On propagators and vertices of Yang-Mills theory from their equations of motion

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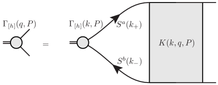
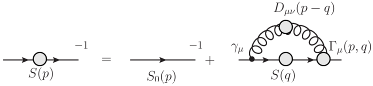
Hadronic bound states

Bound state equations: E.g., meson



Ingredients:

- Interaction kernel K
- Quark propagator S



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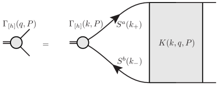

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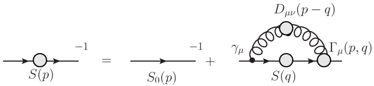
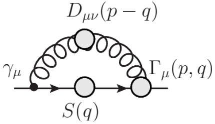


Approaches:

- Phenomenological (bottom-up): Model interactions
- From first principles (top-down): Piecing together the elementary pieces

The elementary pieces



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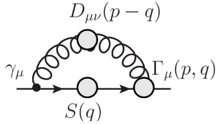
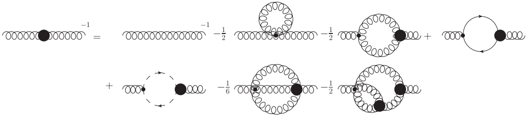
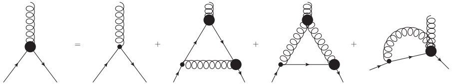


Gluon propagator $D_{\mu\nu}(p^2)$:



Quark-gluon vertex $\Gamma_\mu(p,q)$:



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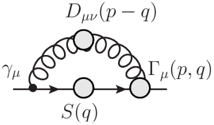

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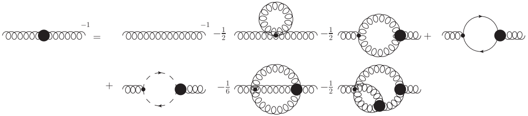

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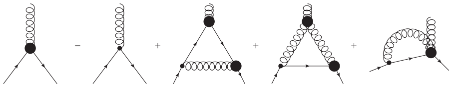

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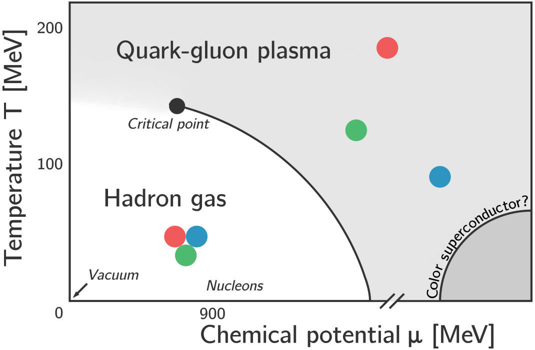
Note: Effective interaction via $g^2 D_{\mu\nu}(p)\Gamma_\mu(p,q) \rightarrow Z_2 \widetilde{Z}_3 D^{(0)}_{\mu\nu}(p)\gamma_\mu \mathcal{G}((p+q)^2)$

Another example: QCD phase diagram

Questions:

- Phases and transitions between them, critical point
- Experimental signatures



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Theoretical challenges:

- Model description
- Mathematical, e.g., complex action for lattice QCD
- Complexity, e.g., truncations of function eqs.
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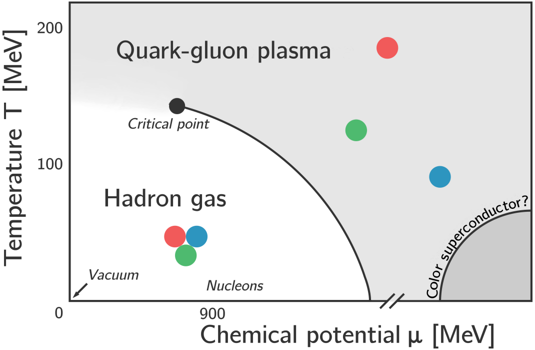

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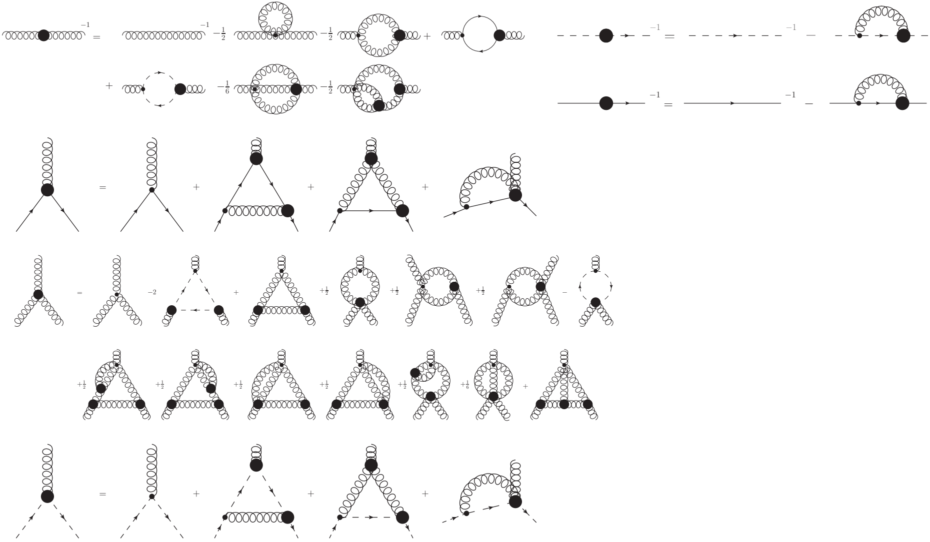
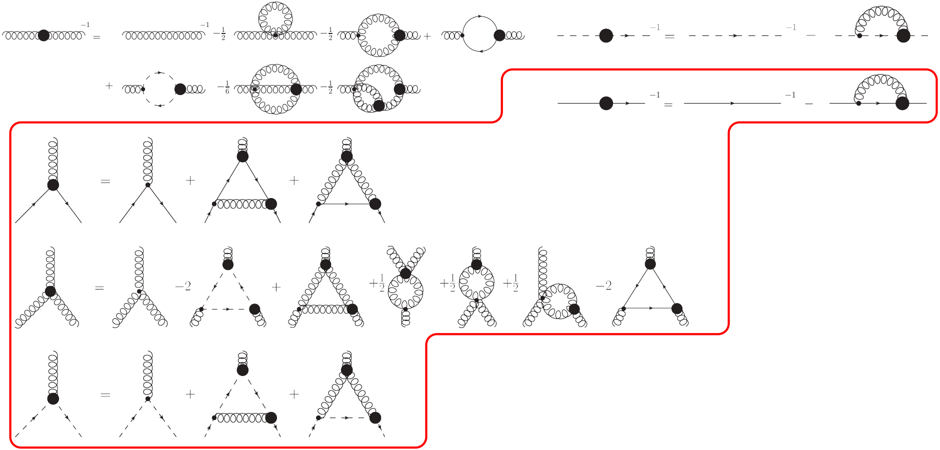
  higher loop contributions?
- Systematics and tests?
  comparison to other methods, self-tests?

Dyson-Schwinger equations



Coupled systems of Dyson-Schwinger equations



quark propagator + 3-point functions: [Williams, Fischer, Heupel '15] $\rightarrow$ application to bound states

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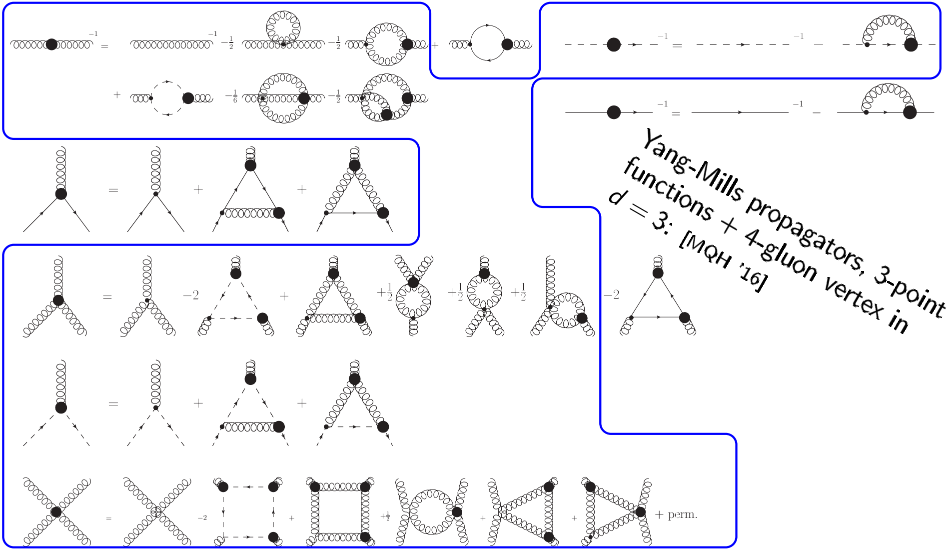

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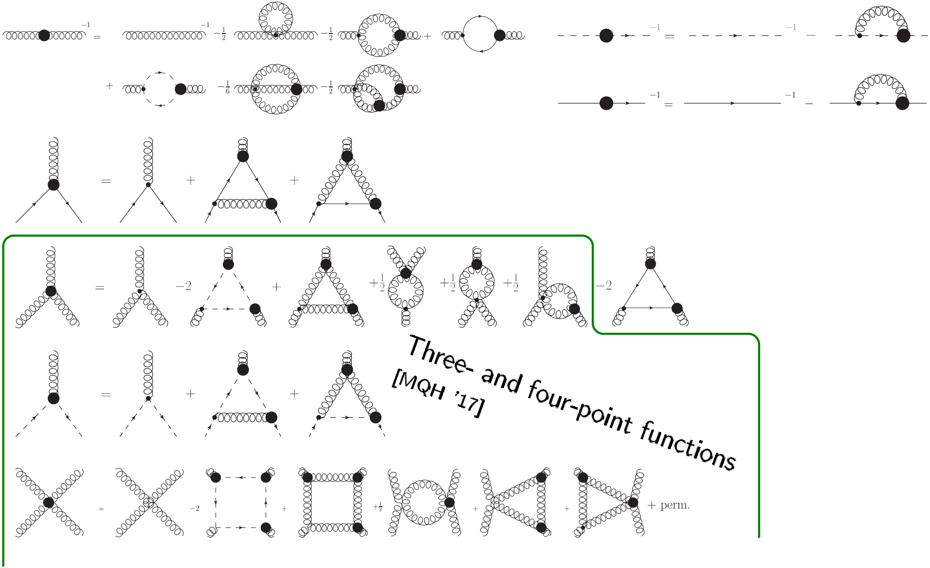
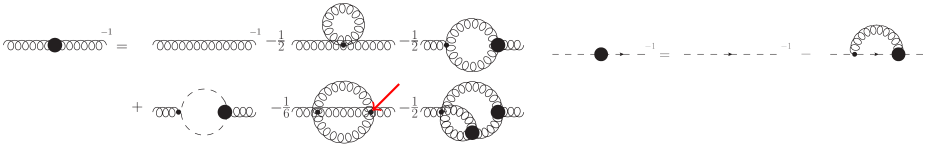
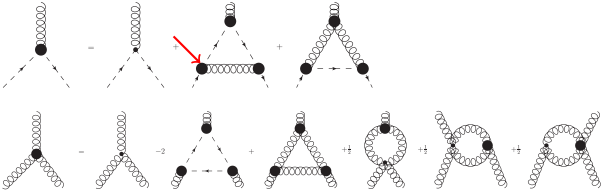


3PI system of equations

Three-loop expansion of PI effective action [Berges '04]:





Setting the scale

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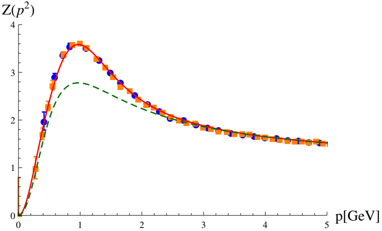
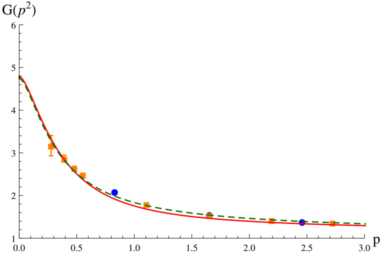
Observables of Yang-Mills theory, e.g., glueballs to fix the scale. $\rightarrow$ Impractical.

More convenient: Take scale from lattice calculations of the gluon propagator. Scale via string tension of $\sigma = (440\,\text{MeV})^2$.

Example of a bottom-up calculation

Propagators and ghost-gluon vertex with three-gluon vertex model:
One-loop truncation of gluon propagator with an optimized effective model (contains zero crossing) [MQH, von Smekal '13; lattice: Sternbeck '06]:





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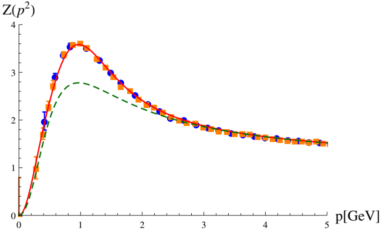

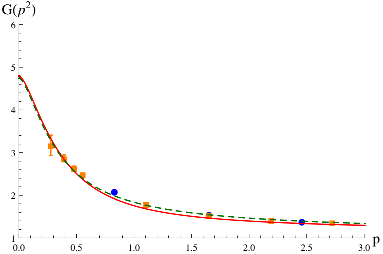

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QCD is only this:

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left(F_{\mu\nu}F^{\mu\nu}\right) + \sum_j \bar{\varphi}_j\left[i\gamma^\mu D_\mu - m_j\right]\varphi_j$$

WOBEI $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + ig[A_\mu, A_\nu]$

UND $D_\mu = \partial_\mu + igA_\mu$

Can we do with only that?

A lesson from three dimensions?

Three-dimensional Yang-Mills theory is finite.

$\rightarrow$ No renormalization

$\rightarrow$ Leading pertubative contributions $\propto g^2/p$

$\Rightarrow$ Testbed for functional calculations.

Various methods employed:

- Lattice: [Bornyakov, Cucchieri, Maas, Mendes, Mitrjushkin, Rogalyov, ...]
- Coupled propagator DSEs: [Maas, Wambach, Grüter, Alkofer '04]
- (R)GZ: [Dudal, Gracey, Sorella, Vandersickel, Verschelde '08]
- DSEs of PT-BFM: [Aguilar, Binosi, Papavassiliou '10]
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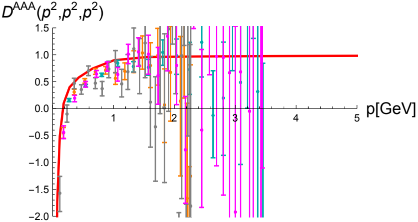
Study effect of individual diagrams...

Cancellations in three-gluon vertex



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

- Close to tree-level above 1 GeV
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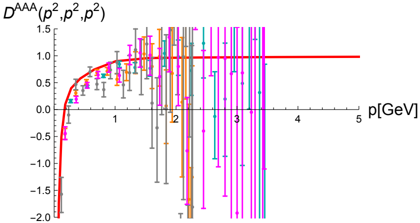

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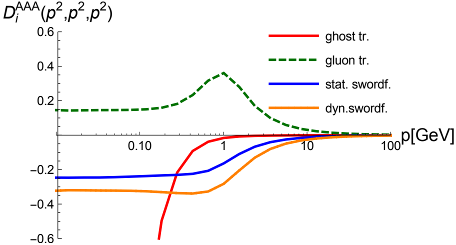

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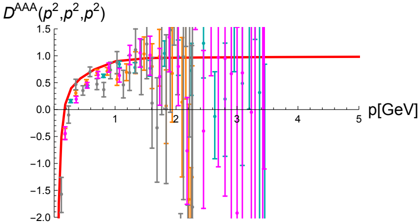

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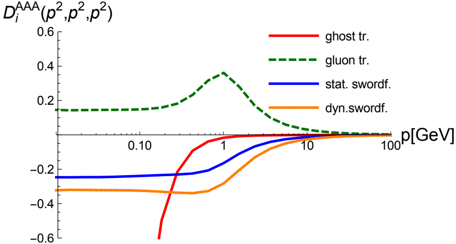

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→ In four dimensions similar qualitative effects, but renormalization complicates things.

UV behavior of the gluon propagator

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

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

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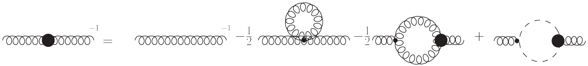
One-loop anomalous dimension

Origin in resummation of higher order diagrams.

However, one-loop truncation discards some terms.



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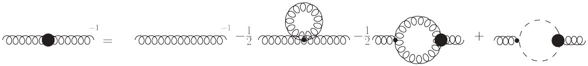

$\rightarrow$ Puts constraints on UV behavior of vertices if one wants a self-consistent solution [von Smekal, Hauck, Alkofer '97].

Fixing the UV behavior of the gluon propagator I

First possibility:

Modify the UV behavior of the integrand, e.g., replace the renormalization constant by a momentum dependent function [von Smekal, Hauck, Alkofer '97] ('RG improvement'), adapt employed models.

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Examples:

- Yang-Mills propagators, e.g., [von Smekal, Hauck, Alkofer '97; Fischer, Alkofer '02; MQH, von Smekal '12, '14]
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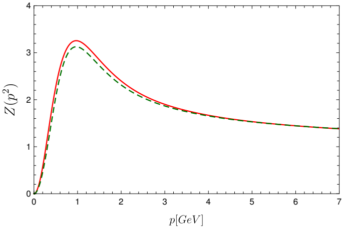
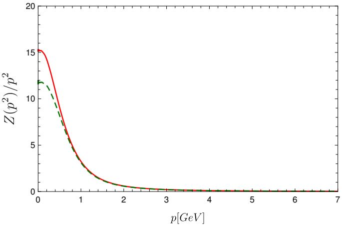
IR completion has an effect on the gluon propagator [MQH, von Smekal '14]:





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Include higher perturbative terms.
Worked out analytically for ϕ^3-theory [MQH '18].

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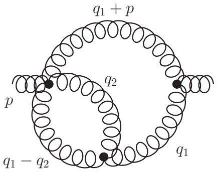

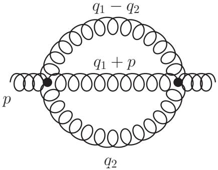

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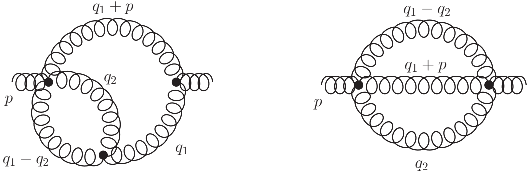
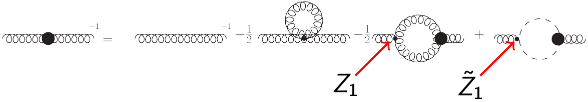


$\rightarrow$ Contributions also from renormalization constants in front of one-loop diagrams.



$\Rightarrow$ All two-loop contributions in the gluon propagator are included.
And higher contributions...

Resummed behavior

Minimal requirements to obtain one-loop resummed behavior:

- Squint diagram (sunset has no $g^4 \ln^2 p^2$)
- Correct anomalous dimensions of three-point functions
- Correct renormalization (constants)

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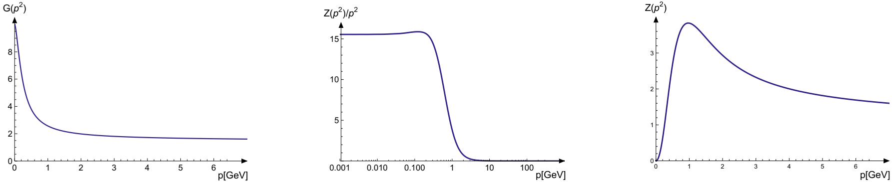
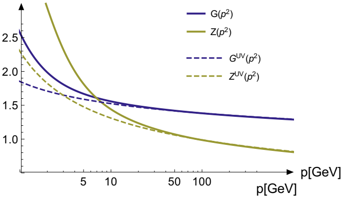


[propagator+ghost-gluon eqs. full, 3-gluon vertex model, bare 4-gluon vertex]

- Resummed behavior is recovered
  [MQH '17].



Extending truncations

Various ways to extend truncations:

- Vertex tensors beyond tree-level tensor
- Include neglected diagrams
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Extensions also test the previous truncations!

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In the following:

- Three-gluon vertex
- Four-point functions
- Coupling the equations

Three-gluon vertex DSE

Talk by Papavassiliou: "Three-gluon vertex: The new frontier"

[Cucchieri, Maas, Mendes '08; Alkofer, MQH, Schwenzer '09; Pelaez, Tissier, Wschebor '13; Aguilar et al. '13; Blum, et al. '14; Eichmann, Alkofer, Vujinovic '14; Cyrol et al. '16; Williams, Fischer, Heupel '16; Sternbeck '16; Athenodorou et al. 16; Duarte et al. '16; Boucaud et al. '17]

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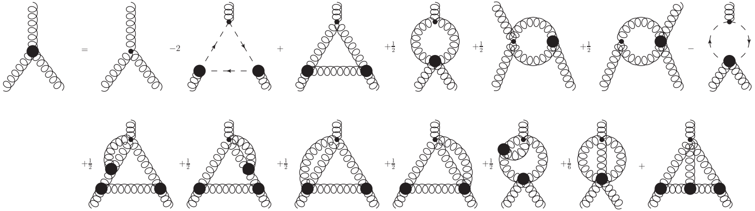
Full DSE:



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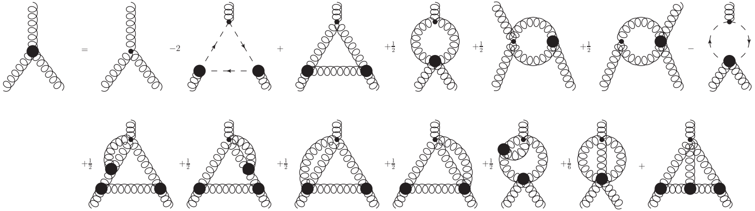
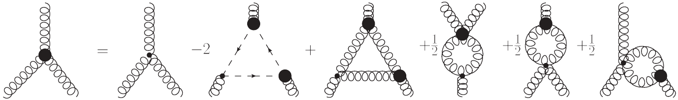


Perturbative one-loop truncation [Blum, MQH, Mitter von Smekal '14; Eichmann, Alkofer, Vujinovic '14; Williams, Fischer, Heupel '16]:



Three-gluon vertex DSE

Talk by Papavassiliou: "Three-gluon vertex: The new frontier"

[Cucchieri, Maas, Mendes '08; Alkofer, MQH, Schwenzer '09; Pelaez, Tissier, Wschebor '13; Aguilar et al. '13; Blum, et al. '14; Eichmann, Alkofer, Vujinovic '14; Cyrol et al. '16; Williams, Fischer, Heupel '16; Sternbeck '16; Athenodorou et al. 16; Duarte et al. '16; Boucaud et al. '17]

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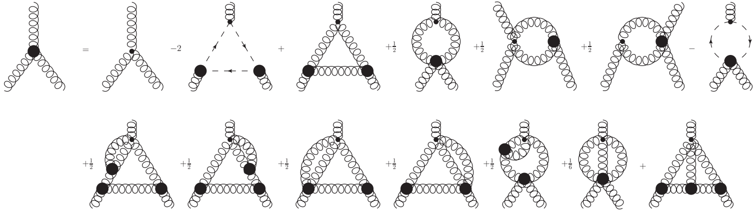
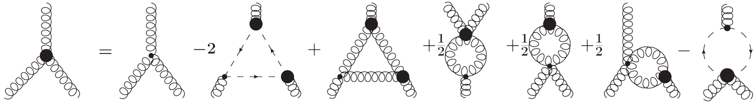
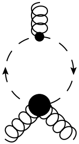


Non-perturbative one-loop truncation [MQH '17]:



Influence of two-ghost-two-gluon vertex



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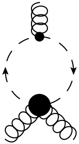
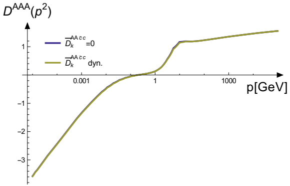


Coupled system of ghost-gluon, three-gluon and four-gluon vertices with and without two-ghost-two-gluon vertex [MQH '17]:



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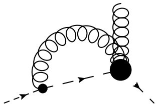

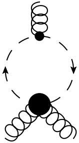

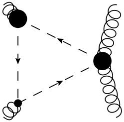

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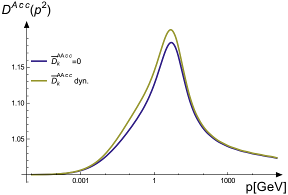
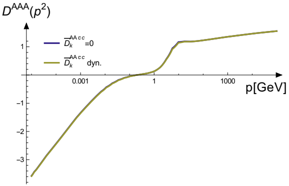
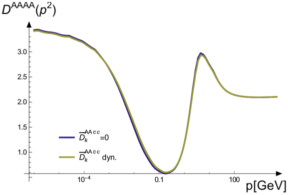
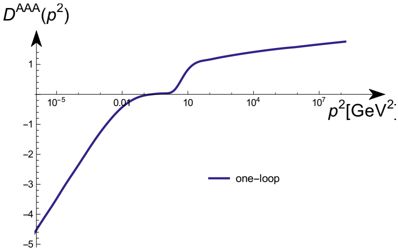






- Small influence on ghost-gluon vertex ($< 1.7\%$)
- Negligible influence on three- and four-gluon vertices.

Three-gluon vertex results



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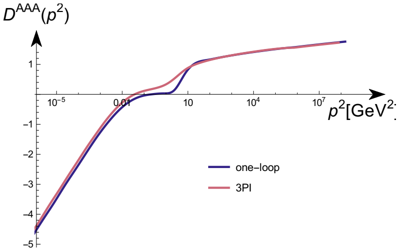

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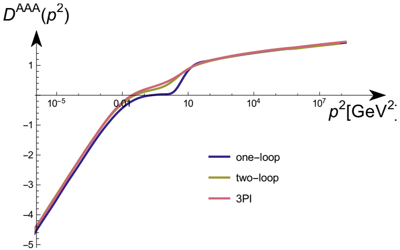

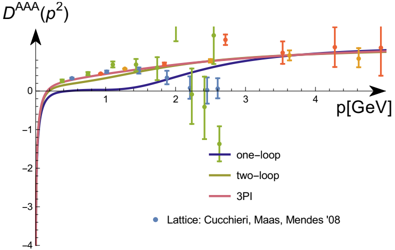

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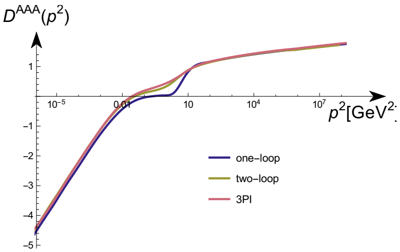
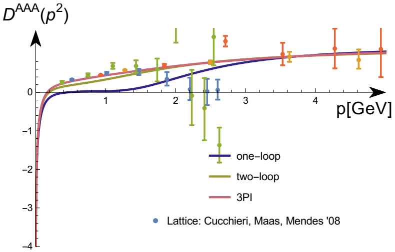
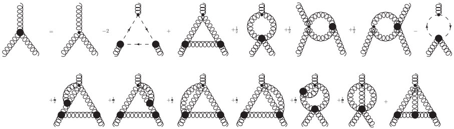




- Two-loop truncation: All diagrams except the one with a five-point function.
- One-momentum configuration approximation.



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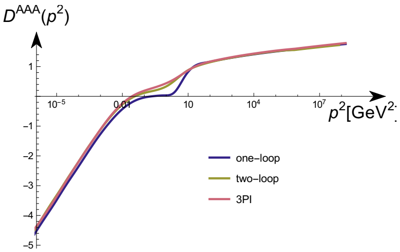
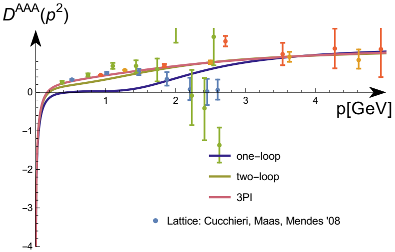
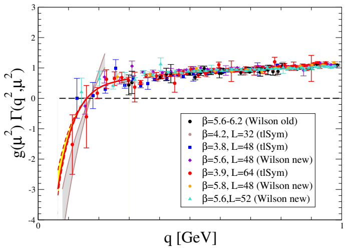




- Difference between two-loop DSE and 3PI smaller than lattice error.
- Zero crossing in agreement with other approaches, e.g., [Pelaez et al. '13; Aguilar et al. '13; Cyrol et al. '15; Athenodorou et al. '16; Duarte et al. '16; Sternbeck et al. '17]



[Athenodorou et al. '16, '18]

The two-ghost-two-gluon vertex

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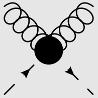


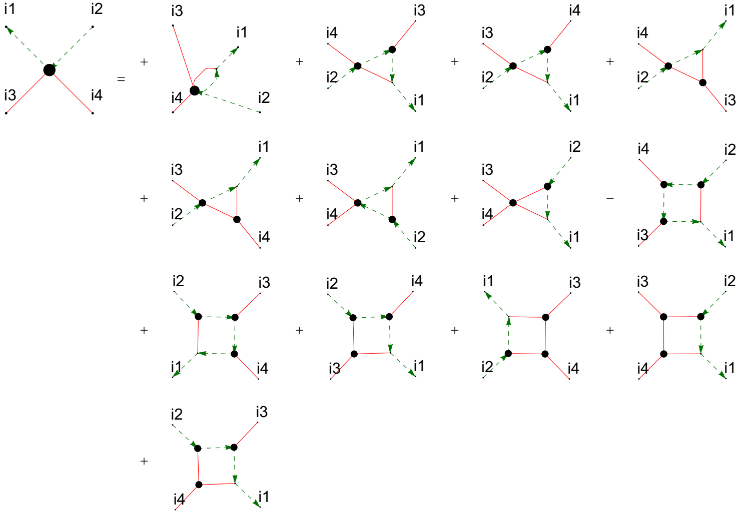
$$\Gamma^{AA\bar{c}c,abcd}_{\mu\nu}(p,q;r,s) = g^4 \sum_{k=1}^{40} \rho^{k,abcd}_{\mu\nu} D^{AA\bar{c}c}_{k(i,j)}(p,q;r,s)$$

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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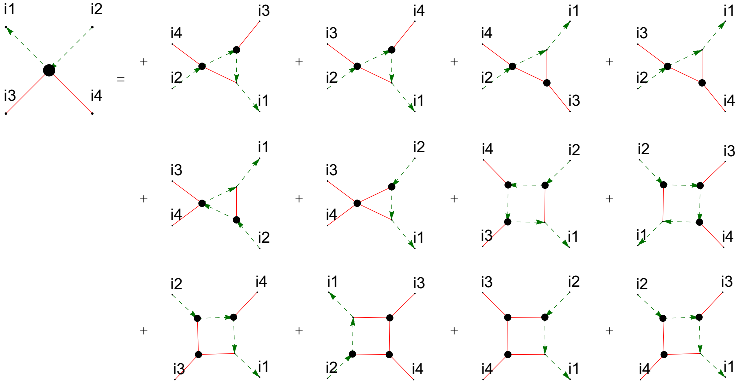
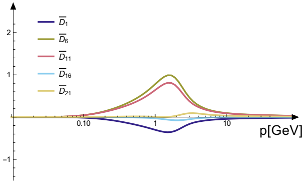
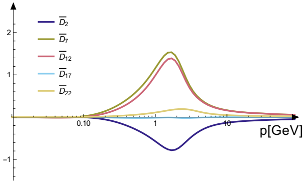


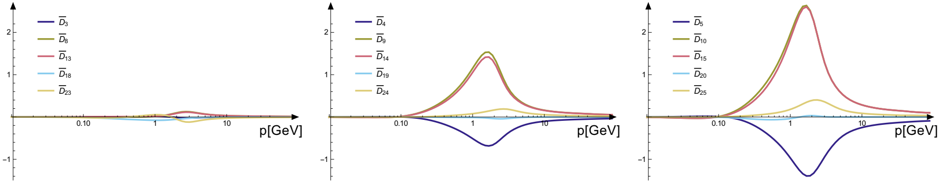
Results for the two-ghost-two-gluon vertex

Kinematic approximation: one-momentum configuration

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







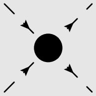
→ Two classes of dressings: 13 very small, 12 not small

→ No nonzero solution for $\{\sigma_6, \sigma_7, \sigma_8\}$ found. [MQH '17]

Results for the four-ghost vertex

Kinematic approximation: one-momentum configuration

Four-ghost vertex



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

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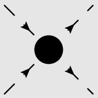
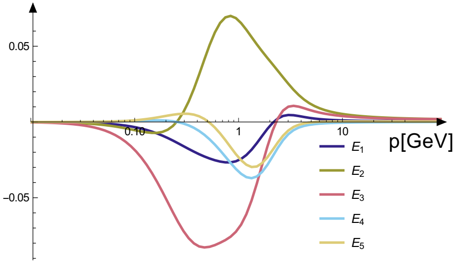


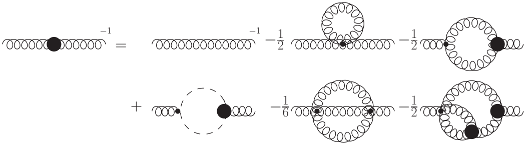
$$\Gamma^{\bar{c}\bar{c}cc,abcd}(p,q,r,s) = \color{red}{g^4} \sum_{k=1}^{8} \sigma^{k,abcd} E_k^{\bar{c}\bar{c}cc}(p,q,r,s).$$

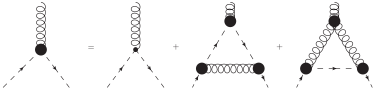


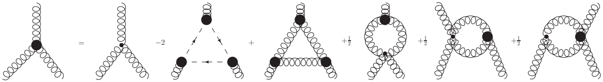
→ All dressings very small.

[MQH '17]

3PI system of primitively divergent correlation functions

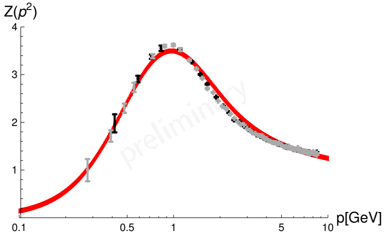






Results for fully coupled 3PI system

[lattice: Sternbeck '06]



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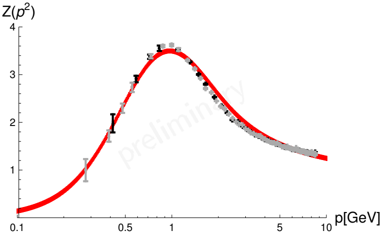

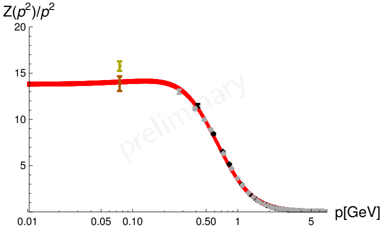

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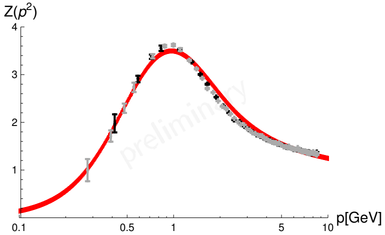

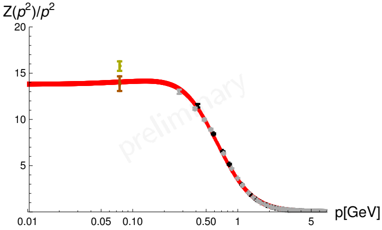

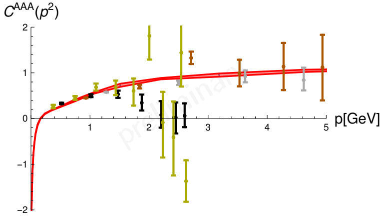

[lattice: Cucchieri, Maas, Mendes '08]

- Details of renormalization crucial!
- Other details also important.
- Very small angle dependence of three-gluon vertex.
- Slight bending down of gluon propagator in IR.

Open checks

- Effects of larger tensor bases, in particular of the three-gluon vertex
- Renormalization

What tests can be done?

Couplings

Couplings can be defined from every vertex, e.g., [Allés et al. '96; Alkofer et al., '05; Eichmann et al. '14]:

$$\begin{aligned}\alpha_{\text{ghg}}(p^2) &= \alpha(\mu^2)\left(D^{A\bar{c}c}(p^2)\right)^2 G^2(p^2)Z(p^2),\\ \alpha_{3\text{g}}(p^2) &= \alpha(\mu^2)\left(C^{AAA}(p^2)\right)^2 Z^3(p^2),\\ \alpha_{4\text{g}}(p^2) &= \alpha(\mu^2)F^{AAAA}(p^2)Z^2(p^2).\end{aligned}$$

They must agree perturbatively (STIs). This agreement is important also in coupled systems of functional equations and constitutes a highly non-trivial check of a truncation [Mitter, Pawlowski, Strodthoff '14].

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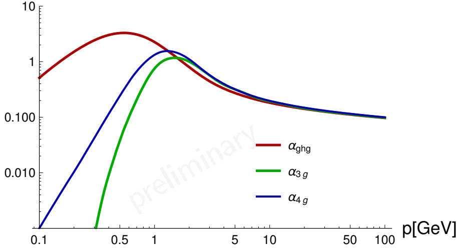

Ghost-gluon vs. other couplings: Further checks required.

Renormalization with a hard UV cutoff

The breaking of gauge covariance by the UV regularization leads to spurious (quadratic) divergences.

Renormalization with a hard UV cutoff

The breaking of gauge covariance by the UV regularization leads to spurious (quadratic) divergences.

Due to the anomalous running, this behaves as (at one-loop resummed level)

$$\frac{\Lambda_{\mathrm{QCD}}^2}{p^2}(-1)^{2\delta}\Gamma(1+2\delta,-\ln(\Lambda^2/\Lambda_{\mathrm{QCD}}^2))$$

Note: Appears already perturbatively!

Many ways to deal with them, e.g., Brown-Pennington projector, modifications of integrands/vertices, fitting, seagull identities, ...

Examples for renormalization with a hard UV cutoff

Here: Second renormalization condition

Breaking of gauge covariance $\rightarrow$ mass counter term [Collins '84]

Renormalization condition: $D(0) = c$ [Meyers, Swanson '14]

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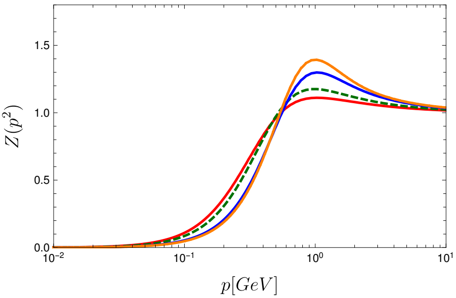
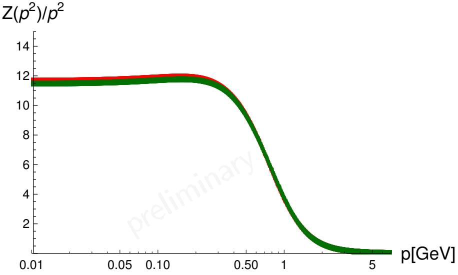
Extreme example: One-loop truncation with bare vertices in three dimensions [MQH '16].



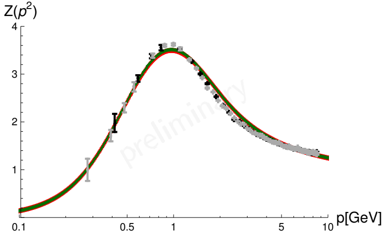
Better example: Full system with one-momentum configuration approximation.



Results for fully coupled 3PI system revisited

Vary the renormalization condition $D(0)$:

[lattice: Sternbeck '06]



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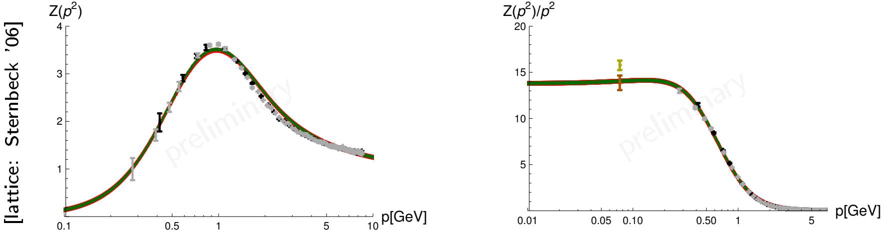

$\rightarrow$ Two solutions on top of each other. $D(0)$ is not a parameter of the system.

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Four-point functions have 6 kinematic variables.

Organize via S_4 permutation group [Eichmann, Fischer, Heupel '15] and restrict to singlet and doublet. $\rightarrow$ Three variables.

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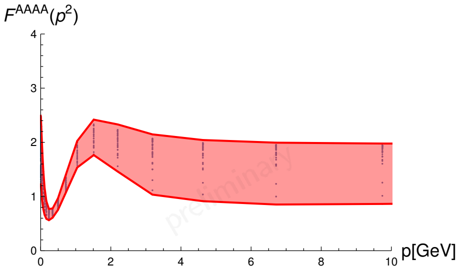

Deviations from leading perturbative behavior small, but larger angle dependence than three-gluon vertex.

Summary and conclusions

Towards a systematic understanding of truncations of functional equations to establish them as a first principles method.

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- Add quarks
- Finite temperature
- Bound states
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Thank you for your attention!