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Parameter fitting in three-flavor Nambu–Jona-Lasinio model with various regularizations

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Abstract

We study the three-flavor Nambu–Jona-Lasinio model with various regularization procedures. We perform parameter fitting in each regularization and apply the obtained parameter sets to evaluate various physical quantities, several light meson masses, decay constant and the topological susceptibility. The model parameters are adopted even at very high cutoff scale compare to the hadronic scale to study the asymptotic behavior of the model. It is found that all the regularization methods except for the dimensional one actually lead reliable physical predictions for the kaon decay constant, sigma meson mass and topological susceptibility without restricting the ultra-violet cutoff below the hadronic scale.

1. Introduction

Nonet mesons are interesting composite hadronic objects which have been seriously studied in theoretical and experimental particle physics. The elementary objects composing mesons are quarks and gluons, and the first principle theory of them is quantum chromodynamics (QCD).

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Then one of our goals is to explain all the information on hadrons from QCD. The most reliable approach is to consider the discretized version of QCD, called the lattice QCD, whose technologies are developing day by day. It is, however, still difficult to study hadrons from the first principle, so the approaches by using some effective models become one of our options.

In this paper we employ the Nambu–Jona-Lasinio (NJL) model [1] being one of frequently used models for the investigations of hadronic particles. The three-flavor model with $U_{\rm A}(1)$ anomaly [2] called Kobayashi–Maskawa–'t Hooft (KMT) term [3] successfully describes the nonet meson properties (for reviews, see, e.g., [4–9]). The model is not renormalizable, since it contains the higher dimensional operators, four- and six-point fermion interactions. Therefore the model predictions inescapably depend on the regularization procedures. Also, the model shows parameter dependence in each regularization method. Then we have launched a plan to perform the systematical analyses on both the regularization and parameter dependence.

Here we are going to study the model with five regularizations: the three-dimensional (3D) and four-dimensional (4D) sharp cutoff schemes, Pauli–Villars (PV), the proper-time (PT) and the dimensional regularizations (DR), as the straightforward extension of the work with the two-flavor model [10]. The 3D cutoff drops the higher momentum contribution in the space direction, which is the most frequently used method due to its simple physical interpretation and nice numerical behavior. Similarly, the 4D cutoff method kills the amplitudes from higher momentum in the four-dimensional Euclidean momentum space. The PV way reduces high momentum contribution by subtracting the amplitudes from virtual heavy particles [11–13]. The PT method introduces the exponentially dumping factor in the integral, then make divergent loop integrals finite [12,14]. The DR prescription modifies an integral kernel through changing the space–time dimension so as to make divergent integrals finite. The model has been examined in detail with various regularizations, see, e.g., for the 4D [5,6,15–19], PV [5,20–23], PT [16,24–31] and DR [17–19,33–38]. The NJL model is regarded as a low energy effective model of QCD; it is the simplest model to induce dynamical chiral symmetry breaking and often applied to investigate physics near the QCD phase transition. To apply the model to the nonet mesons η and η' mesons may be not easy enough compared with the QCD scale. Since the model loses validity at higher energy, it should be essential to evaluate the safety and effectiveness of the model with the regularization procedures. It is to be noted that the model has non-negligible parameter dependence even within the same regularization procedure [10]. In particular, some physical quantities, such as the transition temperature on the chiral symmetry breaking, are crucially affected by the model parameters. Moreover, there exists some room for the choice of parameters since input physical quantities for setting the parameters are usually less than the number of the parameters, then several parameter sets are employed depending on working groups [6,7,17,22,31]. Therefore it is also important to test the parameter dependence on the model predictions. A lot of works have been devoted to the searches on the model parameters with various regularizations [10,16–19,34]. For the sake of seeing the regularization and parameter dependence on the physical quantities, in this article, we shall perform the systematical parameter fitting in the three flavor model.

The paper is constructed as follows: Section 2 presents the model treatments and the regularization procedures. We will carry on the detailed parameter fitting in Section 3. Section 4 is devoted to the investigations on the physical predictions. We give some discussions on the parameter fitting in Section 5. Some concluding remarks are put in Section 6. Appendix shows the explicit equations for the meson properties and topological susceptibility.