Fluctuations and the QCD phase diagram

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on

Chiral Symmetry and Confinement in Cold Quark Matter

Trento, Italy

QCD Phase Transitions

QCD $\longrightarrow$ two phase transitions:

1. restoration of chiral symmetry

   $$SU_{L+R}(N_f) \longrightarrow SU_L(N_f) \times SU_R(N_f)$$

   order parameter:

   $$\langle \bar{q}q \rangle \begin{cases} > 0 \Leftrightarrow \text{symmetry broken, } T < T_c \\ = 0 \Leftrightarrow \text{symmetric phase, } T > T_c \end{cases}$$

2. de/confinement

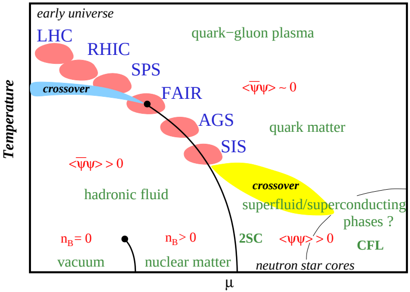
   order parameter: Polyakov loop variable

   $$\Phi \begin{cases} = 0 \Leftrightarrow \text{confined phase, } T < T_c \\ > 0 \Leftrightarrow \text{deconfined phase, } T > T_c \end{cases}$$

   $$\Phi = \left\langle \mathrm{tr}_c \mathcal{P} \exp \left(i \int_0^\beta d\tau A_0(\tau, \vec{x}) \right) \right\rangle / N_c$$

alternative: ➜ dressed Polyakov loop (or dual condensate)

it relates chiral and deconfinement transition to spectral properties of Dirac operator

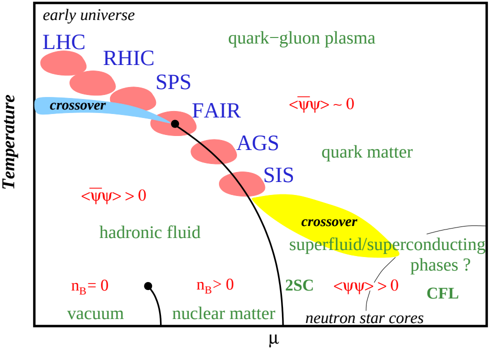


At densities/temperatures of interest only model calculations available

effective models:

1. Quark-meson model — or other models e.g. NJL
2. Polyakov–quark-meson model — or PNJL models

The conjectured QCD Phase Diagram



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Open issues:

related to chiral & deconfinement transition

- ▷ existence of CEP?
- ▷ its location?
- ▷ additional CEPs?
  How many?
- ▷ coincidence of both transitions at $\mu = 0$?
- ▷ quarkyonic phase at $\mu > 0$?
- ▷ chiral CEP/
  deconfinement CEP?
- ▷ so far only MFA results
  effect of fluctuations
  (e.g. size of crit. reg.)?
- ▷ ...

Outline

- Three-Flavor Chiral Quark-Meson Model
- ...with Polyakov loop dynamics
- The important role of fluctuations
- Finite density extrapolations

$N_f = 3$ Quark-Meson (QM) model

- Model Lagrangian: $\mathcal{L}_{\text{qm}} = \mathcal{L}_{\text{quark}} + \mathcal{L}_{\text{meson}}$

Quark part with Yukawa coupling h:

$$\mathcal{L}_{\text{quark}} = \bar{q}(i\partial\!\!\!/ - h\frac{\lambda_a}{2}(\sigma_a + i\gamma_5\pi_a))q$$

Meson part: scalar σ_a and pseudoscalar π_a nonet

fields: $M = \sum_{a=0}^{8} \frac{\lambda_a}{2}(\sigma_a + i\pi_a)$

$$\mathcal{L}_{\text{meson}} = \text{tr}[\partial_\mu M^\dagger \partial^\mu M] - m^2 \text{tr}[M^\dagger M] - \lambda_1 (\text{tr}[M^\dagger M])^2 - \lambda_2 \text{tr}[(M^\dagger M)^2] + c[\det(M) + \det(M^\dagger)]$$
$$+ \text{tr}[H(M + M^\dagger)]$$

- explicit symmetry breaking matrix: $H = \sum_a \frac{\lambda_a}{2} h_a$
- $U(1)_A$ symmetry breaking implemented by 't Hooft interaction

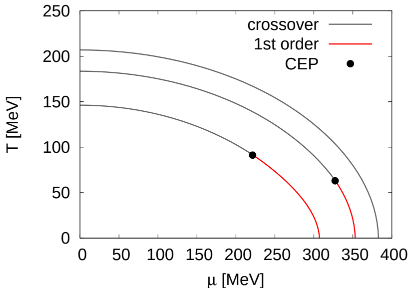
Phase diagram for $N_f = 2+1 \quad (\mu \equiv \mu_q = \mu_s)$

- Model parameter fitted to (pseudo)scalar meson spectrum:
- PDG: $f_0(600)$ mass=$(400 \ldots 1200)$ MeV $\rightarrow$ broad resonance

➜ existence of CEP depends on m_σ!

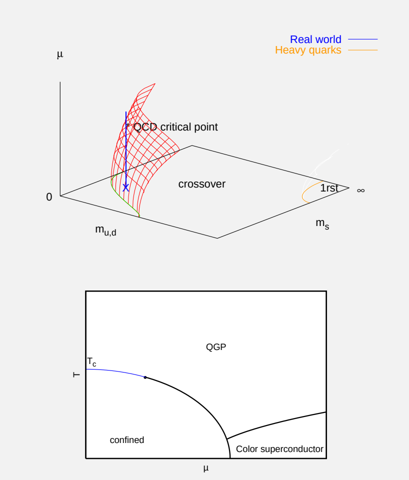
Example: $m_\sigma = 600$ MeV (lower lines), 800 and 900 MeV (here mean-field approximation)

with $U(1)_A$ **[BJS, M. Wagner '09]**

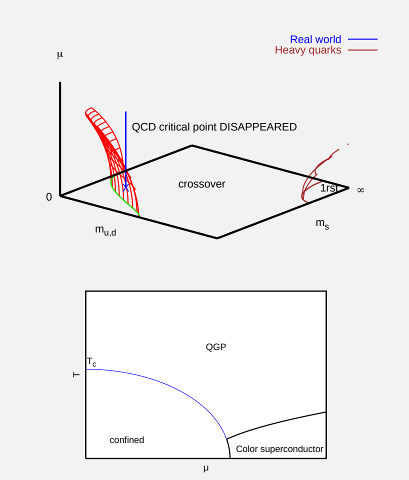


Mass sensitivity (lattice, $N_f = 3, \mu_B \neq 0$)

Standard scenario: $m_c(\mu)$ **increasing**



Nonstandard scenario: $m_c(\mu)$ **decreasing**

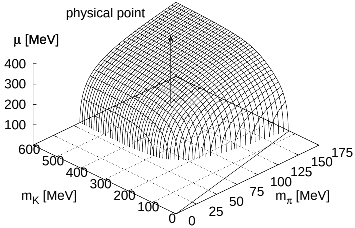


[de Forcrand, Philipsen: hep-lat/0611027]

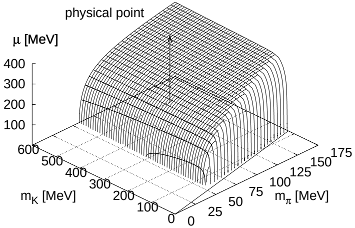
Chiral critical surface ($m_\sigma = 800$ MeV)

➜ standard scenario for $m_\sigma = 800$ MeV (as expected)

with $U(1)_A$



without $U(1)_A$



[BJS, M. Wagner, '09]

Note: 't Hooft coupling μ-independent

PNJL with (unrealistic) large vector int. $\rightarrow$ bending of surface

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- ○ The important role of fluctuations
- ○ Finite density extrapolations

Polyakov-quark-meson (PQM) model

- Lagrangian $\mathcal{L}_{\text{PQM}} = \mathcal{L}_{\text{qm}} + \mathcal{L}_{\text{pol}}$ with $\mathcal{L}_{\text{pol}} = -\bar{q}\gamma_0 A_0 q - \mathcal{U}(\phi, \bar{\phi})$

- **polynomial Polyakov loop potential:** **Polyakov 1978, Meisinger 1996, Pisarski 2000**

$$\frac{\mathcal{U}(\phi, \bar{\phi})}{T^4} = -\frac{b_2(T, T_0)}{2}\phi\bar{\phi} - \frac{b_3}{6}\left(\phi^3 + \bar{\phi}^3\right) + \frac{b_4}{16}\left(\phi\bar{\phi}\right)^2$$

with

$$b_2(T, T_0) = a_0 + a_1(T_0/T) + a_2(T_0/T)^2 + a_3(T_0/T)^3$$

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- **logarithmic potential:** **Rössner et al. 2007**

$$\frac{\mathcal{U}_{\text{log}}}{T^4} = -\frac{1}{2}a(T)\bar{\phi}\phi + b(T)\ln\left[1 - 6\bar{\phi}\phi + 4\left(\phi^3 + \bar{\phi}^3\right) - 3\left(\bar{\phi}\phi\right)^2\right]$$

with

$$a(T) = a_0 + a_1(T_0/T) + a_2(T_0/T)^2 \quad \text{and} \quad b(T) = b_3(T_0/T)^3$$

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- **Fukushima** **Fukushima 2008**

$$\mathcal{U}_{\text{Fuku}} = -bT\left\{54e^{-a/T}\phi\bar{\phi} + \ln\left[1 - 6\bar{\phi}\phi + 4\left(\phi^3 + \bar{\phi}^3\right) - 3\left(\bar{\phi}\phi\right)^2\right]\right\}$$

with

a controls deconfinement b strength of mixing chiral & deconfinement

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in presence of dynamical quarks: $T_0 = T_0(N_f, \mu)$ **BJS, Pawlowski, Wambach, 2007**

N_f	0	1	2	$2+1$	3
T_0 [MeV]	270	240	208	187	178

$\mu \neq 0 :$ $\bar{\phi} > \phi$

since $\bar{\phi}$ is related to free energy gain of antiquarks

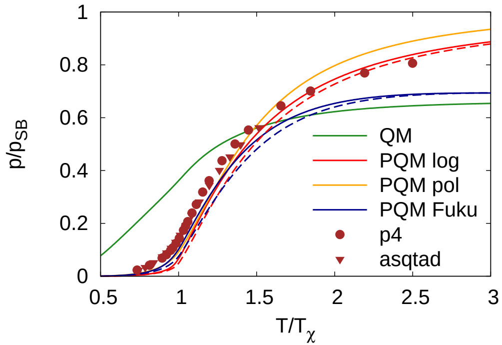
in medium with more quarks $\rightarrow$ antiquarks are more easily screened.

QCD Thermodynamics $N_f = 2 + 1$

[BJS, M. Wagner, J. Wambach '10]

SB limit: $\frac{p_{SB}}{T^4} = 2(N_c^2 - 1)\frac{\pi^2}{90} + N_f N_c \frac{7\pi^2}{180}$

(P)QM models (three different Polyakov loop potentials) versus QCD lattice simulations



- ▷ solid lines: PQM with lattice masses (HotQCD)

  $m_\pi \sim 220, m_K \sim 503$ MeV
- ▷ dashed lines: (P)QM with realistic masses

lattice data: [Bazavov et al. '09]

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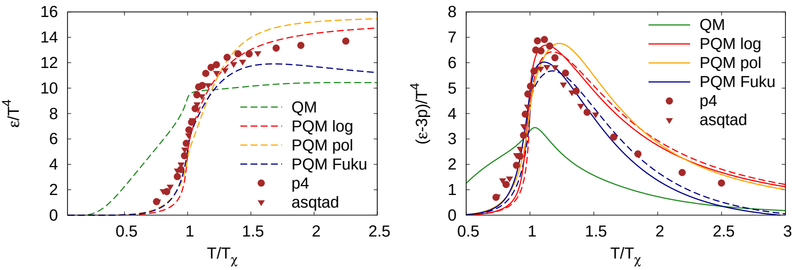

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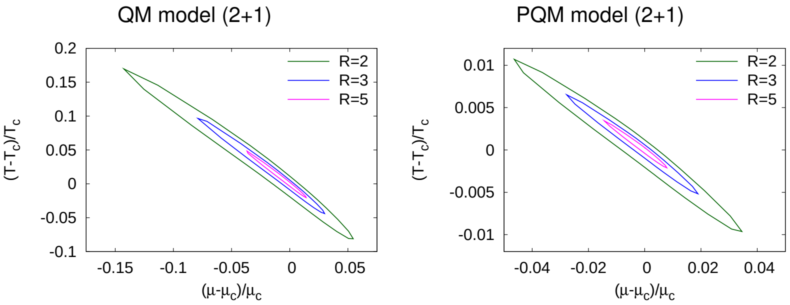
[Bazavov et al. '09]

Critical region

contour plot of **size of the critical region** around CEP

defined via fixed ratio of susceptibilities: $R = \chi_q/\chi_q^{\text{free}}$

➜ compressed with Polyakov loop



[BJS, M. Wagner; in preparation]

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Importance of Dirac term

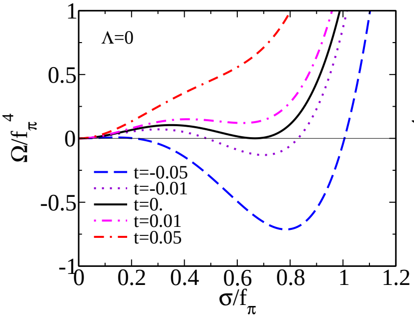
[V. Skokov, B. Friman, K.Redlich, BJS; arXiv:1005.3166]

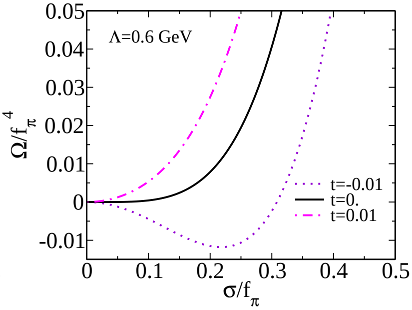
Thermodynamic potential (numerical results for $\mu = 0$)

$$\Omega = U_{\text{Pol}} + U_{\text{meson}} + \Omega_{q\bar{q}} \qquad \text{with}$$

$$\Omega_{q\bar{q}} = -2N_f \int \frac{d^3p}{(2\pi)^3} \left\{ N_c E_q \theta(p^2 - \Lambda^2) + T \ln N_q + T \ln N_{\bar{q}} \right\}$$

$$N_q = 1 + 3\Phi e^{-\beta(E_q - \mu)} + 3\bar{\Phi} e^{-2\beta(E_q-\mu)} + e^{-3\beta(E_q-\mu)}$$





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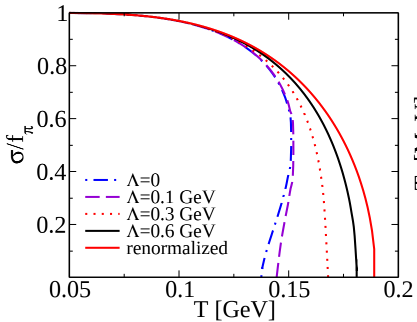

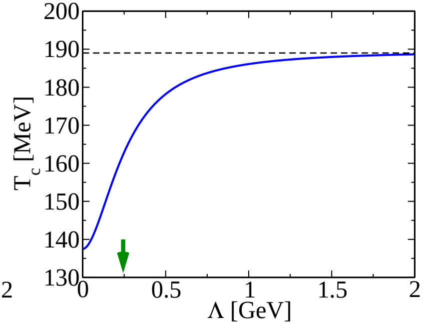

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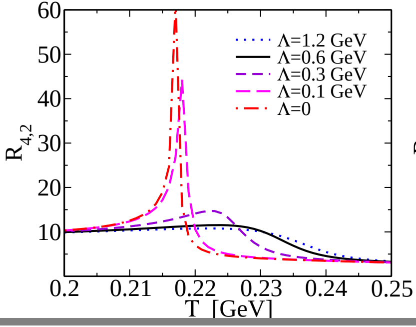
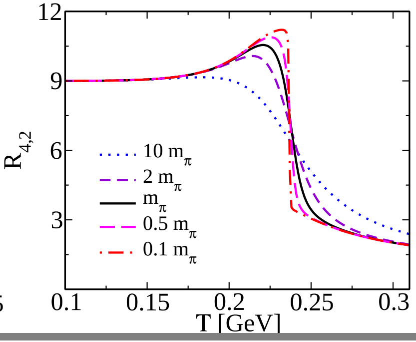




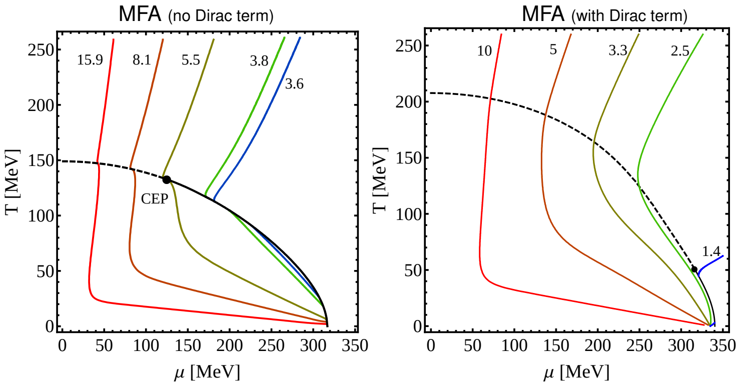
Isentropes $s/n = \text{const}$ and Focussing

[E. Nakano, BJS, B.Stokic, B.Friman, K.Redlich '10]

here: $N_f = 2$ QM model: kink in MFA are washed out in FRG

→ no focussing if fluctuations taken into account

a) influence of Dirac term   b) smallnest of critical region



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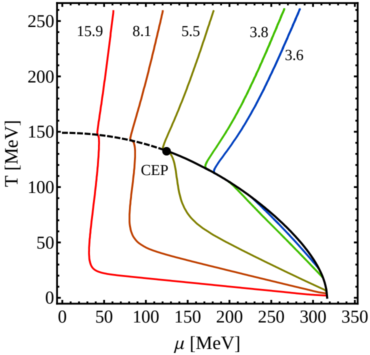
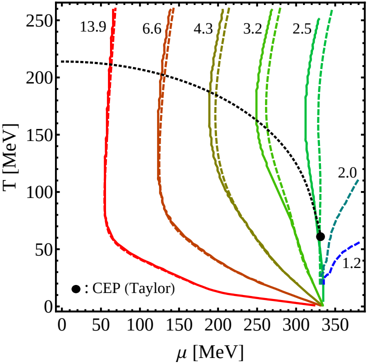
MFA (no Dirac term)



FRG (full grid and Taylor expansion)



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kink structure at boundary in mean field approximation

$\Rightarrow$ remnant of first-order transition in chiral limit

if Dirac term neglected

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in presence of dynamical quarks: $T_0 = T_0(N_f, \mu)$ **BJS, Pawlowski, Wambach, 2007**

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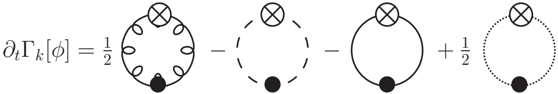
since $\bar{\phi}$ is related to free energy gain of antiquarks

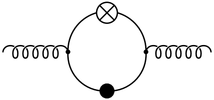
in medium with more quarks → antiquarks are more easily screened.

$\mathbf{T}_0(N_f, \mu)$ modification

full QCD FRG flow: gluon , ghosts, quark and meson (via hadronization) fluctuations
cf talk by J.M.Pawlowski



in presence of dynamical quarks
gluonic contribution modified:



pure YM flow
(→ Polyakov loop potential):

$$T_0 \leftrightarrow \Lambda_{QCD} \quad : \quad T_0 \rightarrow T_0(N_f, \mu)$$

[BJS, Pawlowski, Wambach, 2007]
[Herbst, Pawlowski,BJS; in preparation]

Phase diagram $N_f = 2 + 1$

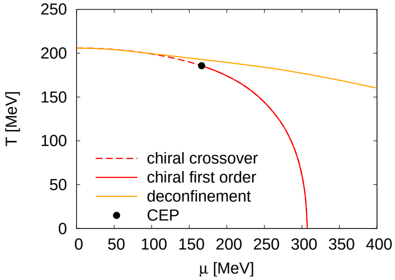
[BJS, M. Wagner; in preparation]

influence of Polyakov loop

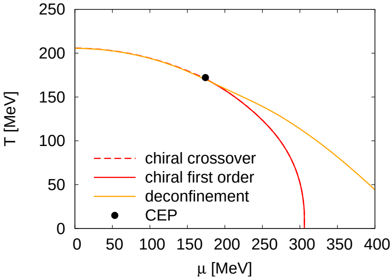
Logarithmic Polyakov loop potential

Mean-field approximation

$T_0 = 270$ MeV (constant)



$T_0(\mu)$ (i.e. with μ corrections)



shrinking of possible quarkyonic phase

Functional Renormalization Group

similar conclusion if **fluctuations** are included cf. talk by Jan Pawlowski (yesterday)

[Wetterich '93]

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \mathrm{Tr}\, \partial_t R_k \left(\frac{1}{\Gamma_k^{(2)} + R_k} \right) \qquad ; \qquad \Gamma_k^{(2)} = \frac{\delta^2 \Gamma_k}{\delta\phi\delta\phi}$$

$\Gamma_k[\phi]$ scale dependent effective action ; $t = \ln(k/\Lambda)$; R_k regulators

PQM truncation $N_f = 2$ **T.K.Herbst,J.M. Pawlowski, BJS, in preparation**

$$\Gamma_k = \int d^4x \left\{ \bar\psi \left(\not{D} + \mu\gamma_0 + ih(\sigma + i\gamma_5 \vec\tau\vec\pi) \right) \psi + \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec\pi)^2 + \Omega_k[\sigma, \vec\pi, \Phi, \bar\Phi] \right\}$$

Initial action at UV scale Λ:

$$\Omega_\Lambda[\sigma, \vec\pi, \Phi, \bar\Phi] = U(\sigma, \vec\pi) + \mathcal{U}(\Phi, \bar\Phi) + \Omega_\Lambda^\infty[\sigma, \vec\pi, \Phi, \bar\Phi]$$

$$U(\sigma, \vec\pi) = \frac{\lambda}{4}(\sigma^2 + \vec\pi^2 - v^2)^2 - c\sigma$$

Functional Renormalization Group

[Wetterich '93]

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Flow equation for PQM $\mathrm{N_f} = 2$ **T.K.Herbst,J.M. Pawlowski, BJS, in preparation**

$$\partial_t \Omega_k = \frac{k^5}{12\pi^2} \left[-\frac{2N_f N_c}{E_q} \left\{ 1 - N_q(T,\mu;\Phi,\bar\Phi) + N_{\bar q}(T,\mu;\Phi,\bar\Phi) \right\} + \frac{1}{E_\sigma} \coth\left(\frac{E_\sigma}{2T}\right) + \frac{3}{E_\pi} \coth\left(\frac{E_\pi}{2T}\right) \right]$$

with $E_{\sigma,\pi,q} = \sqrt{k^2 + m^2_{\sigma,\pi,q}}\,,\ m_\sigma^2 = 2\Omega_k' + 4\sigma^2\Omega_k''\,,\ m_\pi^2 = 2\Omega_k'\,,\ m_q^2 = g^2\sigma^2$

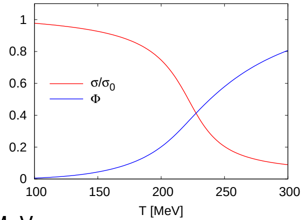
and

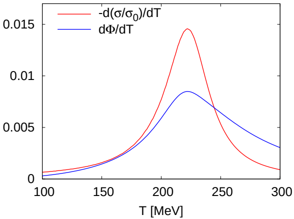
$$N_q(T,\mu;\Phi,\bar\Phi) = \frac{1 + 2\bar\Phi e^{\beta(E_q-\mu)} + \Phi e^{2\beta(E_q-\mu)}}{1 + 3\bar\Phi e^{\beta(E_q-\mu)} + 3\Phi e^{2\beta(E_q-\mu)} + e^{3\beta(E_q-\mu)}}$$

$$N_{\bar q}(T,\mu;\Phi,\bar\Phi) = N_q(T,-\mu;\Phi,\bar\Phi)|_{\mu\to-\mu}$$

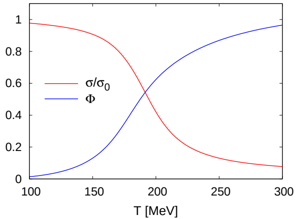
$\mu = 0$: order parameters and T-derivatives

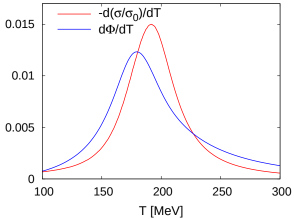
$T_0 = 270$ MeV



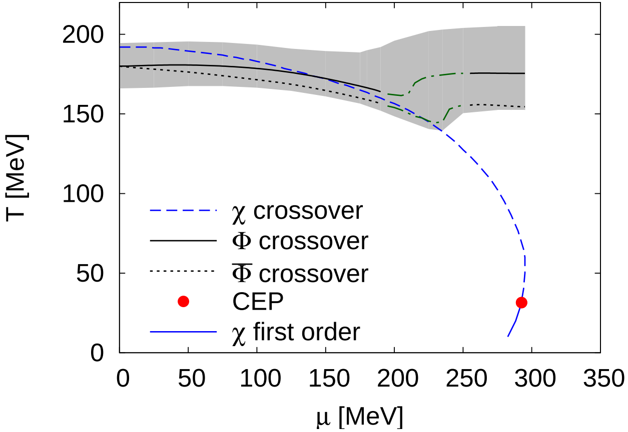


$T_0 = 208$ MeV



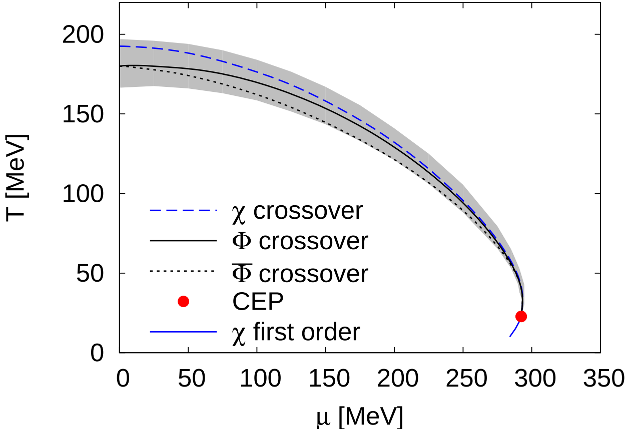


Phase diagram $T_0 = 208$ MeV



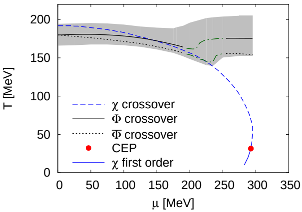
[Herbst, Pawlowski,BJS; in preparation]

Phase diagram $T_0(\mu), T_0(0) = 208$ MeV

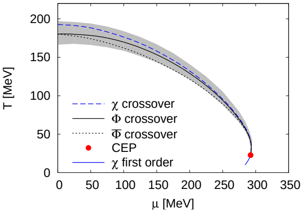


[Herbst, Pawlowski,BJS; in preparation]

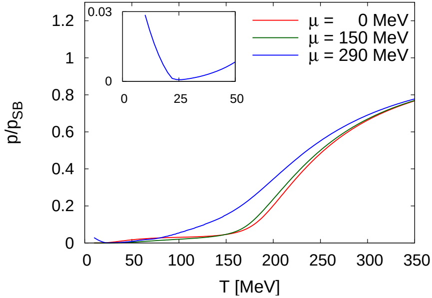
Thermodynamics

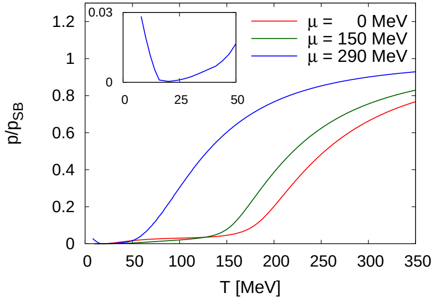


$T_0 = 208$ MeV

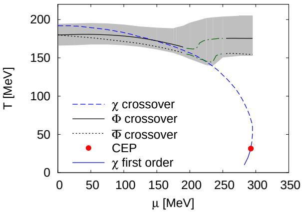


$T_0(\mu)$ MeV

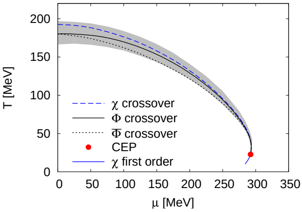




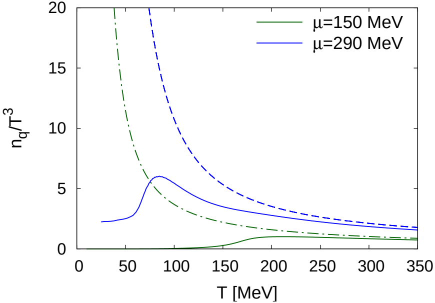
Thermodynamics

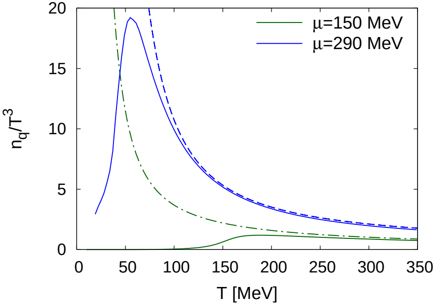


$T_0 = 208$ MeV

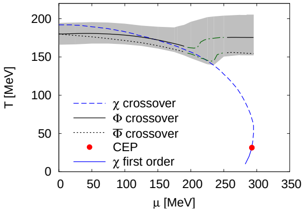


$T_0(\mu)$ MeV

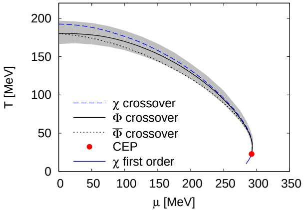




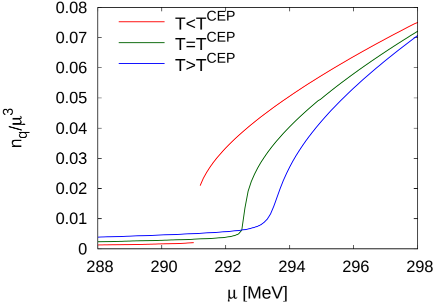
Thermodynamics

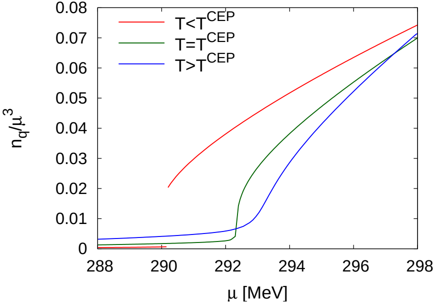


$T_0 = 208$ MeV

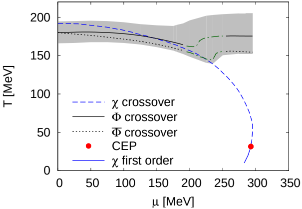


$T_0(\mu)$ MeV

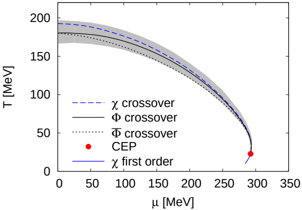




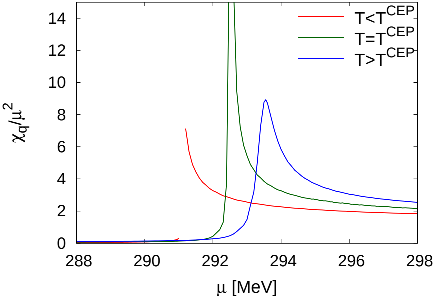
Thermodynamics

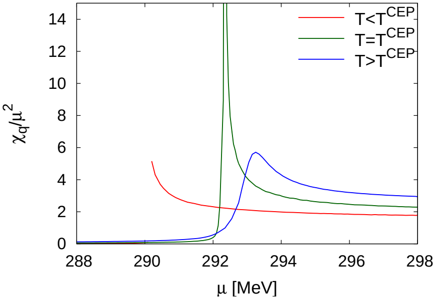


$T_0 = 208$ MeV



$T_0(\mu)$ MeV





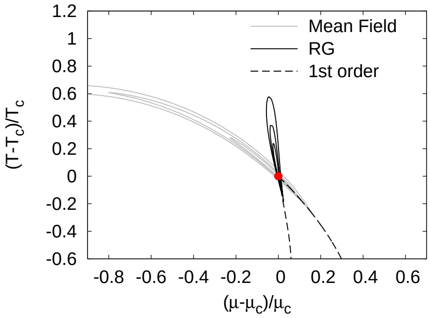
Critical region

similar conclusion if **fluctuations** are included

fluctuations via Functional Renormalization Group

comparison: $N_f = 2$ **QM model**

Mean Field $\leftrightarrow$ RG analysis

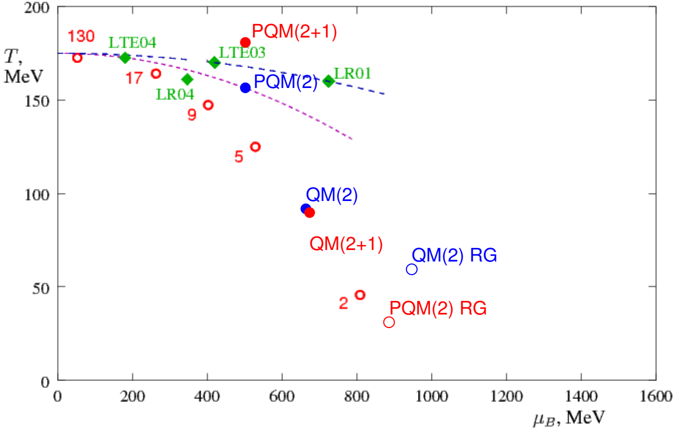


[BJS, J. Wambach '06]

Critical Endpoints

model studies vs. lattice simulations

Blue points: models   Lines & green points: lattice   Red circles: Freezeout points for HIC



lattice methods:

- reweighting
- imaginary μ_B
- Taylor expansion around $\mu_B = 0$

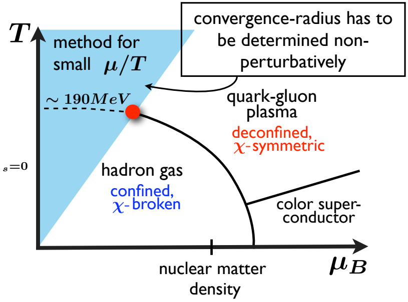
Outline

- ○ Three-Flavor Chiral Quark-Meson Model
- ○ ...with Polyakov loop dynamics
- ○ The important role of fluctuations
- ○ **Finite density extrapolations**

Finite density extrapolations $N_f = 2 + 1$

Taylor expansion:

$$\frac{p(T,\mu)}{T^4} = \sum_{n=0}^{\infty} c_n(T) \left(\frac{\mu}{T}\right)^n \quad \text{with} \quad c_n(T) = \frac{1}{n!} \frac{\partial^n \left(p(T,\mu)/T^4\right)}{\partial (\mu/T)^n}\Bigg|_{\mu=0}$$



[C. Schmidt '09]

convergence radii:

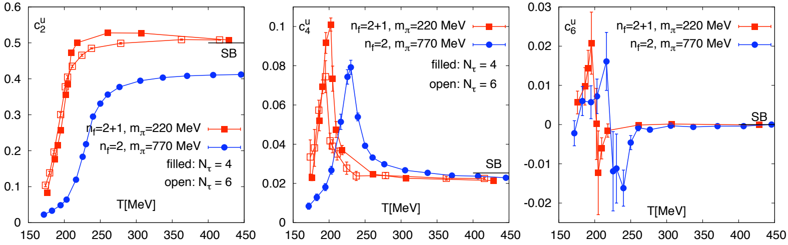
limited by first-order line?

$$\rho_{2n} = \left|\frac{c_2}{c_{2n}}\right|^{1/(2n-2)}$$

Finite density extrapolations $N_f = 2 + 1$

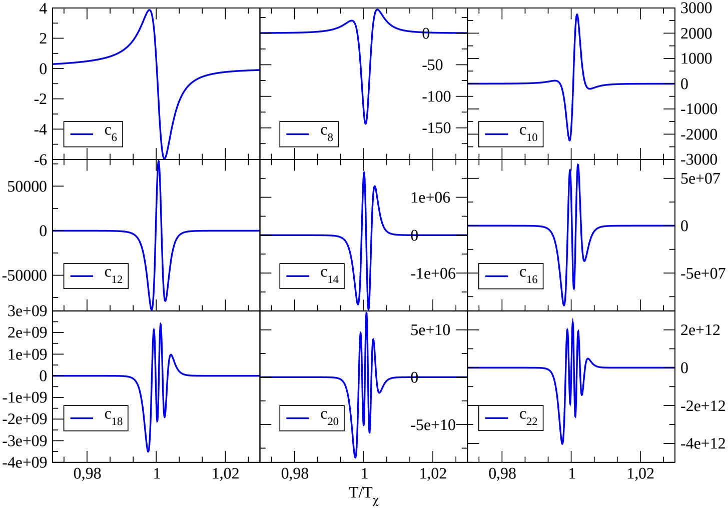
Taylor expansion:

$$\frac{p(T,\mu)}{T^4} = \sum_{n=0}^{\infty} c_n(T) \left(\frac{\mu}{T}\right)^n \quad \text{with} \quad c_n(T) = \frac{1}{n!} \frac{\partial^n \left(p(T,\mu)/T^4\right)}{\partial \left(\mu/T\right)^n}\Bigg|_{\mu=0}$$

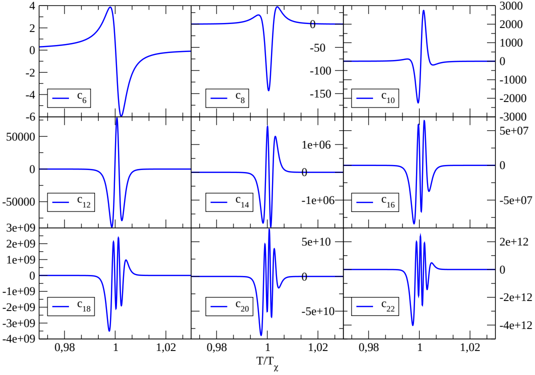


[Miao et al. '08]

Taylor coefficients c_n numerically known to high order, e.g. $n = 22$



Finite density extrapolations $N_f = 2 + 1$



- ▷ this technique applied to PQM model
- ▷ investigation of convergence properties of Taylor series
- ▷ properties of c_n
  - oscillating
  - increasing amplitude
  - no numerical noise
  - small outside transition region
  - number of roots increasing
  - 26th order

[F. Karsch, BJS, M. Wagner, J. Wambach; in preparation]

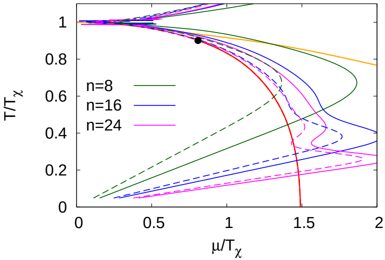
Can we locate the QCD critical endpoint with the Taylor expansion ?

Susceptibility $N_f = 2 + 1$ PQM model

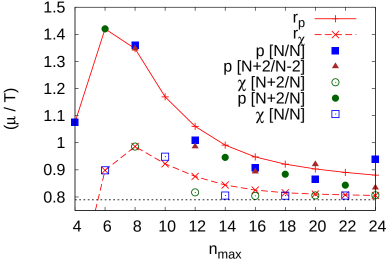
Findings:

- simply Taylor expansion: slow convergence
  high orders needed
  disadvantage for lattice simulations
- Taylor applicable within convergence radius
  also for $\mu/T > 1$

$$r_{2n} = \left| \frac{c_{2n}}{c_{2n+2}} \right|^{1/2}, \quad r^{\chi}_{2n} = \left| \frac{(2n+2)(2n+1)}{(2n+3)(2n+4)} \right|^{1/2} r_{2n+2}$$



Padé [N/N]



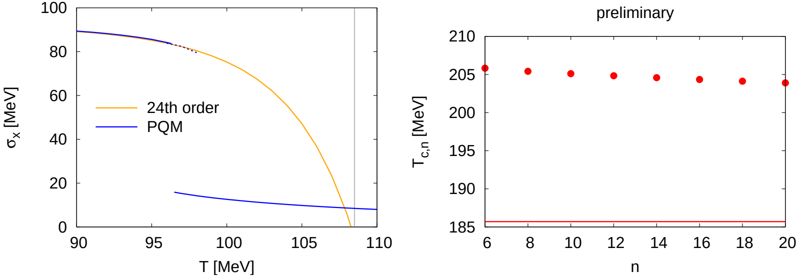
Susceptibility $N_f = 2 + 1$ PQM model

Findings:

- simply Taylor expansion: slow convergence
  high orders needed
  disadvantage for lattice simulations

- Taylor applicable within convergence radius
  also for $\mu/T > 1$

- but 1st order transition not resolvable
  expansion around $\mu = 0$



Summary

- $N_f = 2$ and $N_f = 2+1$ chiral (Polyakov)-quark-meson model study

➜ Mean-field approximation and FRG

- finite density extrapolation via novel AD technique

Findings:

▷ matter **back-reaction to YM sector**:
$T_0 \Rightarrow T_0(N_f, \mu)$

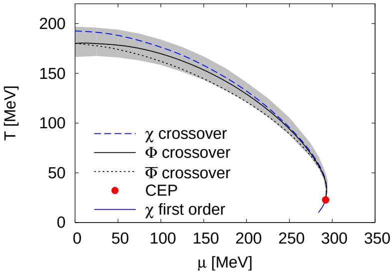
▷ **FRG with PQM truncation**: Chiral & deconfinement transition **coincide** for $N_f = 2$ with $T_0(\mu)$-corrections

▷ same conclusion for $N_f = 2+1$?

▷ **role of quantum fluctuations**

effects of Dirac term in a mean-field approximation

▷ **convergence properties** of Taylor expansion technique
$c_n(T) \to$ **high order available**



Outlook:

- include glue dynamics with FRG $\longrightarrow$ full QCD

Schladming Winter School

49. Internationale Universitätswochen für Theoretische Physik

Physics at all scales:
The Renormalization Group

Schladming, Styria, Austria, February 26 - March 5, 2011

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If you wish to apply, please access the web page and complete the registration form as soon as possible, but not later than **February 18, 2011**. More Information about the school can be found on the web page as well.

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