QCD at Finite Temperature and Density in a functional approach

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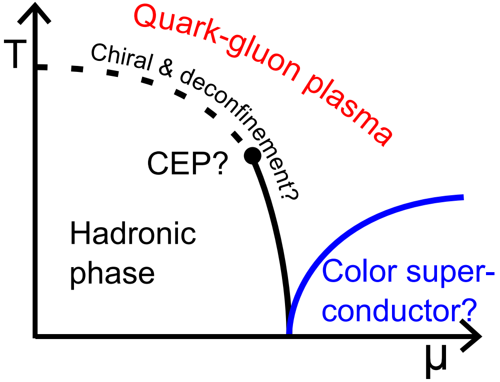
September 18, 2011

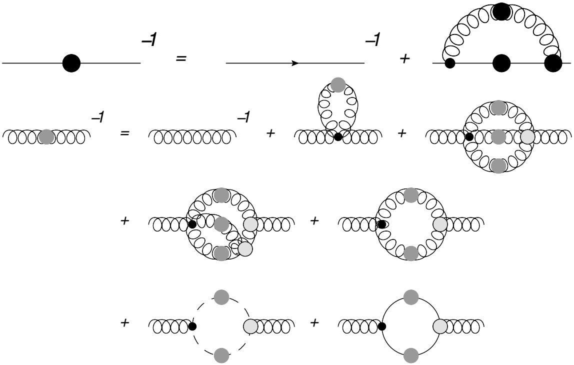
Partly published in
C. S. Fischer, JL, J. A. Mueller,
Phys.Lett. B702 (2011) 438-441

The phase diagram of QCD



Dyson-Schwinger equations

Derive from generating functional Z_{QCD}:



$+$ DSEs for all higher *n*-point functions

Order parameters: chiral symmetry breaking

Quark DSE

$$S^{-1} = Z_2 S_0^{-1} + \Sigma$$

$\Rightarrow$ Quark condensate:

$$\langle \bar{\psi}\psi \rangle = \mathrm{Tr}[S]$$

$\Rightarrow$ chiral symmetry breaking

Order parameters: confinement

Dressed Polyakov loop:

$$\Sigma_{\pm 1} = \int \frac{d\varphi}{2\pi} e^{\mp i\varphi} \langle \bar{\psi}\psi \rangle_\varphi$$

Reduces to (conjugated) Polyakov loop as $m \to \infty$
$\Rightarrow$ confinement/deconfinement

C. Gattringer, Phys. Rev. Lett. **97** (2006)
F. Synatschke, A. Wipf, C. Wozar, Phys. Rev. **D75** (2007)
E. Bilgici, F. Bruckmann, C. Gattringer, C. Hagen, Phys. Rev. **D77** (2008)

Truncation scheme

Vertex Ansatz:

$$\Gamma_\mu(p,k;q) = \gamma_\mu \cdot \Gamma(p^2,k^2,q^2) \cdot \left(\delta_{\mu,4} \frac{C(p)+C(q)}{2} + \delta_{\mu,i} \frac{A(p)+A(q)}{2} \right)$$

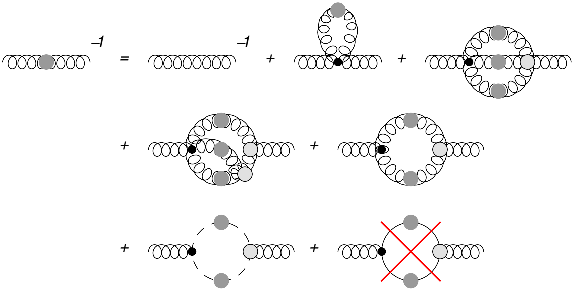
Program for the gluon:

Step 1 Quenched QCD

Step 2 Unquenching with HTL

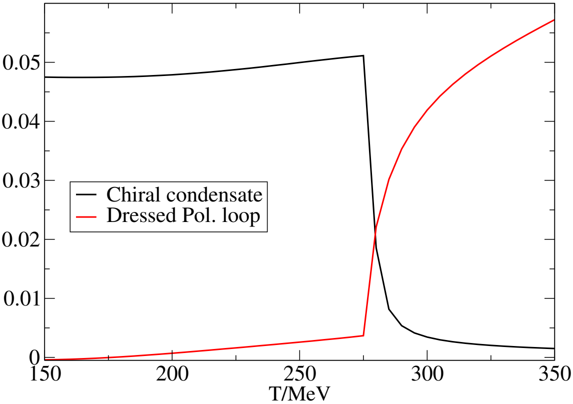
Step 3 Unquenching with dressed quarks

Quenched QCD



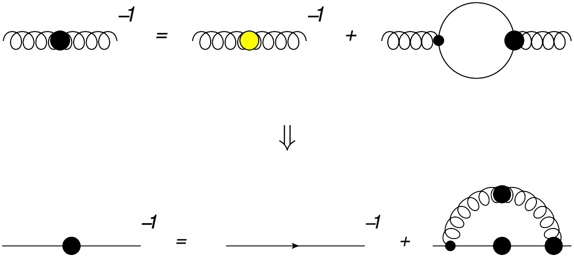
⇒ from lattice QCD (Fischer, Maas, Mueller EPJ C68)

Quenched QCD



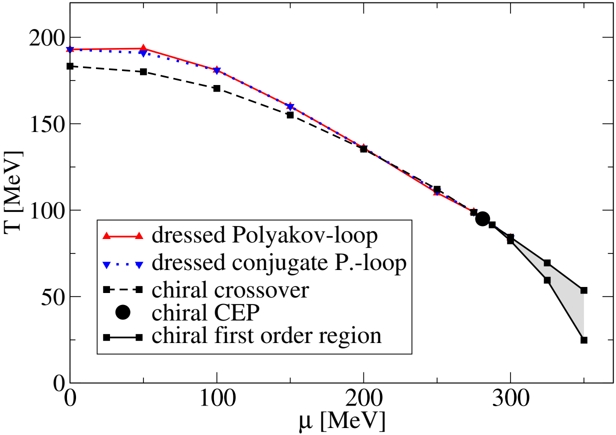
⇒ Chiral and deconfinement transitions at T_c from the lattice

Unquenching QCD with HTL



Bare quarks ⇒ Hard Thermal Loop approximation ($N_f = 2$)

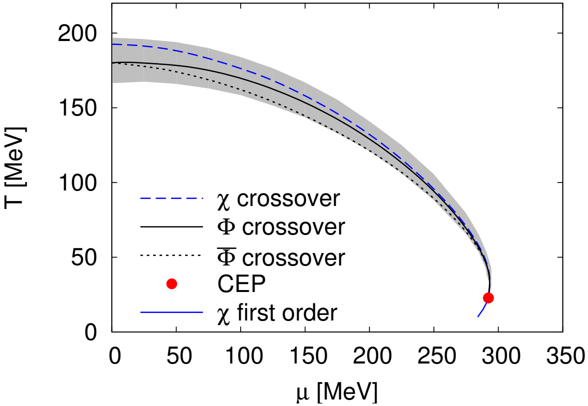
Unquenched QCD with HTL: phase diagram



Fischer, JL, Mueller PL**B702**

Coinciding chiral and deconfinement transitions, $\mu_E / T_E \approx 3$

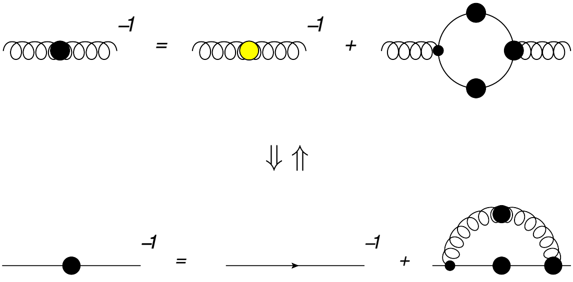
Compare: PQM model



Herbst, Pawlowski, Schaefer, arXiv:1008.0081

Both models use HTL quark loops, similar results.

Unquenched QCD with dressed quarks

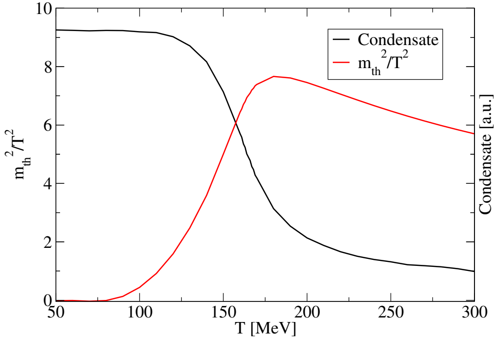


$\Rightarrow$ coupled equations

Screening mass contribution

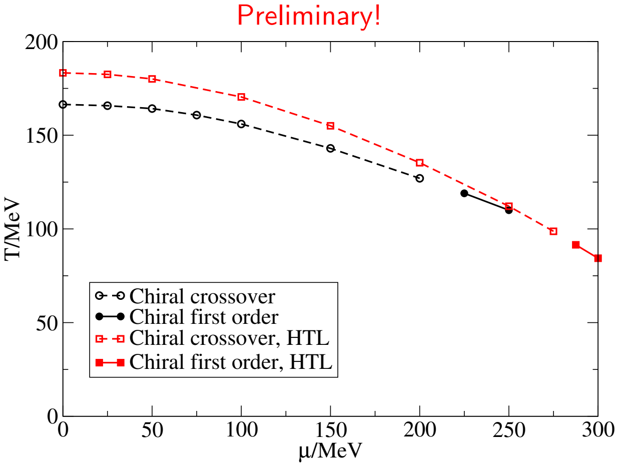
$$m_{th}^2 = \Pi_L(0)/2$$

Preliminary!



$\Rightarrow$ Back-coupling leads to steeper crossover

Phase diagram



$\Rightarrow$ CEP moves to smaller μ, $\mu_E / T_E \approx 1.7$

Summary & Outlook

- Quenched gluon from lattice
- Quark loop moves CEP to larger μ (comparable to PQM)
- Deconfinement coincides with chiral symmetry restoration
- Back-coupling quark and gluon moves CEP to smaller μ

Coming next:

- $N_f = 2 + 1 \rightarrow$ better comparison to lattice QCD
- Improved vertex: hadronic back reaction

Dual condensates I

The dual condensates[1,2,3]:

$$\Sigma_n = \int \frac{d\varphi}{2\pi} e^{-i\varphi n} \langle \bar{\psi}\psi \rangle_\varphi$$

where $\langle \bar{\psi}\psi \rangle_\varphi$ is a condensate for shifted boundary conditions:

$$\psi(\vec{x}, 1/T) = e^{i\varphi}\psi(\vec{x}, 0) \quad \varphi \in [0, 2\pi]$$

- Σ_n corresponds to loops that wind n-times around the time direction
- Spatial fluctuations are included but $1/m$ suppressed

[1] C. Gattringer, Phys. Rev. Lett. **97** (2006)
[2] F. Synatschke, A. Wipf, C. Wozar, Phys. Rev. **D75** (2007)
[3] E. Bilgici, F. Bruckmann, C. Gattringer, C. Hagen, Phys. Rev. **D77** (2008)

Dual condensates II

- $\Rightarrow \Sigma_{\pm 1}$ is the Polyakov loop for $m \to \infty$
- $\Sigma_{+1} \to$ dressed Polyakov loop
- $\Sigma_{-1} \to$ conjugated dressed Polyakov loop

$\Rightarrow$ order parameters for confinement, accessible by functional methods

- **small** in the confined phase
- **large** in the quark-gluon plasma
- crossover, since finite quark masses are used

Quark-gluon vertex

$$\Gamma_\mu(p,k;q) = \gamma_\mu \cdot \Gamma(p^2,k^2,q^2) \cdot \left(\delta_{\mu,4} \frac{C(p)+C(q)}{2} + \delta_{\mu,i} \frac{A(p)+A(q)}{2} \right)$$

HTL: $\Gamma(p^2,k^2,q^2) = \frac{d_1}{d_2+q^2} + \frac{q^2}{\Lambda^2+q^2} \left(\frac{\beta_0 \alpha(\mu) \ln[q^2/\Lambda^2+1]}{4\pi} \right)^{2\delta}$

Dressed: $\Gamma(p^2,k^2,q^2) = \left(1 + \frac{a}{q^2+b}\right) \left(1 + \frac{a}{p^2+k^2+b}\right)$

Curvature at $\mu = 0$

$$\frac{T_c(\mu)}{T_c(0)} = 1 - \kappa \left(\frac{\mu}{T}\right)^2 + \mathcal{O}((\mu/T)^4)$$

Lattice, $N_f = 2 + 1$: $\kappa \approx 0.06$ Karsch et.al Phys. Rev. **D83** (2011) 014504
This work, $N_f = 2$: $\kappa \approx 0.15$
$N_f = 2 + 1$ in progress...