STUDY OF THE REACTION $np \to np\pi^+\pi^-$ AT INTERMEDIATE ENERGIES

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Abstract

The reaction $np \to np\pi^+\pi^-$ was studied at the various momenta of incident neutrons. It was shown that the characteristics of the reaction at the momenta above 3 GeV/c could be described by the model of reggeized π exchange (OPER). At the momenta below 3 GeV/c, it was necessary to use additionally the mechanism of one baryon exchange (OBE).

1 Introduction: study of inelastic np interactions at accelerator facility of LHEP JINR

The data about inelastic np interactions were obtained due to irradiation of 1m hydrogen bubble chamber (4π geometry) by quasimonochromatic neutron beam ($\delta P < 2.5\%$) at the following incident momenta:
P_0=1.25, 1.43, 1.73, 2.23, 3.10, 3.83, 4.10 and 5.20 GeV/c

The unique of fullness and precision data are obtained [1]. It permits to carry out the detailed study of inelastic np interactions in a wide region of energies.

2 The reaction $np \to np\pi^+\pi^-$ at $P_0 > 3$ GeV/c

This reaction is characterized by:

- plentiful production of the Δ-resonance (see Fig.2),
- large peripherality of the secondary nucleons.

To study the mechanism of the reaction it was chosen the model of reggeized π exchange (OPER), developed in ITEP [2].

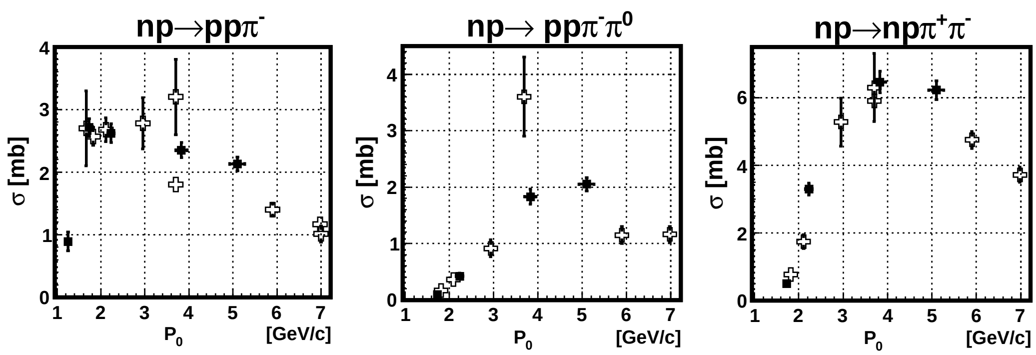

Figure 1: Cross-sections of some inelastic np interactions (black squares - our data)

The advantages of OPER model are:

- small number of free parameters (3 in our case),
- wide region of the described energies (2÷200 GeV),
- calculated values are automatically normalized to the reaction cross-section.

The following main diagrams correspond to the reaction $np \to np\pi^+\pi^-$ within the framework of OPER model:

Matrix element for the diagrams a, b and c from Fig. 3 is written in the following form:

$$M_1 = T_{\pi N \to \pi N} F_2 T_{\pi N \to \pi N}/(t - m_\pi^2),$$

where $T_{\pi N \to \pi N}$ - amplitude of elastic $\pi N \to \pi N$ scattering off mass shell,

F_2 - form-factor, going away off mass shell of $T_{\pi N \to \pi N}$ amplitudes,

$1/(t - m_\pi^2)$ - π-meson propagator.

The data of elastic $\pi N \to \pi N$ were taken from PWA [3].

The analysis shows, that interference between diagrams 3a ,3b and 3c is negligible [4].

The study has shown that it is not necessary to take into account the contribution of the "hanged" diagrams (Fig.)into the reaction cross-sections at $P_0 < 10$ GeV/:

It was shown in [5] that the use of some specific cuts permits to select the kinematic region of the reaction $np \to np\pi^+\pi^-$ in which the contribution of the diagrams 3a, 3b and 3c consists up to 95 % at $P_0 > 3$ GeV/c.

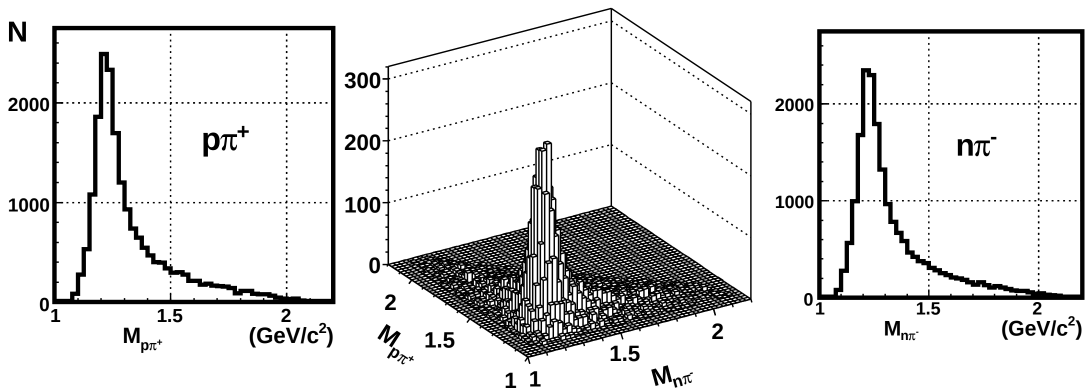

Figure 2: The distributions of $M_{p\pi^+}$ and $M_{n\pi^-}$ from the reaction $np \to np\pi^+\pi^-$ at $P_0 = 3$ GeV/c

Fig.5 shows some distributions for the reaction $np \to np\pi^+\pi^-$ for this region at P_0=5.20 GeV/c (solid curves - results of calculations using OPER model).

But the diagrams shown in Fig.3 are insufficient to describe totally the characteristics of the reaction $np \to np\pi^+\pi^-$. It is necessary to take into account the diagrams of the following type:

the matrix element for which is written in the following form:

$$M_3 = G\bar{u}(q_N)\gamma_5 u(Q_N)F_1 T_{\pi N\to\pi\pi N}/(t - m_\pi^2),$$

where $T_{\pi N\to\pi\pi N}$ - off mass shell amplitudes of inelastic $\pi N \to \pi\pi N$ - scattering that are known much worse than elastic $T_{\pi N\to\pi N}$ amplitudes. Therefore it is necessary to do a parametrization of the inelastic $\pi N \to \pi\pi N$-scattering (see Appendix).

It permits to get a good description of the experimental characteristics of the reaction $np \to np\pi^+\pi^-$ at P_0=5.20 GeV/c (Fig.7) taking into account OPER diagrams shown in Fig.3 and Fig.6 :

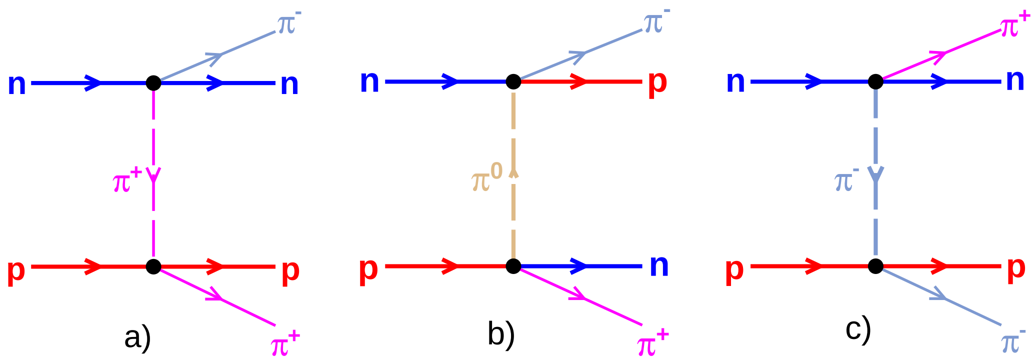

Figure 3: OPER diagrams 2×2 for the reaction $np \to np\pi^+\pi^-$

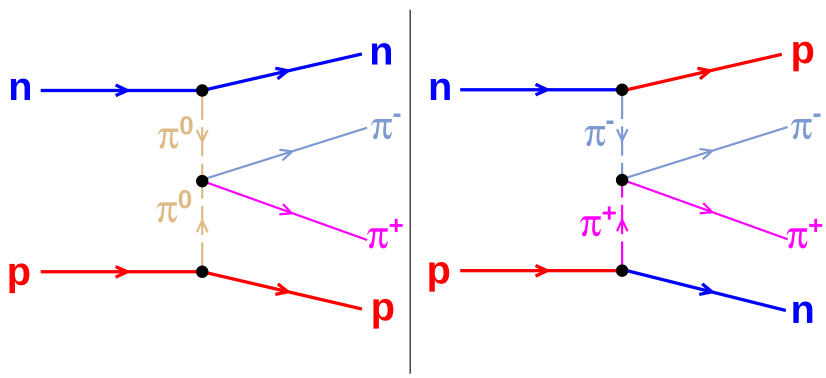

Figure 4: "Hanged" OPER diagram for the reaction $np \to np\pi^+\pi^-$

3 The reaction $\bar{p}p \to \bar{p}p\pi^+\pi^-$ at $P_0 = 7.23$ GeV/c

Using OPER model we try to describe the experimental distributions from the reaction $\bar{p}p \to \bar{p}p\pi^+\pi^-$ at $P_0 = 7.23$ GeV/c [5]

It is observed a good agreement between experimental data and theory in Fig.8.

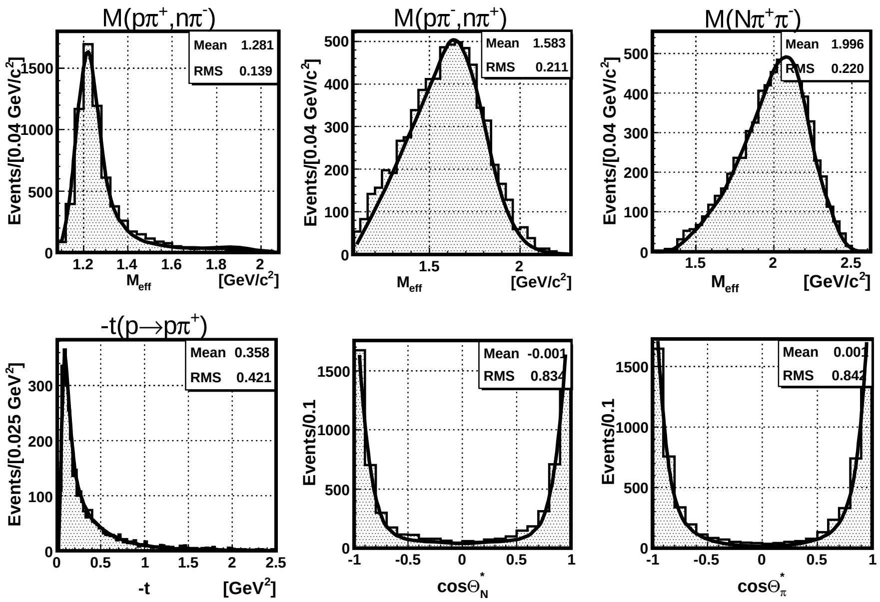

Figure 5: Distributions for the reaction $np \to np\pi^+\pi^-$ at P_0=5.20 GeV/c obtained due to specific cuts.

4 The reaction $np \to np\pi^+\pi^-$ at $P_0 < 3$ GeV/c

The study of effective mass spectra of np - combinations at P_0=1.73 and 2.23 GeV/c (Fig.9) shows the clear peack close the threshold ($M_{np} = m_n + m_p$) that can not be described within the framework of OPER-model using the diagrams from Fig.3 and Fig.6.

The model of Regge poles with baryon exchange and nonlinear trajectories, suggested in [6] was used to describe these features. The following diagrams of one baryon exchange (OBE) were taken into account within the framework of this model:

The vertex function of elastic $np \to np$ scattering was calculated using the data from [7].

The vertex functions of $\Delta N \to np$, $NN \to \Delta N$ and $\Delta N \to \Delta N$ scattering were calculated corresponding to [8]. In result one can get the good description of the experimental distribution from the reaction $np \to np\pi^+\pi^-$ at P_0 = 1.73 and 2.23 GeV/c (Fig.9 and Fig.11).

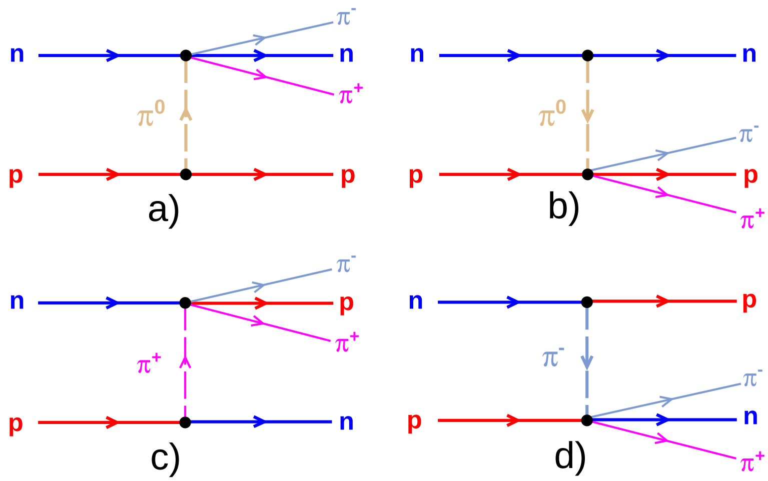

Figure 6: OPER diagrams 1×3 for the reaction $np \to np\pi^+\pi^-$

5 OPER model and other reactions

The other reactions of np interactions are scheduled to study by means of OPER model:

$np \to pp\pi^-$	vertex functions 1×2
$np \to pp\pi^-\pi^0$	vertex functions 2×2 and 1×3
$np \to pp\pi^+\pi^-\pi^-$	vertex functions 2×3
$np \to pp\pi^+\pi^-\pi^-\pi^0$	vertex functions 3×3
$np \to np\pi^+\pi^-\pi^+\pi^-$	vertex functions 3×3

Similar reactions of pp, $\bar{p}p$ and πN interactions also can be described by OPER model. The following reactions were simulated for HADES experiment:

$pp \to pp\pi^+\pi^-$ at T_{kin}=3.5 GeV

$np \to np\pi^+\pi^-$ at T_{kin}=1.25 GeV

$np \to npe^+e^-$ at T_{kin}=1.25 GeV with vertex function of $\gamma N \to Ne + e^-$.

Since the $\pi N \to \pi N$ and $\pi N \to \pi\pi N$ vertex functions are taken in helicity representation it seems to be perspective to use OPER model for description of the reaction with polarized particles.

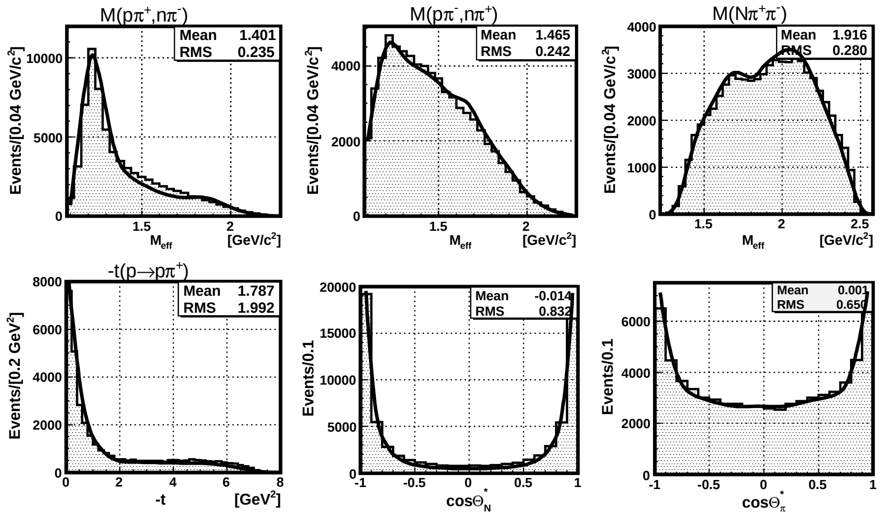

Figure 7: Distributions for the reaction $np \to np\pi^+\pi^-$ at P_0=5.20 GeV/c

6 Conclusion

Reaction $np \to np\pi^+\pi^-$ is characterized by the plentiful production of the Δ resonance and the large peripherality of the secondary particles. The experimental data are successfully described by the further development of OPER model.

However at $P_0 < 3$ GeV/c it is necessary to take into account another mechanism of the reaction (such as OBE).

OPER model permits to describe another $N(\bar{N}) - N$ reactions with the production of some π-mesons. The further development of OPER-model can be very promising to describe the production of e^+e^--pairs in hadronic interactions.

OPER model can be used as an effective tool to simulate various reactions of hadronic interactions.

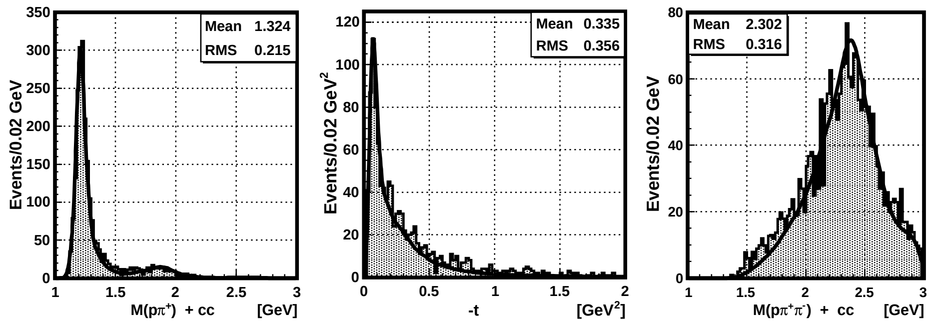

Figure 8: Distributions for the reaction $\bar{p}p \to \bar{p}p\pi^+\pi^-$ at $P_0 = 7.23$ GeV/c

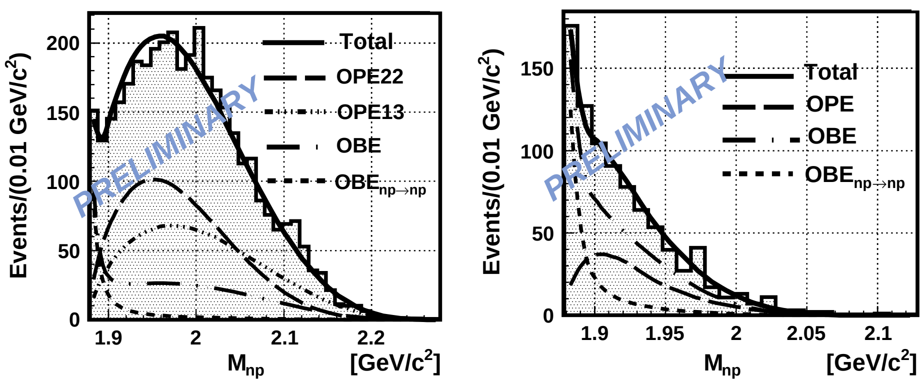

Figure 9: The distributions of M_{np} for treaction $np \to np\pi^+\pi^-$ at $P_0 = 2.23$ GeV/c (left) and 1.73 GeV/c (right).

7 Appendix: Parametrization of $\pi N \to \pi\pi N$ reactions

Within the framework of Generalized Isobar Model (GIM) [9] $\pi N \to \pi\pi N$ reactions are described as quasi-two body ones ($a + b \to c + d$):

$\pi N \to N^*(\Delta^*) \to \Delta\pi,$
$\pi N \to N^*(\Delta^*) \to N\rho$
$\pi N \to N^*(\Delta^*) \to N\epsilon$
$\pi N \to N^*(\Delta^*) \to N^*_{1440}\pi$

with the consequent decays:

$\Delta \to N\pi,$

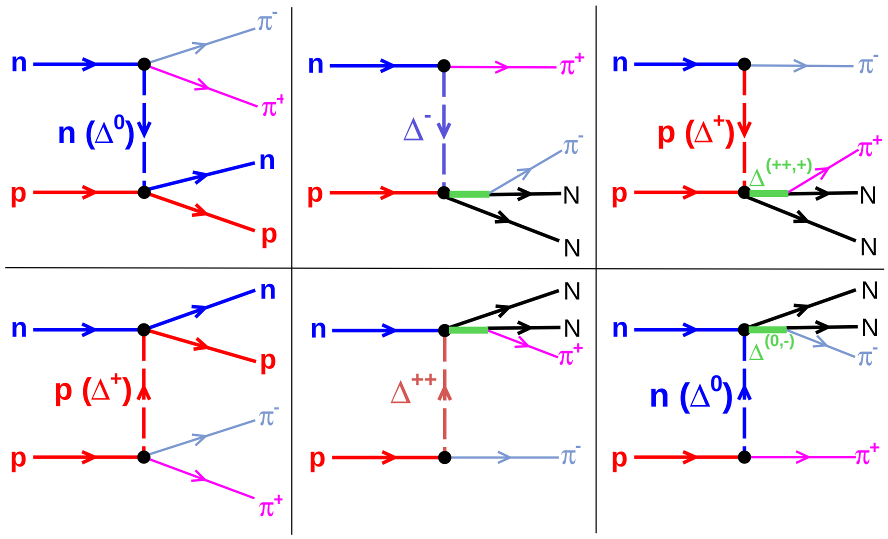

Figure 10: OBE diagrams for the reaction $np \to np\pi^+\pi^-$

$$\begin{aligned}&\rho \to \pi\pi,\\ &\rho \to \pi\pi,\\ &N^*_{1440} \to N\pi\end{aligned}$$

The parameters of the following resonances (**** and ***) were taken from Review of Particle Properties:

$N^*(1440)P11$	$D^*(1600)P33$
$N^*(1520)D13$	$D^*(1620)S31$
$N^*(1675)D15$	$D^*(1700)D33$
$N^*(1680)F15$	$D^*(1900)S31$
$N^*(1720)P13$	$D^*(1905)F35$
$N^*(2000)F15$	$D^*(1910)P31$
$N^*(2080)D13$	$D^*(1920)P33$
$N^*(2190)G17$	$D^*(1940)D33$
	$D^*(1950)F37$

The spin and isospin relations were taken account.

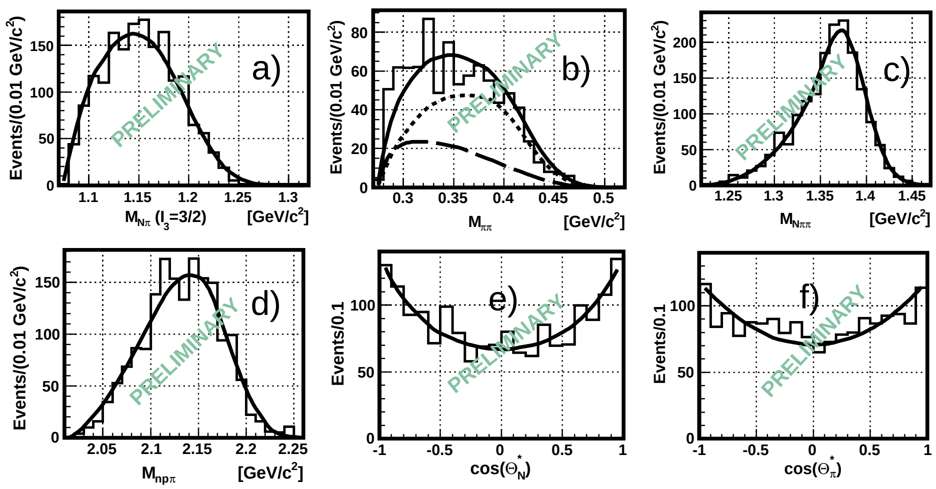

Figure 11: Distributions for the reaction $np \to np\pi^+\pi^-$ at P_0=1.73 GeV/c

For quasi two-body reactions like $a + b \to c + d$ one can write

$$d\sigma = \frac{1}{(2S_a+1)(2S_b+1)} \left(\frac{2\pi}{p}\right)^2 \sum_{\lambda_i} |<\lambda_d \lambda_c|T|\lambda_b \lambda_a>|^2 \times dPS\,,$$

$$<\lambda_d \lambda_c|T|\lambda_b \lambda_a> = \frac{1}{4\pi} \sum_j (2j+1) <\lambda_d \lambda_c|T_j|\lambda_b \lambda_a> e^{i(\lambda-\mu)\varphi} d^j_{\lambda\mu}(\theta)\,.$$

where $\lambda = \lambda_a - \lambda_b$, $\mu = \lambda_c - \lambda_d$ - helicity variables,
$d^j_{\lambda\mu}(\theta)$ - rotation matrixe,
dPS - phase space element.

The polarization components of the particles c and d from the reaction $a + b \to c + d$ is suiteable to express through the elements of the spin density matrix (for example, for particle d):

$$\rho^d_{mm\prime} = \frac{1}{N} \sum_{\lambda_c \lambda_b \lambda_a} <m\prime \lambda_c|T|\lambda_b \lambda_a>^* <m\lambda_c|T|\lambda_b \lambda_a>$$

where normalization factor for Spρ=1:

$$N = \sum_{m\lambda_c \lambda_b \lambda_a} <m\lambda_c|T|\lambda_b \lambda_a>^2\,.$$

Example:

$$\pi + N \to N^*_{1680} \to \Delta + \pi \to (N + \pi) + \pi$$

$$< \lambda_\Delta|T|\lambda_N >= C^{\frac{5}{2},-\lambda_N}_{3,0;\frac{1}{2},-\lambda_\Delta} C^{\frac{5}{2},-\lambda_\Delta}_{1,0;\frac{3}{2},-\lambda_\Delta} d^{\frac{5}{2}}_{-\lambda_N,-\lambda_\Delta}(\theta) \times R_J,$$

where R_J is taken in Breight-Wigner form.

Then it is easy to get the angular distribution of Δ (in CMS):

$$\frac{d\sigma(s,t)}{d\Omega} \sim (1 + 2\cos^2\theta_\Delta) \mid R_J \mid^2 = (1 + 2\cos^2\theta_\Delta) \times BW(\sqrt{s}, M_R, \Gamma_R)$$

If particle d is unstable: $d \to \alpha + \beta$ ($d \to \Delta + \pi$) then in the rest system of the particle d:

$$W_\Delta = \frac{3}{4\pi}\Big\{\rho_{33}\sin^2\theta + \frac{1}{3}\rho_{11}(1+3\cos^2\theta) - \frac{2}{\sqrt{3}} Re\rho_{3-1}\sin^2\theta\cos 2\varphi - \frac{2}{\sqrt{3}} Re\rho_{31}\sin 2\theta\cos\varphi\Big\}$$

- is the normalized angular distribution of the decay products.

To compare with experimental data the following cross-sections were calculated using GIM (Fig.12):

One can see a satisfactory description of cross-sections, except $\pi^+ p \to n\pi^+\pi^+$. May be it is necessary to take into account S-wave of $\pi^+\pi^+$ scattering with I=2 in GIM.

Some distributions of the reaction $\pi^- p \to n\pi^+\pi^-$ were calculated at various energies to study a quality of the application of GIM (Fig.13):

It is observed a good agreement between experimental data and theory.

References

[1] C.Besliu et al. YaF, 43:888-892,1986.

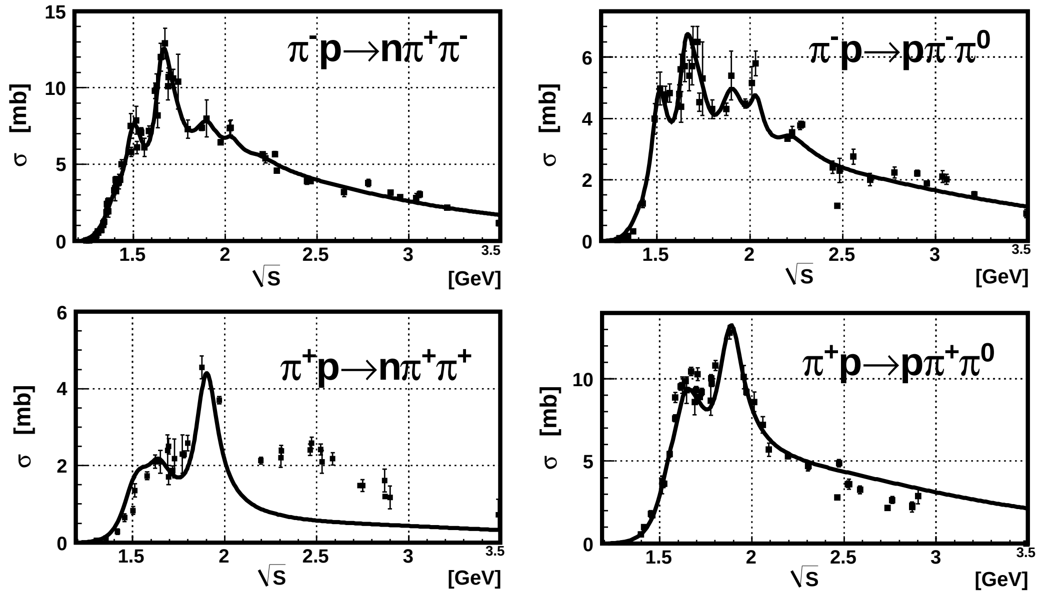

Figure 12: Cross-sections of the $\pi n \to \pi\pi N$ reactions.

[2] L.Ponomarev. Part. and Nucl., v.7(1), pp. 186-248, 1976, JINR, Dubna (in russian).

[3] R.A. Arndt et al. IJMP A18(3), 2003, p. 449.

[4] A.P.Jerusalimov et al. JINR Rapid Comm., v.35(2) pp.21-26, 1989, JINR, Dubna (in russian).

[5] G.W. van Appeldorn et al, NP B156 (1979),pp. 110-125.

[6] A.B. Kaydalov and A.F. Nilov. YaF, v.41(3),pp. 768-776, 1985 ;
YaF, v.52(6), pp. 1683-1696, 1990.

[7] NN and ND interactions - a compilation. UCRL-20000 NN, august 1970.

[8] V.Barashenkov and B.Kostenko. JINR Comm. 4-84-761, 1984, JINR, Dubna.

[9] D.J. Herndon et al. PR D11, 3165 (1975);
D.M.Manley and E.M. Saleski, PR D45, 4002 (1992).

[10] J.Dolbeau et al. NP B78, 233(1974).

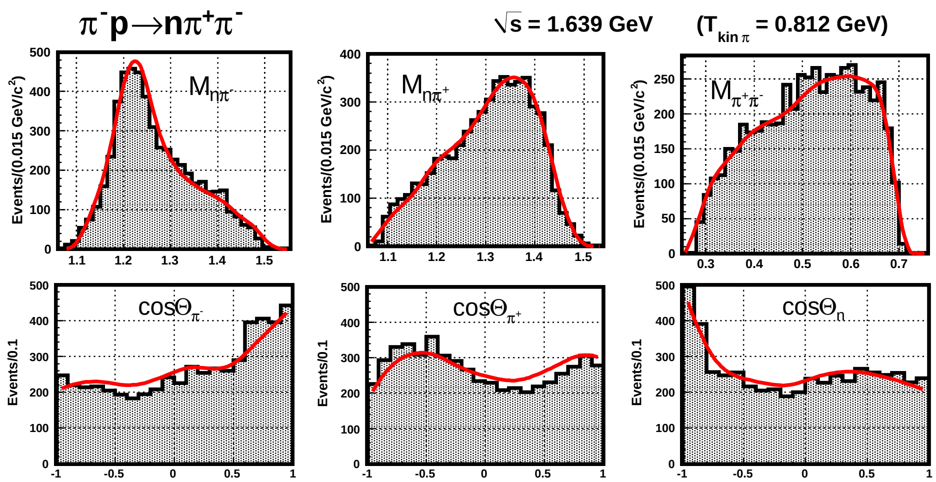

Figure 13: Some distributions from the reaction $\pi^- p \to \pi^+\pi^- n$ at T_{kin}=1.0 GeV [10]