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Single and Double Pion Production in pp Collisions in HADES

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Pion production in NN collisions is one of the sources of information on the NN interaction and on nucleon resonance properties. Two-pion production, in particular, is an outstanding subject, since it connects $\pi\pi$ dynamics with baryon and baryon-baryon degrees of freedom. In the few GeV energy regime, $\Delta\Delta$ excitation becomes the leading process. The one- and two-pion production in pp and np reactions has been investigated with HADES in exclusive measurements for beam kinetic energies of 1.25 and 2.2 GeV using missing mass technique. Total and differential cross sections have been obtained for the channels $pn\pi^+$, $pp\pi^0$, $pp\pi^+\pi^-$ and $pn\pi^+\pi^-$.

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1. Introduction

The six-sector High-Acceptance DiElectron Spectrometer (HADES) operates at the GSI Helmholtzzentrum fuer Schwerionenforschung in Darmstadt taking beams from the heavy-ion synchrotron SIS18. Technical aspects of the detector are described in [24]. HADES was designed to investigate dielectron production in heavy-ion collisions in the 1-2 AGeV beam kinetic energy range. One of the main goal of the HADES experiment is to study the properties of hadrons inside the hot and dense nuclear medium via their dielectron decays [1, 2, 3].

One specific issue of heavy-ion reactions in that regime is the important role played by the baryonic resonances, which propagate and regenerate due to the long life-time of the dense hadronic matter phase. The $\Delta(1232)$ resonance is the most copiously produced but, with increasing incident energy, higher lying resonances also contribute to pion production. A detailed description of the resonance excitation and coupling to the pseudoscalar and vector mesons is important for the interpretation of the dilepton spectra measured by HADES. Baryonic resonances are indeed important sources of dileptons through two mechanisms: their Dalitz decays (e.g. $\Delta/\ N^* \to Ne^+e^-$) and the mesonic decay with subsequent dielectron production.

Simultaneous measurement of one and two-pion production channels can bring information on the baryonic resonances excitation. Two-pion production, in particular, is an important subject since it connects $\pi\pi$ dynamics with baryon and baryon-baryon degrees of freedom. In our energy regime, $\Delta\Delta$ excitation starts to became important process [8, 9]. We report on one- and two-pion production in pp and np reactions investigated with HADES in exclusive measurements for the beam kinetic energies 1.25 and 2.2 GeV.

2. HADES experiment

The HADES detector [4], as shown in Fig.1, consists of 6 identical sectors covering the full azimuthal range and polar angles from 15° to 85° with respect to the beam direction. Each sector contains: A Ring Imaging CHerenkov (RICH) detector used for electron identification; two sets of Mini-Drift Chambers (MDC) with 4 modules per sector placed in front and behind the magnetic field to determine momenta of charged particles; the Time Of Flight detectors (TOF/TOFINO) and the Pre-Shower detector improving the electron identification. For reaction time measurement in heavy-ion reactions, a diamond START detector is located in front of the target. An (e^+,e^-) invariant mass resolution at the ω peak of $\simeq$ 2.7% and a momentum resolution for protons of $\simeq$ 3% can be achieved. The first level trigger is obtained by a fast multiplicity signal coming from the TOF/TOFINO wall, combined with a signal from the START detector, while the second level trigger is made by using the informations from the RICH and Pre-Shower to select the lepton candidates.

In the experiments discussed here a proton beam with a kinetic energy of T_p = 1.25 GeV and 2.2 GeV (corresponding to a c.m. energy $\sqrt{s_{NN}}$ = 2.42 GeV and 2.765 GeV, respectively) and an intensity of about 10^7 particles per second impinged on a 5 cm long liquid hydrogen cell with a total areal thickness of 0.35 g/cm^2. As no dedicated start detector was present in this experimental

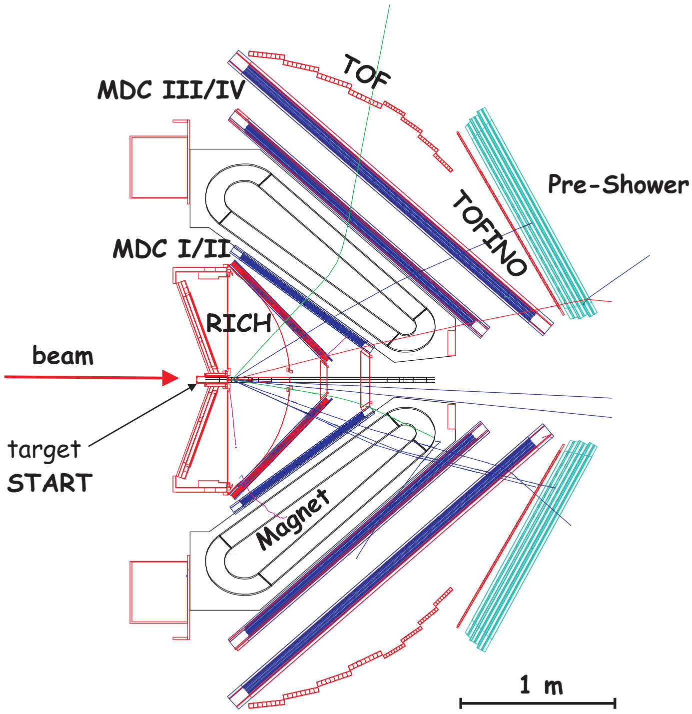

Figure 1: (Color online) Schematic view of the HADES detector as implemented in the simulation. Simulated particle tracks are shown as well.

run, the start time for the time-of-flight measurement was reconstructed event-by-event from the most optimal fit of different event hypotheses to the global event data [**?**].

2.1 Results

As mentioned in the introduction, it is important to constrain the models predicting the cross section and the production mechanisms of the Δ resonance. In order to do that the hadronic channels (pp $\rightarrow$ n$p\pi^+$ and pp $\rightarrow$ ppπ^0) have been measured and studied in parallel to the leptonic channels.

The pp $\rightarrow$ npπ^+ channel is studied using the reconstruction of the undetected neutron. The reaction was selected first by the charged particle identification based on momentum and reconstructed time of flight, then a (p,π^+) missing mass cut was imposed around the neutron mass. This cut efficiently suppresses the background coming from misidentified protons and two-π contributions.

The ppπ^0 reaction was extracted from the (p,p) missing mass spectrum by subtracting the background under the π^0 peak after suppression of the pp elastic and two-pion contribution.

The absolute normalization of the data has been achieved by a simultaneous measurement of elastic scattering for which the cross section is known. Error bars include statistical and systematic errors.

Experimental data have been compared with the original and modified version of the resonance model [5] using model A and model B (for details see Table 1). Model A: final state interactions and vertex modifications; Model B: Model A plus fine tuning of angular distributions and inclusion

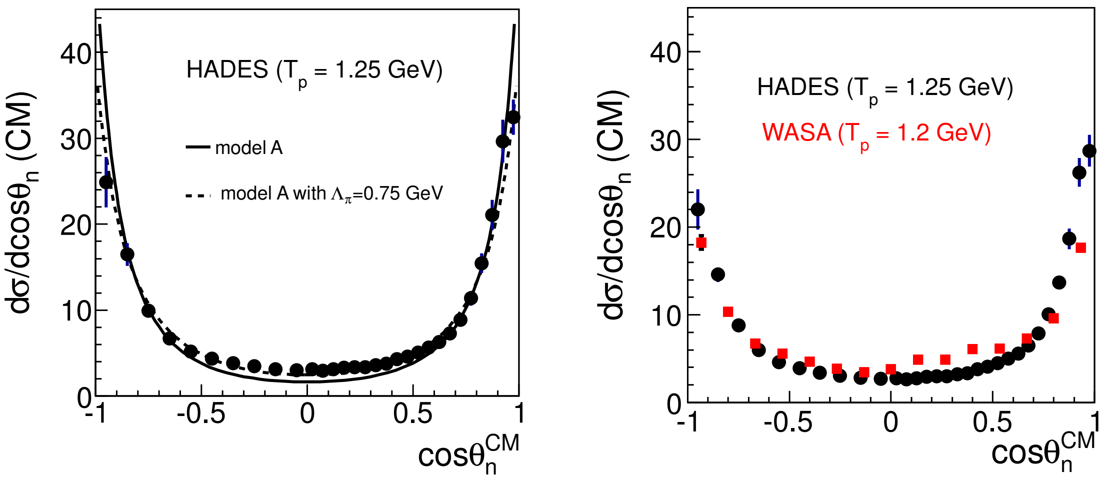

Figure 2: Angular distribution of neutron in centre of mass system after acceptance correction for the pp→pnπ^+ reaction. (left) Comparison of the HADES data to simulation based on [5] and model A. Both simulation curves are normalized to reproduce the integrated experimental yield. (right) Comparison of HADES and WASA data [7].

of higher resonances. A comparison to different spectra has been made. In particular the neutron angular distribution in the center of mass system measured in the pp →pnπ^+ channel, has been investigated, since it is sensitive to the angular distribution of Δ resonance production (dominant process is pp → nΔ^{++}). The acceptance corrected experimental spectra are presented in Fig. 2 (black points) together with a slightly modified resonance model "model A" (for details of the modification, see Tab.1). The distribution shows strong forward/backward peaking, as expected due to the peripheral character of the Δ resonance. The original Teis model (black solid line) shows an underestimation at $\cos\theta_n \approx 0$, which is improved by changing the cut-off parameter (Λ_π) (black dashed line). In addition, in a Fig. 2 comparison between HADES and WASA measurement is presented. WASA data were taken from [7] and normalized to the cross-section obtained by HADES. One can see reasonable quantitative agreement, keeping in mind, that the WASA data are presented without systematic errors.

Fig. 3 exhibits the projection on the (p,π^0) (Left), (p,π^+) (middle) and (n,π^+) (right) invariant masses for T_p = 1.25 and 2.2 GeV. The data are corrected for reconstruction efficiencies.

The prominent peak of $M_{inv}(p, \pi^+)$ and $M_{inv}(p,\pi^0)$ around 1.23 GeV/c^2 confirms that most of the pions are produced via Δ decay, which is consistent with the resonance model . However, the data present some deviations with respect to the model A, which is close to the original Teis model ([5]). This, together with the above mentionned failure in the description of the angular distribution motivates some changes in the model. A better description of the yield and shape of the missing mass spectra is indeed obtained after some modifications which are included in model B (see Tab. 1 for details). Due to the dominance of the Δ(1232) resonance, the two channels are correlated by isospin symmetry: $\sigma(pp \to n\Delta^{++}) \sim 3(pp \to p\Delta^+)$, leading to $\sigma(pp \to np\pi^+) \sim 5\ (pp \to pp\pi^0)$. Adding a N^* contribution seems also reasonable and the invariant mass distributions are rather well reproduced by the pp → nΔ^{++} and pp → pΔ^+ simulations. At 2.2 GeV, the contribution of higher

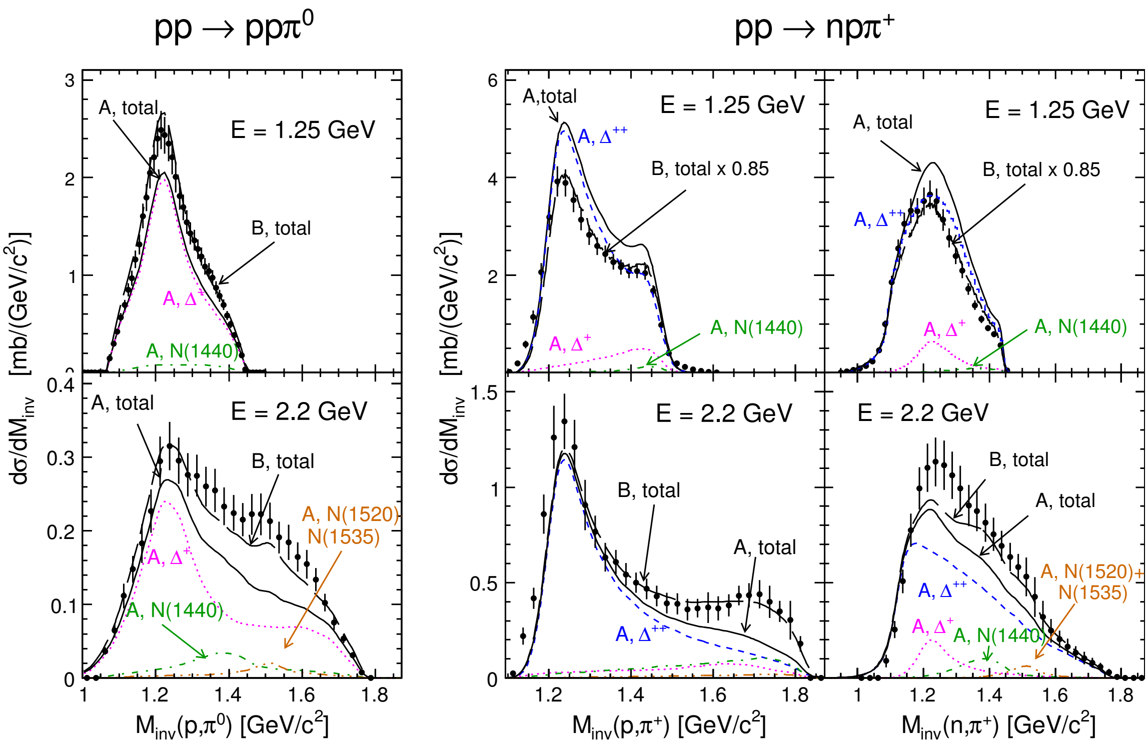

Figure 3: (Color online) Invariant mass distributions measured of (p,π^0) (Left), (p,π^+) (Middle) and (n,π^+) (Right) measured in pp $\rightarrow$ ppπ^0 and pp $\rightarrow$ npπ^+ at 1.25 GeV (top row) and 2.2 GeV (bottom row). HADES data (full dots) are compared within the experimental acceptance to the predictions of the modified resonance model (see text).

lying resonances is clearly visible at high invariant masses.

T$_p$/Model	Model A	Model B
1.25 [GeV]	[5], (1)	Model A, (2)
2.2 [GeV]	[5], (1)	Model A, (3)

Table 1: Summary of the modifications introduced to the resonance model [5] in order to better fit the data: (1) pp and pn final state interactions have been implemented using the Jost function and adjustment of the cut-off parameter (Λ_π) entering the $\pi N\Delta$ and π NN vertex form factor has been changed from 0.63 to 0.75 GeV, (2) the Δ production angular distribution has been further adjusted to reproduce the measured neutron angular distribution, (3) the cross section of the higher lying resonances has been increased and a non-resonant contribution has been added.

Furthermore, as another important platform for studying resonances properties, double-pion production in nucleon-nucleon collisions is of great interest.

Several theoretical models for double pion production have been suggested in the energy range from the production threshold up to several GeV [11], [12]. A full reaction model describing the double pion production in NN collisions has been developed by Alvarez-Ruso [8]. More advanced calculations by Cao, Zou and Xu, that include relativistic corrections based on the calculations of Ref. [8] have recently been published [9]. These models include and study both the resonant and the non-resonant terms of $\pi\pi$-production. The models predict that at energies near threshold the $\pi\pi$ production is dominated by the excitation of one of the nucleons into the Roper resonance $N^*(1440)P11$ via σ-exchange, followed by its s-wave decay $N^* \to N(\pi\pi)_{s-wave}$ (where I indicates the isospin of the I=0 $\pi\pi$ system). As the beam energy increases, the p-wave decay $N^* \to \Delta(1232)\pi \to N(\pi\pi)$ gives an increasing contribution to the cross section. At higher energies the double $\Delta(1232)$ excitation (dominantly via $(\pi - \rho)$-exchange) is expected to be the dominant reaction mechanism for $\pi\pi$ production.

Such reactions have been studied experimentally at intermediate and higher energy regions [13, 14]. Recently, exclusive high-statistics measurements have become available from near threshold (Tp=650 MeV) up to Tp=1.3 GeV from the PROMICE/WASA [15, 16, 17], CELSIUS/WASA [18, 19, 20, 21] COSY-TOF [22] and ANKE [23] experiments. The analysis of the data obtained from these experiments, with the exception of ANKE (where only pp final states in the diproton 1S0 quasi-particle state have been considered), indicate that in case of pp collisions (isovector channel) only two t-channel reaction mechanisms dominate: the excitation of the Roper resonance N*(1440) (via σ-exchange) at energies close to threshold [16, 19], and the excitation of the $\Delta\Delta$ system (via $(\pi - \rho)$- exchange) at energies Tp §1.3 GeV [21]. Model predictions are found to be in good agreement with the experimental re- sults at energies close to threshold. At energies Tp§1 GeV, the Roper resonance contribution is over-predicted in the theoretical calculations. However, the predicted $\Delta\Delta$ excitation is in accordance with the data, if relativistic corrections are taken into account. A detailed description of the relativistic corrections applied to the model calculations of Ref. [8] can be found in Refs. [20, 21]. On the other hand, the ANKE results reveal dominance of the $\Delta\Delta$ excitation already at Tp=0.8 GeV.

Here we present preliminary results obtained for the analysis of 2 channels: (1) pp $\to pp\pi^+\pi^-$ and (2) pn $\to$ pn $\pi^+\pi^-$ which have been presented in comparison to model predictions [5, 6] including double-Δ and N(1440) excitation. Both channels were selected by identifying all charged hadrons involved in the reaction and applying a missing mass cut ($M_{pp\pi^+\pi^-}$ in case (1) and $M_{p\pi^+\pi^-}$ in case of (2)). It turns out that the invariant mass ($M_{\pi^+\pi^-}$) and the opening angle in CM ($\cos\delta_{\pi^+\pi^-}$) of the pion pair are the most sensitive distributions to the different model contributions. Fig 4 exhibits an experimental distributions of the invariant mass and opening angle of $\pi^+\pi^-$ in comparison to the pure phase space (PHPS) calculations. The PHPS calculations has been normalized to the experimental yield. It is seen, that both experimental distributions deviate from PHPS calculations. Some enhancement can be observed at low $\pi^+\pi^-$ invariant masses, which is not present in the simulation with the PHPS only.

This peak at small invariant masses appears in the models [8] [9] as being due to the $\Delta\Delta$ excitation and to the decay channel of the Ropper resonance N(1440) into $N\Delta$ (N* $\to$N Δ).

2.2 Conclusion

The aim of measuring one and two-pion production in elementary reactions with HADES are three fold: (1) to study the detector response, and cross-check the analysis of dilepton channels, (2) to test the ingredients of the transport models used for the dielectron production, which are

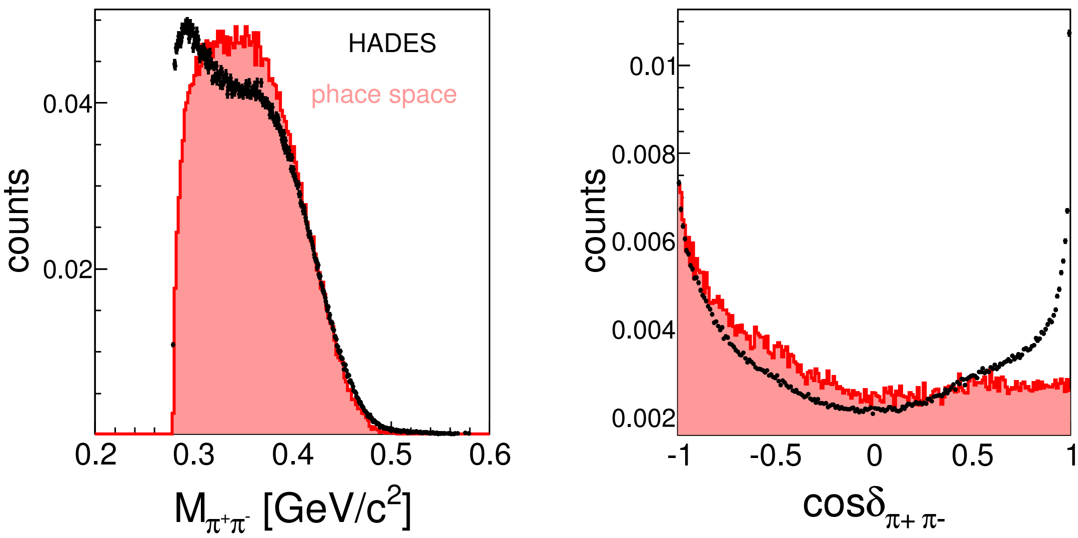

Figure 4: Distribution of the $\pi^+\pi^-$ invariant mass $M_{\pi^+\pi^-}$ (left) and the $\pi^+\pi^-$ opening angle in the centre of mass $\delta_{\pi^+\pi^-}$ (right) for the pp $\rightarrow pp\pi^+\pi^-$ reaction at beam energy T_p = 1.25 GeV are shown in comparison to the phase space calculation. Both spectra are inside the HADES acceptance and efficiency. The simulation is normalized to reproduce the measured experimental yield. Only statistical errors are shown.

based on resonance models and (3) to obtain a parametrization of meson and baryon resonance production for dielectron channels analysis.

HADES provides high statistics data in one and two-pion production channels, which complements measurements of previous experiments. For the one pion channel, which is dominated by Δ resonance, the data have been compared to the resonance model usually used in transport models, and modifications have been proposed to better reproduce the data. The ongoing analysis of the two-pion production and comparison to the models will bring constraints on double-Δ production as well as N(1440) production and decay mechanisms.

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