ELSEVIER

6 November 1997

PHYSICS LETTERS B

Physics Letters B 413 (1997) 217–224

A study of the centrally produced $\pi^+\pi^-\pi^+\pi^-$ channel in pp interactions at 450 GeV/c

WA102 Collaboration

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Dedicated to the memory of our colleague and friend Yuri Prokoshkin

PII S0370-2693(97)01140-4

Received 10 July 1997; revised 4 September 1997
Editor: L. Montanet

Abstract

The reaction $pp \to p_f(\pi^+\pi^-\pi^+\pi^-)p_s$ has been studied at 450 GeV/c in an experiment designed to search for gluonic states. A spin analysis has been performed and the dP_T filter applied. In addition to the well known $f_1(1285)$ there is evidence for two $J^{PC} = 2^{-+}$ states called the $\eta_2(1620)$ and $\eta_2(1875)$ and a broad scalar called the $f_0(2000)$. The production of these states as a function of the dP_T kinematical filter shows the behaviour expected for $q\bar{q}$ states. In contrast, there is evidence for two states at 1.45 GeV and at 1.9 GeV which do not show the behaviour observed for $q\bar{q}$ states.

The WA76 and WA91 Collaborations have studied the centrally produced $\pi^+\pi^-\pi^+\pi^-$ final state in the reaction

$$pp \to p_f(\pi^+\pi^-\pi^+\pi^-)p_s \tag{1}$$

at 85 [1], 300 [2], and 450 GeV/c [3]. The subscripts f and s indicate the fastest and slowest particles in the laboratory respectively. In addition to the $f_1(1285)$, which was observed at all energies, the WA76 Collaboration observed two new states at 1.45 and 1.9 GeV in their 300 GeV/c data [2]. In contrast, no clear evidence was seen for these states in the 85 GeV/c data of the same experiment [1]. The increase in cross section with increased incident energy [2] is consistent with the formation of these states via a double Pomeron exchange mechanism, which is predicted to be a source of gluonic states [4].

The WA91 experiment [3], which studied reaction (1) at 450 GeV/c, confirmed the existence of these states and, from a spin analysis, showed that the peak at 1.45 GeV had $I^GJ^{PC} = 0^+0^{++}$ and that the peak at 1.9 GeV had $I^GJ^{PC} = 0^+2^{++}$; hence they were called the $f_0(1450)$ and $f_2(1900)$ respectively. In a reanalysis of this data [5], the WA91 Collaboration showed that it was possible to describe the $f_0(1450)$ as being due to the interference between the $f_0(1300)$ and the $f_0(1500)$.

This paper presents new results from the WA102 experiment which is a continuation of the WA76 and WA91 programme and has more than a factor of five increase in statistics. This enables a detailed spin analysis to be performed and also a study as a function of dP_T, which is the difference in the transverse momentum vectors of the two exchanged particles [6] and has been proposed as a glueball-$q\bar{q}$ filter [7].

The data come from experiment WA102 which has been performed using the CERN Omega Spectrometer. The layout of the Omega Spectrometer used in this run is similar to that described in Ref. [8] with the replacement of the OLGA calorimeter by GAMS 4000 [9].

Reaction (1) has been isolated from the sample of events having six outgoing tracks by first imposing the following cuts on the components of the missing momentum: $|\text{missing } P_x| < 14.0$ GeV/c, $|\text{missing } P_y| < 0.12$ GeV/c and $|\text{missing } P_z| < 0.08$ 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.

The quantity Δ, defined as $\Delta = MM^2(p_f p_s) - M^2(\pi^+\pi^-\pi^+\pi^-)$, was then calculated for each event and a cut of $|\Delta| \leq 3.0$ (GeV)^2 was used to select the $\pi^+\pi^-\pi^+\pi^-$ channel. Events containing a fast $\Delta^{++}(1232)$ were removed if $M(p_f\pi^+) < 1.3$ GeV, which left 1 167 089 centrally produced events.

Fig. 1a shows the acceptance corrected $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum renormalised to the total number of observed events. The mass spectrum is very similar to that observed by experiments WA76 and

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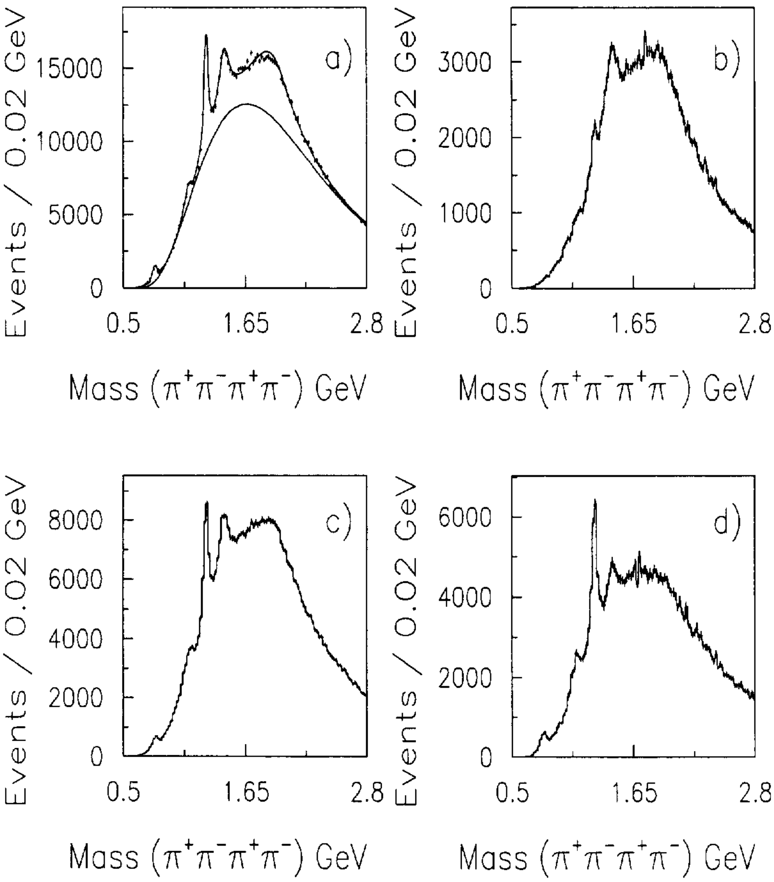

Fig. 1. The $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum a) for the total data with fit using 3 Breit-Wigners b) for $dP_T \le 0.2$ GeV, c) for $0.2 \le dP_T \le 0.5$ GeV and d) for $dP_T \ge 0.5$ GeV.

WA91, namely, a clear peak at 1.28 GeV associated with the $f_1(1285)$, a peak at 1.45 GeV called the $f_0(1450)$, which is possibly due to an interference effect between the $f_0(1300)$ and $f_0(1500)$, and a broad enhancement at 1.9 GeV called the $f_2(1900)$. The mass spectrum has been fitted using three Breit-Wigners representing the $f_1(1285)$, the 1.45 GeV peak and the $f_2(1900)$ plus a background of the form $a(m - m_{th})^b \exp(-cm - dm^2)$, where m is the $\pi^+\pi^-\pi^+\pi^-$ mass, m_{th} is the $\pi^+\pi^-\pi^+\pi^-$ threshold mass and a, b, c, d are fit parameters. Reflections from the $\eta\pi^+\pi^-$ decay of the η' and $f_1(1285)$ give small enhancements in the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum in the 0.8 and 1.1 GeV regions due to a slow π^0 from the decay of an η falling within the missing momentum cuts. In order to get a correct description of the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum two histograms representing a Monte Carlo simulation of each reflection have been included in the fit. The Breit-Wigner describing the $f_1(1285)$ has been convoluted with a Gaussian with $\sigma = 12$ MeV representing the experimental resolution in this mass region. The masses and widths determined from the fit are

$$M_1 = 1281 \pm 1 \ \text{MeV} \qquad \Gamma_1 = 24 \pm 3 \ \text{MeV}$$
$$M_2 = 1445 \pm 4 \ \text{MeV} \qquad \Gamma_2 = 95 \pm 15 \ \text{MeV}$$
$$M_3 = 1920 \pm 20 \ \text{MeV} \qquad \Gamma_3 = 450 \pm 60 \ \text{MeV}.$$

Close and Kirk [7] have proposed that when the centrally produced system is analysed as a function of the parameter dP_T, which is the difference in the transverse momentum vectors of the two exchange particles [6], states with large (small) internal angular momentum will be enhanced at large (small) dP_T. A study of the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum as a function of dP_T is presented in Figs. 1b), c) and d) for $dP_T \leq 0.2$ GeV, $0.2 \leq dP_T \leq 0.5$ GeV and $dP_T \geq 0.5$ GeV respectively. A dramatic effect is observed; the $f_1(1285)$ signal has virtually disappeared at low dP_T whereas the $f_0(1450)$ and $f_2(1900)$ signals remain.

A fit to Figs. 1b), c) and d) has been performed (not shown) using the resonance parameters fixed from the fit to the total mass spectrum. A poor quality fit results which indicates that the underlying resonance structure may be more complicated. In order to try to understand the resonances that are present in the system an extraction of the partial waves is required.

A spin-parity analysis of the $\pi^+\pi^-\pi^+\pi^-$ channel has been performed using an isobar model [3]. Assuming that only angular momenta up to 2 contribute, the intermediate states considered are

$$\begin{array}{lllll} \sigma\sigma, & \sigma(\pi^+\pi^-)_{S\text{-wave}}, & \sigma(\pi^+\pi^-)_{P\text{-wave}}, & \sigma(\pi^+\pi^-)_{D\text{-wave}}, & \sigma\rho^0, \\ \rho^0\rho^0, & \rho^0(\pi^+\pi^-)_{S\text{-wave}}, & \rho^0(\pi^+\pi^-)_{P\text{-wave}}, & \rho^0(\pi^+\pi^-)_{D\text{-wave}}, & \\ a_1(1260)\pi, & a_2(1320)\pi, & f_2(1270)\sigma, & f_2(1270)(\pi^+\pi^-)_{S\text{-wave}}, & \\ f_2(1270)\rho^0, & f_2(1270)f_2(1270) & & & \end{array}$$

where σ stands for the low mass $\pi\pi$ S-wave amplitude squared. Two parameterisations of the σ have been tried, that of Au, Morgan and Pennington [10] and that of Zou and Bugg [11]. The amplitudes have been calculated in the spin-orbit (LS) scheme using spherical harmonics.

In order to perform a spin parity analysis the log likelihood function, $\mathcal{L}_j = \sum_i \log P_j(i)$, is defined by combining the probabilities of all events in 40 MeV $\pi^+\pi^-\pi^+\pi^-$ mass bins from 1.02 to 2.82 GeV. The incoherent sum of various event fractions a_j is calculated so as to include more than one wave in the fit,

$$\mathcal{L} = \sum_i \log\left(\sum_j a_j P_j(i) + \left(1 - \sum_j a_j\right)\right) \tag{2}$$

where the term $(1 - \sum_j a_j)$ represents the phase space background. The negative log likelihood function $(-\mathcal{L})$ is then minimised using MINUIT [12]. Coherence between different J^P states and between different isobar amplitudes of a given J^P have been neglected in the fit. Different combinations of waves and isobars have been tried and insignificant contributions have been removed from the final fit. As was already mentioned in the WA91 publication [3], in the analysis of the $f_1(1285)$ and the $f_0(1450)$ peak there is little change in the result if the $\rho\rho$ amplitude is used instead of the $\rho(\pi\pi)_{P\text{-wave}}$. Using Monte Carlo simulations it has been found that the feed-through from one spin parity to another is negligible and that the peaks in the spin analysis can not be produced by phase space or acceptance effects.

The results of the best fit are shown in Fig. 2 for the total data sample and in Fig. 3 for three ranges of dP_T. The $f_1(1285)$ is clearly seen in the $J^P = 1^+$ $\rho\rho$. Superimposed on the $J^P = 1^+$ $\rho\rho$ wave for the total sample is the Breit Wigner convoluted with a Gaussian used to describe the $f_1(1285)$ in the fit to the mass spectrum. As can be seen the $f_1(1285)$ is well represented in both size and shape. From Fig. 3 it can be seen that the $f_1(1285)$ dies away for $dP_T \leq 0.2$ GeV.

The $J^P = 0^+\rho\rho$ distribution in Fig. 2 shows a peak at 1.45 GeV together with a broad enhancement around 2 GeV. In order to test if the peak at 1.45 GeV is due to $\sigma\sigma$ rather than $\rho\rho$ the change in log likelihood in the four 40 MeV bins around 1.45 GeV has been calculated by replacing the $J^P = 0^+\rho\rho$ amplitude by the $J^P = 0^+\sigma\sigma$ amplitude. Both the Au, Morgan and Pennington [10] and the Zou and Bugg [11] parameterisations have been tried. However, there is very little difference between the two, and both result in a decrease of the likelihood $(\Delta\mathcal{L})$ of at least 9000, corresponding to $n = \sqrt{2\Delta\mathcal{L}} = 134$ standard deviations. This raises a possible problem in interpreting the peak at 1.45 GeV with the $f_0(1500)$ since the analysis of the 4π channel in $p\bar{p}$ by Crystal Barrel [13] and in radiative J/ψ decay [14] shows that the $f_0(1500)$ decays via $\sigma\sigma$. A Monte

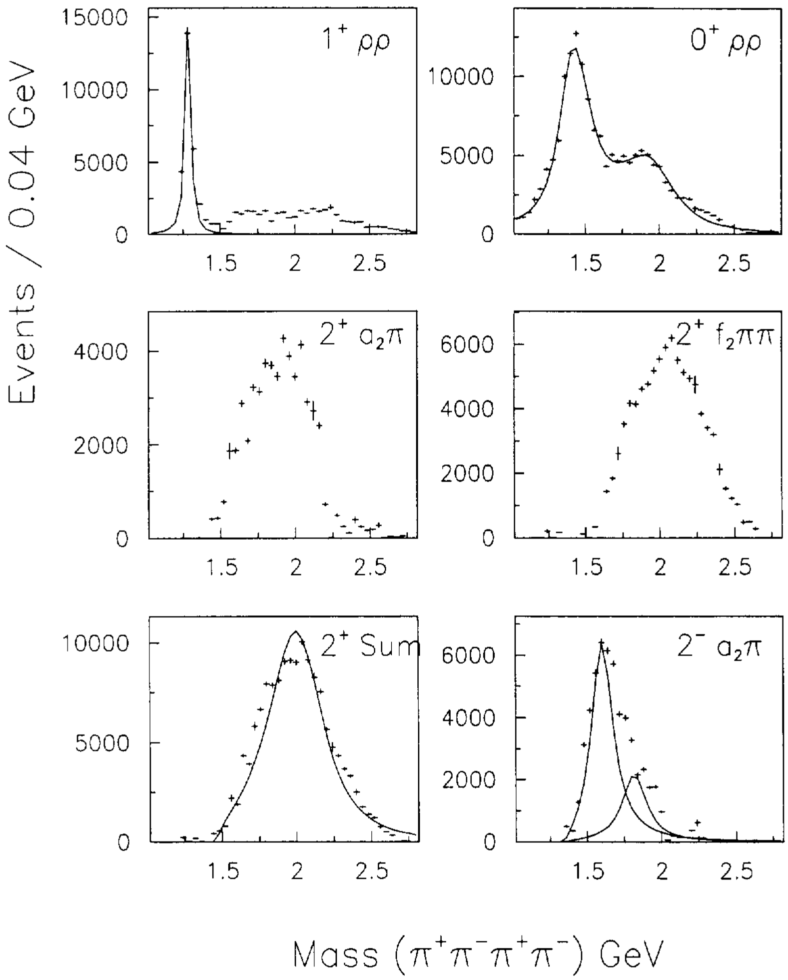

Fig. 2. Results of the spin parity analysis. The superimposed curves are the resonance contributions coming from the fits described in the text.

Carlo simulation has been performed in which the $f_0(1300)$ is made to decay equally to $\sigma\sigma$ and $\rho\rho$ and the $f_0(1500)$ is made to decay to $\sigma\sigma$ only. The data produced in this way is then passed through the spin analysis chain. The results of this analysis are very dependent on the interference model used but under certain circumstances it is possible to extract a result of pure $\rho\rho$ as is observed in the experimental data. Hence, a possible explanation could be that the interference between the $f_0(1300)$ and $f_0(1500)$ produces the observed $\rho\rho$ decay. This question should be answered in the future by a study of centrally produced $4\pi^0$ events.

From Fig. 3 it can be seen that the peak in the $J^P = 0^+\rho\rho$ wave around 1.45 GeV remains for $dP_T \leq 0.2$ GeV while the $J^P = 0^+$ enhancement at 2.0 GeV becomes less important: which shows that the dP_T effect is not simply a J^P filter. A fit has been performed to the $J^P = 0^+\rho\rho$ amplitude in Fig. 2 in the 1.45 GeV region using a single Breit-Wigner and gives a mass of 1445 $\pm$ 4 MeV and a width of 200 $\pm$ 20 MeV. The mass is compatible with the fit to the total mass spectrum although the width is broader; it is nonetheless compatible with a fit performed to the mass spectrum for $dP_T \leq$ 0.2 GeV. A similar fit has been performed to the $J^P = 0^+\rho\rho$ distributions shown in Fig. 3. The mass and width found in each interval are constant within the

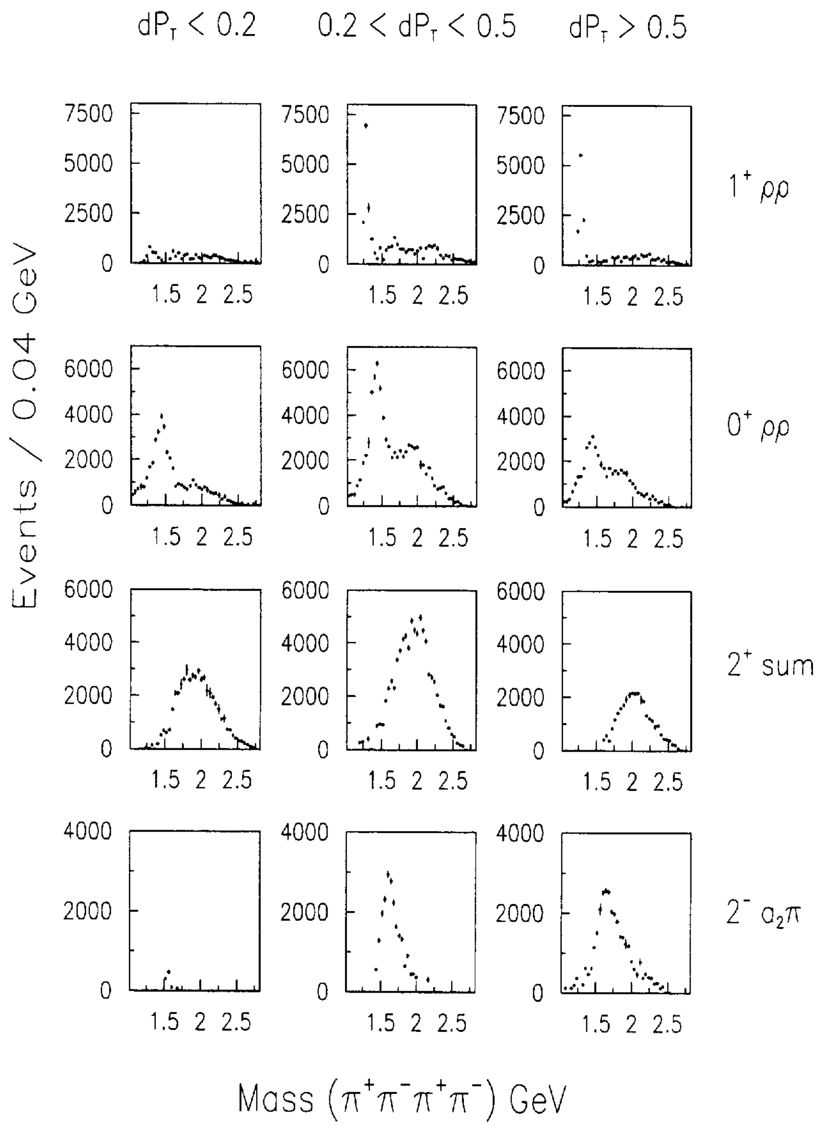

Fig. 3. Results of the spin parity analysis as a function of dP_T.

errors of the fit. This would indicate that either the peak is due to a single resonance or that if it is due to interference between the $f_0(1300)$ and $f_0(1500)$ then both states have a similar dP_T dependence.

In order to test the interference hypothesis a fit has first been performed to the total $J^P = 0^+\rho\rho$ distribution in Fig. 2 using a K matrix formalism [15] including poles to describe the interference between the $f_0(1300)$, the $f_0(1500)$ and a possible state at 2 GeV. The result of the fit is superimposed on the $J^P = 0^+\rho\rho$ distribution shown in Fig. 2 and well describes the data. The resulting resonance parameters are given in Table 1. The parameters of the $f_0(1300)$ and $f_0(1500)$ are very similar to those found by Crystal Barrel [16].

As can be seen from Fig. 2 neither the $J^P = 2^+$ $a_2(1320)\pi$ nor the $J^P = 2^+$ $f_2(1270)(\pi\pi)_{S\text{-wave}}$ alone can describe the $f_2(1900)$ peak observed in the mass spectrum. However, the sum of the two waves accounts for most of the $f_2(1900)$ signal. The $a_2(1320)\pi$ distribution and the $f_2(1270)(\pi\pi)_{S\text{-wave}}$ distribution peak at

Table 1
Parameters of resonances in the fit to the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum and waves

	Mass (MeV)	Width (MeV)	Observed decay mode	$I(J^{PC})$
$f_1(1285)$	1281 ± 1	24 ± 3	$\rho\pi\pi$	$0(1^{++})$
$f_0(1300)$	1290 ± 15	290 ± 30	$\rho\pi\pi$	$0(0^{++})$
$f_0(1500)$	1510 ± 20	120 ± 35	$\rho\pi\pi$	$0(0^{++})$
$f_0(2000)$	2020 ± 35	410 ± 50	$\rho\pi\pi$	$0(0^{++})$
$f_2(1900)$	1960 ± 30	460 ± 40	$a_2(1320)\pi$ $f_2(1270)\pi\pi$	$0(2^{++})$
$\eta_2(1620)$	1620 ± 20	180 ± 25	$a_2(1320)\pi$	$0(2^{-+})$
$\eta_2(1875)$	1840 ± 25	200 ± 40	$a_2(1320)\pi$	$0(2^{-+})$

different masses which suggests that the $f_2(1900)$ could be composed of two $J^{PC}=2^{++}$ resonances but neither distribution is well represented by a Breit-Wigner. However, the sum of the $J^P=2^+$ $a_2(1320)\pi$ and $J^P=2^+$ $f_2(1270)(\pi\pi)_{S\text{-wave}}$ waves has been fitted with a single Breit-Wigner, giving a better description, with $M = 1960 \pm 30$ MeV and $\Gamma = 460 \pm 40$ MeV. These values are compatible with those coming from the fit to the total mass spectrum.

In addition to these waves, an extra wave, not required in the WA76 and WA91 analyses, is found to be necessary in the fit, namely the $J^P=2^-$ $a_2(1320)\pi$ wave. The addition of this wave increases the log likelihood by 2700. The resulting $J^P=2^-$ $a_2(1320)\pi$ wave is shown in Fig. 2 where a broad enhancement is observed which peaks at 1.6 GeV. Other experiments have observed evidence for $J^{PC}=2^{-+}$ states in this region. In the reaction $\gamma\gamma \to \eta\pi\pi$ the Crystal Ball Collaboration [17] reported a $J^{PC}=2^{-+}$ state decaying to $a_2(1320)\pi$ and $a_0(980)\pi$ with a mass of 1881 ± 32 ± 40 MeV and a width of 221 ± 92 ± 44 MeV. In $p\bar{p}$ interactions the Crystal Barrel Collaboration [18] reported the observation of two $J^{PC}=2^{-+}$ states in the $\eta\pi\pi$ final state. The first state, called the $\eta_2(1620)$, had a mass of 1645 ± 14 ± 5 MeV and a width of 180 ± 40 ± 25 MeV and the second state, called the $\eta_2(1875)$, had a mass of 1875 ± 20 ± 35 MeV and a width of 250 ± 25 ± 45 MeV.

As can be seen from Fig. 2 the $J^P=2^-$ $a_2(1320)\pi$ wave observed in this experiment is consistent with the two η_2 resonances discussed above with both states decaying to $a_2(1320)\pi$. The masses and widths found from the fit are given in Table 1.

In order to calculate the contribution of each resonance as a function of the dP_T the distributions in Fig. 3 have been fitted with the parameters of the resonances fixed to those obtained from the fits to the total data. The results of the fits are given in Table 2.

As is observed from Figs. 1 and 3 and from Table 2 the $f_1(1285)$ signal almost disappears at small dP_T. In addition, the $2^{-+}a_2(1320)\pi$ signal is also suppressed at small dP_T. This behaviour is consistent with the signals being due to standard $q\bar{q}$ states [7]. Experiments WA76 and WA91, due to the trigger conditions used, studied

Table 2
Resonance production as a function of dP_T expressed as a percentage of its total contribution

	$dP_T \le 0.2$ GeV	$0.2 \le dP_T \le 0.5$ GeV	$dP_T \ge 0.5$ GeV
$f_1(1285)$	5.8 ± 0.4 ± 0.6	49.3 ± 1.3 ±2.3	44.8 ± 0.8 ± 1.9
$f_0(1300)$	28.4 ± 1.0 ± 2.0	43.2 ± 1.0 ± 2.5	28.4 ± 2.0 ± 2.0
$f_0(1500)$	30.8 ± 1.0 ± 2.0	50.5 ± 1.0 ± 2.5	18.8 ± 2.0 ± 2.0
$f_0(2000)$	12.2 ± 2.0 ± 1.5	53.1 ± 2.0 ± 4.0	34.7 ± 2.5 ± 3.0
$f_2(1900)$	31.1 ± 2.0 ± 0.5	49.2 ± 2.0 ± 2.3	19.7 ± 1.0 ± 1.9
$\eta_2(1620)$	2.4 ± 1.0 ± 0.5	50.6 ± 3.4 ± 5.0	46.8 ± 3.3 ± 4.6
$\eta_2(1875)$	0.4 ± 0.4 ± 0.8	39.3 ± 6.0 ± 5.0	60.3 ± 6.0 ± 5.0

events that were preferentially at smaller dP_T and in addition both experiments had much smaller statistics. For these reasons the $2^{-+} a_2(1320)\pi$ wave was found to be not sufficiently significant in the previous analyses and therefore was not included in the final fit.

The $0^{++} \rho\rho$ wave shows that the $f_0(1450)$ peak is still prominent at small dP_T. If the peak is interpreted as the interference between the $f_0(1300)$ and $f_0(1500)$ then, as can be seen from Table 2, both must have a similar dP_T dependence. The broad peak at 2.0 GeV in the $0^{++} \rho\rho$ wave, called the $f_0(2000)$, is less prominent at small dP_T and is more consistent with other $q\bar{q}$ states.

The ratio of the number of events in the $J^P = 2^+$ $a_2(1320)\pi$ and $J^P = 2^+$ $f_2(1270)(\pi\pi)_{S\text{-wave}}$ distributions remains constant as a function of dP_T. In Fig. 3 the sum of these two waves is presented. The peak of the distribution does vary with dP_T which may suggest a more complex underlying structure. However, the majority of the signal can be explained as being due to a $f_2(1900)$ whose parameters are given above. As can be seen from this figure and from Table 2 at small dP_T the $f_2(1900)$ signal is still important. This is the first evidence of a non-zero spin resonance produced at small dP_T and hence shows that the dP_T effect is not just a $J^P = 0^+$ filter.

It is interesting to note that the prominence of the $f_0(1450)$ and $f_2(1900)$ signals in Fig. 1b) for $dP_T \leq 0.2$ GeV is not only due to the fact that the $f_0(1450)$ and $f_2(1900)$ signals are strong at small dP_T but also due to the fact that the η_2 signals are suppressed.

In summary, in the centrally produced $\pi^+\pi^-\pi^+\pi^-$ mass spectrum two interesting structures are observed at 1.45 and 1.9 GeV. A spin analysis shows that the underlying resonance structure is more complex. The peak at 1.45 GeV is found to have $J^{PC} = 0^{++}$ and to decay to $\rho\rho$; it can either be described as a single Breit-Wigner or as an interference between the $f_0(1300)$ and $f_0(1500)$. The peak observed at 1.9 GeV appears as a broad enhancement in the mass spectrum and is found to decay to $a_2(1320)\pi$ and $f_2(1270)\pi\pi$ with $J^{PC} = 2^{++}$. Due to the difficulty in describing the individual $a_2(1320)\pi$ and $f_2(1270)\pi\pi$ contributions by a Breit Wigner it is likely that this is one state, called the $f_2(1900)$, with two decay modes. Confirmation is found for two $J^{PC} = 2^{-+}$ resonances, called the $\eta_2(1620)$ and $\eta_2(1875)$ decaying to $a_2(1320)\pi$. There is also evidence for a broad state with $J^{PC} = 0^{++}$ decaying to $\rho\rho$, called the $f_0(2000)$.

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