

Chiral symmetry breaking in continuum QCD

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Gießen, February 10, 2016



fQCD collaboration - QCD (phase diagram) with FRG:

J. Braun, A. K. Cyrol, L. Fister, W. J. Fu, T. K. Herbst, MM

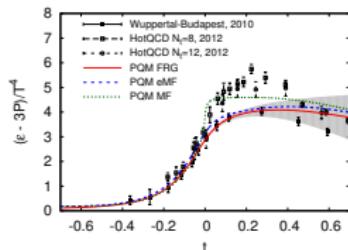
N. Müller, J. M. Pawłowski, S. Rechenberger, F. Rennecke, N. Strodthoff

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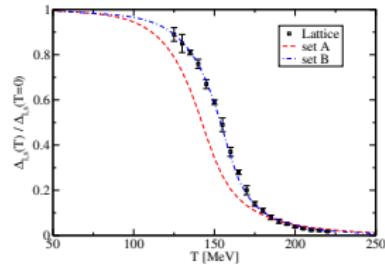
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- 5 Phenomenological Application: η' -meson mass at chiral crossover
- 6 Conclusion

QCD phase diagram with functional methods

- works well at $\mu = 0$: agreement with lattice



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

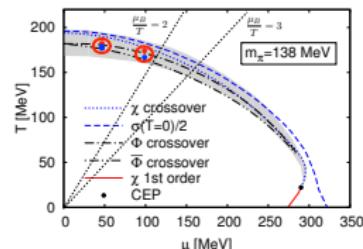


[Luecker, Fischer, Welzbacher, 2014]

[Luecker, Fischer, Fister, Pawłowski, '13]

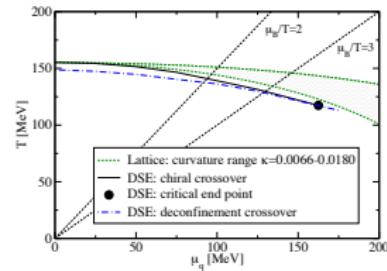
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- different results at large μ
(possibly already at small μ)



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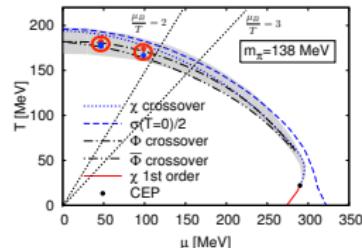
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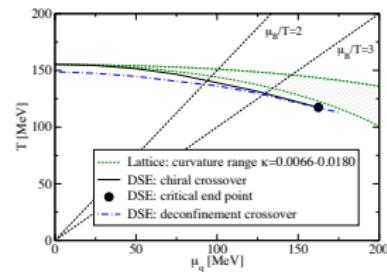
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- calculations need model input:
 - ▶ Polyakov-quark-meson model with FRG:
 - ★ initial values at $\Lambda \approx \mathcal{O}(\Lambda_{\text{QCD}})$
 - ★ input for Polyakov loop potential
 - ▶ quark propagator DSE:
 - ★ IR quark-gluon vertex



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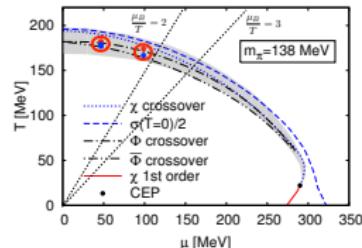
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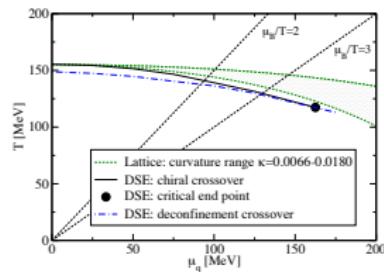
possible explanation for disagreement:

- $\mu \neq 0$: relative importance of diagrams changes
 \Rightarrow summed contributions vs. individual contributions



[Herbst, Pawlowski, Schaefer, 2013]

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Back to QCD in the vacuum (Wetterich equation)

- use only perturbative QCD input
 - ▶ $\alpha_s(\Lambda = \mathcal{O}(10) \text{ GeV})$
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- Wetterich equation with initial condition $S[\Phi] = \Gamma_\Lambda[\Phi]$

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

The equation shows the Wetterich equation for the effective action Γ_k . The left side is $\partial_k \Gamma_k[A, \bar{c}, c, \bar{q}, q]$, where A represents the gauge field, and \bar{c}, c, \bar{q}, q represent quark and antiquark fields. The right side is $\frac{1}{2}$ minus two terms. The first term is represented by a circle with a cross inside, with a wavy line (loop) attached to its top-left edge. The second term is represented by a circle with a cross inside, with a dotted line (loop) attached to its bottom-left edge. Both circles have arrows indicating a clockwise direction.

$$\Rightarrow \text{effective action } \Gamma[\Phi] = \lim_{k \rightarrow 0} \Gamma_k[\Phi]$$

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The equation shows the Wetterich equation for the effective action Γ_k . It is equal to half the difference between two Feynman diagrams. Diagram 1 consists of a circle with a wavy boundary and a cross inside. Diagram 2 consists of a dotted circle with a cross inside.

$$\Rightarrow \text{effective action } \Gamma[\Phi] = \lim_{k \rightarrow 0} \Gamma_k[\Phi]$$

- ∂_k : integration of momentum shells controlled by regulator
- full field-dependent equation with $(\Gamma^{(2)}[\Phi])^{-1}$ on rhs
- gauge-fixed approach (Landau gauge): ghosts appear

Vertex Expansion

- approximation necessary - vertex expansion

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

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- functional derivatives with respect to $\Phi_i = A, \bar{c}, c, \bar{q}, q$:
⇒ equations for 1PI n -point functions, e.g. gluon propagator:

$$\partial_t \text{ (gluon loop)}^{-1} = \text{ (gluon loop with insertion)} - 2 \text{ (gluon loop with insertion)} + \frac{1}{2} \text{ (gluon loop with insertion)}$$

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- want “apparent convergence” of $\Gamma[\Phi] = \lim_{k \rightarrow 0} \Gamma_k[\Phi]$

“Quenched” Landau gauge QCD

- two crucial phenomena: $S\chi$ SB and confinement
- similar scales - hard to disentangle
- quenched QCD: allows separate investigation:

see e.g. [Williams, Fischer, Heupel, 2015]

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- quenched QCD: allows separate investigation:
- matter part [MM, Strodthoff, Pawłowski, 2014]
(with FRG-YM propagators from [Fischer, Maas, Pawłowski, 2009], [Fister, Pawłowski, unpublished])
- recent results for YM propagators [Cyrol, Fister, MM, Pawłowski, Strodthoff, to be published]

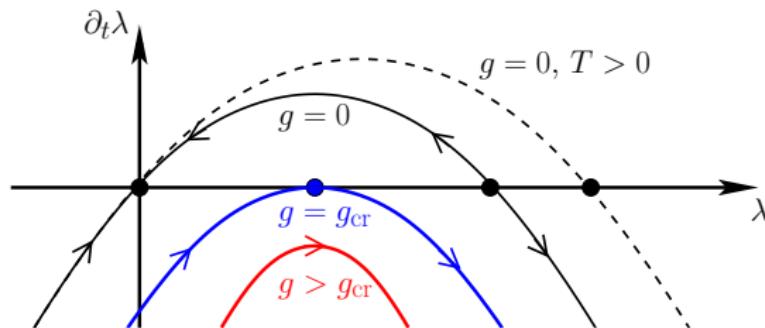
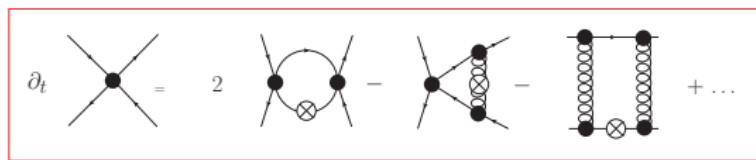
Chiral symmetry breaking

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

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- resonance \Rightarrow singularity without momentum dependency

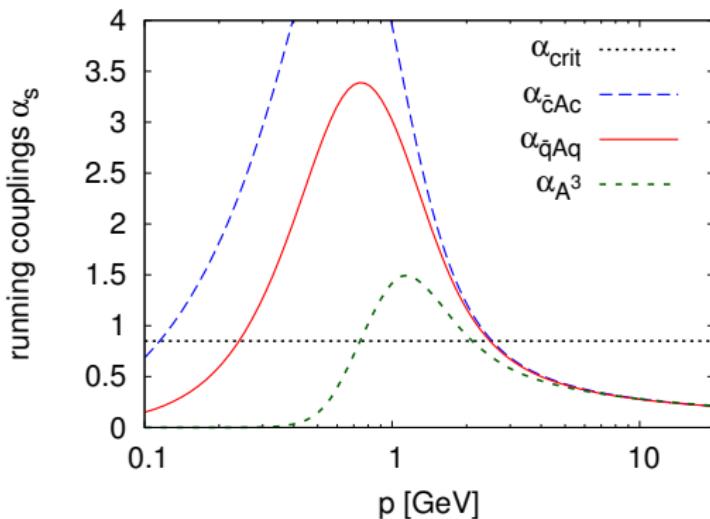
$$\partial_t \lambda = a \lambda^2 + b \lambda \alpha + c \alpha^2, \quad b > 0, \quad a, c \leq 0$$



[Braun, 2011]

Effective running couplings

[MM, Pawlowski, Strodthoff, 2014]



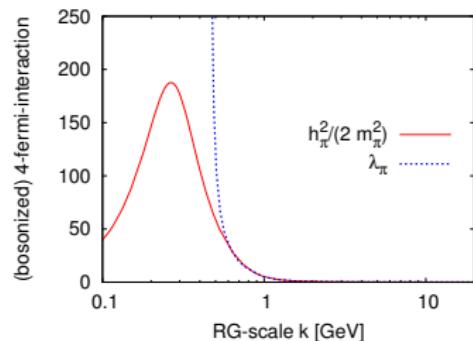
- agreement in perturbative regime required by gauge symmetry
- non-degenerate in nonperturbative regime: reflects gluon mass gap
- $\alpha_{\bar{q}A q} > \alpha_{\text{cr}}$: necessary for chiral symmetry breaking
- area above α_{cr} very sensitive to errors

4-Fermi vertex via dynamical hadronization

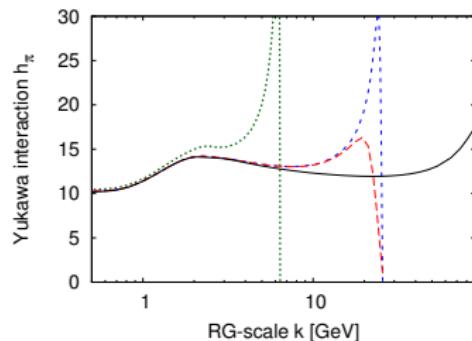
[Gies, Wetterich, 2002]

- change of variables: particular 4-Fermi channels \rightarrow meson exchange
- efficient inclusion of momentum dependence \Rightarrow no singularities
- identifies relevant effective low-energy dofs from QCD

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



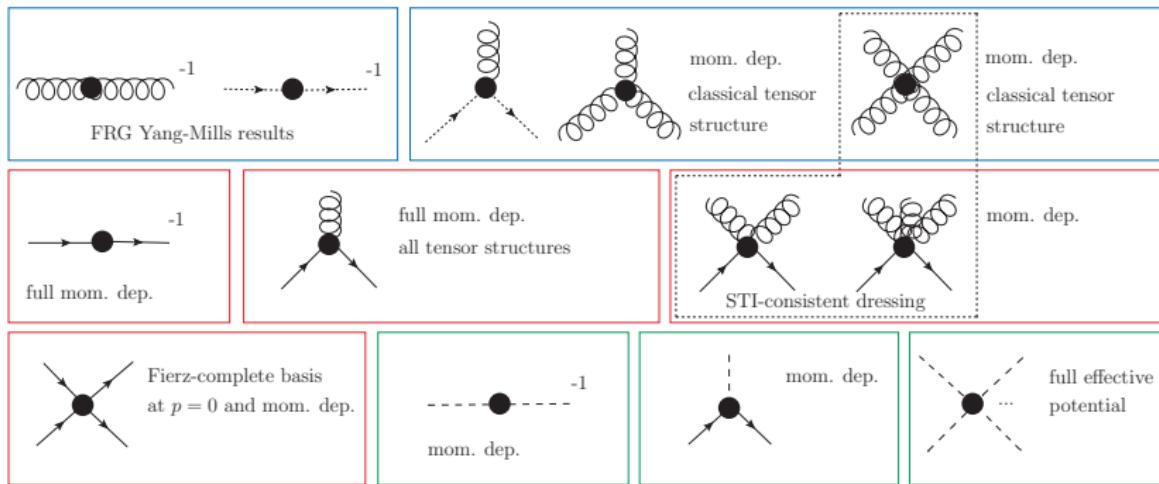
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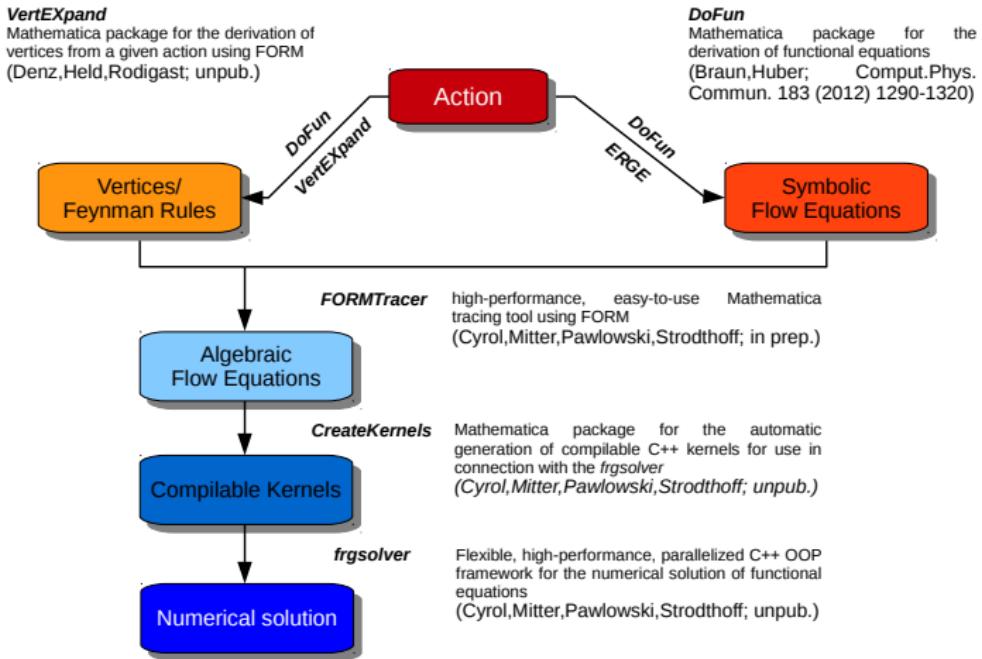
[Braun, Fister, Haas, Pawlowski, Rennecke, 2014]

[MM, Strodthoff, Pawlowski, 2014]

Vertex Expansion in the matter system



Derivation of equations



[Cyrol, MM, Pawlowski, Strodthoff, 2013-2016]

Equations in the matter system

[MM, Strodthoff, Pawłowski, 2014]

$$\partial_t \text{---}^{-1} = \begin{array}{c} \text{Diagram 1} \\ + \end{array} \begin{array}{c} \text{Diagram 2} \\ + \frac{1}{2} \end{array} \begin{array}{c} \text{Diagram 3} \\ - \end{array}$$
$$+ \begin{array}{c} \text{Diagram 4} \\ + \end{array} \begin{array}{c} \text{Diagram 5} \\ - \end{array} \begin{array}{c} \text{Diagram 6} \\ - \end{array}$$

$$\partial_t \text{---} = \begin{array}{c} \text{Diagram 1} \\ - \end{array} \begin{array}{c} \text{Diagram 2} \\ - \end{array} \begin{array}{c} \text{Diagram 3} \\ - \end{array} \begin{array}{c} \text{Diagram 4} \\ - \end{array} \begin{array}{c} \text{Diagram 5} \\ - \frac{1}{2} \end{array} \begin{array}{c} \text{Diagram 6} \\ d \end{array}$$
$$+ 2 \begin{array}{c} \text{Diagram 7} \\ - \end{array} \begin{array}{c} \text{Diagram 8} \\ + \text{perm.} \end{array}$$

$$\partial_t \text{---} = \begin{array}{c} \text{Diagram 1} \\ - 2 \end{array} \begin{array}{c} \text{Diagram 2} \\ - \end{array} \begin{array}{c} \text{Diagram 3} \\ - \end{array} \begin{array}{c} \text{Diagram 4} \\ - \end{array} \begin{array}{c} \text{Diagram 5} \\ - \end{array} \begin{array}{c} \text{Diagram 6} \\ - \end{array}$$
$$- \begin{array}{c} \text{Diagram 7} \\ - \end{array} \begin{array}{c} \text{Diagram 8} \\ - \end{array} \begin{array}{c} \text{Diagram 9} \\ + \text{perm.} \end{array}$$

Equations in the matter system

[MM, Strodthoff, Pawłowski, 2014]

$$\partial_t \text{ (coil)} = - \text{ (triangle)} + 2 \text{ (dashed triangle)} - \text{ (coil triangle)} + \text{ perm.}$$

$$\partial_t \text{ (coil)}^{-1} = \text{ (coil arc)} + \text{ (dashed arc)} + \frac{1}{2} \text{ (coil loop)} + \text{ (dashed loop)} + \text{ (coil circle)} - \text{ (dashed circle)}$$

$$\partial_t \text{ (coil)} = - \text{ (triangle)} - \text{ (coil triangle)} + \text{ perm.}$$

$$\begin{aligned} \partial_t \text{ (coil)} &= - \text{ (triangle)} - \text{ (coil triangle)} - \text{ (dashed triangle)} - \text{ (coil loop)} - \text{ (dashed loop)} - \frac{1}{2} \text{ (coil circle)} \\ &+ 2 \text{ (dashed circle)} - \text{ (coil circle)} + \text{ perm.} \end{aligned}$$

$$\begin{aligned} \partial_t \text{ (cross)} &- 2 \text{ (coil cross)} - \text{ (dashed cross)} - \text{ (coil cross)} - \text{ (dashed cross)} - \text{ (coil cross)} - \text{ (dashed cross)} \\ &- \text{ (coil cross)} - \text{ (dashed cross)} - \text{ (coil cross)} - \text{ (dashed cross)} + \text{ perm.} \end{aligned}$$

Equations in the matter system

[MM, Strodthoff, Pawłowski, 2014]

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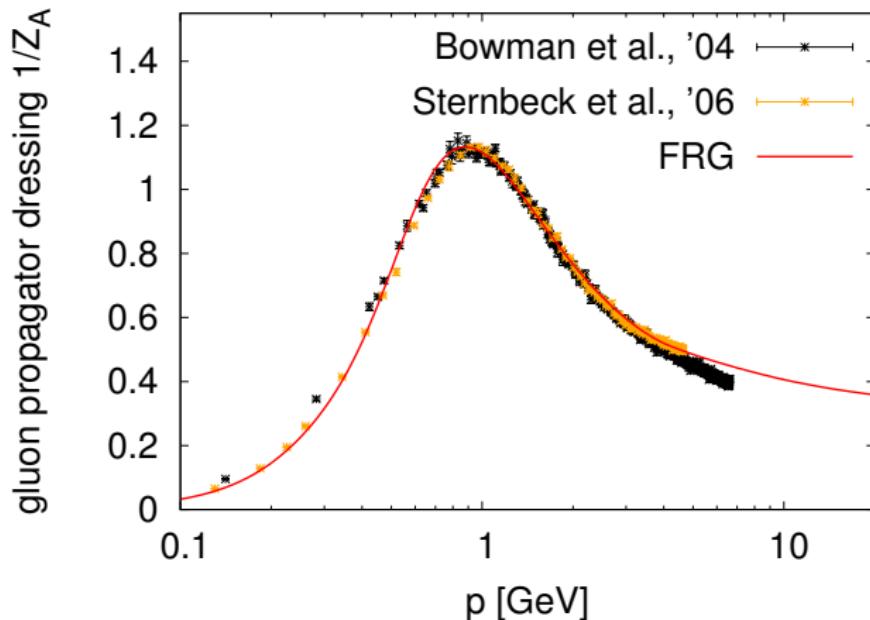
$$\partial_t \text{ (diagram)}^{-1} = -2 \text{ (diagram)} + \text{ (diagram)} + \frac{1}{2} \text{ (diagram)}$$

$$\partial_t \text{ (diagram)} = - \text{ (diagram)} - \text{ (diagram)} - \text{ (diagram)} + 2 \text{ (diagram)} + \text{ perm.}$$

Gluon FRG input

[Fischer, Maas, Pawłowski, 2009], [Fister, Pawłowski, unpublished]

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

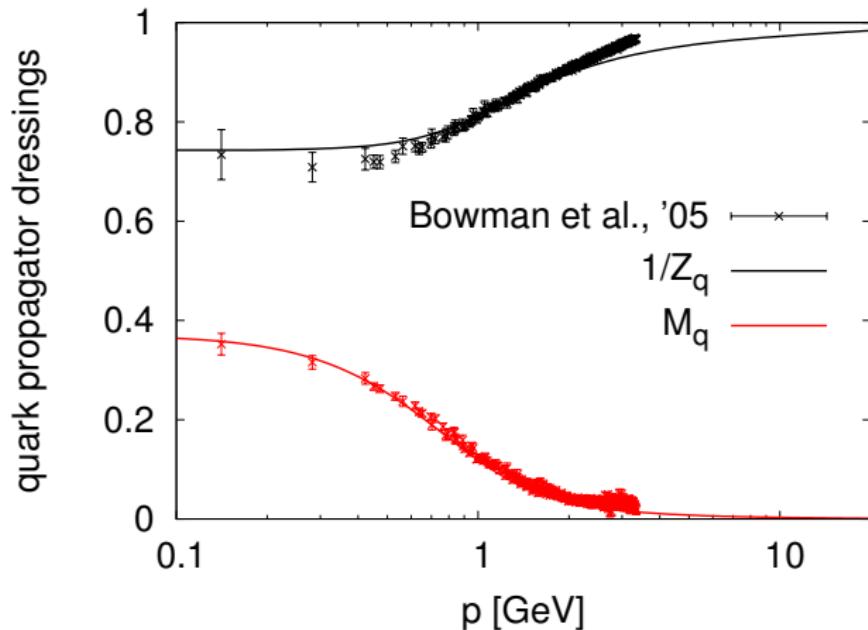


- FRG result \Rightarrow self-consistent calculation within FRG approach
- sets the scale in comparison to lattice QCD

Quark propagator

[MM, Pawłowski, Strodthoff, 2014]

- $\Gamma_{\bar{q}q}^{(2)}(p) \propto Z_q(p) \not{p} + M(p)$

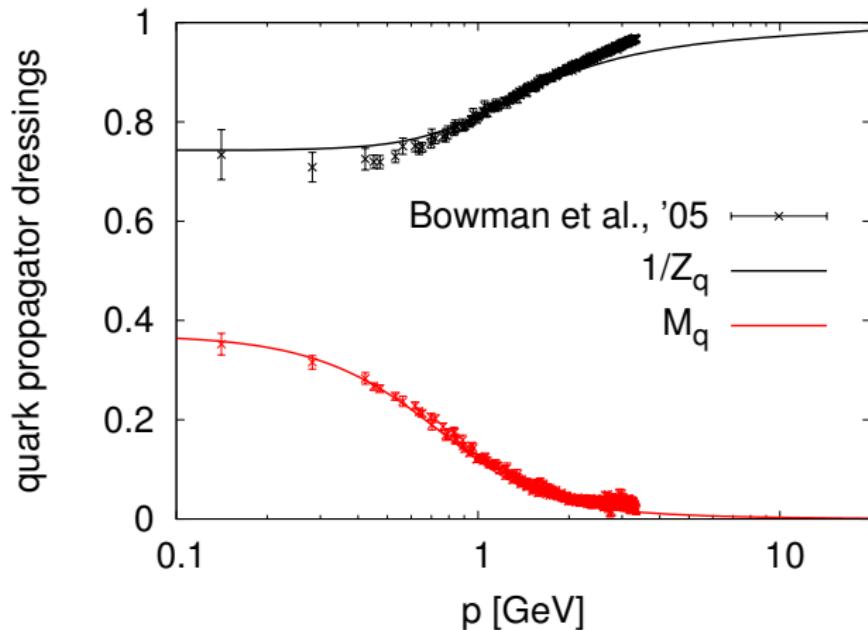


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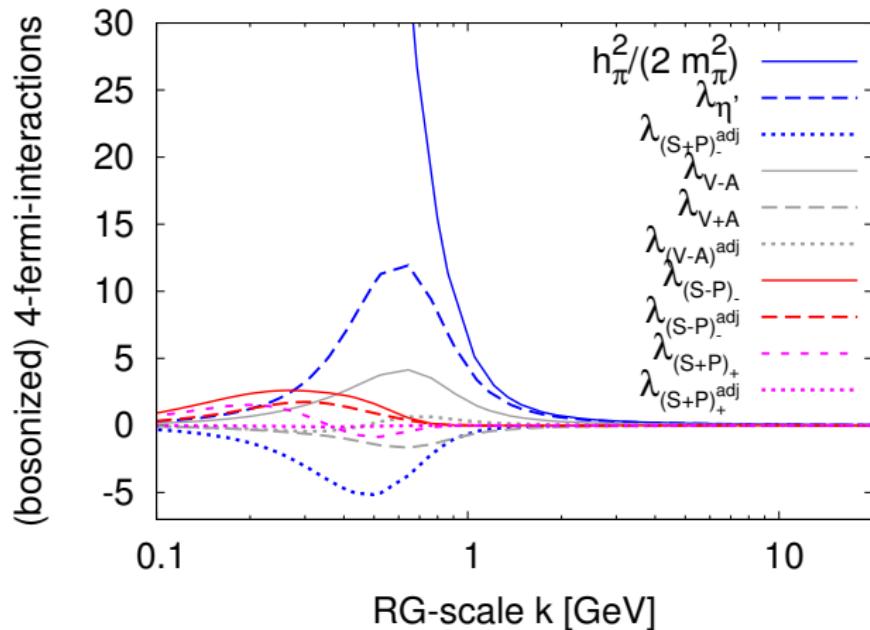
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- FRG vs. lattice: bare mass, quenched, scale
- agreement not sufficient: need apparent convergence at $\mu \neq 0$

other 4-Fermi channels (mesons)

[MM, Pawłowski, Strodthoff, 2014]



- bosonized only σ - π -channel \Rightarrow sufficient diquark momentum configuration more important
- other channels: quantitatively not important in loops

Quark-gluon interactions I

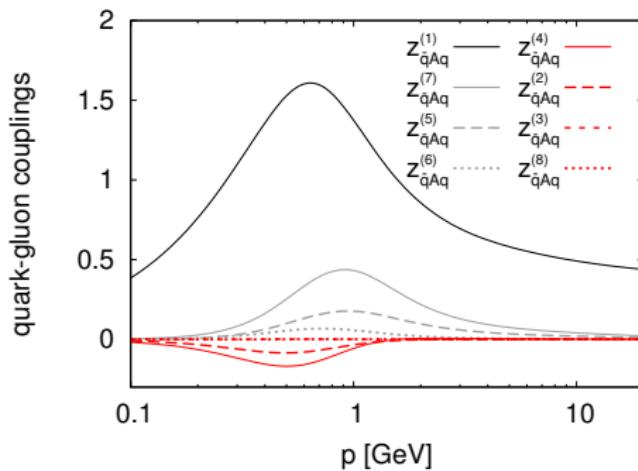
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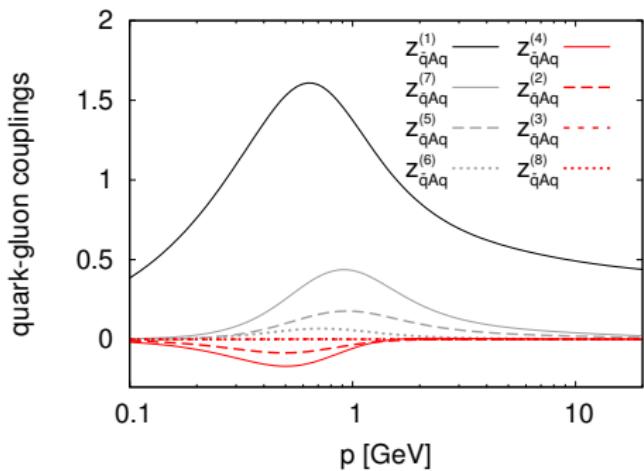


- vertex strength:
reflects gluon gap
- 8 tensors (transversally projected):
 - ▶ classical tensor
 - ▶ chirally symmetric
 - ▶ break chiral symmetry

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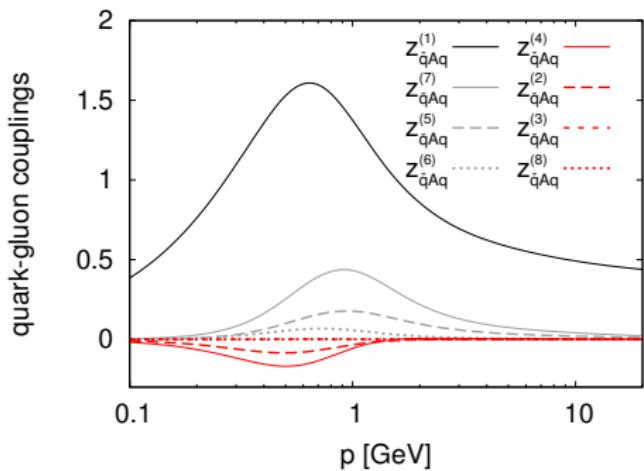
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- important non-classical tensors: c.f., [Hopfer et al., 2012], [Williams, 2014], [Aguilar et al., 2014]
 - ▶ $\bar{q}\gamma_5\gamma_\mu\epsilon_{\mu\nu\rho\sigma}\{F_{\nu\rho}, D_\sigma\}q$ ($\frac{1}{2}\mathcal{T}_{\bar{q}Aq}^{(5)} + \mathcal{T}_{\bar{q}Aq}^{(7)}$): increases Z_q /decreases M_q considerably
 - ▶ anom. chromomagn. momentum ($\mathcal{T}_{\bar{q}Aq}^{(4)}$) increases M_q moderately

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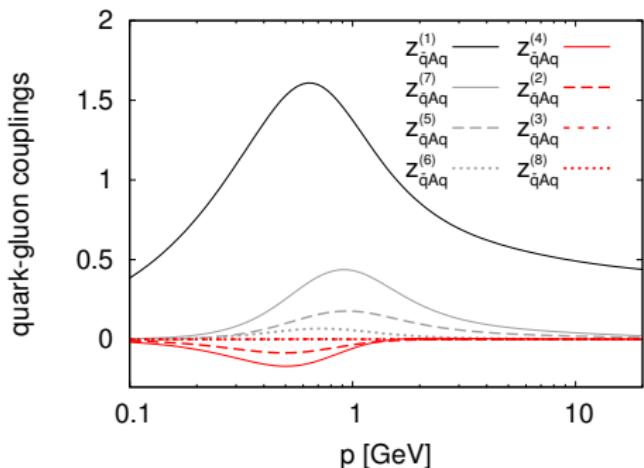
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- ⇒ considerably less chiral symmetry breaking with full tensor basis
- also important ingredient for bound-state equations

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in particular $\bar{q} \gamma_5 \gamma_\mu \epsilon_{\mu\nu\rho\sigma} \{F_{\nu\rho}, D_\sigma\} q$:

- ▶ contributes to $\bar{q} A q$, $\bar{q} A^2 q$ and $\bar{q} A^3 q$
- ▶ contains important non-classical tensors ($\bar{q} A q$)
- ▶ considerable contribution to quark-gluon vertex ($\bar{q} A^2 q$)
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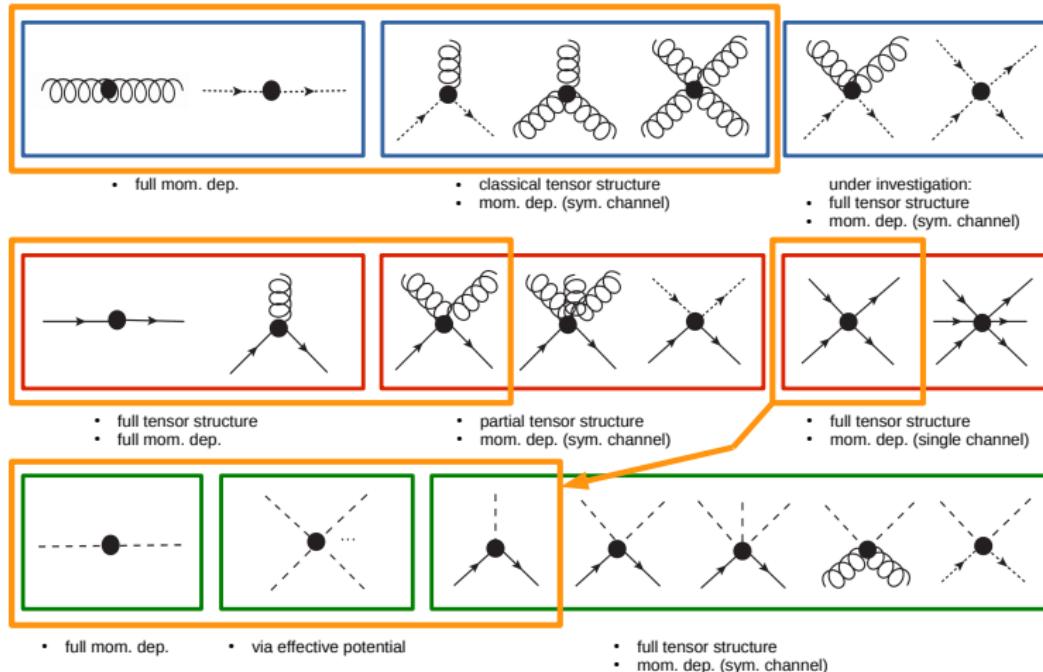
- explicit calculations of $AA\bar{q}q$ -vertex:

[MM, Pawłowski, Strodthoff, in prep.]

- ▶ full basis: 63 chirally symmetric tensor elements
- ▶ 15 chirally symmetric tensor elements ($\bar{\psi} \not{D}^3 \psi$):
 - ★ all seem important
 - ★ order of effect similar to $\bar{q} \gamma_5 \gamma_\mu \epsilon_{\mu\nu\rho\sigma} \{F_{\nu\rho}, D_\sigma\} q$
 - ★ why? underlying principle?

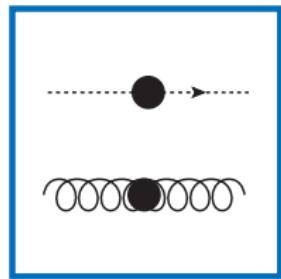
Stability of truncation (apparent convergence)

Expansion of effective action in 1PI correlators

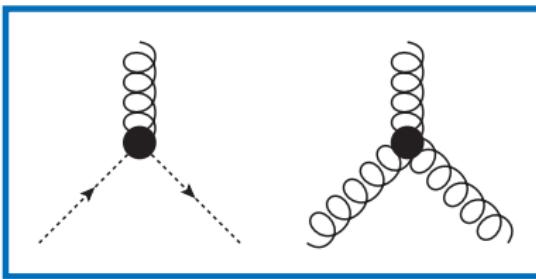


Vertex Expansion in YM theory

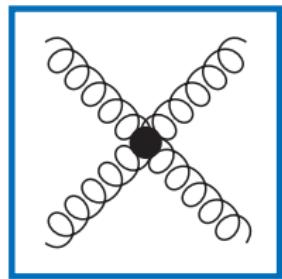
[Cyrol, Fister, MM, Strodthoff, Pawłowski, to be published]



full. mom. dep.



full. mom. dep.



sym. point and
tadpole config.

Equations in YM theory

[Cyrol, Fister, MM, Strodthoff, Pawlowski, to be published]

$$\partial_t \cdots \cdots^{-1} = \cdots \circlearrowleft \otimes \circlearrowright \cdots + \cdots \circlearrowleft \otimes \circlearrowright \cdots$$

$$\partial_t \cdots \cdots^{-1} = \cdots \circlearrowleft \otimes \circlearrowright \cdots - 2 \cdots \circlearrowleft \otimes \circlearrowright \cdots + \frac{1}{2} \cdots$$

$$\partial_t \cdots \cdots = - \cdots \circlearrowleft \otimes \circlearrowright \cdots - \cdots \circlearrowleft \otimes \circlearrowright \cdots + \text{perm.}$$

$$\partial_t \cdots \cdots = - \cdots \circlearrowleft \otimes \circlearrowright \cdots + 2 \cdots \circlearrowleft \otimes \circlearrowright \cdots - \cdots \circlearrowleft \otimes \circlearrowright \cdots + \text{perm.}$$

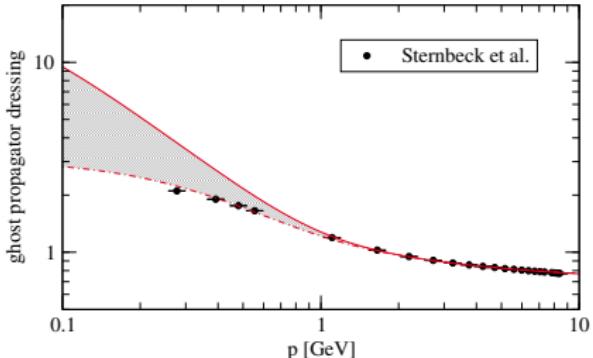
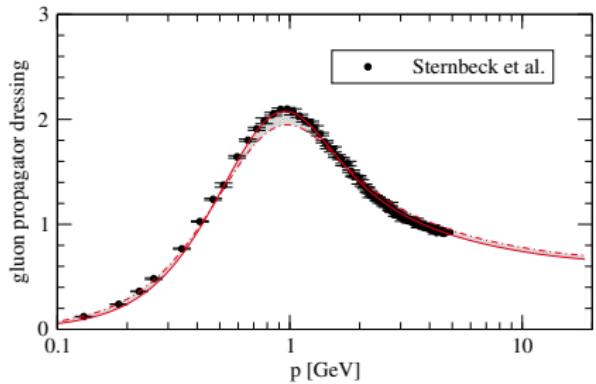
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YM propagators

[Cyrol, Fister, MM, Pawłowski, Strodthoff, to be published]

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

- $\Gamma_{\bar{c}c}^{(2)}(p) \propto Z_c(p) p^2$

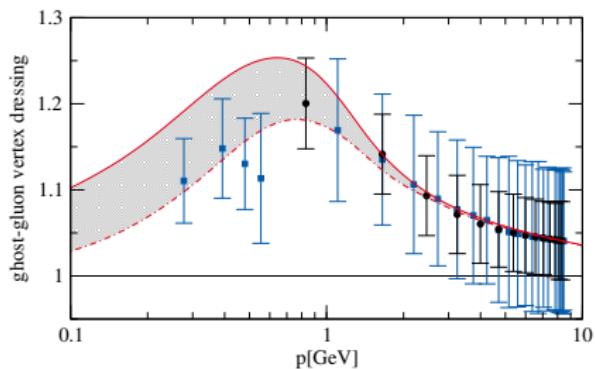


- band: family of decoupling solutions bounded by scaling solution

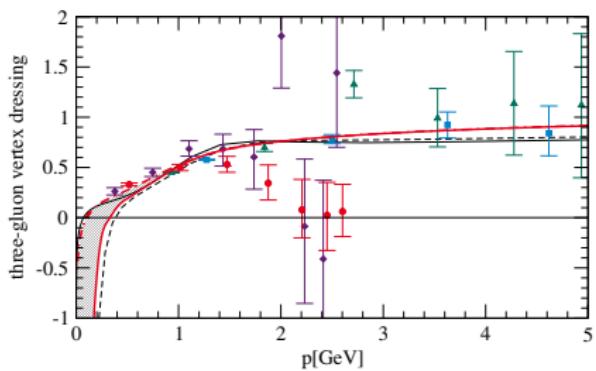
YM vertices I

[Cyrol, Fister, MM, Pawłowski, Strodthoff, to be published]

- comparison to Sternbeck '06



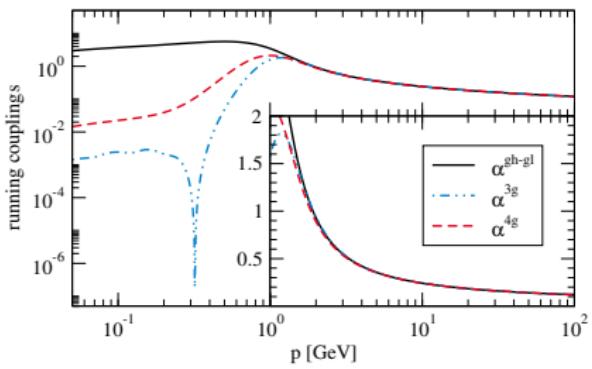
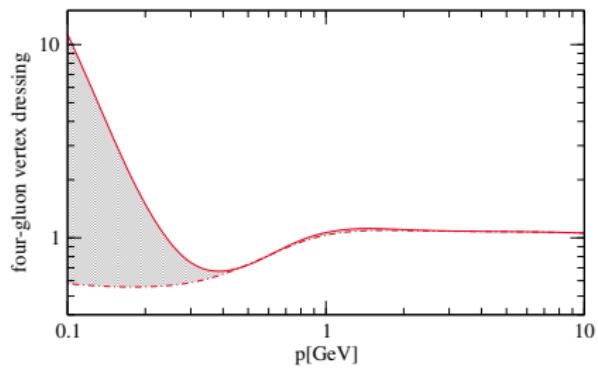
- comparison to Cucchieri, Maas, Mendes, '08
Blum, Huber, MM, von Smekal '14



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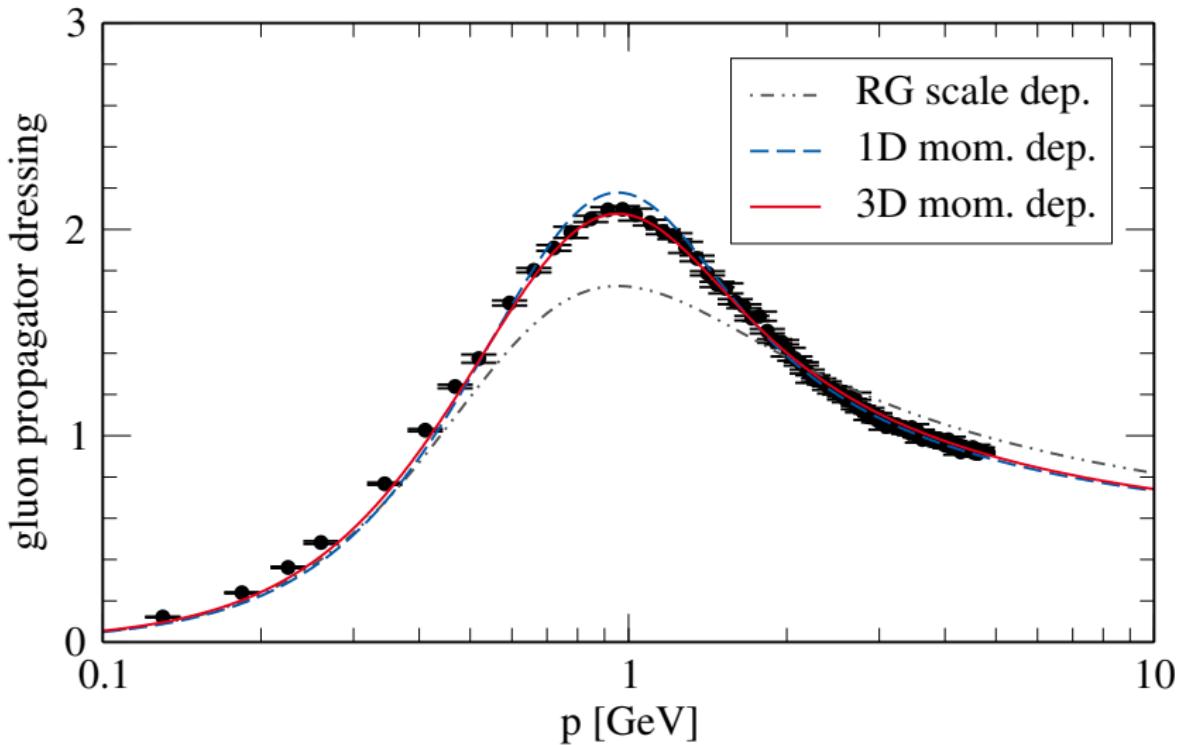
YM vertices II

[Cyrol, Fister, MM, Pawłowski, Strodthoff, to be published]

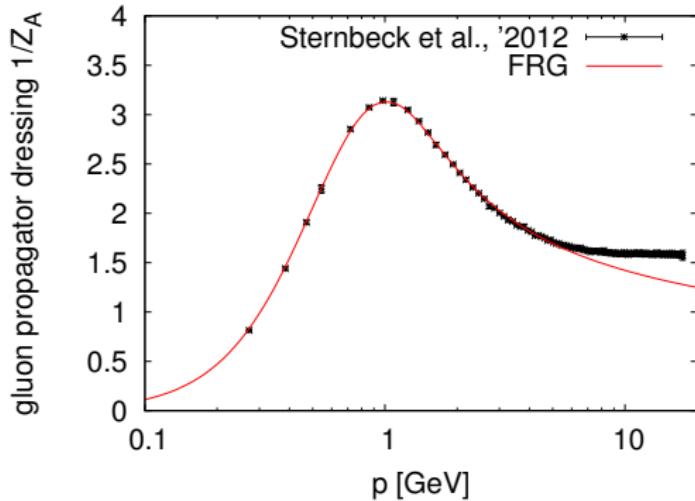


Apparent Convergence

[Cyrol, Fister, MM, Pawlowski, Strodthoff, to be published]



Outlook: unquenched gluon propagator



- self-consistent solution of classical propagators and vertices (1D)
- massless quarks

[Cyrol, MM, Pawłowski, Strodthoff, in preparation]

η' -meson (screening) mass at chiral crossover

- small η' -meson mass above chiral crossover?

[Kapusta, Kharzeev, McLerran, 1998]

- drop in η' mass at chiral crossover?

[Csörgo et al., 2010]

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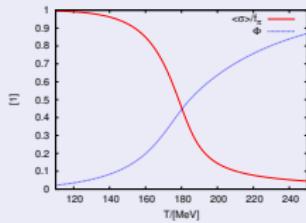
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chiral crossover: Polyakov-Quark-Meson model (extended mean-field)



- $N_f = 2$ quark and meson degrees of freedom
- describes chiral crossover
- (de-)confinement via Polyakov loop potential
- $U(1)_A$ -anomaly: mesonic 't Hooft determinant

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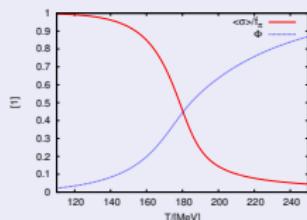
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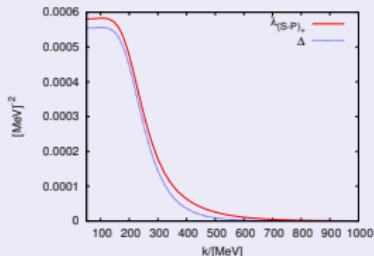
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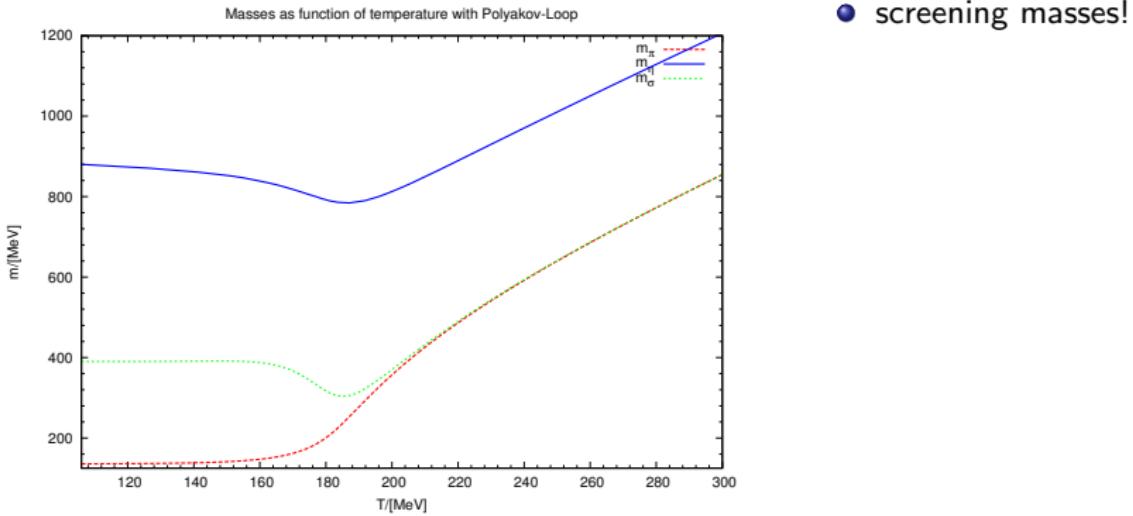
't Hooft determinant

[Heller, MM, 2015]



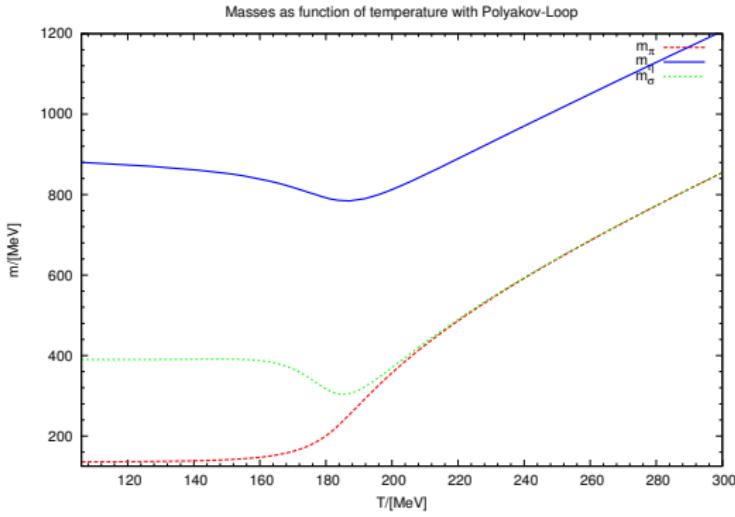
- RG-scale dependence from fQCD
- temperature dependence $k(T)$:
 - ▶ $\lambda_{(S-P)+,fQCD}(k) \equiv \lambda_{(S-P)+,PQM}(T)$

η' -meson (screening) mass at chiral crossover: result



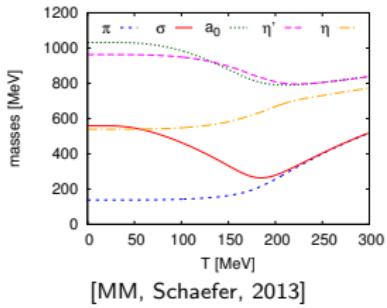
[Heller, MM, 2015]

η' -meson (screening) mass at chiral crossover: result



[Heller, MM, 2015]

- screening masses!
- QM-Model $N_f = 2 + 1$:



- chiral symmetry restoration:
⇒ drop in $m_{\eta'}$

Summary and Outlook

(quenched) QCD with functional RG

- QCD phase diagram: need for quantitative precision
- vacuum:
 - ▶ sole input $\alpha_S(\Lambda = \mathcal{O}(10) \text{ GeV})$ and $m_q(\Lambda = \mathcal{O}(10) \text{ GeV})$
 - ▶ good agreement with lattice simulations (sufficient?)
 - ▶ (non-perturbative) results:
 - ★ quark-propagator
 - ★ quark-gluon vertex
 - ★ 4-Fermi interaction channels
 - ★ YM-system
 - ▶ phenomenology: η' -meson and pion mass splitting

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- unquenching (first results)
- finite temperature/chemical potential
- more checks on convergence of vertex expansion
- bound-state properties (form factor, PDA...)