QCD from quark, gluon, and meson correlators

Mario Mitter

Brookhaven National Laboratory

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fQCD collaboration - QCD (phase diagram) with FRG:


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large part of this effort: vacuum QCD and YM-theory

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why?
QCD from the effective action (gauge fixing necessary)

\[ \Gamma[\Phi] = \sum_n \int_{\{p_i\}} \Gamma^{(n)}_{\Phi_1 \cdots \Phi_n} (p_1, \ldots, p_{n-1}) \Phi^1(p_1) \cdots \Phi^n(-p_1 - \cdots - p_{n-1}) \]
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\[ \Gamma[\Phi] = \sum_n \int_{\{p_i\}} \Gamma_{\phi_1...\phi_n}^{(n)}(p_1, \ldots, p_{n-1}) \Phi^1(p_1) \cdots \Phi^n(-p_1 - \cdots - p_{n-1}) \]

- full information about QFT encoded in \( \Gamma[\Phi]/\text{correlators} \):
  - bound state spectrum: pole structure of the \( \Gamma^{(n)} \)
    e.g. [Roberts, Williams, '94], [Alkofer, Smekal, '00], [Eichmann, Sanchis-Alepuz, Williams, Alkofer, Fischer, '16]
  - form factors: photon-particle correlators
    e.g. [Cloet, Eichmann, El-Bennich, Klahn, Roberts, '08], [Sanchis-Alepuz, Williams, Alkofer, '13]
  - decay constants
    e.g. [Maris, Roberts, Tandy, '97], [MM, Pawlowski, Strodthoff, in prep.]
  - thermodynamic quantities: \( \Gamma[\Phi] \propto \text{grand potential} \)
    \( \star \) equation of state
    e.g. [Herbst, MM, Pawlowski, Schaefer, Stiele, '13]
    \( \star \) fluctuations of conserved charges
    e.g. [Fu, Rennecke, Pawlowski, Schaefer, '16]
  - further quantities: \( \Gamma[\Phi] \propto \text{eff. potential, propagators, 't Hooft determinant} \)
    \( \star \) chiral condensate(s)/\( \langle \sigma \rangle \)
    e.g. [Schaefer, Wambach '04], [Fischer, Luecker, Mueller '11], [MM, Schaefer, '13]
    \( \star \) (dressed) Polyakov loop
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    \( \star \) axial anomaly
    e.g. [Grahl, Rischke, '13], [MM, Schaefer, '13], [Fejos, '15], [Heller, MM, '15]
    \( \star \) spectral functions
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e.g. Debye mass in $SU(3)$ YM theory [Cyrol, MM, Pawlowski, Strodthoff, 2017]

- correlators from Functional Renormalisation Group (FRG)
- screening mass:
  fit to exponential decay of chromo-electric gluon propagator

\begin{itemize}
  \item excellent agreement with 2$^{\text{nd}}$-order HTL perturbation theory for $T \gtrsim 0.6$ GeV
  \item smooth transition to nonperturbative regime
\end{itemize}
e.g. Center symmetry order parameters

- quenched (scalar) Quantum Chromodynamics
- correlators from Dyson-Schwinger equation (DSE)
- lattice gluon input and vertex models

\[ \int_0^{2\pi} d\varphi T \sum_n D^2_\varphi(\vec{\nu} = \vec{0}, \omega_n(\varphi)) \]

\[ \frac{1}{4} tr_D S(\vec{0}, \omega_n(\varphi)) \]

- cf. e.g. [Fischer '09], [Braun, Haas, Marhauser, Pawlowski, '09],…
e.g. EOS and axial anomaly in “QCD-enhanced” models

- equation of state
- $N_f = 2 + 1$ PQM model with FRG
- unquenched Polyakov-loop potential from [Braun, Haas, Marhauser, Pawlowski, ’11]

$\eta'$-meson screening mass

- $N_f = 2$ PQM model, extended MF
- running 't Hooft determinant from [MM, Pawlowski, Strodthoff, ’14]

[Heller, MM, ’15].

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- phase diagrams
- spectral functions
- fluctuations of conserved charges

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

[Haas, Stiele, Braun, Pawlowski, Schaffner-Bielich, ’13]

[Herbst, MM, ’15]

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Nonperturbative QCD

- two crucial phenomena: $S^{\chi}\text{SB}$ and confinement
- very sensitive to small quantitative errors
- similar scales - hard to disentangle
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crawling towards QCD at finite density:

- quenched matter part
- pure $SU(N)$ YM-theory
- $N_f = 2$ QCD
- YM-theory at finite temperature $T > 0$
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Use results from lattice gauge theory to check truncation:

*what do we need from the lattice?*
(Euclidean) Correlation functions with the FRG

- $S[\Phi] = \Gamma_\Lambda[\Phi]$: use only perturbative QCD input
  - $\alpha_S(\Lambda = \mathcal{O}(10) \text{ GeV})$
  - $m_q(\Lambda = \mathcal{O}(10) \text{ GeV})$
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- integration of momentum shells:
  \[
  \partial_k \Gamma_k[A, \bar{c}, c, \bar{q}, q] = \frac{1}{2} \quad \square - \square - \square
  \]
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- Integration of momentum shells:

\[
\partial_k \Gamma_k[A, \bar{c}, c, \bar{q}, q] = \frac{1}{2} \Rightarrow \text{full non-perturbative quantum effective action}
\]
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- gauge-fixed approach (Landau gauge): ghosts appear
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- gauge-fixed approach (Landau gauge): ghosts appear

- functional derivatives $\Rightarrow$ equations for correlators

- aim for “apparent convergence” of $\Gamma[\Phi] = \lim_{k \to 0} \Gamma_k[\Phi]$
Mesons via dynamical hadronization [Gies, Wetterich, 2002]

- change of variables: particular 4-Fermi channels $\rightarrow$ meson exchange
- efficient inclusion of pole structure $\Rightarrow$ no spurious singularities
- low-energy effective model parameters from QCD - range of validity

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

Braun, Fister, Haas, Pawlowski, Rennecke, 2014

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Mesons via dynamical hadronization

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- low-energy effective model parameters from QCD - range of validity

\[
\partial_k \Gamma_k = \frac{1}{2} - \lambda \pi + \frac{1}{2}
\]

[MM, Strodthoff, Pawlowski, 2014]  
[Braun, Fister, Haas, Pawlowski, Rennecke, 2014]  
[MM, Strodthoff, Pawlowski, 2014]
$N_f = 2$ Landau-gauge QCD

Truncation:

systematics of improving the truncation?
$N_f = 2$ Landau-gauge QCD

Truncation:

$\Gamma^{(2)}_{AA}(p)$  $\Gamma^{(2)}_{\bar{c}c}(p)$  $\Gamma^{(3)}_{A\bar{c}c}(p)$  $\Gamma^{(3)}_{A^3}(\bar{p})$  $\Gamma^{(4)}_{A^4}(\bar{p})$

classical tensor  classical tensor

$\Gamma^{(2)}_{\bar{q}q}(p)$  $\Gamma^{(3)}_{A\bar{q}q}(p, q)$  $\Gamma^{(4)}_{A^2\bar{q}q}(\bar{p})$  $\Gamma^{(5)}_{A^3\bar{q}q}(\bar{p})$  $\Gamma^{(4)}_{\bar{q}qq\bar{q}}(p, p, -p)$

$\bar{q}D^n q$ complete, $n \leq 3$  mom.-ind. tensors

$\Gamma^{(2)}_{\phi\phi}(p)$  $\Gamma^{(3)}_{\bar{q}q\phi}(p, -p)$  $\Gamma^{(4)}_{\bar{q}q\phi\phi}(\bar{p})$  $\Gamma^{(5)}_{\bar{q}q\phi\phi\phi}(\bar{p})$  $\Gamma^{(n)}_{\phi^n}(0)$

$\phi \in \{\sigma, \bar{\pi}\}$  “classical” tensor  “classical” tensor  “classical” tensor

systematics of improving the truncation?

$\Rightarrow$ BRST-invariant operators, e.g. $\bar{\psi}D^n\psi$
Some representative equations (numerics-heavy)

[MM, Strodthoff, Pawlowski, 2014],

[Cyrol, Fister, MM, Strodthoff, Pawlowski, 2016]

cf. FormTracer [Cyrol, MM, Strodthoff, 2016]
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Chiral symmetry breaking

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

\begin{align*}
\partial_t \lambda &= 2\lambda + a\lambda^2 + b\lambda^4 + c\lambda^4, \quad b > 0, \quad a, c \leq 0,
\end{align*}

$\partial_t = -2 + \ldots$

$g > g_{cr}$

$g = g_{cr}$

$g = 0, \quad T > 0$
Chiral symmetry breaking

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

- $\beta$-function of momentum independent 4-Fermi interaction:

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

[Braun, 2011]
agreement in perturbative regime required by Slavnov-Taylor identities
- 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
  $\Rightarrow$ use STI in perturbative regime
Quark propagator

\[ \Gamma_{\bar{q}q}(p) = Z_q(p) \left( \frac{1}{p} + M(p) \right) \]

- \( S_{\chi\text{SB}}: M_q(0) \gg M_q(p \gg \Lambda_{\text{QCD}}) \)
- FRG vs. lattice: bare mass, scale setting, lattice \( Z_q \)?
- very sensitive to \( \bar{q}qA \)-interaction, relative scales

Quark-gluon interactions

- quark-gluon interaction most crucial for chiral symmetry breaking
- transverse tensor basis (8 tensors), e.g. $\gamma^\mu$, $i(p + q)\gamma^\mu$, $\frac{1}{2}[p, q]\gamma^\mu$
- $\lambda^{(i)}(p, q) \to \lambda^{(i)}(p^2, q^2, p \cdot q)$
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- 3 leading tensors:
  - Classical tensor: constrained by STI at large momenta
  - Chirally symmetric
  - Break chiral symmetry

- Systematic lattice error?
Quark-gluon interactions

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chirally symmetric tensors from operator \( \bar{q} \not D^3 q \) worsen result
- counteracted by tensor structures in \( \Gamma^{(4)}_{A\bar{A}q} \) and \( \Gamma^{(5)}_{A\bar{A}^2q} \) from \( \bar{q} \not D^3 q \)
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- chirally symmetric tensors from operator $\bar{q} \slashed{D}^3 q$ worsen result
- counteracted by tensor structures in $\Gamma_A^{AA\bar{q}q}$ and $\Gamma_A^{A\bar{3}\bar{q}q}$ from $\bar{q} \slashed{D}^3 q$ 

$\Rightarrow$ expansion in BRST-invariant operators improves convergence?


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Gluon propagator

\[ \Gamma_{AA}(p) = Z_A(p) \ p^2 \left( \delta^{\mu\nu} - p^\mu p^\nu / p^2 \right) \]

- infrared suppression ⇔ “confinement”
- insensitive to pion mass
- smooth transition to pert. theory
- scaling solution: lattice comparison?

More correlators

[Yukawa interaction dressings]

- $p \lambda_{qq\pi}$
- $p^2 \lambda_{qq\pi}$
- $p^2 \lambda_{qq\pi}^{(V-A)}$
- $p^2 \lambda_{qq\pi}^{(V+A)}$
- $p_{qq\pi}$

[Four-fermi vertex dressings]

- $p^2 \lambda_{qq\pi}$
- $p^2 \lambda_{qq\pi}^{(S+P)}$
- $p^2 \lambda_{qq\pi}^{(S-P)}$
- $p^2 \lambda_{qq\pi}^{(V-A)}$
- $p^2 \lambda_{qq\pi}^{(V+A)}$

[2-quark-2-gluon vertex dressings]

- $p^2 \lambda_{qq\pi}$
- $p^2 \lambda_{qq\pi}^{(S+P)}$
- $p^2 \lambda_{qq\pi}^{(S-P)}$
- $p^2 \lambda_{qq\pi}^{(V-A)}$
- $p^2 \lambda_{qq\pi}^{(V+A)}$

$m_\pi = 140$ MeV
Pure $SU(N)$ YM-theory

[Cyrol, Fister, MM, Pawlowski, Strodthoff, '16]

[Cyrol, MM, Pawlowski, Strodthoff, '17]

Truncation (blue: magnetic (transverse) leg, red: electric (longitudinal) leg):

\[
\frac{1}{Z_c(\bar{p})} \quad \lambda_{\bar{c}cA}^M(\bar{p}) \quad \lambda_{A^3}^M(\bar{p}) \quad \lambda_{A^4}^M(\bar{p})
\]

\[
\frac{1}{Z_A^M(\bar{p})} \quad \frac{1}{Z_A^E(\bar{p})} \quad \lambda_{A^3}^E(\bar{p}) \quad \lambda_{A^4}^E(\bar{p})
\]
Vacuum

[Cyrol, Fister, MM, Pawlowski, Strodthoff, 2016]

- truncation: momentum dependent dressing functions for all classical tensors
- hardest part of solution: fulfilling the modified STI (⇒ scaling solution)
• truncation: momentum dependent dressing functions for all classical tensors
• hardest part of solution: fulfilling the modified STI (⇒ scaling solution)

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

• IR-suppression ⇔ “confinement”
• smooth transition to perturbation theory

running couplings

degeneracy at large \( p \) due to STI

test of truncation

Propagators at $T \neq 0$

Zeroth mode correlation functions

SU(2)

SU(3)

[Cyrol, MM, Pawlowski, Strodthoff, '17]


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Propagators at $T \neq 0$

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Zeroth mode correlation functions

$SU(2)$

$SU(3)$


Backgrounds, ghost and zero crossing \cite{Cyrol, MM, Pawlowski, Strodthoff, '17}

\(\langle \tilde{A}_0 \rangle\) important near \(T_c\), cf. \cite{Herbst et al., '15}
Backgrounds, ghost and zero crossing

$\langle \tilde{A}_0 \rangle$ important near $T_c$, cf. [Herbst et al., '15]

![Graph showing $\langle \tilde{A}_0 \rangle$ vs. $T$]

Magnetic zero crossing in 3g-vertex

![Graph showing magnetic zero crossing]

Ghost propagator dressing

![Graph showing ghost propagator dressing vs. $p$]

Magnetic three-gluon vertex dressing

![Graph showing magnetic three-gluon vertex dressing vs. $p$]
Status and Outlook

- vacuum QCD
  - QCD from \( \alpha_s(\Lambda = \mathcal{O}(10) \text{ GeV}) \) and \( m_q(\Lambda = \mathcal{O}(10) \text{ GeV}) \)
  - good agreement with lattice correlators
  - more checks on convergence of vertex expansion

finite temperature YM-theory:
  - good agreement with magnetic lattice correlators
  - electric correlators: argued for importance of backgrounds near \( T_c \)
  - Debye mass consistent with HTL perturbation theory at \( T \gtrsim 0.6 \text{ GeV} \).

next stop: QCD @ \( T, \mu > 0 \)
  - equation of state
  - fluctuations of conserved charges
  - order parameters

further applications:
  - input for "QCD-enhanced" models
  - other strongly-interacting theories
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  - good agreement with magnetic lattice correlators
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  - Debye mass consistent with HTL perturbation theory at $T \gtrsim 0.6 \text{ GeV}$

- next stop: QCD @ $T, \mu > 0$
  - equation of state
  - fluctuations of conserved charges
  - order parameters
Status and Outlook

- **vacuum QCD**
  - QCD from $\alpha_S(\Lambda = \mathcal{O}(10) \text{ GeV})$ and $m_q(\Lambda = \mathcal{O}(10) \text{ GeV})$
  - good agreement with lattice correlators
  - more checks on convergence of vertex expansion

- **finite temperature YM-theory:**
  - good agreement with magnetic lattice correlators
  - electric correlators: argued for importance of backgrounds near $T_c$
  - Debye mass consistent with HTL perturbation theory at $T \gtrsim 0.6 \text{ GeV}$

- **next stop: QCD @ $T, \mu > 0$**
  - equation of state
  - fluctuations of conserved charges
  - order parameters

- **further applications:**
  - input for “QCD-enhanced” models
  - other strongly-interacting theories