Phases of Strongly Interacting Matter

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NUPECC meeting

Vienna, Austria

presentation by W. Plessas $\Longrightarrow$ Spectroscopy & excitations of hadrons

now more fundamental investigations (from first principles)

Hadron physics group:

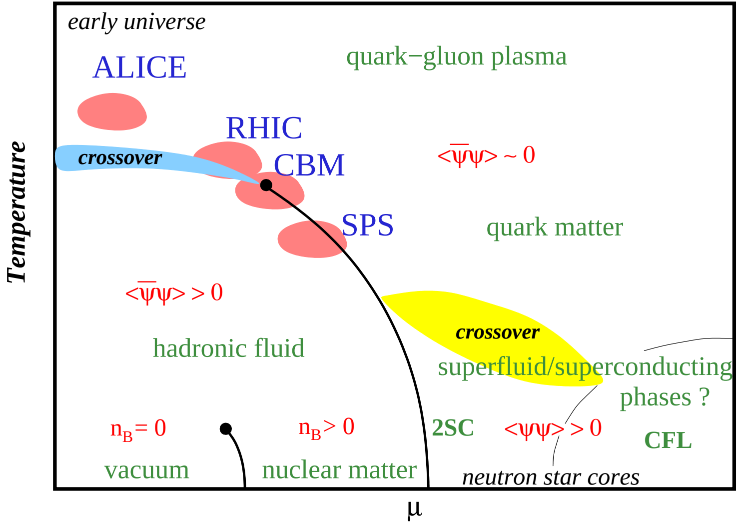
- Lattice Gauge Field Theory
  http://physik.uni-graz.at/∼cbl/lattice/
- Continuum strong-coupling QFT
  http://physik.uni-graz.at/itp/sicqft/
- Few Body Physics
  http://physik.uni-graz.at/itp/projekte.html#suba/

5 Profs.	R. Alkofer, Ch. Gattringer, Ch. Lang, W. Plessas, W. Schweiger
6 PD	L. Glozman, A. Krassnigg, A. Maas, T. Melde, D. Nicmorus, B.-J. Schaefer
16 PhD	...
# Diploma	...

The lattice group at the Karl-Franzens University (C. Gattringer, C.B. Lang et al.) is investigating various QCD related questions:

- Simulations with light dynamical quarks
  $\Longrightarrow$ presentation by W. Plessas
- Spectroscopy of excited hadrons
  $\Longrightarrow$ presentation by W. Plessas
- Understanding the QCD phase diagram
  $\Longrightarrow$ this talk
- Hadronic matrix elements, Algorithms ....

The conjectured QCD Phase Diagram



QCD: two phase transitions:

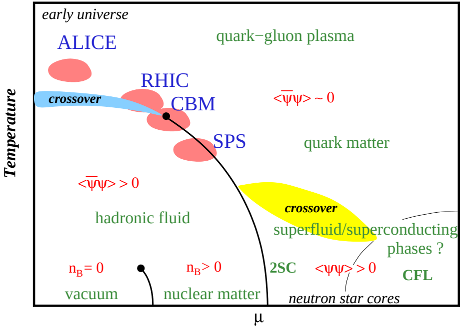
1. restoration of chiral symmetry

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

   order parameter:

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

   associate limit: $m_q \to 0$



chiral transition: spontaneous restoration of global $SU_L(N_f) \times SU_R(N_f)$ at high T

QCD: two phase transitions:

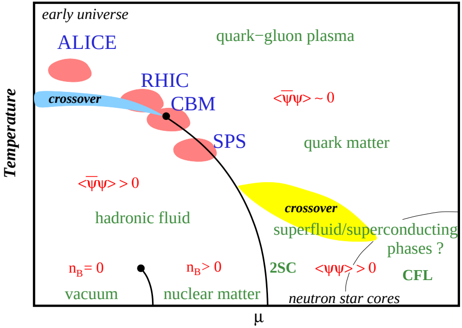
1. restoration of chiral symmetry
2. de/confinement (center symmetry)

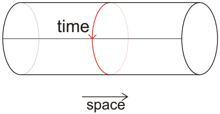
order parameter:

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

$$\Phi = \frac{1}{N_c} \langle \mathrm{tr}_c \mathcal{P} e^{i \int_0^\beta d\tau A_0(\tau, \vec{x})} \rangle$$

associate limit: $m_q \to \infty$



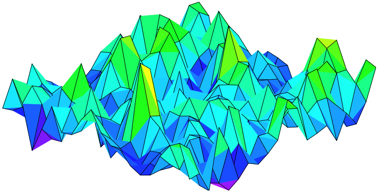


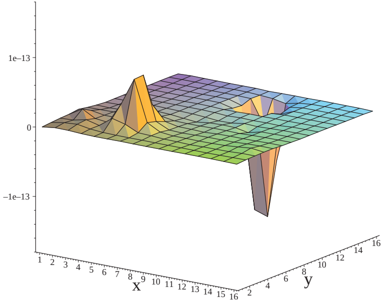
➜ related to free energy of a static quark state: $\Phi = e^{-F_q}$

$$\exp\left(-\frac{F_{\bar{q}q}(r,T)}{T}\right) = \langle \mathrm{tr}_c \mathcal{P}(x) \mathrm{tr}_c \mathcal{P}^\dagger(y) \rangle / N_c^2$$

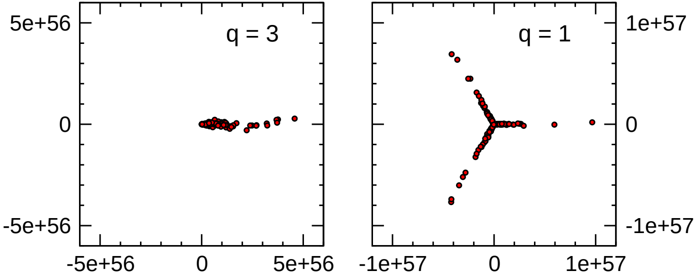
What are the relevant excitations and symmetries that drive the QCD phase transition?

- Filtering techniques based on low lying eigenvectors of the Dirac operator combined with a variation of the fermionic boundary conditions were developed.
- Using these filtering techniques it was shown that KvBLL calorons and dyons play a role in driving the QCD phase transition.
- More recently the boundary condition techniques were used to develop a new order parameter, the dual chiral condensate.
- The dual chiral condensate can be used to study a possible link between deconfinement and the restoration of chiral symmetry. This question is currently investigated in various settings.





- New techniques for working with lattice QCD at a fixed quark or baryon number are being developed.
- A dimensional reduction formula for the fermion determinant allows to very efficiently calculate ‘canonical determinants’ in a fixed quark number sector.
- The canonical determinants transform in a simple way under center transformations.
- Currently we analyze the role of center symmetry for the QCD phase structure.



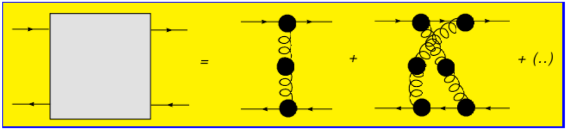
Functional methods for Green Functions

Dyson-Schwinger Equations (DSE) & Functional Renormalization Group (FRG)

- chiral symmetry breaking & color superconductivity
- scalar quark confinement
- axial $U_A(1)$ anomaly & $m_{\eta'}$
- QCD phase diagram & $\rightarrow$ CEP?

Dynamically induced scalar quark confinement

"Quenched´´ quark-antiquark potential



infrared divergent such that

$$V(\mathbf{r}) = \int \frac{d^3p}{(2\pi)^3} H(p^0 = 0, \mathbf{p}) e^{i\mathbf{pr}} \quad \sim \quad |\mathbf{r}|$$

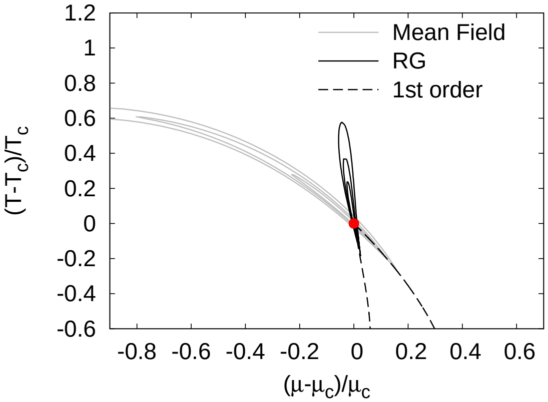
i.e. linear, dominantly scalar, quark confinement!

[BJS, J. Wambach '06]

similar conclusion if fluctuations are included

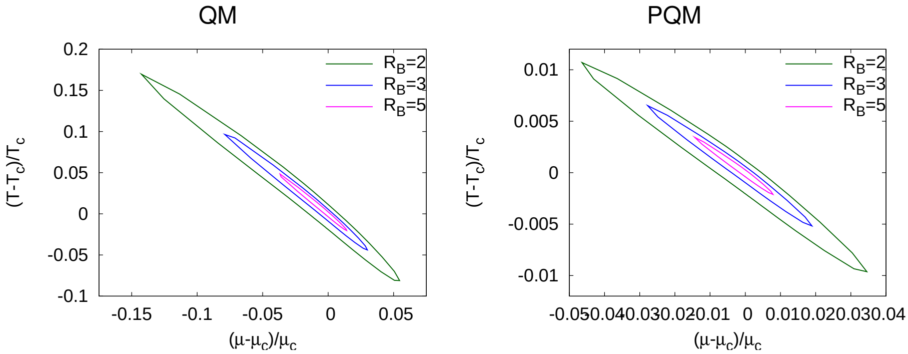
(here $N_f = 2$ QM model)

Mean Field $\leftrightarrow$ RG analysis



Critical region $N_f = 2 + 1$

contour plot of size of the critical region around CEP: $R_B = \chi_q / \chi_q^{\text{free}}$

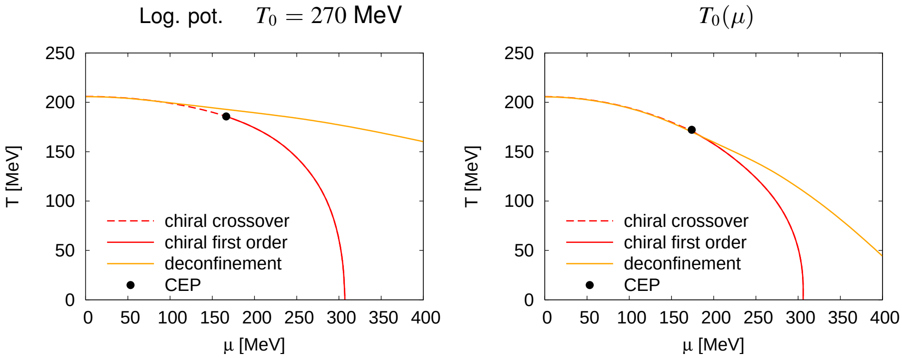


➜ compressed with Polyakov loop

[BJS,M.Wagner,J.Wambach to be published '09]

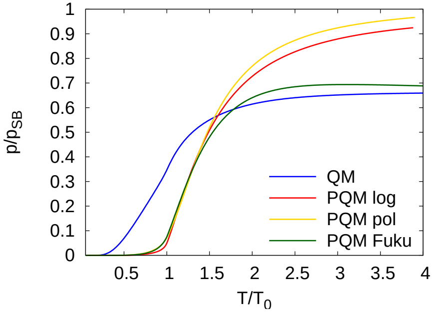
[BJS, M. Wagner, J. Wambach; to be published '09]

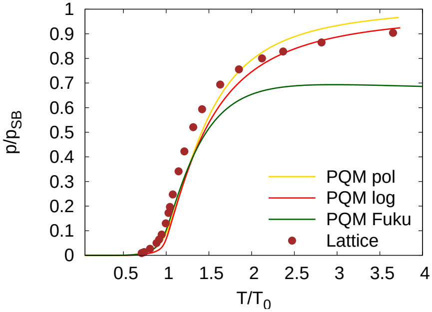
influence of Polyakov loop



[BJS, M. Wagner, J.Wambach; to be published ’09]

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





$m_\pi \sim 220$ MeV $\qquad N_\tau = 6$

[Cheng et al. ’08]

[BJS, M. Wagner, J.Wambach; to be published '09]

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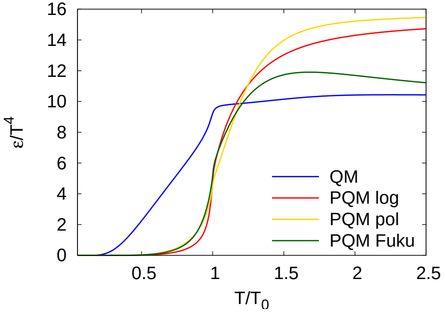

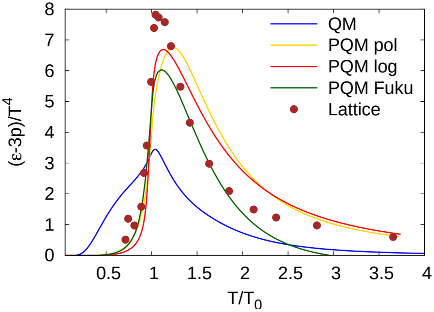

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Facility for Antiproton and Ion Research project @ Darmstadt