Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
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Mainz Institute for Theoretical Physics

Scattering Amplitudes and Resonance Properties from Lattice QCD

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Most of hadrons are strongly decaying resonances. This also includes candidates for exotic hadrons that have been discovered in experiments. Properties of the hadronic resonances have to be inferred from underlying scattering amplitudes for the decay products. These properties include resonance masses, decay widths, and electro-weak matrix elements. Lattice QCD allows extraction of two-hadron scattering amplitudes from first-principles QCD. The purpose of the workshop was to discuss formalisms to extract scattering amplitudes and actual lattice results and their implications for relevant hadronic systems.

The formalisms that will allow extraction of three-hadron scattering amplitudes are almost complete, but they still have to be applied in practice to results from lattice QCD simulations. With regard to this topic, the aim was to discuss several approaches to this challenging problem and to find the most practical ways to initiate applications. To this end, the workshop brought together formal experts as well as lattice practitioners in order to review the status of these calculations and discuss future prospects

The topological workshop was attended by 24 participants. Four participants were from the phenomenology community with strong links to lattice studies, one participant was actively involved in theory as well as in experiments, while the remaining participants were part of the lattice community. The daily schedule typically consisted of four 45 minute talks, including significant time for discussions. The environment at the MITP fostered vigorous discussions also outside of dedicated sessions, both in the coffee room and in smaller group meetings in individual offices, including those set aside for the purpose. Participants actively used the time for the discussion during the coffee breaks, lunch time and remaining time in the afternoons.

A major focus was on two-hadron scattering amplitudes, determined from the energies of eigen-states using Lüscher's formalism. An application to the shallow bound states in the meson sector considered scalar and axial D_s mesons (Sara Collins). The first extraction of baryon-baryon interactions using the powerful distillation technique considered the H dibaryon bound state (Andrew Hanlon). The energy determination has improved greatly in precision and reliability, yielding great promise for future studies. High-precision extraction of $\pi\pi$ scattering amplitudes showed the feasibility of using this formalism on larger volumes. The extracted time-like pion form-factor is an important

input in the hadronic-vacuum-polarization contribution to the $(g-2)_\mu$ (John Bulava). The successful application to extract the dynamically-coupled partial-wave amplitudes for the scattering of hadrons with spin was demonstrated (Christopher Thomas). Several partial waves are dynamically coupled to a given channel J^P in this case, even in the continuum. The scattering matrix for three coupled two-hadron channels was extracted for the challenging scalar isoscalar sector which features the σ and f_0 scalar resonances (David Wilson). The charmonium resonances that appear in the one- and two-channel scattering were addressed (M. Padmanath). The lattice scattering amplitudes suggest a new paradigm for heavy-light meson spectroscopy in which some of the lightest states do not belong to a $\bar{q}q$ nonet (Christoph Hanhart). Further scattering studies on the lattice were motivated by a review of interesting experimental observables (Alessandro Pilloni).

Resonances also appear in strongly-coupled scenarios of beyond-the-Standard-Model physics, and the first application of the Lüscher formalism to study a vector resonance in a composite Higgs model was discussed (Tadeusz Janowski). The energies of two- as well as three-particle systems also were determined from the sudden jumps in the particle number as a function of the chemical potential within the finite-density systems. The resulting scattering amplitudes agree with the conventional approach for the considered φ^4 theory, where the finite-density sign problem was solved by means of the world-line techniques (Christof Gattringer).

An alternative approach to determine scattering amplitudes using the Nambu-Bethe-Salpeter wave functions has been developed by the HAL QCD collaboration. A detailed description of the formalism, including its advantages and disadvantages relative to the Lüscher approach, was presented as well as an application to exotic Z_c and baryon-baryon interactions (Sinya Aoki). The interesting $bb\bar{q}_1\bar{q}_2$ systems were considered for a pair of static b-quarks, where Born-Oppenheimer potentials were extracted as a function of distance between them. The resulting potential between a pair of B mesons leads to exotic tetraquark bound states as well as resonances (Marc Wagner and Pedro Bicudo).

The strong decay $B_0^* \to B\pi$ near threshold was addressed using the three-point function as proposed by C. Michael (Benoit Blossier). An overview of the theoretical issues arising in the development of a three-particle quantization condition and a status report on the different approaches being followed were presented. A major emphasis is now on making the formalism practical by appropriate truncations (Steve Sharpe). The latter point was further emphasized in the context of the "finite-volume unitarity" approach by the presentation of the predicted energy levels of the 3π+system using experimental results for phase shifts and chiral perturbation theory (Michael Döring). The large-volume expansion of the shifts of free three-particle energy levels has been extended from the ground state to excited states, opening a new window for determining two- and three-particle scattering parameters (Akaki Rusetsky). The non-relativistic effective field theory approach was presented explained with regard to its strengths and limitations

(Hans-Werner Hammer). Recent work within simple models studying three- and four-body resonances was also discussed (Hans-Werner Hammer). A few talks considered general improvements that will be valuable for scattering studies in the future. Identification of underlying spin and parity for mesons in flight within the single-hadron approach will be valuable for resonance studies beyond this simplifying approximation (M. Padmanath). Reduction of the statistical noise based on the factorization of the fermion determinant seems promising for a wide variety of applications (Marco Ce).

The lattice QCD community is making an impressive progress in ab-initio studies of hadronic resonances and scattering amplitudes. Many of the most exciting problems, however, still have to be addressed. These include, for example, extraction of the coupled-channel scattering matrices related to exotic hadrons by means of Lüscher's approach and a lattice determination of three-body scattering amplitudes in QCD. The MITP workshop reflected both the past successes as well as the future challenges.