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

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Abstract

A partial wave analysis of the centrally produced $\pi^0\pi^0$ channel has been performed in pp collisions using an incident beam momentum of 450 GeV/c. An unambiguous physical solution has been found. Evidence is found for the $f_0(980)$,

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$f_0(1300)$ and $f_0(1500)$ in the the S-wave, and the $f_2(1270)$ is observed dominantly in the D_0-wave. In addition, there is evidence for a broad enhancement in the D-wave below 1 GeV.

The study of the $\pi^0\pi^0$ system produced in $p\bar{p}$ annihilations [1] and π induced interactions [2,3] has revealed that the $\pi\pi$ S-wave has a complicated structure which indicates the presence of several scalar states. Some of these states may have a significant gluonic component. In order to understand more fully the gluonic nature of these scalar mesons a systematic study is required using as many decay modes and production processes as possible. This paper presents a study of the $\pi^0\pi^0$ final state formed in central pp interactions which are predicted to be a source of gluonic final states via double Pomeron exchange [4] and gives new information which may help in understanding the scalar meson spectrum.

The reaction

$$pp \to p_f(\pi^0\pi^0)p_s \quad (1)$$

has been studied at 450 GeV/c. The subscripts f and s indicate the fastest and slowest particles in the laboratory respectively. The WA102 experiment has been performed using the CERN Omega Spectrometer, the layout of which is described in Ref. [5]. Reaction (1) has been isolated from the sample of events having two outgoing charged tracks and four γs reconstructed in the GAMS-4000 calorimeter, by first imposing the following cuts on the components of the missing momentum: |missing $P_x| < 10.0$ GeV/c, |missing $P_y| < 0.25$ GeV/c and |missing $P_z| < 0.25$ GeV/c, where the x axis is along the beam direction. A correlation between pulse-height and momentum obtained from a system of scintillation counters was used to ensure that the slow particle was a proton.

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. Events belonging to reaction (1) have been selected using a kinematical fit (6C fit, four-momentum conservation being used and the masses of two π^0s being fixed). By requiring that the χ^2 value for the $\pi^0\pi^0$ hypothesis is $\chi^2 < 12.6$, a total of 208 452 events have been selected.

The $p_f\pi^0$ effective mass spectrum (Fig. 1b)) shows a clear $\Delta^+(1232)$ signal which has been removed by requiring $M(p_f\pi^0) > 1.5$ GeV. There is no evidence for Δ production in the $p_s\pi^0$ effective mass spectrum (not shown).

The resulting centrally produced $\pi^0\pi^0$ effective mass distribution is shown in Fig. 1c) and consists of 166 597 events. A peak corresponding to the $f_2(1270)$ and a sharp drop at 1 GeV can be observed.

A Partial Wave Analysis (PWA) of the centrally produced $\pi^0\pi^0$ system 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 by the momentum vector of the exchanged particle with the greatest four-momentum transferred in the $\pi^0\pi^0$ centre of mass. The y axis is defined by the cross product of the two exchanged particles in the pp centre of mass. The two variables needed to specify the decay process were taken as the polar and azimuthal angles (θ, ϕ) of the π^0 in the $\pi^0\pi^0$ centre of mass relative to the coordinate system described above.

The acceptance corrected moments $\sqrt{4\pi}\,t_{LM}$, defined by

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

have been rescaled to the total number of observed events and 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 which

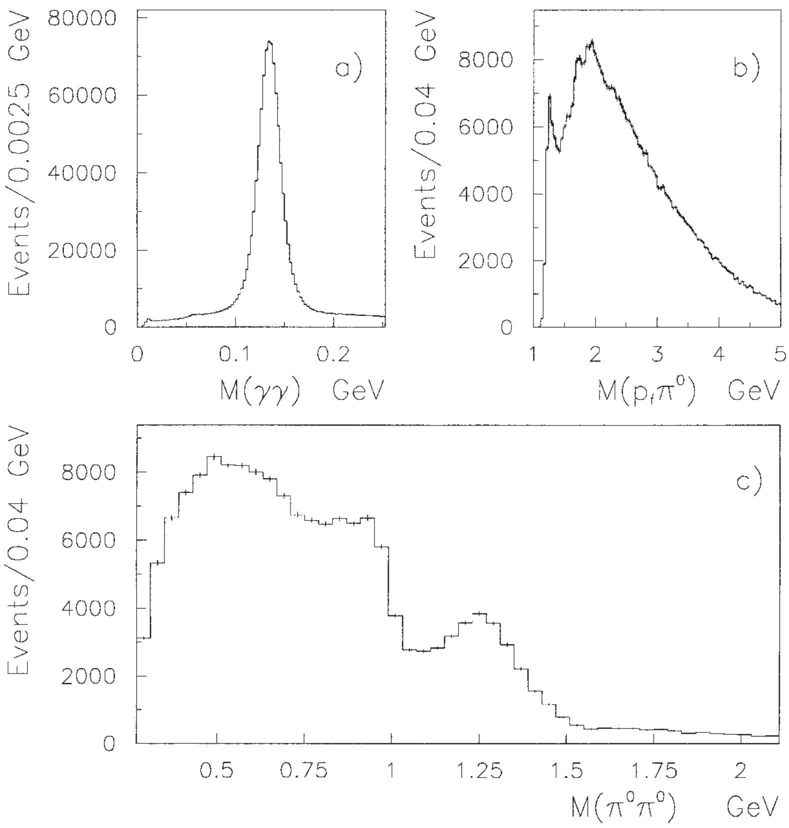

Fig. 1. a) Effective $\gamma\gamma$ mass for 4γ-events when the mass of the other γ-pair lies within the π^0 mass band, b) the $M(p_f\pi^0)$ and c) the centrally produced $\pi^0\pi^0$ effective mass spectrum.

indicates the presence of D-waves. This type of structure has not been observed in π induced reactions [2,3]. In order to see if this effect is due to acceptance problems or problems due to non-central events, we have reanalysed the data using a series of different cuts. Firstly, we required that $M(p_f\pi^0) > 2.0$ GeV; however, it was found that 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 did not change. In order to investigate any systematic effects we have also analysed the central $\pi^+\pi^-$ data and a similar structure is also found in the $L = 2$ and $L = 4$ moments [6].

It is interesting to compare the above result with previously published data on other centrally produced $\pi\pi$ systems. In preliminary results from the E690 experiment at Fermilab, activity at a similar level is observed in the t_{40} moment below 1 GeV [7]. There is also evidence for this structure in the $\pi^0\pi^0$ data from the CERN NA12/2 experiment [8]. The AFS experiment at the CERN ISR also observed moments that the t_{40} moment deviated from zero in this mass region; however, in their analysis they claimed this deviation was due to problems of the Monte Carlo simulating low energy tracks [9].

This structure does indeed seem to be a real effect which is present in centrally produced $\pi\pi$ systems. It has recently been suggested [10,11] that central production may be due to the fusion of two vector particles and this may explain why higher angular momentum systems can be produced at lower masses.

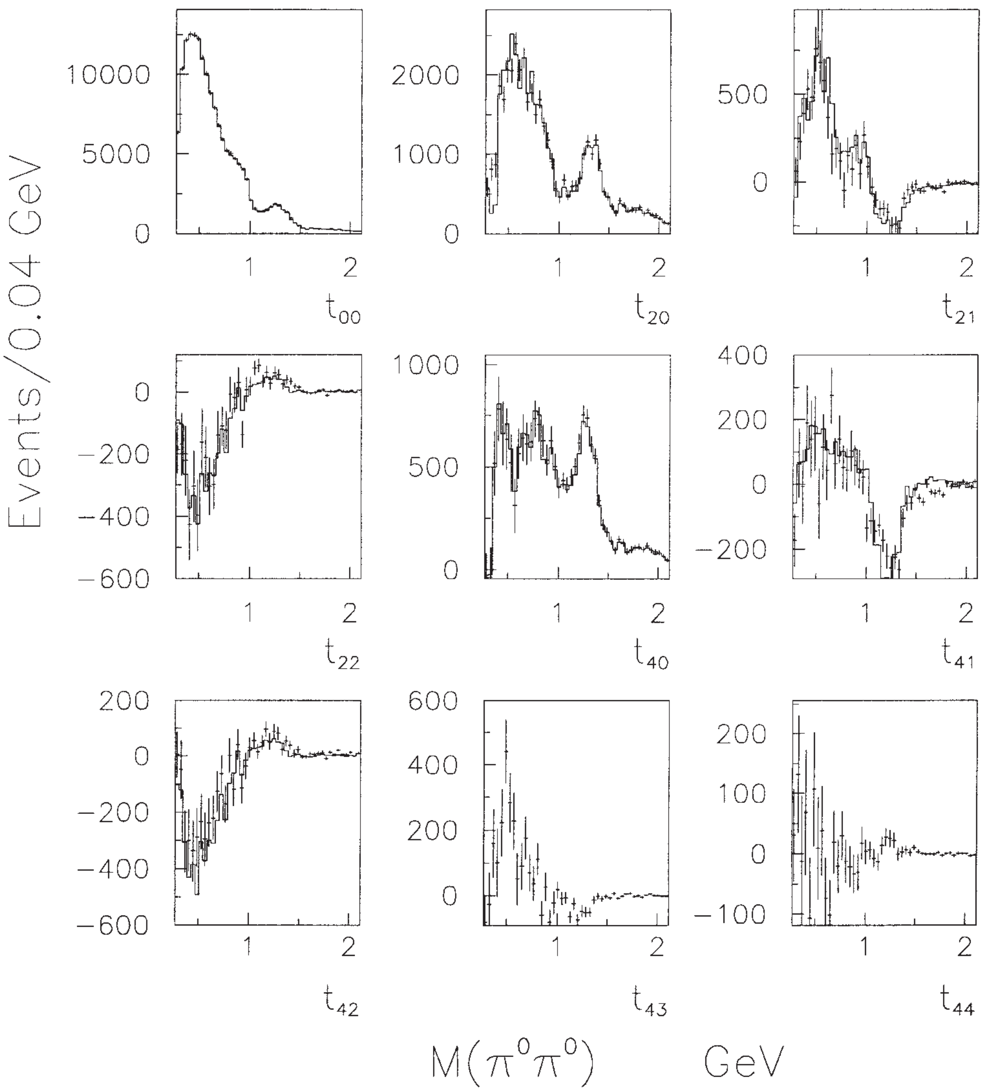

Fig. 2. The $\sqrt{4\pi}\,t_{LM}$ moments from the data. Superimposed as a solid histogram are the resulting moments calculated from the PWA of the $\pi^0\pi^0$ final state.

The amplitudes used for the PWA are defined in the reflectivity basis [12]. In this basis the angular distribution is given by a 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, one wave in each reflectivity can be set to be real (S_0^- and D_1^+ for example) and hence two phases can be set to zero ($\phi_{S_0^-}$ and $\phi_{D_1^+}$ have been chosen). This results in 6 parameters to be determined from the fit to the angular distributions.

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

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

has been minimised, where N is the number of events in a given mass bin, ϵ_{LM} are the efficiency corrections calculated in the centre of the bin and t_{LM} are the moments of the angular distribution. The moments calculated from the partial amplitudes are shown superimposed on the experimental moments in Fig. 2. As can be seen the results of the fit well reproduce the experimental moments.

The system of equations which express the moments via the partial wave amplitudes is non-linear which leads to inherent ambiguities. For a system with S and D waves there are two solutions for each mass bin. In each mass bin one of these solutions is found from the fit to the experimental angular distri-

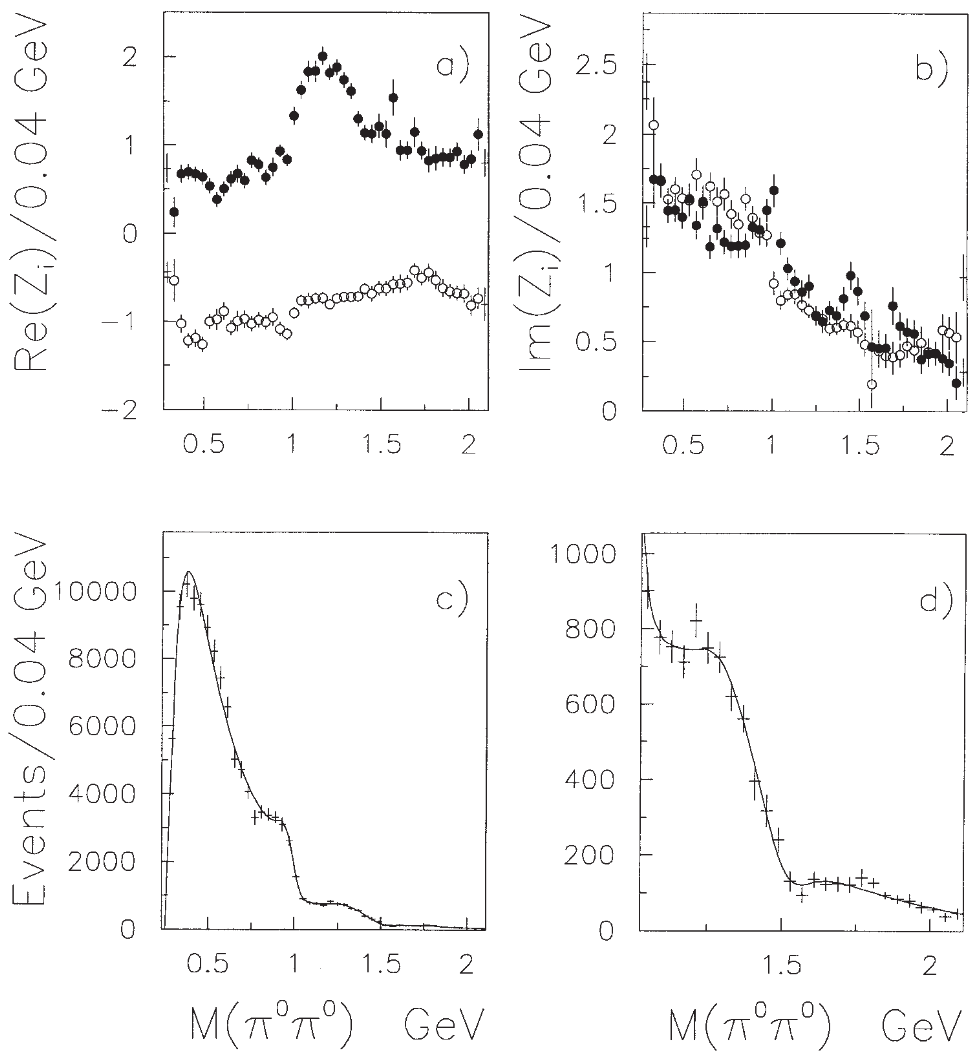

Fig. 3. a) The real and b) Imaginary parts of the roots (see text) as a function of mass obtained from the PWA. c) and d) The $\pi^0\pi^0$ S_0^- wave with fit described in the text.

butions, the other one can then be calculated by the method described in Ref. [12]. In the case under study the bootstrapping procedure is trivial because the Barrelet function has only two roots and their real and imaginary parts do not cross zero as functions of mass, as seen in Fig. 3a) and b). In order to

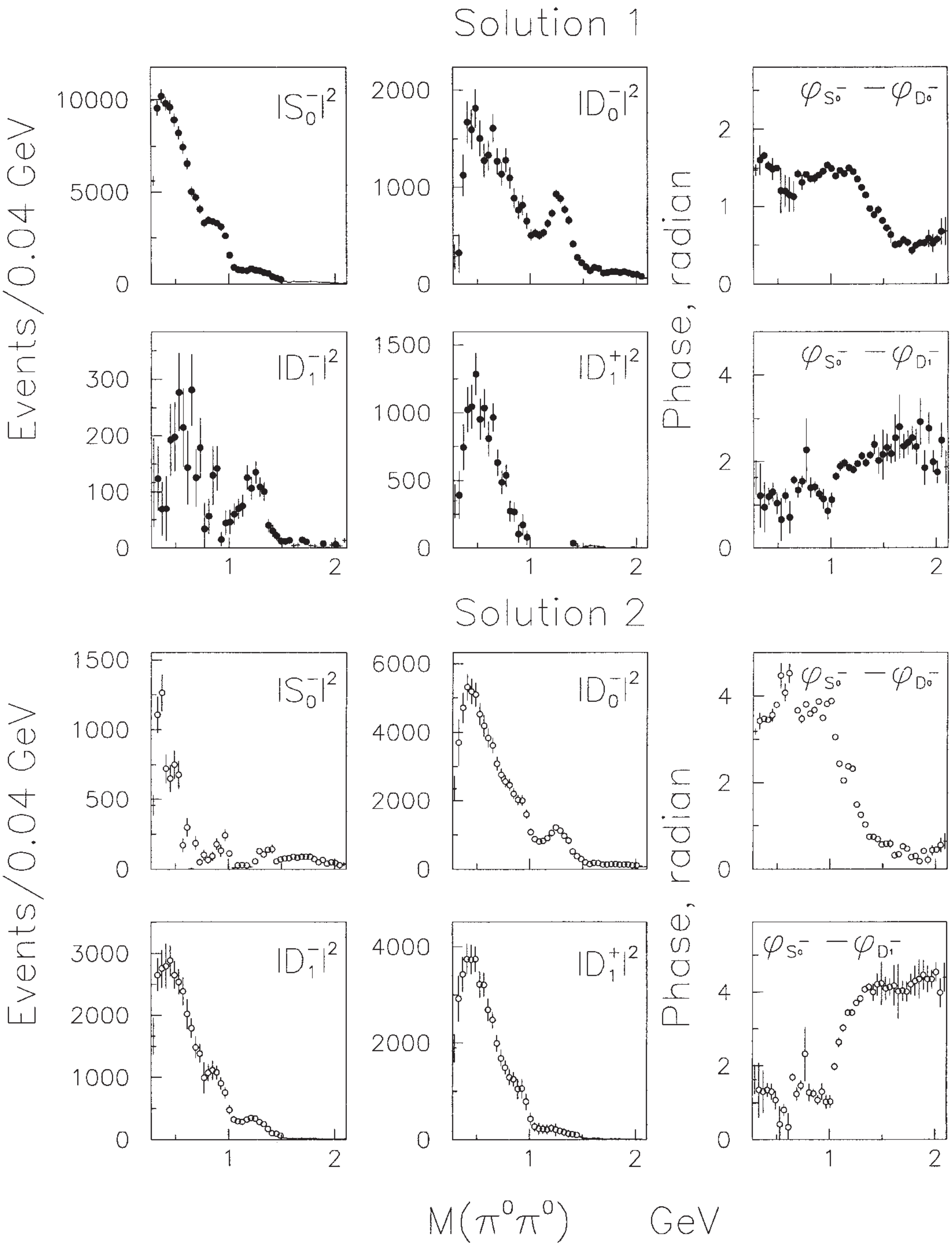

Fig. 4. The physical (solid circles) and unphysical (open circles) solutions from the PWA of the $\pi^0\pi^0$ final state.

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

$$\sqrt{4\pi}\,t_{00} = |S_0|^2 + |D_0^-|^2 + |D_1^-|^2 + |D_1^+|^2$$
$$\sqrt{4\pi}\,t_{20} = \frac{\sqrt{5}}{7}(2|D_0^-|^2 + |D_1^-|^2 + |D_1^+|^2)$$
$$+ 2|S_0||D_0^-|\cos(\phi_{S_0} - \phi_{D_0^-})$$
$$\sqrt{4\pi}\,t_{21} = \frac{\sqrt{10}}{7}|D_1^-||D_0^-|\cos(\phi_{D_1^-} - \phi_{D_0^-})$$
$$- \sqrt{2}|S_0||D_1^-|\cos(\phi_{S_0} - \phi_{D_1^-})$$
$$\sqrt{4\pi}\,t_{22} = \frac{\sqrt{15}}{7\sqrt{2}}(|D_1^-|^2 - |D_1^+|^2)$$
$$\sqrt{4\pi}\,t_{40} = \frac{6}{7}|D_0^-|^2 - \frac{4}{7}(|D_1^-|^2 + |D_1^+|^2)$$
$$\sqrt{4\pi}\,t_{41} = \frac{2\sqrt{15}}{7}|D_0^-||D_1^-|\cos(\phi_{D_0^-} - \phi_{D_1^-})$$
$$\sqrt{4\pi}\,t_{42} = \frac{\sqrt{10}}{7}(|D_1^-|^2 - |D_1^+|^2)$$

link the solutions in adjacent mass bins, the roots are sorted over real parts in each bin in such a way that the real part of the first root should be larger than the real part of the second root (real parts of the two 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 both 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, such as requiring that at threshold the S-wave is the dominant wave. For one solution the D-waves are the dominant contribution near threshold. This solution has been rejected as unphysical. The S-wave for the physical solution is characterised by a broad enhancement below 1 GeV and two shoulders, at 1 and 1.4 GeV. Broad enhancements are also seen in the three D-waves at low mass, but the intensities of the D-waves near threshold are several times smaller than that of the S-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.

In order to obtain a satisfactory fit to the S_0 wave from threshold to 2 GeV it has been found to be necessary to use three interfering Breit-Wigners to describe the $f_0(980)$, $f_0(1300)$ and $f_0(1500)$ and a background of the form $a(m - m_{th})^b \exp(-cm - dm^2)$, where m is the $\pi^0\pi^0$ mass, m_{th} is the $\pi^0\pi^0$ threshold mass and a, b, c, d are fit parameters. The Breit-Wigners have been convoluted with a Gaussian to account for the experimental mass resolution. The fit is shown in Fig. 3c) for the entire mass range and in Fig. 3d) for masses above 1 GeV. The parameters used to describe the $f_0(1300)$ and $f_0(1500)$ are those found from a fit to the $\pi^+\pi^-$ mass spectrum of the same experiment [6], namely

$$f_0(1300)\ \ M = 1308\,\text{MeV}, \quad \Gamma = 222\,\text{MeV}$$
$$f_0(1500)\ \ M = 1502\,\text{MeV}, \quad \Gamma = 131\,\text{MeV}.$$

The parameters found for the $f_0(980)$ are

$$f_0(980)\ \ M = 986 \pm 10\,\text{MeV}, \quad \Gamma = 76 \pm 15\,\text{MeV},$$

and as can be seen, the fit well describes the $\pi^0\pi^0$ S_0-wave spectrum.

In conclusion, a partial wave analysis of a high statistics sample of centrally produced $\pi^0\pi^0$ events has been performed. An unambiguous physical solution has been found. 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 $f_0(980)$ and the S-wave background, the $f_0(1300)$ and the $f_0(1500)$. The D-wave shows evidence for the $f_2(1270)$ and a broad enhancement below 1 GeV. It is interesting to note that the $f_2(1270)$ is produced dominantly with $m = 0$.

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