QCD from quark, gluon, and meson correlators

Mario Mitter

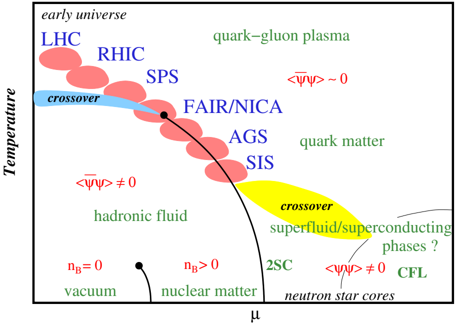
cf. poster Anton K. Cyrol

Brookhaven National Laboratory

Bad Honnef, April 2018

fQCD collaboration - QCD (phase diagram) with FRG:

J. Braun, L. Corell, A. K. Cyrol, W. J. Fu, M. Leonhardt, MM, J. M. Pawlowski, M. Pospiech, F. Rennecke, N. Strodthoff, N. Wink, . . .



[Schaefer, Wagner, '08]

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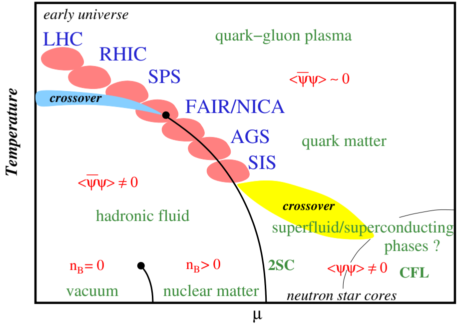

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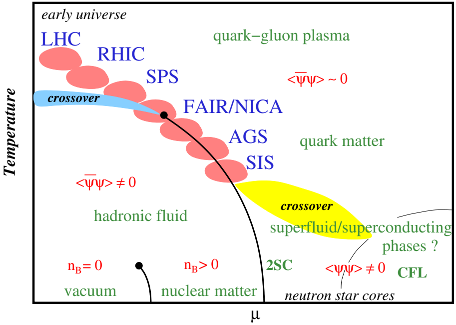

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why no phase diagram yet? what do we still need?

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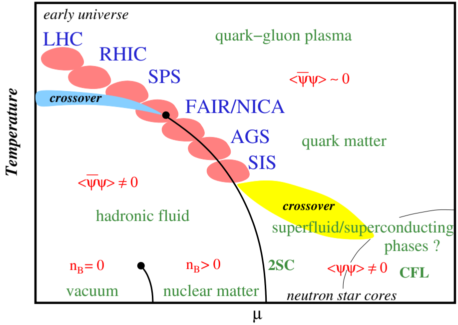

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hard road towards first-principles QCD from FRG

QCD from the effective action (gauge fixing necessary)

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

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    e.g. [Roberts, Williams, '94], [Alkofer, Smekal, '00], [Eichmann, Sanchis-Alepuz, Williams, Alkofer, Fischer, '16]
  - form factors: photon-particle correlators

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    - ⋆ fluctuations of conserved charges e.g. [Fu, Rennecke, Pawlowski, Schaefer, '16]

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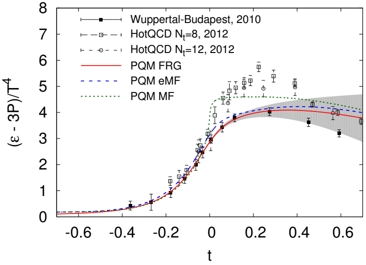
  - further quantities: $\Gamma[\Phi] \propto$ eff. potential, propagators, 't Hooft determinant
    - ⋆ chiral condensate(s)/$\langle\sigma\rangle$
      e.g. [Schaefer, Wambach '04], [Fischer, Luecker, Mueller '11], [MM, Schaefer, '13]
    - ⋆ (dressed) Polyakov loop
      e.g. [Fischer, '09], [Braun, 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. 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
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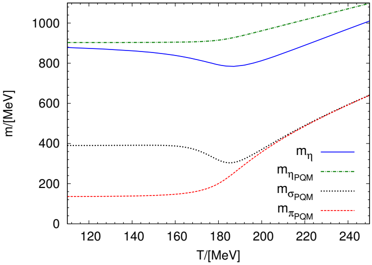

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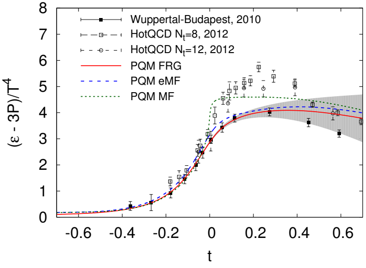

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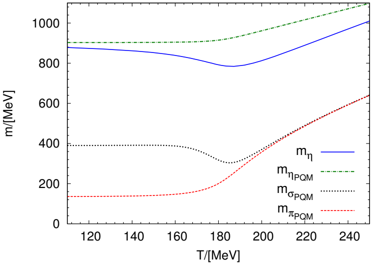

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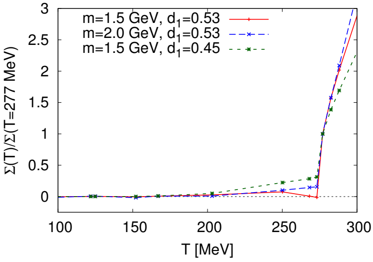
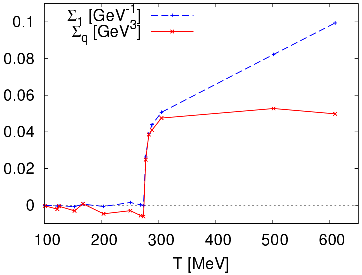
- phase diagrams e.g. [Schaefer, Wambach '04], [Fischer, Luecker, Mueller '11], [MM, Schaefer, '13]
- spectral functions e.g. [Tripolt, Strodthoff, Smekal, Wambach, '14]
- fluctuations of conserved charges e.g. [Fu, Rennecke, Pawlowski, Schaefer, '16]

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:

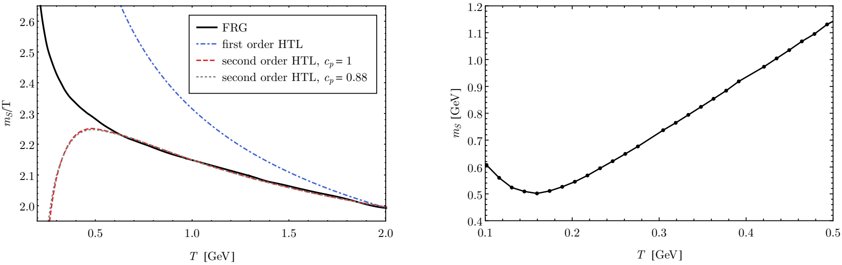
$$\int_0^{2\pi} d\varphi\, T \sum_n \left[\frac{1}{4} tr_D\; S(\vec{0}, \omega_n(\varphi))\right]^2$$

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

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

Nonperturbative QCD

hard problem: quantitatively reliable first-principles method @ large $\frac{\mu}{T}$

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crawling towards QCD at finite temperature and density:

- quenched matter part [MM, Strodthoff, Pawlowski, 2014]
- pure $SU(N)$ YM-theory: 4D and 3D [Cyrol, Fister, MM, Pawlowski, Strodthoff, 2016]
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- (YM-theory at finite temperature $T > 0$ [Cyrol, MM, Strodthoff, Pawlowski, 2017])

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main finding: very sensitive to small quantitative errors in α_{pert}:
$\Rightarrow$ *need "BRST-consistency"!*

(Euclidean) Correlation functions with the FRG

- mass-like IR regulator:
  - $S[\Phi] \to S[\Phi] + \langle \Phi, R_k \Phi \rangle$
  - (renormalised) initial action $\Gamma_{\Lambda\to\infty}[\Phi] = S[\Phi]$

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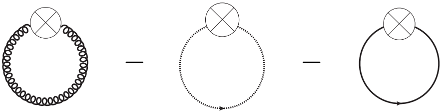

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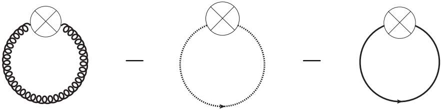

$\Rightarrow$ full non-perturbative quantum effective action

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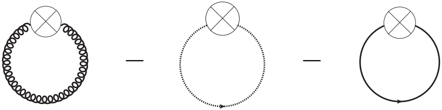


$\Rightarrow$ full non-perturbative quantum effective action

- gauge-fixed approach (Landau gauge): ghosts appear
- aim for "apparent convergence" of $\Gamma[\Phi] = \lim\limits_{k\to 0} \Gamma_k[\Phi]$

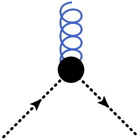
Truncation for $SU(N)$ YM-theory

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

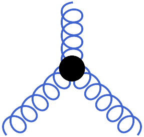
classical tensors with momentum dependent-dressings:

$1/Z_A(p)$

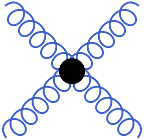
$1/Z_c(p)$



$\lambda_{\bar{c}cA}(p,q,z)$



$\lambda_{A^3}(p,q,z)$



$\lambda_{A^4}(\bar{p})/\lambda_{A^4}(p,q,z)$

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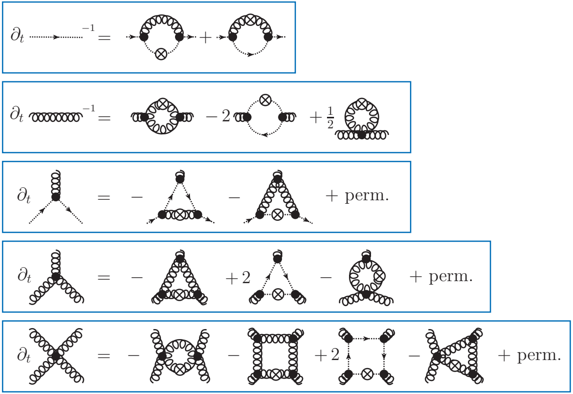

- set of coupled equations: cf. DoFun [Huber, Braun, '11], FormTracer [Cyrol, MM, Strodthoff, '16]

  all propagators/vertices dressed and momentum-dependent

(Some) numerical results

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

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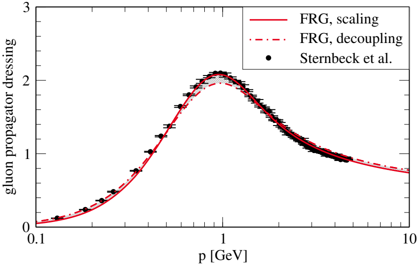
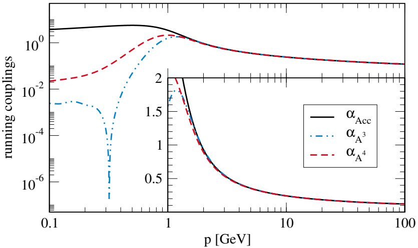
- $\Gamma^{(2)}_{AA}(p) \propto Z_A(p)\, p^2 \,\left(\delta^{\mu\nu} - p^\mu p^\nu / p^2\right)$
- IR-suppression $\Leftrightarrow$ "confinement"
- smooth transition to perturbation theory

- running couplings
- degeneracy at large p
  $\Rightarrow$ "BRST-consistency"





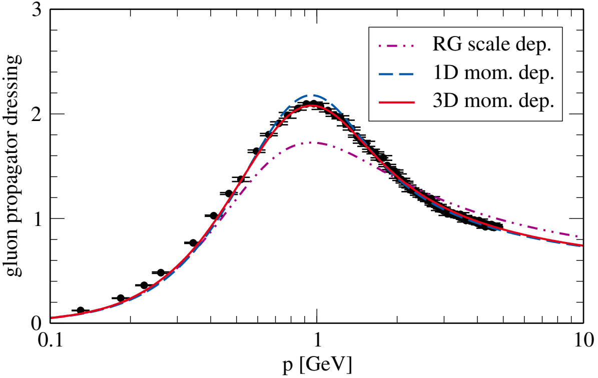
lattice data: A. Sternbeck, E. M. Ilgenfritz, M. Muller-Preussker, A. Schiller, and I. L. Bogolubsky, PoS LAT2006, 076.

Apparent convergence in 4D

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

lattice data: [Sternbeck, Ilgenfritz, Muller-Preussker, Schiller, Bogolubsky, '06]

- different approximations for vertex dressing functions:



- RG scale dep.: $\lambda_X(k;p,q,z) \equiv \lambda_X(k)$
- 1D mom dep.: $\lambda_X(k;p,q,z) \equiv \lambda_X(k;\bar{p})$
- 3D mom dep.: $\lambda_{\bar{c}cA/A^3}(k;p,q,z)$ and $\lambda_{A^4}(k;\bar{p})/\lambda_{A^4}(k;p,q,z)$

Apparent convergence in 3D cf. talk Huber

[Corell, Cyrol, Fister, MM, Pawlowski, Strodthoff, '18]

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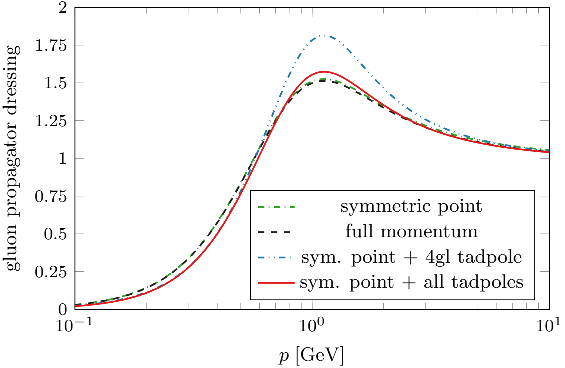
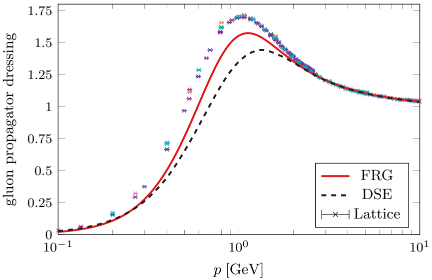


- symmetric point: $\lambda_X(k; p, q, z) \equiv \lambda_X(k; \bar{p})$
- full momentum: $\lambda_{\bar{c}cA/A^3}(k; p, q, z)$ and $\lambda_{A^4}(k; \bar{p})/\lambda_{A^4}(k; p, q, z)$
- +4gl tadpole: all tensors of 4-gl vertex in propagator tadpoles
- all tadpoles: all tensors of all vertices in propagator tadpoles

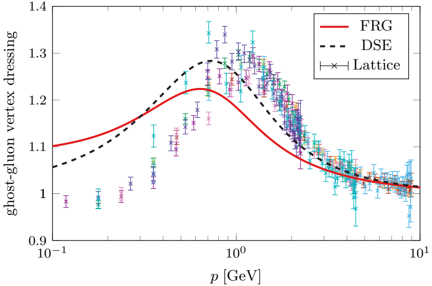
Two more observations in 3D YM theory

[Corell, Cyrol, Fister, MM, Pawlowski, Strodthoff, '18]

- gluon propagator dressing: does not agree as well with lattice



- ghost-gluon vertex dressing: shows a scale mismatch



lattice data: [Cucchieri, Maas, Mendes, '06 and '08], [A. Maas '15 and in preparation]

DSE data: [M. Huber 2016]

What do we learn from the comparison of 3D and 4D YM?

[Corell, Cyrol, Fister, MM, Pawlowski, Strodthoff, '18]

- effect of non-classical contributions seems more important in 3D

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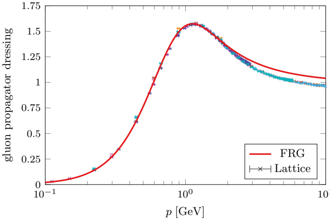

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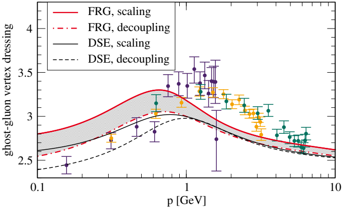

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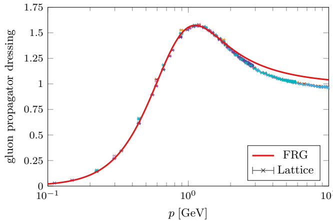

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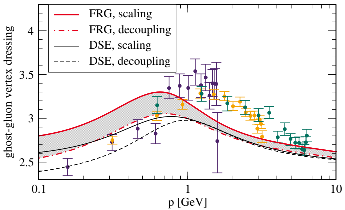


- QCD? important higher-order contributions cf. talk Serreau

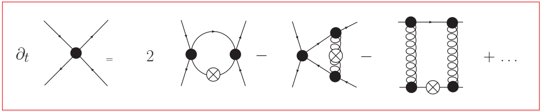
Chiral symmetry breaking

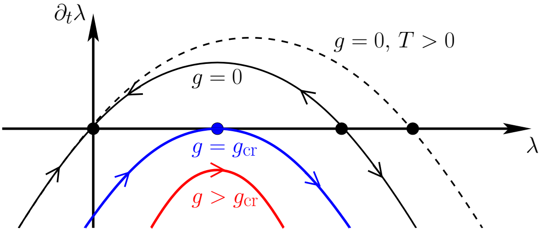
- χSB $\Leftrightarrow$ resonance in 4-Fermi interaction λ (pion pole):

Chiral symmetry breaking

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

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

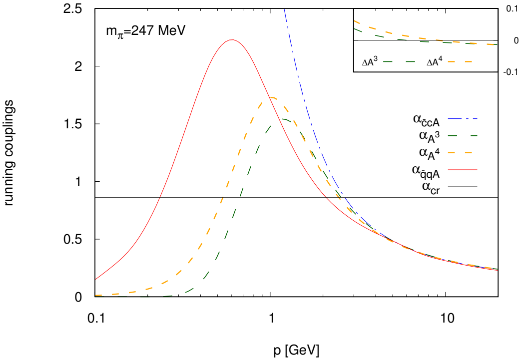




[Braun, 2011]

(transverse) running couplings

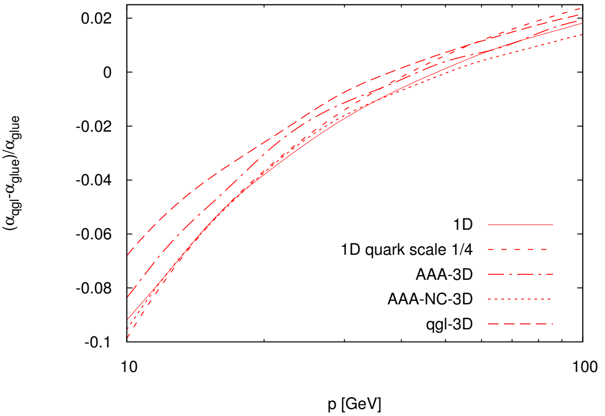
[Cyrol, MM, Pawlowski, Strodthoff, 2017]



- 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

  $\Rightarrow$ have use STI in perturbative regime

FRG running couplings: relative deviation



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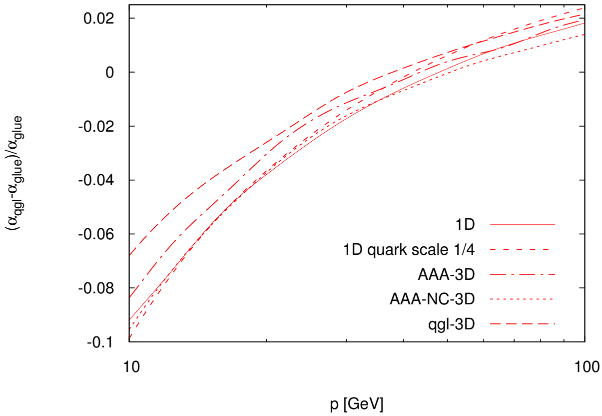

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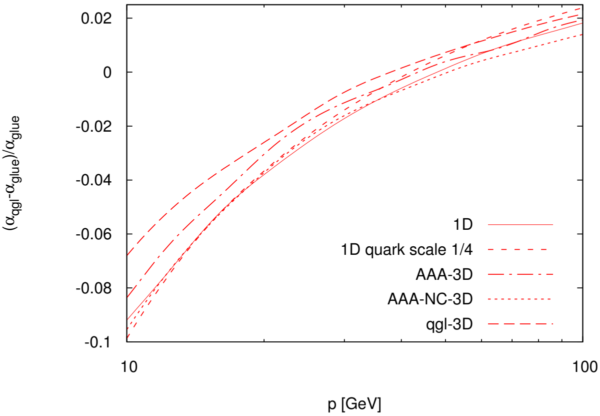

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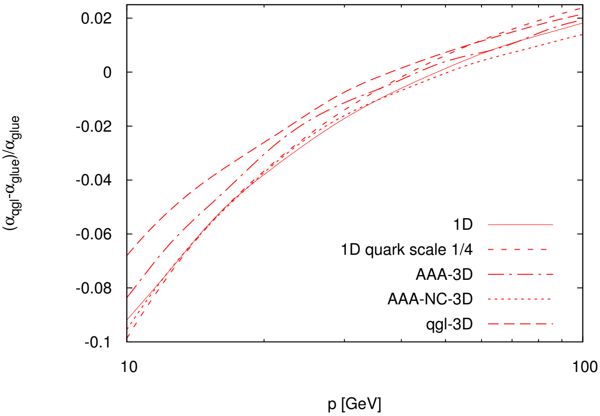

- scale mismatch between matter and ghost-glue sector ⇒ better with $\Gamma_{AA\bar{q}q}$
- importance of non-classical/higher loop contributions
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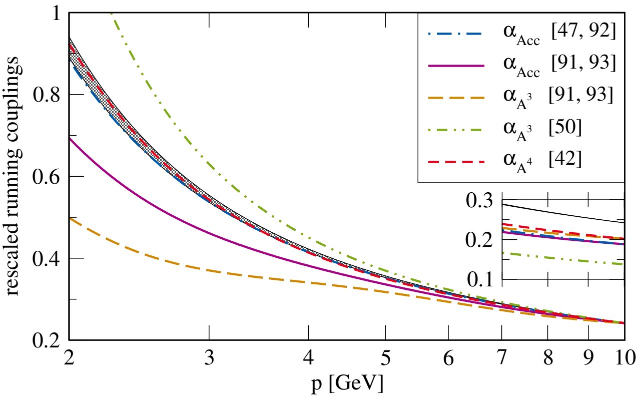
⇒ similarities to 3D YM (the testing case)

Running couplings: YM theory with FRG and DSE

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



[42] [A. Cyrol, M. Huber, L. v. Smekal, '15],

[47] [M. Huber, L. v. Smekal, '13],, [92] [M. Huber, private communications]

[50] [A. Blum, M. Huber, MM, L. v. Smekal, '14]

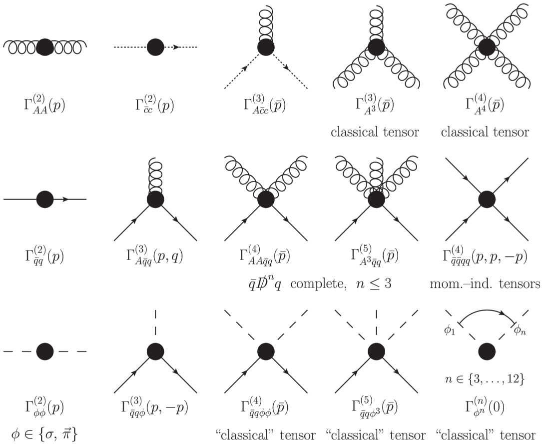
[91] [R. Williams, '14], [93] [R. Williams, private communications]

(maybe most) important self-consistency check!

$N_f = 2$ Landau-gauge QCD

[Cyrol, MM, Pawlowski, Strodthoff, 2017]

Truncation:



systematics of improving the truncation?

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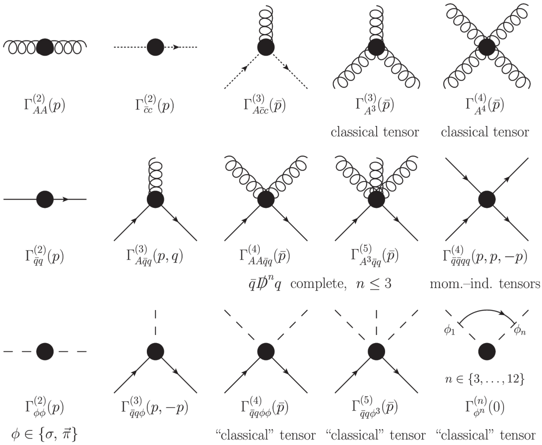


systematics of improving the truncation?

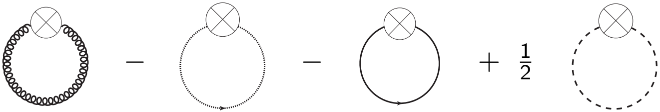
$\Rightarrow$ BRST-invariant operators, e.g. $\bar{\psi}\not{D}^n\psi$

Mesons via dynamical hadronization

[Gies, Wetterich, 2002]

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

$$\partial_k \Gamma_k = \frac{1}{2}$$



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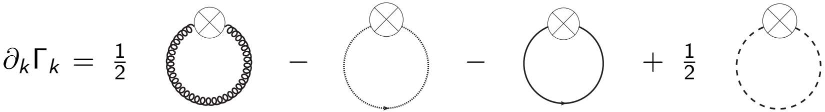

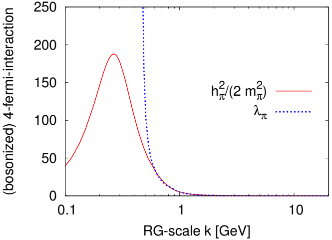

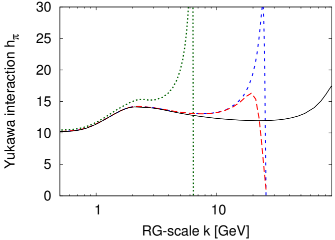

[MM, Pawlowski, Strodthoff, 2014]

[Braun, Fister, Pawlowski, Rennecke, 2014]

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Some representative equations (numerics-heavy)

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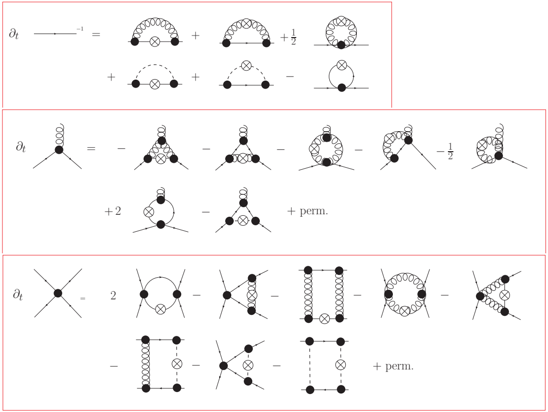
cf. FormTracer [Cyrol, MM, Strodthoff, 2016]



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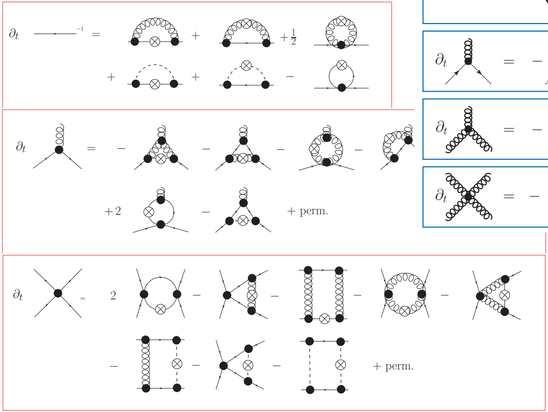

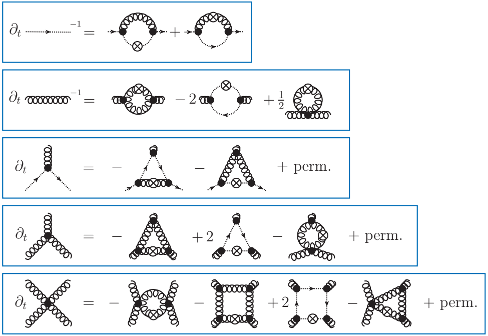

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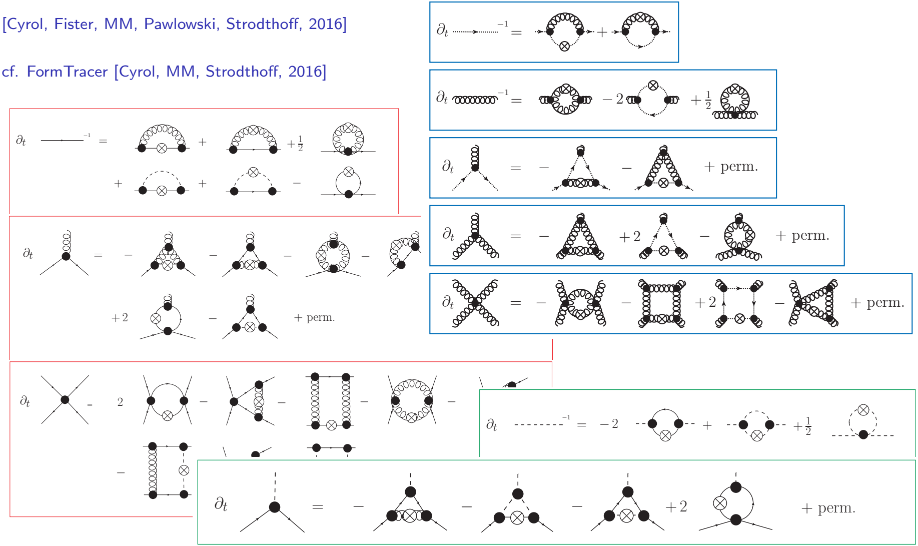
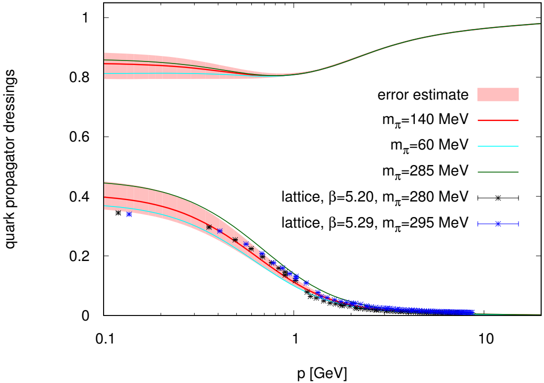


Quark propagator

[Cyrol, MM, Pawlowski, Strodthoff, 2017]

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



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

lattice data: O. Oliveira, A. Kızlersu, 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
- transverse tensor basis (8 tensors), e.g. $\gamma^\mu,\ \mathrm{i}\left(\not{p}+\not{q}\right)\gamma^\mu,\ \frac{1}{2}\left[\not{p},\not{q}\right]\gamma^\mu$
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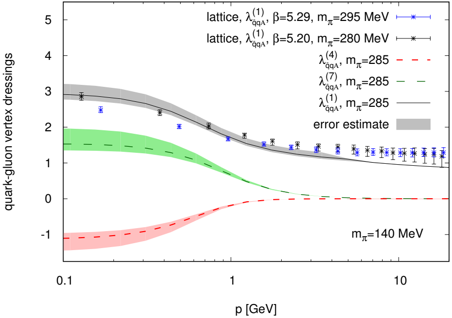

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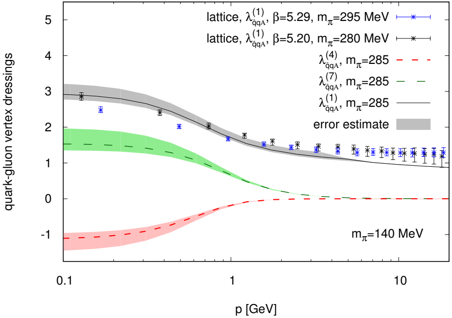

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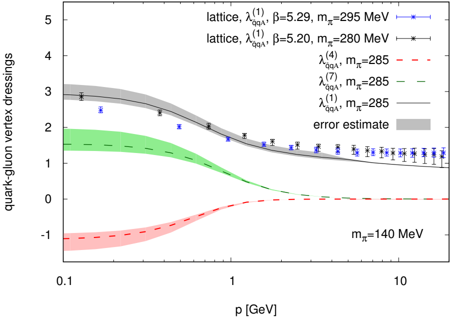

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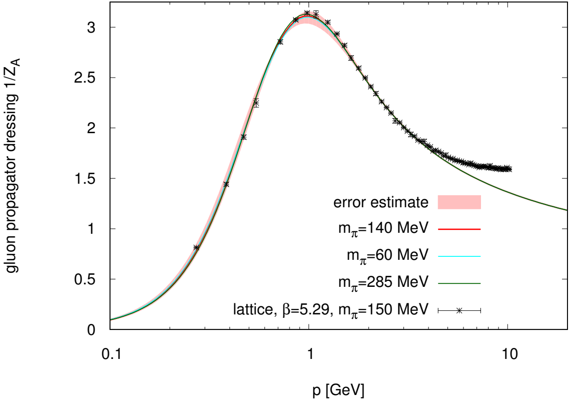
$\Rightarrow$ more evidence for importance of "BRST-connected" operators

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]

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

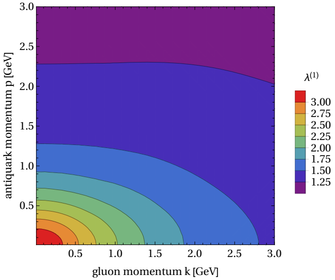


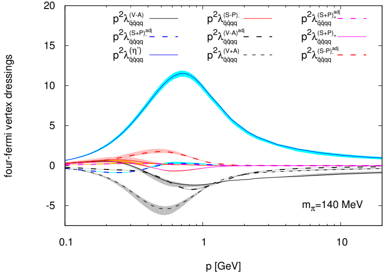
- infrared suppression ⇔ "confinement"
- insensitive to pion mass
- smooth transition to pert. theory
- scaling solution: lattice comparison?

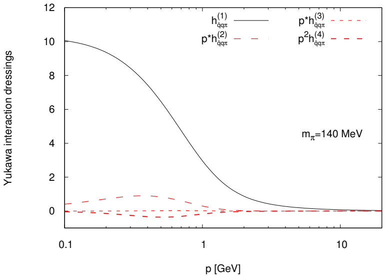
lattice data: A. Sternbeck, K. Maltman, M. Müller-Preussker, L. von Smekal, PoS LATTICE2012 (2012) 243.

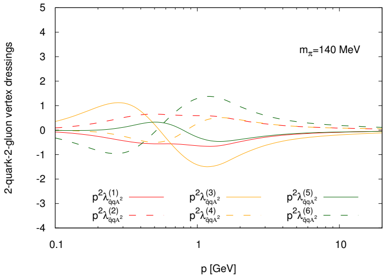
More correlators

[Cyrol, MM, Pawlowski, Strodthoff, 2017]







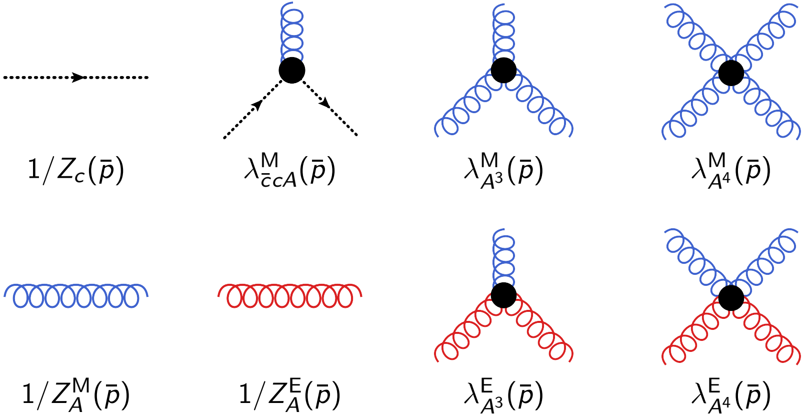


Pure $SU(N)$ YM-theory at $T > 0$

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

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

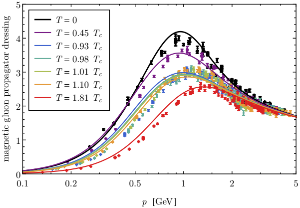
Truncation (blue: magnetic (transverse) leg, red: electric (longitudinal) leg):



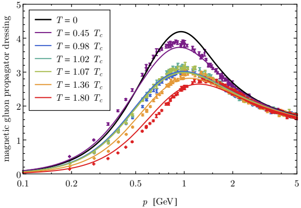
YM Propagators at $T \neq 0$

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

Zeroth mode correlation functions



$SU(2)$



$SU(3)$

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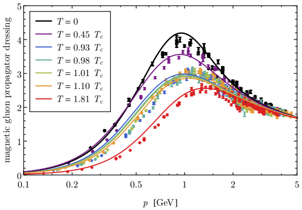
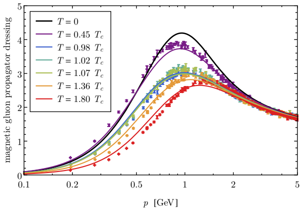
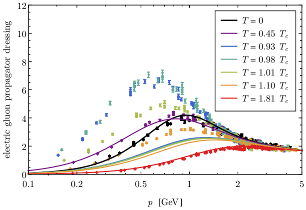
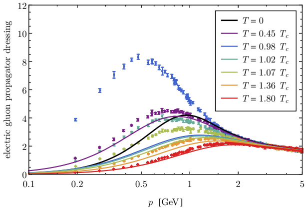




$SU(2)$ $SU(3)$



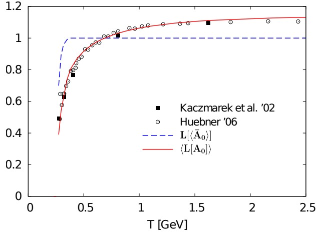


lattice data: A. Maas, J. M. Pawlowski, L. von Smekal, D. Spielmann, Phys.Rev. D85 (2012) 034037. ($SU(2)$)

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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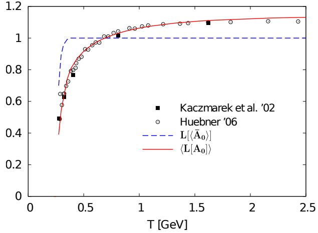
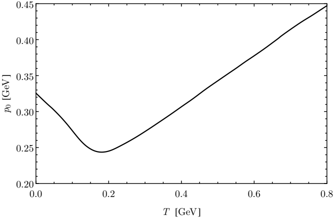
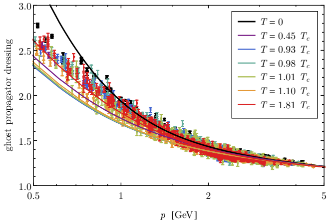
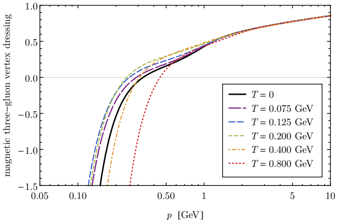


magnetic zero crossing in 3g-vertex







Status and Outlook

- QCD/YM-theory from $\alpha_S(\Lambda = \mathcal{O}(10)\ \text{GeV})$ and $m_q(\Lambda = \mathcal{O}(10)\ \text{GeV})$ with FRG
- in general very good agreement with lattice correlators
- at the stage of improving quantitative reliability
- need BRST-consistency: at least two ways out
- long-term goal: QCD @ $T, \mu > 0$
  - equation of state
  - fluctuations of conserved charges
  - order parameters
- further applications:
  - input for "QCD-enhanced" models
  - direct calculation of low-energy constants cf. talk Eser
  - other strongly-interacting theories
  - ...