Hadrons and Quarks in an Effective Chiral Model

Philip Rau1,2, Jan Steinheimer4, Stefan Schramm2, Horst Stöcker1,3

1Institut für Theoretische Physik, Goethe Universität, Frankfurt am Main; 2Frankfurt Institute for Advanced Studies (FIAS), Frankfurt am Main; 3GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt; 4Lawrence Berkeley National Laboratory, Berkeley

rau@th.physik.uni-frankfurt.de

SU(3)-flavor $\sigma-\omega$ model, using non-linear realization of chiral symmetry [1,2,3]. Mean field Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{int}} + \mathcal{L}_{\text{meson}}$$

includes a kinetic term, interactions between quarks and baryons of species $i$ with scalar/vector meson fields

$$\mathcal{L}_{\text{int}} = \mathcal{L}_{\text{BS}} + \mathcal{L}_{\text{KV}} - \sum_i \bar{\psi}_i \left[ \gamma_0 (g_{\omega} \sigma + g_{\delta} \Delta) + m_i \right] \psi_i,$$

and mesonic part, which includes mass terms, all meson self-interactions, and explicit chiral symmetry breaking.

Effective masses: $m_i^* = g_{\omega} \sigma + g_{\delta} \Delta + \delta m_i$.

Effective potential: $\mu_i^* = g_{\omega} \sigma + g_{\delta} \Delta$.

Vector coupling strength of baryon resonances scaled via parameter $r_v$. Similar to PNJL, here, quarks couple to a Polyakov loop potential $\Phi$. Hadron suppression at high $T$ and $\mu$ by an excluded volume mechanism.

Model includes: three lightest quarks; scalar, pseudoscalar, and vector mesons; baryonic octet, and all hadronic resonances up to $m = 2.6$ GeV.

**Chiral transition:** [Fig. 1(a)]
- hadrons only: $T_c = 165$ MeV,
- quarks & hadrons: $T_c = 175$ MeV (slow decrease of $\sigma$ at larger $T$).

Fig. 2 shows impact of resonance couplings on phase diagram of purely hadronic model. No first order phase transition for $r_v \geq 0.6$.

**Thermodynamics**

Thermodynamic quantities (Fig. 3, 4) derived from grand canonical potential

$$\frac{\Omega}{V} = -\mathcal{L}_{\text{int}} - \mathcal{L}_{\text{meson}} + \frac{\Omega_{\text{th}}}{V} - U_{\text{Pol}},$$

with thermal contribution from quarks, baryons, mesons $\Omega_{\text{th}} = \Omega_{\text{eq}} + \Omega_{\text{BB}} + \Omega_{\text{M}}$.

**Susceptibilities**

Fluctuations of conserved charges at $T_c$ reflected in susceptibility coefficients $c_n$. Taylor expanding the pressure $p = -\Omega/V$ with respect to $\mu/T$

$$\frac{p(T,\mu_B)}{T^4} = \sum_{n=0}^{\infty} c_n(T) \left( \frac{\mu_B}{T} \right)^n$$

leads to susceptibility coefficients (Fig.6)

$$c_n(T) = \frac{1}{n!} \left( \frac{\partial^n (p(T,\mu_B)/T^4)}{\partial (\mu_B/T)^n} \right)_{\mu_B=0}.$$

Susceptibilities very sensitive to the vector coupling strength of resonances and quarks. Only baryon couplings $r_v \approx 1$ give results in the range of lattice data. These values for $r_v$ rule out a first order phase transition and a CEP in our model.

**Summary**

- SU(3)-flavour $\sigma-\omega$ model with quarks & hadrons up to $m = 2.6$ GeV,
- pure hadronic model: good agreement up to $T_c$ with lattice data (stout action) for $r_v \approx 1$,
- Susceptibilities sensitive to vector couplings of quarks & resonances,
- reasonable vector couplings rule out 1st order phase transition and CEP.

References: