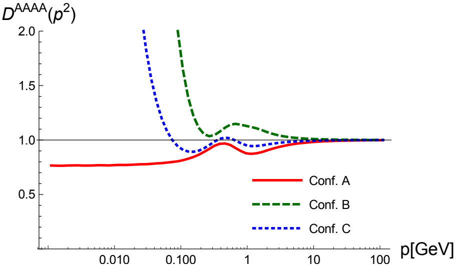
[MQH '16; lattice: Cucchieri, Maas, Mendes '08]



- Close to tree-level above 1 GeV
- Good agreement with lattice data.
- Linear IR divergence [Pelaez, Tissier, Wschebor '13; Aguilar et al. '14]

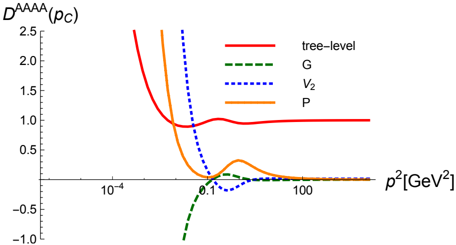
Four-gluon vertex

Different momentum configurations:



[MQH '16]

Different projections:



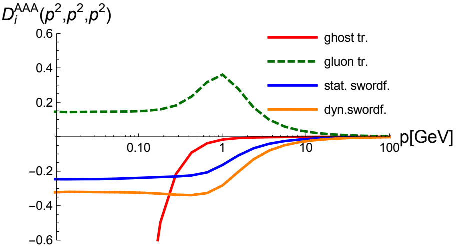
Four-gluon vertex:

- Close to tree-level down to 1 GeV

→ Corrections small individually?

Cancellations in gluonic vertices

Three-gluon vertex:



[MQH '16]

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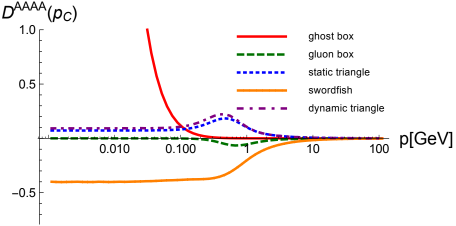

- Individual contributions large.
- Sum is small!

Cancellations in gluonic vertices

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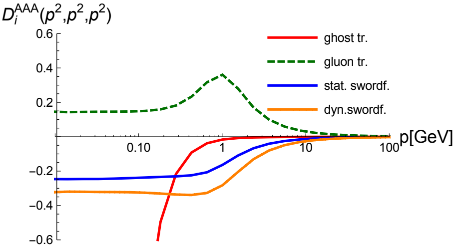

[MQH '16]

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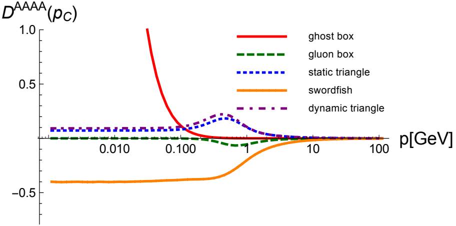

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$\Downarrow$

Higher contributions:

- Higher vertices close to 'tree-level'? $\rightarrow$ Small.
- If pattern changes (higher vertices large): cancellations required.

Solution from the 3PI effective action

Different set of functional equations:
equations of motion from 3PI effective action (at three-loop level)

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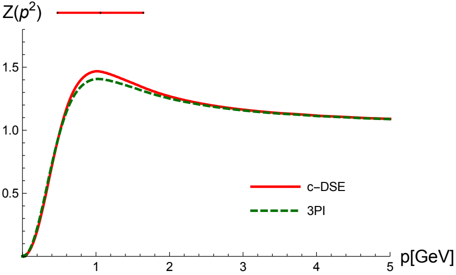
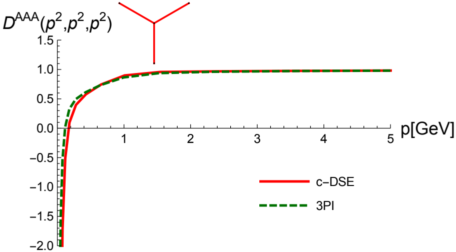




→ Very similar results.

[MQH '16]

Summary about three dimensions

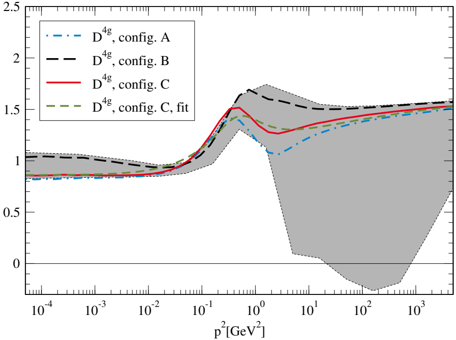
- Hierarchy of correlation functions and diagrams
- Cancellations
- Some degree of stability (but no complete list of checks done) when
  - varying *system* of equations.
  - varying *equations* of system.
- Discrepancies with lattice results:
  - Nonperturbative gauge fixing?
  - Lattice systematics?
  - Missing diagrams for vertices?
  - Incomplete tensor bases for some vertices?

Extending truncations in four dimensions:
Include four-point functions.

Four-gluon vertex

Full calculation with fixed input:
[Cyrol, MQH, von Smekal '14]

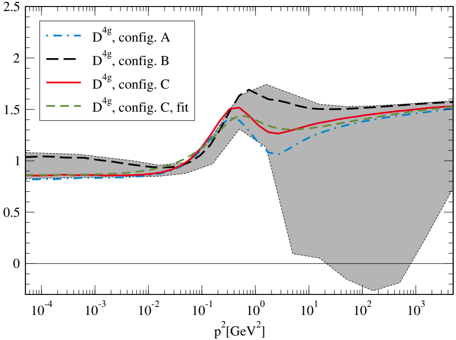
Computationally expensive!

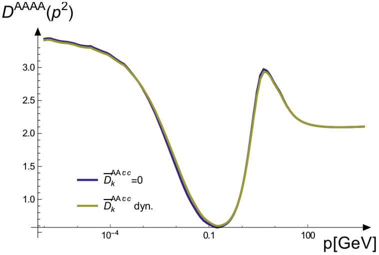


Four-gluon vertex

Full calculation with fixed input:
[Cyrol, MQH, von Smekal '14]

Computationally expensive!





Three-gluon vertex has small angle dependence.
→ For dynamic inclusion: Resort to a one-momentum approximation (symmetric point); see also FRG calculations by fQCD collaboration.

Effect of four-gluon vertex

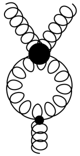
In three-gluon vertex DSE:

Important for convergence within current truncations in $d = 4$

[Blum, MQH, Mitter, von Smekal '14;

Eichmann, Williams, Alkofer, Vujinovic '14; MQH '17]

$\rightarrow$ Related to renormalization.



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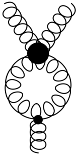

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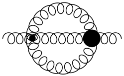
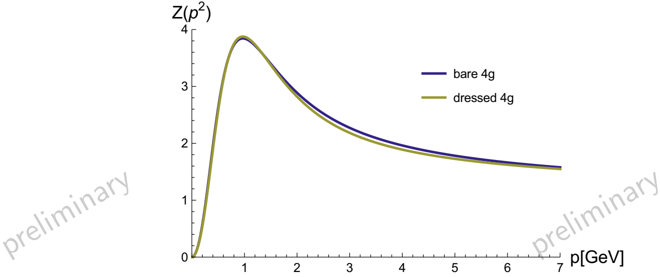
In gluon propagator: Via sunset diagram, small contribution of tree-level dressing; model studies: [Mader, Alkofer '13; Meyers, Swanson '14]





Extending truncations of three-point functions

Extend truncations of equations of three-point functions by adding the two-ghost-two-gluon vertex:

Extending truncations of three-point functions

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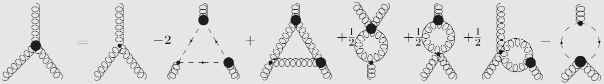

→ One-loop complete equation.

Extending truncations of three-point functions

Extend truncations of equations of three-point functions by adding the two-ghost-two-gluon vertex:

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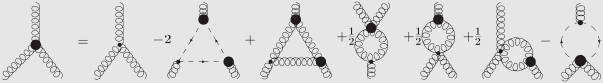
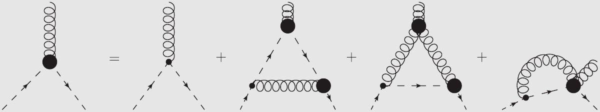


→ One-loop complete equation.

Ghost-gluon vertex



→ Complete equation.

Four-ghost vertex:

In alternative ghost-gluon vertex DSE and in four-point functions.

Four-point functions: Color space

15 possibilities:

$$\begin{aligned} \delta\,\delta &: \quad 3\,\text{combinations} \\ f\,f &: \quad 3\,\text{combinations} \\ d\,d &: \quad 3\,\text{combinations} \\ d\,f &: \quad 6\,\text{combinations} \end{aligned}$$

Four-point functions: Color space

15 possibilities:

- $\delta\,\delta$: 3 combinations
- $f\,f$: 3 combinations
- $d\,d$: 3 combinations
- $d\,f$: 6 combinations

9/8/3 linearly independent in $SU(N/3/2)$, $N > 3$
[Pascual, Tarrach '80].

$SU(3)$: $\{\sigma_1, \dots, \sigma_8\}$ chosen with these symmetries:

	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7	σ_8
$a \leftrightarrow b$	+	+	+	-	-	-	-	+
$c \leftrightarrow d$	+	+	+	-	-	+	-	-

$\{\sigma_1, \dots, \sigma_5\}$ orthogonal to $\{\sigma_6, \sigma_7, \sigma_8\}$. $\rightarrow$ $\{\sigma_6, \sigma_7, \sigma_8\}$ decouple.

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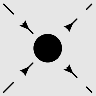
Four-ghost vertex



$$\Gamma^{\bar{c}\bar{c}cc,abcd}(p,q,r,s) = g^4 \sum_{k=1}^{8} \sigma^{k,abcd} E_k^{\bar{c}\bar{c}cc}(p,q,r,s).$$

The two-ghost-two-gluon vertex: Lorentz space

Non-primitively divergent correlation function $\rightarrow$ no guide from tree-level tensor $\rightarrow$ Use full basis.

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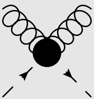
Two-ghost-two-gluon vertex



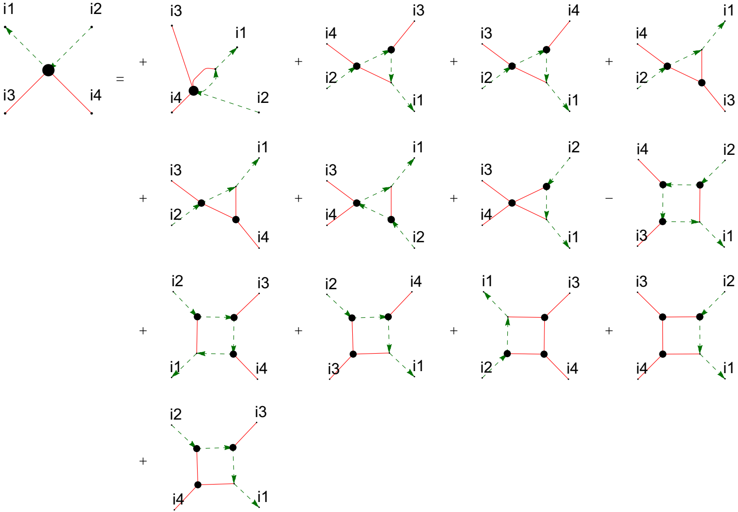
$$\Gamma^{AA\bar{c}c,abcd}_{\mu\nu}(p,q;r,s) = g^4 \sum_{k=1}^{40} \rho^{k,abcd}_{\mu\nu} D^{AA\bar{c}c}_{k(i,j)}(p,q;r,s)$$

with

$$\rho^{k,abcd}_{\mu\nu} = \sigma^{abcd}_i \tau^j_{\mu\nu}, \qquad k = k(i,j) = 5(i-1) + j$$

The two-ghost-two-gluon vertex DSE

2 DSEs, choose the one with the ghost leg attached to the bare vertex
$\rightarrow$ Truncation discards only one diagram.



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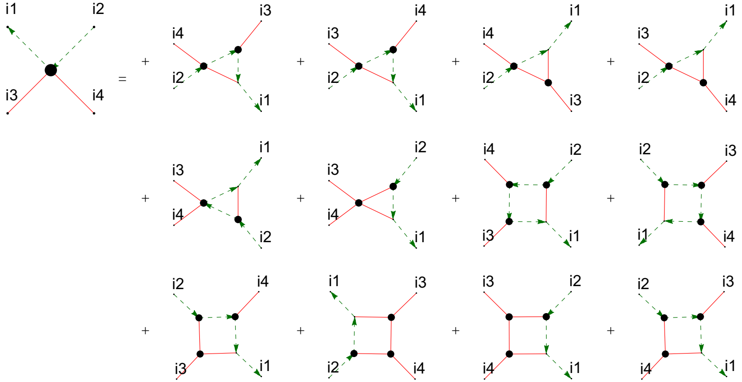
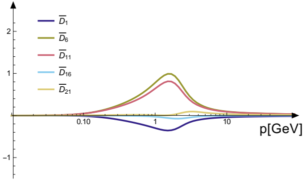
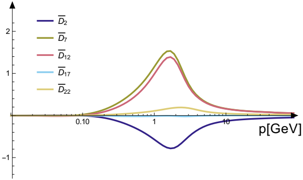


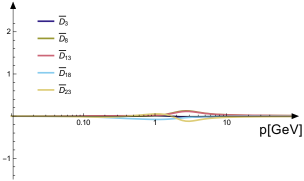
Results for the two-ghost-two-gluon vertex

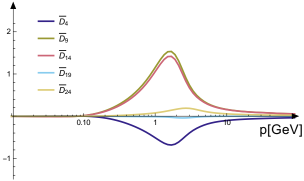
Kinematic approximation: one-momentum configuration

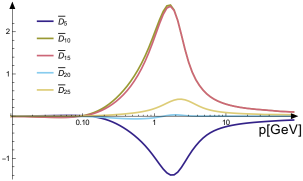
- Dimensionless dressing functions $\overline{D}_k$.
- Each plot one Lorentz tensor.









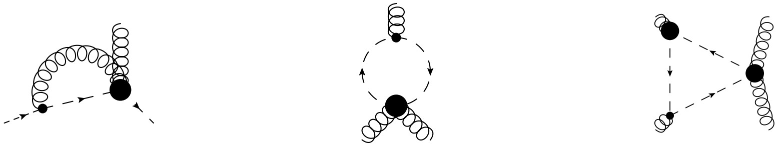


$\rightarrow$ Two classes of dressings: 13 very small, 12 not small

$\rightarrow$ No nonzero solution for $\{\sigma_6, \sigma_7, \sigma_8\}$ found. [MQH, EPJC (2017)]

Influence of two-ghost-two-gluon vertex

Coupled system of ghost-gluon, three-gluon and four-gluon vertices with and without two-ghost-two-gluon vertex:



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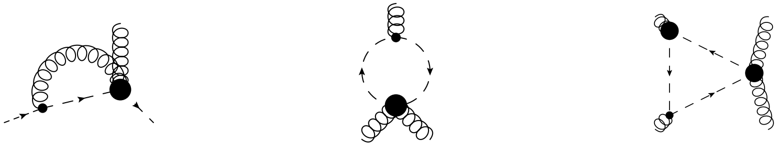
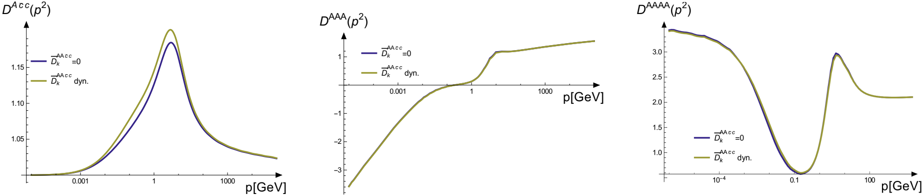


Color space: $\{\sigma_6, \sigma_7, \sigma_8\}$ do not appear here!



- Small influence on ghost-gluon vertex ($< 1.7\%$)
- Negligible influence on three- and four-gluon vertices.

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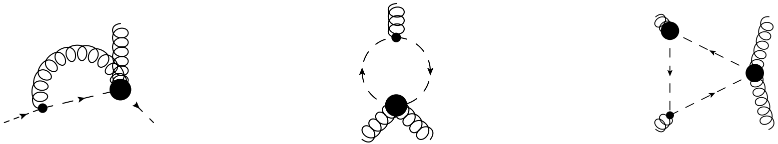

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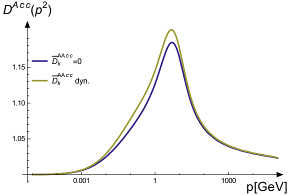

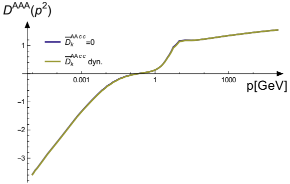

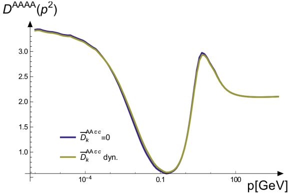

- Small influence on ghost-gluon vertex ($< 1.7\%$)
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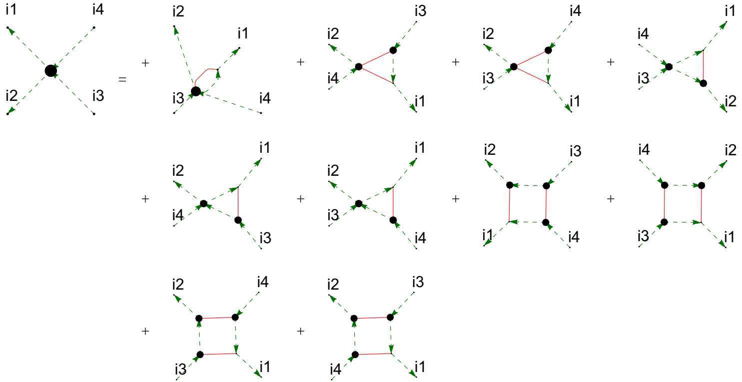
  (Color space: Only small dressings couple to three-gluon vertex.)

[MQH, EPJC (2017)]

The four-ghost vertex DSE

→ Truncation discards only one diagram.



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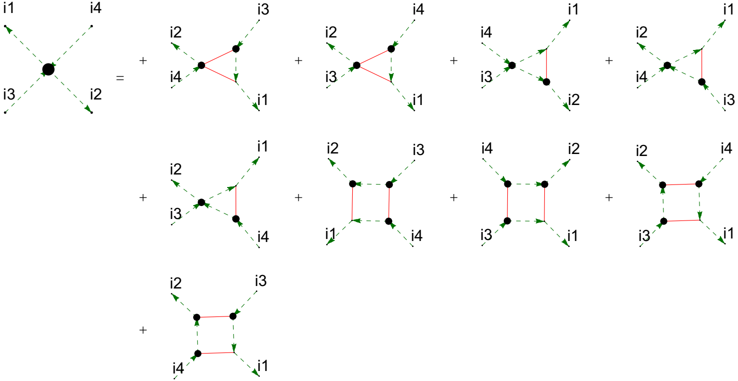
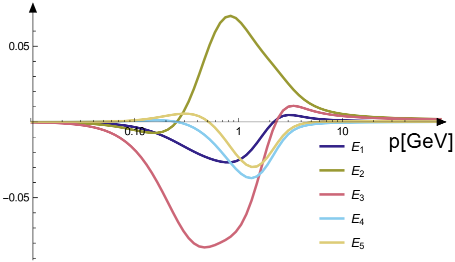


Results for the four-ghost vertex

Kinematic approximation: one-momentum configuration



→ All dressings very small.

[MQH, EPJC (2017)]

E_6, E_7, E_8 $(\{\sigma_6, \sigma_7, \sigma_8\})$

Decouple into a homogeneous, linear equation. → Trivial solution always exists.
Nontrivial one? → None found.
(Same applies to two-ghost-two-gluon vertex.)

Summary and conclusions

Based on

- tests in $d = 3$ including comparison with 3PI calculations
- analysis of one-loop resummation
- testing non-primitively divergent correlation functions

a non-perturbative hierarchy of correlations functions and diagrams can be identified.

Three- and four-gluon vertices:

1. Cancellations between diagrams
2. Negligible diagrams

Two-loop diagrams in propagators:

Required quantitatively and for self-consistency.

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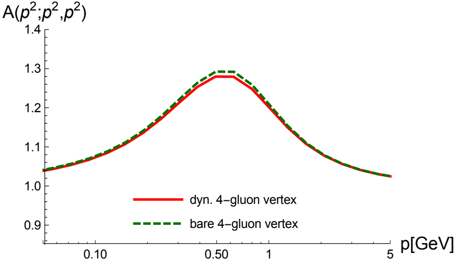
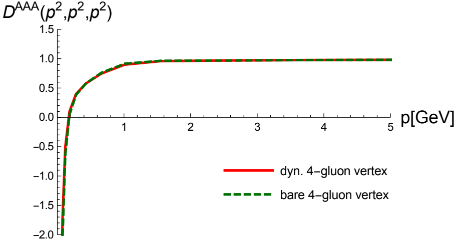
Thank you for your attention!

Influence of four-gluon vertex on three-point functions





[MQH '16]

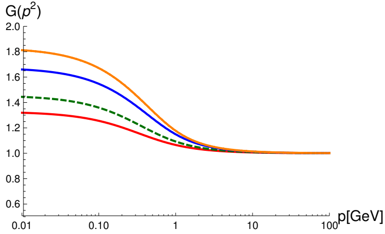
- Influence of four-gluon vertex small.

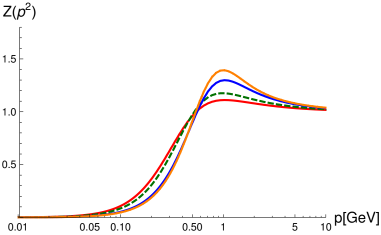
Family of solutions in three dimensions

Cf. FRG results: Bare mass parameter from modified STIs [Cyrol, Fister, Mitter, Pawlowski, Strodthoff '16].

DSEs: Enforce family of solutions by fixing the gluon propagator at $p^2 = 0$.

Simple toy system with bare vertices [MQH, 1606.02068]:





$\Rightarrow$ Possibility of family of solutions.

NB: Effect overestimated here since vertices are fixed.