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Search for light Exotics in Coupled Channel PWA with PAWIAN

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Summary. — The light meson regime still is not too well understood and holds many open questions that can only be answered using sophisticated analysis strategies to describe the data. In particular, searching and investigating exotic states e.g. glueballs, hybrids and tetraquarks is a challenge among the many broad and overlapping resonances. Combining data of different production mechanisms in coupled channel partial wave analyses, as e.g. gluon-poor two-photon fusion events and gluon-rich reactions, helps to disentangle the highly populated light meson spectrum. To do so, sophisticated dynamical models need to be applied respecting unitarity and analyticity. Such models are, among others, implemented in the here used partial wave analysis package PAWIAN. Applied methods together with new results on coupled channel analyses are discussed.

1. – Introduction

Quantum Chromo Dynamics (QCD), the theory of the strong force, allows besides bound states of quarks also for bound states of gluons. Such exotic particles that go beyond a $\bar{q}q$ inner structure are e.g. Glueballs that consist only of gluons, Hybrids which are $q\bar{q}$ states with additional gluonic degrees of freedom, and Tetraquarks or Molecules which are composed of four quarks in different binding configurations (c.f. Fig. 1).
Due to the highly populated light meson spectrum, the description and identification of such candidates is experimentally challenging. In addition, since light mesons occur in the non-perturbative regime of QCD they also impose a huge theoretical challenge.

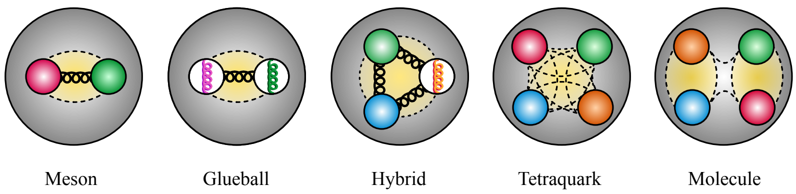

Fig. 1.: Schematic constituent picture of "ordinary" and exotic matter.

2. – The Software Package PAWIAN

The PAWIAN (PArtial Wave Interactive ANalysis Software) package is a partial wave analysis software package developed at the Ruhr-University Bochum. It supports various different reactions from $\bar{p}p$ annihilation, $\pi^- p$ scattering, $\pi\pi$ scattering data, central production, e^+e^- annihilation to two-photon fusion. In the first place, PAWIAN was developed dedicated to the physics cases at the future $\overline{\text{P}}$ANDA experiment and was then extended towards other hadron spectroscopy experiments. This enables to perform sophisticated coupled channel partial wave analyses, by combining various different reaction types and to exploit the physics benefits of each to the fullest.
PAWIAN was already successfully used in various publications [13, 18, 9, 1, 4] and theses from which a small subset will be discussed in this paper.
The software is designed to be user-friendly and modular as possible and allows the user to setup the amplitude model, fit hypotheses and fit settings by configuration files. Different spin-formalisms are supported as the widely-used helicity- and partly the Lorentz-invariant Rarita-Schwinger formalism. Various different descriptions of the dynamical part of the amplitude can be selected which is among more simple descriptions e.g. the well-known Breit-Wigner parametrization, or Flatté-formalism, the more sophisticated K-matrix formalism respecting the fundamental constraints of unitarity and analyticity. The minimization is performed in an event-based maximum likelihood fit using the MINUIT2 minimization package. In addition support for genetic minimization is implemented. PAWIAN provides extended support for parallel processing in a server-client mode which allows a straight-forward use on e.g. computer clusters.
Dedicated applications are available for the determination of different goodness-of-fit criteria, histogramming as well as sophisticated tools for extracting physical quantities like pole positions and coupling strengths for the production and the decay.
The packaged comes with an integrated Monte-Carlo generator that allows to generate events based on a user-defined decay model or an obtained fit result based on real data. PAWIAN is written in C++ and follows an object-oriented approach with a wide range of flexibility. The software code therefore allows to add user-defined amplitudes and dynamical descriptions. Further detailed information [9, 10, 19] and access to the code can be found in [24].

3. – Investigation of the lightest Hybrid Candidate

The picture of the observed π_1 states with spin-exotic quantum numbers $I^G(J^{PC}) = 1^-(1^{-+})$ is poorly understood in the light meson sector and controversially discussed. Lattice QCD calculations [22, 15, 16, 31] and phenomenological QCD studies [28, 27] predict only one state at a mass of 2 GeV/c^2 or slightly below. Experimentally, three different resonances with $I^G(J^{PC}) = 1^-(1^{-+})$ quantum numbers have been reported. The lightest one, the $\pi_1(1400)$, has only been seen in the $\pi\eta$ decay mode by several experiments [11, 14, 29, 3, 2, 26, 5]. In contrast, for the $\pi_1(1600)$ no coupling to $\pi\eta$ has been observed, but it has been seen in the decay to $\pi\eta'$, $\rho\pi$, $f_1(1285)\pi$ and $b_1(1235)\pi$ [6, 12, 17, 20, 23, 8]. The third state is the $\pi_1(2015)$, which has the poorest evidence and is thus listed in the Review of Particle Physics (RPP) as a further state. A blind spot in the majority of the previous analyses is the extraction of the resonance parameters using Breit-Wigner parameterizations. In a sophisticated re-analysis of COMPASS data of the reactions $\pi^- p \to \eta^{(\prime)}\pi p$ performed by the JPAC group [25] utilizing the N/D method, it turned out that the two candidates for a spin-exotic state,

$\pi_1(1400)$ and $\pi_1(1600)$, can be described by only one pole with a coupling to $\pi\eta$ and $\pi\eta'$. The Crystal Barrel Collaboration observed a significant π_1 contribution in $\bar{p}p$ annihilations in flight for the first time with a coupling to $\pi\eta$ in the reaction $\bar{p}p \to \pi^0\pi^0\eta$ [10] performing a coupled-channel analysis of the reactions $\bar{p}p \to \pi^0\eta\eta$, $K^+K^-\pi^0$ and scattering data using the K-matrix formalism. In order to shed more light on the hybrid candidates and to expliot the various data samples, an extended coupled channel analysis of this $\bar{p}p$ data together with data from 11 different $\pi\pi$ scattering channels and the P- and D-waves in the $\pi\eta$ and $\pi\eta'$ systems measured by COMPASS [7] was performed. The dynamics were treated in K-matrix approach by taking into account the analyticity with Chew-Mandelstam functions [30]. The statistical uncertainties were estimated by the re sampling boostrap method. Besides a simultaneous extraction of about 50 different resonance properties of various contributing resonances, it was as possible to describe the π_1 wave as well by only one pole in the K-matrix decaying into $\pi\eta$ and $\pi\eta'$ [18]. The corresponding pole mass and width was determined to be $M = (1623 \pm 47\,^{+24}_{-75})\,\mathrm{MeV}/c^2$ and $\Gamma = (455 \pm 88\,^{+144}_{-175})\,\mathrm{MeV}$, respectively. The relative ratio of decay widths of the $\pi\eta'$ and $\pi\eta$ final states was measured to be $\Gamma_{\pi\eta'}/\Gamma_{\pi\eta} = 5.54 \pm 1.10^{+1.80}_{-0.27}$, which is in agreement with lattice predictions [16] within the rather large uncertainties on both sides.

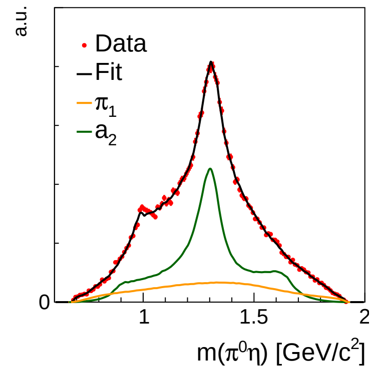

Fig. 2.: Invariant mass distribution of the $\pi^0\pi^0\eta$ channel in $\bar{p}p$ data. [18]

Figures 2 and 3 show the simultaneous fit result of the π_1 contribution in the $\pi^0\eta$ invariant mass projection from $\bar{p}p \to \pi^0\pi^0\eta$ and in the COMPASS data, respectively. It is astonishing that a single pole can create shapes in the invariant $\pi\eta$ and $\pi\eta'$ mass which are 200 MeV/c^2 apart and this shows the importance of proper dynamical models in the interpretation of pole parameters. Hopefully, both results help to clarify the nature of the lightest hybrid.

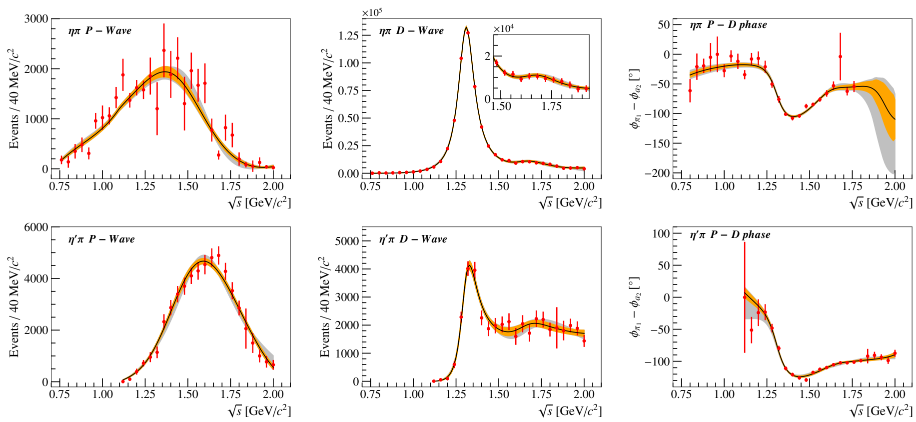

Fig. 3.: Fits to the $\pi\eta$ (upper row) and $\pi\eta'$ (lower row) data from COMPASS. The data are represented by red, the best fit is shown in black while the yellow and gray bands represent the statistical and systematic uncertainty, respectively. [18]

4. – Coupled Channel Analysis of Two-Photon Data at BESIII

Measurements at e^+e^- colliders provide access to two-photon reactions which are considered to be gluon poor. Since photons couple only to electric charge in first order, the production of exotic states with explicit gluonic degrees of freedom, such as glueballs or hybrids, is expected to be suppressed. Therefore, two-photon reactions act as anti-glueball filter and measuring the production strength of a state in two-photon production, offers direct information on the inner structure. Here, a coupled channel PWA of the reactions $\gamma\gamma \to \pi^0\pi^0$, $\pi^0\eta$ and K^+K^- has been performed for the first time [21]. All available data samples in the beam energy range between $\sqrt{s} = 3.7 - 4.7\,\text{GeV}$, corresponding to an integrated luminosity of 21.7 fb^{-1} collected by the BESIII experiment, were used. By applying event-based background rejection methods, very pure data samples have been selected. The data were described using the K-matrix formalism under the P-vector approach and the resonance parameters were fixed to a parameterization obtained from a recent coupled channel analysis [18].
The obtained fit result for all three channels is shown in Figure 4. The final results of this analysis, including a publication, is foreseen in the near future.

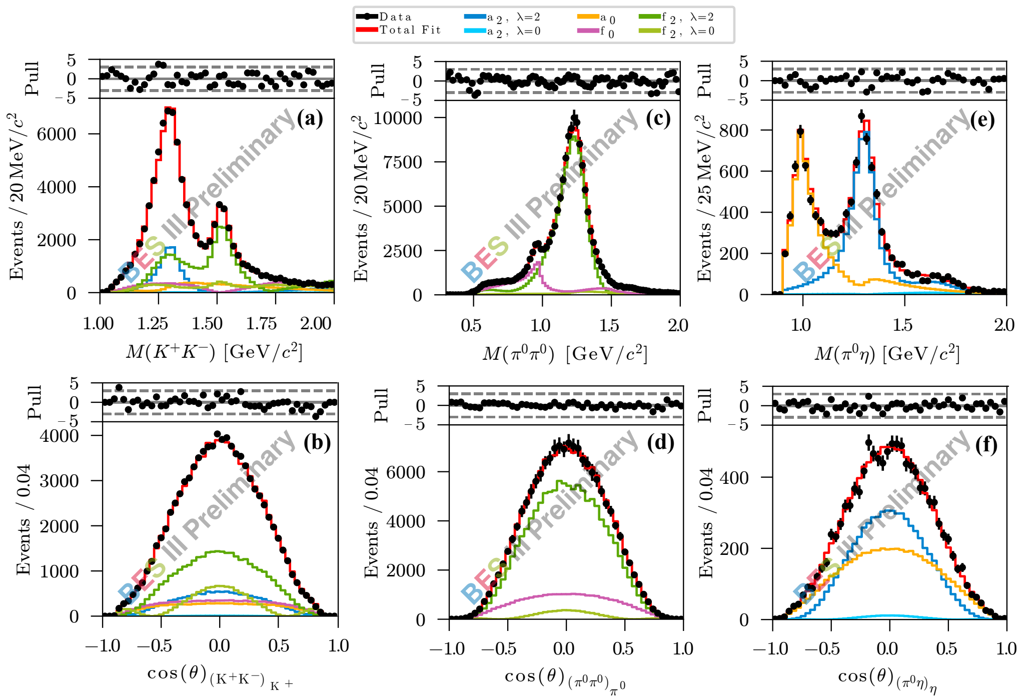

Fig. 4.: Contributions and total fit result obtained from the best fit hypothesis for the invariant K^+K^- mass distribution (a), helicity angle of one kaon in the K^+K^- rest frame (b). In analogy the corresponding distributions are shown for the $\pi^0\pi^0$ system in Figures (c) and (d) and the $\pi^0\eta$ system in Figures (e) and (f), respectively.

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