Chiral symmetry breaking in continuum QCD

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Hirschegg, January 20, 2016

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European Research Council
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Bundesministerium für Bildung und Forschung

fQCD collaboration:

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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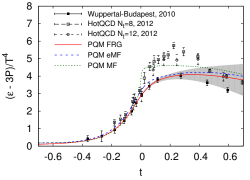
QCD phase diagram with functional methods

cf. talks J. M. Pawlowski, C. Fischer

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



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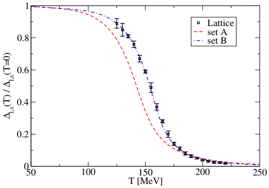

[Luecker, Fischer, Welzbacher, 2014]

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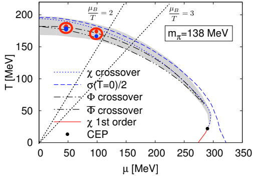
- different results at large μ (possibly already at small μ)



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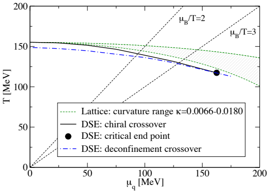

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  - Polyakov-quark-meson model with FRG:
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    - input for Polyakov loop potential
  - quark propagator DSE:
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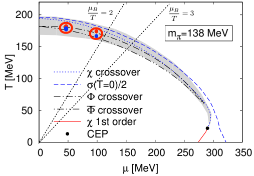

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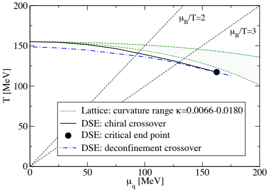

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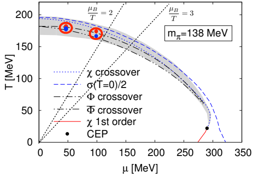

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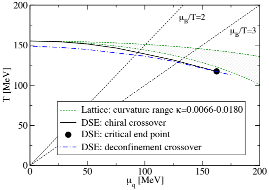

possible explanation for disagreement:

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

[Luecker, Fischer, Fister, Pawlowski, '13]

Back to QCD in the vacuum

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  - $\alpha_S(\Lambda = \mathcal{O}(10)\ \text{GeV})$
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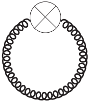
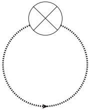
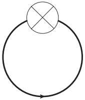
$\partial_k \Gamma_k = \frac{1}{2}$  $-$  $-$ 

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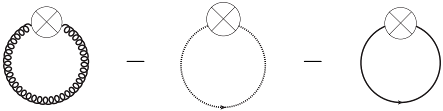

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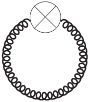
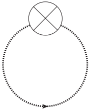
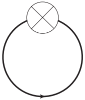
$\partial_k \Gamma_k = \frac{1}{2}$  $-$  $-$ 

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

- approximations necesssary - vertex expansion:
  derivatives $\Rightarrow$ equations for 1PI *n*-point functions
- $\lim_{k \to 0} \Gamma_k[\Phi]$ should not depend on approximation in the vacuum

“Quenched” Landau gauge QCD [MM, Strodthoff, Pawlowski, 2014]

- two crucial phenomena: SχSB and confinement
- similar scales - hard to disentangle see e.g. [Williams, Fischer, Heupel, 2015]
- quenched QCD: allows separate investigation

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- two crucial phenomena: SχSB and confinement
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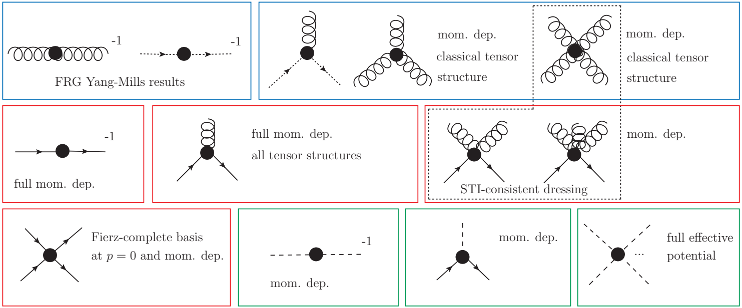
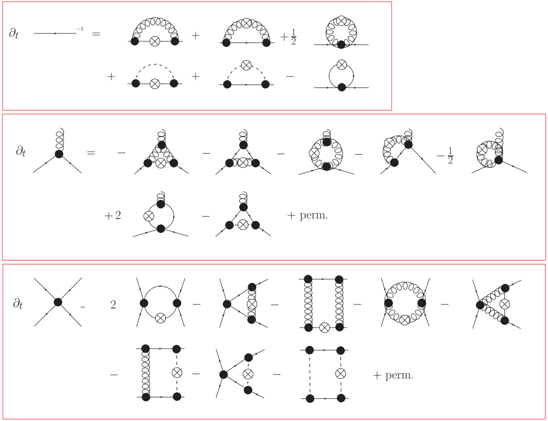
- YM propagators: FRG input — [Fischer, Maas, Pawlowski, 2009], [Fister, Pawlowski, unpublished]
- matter part:



Equations

[MM, Strodthoff, Pawlowski, 2014]



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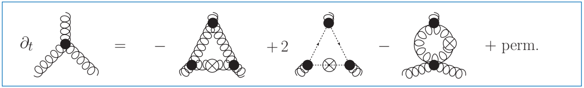

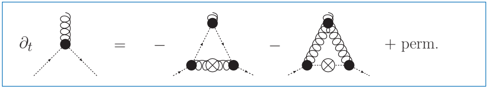

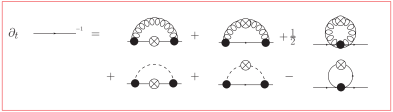

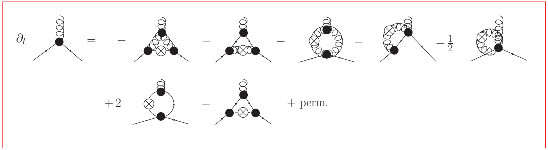

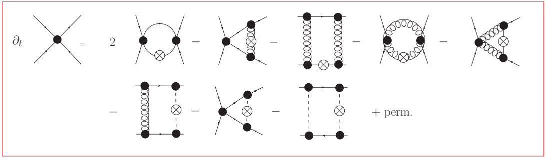

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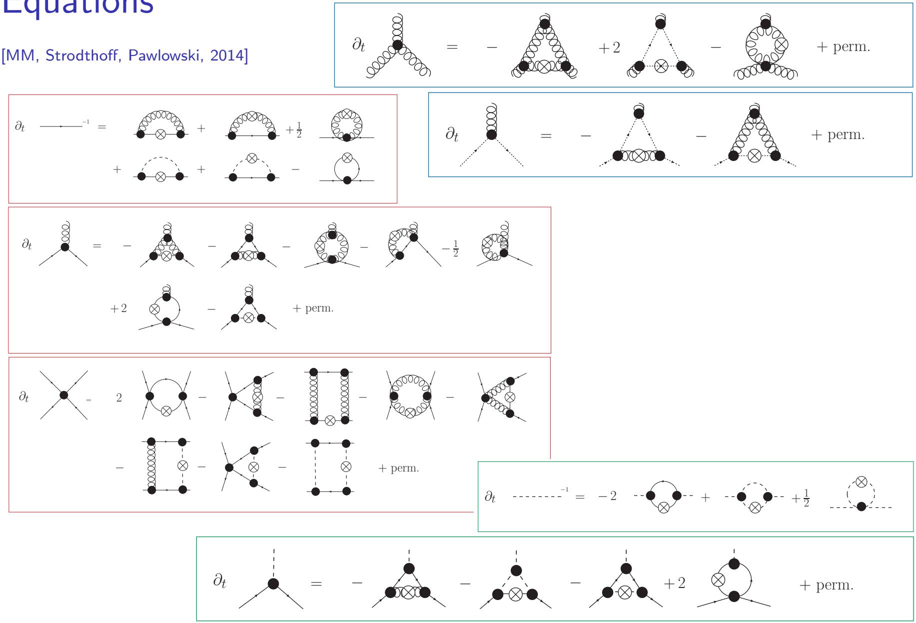
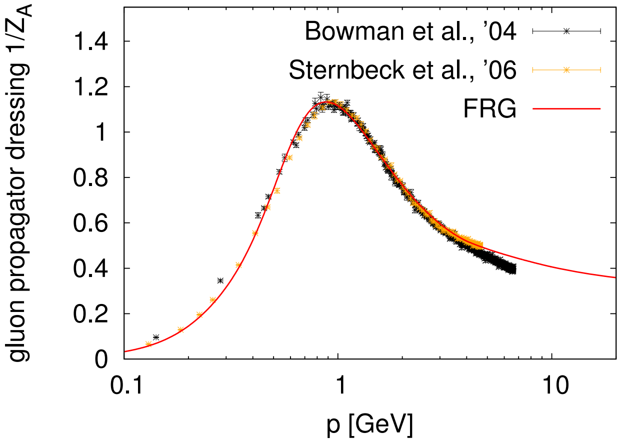


Gluon FRG input

[Fischer, Maas, Pawlowski, 2009], [Fister, Pawlowski, unpublished]

cf. talk J. M. Pawlowski



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

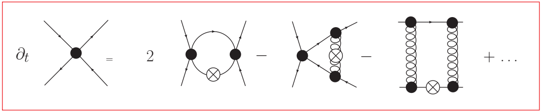
Chiral symmetry breaking

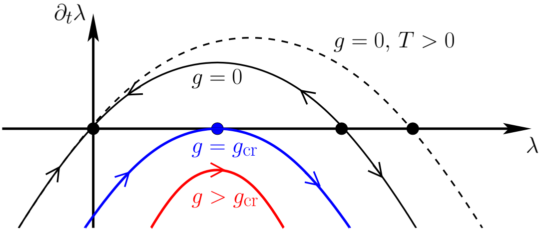
- χSB $\Leftrightarrow$ resonance in 4-Fermi interaction λ (pion pole):

Chiral symmetry breaking

- χSB $\Leftrightarrow$ resonance in 4-Fermi interaction λ (pion pole):
- resonance $\Rightarrow$ singularity without momentum dependency

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

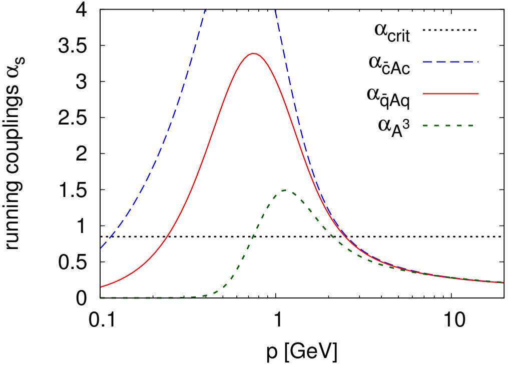




[Braun, 2011]

Effective running couplings

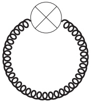
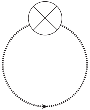
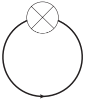
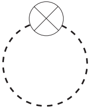
[MM, Pawlowski, Strodthoff, 2014]

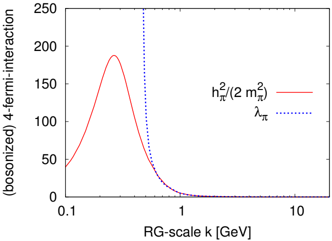


- agreement in perturbative regime required by gauge symmetry
- non-degenerate in nonperturbative regime: reflects gluon mass gap
- $\alpha_{\bar{q}Aq} > \alpha_{cr}$: necessary for chiral symmetry breaking
- area above α_{cr} very sensitive to errors

4-Fermi vertex via dynamical hadronization [Gies, Wetterich, 2002]

- change of variables: particular 4-Fermi channels $\to$ meson exchange
- efficient inclusion of momentum dependence $\Rightarrow$ no singularities
- identifies relevant effective low-energy dofs from QCD

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



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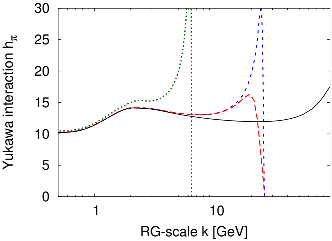

[Braun, Fister, Haas, Pawlowski, Rennecke, 2014]

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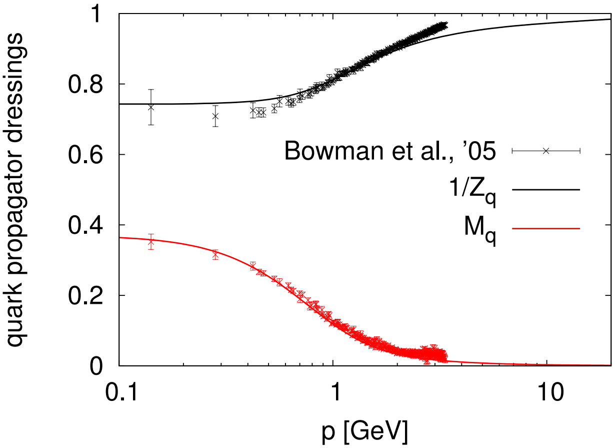
Quark propagator

[MM, Pawlowski, Strodthoff, 2014]



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

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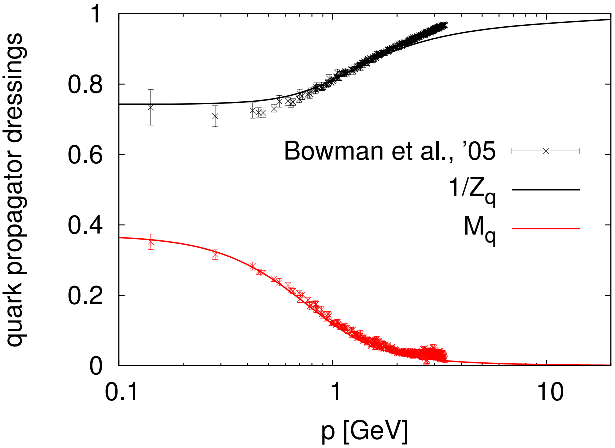
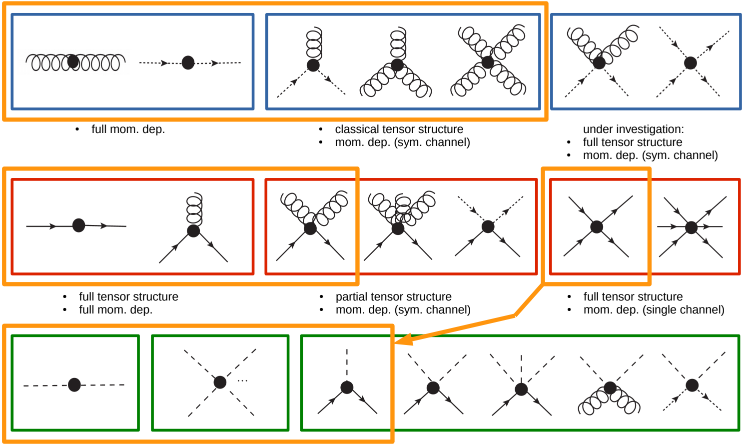


- FRG vs. lattice: bare mass, quenched, scale
- agreement with lattice not sufficient for $\mu \neq 0$
  $\Rightarrow$ need convergence in vertex expansion

Stability of truncation

Expansion of effective action in 1PI correlators



- full mom. dep.

- classical tensor structure
- mom. dep. (sym. channel)

under investigation:
- full tensor structure
- mom. dep. (sym. channel)

- full tensor structure
- full mom. dep.

- partial tensor structure
- mom. dep. (sym. channel)

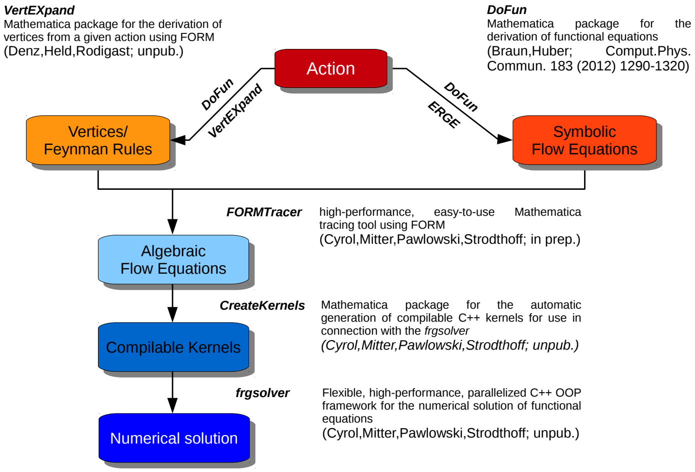
- full tensor structure
- mom. dep. (single channel)

- full mom. dep.

- via effective potential

- full tensor structure
- mom. dep. (sym. channel)

Workflow



[Cyrol, MM, Pawlowski, Strodthoff, 2013-2016]

η'-meson (screening) mass at chiral crossover

- small η'-meson mass above chiral crossover? [Kapusta, Kharzeev, McLerran, 1998]
- experiment: drop in η' mass at chiral crossover [Csörgo et al., 2010]

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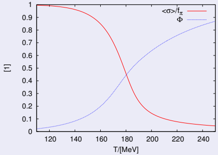
chiral crossover: Polyakov-Quark-Meson model (extended mean-field)



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

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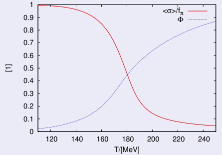

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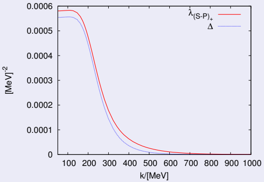
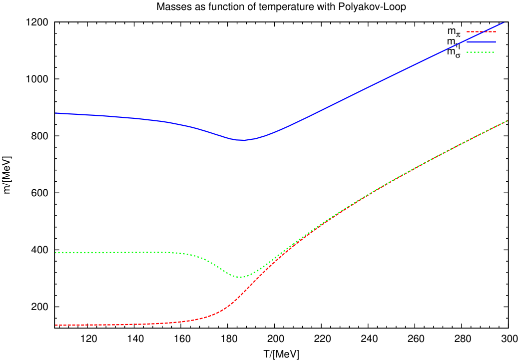
[Heller, MM, 2015]



- RG-scale dependence from fQCD
- temperature dependence $k(T)$:
  - $\lambda_{(S-P)_+,fQCD}(k) \equiv \lambda_{(S-P)_+,PQM}(T)$

η'-meson (screening) mass at chiral crossover: result



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- screening masses!

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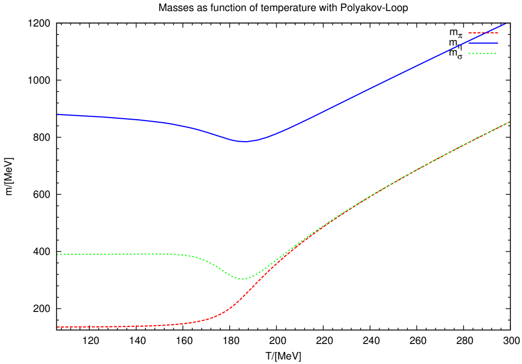
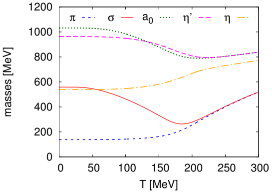


[Heller, MM, 2015]

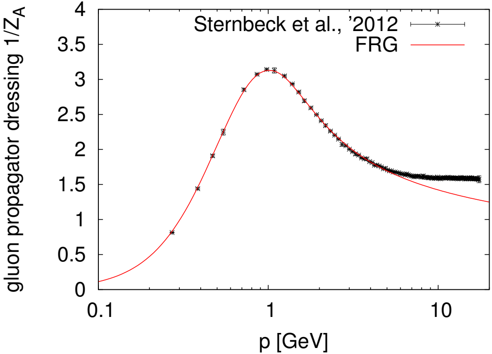
- screening masses!
- QM-Model $N_f = 2 + 1$:



[MM, Schaefer, 2013]

- chiral symmetry restoration:
  $\Rightarrow$ drop in $m_{\eta'}$

Outlook: unquenched gluon propagator



[Cyrol, MM, Pawlowski, Strodthoff, in preparation]

- self-consistent solution of classical propagators and vertices
- massless quarks: quark mass gap seems unimportant

Summary and Outlook

(quenched) QCD with functional RG

- QCD phase diagram: need for quantitative control
- 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)
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- unquenching (partially done)
- finite temperature/chemical potential
- more checks on convergence of vertex expansion
- bound-state properties (form factor,PDA. . .)