

QCD from quark, gluon, and meson correlators

Mario Mitter

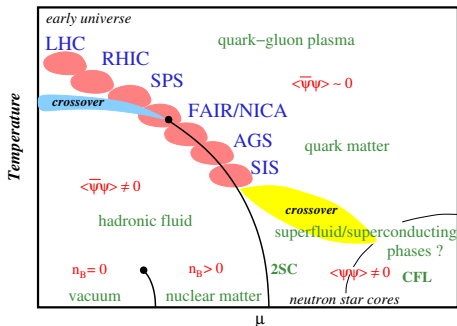
Brookhaven National Laboratory

Giessen, January 2018



fQCD collaboration - QCD (phase diagram) with FRG:

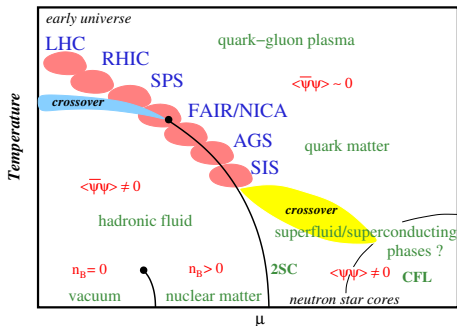
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[Schaefer, Wagner, '08]

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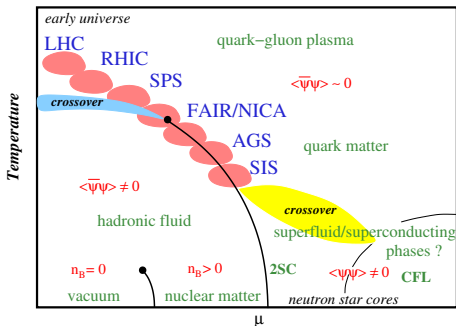


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large part of this effort: vacuum QCD and YM-theory

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why?

QCD from the effective action (gauge fixing necessary)

$$\Gamma[\Phi] = \sum_n \int_{\{p_i\}} \Gamma_{\Phi_1 \dots \Phi_n}^{(n)}(p_1, \dots, p_{n-1}) \Phi^1(p_1) \dots \Phi^n(-p_1 - \dots - p_{n-1})$$

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- ▶ bound state spectrum: pole structure of the $\Gamma^{(n)}$

e.g. [Roberts, Williams, '94], [Alkofer, Smekal, '00], [Eichmann, Sanchis-Alepuz, Williams, Alkofer, Fischer, '16]

- ▶ form factors: photon-particle correlators

e.g. [Cloet, Eichmann, El-Bennich, Klahn, Roberts, '08], [Sanchis-Alepuz, Williams, Alkofer, '13]

⇒ decay constants

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- ▶ thermodynamic quantities: $\Gamma[\Phi] \propto$ grand potential

- ★ equation of state

e.g. [Herbst, MM, Pawłowski, Schaefer, Stiele, '13]

- ★ fluctuations of conserved charges

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- ▶ further quantities: $\Gamma[\Phi] \propto$ eff. potential, propagators, 't Hooft determinant

- ★ chiral condensate(s)/ $\langle \sigma \rangle$

e.g. [Schaefer, Wambach '04], [Fischer, Luecker, Mueller '11], [MM, Schaefer, '13]

- ★ (dressed) Polyakov loop

e.g. [Fischer, '09], [Braun, Haas, Marhauser, Pawłowski, '09], [MM, et al., '17]

- ★ axial anomaly

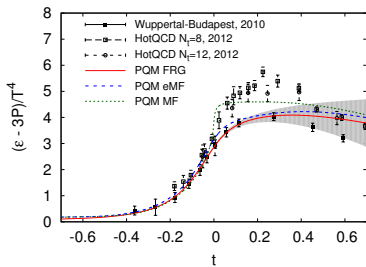
e.g. [Grahl, Rischke, '13], [MM, Schaefer, '13], [Fejos, '15], [Heller, MM, '15]

- ★ spectral functions

e.g. [Tripolt, Strodthoff, Smekal, Wambach, '14]

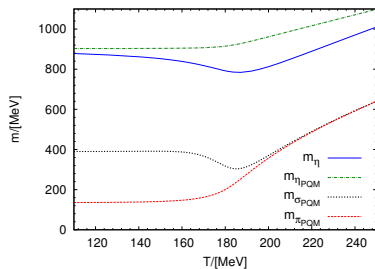
e.g. EOS and axial anomaly in “QCD-enhanced” models

- equation of state
- $N_f = 2 + 1$ PQM model with FRG
- unquenched Polyakov-loop potential from [Braun, Haas, Marhauser, Pawłowski, '11]
- η' -meson screening mass
- $N_f = 2$ PQM model, extended MF
- running 't Hooft determinant from [MM, Pawłowski, Strodthoff, '14]



[Herbst, MM, Pawłowski, Schaefer, Stiele, '13]

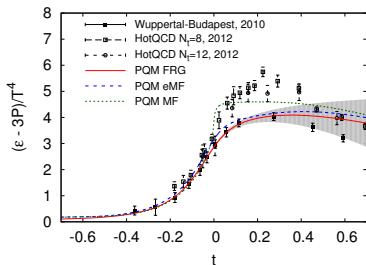
[Haas, Stiele, Braun, Pawłowski, Schaffner-Bielich, '13]



[Heller, MM, '15]

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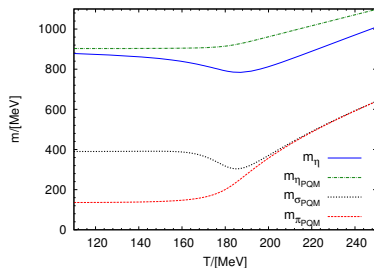
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- phase diagrams
- spectral functions
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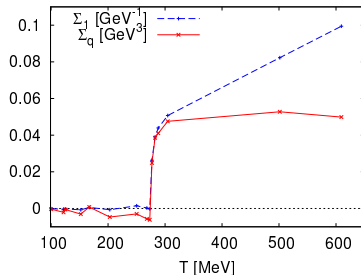
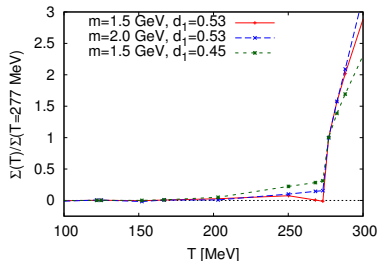
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[Heller, MM, '15]

e.g. Center symmetry order parameters [MM, Hopfer, Schaefer, Alkofer, 2017]

- quenched (scalar) Quantum Chromodynamics
- correlators from Dyson-Schwinger equation (DSE)
- lattice gluon input and vertex models



from scalar propagator:

$$\int_0^{2\pi} d\varphi T \sum_n D_\varphi^2(\vec{p} = \vec{0}, \omega_n(\varphi))$$

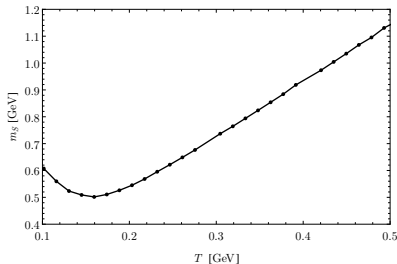
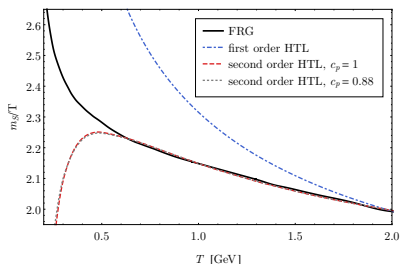
from quark propagator:

$$\int_0^{2\pi} d\varphi T \sum_n \left[\frac{1}{4} \text{tr}_D S(\vec{0}, \omega_n(\varphi)) \right]^2$$

- cf. e.g. [Fischer '09], [Braun, Haas, Marhauser, Pawłowski, '09],...

e.g. Debye mass in $SU(3)$ YM theory [Cyrol, MM, Pawłowski, Strodthoff, 2017]

- correlators from Functional Renormalisation Group (FRG)
- screening mass:
fit to exponential decay of chromo-electric gluon propagator



- excellent agreement with beyond leading order Debye mass of [Arnold, Yaffe, '95] for $T \gtrsim 0.6$ GeV
- smooth transition to nonperturbative regime

Nonperturbative QCD

- two crucial phenomena: S_χ SB and confinement
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- similar scales - hard to disentangle

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crawling towards QCD at finite density:

- quenched matter part [MM, Strodthoff, Pawłowski, 2014]
- pure $SU(N)$ YM-theory [Cyrol, Fister, MM, Pawłowski, Strodthoff, 2016]
- $N_f = 2$ QCD [Cyrol, MM, Strodthoff, Pawłowski, 2017]
- YM-theory at finite temperature $T > 0$ [Cyrol, MM, Strodthoff, Pawłowski, 2017]

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- use results from lattice gauge theory to check truncation:
what do we need from the lattice?

(Euclidean) Correlation functions with the FRG

- mass-like IR regulator:
 - ▶ $S[\Phi] \rightarrow S[\Phi] + \langle \Phi, R_k \Phi \rangle$
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- gauge-fixed approach (Landau gauge): ghosts appear
- functional derivatives \Rightarrow equations for correlators
- aim for “apparent convergence” of $\Gamma[\Phi] = \lim_{k \rightarrow 0} \Gamma_k[\Phi]$

Mesons via dynamical hadronization

[Gies, Wetterich, 2002]

- change of variables: particular 4-Fermi channels \rightarrow meson exchange
- efficient inclusion of pole structure \Rightarrow no spurious singularities
- low-energy effective model parameters from QCD - range of validity

$$\partial_k \Gamma_k = \frac{1}{2} \left(\text{diagram 1} - \text{diagram 2} - \text{diagram 3} + \frac{1}{2} \text{diagram 4} \right)$$

The diagrammatic equation shows the derivative of the effective action Γ_k with respect to the source k . It is expressed as a sum of four diagrams, each featuring a vertex (a circle with an 'X') and a loop structure:

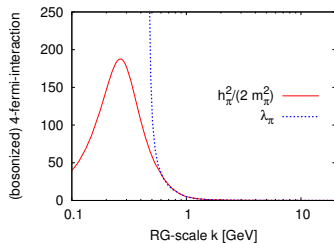
- Diagram 1: A loop with a wavy internal line (representing a meson) and a solid external line.
- Diagram 2: A loop with a solid internal line and a solid external line.
- Diagram 3: A loop with a solid internal line and a dashed external line.
- Diagram 4: A loop with a dashed internal line and a dashed external line.

Mesons via dynamical hadronization

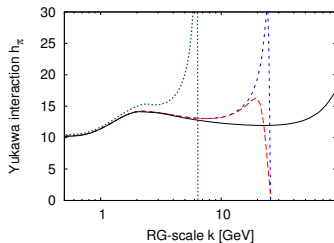
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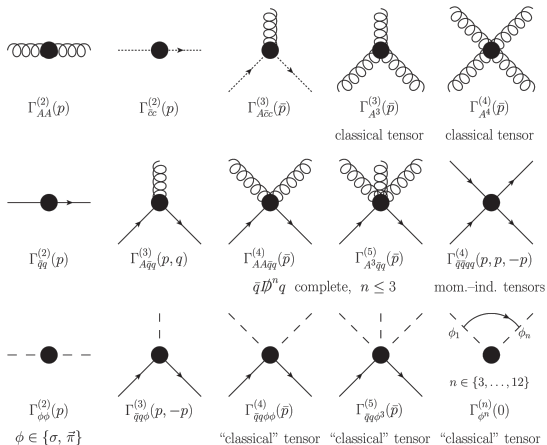
[Braun, Fister, Pawłowski, Rennecke, 2014]

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$N_f = 2$ Landau-gauge QCD

[Cyrol, MM, Pawłowski, Strodthoff, 2017]

Truncation:

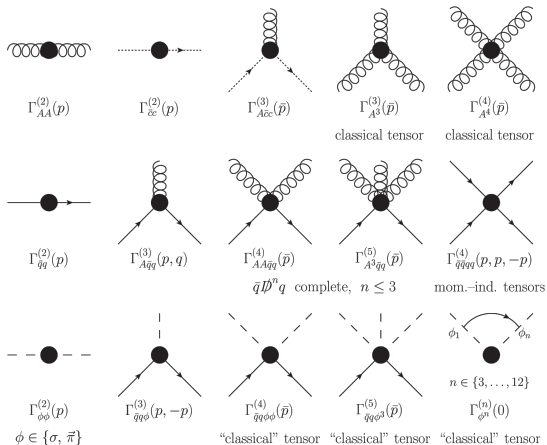


systematics of improving the truncation?

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Truncation:



systematics of improving the truncation?

\Rightarrow BRST-invariant operators, e.g. $\bar{\psi}\not{D}^n\psi$

Some representative equations (numerics-heavy)

[MM, Strodthoff, Pawlowski, 2014],

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cf. FormTracer [Cyrol, MM, Strodthoff, 2016]

$$\partial_t \longrightarrow^{-1} = \text{diagram 1} + \text{diagram 2} + \frac{1}{2} \text{diagram 3} + \text{diagram 4} + \text{diagram 5} - \text{diagram 6}$$

$$\partial_t \text{diagram 7} = - \text{diagram 8} - \text{diagram 9} - \text{diagram 10} - \text{diagram 11} - \frac{1}{2} \text{diagram 12} + 2 \text{diagram 13} - \text{diagram 14} + \text{perm.}$$

$$\partial_t \text{diagram 15} - 2 \text{diagram 16} - \text{diagram 17} - \text{diagram 18} - \text{diagram 19} - \text{diagram 20} - \text{diagram 21} - \text{diagram 22} - \text{diagram 23} + \text{perm.}$$

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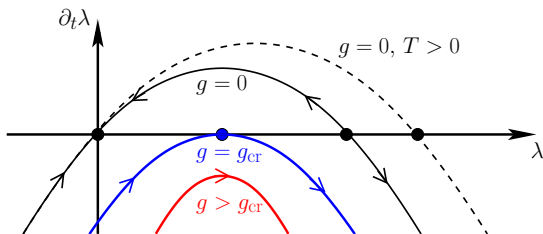
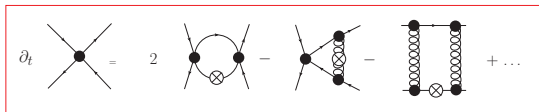
Chiral symmetry breaking

- χ SB \Leftrightarrow resonance in 4-Fermi interaction λ (pion pole):

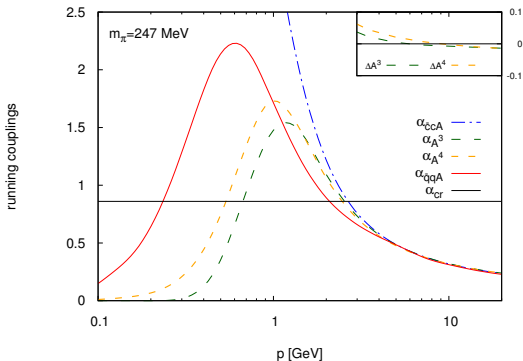
Chiral symmetry breaking

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- β -function of momentum independent 4-Fermi interaction:

$$\partial_t \lambda = 2\lambda + a\lambda^2 + b\lambda\alpha + c\alpha^2, \quad b > 0, \quad a, c \leq 0$$

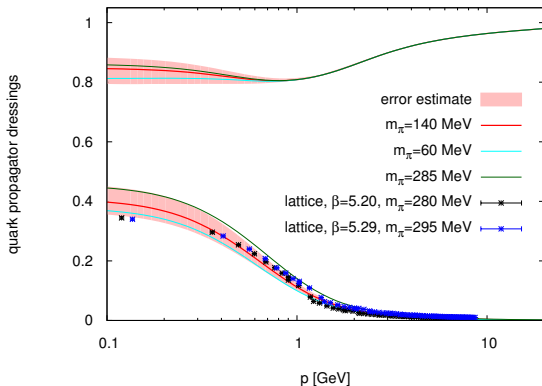


[Braun, 2011]



- agreement in perturbative regime required by Slavnov-Taylor identities
- non-degenerate in nonperturbative regime: reflects gluon mass gap
- $\alpha_{\bar{q}Aq} > \alpha_{cr}$: necessary for chiral symmetry breaking
- area above α_{cr} very sensitive to errors
 \Rightarrow use STI in perturbative regime

- $\Gamma_{\bar{q}q}(p) = Z_q(p) (\not{p} + M(p))$



- $S_{\chi SB}: M_q(0) \gg M_q(p \gg \Lambda_{QCD})$
- FRG vs. lattice: bare mass, scale setting, lattice Z_q ?
- very sensitive to $\bar{q}qA$ -interaction, relative scales

lattice data: O. Oliveira, A. Kzlersu, P. J. Silva, J.-I. Skullerud, A. Sternbeck, A. G. Williams, arXiv:1605.09632 [hep-lat].

Quark-gluon interactions

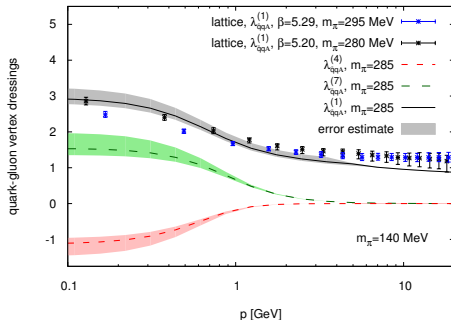
[Cyrol, MM, Pawłowski, Strodthoff, 2017]

- quark-gluon interaction most crucial for chiral symmetry breaking
- transverse tensor basis (8 tensors), e.g. γ^μ , $i(\not{p} + \not{q}) \gamma^\mu$, $\frac{1}{2} [\not{p}, \not{q}] \gamma^\mu$
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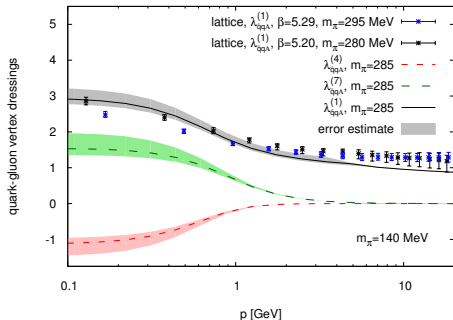


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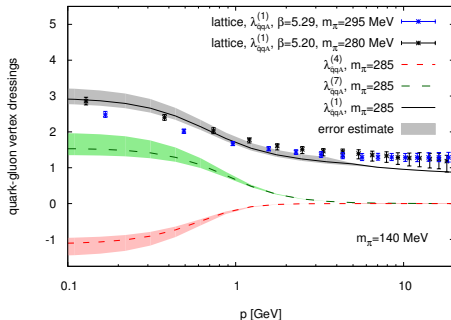
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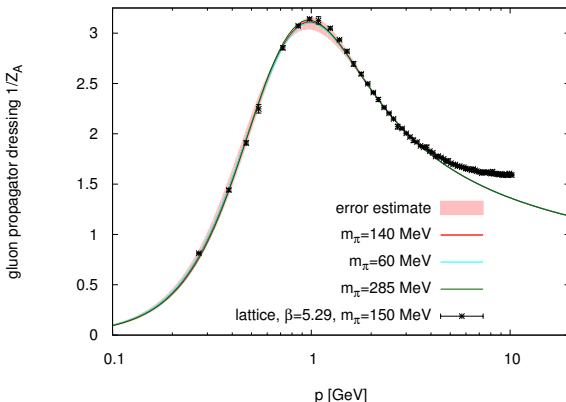
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- \Rightarrow expansion in BRST-invariant operators improves convergence?

lattice data: O. Oliveira, A. Kzlersu, P. J. Silva, J.-I. Skullerud, A. Sternbeck, A. G. Williams, arXiv:1605.09632 [hep-lat].

Gluon propagator

[Cyrol, MM, Pawłowski, Strodthoff, 2017]

- $\Gamma_{AA}(p) = Z_A(p) p^2 (\delta^{\mu\nu} - p^\mu p^\nu / p^2)$

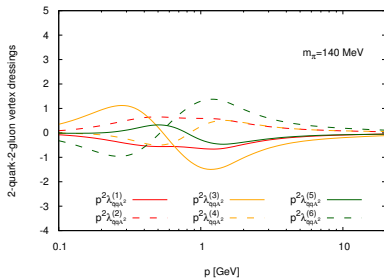
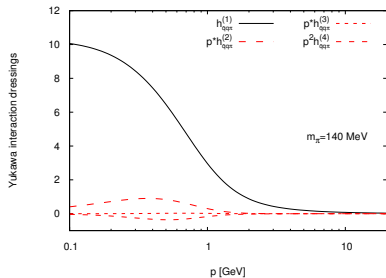
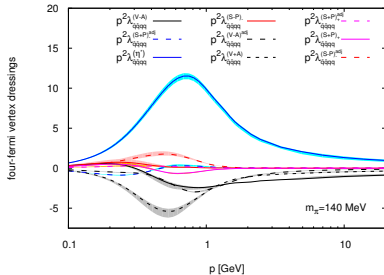
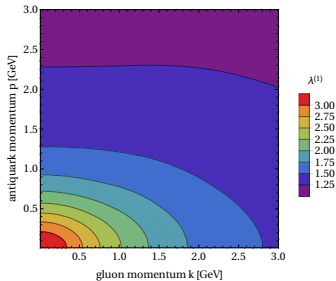


- infrared suppression \Leftrightarrow “confinement”
- insensitive to pion mass
- smooth transition to pert. theory
- scaling solution: lattice comparison?

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

More correlators

[Cyrol, MM, Pawłowski, Strodthoff, 2017]

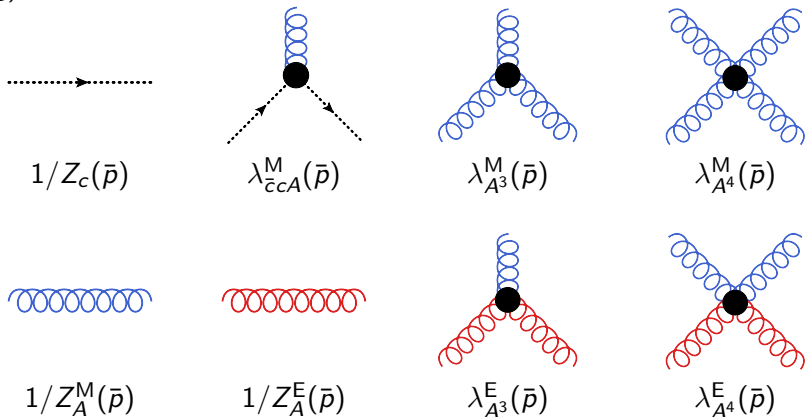


Pure $SU(N)$ YM-theory

[Cyrol, Fister, MM, Pawłowski, Strodthoff, '16]

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Truncation (blue: magnetic (transverse) leg, red: electric (longitudinal) leg):

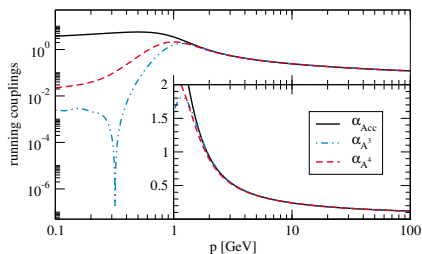
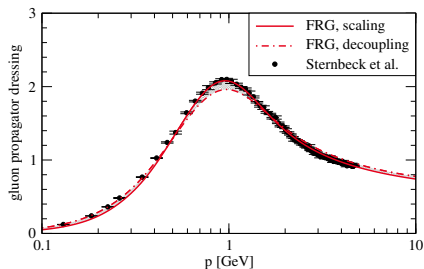


- truncation: momentum dependent dressing functions for all classical tensors
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- $\Gamma_{AA}^{(2)}(p) \propto Z_A(p) p^2 (\delta^{\mu\nu} - p^\mu p^\nu / p^2)$
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- running couplings
- degeneracy at large p due to STI
- test of truncation

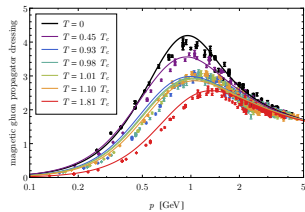


lattice data: A. Sternbeck, E. M. Ilgenfritz, M. Müller-Preussker, A. Schiller, and I. L. Bogolubsky, PoS LAT2006, 076.

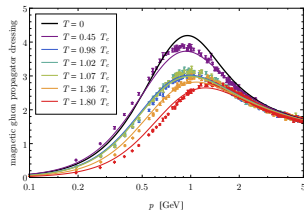
Propagators at $T \neq 0$

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Zeroth mode correlation functions



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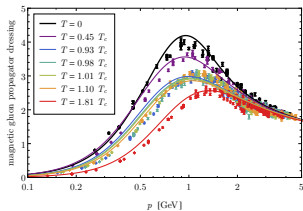


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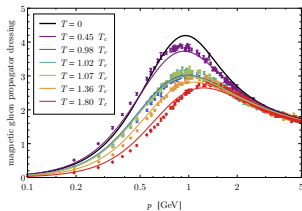
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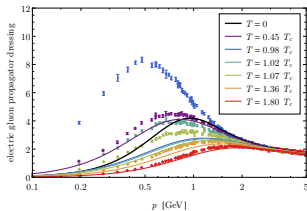
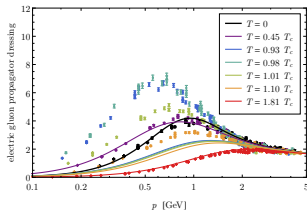
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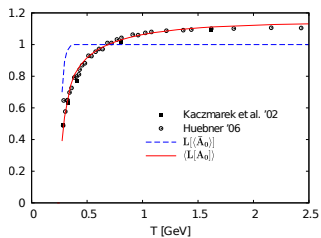
lattice data: A. Maas, J. M. Pawłowski, L. von Smekal, D. Spielmann, Phys.Rev. D85 (2012) 034037. ($SU(2)$)

P. J. Silva, O. Oliveira, P. Bicudo, and N. Cardoso, Phys. Rev. D89, 074503 (2014). ($SU(3)$)

Backgrounds, ghost and zero crossing

[Cyrol, MM, Pawlowski, Strodthoff, '17]

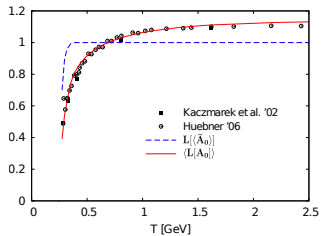
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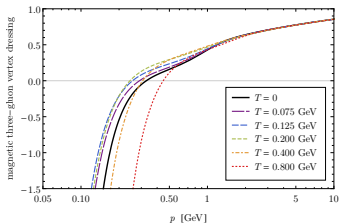
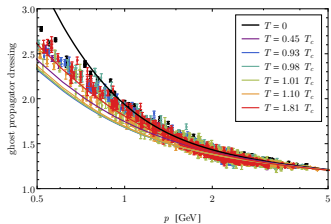
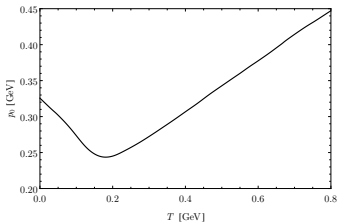
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magnetic zero crossing in 3g-vertex



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