

Partial Wave Analysis of HADES Data for Two-Pion Production in Pion-Nucleon Reactions

I. Ciepał^{1,*}
for the HADES collaboration

¹Institute of Nuclear Physics PAS, Kraków, Poland

Abstract. Pion beams are important tools to study features of baryonic resonances and their decay channels because resonances are produced in s-channel at fixed mass equal to \sqrt{s} . In 2014 the HADES collaboration has performed systematic measurements in the second resonance region scanning around the mass of the $N^*(1520)$. Pion beams at four momenta (0.654, 0.686, 0.738 and 0.787 GeV/c) impinging on polyethylene and carbon targets have been used. With the use of the multichannel Partial Wave Analysis (PWA) the role of the $N^*(1520)$ resonance in conjunction with the intermediate ρ -meson production has been studied. Preliminary results at 0.654 GeV/c on exclusive production of two pions ($n\pi^+\pi^-$ and $p\pi^-\pi^0$) in the final state are presented.

1 Motivation

HADES has proposed an experimental program [1, 2] focused on combined measurements of hadron and dielectron production in pion induced reactions [3–7]. It offers a great opportunity to unambiguously fix the description of baryonic resonances and their coupling to the light vector mesons ρ and ω . The combined analysis of hadronic and electromagnetic channels is crucial for validation of the Vector Meson Dominance model and will help to understand the ρ -meson production mechanism [5]. For example, studies of two pion $n\pi^+\pi^-$ and $p\pi^-\pi^0$ channels are important to obtain the branching ratio of resonances in the ρN decay channel, that is one of the main goals of the HADES experiment. On the other hand, investigations of the dielectron channel like $\pi^-p \rightarrow ne^+e^-$, which has been measured in the same experiment allows one to understand the role of the ρ meson in electromagnetic transitions in the time-like region [3–5, 8]. Therefore, to understand resonance production mechanisms a systematic energy scan and high precision data are needed.

In 2014 a large dataset of π^-p scattering has been obtained at the four pion beam momenta 0.654, 0.686, 0.738 and 0.787 GeV/c [6, 7]. The data have been included into the multichannel PWA developed by the Bonn-Gatchina group [9]. Separations of cross sections of the two-pion final states ($\pi^+\pi^-$ and $\pi^0\pi^-$) into dominant channels have been performed and compared to other data. In particular the ρ -N coupling is investigated in context of electromagnetic transition form-factors.

2 Experiment with pion beams

The High Acceptance Di-Electron Spectrometer (HADES) [10], installed at GSI Helmholtzzentrum/FAIR in Darmstadt, was designed to measure dielectrons in the 1-3.5 AGeV energy range. Its purpose is to measure and reconstruct products of heavy ion, proton and pion collisions up to a few AGeV. It allows to study both hadron and rare dilepton production in $N + N$, $\pi + N$, $p + A$, $A + A$ collisions. It provides high acceptance (18° - 85°) in polar and almost full azimuthal angles, good charged particle identification (p/K/ π /e) and good mass resolution of 2-3% for e+e- pairs in the light vector meson mass range.

The HADES setup together with a secondary pion beam is a very unique apparatus in the world which allows for the first time combined measurement of dielectron and hadron production. The secondary pion beam is produced in reaction of ^{14}N on ^9Be target with an intensity of 10^6 pions/spill. The dedicated tracking system CERBEROS [1, 11] allows for a reconstruction of the momentum of each pion beam particle with a resolution of 0.3%.

The experiment has been performed with the $(\text{C}_2\text{H}_4)_n$ (polyethylene) target and separately with the pure carbon target in order to subtract the carbon contribution from the polyethylene data. The subtraction procedure involves first establishing the ratio between yields collected with the polyethylene and carbon targets based on the π^-p missing mass squared spectrum. The procedure takes into account also simulated spectra for all channels of interest: π^-p elastic scattering, $n\pi^+\pi^-$ and $p\pi^-\pi^0$. A global χ^2 minimization is performed based on weighting factors assigned to each of the components which are free parameters in the fit. The fitting procedure was iterated by changing also the tracking resolution and beam

*e-mail: izabela.ciepal@ifj.edu.pl

momentum value until minimum in the χ^2 was obtained. In the next step, events of the same kinematics from the polyethylene target and carbon target were grouped into bins of similar missing mass values. Then, for each carbon-polyethylene track a minimization function is calculated as a sum of squared difference between a given observable (momentum, polar and azimuthal angles, invariant masses and the angles defined in the helicity and Gottfried-Jackson frames) obtained with polyethylene and carbon targets, respectively. This method delivers pure pion-proton reaction candidates. For details see Ref. [7].

The data normalization is based on the π^-p elastic scattering. The acceptance and efficiency corrected data in the $\theta_{\pi^-}^{CM}$ range of $60^\circ - 110^\circ$ are normalized to the distribution from the SAID database [12] of the known cross section. For details see Ref. [6].

3 Partial wave analysis

The partial wave analysis of the HADES data was performed in cooperation with the Bonn-Gatchina group [13]. This approach [13–15] was developed for the combined analysis of the pion nucleon scattering and photo-production and is based on the so-called isobar model, introduced already in [16]. It is a two step process with the intermediate formation of meson-baryon two-particle states like $\pi\Delta$, $\rho(I=1)N$, $\sigma(I=0)N$. In the next step the resonances: ρ , σ and Δ decay into $\pi\pi$ and $N\pi$ final states, respectively. In this framework the world data on two-pion production reactions measured in pion-nucleon and photon-nucleon collisions [17–21] are taken into account together with the HADES data in an event-by-event maximum-likelihood method allowing for the extraction of contributions from different partial waves. In the energy range corresponding to the HADES data the largest contributions to the two-pion final states are: $\Delta(1232)\pi$, $N(1440)\pi$, $N(938)\sigma$ and $N(938)\rho$. The amplitudes of $N(1535)\pi$ and $N(1520)\pi$ are also included, but the resulting contributions are negligible.

4 Differential distributions of $n\pi^+\pi^-$ and $p\pi^-\pi^0$

A three-body decay phase space can be represented with two-dimensional Dalitz plots (the invariant masses squared of two of the three possible particle pairs) or alternatively with angular distribution in the helicity frame, which describe the angular dependence of the decay. The helicity frame is the rest frame of two final-state particles and the helicity angle is the angle between one of the particles with respect to the third one boosted to the two-particle rest frame. The helicity angles are also sensitive to the production of resonances. It should be stressed that the helicity projections have full coverage in the HADES acceptance after applying the acceptance corrections procedure described in more details in Refs. [6, 7].

In Fig. 1 the Dalitz plots for 0.654 GeV/c pion beam momentum are presented for the data (top panel) and PWA

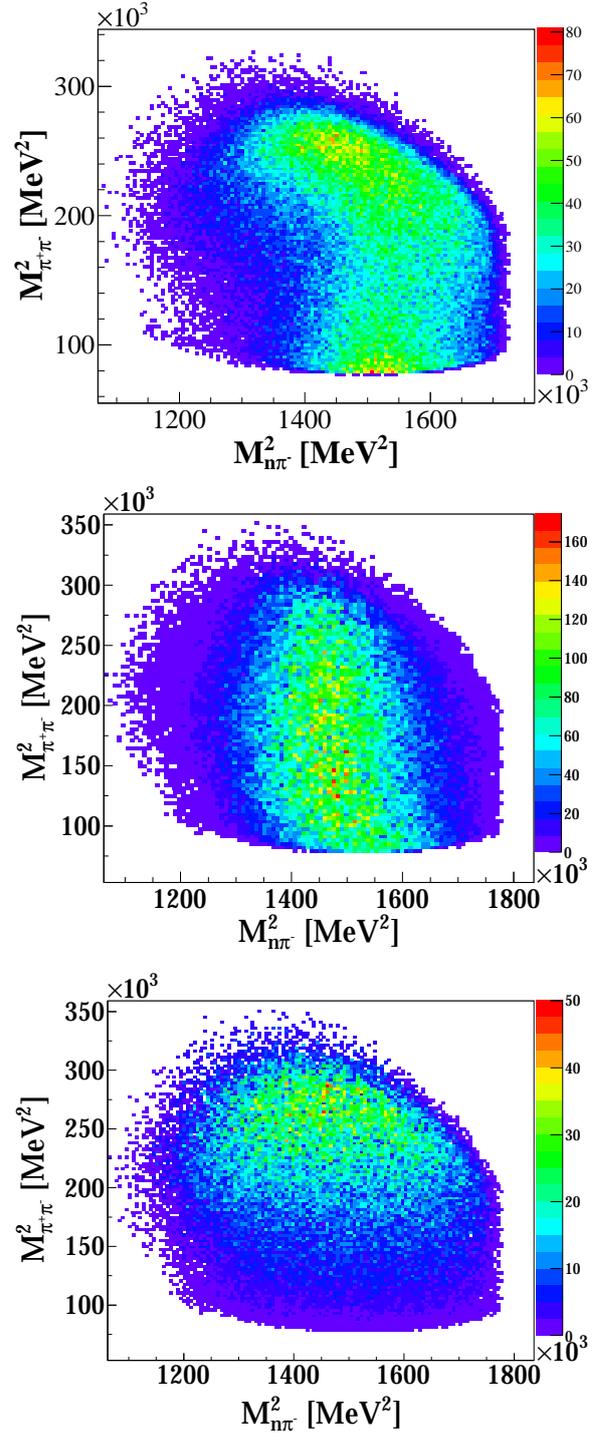


Figure 1. (Color online) Dalitz plots of $\pi^-p \rightarrow n\pi^+\pi^-$ for data (top panel) and for the channels $\Delta\pi$ (middle panel) and $N\rho$ (bottom panel) obtained from PWA at 0.654 GeV/c pion beam momentum.

solutions for the two contributions: for $\Delta\pi$ (middle panel) and $N\rho$ (bottom panel). The enhancements corresponding to the Δ and ρ resonances visible in the data are nicely explained with the PWA plots.

Two examples of PWA decomposition for the angular distributions in different helicity frames are presented in Fig. 2. The total cross section (black line) is decom-

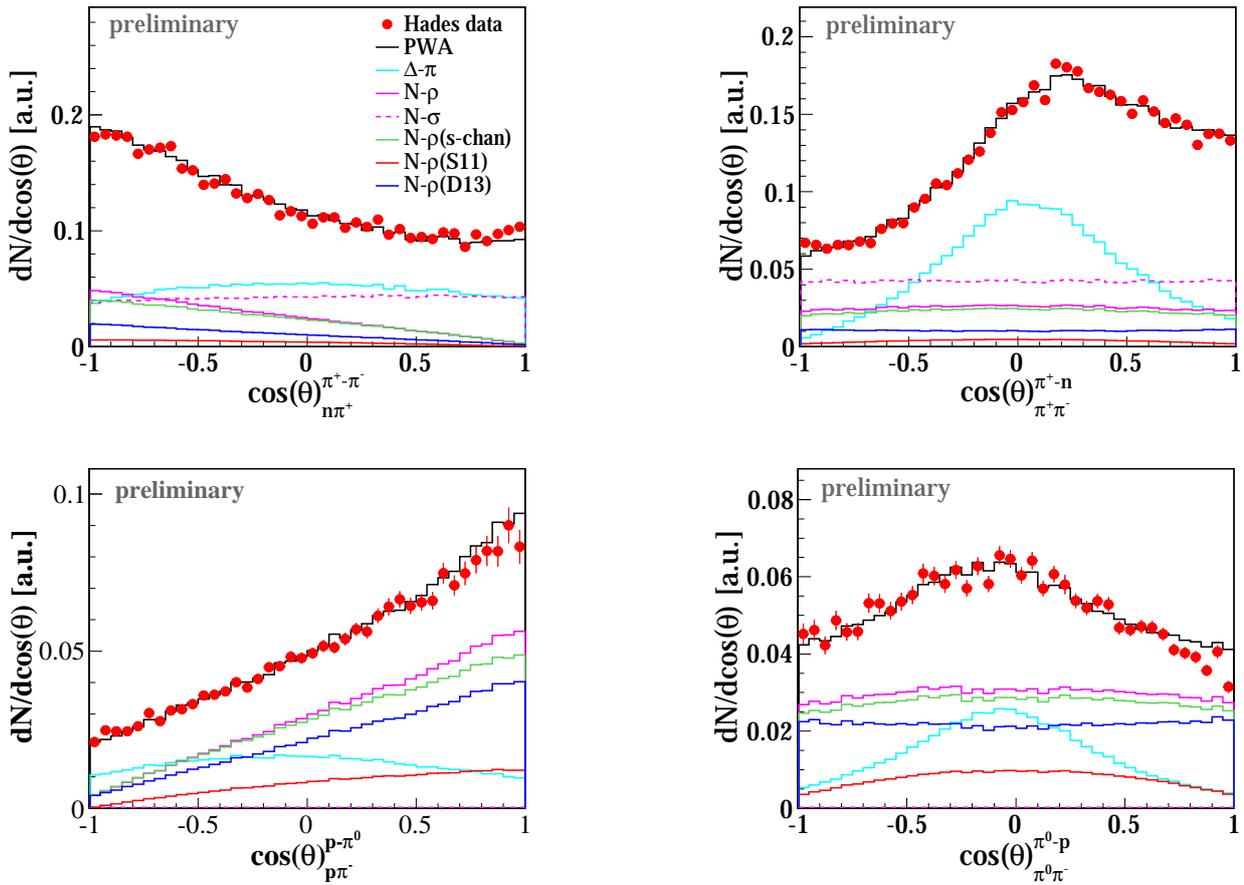


Figure 2. (Color online) Differential distributions of pions in the nucleon-pion (left column) and nucleons in the pion-pion (right column) helicity frames for the $\pi^+ p \rightarrow n\pi^+\pi^-$ (upper row) and $\pi^- p \rightarrow p\pi^0\pi^-$ (lower row) reaction channels obtained at 0.654 GeV/c pion beam momentum. Colour lines represent various final state contributions (indicated in the legend).

posed into final state contributions like $\Delta\pi$, $N\rho$, $N\sigma$. In the notation of the helicity angles (e.g. $\cos\theta_{n\pi^+\pi^-}^{\pi^+\pi^-}$), the subscript refers to the choice of two-particle rest frame ($n\pi^+$) and the exponent to the choice of particles for the calculation of angle (π^+ with respect to π^-). In the case of the pion-pion ($\pi^+\pi^-$, $\pi^0\pi^-$) helicity frame the Δ resonance is clearly visible as in the corresponding Dalitz plot in Fig. 1 (middle panel). The other components $N\sigma$ and $N\rho$ are rather uniform and in the $\pi^0\pi^-$ channel the $N\sigma$ is completely missing. In the case of the nucleon-pion ($n\pi^+$, $p\pi^-$) helicity frame the effect of the ρ meson is seen as an enhancement of large opening angles between the pion and the nucleon, what corresponds to the Dalitz plot in Fig. 1 (bottom panel). As a complement, also the $N\rho$ contributions originating from the s -channel, $S11$ and $D13$ waves are drawn allowing to study the ρ production mechanism. The $N\rho$ component is more dominant in the $p\pi^-\pi^0$ channel and ρ is mostly produced in the resonant s -channel.

5 Summary and outlook

The HADES data greatly improve the world database of two-pion production in pion-induced experiments in the energy range around the mass of the $N^*(1520)$ resonance.

The analysis (in progress) will allow to obtain the branching ratio of $N^*(1520)$ resonance in the ρN decay channel and other two-pion production modes. The production of the ρ -meson is of utmost importance for the dielectron channel $\pi^- p \rightarrow n e^+ e^-$, which has been measured in the same experiment [5, 8]. The $e^+ e^-$ exclusive analysis allows for the direct investigation of the $N^*(1520)$ resonance Dalitz decay and coupling to the ρN channel. Yet another information on the electromagnetic structure of the baryon transition can be extracted from the angular distributions of the dielectrons via fit of the spin-density matrix elements [22], which allows to parametrize the differential cross sections in a model independent way. This can be compared to the similar analysis in two-pion channels obtained from PWA.

Studies of distributions in the Gottfried-Jackson frame and analysis of data collected for other beam momenta are on-going. The ultimate goal is to extract excitation functions for the resonance contributions and branching ratios for the $N\rho$ channel.

The pion beam program will be continued in 2021 once the SIS18 will have been upgraded to serve as an injector for the FAIR facility. Recently, the HADES setup has been equipped with a large area electromagnetic

calorimeter (ECAL) enabling measurements of real photons and neutral mesons via their photonic decays. The reconstruction of neutral mesons is of large importance for the complete understanding of π^- -N reaction dynamics and for the complete partial wave analysis of $\pi^- p$ reactions.

6 Acknowledgements

The collaboration gratefully acknowledges the support by SIP JUC Cracow (Poland), 2017/26/M/ST2/00600; TU Darmstadt (Germany), VH-NG-823; GU Frankfurt (Germany), BMBF:05P15RFFCA, HIC for FAIR, ExtreMe Matter Institute EMMI; TU München, Garching (Germany), MLL München, DFG EClust 153, BmBF 05P15WOFCA; JLU Giessen (Germany), BMBF:05P12RGGHM; NRNU MEPhI Moscow Excellence project 02.a03.21.0005, MSERF 3.3380.2017/4.; 6 IPN, IN2P3/CNRS (France); NPI CAS Rez (Czech Republic), MSMT OP VVV CZ.02.1.01/0.0/0.0/16 013/0001677, MSMT LM2015049.

References

- [1] J. Adamczewski-Musch *et al.* (HADES Collab.), *Eur. Phys. J. A* **53**, 188 (2017)
- [2] Proposal for experiments at SIS18 during FAIR Phase0, Properties of hadron resonances and baryon rich matter, (HADES Collab.), GSI 2017
- [3] F. Scozzi, *EPJ Web of Conf.* **130**, 07021 (2016)
- [4] B. Ramstein, *EPJ Web Conf.* **199**, 01008 (2018)
- [5] B. Ramstein, “Studying time-like electromagnetic baryonic transitions with HADES in pion induced reactions”, NSTAR2019
- [6] I. Ciepał, *EPJ Web Conf.* **199**, 01024 (2018)
- [7] W. Przygoda, *EPJ Web of Conf.* **130**, 01021 (2016)
- [8] P. Salabura, “Exploring time like transitions in pp , $\pi^- p$ heavy ion reactions with HADES”, NSTAR2019
- [9] A. V. Sarantsev, *JPS Conf. Proc.* **10**, 010005 (2016)
- [10] G. Agakichiev *et al.* (HADES Collab.), *Eur. Phys. J. A* **41**, 243 (2009)
- [11] R. Lalik *et al.*, 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013)
- [12] CNS Data Analysis Center, SAID Home Page, <http://gwdac.phys.gwu.edu> (2018)
- [13] pwa.hiskp.uni-bonn.de
- [14] A. Anisovich, E. Klempt, A. Sarantsev and U. Thoma, *Eur. Phys. J. A* **24**, 111 (2005)
- [15] A. Anisovich *et al.*, *Phys. Rev. D* **84**, 076001 (2011)
- [16] D. M. Manley *et al.*, *Phys. Rev. D* **30**, 904 (1984)
- [17] S. Prakhov *et al.* (Crystal Ball Collab.), *Phys. Rev. C* **69**, 045202 (2004)
- [18] V. L. Kashevarov *et al.* ((Crystal Ball at MAMI, TAPS, and A2 Collab.), *Phys. Rev. C* **85**, 064610 (2012)
- [19] J. Ahrens *et al.* (GDH and A2 Collab.), *Phys. Lett. B* **624**, 173 (2005)
- [20] U. Thoma *et al.* (CB-ELSA Collab.), *Phys. Lett. B* **659**, 87 (2008)
- [21] M. Battaglieri *et al.* (CLAS Collab.), *Phys. Rev. D* **80**, 072005 (2009)
- [22] E. Speranza, M. Zetenyi, B. Friman, *Phys. Lett. B* **764**, 282 (2017)