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Recent results with upgraded VES setup: $\pi^- 3\pi^0$ and other systems

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Abstract. Status of the VES setup upgrade is shortly reviewed. A number of one-prong multi-photon final states not (or badly) accessible with the VES before, such as the $\pi^- 3\pi^0$, $\pi^-\eta\pi^0$ in background favorable mode $\pi^- 4\gamma$ and others, becomes promising for the study. An overview of new data set is presented. The preliminary results of PWA of the $\pi^- 2\pi^0$ system show a clear signal of the $f_0(980)$ in the $\pi(1800)$ decay.

1 Introduction

Experiment VES [1] is aiming at light meson spectroscopy since long time. The major approach is a study with a general purpose spectrometer of (quasy)exclusive forward production of meson systems in meson - nuclear collisions at moderate (25-40 GeV/c^2) energies.

During last few years an extensive upgrade of the VES setup was conducted and now is close to end. The modernization concerns the major outdated detectors and some systems including triggering scheme. The status of the renewal is shortly presented in Sec. 2.

The new arrangement of the run with the setup makes it possible to collect data sample of final states not accessible with the VES before. The preliminary survey of new data is given in Sec. 3.

One of the promising systems for the analyses is $\pi^-\pi^0\pi^0$, which is presented in more details in Sec. 4.

2 Upgrade of the VES setup

The major detectors and systems of the VES are: beam tracking system, large aperture magnetic spectrometer with a set of trackers (proportional and drift chambers), Electromagnetic Calorimeter (EMC), Multicell Cherenkov Counter (MCC) for K/π identification of secondary particles, and scintillation counters for triggering. The list of major improvements is as follows:

- New fast and flexible data acquisition (DAQ) system [2] developed. Mean dead time per typical event is $\approx 22\ \mu$s; up to 4×10^4 events can be taken during 2 s "spill" of ten seconds cycle of the accelerator.
- Fully upgraded EMC with high radiation hardness and finer granularity made of fine-segmented lead - scintillator "shashlyk" modules is installed. It is equipped with faster ADCs. The tests with electron beam give the energy resolution (σ) of $\approx 2.7\%$ and coordinate resolution of ≈ 2 mm at 10 GeV/c^2. A resulting typical π^0 (η) signal in physical data has FWHM$\approx$ 18 (60) MeV/c^2,

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- Chambers of Mylar Drift Tubes of 30 mm in diameter are to replace obsolete Drift chambers as Large Area Trackers (LAT, $\approx 2.5 \times 2\ m^2$) (to be finished in October of year 2012). The beam test of full scale prototype has shown its coordinate resolution of $\sigma \approx 220\ \mu$m.
- New front end electronics for tracking detectors is developed and installed. The on-chamber FPGA-based TDC board with 2.5 ns time resolution (LSB) has just 1.5 μs dead time (time for registering) at highest occupancy (up to 32 active channels). It stores processed hits for one cycle in a buffer memory and then sends formatted data to the DAQ computer.
- A performance of MCC is improved: some deformed mirrors are replaced; new PMT amplifiers are installed; stability of refraction index of the radiator is increased.
- Beam momentum spectrometer with $\sim$ 1% resolution at $\sim$ 28 GeV/c is constructed.
- Detector Control System is implemented which greatly improved the stability of the facility operation.
- New or improved software for corresponding new/improved systems developed.

In the end of year 2011 one-month run was conducted with the upgraded setup. About $2 * 10^{11}$ beam particles of mean momentum $\approx$ 28 GeV/c were put on berillium target of 4 cm thick. The new faster FE electronics and DAQ system allowed to work with almost unselective trigger on interaction mainly in beam fragmentation region. No demand for multiplicity of charged particles was set in trigger anymore, so a scintillator multiplicity counter and large scintillating hodoscope used for this purpose before were taken away of the setup.

For commissioning in the run a first plane of DT-chambers out of six planned in course of the LAT upgrade was installed. So, with currently weakened resolution and track finding for multi-prong events and with finalized EM-calorimetry, the run was devoted primarily to the collection of one-prong events inaccessible with the VES before.

3 Overview of new data

Typical selection criteria for various (quasi)exclusive 1-prong systems are listed below:

- A single beam track is measured
- Topology: one fast negatively charged particle and N γ (N=2, 4, ...) are registered
- Vertex is within target
- γ Pairing into neutral mesons (π^0, η) (with control bands for background sample)
- Sum of momenta of all registered (charged and neutral) particles is close to beam momentum

The last issue of the list is for the selection of (quasi)exclusive reactions (neglecting possible soft particles in nucleon vertex). The separation of ”exclusivity” peak in momentum distribution from a background depends on the reaction and on reconstruction characteristics: pattern recognition and resolution of the tracking and calorimetry.

The new DT plane is not included yet in regular reconstruction programme with which the presented results are obtained. However, a preliminary algorithm with DT gives a strong improvement of tracking, leading to much better ”exclusivity” of the selected systems.

The statistics of few systems shown in table 1 is based on one half of recorded data processed so far. The estimate is within about 30% uncertainty.

In the $\pi^-3\pi^0$ sample (see Fig.1) there is a clear signal of $\pi^-\eta(\rightarrow 3\pi^0)$ system which is about eight times less intensive than that in $\pi^-\eta(\rightarrow 2\gamma)$ channel. More losses due to acceptance and absorption in case of 6 γ is the reasoning of the large difference between two modes with comparable branching fractions. Two other channels of $\pi^-\eta$ in addition to the previously studied $\pi^-\eta(\rightarrow \pi^+\pi^-\pi^0)$ [3] can be used for a cross-check and evaluation of systematic uncertainties, in particular in the study of the exotic wave $J^{PC} = 1^{-+}$.

The production of actual $\pi^-3\pi^0$ system proceeds through $G = -1$ reggeon (presumably OPE) exchange which from experimental point of view generally has more background than diffractive reactions. The statistics in the table is shown without distinguishing of the exclusive process from background. The only $\rho(770)$ signal in the $\pi^-\pi^0$ mass spectrum is visible, although not very prominent. In the $\pi^0\pi^0$ channel there is a signal of the K^0 decay. No evident signal of f_0 mesons, as well as other

Table 1. Statistic estimate for various systems with one-prong topology

system/final state	Nmb. of events registered	comments
$\pi^-\pi^0$	$3.5 * 10^6$	
$\pi^-\pi^0\pi^0$	$4 * 10^6$	diffractive, quite pure
$\pi^-3\pi^0$	$0.2 * 10^6$	R - exchange, more bckg.
$\pi^-\eta(\to 2\gamma)$	$0.2 * 10^6$	
$\pi^-\eta(\to 3\pi^0)$	$2.6 * 10^4$	smaller acceptance due to 4 more γ
$\pi^-\pi^0\eta(\to 2\gamma)$	$0.2 * 10^6$	
$\pi^-\eta(\to 2\gamma)\eta(\to 2\gamma)$	10^4	diffractive, rather pure

resonances, is observed. So, an isobar structure of waves in a possible Partial Wave Analyses (PWA) is unclear.

The $\pi^-\pi^0\eta$ system is interesting for the search for isospin symmetry breaking decay $\pi^-(1800) \to \pi^- a_0(980) \to \pi^-\pi^0\eta$, one of possible mechanisms of which is the $f_0(980) - a_0(980)$ mixing. The disadvantage of the previously tested [4] 3-prong sample with charged $\eta \to \pi^+\pi^-\pi^0$ decay channel against one-prong topology ($\eta \to \gamma\gamma$) is the 4-fold combinatorics in the η reconstruction.

The major background to the $\pi^-\pi^0\eta_{\gamma\gamma}$ comes from combinatorial $\gamma\gamma$ pairing from copious diffractive production of the $\pi^-\pi^0\pi^0$. After the rejection of events having at least one combination of 4 γ compatible with $2\pi^0$ the sought signal of the $\pi^0\eta$ becomes clearly visible, with rather high statistics.

In the $\pi^-\eta$ and $\pi^0\eta$ mass spectra there are signals of the $a_0(980)$ and $a_2(1320)$ mesons. The prospects for deeper study including PWA depends on a progress in reconstruction and selection procedures which is required to improve mass resolution and purity of the sample.

The diffractively produced $\pi^-\eta(2\gamma)\eta(2\gamma)$ system is separated with rather good "exclusivity". The statistics of $\sim 10^4$ events exceeds that of earlier VES [5] and E852 [6] publications.

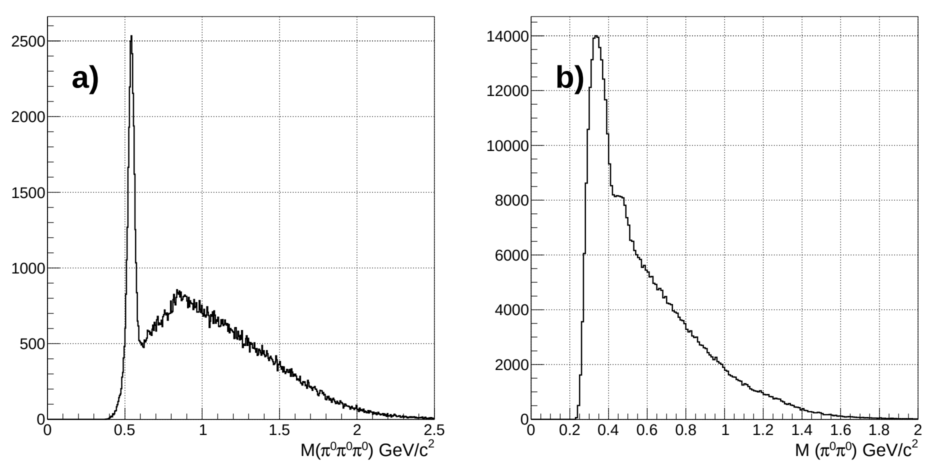

Fig. 1. The spectra of $m(3\pi^0)$ (a) and $m(2\pi^0)$ outside $\eta \to 3\pi^0$ region (b) in the $\pi^-3\pi^0$ system.

4 Analyses of the $\pi^-\pi^0\pi^0$ system

The selection of the reaction $\pi^- Be \to \pi^-\pi^0\pi^0 Be$ in the new VES data is demonstrated by kinematical distributions which are shown in Fig.2. The total momentum $P(3\pi)$ distribution demonstrates reasonable exclusivity for the reaction. The rapidly falling spectrum of momentum transferred squared

$t' = |t| - |t|_{min}$ in the lower vertex is typical for reggeon exchange production mechanism and specifically clearly shows both incoherent and coherent diffraction. The spectrum of the 3 pion system invariant mass has the well known $a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ structures.

For further analysis the data were divided in three samples according to ranges of t'.

The lowest range $0 < t' < 0.03$ GeV$^2/c^2$ corresponds to the coherent diffraction on Be nucleus and contains $\approx 1.9 \cdot 10^6$ events. Analysis of comparable statistics for the region of coherent diffraction was never published for $\pi^-\pi^0\pi^0$ final state. Its counterpart $\pi^-\pi^-\pi^+$ system was analysed by VES with the highest statistics ($\approx 10^7$ events) of mostly coherent production much earlier [7].

The middle region of $0.03 < t' < 0.1$ GeV$^2/c^2$ with $\approx 0.8 \cdot 10^6$ events is transitional from coherent to incoherent diffraction.

Finally, the highest range $0.1 < t' < 1$ GeV$^2/c^2$ with $\approx 0.9 \cdot 10^6$ events corresponds to incoherent production where the data is known to have similar features to the interaction on the nucleon target. Here the statistics of processed VES data can be compared with COMPASS sample [8] of $\approx 10^6$ events on the proton target and with $\approx 4 \cdot 10^6$ events in the analysis [9].

The mass independent PWA of the data in rather narrow intervals of 3-body invariant mass and in three t' regions was performed. The PWA program of Illinoise Universty was elaborated further by Protvino and Munich groups in order to improve the fitting efficiency and to implement a number of new features for differential cross-section model.

The kinematics of the reaction is treated in the Gottfried-Jackson system. The density matrix was restricted to the rank 2. The basis with the "reflectivity" $\epsilon = \pm 1$ with respect to the production plane is used, which corresponds to an exchange "naturality" η at high energy limit.

The angular part of the amplitudes is built within helicity formalism and using LS-coupling to the total spin J. The isobars with the isospin I equal to 1 and 0 are introduced for the construction of decay amplitudes respectively in the $\pi^-\pi^0$ and $\pi^0\pi^0$ channels. So the partial wave is characterized with a set of quantum numbers $J^{PC}M^{\eta}L(isobar)$, where $M \geq 0$ is a spin projection number.

The fit of parameters of the PWA uses the event-by-event extended maximum-log-likelihood method. Intensities of waves which are the corresponding diagonal elements of the spin-density matrix are obtained as function of $m(3\pi)$ in separate t' ranges.

The presented preliminary PWA in three t' intervals comprises a rather wide set of 36 natural parity ($\eta = +1$) and of 7 unnatural ($\eta = -1$) parity waves, and the "FLAT" pseudo wave. The $\rho(770)$ and $\rho_3(1690)$ for $I = 1$; the $f_0(980)$, $f_0(1400)$ (elastic $\pi\pi_S$ with the $f_0(980)$ subtracted), $f_0(1500)$ and $f_2(1270)$ for I=0 isobars were introduced.

The simplified model of the setup accounts for the most influencing geometrical apertures of the EMC and of a "beam killer" counter which is placed on the nominal beam trajectory downstream of the magnet and enters the trigger in the anti-coincidence.

The most stable partial waves are shown in Fig.3 for three regions of t'.

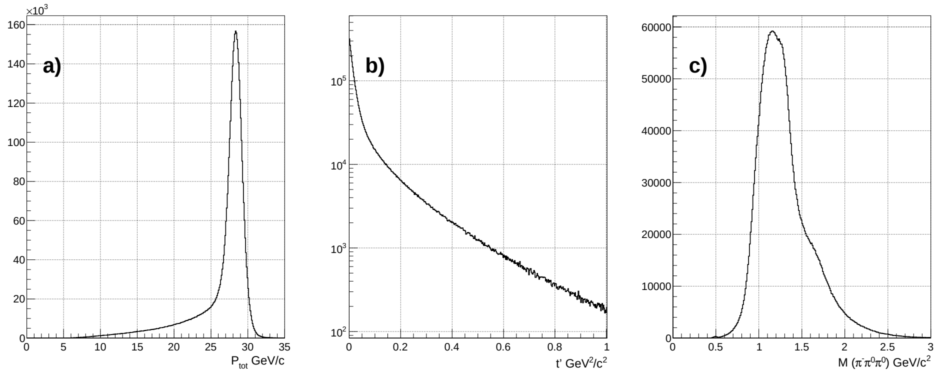

Fig. 2. Kinematical distributions in $\pi^-\pi^0\pi^0$ system.

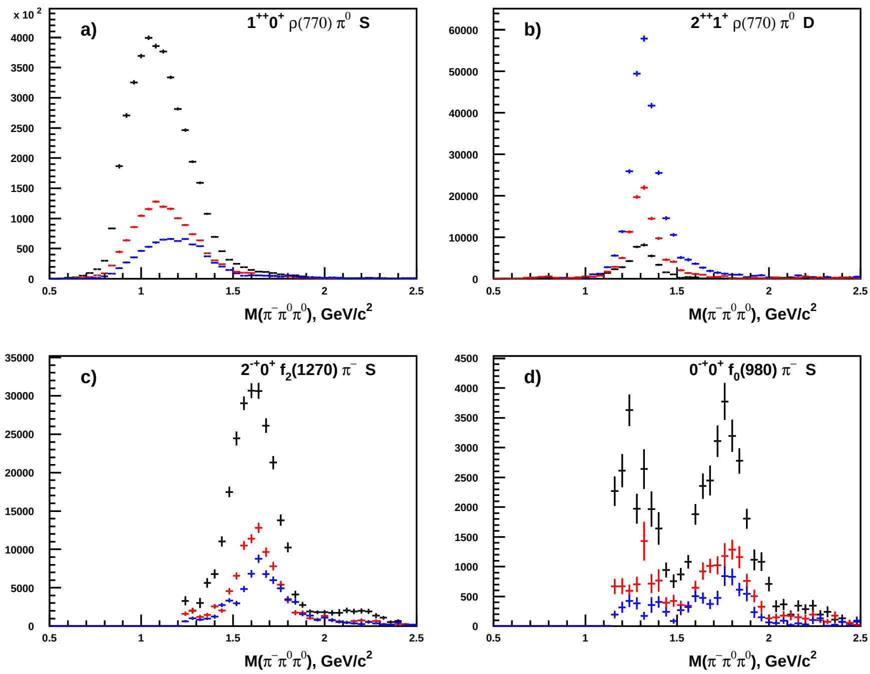

Fig. 3. Major partial waves in the $\pi^-\pi^0\pi^0$ system for low (in black), medium (in red) and high (blue) t' regions.

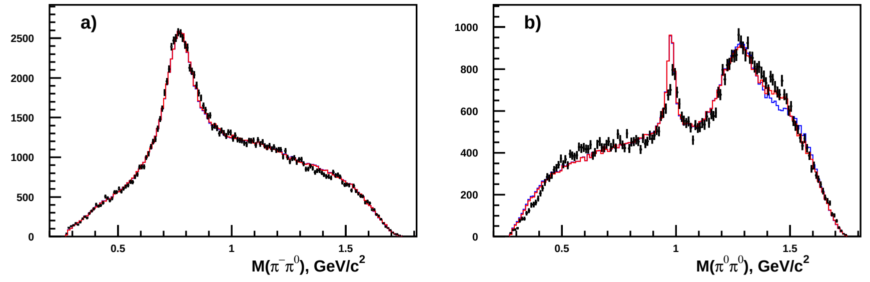

Fig. 4. The $m(\pi^-\pi^0)$ and $m(\pi^0\pi^0)$ spectra for low t' and $\pi(1800)$ region: black for real data, blue and red for PWA solution without and with the $f_0(1500)$.

For low t' amplitudes with quantum numbers $J^{PC} = 0^{-+}, 1^{++}, 2^{-+}, ...$ and spin projection $M = 0$ dominate. They demonstrate high degree of coherence between them which is very promising for future study of their resonant nature. The interesting feature of the data is that, in contrast to $\pi^-\pi^-\pi^+$ case, dominating $\rho^-(770)$ is "decoupled" from signals in $\pi^0\pi^0$ system coming from various f_0 mesons, which is especially expressed in the region of $\pi(1800)$ resonance.

The corresponding two-particles mass spectra $\pi^-\pi^0$ and $\pi^0\pi^0$ for $1.74 < M(3\pi) < 1.90$ GeV/c^2 are shown in Fig. 4. The first picture demonstrates clean $\rho(770)$ signal while the second shows very prominent narrow peak of the $f_0(980)$ and also the $f_2(1270)$ signals. The enhancement of the $f_0(980)$ at low t' and in the $\pi(1800)$ region is attributed to the $0^{-+} f_0(980)\pi^-$ wave intensity (fig. 3d).

Having the clear observation of the $f_0(980)$ in the raw mass spectrum and taking into account the $\pi(1800) \to f_0(1500)\pi$ decay [10], it is intriguing to see an evidence of the $f_0(1500)$ in the system under study. So the PWA was performed without and with $0^{-+} f_0(1500)\pi^-$ amplitude, where the $f_0(1500)$ is introduced as Breit-Wigner resonance with PDG parameters. The $m(\pi^0\pi^0)$ distribution from the data is compared with spectra of the two solutions, shown in Fig. 4b by curves. The inclusion of the $f_0(1500)$ results in a visible improvement of description of a shoulder in the 1.4-1.5 Gev/c^2 region. Nevertheless the figure shows still unsatisfactory description of $m(\pi^0\pi^0)$ by PWA model, especially in the low mass region. It is probably connected with our inflexible parameterization of broad $(\pi\pi)_S$ component.

Transition from low to high t' (see Fig.3) gives the significant relative reduction of $M = 0$ states but, in contrast, increase of $J^{PC}M^{\eta} = 2^{++}1^{+}$, which happens due to factor t'^{M} in the cross-section. In general this makes high t' data rich of partial waves with $J^{PC} = 1^{-+}, 2^{++}, 3^{-+}, 4^{++}$, including possible highly disputed spin-exotic 1^{-+} states, which are still subject of further study.

5 Conclusion

The upgrade of the VES setup is close to its completion. The first new data are already available. The ongoing processing is focused on the exclusive one-prong systems production. Due to modest beam energy and the relative ”transparency” for the gamma quanta the facility is competitive for non-pomeron exchange and/or multi-γ modes.

The $\pi^-2\pi^0$ is the very prospective candidate for the first PWA in the coherent production region. It opens an access to $J^{PC} = 0^{-+} \to (\pi^0\pi^0)_S\pi^-$ decays, in particular there is a clear signal of the $f_0(980)$ in the $\pi(1800)$ region. The incoherent region is interesting for the study of the $J^{PC} = 1^{-+}$ exotic wave.

Big samples of poorly known $\pi^-3\pi^0$ and $\pi^-\pi^0\eta$ systems are also ready for analyses.

Strong improvement of tracking, more data and more systems are expected soon.

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