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Single-pion production in proton-proton collisions at 1.25 GeV: measurements by HADES and a PWA

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Abstract. We report on the single-pion production in proton-proton collisions at a kinetic energy of 1.25 GeV based on data measured with HADES. Exclusive channels $np\pi^+$ and $pp\pi^0$ were studied simultaneously. The parametrization of production cross sections of the one-pion final states by means of the resonance model has been obtained. Independently, the extraction of the leading partial waves in the data were analyzed within the framework of the partial wave analysis (PWA). Contributions for the production of $\Delta(1232)$ and $N(1440)$ intermediate states have been deduced.

1 Proton-proton collisions at 1.25 GeV with HADES

The High-Acceptance Di-Electron Spectrometer (HADES) [1], installed at GSI Darmstadt on SIS18, provides high acceptance, good particle ($p/K/\pi/e$) identification and good mass resolution of $2-3\%$ for dielectrons in the light vector meson mass range. It allows to study both hadron and rare dilepton production in $N+N$, $p+A$, $A+A$ and pion-induced collisions at a beam energy range of a few $AGeV$. In the reaction $p+p$, discussed below, the beam energy (1.25 GeV) is below the η meson production threshold (in a free proton-proton reaction) to favour $\Delta(1232)$ production. To study one-pion production only events with one proton and one pion ($p\pi^+$) and two protons (pp) were identified with the help of missing mass technique. Our data are compared with results of a resonance model approach and a PWA.

2 Resonance model approach

To describe the data the resonance model of Teis *et al.* [3] was implemented (for details, see [2]). It incorporates the one-pion exchange (OPE) model by Dmitriev and Sushkov [5] which assumes a dominance of the one-pion exchange contribution to the inelastic amplitude. In this phenomenological model, only the P_{33} partial wave was taken into account in the intermediate πN channel and pole diagram matrix elements were calculated using a form factor function with the cut-off parameter Λ_π = 0.75 obtained by fitting the HADES data. The model adds incoherently also a P_{11} contribution but with rather small cross section (see below). Despite the simplicity, the model predicts shapes of various differential spectra for one-pion production (see [6, 7]) yet unravelling some discrepancies in cross sections.

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This approach assumes the following cross sections at the input: for the $np\pi^+$ final state 19.3 mb with the following, incoherently added, contributions Δ^{++} 16.9 mb, Δ^+ 1.86 mb, $N(1440)$ 0.54 mb and for the $pp\pi^0$ final state 4.03 mb (where the contributions are Δ^+ 3.76 mb, $N(1440)$ 0.27 mb). However, the HADES data, indicate rather lower values. Thanks to good acceptance coverage in the $np\pi^+$ channel the data were corrected by means of a 2-dimensional ($cos\theta_{CM}^{p\pi^+}$ vs $M_{inv}^{p\pi^+}$) acceptance and efficiency correction matrix resulting in the cross section of 16.5 ± 2.0 mb (which is 85% of a resonance model prediction, see Fig. 1 left - open squares). For the $pp\pi^0$ channel the HADES acceptance for two protons is limited, and data correction depends on the model. A parametrisation of the Δ^{++} production in the center of mass frame have been obtained from the $np\pi^+$ data (as 2-dimensional function of invariant mass $M_{inv}^{p\pi^+}$ and $cos\theta_{CM}^{p\pi^+}$ and applied for the Δ^+ excitation in $pp\pi^0$). Various projections (on the invariant mass, momentum, polar angle in CM, helicity and Gottfried-Jackson frame) describe data quite well and allow for the similar acceptance data correction with the model-driven extrapolation. The obtained cross section is again smaller than the resonance model prediction and amounts to 3.4 ± 0.8 mb (see Fig. 1 right - open squares). The main uncertainties come from the very forward (backward) angles, where the HADES spectrometer acceptance is worse or missing. To tackle the question which fraction of the cross section is given by the production of the resonances (mainly Δ isobar) and the subsequent partial wave analysis is performed.

3 Partial Wave Analysis approach

The extraction of the contributions from different partial waves has been obtained by means of an event-by-event partial wave analysis (PWA) based on the maximum likelihood method (provided by the Bonn-Gatchina group). Here we present briefly the formalism, the detailed description can be found in [8] and [9, 10].

The cross section

$$d\sigma = \frac{(2\pi)^4 |A|^2}{4|\vec{k}|\sqrt{s}}\, d\Phi_3(P, q_1, q_2, q_3)\,, \qquad P = k_1 + k_2\,, \tag{1}$$

describes the production of three particles with the four-momenta q_1, q_2 and q_3, from two colliding particles with four-momenta k_1 and k_2. The quantity A is the reaction amplitude, $\vec{k}$ is the 3-momentum of the initial particle calculated in the CM frame of the reaction, $s = P^2 = (k_1 + k_2)^2$ and $d\Phi_3$ is the invariant three-particle phase volume.

The total amplitude is defined as a sum of partial wave amplitudes

$$A = \sum_{\alpha} A^{\alpha}_{tr}(s) Q^{in}_{\mu_1 \ldots \mu_J}(S, L, J) A_{2b}(i, S_2, L_2, J_2)(s_i) \times Q^{fin}_{\mu_1 \ldots \mu_J}(i, S_2, L_2, J_2, S', L', J) \tag{2}$$

where S, L, J are spin, orbital momentum and total angular momentum of the pp system, S_2, L_2, J_2 are spin, orbital momentum and total angular momentum of the two-particle system in the final state and S', L' are spin and orbital momentum between final two-particle subsystem and the third final particle with momentum q_i. The invariant mass of two-body system is calculated as $s_i = (P - q_i)^2$. The multi-index α denotes all possible combinations of the $S, L, J, S_2, L_2, J_2, S', L'$ and i, $A^{\alpha}_{tr}(s)$ is the transition amplitude and $A_{2b}(i, S_2, L_2, J_2)(s_i)$ describes the re-scattering processes in the final two-particle channel (for example the production of $\Delta(1232)$). The exact form of the operators for the initial (Q^{in}) and final (Q^{fin}) states can be found in [8].

We use the spectroscopic notation ${}^{2S+1}L_J$ for the description of the initial state, the system of two final particles and the system "spectator and two-particle final state". The best description of the transition amplitude was obtained with the parametrization

$$A^{\alpha}_{tr}(s) = \frac{a^{\alpha}_1 + a^{\alpha}_3\sqrt{s}}{s - a^{\alpha}_4}\, e^{ja^{\alpha}_2}, \tag{3}$$

where a^{α}_i's are real values. For the description of the final pp interaction we use a modified scattering-length approximation

$$A^{\beta}_{2b}(s_i) = \frac{\sqrt{s_i}}{1 - \frac{1}{2}r^{\beta}q^2 a^{\beta}_{pp} + jqa^{\beta}_{pp}q^{2L}/F(q, r^{\beta}, L)}, \tag{4}$$

where multi-index β denotes possible combinations of kinematical channel i and quantum numbers S_2, L_2 and J_2; a^{β}_{pp} is the pp scattering length and r^{β} is the effective range of the pp system. The $F(q, r, L)$ is the Blatt-Weisskopf form factor and q is the relative momentum in the final two-nucleon system.

The pp is a 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) ${}^1D_2$, ${}^3P_2$, ${}^3F_2$, (J=3) ${}^3F_3$ and (J=4) ${}^3F_4$, ${}^1G_4$, ${}^3H_4$. The final states are limited to S, P, D, F, G and H wave states with the two possible intermediate resonance states $P_{33}(\Delta^{1232})$ and $P_{11}(N^{1440})$. Data samples containing 60.000 events for each ($pn\pi^+$ and $pp\pi^0$) channel with the estimated event-by-event signal/(signal+background) weight were prepared for the partial wave analysis, together with the full-scale phase space simulation of the same channels. The analysis was preformed including other available data (see [11], eleven measurements for $pp\pi^0$ and two for the $pn\pi^+$ channel) covering mostly lower beam energies. The stability of solutions was investigated based on a few parametrisations of the transition amplitude A_{tr} (with energy dependence) and various descriptions of resonance states (Δ and N^*). The obtained solutions generally describe the HADES data very well in various projections (CM angular distributions, invariant masses, angular distributions in the helicity and the Gottfried-Jackson frames). Finally, the experimental data were then acceptance and efficiency corrected with the 2-dimensional correction (as described above for the resonance model case), see Fig. 1.

We have found that, unlike in proton-proton collisions at lower energies (see [9, 10]), higher partial waves are necessary for a proper data description. They manifest themselves in the very forward/backward peaked contributions in the angular distributions of the $p\pi^+$ and $p\pi^0$ systems in CM frame and therefore contributing strongly to the cross section. The cross sections by the PWA model are 16.4 mb and 4.2 mb, respectively. Especially in the $pp\pi^0$ case, this value is bigger compared to the resonance model. The analysis shows the dominant $P_{33}(\Delta^{1232})$ contribution in $np\pi^+$ at the level of 80%, stemming from the ${}^3P_2$, ${}^3P_1$ and ${}^3F_4$ incoming partial waves. In the case of $pp\pi^0$, the intermediate $P_{33}(\Delta^{1232})$ state amounts 71% from the ${}^3P_2$, ${}^3F_4$ and ${}^3F_2$ as the major contributors. The $P_{11}(N^{1440})$ contribution reaches several percent (10% and 15% for $np\pi^+$ and $pp\pi^0$ channels, respectively) what is noticeably more than the resonance model results.

It is necessary to mention that the results are influenced by the interferences of waves with the Roper production in πN and non-resonant pn systems. The uncertainties will be reduced when high energy data ($p + p$ at 3.5 GeV, measured by the HADES Collaboration, see [12]) are included in the analysis. These data should better define both contributions from the high total angular momentum partial waves and contributions of the $P_{11}(N^{1440})$ in the intermediate state.

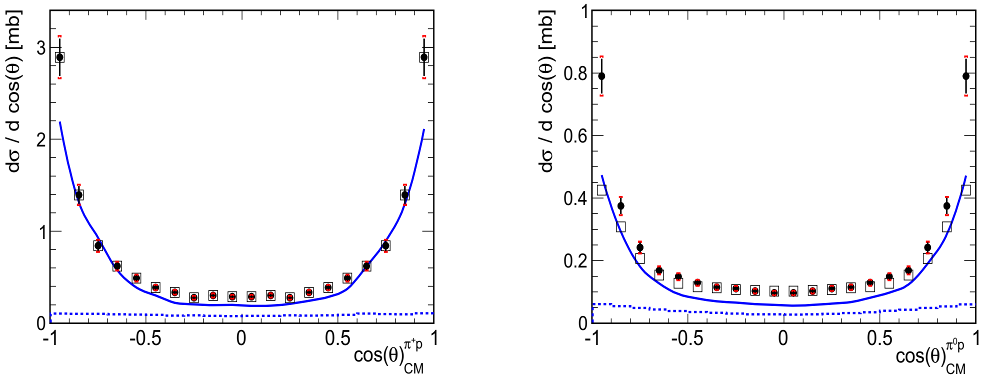

Figure 1. Angular distributions of the $p\pi^+$ (left) and ($p\pi^0$) system in the CM frame with acceptance corrections based either on the PWA solution (black dots) or on the modified OPE model (open squares). The angular distribution was symmetrically mirrored due to better acceptance in the backward (left) or the forward (right) hemisphere. PWA components: blue solid curve - $P_{33}(\Delta^{1232})$ contribution, blue dotted curve - $P_{11}(N^{1440})$ contribution. Vertical error bars represent systematic errors, red horizontal bars - normalization error (for details, see [2]).

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