Functional methods in QCD

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Humboldt Kolleg - Discoveries and open puzzles in particle physics and cosmology
Kitzbühel, Austria

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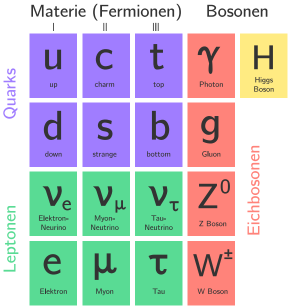
FWF Der Wissenschaftsfonds.
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
DFG Deutsche Forschungsgemeinschaft

Elementary particles

Standard model of particle physics:
Elementary particles that make up the universe (or at least 5% of it)



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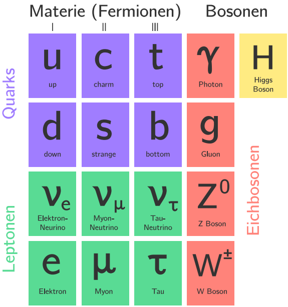


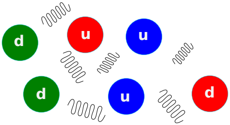
Strong interaction: Quarks and gluons (u,d,c,s,t,b,g) described by quantum chromodynamics

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

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

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

Bound states of QCD

Quarks and gluons: 

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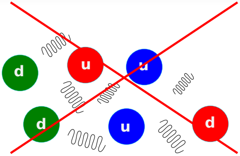
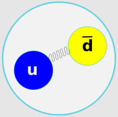
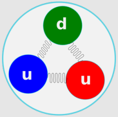
Quarks and gluons: 

Hadrons

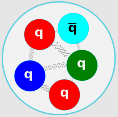
Mesons



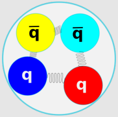
Baryons



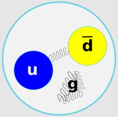
Pentaquarks



Tetraquarks



Hybrids

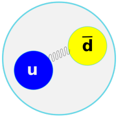


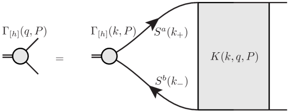
Glueballs

Calculate their properties?

Hadronic bound states from bound state equations

Example: Meson





Integral equation: $\Gamma(q,P) = \int dk\, \Gamma(k,P)\, S(k_+)\, S(k_-)\, K(k,q,P)$

Hadronic bound states from bound state equations

Bethe-Salpeter amplitude

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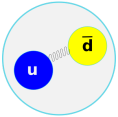

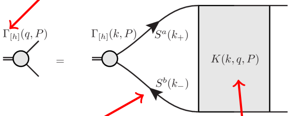

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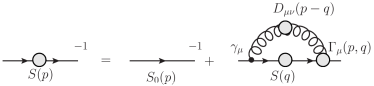
Ingredients:

- Quark propagator S



Nonperturbative diagram: full momentum dependent dressings → numerical solution

- Interaction kernel K

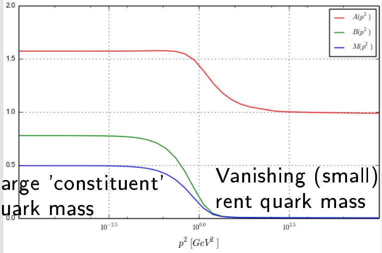
Solving the quark gap equation

Generic solution

Momentum dependent mass:

$$M(p^2) = B(p^2)/A(p^2)$$

$\rightarrow$ Breaking of chiral symmetry creates mass.



Large 'constituent' quark mass

Vanishing (small) current quark mass

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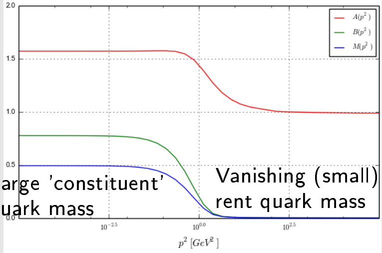

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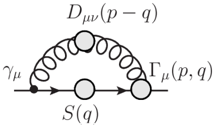
For given interaction and gluon propagator:

- Euclidean momenta: Student 'warm-up'
- Analytic behavior: Depends on input, tricky, open questions

The elementary pieces: Bottom-up



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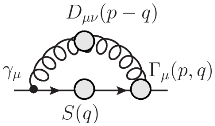
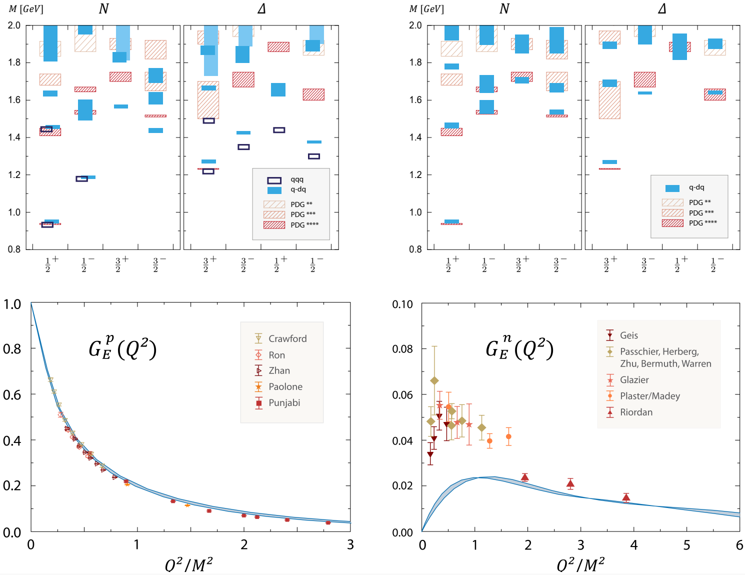


Use models crafted such that phenomenology comes out right.
Use symmetries as guidelines, e.g., chiral symmetry $\rightarrow$ axial-vector WTI.

Example

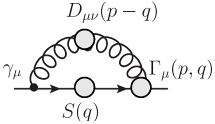
Effective interaction via $g^2 D_{\mu\nu}(p)\Gamma_\mu(p,q) \rightarrow Z_2 \widetilde{Z}_3 D^{(0)}_{\mu\nu}(p)\gamma_\mu \mathcal{G}((p+q)^2)$

Bottom-up example: Baryons from rainbow-ladder



[Eichmann '11; Eichmann, Fischer, Sanchis Alepuz '16]

The elementary pieces: Top-down



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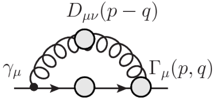
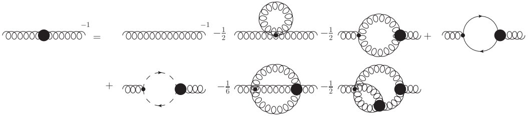


Gluon propagator $D_{\mu\nu}(p^2)$:



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- Untruncated equation (incl. two-loops) recently [Meyers, Swanson '14; MQH '17]

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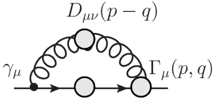

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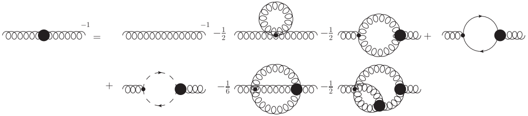

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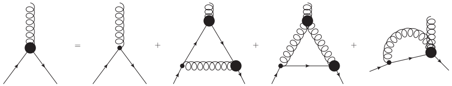
Quark-gluon vertex $\Gamma_\mu(p,q)$:



- Technically demanding, handful of results, e.g., [Hopfer, Windisch, Alkofer 13; Aguilar, Binosi, Papavassiliou '14; Mitter, Pawlowski, Strodthoff '14; Williams, Fischer, Heupel '15; Cyrol et al. '17; Aguilar, Cardona, Ferreira, Papavassiliou '18]

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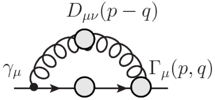
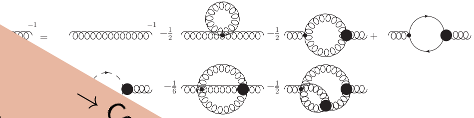


Gluon propagato



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⇒ Understanding of pure QCD required (Yang-Mills theory).
→ Couple to infinity of equations.
→ Gluonic part is crucial.

Yang-Mills theory

Consider quarks to be infinitely heavy.

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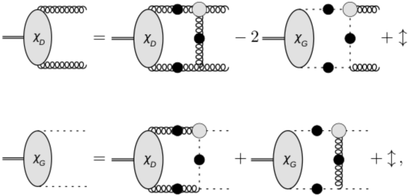
Bound states of Yang-Mills theory: Glueballs

Similar bound state equation:



[Sanchis-Alepuz, Fischer, Kellermann, von Smekal '15]

Ingredients: Gluon and ghost propagators, gluonic vertices, interaction kernels

Bottom-up vs. top-down

Bottom-up:

- Modeling to describe certain quantities, symmetries as guiding principles
- Example: Rainbow-ladder truncation with Maris-Tandy interaction:

  1 function, 2 parameters
  $$\mathcal{G}(k^2)$$

  → Good description of, e.g., pseudoscalars

Top-down:

- 9 dressings for gluon propagator and quark-gluon vertex:
  $$D(k^2),\ \Gamma_i^{A\bar{q}q}(p,q,r),\ i=1,\ldots,8$$
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Upgrades:

More parameters?

Include more terms of *known equations*.

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- Glueballs: Limited information for modeling (equivalent to Maris-Tandy interaction not known)

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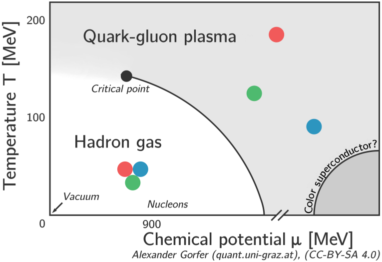

Image: Alexander Gorfer (quant.uni-graz.at), (CC-BY-SA 4.0)

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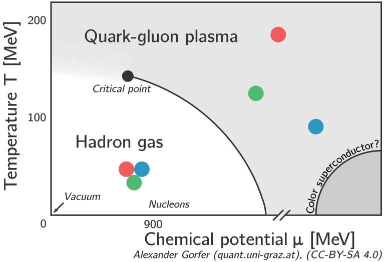
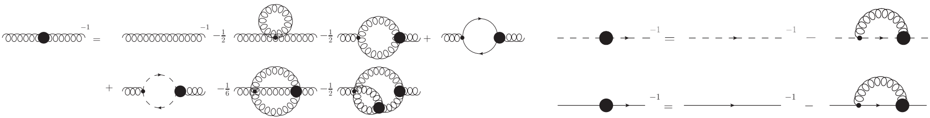
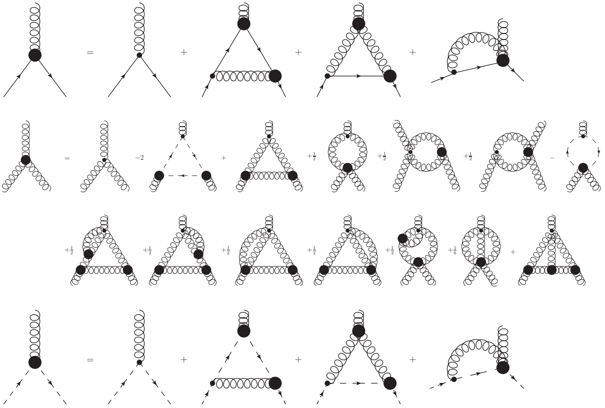


Error estimation difficult!

Image: Alexander Gorfer (quant.uni-graz.at), (CC-BY-SA 4.0)

Dyson-Schwinger equations





Infinitely large coupled system of integral equations.

Truncations

- Emergence of structures?

hierarchies? negligible contributions?

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- Systematics and tests?

  comparison to other methods? self-tests? necessary conditions?

Perturbative resummation for propagators from DSEs

Normally, employed models contain an RG improvement term to recover the one-loop resummed behavior, e.g., [von Smekal, Hauck, Alkofer '97; MQH, von Smekal '12].

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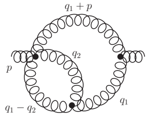
Emergence from DSEs [MQH '17, '18]:

- 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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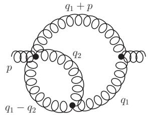

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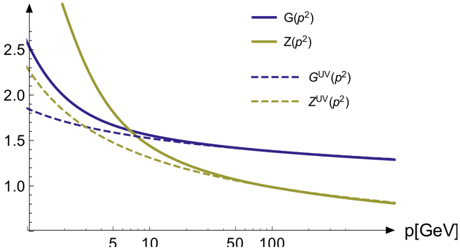
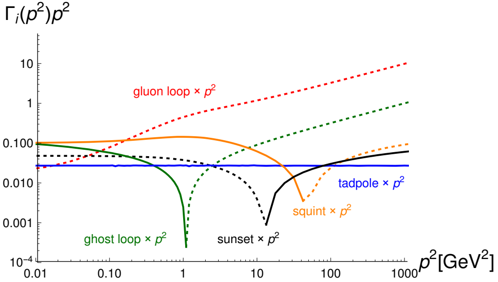


[MQH '17]

Diagram hierarchies



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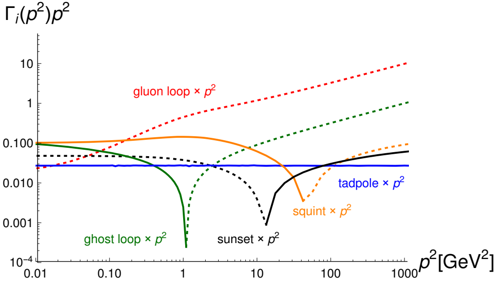

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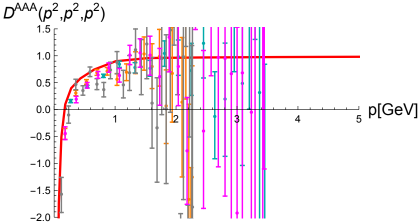
- We cannot expect to have a clear hierarchy of diagrams, since we consider all scales.

Truncated DSEs *cannot* be assigned a concrete order of the coupling. They contain all contributions up to a certain order and some beyond.

Diagrams of the three-gluon vertex



[lattice: Cucchieri, Maas, Mendes '08]

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- Good agreement with lattice data.
- Similar results from FRG [Corell et al. '18]

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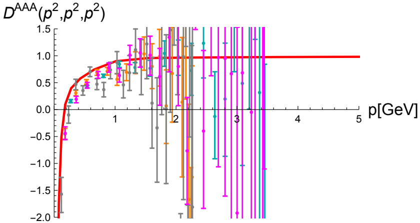

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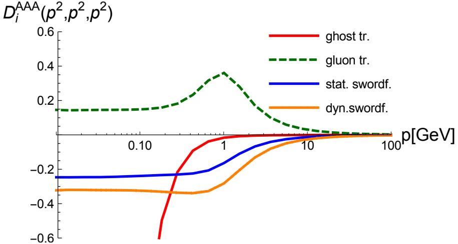

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- Classes of diagrams identified. $\rightarrow$ Each class has to be treated as a whole.

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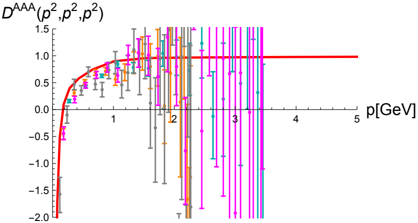

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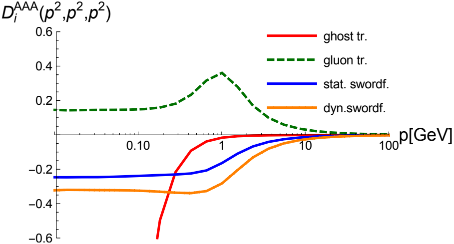

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→ In four dimensions similar qualitative effects, but renormalization complicates things.

Three-gluon vertex DSE

[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; Aguilar, Ferreira, Figueiredo, Papavassiliou '19]

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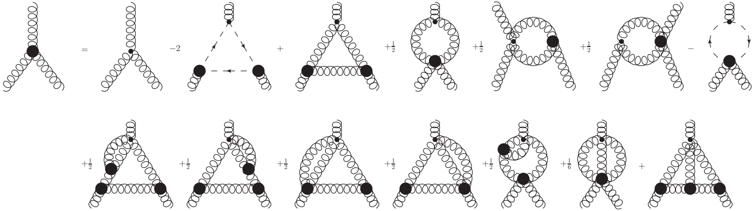
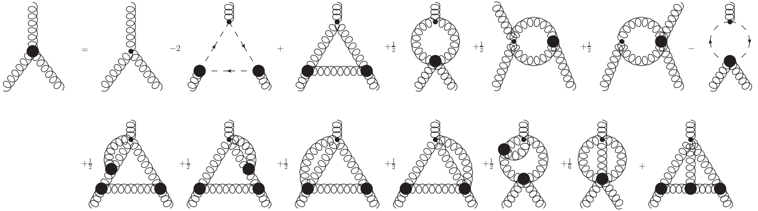
Full DSE:



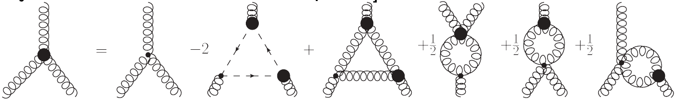
Three-gluon vertex DSE

[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; Aguilar, Ferreira, Figueiredo, Papavassiliou '19]

Full DSE:



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



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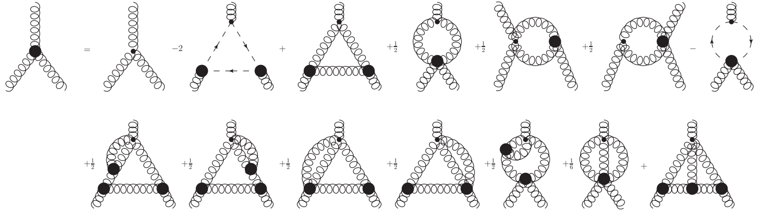
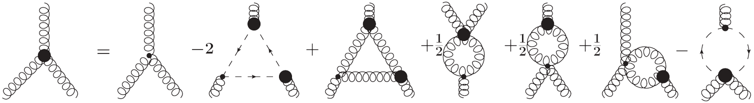
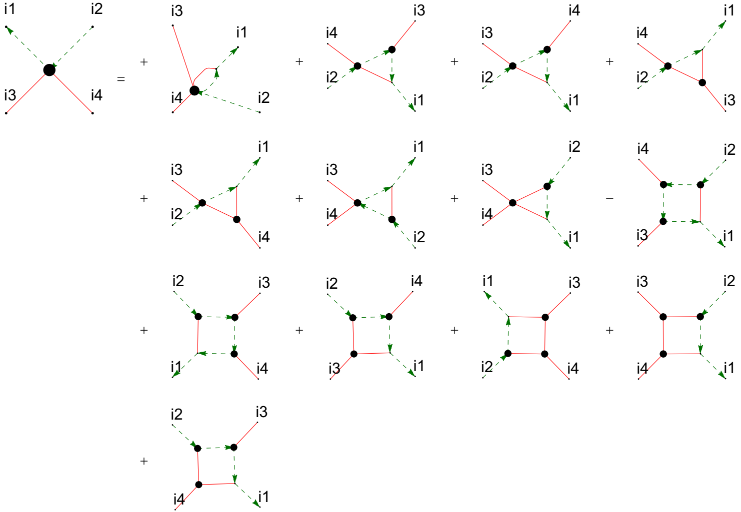


Nonperturbative one-loop truncation [MQH '17]:



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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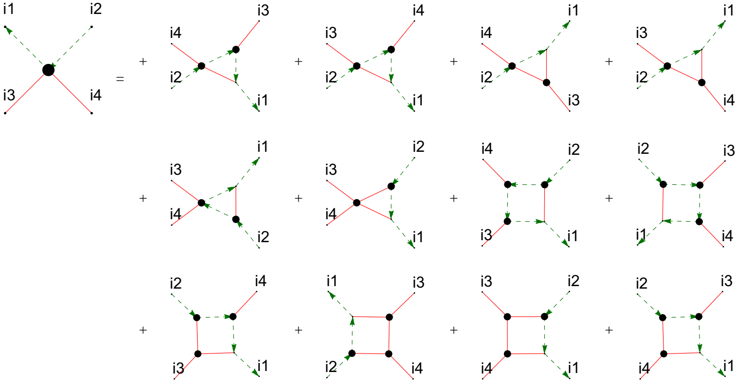
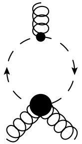


Influence of two-ghost-two-gluon vertex



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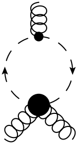
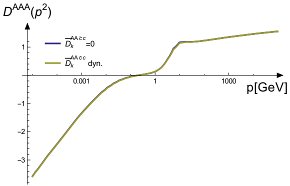


Coupled system of ghost-gluon, three-gluon and four-gluon vertices with and without two-ghost-two-gluon vertex [MQH '17]:



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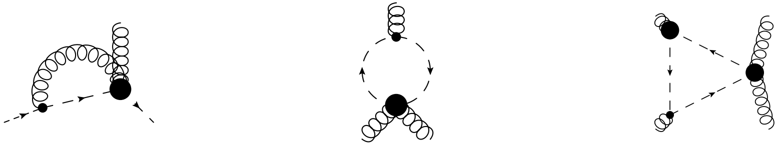

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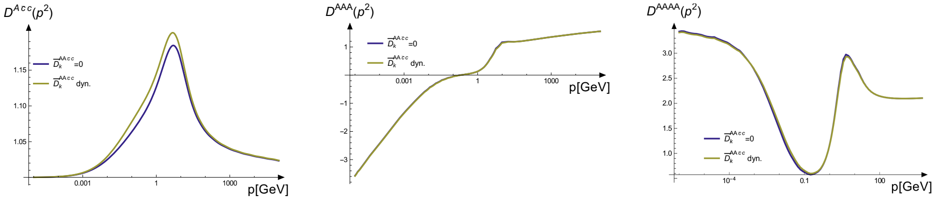
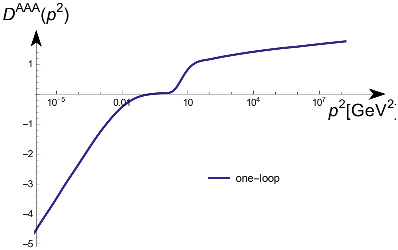


- Color structure: only small dressings in the three-gluon DSE → no change.
- Small influence on ghost-gluon vertex ($< 1.7\%$)

Three-gluon vertex: Equations and truncations



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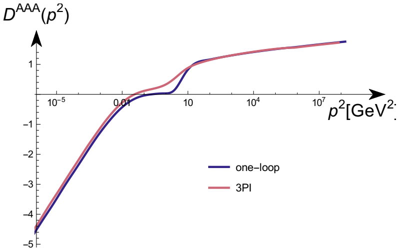

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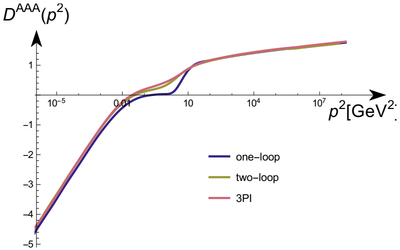

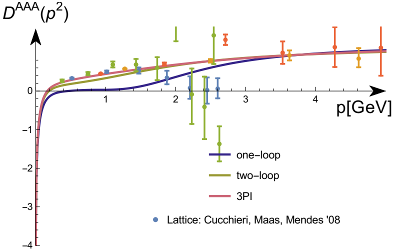

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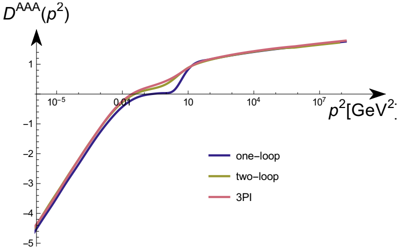
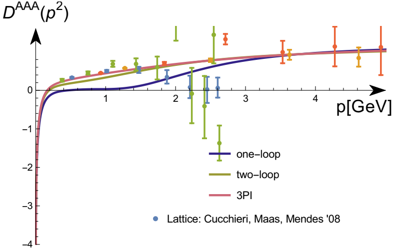
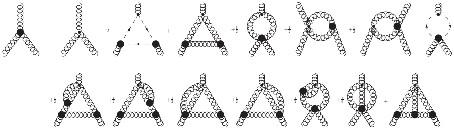




- Two-loop truncation: All diagrams except the one with a five-point function.
- One-momentum configuration approximation.



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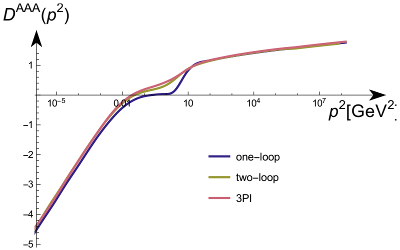
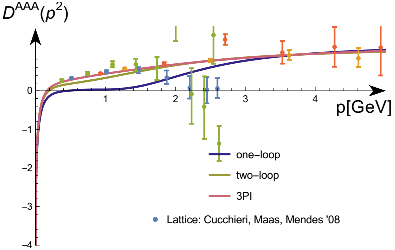
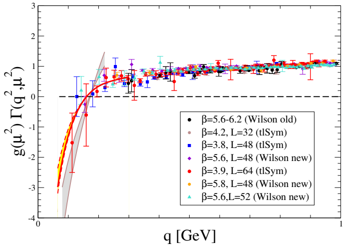




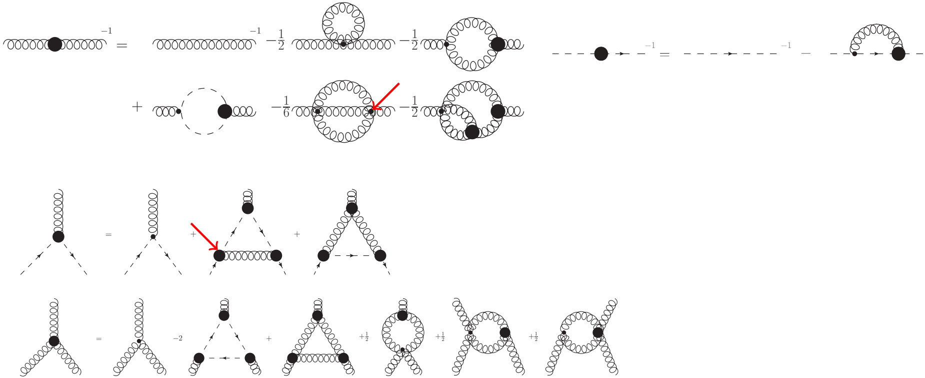
- Difference between two-loop DSE and 3PI smaller than lattice error.
- Zero crossing in agreement with other approaches, e.g., [Pelaez et al. '13; Aguilar et al. '13; Cyrol et al. '16; Athenodorou et al. '16; Duarte et al. '16; Sternbeck et al. '17]



[Athenodorou et al. '16, '18]

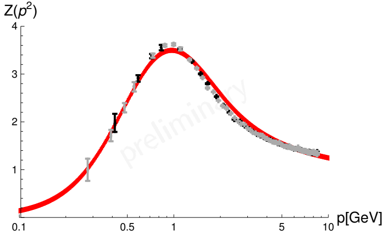
3PI system of primitively divergent correlation functions

Three-loop expansion of 3PI effective action [Berges '04]:
Expansion in dressed three-point functions



Results for fully coupled 3PI system

[lattice: Sternbeck '06]



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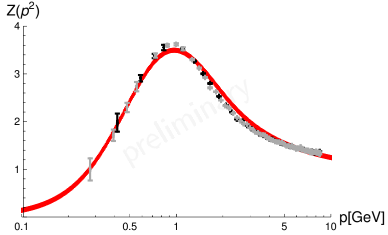

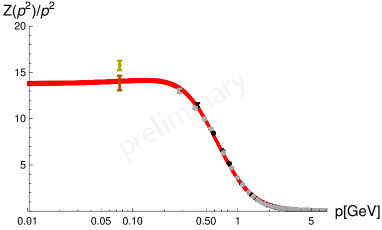

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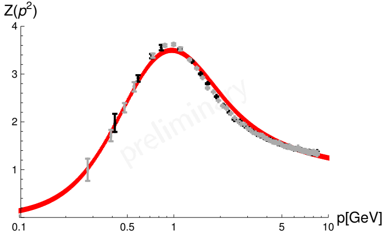

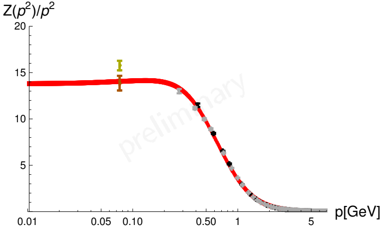

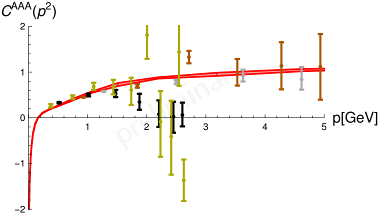

[lattice: Cucchieri, Maas, Mendes '08]

- Details of renormalization crucial!
- 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]:

$$\alpha_{\text{ghg}}(p^2) = \alpha(\mu^2)\left(D^{A\bar{c}c}(p^2)\right)^2 G^2(p^2)Z(p^2),$$
$$\alpha_{3\text{g}}(p^2) = \alpha(\mu^2)\left(C^{AAA}(p^2)\right)^2 Z^3(p^2),$$
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- Must agree perturbatively (STIs). Important in coupled systems of functional equations. → Highly non-trivial check of a truncation [Mitter, Pawlowski, Strodthoff '14].
- Scales must match: $\Lambda^2_{\text{QCD}} = s\, e^{-\frac{1}{4\pi\alpha(s)\beta_0}}$, s pert. scale: Must match for each diagram

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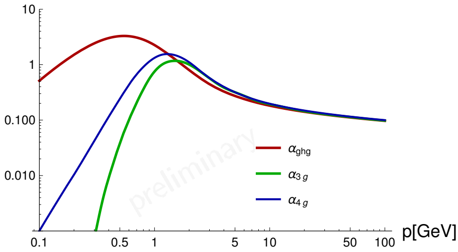

Ghost-gluon vs. other couplings: Further checks required.

Renormalization with a hard UV cutoff

Introduces quadratic divergences.
Note: Appears already perturbatively!

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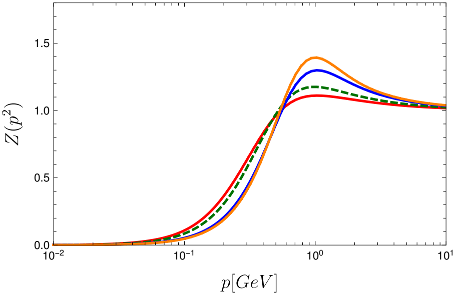
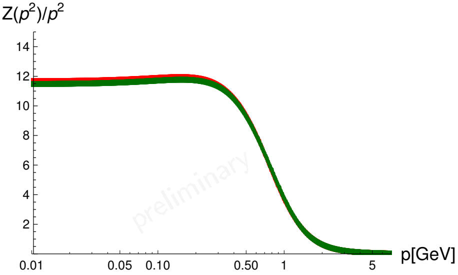
The breaking of gauge covariance by the UV regularization leads to spurious (quadratic) divergences.

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

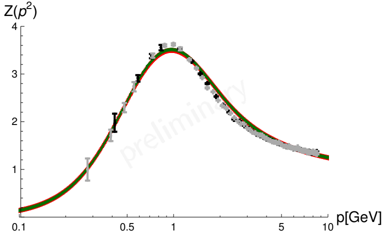


Better example: Full system with one-momentum configuration approximation.



Results for fully coupled 3PI system revisited

[lattice: Sternbeck '06]



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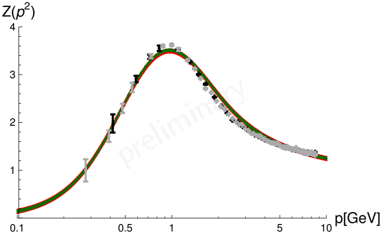

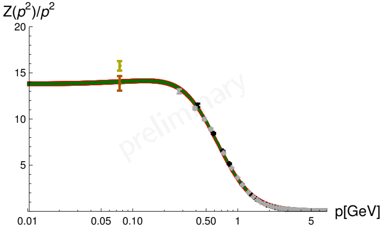

→ Two solutions on top of each other. No model dependence anymore!

→ Provides a self-test of a truncation.

Summary and conclusions

Towards a systematic understanding of truncations of functional equations to access their full potential.

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- Non-classical tensors in gluonic vertices
- Add quarks
- Finite temperature
- Bound states
- Finite density
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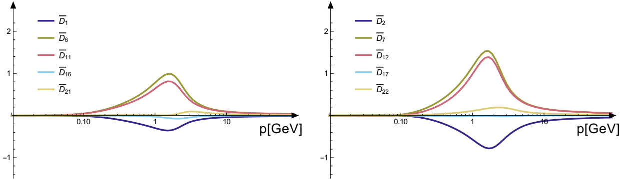
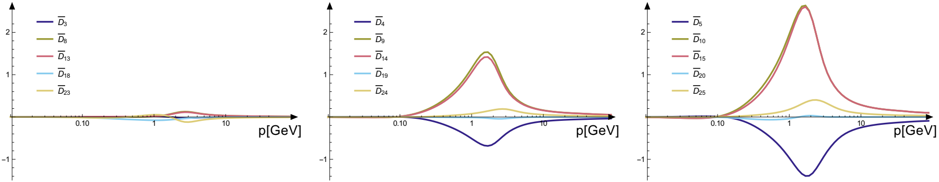
Thank you for your attention!

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]