Fluctuations and the QCD phase diagram

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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:

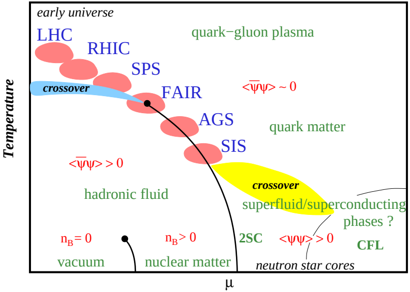
   $$\langle \bar{q} q \rangle \begin{cases} > 0 \Leftrightarrow \text{symmetry broken, } T < T_c \\ = 0 \Leftrightarrow \text{symmetric phase, } T > T_c \end{cases}$$

2. de/confinement

   order parameter: Polyakov loop variable

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

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



At densities/temperatures of interest
only model calculations available

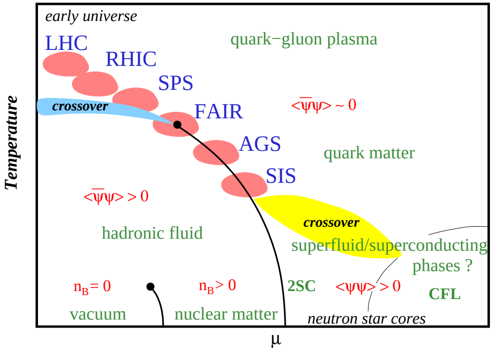
alternative: ➜ dressed Polyakov loop (or dual condensate)

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

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:

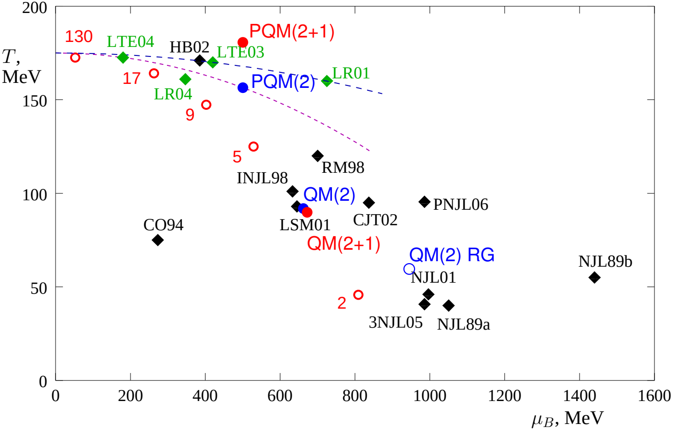
related to chiral & deconfinement transition

- ▷ 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.)?
- ▷ ...

Charts of QCD Critical End Points

model studies vs. lattice simulations

Black points: models | Lines & green points: lattice | Red points: Freezeout points for HIC



Stephanov '05 & '07

lattice methods:

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

Outline

- Three-Flavor Quark-Meson Model
- ...with Polyakov loop dynamics
- Beyond mean field approximation
- Finite density extrapolations

$\mathbf{N_f = 3}$ Quark-Meson (QM) model

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

Quark part with Yukawa coupling g:

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

Meson part: scalar σ_a and pseudoscalar π_a nonet

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

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

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

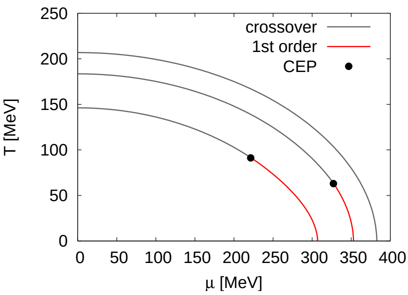
Phase diagram for $N_f = 2 + 1 \quad (\mu \equiv \mu_q = \mu_s)$

- 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]**



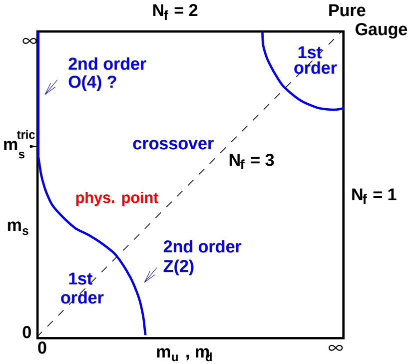
Mass sensitivity

Chiral limit: RG arguments $\rightarrow$ for $N_f \geq 3$ first-order [Pisarski, Wilczek '84]

Columbia plot: **[Brown et al. '90]**

$T_d^{N_c=3} \sim 270$ MeV

$T_\chi \sim 150 \ldots 190$ MeV



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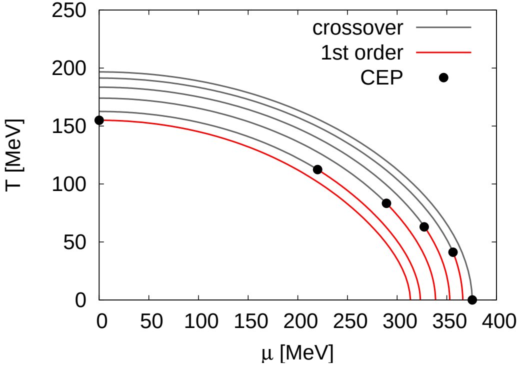
Chiral limit: RG arguments → for $N_f \geq 3$ first-order [Pisarski, Wilczek '84]

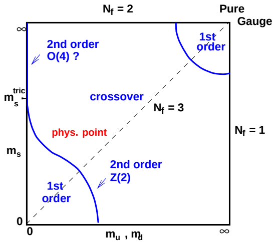
- variation of m_π and m_K:

  $m_\pi / m_\pi^* = 0.49$ (lower line), $0.6, 0.8 \ldots, 1.36$ (upper line)

  $m_\pi^* = 138$ MeV , $m_K^* = 496$ MeV , fixed ratio $m_\pi / m_K = m_\pi^* / m_K^*$

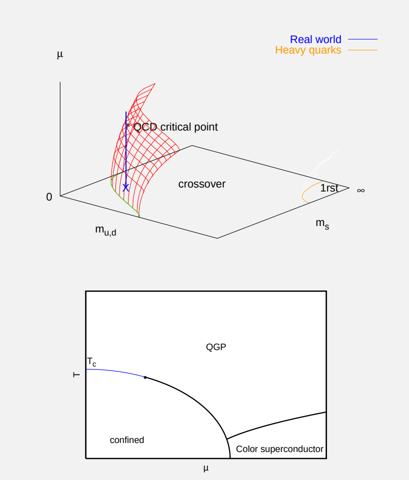
with $\mathbf{U(1)_A}$, $\mathbf{m_\sigma = 800}$ MeV



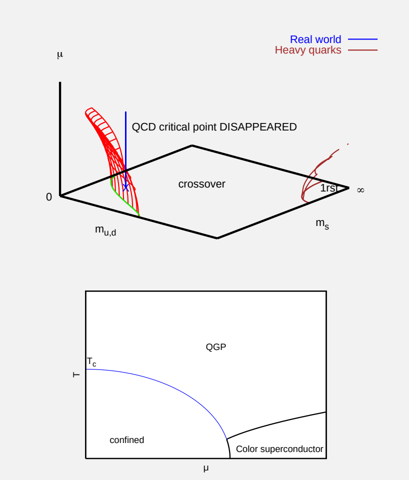


Mass sensitivity (lattice, $N_f = 3, \mu_B \neq 0$)

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



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

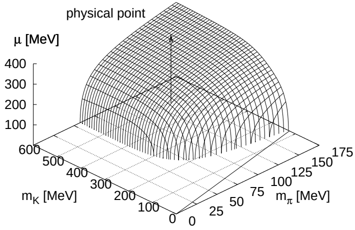


[de Forcrand, Philipsen: hep-lat/0611027]

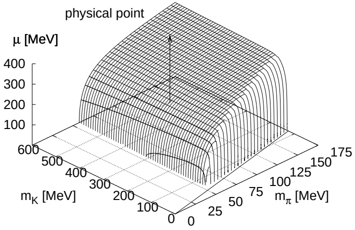
Chiral critical surface ($m_\sigma = 800$ MeV)

➜ 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

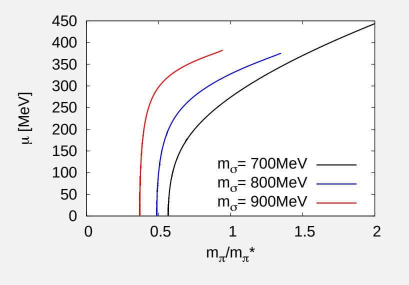
PNJL with (unrealistic) large vector int. $\longrightarrow$ bending of surface

Chiral critical surface for different m_σ

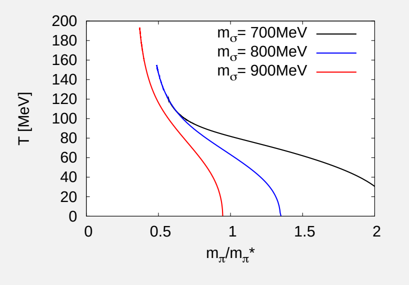
▷ CEP vanishes for $m_\sigma > 800$ MeV → **non-standard scenario possible?**

No ➜ three cuts of critical surface along fixed m_π / m_K ratio through physical point

critical μ_c



critical T_c



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- ○ Three-Flavor Quark-Meson Model
- ○ **...with Polyakov loop dynamics**
- ○ Beyond mean field approximation
- ○ Finite density extrapolations

Polyakov-quark-meson (PQM) model

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

- **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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with

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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

Polyakov-quark-meson (PQM) model

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with

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

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

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

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

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

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- ...with Polyakov loop dynamics
- **Beyond mean field approximation**
- Finite density extrapolations

Phase diagram $N_f = 2 + 1$

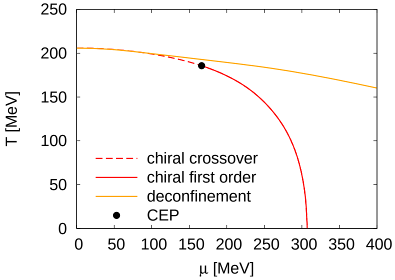
[BJS, M. Wagner; in preparation '10]

influence of Polyakov loop

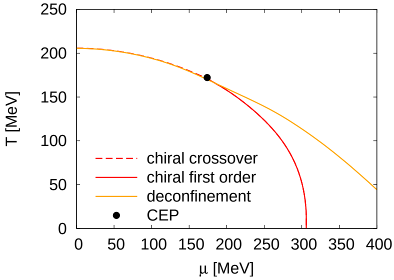
Logarithmic Polyakov loop potential

Mean-field approximation

$T_0 = 270$ MeV (constant)



$T_0(\mu)$ (i.e. with μ corrections)



shrinking of possible quarkyonic phase

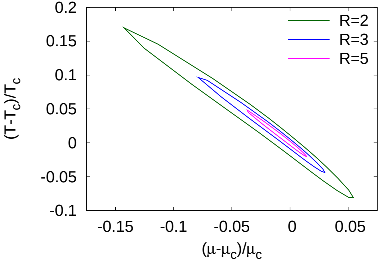
Critical region

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

QM model (2+1)



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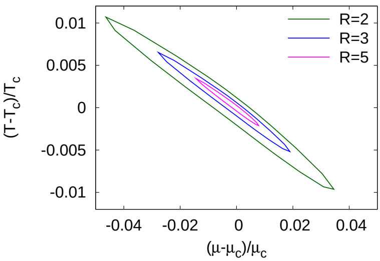


[BJS, M. Wagner; in preparation '10]

Functional Renormalization Group

similar conclusion if **fluctuations** are included

[Wetterich '93]

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

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

Flow equation for PQM $\mathbf{N_f = 2}$ **T.K.Herbst,J.M. Pawlowski, BJS, in preparation '10**

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

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

and

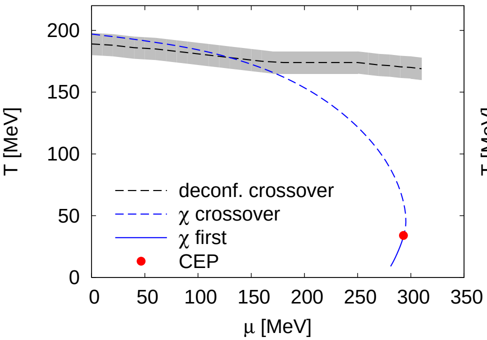
$$F_q(\Phi, \Phi^*) = \frac{-1 - \Phi^* e^{\beta(E_q - \mu)} + \Phi e^{2\beta(E_q - \mu)} + e^{3\beta(E_q - \mu)}}{1 + 3\Phi^* e^{\beta(E_q - \mu)} + 3\Phi e^{2\beta(E_q - \mu)} + e^{3\beta(E_q - \mu)}}$$

$$F_{\bar{q}}(\Phi, \Phi^*) = F_q(\Phi^*, \Phi)|_{\mu \to -\mu}$$

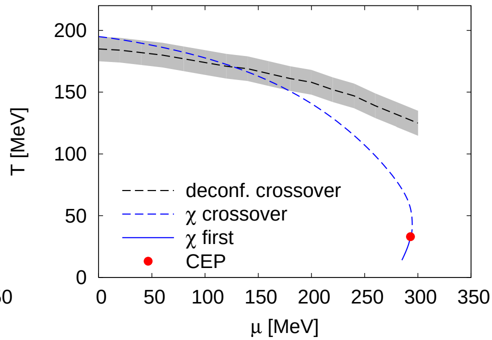
Functional Renormalization Group

Phase diagram

T_0 fixed



$T_0(\mu)$



T.K. Herbst, J.M. Pawlowski, BJS; in preparation ’10

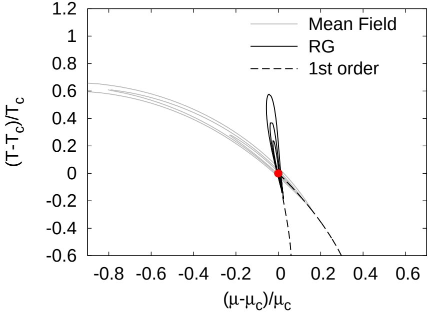
Critical region

similar conclusion if **fluctuations** are included

fluctuations via Functional Renormalization Group

comparison: $\mathbf{N_f = 2}$ **QM model**

Mean Field $\leftrightarrow$ RG analysis



[BJS, J. Wambach '06]

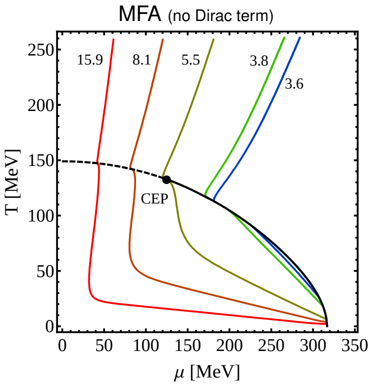
Isentropes $s/n = const$ and Focussing

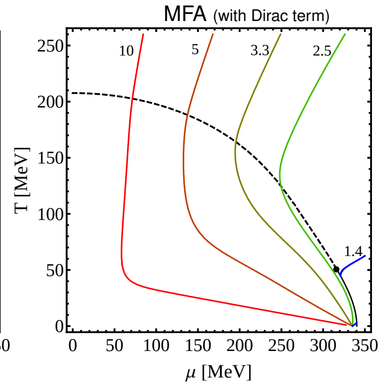
[E. Nakano, BJS, B.Stokic, B.Friman, K.Redlich '10]

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

$\rightarrow$ no focussing if fluctuations taken into account

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





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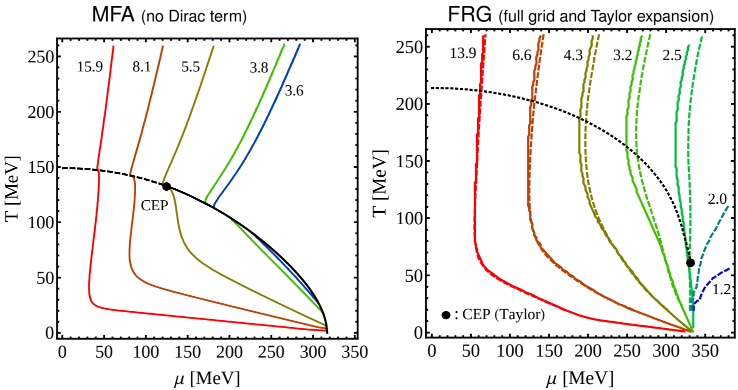

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kink structure at boundary in mean field approximation

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

if Dirac term neglected

Importance of Dirac term

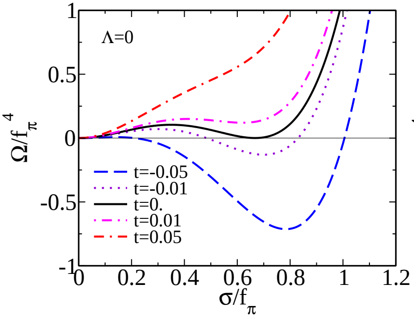
[V. Skokov, B. Friman, K.Redlich, BJS; in preparation '10]

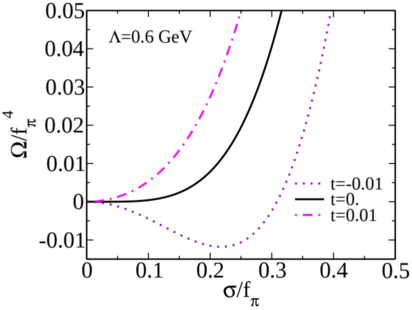
Thermodynamic potential (numerical results for $\mu = 0$)

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

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

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





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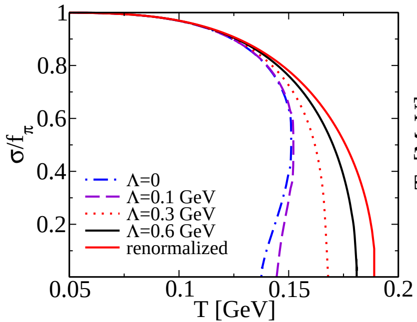

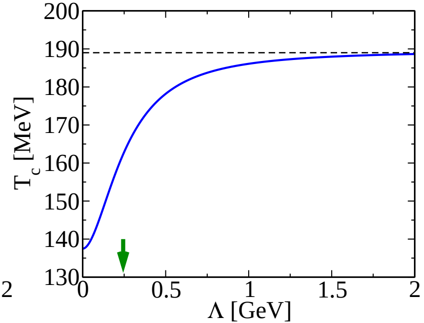

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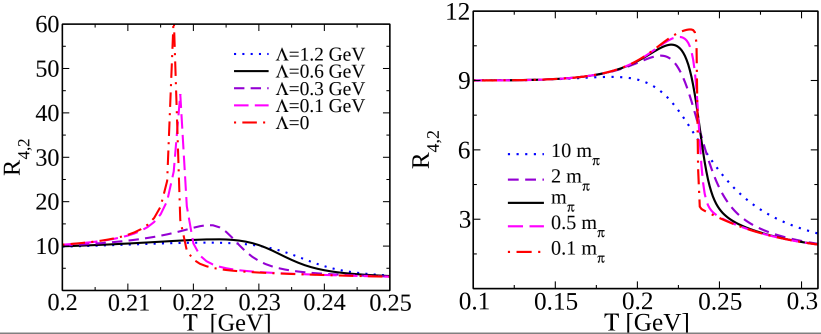
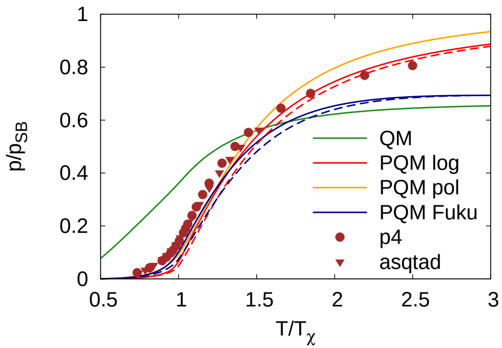


QCD Thermodynamics $N_f = 2 + 1$

[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

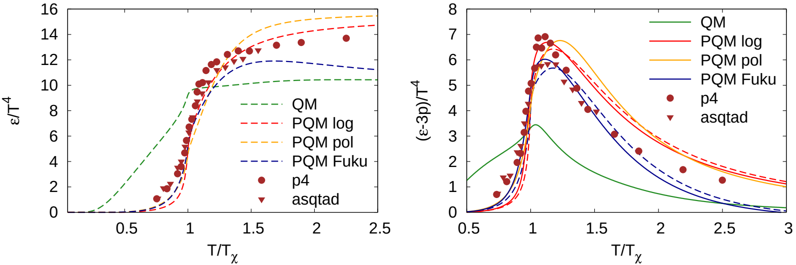
lattice data: [Bazavov et al. '09]

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: $m_\pi \sim 220, m_K \sim 503$ MeV (HotQCD)

[Bazavov et al. '09]

Outline

- ○ Three-Flavor Quark-Meson Model
- ○ ...with Polyakov loop dynamics
- ○ Beyond mean field approximation
- ○ **Finite density extrapolations**

Finite density extrapolations $\mathbf{N_f = 2 + 1}$

Taylor expansion:

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

high temperature limits:

$$c_0(T \to \infty) = \frac{7 N_c N_f \pi^2}{180} \,,$$

$$c_2(T \to \infty) = \frac{N_c N_f}{6} \,,$$

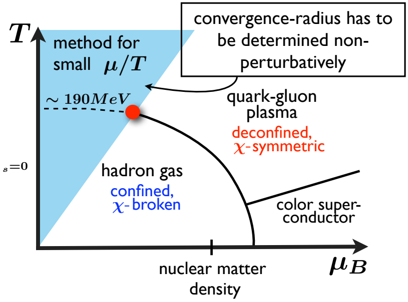
$$c_4(T \to \infty) = \frac{N_c N_f}{12\pi^2}$$

$$c_n(T \to \infty) = 0 \text{ for } n > 4.$$

Finite density extrapolations $\mathrm{N_f} = 2+1$

Taylor expansion:

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



[C. Schmidt '09]

convergence radii:

limited by first-order line?

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

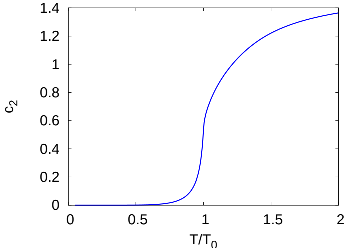
Finite density extrapolations $N_f = 2+1$

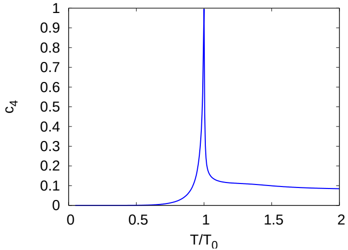
Taylor expansion:

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

first three coefficients:

c_0: pressure at $\mu = 0$

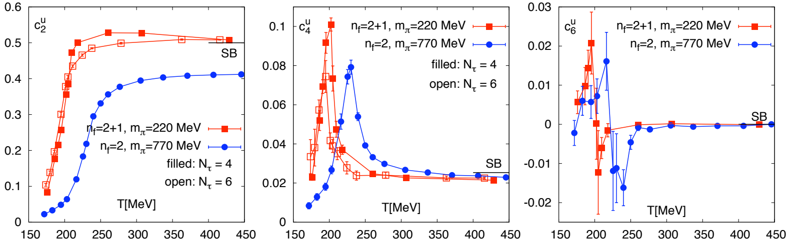




Finite density extrapolations $N_f = 2 + 1$

Taylor expansion:

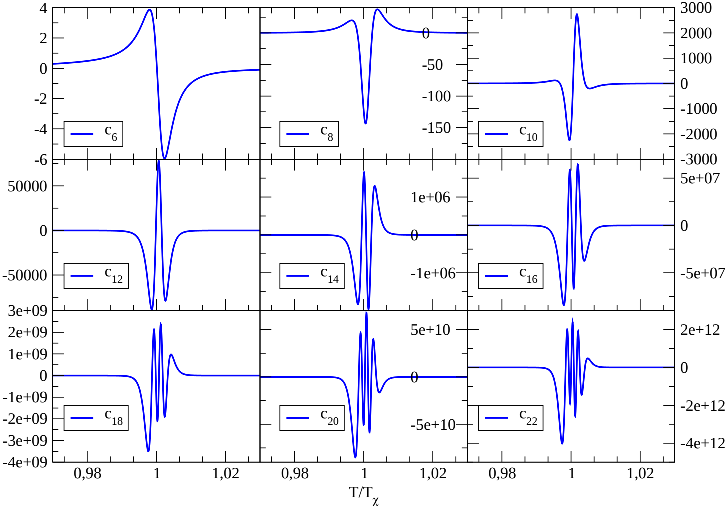
$$\frac{p(T,\mu)}{T^4} = \sum_{n=0}^{\infty} c_n(T) \left(\frac{\mu}{T}\right)^n \quad \text{with} \quad c_n(T) = \frac{1}{n!} \frac{\partial^n \left(p(T,\mu)/T^4\right)}{\partial \left(\mu/T\right)^n}\Bigg|_{\mu=0}$$



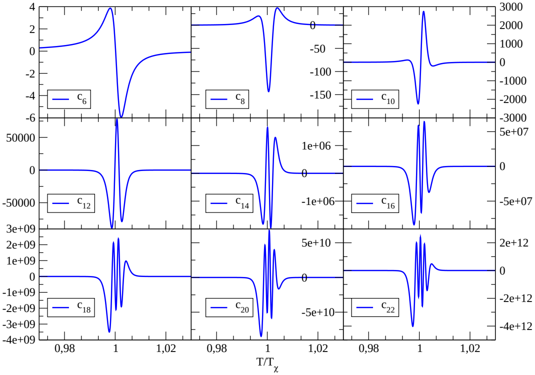
[Miao et al. '08]

New method: based on algorithmic differentiation **[M. Wagner, A. Walther, BJS, CPC '10]**

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



Finite density extrapolations $N_f = 2 + 1$

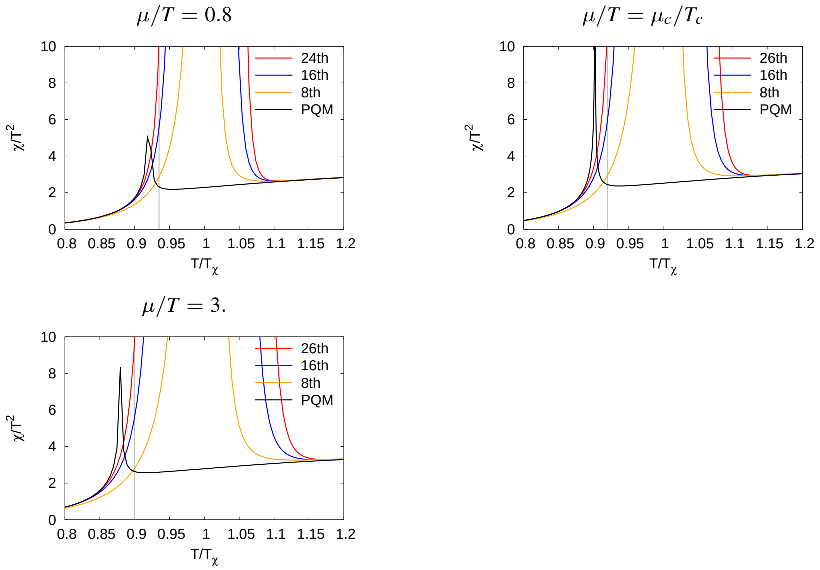


- ▷ this technique applied to PQM model
- ▷ investigation of convergence properties of Taylor series
- ▷ properties of c_n
  - oscillating
  - increasing amplitude
  - no numerical noise
  - small outside transition region
  - number of roots increasing
  - 26th order

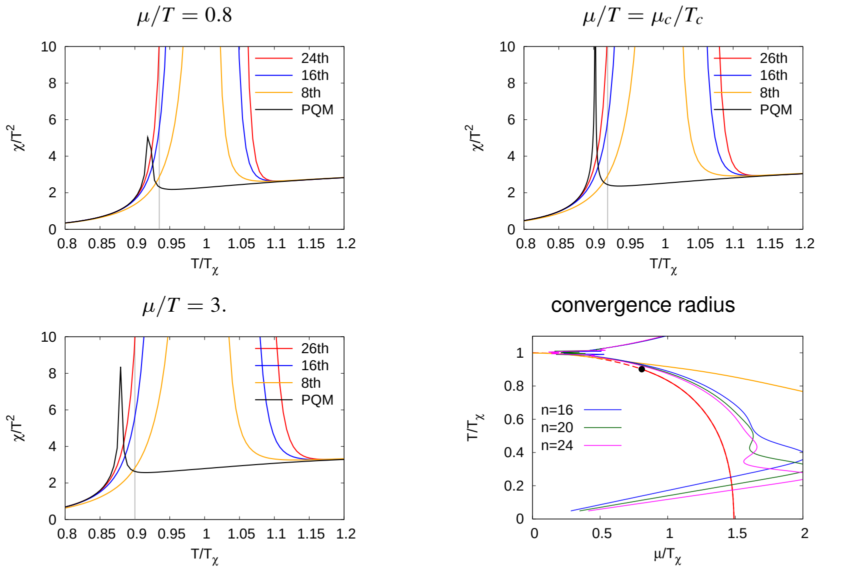
[F. Karsch, BJS, M. Wagner, J. Wambach; in preparation ’10]

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

Susceptibility $N_f = 2 + 1$ PQM model



Susceptibility $N_f = 2 + 1$ PQM model



Susceptibility $N_f = 2+1$ PQM model

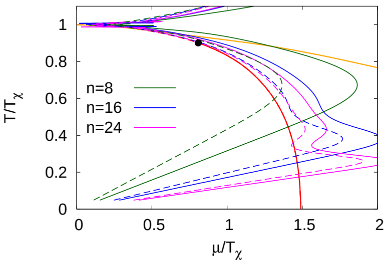
Findings:

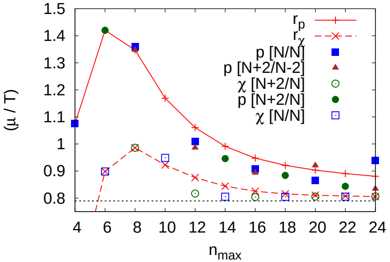
- simply Taylor expansion: slow convergence
  high orders needed
  disadvantage for lattice simulations

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

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

Padé [N/N]

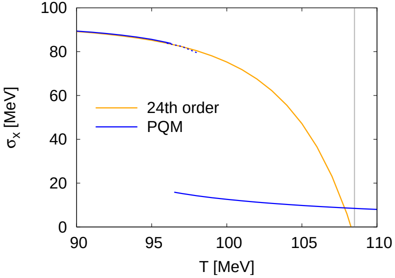


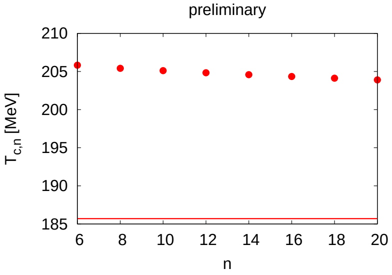


Susceptibility $N_f = 2 + 1$ PQM model

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

  with and without axial anomaly

- novel AD technique: high order Taylor coefficients, here: $\mathbf{n} = \mathbf{26}$

Findings:

▷ Parameter in Polyakov loop potential: $T_0 \Rightarrow T_0(N_f, \mu)$

▷ Chiral & deconfinement transition possibly **coincide** for $N_f = 2$ with $T_0(\mu)$-corrections but possibly not for $N_f = 2 + 1$

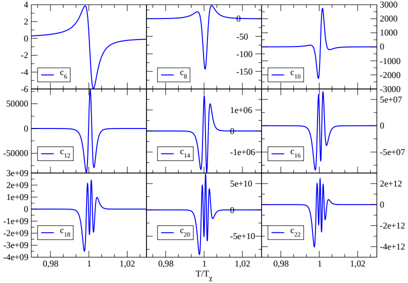
▷ Mean-field approximation encouraging

but effects of Dirac term point to interesting physics if fluctuations are considered

▷ **FRG with PQM truncation**

▷ Taylorcoefficient $c_n(T) \longrightarrow$ **high order available**

⇒ **convergence properties** of Taylor expansion



Outlook:

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