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. Pawlowski, S. Rechenberger, F. Rennecke, N. Strodthoff
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QCD phase diagram with functional methods

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

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

[Luecker, Fischer, Welzbacher, 2014]

[Luecker, Fischer, Fister, Pawlowski, '13]
QCD phase diagram with functional methods

- works well at \( \mu = 0 \): agreement with lattice
- different results at large \( \mu \)
  (possibly already at small \( \mu \))

[Herbst, Pawlowski, Schaefer, 2013]
[Braun, Haas, Pawlowski, unpublished]
QCD phase diagram with functional methods

- works well at $\mu = 0$: agreement with lattice
- different results at large $\mu$
  (possibly already at small $\mu$)

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

[Herbst, Pawlowski, Schaefer, 2013]
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QCD phase diagram with functional methods

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possible explanation for disagreement:

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

\[\text{[Herbst, Pawlowski, Schaefer, 2013]}\]
\[\text{[Braun, Haas, Pawlowski, unpublished]}\]
Back to QCD in the vacuum (Wetterich equation)

- use only perturbative QCD input
  - $\alpha_s(\Lambda = \mathcal{O}(10) \text{ GeV})$
  - $m_q(\Lambda = \mathcal{O}(10) \text{ GeV})$
Back to QCD in the vacuum (Wetterich equation)

- use only perturbative QCD input
  - $\alpha_S(\Lambda = \mathcal{O}(10) \text{ GeV})$
  - $m_q(\Lambda = \mathcal{O}(10) \text{ GeV})$

- Wetterich equation with initial condition $S[\Phi] = \Gamma_\Lambda[\Phi]$

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

$\Rightarrow$ effective action $\Gamma[\Phi] = \lim_{k \to 0} \Gamma_k[\Phi]$
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\[
\partial_k \Gamma_k[A, \bar{c}, c, \bar{q}, q] = \frac{1}{2} \quad - \quad - \quad -
\]

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

- $\partial_k$: 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

\[ \Gamma[\Phi] = \sum_n \int_{p_1, \ldots, p_{n-1}} \Gamma_{\phi_1 \cdots \phi_n}^{(n)} (p_1, \ldots, p_{n-1}) \Phi^1(p_1) \cdots \Phi^n(-p_1 - \cdots - p_{n-1}) \]
Vertex Expansion

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- functional derivatives with respect to \( \Phi_i = A, \bar{c}, c, \bar{q}, q \):

  \[ \Rightarrow \text{equations for 1PI } n\text{-point functions, e.g. gluon propagator:} \]

\[ \partial_t \begin{array}{c} -1 \\ \end{array} = -2 \begin{array}{c} \text{propagator} \\ \end{array} + \frac{1}{2} \]
Vertex Expansion

- approximation necessary - vertex expansion

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

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

\[ \partial_t \left( \begin{array}{c}
  1 \\
  -2 \\
  + \frac{1}{2}
\end{array} \right) = \begin{array}{c}
  \begin{array}{c}
  \text{Diagram 1}
  \end{array} \\
  \begin{array}{c}
  \text{Diagram 2}
  \end{array}
\end{array} \]

- want “apparent convergence” of \( \Gamma[\Phi] = \lim_{k \to 0} \Gamma_k[\Phi] \)
“Quenched” Landau gauge QCD

- two crucial phenomena: \( S\chiSB \) and confinement
- similar scales - hard to disentangle
- quenched QCD: allows separate investigation:

see e.g. [Williams, Fischer, Heupel, 2015]
“Quenched” Landau gauge QCD

- two crucial phenomena: $S\chi_{SB}$ and confinement
- similar scales - hard to disentangle see e.g. [Williams, Fischer, Heupel, 2015]
- quenched QCD: allows separate investigation:
  - matter part [MM, Strodthoff, Pawlowski, 2014]
    (with FRG-YM propagators from [Fischer, Maas, Pawlowski, 2009], [Fister, Pawlowski, unpublished])
  - recent results for YM propagators [Cyrol, Fister, MM, Pawlowski, Strodthoff, to be published]
Chiral symmetry breaking

- $\chi_{SB} \Leftrightarrow$ resonance in 4-Fermi interaction $\lambda$ (pion pole):
Chiral symmetry breaking

- $\chi_{SB} \Leftrightarrow$ resonance in 4-Fermi interaction $\lambda$ (pion pole):
- resonance $\Rightarrow$ singularity without momentum dependency

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

[Braun, 2011]
Effective running couplings

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

[MM, Pawlowski, Strodthoff, 2014]
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

\[ \partial_k \Gamma_k = \frac{1}{2} \]

\[ \frac{h^2}{2 m^2} \]

\[ \lambda_\pi \]

\[ Y_{\text{Yukawa}} \]

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\[ \frac{h^2}{2 m^2} \]

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[MM, Strodthoff, Pawlowski, 2014]

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

[MM, Strodthoff, Pawlowski, 2014]
Vertex Expansion in the matter system

FRG Yang-Mills results

-1

Mom. dep.

Classical tensor structure

Mom. dep.

Classical tensor structure

-1

Mom. dep.

Full mom. dep.

All tensor structures

STI-consistent dressing

-1

Mom. dep.

Full effective potential

Fierz-complete basis at $p = 0$ and mom. dep.

Mom. dep.

Mom. dep.

Mom. dep.

Mom. dep.
Derivation of equations

**VertEXPand**  
Mathematica package for the derivation of vertices from a given action using FORM  
(Denz, Held, Rodigast; unpub.)

**DoFun**  
Mathematica package for the derivation of functional equations  
(Braun, Huber; Comput. Phys. Commun. 183 (2012) 1290-1320)

**Action**

**Vertices/Feynman Rules**

**DoFun**  
**VertEXPand**

**Symbolic Flow Equations**

**ERGE**

**FORMTracer**  
high-performance, easy-to-use Mathematica tracing tool using FORM  
(Cyrol, Mitter, Pawlowski, Strodthoff; in prep.)

**CreateKernels**  
Mathematica package for the automatic generation of compilable C++ kernels for use in connection with the frgsolver  
(Cyrol, Mitter, Pawlowski, Strodthoff; unpub.)

**Compilable Kernels**

**frgsolver**  
Flexible, high-performance, parallelized C++ OOP framework for the numerical solution of functional equations  
(Cyrol, Mitter, Pawlowski, Strodthoff; unpub.)

**Numerical solution**

[Cyrol, MM, Pawlowski, Strodthoff, 2013-2016]
Equations in the matter system

[MM, Strodthoff, Pawlowski, 2014]

\[ \partial_t^{-1} = \left( \begin{array}{c} \text{diagram 1} \\ \text{diagram 2} \\ \text{diagram 3} \end{array} \right) \]

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Equations in the matter system

\[ \partial_t \chi_{SB} = -2 \chi_{SB} + \chi_{SB} - \chi_{SB} + \text{perm.} \]
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\[ \partial_t \chi_{SB} = \sum \text{perm.} \]

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Gluon FRG input

- \( \Gamma^{(2)}_{AA}(p) \propto Z_A(p) p^2 \left( \delta^{\mu\nu} - p^\mu p^\nu / p^2 \right) \)

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

\[ \Gamma_{qq}^{(2)}(p) \propto Z_q(p) \not p + M(p) \]

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

Bowman et al., '05

1/Z\(_q\)

M\(_q\)
Quark propagator

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

FRG vs. lattice: bare mass, quenched, scale
agreement not sufficient: need apparent convergence at $\mu \neq 0$
other 4-Fermi channels (mesons)

(bosonized) 4-fermi-interactions

\[ \frac{h^2\pi^2}{2m^2} \]

\[ \lambda_{\eta'} \]

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

\[ \lambda_{V-A} \]

\[ \lambda_{V+A} \]

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

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

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

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

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

- bosonized only $\sigma-\pi$-channel $\Rightarrow$ sufficient
diquark momentum configuration more important

- other channels: quantitatively not important in loops
Quark-gluon interactions I

- Quark-gluon interaction most crucial for chiral symmetry breaking
- Full tensor basis ⇒ sufficient chiral symmetry breaking strength?
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- Full tensor basis $\Rightarrow$ sufficient chiral symmetry breaking strength?

\[ p \text{ [GeV]} \]

- Vertex strength: reflects gluon gap
- 8 tensors (transversally projected):
  - Classical tensor
  - Chirally symmetric
  - Break chiral symmetry

\[ Z_{qAq}^{(1)} \quad Z_{qAq}^{(4)} \quad Z_{qAq}^{(7)} \quad Z_{qAq}^{(5)} \quad Z_{qAq}^{(6)} \quad Z_{qAq}^{(8)} \]
Quark-gluon interactions I

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![Diagram showing quark-gluon couplings vs. p [GeV]]

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

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

⇒ considerably less chiral symmetry breaking with full tensor basis
Quark-gluon interactions I

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**Graph: quark-gluon couplings vs. $p$ [GeV]**

- vertex strength: reflects gluon gap
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  - classical tensor
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$\Rightarrow$ considerably less chiral symmetry breaking with full tensor basis
- also important ingredient for bound-state equations
Quark-gluon interactions II

- missing strength?

\[\psi / D \nabla \psi\]

- [MM, Pawlowski, Strodthoff, 2014]

- In particular

\[\bar{q} \gamma^5 \gamma^\mu \epsilon_{\mu\nu\rho\sigma} \begin{pmatrix} F_{\nu\rho} \cr D_{\sigma} \end{pmatrix} q: \]

- Thus contributes to \[\bar{q}Aq, \bar{q}Aq^2 q\]

- Contains important non-classical tensors (\[\bar{q}Aq\])

- Considerable contribution to quark-gluon vertex (\[\bar{q}Aq^2\])

- Contribution to \[\bar{q}Aq^3\] seems unimportant

- Explicit calculations of \[AA\bar{qq}-vertex: \]

\[\bar{q}A\bar{q}q, \bar{q}Aq^2, \bar{q}Aq^3\] 15 chirally symmetric tensor elements (\[\bar{\psi} / D^3 \psi\]):

- \[\bar{\psi} / D^3 \psi\]: All seem important

- Order of effect similar to \[\bar{q} \gamma^5 \gamma^\mu \epsilon_{\mu\nu\rho\sigma} \begin{pmatrix} F_{\nu\rho} \cr D_{\sigma} \end{pmatrix} q\]

- Why? Underlying principle?
Quark-gluon interactions II

- missing strength?
- expansion in tensor structures → expansion in operators $\bar{\psi} D^n \psi$

[MM, Pawlowski, Strodthoff, 2014]
Quark-gluon interactions II

- missing strength?
- expansion in tensor structures → expansion in operators $\bar{\psi} \Phi^n \psi$

[MM, Pawlowski, Strodthoff, 2014]

in particular $\bar{q} \gamma_5 \gamma_\mu \epsilon_{\mu\nu\rho\sigma} \{F_{\nu\rho}, D_\sigma\} q$:
  - contributes to $\bar{q}Aq$, $\bar{q}A^2 q$ and $\bar{q}A^3 q$
  - contains important non-classical tensors ($\bar{q}Aq$)
  - considerable contribution to quark-gluon vertex ($\bar{q}A^2 q$)
  - contribution to $\bar{q}A^3 q$ seems unimportant
Quark-gluon interactions II

- missing strength?
- expansion in tensor structures $\rightarrow$ expansion in operators $\bar{\psi} \slashed{D}^n \psi$

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[MM, Pawlowski, Strodthoff, 2014]

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 (\( \bar{q} A^2 q \))
- contribution to \( \bar{q} A^3 q \) seems unimportant

- explicit calculations of \( AA\bar{q}q \)-vertex:

  - full basis: 63 chirally symmetric tensor elements
  - 15 chirally symmetric tensor elements (\( \bar{\psi} D^3 \psi \)):
    - 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

- Full mom. dep.
- Classical tensor structure
- Mom. dep. (sym. channel)
- Full tensor structure
- Full mom. dep.

Under investigation:
- Full tensor structure
- Mom. dep. (sym. channel)

- Full tensor structure
- Partial tensor structure
- Mom. dep. (sym. channel)
- Full tensor structure
- Mom. dep. (single channel)

- Full mom. dep.
- Via effective potential
- Full tensor structure
- Mom. dep. (sym. channel)
Vertex Expansion in YM theory [Cyrol, Fister, MM, Strodthoff, Pawlowski, to be published]

full. mom. dep.

full. mom. dep.

tadpole config.

sym. point and tadpole config.
Equations in YM theory

\[ \partial_t - 1 = \text{diagram} + \text{diagram} \]

\[ \partial_t - 1 = \text{diagram} - 2 \text{diagram} + \frac{1}{2} \text{diagram} \]

\[ \partial_t = - \text{diagram} - \text{diagram} + \text{perm.} \]

\[ \partial_t = - \text{diagram} + 2 \text{diagram} - \text{diagram} + \text{perm.} \]

\[ \partial_t = - \text{diagram} - \text{diagram} + 2 \text{diagram} - \text{diagram} + \text{perm.} \]
YM propagators

\[ \Gamma^{(2)}_{AA}(p) \propto Z_A(p) \, p^2 \left( \delta^{\mu\nu} - p^\mu p^\nu / p^2 \right) \]

\[ \Gamma^{(2)}_{cc}(p) \propto Z_c(p) \, p^2 \]

- band: family of decoupling solutions bounded by scaling solution
YM vertices I

- comparison to Sternbeck ’06
- comparison to Cucchieri, Maas, Mendes, ’08
  Blum, Huber, MM, von Smekal ’14

- band: family of decoupling solutions bounded by scaling solution
Outlook: unquenched gluon propagator

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

[Gießen, February 2016 26 / 29]
\( \eta' \)-meson (screening) mass at chiral crossover

- small \( \eta' \)-meson mass above chiral crossover? [Kapusta, Kharzeev, McLerran, 1998]
- drop in \( \eta' \) mass at chiral crossover? [Csörgo et al., 2010]
$$\eta'$$-meson (screening) mass at chiral crossover

- small $$\eta'$$-meson mass above chiral crossover?  
- drop in $$\eta'$$ mass at chiral crossover?

[Kapusta, Kharzeev, McLerran, 1998]

[Csörgó et al., 2010]

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
\( \eta' \)-meson (screening) mass at chiral crossover

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### Chiral Crossover: Polyakov-Quark-Meson Model (Extended Mean-Field)

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

\[ N_f = 2 \]

\( \Phi \)

\( \sigma \)

\( f_{\pi} \)

\( S \)

\( P \)

\( A \)

\( \lambda(S-P)_\perp \), \( f_{\text{QCD}}(T) \equiv \lambda(S-P)_\perp,PQM(T) \)

### ’t Hooft Determinant

- RG-scale dependence from \( f_{\text{QCD}} \)
- temperature dependence \( k(T) \):
  \[ \lambda(S-P)_\perp,f_{\text{QCD}}(k) \equiv \lambda(S-P)_\perp,PQM(T) \]
$\eta'$-meson (screening) mass at chiral crossover: result

Masses as function of temperature with Polyakov-Loop

[Heller, MM, 2015]

screening masses!
\( \eta' \)-meson (screening) mass at chiral crossover: result

- screening masses!
- QM-Model \( N_f = 2 + 1 \):

  - chiral symmetry restoration:  
    \[ \Rightarrow \text{drop in } m_{\eta'} \]
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: $\eta'$-meson and pion mass splitting
Summary and Outlook

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