Isospin Decomposition of the Basic Double-Pionic Fusion in the Region of the ABC Effect

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Abstract

Exclusive and kinematically complete high-statistics measurements of the basic double pionic fusion reactions $pn \to d\pi^0\pi^0$, $pn \to d\pi^+\pi^-$ and $pp \to d\pi^+\pi^0$ have been carried out simultaneously over the energy region of the ABC effect using the WASA detector setup at COSY. Whereas the isoscalar reaction part given by the $d\pi^0\pi^0$ channel exhibits the ABC effect, *i.e.* a low-mass enhancement in the $\pi\pi$-invariant mass distribution, as well as the associated resonance structure in the total cross section, the isovector part given by the $d\pi^+\pi^0$ channel shows a smooth behavior consistent with the conventional t-channel $\Delta\Delta$ process. The $d\pi^+\pi^-$ data are very well reproduced by combining the data for isovector and isoscalar contributions, if the kinematical consequences of the isospin violation due to different masses for charged and neutral pions are taken into account.

Keywords: ABC Effect and Resonance Structure, Double Pion Production, Isospin Decomposition

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1. Introduction

The so-called ABC effect denotes a pronounced low-mass enhancement in the $\pi\pi$-invariant mass spectrum of double-pionic fusion reactions. It is named after Abashian, Booth and Crowe [1], who first observed it in the inclusive measurement of the $pd \rightarrow {}^3$He X reaction in the kinematic region corresponding to the production of two pions. Recent exclusive measurements of the $pn \rightarrow d\pi^0\pi^0$ reaction revealed the ABC effect to be associated with a narrow resonance structure in the energy dependence of the total $pn \rightarrow d\pi^0\pi^0$ cross section [2, 3]. For this resonance structure the quantum numbers $I(J^P) = 0(3^+)$ have been determined as well as a mass of m = 2.37 GeV. The latter is about 80 MeV below the nominal mass of $2m_\Delta$ of a conventional mutual excitation of the two participating nucleons into their $\Delta(1232)P_{33}$ state by t-channel meson exchange [4]. The observed width of only about 70 MeV is more than three times smaller than that of the conventional $\Delta\Delta$ process.

In this scenario the isovector double-pionic fusion reaction $pp \rightarrow d\pi^+\pi^0$ should exhibit neither an ABC effect in the $\pi^+\pi^0$-invariant mass spectrum nor an ABC resonance structure in the total cross section. So far there has been only one exclusive and kinematically complete measurement of this reaction performed at CELSIUS at a beam energy of 1.1 GeV [5]. The measured $\pi^+\pi^0$-invariant mass spectrum does not show any low-mass enhancement, but rather a low-mass suppression. The latter is in accordance with the constraint from Bose symmetry that an isovector pion pair cannot be in relative s-wave, but in relative p-wave. In addition to this measurement there are few low-statistics bubble chamber total cross section data spread over the energy region from threshold up to $\sqrt{s} = 3$ GeV [6, 7]. All these data are consistent with a t-channel $\Delta\Delta$ process [5]. This process has been shown to be the leading two-pion production process at beam energies above 1 GeV [8, 9, 10, 11] - at least for pp induced two-pion production.

The third basic double-pionic fusion reaction, the $pn \rightarrow d\pi^+\pi^-$ reaction, contains both isoscalar and isovector contributions. From isospin conservation we expect for the angle integrated cross sections [7]

$$\sigma(pn \rightarrow d\pi^+\pi^-) = 2\sigma(pn \rightarrow d\pi^0\pi^0) + \frac{1}{2}\sigma(pp \rightarrow d\pi^+\pi^0). \quad (1)$$

For this reaction there are bubble chamber measurements from DESY [12] and JINR Dubna [13], which also provide some low-statistics differential distributions. However, their statistical precision is not good enough to clearly decide whether the ABC effect is present in this reaction or not. On the other hand inclusive single-arm magnetic spectrometer measurements of high statistics show convincing evidence for the presence of the ABC effect in this reaction [14].

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2. Experiment

We have carried out exclusive and kinematically complete measurements of these three basic double-pionic fusion reactions over the main region of the ABC effect by impinging a proton beam of $T_p = 1.2$ GeV on the deuterium pellet target of the WASA detector facility at COSY [15, 16]. By the simultaneous observation of all three reaction channels systematic uncertainties in the measurements are minimized. The quasi-free reactions $pd \rightarrow d\pi^0\pi^0 + p_{spectator}$, $pd \rightarrow d\pi^+\pi^- + p_{spectator}$ and $pd \rightarrow d\pi^+\pi^o + n_{spectator}$ have been selected by requiring a deuteron track in the forward detector as well as signals induced by pions in the central detector. The tracks from charged pions, which are bent due to the magnetic field supplied by a superconducting solenoid, have been reconstructed from the hit patterns recorded by a mini drift chamber consisting of 1738 drift tubes (straws). The photons originating from the π^0 decay have been registered in a scintillating electromagnetic calorimeter consisting of 1012 sodium doped CsI crystals.

That way the four-momentum of the unobserved spectator nucleon has been reconstructed by applying a kinematic fit with three, one and two overconstraints for events originating from $pd \rightarrow d\pi^0\pi^0 + p_{spectator}$, $pd \rightarrow d\pi^+\pi^- + p_{spectator}$ and $pd \rightarrow d\pi^+\pi^o + n_{spectator}$ reactions, respectively. The measured spectator momentum distributions are as shown in Fig. 1 of Ref. [2] for the case of the $pd \rightarrow d\pi^0\pi^0 + p_{spectator}$ reaction. As in Ref. [2] we only use spectator momenta < 0.16 GeV/c for the further data analysis. This implies an energy range of 2.3 GeV $< \sqrt{s} <$ 2.5 GeV being covered due to the Fermi motion of the nucleons in the target deuteron. For a target at rest this energy range would correspond to incident lab energies of 1.07 GeV $< T_p <$ 1.39 GeV.

Efficiency and acceptance corrections of the data have been determined by MC simulations of reaction process and detector setup. The absolute normalization of the data could be done as in previous measurements [2, 3] by normalizing to the simultaneously measured quasi-free η production $pd \rightarrow d\eta + p_{spectator}$ together with its $3\pi^0$ decay and comparison to previous results [17]. However, since the η production threshold is just in the middle of the energy range considered here and its cross section is still very small in this energy range, this control channel is of correspondingly low statistics. Taking into account the substantial systematic uncertainties associated with this threshold region normalization uncertainties get as large as 30 - 50 %. Therefore we normalize our data in absolute scale to the Dubna datum for the $np \rightarrow d\pi^+\pi^-$ reaction at $\sqrt{s} = 2.33$ GeV (T_n = 1.03 GeV, open square symbol in Fig. 1, bottom) [13], which is $\sigma = 0.270(15)$ mb obtained by use of a neutron beam with a 1% momentum resolution. That way we also achieve simultaneously good agreement with the second Dubna point at $\sqrt{s}$ = 2.51 GeV, – see Fig. 1, bottom. We find also good agreement to all previous total cross section results for the $pp \rightarrow d\pi^+\pi^0$ reaction [5, 6, 7] – see Fig. 1, top.

Concerning the absolute scale for the $pn \rightarrow d\pi^0\pi^0$ reaction there are seemingly large discrepancies to the previously published data [2]. In those data there is a 30% discrepancy in absolute normalization between data sets taken at $T_p = 1.2$ and 1.4

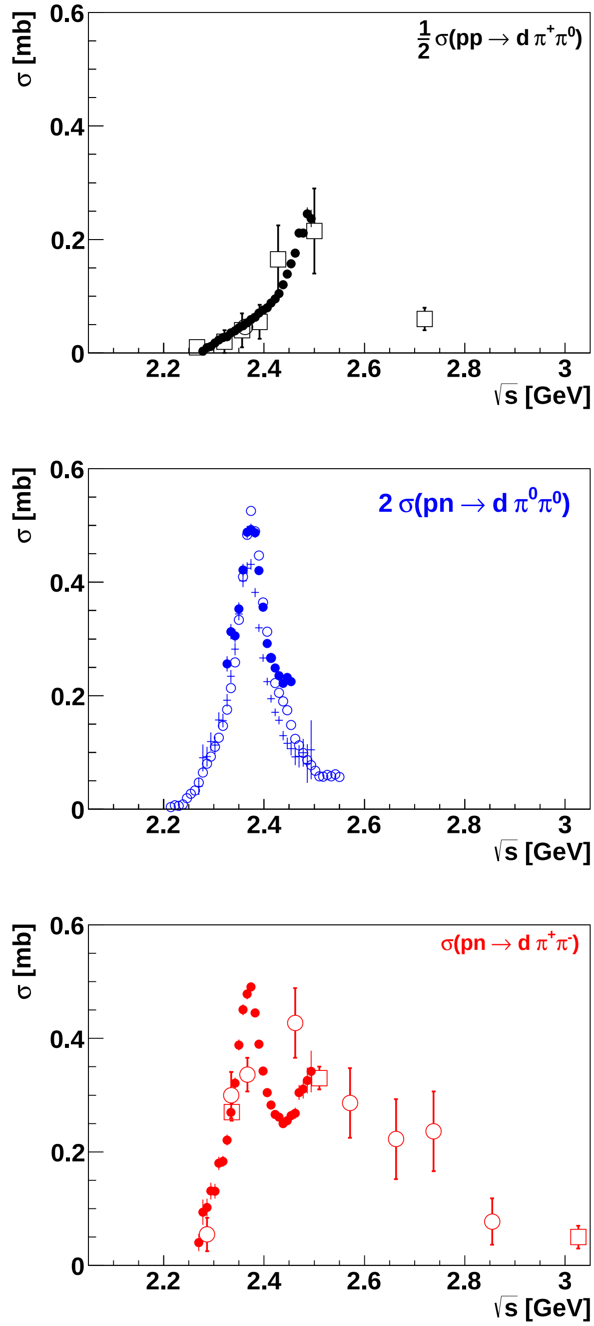

Figure 1: Total cross sections of the basic double-pionic fusion reactions $pN \to d\pi\pi$ of different isospin systems in dependence of the center-of-mass energy $\sqrt{s}$ from threshold ($\sqrt{s}$ = 2.15 GeV) until 3.2 GeV. Top: the purely isovector reaction $pp \to d\pi^+\pi^0$, middle: the purely isoscalar reaction $pn \to d\pi^0\pi^0$, bottom: the isospin mixed reaction $pn \to d\pi^+\pi^-$. Filled symbols denote results from this work, open symbols from previous work [5, 6, 7, 2, 12, 13]. The results from Ref. [2] have been renormalized – see text. The crosses denote the result for the $pn \to d\pi^0\pi^0$ reaction by using eq. (1) with the data for the $pn \to d\pi^+\pi^-$ and $pp \to d\pi^+\pi^0$ channels as input.

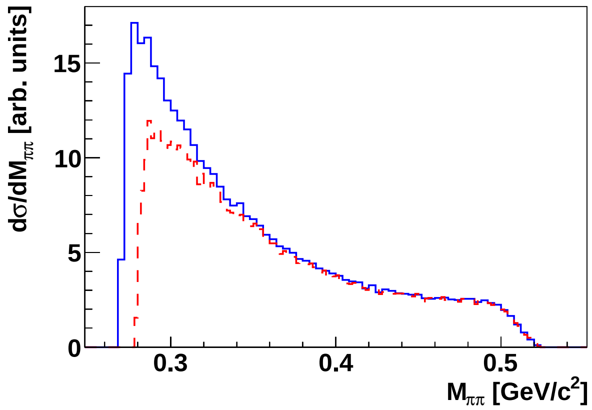

Figure 2: Distribution of the simulated $\pi\pi$-invariant mass in the ABC region for the production of a $\pi^0\pi^0$ (solid) and a $\pi^+\pi^-$ (dashed) pair, respectively. Shown are (acceptance and efficiency corrected) ABC model calculations [2] for $\sqrt{s}$ = 2.37 GeV. The different thresholds at the low-mass side due to the mass difference between charged and neutral pions lead to a substantial difference in the spectra and consequently of the corresponding cross sections.

GeV. Whereas the lower energy data cover just the η threshold region as discussed above, the higher energy data are already substantially above this threshold, where the η production cross section is already close to saturation with a much smaller energy dependence. This situation looks much more reliable for an absolute normalization and readjusting the data taken at T_p = 1.0 and 1.2 GeV to the 1.4 GeV data lowers the peak cross section already to 0.34 mb. In addition the η production data [17], where we have normalized to, have themselves an absolute normalization uncertainty of additional 30%, so that finally our new result of a peak cross section of 0.27 mb is not at variance with the previous result. The new result means a renormalization of the previous T_p = 1.4 GeV data by a factor of 0.79 and of the previous data taken at T_p = 1.0 and 1.2 GeV by a factor of 0.63.

3. Results and Discussion

Fig. 1 exhibits the observed energy dependence of the total cross section for the three double-pionic fusion reactions to the deuteron. The results of this work are given by the filled symbols and compared to previous measurements (open symbols) at CELSIUS [5], KEK [6, 7], COSY[2], DESY [12] and JINR Dubna [13].

On top of Fig. 1 the purely isovector reaction $pp \to d\pi^+\pi^0$ is shown. In the energy region covered by this experiment our data exhibit a smooth monotonical rise of the cross section with energy – in good agreement with previous data. Over the full energy region the measurements exhibit a broad structure, which is taken into account very well by calculations of the *t*-channel $\Delta\Delta$ process, which produces a resonance-like structure peaking at $\sqrt{s} \approx 2m_\Delta$ with a width of about 230 MeV, *i.e.* twice the Δ width – see Fig. 6 in Ref. [5].

For the isospin mixed (I = 0 and 1) reaction $pn \to d\pi^+\pi^-$ the observed energy dependence of the total cross section is

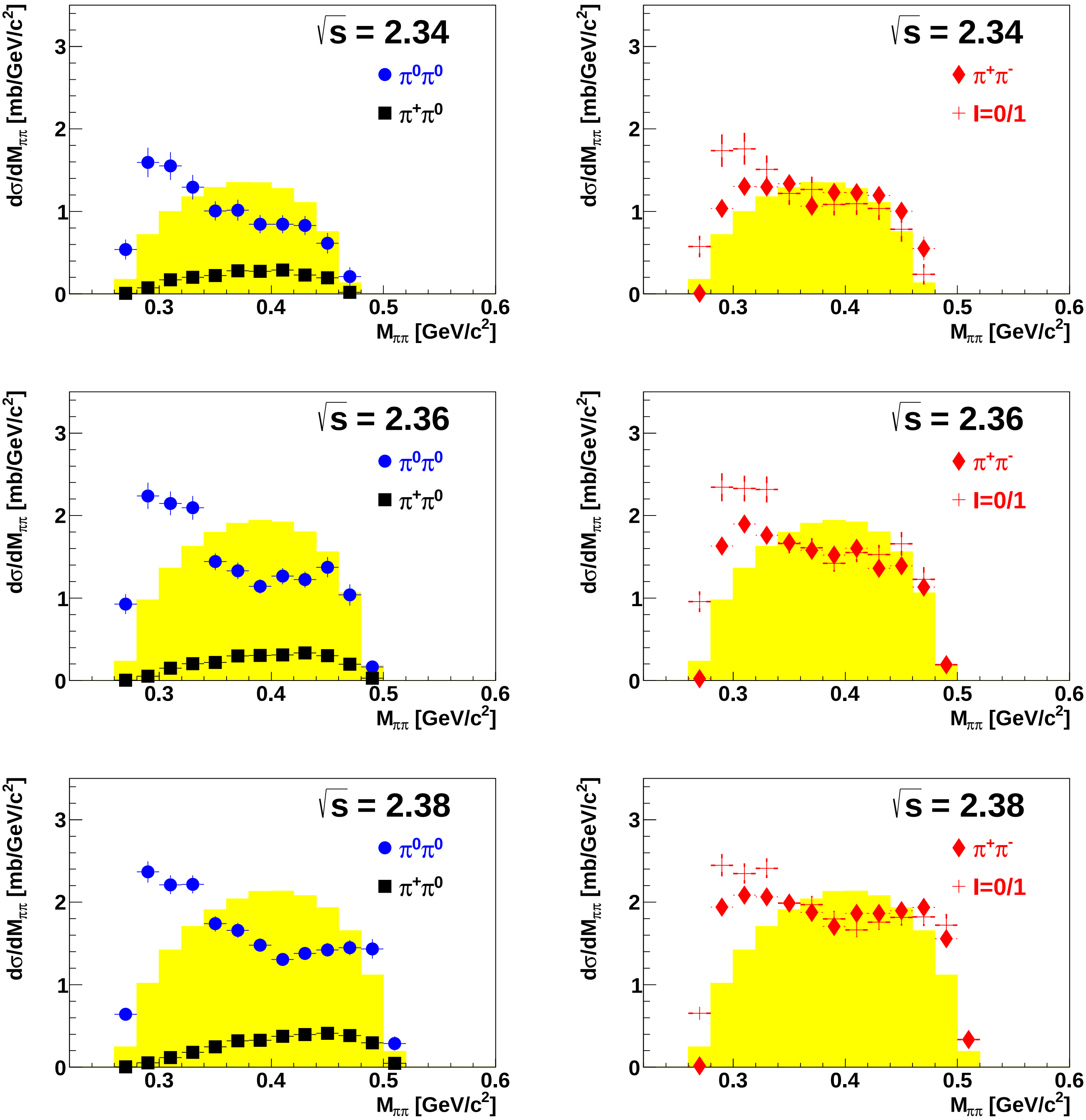

Figure 3: Distribution of the $\pi\pi$-invariant mass for the three basic double-pionic fusion reactions at $\sqrt{s}$ = 2.34 GeV, 2.36 and 2.38 GeV using an energy bin width of 0.02 GeV. On the left the results are shown for the $\pi^0\pi^0$ (circles) and $\pi^+\pi^0$ (squares) systems multiplied by isospin factors 2 and $\frac{1}{2}$, respectively – see equation (1). On the right the results for the isospin-mixed $\pi^+\pi^-$ system are shown. Data from the $pn \to d\pi^+\pi^-$ measurement are given by diamonds, whereas the sum of isoscalar and isovector contributions according to equation (1) is shown by crosses. The light-shaded areas denote phase space distributions.

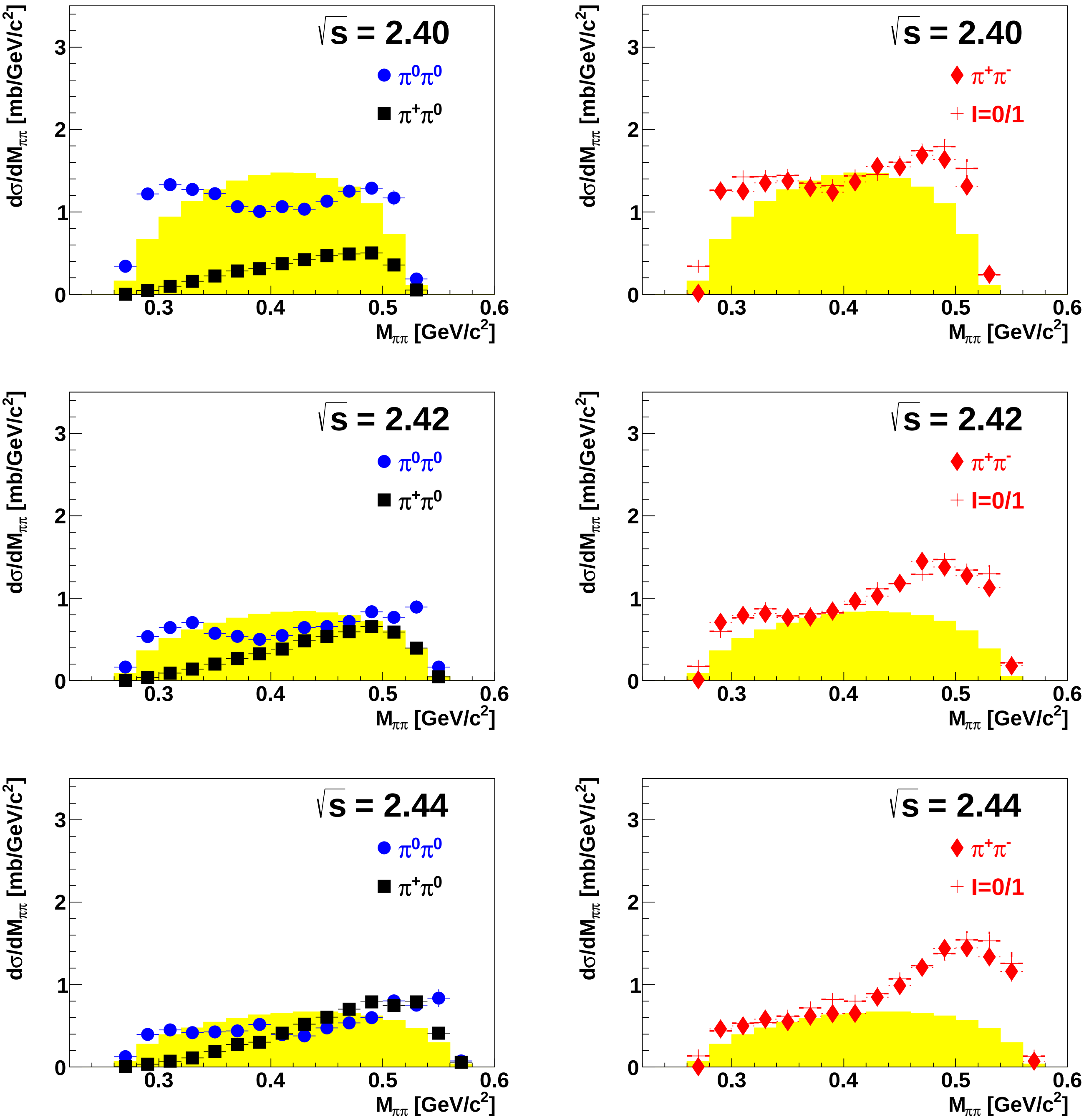

Figure 4: The same as Fig. 3, but for $\sqrt{s}$ = 2.40, 2.42 and 2.44 GeV

depicted at the bottom of Fig. 1. Open symbols refer to previous bubble chamber measurements at DESY (circles) [12] and Dubna (squares) [13]. Our new data for this channel fit well to the previous results, which have been obtained partially with a neutron beam of substantial energy spread – particularly in case of the DESY data. Hence it is not surprising that in the latter the narrow structure around $\sqrt{s}$ = 2.37 GeV appearing in our data is not seen.

The middle part in Fig. 1 shows the results for the purely isoscalar case given by the $pn \to d\pi^0\pi^0$ reaction. Open symbols denote our previous measurement [2]. In order to get best overlap with our present results (filled circles), the previous data taken at T_p = 1.0 and 1.2 GeV have been rescaled by 0.63 and those taken at T_p = 1.4 GeV by 0.79 — see discussion on absolute normalization in the previous section. Also shown are the results (crosses) for the extraction of the isoscalar cross section from the measured $pn \to d\pi^+\pi^-$ and $pp \to d\pi^+\pi^0$ cross sections by use of the isospin relation eq. (1). These derived results are consistent in shape with the directly measured ones. However, they are systematically smaller with increasing energy. The reason for this is the isospin violation in the pion mass. Since the mass of two neutral pions is 10 MeV smaller than that of two charged pions the available phase spaces for neutral and charged pion pairs differ accordingly. Since in addition the ABC effect and its associated form-factor in the model description [2] push the strength distribution in the $M_{\pi\pi}$ spectra towards the low-mass threshold, this kinematic effect gets substantial, as displayed in Fig. 2, reaching 25% in the integrated cross section, *i.e.* in total cross section. Hence all the three data sets are consistent with each other – and the narrow resonance structure, which was determined in Ref. [2] to have $I(J^P) = 0(3^+)$, appears in both the purely isoscalar $pn \to d\pi^0\pi^0$ and in the isospin-mixed $pn \to d\pi^+\pi^-$ reaction, but not in the purely isovector $pp \to d\pi^+\pi^0$ channel.

The measured $M_{\pi\pi}$ distributions are shown in Figs. 3 and 4 for six energy bins across the measured energy region. The bin width here and in all plots shown in subsequent figures is 20 MeV. On the left side the $M_{\pi^0\pi^0}$ (circles) and $M_{\pi^+\pi^0}$ (squares) distributions as derived from the $pn \to d\pi^0\pi^0$ and $pp \to d\pi^+\pi^0$ reactions are shown. They have been multiplied by the isospin factors 2 and $\frac{1}{2}$, respectively, in order to give the proper isoscalar and isovector contributions as needed for the isospin decomposition of the $pn \to d\pi^+\pi^-$ reaction, see eq. (1). The observed $M_{\pi^+\pi^-}$ spectra for the latter reaction are shown by diamonds at the right side in Fig. 3. They are compared to the sum (crosses) of isoscalar and isovector contributions, as plotted on the left side. Again we find good agreement between the directly measured $\pi^+\pi^-$ data and the ones reconstructed from the two isospin components. The only major difference is at the kinematic threshold at low masses due to the pion mass effect discussed above and shown in Fig. 2.

For all three channels the invariant-mass distributions are markedly different from pure phase-space distributions, which are given in Figs. 3 and 4 by the shaded histograms. As demonstrated by the six selected energy bins in Figs. 3 and 4, the $M_{\pi^+\pi^-}$ spectra undergo quite some change in their shape across the inspected energy region, although the $M_{\pi^0\pi^0}$ and $M_{\pi^+\pi^0}$ spectra

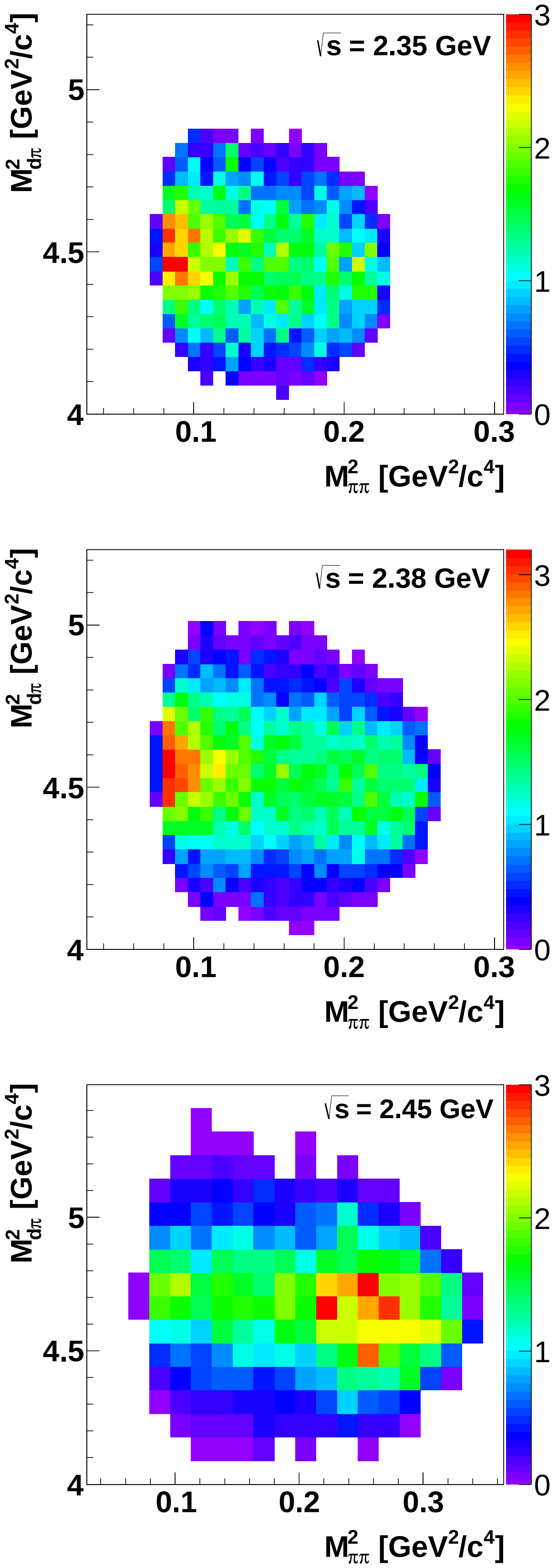

Figure 5: Dalitz plot of $M^2_{d\pi^+}$ versus $M^2_{\pi^+\pi^-}$ for the $pn \to d\pi^+\pi^-$ reaction at $\sqrt{s}$ = 2.35 GeV (top), 2.38 GeV (middle) and 2.45 GeV (bottom).

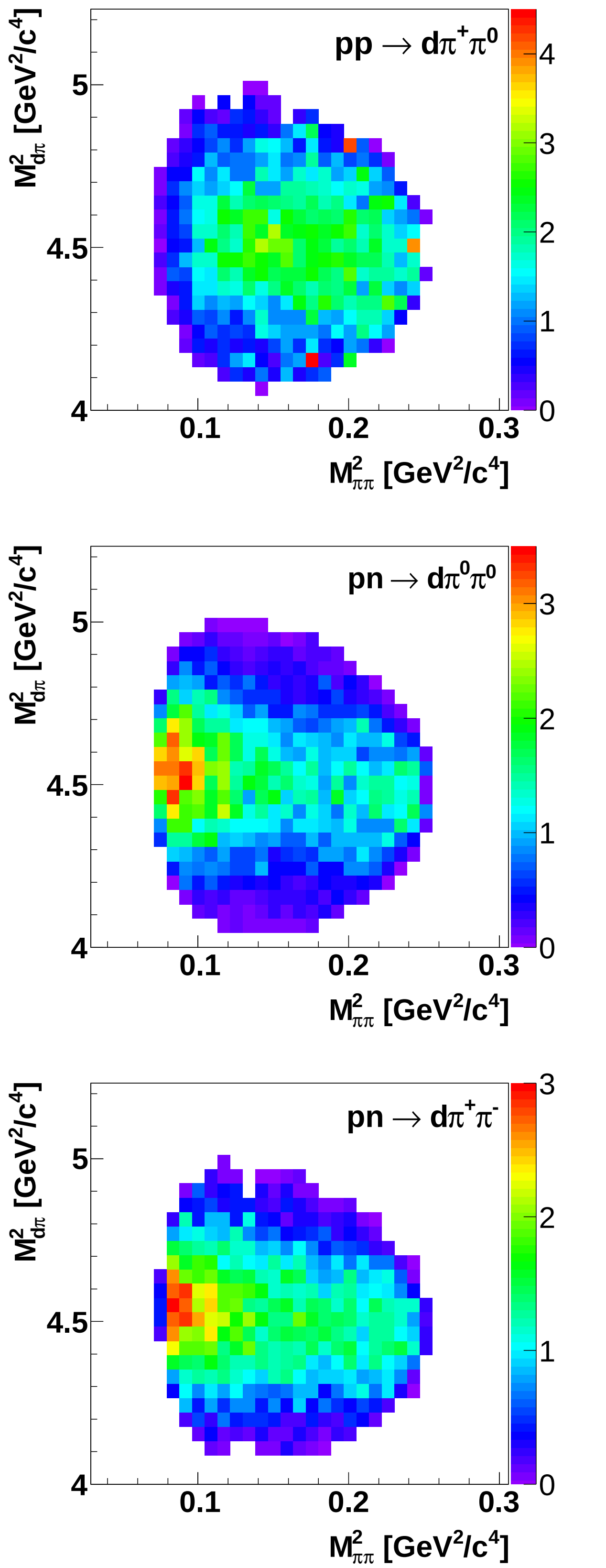

Figure 6: Dalitz plots of $M^2_{d\pi}$ versus $M^2_{\pi\pi}$ at $\sqrt{s}$ = 2.37 GeV for the reactions $pp \to d\pi^+\pi^0$ (top, isovector), $pn \to d\pi^0\pi^0$ (middle, isoscalar) and $pn \to d\pi^+\pi^-$ (bottom, isospin-mixed).

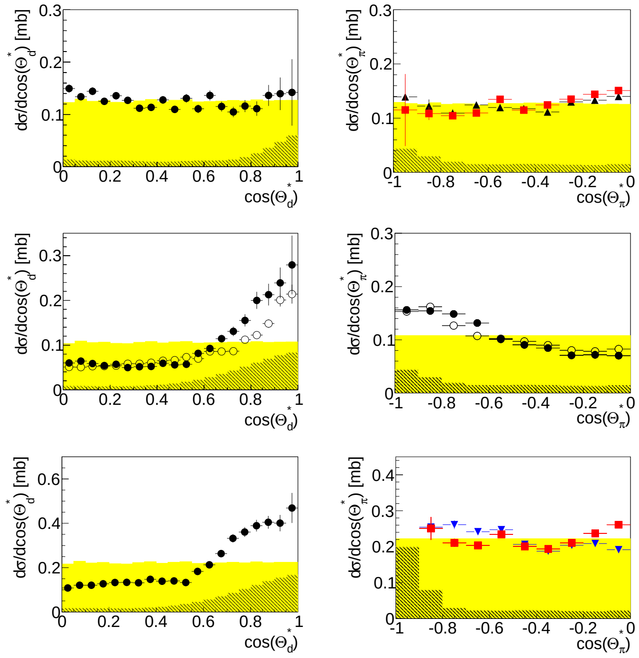

Figure 7: Center-of-mass angular distributions for deuterons (left) and pions (right) at $\sqrt{s}$ = 2.37 GeV for reactions $pp \to d\pi^+\pi^0$ (top, isovector), $pn \to d\pi^0\pi^0$ (middle, isoscalar) and $pn \to d\pi^+\pi^-$ (bottom, isospin-mixed). The filled circles denote the results from this work, the open circles the renormalized results from Ref. [2]. Filled squares denote π^+ distributions, filled triangles π^0 (top figure) and filled reversed triangles π^- (bottom figure) distributions. Shaded and hatched areas represent phase-space distributions and systematic uncertainties, respectively.

are stable in their shape over the considered region. The reason for this can be understood from the fact that the isovector part grows continuously and rapidly with increasing energy, thus increasing steadily its influence in the $M_{\pi^+\pi^-}$ spectra. In consequence also the Dalitz plot for the $pn \to d\pi^+\pi^-$ reaction changes accordingly over the energy region considered – as demonstrated for three energies in Fig. 5.

In Fig. 6 the Dalitz plots for all three reactions are compared at $\sqrt{s}$ = 2.37 GeV, the peak cross section of the ABC effect. In all three cases we clearly observe the horizontal band, which is due to the excitation of the ΔΔ system. Hence opposite to the $M^2_{\pi\pi}$ distribution the $M^2_{d\pi}$ distribution is similar in all three cases.

Finally we compare in Fig. 7 the center-of-mass (cms) angular distributions of deuterons and pions. Whereas they are close to isotropic in the isovector case – as already noted in Ref. [5], they are strongly anisotropic in the isoscalar case. The latter was used for the determination of the spin $J = 3$ of the isoscalar resonance structure [2]. The angular distributions for the $pn \to d\pi^+\pi^-$ reaction are in between both cases – as expected for the isospin mixed situation. Due to the reduced detection efficiency for charged particles at small lab angles the systematic uncertainties (hatched histograms in Fig. 7) are largest there.

In the $pp \to d\pi^+\pi^0$ and $pn \to d\pi^+\pi^-$ reaction the charge states of the produced pion pair are non-identical and hence can be distinguished experimentally. We therefore plot in Fig. 7 the angular distributions for both pions of the produced pair. As a result we see that π^+ (filled squares) and π^0 (filled triangles) distributions agree within uncertainties in case of the $pp \to d\pi^+\pi^0$ reaction. A similar situation is observed for the π^+ and π^- (filled reversed triangles) distributions in case of the $pn \to d\pi^+\pi^-$ reaction. This suggests that the pion production mechanism should be identical for both pions of the produced pair – as it is the case for a two-pion decay of an exited nucleon state or an intermediate $\Delta\Delta$ system, which has been already postulated on the basis of the Dalitz plots.

4. Summary and Conclusions

The first exclusive and kinematically complete measurements of solid statistics have been carried out for all three basic double-pionic fusion channels simultaneously in the energy range 2.3 GeV < $\sqrt{s}$ < 2.5 GeV — the energy region of the ABC effect and its associated narrow resonance structure around 2.37 GeV. This effort has been achieved by exploiting quasifree kinematics with a proton beam impinging on a deuterium target.

The data for the isoscalar $d\pi^0\pi^0$ channel are in good agreement with our previous measurement, though we find a substantially lower total cross section for this channel. However, the 40% lower total cross section obtained now is still within the systematic uncertainties involved in the absolute normalization of our data. Again, the data are characterized by the pronounced ABC effect associated with a pronounced narrow resonance structure in the total cross section.

In contrast to the isoscalar $d\pi^0\pi^0$ channel the isovector $d\pi^+\pi^0$ channel exhibits no ABC effect and no resonance structure — just a monotonically rising total cross section.

The data for the isospin mixed $d\pi^+\pi^-$ channel agree as expected with the combined results for isoscalar and isovector channels – after accounting for the isospin violation due to the different masses of neutral and charged pions. The only previous data in this channel have been low-statistics bubble-chamber measurements mainly using neutron beams of poor momentum resolution. From inspection of Fig. 1 it gets immediately clear that experiments under such conditions had no chance to discover the small narrow structure in the total $pn \to d\pi^+\pi^-$ cross section, which gives the hidden hint for the ABC resonance structure in this reaction. Hence it is not surprising that it was left to the first measurements of the $\pi^0\pi^0$ production [2, 3] to reveal the resonance structure underlying the ABC effect in an environment of low background from conventional processes.

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