PoS PROCEEDINGS OF SCIENCE

Partial wave analyses of the $\pi^-\pi^0\pi^0$ and $\pi^-\pi^0$ systems with VES setup

Yu. Khokhlov[∗ a,b], **V. Dorofeev**[a], **A. Ekimov**[a], **V. Gotman**[a], **A. Ivashin**[a], **I. Kachaev**[a], **V. Kalendarev**[a], **M. Kholodenko**[a], **V. Konstantinov**[a], **S. Kravchenko**[b], **V. Matveev**[a], **M. Mikhasenko**[a], **E. Nazarov**[a], **V. Nikolaenko**[a,b], **A. Plekhanov**[a], **B. Polyakov**[a‡], **D. Ryabchikov**[a], **Yu. Salomatin**[a], **V. Sugonyaev**[a], **E. Volkov**[a], **A. Zaitsev**[a,b]
[†]

[a] *Institute for High Energy Physics, Protvino, Russia*
[b] *Moscow Institute of Physics and Technology, Dolgoprudny, Russia*
E-mail: Yury.Khokhlov@ihep.ru

Reactions of pion-nuclear interaction with beryllium target at 28 GeV with a single track of fast charged particle in the final state (one-prong topology) became accessible for the study with the upgraded VES setup. Studies of two of them are presented.
The Partial Wave Analysis (PWA) of the $\pi^-\pi^0\pi^0$ system was performed. The preliminary results on the resonance structure of this system are presented. The highest statistics in the world for this system and the advanced PWA technique permit us to study detailed dependence of the waves on the momentum transfer squared $|t|$. New parameterization of the $\pi^0\pi^0$ S-wave amplitude was extracted from the data.
The very high statistics on the $\pi^-\pi^0$ system was obtained, which exceeds predecessors by three orders of magnitude. It will be used for a study of the $|t|$ dependence of the $\rho(770)$ production density matrix. The feasibility of the corresponding PWA is evaluated. The results of PWA of the $\pi^-\pi^0\pi^0$ system were used to estimate the major background for $\pi^-\pi^0$ production.

XV International Conference on Hadron Spectroscopy
4-8/11/2013
Nara, Japan

[∗]Speaker.
[†]The work is partly supported by RFBR grant 13-02-00576 and Presidential grant NSh-999.2014.2.
[‡] Deceased.

1. The VES setup and events preselection

The VES is a general purpose magnetic spectrometer with electromagnetic calorimetry installed at a secondary beam line of the U-70 accelerator of IHEP. Recently the access to the one-prong events became possible, first in a commissioning run following the setup upgrade ([1]). Then new data were collected in two runs with the fully operational setup. The present analyses are based on data taken in the fall of year 2012.

Exclusive production of a meson system X in the reaction $\pi^- N \to N' X$ is studied. The typical cuts and criteria for the events selection are following: a track for a beam particle, identified as a pion, and a proper number of tracks for outgoing particles are reconstructed in the magnetic spectrometer; a vertex is reconstructed within a volume around the target; the required number of γ candidates are reconstructed in the electromagnetic calorimeter (EMC).

Then a coupling of γ-quanta into neutral pion(s) are requested according to the $M_{\gamma\gamma}$ resolution. Events with $|M_{\gamma_1\gamma_2} - M_{\pi^0}| < 20$ MeV/c^2 and $(M_{\gamma_1\gamma_2} - M_{\pi^0})^2 + (M_{\gamma_3\gamma_4} - M_{\pi^0})^2 < (20\ \text{MeV}/c^2)^2$ are retained for the $\pi^-\pi^0$ and $\pi^-\pi^0\pi^0$ systems, respectively.

Finally events were selected with the total momentum of secondary particles being close to the nominal beam momentum.

2. PWA of the $\pi^-\pi^0\pi^0$ system

The system of three charged pions was a classical object for the partial wave analyses (PWA) for a long time, while its counterpart with two π^0s is less studied. The PWA of the latter complements the study of the resonances in 3-pion system. All-charged and semi-neutral decay modes of "true" resonances should be related through the isospin couplings.

The current analysis is based on the world largest sample of about $16 \cdot 10^6$ events. This includes the kinematical region of small momentum transfer squared $|t|$ which is absent in [2], [3].

The analysis is performed within an advanced PWA framework. The mass independent PWA (MI-PWA) in the full phase space of 3-body system was performed in 40 MeV/c^2 bins over the $0.5 < M_{3\pi} < 2.5\ \text{GeV}/c^2$ range in ten unequal slices for $|t| < 1\ \text{GeV}^2/c^2$. A fashion of constructing the density matrix and a set of partial waves coupled to the matrix elements are variations of the model. We use submatrix of rank $r = 1$ (2) for the "reflectivity" $\varepsilon = +1$ (-1) part corresponding to the natural (unnatural) parity of the exchanged reggeon in the t-channel.

The parameterization of the density matrix is $\rho_{ij} = T_i T_j^* r_{ij}$ where T_i are the complex production vectors, $r_{ij} = 1$ for states i, j with the same spin projection M and $|r_{M=0,M=1}| \leq 1$ is real parameter (incoherence) otherwise.

Our basic set has 42 waves noted as $J^{PC}M^{\varepsilon}(isobar)L$. The $\rho(770)$, $f_2(1270)$ and $\rho_3(1690)$ are included in the isobar model. Scalar sector, namely $\pi^0\pi^0$ in S-wave, is described especially. The major results presented here are obtained with the "standard" parameterization based on a modified AMP M-solution [4]. The explicit $f_0(980)$ resonance substitutes the corresponding pole in the original AMP-M [5]. The Breit-Wigner $f_0(1500)$ is also added.

The normalization integrals are calculated with a Monte-Carlo method using a Geant-based model of the setup and regular reconstruction programme.

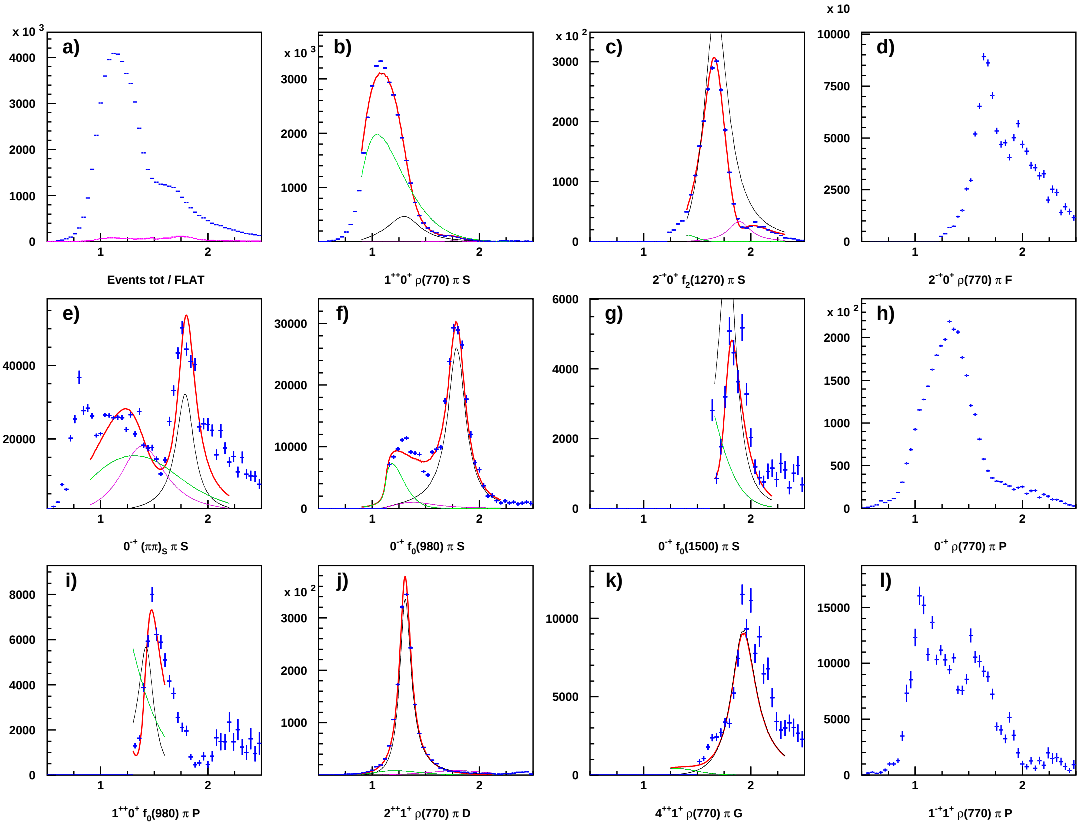

Figure 1: The PWA of the $\pi^-\pi^0\pi^0$. (a) Number of events corrected for acceptance (blue) and the FLAT wave contribution (magenta); (b-l) intensities of waves $I^G(J^{PC})M^{\varepsilon}(isobar)L$ (blue histograms) and mass-dependent fit: full function (red) with background (green) and resonance(s) (black, magenta).

Intensities of the major waves and also some smaller but stable ones are depicted in the Fig. 1. Intensities drawn are sums over all $|t|$ slices.

As a second stage of the analysis, the intensities and non-diagonal density matrix elements for subset of resulting waves of MI-PWA are simultaneously fitted with a set of mass-dependent functions. The function in each wave consists of a coherent sum of Breit-Wigner term(s) and a background term which is phase-space factor damped with $e^{-\alpha q^2}$ with a constant phase. Here q is a breakup momentum at a given mass $M_{3\pi}$ and the nominal $M(isobar)$, α is the model parameter.

The preliminary parameters of the 3π resonances obtained with this model are collected in Tab. 1. It should be noted that parameters of the following resonances: $a_1(1640)$, $a_2(1700)$, $\pi_2(1880)$ and $\pi(1300)$ have large systematic uncertainties. This concerns also a small signal in the 1^{++} $f_0(980)\pi$ wave, which shows a clean and fast variation of its intensity and phase at $M(3\pi) \approx 1.42$ GeV/c^2.

As phenomenology of the $(\pi\pi)_S$ structures is still questionable, a novel approach of "free" amplitude parameterization ([4]) was tried as an alternative to the standard one. In current approach, used also in [3], the scalar amplitude is parameterized with a complex step-like function of $\pi\pi$ invariant mass independently in each M(3π) bin for three 3π amplitudes with $J^{PC}M^{\varepsilon} = 0^{-+}0^+$, $1^{++}0^+$ and $2^{-+}0^+$. The most prominent resonant-like behavior of the $\pi\pi$ S-wave is observed for 0^{-+} amplitude at the position of the $\pi(1800)$ (Fig.2).

Table 1: Breit-Wigner parameters of resonances in the mass dependent fit. Errors are systematical and cover ranges of parameters obtained from variations of the model.

Resonance	$J^{PC}M^{\varepsilon}$ and decay modes	Mass, MeV/c^2	Width, MeV/c^2
$a_1(1260)$	$1^{++}0^+$ $\rho\pi$ S	$1327. + 0. - 17.$	$366. + 35. - 10.$
$a_1(1640)$	$1^{++}0^+$ $\rho\pi$ S	$1763. + 64. - 11.$	$217. + 13. - 10.$
$a_1(1420)$	$1^{++}0^+$ $f_0(980)\pi$ P	$1428. + 10. - 5.$	$174 + 20. - 10.$
$a_2(1320)$	$2^{++}1^+$ $\rho\pi$ D	$1317. + 6. - 3.$	$133. + 0. - 10.$
$a_2(1700)$	$2^{++}1^+$ $\rho\pi$ D	$1788. + 15. - 40.$	$700. + 0. - 125.$
$\pi_2(1670)$	$2^{-+}0^+$ $f_2\pi$ S	$1660. + 5. - 7.$	$287. + 5. - 56.$
$\pi_2(1880)$	$2^{-+}0^+$ $f_2\pi$ S	$1890. + 24. - 5.$	$247. + 0. - 40.$
$a_4(2040)$	$4^{++}1^+$ $\rho\pi$ G	$1915. + 27. - 0.$	$286. + 17. - 70.$
$\pi(1300)$	$0^{-+}0^+$ $f_0(980)\pi$, $(\pi\pi)_S\pi$	$1340. + 60. - 140.$	$540. + 250. - 200.$
$\pi(1800)$	$0^{-+}0^+$ $f_0(980)\pi$, $(\pi\pi)_S\pi$	$1790. + 8. - 1.$	$204. + 11. - 12.$

3. Analysis of the $\pi^-\pi^0$ system

The exclusive production of $\pi^+\pi^-$ and $\pi^0\pi^0$ systems was thoroughly studied in a series of high-statistics experiments, while in the $\pi^\pm\pi^0$ case the statistics in previous experiments were rather poor [6].

The interest in the $\pi^-\pi^0$ system is a study of the $\rho(770)$ production density matrix as a function of $|t|$, which could give a detailed information on the production mechanisms. On the contrary to the $\pi^+\pi^-$ system where $\rho(770)$ overlaps with large S-wave , the latter should vanish in the $\pi^{-(+)}\pi^0$ system, as well as other L-even waves (neglecting possible isospin $I = 2$ contribution).

Current experiment has collected about $6 \cdot 10^6$ events in the mass and momentum transfer ranges under study: $0.3 < M_{2\pi} < 1.5$ GeV, $|t| < 1$ GeV^2/c^2. Restricting with the spin $J_{max} = 1$, there are four L_ε waves in the PWA: S_0, P_0, P_- in one interfering block and P_+ separately. The 2-fold well-known discrete ambiguity of the PWA results is clearly seen in Fig. 3. To resolve it we

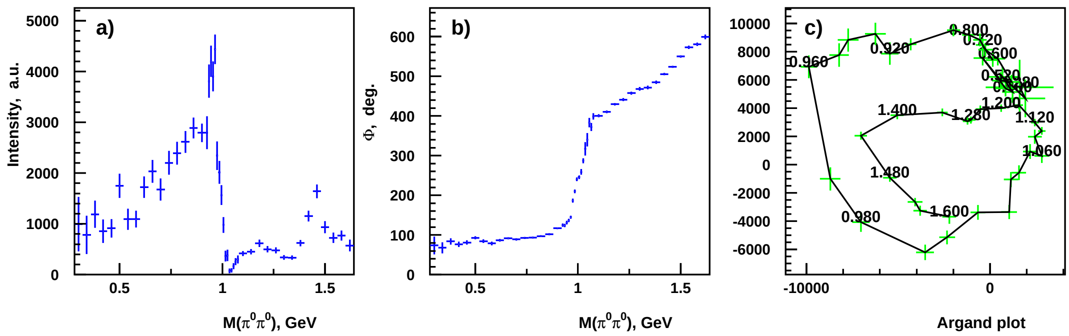

Figure 2: The overall production-and-decay $(\pi\pi)_S$ amplitude in free parameterization for the $0^{-+}(\pi\pi)_S\pi$ wave as a function of $M_{2\pi}$ in the mass range $1780 < M_{3\pi} < 1860$ MeV/c^2. From left to right: amplitude squared; phase; the amplitude in complex plane. $M_{2\pi}$ is shown as numbers near the markers.

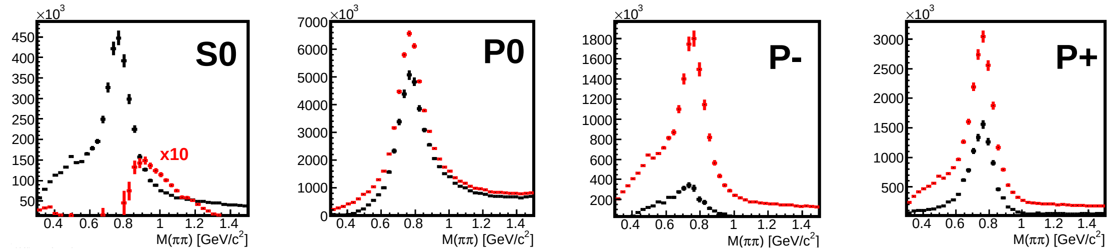

Figure 3: Intensities of waves in the PWA of $\pi^-\pi^0$. Solution with the lowest (highest) intensity of S_0 is colored red (black) in all waves.

take the solution with the lower $|S_0|$ in each bin as a physical one.

The problem in this analysis is a large background from the abundant diffractive production of the $\pi^-\pi^0\pi^0$, which events "leak" into the $\pi^-\pi^0$ system due to losses of γ-quanta and finite mass and energy resolution. The analysis presented in section 2 was used to evaluate this background. The 3π events were generated according to the PWA results, traced through the model of the setup, reconstructed with a regular programme and subjected to the $\pi^-\pi^0$ selection criteria. Leakage probability about 6% from 3π to 2π was obtained, which corresponds to Signal-to-Background ratio $S/B \approx 0.5 \pm 0.1$ in the $\pi^-\pi^0$ data sample.

Finally, the simulated background was subjected to the 2-particles PWA with the aim to subtract its contribution from the real data. Better measurement of the background is required to proceed further in this direction.

4. Conclusion

The largest statistics ever collected for exclusive production of the $\pi^-2\pi^0$ and $\pi^-\pi^0$ systems permit us to perform a very detailed PWA of these systems.

The parameters of the set of resonances included in the model of the three-pion mass-dependent PWA are determined. Some of these resonances are not considered as established; results are considered as preliminary. S-wave $\pi^0\pi^0$ amplitude as a function of $M_{3\pi}$ was extracted in a model independent way.

The feasibility of the PWA of the $\pi^-\pi^0$ is demonstrated. For the conclusive result for this reaction better control over the background is needed.

References

[1] Yu. Khokhlov et al., EPJ Web of Conferences 37, 01029 (2012)

[2] A.R. Dzierba et al., Phys. Rev. D **73** (2006) 072001

[3] S. Paul for the COMPASS Coll., http://arxiv.org/pdf/1312.3678v1.pdf

[4] I. Kachaev. PWA tools and methods developed by VES group. Talk at ATHOS-2013, http://www.athos2013.de

[5] K.L. Au, D. Morgan, M.R. Pennington, Phys. Rev. D **35** (1987) 1633

[6] L. Byerly et al., Phys. Rev. D **7** (1973) 637; B.Y. Oh et al., Phys. Rev. D **1** (1970) 2494; J. Pisut and M. Roos, Nucl. Phys. B **6** (1968) 325