

# PWA tools in Hadronic Spectroscopy

## Mainz

Feb 18–20, 2013 in Mainz, Germany

### ABSTRACT

The mini-proceedings of the Workshop on PWA tools in Hadronic Spectroscopy held in Mainz from February 18<sup>th</sup> to 20<sup>th</sup>, 2013.

The web page of the conference, which contains all talks, can be found at

<http://conference.kph.uni-mainz.de/pwa2013/>

We acknowledge the support of Deutsche Forschungsgemeinschaft DFG through the Collaborative Research Center “The Low-Energy Frontier of the Standard Model” (SFB 1044).

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# 1 Introduction – Scope of the workshop

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## 1.1 Motivation

The understanding of scattering amplitudes and the interpretation of resonances is one of the most challenging tasks in modern hadron physics. Usually, these resonances are interpreted in terms of excitation spectra of hadrons. In this case the properties of a resonance, defined by a pole of the scattering amplitude in the complex energy plane, are related to universal properties of a hadron. The position of these poles are independent of the initial and final state of a particular reaction and should be compared to the spectrum predicted by QCD. In order to determine such resonance parameters in different reactions, an immense experimental effort started during the last decade.

There is an unprecedented increase in high precision measurements of single and double spin observables in photo-induced meson production at ELSA, JLAB and MAMI. Even if the experiments are still ongoing it is already obvious from preliminary results that these data will have a significant impact on our knowledge of baryon resonances.

Completely different approaches to hadron spectroscopy are presently being developed at the BES-III  $e^+e^-$  collider, where decays like  $J/\psi \rightarrow \bar{N}N^* \rightarrow \bar{N}N\pi$  have been observed, or at the COMPASS experiment at CERN, where high statistics measurements of diffractive  $pp$ ,  $\pi p$  and  $Kp$  collisions clearly show baryon and meson resonances in different final states. Furthermore, the HADES experiment at GSI started to study resonances in direct  $pp$  collisions.

One important milestone in hadron spectroscopy will be the combination of all this new empirical information from very different experiments. This requires the mutual understanding of the techniques and model assumptions used by the different communities in data analysis and for the extraction of partial wave amplitudes and resonance parameters. The aim of this workshop was to deepen this mutual understanding and to start a discussion about the development of common tools and analysis techniques.

## 2 Short summaries of the talks

### 2.1 Improved Breit-Wigner Formula

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Fundamental properties of a simple narrow resonance are the mass  $M$ , roughly equal to the peak position of the cross section, and the decay width  $\Gamma$ , which is related to the width of the bell shape. These parameters, along with the branching fraction  $x$ , are known as the Breit-Wigner parameters [1]. However, resonance peaks are usually very wide, and the shape can be so deformed that it is not at all clear where exactly is the mass, or what would be the width of that resonance. In those cases, resonance parameters are assumed to have energy dependence. This dependence is often defined differently for different resonances.

With model dependent parameterizations, the simple connection between physical properties of a resonance and its model parameters is lost, and the choice of the “proper” resonance parameters becomes the matter of preference. This makes the comparison between cited resonance parameters quite confusing and potentially hinders the direct comparison between microscopic theoretical predictions (for example [2]), and experimentally obtained resonance properties [3]. To clarify this situation we devised a simple model-independent formula for resonant scattering, with well defined resonance physical properties, which will be capable of successfully fitting the realistic data for broad resonances [4].

These Breit-Wigner parameters are uniquely defined and model independent, with directly observable mass as the peak of the squared amplitude (a  $T$ -matrix element or partial wave). However, they strongly depend on shape parameter that corresponds to the complex residue phase, and which may change from reaction to reaction. Consequently, for the same pole position, there will be different Breit-Wigner masses and widths in different channels.

In Ref. [4], we have shown that the original Breit-Wigner formula can be considerably improved by including a single additional phase parameter. Moreover, our results suggest that this parameter seems to be equal to the half of the resonance residue phase, regardless of the resonance inelasticity. The improved Breit-Wigner formula has two equivalent forms that can be used to estimate either the pole, or the Breit-Wigner parameters in a model independent way. Analysis of the results for the both sets of the resonance parameters has shown us that in the PDG tables [3] there are values that do not correspond either to pole, or to Breit-Wigner values. Such an outcome undermines the proper matching between microscopic theories (such as the lattice QCD [2]) and experiment, and should be properly addressed in the PDG notes.

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## 2.2 Coupled-channel dynamics in meson-baryon scattering

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Mapping out the spectrum of excited baryons from data is a cornerstone to the understanding of the strong interaction. With the advent of high-precision photo and electroproduction data [1-3] there is finally the chance to come to more conclusive answers regarding the resonance content, that have been searched for since a long time [4-18]. Also, the dynamical nature of several baryonic resonances remains subject of investigation [19-22].

One challenge in the study of excited baryons is to combine the data of different reactions in a global analysis while respecting unitarity, analyticity [23,24], gauge invariance [25,26] and other theoretical requirements such as chiral constraints. For example, if branch points in the complex plane are missing in an analysis tool, their absence might be masked by erroneous resonance signals [27].

Recent results of the analysis of pion photoproduction [25] and the world data of pion-induced  $\pi N$ ,  $\eta N$ ,  $K\Lambda$ , and  $K\Sigma$  production are presented [28], developed at the Forschungszentrum Jülich, the Universities of Bonn and of Athens (GA), and The George-Washington University [23-29]. The amplitude allows for the reliable extraction of resonance poles and residues that are determined up to  $J^P = 9/2^\pm$ .

Universal principles like (coupled-channel) unitarity also apply to the analysis of upcoming data of resonances decaying in the finite volume of lattice simulations. As quark masses drop towards physical values the eigenvalue spectrum becomes dominated by finite-volume effects. Hadronic methods such as coupled-channel analysis [30] can be adapted to the analysis of eigenvalues, in particular when moving frames lead to additional partial wave mixing [31], or if chiral extrapolations are required [32]. Effective Lagrangian methods [33] or unitarized chiral interactions [34] can provide adequate frameworks.

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## 2.3 Using the Bonn-Gatchina PWA to constrain the production of an $\bar{K}NN$ -cluster in p+p collisions

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In the given talk, I focused on the reaction:

$$p + p \rightarrow p + K^+ + \Lambda, \quad (1)$$

at a beam kinetic energy of 3.5 GeV. This reaction is the simplest way for open strangeness production in p+p collisions. Our particular aim is to study the possible formation of an intermediate “ $ppK^-$ ” bound-state and its coupling to the  $p + \Lambda$  final state:

$$p + p \rightarrow \bar{K}NN + K^+ \rightarrow p + \Lambda + K^+. \quad (2)$$

The possible existence of bound states of  $\bar{K}$  and nucleons was first mentioned in [1] but this issue triggered theoretical efforts only when Y. Akaishi and T. Yamazaki predicted that due to the strong binding between the kaon and the nucleons extreme dense systems might be formed [2, 3]. Meanwhile, several theoretical investigations have been performed by various groups, confirming the existence of such states but giving also a wide range of predictions for possible masses and width of the simplest bound state of a kaon and two nucleons ( $\bar{K}NN$ ), see [4] and references therein.

The question, whether such a new state is produced in Reaction (1) or not can only be answered if one understands the standard production process of  $p + K^+ + \Lambda$  in proton proton collisions. Here, several experiments have shown that the final state of  $K^+ + \Lambda$  is dominated by the decay of  $N^{*+}$  resonances [5, 6, 7, 8, 9]. This fact heavily influences the dynamics of the reaction. In order to find an additional signal beyond the known  $p + K^+ + \Lambda$  production we have to determine the properties of the  $N^{*+}$ -resonances that are the main source of the  $K^+ + \Lambda$  yield.

To cope with this task, we have used the Bonn-Gatchina Partial wave analysis framework [3]. Besides ordinary non-resonant production of  $p + K^+ + \Lambda$  the following final state is included in the framework:

$$p + p \rightarrow p + N^{*+} \rightarrow p + \Lambda + K^+. \quad (3)$$

We have scanned the PDG tables [12] to find suited candidates for  $N^{*+}$  resonances. The following resonances were selected:  $N(1650)$ ,  $N(1710)$ ,  $N(1720)$ ,  $N(1875)$ ,  $N(1880)$ ,  $N(1895)$  and  $N(1900)$  as the energy of 3.5 GeV is above their production threshold in proton+proton collisions and as they have a measured decay branching into  $K^+ + \Lambda$ . The data that we interpret with help of the PWA were collected with the HADES spectrometer [11]. Out of  $1.2 \cdot 10^9$  p+p collisions two data-samples corresponding to the final state  $p + K^+ + \Lambda$ , with a statistic of 13,000 and 8,000 events, could be extracted. The 21,000 events were fitted with the sum of several transition amplitudes including resonant and non-resonant production of

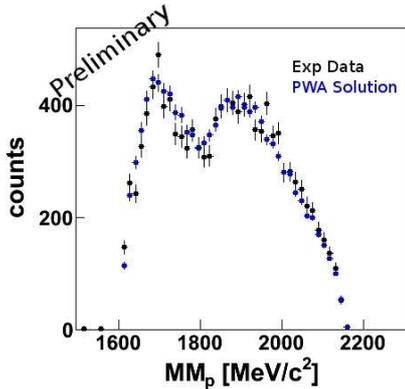


Figure 1:  $\Lambda K^+$  invariant mass. Data with a PWA solution.

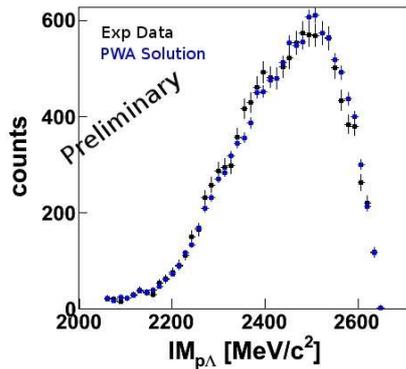


Figure 2: Invariant mass of  $\Lambda p$  compared to a PWA solution.

the tree final state particles. To account for the fact that there is an ambiguity which resonances participate in the process, a systematic variation of the number of included resonant and non-resonant waves was performed. Figures 1 and 2 show the best PWA solution for the data set with 13,000 events. The solution can describe the data remarkably well.

The PWA solution is a model for the background-only hypothesis of the analysis, as it includes no production of a kaonic cluster. One can perform a statistical test of this hypothesis to find incompatibilities of the hypothesis with the data which might be explained with the presence of an additional signal in the data [13]. Thus, we have computed a local p-value as a function of the  $p\Lambda$  invariant mass, which has revealed that the data are compatible with the background-only hypothesis. We will, thus, concentrate on extracting an upper limit of the production cross section of a kaonic cluster produced in p+p collisions at 3.5 GeV with a branching in  $p\Lambda$ . As the expected cross section is very small we intend to use the  $CL_s$  method for this purpose [14].

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## 2.4 Partial Wave Extraction from Near-Threshold Neutral Pion Photoproduction Data

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Since the development of chiral perturbation theory in the nucleon sector [1, 2], neutral pion photoproduction in the near-threshold region [4, 5] has played a pivotal role in our understanding of chiral symmetry [6, 7, 8, 9, 10, 11] and, henceforth, Quantum Chromodynamics in the low energy regime [3].

The latest experiment by the A2 and CB-TAPS collaborations at MAMI/Mainz has measured the energy dependence of the photon beam asymmetry together with the differential cross section of the  $\vec{\gamma}p \rightarrow \pi^0 p$  process allowing to extract the relevant partial waves in an almost model independent way [12]. With these high quality data it has been possible to assess the energy range where state-of-the-art Heavy Baryon Chiral Perturbation Theory [13] and Relativistic Chiral Perturbation Theory [14] can be applied, obtaining an upper limit of  $\sim 170$  MeV of photon energy in the laboratory frame.

The next step to improve the agreement between theory and experiment in the near threshold region is the explicit inclusion of the  $\Delta(1232)$  resonance in the chiral calculations [15, 16, 17, 18, 19].

Experimental data on the F and T asymmetries are currently under analysis [20] and will, hopefully, allow to test our knowledge on D waves as well as to obtain the  $\beta$  parameter associated to unitarity [21].

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## 2.5 Truncated PWA of a complete experiment for photoproduction of two pseudoscalar mesons

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A truncated partial wave analysis for the photoproduction of two pseudoscalar mesons on nucleons is discussed. For the partial wave decomposition of the amplitude the method developed in Ref. [1] is used. Here a special coordinate frame is chosen in which the  $z$ -axis is taken along the normal to the final state plane spanned by the momenta of the final particles. In this case one can take as independent kinematical variables the energies of two of the three final particles and three angles, determining the orientation of the final state plane with respect to the photon beam. Then the amplitudes corresponding to a definite value of the total angular momentum  $J$  and its projection  $M$  on the  $z$ -axis are obtained through an expansion of the helicity amplitudes over a set of Wigner functions (rotation matrices).

To find a complete set of observables, we have applied a criterion, which has been developed previously for photo- and electrodisintegration of a deuteron [2, 3]. It allows one to find a 'minimal' set in order to determine the partial wave amplitudes up to possible discrete ambiguities. To resolve the remaining ambiguities a second criterion from Ref. [4] is adopted for the truncated PWA. In the simplest case of  $J_{max} = 1/2$  these two criteria turn out to be sufficient for an unambiguous determination of the eight independent partial wave amplitudes. The corresponding 'fully' complete set includes beyond the unpolarized cross section, helicity beam asymmetry, as well as nucleon recoil polarization along the  $z$  and one of the  $x$  or  $y$  axes with and without circular polarization of the photon beam.

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## 2.6 Common PWA Framework for PANDA

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The spectroscopy program of future high-precision experiments like PANDA at FAIR implies the study of creation processes and the analysis of the distribution of hadronic decay particles to understand the nature of hadrons, as one cannot study their quark content directly due to confinement. Reaching unprecedented statistics and excellent resolution with new experiments a detailed and complex modeling of the strong interaction processes is required. To determine the quantum numbers of resonances and suppress non-resonant background as well as contributions from other waves, one has to deconvolute the final state of interest into separate spin-parity components by performing a partial wave analysis (PWA). As the number of parameters to be determined by the fit increases rapidly with the number of possible waves and therefore with the energy of the system, PANDA most likely will have to deal with hundreds of free parameters per fit. This makes the analyses a very demanding exercise in terms of computing resources, analysis management and quality assurance.

Currently available software is often tailored to the needs of one experiment or even specific channels requiring a large effort to use it for other needs e.g. other initial states or specific formalisms. Therefore, a new software package should also consider the latest and future developments in theory and provide a modular framework to make use of new or modified modeling approaches.

The Common PWA Framework for PANDA is designed to avoid the limitations of the available software packages and to take into account the experience from the whole community. Therefore we conducted a comprehensive survey and collected the requirements for this software package in a document which specifies the capabilities of the framework and defines the different modules. The main requirements were: Separation of physics models, data handling and fitting techniques, usage in multiple experiments, simultaneous fitting of multiple data sets, extendable with various models and formalisms, full freedom of modeling of physics amplitudes, easy usage of various optimization routines and caching and parallelization in different stages. To provide a playground for the framework design, a first environment with a simple fit routine was set up. It will be used as a base for further extensions, provides basic tools and most importantly it demonstrates the modular design.

## 2.7 Experimental Studies of the $N^*$ Structure with CLAS and CLAS12

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Baryon spectroscopy can establish more sensitively, and in an almost model-independent way, nucleon excitations and non-resonant reaction amplitudes by complete measurements of pseudo-scalar meson photoproduction off nucleons. However, beyond baryon spectroscopy at the real photon point  $Q^2 = 0 (GeV/c)^2$ , electron scattering experiments can also investigate the internal hadronic structure at various distance scales by tuning the four-momentum transfer from  $Q^2 \approx 0 (GeV/c)^2$ , where the meson cloud contributes significantly to the baryon structure, over intermediate  $Q^2$ , where the three constituent-quark core starts to dominate, to  $Q^2$  up to  $12 (GeV/c)^2$ , attainable after the  $12 GeV$  upgrade at JLab, where the constituent quark gets more and more undressed towards the bare current quark [1, 2]. Although originally derived in the high  $Q^2$  limit, constituent counting rules describe in more general terms how the transition form factors and the corresponding helicity amplitudes scale with  $Q^2$  dependent on the number of effective constituents. Recent results for  $Q^2 < 5 (GeV/c)^2$  [3, 4, 5] already indicate for some helicity amplitudes, like  $A_{1/2}$  for the electroexcitation of the  $N(1520)D_{13}$ , the onset of proper scaling assuming three constituent quarks. This further indicates that in this case the meson-baryon contributions become negligible in comparison to those of a three constituent-quark core, which coincides nicely with the EBAC dynamical coupled channel calculation [1, 6, 7]. Along the same line of reasoning perturbative QCD (pQCD) predicts in the high  $Q^2$ -limit by neglecting higher twist contributions that helicity is conserved. The fact that this predicted behavior sets in at much lower  $Q^2$  values than expected [1, 4] challenges our current understanding of baryons even further. For  $N(1520)D_{13}$  the helicity conserving amplitude  $A_{1/2}$  starts to dominate the helicity non-conserving amplitude  $A_{3/2}$  at  $Q^2 \approx 0.7 (GeV/c)^2$ , as typically documented by the zero crossing of the corresponding helicity asymmetry  $A_{hel} = (A_{1/2}^2 - A_{3/2}^2)/(A_{1/2}^2 + A_{3/2}^2)$ . The  $N(1685)F_{15}$  resonance shows a similar behavior with a zero crossing at  $Q^2 \approx 1.1 (GeV/c)^2$ , whereas the  $\Delta(1232)P_{33}$  helicity asymmetry stays negative with no indication of an upcoming zero crossing; and even more surprising are the preliminary results for the  $N(1720)P_{13}$   $A_{1/2}$  amplitude, which decreases so rapidly with  $Q^2$  that the helicity asymmetry shows an inverted behavior with a zero crossing from positive to negative around  $Q^2 \approx 0.7 (GeV/c)^2$  [8]. These essentially different behaviors of resonances underlines that it is necessary but not sufficient to extend the measurements of only the elastic form factors to higher momentum transfer. Hence to comprehend QCD at intermediate distance scales where dressed quarks are the dominating degrees of freedom and to explore interactions of dressed quarks as they form various baryons in distinctively different quantum states, the  $Q^2$  evolution of exclusive transition form factors to various resonances up to  $12 (GeV/c)^2$  are absolutely crucial [9].

The status quo in the baryonic structure analysis endeavor are currently based on three corner stones. First, the analysis of the  $N\pi$  channel data is carried out in two phenomeno-

logically different approaches based on fixed- $t$  dispersion relations and a unitary isobar model [4, 10]. The main difference between the two approaches is the way the non-resonant contributions are derived. The  $p\pi^+\pi^-$  CLAS data is analyzed within a unitarized phenomenological meson-baryon model [3, 11] that fits nine independent differential cross sections of invariant masses and angular distributions. The good agreement of the resonant helicity amplitude results in the single- and double-pion channels, that have fundamentally different non-resonant contributions and model-dependencies, provides evidence for the reliable extraction of the  $\gamma_v NN^*$  electrocoupling amplitudes. Second, the high  $Q^2$  behavior is most consistently described by relativistic light-front quark models, like [1, 12, 13, 14, 15], but their description of the low  $Q^2$  behavior is less satisfactory; and new QCD-based approaches, such as Lattice QCD and Dyson-Schwinger equations of QCD, start to capture the dynamical generation of mass [1]. Third, the Excited Baryon Analysis Center (EBAC), now the ANL-Osaka collaboration, calculates, based on a full dynamical coupled-channel analysis [1, 6, 7], meson-baryon dressing (meson-cloud) contributions that seem to bridge the gap between the relativistic light-front quark models and the measured results at low  $Q^2$ .

Digging deeper into the baryonic structure by increasing the momentum transfer beyond  $5 (GeV/c)^2$  [9] opens a unique window to investigate the dynamic momentum-dependent structure of the constituent quarks, and will allow us to address the central and most challenging questions in present-day hadron physics: a) how more than 98% of hadron masses are generated non-perturbatively, b) how quark/gluon confinement and dynamical chiral symmetry breaking emerge from QCD, and c) how the non-perturbative strong interaction generates the ground and excited nucleon states with various quantum numbers from quarks and gluons.

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## 2.8 Partial-Wave Analyses at COMPASS

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(COMPASS) [1] is a multi-purpose fixed-target experiment at the CERN Super Proton Synchrotron (SPS) aimed at studying the structure and spectrum of hadrons. One main goal of COMPASS is to search for mesonic states beyond the constituent quark model that are predicted by models and lattice QCD [2]. During 2008 and 2009 COMPASS acquired large data samples of diffractive-dissociation and central-production reactions using 190 GeV pion and proton beams on hydrogen and nuclear targets. The focus of the COMPASS analyses lies on pion-induced single-diffractive reactions of the form  $\pi^- + A \rightarrow X^- + A$ , where the intermediate state  $X^-$  decays into the final states  $\pi^- \eta$ ,  $\pi^- \eta'$ ,  $\pi^- \pi^+ \pi^-$ ,  $\pi^- \pi^0 \pi^0$ ,  $\pi^- \eta \eta$ , or  $\pi^- \pi^+ \pi^- \pi^+ \pi^-$ . At COMPASS energies these reactions are dominated by Pomeron exchange. In the partial-wave analyses (PWA) it is assumed that production and decay of the  $X^-$  factorize and that they can be described by two amplitudes  $T_i$  and  $A_i$ , respectively. Using the isobar model [3] and the helicity formalism [4] the decay amplitudes  $A_i$  can be calculated with no free parameters. The intermediate resonances that appear in the isobar model are usually described using relativistic Breit-Wigner parametrizations that include Blatt-Weisskopf centrifugal barrier penetration factors [5]. For intermediate  $\pi\pi_{S\text{-wave}}$  isobars the  $M$  solution from [6] is used. This parameterization does not include the  $f_0(980)$  which is added as a separate independent isobar. Parity conservation at the  $X^-$  production vertex is taken into account by using the reflectivity basis [7]. In the high-energy limit the reflectivity quantum number corresponds to the naturality of the exchange particle in the used Gottfried-Jackson  $X^-$  rest frame [8].

The mass dependence of the production amplitudes  $T_i(m_X)$  is determined by extended maximum likelihood fits to the observed multi-dimensional kinematic distributions of the final state particles. These fits are performed in narrow bins of  $m_X$  taking into account interference effects and detector acceptance. In the case of the two-pseudoscalar final states, mathematical ambiguities arise that have to be taken into account [9]. In a second step the mass dependence of the spin-density matrix, which is given by the production amplitudes determined in the first fit, is fitted by a coherent sum of Breit-Wigner and background terms.

Two PWA packages are used for the analyses: One is a Fortran program that was originally developed at Illinois [10] and later modified at Protvino and Munich. The other one [11] is a C++ framework originally based on the PWA2000 package [12].

First results show significant intensity in waves with spin-exotic  $J^{PC} = 1^{-+}$  quantum numbers, which are forbidden for ordinary  $q\bar{q}$  states, in the  $\pi^- \eta$  and  $\pi^- \eta'$  [13] as well as in the  $\pi^- \pi^+ \pi^-$  and  $\pi^- \pi^0 \pi^0$  decay channels [14]. Their resonance interpretation is, however, still unclear. The data seem to contain significant background contribution from non-resonant Deck-like processes [15] that need to be understood.

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## 2.9 Theory of Two-Pion Production

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A field-theory description of the photoproduction of two pions off the nucleon is presented that applies to real as well as virtual photons in the one-photon approximation. The approach is an extension of the field theory for  $\gamma N \rightarrow \pi N$  of Haberzettl [1] whose practical implementation [2, 3] was recently shown [4] to provide an excellent description of observables over a wide range of energies.

The Lorentz-covariant theory for  $\gamma N \rightarrow \pi\pi N$  is complete at the level of all explicit three-body mechanisms of the interacting  $\pi\pi N$  system based on three-hadron vertices. The modifications necessary for incorporating  $n$ -meson vertices for  $n \geq 4$  are discussed. The resulting reaction scenario subsumes and surpasses all existing approaches to the problem based on hadronic degrees of freedom. The full three-body dynamics of the interacting  $\pi\pi N$  system is accounted for by the Faddeev-type ordering structure of the Alt-Grassberger-Sandhas equations [5]. The formulation is valid for hadronic two-point and three-point functions dressed by arbitrary internal mechanisms — even those of the self-consistent non-linear Dyson-Schwinger type (subject to the three-body truncation) — provided all associated electromagnetic currents are constructed to satisfy their respective (generalized) Ward-Takahashi identities [1, 2, 3]. The latter is a *necessary* condition for maintaining microscopic consistency of all contributing electromagnetic reaction mechanisms. Following the basic prescription given in Ref. [1], it was shown in Refs. [2, 3], in particular, how the necessary full off-shell behavior of the Ward-Takahashi identities can be restored even if, for practical reasons, some of the underlying reaction dynamics needs to be truncated because of its complexity.

It is shown that coupling the photon to the Faddeev structure of the underlying hadronic two-pion production mechanisms results in a natural expansion of the full two-pion photo-production current  $M_{\pi\pi}^\mu$  in terms of multiple loops involving two-body subsystem scattering amplitudes of the  $\pi\pi N$  system that preserves gauge invariance as a matter of course order by order in the number of loops. A closed-form expression is presented for the entire gauge-invariant current  $M_{\pi\pi}^\mu$  with complete three-body dynamics. Individually gauge-invariant truncations of the full dynamics most relevant for practical applications at the no-loop, one-loop, and two-loop levels are discussed in detail.

The full description of the theory is forthcoming [6].

*Acknowledgments:* This work was supported in part by the National Research Foundation of Korea funded by the Korean Government (Grant No. NRF-2011-220-C00011).

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## 2.10 Remarks about resonances

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The presentation was a personal collection of general remarks about properties of resonances and what it takes to extract them reliably from data. Most illustrating examples were taken from the meson sector.

The central statement is that resonances are uniquely defined via their pole positions and residues. Based on residues it is, e.g., possible to define a branching ratio even for broad resonances by using the narrow width formula also in this case — this method was proposed to quantify  $\sigma \rightarrow \gamma\gamma$  in Ref. [1] and is also proposed for baryons in Ref. [2], p. 1269. However, one should not be tempted to use pole parameters and residues directly in the parametrization of the  $T$ -matrix, if a parametrization of the amplitude over a larger energy range is the goal, for such a parametrization of Breit-Wigner type violates unitarity and analyticity — e.g. it will automatically produce complex scattering lengths.

A better method is to use a parametrization that is consistent with unitarity by construction as done in Ref. [3]. In this work it is shown that even the pole of the  $\sigma$  gets quite well constrained, if one starts from theoretically well motivated parametrizations — that include the left hand cut as well as the two lowest right hand cuts — and fits high quality data, available in a relatively small energy range. The resulting scatter in pole positions is comparable to that of phenomenological studies that also describe the low energy data — c.f. Ref. [2], p. 708. In case of  $\pi\pi$ -scattering it is possible to even further improve the quality of the pole determination by using Roy equations [4].

For a proper extraction of pole parameters it is essential that different reactions are analyzed consistently. This requires especially that scattering as well as different production reactions are studied together. However, the left hand cuts of these different processes are different and as a result any factorization ansatz that writes the production amplitude as being proportional to the scattering  $T$ -matrix, as it is used, e.g., in  $K$ -matrix approaches, has an intrinsic, uncontrollable uncertainty. A way around this is to either keep all real parts in the loops, or to use dispersion theory. An example of a consistent dispersive treatment of  $\pi\pi$ -scattering, and the pion vector form factor that also allows for the explicit inclusion of higher resonances is given in Ref. [5].

Last but not least one should mention the role of chiral symmetry. As a consequence of the Goldstone theorem pions should decouple from matter in the chiral limit at vanishing momenta. As a consequence the interaction of pions with, e.g., resonances should either go via derivatives or via quark mass insertions. In Ref. [6] it is shown that only then the resonances in the  $S_{11}$  pion-nucleon channel decouple from the threshold as required by chiral symmetry.

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## 2.11 Study of baryon excited status at BES

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The report gives an experimental review of the baryon excited study at BES. BES has its advantages to study baryon excited states [1]. For  $J/\psi \rightarrow N\bar{N}\pi$  and  $J/\psi \rightarrow N\bar{N}\pi\pi$ ,  $N\pi$  and  $N\pi\pi$  systems are limited to be pure isospin 1/2 because the isospin conservation. And not only excited baryon states, but also excited hyperons can be studied in the charmonium decays. In the partial wave analysis, the data are fitted applying an unbinned maximum likelihood fit. The amplitudes are constructed using the relativistic covariant tensor amplitude formalism [2, 3]. A powerful tool FDC-PWA [4, 5] had been developed to generate the FORTRAN sources of PWA.

$N^*$  production in  $J/\psi \rightarrow p\bar{p}\eta$  was studied with  $7.8 \times 10^6$   $J/\psi$  BESII events [6]. Two  $N^*$  resonances were observed. In the analysis of  $J/\psi \rightarrow p\bar{n}\pi^- + \text{c.c.}$ , a possible missing  $N^*$  named N(2065) was observed with  $5.8 \times 10^7$   $J/\psi$  events at BESII [7]. N(2065) was also observed in the decay of  $J/\psi \rightarrow p\bar{p}\pi^0$  with BESII data samples [8]. With  $106 \times 10^6$   $\psi(3686)$  events collected at BESIII [9], PWA of  $\psi(3686) \rightarrow p\bar{p}\pi^0$  was performed. Two new  $N^*$  are observed, N(2300)(1/2+) and N(2570)(5/2-) [10]. PWA of  $\psi(3686) \rightarrow p\bar{p}\eta$  was performed either. Other baryon related papers published by BESIII can be found in the reference [11, 12, 13].

BESIII had collected more than 1.2 billion  $J/\psi$ , 0.5 billion  $\psi(3686)$  and  $2.9 \text{ fb}^{-1}$   $\psi(3770)$ , more and more results can be expected.

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## 2.12 Partial-Wave Analyses at Kent State University

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An overview of the recent single-energy partial-wave analyses performed at Kent State University is discussed. These analyses included data for  $\bar{K}N$  scattering to  $\bar{K}N$ ,  $\pi\Lambda$ , and  $\pi\Sigma$  final states as well as data for  $\pi N$  scattering to  $\eta N$  and  $K\Lambda$  final states. Energy-dependent solutions were obtained by incorporating our single-energy solutions into global multichannel fits. The resulting energy-dependent solutions provided a wealth of information about  $N^*$  and  $\Delta$  resonances, as well as information about  $\Lambda^*$  and  $\Sigma^*$  resonances.

Our  $\bar{K}N$  analyses began with a multichannel fit [1] of published partial-wave amplitudes from scattering to various final states, including  $\bar{K}N$  [2],  $\bar{K}^*(892)N$  [3],  $\bar{K}\Delta$  [4],  $\pi\Lambda$  [2],  $\pi\Lambda(1520)$  [5],  $\pi\Sigma$  [2], and  $\pi\Sigma(1385)$  [6]. The channels  $\sigma\Lambda$ ,  $\sigma\Sigma$ , and  $\eta\Sigma$  (for  $S_{11}$ ) were included as “dummy” channels (channels without data) in order to satisfy unitarity of the partial-wave  $S$ -matrix. In addition, our fits included Crystal Ball data [7] for  $K^-p \rightarrow \eta\Lambda$ , which was used to determine the  $S_{01}$  amplitude for the  $\eta\Lambda$  channel. The resulting global multichannel fits resulted in an energy-dependent solution that described all of these various channels in a manner consistent with  $S$ -matrix unitarity.

Our next step was to carry out single-energy partial-wave analyses (PWAs). Single-energy fits were performed separately for (i)  $K^-p \rightarrow K^-p$  and  $K^-p \rightarrow \bar{K}^0 n$ , for (ii)  $K^-p \rightarrow \pi^0\Lambda$ , and for (iii)  $K^-p \rightarrow \pi^+\Sigma^-$ ,  $K^-p \rightarrow \pi^0\Sigma^0$ , and  $K^-p \rightarrow \pi^-\Sigma^+$ . Data were analyzed in c.m. energy bins of width 20 MeV up to a maximum c.m. energy of 2100 MeV [8]. Once we had a complete set of amplitudes from our own single-energy PWAs, we carried out global multichannel energy-dependent fits using a procedure similar to that in Ref. [1].

More recently, single-energy partial-wave analyses up to a maximum c.m. energy of about 2100 MeV have been completed for the isospin-1/2 reactions  $\pi^-p \rightarrow \eta n$  and  $\pi^-p \rightarrow K^0\Lambda$  [9,10]. Data for these reactions were analyzed in c.m. energy bins of width 30 MeV. Global energy-dependent fits of the resulting amplitudes were performed using a parametrization discussed in Ref. [11].

The fits were constrained by including partial-wave amplitudes for related reactions, including the SAID SP06 solution for  $\pi N \rightarrow \pi N$  [12], the SAID FA07 solution for  $\gamma N \rightarrow \pi N$ , and the solution of Manley *et al.* [13] for  $\pi N \rightarrow \pi\pi N$ . We found significant couplings of  $S_{11}(1535)$  and  $P_{11}(1710)$  to both  $\eta N$  and  $K\Lambda$ . Our results [14], in fact, confirmed the existence of  $P_{11}(1710)$  for which no evidence was found in the analysis by Arndt *et al.* [12]. We found all resonances, including a number of new states, recently found independently in the Bonn-Gatchina analysis [15]. Our results for  $P_{11}(1880)$ ,  $F_{15}(1860)$ ,  $P_{13}(1900)$ , and  $D_{15}(2060)$  are in good agreement with those of the Bonn-Gatchina analysis, which strengthens the evidence for these newly proposed states.

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## 2.13 Hunting Resonance Poles with Rational Approximants

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The non-perturbative regime of QCD is characterized by the presence of physical resonances, complex poles of the amplitude in the transferred energy at higher (instead of the physical one) complex Riemann sheets. From the experimental point of view, one can obtain information about the spectral function of the amplitude through the time-like region ( $q^2 > 0$ ) and also about its low-energy region through the experimental data on the space-like region ( $q^2 < 0$ ).

Based on the mathematically well defined Padé Theory [1, 2], we have developed a theoretically safe new procedure for the extraction of the pole mass and width of resonances [3, 4, 5]. The method uses a sequence of Padé Approximants (PA) as a fitting functions to the available experimental data on the real axis to extract such parameters. PA are rational functions with coefficients identical to the Taylor expansion of the function to be approximated. Padé Theory provides, then, with a set of convergence theorem for such sequence of approximants (for example, when the function obeys a dispersion relation given in terms of a positive definite spectral function, see [1, 6, 7, 8]; and when is a meromorphic function, see [9, 10, 11] or [12] for a summary).

The standard procedure is to construct the PA from the Taylor expansion of the function at the origin of energies ( $q^2 = 0$ ). When this expansion is not known, one can use a sequence of PA as a fitting functions to the experimental data to obtain such Taylor expansion up to a certain order [13, 14]. Despite the nice convergence and the systematical treatment of the errors with this method, the procedure does not allow to obtain properties of the amplitude above the threshold. The reason is simple: the convergence of a sequence of PA centered at the origin of energies is limited by the presence of the production brunch cut [2]. The PA sequence converge everywhere except on the cut, so one cannot access the Second Riemann sheet in such a way. Still, the mathematical Padé Theory allows to produce a model-independent determination of resonance poles when certain conditions are fulfilled. The most important one is to center the PA sequence above the branch-cut singularity (beyond the first production threshold) instead of at origin of energies, and use time-like data for the fit. In this context one invokes the Montessus de Ballore's theorem [15] to unfold the Second Riemann sheet of an amplitude and search the position of the resonance pole in the complex plane (for details see [3, 4, 5]). Our approach is similar to the one presented in [16] but with the expansion point at the real axis instead of around the pole position.

This model-independent method does not depend on a particular Lagrangian realization or modelization on how to extrapolate from the data on the real energy axis into the complex plane.

This work is performed in collaboration with Juan José Sanz Cillero and supported by the Deutsche Forschungsgemeinschaft DFG through the Collaborative Research Center The

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## 2.14 A new method for extracting poles from single channel data - some results

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We present results obtained from a new method [1] of extraction of poles of partial wave T- matrix.

As an input we have used single energy (SE) and energy dependent (ED) solutions for electromagnetic multipoles from isobar model MAID [3] and the model-independent GWU-SAID analysis [4].

There are many cuts and corresponding branchpoints in analytic structure of partial waves.

In the method, choosing of branchpoint positions is of crucial importance. Our calculations show that a good and reliable fit to the partial wave data may be obtained by using three Pietarinen expansions introducing three branchpoints and three corresponding cuts.

One effective cut and corresponding Pietarinen expansion is used to represent all cuts below physical  $\pi N$  threshold. Concerning remaining two Pietarinen expansions we applied two strategies. In first strategy the branchpoints coincide with the physical thresholds ( $\pi N$ ;  $\pi\pi N$  or  $\eta N$ ). This strategy is applied when fitting SE solutions. In the second strategy, branchpoint positions are free parameters in a fit and are effective branchpoints. This strategy is applied when fitting ED solutions because, as a rule, such data assume certain, unknown analytic structure of partial wave.

The method gives reliable results for both input data sets (SE, ED solutions).

Presented method is well suited for obtaining a global fit to the photoproduction and pion-nucleon scattering data, and also for extraction of baryon resonance parameters from photoproduction data and from single-channel pion-nucleon data as well.

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## 2.15 From Raw Data to Resonances

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Particle physics at small distances is well understood although this is not true for large distances when hadronization, light mesons and resonances are considered. These are barely understood compared to their abundance. A deeper understanding of the interaction and dynamics of light hadrons will improve the knowledge about non-perturbative QCD. We need appropriate parameterizations for the multi-particle phase space and a translation from parameters to effective degrees of freedom.

The analysis is usually performed by fitting models to the experimentally derived phase space distributions. Performing this kind of analysis is extremely difficult and error prone and a systematic treatment is both necessary and also very demanding. The goals are the unambiguous determination of masses, line-shapes and decay ratios and/or pole positions and couplings. In contrast to other complex optimization processes, like in technology issues and finance, it is important to target the correct solution and not just a good solution, since many solutions may end up with a fair numerical explanation of the data, while they differ dramatically in their physical content and interpretation.

The presentation covers a short review on the different steps in a concrete analysis process covering general considerations, the course of action in a realistic analysis and various detailed subtopics.

To arrive at the ultimate goal it has to be considered which processes take place (interactions, scales), what are the conserved properties (in term of kinematics and quantum numbers) and what are relevant parameters (order of magnitude and relationships) and if factorization is a relevant aspect. The general course of actions is very similar among the various analyses. It starts with data analysis, modeling of the interaction, the quality assured fitting to the data and finally the review and publication.

Important details are the consideration of relevant phase space observables and the treatment of various kinds of background. Since the necessary amplitudes are highly complex numerical and mathematical problems have to be investigated and solved for stable and verifiable solutions and unambiguous interpretation of the data.

Most aspects appear in almost every kind of reaction and therefore similar technologies are necessary and it is of great importance to form a unified community to exchange the experience in these analyses to shoulder the demand from the emerging high statistics experiments all over the world.

## 2.16 The study of the proton-proton collisions at the beam momentum 2 GeV/c measured with HADES within Bonn-Gatchina PWA

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HADES is a versatile magnetic spectrometer installed at GSI Darmstadt on SIS18 [1]. Thanks to its high acceptance, powerful particle ( $p/K/\pi/e$ ) identification and very good mass resolution (2 – 3% for dielectrons in the light vector meson mass range) it allows to study both hadron and rare dilepton production in  $N + N$ ,  $p + A$ ,  $A + A$  collisions at a few AGeV beam energy range. In  $p+p @ 1.25 \text{ GeV}$ , intermediate  $\Delta(1232)$  resonance is expected to play a dominant role in the pion production but is not sufficient to describe fully the data. The resonance cross section was determined from exclusive  $pp\pi^0$  and  $pn\pi^+$  channels [2] in the framework of OPE model with the accuracy of 20 – 30%. Investigation of these reaction channels by means of the PWA (Partial Wave Analysis) was also done [3] by the Bonn-Gatchina group at a smaller beam energy [4]. It revealed a dominant contribution of  $\Delta(1232)p$  intermediate state but also sizeable non-resonant terms and interference effects.

In this work we report on the partial wave analysis of the single pion production in proton-proton collisions (as in [2]) measured with the HADES spectrometer. The  $pp$  is pure isospin  $I = 1$  state and at this beam energy the following initial  $pp$ -states contribute (J=0)  $^1S_0$ ,  $^3P_0$ , (J=1)  $^3P_1$ , (J=2)  $^1D_2$ ,  $^3P_2$ ,  $^3F_2$ . The higher total angular momentum contributions (i.e.  $^3F_3$  for J=3) seem not to improve the obtained solutions. The final states are limited to  $S$ -,  $P$ - and  $D$ -wave states with two possible intermediate resonance states  $P_{33}(1232)$  and  $P_{11}(1440)$ . The data samples (for both channels  $pp\pi^0$  and  $pn\pi^+$ ) of 60000 events were analysed with the event-by-event background estimation (Q-factors). The analysis was performed with other available data (see [5], 11 measurements for  $pp\pi^0$  and only one for  $pn\pi^+$  channel) covering mostly lower beam energies. The stability of solutions was investigated based on a few parametrisations of the transition amplitude  $A_{tr}$  (with total energy dependence) and various descriptions of resonance states ( $\Delta$  and  $N^*$ ). The obtained solutions are still preliminary but generally describe the HADES data very well in various projection observables (CM angular distributions, invariant masses, angular distributions in the helicity and the Godfrey-Jackson frames). The analysis shows the dominant  $P_{33}(1232)$  contribution in the  $pp\pi^0$  at the level of 90% ( $\pm 10\%$ ) which is an important message for the dilepton analysis where BR of  $\Delta$  Dalitz decay can be identified (in the  $pe^+e^-$  channel).

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## 2.17 Positivity constraints in $\pi N$ scattering

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In the ongoing work presented here [1] we propose the use of general S–matrix arguments such as analyticity, crossing and unitarity, to constrain  $\pi N$  interaction and its chiral effective theory description [2]–[5]. We follow a procedure similar to that in  $\pi\pi$ –scattering. There one finds that suitable combinations of isospin amplitudes become real and positive-definite within the “upper part” of the Mandelstam triangle ( $0 < t < 4M_\pi^2$ ,  $s < 4M_\pi^2$ ,  $u < 4M_\pi^2$ ) [6]–[9]. These derivations are based on fixed- $t$  dispersion relations where the isospin combinations are arranged in such a way that both  $s$  and crossed channels have positive-definite spectral functions. This allows the extraction of bounds on particular combinations of Chiral Perturbation Theory ( $\chi$ PT) couplings and the check of the convergence of the chiral expansion.

A previous study in the case of  $\pi N$  forward scattering was done in Ref. [10]. Here we propose an improvement of the bounds through a full scanning of the “upper part” of the  $\pi N$  Mandelstam triangle ( $0 < t < 4M_\pi^2$ ,  $s < (m_N + M_\pi)^2$ ,  $u < (m_N + M_\pi)^2$ ), not just the forward case  $t = 0$ . This should allow us to clarify if there is a clear improvement in the convergence in Covariant Baryon  $\chi$ PT (CB $\chi$ PT) when going from  $\mathcal{O}(p^3)$  to  $\mathcal{O}(p^4)$  [2, 3]. Likewise, this can be relevant to constrain the extension of CB $\chi$ PT with the inclusion of the  $\Delta$  resonance [11] and to stabilize the phenomenological fits, providing an extra criterium to discern “good” and “bad” fit solutions.

The crucial ingredient for the positivity analysis is the partial wave (PW) decomposition of the full scattering amplitude and its later reconstruction through a summation of partial waves [12]. We write down a fixed- $t$  dispersion relation for the isospin amplitudes and look for combinations of the  $\pi N$  scattering functions  $A^I(\nu, t)$  and  $B^I(\nu, t)$  (with  $\nu \equiv (s - u)/(4m_N)$ ) that have a positive-definite  $s$ –channel spectral function. In a second step, one looks for isospin combinations that arrange a positive definite  $u$ –channel spectral function [10, 13].

A first study of the  $\mathcal{O}(p^3)$  results in pure CB $\chi$ PT [2, 3], i.e., without the  $\Delta$ , points out problems in the fulfillment of the extracted bounds for the corresponding low-energy constants. At tree-level at this order one can obtain the chiral coupling bound

$$|6\nu d_3| \leq c_2 + (\alpha - 1)[c_2 - 2m_N(d_{14} - d_{15})], \quad (4)$$

with  $|\alpha - 1| \leq t/(4m_N M_\pi)$  and  $\nu$  and  $t$  in the referred “upper part” of the Mandelstam triangle [1]. However, preliminary studies seem to hint an improvement in the bound when the  $\mathcal{O}(p^3)$  one-loop contributions are taken into account. This analysis is currently ongoing [1].

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<sup>1</sup> I would like to thank the organizers for the nice scientific environment and interesting discussions during the workshop. In addition, I would like to thank the collaborators D.L. Yao and H.Q. Zheng for their comments and suggestions to the present note.

Furthermore, the  $\mathcal{O}(p^4)$  outcomes fulfill again the bounds at tree-level, indicating how the inclusion of higher chiral corrections improve the convergence of the CB $\chi$ PT expansion [3]. Likewise, an overview of previous Heavy Baryon  $\chi$ PT results at  $\mathcal{O}(p^4)$  [4] shows that the best fit solutions are those that fulfill our positivity bounds.

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## 2.18 Baryon spectroscopy with pion- and photon induced reactions

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Lattice QCD calculations predict more states than observed from the analysis of experimental data. This raises the question on the extraction of resonance properties in scattering experiments. Since the most information on the baryon spectra comes from the analysis of the pion-nucleon elastic scattering it is necessary to investigate the less studied case of multiparticle production. Thus the investigation e.g. of the two-pion production would provide an additional information on the excitation spectra of the nucleon.

The aim of the present work is twofold. First we extend the coupled-channel unitary Lagrangian model (Giessen model) [1,2] to incorporate two-pion final state into analysis. The  $2\pi N$  final state is treated in the isobar approximation with  $\sigma N$ ,  $\pi\Delta$ , and  $\pi\Delta$  in the intermediate subchannels. This formulation maintains two-body unitarity by construction.

Using the developed model we perform calculation of the  $\pi^- p \rightarrow 2\pi^0 n$  production in the first resonance energy region. One of the interesting questions here is the production rate of the sigma meson due to the t-channel pion exchange. Using the values  $m_\sigma = 600$  MeV and  $\Gamma_\sigma = 600$  MeV the coupling constant  $g_{\sigma\pi\pi} \approx 2$  has been derived. The calculated  $2\pi^0 N$  differential cross section was compared with the experimental data [3]. Our results demonstrate a small contribution from the t-channel pion exchange to the process  $\pi^- p \rightarrow \sigma N \rightarrow \pi^0\pi^0 n$  what is in line with this conclusion made in [4].

A good description of the differential cross sections and mass-distribution [4] can already be achieved by including the  $P_{11}(1440)$ -resonance in to the calculations. We conclude that the contribution from other states is small. However for c.m. energies above 1.5 GeV the effect from the  $D_{13}(1520)$  resonance should also be taken into account.

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## 2.19 Role of the Final State Interactions in Extraction of Interaction Parameters

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An accurate evaluation of the electromagnetic couplings  $N^*(\Delta^*) \rightarrow \gamma N$  from meson photoproduction data remains a paramount task in hadron physics. A wealth of new data for meson photoproduction is becoming available from nuclear facilities worldwide. These measurements are now beginning to have a significant impact on both the resonance spectrum and its decay properties.

Here we focus on the single-pion production data and note that a complete solution requires couplings from both charged and neutral resonances, the latter requiring  $\pi^-p$  and  $\pi^0n$  photoproduction off a neutron target, typically a neutron bound in a deuteron target. In addition to being less precise, experimental data for neutron-target photoreactions are much less abundant than those utilizing a proton target, constituting only about 15% of the present World database [2]. At low to intermediate energies, this lack of neutron-target data is partially compensated by experiments using pionic beams, e.g.,  $\pi^-p \rightarrow \gamma n$ , as has been measured. However, the disadvantage of using the reaction  $\pi^-p \rightarrow \gamma n$  is the 5 to 500 times larger cross sections for  $\pi^-p \rightarrow \pi^0n \rightarrow \gamma\gamma n$ , depending on photon energy,  $E_\gamma$ , and pion production angle,  $\theta$ .

Extraction of the two-body ( $\gamma n \rightarrow \pi^-p$  and  $\gamma n \rightarrow \pi^0n$ ) cross sections requires the use of a model-dependent nuclear correction, which mainly come from final state interactions (FSI). As a result, our knowledge of the neutral resonance couplings is less precise as compared to the charged values [1].

We recently applied our FSI corrections [3] to CLAS  $\gamma d \rightarrow \pi^-pp$  data [4] to get elementary cross sections for  $\gamma p \rightarrow \pi^-p$  for the broad energy range,  $E_\gamma=1000$  through 2700 MeV [5]. Then we did the same for the MAMI-B GDH experiment [6] to get  $\gamma p \rightarrow \pi^-p$  around the  $\Delta$ -isobar [7].

To accomplish a state-of-the-art analysis, we included FSI corrections using a diagrammatic technique, taking into account a kinematical cut with momenta less (more) than 200 MeV/ $c$  for CLAS and 270 MeV/ $c$  for MAMI-B for slow (fast) outgoing protons. The FSI correction factor for both CLAS and MAMI-B kinematics was found to be small,  $\Delta\sigma/\sigma < 10\%$ . However, these new cross sections departed significantly from our predictions, at the higher energies, and greatly modified the fit result.

New neutron  $A_{1/2}$  and  $A_{3/2}$  couplings shown sometimes a significant deviation from our previous determination and PDG average values, for instance, for  $N(1650)1/2^-$  and  $N(1675)5/2^-$  [5].

Connection between scattering and decay processes provides a solid theoretical ground for describing some hadronic effects – “Watson’s theorem” [8]. For pion photoproduction,

isospin amplitudes have to satisfy Watson's theorem below the  $2\pi$ -threshold allowing for a smooth departure from constraint at high energies.

$$a \tan\left(\frac{ImA_l}{ReA_l}\right) = \delta_l(\pi N).$$

Above  $2\pi$ -threshold, the rule may still be true, if inelasticity of the corresponding  $\pi N$ -elastic amplitude is small (as, e.g., for  $P_{33}$ .)

We evaluated results of several pion photoproduction analyses such as SAID, MAID, EBAC, Giessen, and BnGa and compare  $\pi N$  phases coming from  $\pi N$  and pion photoproduction amplitudes on proton target. SAID uses  $\pi N$  PWA results as a constraint for analysis of pion photoproduction data. Most of pion photoproduction analyses are doing the same and uses SAID  $\pi N$  outcome or its modification as input.

Our short summary is

- i) Phases coming from  $\pi N$  amplitudes of different analyses are consistent.
- ii) Some phases coming from different pion photoproduction analyses are consistent to each other and phases coming from  $\pi N$  amplitudes: *3/2-Isospin Amplitudes*: E0+, E1+, and M1+.
- iii) Some phases coming from different pion photoproduction analyses are inconsistent to each other and phases coming from  $\pi N$  amplitudes: *3/2-Isospin Amplitudes*: M1-, E2-, M2-, E2+, and M2+; *1/2- Isospin Amplitudes*: E0+, M1-, E1+, M1+, E2-, M2-, E2+, and M2+.
- iv) Some phases coming from  $E$  and  $M$  multipoles are inconsistent to each other and phases coming from  $\pi N$  amplitudes.

**Acknowledgments:** This work was supported in part by the U.S. DOE Grant No. DE-FG02-99ER41110, by the Russian RFBR Grant No. 02-0216465 and by the Russian Atomic Energy Corporation "Rosatom" Grant No. NSb-4172.2010.2.

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## 2.20 New single-channel pole extraction method

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We present a new approach to quantifying pole parameters of single-channel processes based on Laurent expansion of partial wave T-matrices [16]. Instead of guessing the analytical form of non-singular part of Laurent expansion as it is usually done, we represent it by the convergent series of Pietarinen functions with well defined analytic properties [2, 3, 4, 5]. As the analytic structure of non-singular term is usually very well known (physical cuts with branchpoints at inelastic thresholds, and unphysical cuts in the negative energy plane), we show that we need one Pietarinen series per cut, and the number of terms in each Pietarinen series is automatically determined by the quality of the fit. The method is tested on a toy-model constructed from two known poles, various background terms, and two physical cuts, and shown to be robust and confident up to three Pietarinen series. We also apply this method to Zagreb CMB amplitudes for the N(1535) 1/2- resonance [6], and confirm the applicability of the procedure for this case too. Finally, we show preliminary results for fitting complete set of  $\pi N$  elastic single energy partial wave amplitudes from GWU/SAID [2], and a complete set of single energy and energy dependent photoproduction multipoles from MAID [1] and GWU/SAID [2]. The global agreement of the fit with all input data is always achieved, and the stability and reliability of extracted resonance parameters shows that this formalism can with full success be used for fitting a wide class of experimental data. The procedure is very similar as when Breit-Wigner functions are used, but with one modification: Laurent expansion with Pietarinen series is replacing the standard Breit-Wigner T-matrix form.

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## 2.21 Hadron Spectroscopy: Supporting PWA at JLab

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I discuss goals of the new Physics Analysis Center that is being formed as a joint effort between JLab and Indiana University. The center will oversee development of theoretical, phenomenological and computational tools for analysis of large data sets from experiments in hadron spectroscopy. The center will facilitate interactions between practitioners in the physics of strong interactions by creating a forum for exchange of knowledge through collaboration meetings, workshops and summer schools. The official operations of the Center will begin in the Fall of 2013.

One of the main physics goals in strong interactions physics is to identify gluonic excitations, and specifically, manifestations of gluonic degrees of freedom in the spectrum of hadrons [1, 2, 3]. Lattice gauge simulations[4, 5, 6] have now produced the spectrum of gluonic excitations which appear to have multiplet structure analogous to that of the quark model for ordinary hadrons [7, 8]. There is strong experimental evidence, in at least one case; the  $\eta'\pi$  production of exotic partial wave with resonant characteristics [9, 10, 11]

The immediate goal of the Physics Analysis Center will be to provide theoretical support needed to construct reaction amplitudes that fulfill the S-matrix matrix constraints, and take advantage of modern development in lattice gauge simulations and other theoretical approaches [12].

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## 2.22 Complete Experiments for PWA and Baryon Resonance Extraction

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The current status of partial wave analysis, mainly from single-pion photoproduction on protons, is discussed and results of the isobar model MAID [1], the model-independent GWU-SAID [2] analysis and the Bonn-Gatchina [3] coupled-channels analysis are compared. Except for a few dominant partial waves, as P33, most other waves disagree among the different analyses, which can mainly be attributed to the incomplete data base of photoproduction observables.

To improve this situation, possibilities of a model-independent partial wave analysis for pion, eta or kaon photoproduction are discussed in the context of ‘complete experiments’. It is shown that the helicity amplitudes obtained from at least 8 polarization observables [4-7] including beam, target and recoil polarization can not be used to analyze nucleon resonances. However, a truncated partial wave analysis, which requires only 5 observables will be possible with minimal model assumptions [8-12].

The result of such complete experiments will be almost model independent single-energy partial wave amplitudes, which will be the ideal starting point for baryon resonance extraction by using models like isobar or dynamical models in single-channel or coupled channel analysis. Furthermore, pole extraction methods, which are discussed during this workshop can be applied as speed-plot [14] and time-delay techniques, regularization method [15], Laurent expansion, Pietarinen expansion [16], Pade approximation [17], pole fitting methods [18] and, whenever possible, analytical continuation into the complex region.

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## 2.23 Studies on a complete experiment for pseudoscalar meson photoproduction

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In the reaction of photoproduction of single pseudoscalar mesons, there exists the possibility of measuring 16 distinct polarization observables for every fixed value of both energy and angle ( $W, \theta$ ) [1]. One observable is the unpolarized differential cross section, however there also exist 3 single polarization observables and 12 double polarization observables grouped into the classes beam-target, beam-recoil and target-recoil. It is anticipated that the in principle accessible volume of experimental information will aid the disentanglement of the strongly overlapping resonances of the nucleon.

Since the beginning of the 1970s the problem of the so called complete experiment started to emerge in the literature [2]. It consists of the question which minimum subsets of all 16 polarization observables are sufficient in order to maximally constrain the underlying amplitudes. This optimization problem is important in the context of currently ongoing polarization measurements at facilities like ELSA, MAMI and JLAB.

In the 1990s it was shown that 8 carefully chosen observables suffice to yield a complete experiment [3]. However, in the low energy area of the reaction and in connection to a maximally model independent truncated partial wave analysis, there exists the realistic chance for achieving completeness with even less than 8 observables [4].

The above mentioned results are discussed and a new preliminary study on the ambiguities of the single spin observables, which was performed using the formalism of reference [4], is presented.

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