QCD Phases and Thermodynamics of a Nonlocal PNJL Model Including Strange Quarks ◇

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Low-energy QCD in its sector with $N_\mathrm{f} = 3$ flavours of almost massless up and down quarks ($m_u \approx m_d \sim \mathcal{O}(5\,\mathrm{MeV})$) and a slightly heavier strange quark ($m_s \sim \mathcal{O}(100\,\mathrm{MeV})$) is known to have the following characteristic symmetry breaking pattern: the Goldstone bosons related to spontaneously broken chiral $\mathrm{SU}(3) \times \mathrm{SU}(3)$ symmetry are identified with the pions and kaons. Their masses originate from explicit symmetry breaking by the non-zero u-, d- and s-quark masses. The unusually large mass of the η' meson is understood as a consequence of the axial anomaly in QCD, the breaking of the axial $\mathrm{U}(1)_\mathrm{A}$ symmetry, e. g. through instanton effects.

The present work extends a nonlocal version of the Nambu–Jona-Lasinio (NJL) model (developed in Ref. [1] for the two-flavour case) to $N_\mathrm{f} = 3$ including the $\mathrm{U}(1)_\mathrm{A}$ breaking 't Hooft interaction terms. The model includes an effective gluon propagator which describes instanton effects in the low-momentum region, and asymptotic freedom at high-momentum scales. Altogether, this approach is able to reproduce the pseudoscalar meson spectrum, including the η-η' mass-splitting.

The model that we have constructed differs from full Schwinger-Dyson (SD) equations only by the assumption, that the impact of the angular dependence in the integrals can be neglected. A comparison to fully self-consistent SD calculations corroborates this approach. Fundamental current algebra relations such as the Goldberger–Treiman- and the Gell-Mann–Oakes–Renner relations are exactly fulfilled.

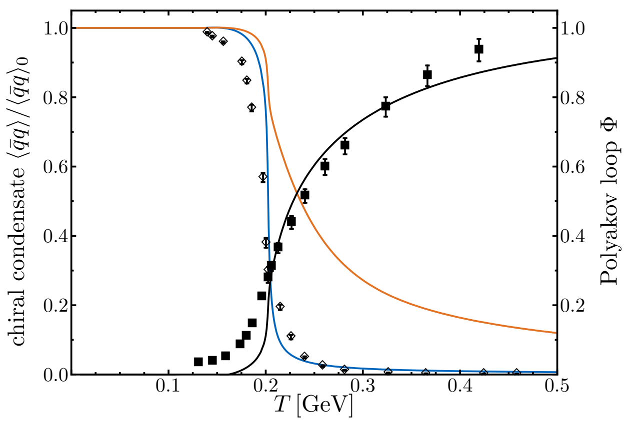

Fig. 1: Temperature dependence of the up- and down quark condensates $\langle\bar{u}u\rangle = \langle\bar{d}d\rangle$ (blue line) and the strange quark condensate $\langle\bar{s}s\rangle$ (orange line) on the left hand side, and Polyakov loop Φ on the right hand side. The results are compared to lattice data of Ref. [4].

This nonlocal PNJL model has been applied to QCD thermodynamics, incorporating the coupling to a gluonic background field (Polyakov loop) field. The chiral condensates serve as order parameters for the chiral transition while the confinement-deconfinement transition is controlled by the Polyakov loop. The resulting approach is a consistent nonlocal, three-flavour extension of the PNJL model with local two-flavour couplings [2,3]. As before, the dynamical entanglement of the fermionic and the gluonic sector is of crucial importance in order to reproduce lattice results. While the transition temperatures for each individual sector differ significantly by roughly 100 MeV, the coupling of the fermions to the Polyakov loop intertwines these sectors so that the chiral and confinement-deconfinement transitions coincide at a common transition temperature T_c close to 200 MeV (see Fig. 1).

Corrections of order $1/N_\mathrm{c}$ beyond the mean field approximation have also been investigated, in particular those concerning mesonic quark-antiquark correlations. Mesonic corrections turn out to be important below the transition temperature T_c and decrease rapidly above T_c. Furthermore, below T_c the mesonic contributions can be described roughly by those of an ideal gas of mesons (see Fig. 2).

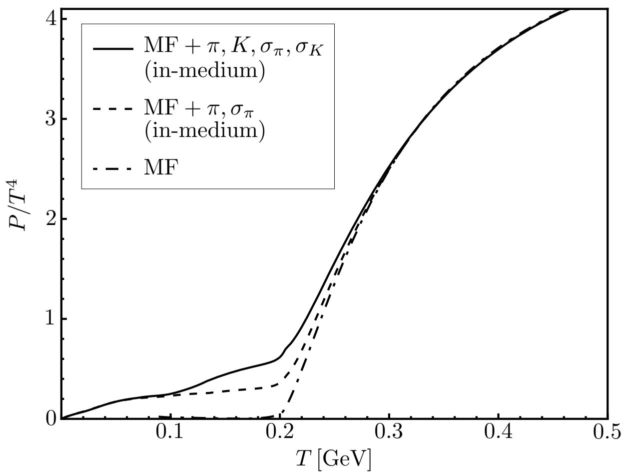

Fig. 2: Temperature dependence of the pressure: The dashed-dotted line shows the mean field contributions, the dashed line the mean field result with addition of the contributions of the pions and the corresponding scalar $q\bar{q}$ mode (σ_π). The full result including contributions both from pions and kaons with corresponding sigma-fields is shown by the solid line.

References

[1] T. Hell, S. Rößner, M. Cristoforetti and W. Weise, Phys. Rev. **D79** (2009) 014022
[2] S. Rößner, T. Hell, C. Ratti and W. Weise, Nucl. Phys. **A814** (2008) 118
[3] S. Rößner, C. Ratti and W. Weise, Phys. Rev. **D75** (2007) 034007
[4] M. Cheng *et al.*, Phys. Rev. **D77** (2008) 014511

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