International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy

Sunday 12 March 2017 - Friday 17 March 2017

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Book of Abstracts

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Amplitude Analysis for exotic states

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The microscopic nature of the XYZ states remains an unsettled topic. We show how a thorough amplitude analysis of the data can help constraining models of these states.
Specifically, we consider the case of the Zc(3900) peak and discuss possible scenarios of a QCD state, virtual state, or a kinematical enhancement. We conclude that
current data are not precise enough to distinguish between these hypotheses, however, the method we propose, when applied to the forthcoming high-statistics measurements
should shed light on the nature of these exotic enhancements.

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Amplitude analyses for CP violation measurements in beauty and charm

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Their unique sensitivity to phases makes PWA / amplitude analyses a powerful tool for precision CP violation measurements in beauty and charm decays. The role and limitations of amplitude models in these measurements are discussed. Methods overcoming limitations of existing amplitude models through model independent approaches are presented, and how high quality amplitude models are still required to reach optimal sensitivity even for model-unbiased approaches. Recent experimental results of CP violation and related measurements in multibody beauty and charm decays will be presented.

Session / **9**

Amplitude analysis for diffractive resonance production

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We present some results on the analysis of $\eta\pi$ resonances from peripheral scattering of pions off of nuclear targets. This analysis is motivated by the recent results by the COMPASS collaboration. The theoretical models emphasize final state interactions which satisfy S-matrix principles. We show how the model fits to COMPASS results, and obtain the resonance content for the $\eta\pi$ D-wave sector.

Session / **49**

Analysis of $\pi^-\pi^-\pi^+$ COMPASS data: role of $a_1(1260)$ meson and Deck process.

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The mass-dependent analysis of $\pi^-\pi^-\pi^+$ COMPASS data on the proton target is discussed. The analysis is based on the currently worlds largest data set of 46 000 000 events, which allows us to divide the data into 100 mass bins and 11 intervals of momentum transfer squared t'. The fit model includes Breit-Wigner amplitudes which are describing resonant contributions while flexible-shaped background terms account for non-resonating processes. The $a_1(1260)$ resonance is observed in $J^{PC}M^{\epsilon} = 1^{++}0^+\rho\pi S$-wave, which contributes about 30

Session / **51**

Automated wave-set generation in three-pion final states

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The measurement of the excitation spectrum of light-quark hadrons often requires to apply partial-wave analysis methods. The building blocks of the physical models used in such analyses are the partial waves, which describe the quantum numbers and the decay paths of the resonances. In diffractive reactions, in principle, infinitely many of these waves can contribute. However, for finite data samples, only a finite number of waves carry relevant information. Finding these waves is in general a difficult task. We present a method that imposes constraints in the form of prior probability density functions on the individual waves in order to build sparse models from systematically constructed sets of possible partial waves. As an example, we show results of the application of this method to simulated data for diffractively produced $\pi^-\pi^-\pi^+$ events.

Session / **44**

Baryon Partial Wave Analysis

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With new data of unprecedented accuracy from ELSA, JLab, MAMI, and other facilities the reliable extraction of the the spectrum of excited baryons becomes into reach. Besides experimental advances, the phenomenological analysis of the data has made much progress in the last years. Different partial-wave analysis efforts start to converge although, especially at high energies, the identification of broad and overlapping states remains a challenge. Recent developments in the spectroscopy of light baryons will be presented addressing formal advances, inclusion of new data, and statistical aspects. An attempt to identify remaining obstacles towards the reliable extraction of resonances is made.

Session / **43**

Baryon Spectoscopy

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One of the open challenges in subnuclear physics is to understand the non-perturbative regime of Quantum Chromodynamics, including the world of the nucleon and its excitations. One of the key issues is to identify the relevant degrees-of-freedom and the effective forces between them. A necessary step towards this aim is undoubtedly a precise knowledge of the experimental spectrum and the properties of baryon resonances.
Recently, large progress has been made e.g. based on photoproduction experiments providing not only differential cross section measurements but also high quality single and double polarization observables.

In the talk, among others results, these results will be discussed.

Session / **10**

Bayesian methods for extracting low energy constants in EFTs

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Properly constructed effective field theories (EFTs) hold the promise of model independence and order-by-order convergence of observable calculations.
EFTs have free parameters, the so-called low-energy constants (LECs), that often must be fixed using low-energy data relative to the breakdown scale of the EFT. We have developed a Bayesian framework for EFT parameter estimation that uses priors to encode information about LEC naturalness and EFT convergence. This allows us to avoid common parameter estimation problems and makes all assumptions explicit. Bayesian model selection is used to guide the parameter estimation by testing our assumptions about naturalness and making quantitative estimates of how many parameters can actually be constrained by the data available. Bayesian model checking is also used to verify whether EFT predictions converge as expected and to estimate the intrinsic breakdown of the theory.

Session / **13**

Bonn-Gatchina PWA of photoproduction data on the neutron

Victor Nikonov[1]

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Results of the latest BnGa PWA analysis of the photoproduction data on neutron is pesented. New CLAS data on hyperon photoproduction are included in the analysis. We also present the analysis of latest MAMI data.

Session / **19**

Complete Sets of Experiments and TPWA

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We compare the methods of amplitude reconstruction, for a complete experiment and a truncated partial wave analysis, applied to the photoproduction of pseudo-scalar mesons~[1]. A complete experiment analysis (CEA) determines 4 complex amplitudes up to an overall phase $\phi_0(E,\theta)$ at any given energy and angle and requires a minimum set of 8 observables that must include beam-, target- and recoil polarization, e.g. $\{d\sigma/d\Omega, \Sigma, T, P, F, G, C_x$ and $O_x\}$. On the other hand, a truncated partial wave analysis (TPWA) determines $4\,L_{max}$ complex multipoles up to an overall phase $\phi_0(E)$ at any given energy and is valid for all angles. The TPWA requires a minimum set of only 4 observables, where either target- or recoil polarization can be totally avoided. E.g., the set $\{d\sigma/d\Omega, \Sigma, F$ and $H\}$ is already complete. Examples are given for different order of truncation.

In an extension of this work we also discuss complete electroproduction experiments that require 12 observables for a CEA, whereas a TPWA can already be performed with only 6 observables. And again, either target or recoil polarization can be avoided.

[1] R.~L.~Workman, L.~Tiator, Y.~Wunderlich, M.~D\"oring and H.~Haberzettl, Phys.\ Rev.\ C {\bf 95}, 015206 (2017).

Session / **17**

Constraining single energy partial wave analysis

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We perform partial wave analysis of the eta photo production data. In an iterative procedure, fixed-t amplitude analysis (FT AA) and conventional single energy partial wave analysis (SE PWA) are coupled in such a way that output from one analysis is used as an constraint in another. The fixed-t analyticity in the fixed-t amplitude analysis is imposed by using Pietarinen's expansion method known from Karlsruhe-Helsinki analysis of pion-nucleon scattering data. As a result, multipoles are consistent with fixed-t analyticity and with fixed-s analyticity as well. By construction, invariant amplitudes fulfill required crossing symmetry.

Session / 20

Decay angular distributions of K* and D* vector mesons in pion-nucleon interaction

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We discuss production of vector K^* and D^* mesons in $\pi^- p$ interaction with their subsequent decay into pseudoscalar $K + \pi$ and $D + \pi$ mesons, respectively. Our consideration is based on modified quark-gluon string model which includes spin variables and allows to determine decay distributions of the outgoing pseudoscalars. These distributions are sensitive to the vector meson production mechanism and can be used for its determination. We find the relative importance of vector-meson Reggeon exchange to others for the cross sections. Result of present study may be used in projects of future experimental programs with the pion beams (for instance, at J-PARC facility).

Session / 30

Dipion resonance photoproduction on nucleons

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The t-channel reggeon exchange is the dominant mechanism of the high energy photoproduction of di-meson resonances on nucleons. The resulting amplitude naturally factorizes into initial production of meson pairs and subsequent final state interaction, which can be described in terms of binary amplitudes satisfying the constraints of unitarity and analyticity. However, for the final states consisting of 3 bodies as is the case here, the overall high energy of the system does not preclude that the 2-particle meson-nucleon subsystem is in fact low energetic and instead of using the Regge approach it should be described in terms low energy (baryon) resonance dynamics. This applies in particular to resonances observed in the photoproduced pi+pi- system. To fully describe such a system we have created the model which incorporates both the low energy meson-baryon dynamics, parametrized in terms of SAID elastic pi-N amplitudes [1] (up to pi-N effective mass of 2 GeV) and high energy regime parametrized in terms of reggeon exchanges [2] (above that limit). We use this approach to describe the two pion photoproduction in the D-wave, with particular emphasis put on the emergence of tensor-isoscalar resonances. The pi-pi rescattering is described in terms of unitary amplitudes satisfying once subtracted dispersion relations and with crossing symmetry properly imposed. Based on that, we calculate the photoproduction cross sections and mass distributions with clearly identifiable signals of isoscalar tensor meson production.

Literature:

1. R. Workman, R. Arndt, W. Briscoe, M. Paris, I. Strakovsky, Phys.Rev. C86, 035202 (2012)
2. Ł. Bibrzycki, R. Kamiński, Phys.Rev. D87, 114010 (2013)

3. P. Bydžovský, R. Kamiński, V. Nazari, Phys.Rev. D94, 116013 (2016)

Session / **75**

Discussion - Open stage

This slot is open for issues to be discussed in greater detail. Discussion topics should be prepared on 1-2 slides or introduced orally.

Session / **47**

Discussion session for baryons within the PDG

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Recent activities of the PDG are reviewed together with plans for further improvements. Topics include the criteria for including new results and changes in the presentation of particle properties.

Session / **28**

Dispersive Analysis of η' –> η π π Decays

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The decay channel $\eta' \to \eta\pi\pi$ offers several features of interest: due to final-state interactions it can be used to constrain $\eta\pi$ scattering. It is also an essential input for a study of inelastic effects in the decay $\eta' \to 3\pi$. In the past, extensions of chiral perturbation theory have been employed to describe this decay.
In this talk, I will present a dispersive analysis of the decay amplitude that is based on the fundamental principles of analyticity and unitarity. In this framework the leading final-state interactions are fully taken into account. Our dispersive representation relies only on input for the $\pi\pi$ and $\eta\pi$ scattering phase shifts. Isospin symmetry allows us to describe both the charged and neutral decay channel in terms of the same function.
The dispersion relation contains three subtraction constants that cannot be fixed by unitarity. We determine these parameters by a fit to Dalitz-plot data from the VES and BES-III experiments and show that the result fulfills the prediction of a low-energy theorem.
We compare the dispersive fit to variants of chiral perturbation theory.

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Dispersive analysis of $\bar{B}_{d,s}0 \to J/\psi\{\pi\pi, \bar{K}K, \pi\eta\}$ decays

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Within the framework of dispersion theory we analyze the decays $\bar{B}^0_{d,s} \to J/\psi M_1 M_2$ with $M_1 M_2$ being an scalar isoscalar or isovector pair of pseudoscalars, $\pi\pi$, $\bar{K}K$ or $\pi\eta$. In a fit of the $\bar{B}^0_{d,s} \to J/\psi\pi\pi$ spectrum to data we fix several parameters, whose number is reduced significantly compared to a phenomenological analysis. Using these fit results we give predictions for the other final states, solely based on coupled-channel relations between the $\pi\pi$ and $\bar{K}K$ and the $\pi\eta$ and $\bar{K}K$ pairs, respectively, and isospin relations. These relations allow to deduce crucial information on $\pi\eta$ scattering and to compare the $f_0(980)$ vs. the $a_0(980)$ signal, which dominate the considered spectra in the isoscalar or isovector meson-pair final-states, respectively.

Session / 31

Electroexcitation of Nucleon Resonances: Status and Future

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Transition form factors are uniquely suited to trace the evolution of baryon degrees of freedom by measuring exclusive single-meson and double-pion electroproduction cross sections off the free proton. Recent efforts try to access their isospin dependence by analyzing the cross sections off the quasi-free neutron and proton in Deuterium. In the near future, these exclusive measurements will be extended to higher momentum transfers with CLAS12 and the energy-upgraded CEBAF beam to study the strong interaction where the dressed quark degrees of freedom dominate. Recent and preliminary results will highlight the status of the analyses and an experimental outlook will outline what shall and may be achieved in the new era of the 12-GeV upgraded transition form factor program.

This work is supported in part by the National Science Foundation under Grant PHY 1505615.

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Excited Hadrons on the Lattice

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It took more than 40 years until Lattice QCD tools have become evolved far enough to address excited hadrons in a reliable way. Still, we are confined to the low lying resonances with a few coupled two-hadron channels, mostly in the meson-meson sector. Phase shifts at a few energy values for simple system have been determined in this first principles approach. Meson-nucleon results are scarce. The theory for decay channels with more than two hadrons is becoming ready, the practical applications are progressing. Comparison of lattice results with model calculations are helpful. I will survey what has been done and how.

Session / **15**

Exclusive diffractive resonance production in proton-proton collisions at the LHC

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A model for exclusive diffractive resonance production in proton-proton collisions at the LHC is presented. Cross sections are calculated by folding the Pomeron-Pomeron total cross section (*) with the Donnachie-Landshoff parameterisation of the Pomeron flux in the proton(**). The single differential cross section dsigma/dM as well as the double differential cross section dsigma/dMdp_T will be shown for the resonances f0(980) and f2(1270).
The range of x-values of the Pomeron flux accessible in these measurements will be addressed.

*) R.Fiore, L.Jenkovszky, R.Schicker, Resonance production in Pomeron-Pomeron collisions at the LHC, Eur. Phys. J. C76 (2016) 1, 38

**) A.Donnachie, P.V.Landshoff, Hard diffraction: Production of high p_T jets, W or Z, and Drell-Yan pairs, Nucl. Phys. B303 (1988), 634

Session / **55**

Existing and future experimental possibilities in hadron spectroscopy

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Despite of numerous experimentally observed signals of XYZ states, and impressive progress in the interpretation from the theory side, the quest for understanding the overall pattern is still on. In particular one of the questions for the present and the near-term future is, which particular new, yet-unobserved states with which quantum numbers would give us more information, if XYZ states are molecules, tetraquarks, hadroquarkonium or maybe hybrids. Then, after identifying some key

candidate states, we will try to review, which present or future experiment would be suited for which states, and compare some advantages and disadvantages.

Session / **41**

Exotic hadrons at LHCb

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Recent results in studies of exotic states at LHCb are presented in this talk. The results include observation of pentaquark states in Lambda_b decays, studies of B -> psi' K pi and B -> jpsi phi K channels with contributions of tetraquark candidates, search for X(5568) in Bs pi channel, and the most recent constraints on the quantum numbers of molecular candidate Lambda_c(2940) from Lambda_b -> D0 p pi analysis. Analysis techniques used and challenges faced in these studies are discussed.

Session / **60**

Exotic mesons with heavy quarks

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Recent progress in the determination of the heavy meson spectrum from lattice QCD are reviewed with a focus on exotic states. I interpret the term “exotic” widely, using it to refer to hadrons with masses and/or properties not expected from calculations in simple potential models. Among these, I will highlight some recent calculations for XYZ charmonium-like states. Furthermore a lattice QCD calculation for the X(5568), claimed by the D0 collaboration but not seen by LHCb, is presented. The short review is concluded with an overview of recent lattice calculations regarding (explicitly exotic) double-heavy tetraquark states.

Session / **4**

Finite Enery Sum Rules in Baryon and Meson Spectroscopy

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Analyticity provides constraints on the imaginary part of the amplitudes. The so-called finite energy sum rules. By relating the resonance region to the high-energy one, they can provide information useful to reduce the ambuigties in extracting baryons and mesons properties.
In this talk I will review their status in modern applications.

Session / **6**

Finite-Energy Sum Rules in Eta Photoproduction off the Nucleon

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Pseudoscalar-meson photoproduction on the nucleon is of current interest for hadron reaction studies. At low energies it provides information about the nucleon spectrum, while at high energies it reveals details of the residual hadron interactions due to cross-channel particle (Reggeon) exchanges. These two regimes are analytically connected, a feature that can be used to relate properties of resonances in the direct channel to Reggeons in the cross channels. In practice this can be accomplished through dispersion relations and finite-energy sum rules (FESR) [1].

At high energies ($E_{\text{lab}} > 4$ GeV), only the unpolarized differential cross section has been measured, providing little constraints on theoretical models. Forthcoming data from the GlueX experiment at Jefferson Lab are expected to improve the situation.

Even though photons couple to both isospin $I = 0, 1$ states, there are some notable differences between high energy photoproduction of the η ($I = 0$) and the π^0 ($I = 1$). In contrast to the η, the π^0 differential cross section has a dip in the momentum transfer range, $-t \sim 0.5 - 0.6$ GeV^2. The dip in π^0 photoproduction is expected to be associated with zeros in the residues of the dominant ρ/ω Regge exchanges [2,3]. It is an open question, what mechanisms are responsible for filling in the dip in eta photoproduction. It is often assumed that large unnatural contributions come into play. Finite-energy sum rules can provide clues here by relating the t-dependence of Regge amplitudes to that of the low-energy amplitude, usually described in terms of a finite number of partial waves. Early attempts could not resolve this issue due to the low quality of the data and the large uncertainties in the parametrization of the partial waves. Nowadays, however, there are several models that have been developed for the resonance region of η photoproduction allowing for a more precise FESR analysis.

The largest uncertainty in η photoproduction stems from the unnatural parity Regge exchanges. These contributions can be isolated through photon beam asymmetry measurement. Such measurement will soon be published by the GlueX collaboration. The experiment uses linearly polarized photons with energy $E_\gamma^{\text{lab}} \sim 9$ GeV and it has simultaneously measured η and π^0 production. Those data will reduce the systematic uncertainties and provide a better constraint on Regge amplitudes.

We have analyzed $\gamma N \to \eta N$ within a FESR framework [4]. Using these sum rules, one is able to obtain the t-dependence of the high-energy Regge residues using low-energy models. We found that a residue nonsense-wrong signature zero (NWSZ) seems to be lacking in the t-channel helicity flip amplitude of the ρ residue. Including this in our model results in a mechanism where the dip in η photoproduction is filled up with natural contributions, rather than genuinely assumed unnatural b exchange [5]. The upcoming GlueX results will be able to either confirm or refute this explanation: photon beam asymmetry close to $\Sigma = +1$ within the range $-t \approx 0.5 - 0.6$ GeV^2 indicate that the absence of a dip in eta photoproduction should indeed be attributed to natural exchanges.

[1] V. Mathieu, I. V. Danilkin, C. Fernández-Ramírez, M. R. Pennington, D. Schott, A. P. Szczepaniak, and G. Fox, Phys. Rev. D92, 074004 (2015).
[2] V. Mathieu, G. Fox, and A. P. Szczepaniak, Phys. Rev. D92, 074013 (2015).
[3] V. Mathieu et al., In preparation.
[4] J. Nys, V. Mathieu, C. Fernández-Ramírez, A. N. Hiller Blin, A. Jackura, M. Mikhasenko, A. Pilloni,

A. P. Szczepaniak, G. Fox, and J. Ryckebusch (JPAC), (2016), arXiv:1611.04658 [hep-ph].
[5] F. D. Gault and A. D. Martin, Nucl. Phys. B32, 429 (1971).

Session / **42**

First results from freed-isobar analysis with extended wave-sets

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The COMPASS experiment has collected a very large data set of 50 million diffractively produced $\pi^-\pi^+\pi^-$ events using a $190\,\mathrm{GeV}/c$ negatively charged hadron beam. In addition to the results of an extensive Partial-Wave Analysis (PWA) of this data, we recently published first results of a so-called freed-isobar PWA. In this approach, fixed parametrizations of intermediate $\pi^+\pi^-$ resonances are replaced by piecewise constant functions, which leads to a less biased extraction of two- and three-particle amplitudes. The success of this first analysis, which was limited to 3 partial waves with $J^{PC} = 0^{++}$ of the two-pion subsystem, led to an extension of the method to include also waves with $J^{PC} = 1^{--}$ and 2^{++} two-pion subsystems. First results from Monte Carlo studies will be presented. We will also discuss the ambiguities that arise in these extended free-isobar PWAs and will show how to resolve them.

Session / **67**

Future perspectives for baryon and meson spectroscopy

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We discuss perspectives of future spectroscopic studies using existing and planned electron-positron and proton-proton colliders. While for mesons of light quarks prospects are mostly related to VEPP-2000 in Novosibirsk and BEPC2 in Beijing, heavier mesons as well as baryons will be readily produced at the Super-tau-charm factory in Novosibirsk or China, KEKB at KEK, LHC and future facilities at CERN.

Session / **66**

Hadron resonance gas, hadron production in ultra-relativistic nuclear collisions, and the QCD phase diagram

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We will provide the connection between hadron production in ultra-relativistic nuclear collisions and the hadron mass spectrum. In particular, we will demonstrate that all hadron resonances are

important up to a mass of about 2.5 GeV, but details (quantum numbers, widths, etc) of resonances above a mass of 2 GeV are not so important because of Boltzmann suppression. We will also discuss the precision and predictive power of this analysis and emphasize the connection of the three main parameters determined by the analysis (temperature T, baryo-chemical potential mu_b, and fireball volume V) to the values obtained from the QCD phase boundary as determined from Lattice QCD studies.

Session / **61**

Hadron-Hadron scattering from Lattice QCD

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We present our recent results on hadron-hadorn scattering from lattice QCD. This includes pion-pion scattering in different isospin channels, in particular I=0, and kaon-kaon with I=0. Eventually we discuss our current attemts to investigate pion-nucleon scattering with the pion mass at its physical value.

Session / **52**

Heavy-flavor hadron spectroscopy

Tomasz Skwarnicki[1]

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Progress in heavy-flavor hadron spectroscopy since the previous PWA/ATHOS meeting will be reviewed. Majority of the new results are concerned with candidates for exotic hadrons with the quark content matching tetraquark and pentaquark states. Clarifying the nature of these candidates often relies heavily on amplitude analyses, making this meeting particularly relevant for such studies. The recent results, together with their limitations and possible interpretations will be discussed.

Session / **36**

K π scattering analysis with Forward Dispersion Relations and other analytic methods

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A precise determination of pion-kaon scattering amplitudes is very relevant for our understanding of both light meson physics as well as input for analysis of other hadronic decays. In this talk we first present our analysis of the fulfillment of Forward Dispersion Relations by the existing data up to 1.75 GeV, and by imposing these relations as constraints on the fits, we provide a set of simple data parameterizations that satisfy Forward Dispersion Relations while simultaneously describing

the data up to 1.6 GeV. Finally, we present a determination of the mass, width and coupling of the resonances that appear in kaon-pion scattering below 1.8 GeV.

Session / **39**

LHCb analysis tools for finding resonances

Greig Cowan[1]

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I will give an overview of the analysis methods that are used by the LHCb collaboration to investigate (exotic) hadron states in the heavy-quark sector. Emphasis will be placed on amplitude analysis techniques that are employed to extract parameters of the exotic hadrons, using the recently discovered pentaquark and X -> JpsiPhi tetraquark candidates as examples.

Session / **7**

Latest Results from GlueX

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GlueX at Jefferson Lab aims to study the meson spectrum with an emphasis on light hybrid mesons. To this end, a linearly-polarized 9 GeV photon beam impinges on a hydrogen target contained within a hermetic detector with near-complete neutral and charged particle coverage. In spring of 2016, the experiment completed its commissioning and took its first substantial data in the design configuration. With the size of this data set, GlueX already exceeds previous experiments for polarized photoproduction in this energy regime. The planned schedule and a selection of early results will be presented. Furthermore, the strategy to map the light meson spectrum with amplitude analysis tools will be outlined.

Session / **14**

Laurent+Pietarinen method in baryon spectroscopy

Mirza Hadzimehmedovic[1] ; Hedim Osmanovic[2] ; Jugoslav Stahov[2] ; Rifat Omerovic[2] ; Alfred Svarc[3] ; Lothar Tiator[4] ; Ron Workman[5] ; Eberhard Klempt[6] ; Alexei Anisovich[6]

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Fundamentals of the new, robust, pole extraction method based on representing the regular part of Laurent expansion of partial wave amplitude with quickly converging Pietarinen series are repeated. An overview of all recent applications of this method with summary of obtained results is made. Preliminary results in extracting baryon transition form factors at the pole and analysis of lowest Kaon photoproduction multipoles are also discussed. New possibilities are presented.

Session / **11**

Lepton flavour violation in semileptonic tau decays

Alejandro Celis[1]

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The non-conservation of lepton flavour number has only been observed so far in neutrino oscillations. The observation of this phenomena in the charged lepton sector would provide clean evidence of new dynamics beyond the Standard Model.

I plan to discuss the physics of lepton flavour violating tau decays in semileptonic modes with particular attention on the determination of the relevant hadronic matrix elements. I plan to illustrate the role of these decay channels in constraining new physics scenarios by considering few specific examples. In particular, I will consider the possibility that the observed Higgs boson has flavour violating couplings to leptons.

Session / **18**

Light-meson spectroscopy at VEPP2000

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Latest results of experiments at the VEPP-2000 e+e- collider with the SND and CMD-3 detectors are presented. In particular, the accuracies of several decays of the vector mesons rho(770), omega(783), phi(1020) are improved. New hadronic final states a0(980)rho, a0(980)omega in e+e- annihilation are observed.

Session / **23**

Mathematical aspects of phase rotation ambiguities

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As it is well-known for a long time now, the observables in a single-channel scattering problem remain invariant once the amplitude is multiplied by an overall phase. This phase is generally allowed to depend on a full set of independent kinematic variables for the considered process. For a 2-body reaction, this means that the phase can depend on energy and angle.

For partial wave analysis problems, ambiguities that originate from a phase rotation are generally referred to as *continuum ambiguities*. However, once partial waves are extracted by fitting a polynomial amplitude in a truncated partial wave analysis (TPWA), so-called *discrete ambiguities* are also known to occur. The names of both types of ambiguities refer to the regions in amplitude space where the observables are unchanged. Such can be either continuously connected regions, or sets of discrete points.

This talk will elaborate the effect that general full continuum ambiguities, i.e. arbitrary phase rotations, have on the level of partial waves. Then, also discrete ambiguities in TPWA problems are illustrated and formalized. Finally, the connections between both types of ambiguities are worked out. All illustrations proceed on simple toy-model examples for spinless $2 \longrightarrow 2$ scattering.

Session / 64

Meson spectroscopy (theory)

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Large data sets in light meson spectroscopy from fixed target experiments are challeng-ing standard analysis methods in meson spectroscopy. On the one hand, they allow for innovative methodology but at the same time require a more profound and exact under-standing of underlying hadronic physics. Partial wave analysis now is a standard tool used across all experiments including heavy meson decays. This has lead to a large number of new results for light mesons but also raises the issue of systematic biases in individual analysis, including the path towards interpretation. However, the level of complexity in PWA is still different for various types of analysis.

It is a challenging theoretical problem to determine the underlying, analytical reaction amplitudes. There are possible overlapping resonances, threshold cusps, background and particle exchanges and precision data requires analysis that is based on principles of relativistic scattering such as unitarity, analyticity, crossing symmetry and considers QCD specific features, e.g., chiral symmetry.

In this session, will discuss new results and developments and point towards their ap-plications across this wide field of analyses from light to heavy meson spectroscopy.

Session / 24

Meson-meson amplitudes, constraints and new methods

Robert Kaminski[1]

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An overview of the most effective methods used for parameterization of meson-meson amplitudes below 2 GeV will be presented. Theoretical constraints imposed on the amplitudes and requirements for amplitudes will be discussed.
The most widely discussed will be the pion-pion amplitudes in all important partial waves (S, P, D and F). All these methods, constraints and new results

can greatly facilitate analysis of two body interactions in the final states, inter alia, in the photoproduction processes or decays of heavy mesons.

Session / **54**

Multi-body amplitude analyses at Belle

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Belle experiment performed a study of several multibody decays
of B and Υ-mesons with multidimensional phase-space
analysis of the final states. Such analysis allows to separate
contributions
of different intermediate states and determine their quantum numbers.
We present some recent results on $\bar{B}^0 \to D^{*+}\omega\pi^-$, $\bar{B}^0 \to J/\psi K^-\pi^+$, $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$,
$\Upsilon(10860) \to \Upsilon(\mathrm{nS})\pi^0\pi^0$ decays as well as techniques which
were used for these analyses.

Session / **56**

New methods, results and challenges in light meson spectroscopy

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Large data sets in light meson spectroscopy from fixed target experiments are challeng-ing standard analysis methods in meson spectroscopy. On the one hand, they allow for innovative methodology but at the same time require a more profound and exact under-standing of underlying hadronic physics. Partial wave analysis now is a standard tool used across all experiments including heavy meson decays. This has lead to a large number of new results for light mesons but also raises the issue of systematic biases in individual analysis, including the path towards interpretation. However, the level of complexity in PWA is still different for various types of analysis.

It is a challenging theoretical problem to determine the underlying, analytical reaction amplitudes. There are possible overlapping resonances, threshold cusps, background and particle exchanges and precision data requires analysis that is based on principles of relativistic scattering such as unitarity, analyticity, crossing symmetry and considers QCD specific features, e.g., chiral symmetry.

In this session, will discuss new results and developments and point towards their ap-plications across this wide field of analyses from light to heavy meson spectroscopy.

Session / **50**

News from Bonn-Gatchina PWA

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The status of the Bonn-Gatchina analysis of the meson and photo-induced reactions is reported. A number of new results obtained from the analysis of the new data on the meson photoproduction are presented and the property of the observed baryon states are discussed.

Session / **25**

On proton deformation: A model independent extraction of EMR from recent photoproduction data.

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The most recent $\gamma p \to p\pi^0$ [1,2,3] and $\gamma p \to n\pi^+$ data have been used
for multipole amplitude extraction at the $\Delta^+(1232)$ resonance.
The data have been analysed in a novel way, utilizing the Athens Model Independent Analysis Scheme (AMIAS),
yielding precise results with little, if any, model error. The benchmark quantity in nucleon deformation,
$EMR = E1 +^{3/2} / M1+^{3/2}$, was determined to be: $-(2.5^{+0.3}_{-0.2} stat)\%$ and
$-(2.5^{+0.4}_{-0.3} stat + syst)\%$,
consistent with previous results but for the first time free of model error.
Non resonant amplitudes up to L = 5 have also been extracted which test the
sophisticated phenomenological model used in nucleon resonance research.
The elaborate analysis scheme and its comparison to the traditional methods will be presented at the conference.

Session / **65**

PDG Baryons

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“On the definition of branching ratios for overlapping hadron resonances”,

Hadron resonances are wide and may overlap. This fact renders the definition of a branching ratio difficult. In a simulation, different definitions of the branching ratio are compared. Branching ratios can also be defined at the pole position. Applications of this definition for baryons and mesons are presented.

“On the star rating of the Particle Data Group for baryon resonances”.

Criteria are presented which are used to decide if published results on baryon properties are listed in the Review of Particle Properties. It is discussed which results go “above the line” or “below the line”, and what requirements need to be met to promote a new resonance to have a new RPP entry or to have more stars added to a resonance.

Session / **63**

PHASE

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PHASE - the Panel on Hadronic Amplitudes - is a proposal to form a joint panel of theorists and experimentalists, who are engaged in the investigation of the structure of hadronic amplitudes. This panel will curate the collaborative infrastructure needed to develop consistent data analysis techniques across experiments and enable joint analyses of multiple data sets. Such global analyses will only become possible through cooperation within the community and will significantly reduce systematic uncertainties on the extracted physics across a wide range of energies and processes.
This presentation will introduce the proposal, which can also be found online at https://www.authorea.com/136761/I55
We will follow up with an open discussion to collect feedback from the community.

Session / **33**

Parametrisation for near-threshold states

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In recent years various near-threshold narrow
peaks were observed in heavy quarknoium mass regions, such as $X(3872)$, $Z_c(3900)$, $Z_c(4020)$, $Z_b(10610)$ and $Z_b(10650)$, which are located close to the $D\bar{D}^*$, $D\bar{D}^*$, $D^*\bar{D}^*$, $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds in an S wave, respectively. Once there is a strongly coupled S-wave threshold nearby, the Breit-Wigner parametrisation does not work anymore. In this talk, we introduction a practical parametrisation for the line shapes of these near-threshold states which satisfies the unitarity and analyticity requirement of S matrix. This parametrisation scheme can accommodate arbitrary number of elastic and inelastic channels, which is easy and reliable for both experimental and theoretical analysis. As an application, the line shapes of the two Z_b states can be very well described. Furthermore, we also discuss whether their line shapes can be interpreted as the cusp effects.

Session / **48**

Partial Wave Analysis Activities at Bochum

Bertram Kopf[None]

This talk will summarize the Partial Wave Analysis (PWA) activities carried out at Ruhr-Universitaet Bochum. The key objective is to realize a powerful, user-friendly and highly modular PWA software package with the ability to provide amplitudes in different formalisms and to support single and coupled channel analyses with data obtained from different hadron spectroscopy experiments.
After a brief overview of the present status of the software package PAWIAN (Partial Wave Interactive Analysis) results from recent analyses, focused on important aspects of the pbar p and e+ e- annihilation processes are summarized. Finally rough ideas on how to consider analyticity and unitarity in PAWIAN will be briefly discussed.

Session / **5**

Phase ambiguities in complete experiments and PWA

Author(s): Alfred Svarc[1]

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For quite some time it is well known that single-channel physical observables are invariant with respect to a general energy and angle dependent phase rotation. This invariance is called continuum ambiguity. We show that, contrary to well-behaved energy dependent invariance, angle dependent phase rotation mixes multipoles, and changes their analytic structure. A direct consequence is that without determining the angular dependence of the free phase, partial wave decomposition is non-unique.

Session / **8**

PyPWA: A Partial-Wave/Amplitude-Analysis Software Framework

Carlos Salgado[1]

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We are developing a software framework for Partial Wave and Amplitude Analysis called PyPWA. The PyPWA project aims to develop modular and flexible software that links to existing codes and Python libraries. The software also provides direct access to the JLab computing resources. The software contains a general-shell where amplitude's parameters (or any parametric model) can be estimated from the data. The package also includes software to produce simulated data-sets. Another component contains a specific realization of the isobar model in polarized photo-production (with room to include Deck-type diagrams and other isobar model extensions). We are also implementing Bayasian's type model selection and global minimization (using Nestle - a nested MC) and parallelism and vectorization using the Intel's Xeon Phi family of coprocessors.

Session / **58**

Report of the Meson PDG group

Christoph Hanhart[None]

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The meson team is responsible for all aspects concerning unstable (with respect to the strong interaction) mesons within the Particle Data Group. This includes a literature scan, encoding of data into
the data base as well as the preparation of additional materials in tailor-made reviews. In the presentation I briefly describe the current activities of the PDG meson team.

Session / **59**

Resonances in coupled-channel scattering from lattice QCD

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"The majority of excited hadrons are seen as resonances in the scattering of lighter stable hadrons like pions and kaons. Many resonances decay into multiple final states necessitating coupled-channel analyses, and recently it has become possible to obtain coupled-channel scattering amplitudes from lattice QCD. I will describe one of these calculations, beginning with the computation of the finite-volume spectra, that are used to constrain infinite-volume scattering t-matrices, from which the complex resonance poles can be extracted. Several recent applications of these methods will be described, including the first extraction of a strongly-coupled coupled-channel scattering amplitude from lattice QCD where an a0 resonance was found in pi-eta K-Kbar scattering."

Session / **45**

Resonant π_2 poles from 3 π data.

Author(s): Mikhail Mikhasenko[1]

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High-energy peripheral reactions provide an excellent opportunity to study the excitation spectrum of hadrons. The COMPASS experiment at CERN has collected 5×10^6 events of the diffractive scattering of pions to the 3-pion final state.
Partial wave analysis techniques have been employed to obtain an expansion of the reaction cross section in terms of partial waves with quantum numbers $J^{PC}\, M^{\varepsilon}$.
Since around hundred of observed resonances in light sector are coupled to pionic systems the spin-density matrices from COMPASS PWA are extremely valuable data to identify ordinary and, possibly, exotic mesons.

The aim of our analysis is to extract three pion scattering amplitudes from mass-dependence of the COMPASS spin-density matrices using analyticity and unitarity constraints.

Three-body unitarity problem is very difficult and has not been completely solved.
Our approximation of those constraints is reduced in the isobar model by quasi-two-body ($\pi\pi$-subchannnel resonance + pion) unitarity requirements.
K-matrix approach is used to parametrize scattering matrix.
We invoke an unitarization procedure to incorporate non-resonant long-range production processes via pion exchange, i.e. "Deck"-like processes.

The developed theoretical framework is applied to the COMPASS data.
We discuss resonant pole positions of π_2 mesons located at the unphysical sheet, spurious poles caused by the parametrization and stability of solutions with respect to the changes in the model.

Session / **34**

Roy-Steiner-equation analysis of pion-nucleon scattering

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A precise understanding of low-energy pion-nucleon interactions is central for many areas in nuclear and hadronic physics, ranging from the scalar couplings of the nucleon to the long-range part of two-pion-exchange potentials and three-nucleon forces in Chiral Effective Field Theory. We present a calculation that combines the general principles of analyticity, unitarity, and crossing symmetry with modern high-precision data of hadronic atoms, leading to a phenomenological description of the pion-nucleon amplitude with unprecedented rigor and accuracy. Consequences for the pion-nucleon sigma-term and the matching to Chiral Perturbation Theory will be also discussed.

Lecture / **71**

S-matrix constraints in hadron phenomenology

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Session / **26**

Space-like and time-like electromagnetic baryonic transitions (Trento Workshop)

Author(s): Philip Cole[1]

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The study of electromagnetic transitions opens a window into the very nature of the strong interaction. And, indeed, such a study of how a ground-state nucleon transitions to an excited state, over a broad range of q^2, will provide keen insight into the evolution of how dynamically-generated masses emerge from the asymptotically-free, nearly massless quarks of perturbative QCD as well as provide information on the ancillary effects from the meson-baryon cloud. The space-like ($q^2 < 0$) region has been explored more intensively, particularly at JLab, but efforts have also begun in studying the time-like ($q^2 > 0$) region at GSI. We are living in exciting times whereby near-future prospects exist in extracting high-quality data in both the space-like and time-like regimes (JLab12 and FAIR, for example). We shall present the conceptual framework of an upcoming ECT*meeting entitled {\it Space-like and time-like electromagnetic baryonic transitions}, which will convene in Trento, Italy from 8-12 May 2017 (http://www.ectstar.eu/node/2220). This ECT* workshop will bring together several disparate experimental and theoretical communities and thereby will serve to help in making the very first steps towards a much needed consistent description spanning these two kinematical regimes in q^2. These discussions at the ECT* meeting will further include photoproduction measurements (ELSA, JLab, LEPS, and MAMI), wherein the $q^2 = 0$ point anchors the connection between space-like and time-like regions and meson-beam data (GSI, FAIR, and J-PARC) and amply complements the requisite information for baryon spectroscopy. Finally, studies of in-medium vector meson spectral function modifications, which are related to the electromagnetic transitions in the time-like region will also be addressed.

Session / **27**

Strange and Exotic Baryons at MAMI

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Finding evidence for the existence of exotic states is one of the most exciting aspects of modern hadron physics. In the meson sector, it is possible to have a 'smoking gun' signature of a genuine exotic nature provided by certain charge-mass combinations and J^{PC}-configurations that cannot be explained by a quark-antiquark pair. Observations of several candidates were claimed by experiments such as Belle, BES, BaBar and LHCb. On the other hand, the existence of exotic baryons is much more controversial, especially since the unprecedented episode of the rise and fall of the $uudd\bar{s}$ pentaquark. Recently though, the matter of pentaquarks has been resurrected by the observation of a $c\bar{c}uud$ pentaquark as claimed by the LHCb collaboration. Although there are arguments favoring the inclusion of heavy quarks in stable pentaquarks, the question remains if such and other exotic states could also be formed by u, d and s quarks only.

The tagged-photon beam experiment A2 at the MAMI electron accelerator facility in Mainz allows the study of several photoproduction reactions in which exotic baryons could be involved in. A selection of current activities and recent results will be discussed: In η photoproduction off the neutron, the presence of an unusually narrow resonance is one possible explanation for a sharp structure seen in the total cross section. Recently, new insights could be gained by the measurement of spin-dependent cross sections. Experimental data allowing to search for an exotic state in the KN system of $\gamma d \to \Lambda KN$ are also available and undergoing analysis. Furthermore, analyses looking for a signature of the dibaryon supposedly discovered by the WASA-at-COSY collaboration have been started. Finally, a newly approved experiment dedicated to the study of the $\Lambda(1405)$ will be presented.

Session / **53**

Studies of the a1(1260) from tau lepton decays at CLEO

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The combination of leptonic production and selection rules imposed by the weak hadronic current make the experimental study of hadronic final states in tau decay particularly clean. In this presentation we describe studies carried out nearly 20 years ago at CLEO-II of the a1(1260) meson in tau decays to neutrino plus three pions. Notable results include identification of significant contributions from isoscalars in the a1 substructure as well as features that emerge from a high-statistics analysis of the a1 lineshape.

Session / **12**

Studying the Pc(4450) resonance in J/psi photoproduction off protons

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We study the $P_c(4450)$ structure in J/ψ photoproduction, and discuss the feasibility of observing it in the CLAS12 experiment at the Jefferson Lab. This resonance-like structure has recently been observed in the $J/\psi\ p$ spectrum by the LHCb collaboration.

Our study presents a first estimate of the upper limit for the branching ratio of the $P_c(4450)$ to the $J/\psi\ p$ channel. We take into account the experimental resolution effects, and predict that it will be possible to observe a sizable cross section close to the J/ψ production threshold. This will shed light on the nature of the $P_c(4450)$ resonance in the future photoproduction measurements.

Furthermore, we give a study of the angular distributions of the differential cross sections, analyzing their sensitivity on the photocoupling sizes. With this information, the latter can also be constrained experimentally.

Session / 70

Systematic Errors in Particle Physics

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We consider some issues in the estimation of systematic errors as commonly performed by particle physicists. This is important in an era when large data samples reduce statistical errors to very small values,so that systematic uncertainties dominate. We highlight inconsistencies in the definitions and techniques currently used by some analysts, and offer guidelines for a more rigorous approach. Such estimates are more accurate, and in general smaller, than those from traditional practice.

Session / 62

The HASPECT networking

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Fundamental interactions of components of matter are not yet fully understood. Some basic questions such as: how do the quarks, light constituents of the proton and neutron sum up to provide the visible mass of nucleons? Why the mediator of the strong interaction does not show up in the spectrum of hadrons? Are the three quarks and quark-antiquarks configurations the only
possible? The answer to these questions requires a sophisticated procedure that involves both experiments and theories necessary to interpret data.
To face the challenge presented by new hadron spectroscopy experiments in which a huge amount of high-quality data will be produced, we need to develop a set of tools to optimize each step in the analysis. Data need to be collected, analyzed, transferred, accessed and stored in a convenient and accessible repository. Reconstructed four-momenta need to be feed to sophisticated partial-wave analyses that, making use of experimental and theoretical constraints,

provide reliable results. Observables need to be compared to the best existing solution of the fundamental
theory of the strong interaction provided by the Lattice-QCD and interpreted by using effective models that pick out the underlying dominant mechanisms of the theory. This complex analysis chain requires that the different skills and competences that are present in the hadron physics community be shared among groups and collaborations. Parallel computing, algorithmic optimization, cloud technology, massive data management, together with a thorough and well founded theoretical framework that can be used to analyze data require that experts share information and techniques to produce reliable results.
The goal of HASPECT networking is exactly to address this problem supporting exchanges and establishing links among these different communities, all involved in the same business: hadron physics laboratories in Europe (CERN, GSI, BONN, MAINZ) need to interact with their counterpart in US (JLab) and Asia (BESIII and Belle). The theoretical community needs to establish a contact with experimental collaborations that are performing the experiments and event-based analyses. Sophisticated computing techniques need to be merged with the specific requirements of a well-motivated and solid phenomenological scheme to perform high-level analysis necessary for physics interpretation. Senior scientists need to transfer their competences and their background to the new generation of researchers that will be the resource of the future.

Session / **22**

The a_1(1260) lineshape measured in D -> 4pi decays

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The decay $D^0 \to \pi^+\pi^-\pi^+\pi^-$, with $D^0 \to a_1(1260)^+\pi^-$ being the dominant intermediate state, provides an excellent environment to study the properties of the $a_1(1260)$ meson. We present new measurements of the $a_1(1260)$'s mass and width using data collected with the CLEO-c detector. The $a_1(1260)$ contribution is disentangled from the other occurring decay channels by means of a full five-dimensional amplitude analysis. A state-of-the-art parameterization of the $a_1(1260)$ lineshape is used taking into account the resonant three-pion substructure. In addition, several other lineshape models are tested. As we observe a significant dependence of the measured width on the chosen parameterization, a quasi-model-independent study of the lineshape is performed as well.

Session / **40**

The eta -> 3 pi and eta pi -> pi pi amplitudes from the chiral expansion and an extended Khuri-Treiman dispersive formalism

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The considerable amount of data on three-body decays of mesons which has become available in recent years has revived interest in the dispersive formalism of Khuri and Treiman as a powerful analysis tool. We consider here the isospin breaking eta -> 3 pi amplitude which is specific in that both the low-energy chiral expansion and dispersion relation techiques can be applied. We reconsider an approach in which both methods are combined such as to produce a unique, parameter-free (except for an overall factor) amplitude in the physical region. We develop an extension of the KT formalism which includes both eta-pi rescattering as well as inelastic rescattering to KKbar. We compare the predicted amplitude with the recent high-precision experimental results from KLOE, BESIII and WASA. Consequences for the isospin breaking quark mass ratio are presented.

Lecture / **72**

Tools and methods in baryon spectroscopy

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Lecture / **16**

Tools and methods in meson spectroscopy

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Session / **57**

Triangles and rescattering in light- and heavy-meson decay

Eulogio Oset[None]

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I shall give a brief introduction to triangle singularities (TS), with a new pedagogical way to face them. Then I will report on the interpretation of the $f_1(1420)$ as a decay mode of the $f_1(1285)$ into $\pi a_0(980)$ through a TS, and $K^*\bar{K}$. Then I briefly report on the $f_2(1810)$ and make predictions for the decay $\bar{B} \to \bar{K}\pi D^*_{s0}(2317)$, which shows a peak due to a TS. Concerning rescattering in decays of particles, I shall describe the $\chi_{c1} \to \pi^+\pi^-\eta$ decay measured at BESIII and make predictions for $\eta_c \to \pi^+\pi^-\eta$ decay.

Session / **29**

Two pole structure of D*0(2400)

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The D*0(2400) is the known lightest non-strange scalar meson. In this talk, we study the D-pi, D-eta, and Ds Kbar scattering amplitudes in the context of unitarized Heavy Meson Chiral Perturbation Theory. We show that there are actually two poles in this energy region. Having fixed the value of the free parameters from previous works, we make a prediction of the energy levels of the system (and its volume dependence), and perform a comparison of these levels with those obtained in a recent LQCD simulation. A very good agreement is found, which is considered as a strong support to the two pole structure for the D*0(2400). Further developments regarding this state and related predictions in other sectors are also performed.

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Welcome

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X (3872) line shapes

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We introduce a near-threshold parameterization that is more general than the effective-range expansion
up to and including the effective-range because it can also handle with a near-threhold zero in the $D^0\bar{D}^{*0}$ S-wave. In terms of it we analyze the CDF data on inclusive $p\bar{p}$ scattering to $J/\psi\pi^+\pi^-$, and the Belle and BaBar data on charged B decays to $K\,J/\psi\pi^+\pi^-$ and $K D\bar{D}^0\pi^0$ around the $D^0\bar{D}^{*0}$ threshold. It is shown that data can be reproduced with a similar quality for the X(3872) being a bound {\it and/or} virtual state. We also find that the X(3872) might be two virtual-state poles, that give rise to a second-order S-matrix pole in the limit in which the small D^{*0} width vanishes. The $D^0\bar{D}^{*0}$ compositeness coefficient ranges from nearly 0 up to 1 in different scenarios.

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η and η' photoproduction with ηMAID including Regge phenomenology

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We present a new version of the ηMAID model for η and η'
photoproduction on proton and neutron.
The model includes 23 nucleon resonances parameterized with Breit-Wigner shapes.
The background is described by vector and axial-vector meson exchanges in the

t channel using the Regge cut phenomenology.
Parameters of the resonances were obtained from a fit to the new experimental data of the A2 Collaboration and available data from CBELSA/TAPS, CLAS, and GRAAL Collaborations.
%for η and η' photoproduction on protons and neutrons.
Dominant role of $1/2^-$ resonances is discussed.
The total cross section for η photoproduction demonstrates a cusp at the energy W$\sim$1.9~GeV.
The cusp is explained as a threshold effect due to the opening $\eta' p$ decay channel of the $N(1895)1/2^-$ resonance.