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High spin resonances produced in $\pi^+\pi^-\pi^-$ and $\pi^-\pi^0\pi^0$ systems at VES setup

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Abstract. A study of high spin resonances produced in $\pi^+\pi^-\pi^-$ and $\pi^-\pi^0\pi^0$ systems with 29 GeV/c π^- beam on Be target is presented. About 87 million events for the first one and 32 million events for the second one are collected with VES setup in a wide range of transfer momentum squared $0 < |t'| < 1$ GeV^2/c^2. For both reactions this is the largest statistics in the world. The data are analysed using the PWA formalism of full rank density matrix and rank 1 density matrix. The $a_3(1875)$ and $a_4(2040)$ meson parameters are given and their production mechanism is discussed.

1 Preface

Large statistics for the reactions $\pi^-A \to \pi^+\pi^-\pi^- A$ and $\pi^-A \to \pi^-\pi^0\pi^0 A$ are collected with VES setup. Here we use data collected in the fall of 2012 and the spring of 2013. Brief description of the upgraded VES setup can be found in [1].

In this article we present results for high spin resonanses $a_3(1875)$ and $a_4(2040)$ in $\pi^+\pi^-\pi^-$ and $\pi^-\pi^0\pi^0$ final states, obtained with two independent analyses, PWA with full rank density matrix and PWA with rank 1 density matrix. For full rank density matrix we will extract its largest eigenvalue (LEV), which can be considered as third analysis method. All three methods confirm the existence of these resonances in these final states. General properties of the data are shown in Figs. 1 a),b). Here results for $\pi^+\pi^-\pi^-$ final state are drawn in black while results for $\pi^-\pi^0\pi^0$ are drawn in red (grey in b/w figures). The analysis was performed in six momentum transfer squared regions $|t'|$ = 0–0.015–0.033–0.06–0.09–0.20–1.00 GeV^2/c^2 and in 20 MeV/c bins over $M(3\pi)$. Due to limited space the sums over all $|t'|$ regions are drawn below.

2 Method of the analysis

PWA with full rank density matrix is based on Illinois PWA [2]. Isobar model is used, namely sequential decay of 3π system via $\pi\pi$ subsystems. Partial wave has quantum numbers $J^P LM^\eta R$ where J^P is spin and parity for 3π system, M^η is projection of spin and exchange naturality, R is the known resonance in $\pi\pi$ system, L is orbital momentum in Rπ decay. Isospin and G-parity $I^G = 1^-$ are the same for both 3π final states. Amplitudes are constructed using d-functions. Relativistic corrections according to [3, 4] are not used. Two particle states f_0, ρ, f_2, ρ_3 in $\pi\pi$ subsystems are described by relativistic Breit-Wigner functions with parameters from PDG [6]. To describe broad part of $\pi\pi$ S-wave we use modified M solution from [5].

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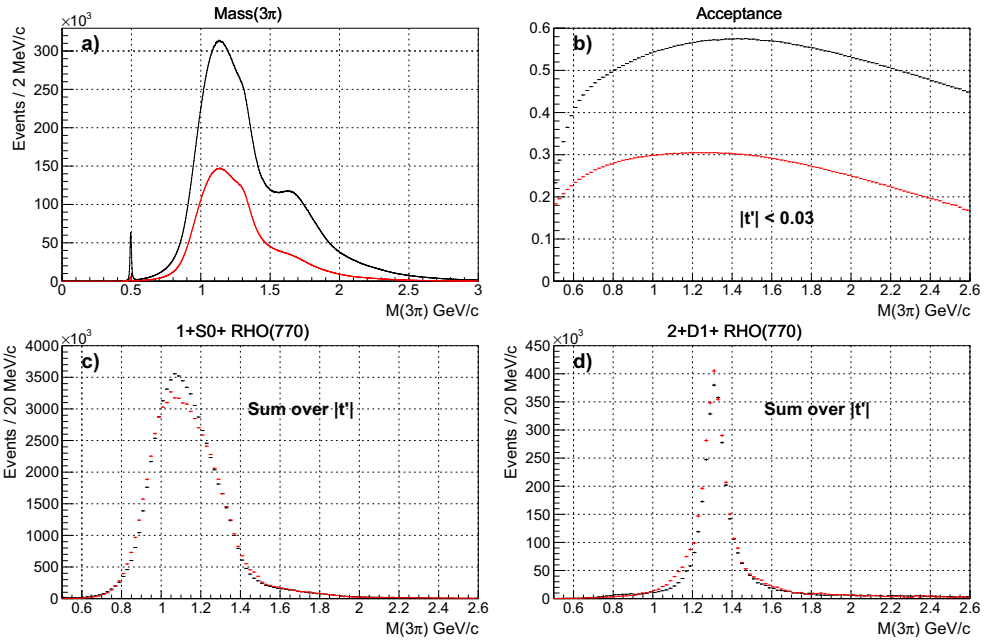

Figure 1. Graph of a) $M(3\pi)$, b) acceptance, c) intensity of wave $1^+S\,0^+\rho(770)\pi$, d) intensity of wave $2^+D1^+\rho(770)\pi$. Color code: black for $\pi^+2\pi^-$, red (gray in b/w) for $\pi^-2\pi^0$ final states.

We name this pseudo state ε, it should describe among other things $f_0(1370)$ and $f_0(500)$. Narrow $f_0(975)$ and $f_0(1500)$ are included separately. Positive definite density matrix of unlimited rank and event by event extended log likelihood fit are used to describe data.

Alternative PWA with rank one density matrix uses exactly the same isobar model. Another matrix element generator is used, based on Zemach tensors. Amplitudes are also not relativistic, namely the boost from (123) rest frame to (12) rest frame is discarded. Exactly the same two particle amplitudes are used, including description of $\pi\pi$ S-wave. Data are described by a set of complex coupling coefficients, which is equivalent to rank one density matrix.

For any positive definite matrix, there exists its coherent part, which is the largest part of the matrix, which has rank one and behaves like vector of amplitudes. It corresponds to the largest eigenvalue and corresponding eigenvector of density matrix. This is not a separate fit but a kind of postprocessing for PWA with full rank density matrix. We have found that this metod, named LEV below, is somewhere in between full rank and rank one methods and can give a deep insight into the structure of density matrix.

The same GEANT4 based model is used to describe the acceptance of the VES setup for both PWA methods and both final states.

3 Fit results

All intensities produced by PWA program are account for acceptance. We have found that after this correction the most of large waves are in accordance with isospin relations for both 3π systems. This can be seen for $1^+S\,0^+\rho(770)\pi$, $2^+D1^+\rho(770)\pi$, full rank PWA and sum over $|t'|$ in Figs. 1 c), d).

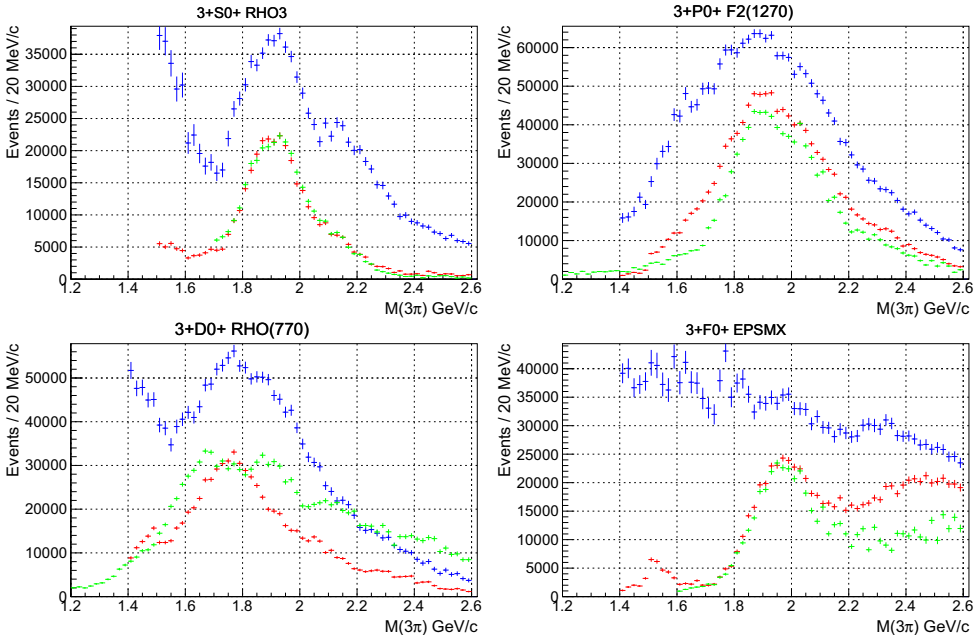

Figure 2. For the system $\pi^+2\pi^-$ intensities of waves a) $3^+S0^+\rho_3(1690)\pi$ b) $3^+P0^+f_2(1270)\pi$ c) $3^+D0^+\rho(770)\pi$ d) $3^+F0^+\varepsilon\pi$

Four waves with $J^P = 3^+$ for $\pi^+2\pi^-$ system are shown in Fig. 2. For this picture and the following Figs. 3,4 blue points correspond to full rank method, green points to rank one method and red points to largest eigenvalue of full rank density matrix. One can see that in Fig. 2 a) the wave $3^+S0^+\rho_3(1690)\pi$ displays clean resonant behavior at $M(3\pi) \sim 1.9$ GeV/c^2 in the results of all three analysis methods. Waves $3^+P0^+f_2(1270)\pi$ and $3^+D0^+\rho(770)\pi$ in Figs. 2 b), c) display broad bumps without clean interpretation at various $M(3\pi)$ for different analysis methods. Wave $3^+F0^+\varepsilon\pi$ in Fig. 2 d) displays resonant behavior at $M(3\pi) \sim 1.9$ GeV/c^2 for two "coherent" methods only, namely for rank one and largest eigenvalue. We interpret this as a decay of $a_3(1875)$, which is omitted in summary tables of PDG.

The same waves with $J^P = 3^+$ for $\pi^-2\pi^0$ system are shown in Fig. 3. The same conclusions as for $\pi^+2\pi^-$ system can be stated for $\rho_3(1690)\pi$, $f_2(1270)\pi$ and $\rho(770)\pi$ decay channels in Figs. 3 a),b),c). For the wave $3^+F0^+\varepsilon\pi$ in Fig. 3 d) minor resonant activity in rank one fit or no activity at all can be seen. It is known from isospin consideration that all waves for $\pi^-2\pi^0$ final state state coupled to $\pi^0\pi^0$ have factor 1/2 in cross section. So channel $3^+F0^+\varepsilon\pi$ in $\pi^-2\pi^0$ system is suppressed by 2× smaller cross section and 2× smaller acceptance (see Fig. 1 b)) with respect to $\pi^+2\pi^-$ system.

Two waves with $J^P = 4^+$, namely $4^+G1^+\rho(770)\pi$ and $4^+F1^+f_2(1270)\pi$, for both $\pi^+2\pi^-$ and $\pi^-2\pi^0$ systems, are shown in Figs. 4 a),b) and Figs. 4 c),d). For all these waves one can see clean resonant behavior at $M(3\pi) \sim 2$ GeV/c^2 in all three analysis methods. We interpret this as a decay of $a_4(2040)$. Its decay into $\pi^-2\pi^0$ system is not listed in PDG. Figure 5 shows $|t'|$ dependence for these two waves, system $\pi^+2\pi^-$. Both $|t'|$ distributions has proper shape, namely tends to zero at $|t'| \to 0$, which is expected for the waves with $M = 1$. The ratio of these distributions is approximately constant, which is expected for two decay modes of one resonanse.

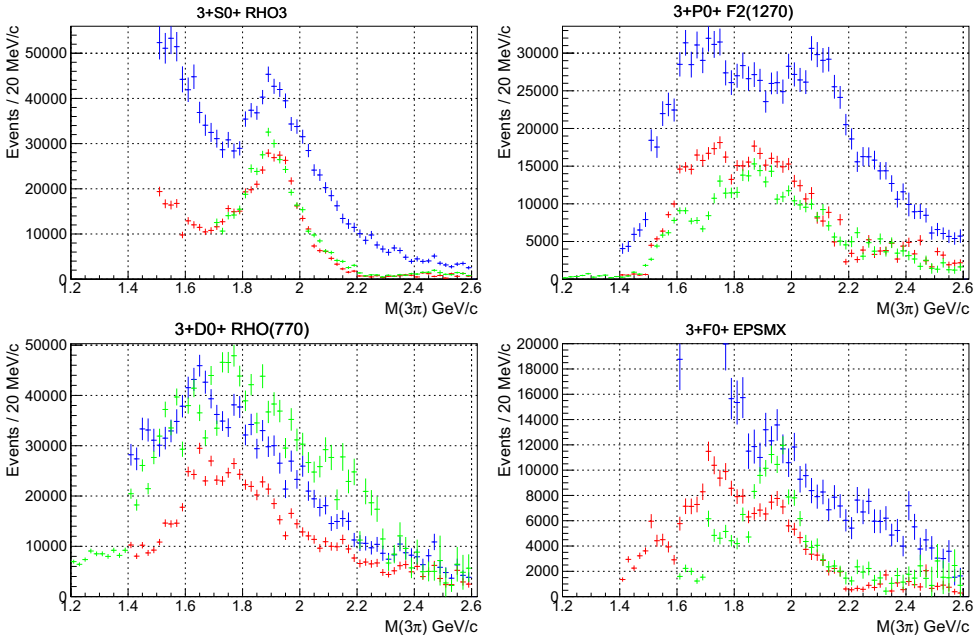

Figure 3. For the system $\pi^-2\pi^0$ intensities of waves a) $3^+S0^+\rho_3(1690)\pi$ b) $3^+P0^+f_2(1270)\pi$ c) $3^+D0^+\rho(770)\pi$ d) $3^+F0^+\varepsilon\pi$

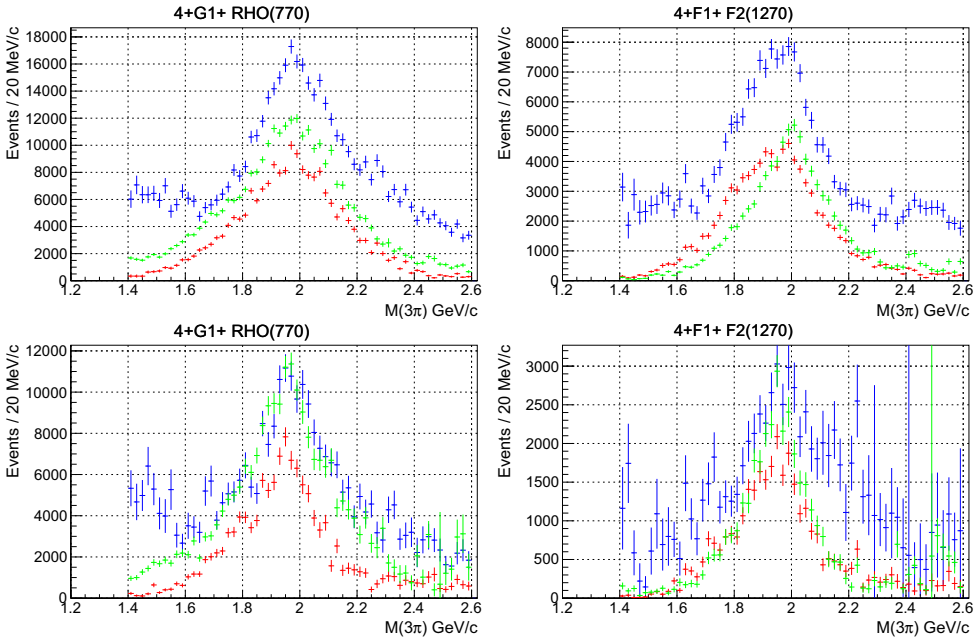

Figure 4. Intensities of waves a) $4^+G1^+\rho(770)\pi$, b) $4^+F1^+f_2(1270)\pi$ for the system $\pi^+2\pi^-$; c), d) the same for the system $\pi^-2\pi^0$

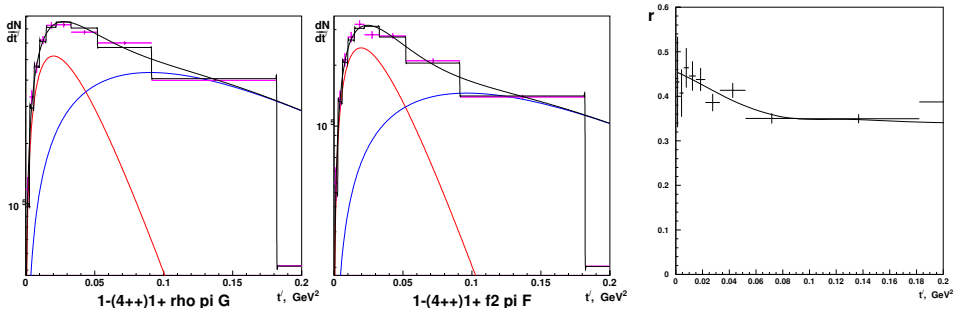

Figure 5. From left to right: distributions over $|t'|$ for the waves $4^+G1^+\rho(770)\pi$ and $4^+F1^+f_2(1270)\pi$, system $\pi^+2\pi^-$; the ratio of these distributions. Step-like black curve represents mean values over bins for fitting function (continuous black curve); magenta crosses are PWA results.

4 Conclusions

Mass-independent PWA is done for $\pi^+\pi^-\pi^-$ and $\pi^-\pi^0\pi^0$ data with both unlimited rank and rank one PWA models. Results for two systems follow isotopic relation for the most waves and are in a good agreement between different PWA methods, especially between LEV and rank one density matrix. Background looks suppressed in these "coherent" methods with respect to PWA with full rank density matrix. Parameters of $a_3(1875)$ (PDG status — not confirmed) are measured. For $3^+S0^+\rho_3\pi$ in both $\pi^+\pi^-\pi^-$ and $\pi^-\pi^0\pi^0$

$$M = 1905 \pm 15\,\mathrm{GeV/c^2} \quad \Gamma = 250 \pm 30\,\mathrm{GeV/c^2}. \tag{1}$$

Broad bumps without clean resonant behavior is found in $f_2\pi$ and $\rho\pi$ channels. For $\varepsilon\pi$ state resonant activity in coherent part of density matrix is seen in $\pi^+2\pi^-$ but not in $\pi^-2\pi^0$ which suffers here on the lack of statistics. Decay of $a_4(2040)$ into both $\pi^+\pi^-\pi^-$ and $\pi^-\pi^0\pi^0$ final states and both $\rho(770)\pi$ and $f_2(1270)\pi$ channels is seen with

$$M = 1980 \pm 10\,\mathrm{GeV/c^2} \quad \Gamma = 300 \pm 40\,\mathrm{GeV/c^2}. \tag{2}$$

$$\frac{Br(a_4^- \to f_2\pi^-)Br(f_2 \to \pi^+\pi^-)}{Br(a_4^- \to \rho^0\pi^-)Br(\rho^0 \to \pi^+\pi^-)} = 0.45 \pm 0.03 \tag{3}$$

$$\frac{Br(a_4^- \to f_2\pi^-)Br(f_2 \to \pi^0\pi^0)}{Br(a_4^- \to \rho^-\pi^0)Br(\rho^- \to \pi^0\pi^-)} = 0.23 \pm 0.03 \tag{4}$$

The second ratio is absent in PDG. Two ratios are in good agreement with isospin symmetry.
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