QCD and dynamical hadronization

Mario Mitter

Ruprecht-Karls-Universität Heidelberg

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FWF
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GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

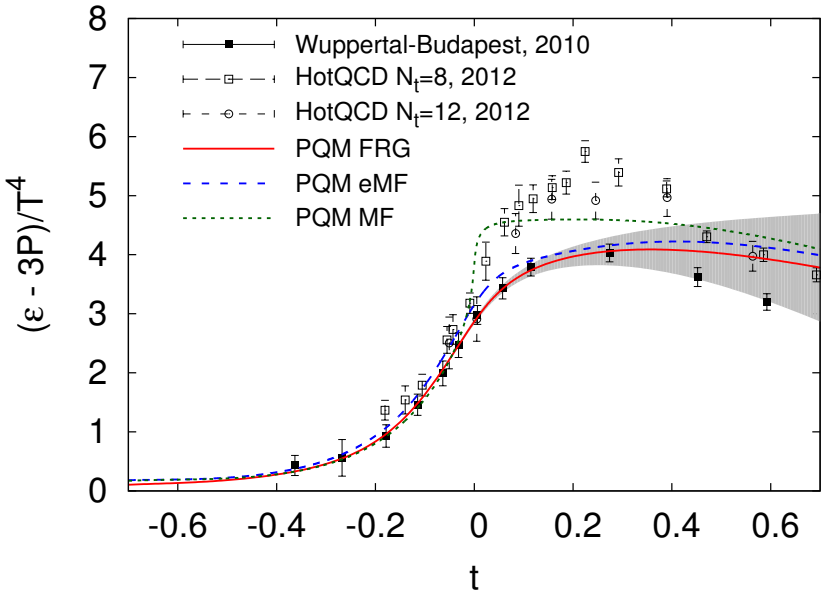
talk based on:
MM, J. Pawlowski, N. Strodthoff, in prep.

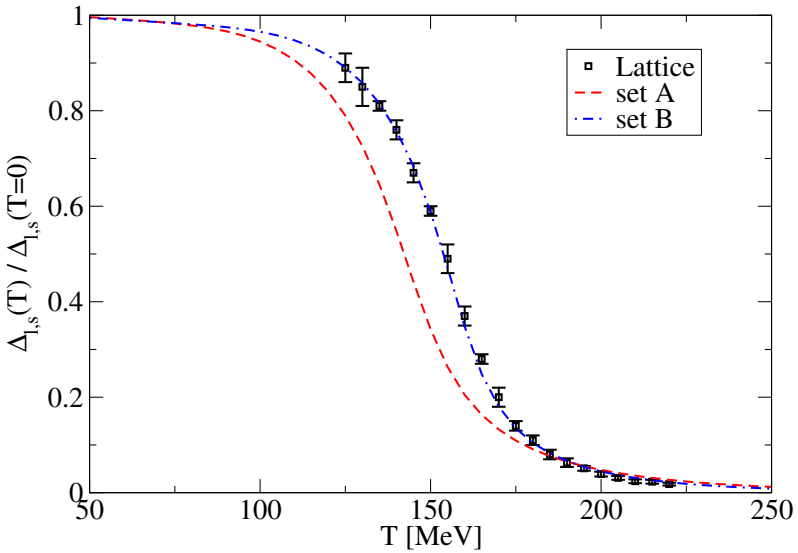
part of collaboration:
J. Braun, L. Fister, T. K. Herbst, MM
J. M. Pawlowski, F. Rennecke, N. Strodthoff

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, Pawlowski, Schaefer, Stiele, 2013]



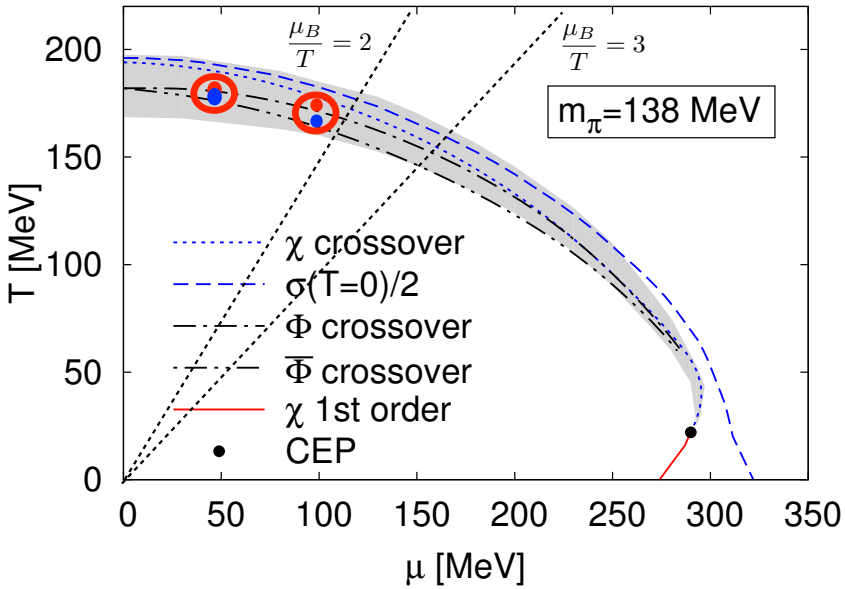


- chiral condensate
- $2+1$ flavor quark propagator Dyson-Schwinger equation

[Luecker, Fischer, Welzbacher, 2014]

[Luecker, Fischer, Fister, Pawlowski, 2013]

Functional appr. to QCD phase diagram (cf. talk *B.-J. Schaefer*)



- 2-flavor Polyakov loop extended quark-meson model
- functional renormalization group

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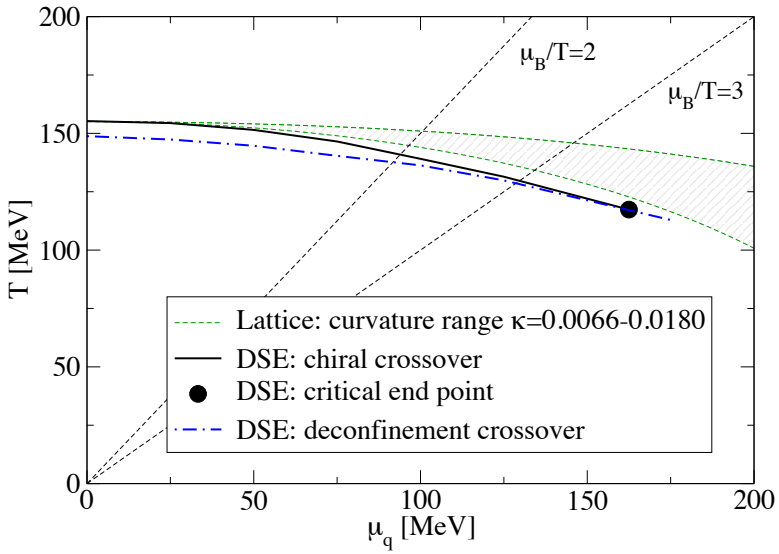
- 2(+1)-flavor quark propagator Dyson-Schwinger equation

[Luecker, Fischer, Fister, Pawlowski, 2013]



Back to QCD in the vacuum

- shown results used model input:
  - quark-meson model:
    - ★ inital values at $\Lambda \approx \mathcal{O}(\Lambda_{\mathrm{QCD}})$
    - ★ deconfinement dynamics via Polyakov loop potential
  - quark propagator DSE:
    - ★ quark-gluon vertex
- $\mu \neq 0$: relative scales of fluctuations

  cf. talk N. Strodthoff, [A. Helmboldt, J. Pawlowski, N. Strodthoff, in prep.]

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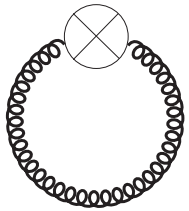
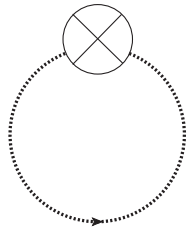
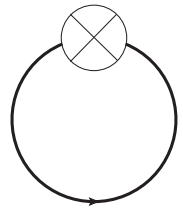
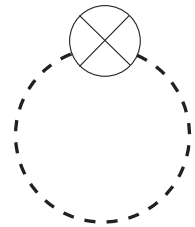
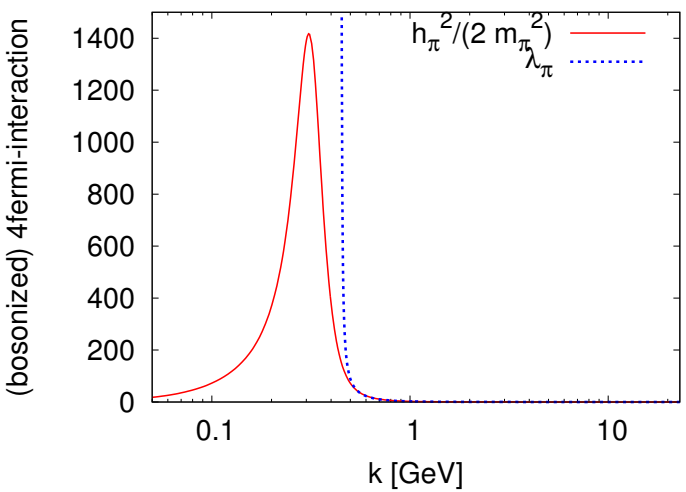
  cf. talk N. Strodthoff, [A. Helmboldt, J. Pawlowski, N. Strodthoff, in prep.]

- use only QCD input
  - $\alpha_S(\mathcal{O}(10)\ \mathrm{GeV})$
  - $m_q(\mathcal{O}(10)\ \mathrm{GeV})$
- keep simple low-energy effective description (quark-meson model)

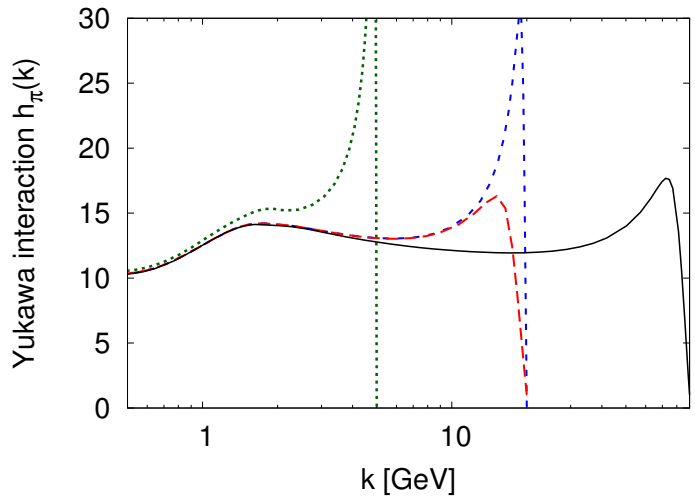
Dynamical hadronization (cf. talk *F. Rennecke*)

[Gies, Wetterich, 2002]

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



[MM, Strodthoff, Pawlowski, in prep.]

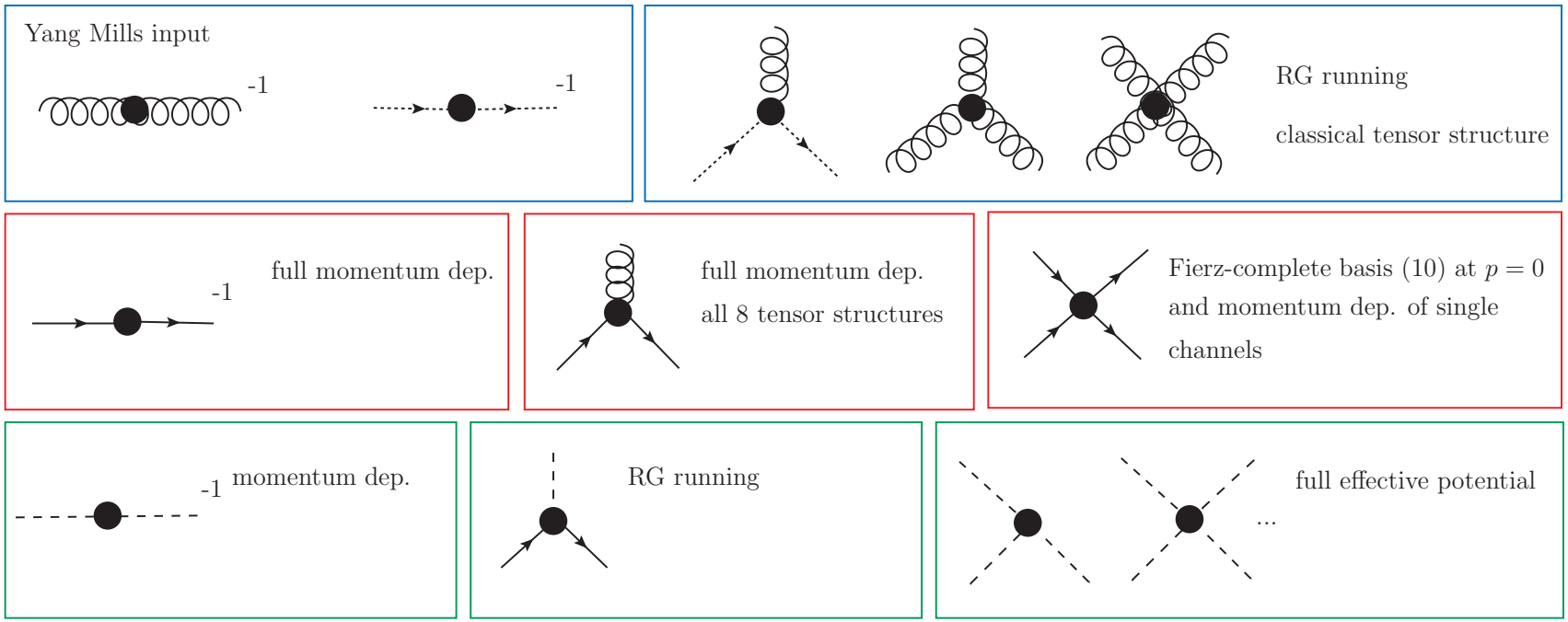


[Braun, Fister, Haas, Pawlowski, Rennecke, in prep.]

[MM, Strodthoff, Pawlowski, in prep.]

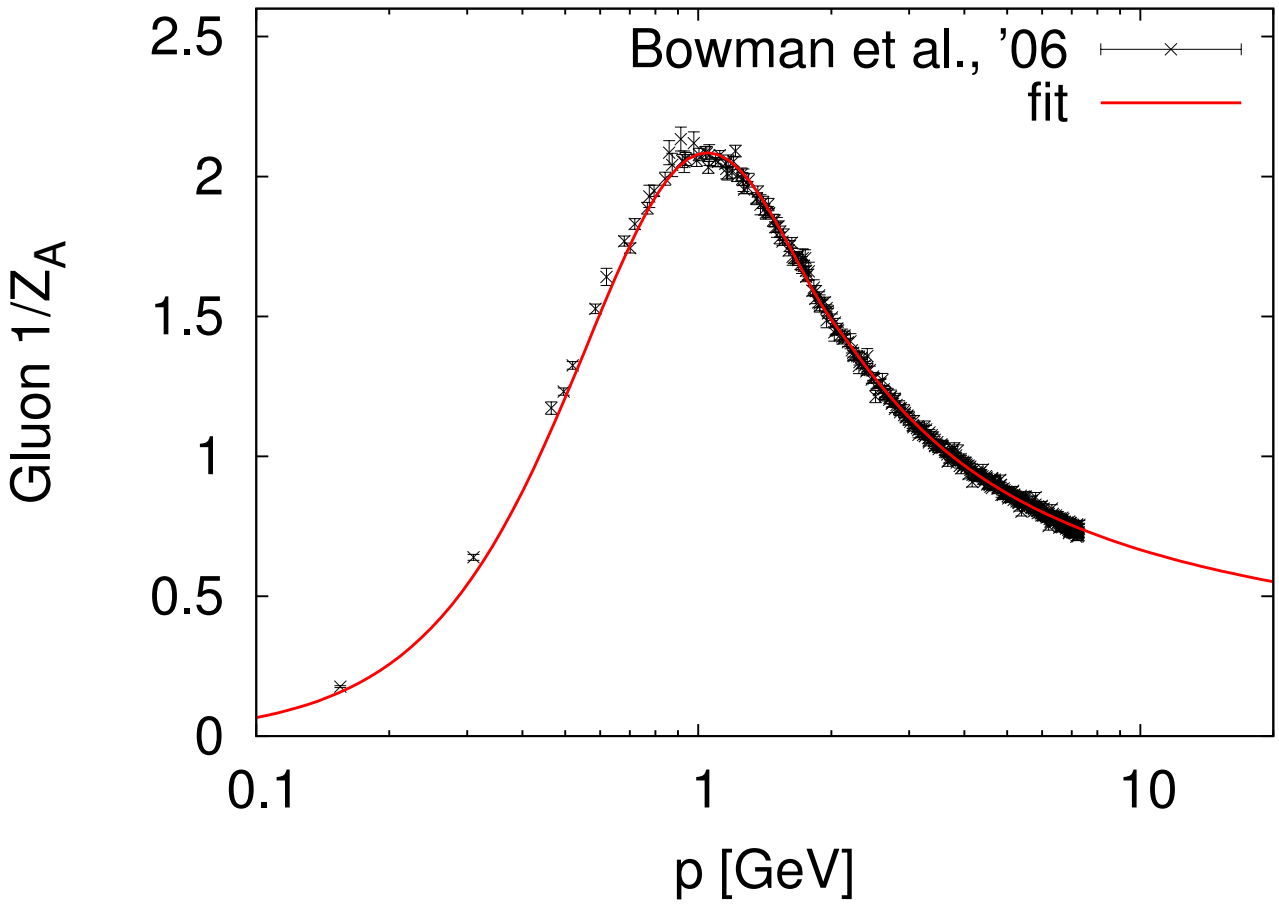
Truncation

[MM, Strodthoff, Pawlowski, in prep.]



Quenched gluon from lattice QCD

[Bowman, et al., 2004]



- k-dependence via $R_k \Rightarrow$ RG-upgrade cf. talk *L. Fister*, [Fister, Pawlowski, in prep.]
- ghost propagator perturbative/FRG

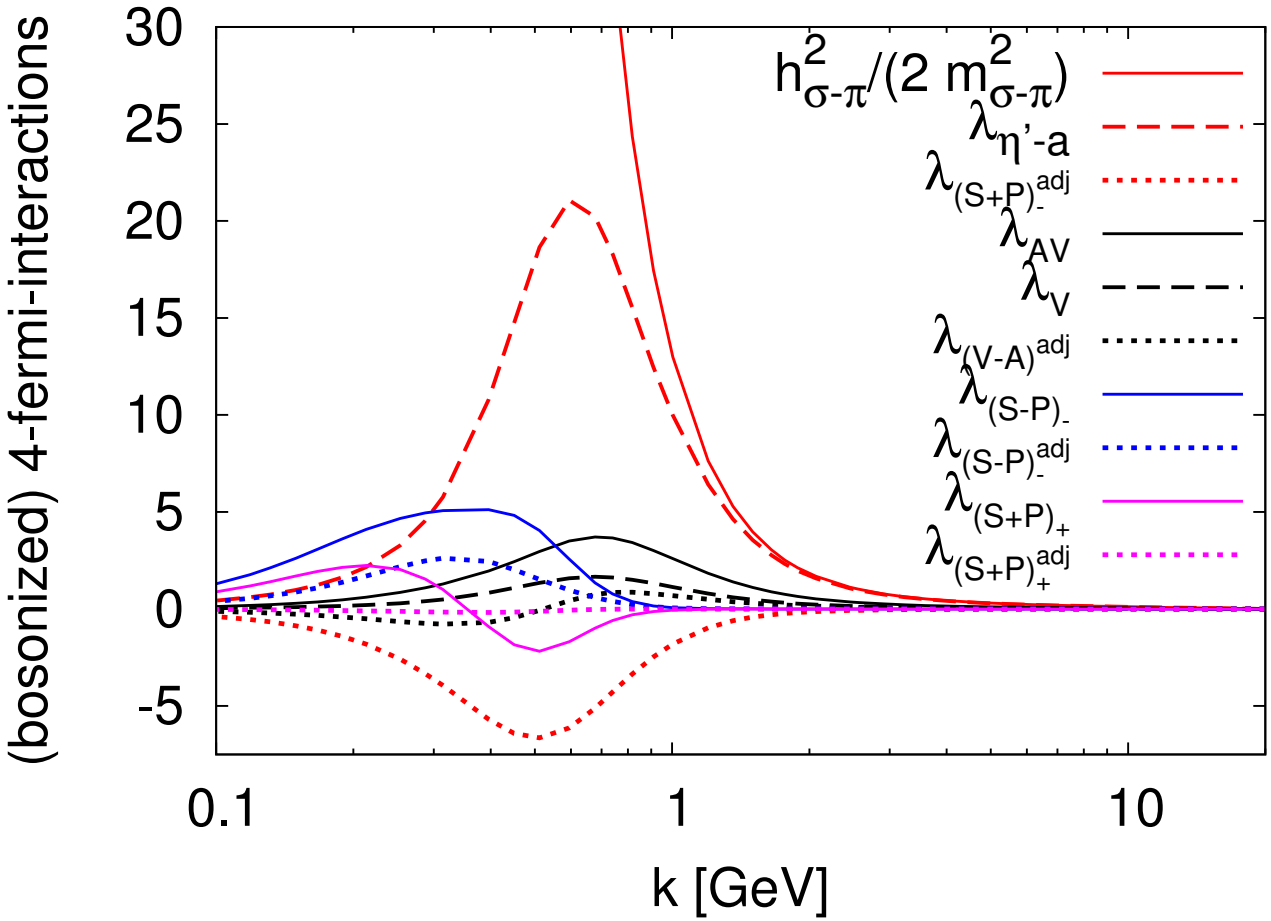
Fierz complete basis for 4-Fermi interaction

- chiral symmetry breaking $\Leftrightarrow$ resonance in 4-Fermi interaction(s)
- Fierz ambiguity resolved by complete basis:
  - 4 symmetric channels: $(\text{S-P})_+$, V, AV, $(\text{V-A})^{\text{adj}}$
  - 2 $SU(N_f)_A$-breaking channels
  - 2 $U(1)_A$-breaking channels: $(\text{S+P})_-^{(\text{adj})}$ ('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?

4-Fermi channels

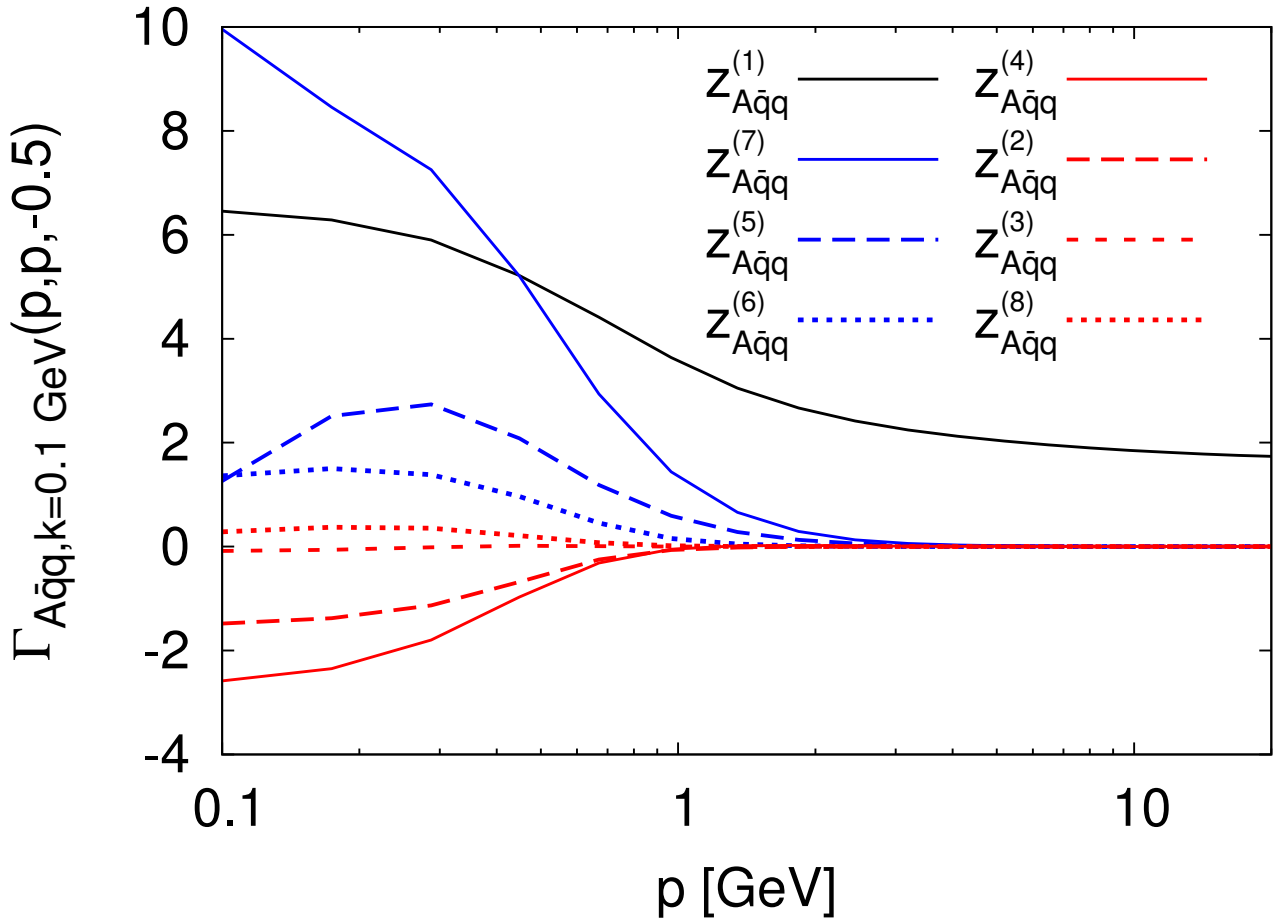
[MM, Pawlowski, Strodthoff, in prep.



- bosonized only σ-π-channel $\Rightarrow$ sufficient
- chiral symmetry breaking: considerable contribution to η-$\vec{a}$-channel

Quark-gluon vertex

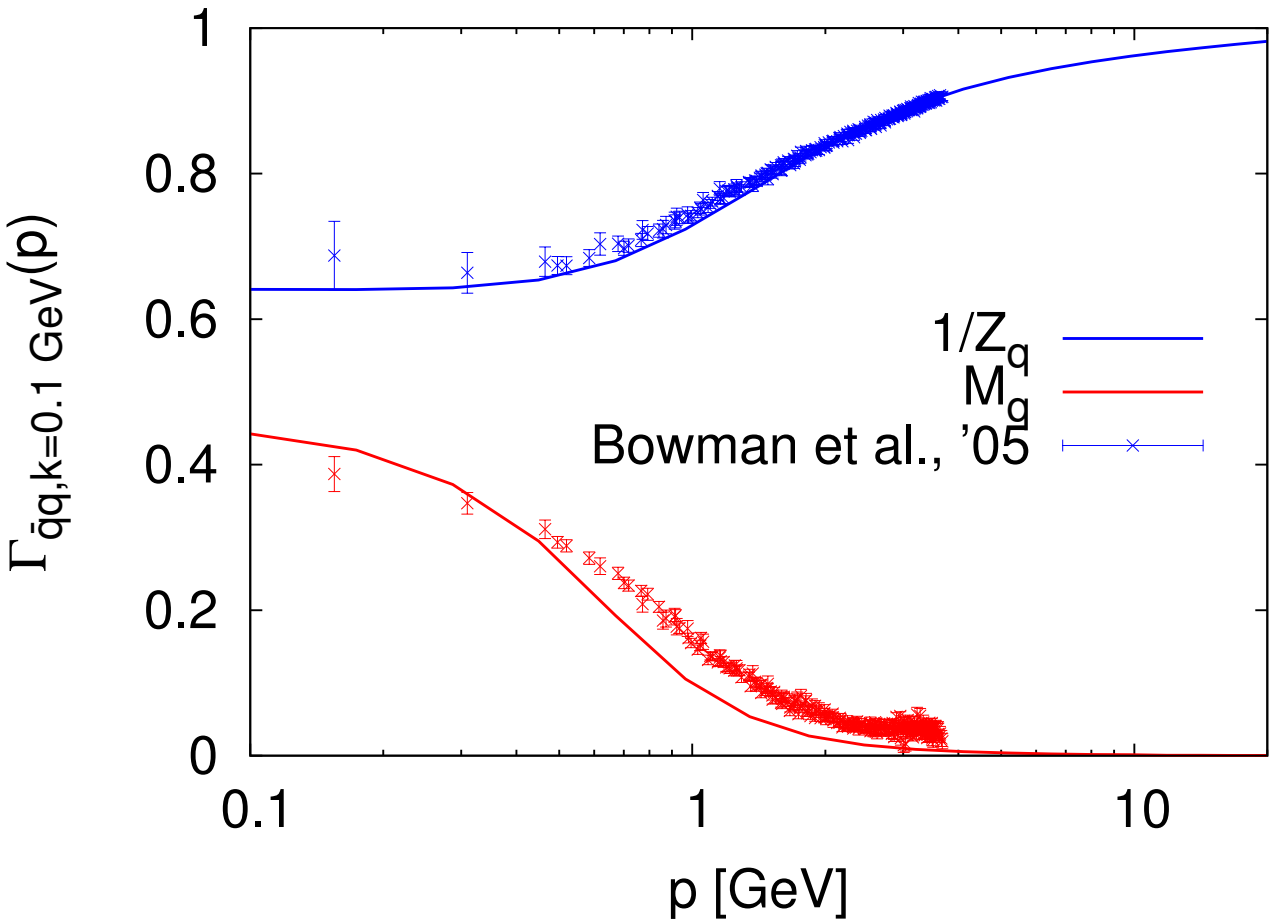
[MM, Pawlowski, Strodthoff, in prep.]



- shown: symmetric point, calculated: full momentum-dependence
- important for bound-state equations [Williams, 2014]

Quark propagator

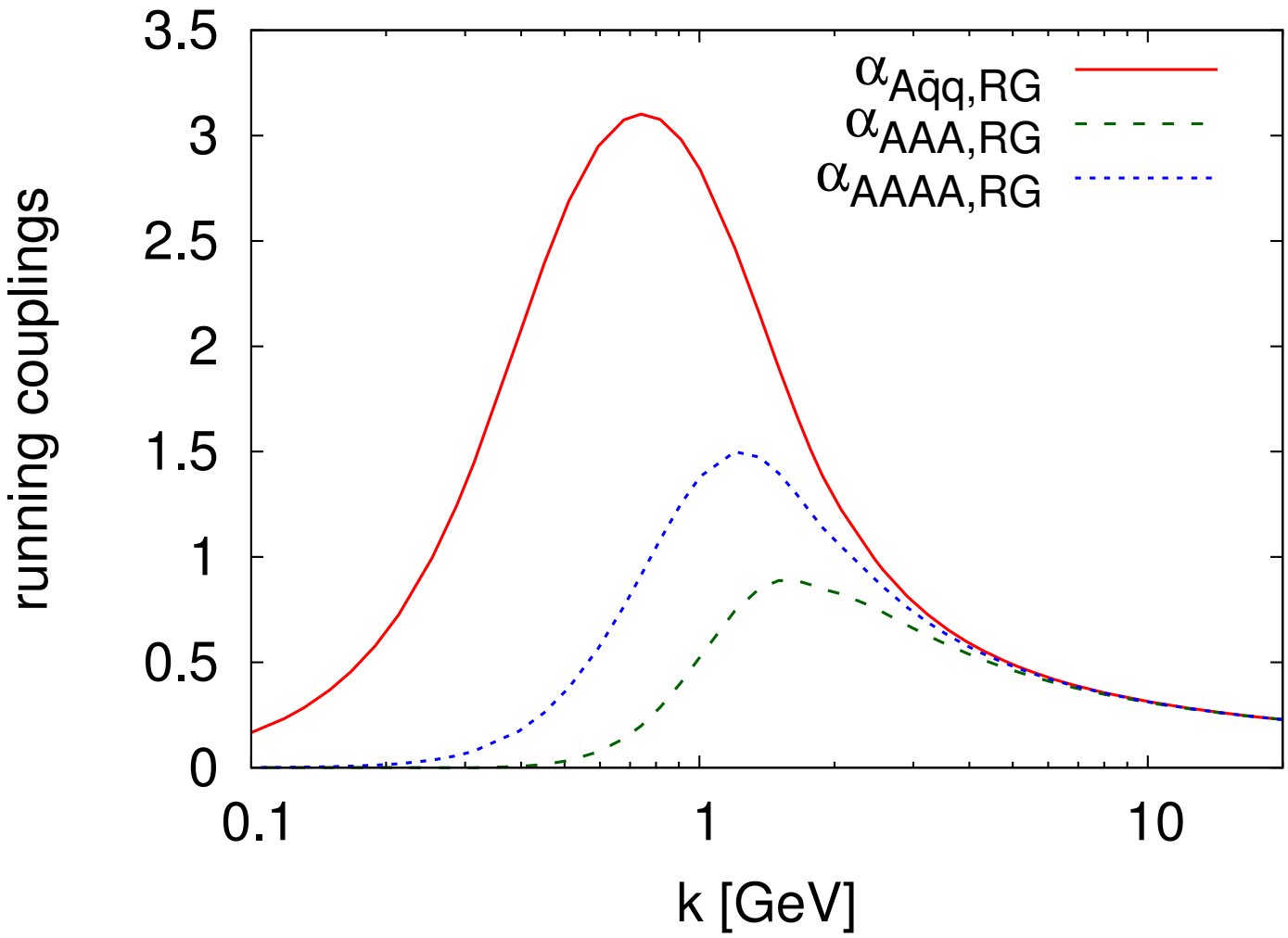
[MM, Pawlowski, Strodthoff, in prep.]



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

Running Couplings

[MM, Pawlowski, Strodthoff, in prep.]



$$\alpha_{A\bar{q}q,\mathrm{RG}}(k) = \frac{\left(z^{(1)}_{A\bar{q}q,k}(0)\right)^2}{4\pi}, \quad \alpha_{AAA,\mathrm{RG}}(k) = \frac{\left(z_{AAA,k}\right)^2}{4\pi}, \quad \alpha_{AAAA,\mathrm{RG}}(k) = \frac{z_{AAAA,k}}{4\pi}$$

Stability of truncation

- approximations within included correlation functions:
  - quark propagator and quark-gluon vertex fully included
  - field dependence of Yukawa interaction: 5% [Pawlowski, Rennecke, 2014]
  - more momentum dependencies:
    - ★ mesonic sector: small

      [Helmboldt, Pawlowski, Strodthoff, in prep.]
    - ★ rebosonization
    - ★ quark propagator in mesonic equations
    - ★ YM-vertices: ...
- effect of higher vertices:
  - influence (momentum inde. tensors) of other 4-point functions small
  - fermionic 6- and 8-point functions: included (partially) via mesons
- $U(1)_A$-anomaly: small in first checks [Pawlowski, 1996]
- glue input:
  - Λ_{QCD} from lattice data at large momenta: work in progress

chiral symmetry and confinement [Fister, MM, Pawlowski, Strodthoff, in prep.]

- matter sector:
  - strength of chiral symmetry breaking depends on glue gap
  - gap and N_f small enough $\Rightarrow$ symmetry breaking

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- matter sector:
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  - gap and N_f small enough $\Rightarrow$ symmetry breaking
- glue sector: cf. talk *L. Fister* on tuesday
  - unquenching with chiral quark(s): $m_{glue} = 0$

Summary and Outlook

- get rid of model-dependence in FRG:
  (quenched) QCD with dynamical hadronization
- largest truncation with functional methods to date
- results:
  - Fierz-complete basis for 4-Fermi channels
  - quark-gluon vertex
  - quark-propagator
  - running couplings from different vertices
- interplay of chiral symmetry breaking and confinement

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