QCD and dynamical hadronization

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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

\[ m_\pi = 138 \text{ MeV} \]

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

\[ \mu_B / T = 2 \]
\[ \mu_B / T = 3 \]

\[ T \text{ [MeV]} \]
\[ \mu \text{ [MeV]} \]
\[ m_\pi = 138 \text{ MeV} \]

\[ \chi \text{ crossover} \]
\[ \sigma(T=0)/2 \]
\[ \Phi \text{ crossover} \]
\[ \chi 1\text{st order} \]
\[ \text{CEP} \]

\[ \mu_B \]
\[ T \]
\[ \mu_q \]

Lattice: curvature range \( \kappa = 0.0066-0.0180 \)

DSE: chiral crossover
DSE: critical end point
DSE: deconfinement crossover

[Herbst, Pawlowski, Schaefer, 2013]

[Luecker, Fischer, Fister, Pawlowski, 2013]
Back to QCD in the vacuum

- shown results used model input:
  - quark-meson model:
    - initial values at $\Lambda \approx O(\Lambda_{QCD})$
    - 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.]
Back to QCD in the vacuum

- shown results used model input:
  - quark-meson model:
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- $\mu \neq 0$: relative scales of fluctuations
  - cf. talk N. Strodthoff, [A. Helmboldt, J. Pawlowski, N. Strodthoff, in prep.]
- use only QCD input
  - $\alpha_S(O(10)$ GeV)
  - $m_q(O(10)$ GeV)
- keep simple low-energy effective description (quark-meson model)
Dynamical hadronization
(cf. talk F. Rennecke)

\[ \partial_k \Gamma_k = \frac{1}{2} - \lambda_{\pi}^2/(2 m_{\pi}^2) - \frac{1}{2} + \frac{1}{2} \]

\[ h_{\pi}^2/(2 m_{\pi}^2) \]

\[ \lambda_{\pi} \]

\[ h_{\pi}(k) \]

\[ k [GeV] \]

\[ k [GeV] \]

[MM, Strodthoff, Pawlowski, in prep.]

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

[MM, Strodthoff, Pawlowski, in prep.]
Truncation

[MM, Strodthoff, Pawlowski, in prep.]

Yang Mills input

-1

-1

RG running

classical tensor structure

-1

full effective potential

-1

classical tensor structure

-1

full momentum dep.

-1

momentum dep.

-1

full momentum dep.

all 8 tensor structures

Fierz-complete basis (10) at $p = 0$

and momentum dep. of single

channels

RG running

full momentum dep.

...
Quenched gluon from lattice QCD

![Graph showing quenched gluon from lattice QCD](image)

- $k$-dependence via $R_k \Rightarrow$ RG-upgrade
- ghost propagator perturbative/FRG

Bowman et al., ’06

cf. talk L. Fister, [Fister, Pawlowski, in prep.]
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?
**4-Fermi channels**

(bosonized) 4-fermi-interactions

\[ h_\sigma^2 / (2 m_{\sigma-\pi}^2) \]

\[ \lambda_{\eta'-a} \]

\[ \lambda_{(S+P)^{adj}} \]

\[ \lambda_{AV} \]

\[ \lambda_{V} \]

\[ \lambda_{(V-A)^{adj}} \]

\[ \lambda_{(S-P)^{adj}} \]

\[ \lambda_{(S+P)^+} \]

\[ \lambda_{(S+P)^{adj}+} \]

- bosonized only \( \sigma-\pi \)-channel \( \Rightarrow \) sufficient
- chiral symmetry breaking: considerable contribution to \( \eta-\bar{a} \)-channel
Quark-gluon vertex

-4
-2
0
2
4
6
8
10
0.1 1 10
Γ Aq-q,k=0.1 GeV (p,p,-0.5)
p [GeV]
zAq-q
(1)
zAq-q
(7)
zAq-q
(5)
zAq-q
(6)
zAq-q
(4)
zAq-q
(2)
zAq-q
(3)
zAq-q
(8)

- shown: symmetric point, calculated: full momentum-dependence
- important for bound-state equations

[MM, Pawlowski, Strodthoff, in prep.]
Quark propagator

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

Bowman et al., '05

$1/Z_q$

$M_g$

$\Gamma_{q,q,k=0.1 \text{ GeV}}(p)$
Running Couplings

\[ \alpha_{A\bar{q}q,\text{RG}}(k) = \left( \frac{z_{A\bar{q}q,k}^{(1)}(0)}{4\pi} \right)^2, \quad \alpha_{AAA,\text{RG}}(k) = \frac{z_{AAA,k}^2}{4\pi}, \quad \alpha_{AAAA,\text{RG}}(k) = \frac{z_{AAAA,k}}{4\pi} \]
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
    - 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:
  - $\Lambda_{QCD}$ 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
chiral symmetry and confinement

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

- glue sector:
  - unquenching with chiral quark(s): $m_{\text{glue}} = 0$

 cf. talk L. Fister on tuesday
get rid of model-dependence in FRG:
(quinched) 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
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

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