One and Two-pion production in pp reactions with the High Acceptance Di-Electron Spectrometer at GSI

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Abstract
We present exclusive meaurements of the pp→pnπ^+ and pp→ppπ^0 reactions at 1.25 GeV, 2.2 GeV and 3.5 GeV and of the pp→pp$\pi^+\pi^-$ reaction at 1.25 GeV with the High Acceptance Di-Electron Spectrometer at GSI. Total and differential cross-sections for the one-pion production channels are analyzed with the resonance model to extract the differential baryonic resonance contributions. A comparison of the two-pion production channels to effective

lagrangian model predictions is on-going. The two-pion invariant mass and opening angle distributions show sensitivity to the double $\Delta(1232)$ and N(1440) $\rightarrow \Delta\pi$ decays.

1 Introduction

The High Acceptance DiEelectron Spectrometer (HADES) [1] installed at GSI in Darmstadt was built to investigate dielectron production in heavy-ion collisions in the 1-3.5 AGeV range [2] in order to study the properties of vector mesons in the hot and dense nuclear medium. Proton-nucleus reactions are also investigated to probe cold nuclear matter [3]. Moreover, the experimental programme also comprises elementary reactions (pp, quasi-free np and a project of measurements with a pion beam) to study more selectively the different dilepton sources. In particular, baryonic resonances are important sources of dileptons through two mechanisms: their Dalitz decays (e.g. Δ/N* $\rightarrow N$e$^+$e$^-$) and the mesonic decay with subsequent dilepton decay ($\pi^0\rightarrow \gamma$e$^+$e$^-$, $\eta \rightarrow \gamma$e$^+$e$^-$, $\omega/\rho \rightarrow$e$^+$e$^-$). The possibility to measure simultaneously one and two-π production with the HADES detector is therefore a great advantage, since it constrains the hadronic cocktail used to describe the dilepton production. More generally, such data provide quantitative information on hadronic interactions, as well as resonance excitations and resonance properties.

Although one-pion production was studied quite extensively in the past, only very few experiments measured precise differential spectra (see [4] and references therein). When the incident energy increases from 1 to 3.5 GeV, the effect of resonances heavier than the $\Delta(1232)$ is expected and little is known about their production mechanisms. The production of $\pi^+\pi^-$ pairs is very complementary, since most baryonic resonances have a large, but poorly determined branching ratio into this channel. The reaction pp$\rightarrow$pp$\pi^+\pi^-$ has also been studied in the past between 0.7 and 2 GeV using bubble chambers [5]. Recently, exclusive high-statistics measurements have become available for incident proton kinetic energies of 650 MeV (*i.e.* near threshold) up to 1.36 GeV from the PROMICE/WASA [6, 7], CELSIUS/WASA [8], COSY-TOF [9] and ANKE [10] experiments. At energies around 1.3 GeV, the branching ratios of the N(1440) resonance into the $\Delta(1232)\pi$ and N$(\pi\pi)_{Swave}$ are an important issue related to the intrinsic structure of the N(1440) resonance. Of high interest is also the relative contribution of double $\Delta(1232)$ and N(1440) excitations, since it depends on their respective production mechanisms and is sensitive e.g. to the exchange of ρ mesons. We report here on exclusive meaurements in the channels pp$\rightarrow$pnπ^+, pp$\rightarrow$ppπ^0 at 1.25 GeV, 2.2 GeV and 3.5 GeV and pp$\rightarrow$pp$\pi^+\pi^-$ at 1.25 GeV.

2 One-pion production channels

The pp$\rightarrow$pn$\pi^+$and pp$\rightarrow$ppπ^0 channels were selected using events with the reconstruction of one proton and one π^+ or two protons. Particle identification was provided by the correlation between time-of-flight measurements and momentum reconstruction. Events from pp elastic scattering were rejected using their angular correlation and events from the two-pion production processes using the missing mass. The absolute normalization of the data was provided with a precision of 6% at 1.25 GeV and 10% at 2.2 GeV and 3.5 GeV by the elastic scattering events for which the cross-section is known. In addition, the data were corrected for reconstruction efficiencies which were determined using simulations, with a precision ranging from 8% at 1.25 GeV to 17% at the highest energies.

Under the assumption that intermediate baryon resonances play a dominant role in π, η and ρ production, a model was developed by Teis et al. [11], based on an incoherent sum of various resonance contributions. The matrix element of the $\Delta(1232)$ production was calculated within the OPE model [12], which had been adjusted to available differential distributions of pion production in the pp$\rightarrow$pnπ^+ channel at incident kinetic energies in the range 0.9-1.5 GeV. The other matrix elements were kept constant and were determined by fitting the total meson production cross sections. As this model, with some variants, is the basis for different transport models (*e.g.* [13]) it is instructive to compare its predictions to the

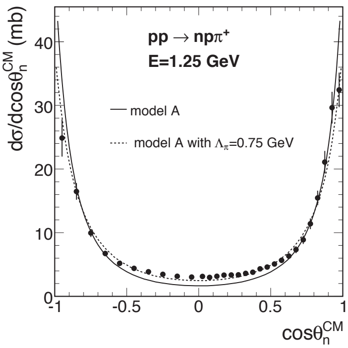

Fig. 1: (Color on-line) Angular distribution of neutron in center-of-mass system after acceptance correction for the pp→pnπ^+ reaction at 1.25 GeV. Data (black points) are compared to simulations based on model A (see text) with Λ_π=0.63 GeV (solid curve) and the modified version with Λ_π=0.75 GeV (dashed curve). Both simulation curves are normalized to reproduce the integrated experimental yield.

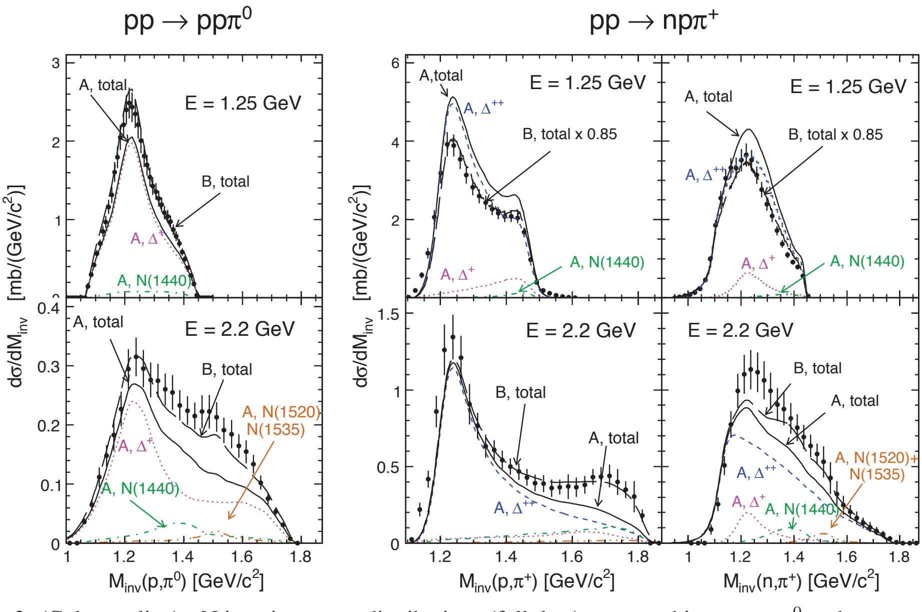

Fig. 2: (Color on-line) πN invariant mass distributions (full dots) measured in pp→ppπ^0 and pp→pnπ^+ reactions at 1.25 GeV (top row) and 2.2 GeV (bottom row). The data are compared inside the detector acceptance on an absolute scale to the predictions of the model A (see text) with contributions of Δ^+(1232) (pink dotted curve), Δ^{++}(1232) (dashed blue curve), N(1440) (green short dash-dotted curve) and N(1520)+N(1535) (long dash-dotted light brown curve). The long dashed curve shows the result of the model B (see text) with a scaling factor of 0.85 applied in the case of pp→pnπ^+ at 1.25 GeV.

measured differential distributions. Fig. 1 shows the neutron angular distribution in the center of mass system measured in the pp→pnπ^+ channel, after acceptance corrections. The error bars on the picture include statistical and point-to-point systematic errors. Since the dominant process is pp$\rightarrow$nΔ^{++}, this distribution reflects the forward/backward peaked Δ resonance production, as expected from the peripheral character of the process. The data are compared with the resonance model A, which is a variant of the Teis model, where we introduced pp and pn Final State Interaction, an anisotropic angular distribution for the N(1440) production, as well as an anisotropic Δ(1232) decay angular distribution (see [4] for details). The model underestimates the data around 90° by 40%. This discrepancy can be reduced to 15% by changing the cut-off parameter Λ_π of the πNΔ vertex.

The distributions of the (p,π^0), (p,π^+) and (n,π^+) invariant masses for T$_p$ = 1.25 and 2.2 GeV are shown in Fig. 2. They are compared both to model A, as above, and to model B which contains modifications allowing for a better reproduction of both angular distributions, yields and invariant masses simultaneously. These modifications are described in more details in [4]. At 1.25 GeV, the Λ_π cut-off parameter was changed from 0.63 GeV to 0.75 GeV and the Δ(1232) production angular distribution was further adjusted to describe the neutron angular distribution in the pp$\rightarrow$pnπ^+ channel. In this way, the proton angular distribution in the pp$\rightarrow$ppπ^0 channel was also better reproduced. At 2.2 GeV, the production cross sections for N(1440), N(1520) and N(1535) resonances were increased and a non-resonant contribution was introduced. Absolute cross sections could be determined after acceptance corrections (Table 1) and were found to be in agreement with existing systematics.

An analysis of the data obtained in the pp$\rightarrow$pnπ^+ and pp$\rightarrow$ppπ^0 channels at 3.5 GeV is also being finalized. The cross-sections for the production of the various resonances were estimated using simultaneous fits of the invariant masses and angular distributions obtained in both isospin channels. For the production of the Δ(1232), the t dependence given by the OPE model [12] was used, while for the other resonances, a dependence of the form $d\sigma/dt = A/t^\alpha$ was chosen, and the parameters A and α were fitted to the data. These cocktails of baryonic resonances are then used to calculate the dielectron yields in the pp$\rightarrow$ppe$^+$e$^-$ reaction.

reaction	pp$\rightarrow$pnπ^+		pp$\rightarrow$ppπ^0	
energy	1.25 GeV	2.2 GeV	1.25 GeV	2.2 GeV
cross section (mb)	17.1 $\pm$ 2.0	14.45 $\pm$ 3.2	3.74 $\pm$ 0.48	4.15 $\pm$ 0.85
acceptance corrections	$\pm$ 1.0	$\pm$1.1	$\pm$ 0.2	$\pm$0.2
normalization	$\pm$ 1.1	$\pm$ 1.6	$\pm$ 0.25	$\pm$ 0.46
efficiency	$\pm$ 1.3	$\pm$2.5	$\pm$0.33	$\pm$ 0.65
event selection	$\pm$ 0.3	$\pm$ 0.7	$\pm$ 0.12	$\pm$ 0.2
statistics	$\pm$ 0.01	$\pm$ 0.01	$\pm$ 0.003	$\pm$ 0.004

Table 1: Cross sections for exclusive one-pion production channels measured by HADES are given with the total error, calculated as the quadratic sum of the statistical and systematic errors listed in the following rows.

3 Two-pion production

Figure 3 exhibits experimental distributions of the invariant mass and opening angle of $\pi^+\pi^-$ in the center-of-mass system in comparison to pure phase space (PHSP) calculations, which have been normalized to reproduce the area of the experimental distribution. Only statistical errors are presented. The systematic errors are about 10% due to the correction on the efficiency and normalisation on pp elastic scattering. It is seen, that both experimental distributions deviate from PHSP calculations. An enhancement can be observed at low $\pi^+\pi^-$ invariant masses which is not present in the simulation with the PHSP only. Correlatively, the PHSP distribution underestimates the yield at small opening angles. A similar effect can be seen with the preliminary data obtained by the HADES collaboration in the pn$\rightarrow$pn$\pi^+\pi^-$ channels [14].

Such effects were also studied by the WASA and COSY-TOF collaborations in the pp→pp$\pi^+\pi^-$ channel from threshold up to 0.8 GeV [6, 7, 9] as well as in pp→pp$\pi^0\pi^0$ from 0.775 GeV up to 1.3 GeV [15,16]. Two lagrangian models were used to analyse these data, [17,18], from respectively Chinese and Spanish groups. A common feature of these models is the dominance of the N(1440) excitation close to threshold and the increase of the double Δ excitation when the incident energy increases. However, the models differ by the importance of the ρ-exchange contribution to the double Δ(1232) excitation and by the relative branching ratios of the N(1440) resonance into the $\Delta(1232)\pi$ and N$(\pi\pi)_{Swave}$. Modifications of the Spanish model have been proposed in [16], which allow for a good description of the differential spectra measured in the pp→pp$\pi^0\pi^0$ reaction by CELSIUS/WASA from 1 to 1.3 GeV. A comparison of the data obtained in the pn→pn$\pi^+\pi^-$ and pp→pp$\pi^+\pi^-$ to the Chinese and Spanish models [17,18] and to the modified version of the Spanish model [16] is on-going. The invariant mass (M$_{\pi^+\pi^-}$) and the opening angle in center-of-mass (cos$\delta_{\pi^+\pi^-}$) of the pion pair are the most sensitive distributions to the different model contributions. A double-hump structure in the $\pi^+\pi^-$ invariant mass distribution, as observed in the experimental data (Fig. 3) also appears in the models as being due either the $\Delta\Delta$ excitation via ρ exchange or to the decay channel of the Roper resonance N(1440) into $\pi\Delta$. No structure in the $\pi\pi$ invariant mass is expected for pure N(1440) →N$(\pi\pi)_{Swave}$ decay. In the pn→d$\pi^0\pi^0$ reaction, a prominent peak at invariant masses is observed (the ABC effect) and interpreted as being due to the presence of an isoscalar resonance in the pn system [19] around 2.4 GeV/c^2. To check this interpretation, a consistent description of the different $\pi\pi$ production channels in pp and pn reactions needs to be achieved. Thus, in addition to the pp→pp$\pi^+\pi^-$ and pn→pn$\pi^+\pi^-$ channels, an analysis of the pn → d $\pi^+\pi^-$ channel measured by HADES is also on-going.

The OPER model [20] based on the exchange of reggeized pions had been successfully used to describe bubble chamber data on np → np$\pi^+\pi^-$ reaction at momenta above 3 GeV/c [21]. This model can be applied for the description of the NN→NN$\pi\pi$ reaction at momenta below 3 GeV/c by taking into account the mechanism of one baryon exchange (OBE) and is therefore also used for the analysis of two pion production channels measured by HADES.

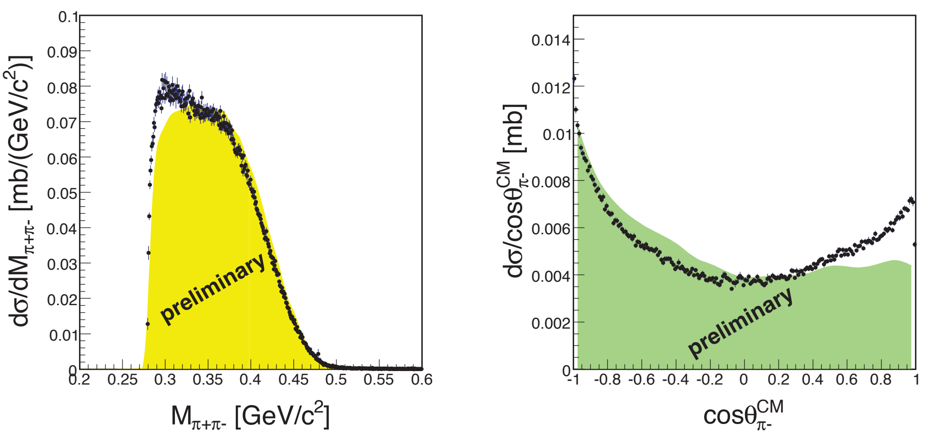

Fig. 3: Distributions of the $\pi^+\pi^-$ invariant mass M$_{\pi^+\pi^-}$ (left) and the $\pi^+\pi^-$ opening angle in the center of mass $\delta_{\pi^+\pi^-}$ (right) for the pp → $pp\pi^+\pi^-$ reaction at an incident beam energy of 1.25 GeV measured in HADES acceptance are shown to corresponding distributions from a phase space calculation. Only statistical errors are shown.

4 Conclusion

The measurement of one and two-pion production in elementary reactions with the HADES experimental set-up allows to test and improve the resonance model, which is the basis of transport models. More generally, the high statistics differential distributions provided by such measurements bring detailed information on baryonic resonance excitation and decay. The $\pi^+\pi^-$ invariant mass and opening angle distributions show sensitivity to the baryonic resonance excitation and decay. The analysis of the $\pi^+\pi^-$ production channels with effective lagrangian models will complement the extensive investigations made by the WASA collaboration in the $\pi^0\pi^0$ channel and will provide tests for a consistent description of double pion production in different isospin states.

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