Study of the reaction $np \rightarrow np\pi^+\pi^-$ at intermediate energies

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Outlook

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4. **The reaction $np \rightarrow np\pi^+ \pi^-$ at $P_0 < 3$ GeV/c**
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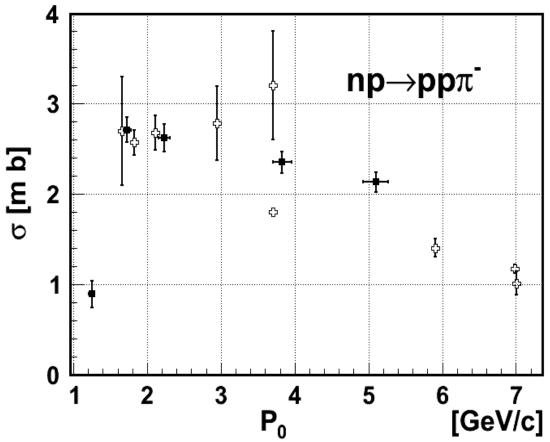
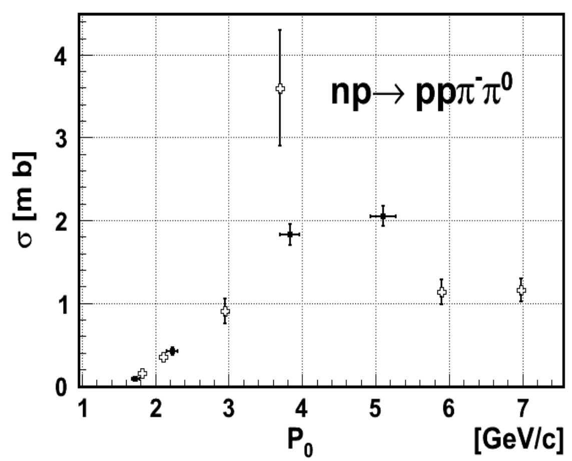
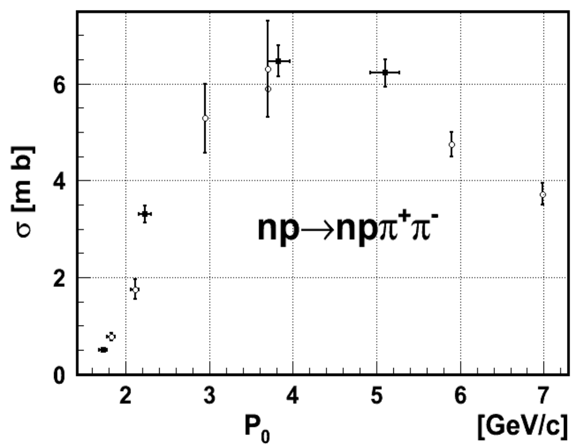
1. Introduction: study of inelastic np interactions at accelerator facility of LHEP JINR

- **Quasimonochromatic neutron channel: δP≈2.5% ,**
  P_0=1.25; 1.43; 1.73; 2.23; 3.10; 3.83; 4.10 and 5.20 GeV/c,
  4π geometry.
- **Cross-sections of inelastic np interactions:**
  (black circles – our data)





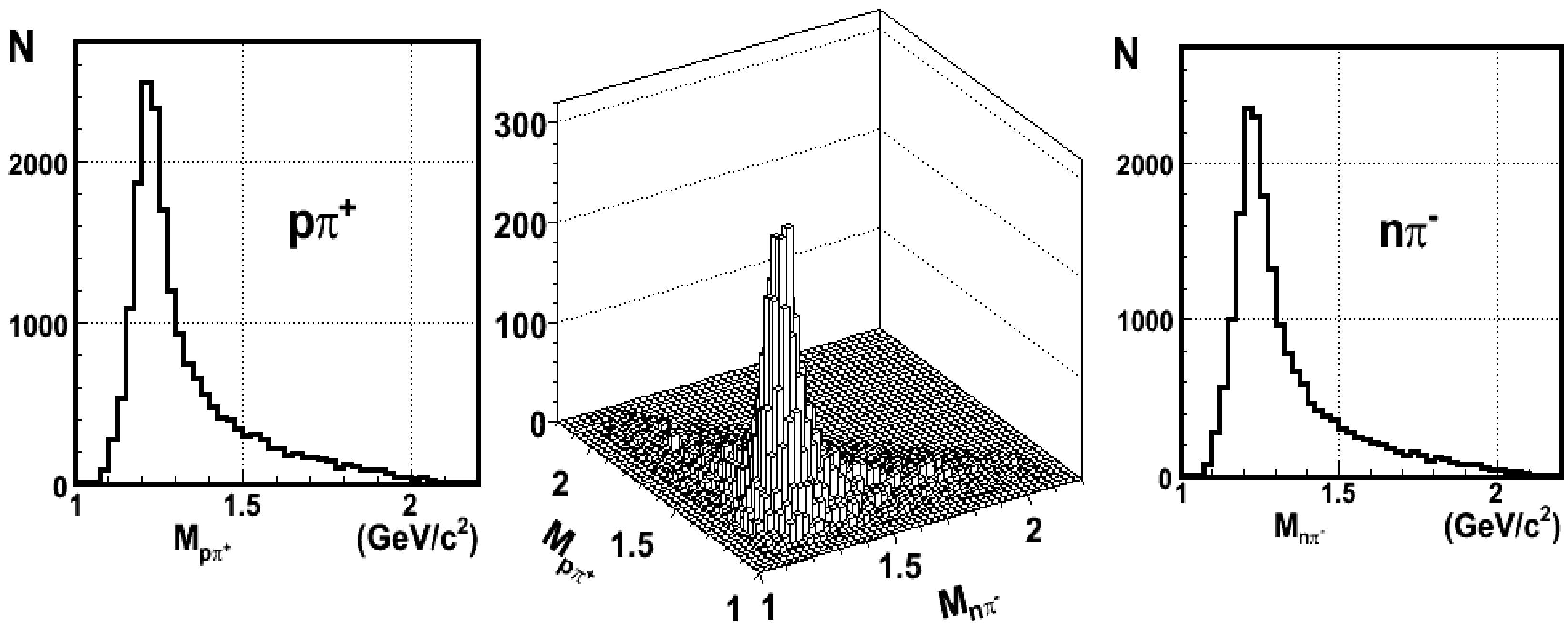


The unique of fullness and precision data are obtained.
It permits to carry out the detailed study of inelastic np interactions in a wide region of energies

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

It is characterized by:

- **plentiful production of the Δ resonance ,**



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

<u>The advantages of OPER model are:</u>

- **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 $np \rightarrow np\pi^+ \pi^-$ within the framework of OPER model:

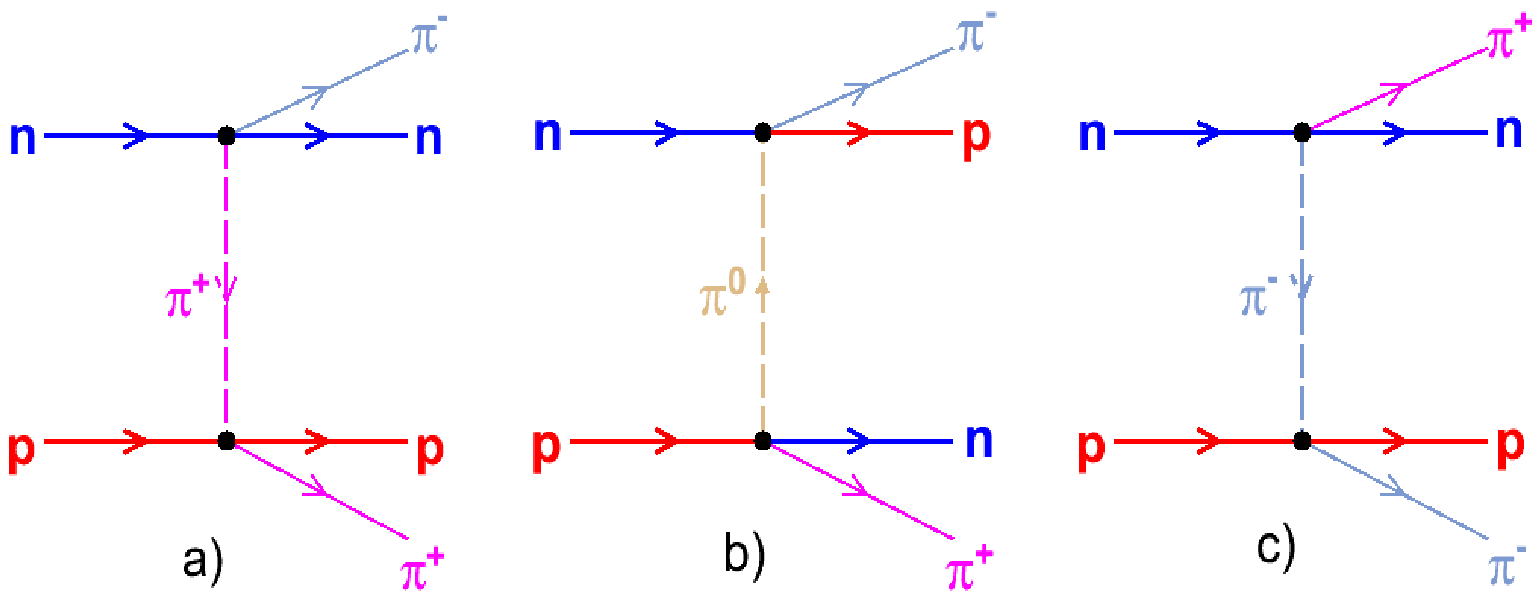


Fig.1

Matrix element for the diagrams 1a ,1b и 1c is written in the following form:

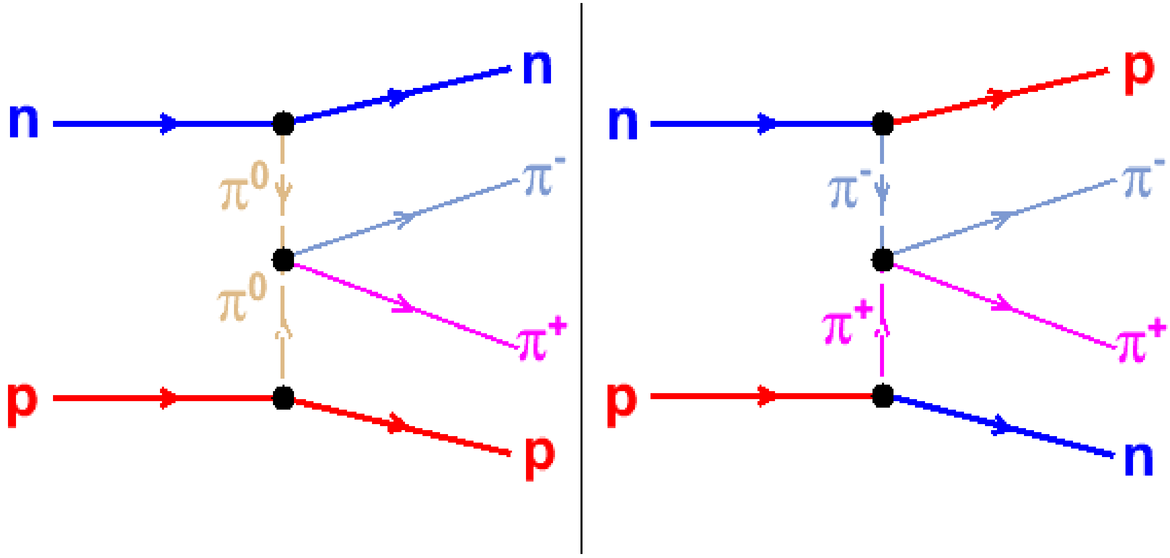
$$M_1 = T_{\pi N \to \pi N} \cdot \mathbf{F_2} \cdot T_{\pi N \to \pi N} / (t - m_\pi^2),$$

where $T_{\pi N\to\pi N}$ – amplitude of elastic ***πN→πN*** 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 ***πN→πN*** were taken from ***PWA*** [R.A. Arndt et al. **IJMP A18(3**), 2003, p. 449]

The analysis shows, that interference between diagrams 1a ,1b и 1c is negligible [A.P.Jerusalimov et al. JINR Rapid Communications, v.35(2) pp.21-26, 1989, JINR, Dubna].

The study has shown that it is not necessary to take into account the contribution of the «hanged» diagrams into the reaction cross-sections at $P_0 < 10$ GeV/c



It was shown in [G.W. van Appeldorn et al, **NP B156** (1979),pp. 110-125] that the use of some specific cuts permits to select the kinematic region of the reaction **np → npπ⁺ π⁻** in which the contribution of the diagrams **1a, 1b и 1c** consists up to 95 % at P_0 > 3 GeV/c.

Fig.2 shows some distributions for the reaction np → npπ⁺ π⁻ for this region at P_0 = 5.20 GeV/c (**blue** curves – results of calculations using OPER model)

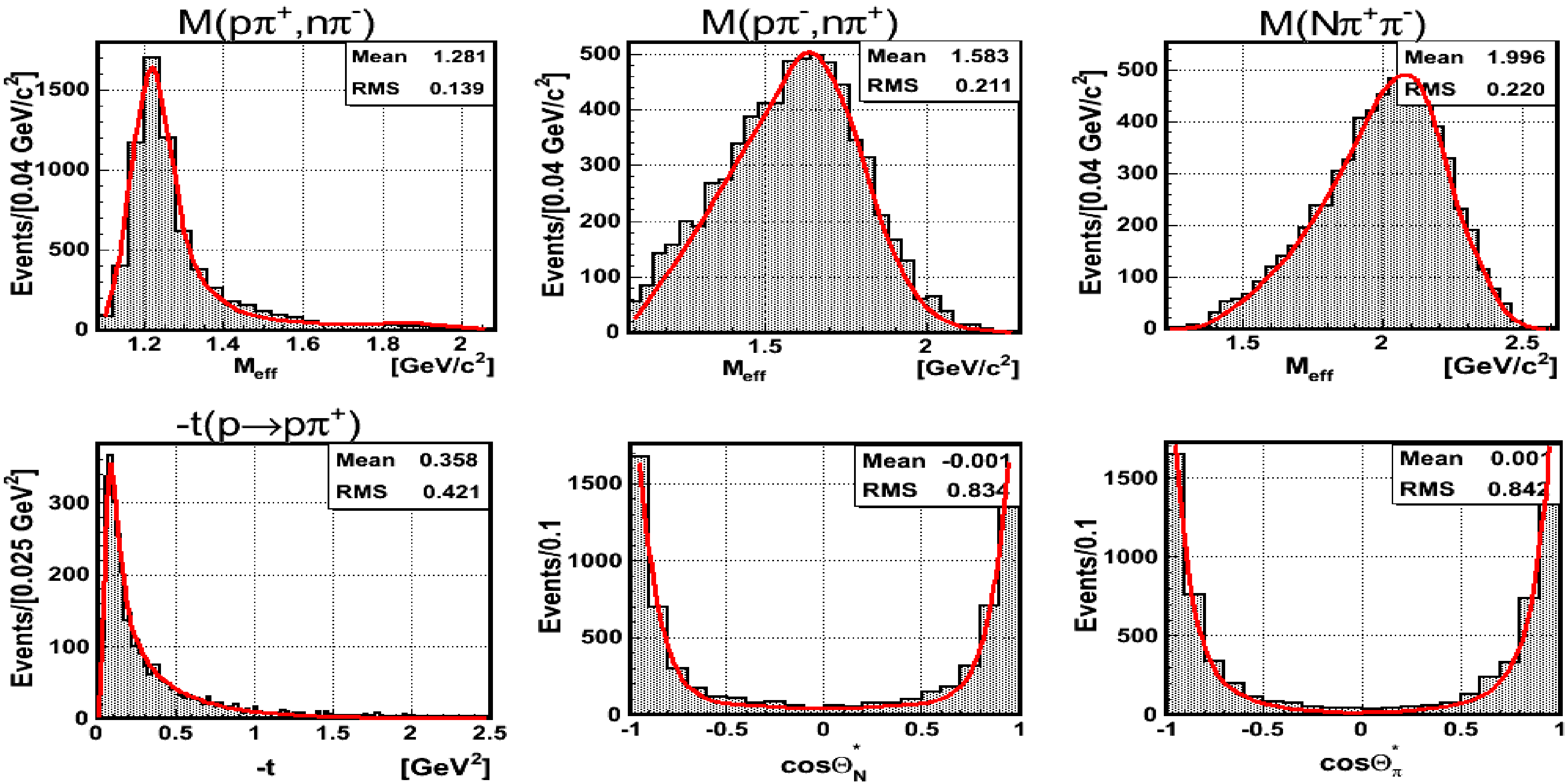


Fig. 2

But the diagrams shown in Fig.1 are insufficient to describe totally the characteristics of the reaction **np → npπ⁺ π⁻.** It is necessary to take into account the diagrams of the following type:

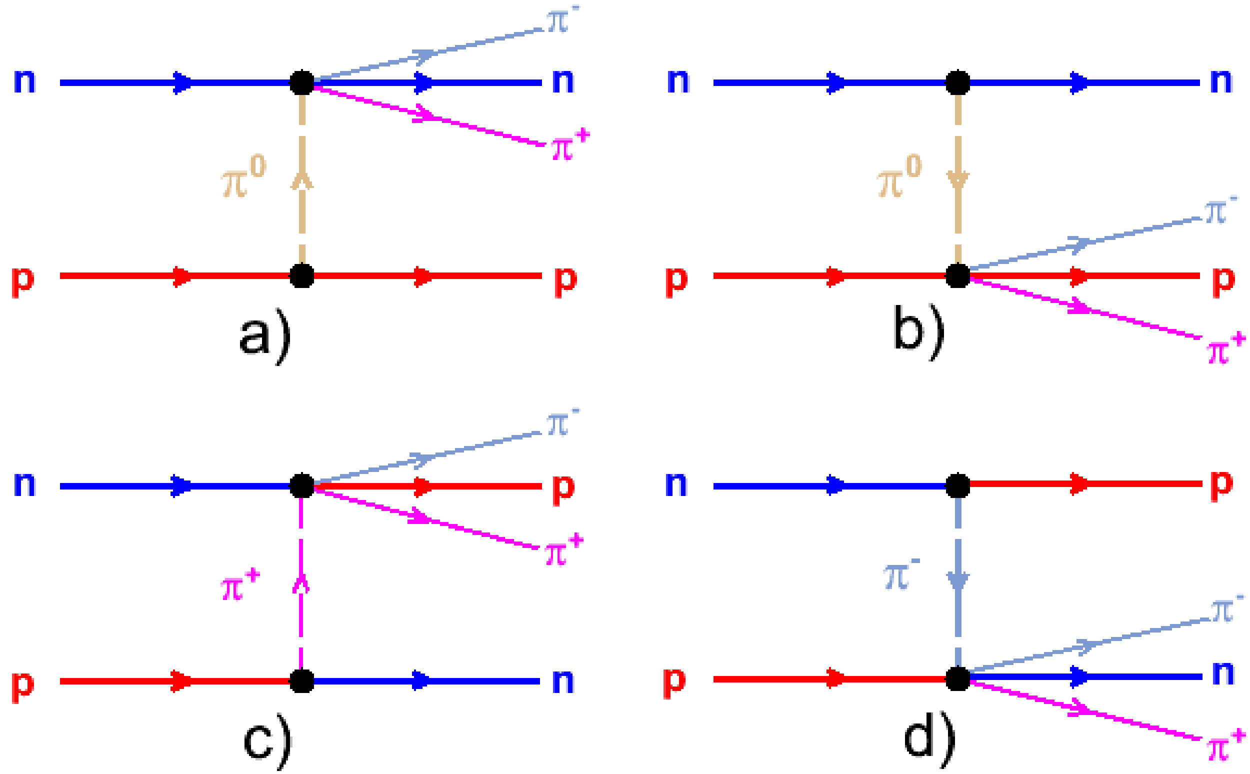


Fig. 3

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

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

where $T_{\pi N\to\pi\pi N}$ - off mass shell amplitudes of inelastic ***πN→ππN*** scattering that are known much worse than $T_{\pi N\to\pi N}$ amplitudes.

Therefore it is necessary to do a parametrization of the inelastic ***πN→ππN*** scattering (see Appendix).

It permits to get a good description of the experimental characteristics of the reaction **np → npπ⁺ π⁻** at P_0=5.20 GeV/c (Fig. 5) taking into account OPER diagrams shown in Fig.1 and Fig.3 :

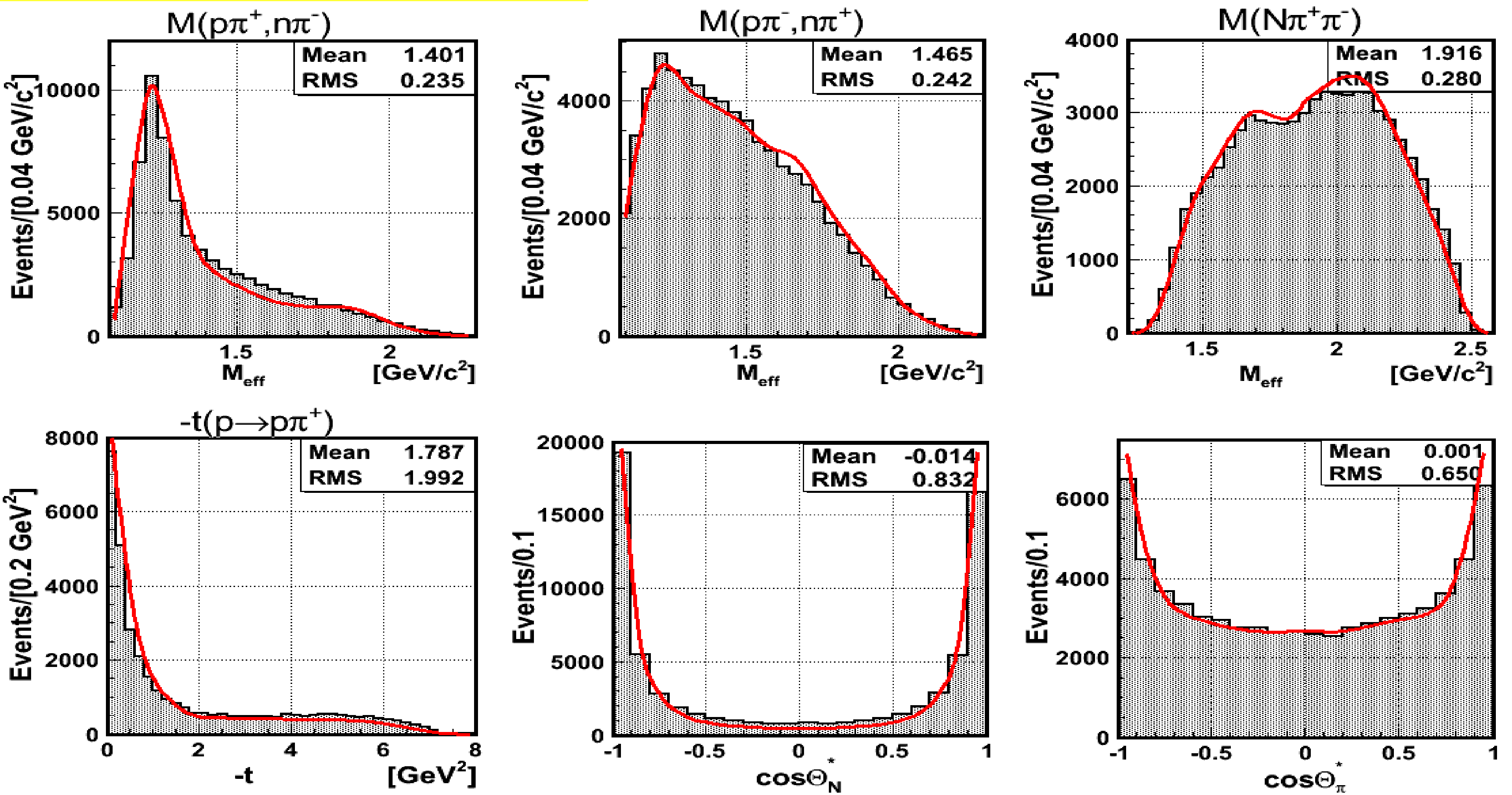
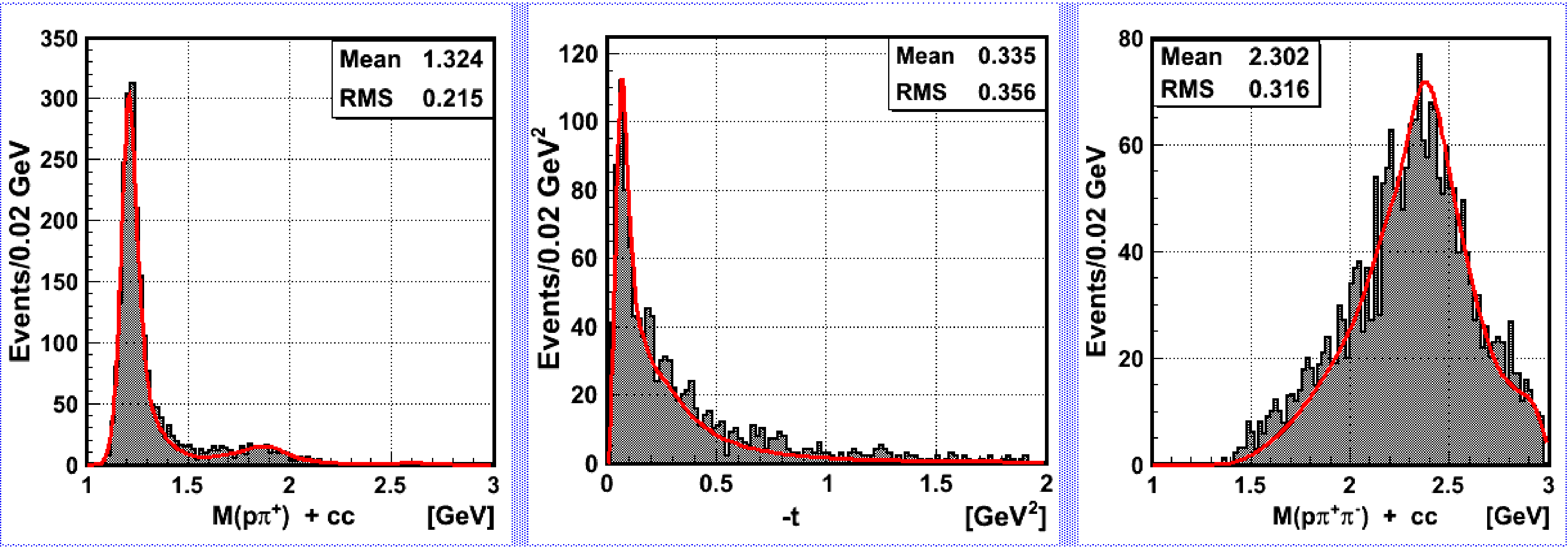


Fig. 4

3. Reaction pbar p → pbar p $\pi^+ \pi^-$ at P_0 = 7.23 GeV/c

Using OPER model we try to describe the experimental distributions from the reaction **pbar p → pbar p $\pi^+ \pi^-$** at P_0 = 7.23 GeV/c

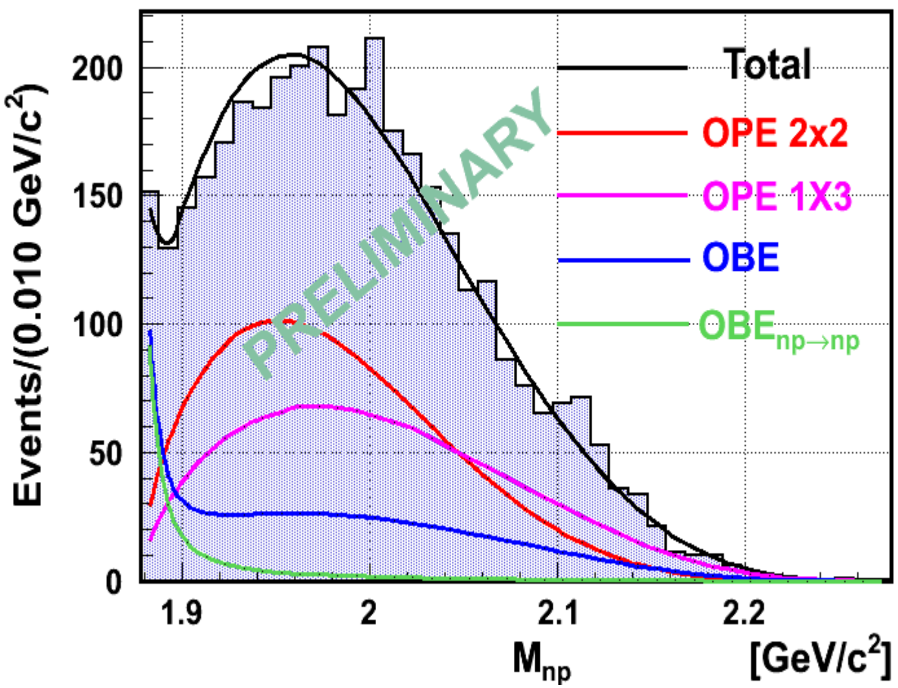
[G.W. van Appeldorn et al, **NP B156** (1979),pp. 110-125]



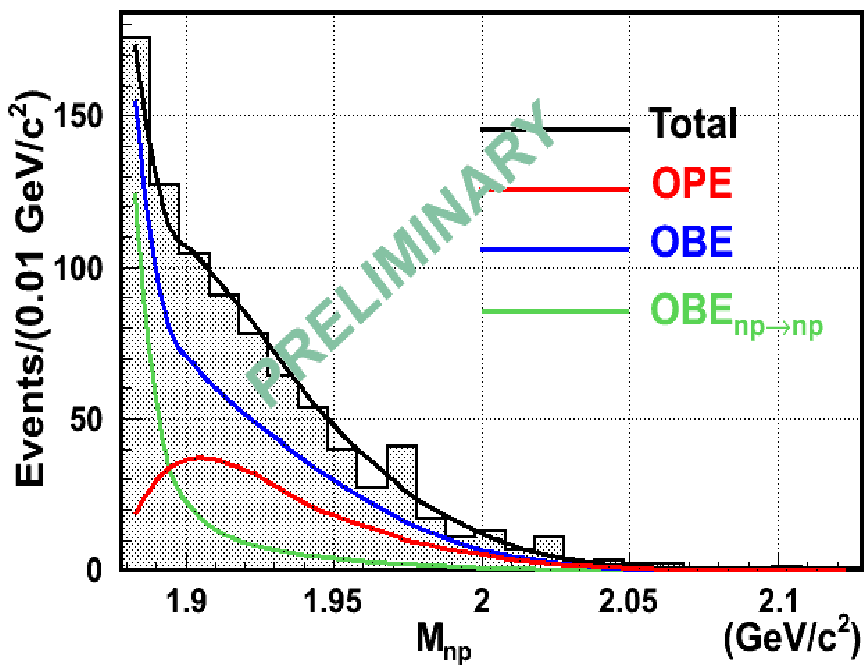
It is observed a good agreement between experimental data and theory.

4. Reaction $np \rightarrow np\pi^+\pi^-$ 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 shows the clear peack close the threshold (**M_{np}= m_n+m_p**) that can not be described within the framework of OPER-model c using the diagrams 1a, 1b, 1c, 3a, 3b, 3c и 3d.



P_0=2,23 ГэВ/с



P_0=1,73 ГэВ/с

The model of Regge poles with baryon exchange and nonlinear trajectories, suggested in [A.B. Kaydalov and A.F. Nilov. **Ya**F, v.**41**(3),pp. 768-776, 1985 ; **YaF**, v.**52**(6), pp. 1683-1696, 1990] was used to describe these features.

The following diagrams of one baryon exchange (OBE) were taken into account within the framework of this model:

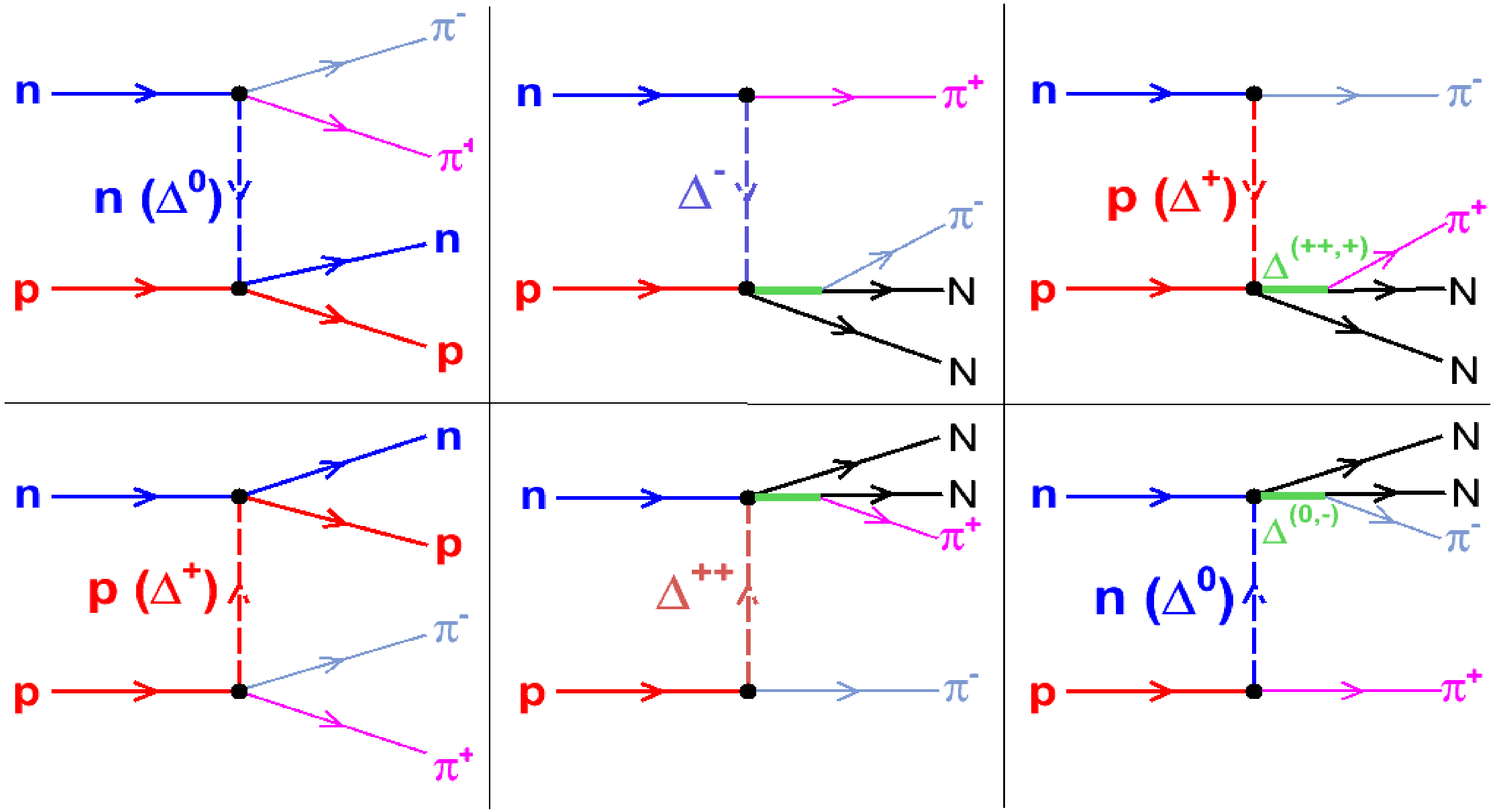
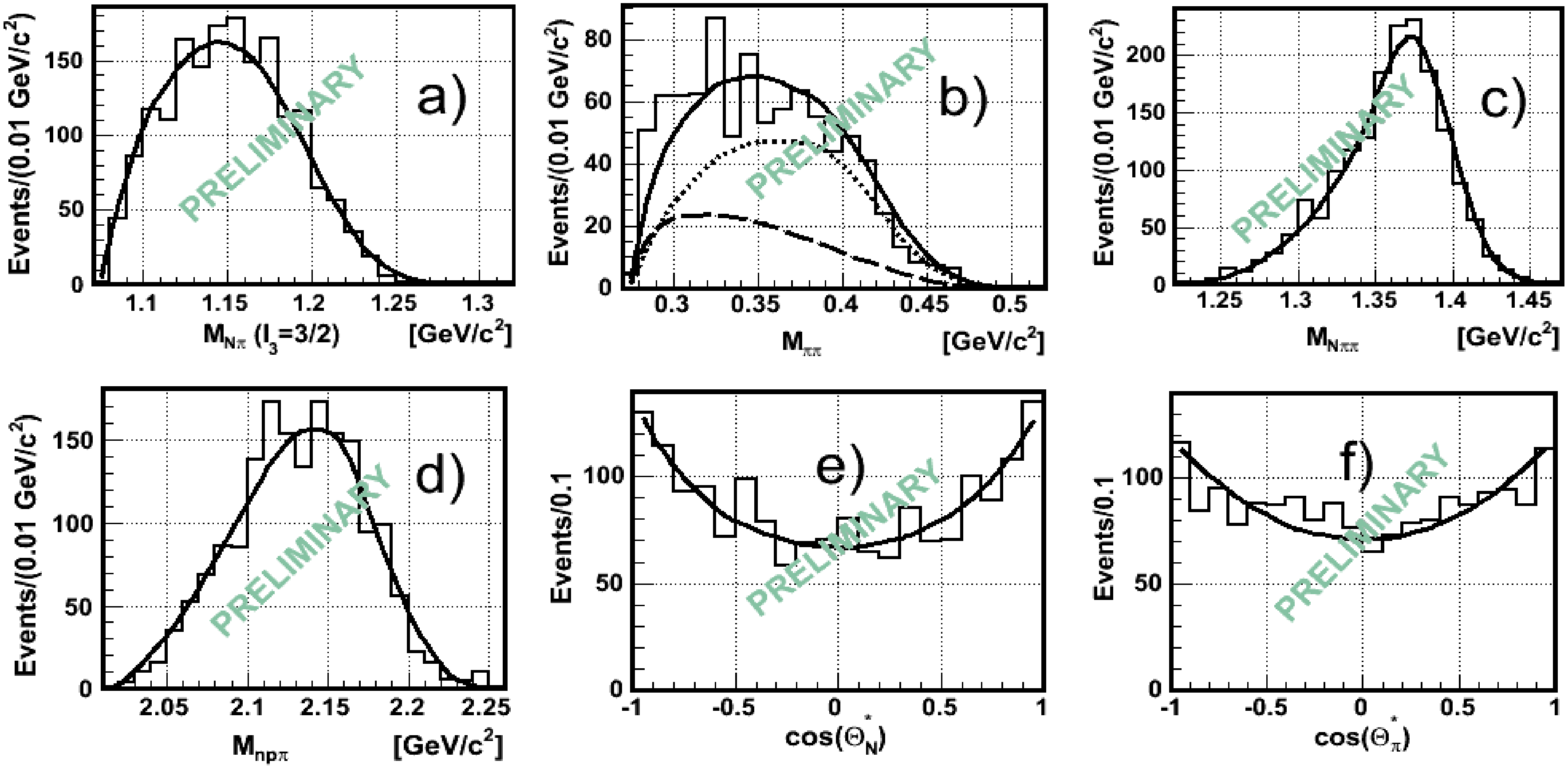


Fig. 6

The vertex function of elastic **np** → **np** scattering was calculated using the data from [NN and ND interactions – a compilation. UCRL-20000 NN, august 1970].

The vertex functions of **ΔN** → **np**, **NN** → **ΔN** и **ΔN** → **ΔN** scattering were calculated corresponding to [В.С. Барашенков и Б.Ф. Костенко. 4-84-761, JINR, Dubna, 1984].

In result one can get the good description of the experimental distribution from the reaction **np** → **np**$\pi^+\pi^-$ at P_0 =1.73 and 2.23 GeV/c.



P_0 =1,73 ГэВ/с

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 x 2**
- $np \to pp\pi^-\pi^0$ — vertex functions **2 x 2** and **1 x 3**
- $np \to pp\,\pi^+\pi^-\pi^-$ — vertex functions **2 x 3**
- $np \to pp\,\pi^+\pi^-\pi^-\pi^0$ — vertex functions **3 x 3**
- $np \to np\,\pi^+\pi^+\pi^-\pi^-$ — vertex functions **3 x 3**

Similar reactions of **p p** − , **pbap p** − and **π N** − 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 $\pi N \to N e^+ e^-$

Since the ***πN→πN*** and ***πN→ππN*** vertex functions are taken in helicity representation it seems to be perspective to use OPER model for description of the reaction with polarized particles.

6. Conclusion

Reaction $np \rightarrow np\pi^{+}\pi^{-}$ at $\underline{P_0 > 3\ GeV/c}$ 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 $\underline{P_0 < 3\ GeV/c}$ it is necessary to take into account another mechanism of the reaction (such as OBE).

OPER – model permits to describe another N(barN)-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.

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

Within the framework of **G**eneralized **I**sobar **M**odel (**GIM**)

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

$\pi N \to \pi\pi N$ reactions are described as quasi-two body ones:

$$\pi N \to N^*(\Delta^*) \to \Delta\, \pi\,,$$
$$\to N^*(\Delta^*) \to N\, \rho\,,$$
$$\to N^*(\Delta^*) \to N\, \varepsilon\,,$$ ε - **S**-wave of ***ππ scattering*** with **I**=0
$$\to N^*(\Delta^*) \to N^*_{1440}\, \pi\,,$$

with the consequent decays :

$$\Delta \to N\, \pi\,,$$
$$\rho \to \pi\, \pi\,,$$
$$\varepsilon \to \pi\, \pi\,,$$
$$N^*_{1440} \to N\, \pi\,.$$

The parameters of the following resonances (**** and ***) were taken from **RPP**

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

For quasi two-body reactions like **a + b → c + d**

πN → N*(Δ*) → Δ π ,

→ N*(Δ*) → N ρ ,

→ N*(Δ*) → N ε ,

→ N*(Δ*) → N^*_{1440} π ,

one can write

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

where

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

$\Lambda=\Lambda_a - \Lambda_b$, $\mu=\Lambda_c - \Lambda_d$ – helicity variables, $d^j_{\lambda\mu}(\theta)$ – rotation matrixes.

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

$$\rho^d_{mm'} = \frac{1}{N}\sum_{\lambda_c\lambda_b\lambda_a} < m'\lambda_c \mid T \mid \lambda_b\lambda_a >^* < m\lambda_c \mid T \mid \lambda_b\lambda_a >$$

where normalization factor for Sp***ρ***=1.

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

Example:

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

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

R_J is taken in Breight-Wigner form

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

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

If particle **d** is unstable: **d** $\rightarrow$ **α + β** (**d** $\rightarrow \Delta + \pi$)

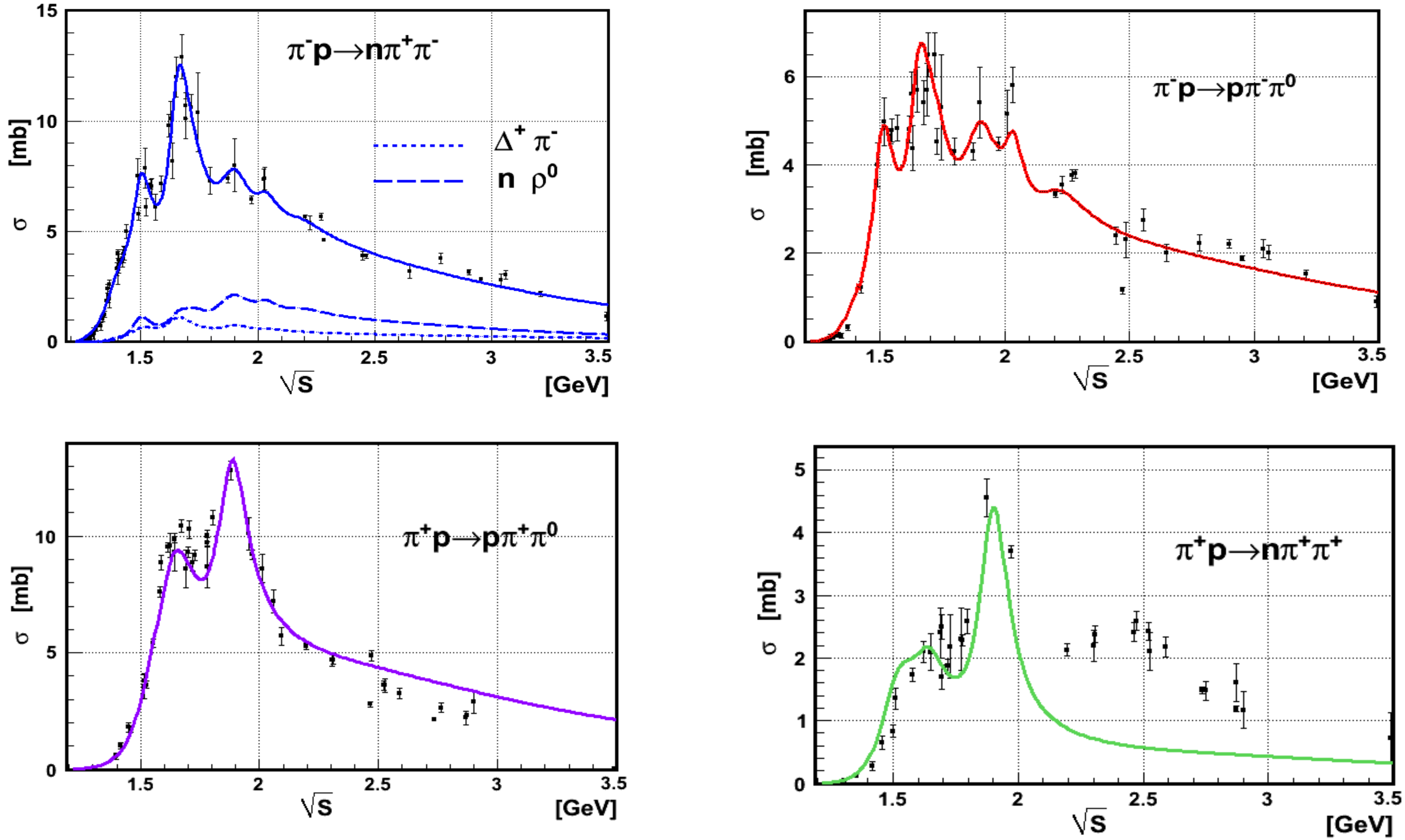
then in the rest system of the particle **d** (**d** $\rightarrow \Delta + \pi$)

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

is the normalized angular distribution of the decay products.

Comparison with experimental data

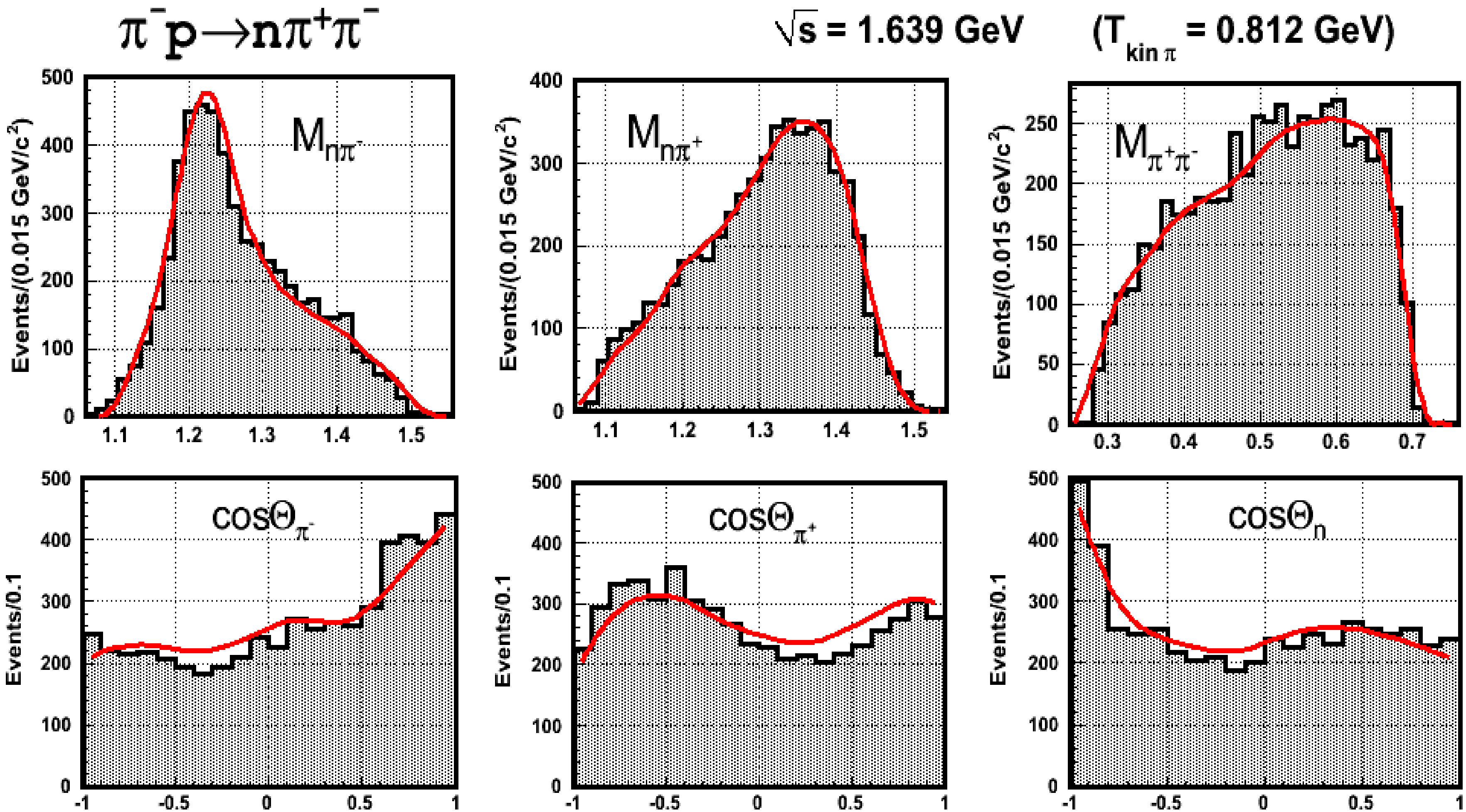
The following cross-sections were calculated using **GIM** :



One can see a satisfactory description of cross-sections, except $\pi^+ p \to n \pi^+ \pi^+$

May be it is necessary to put into **GIM** **S**-wave of $\pi^+\pi^+$ scattering with **I**=2.

Some distributions of the reaction $\pi^- p \rightarrow n \pi^+ \pi^-$ **were calculated at various energies to study a quality of the application of GIM :**



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

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