

# QCD and dynamical hadronization

(in the quenched limit)

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**FWF**

Der Wissenschaftsfonds.

GEFÖRDERT VOM



Bundesministerium  
für Bildung  
und Forschung

talk based on:

MM, J. Pawlowski, N. Strodthoff, in prep.

part of collaboration:

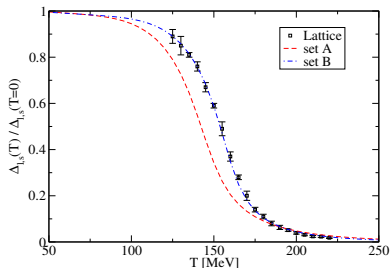
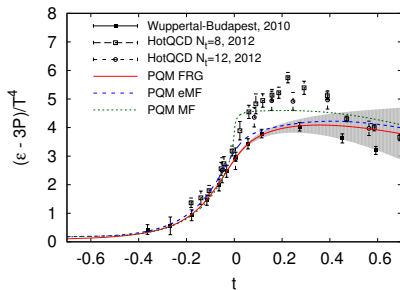
J. Braun, L. Fister, T. K. Herbst, MM

J. M. Pawlowski, F. Rennecke, N. Strodthoff

# Functional approaches to QCD at $T \neq 0$ , $\mu = 0$

- interaction measure
- 2 + 1 flavor Polyakov loop extended quark-meson model
- functional renormalization group

[Herbst, MM, Pawłowski, Schaefer, Stiele, 2013]

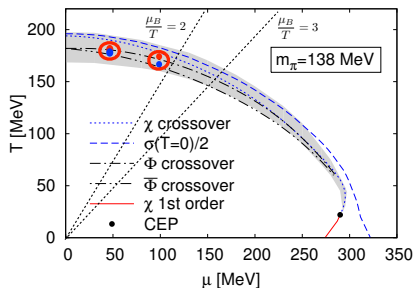


- chiral condensate
- 2 + 1 flavor quark propagator Dyson-Schwinger equation

[Luecker, Fischer, Welzbacher, 2014]

[Luecker, Fischer, Fister, Pawłowski, 2013]

# Functional appr. to QCD phase diagram

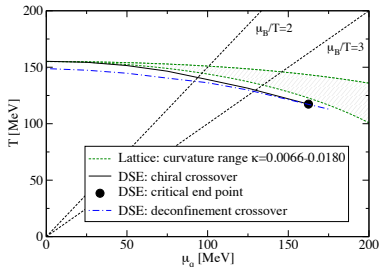


- 2-flavor Polyakov loop extended quark-meson model
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[Herbst, Pawłowski, Schaefer, 2013]

- 2(+1)-flavor quark propagator Dyson-Schwinger equation

[Luecker, Fischer, Fister, Pawłowski, 2013]



# Back to QCD in the vacuum

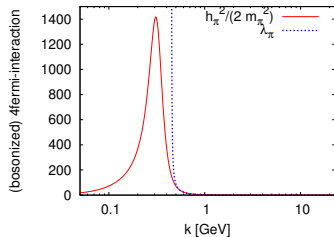
- shown results used model input:
  - ▶ quark-meson model:
    - ★ initial values at  $\Lambda \approx \mathcal{O}(\Lambda_{\text{QCD}})$
    - ★ deconfinement dynamics via Polyakov loop potential
  - ▶ quark propagator DSE:
    - ★ quark-gluon vertex
- $\mu \neq 0$ :
  - ▶ rel. scales of fluctuations [A. Helmboldt, J. Pawłowski, N. Strodthoff, 2014]
  - ▶ balance between different diagrams different from  $\mu = 0$

# Back to QCD in the vacuum

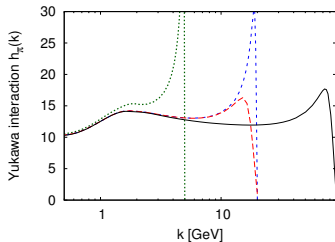
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  - ▶ balance between different diagrams different from  $\mu = 0$
- use only QCD input
  - ▶  $\alpha_S(\mathcal{O}(10) \text{ GeV})$
  - ▶  $m_q(\mathcal{O}(10) \text{ GeV})$
- keep simple low-energy effective description (quark-meson model)

input at perturbative  $k = \mathcal{O}(10)$  GeV:  $\alpha_S$  and  $m_q$  (via  $m_\pi$ )

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



[MM, Strodthoff, Pawlowski, in prep.]

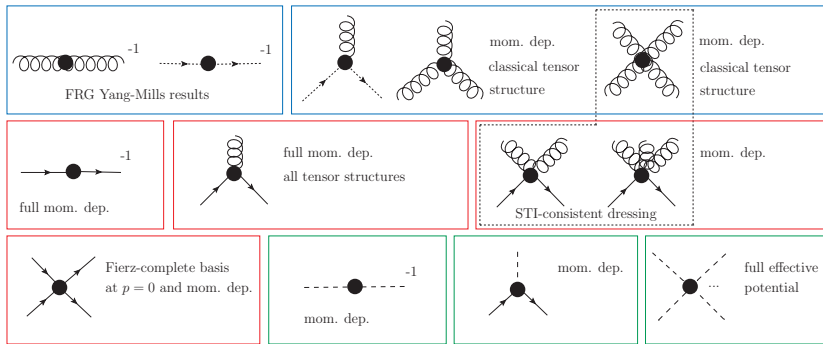


[Braun, Fister, Haas, Pawlowski, Rennecke, in prep.]

[MM, Strodthoff, Pawlowski, in prep.]

# Truncation

[MM, Strodthoff, Pawłowski, in prep.]



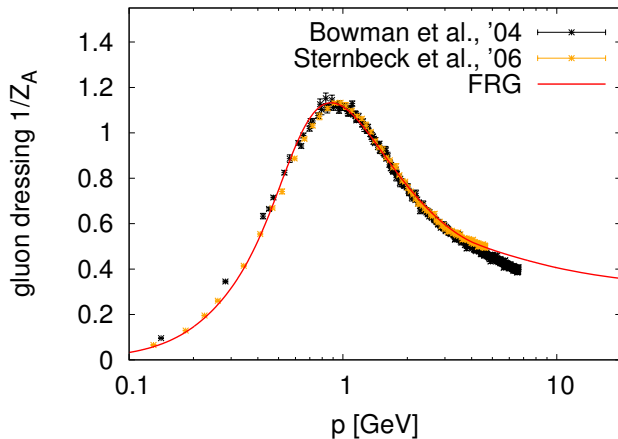
- derivatives of FRG equation: DoFun

[Braun, Huber, 2011]

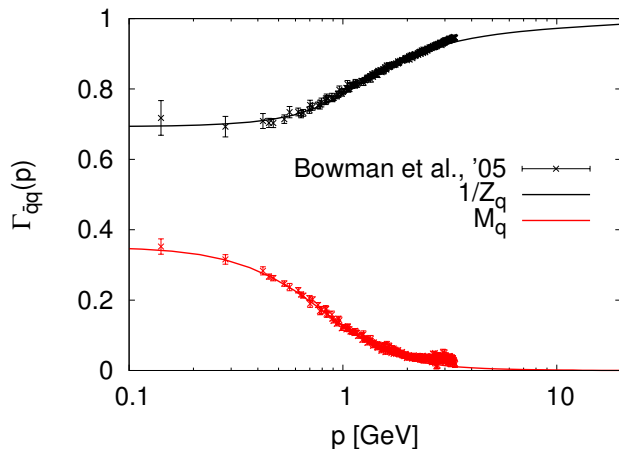
- RG-irrelevant operators created close to  $\Lambda_{QCD}$ :

systematic expansion scheme?

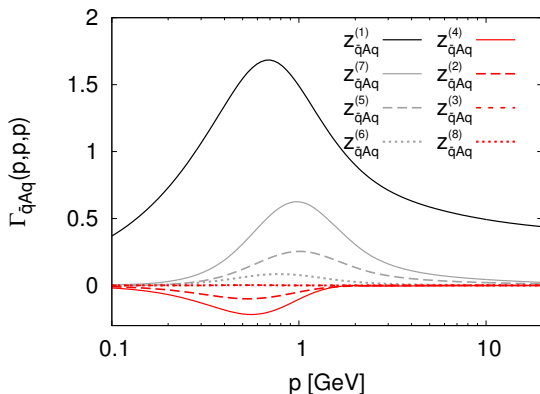




- FRG result  $\Rightarrow$  self-consistent calculation within FRG approach
- sets the scale in comparison to lattice QCD



- FRG bare mass vs. lattice bare mass
- FRG-quenched vs. lattice quenched
- FRG scale vs. lattice scale



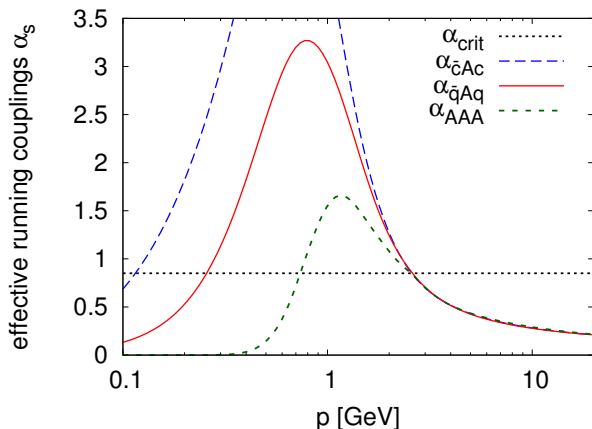
- tensor structures important for bound-state equations:

[Williams, 2014]

- ▶ black: classical structure
- ▶ grey: chirally symmetric
- ▶ red: break chiral symmetry

- single tensors break gauge invariance

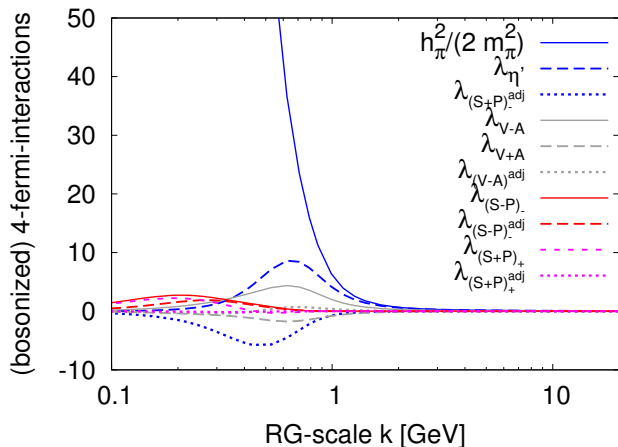
⇒ gauge-invariant completion: higher quark-gluon interactions



- effective running coupling: reflects gluon mass gap
- agreement in perturbative regime nontrivial result
- $\alpha_{CR}$ : critical coupling for chiral symmetry breaking

# Fierz complete basis for 4-Fermi interaction

- chiral symmetry breaking  $\Leftrightarrow$  resonance in 4-Fermi interaction(s)
- Fierz ambiguity resolved by complete basis:
  - ▶ 4 symmetric channels:  $(S-P)_+$ ,  $V$ ,  $AV$ ,  $(V-A)^{\text{adj}}$
  - ▶ 2  $SU(N_f)_A$ -breaking channels
  - ▶ 2  $U(1)_A$ -breaking channels:  $(S+P)_-^{(\text{adj})}$  ('t Hooft determinant(s))
  - ▶ 2  $U(N_f)_A$ -breaking channels
- resonance in one channel  
 $\Rightarrow$  singularities in other channels: missing momentum dependencies
- dynamical hadronization:
  - ▶ bosonize resonant channels
  - ▶ number?



- bosonized only  $\sigma$ - $\pi$ -channel  $\Rightarrow$  sufficient
- chiral symmetry breaking: considerable contribution to  $\eta'$ - $\vec{a}$ -channel

# Stability of truncation

- quark propagator and quark-gluon vertex: all relevant parts included
- approximations within included correlation functions:
  - ▶ field dependence of Yukawa interaction: 10% [Pawlowski, Rennecke, 2014]
  - ▶ momentum dependencies:
    - ★ LPA' in mesonic sector [Helmboldt, Pawlowski, Strodthoff, 2014]
    - ★ momentum dependence of rebosonization via 4-Fermi channel
    - ★ quark propagator in mesonic equations momentum independent
    - ★ single-channel momentum dependence in 4-Fermi interactions
    - ★ momentum dependence on symmetric point in YM-vertices
    - ★ non-classical tensors in YM-vertices
- effect of higher vertices:
  - ▶ fermionic 6- and 8-point functions: included (partially) via mesons
  - ▶ explicit calculation of higher quark-gluon vertices?
- $U(1)_A$ -anomaly: small in first checks [Pawlowski, 1996]
- glue sector:
  - ▶ fully couple momentum dependent YM-vertices with glue propagator

# Summary and Outlook

- get rid of model-dependence in FRG:  
(quenched) QCD with dynamical hadronization
- (too?) good agreement with lattice simulations
  - ▶ largest truncation with functional methods to date
- (non-perturbative) results:
  - ▶ quark-propagator
  - ▶ quark-gluon vertex
  - ▶ running couplings from different vertices
  - ▶ Fierz-complete basis for 4-Fermi channels



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- 
- unquenching
  - finite temperature/chemical potential
  - $U(1)_A$ -anomaly