# A STUDY OF CHARACTERISTICS OF HYBRID MESONS

**VES experiment**[1], presented by V.I. Nikolaenko
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New results obtained by VES experiment during the last year are presented. Apart from the previous statistics at 36 GeV/c, new data for $\pi^-$ and $K^-$ beams at 28 GeV/c are now available. A meson resonance with exotic quantum numbers $I^G J^{PC} = 1^- 1^{-+}$ and mass close to 1.6 $GeV/c^2$ is confirmed at 28 GeV/c in channel $b_1\pi$. New decay channel of resonance $\pi(1800) \to K^0_s K^0_s \pi$ is observed. A system $(K^-\pi^+\pi^-)$ is under investigation, we confirm the existence of pseudoscalor resonance $K_0(1460)$. An $a_3$ resonance is observed in reaction $\pi^- N \to (\pi^-\pi^+\pi^-)N$ at 36 GeV/c.

## Introduction

VES facility is a large angle magnetic spectrometer designed for studies of light meson resonances. It was installed in a beam of unseparated negative particles with momentum between 23 and 46 $GeV/c$ off the IHEP accelerator. Reconstruction of charged tracks was provided by a system of proportional chambers and drift chambers. The spectrometer was equipped by a lead-glass electromagnetic calorimeter and by a gas Cherenkov detector, which is suitable for identification of secondary $K^\pm$ in the momentum range from $\sim 4$ to $\sim 20$ $GeV/c$. A system of three beam Cherenkov detectors provides the identification of initial $\pi^-$ and $K^-$. A minimum bias trigger based on a system of scintilator hodoscopes was used. The trigger selects events with charged multiplicity from 2 to 6.

Published results of this experiment were based mainly on the $\pi^- Be$ interactions at the beam momentum close to 36 $GeV/c$.

New high-statistics data set at 28 $GeV/c$ has been processed during the last year and it is now suitable for Partial Wave Analysis (PWA) [2]. First results of the analyses at 28 $GeV/c$ for exotic wave $J^{PC} = 1^{-+}$, for reactions $\pi^- A \to K^0_s K^0_s \pi^- A$, and $K^- A \to K^-\pi^+\pi^- A$ are presented below.

The last topic discussed in this report concernes new results for the $a_3$ resonance, which is seen in the PWA of $(\pi^-\pi^-\pi^+)$ system at 36 $GeV/c$.

## 1. Exotic wave $J^{PC} = 1^{-+}$

The parity and the C-parity of a bound state of $q\overline{q'}$ pair can be expressed by relations:

$$P = (-1)^{L+1}, \quad C = (-1)^{L+S}, \tag{1}$$

where S is the total spin of two quarks and L is the orbital momentum between quarks. One can see, that combinations like

$$J^{PC} = 0^{--},\ 0^{+-},\ 1^{-+},\ 2^{+-},\ ... \tag{2}$$

are not allowed in this simple scheme. Forbidden states may exist in more complicated models, for example as hybrid mesons or as a consequence of transverse oscillations of the colour string, which connects the $q\overline{q'}$ pair.

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[2] The experimental data were acquired in 1996 run.

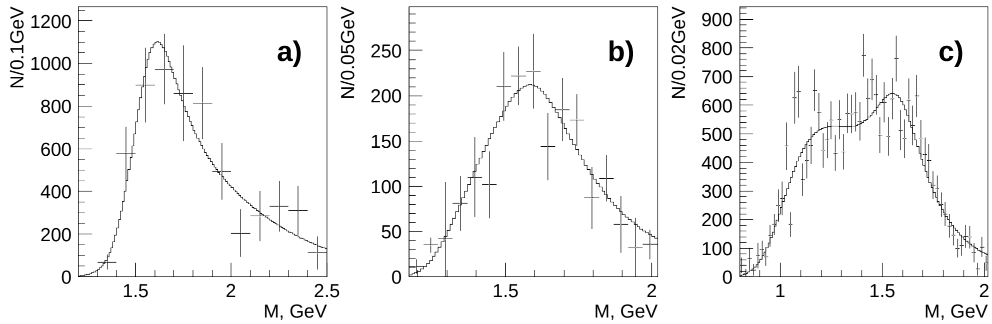


Figure 1: Wave $J^{PC} = 1^{-+}$ observed by VES experiment in $\pi^- N$ interactions at 36 $GeV/c$ in channels: a) $\eta'\pi$; b) $\eta\pi$; c) $\rho^0\pi^-$.

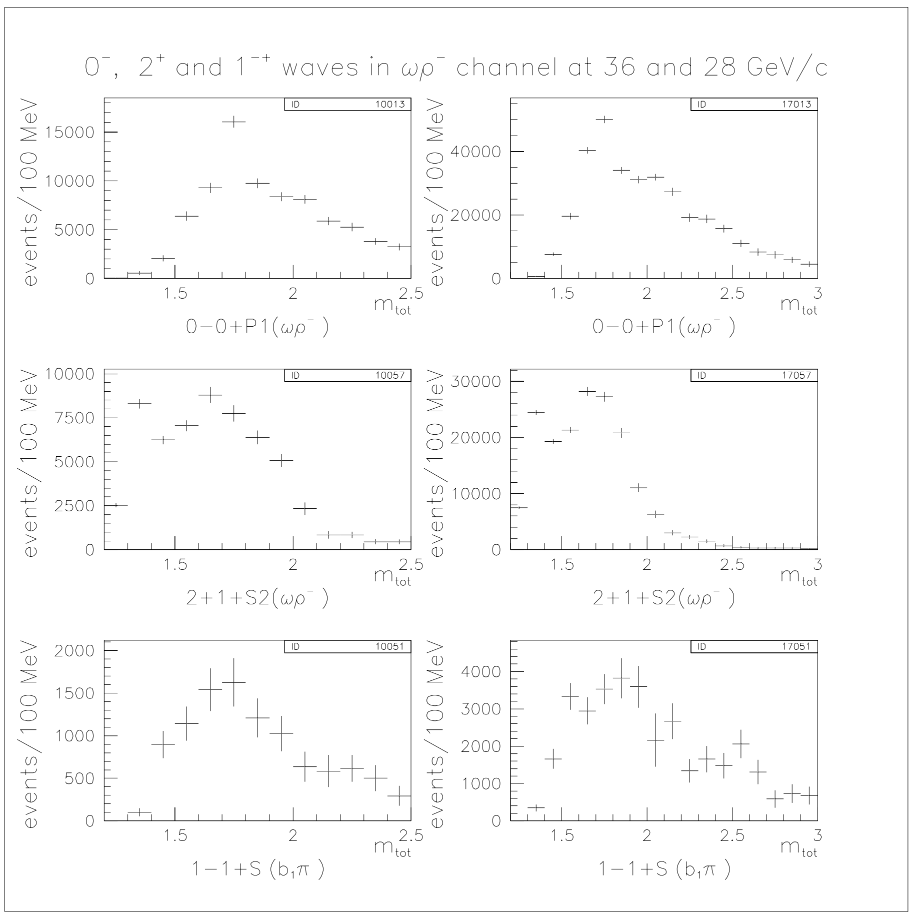


Figure 2: Waves $J^{PC} = 0^{-+}$, $2^{++}$ and $1^{-+}$ in channel $\omega\pi^-\pi^0$ (subchannels $\omega\rho^-$ and $b_1\pi^-$) at 36 $GeV/c$ (left plots) and at 28 $GeV/c$ (right plots). Peculiar shape of the $2^{++}$ wave is caused by $a_2(1320)$ resonance which is seen below and above the $\omega\rho^-$ threshold. Waves identifiers $J^P LM\eta L$ and decay channels are indicated below plots.

The exotic wave $J^{PC} = 1^{-+}$ has been observed by VES experement near $m = 1600\ MeV$ in channels $\eta'\pi$, $\eta\pi$, $\rho\pi^-$ (Fig. 1) and $b_1\pi$ channel. The most clear signal is seen in channel $\eta'\pi$. The branching ratio of channels $\sigma(\eta'\pi)/\sigma(\eta\pi)$ is remarkably high [6]. After taking into account the phase space factors, the ratio of matrix elements squared is of order of 5. However, there are no other well known waves in the $\eta'\pi$ channel which could be used as a reference for the phase motion study of the $1^{-+}$ wave. In this respect the $b_1\pi$ system is better. The wave $1^{-+}$ is well seen here together with large waves $0^{-+}$ and $2^{++}$ (Fig. 2). In general, the resonance interpretation of the $1^{-+}$ wave in the vicinity of 1600 $MeV$ is not established.

The appearence of high statistics data in $\pi^-$ beam at 28 $GeV/c$ makes possible to look for the energy dependence of the $1^{-+}$ wave. As the first step in this direction, the partial wave analysis of the $\omega\pi^-\pi^0$ system at 28 $GeV/c$ is performed. Very preliminary results at 28 $GeV/c$ are shown in Fig. 2. Waves $J^{PC} = 1^{-+}$, $0^{-+}$ and $2^{++}$ are well seen at 36 and 28 $GeV/c$. It is known that the energy dependence of the $2^{++}$ wave is weak in the considered $\sqrt{s}$ interval. Looking for the proportions between observed waves at two energies one can conclude that the energy dependence of the $J^{PC} = 1^{-+}$ wave is also weak.

## 2. Observation of $\pi(1800)$ in mode $(K_s^0 K_s^0 \pi^-)$

Another interesting object is $\pi(1800)$ resonance. Though the quantum numbers are not forbidden in $q\overline{q'}$ model in this case, it is considered as a candidate for non-$q\overline{q'}$ state because of its width ($210 \pm 15$ $MeV$) is too small for being interpretted as second radial exitation of $\pi$ meson [14].

Known decay channels of $\pi(1800)$ are $(\pi^+\pi^-\pi^-)$ including $f_0(980)\pi^-$ and $f_0(1370)\pi^-$, $(\eta\eta\pi^-)$ including $a_0(980)\eta$ and $f_0(1500)\pi^-$, $(\eta\eta'\pi^-)$ and $K_0^*(1430)K^-$.

Improvements in the software of the VES experement and large statistics available in $\pi^-$ beam at 28 $GeV/c$ make now possible the Partial Wave analysis of $(K_s^0 K_s^0 \pi^-)$ system, where one $K_s^0$ is observed in $K_s^0 \to \pi^+\pi^-$ mode and another one in $K_s^0 \to \pi^0\pi^0$ mode.

The following selection criteria have been applied:

- one negative track from the primary vertex and a pair of tracks with different charges from the secondary vertex;
- the distance between primary and secondary vertices is more than 1 cm;
- two tracks from the secondary vertex give the effective mass in the range $0.473 < m(\pi^+\pi^-) < 0.523$ $GeV$;
- the total visible energy lies between 22 and 32 $GeV$;
- there are four electromagnetic showers in the event, originating from the decay $K_s^0 \to \pi^0\pi^0 \to 4\gamma$;
- events with one or two extra showers are accepted if extra showers are consistent with noise in the Gamma Detector (i.e. the energy sum of extra showers is less than 2 $GeV$);
- taking four measured $\gamma$, a kinematical fit to the hypothesis $K_s^0 \to \pi^0\pi^0 \to 4\gamma$ is tried;
- possible permutation ambiguties are resolved on the basis of best $\chi^2$;
- unfitted mass of $K_s^0$ reconstructed in neutral mode lies within limits: $0.463 < m(\pi^0\pi^0) < 0.533$ $GeV$.

Total $\sim 3500$ events have been selected. A standard 3-meson PWA fit is applied with the waves: $J^P Lchannel = (0^-\mathrm{S}\kappa K_0)$, $(0^-\mathrm{S}f_0\pi)$, $(1^+\mathrm{S}K^*(890)K_0)$, $(2^-\mathrm{D}\kappa K_0)$, $(2^-\mathrm{S}f_2(1270)\pi)$, $(2^-\mathrm{S}f_0\pi)$.

Waves $(0^- Sf_0\pi)$ and $(0^- S\kappa K_0)$ demonstrate a peak near 1800 $MeV$ (see Fig. 3). The phase between $(0^- Sf_0\pi)$ and $(0^- S\kappa K_0)$ waves is nearly constant in the vicinity of the peak.

Fit of the sum of two $0^-$ waves to the Breight-Wigner shape yields the mass and width:

$$\mathrm{m} = (1.74 \pm 0.05)\, GeV, \qquad \Gamma = (0.20 \pm 0.10)\, GeV,$$

which are consistent with known parameters of the $\pi(1800)$ resonance.

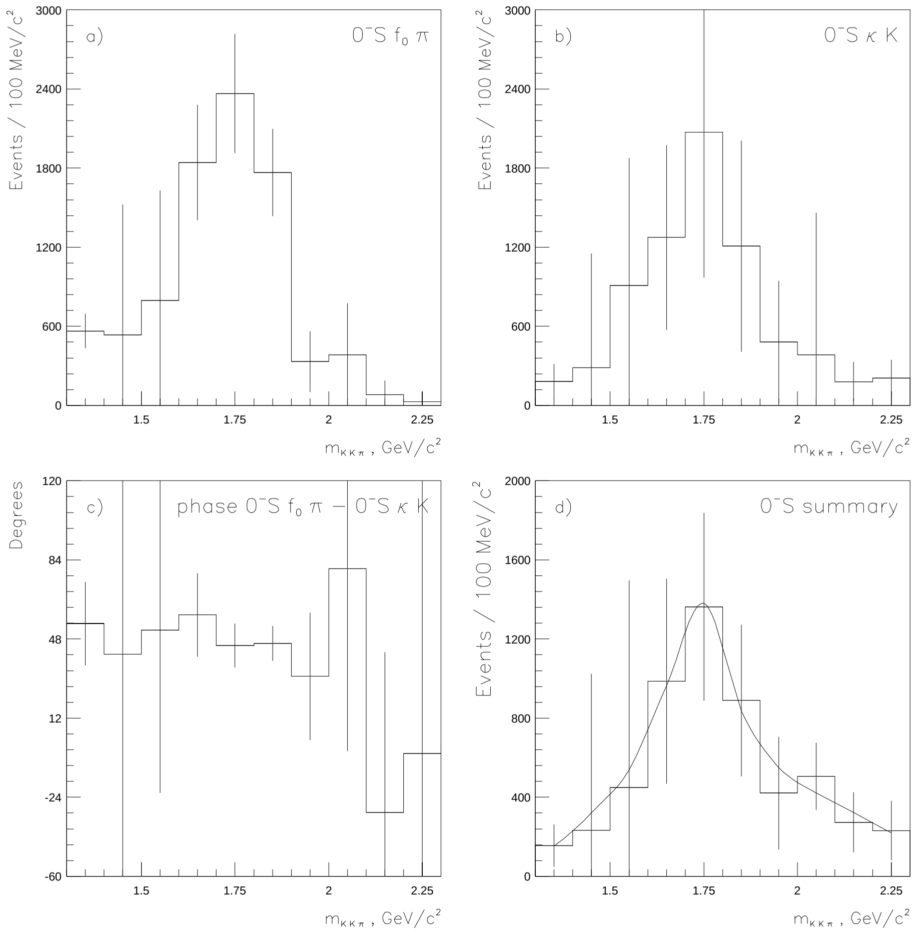


Figure 3: Results of the Partial Wave Analysis of $(K_s^0 K_s^0 \pi^-)$ system for $J^{PC} = 0^{-+}$ wave.

## 3. Reaction $K^- N \rightarrow K^- \pi^+ \pi^- N$

Reaction

$$K^- p \rightarrow (K^- \pi^+ \pi^-) p$$

was studied by ACCMOR collaboration, see [15]. The ACCMOR experiment at 63 $GeV/c$ has statistics $\sim$ 200000 events in the mass range $(1.0 < m(K^- \pi^+ \pi^-) < 2.1\ GeV$.

Being equipped by Cherenkov detectors for identification of initial and secondary charged particles, VES experiment can study properties of $(K^- \pi^+ \pi^-)$ system produced on $Be$ target. This reaction is interesting in many aspects. One of them is a possibility for searching a strange parthner of $\pi(1800)$ resonance.

The following selection criteria are applied in VES experiment:

- kaon beam (no signals in two beam Cherenkov detectors tuned below K-threshold; but a signal seen in the 3-rd one, above K-threshold);
- there are 3 charged secondary tracks (one positive, two negative);
- the energy sum of charged tracks lies in the range (25.,30.) $GeV$;
- there is no $\pi^0$, $\eta$ in the event (accepted events with one ow two low-energy showers in Gamma Detector, which are consistent with noise, i.e. $E_{sum} < 1\ GeV$);

- the momentum transfer cut: $|t'| < 0.7\ GeV^2$;
- at least one secondary negative track is identified by the Cherenkov detector as $K^-$ or $\pi^-$. The identification was found satisfactory in the momentum range from 4.5 to 16.0 $GeV/c$;
- there is no $K^+$ identified by the Cherenkov detector;
- if both negative tracks are identified, then one of them should be identified as a $K^-$ and another one as a $\pi^-$.

Selected sample consists of $\sim 240000$ events with mass $(K^-\pi^+\pi^-)$ in the range $(1.0, 2.1)\ GeV$.

At the next step, the 3-meson PWA program was used (the program which has been developped by G.Ascoli et al, initially for $3\pi$ systems) [16, 17, 18, 19]. It is assumed in this approach that the $(K^-\pi^+\pi^-)$ system decays in two steps, first into an isobar (an intermediate resonance) and an odd pseudoscalar meson, then the isobar decays into two pseudoscalar mesons.

Notations used hereafter: J P M $\eta$ L, where
J stands for the full angular momentum of $(K^-\pi^+\pi^-)$ system,
P is the parity of the $(K^-\pi^+\pi^-)$ system,
L is the orbital momentum between the isobar and the odd meson,
M is the projection of full angular momentum J to the quantization axis,
$\eta$ is the parity of the $(K^-\pi^+\pi^-)$ system with respect to the reflection in the production plane.

Intermediate resonances included into the PWA wave set are:
1)$K^*(890)$; 2)$\rho$; 3)$\epsilon$ (excluded f0(980)); 4)$\kappa$ or $K_0(1430)$; 5)$K^{**}(1430)$ or $K_2(1430)$; 6)$f_2(1270)$; 7)$K^{***}(1780)$ or $K_3(1780)$.

The following wave set is used (here every line corresponds to one line in the density matrix $\rho$):
FLAT (a phase space amplitude, not interfering with other waves)
$J^P LM\eta = 1^+S0+(K^*\pi)$ $\quad 1^+D0+(K^*\pi)$
$1^+S0+(\rho\, K)$ $\quad 1^+P0+(\kappa\, \pi)$
$1^+P0+(\epsilon\, K)$
$0^-P0+(K^*\pi)$ $\quad$ $0^-$P0+$(\rho\, K)$
$0^-S0+(\epsilon\, K)$
$0^-S0+(\kappa\, \pi)$
$2^-P0+(K^*\, \pi)$ $\quad 2^-P0+(\rho\, K)$ $\quad 2^-S0+(K^{**}\pi)$ $\quad 2^-S0+(f_2\, K)$
$1^+S1+(K^*\pi)$ $\quad 1^+S1+(\rho\, K)$
$1^-P1+(K^*\, \pi)$
$2^+D1+(K^*\, \pi)$
$3^+D0+(K^*\pi)$ $\quad 3^+P0+(K^{**}\pi)$ $\quad 3^+S0+(K^{***}\, \pi)$

The PWA fit was performed in 50 MeV bins on m$(K^-\pi^+\pi^-)$, from 1.0 to 3.0 $GeV$. Preliminary results of this analysis are shown in Fig. 4.
The observed cross section between 1.0 and 2.0 $GeV$ is dominated by well known Q- and L-structures (below 1.6 $GeV$ and near 1.8 $GeV$ respectively). The most important wave is $J^P LM\eta = 1^+0+$ (especially in the Q-region), following waves are $0^-0^+$ and $2^-0^+$. The FLAT wave is small below 2.4 $GeV$ (not shown).
The $1^+0+$ wave is observed in 5 decay channels: $(K^*\pi\ S-wave)$, $(\rho\ K)$, $(\kappa\ \pi)$, $(\epsilon\ K)$ and $(K^*\pi\, D-wave)$ (see Fig. 5). The observed cross sections have similar shapes with ACCMOR data. The phases between different channels are also similar, except the phase between $(K^*\pi\ D-wave)$ and $(K^*\pi\ S-wave)$ which varies faster in our experiment than is was observed at 63 $GeV/c$.

A rather complicated structure of Q-region can be described as an interference between two resonances, $K_1(1270)$ and $K_1(1400)$, with different coupling coefficients, and the Deck effect amplitudes in all channels. The Deck effect contribution is not needed only for $K^*\pi$ D-wave. This analysis yields the phases of $(K^*\pi\, S-wave)$ and $(\rho K)$ waves which are used as reference phases for further analysis of $J^P M\eta = 0^-0+$states.

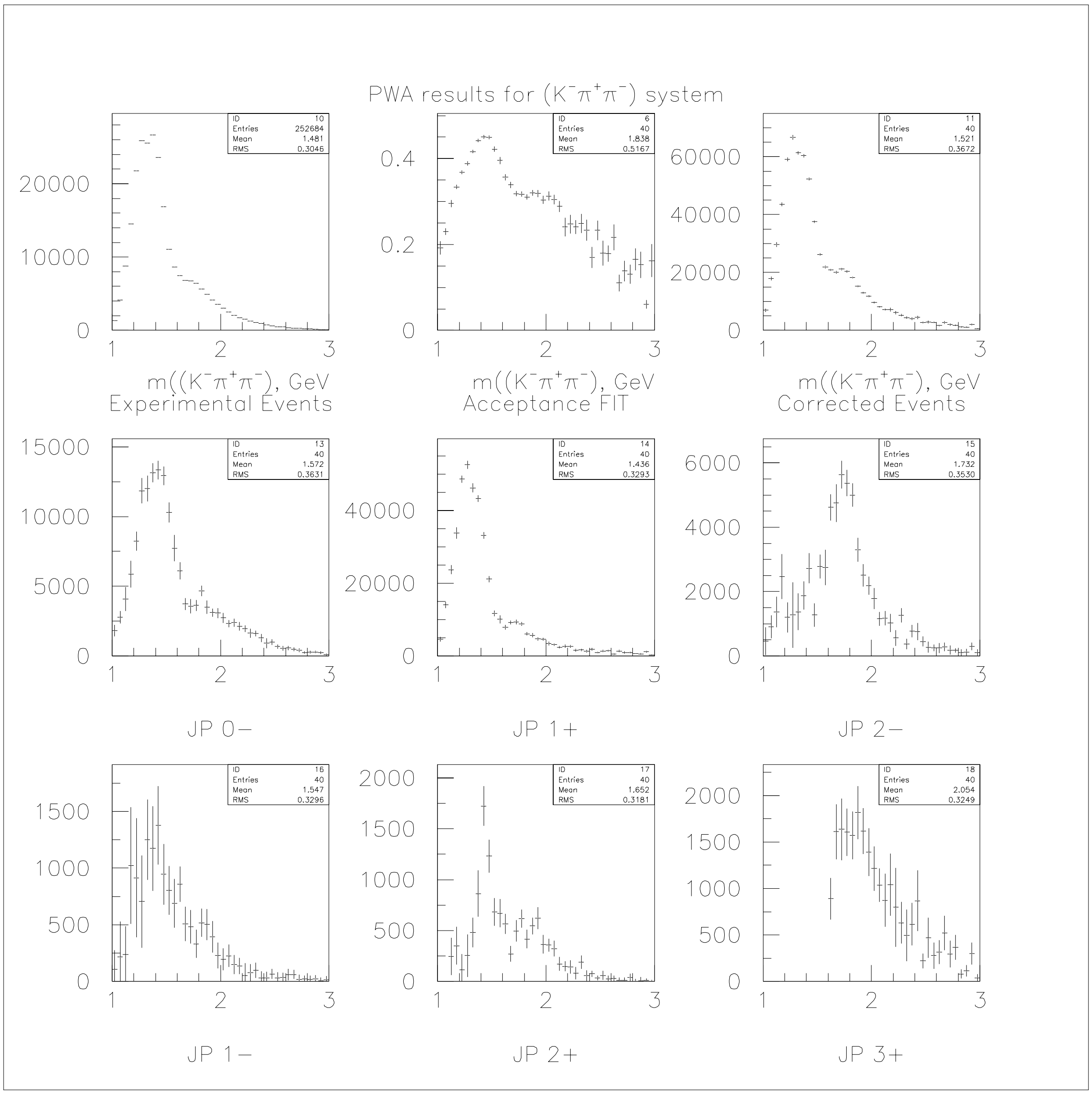


Figure 4: Results of the Partial Wave Analysis of $(K^-\pi^+\pi^-)$-system. Number of experimental events in 50 MeV bins, acceptance, number of corrected events and number of fitted events in different spin-parity waves are shown.

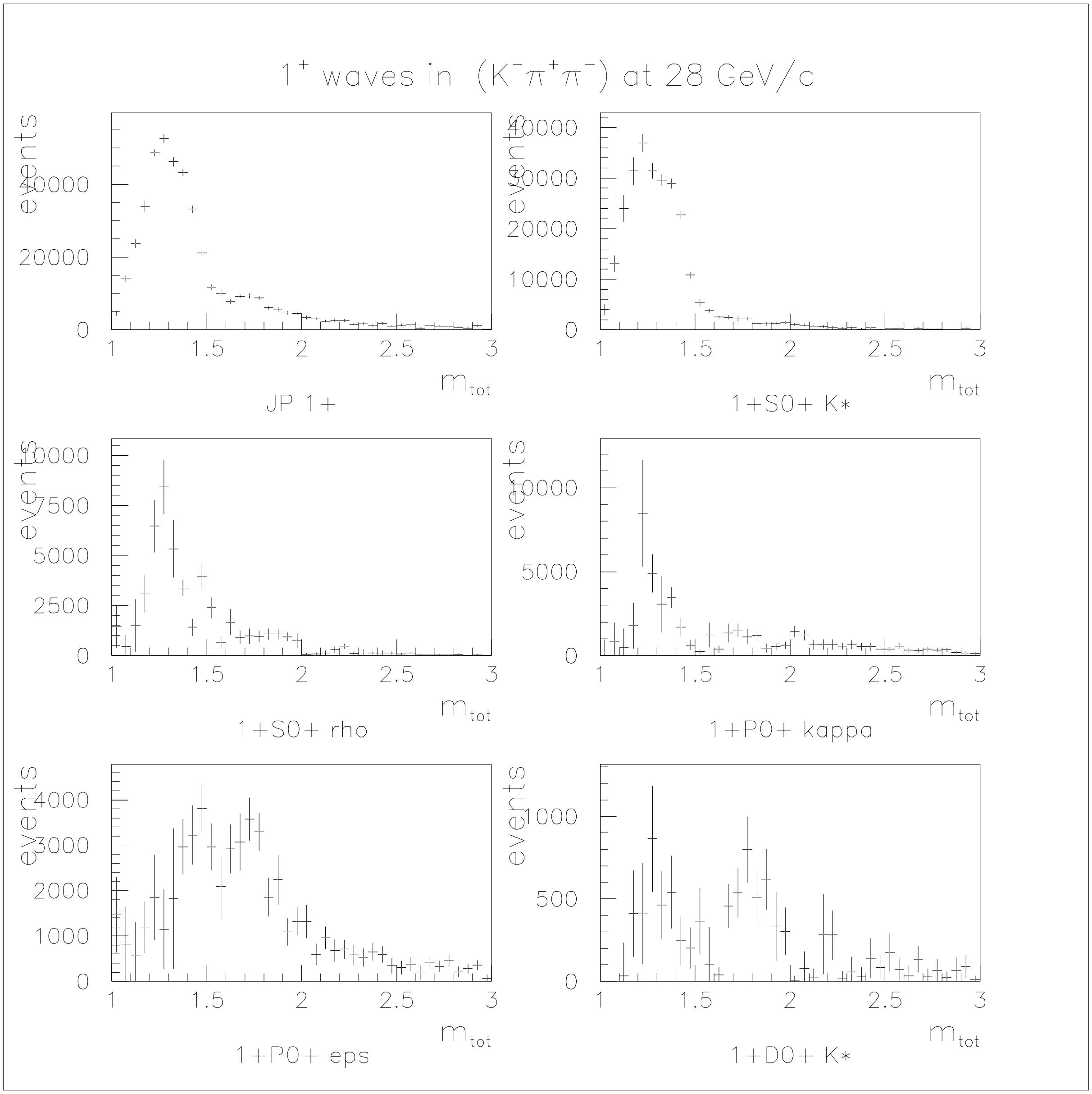


Figure 5: PWA results for $J^P = 1^+$ wave. Number of events in 50 MeV bins for individual channels and for the total sum are shown.

The $0^-0^+$ wave demonstrates a wide peak near 1400 $MeV$ which is known as $K_0(1460)$ resonance (Fig. 6). However this resonance is not considered as well established one in the "Table of particle properties" [20] and needs confirmation. The $0^-0^+$ wave in this experiment is analised in four channels: $(K^*\pi)$, $(\rho K)$, $(\epsilon K)$ and $(\kappa\pi)$. Fig. 6 demonstrates the number of events in every channel as a function of total mass and also the phase measured relative to the dominant waves, $1^+0 + (K^*\pi S - wave)$ or $1^+0 + (K\rho)$. The observed signal cannot be descrbed as a single resonance or as the Deck effect only, and we tried a model with one resonance interfering with Deck amplitudes in all four channels. Results of the fit are shown as smooth lines in Fig. 7. The simultaneous fit of four amplitudes and four phases in the mass region

$$1.0 < m(K^-\pi^+\pi^-) < 1.7\, GeV$$

gives $\chi^2/ND = 157./96$).

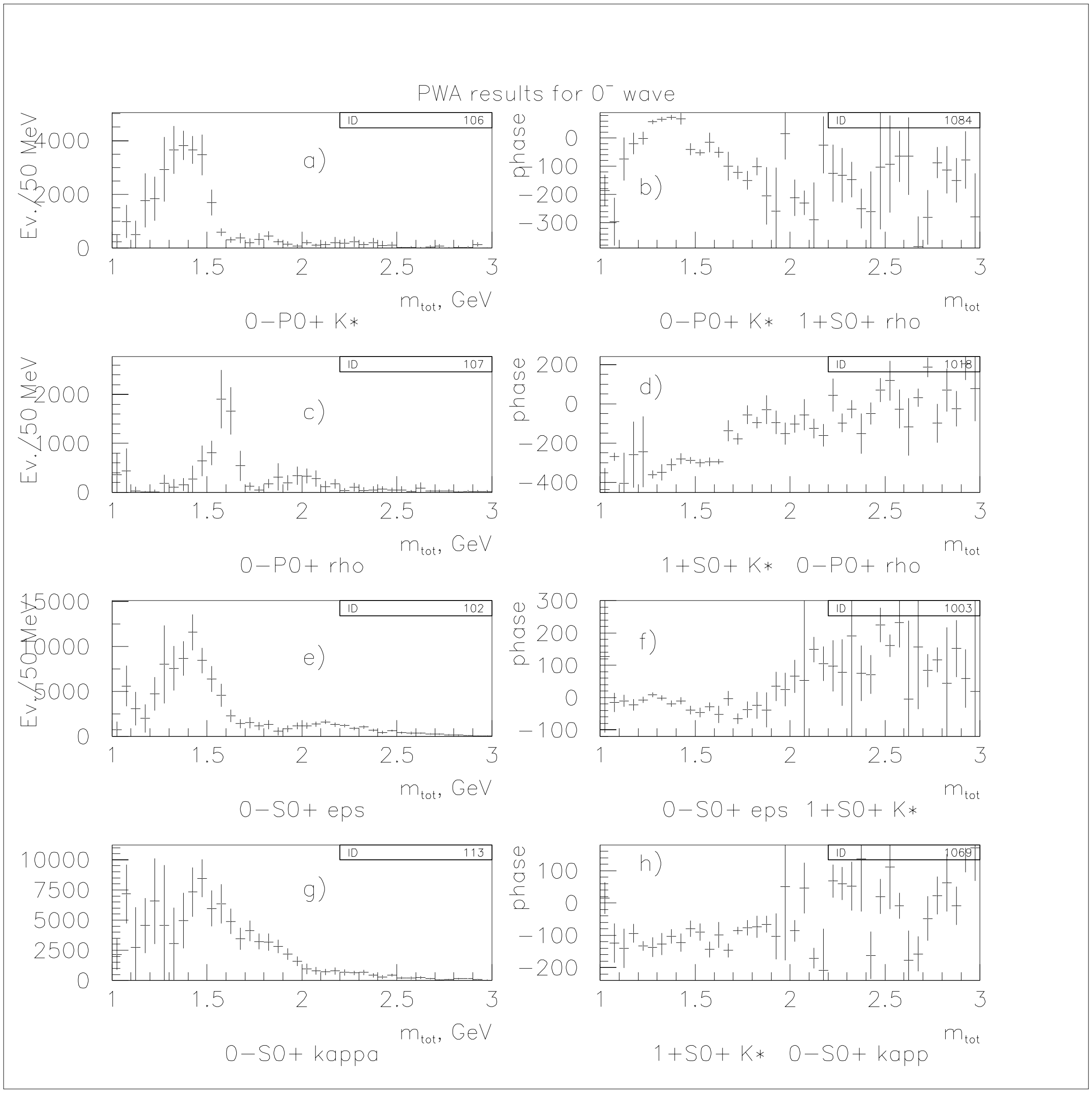


Figure 6: PWA results for $J^P = 0^-$ wave. Number of events and phase with respect to $(1^+ K^*\pi)$ or $(1^+ K\rho)$ wave are given for channels: a-b) $(0^- K^*\pi)$; c-d) $(0^- \rho K)$; e-f) $(0^- \epsilon K)$; g-h) $(0^- \kappa\pi)$;

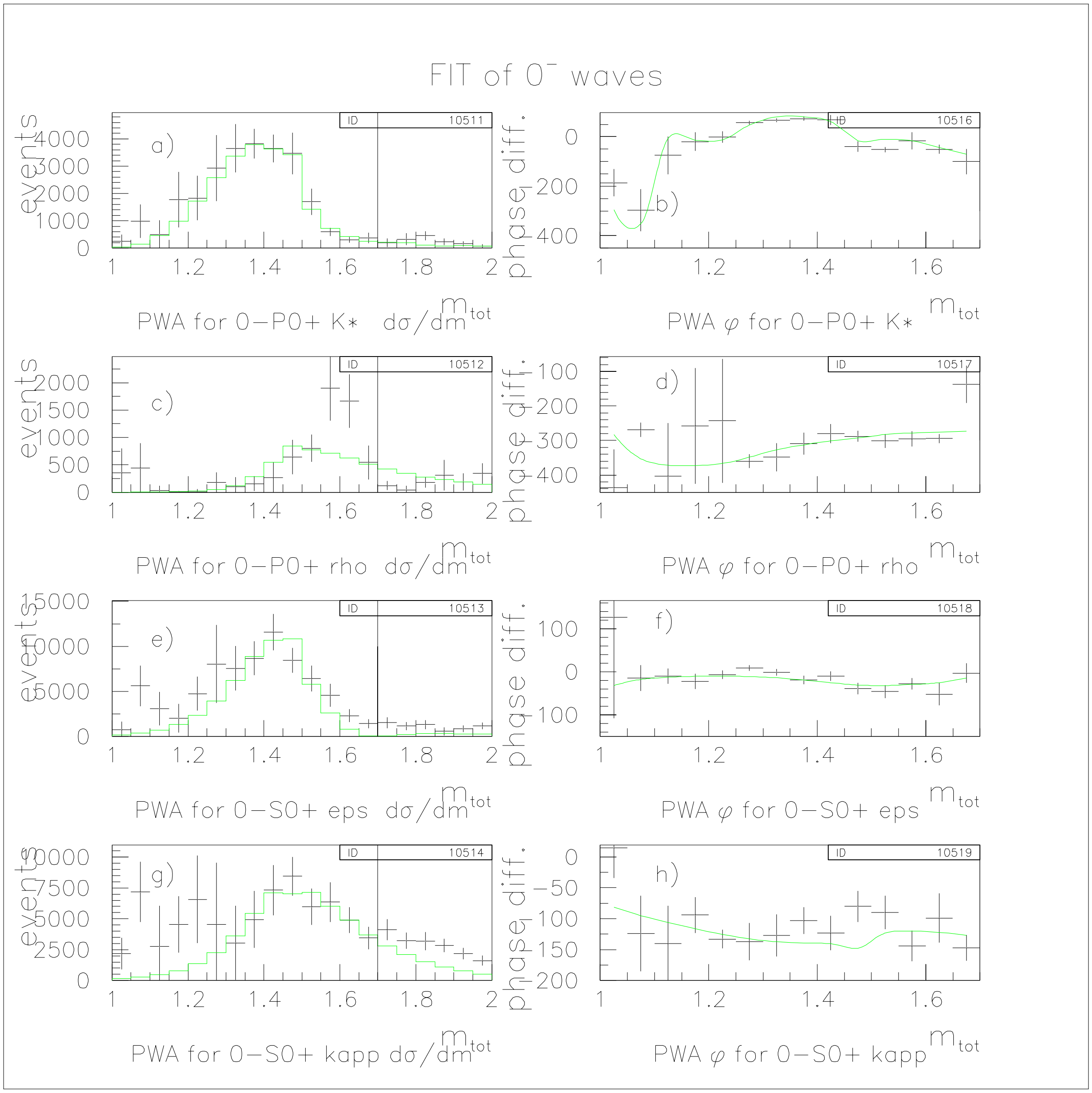


Figure 7: Fit results for $J^P = 0^-$ wave (see text). Number of events and phases are shown for channels: a-b) ($0^-$ $K^*\pi$); c-d) ($0^-$ $\rho K$); e-f) ($0^-$ $\epsilon K$); g-h) ($0^-$ $\kappa\pi$);

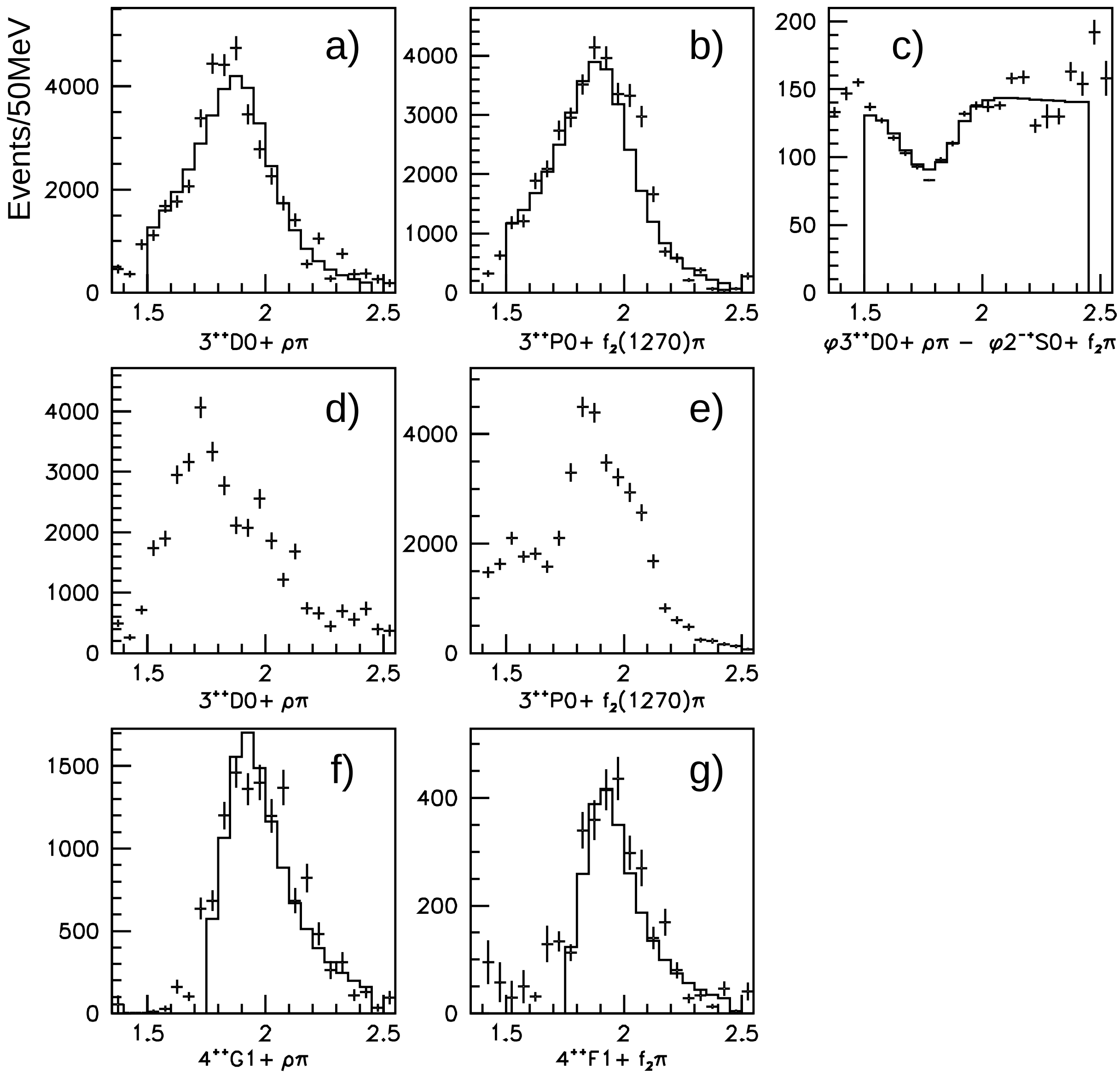


Figure 8: PWA results for waves $J^{PC} = 3^{++}$ and $4^{++}$.
a-c)Fitted number of events for $3^{++}$ channels ($\rho\pi$) and $f_2(1270)\pi$ at high t region, $0.03 < |t| < 0.70\ GeV^2$, and phase for ($\rho\pi$) channel;
d-e) like a-b but for low t, $|t| < 0.03\ GeV^2$;
f-g) fitted number of events for $4^{++}$ channels.

Very preliminary values for mass and width of the $J^P M\eta = 0^-0+$ resonance are: $M = 1400 \pm 40\ MeV,\ \Gamma = 265 \pm 60\ MeV$. (Only statistical errors are given, the systematical ones are under investigation.)

Observed mass is lower than the value measured by ACCMOR collaboration but both measurements are consistent.

Concerning the main subject of our search, a strange partner of $\pi(1800)$, one can see only an indication in channel $\epsilon K$, where a wide structure is observed in the vicinity of 2100 $MeV$.

Another $0^-$ resonance, $K_0(1830)$, which was observed in reaction $K^-p \to (K\phi)p$ at 18 $GeV/c$, is not seen in the $(K^-\pi^+\pi^-)$ system.

## 4. Resonance $J^{PC} = 3^{++}$ produced in $\pi^- N$ interactions at 36 GeV/c

Between the light unflavored resonances, there are well established $a_1(1260)$, $a_2(1320)$, $a_4(2040)$. However, the $a_3$ resonance is missing. There is no good candidate for $a_3$ in the last Review of Particle Properties [21]. So called X(2000) entry in the Meson particle listing contains one candidate at 2200 $MeV$ observed in $\pi^- p \to \Delta^{++} 3\pi$ channel [22], but this observation is not confirmed since 1977.

Careful analysis of reaction $\pi^- N \to (\pi^-\pi^+\pi^-)N$ at 36 $GeV/c$ at the statistics of 8.6 million events has been performed by VES experiment. As the result, an evidence for resonant-like $3^{++}$ wave has been observed (Fig. 8). Parametes of the $3^{++}$ resonance determined from the analysis of the low-t events are:

$$m = (1.865 \pm 0.007 \pm 0.020)\, GeV, \quad \Gamma = (0.38 \pm 0.01 \pm 0.05)\, GeV.$$

The current results for the $a_4$ parameters are:

$$m = (1.982 \pm 0.010 \pm 0.015)\, GeV, \quad \Gamma = (0.32 \pm 0.01 \pm 0.03)\, GeV.$$

Here the first error is statistical, the second one is systematical. It is worth noticing, that observed mass difference between $a_3$ and $a_4$ doesn't match with naive expectations based on analogy with the difference in mass squared of $a_1$ and $a_2$ resonances, and needs explaination.

## Conclusions

- An exotic wave $J^{PC} = 1^{-+}$ in the mass region close to 1600 $MeV$, which was previously observed in different channels in $\pi^- N$ interactions at 36 $GeV/c$, is seen now in system $(\omega\pi^-\pi^0)$ at 28 $GeV/c$.
- New decay mode of $\pi(1800) \to (K_s^\circ K_s^\circ \pi)$ is seen in $\pi^- N$ interactions at 28 $GeV/c$.
- The strange pseudoscalar resonance $K_0(1460)$ is confirmed. This resonance has been observed previously in $K^- p$ interactions at 63 $GeV/c$ and $K^\pm p$ interactions at 13 $GeV/c$ but still is not considered as established.
- Analysis of $(\pi^-\pi^+\pi^-)$ system produced at 36 $GeV/c$ gives an evidence for the $a_3$ resonance with mass $m = (1.865 \pm 0.007 \pm 0.020)$ $GeV$ and width $\Gamma = (0.38 \pm 0.01 \pm 0.05)$ $GeV$. Low mass of this object needs explaination.

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