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A partial wave analysis of the centrally produced $\pi^0\pi^0$ system in pp interactions at 450 GeV/c

GAMS Collaboration

R. Bellazzini [a], F.G. Binon [b], M. Boutemeur [c], A. Brez [a], C. Bricman [d], S.V. Donskov [e], M. Gouanère [d], S. Inaba [f], A.V. Inyakin [e], T. Ishida [f], H. Kawai [g], G.V. Khaustov [e], T. Kinashi [h], M. Kobayashi [f], A.A. Kondashov [e], A.A. Lednev [e], M.M. Massari[a], T. Nakagawa[i], J.P. Peigneux [d], S.A. Polovnikov [e], V.A. Polyakov [e], M. Poulet [d], S.A. Sadovsky [e], V.D. Samoylenko [e], P.M. Shagin [e], H. Shimizu [j], A.V. Shtannikov [e], A.V. Singovsky [e], A.E. Sobol [e], J.P. Stroot [k], V.P. Sugonyaev [e], K. Takamatsu [l], M.R. Torquati [a], T. Tsuru [f], Y. Yasu [f]

[a] *University of Pisa and INFN, Pisa, Italy*
[b] *Universite Libre de Bruxelles, CP 229, B-1050 Brussels, Belgium*
[c] *Ludwigs-Maximilians-Universität München, Sektion Physik, Am Coulombwall 1, D-85748 Garching, Germany*
[d] *Laboratoire d'Annecy de Physique des Particules, F74019 Annecy-de-Vieux, France*
[e] *Institute for High Energy Physics, Protvino, 142284 Russia*
[f] *National Laboratory for High Energy Physics – KEK, Tsukuba, Ibaraki 305, Japan*
[g] *Chiba University, Inage-ku, Chiba 263, Japan*
[h] *Research Center for Nuclear Physics, Osaka, Japan*
[i] *Tohoku University, Aoba-ku, Sendai 980, Japan*
[j] *Yamagata university, Yamagata 990, Japan*
[k] *Institut Interuniversitaire des Sciences Nucleaires, Brussels, Belgium*
[l] *Miyazaki University, Miyazaki 889-21, Japan*

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Abstract

A partial wave analysis of the $\pi^0\pi^0$ system produced centrally in pp collisions at 450 GeV/c shows evidence for the $f_0(980)$, $f_0(1300)$ and $f_0(1500)$ resonances. $f_2(1270)$ is observed dominantly in the D_0^- wave. A broad enhancement is seen in the D-waves below 1 GeV. © 1999 Published by Elsevier Science B.V. All rights reserved.

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In recent years, after more than two decades of searching for the experimental evidence for the QCD predicted gluon bound states (glueballs), considerable progress has been made. On one hand, theoretical predictions from lattice QCD became more accurate. These calculations indicate that the lowest lying glueball should be a scalar in the mass range 1500–1700 MeV [1]. On the other hand, results from high statistics meson spectroscopy experiments became available. In particular, the study of the $\pi^0\pi^0$ system produced in $p\bar{p}$ annihilations [2] and charge exchange reactions [3] has revealed the complicated structure of the $\pi\pi$ S-wave which indicates the presence of several scalar resonances. Some of these might result from the mixing of a glueball with a nearby quark $J^{PC} = 0^{++}$ states. A systematic study of as many decay modes and production processes as possible is required in order to understand more fully the possible gluonic nature of the scalar mesons. Central pp interactions are predicted to be a source of gluonic final states via double Pomeron exchange [4]. A study of the $\pi^0\pi^0$ system produced in such interactions has been performed by two CERN experiments, NA12/2 and WA102, which have used the same photon detector but totally different triggers and proton detectors.

In this paper we continue the study of the $\pi^0\pi^0$ final state [5] formed in the reaction

$$pp \rightarrow p_s X^0 p_f, \quad X^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma \tag{1}$$

carried out with the NA12/2 setup using the 450 GeV/c proton beam of the CERN SPS. The subscripts s and f in (1) indicate the slowest and fastest protons in the laboratory frame. Gammas from π^0 decays were detected with the multiphoton hodoscope spectrometer GAMS-4000 [6]. The fast proton momentum was measured by a magnetic spectrometer with microstrip gas chambers [7] and the slow proton momentum was measured by a recoil proton detector [8].

Reaction (1) has been selected from a sample of events with two outgoing charged tracks and four reconstructed γ-quanta in GAMS-4000. First, a series of cuts has been applied. The energy of each photon was required to be larger than 1 GeV (this threshold is increased to 2 GeV in the GAMS central area). The distance between the photon impact in GAMS and the beam axis had to be larger than 60 mm. The total energy of the fast proton and of the gammas had to lie within a ± 10 GeV interval around the beam energy.

Fig. 1a shows the two photon mass spectrum for 4γ-events when the mass of the other γ-pair lies within a band around the π^0 mass (85–185 MeV). A clear π^0 signal is observed with a small background. The separation of events from reaction (1) has been performed using a kinematical analysis (6C fit, four-momentum conservation and the masses of both π^0s being fixed). A total of 78 995 events with $\chi^2 < 12.6$ for the $\pi^0\pi^0$ hypothesis have been selected.

The $p_f\pi^0$ effective mass spectrum (Fig. 1b) shows evidence for $\Delta^+(1232)$ production. The $\Delta^+(1232)$ signal has been removed by requiring $M(p_f\pi^0) > 1.5$ GeV. Higher threshold cuts on $M(p_f\pi^0)$ (from 1.5 to 2.2 GeV) show that the possible presence of higher mass Δ^+ or N^* do not significantly influence the results. Due to the trigger requirements there is no Δ in the $p_s\pi^0$ effective mass spectrum (not shown).

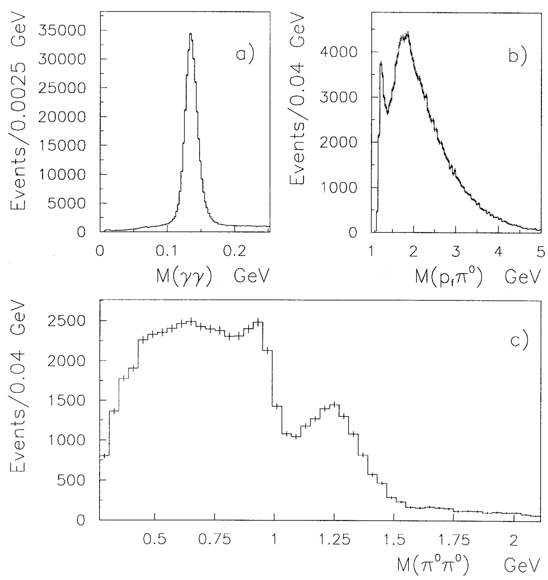

Fig. 1. (a) Effective $\gamma\gamma$ mass for 4γ-events when the mass of the other γ-pair lies within the π^0 mass band, (b) the $M(p_f\pi^0)$ and (c) the centrally produced $\pi^0\pi^0$ effective mass spectrum.

The resulting centrally produced $\pi^0\pi^0$ effective mass distribution (Fig. 1c) includes 55 022 events. A peak corresponding to the $f_2(1270)$ and a sharp drop at 1 GeV are visually observed.

A partial wave analysis (PWA) has been performed assuming the $\pi^0\pi^0$ system is produced by the collision of two particles (referred to as exchanged particles) emitted by the scattered protons. The z axis is defined in the $\pi^0\pi^0$ centre of mass by the momentum vector of the exchanged particle with the largest four-momentum transfer. The y axis is defined by the cross product of the two exchanged particle momenta in the pp centre of mass. The two variables needed to specify the decay process were

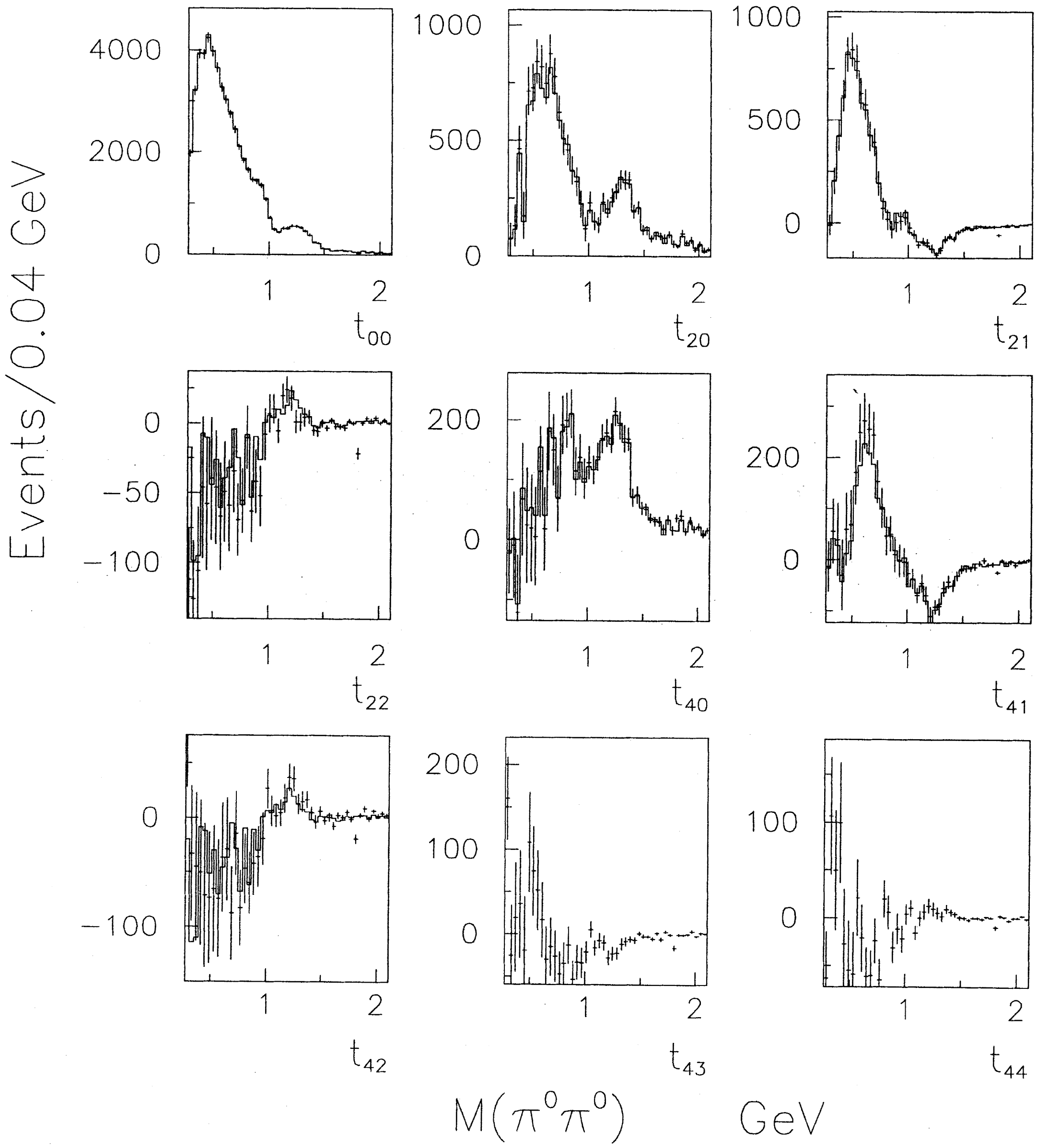

Fig. 2. $\sqrt{4\pi}\,t_{LM}$ moments. The superimposed histograms show moments calculated with the partial amplitudes of the PWA of the $\pi^0\pi^0$ final state.

taken as the polar and azimuthal angels (θ,ϕ) of one π^0 in the $\pi^0\pi^0$ centre of mass relative to the coordinate system described above.

The angular distribution of reaction (1) may be expressed in terms of the moments t_{LM} as follows

$$I(\theta,\phi) = \sum_L t_{L0} Y_L^0(\theta,\phi) + 2\sum_{L,M>0} t_{LM}\,\mathrm{Re}\{Y_L^M(\theta,\phi)\} \quad (2)$$

where $Y_L^M(\theta,\phi)$ is a spherical harmonic. The acceptance corrected moments $\sqrt{4\pi}\,t_{LM}$ are shown in Fig. 2. The moments with $M>2$ (i.e. t_{43} and t_{44}) and all the moments with $L>4$ (not shown) are small and hence only partial waves with spin $l=0$ and 2 and absolute values of spin z-projection $m \le 1$ have been included in the PWA.

An interesting feature of the moments is the presence of some structure in the $L=2$ and $L=4$ moments for $\pi^0\pi^0$ masses below 1 GeV. These indicate the contribution of D-waves. This type of structure has not been observed in charge exchange reactions [3,10]. This effect cannot be explained by an acceptance effect or by non-central events. To demonstrate this, we calculated the moments using different cuts. First, we required that $M(p_f\pi^0) > 2.0$ GeV, however, after acceptance correction the moments were compatible with the set for $M(p_f\pi^0) >$ 1.5 GeV showing that diffractive resonances in the range $1.5 < M(p_f\pi^0) < 2.0$ GeV have a negligible effect on the moments. We have also required that the rapidity gap between any proton and π^0 in the event is greater than 2 units. Again the resulting acceptance corrected moments do not change.

It is interesting to compare this observation with the results of other central production experiments. Preliminary results from the E690 experiment at Fermilab report a similar activity in the moments in the mass region below 1 GeV [11]. There is also evidence for this structure in the data from the WA102 experiment, both in the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels [12,13]. In addition, the AFS experiment at the CERN ISR also observed normalised moments that deviated from zero in this mass region; however in their analysis they claimed that this deviation was due to problems of the Monte Carlo simulation of low energy tracks [14].

It should be noted also that in a reanalysis of the $\pi^- p$ data [15] a low mass D wave structure is observed in the $\pi^+\pi^-$ system, that is predominantly produced at high $|t|$. However, it is produced mainly with $m=2$, unlike the structure observed in the central production.

This structure does indeed seem to be a real effect, which is specifically present in centrally produced data. It has recently been suggested [16,17] that central production may be due to the fusion of two vector particles and that this may explain why higher angular momentum systems may be produced at lower masses.

The amplitudes used for the PWA are defined in the reflectivity basis [9]. In this basis the angular distribution is given by the sum of two non-interfering terms corresponding to negative and positive values of reflectivity. The waves used were of the form J_m^ε with $J = S$ and D, $m = 0,1$ and reflectivity $\varepsilon = \pm 1$. The expressions relating the moments (t_{LM}) and the waves (J_m^ε) are given in Table 1. Since the overall phase for each reflectivity is indeterminate, the only wave in positive reflectivity (D_1^+) and one of the waves in negative reflectivity (we have chosen S_0^- wave) may be set to be real and hence their phases may be set to zero. This results in 6 parameters to be determined from the fit to the angular distributions.

Table 1
The moments of the angular distribution expressed in terms of the partial waves

$$\sqrt{4\pi}\,t_{00} = |S_0^-|^2 + |D_0^-|^2 + |D_1^-|^2 + |D_1^+|^2$$

$$\sqrt{4\pi}\,t_{20} = \frac{\sqrt{5}}{7}(2|D_0^-|^2 + |D_1^-|^2 + |D_1^+|^2 + 2|S_0^-||D_0^-|\cos(\phi_{S_0^-} - \phi_{D_0^-})$$

$$\sqrt{4\pi}\,t_{21} = \frac{\sqrt{10}}{7}|D_1^-||D_0^-|\cos(\phi_{D_1^-} - \phi_{D_0^-}) + \sqrt{2}|S_0^-||D_1^-|\cos(\phi_{S_0^-} - \phi_{D_1^-})$$

$$\sqrt{4\pi}\,t_{22} = \frac{\sqrt{15}}{7\sqrt{2}}(|D_1^-|^2 - |D_1^+|^2)$$

$$\sqrt{4\pi}\,t_{40} = \frac{6}{7}|D_0^-|^2 - \tfrac{4}{7}(|D_1^-|^2 + |D_1^+|^2)$$

$$\sqrt{4\pi}\,t_{41} = \frac{2\sqrt{15}}{7}|D_0^-||D_1^-|\cos(\phi_{D_0^-} - \phi_{D_1^-})$$

$$\sqrt{4\pi}\,t_{42} = \frac{\sqrt{10}}{7}(|D_1^-|^2 - |D_1^+|^2)$$

The PWA has been performed independently in 40 MeV intervals of the $\pi^0\pi^0$ mass spectrum. In each mass bin an event-by-event maximum likelihood method has been used. The function

$$F = -\sum_{i=1}^{N} \ln\{I(\Omega)\} + \sum_{L,M} t_{LM}\epsilon_{LM} \tag{3}$$

has been minimised, where N is the number of events in the given mass bin, ϵ_{LM} are the efficiency moments calculated in the centre of the bin and t_{LM} are the moments of the angular distribution (2) expressed in terms of the partial amplitudes (see Table 1). The moments recalculated from the partial amplitudes are shown superimposed on experimental moments in Fig. 2. As can be seen, both sets of moments agree with each other quite well.

The system of equations which expresses the moments via the partial wave amplitudes is non-linear. This leads to inherent ambiguities such that there are two solutions for each mass bin. One of these is found from the fit to the experimental angular distribution, the other one may be found by the method described in Ref. [9]. In the case under study the bootstrapping procedure is trivial because the Barrelet function has only two roots and their real and imaginary parts doe not cross zero as a function of mass, as seen in Fig. 3a and b. In order to link the solutions between adjacent mass bins, the real parts of the roots are sorted out in each bin in such a way that the real part of the first root should be larger than that of the second root (the real parts of the roots have different signs). For the first solution the imaginary parts of both roots are taken positive, the second solution is obtained by complex conjugation of one of the roots.

The two PWA solutions are shown in Fig. 4. By definition all the solutions give identical moments and identical values of the likelihood. The only way to differentiate between the solutions, if different, is to apply some external physical test, for example, by requiring that at threshold the S_0^- wave is the dominant wave. For one solution the D-waves are the dominant contribution near threshold. This solution can be rejected as the unphysical one. The S_0^- wave for the physical solution is characterized by a broad bump below 1 GeV and two shoulders, at 1 and 1.4 GeV. Broad bumps are also seen in the three D-waves at low mass, but intensities of the D-waves near threshold is several times smaller than that of the S_0^--wave. A peak corresponding to the $f_2(1270)$ is clearly seen in the D_0^--wave, such a peak is less prominent in the D_1^- wave and is absent in the D_1^+-wave.

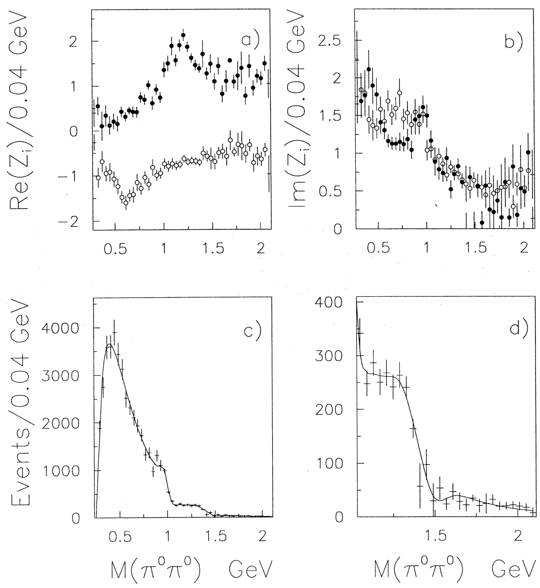

Fig. 3. (a) Real and (b) imaginary parts of the Barrelet roots (see text) as a function of the mass obtained from the PWA. (c) $\pi^0\pi^0$ S-wave with fit described in the text. (d) The same but for the mass region above 1 GeV.

In order to obtain a satisfactory fit to the S_0^--wave from threshold to 2 GeV it has been found necessary to use three Breit–Wigner resonances to describe $f_0(980)$, $f_0(1300)$ and $f_0(1500)$ and a background of the form $G(m) = a(m - 2m_{\pi^0})^b \exp(-cm - dm^2)$, where m is the $\pi^0\pi^0$ mass and a, b, c, d are fit parameters. The convolution with a Gaussian has been made to account the experimental mass resolution ($\alpha_M = 30$ MeV at 1 GeV). The GAMS collaboration [5] has previously shown that the low mass structure in the $\pi^0\pi^0$ system may be interpreted as σ particle [18]. To check this, we performed a fit using Breit–Wigner instead of the $G(m)$ to describe the low mass S_0^--wave. Both of these fits give similar χ^2 values ($\chi^2/N_{\rm dof} = 39/30$ and $43/31$ respectively). In the second case parameters of the low mass Breit–Wigner are found to be $M = 730 \pm 60$ MeV and $\Gamma = 940 \pm 160$ MeV in agreement with

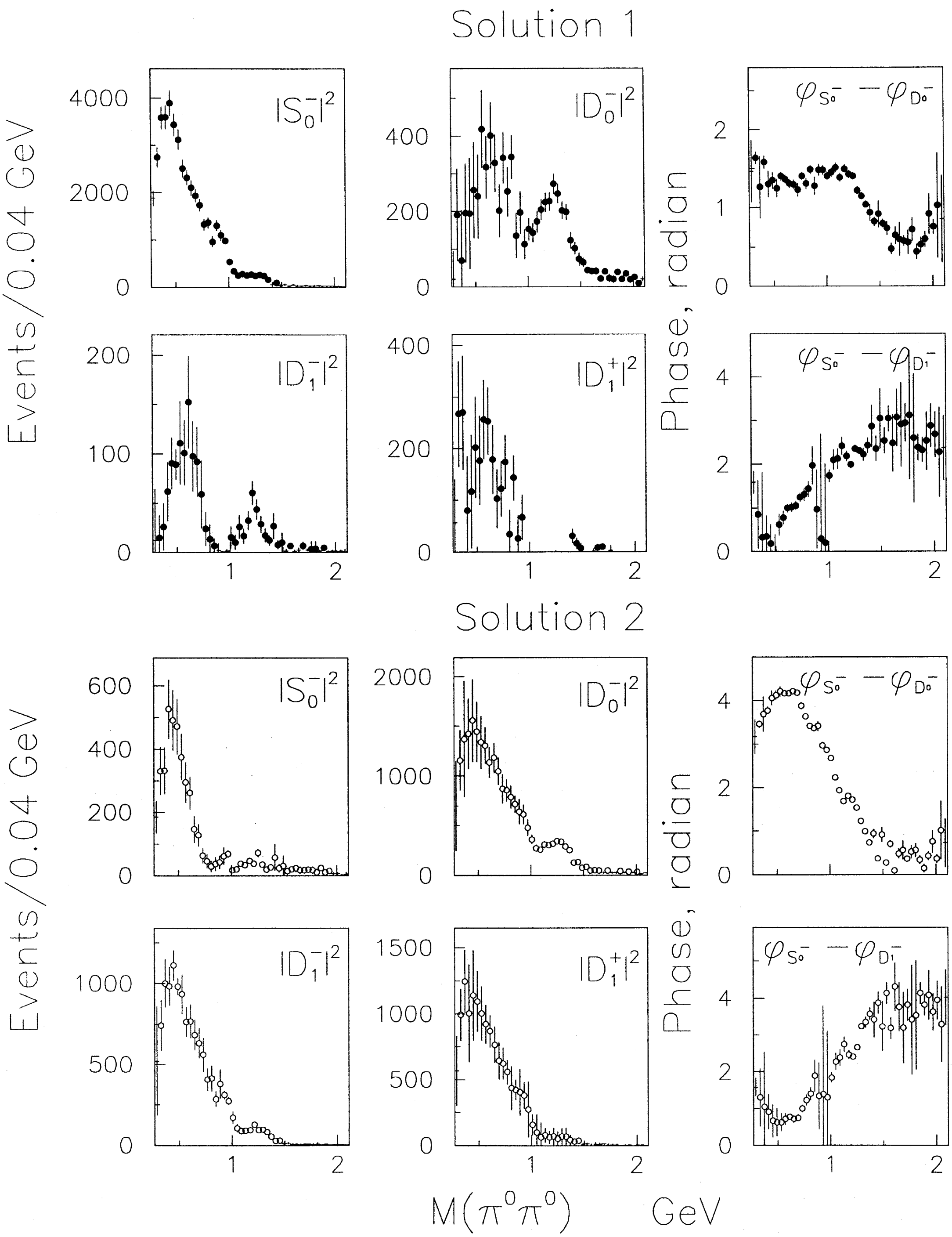

Fig. 4. The physical (solid circles) and unphysical (open circles) solutions from the PWA of the $\pi^0\pi^0$ final state.

values obtained from a former NA12/2 fit to the $\pi^0\pi^0$ mass spectrum [5].

The fit gives the following parameters for the $f_0(980)$, $f_0(1300)$ and $f_0(1500)$:

$f_0(980)$

$$M = 989 \pm 15\,\text{MeV}, \quad \Gamma = 65 \pm 25\,\text{MeV},$$

$f_0(1300)$

$$M = 1315 \pm 50\,\text{MeV}, \quad \Gamma = 255 \pm 60\,\text{MeV},$$

$f_0(1500)$

$$M = 1530 \pm 45\,\text{MeV}, \quad \Gamma = 160 \pm 50\,\text{MeV}.$$

The errors include both the statistical and systematical uncertainties determined by two different choices of the parametrization and the choice of an upper limit to the mass spectrum. Parameters of the scalar resonances agree with the values obtained from the fit to the $\pi^+\pi^-$ mass spectrum of the WA102 experiment [12]. In that fit it was found necessary to add Breit–Wigner to describe $f_0(1710)$ state. In our case including a Breit–Wigner in 1.7 GeV mass region does not decrease χ^2 significantly due to the low statistics above 1.5 GeV. The fit is shown in Fig. 3c for the entire mass range and in Fig. 3d for masses above 1 GeV. As can be seen the fit describes well the $\pi^0\pi^0$ S_0^--wave spectrum.

In conclusion, the partial wave analysis of the centrally produced $\pi^0\pi^0$ system has provided an unambiguous physical solution. The S-wave is found to dominate the mass spectrum and is composed of a broad enhancement at threshold, a sharp drop at 1 GeV due to the interference between the $f_0(980)$ resonance and the S-wave background and another drop around 1.4 GeV due to $f_0(1300)$ and $f_0(1500)$. The D-waves show evidence for the $f_2(1270)$ and a broad enhancement below 1 GeV. It is interesting to notice that the $f_2(1270)$ is produced dominantly with $m = 0$.

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