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Editorial

Topics in light-quark physics

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Abstract This special issue of the European Journal of Physics: Special Topics entitled Topics in Light Quark Physics collects 8 papers with the intention to discuss problems in physical processes involving the particles (mesons and baryons) comprising the lighter part in the spectrum of strong interactions, though some connections to the heavy-quark sector are also discussed. Active and timely problems in this broad field are introduced and covered by experts who root their contributions in the known aspects at the same time that take us to the frontier of knowledge, while introducing in many instances new techniques for present and future further developments. The nature of the lightest scalar resonances, the hunt for the lightest glueballs, the $\Lambda(1405)$ as a paradigmatic example of two-pole resonances, the pion–nucleon sigma term, two- and three-body scattering amplitudes extracted from lattice QCD, the QCD phase diagram, extrapolations in the number of colors of QCD and their use for addressing properties of its spectrum, and new advances to reach renormalized scattering amplitudes with attractive/repulsive singular potentials are all items covered here.

1 Introduction

The physics of light flavors in strong interactions has played a very important historical role in the development of non-perturbative techniques that later on have been applied to many other fields in relation with Quantum Chromodynamics (QCD) and the Standard-Model in general. E.g. it was very influential in the earlier developments of S-matrix theory. At the same time, the development of Quantum Field Theory went on, and it was also strongly influenced by the physics of the reactions involving light-quark hadrons. Within its realm e.g. the development of the basic low-energy Effective Field Theory (EFT) of the Standard Model, namely, Chiral Perturbation Theory (ChPT), took place from the earlier developments of Current Algebra. It also gave rise to hadronic Regge trajectories which prompted the development of the Veneziano Model and its interpretation from the earliest versions of String Theory. Other advances in scattering theory also arose from hadron physics with light quark favors, like the recent one that allows one to calculate the discontinuity of a partial-wave amplitude along the left-hand cut for a potential given.

Nowadays, the hadrons made by light quark flavors play an essential role in the interpretation of many reactions of current interest, like in production processes of heavy quarks and unconventional heavy-quark states, heavy-ion collisions, etc, since in all of them the systems composed by those hadrons are copiously produced. It is also of great interest to understand astrophysical systems like neutron stars. The understanding of light-quark physics is not yet in a satisfactory situation, as strongly realized by the incompatible values of the pion-nucleon sigma terms calculated from lattice QCD & EFT and dispersion relations. There are also many other interesting questions that remain to be settled, with some of them developed and reviewed in this topical issue. The presence of these challenges also post opportunities for further development in this field with possible implications in many other areas. Next, we enumerate and comment on the contributions comprising this special issue on the physics of light-quark flavors.

Peláez et al. on Precision dispersive approaches versus unitarized Chiral Perturbation Theory for the lightest scalar resonances $\sigma/f_0(500)$ and $\kappa/K_0^*(700)$ [1] revise the most precise calculations of their pole positions (and that of the $f_0(980)$ too) that stem from the thorough application of analytical properties of scattering amplitudes satisfying unitarity and crossing symmetry to the present available data on $\pi\pi$ and $K\pi$ scattering, supplemented with Regge theory in the high-energy region. They compare these techniques with some others based on the unitarization of two-body scattering amplitudes calculated in ChPT, which are handicapped by the non-exactly implemented crossing symmetry, lack of multiparticle intermediate states in the s channel and proliferation of ChPT counterterms when higher order ChPT amplitudes are unitarized. Nonetheless, unitarized ChPT provides results typically compatible with the more accurate dispersive approach referred for scattering and the pole positions. In turn, these uni-

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tarization techniques can be connected to QCD more directly, and their dependences on quark masses and the number of color of QCD (N_C) are shown to be useful for discussing the nature of the light resonances $f_0(500)$, $K_0^*(700)$, $\rho(770)$ and $K^*(892)$.

QCD at low energies is a strong-interacting non-Abelian gauge theory. As a pure gauge theory the gap in the QCD spectrum corresponds to the appearance of the lightest glueball. According to the unquenched lattice QCD calculations this glueball would have vacuum quantum numbers with a mass around 1.7 GeV. These quantum numbers are not exotic and then in actual experimental results the glueball should be disentangled from other hadronic resonances, with which it could also mix. Glueballs as the Ithaca of meson spectroscopy by Llanes-Estrada [2] reviews on the essentials of the lightest glueballs in QCD, paying special attention to the scalar, tensor and psuedoscalar glueballs. The author covers the main theoretical schemes to study the glueball spectrum, reasons to favor the identification of the $f_0(1710)$ resonance as the lightest (scalar) glueball, and an in depth phenomenological vision of the problem in close connection with experiments. Emphasis is put on discussing interesting prospects for disentangling experimentally these states, like using high-energy scattering and production reactions employing Regge theory and QCD counting rules for the tensor and scalar glueballs, or the recoil mass technique together with a multibeam analysis for the case of the pseudoscalar ones.

The study of scattering by $\bar{K}N$ and coupled channels related by $SU(3)$ symmetry in the energy region from the $\pi\Sigma$ threshold up to around the $\bar{K}N$ one and higher energies is a basic process in strong interactions. In this energy region, one has the emergence of the $\Lambda(1405)$ resonance which is topically discussed in Review of the $\Lambda(1405)$ by Mai [3], which gives a detailed historical account of this resonance, since its theoretical prediction, later experimental verification, until the most recent findings about its double-pole nature from studies that unitarize the baryon ChPT partial waves, with some standing controversies in the field. Emphasis is put on discussing both the experimental data supporting the understanding for this crucial sector in $SU(3)$ hadron dynamics, such as scattering experiments, kaonic hydrogen, sequential decays, photoexcitation, and an account of future facilities. The theoretical models to study the $\Lambda(1405)$ and related aspects are also reviewed with an emphasis on those based on unitarized chiral amplitudes and potential models.

Brief history of the pion–nucleon sigma term by Alarcón [4] elaborates on the precise calculation of the pion–nucleon sigma term, $\sigma_{\pi N}$, since its first appearance in the literature and first attempts for calculating it, up to the most recent lattice QCD calculations and the ones based on EFT and dispersion relations. The pion–nucleon scattering is a basic process in hadron physics with implications in many other reactions, like chiral symmetry breaking of strong interactions, the origin of mass of the ordinary matter, nuclear matter phenomenology, and searches of physics beyond the Standard Model of particle physics. A characteristic feature of the history of this quantity is that around 50 years its calculated values have changed according to the method of calculation. However, these methods have become more robust during the last years. In the last decades, it has been studied by applying ChPT with one baryon. The simultaneous implementation of the right analytical properties of the scattering amplitudes and the chiral power counting has been an issue since the early applications in the form of heavy-baryon ChPT until the more recent covariant ones employing the extended-on-mass-shell regularization scheme. Thorough dispersive studies have been also considered, like those based on the Roy-Steiner dispersion relations. In this regard, the author pays special attention to the present controversy in the value of $\sigma_{\pi N}$, between the larger ones obtained in the most advanced calculations from ChPT and the Roy-Steiner formalism, on the one hand, and the smaller values that are obtained by lattice QCD, on the other hand.

Multi-particle systems on the lattice and chiral extrapolations: a brief review by Mai et al. [5] discusses the extraction of two- and three-hadron scattering amplitudes and the properties of the low-lying hadronic resonances from finite-volume energy levels, calculated within lattice QCD. This is a field of research developing vividly both at the theoretical and computational level, as it is perfectly reflected in this review. The use of various modifications of the Lüscher finite-volume method has opened a path to calculate infinite-volume scattering amplitudes on the lattice. Many new results have been obtained recently on different two- and three-body scattering processes, including the extraction of resonance poles and their properties from lattice data. Robust parameterizations of the finite and infinite-volume scattering amplitudes relying on fundamental properties of S-matrix theory are required to analyze the lattice QCD energy levels, which should also provide typically extrapolations towards the physical point from quark masses away from it. Different parameterizations of the energy and quark mass dependence are reviewed, with emphasis on unitarized extensions of ChPT. Special attention is paid to three-body systems owing to their central role in contemporary theory and experiment and corresponding increasing interest. Several approaches in the three-body sector to relate the finite-volume spectrum to the infinite-volume amplitudes have been developed and are discussed by the authors, together with their application to extract observables from the first data stemming from lattice QCD.

The QCD phase diagram is a topic of great interest concentrating large efforts both from theory and experiment in recent times, e.g. with well known particle-collider experiments at LHC (CERN) and RHIC (BNL). Light quarks at finite temperature: chiral restoration and the fate of the $U(1)_A$ symmetry by Gómez Nicola [6] reviews about recent results on the essential role that light-quark states play within the QCD phase diagram, including thermal resonances. In particular, the combined use of theoretical techniques such as EFTs, unitarization and Ward Identities, helps to shed light on several important issues regarding the chiral and $U(1)_A$ restoration transitions. Specific analysis is devoted to the contribution of the $f_0(500)$ meson at finite temperature to the scalar susceptibility, the consequences of Ward Identities for the transition pattern in connection with chiral and $U(1)_A$ restoration, and the behavior of the topological susceptibility. Special attention is provided to the connection of these results with lattice QCD analyses as well, e.g. for susceptibilities and screening masses.

One of the methods to study the nature of a resonance in QCD is based on determining the evolution of its pole position as a function of the number of colors of QCD. N_C evolution of the light meson resonances by Guo [7] reviews about this method and the different approaches based on unitarized ChPT amplitudes, dispersive methods, quark models, linear-sigma model approach, etc, that have been used to generate the evolutions of the pole positions with N_C. Special attention is dedicated to the use of the $U(3)$ ChPT version of the hadronic EFT and its unitarization because in the large number of colors of QCD the η_1 becomes another massless pseudoscalar in the chiral limit contrarily to the case at $N_C = 3$. The large N_C limit also presents other challenges for the spectroscopy of light quarks because both local duality (used to relate the vector-scalar spectra) and the Weinberg sum rules (used to relate the scalar-pseudoscalar spectra) should be fulfilled at any number of colors, while at the same time the pole positions of the scalar resonances strongly depend on N_C, according to theoretical calculations. This has triggered a series of studies whose results typically agree regarding the pole trajectories for the lightest vectors resonances $\rho(770)$ and $K^*(890)$ as expected for $\bar{q}q$ resonances. The consensus regarding the N_C trajectories for the scalar resonances is less robust, and it is typically reduced to the region of not too large N_C. The achievements and results from different works are discussed and compared along with this review.

The calculation of the nucleon–nucleon (NN) potentials by applying ChPT with two baryons is nowadays a mature field with potentials calculated already at $\mathcal{O}(p^5)$ or N^{4}LO. These potentials are used in phenomenology by typically solving a Lippmann-Schwinger equation in momentum space. Because of the non-singular character of these potentials, there is the need to regularize them by employing some kind of cutoff to solve the Lippmann-Schwinger equation with ordinary methods. This makes that despite the phenomenological success achieved by this approach, a nonphysical dependence of the results on the cutoff persists. Non-perturbative methods for NN singular interactions by Entem and Oller [8] reviews some of the methods to achieve cutoff-independent results by taking it to infinity. Namely, these methods are renormalization with boundary conditions, renormalization with one counter term in momentum space (or equivalently subtractive renormalization), and the *exact* N/D method. The latter has been developed by exploiting the analytical continuation of the Lippmann-Schwinger equation to complex three-momenta, so that the exact discontinuity of a partial-wave amplitude along the left-hand cut can be calculated for a given regular or singular potential. The authors discuss how at the level of one renormalization condition all the methods mentioned turn out to be equivalent. However, the exact N/D method can go beyond the others as it can handle more than one renormalization condition. In this way, it is illustrated with a non-trivial toy model how this method can also renormalize singular repulsive interactions.

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