Chiral symmetry breaking in continuum QCD

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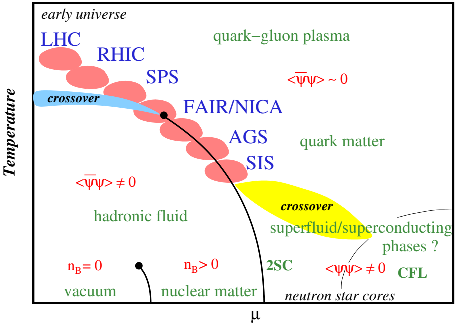
für Bildung
und Forschung

fQCD collaboration - QCD (phase diagram) with FRG:

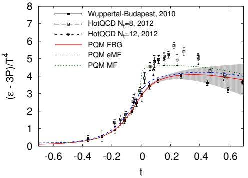
J. Braun, A. K. Cyrol, L. Fister, W. J. Fu, T. K. Herbst, MM
N. Müller, J. M. Pawlowski, S. Rechenberger, F. Rennecke, N. Strodthoff



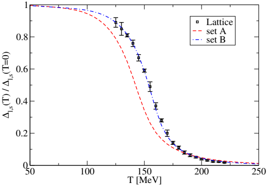
Outline

QCD phase diagram with functional methods

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



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



[Luecker, Fischer, Welzbacher, 2014]

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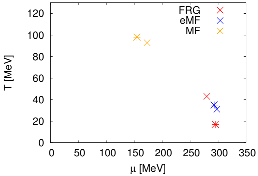

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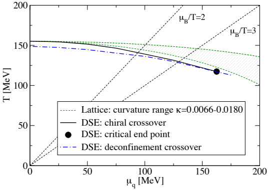

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  - Polyakov-quark-meson model with FRG:
    - inital values at $\Lambda \approx \mathcal{O}(\Lambda_{\mathrm{QCD}})$
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  - quark propagator DSE:
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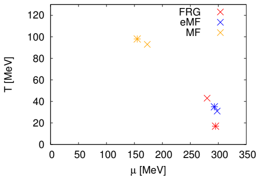

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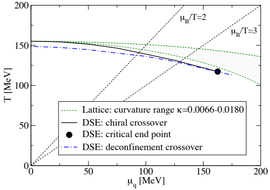

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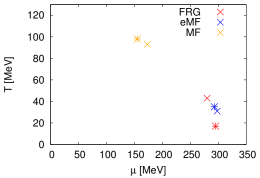

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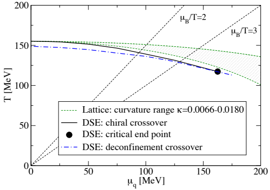

possible explanation for disagreement:

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

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

Back to QCD in the vacuum (Wetterich equation)

- use only perturbative QCD input
  - $\alpha_S(\Lambda = \mathcal{O}(10)\ \text{GeV})$
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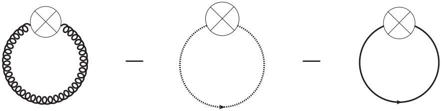
- Wetterich equation with initial condition $S[\Phi] = \Gamma_\Lambda[\Phi]$

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



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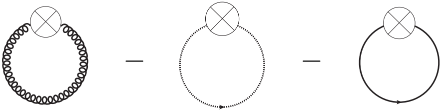

$\Rightarrow$ effective action $\Gamma[\Phi] = \lim_{k\to 0} \Gamma_k[\Phi]$

- ∂_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

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

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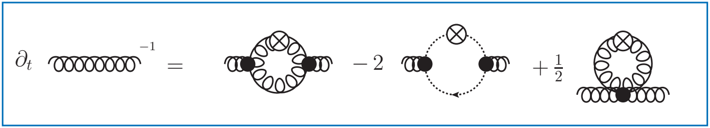
- functional derivatives with respect to $\Phi_i = A, \bar{c}, c, \bar{q}, q$:
  $\Rightarrow$ equations for 1PI n-point functions, e.g. gluon propagator:



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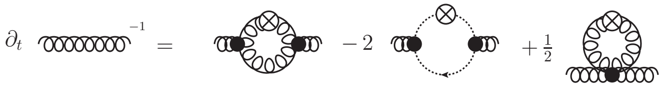

- want "apparent convergence" of $\Gamma[\Phi] = \lim_{k\to 0} \Gamma_k[\Phi]$

“Quenched” Landau gauge QCD

- two crucial phenomena: SχSB and confinement
- similar scales - hard to disentangle see e.g. [Williams, Fischer, Heupel, 2015]
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- matter part — [MM, Strodthoff, Pawlowski, 2014]
- pure YM-theory — [Cyrol, Fister, MM, Pawlowski, Strodthoff, 2016]

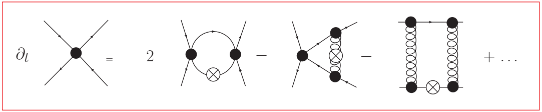
Chiral symmetry breaking

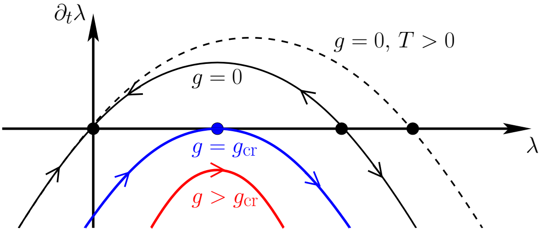
- χSB $\Leftrightarrow$ resonance in 4-Fermi interaction λ (pion pole):

Chiral symmetry breaking

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

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

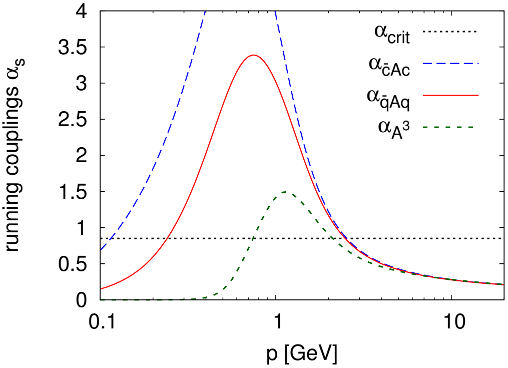




[Braun, 2011]

Effective running couplings

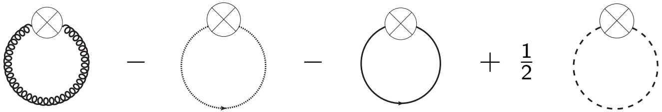
[MM, Pawlowski, Strodthoff, 2014]

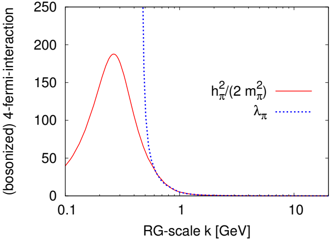


- agreement in perturbative regime required by gauge symmetry
- non-degenerate in nonperturbative regime: reflects gluon mass gap
- $\alpha_{\bar{q}Aq} > \alpha_{cr}$: necessary for chiral symmetry breaking
- area above α_{cr} very sensitive to errors

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

- change of variables: particular 4-Fermi channels → meson exchange
- efficient inclusion of momentum dependence ⇒ no singularities
- calculation of model parameters from QCD

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



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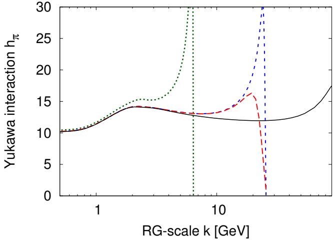

[Braun, Fister, Haas, Pawlowski, Rennecke, 2014]

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Vertex Expansion

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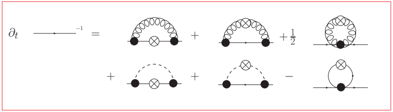

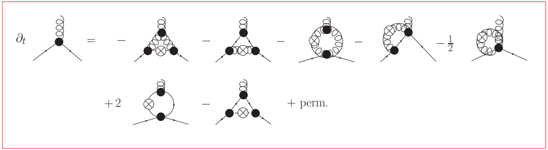

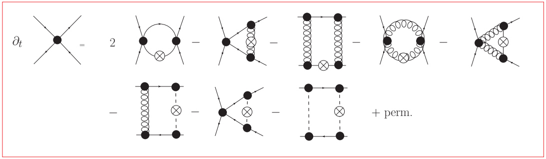

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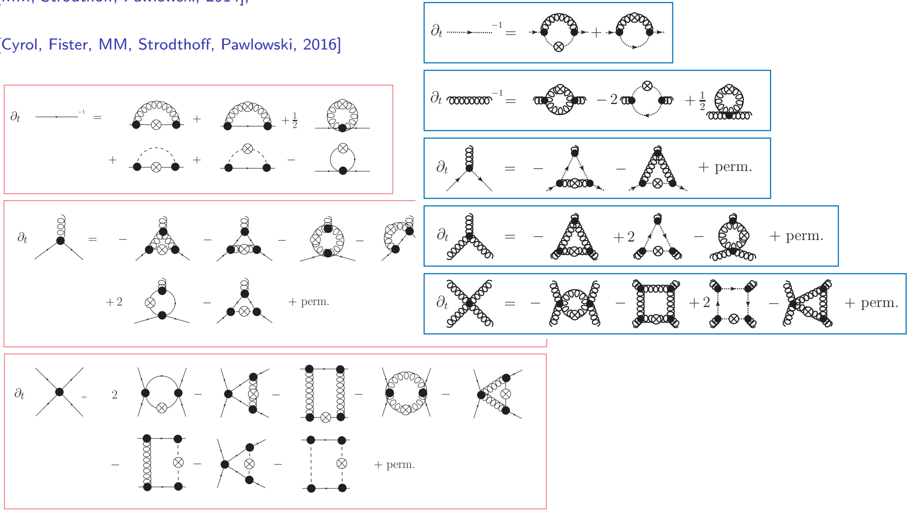

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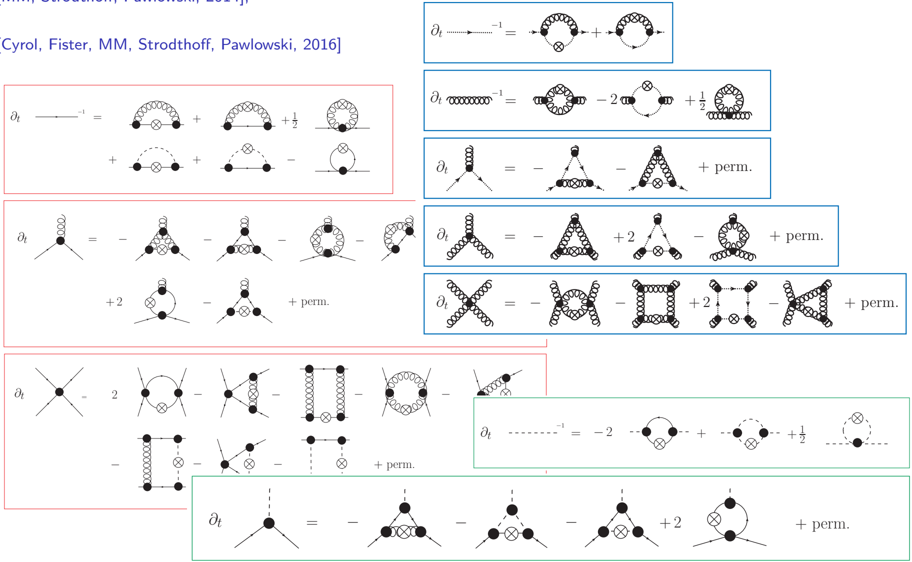
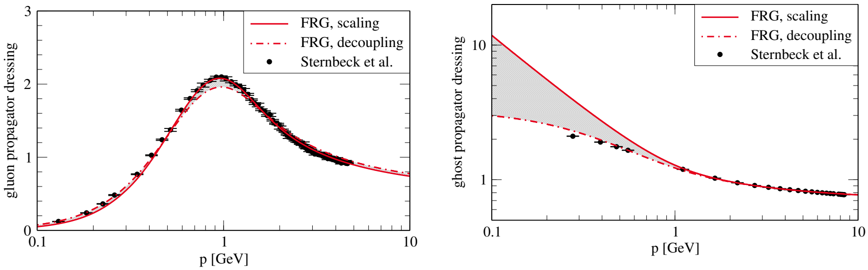


YM propagators

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

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



- band: family of decoupling solutions bounded by scaling solution

YM vertices

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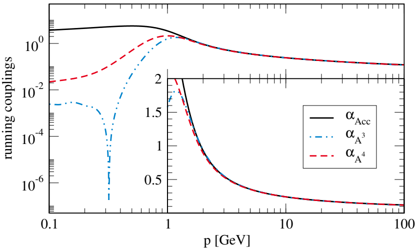
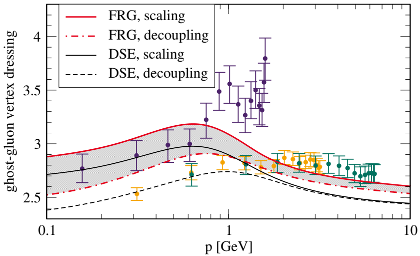


- ghost-gluon vertex: comparison to
  lattice SU(2) [Maas, unpublished]
  DSE [Huber, Smekal, 2012]



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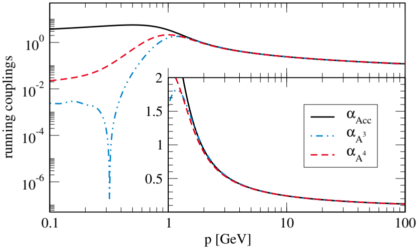

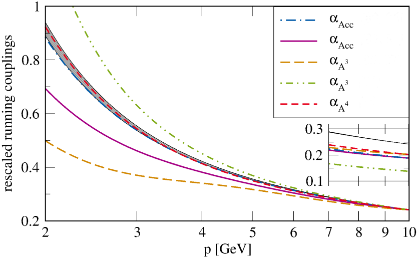

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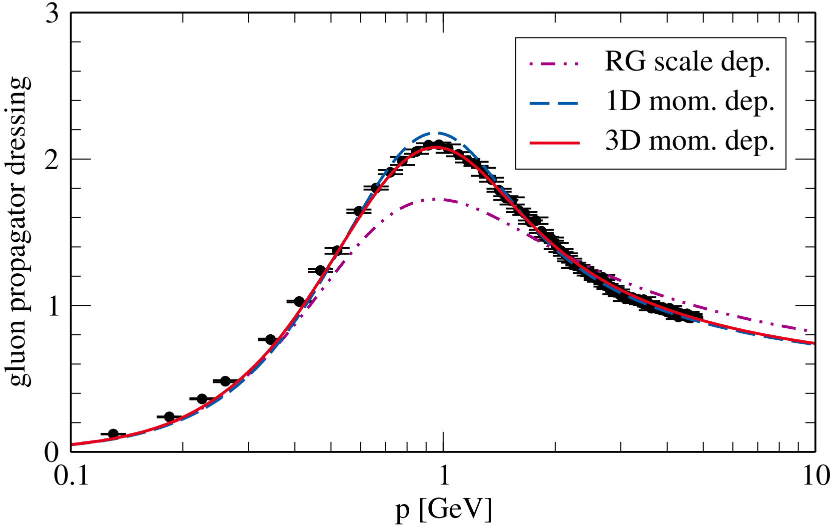
Apparent Convergence

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



Quark propagator

[MM, Pawlowski, Strodthoff, 2014]

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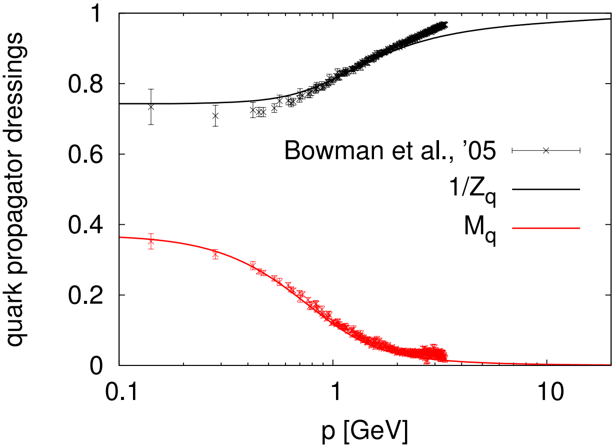

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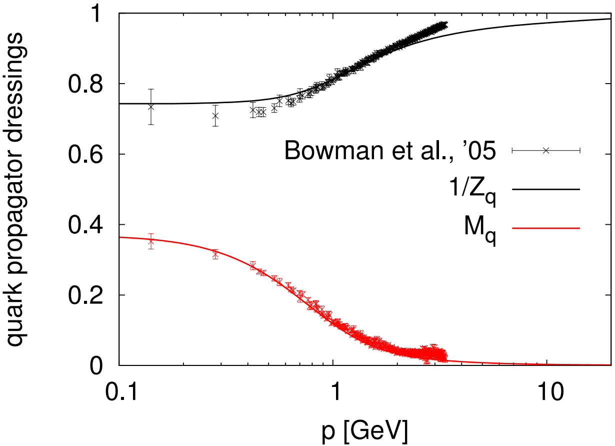
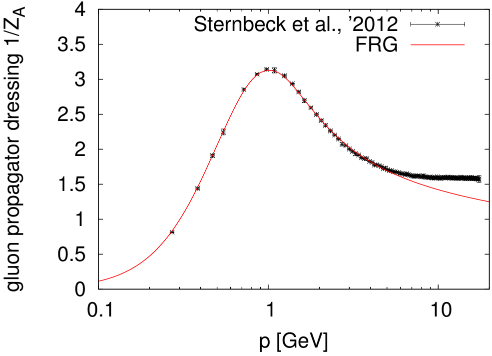


- FRG vs. lattice: bare mass, quenched, scale set via gluon propagator
- agreement not sufficient: need apparent convergence at $\mu \neq 0$

Outlook: unquenched gluon propagator

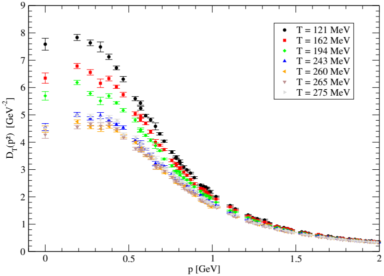


[Cyrol, MM, Pawlowski, Strodthoff, in preparation]

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

Outlook: (transversal) gluon propagator at $T \neq 0$

- **Lattice**
  [Silva, Oliveira, Bicudo, Cardoso, 2013]



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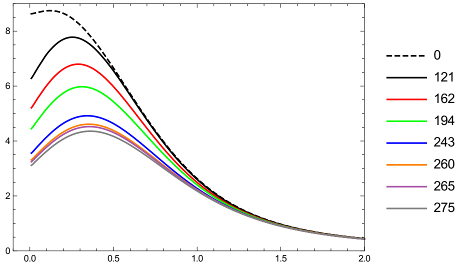

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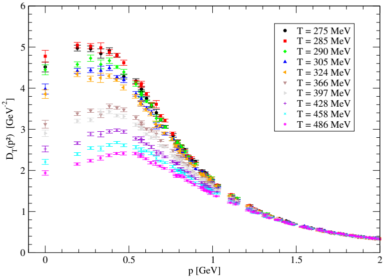

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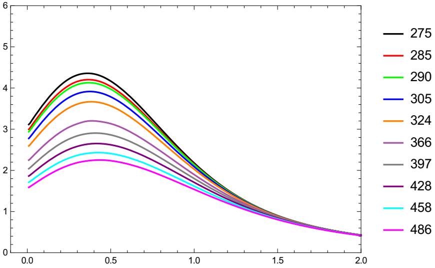

η'-meson (screening) mass at chiral crossover

- small η'-meson mass above chiral crossover? [Kapusta, Kharzeev, McLerran, 1998]
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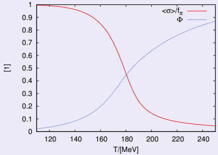
chiral crossover: Polyakov-Quark-Meson model (extended mean-field)



- $N_f = 2$ 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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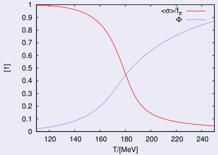

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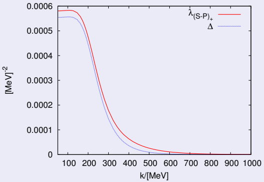
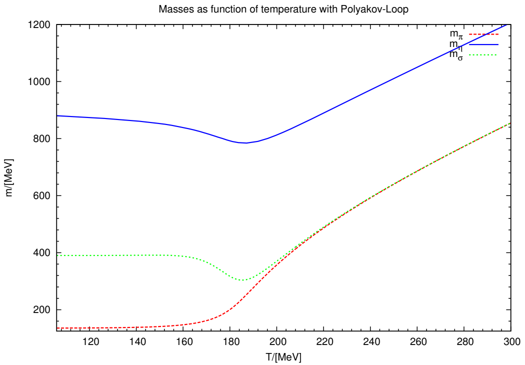
[Heller, MM, 2015]



- 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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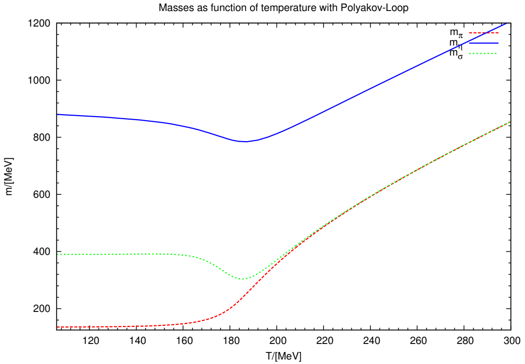

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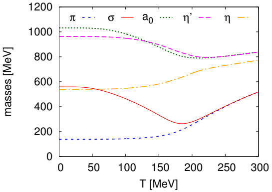
- screening masses!
- QM-Model $N_f = 2+1$:



[MM, Schaefer, 2013]

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

Summary and Outlook

(quenched) QCD with functional RG

- QCD phase diagram: need for quantitative precision
- quenched QCD in vacuum:
  - sole input $\alpha_S(\Lambda = \mathcal{O}(10)$ GeV) and $m_q(\Lambda = \mathcal{O}(10)$ GeV)
  - good agreement with lattice simulations (sufficient?)
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- unquenching (first results)
- finite temperature (first results)
- finite chemical potential
- order parameters, equation of state and fluct. of cons. charges
- more checks on convergence of vertex expansion
- bound-state properties (form factor,PDA. . .)