Landau gauge Yang-Mills correlation functions

Anton Konrad Cyrol

Ruprecht-Karls-Universität Heidelberg

based on

- AKC, Fister, Mitter, Pawlowski, Strodthoff, PRD, arXiv:1605.01856 [hep-ph]
- AKC, Mitter, Strodthoff, FormTracer, arXiv:1610.09331 [hep-ph]
- AKC, Mitter, Pawlowski, Strodthoff, $N_f = 2$ Vacuum QCD, in preparation
- AKC, Mitter, Pawlowski, Strodthoff, $T > 0$ Yang-Mills, in preparation

November 9, 2016

QCD phase diagram with functional methods

fQCD-collaboration:

J. Braun, L. Corell, AKC, L. Fister, W. J. Fu, M. Leonhardt, M. Mitter, J. M. Pawlowski, M. Pospiech, F. Rennecke, N. Strodthoff, N. Wink, . . .

This talk:

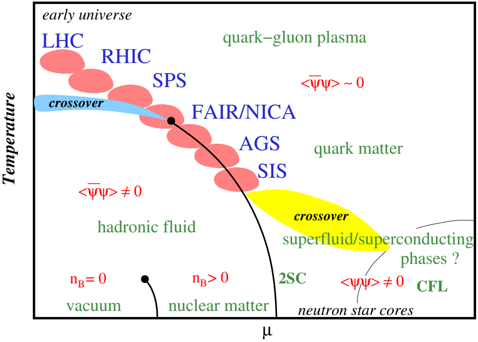
- Vacuum Yang-Mills theory
- Preliminary $T > 0$ results

Aim:

- Qualitative understanding
- Quantitative precision

Motivation:

- No sign problem
- Understanding of confinement
- Prerequisite for QCD



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Prog.Part.Nucl.Phys. 62 (2009) 381

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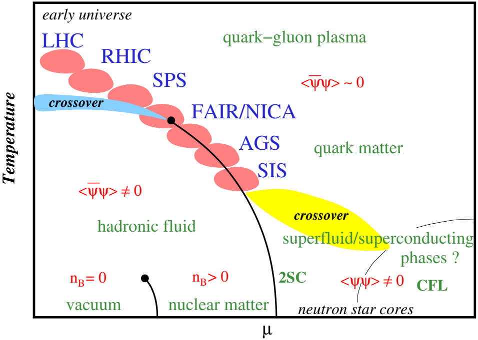

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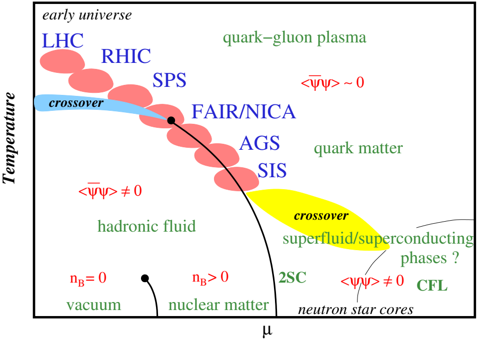

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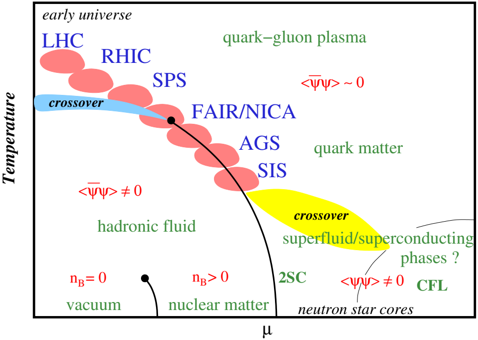

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QCD from the functional renormaliztion group

- Only perturbative QCD input
  - $\alpha_S(\mu = \mathcal{O}(10)$ GeV)
  - $m_q(\mu = \mathcal{O}(10)$ GeV)

- Wetterich equation with initial condition $S[\Phi] = \Gamma_\Lambda[\Phi]$

- Effective action $\Gamma[\Phi] = \lim\limits_{k\to 0} \Gamma_k[\Phi]$

- Exact equation
- ∂_t: integration of momentum shells controlled by regulator
- Full field-dependent equation with $(\Gamma^{(2)}[\Phi])^{-1}$ on rhs

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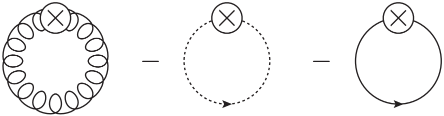

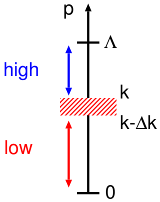

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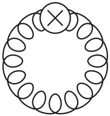
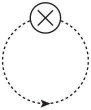
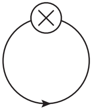
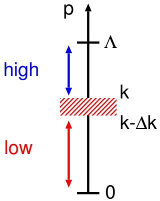
$\partial_t \Gamma_k[\phi] = \ +\frac{1}{2}$  $-$  $-$ 



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Vertex expansion

- Approximation necessary – vertex expansion:

$$\Gamma[\Phi] = \sum_n \int_{p_1,\ldots,p_{n-1}} \Gamma^{(n)}_{\Phi_1\cdots\Phi_n}(p_1,\ldots,p_{n-1})\Phi^1(p_1)\cdots\Phi^n(-p_1-\cdots-p_{n-1})$$

- Wanted: "apparent convergence" of $\Gamma[\Phi] = \lim_{k\to 0}\Gamma_k[\Phi]$
- Current state-of-the-start truncation:
- Functional derivatives of $\Gamma_k[\Phi]$ with respect to fields yield equations

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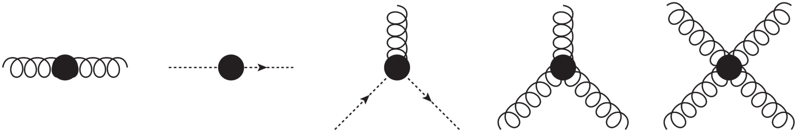
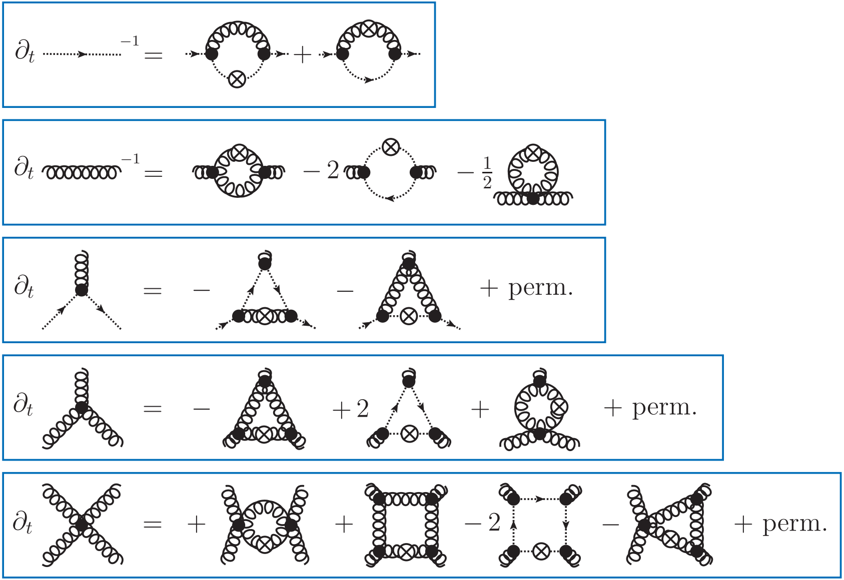


$\Gamma^{(2)}_{AA}(p)$ $\Gamma^{(2)}_{\bar{c}c}(p)$ $\Gamma^{(3)}_{A\bar{c}c}(p,q)$ $\Gamma^{(3)}_{A^3}(p,q)$ $\Gamma^{(4)}_{A^4}(p_{\mathrm{sym}})$

classical tensor classical tensor

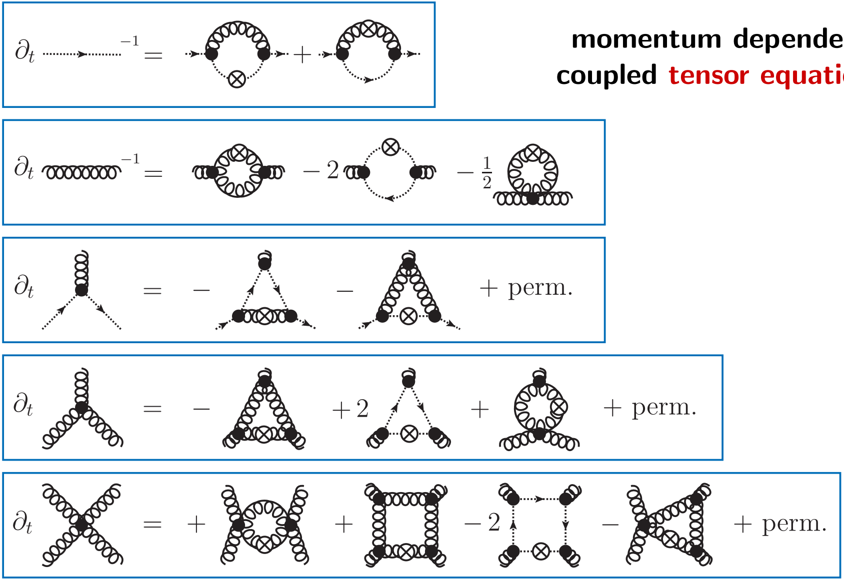
- Functional derivatives of $\Gamma_k[\Phi]$ with respect to fields yield equations

Truncation – closed set of equations



Truncation – closed set of equations

momentum dependent coupled tensor equations



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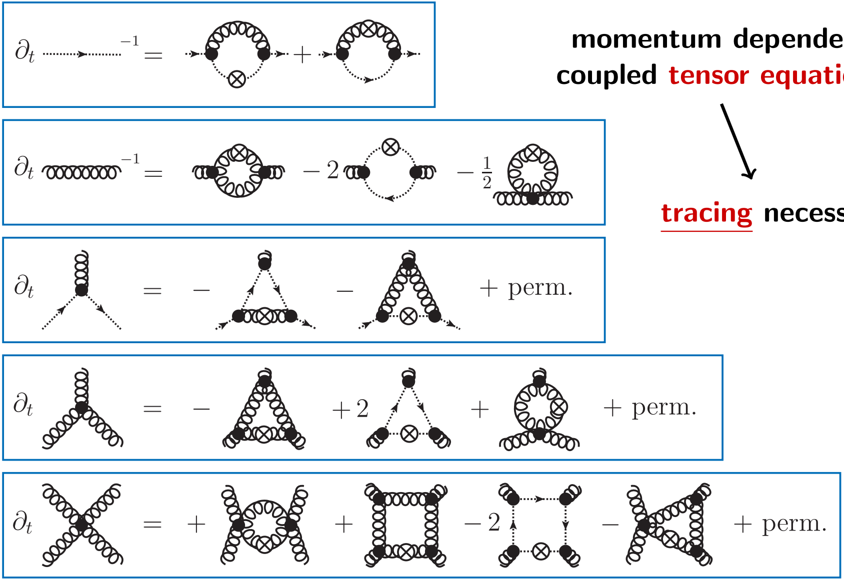


momentum dependent coupled tensor equations

tracing necessary

FormTracer – Mathematica tracing package using FORM

- Mathematica: very powerful, flexible and convenient
- FORM: very fast and efficient

FormTracer uses FORM while it keeps the usability of Mathematica:

- Lorentz/Dirac traces in arbitrary dimensions
- Arbitrary number of group product spaces
- Intuitive, easy-to-use and highly customizable Mathematica frontend
- Support for finite temperature/density applications
- Support for FORM's optimization algorithm
- Convenient installation and update procedure within Mathematica:

Preprint: AKC, Mitter, Strodthoff; arXiv:1610.09331 [hep-ph]

Open source: `https://github.com/FormTracer/FormTracer`

FormTracer – installation and usage

FormTracer.nb - Wolfram Mathematica 11.0

File Edit Insert Format Cell Graphics Evaluation Palettes Window Help

Installing

```
Import["https://raw.githubusercontent.com/FormTracer/FormTracer/master/src/FormTracerInstaller.m"]
```

Tracing

Space-Time

Define syntax for space-time

```
DefineLorentzTensors[δ[μ, ν](*Kronecker delta*), vec[p, μ](*vector*), p.q(*inner product*)];
```

Take traces:

```
FormTrace[vec[p + 2 r, μ] δ[μ, ν] vec[s, ν]]
FormTrace[δ[α, ν] (δ[ν, ρ] + δ[ν, ρ] δ[σ, σ]) δ[ρ, α]]
FormTrace[δ[1, ν] vec[s, ν]]
```

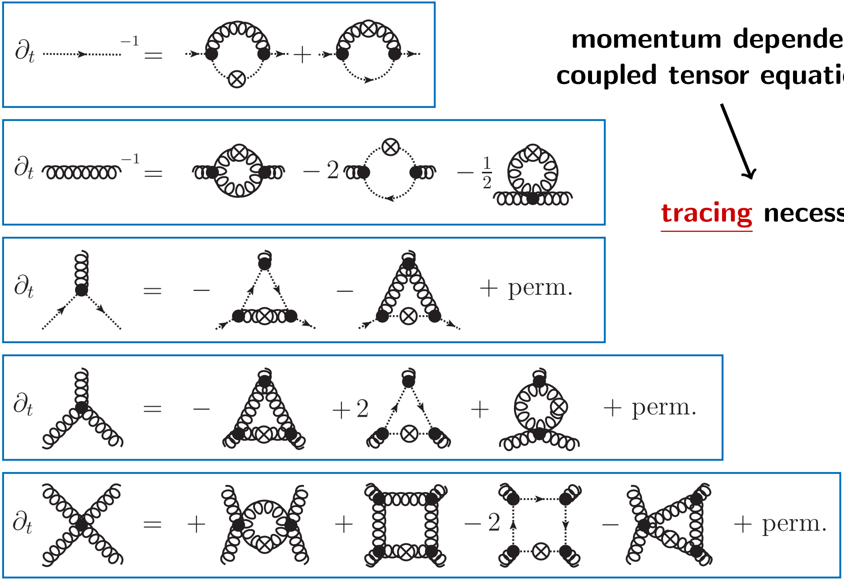
```
s.(p + 2 r)
```

```
20
```

```
vec[s, 1]
```

AKC, Mitter, Strodthoff; arXiv:1610.09331 [hep-ph]

Truncation – closed set of equations



momentum dependent coupled tensor equations

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Regulator breaks BRST symmetry

- Breaking BRST symmetry $\rightarrow$ modified STIs
- mSTIs reduce to STIs at $k = 0$
- $\Longrightarrow$ solve mSTIs to get initial action at $k = \Lambda$
- More practical solution: choose $\Gamma_\Lambda \approx S$ such that STIs are fulfilled $k = 0$

$$\begin{tikzcd} \text{STIs} \arrow[r, bend left, "\text{regulator}"] & \text{mSTIs} \arrow[l, bend left, "k \to 0"] \end{tikzcd}$$

$$\alpha_{A\bar{c}c}(p) = \frac{\alpha(\mu)}{4\pi} \frac{Z^2_{A\bar{c}c}(p)}{Z_A(p)\, Z_c^2(p)}$$

$$\alpha_{A^3}(p) = \frac{\alpha(\mu)}{4\pi} \frac{Z^2_{A^3}(p)}{Z^3_A(p)}$$

$$\alpha_{A^4}(p) = \frac{\alpha(\mu)}{4\pi} \frac{Z_{A^4}(p)}{Z^2_A(p)}$$

Select

$$Z^{k=\Lambda}_{A\bar{c}c}(p) = \text{const.}$$

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such that

$$\alpha_{A\bar{c}c}(\mu) = \alpha_{A^3}(\mu) = \alpha_{A^4}(\mu)$$

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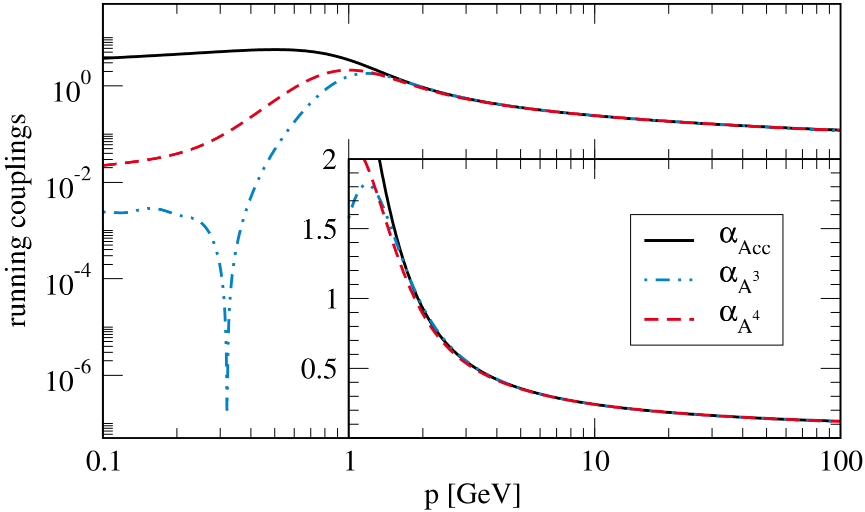
Running couplings (scaling solution)



AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Gluon mass gap

Scaling solution

$$\lim_{p\to 0} Z_c(p^2) \propto (p^2)^{\kappa}$$

$$\lim_{p\to 0} Z_A(p^2) \propto (p^2)^{-2\,\kappa}$$

Decoupling solution

$$\lim_{p\to 0} Z_c(p^2) \propto 1$$

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- **Landau Gauge** gluon STI requires longitudinally mass term to vanish:

$$p_\mu \left([\Gamma^{(2)}_{AA,\mathrm{L}}]^{ab}_{\mu\nu}(p) - [S^{(2)}_{AA,\mathrm{L}}]^{ab}_{\mu\nu}(p) \right) = 0$$

- Splitting between longitudinal and transverse mass term necessary
- Splitting occures "naturally" for scaling solution
- Decoupling solution requires irregular vertices, e.g. a pole in the longitudinal sector
- Unphysical mass parameter at cutoff: $[\Gamma^{(2)}_{AA}]^{ab}_{\mu\nu}(k = \Lambda,\, p) = p^2 + m^2_\Lambda$,
- $m^2_\Lambda \propto c \cdot \Lambda^2$ with $c \ll 1$; parameter can be uniquely determined

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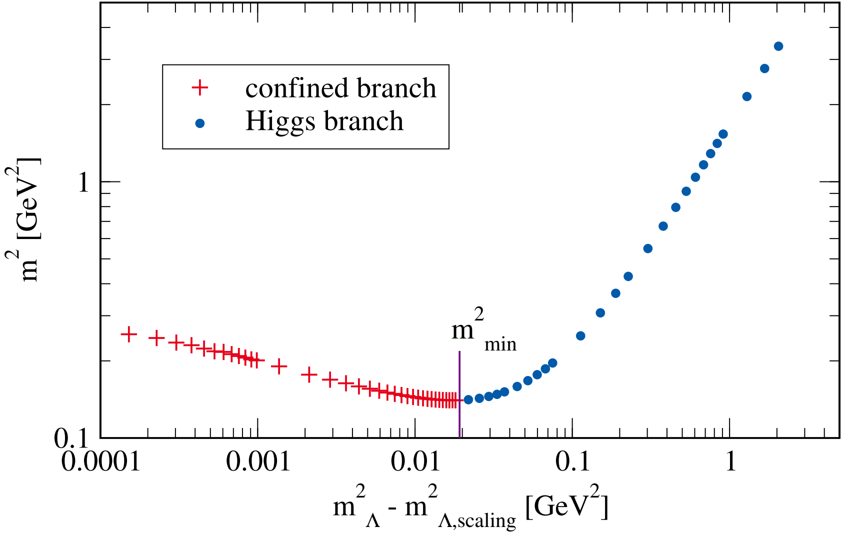
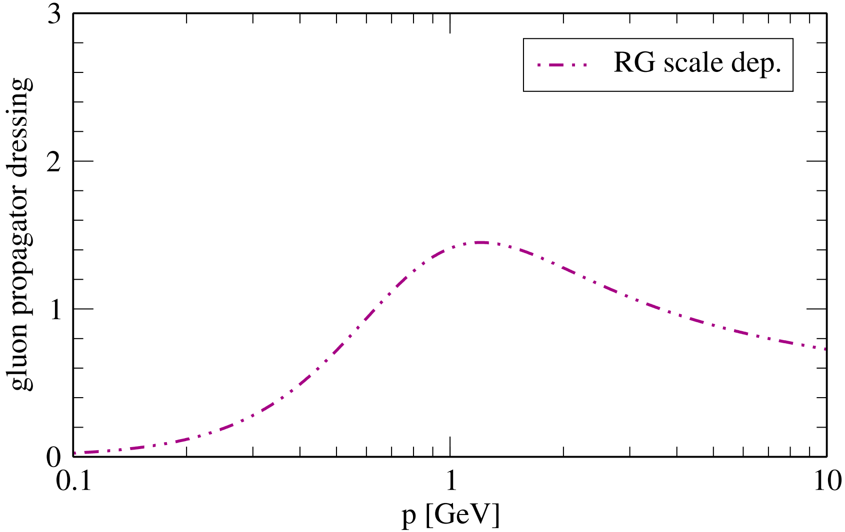
Dynamical mass generation



AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Truncation dependence of the gluon propagator



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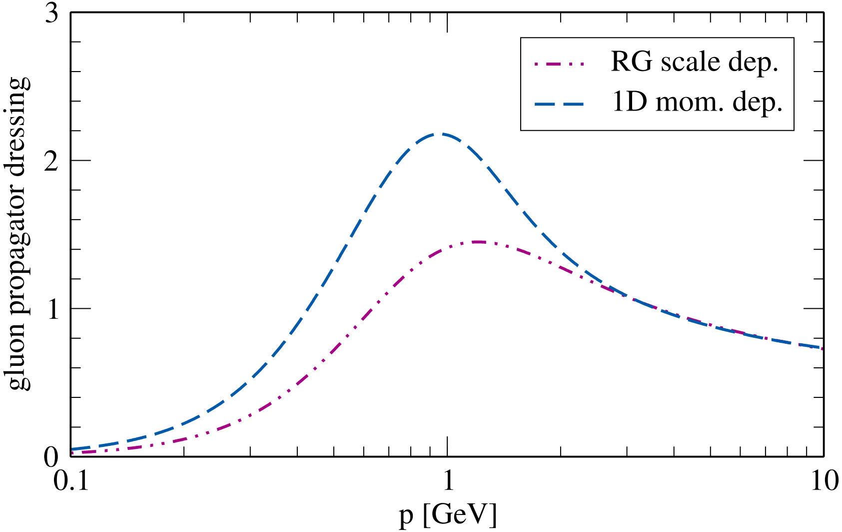

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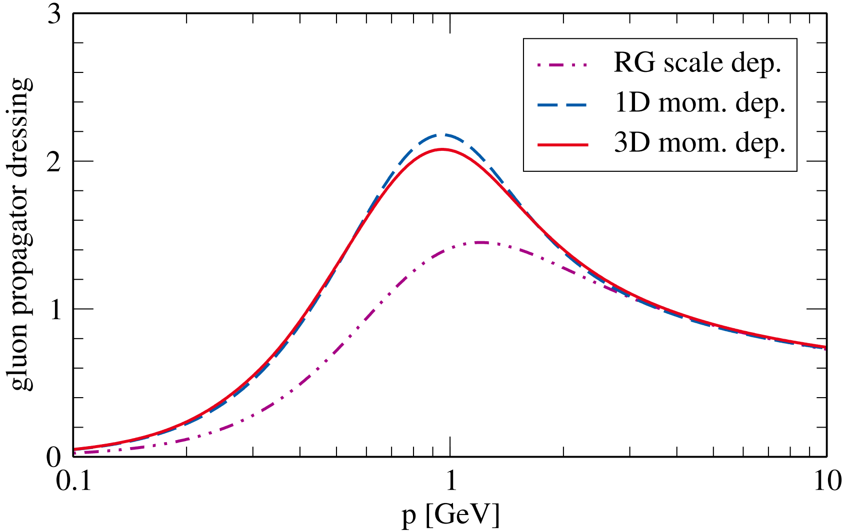

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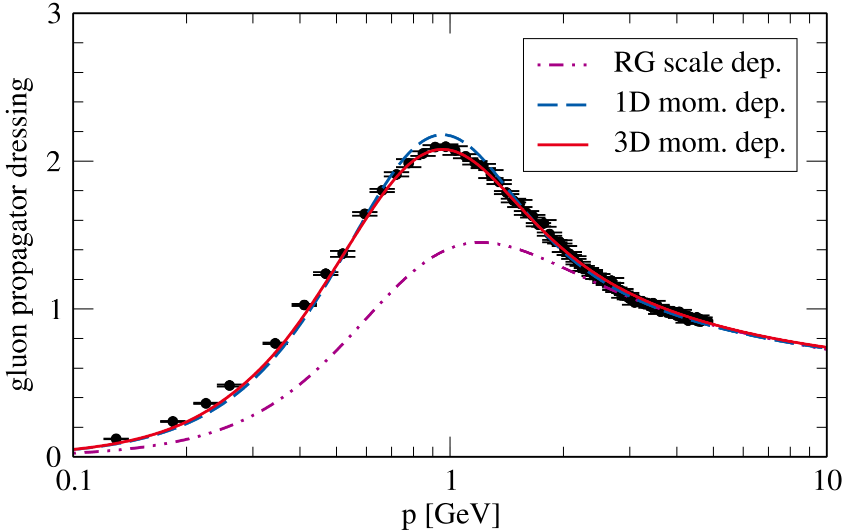
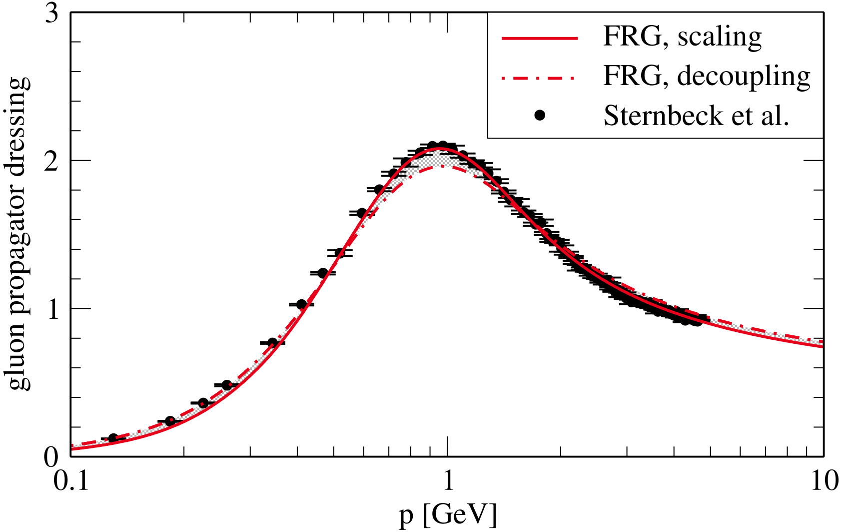


AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016; **Lattice**: Sternbeck et al. 2006

Gluon propagator dressing



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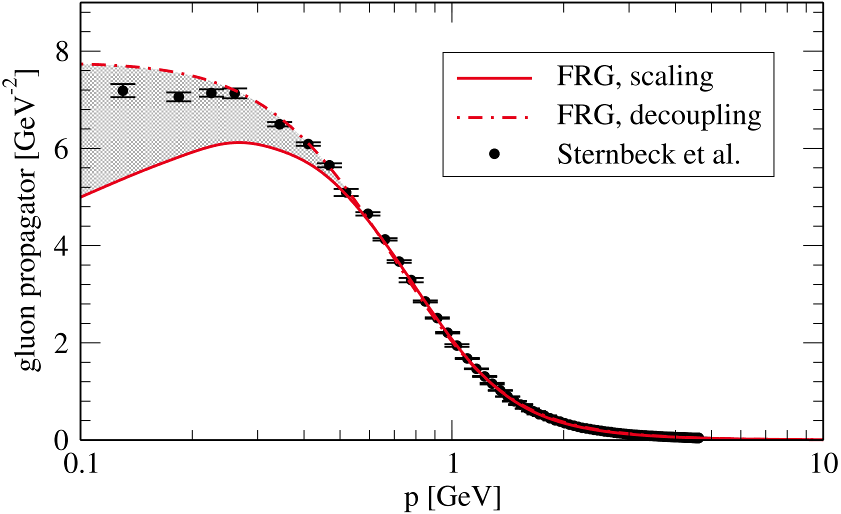

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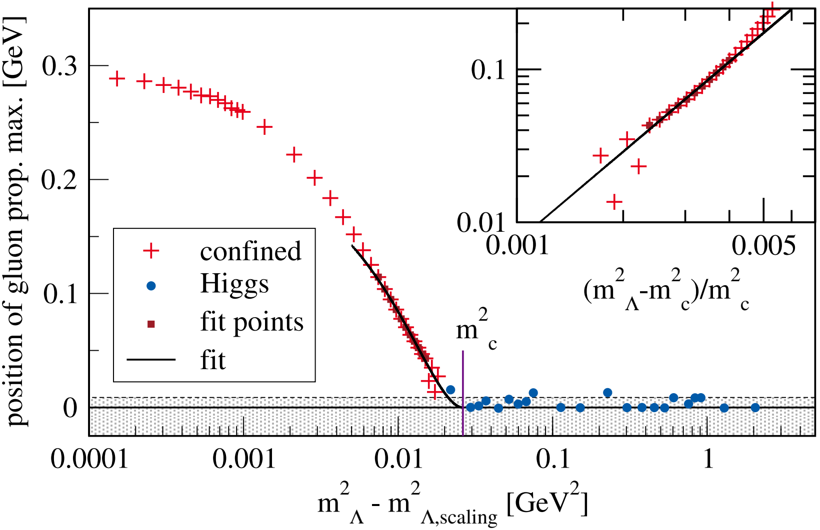
Gluon propagator maximum over UV mass parameter



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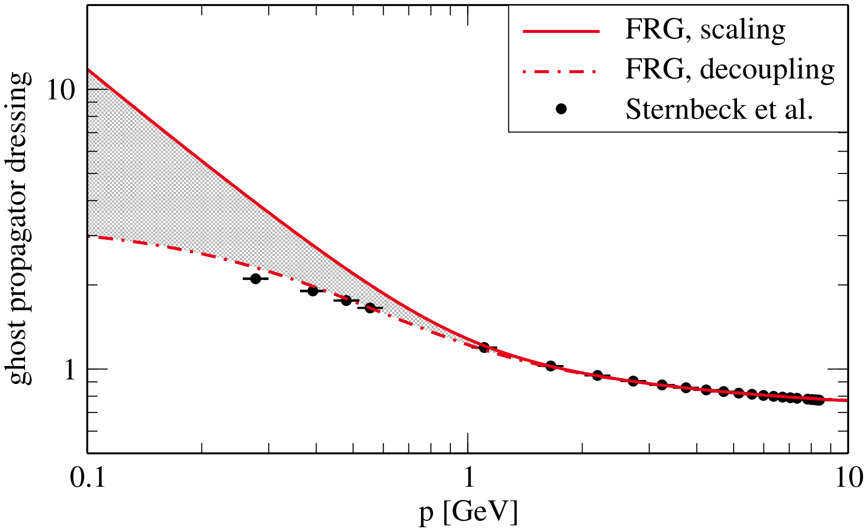
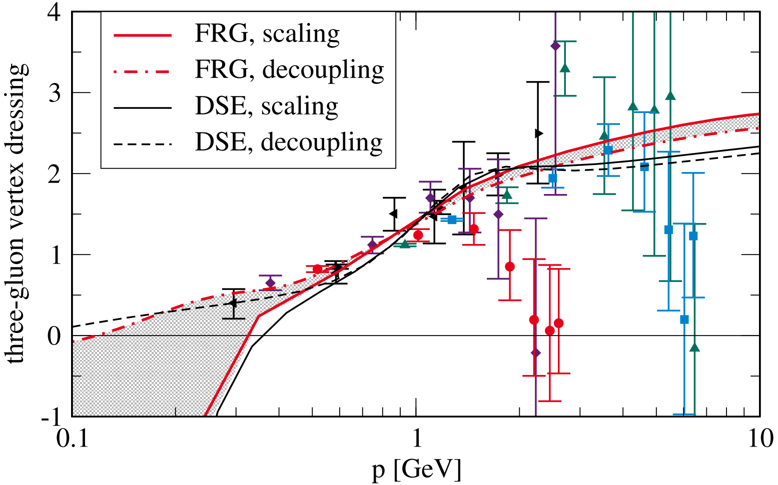
Ghost propagator dressing



AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Three-gluon vertex dressing (symmetric point)



- Zero crossing between 0.1 GeV to 0.33 GeV

AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Finite temperature

Going to finite temperature:

- Introduce Matsubara frequencies:

$$\int \frac{\mathrm{d}^4 p}{(2\pi)^4} \to T \sum_{\omega_n} \int \frac{\mathrm{d}^3 p}{(2\pi)^3}$$

- Thermal Debye mass
- Same parameter-free truncation as in vacuum YM
- Upcoming: full splitting of magnetic and electric components

  Splitting of propagators only: Fister, Pawlowski, 2011

$$P^{\mathrm{T}}_{\mu\nu}(p) = (1-\delta_{0\mu})(1-\delta_{0\nu})\left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{\vec{p}^2}\right) \qquad P^{\mathrm{L}}_{\mu\nu}(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) - P^{\mathrm{T}}_{\mu\nu}(p)$$

- Also upcoming: nonzero Matsubara modes

Following results are preliminary and based on

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Going to finite temperature:

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$$\int \frac{\mathrm{d}^4 p}{(2\pi)^4} \to T \sum_{\omega_n} \int \frac{\mathrm{d}^3 p}{(2\pi)^3}$$

- Thermal Debye mass
- Same parameter-free truncation as in vacuum YM
- Upcoming: full splitting of magnetic and electric components

  Splitting of propagators only: Fister, Pawlowski, 2011

$$P^{\mathrm{T}}_{\mu\nu}(p) = (1-\delta_{0\mu})(1-\delta_{0\nu})\left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{\vec{p}^2}\right) \qquad P^{\mathrm{L}}_{\mu\nu}(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) - P^{\mathrm{T}}_{\mu\nu}(p)$$

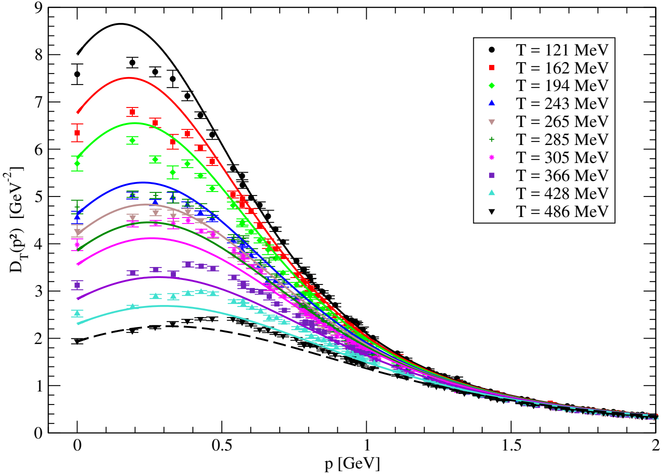
- Also upcoming: nonzero Matsubara modes

Following results are preliminary and based on

- AKC, Mitter, Pawlowski, Strodthoff, $T > 0$ Yang-Mills, in preparation

Temperature dependence of the gluon propagator

Magnetic component compared to averaged components from FRG:



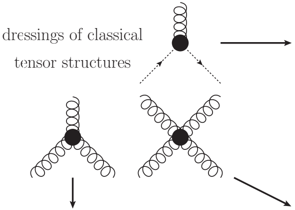
Zeroth mode results:

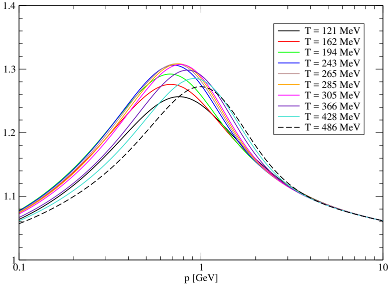
Lattice: Silva, Oliveira, Bicudo, Cardoso, 2013

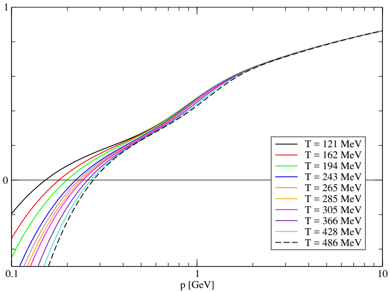
FRG: AKC, Mitter, Pawlowski, Strodthoff, preliminary

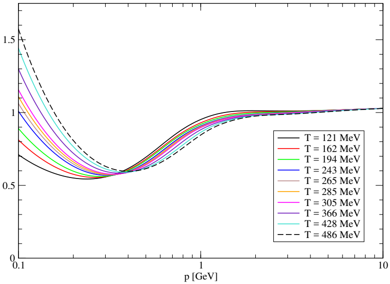
Temperature dependence of vertices

AKC, Mitter, Pawlowski, Strodthoff, preliminary

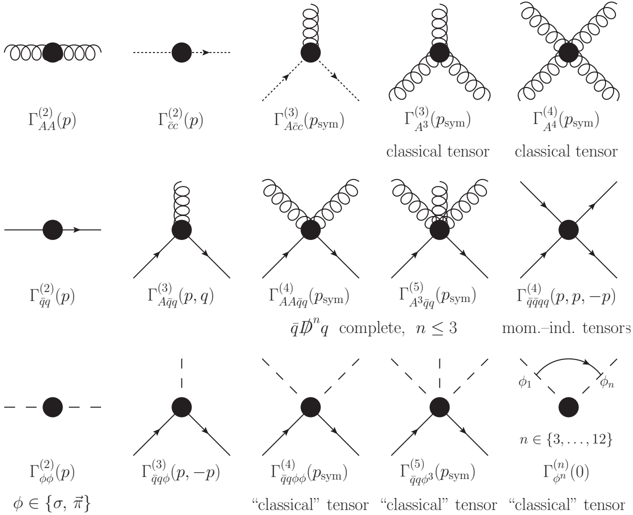






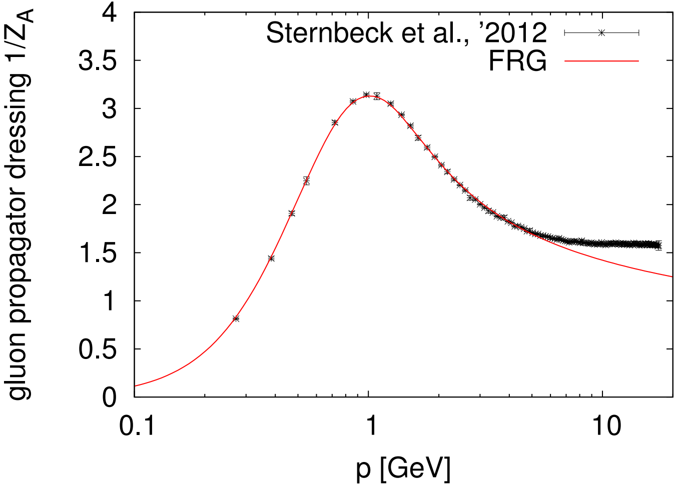


A glimpse at unquenched $N_f = 2$ QCD



AKC, Mitter, Pawlowski, Strodthoff, in preparation

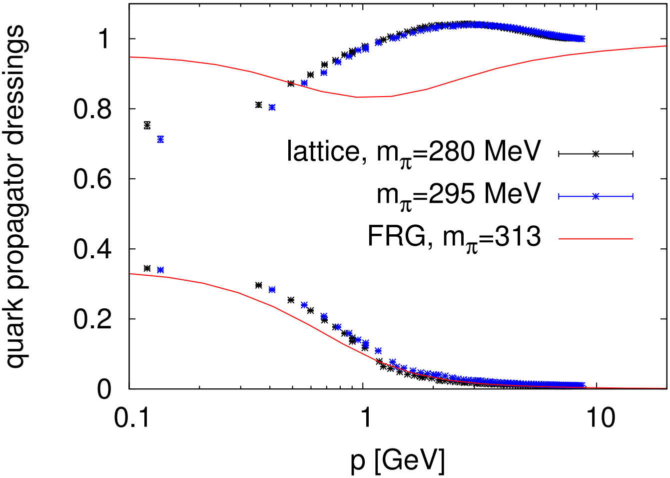
Preliminary unquenched gluon propagator



FRG: AKC, Mitter, Pawlowski, Strodthoff, in preparation

Lattice: A. Sternbeck, K. Maltman, M. Müller-Preussker, L. von Smekal, PoS LATTICE2012 (2012) 243

Preliminary unquenched quark propagator



FRG: AKC, Mitter, Pawlowski, Strodthoff, in preparation

Lattice: Oliveira, Kızılersu, Silva, Skullerud, Sternbeck, Williams, arXiv:1605.09632 [hep-lat]

Conclusion

- FRG first principal approach to QCD, complementary to lattice QCD
- Big numerical effort $\rightarrow$ tools like FormTracer necessary
- BRST symmetry is broken by regulator, proper care needs to be taken
- STI consistent solution computed
- Evidence for dynamical mass generation
- Very good agreement with lattice results

Outlook

- Unquenched $N_f = 2$ QCD, in preparation
- $T > 0$ YM with splitting of el. and mag. components, in preparation
- Bound states (Bethe-Salpeter eq.), decay widths, ...
- Nonzero Matsubara modes, gluon spectral function, ...

Thank you for your attention!

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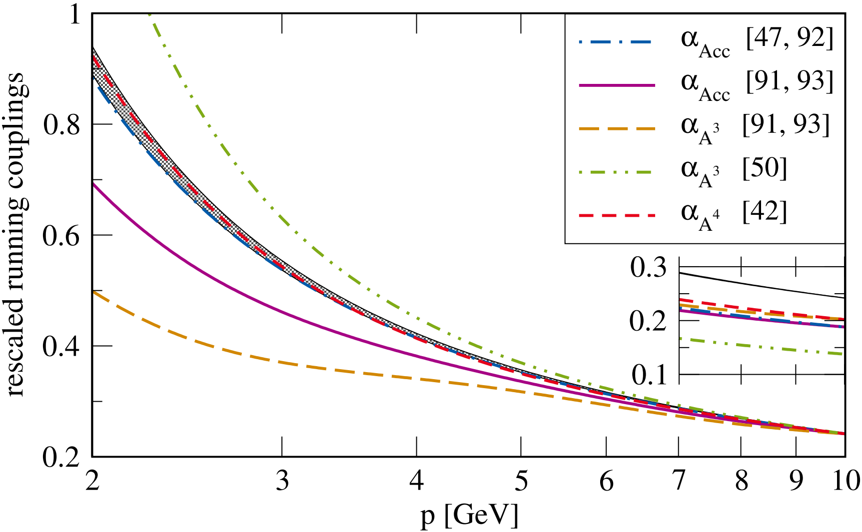
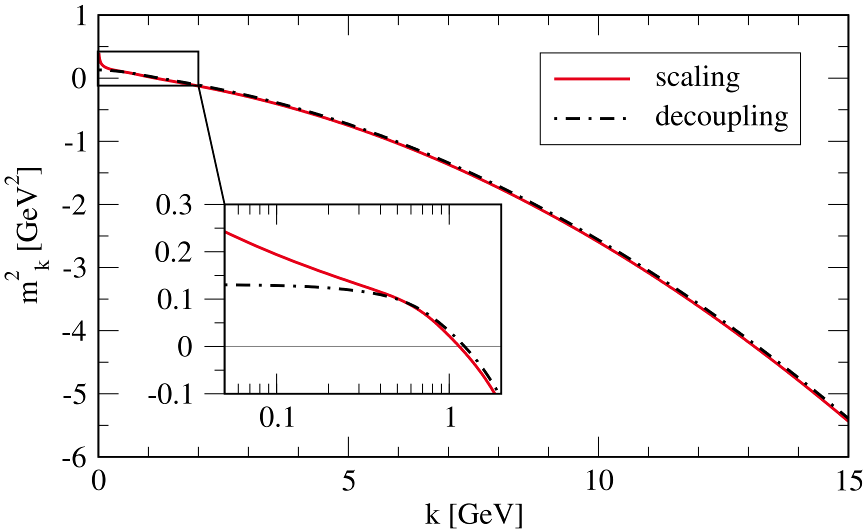
Running couplings in comparison with DSE results



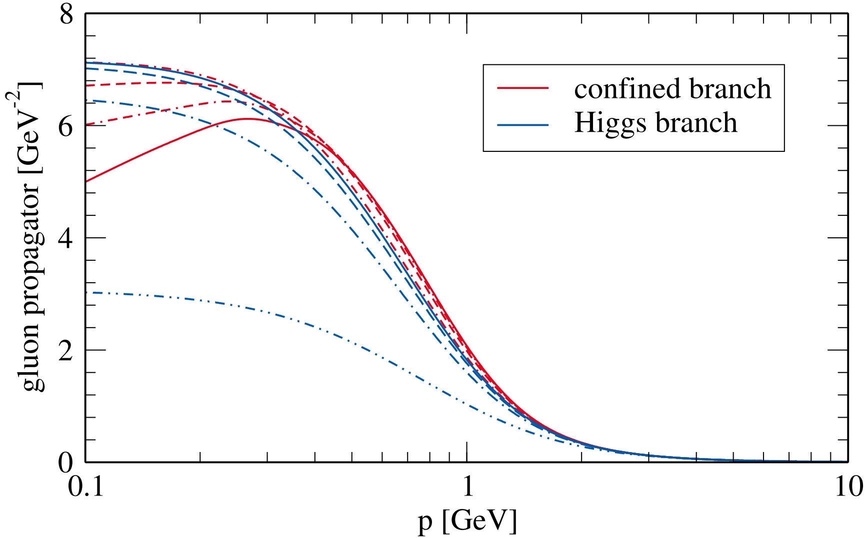
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Running of the gluon mass parameter



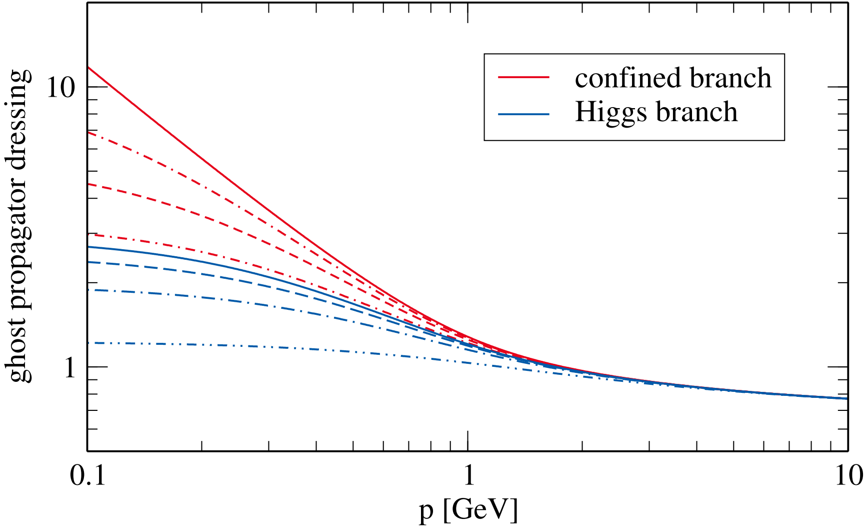
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Gluon propagator



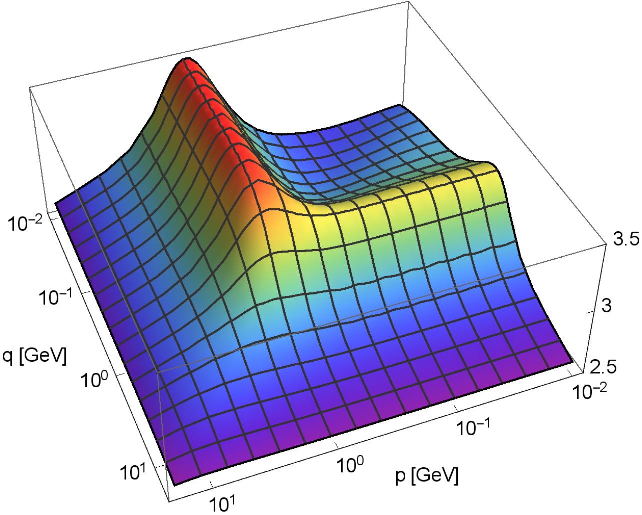
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Ghost propagator dressing



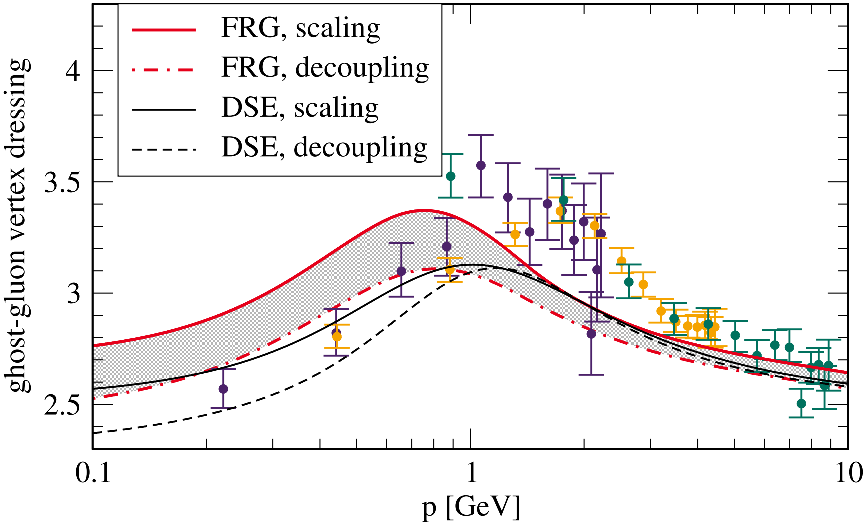
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Momentum dependence of the ghost-gluon vertex



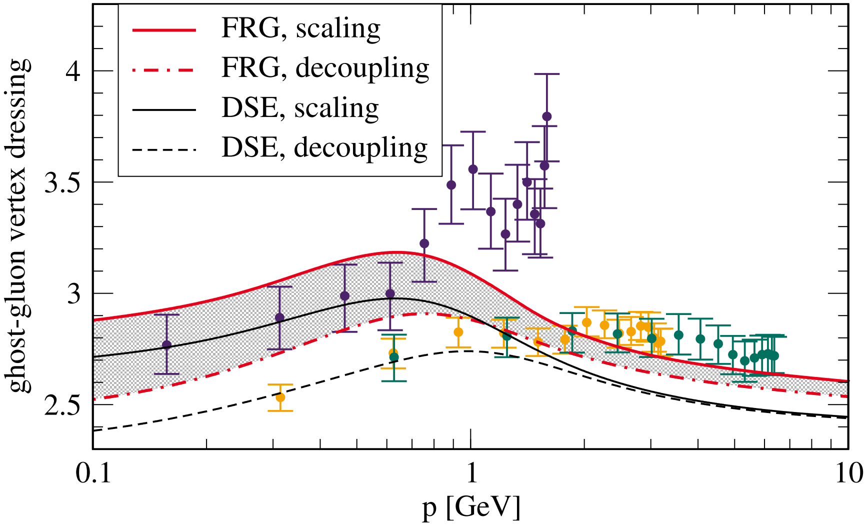
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Ghost-gluon vertex at the symmetric point



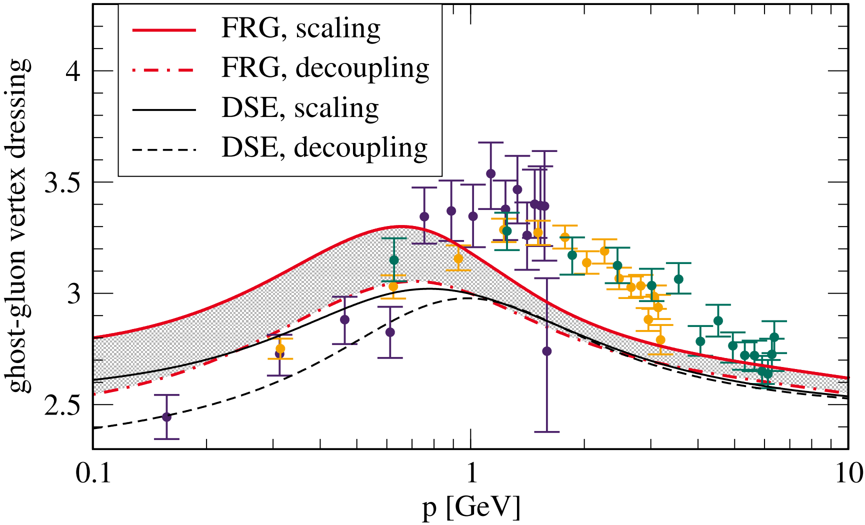
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Ghost-gluon vertex with vanishing gluon momentum



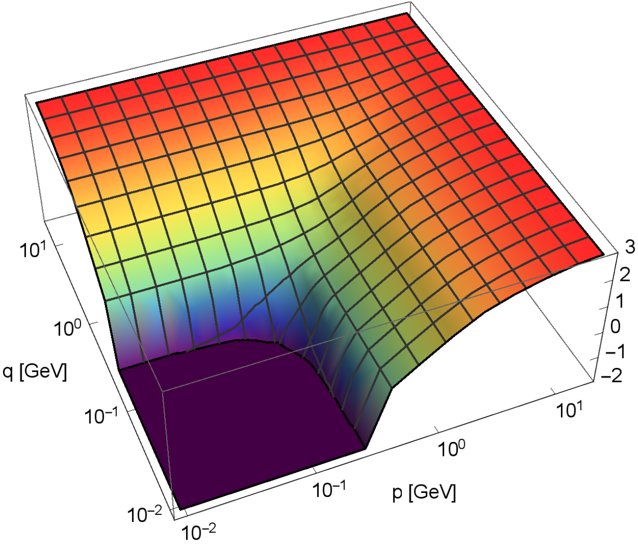
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Ghost-gluon vertex with orthogonal momenta



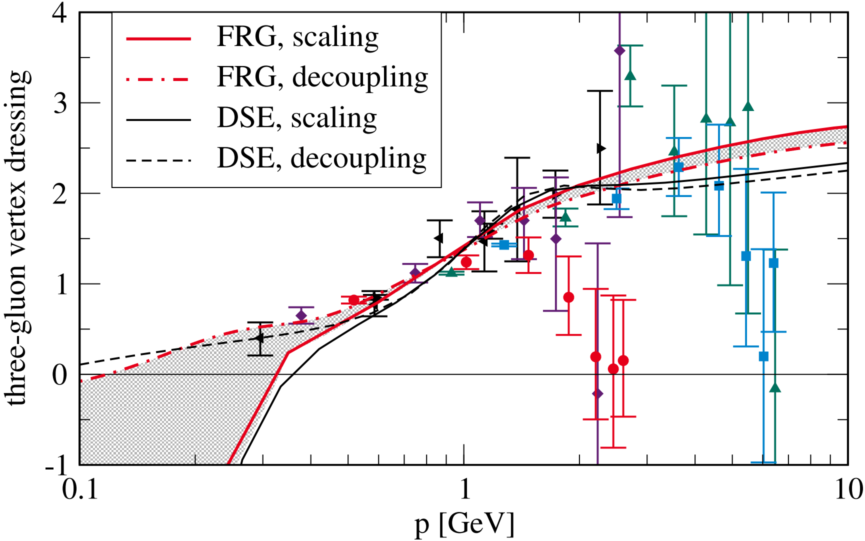
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Momentum dependence of the three-gluon vertex



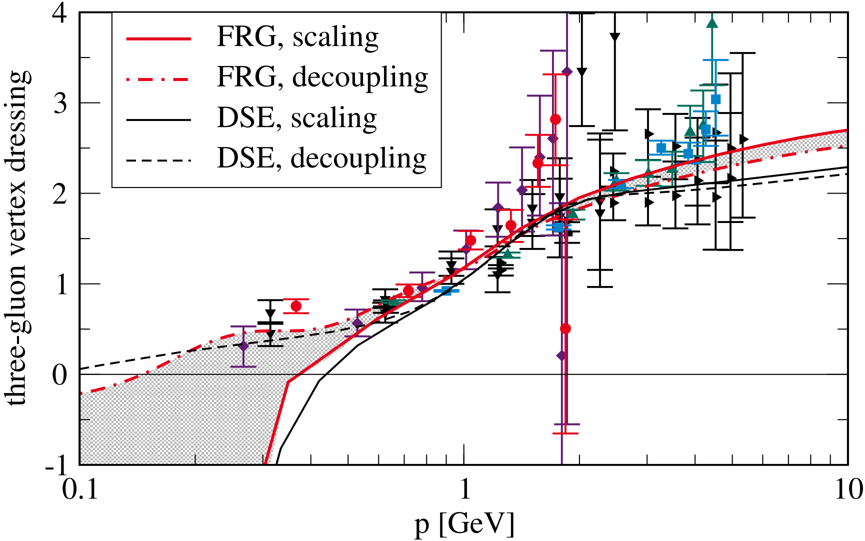
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Three-gluon vertex at the symmetric point



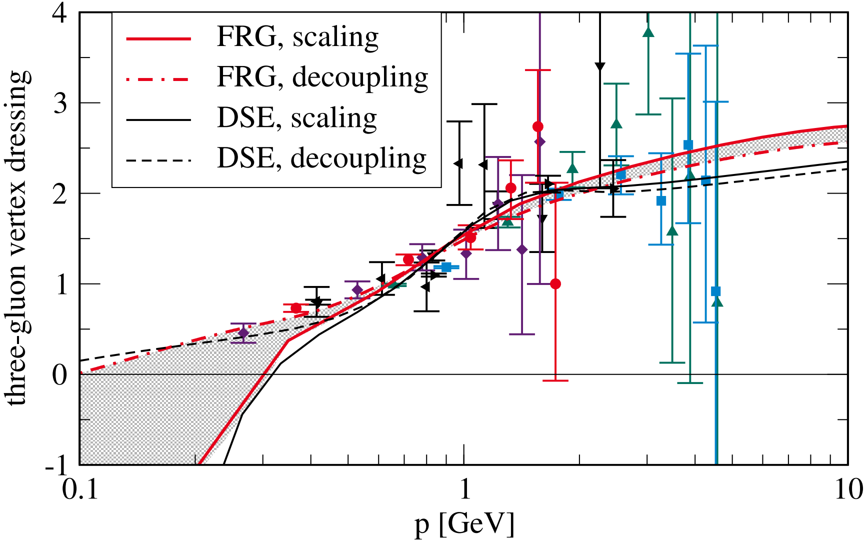
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Three-gluon vertex with vanishing gluon momentum



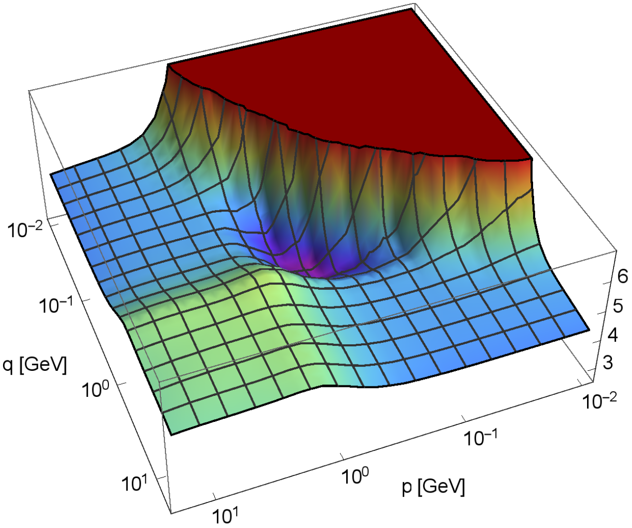
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Three-gluon vertex with orthogonal momenta



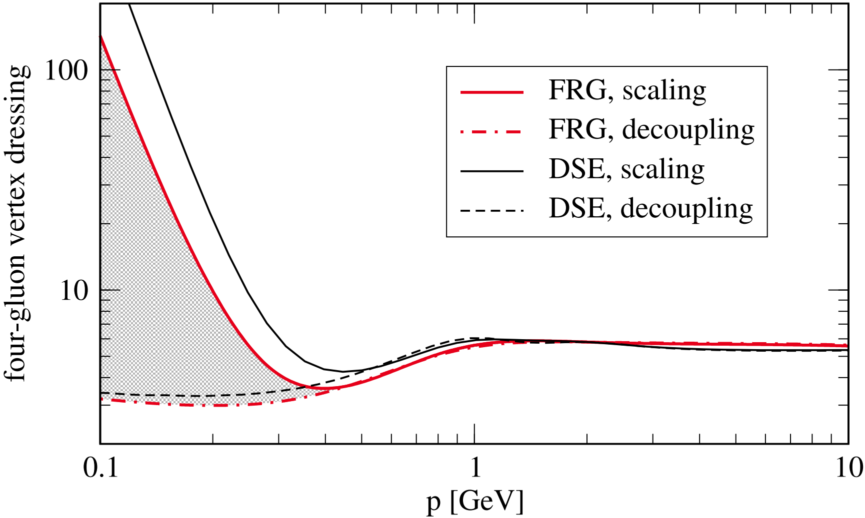
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Momentum dependence of the four-gluon vertex



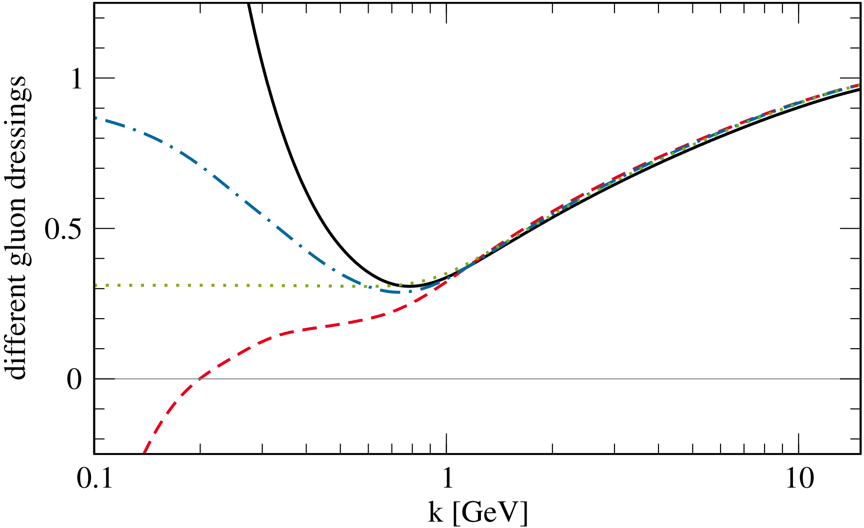
AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Four-gluon vertex at the symmetric point



AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016

Regulator dressing



AKC, Fister, Mitter, Pawlowski, Strodthoff, 2016