QCD from quark, gluon, and meson correlators

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fQCD collaboration - QCD (phase diagram) with FRG:

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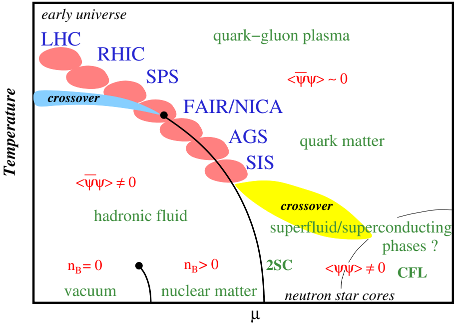

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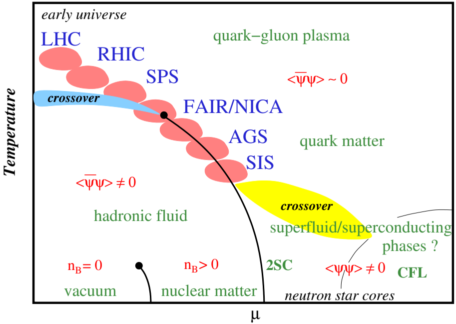

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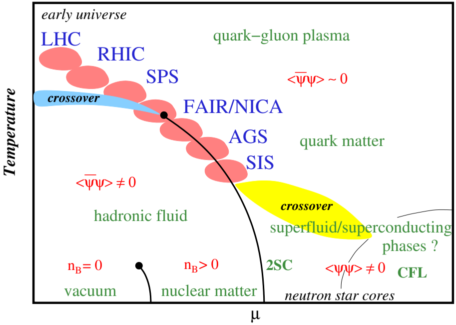

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why?

QCD from the effective action (gauge fixing necessary)

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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

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  - thermodynamic quantities: $\Gamma[\Phi] \propto$ grand potential
    - ★ equation of state e.g. [Herbst, MM, Pawlowski, Schaefer, Stiele, '13]
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  - further quantities: $\Gamma[\Phi] \propto$ eff. potential, propagators, 't Hooft determinant
    - ⋆ chiral condensate(s)/$\langle\sigma\rangle$

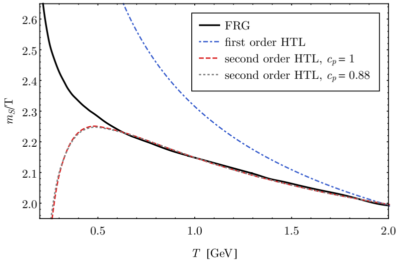
      e.g. [Schaefer, Wambach '04], [Fischer, Luecker, Mueller '11], [MM, Schaefer, '13]
    - ⋆ (dressed) Polyakov loop

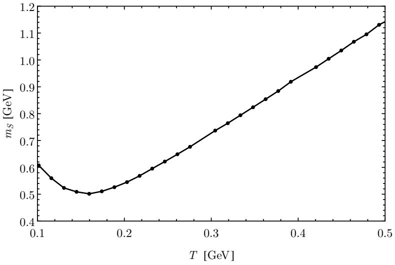
      e.g. [Fischer, '09], [Braun, Haas, Marhauser, Pawlowski, '09], [MM, et al., '17]
    - ⋆ axial anomaly e.g.[Grahl, Rischke, '13], [MM, Schaefer, '13], [Fejos, '15], [Heller, MM, '15]
    - ⋆ spectral functions e.g. [Tripolt, Strodthoff, Smekal, Wambach, '14]

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

- correlators from Functional Renormalisation Group (FRG)
- screening mass:

  fit to exponential decay of chromo-electric gluon propagator

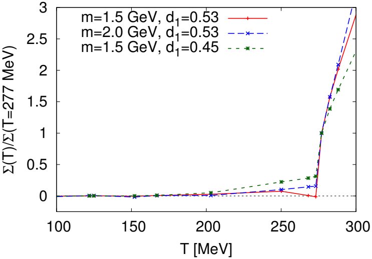


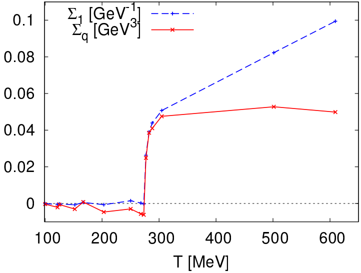


- excellent agreement with 2nd-order HTL perturbation theory for $T \gtrsim 0.6$ GeV
- smooth transition to nonperturbative regime

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:

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

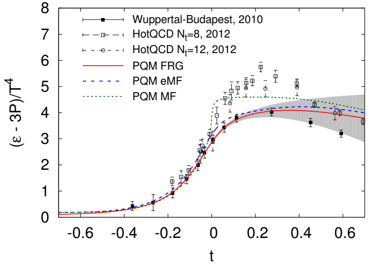
from quark propagator:

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

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

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

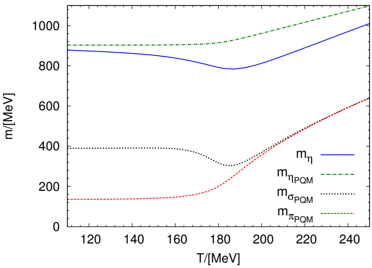
- equation of state
- $N_f = 2+1$ PQM model with FRG
- unquenched Polyakov-loop potential from [Braun, Haas, Marhauser, Pawlowski, '11]



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

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

- η'-meson screening mass
- $N_f = 2$ PQM model, extended MF
- running 't Hooft determinant from [MM, Pawlowski, Strodthoff, '14]



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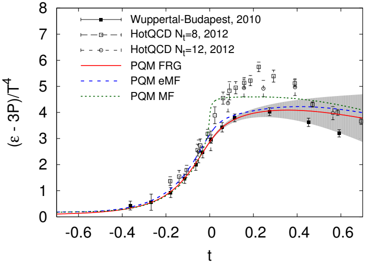

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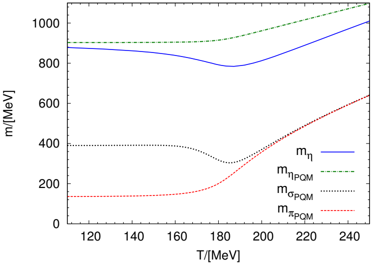

[Heller, MM, '15]

- phase diagrams e.g. [Schaefer, Wambach '04], [Fischer, Luecker, Mueller '11], [MM, Schaefer, '13]
- spectral functions e.g. [Tripolt, Strodthoff, Smekal, Wambach, '14]
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Nonperturbative QCD

- two crucial phenomena: SχSB and confinement
- very sensitive to small quantitative errors
- similar scales - hard to disentangle

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crawling towards QCD at finite density:

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

- $S[\Phi] = \Gamma_\Lambda[\Phi]$: use only perturbative QCD input
  - $\alpha_S(\Lambda = \mathcal{O}(10)$ GeV)
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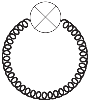
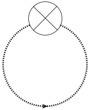
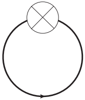
- integration of momentum shells:

$$\partial_k \Gamma_k[A, \bar{c}, c, \bar{q}, q] = \frac{1}{2}$$  $-$  $-$ 

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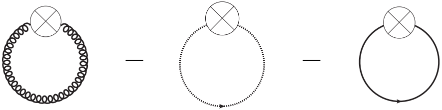

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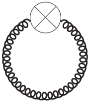
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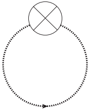
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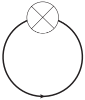

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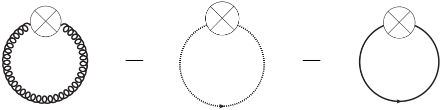

$\Rightarrow$ full non-perturbative quantum effective action

- gauge-fixed approach (Landau gauge): ghosts appear
- functional derivatives $\Rightarrow$ equations for correlators
- aim for "apparent convergence" of $\Gamma[\Phi] = \lim_{k\to 0} \Gamma_k[\Phi]$

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

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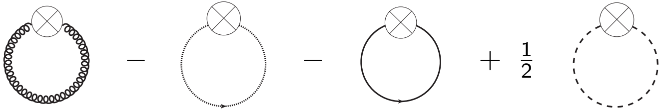

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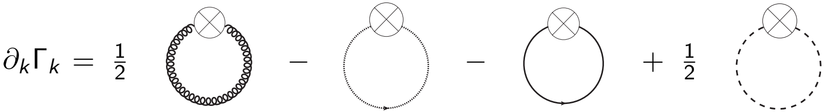
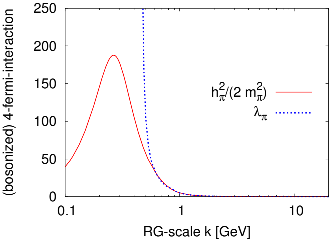
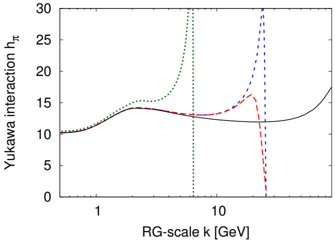




[MM, Strodthoff, Pawlowski, 2014]



[Braun, Fister, Haas, Pawlowski, Rennecke, 2014]

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$N_f = 2$ Landau-gauge QCD

[Cyrol, MM, Pawlowski, Strodthoff, 2017]

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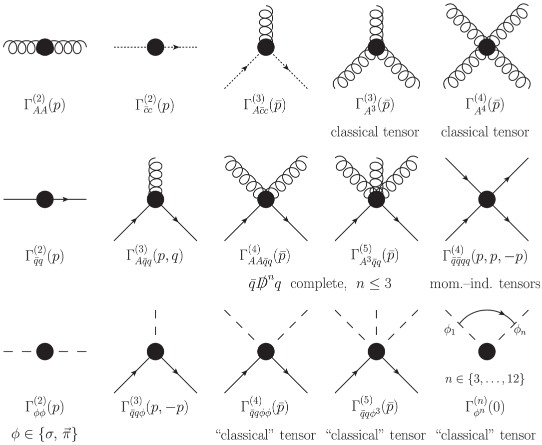

systematics of improving the truncation?

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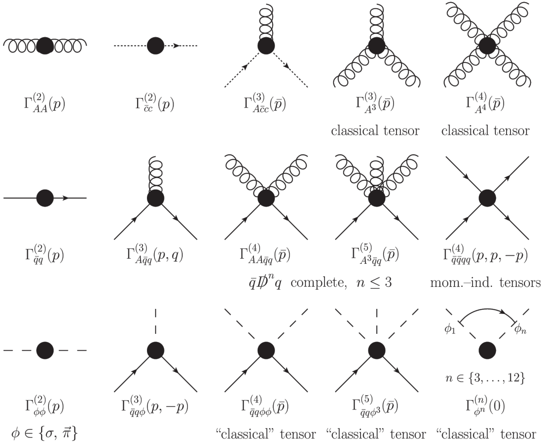


systematics of improving the truncation?

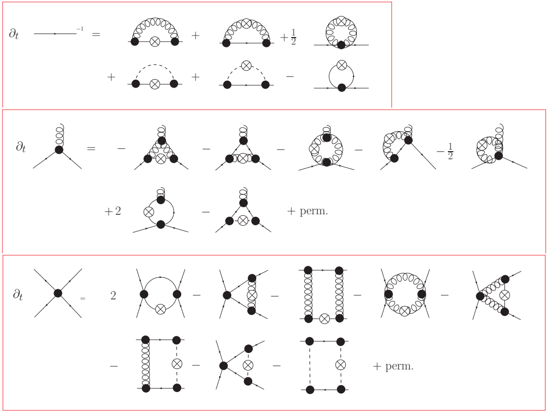
$\Rightarrow$ BRST-invariant operators, e.g. $\bar{\psi}\not{D}^n\psi$

Some representative equations (numerics-heavy)

[MM, Strodthoff, Pawlowski, 2014],

[Cyrol, Fister, MM, Strodthoff, Pawlowski, 2016]

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



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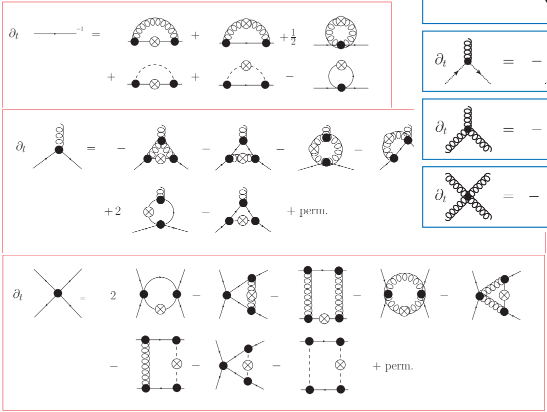

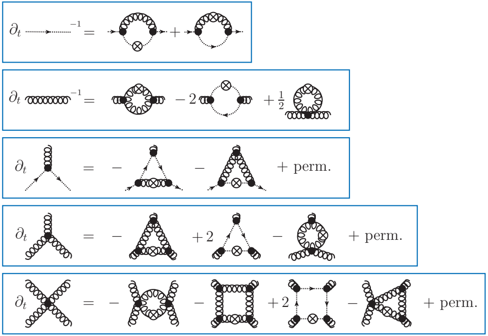

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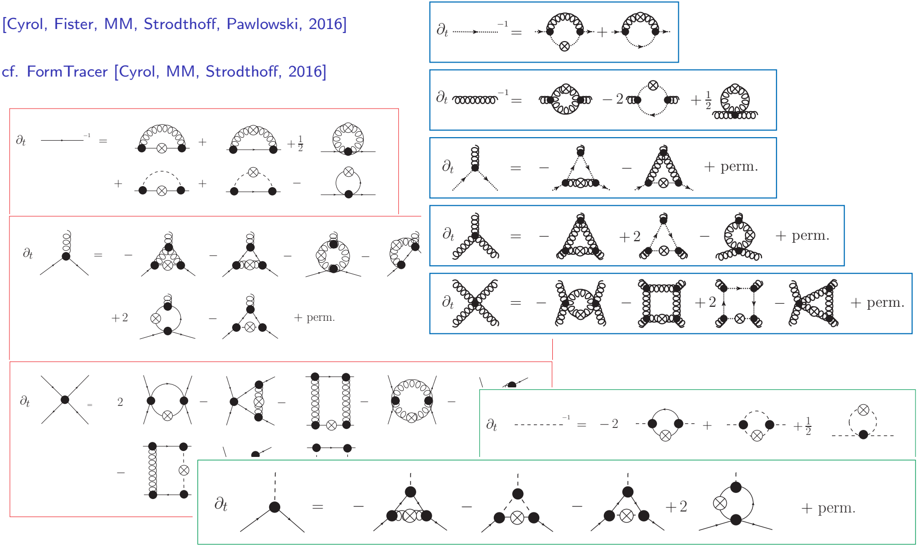


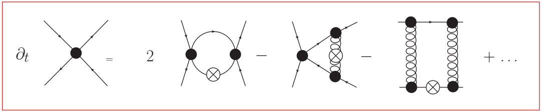
Chiral symmetry breaking

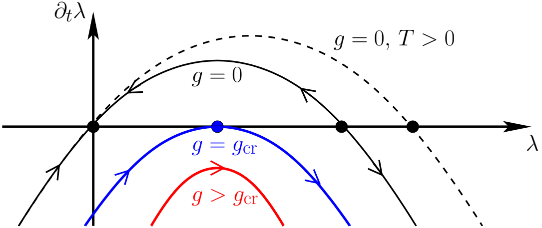
- χSB $\Leftrightarrow$ resonance in 4-Fermi interaction λ (pion pole):

Chiral symmetry breaking

- χSB $\Leftrightarrow$ resonance in 4-Fermi interaction λ (pion pole):
- β-function of momentum independent 4-Fermi interaction:

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

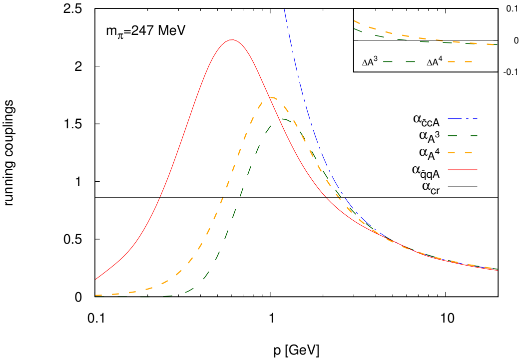




[Braun, 2011]

(transverse) running couplings

[Cyrol, MM, Pawlowski, Strodthoff, 2017]



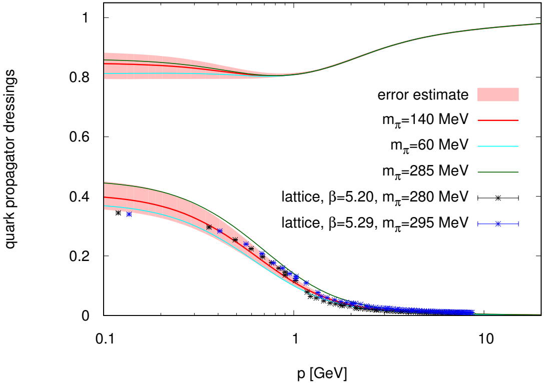
- agreement in perturbative regime required by Slavnov-Taylor identities
- non-degenerate in nonperturbative regime: reflects gluon mass gap
- $\alpha_{\bar{q}Aq} > \alpha_{cr}$: necessary for chiral symmetry breaking
- area above α_{cr} very sensitive to errors

  $\Rightarrow$ use STI in perturbative regime

Quark propagator

[Cyrol, MM, Pawlowski, Strodthoff, 2017]

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



- SχSB: $M_q(0) \gg M_q(p \gg \Lambda_{\mathrm{QCD}})$
- 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, Pawlowski, Strodthoff, 2017]

- quark-gluon interaction most crucial for chiral symmetry breaking
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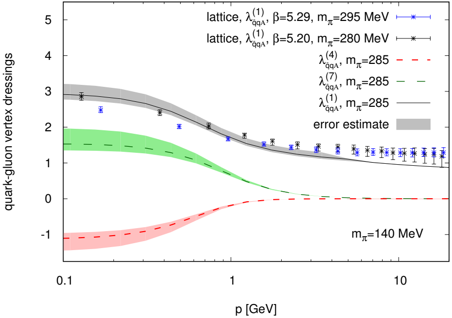

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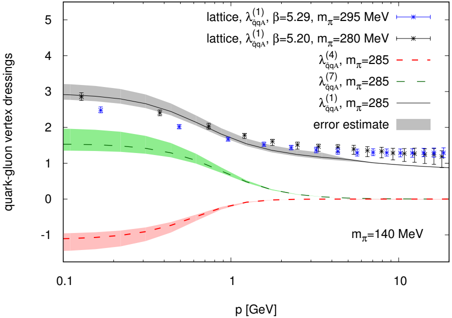

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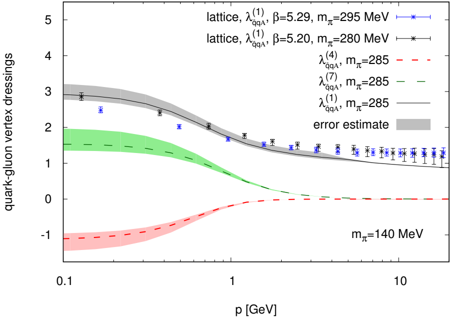

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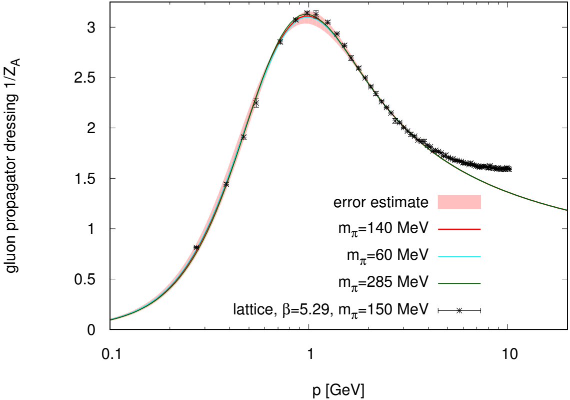
$\Rightarrow$ expansion in BRST-invariant operators improves convergence?

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, Pawlowski, Strodthoff, 2017]

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

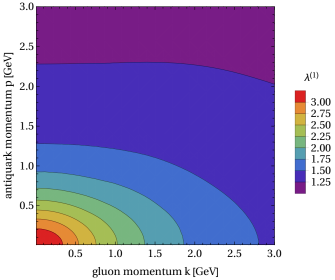


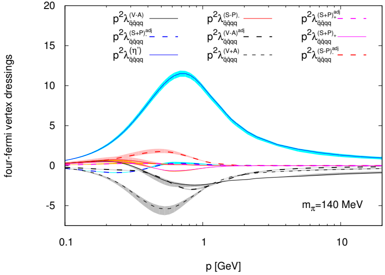
- infrared suppression ⇔ "confinement"
- insensitive to pion mass
- smooth transition to pert. theory
- scaling solution: lattice comparison?

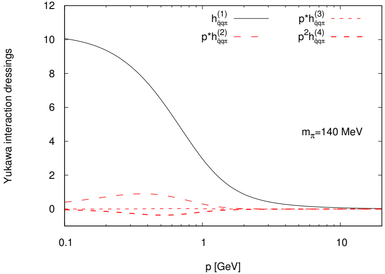
lattice data: A. Sternbeck, K. Maltman, M. Müller-Preussker, L. von Smekal, PoS LATTICE2012 (2012) 243.

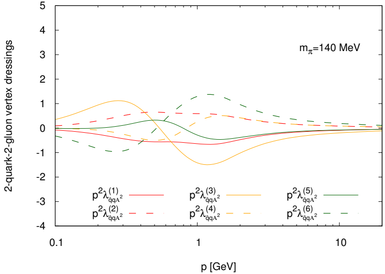
More correlators

[Cyrol, MM, Pawlowski, Strodthoff, 2017]







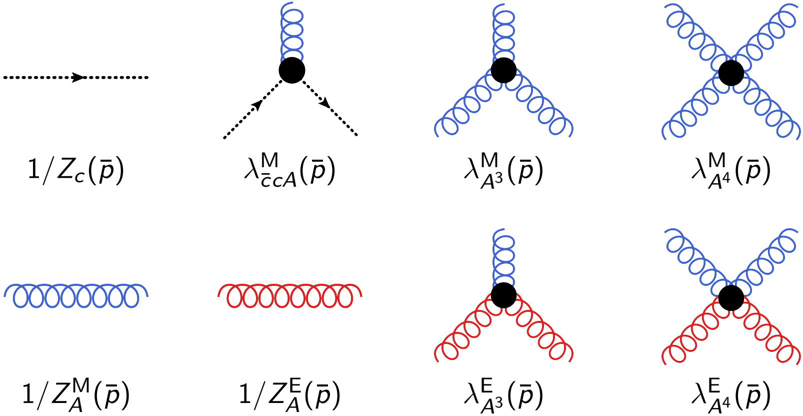


Pure $SU(N)$ YM-theory

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

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

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



Vacuum

[Cyrol, Fister, MM, Pawlowski, Strodthoff, 2016]

- truncation: momentum dependent dressing functions for all classical tensors
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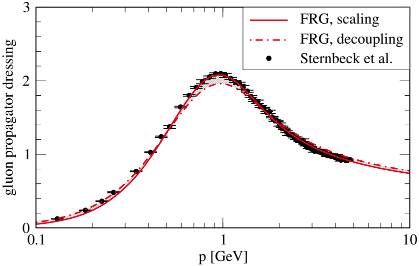
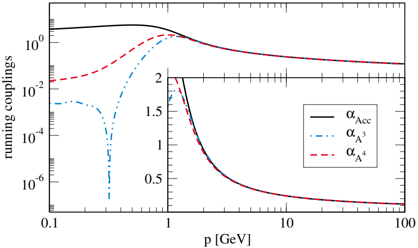
- IR-suppression $\Leftrightarrow$ "confinement"
- smooth transition to perturbation theory

- running couplings
- degeneracy at large p due to STI
- test of truncation



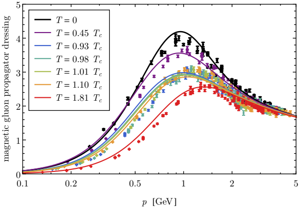


lattice data: A. Sternbeck, E. M. Ilgenfritz, M. Muller-Preussker, A. Schiller, and I. L. Bogolubsky, PoS LAT2006, 076.

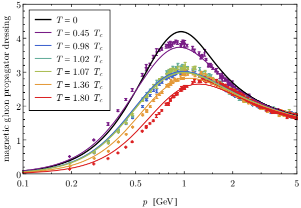
Propagators at $T \neq 0$

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

Zeroth mode correlation functions



$SU(2)$



$SU(3)$

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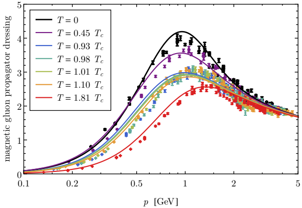

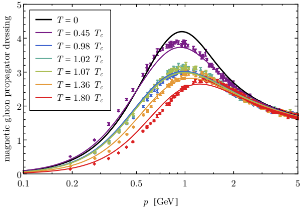

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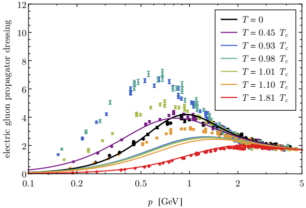
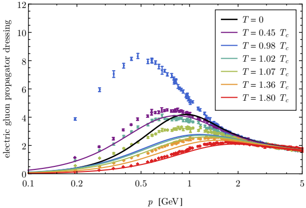


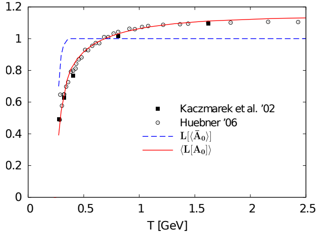


lattice data: A. Maas, J. M. Pawlowski, L. von Smekal, D. Spielmann, Phys.Rev. D85 (2012) 034037. ($SU(2)$)

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]

$\langle \bar{A}_0 \rangle$ important near T_c, cf. [Herbst et al., '15]



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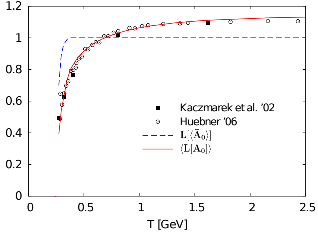
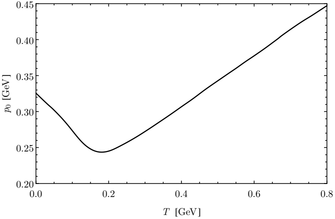
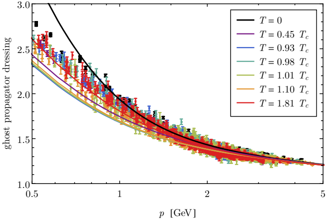
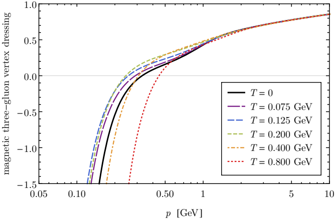


magnetic zero crossing in 3g-vertex







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