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ScienceDirect
Nuclear Physics A 931 (2014) 113–124
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Equation of state and phase diagram of strongly interacting matter

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Received 18 August 2014; received in revised form 17 September 2014; accepted 19 September 2014

Available online 29 September 2014

Abstract

In this work progress on the phase structure and the dynamics of strongly correlated matter with continuum methods is reviewed. First we discuss the set-up of functional approaches to correlation functions in QCD. Particular emphasis is put on the discussion of the mechanisms of confinement and chiral symmetry breaking in such an approach, as well as the embedding of low energy effective theories.

Then, results are discussed concerning the confinement–deconfinement and the chiral phase transition at finite temperature and density. The present correlation function approach also allows to compute real-time correlations, including pole masses, decay constants, spectral functions and transport coefficients.

Keywords: QCD phase structure; Equation of state; Transport coefficients

1. Introduction

In the past decade our theoretical understanding of the phase diagram of strongly correlated matter has been advanced significantly. This progress has been made in a fruitful interplay of first principle methods such as functional approaches to QCD and lattice simulations on the one hand, and low energy effective models on the other hand.

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http://dx.doi.org/10.1016/j.nuclphysa.2014.09.074
0375-9474/

In the present work the functional approach to the QCD phase diagram is reviewed. This approach is based on functional loop relations between correlation functions in QCD, and allows to evolve QCD from the high energy regime for energy and momenta $k \gg \Lambda_{\mathrm{QCD}}$, where perturbation theory works with quantitative precision, to the hadronic regime in the infrared. It is also very amiable to the consistent inclusion of results on correlation functions obtained from other methods such as the lattice, and hence allows for a very important and fruitful combination of these different approaches. Not only can lattice correlation functions be used as input and benchmark in the functional relations (and vice versa), the functional approach also can be used to compute, on the basis of this solidified input, observables that are difficult to compute or out of reach within current lattice methods.

In the past decade the continuum approach to QCD has made rapid qualitative and quantitative progress. Starting from the quantitative computation of Yang–Mills correlation functions and the understanding of the confinement physics, we have obtained a plethora of qualitative as well as quantitative results for pure glue and full dynamical QCD at finite temperature and density.

2. Functional approach to QCD

The approach under discussion is based on relations between quark, gluon, and hadron correlation functions. Such a correlation function approach necessitates a gauge fixing. This is nothing but the choice of the parameterisation in (gluon) field space. It is well-known from the analytic and numerical computation of multi-dimensional integrals that an appropriate parameterisation may simplify considerably the integrations at hand. Accordingly, the gauge fixing should rather be seen as an opportunity instead of a liability. It has turned out over the years, that the Landau gauge, $\partial_\mu A_\mu = 0$, is a very good choice for a number of reasons, both physics and technical ones. One of the most obvious technical ones is the fact that it minimises the number of independent tensor structures as the functional relations for the purely transversal correlation functions form a closed set. A far less obvious one is the fact that correlation functions follows the perturbative momentum dependence for quite long and the transition from the perturbative quark–gluon regime to the hadronic regime is very rapid. In other words, the Landau gauge preserves momentum locality. Moreover, the transversal gluon propagator is gapped, its gap reflecting the mass gap of QCD. Higher correlation functions, though being non-trivial, do not show singularities other than the required kinematic singularities, as well as physical resonances. All these properties facilitate the computations and physics interpretation of the results.

The functional renormalisation group (FRG) equation, Fig. 1(a), and the functional Dyson Schwinger equation (DSE) for QCD, Fig. 1(b), have closed exact one-loop and two-loop structures for the effective action/free energy respectively. As these equations hold in general backgrounds, relations for correlation functions can be derived via taking an appropriate powers of field derivatives. The DSE approach to the QCD phase diagram is reviewed in [3], these proceedings. The FRG equation in Fig. 1(a) is an exact one-loop equations involving loops of full background field dependent propagators, where the loop momenta q^2 are restricted to $q^2 \lesssim k^2$ for a given cutoff scale k, indicated by the crossed circle in Fig. 1(a). Note that the fourth loop in the FRG in Fig. 1(a) does not signal an effective model approach to QCD, but occurs from dynamical hadronisation or rebosonisation as put forward in [4–7], and has been also applied in ultracold atoms (condensate and trimer formation), see e.g. [8,9] and references therein. In particular the dynamical hadronisation facilitates the discussion of chiral symmetry breaking, and is discussed in more detail in Section 3.2.