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A study of the $\omega\omega$ channel produced in central pp interactions at 450 GeV/c

The WA102 Collaboration

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Abstract

The reaction $pp \to p_f(\omega\omega)p_s$ has been studied at 450 GeV/c and a spin analysis of the $\omega\omega$ channel has been performed for the first time in central production. Evidence is found for the $f_2(1910)$ in the $J^{PC} = 2^{++}$ wave with spin projection $J_Z = 2$. This is the only state observed in central production with spin projection $J_Z = 2$. Its dP_T and ϕ dependencies are similar to those observed for other glueball candidates. In addition, evidence is found for a state with $J^{PC} = 4^{++}$ consistent with the $f_4(2300)$. The $f_0(2000)$, previously observed in the $\rho\rho$ final state, is confirmed.

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The $\omega\omega$ channel has been studied in several different production mechanisms. In $\pi^- p$ interactions the $\omega\omega$ final state has been studied by the NA12 [1] and VES [2] collaborations. In both experiments clear signals were observed at 1.6 and 1.9 GeV and were found to have $J^{PC} = 2^{++}$, called the $f_2(1640)$ and $X(1910)$ [3]. In addition, the VES collaboration reported evidence for an $\omega\omega$ decay mode of the $f_4(2050)$ and, more recently, for a $J^{PC} = 4^{++}$ object in the 2.3 GeV region [4]. In $p\bar{p}$ annihilations C. Baker et al., using the data from the Crystal Barrel experiment [5], have reported evidence for a structure similar to the $f_2(1640)$ in the $\omega\omega$ final state but have shown that this state can be interpreted as being due to the $f_2(1565)$ previously observed in the $\pi\pi$ final state [3]. The PDG [3] lists the $X(1910)$ observed in the $\omega\omega$ final state with another $J^{PC} = 2^{++}$ resonance with similar mass and width observed in the $\eta\eta'$ final state. In central production the WA102 experiment did not observe the $f_2(1565)$ in the $\pi\pi$ final state [6], therefore, the centrally produced $\omega\omega$ channel can give information on the validity of the $f_2(1565)/f_2(1640)$ assignment. In addition, in the $\eta\eta'$ final state of the WA102 experiment [7] a peak was observed at 1.9 GeV which was consistent in mass and width with the $X(1910)$. A spin analysis showed that this state was consistent with having $J^{PC} = 1^{-+}$ with spin projection $J_Z = 1$ or $J^{PC} = 2^{++}$ with spin projection $J_Z = 2$. If the latter hypothesis were true then this was the first time that a state had been observed in central production that was produced with spin projection $J_Z = 2$. Hence, if the states observed in $\omega\omega$ and $\eta\eta'$ are the same and the $X(1910)$ has $J^{PC} = 2^{++}$, the $X(1910)$ should be observed in the $J_Z = 2$ projection in the $\omega\omega$ final state. In central production, the $\omega\omega$ final state was previously observed by the WA76 experiment [8] but only 80 events were observed and hence no strong conclusions could be drawn.

In this paper, a study is presented of the $\omega\omega$ final state formed in the reaction

$$pp \to p_f(\omega\omega)p_s \tag{1}$$

at 450 GeV/c. It represents more than a factor of 60 increase in statistics over previous data on the centrally produced $\omega\omega$ final state [8] and, moreover, will present a spin analysis of this channel in central production. The data come from the WA102 experiment which has been performed using the CERN Omega Spectrometer, the layout of which is described in ref. [9]. Reaction (1) has been isolated using the $\pi^+\pi^-\pi^0$ decay mode of both ωs. The reaction

$$pp \to p_f(\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0)p_s$$

has been isolated from the sample of events having six 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| $<$ 17.0 GeV/c, |missing P_y| $<$ 0.16 GeV/c and |missing P_z| $<$ 0.12 GeV/c, where the x axis is along the beam direction. The two photon mass spectrum, when the mass of the other 2γ-pair lies within a band around the π^0 mass (100–170 MeV), shows a clear π^0 signal with small background. Events containing a fast $\Delta^{++}(1232)$ were removed if $M(p_f\pi^+) < 1.3$ GeV, which left 294 463 centrally produced $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$ events.

Fig. 1a) shows a lego plot of $M(\pi^+\pi^-\pi^0)$ versus $M(\pi^+\pi^-\pi^0)$ (four combinations per event). A clear signal of the $\omega\omega$ channel can be observed. Fig. 1b) shows the $\pi^+\pi^-\pi^0$ mass spectrum if the other $\pi^+\pi^-\pi^0$ combination is compatible with being an ω ($0.76 \leq$ M($\pi^+\pi^-\pi^0$) ≤ 0.81 GeV) where a clear ω signal can be observed. A tight cut has been used around the ω signal to increase the signal to background ratio in the selected sample. In order to decrease the background further the parameter λ is introduced which describes the ω decay on the Dalitz plot and is defined as:

$$\lambda = \frac{|\vec{p}_+ \times \vec{p}_-|^2}{\frac{3}{4}(\frac{1}{9}m^2 - m_\pi^2)^2}$$

where $|\vec{p}_+ \times \vec{p}_-|$ is proportional to the decay matrix element for $\omega \to \pi^+\pi^-\pi^0$, $\vec{p}_\pm$ is the three momentum of the $\pi^\pm$ in the ω rest frame and m^2 is the $\pi^+\pi^-\pi^0$ effective mass squared. Superimposed on fig. 1b) as a shaded histogram is the $\pi^+\pi^-\pi^0$ mass distribution for $\lambda > 0.3$. As can be seen the signal to background ratio in the ω region has increased.

The $\omega\omega$ final state has been selected using the $\pi^+\pi^-\pi^0$ mass cuts described above and by requiring that the $\lambda > 0.3$ for each ω candidate. The resulting $\omega\omega$ mass spectrum is shown in fig. 1c) and consists of 5067 events. As can be seen there is a peak in the 1.9 GeV region.

The background below the ω signal has several sources including combinatorics and other channels. The combinatorial background is removed, in part, in the selection procedure. The remaining background is approximately 27 %. Four methods have been used to determine the effects of this background; studying the side bands around the ω signal, studying events that do not balance momentum, studying events that do not pass the λ selection cuts and studying events from the $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ channel. Since the majority of the background is due to other physical channels for example $a_1(1260)a_1(1260)$ or $\omega a_1(1260)$ production, the two methods that best reproduce the background are the one using events that do not pass the λ cut and the other uses events from the $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ channel. These two methods give a very similar representation of the background. In the remainder of this paper the method used to determine the background will be the mean of these two methods. Superimposed on the $\omega\omega$ mass spectrum in fig 1c) as a shaded histogram is the estimate of the background.

A spin analysis of the centrally produced $\omega\omega$ system has been performed using the method described in ref. [10] for the $\rho\rho$ final state modified for the $\omega\omega$ channel. The z axis is defined by the momentum vector of the exchanged particle with the greatest four-momentum transferred in the $\omega\omega$ centre of mass. Assuming that only angular momenta up to 4 contribute, 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 50 MeV $\omega\omega$ mass bins from 1.5 to 3.0 GeV. The incoherent sum of various event fractions a_j is calculated so as to include more than one wave in the fit,

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

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 [11]. Coherence between different J^P states has been neglected in the fit. Different combinations of waves have been tried and insignificant contributions have been removed from the final fit.

It is found necessary to introduce the $J^{PC} = 2^{++}$ wave with both $J_Z = 0$ and 2, the $J^{PC} = 0^{++}$ wave and the $J^{PC} = 4^{++}$ wave with $J_Z = 1$. The results of the best fit are shown in fig. 2.

The $J^{PC} = 2^{++}$ wave with $J_Z = 2$ shows a peak at 1.9 GeV. This wave has been fitted using a spin 2 relativistic Breit-Wigner and a linear background and is shown superimposed. The fit gives M = 1897 $\pm$ 11 MeV, Γ = 202 $\pm$ 32 MeV, parameters consistent with those of the $X(1910)$ found from a fit to the $\eta\eta'$ final state [7]. Hence this consistent with the fact that the $X(1910)$ has $\omega\omega$ and $\eta\eta'$ decay modes, and we shall refer to it as the $f_2(1910)$ hereafter. Correcting for the unseen decay modes and the effects of the detector, the branching ratio $\omega\omega$ /$\eta\eta'$ of the $f_2(1910)$ is 2.6 $\pm$ 0.6. There was no evidence for any wave with $J_Z = 2$ in the $\eta\eta$ final state of the WA102 experiment [12] and hence an upper limit for the branching ratio $\eta\eta$ /$\eta\eta'$ of the $f_2(1910)$ has been calculated to be < 0.2 (90 % CL).

The $J^{PC} = 2^{++}$ wave with $J_Z = 0$ shows a broad enhancement. Superimposed on the wave is a shaded histogram representing the $f_2(1640)$. As can be seen the $J^{PC} = 2^{++}$ wave with $J_Z = 0$ is not compatible with the $f_2(1640)$ observed by other experiments. This non observation does not contradict the claim that the $f_2(1640)$ is an $\omega\omega$ decay mode of the $f_2(1565)$ since this state is also not observed in central production.

The $J^{PC} = 0^{++}$ wave shows some activity near threshold and a broad enhancement around 2 GeV. In a previous analysis of the 4π channel, the WA102 experiment observed a similar structure in the $J^{PC} = 0^{++}$ $\rho\rho$ wave which was identified with the $f_0(2000)$. Superimposed on the wave is a shaded histogram representing the $f_0(2000)$ assuming that the branching ratio $\rho\rho/\omega\omega$ = 3 as expected for a isoscalar resonance. This well represents the wave in the 2 GeV region.

The $J^{PC} = 4^{++}$ wave with $J_Z = 1$ shows no evidence for the $f_4(2050)$ but does show a peak at 2.3 GeV. The change in log likelihood in the three 50 MeV bins around the 2.3 GeV peak produced by introducing the $J^{PC} = 4^{++}$ wave with $J_Z = 1$ is $\Delta\mathcal{L} = 28$. This is the first time that it has been found necessary to introduce any wave with $J > 2$ in the WA102 data. This wave has been fitted using a spin 4 relativistic Breit-Wigner and a linear background and is superimposed on the wave. The fit gives M = 2332 $\pm$ 15 MeV, Γ = 260 $\pm$ 57 MeV parameters consistent with those found by the VES experiment [4]. This state is most likely the $f_4(2300)$ observed previously in other experiments [13] and we shall refer to it as so hereafter.

States that have a decay to $\omega\omega$ might also be expected to have a decay to $\rho\rho$. As was observed above there appears to be evidence for an $\omega\omega$ decay of the $f_0(2000)$ previously observed in the $\rho\rho$ final state. In the previous analysis of the 4π final state [14], no evidence was claimed for either a $J^{PC} = 2^{++}$ $\rho\rho$ wave with $J_Z = 2$ or a $J^{PC} = 4^{++}$ $\rho\rho$ wave with $J_Z = 1$. Because of the large number of possible waves in the 4π final state ($\sim$ 180 for $J \leq 2$) only waves that changed the log likelihood by more than 100 were considered. The $J^{PC} = 2^{++}$ $\rho\rho$ wave with $J_Z = 2$ was rejected because it changed the likelihood by $\sim$ 60. The $J^{PC} = 4^{++}$ $\rho\rho$ wave with $J_Z = 1$ was not considered because only waves with $J \leq 2$ were included in the fit. If the $J^{PC} = 2^{++}$ $\rho\rho$ wave with $J_Z = 2$ and the $J^{PC} = 4^{++}$ $\rho\rho$ wave with $J_Z = 1$ are both introduced into the fit of the $\pi^+\pi^-\pi^+\pi^-$ channel then the log likelihood increases by 58 units in the region of the $f_2(1910)$ and 27 units in the $f_4(2300)$ region. If the signal in the $J^{PC} = 2^{++}$ $\rho\rho$ wave with $J_Z = 2$ is interpreted as being due to the $f_2(1910)$ then after correcting for the unseen decay modes and the effects of the detector the branching ratio $\rho\rho$ /$\omega\omega$ of the $f_2(1910)$ is 2.6 $\pm$ 0.4 consistent with it being at isoscalar resonance. Similarly if the signal in the $J^{PC} = 4^{++}$ $\rho\rho$ wave with $J_Z = 1$ is interpreted as being due the $f_4(2300)$ then after correcting for the unseen decay modes and the effects of the detector the branching ratio $\rho\rho$ /$\omega\omega$ of the $f_4(2300)$ is 2.8 $\pm$ 0.5.

In previous analyses a study has been made of how different resonances are produced as a function of the parameter dP_T, which is the difference in the transverse momentum vectors of the two exchange particles [9, 15], and as a function of the azimuthal angle ϕ which is defined as the angle between the p_T vectors of the two outgoing protons. A study of the background subtracted $\omega\omega$ system over the whole mass range as a function of dP_T has been performed. The fraction of all $\omega\omega$ production has been calculated for $dP_T \leq 0.2$ GeV, $0.2 \leq dP_T \leq 0.5$ GeV and $dP_T \geq 0.5$ GeV and gives 0.12 $\pm$ 0.02, 0.36 $\pm$ 0.02 and 0.52 $\pm$ 0.02 respectively. This results in a ratio of production at small dP_T to large dP_T of 0.23 $\pm$ 0.04. This ratio is much lower than has been observed [16, 17] in the $K^*(892)\overline{K}^*(892)$ and $\phi\phi$ final states. However, the latter final states have been shown to be dominantly due to the $f_2(1950)$ which is produced mainly at small dP_T [18].

The amount of $f_2(1910)$ has also been determined in the same dP_T intervals and gives 0.20 $\pm$ 0.04, 0.62 $\pm$ 0.07 and 0.18 $\pm$ 0.04 respectively. This results in a ratio of production at small dP_T to large dP_T of 1.1 $\pm$ 0.3. This value is consistent with what has been observed for the glueball candidates the $f_0(1500)$, $f_0(1710)$ and $f_2(1950)$ [18, 19, 20].

The azimuthal angle (ϕ) between the p_T vectors of the two protons is shown in fig. 3a) for the background subtracted $\omega\omega$ channel for the entire mass range and in fig. 3b) for the $f_2(1910)$. The distribution for the $f_2(1910)$ is similar to that observed for other glueball candidates [18, 19].

In summary, a spin analysis of the $\omega\omega$ channel has been performed for the first time in central production. Evidence is found for the $f_2(1910)$ in the $J^{PC} = 2^{++}$ wave with spin projection $J_Z = 2$. This is the only state observed in central production with spin projection $J_Z = 2$. Its dP_T and ϕ dependencies are similar to those observed for other glueball candidates. In addition, evidence is found for a state with $J^{PC} = 4^{++}$ consistent with the $f_4(2300)$. The $f_0(2000)$, previously observed in the $\rho\rho$ final state, is confirmed.

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Figures

Figure 1: Selection of the $\omega\omega$ final state: a) M($\pi^+\pi^-\pi^0$) versus M($\pi^+\pi^-\pi^0$), b) M($\pi^+\pi^-\pi^0$) if the other $\pi^+\pi^-\pi^0$ combination is in the ω band ($0.76 \leq$ M($\pi^+\pi^-\pi^0$) ≤ 0.81 GeV). Superimposed as a shaded histogram is the case for $\lambda > 0.3$. c) The $\omega\omega$ mass spectrum. Superimposed as a shaded histogram is an estimation of the background contribution.

Figure 2: Results of the spin analysis for the $\omega\omega$ channel: a) The total mass spectrum, b) 2^{++} $J_Z = 2$, c) 2^{++} $J_Z = 0$, d) 0^{++} and e) 4^{++} $J_Z = 1$. The superimposed curves are the resonance contributions coming from the fits described in the text.

Figure 3: The ϕ distribution for the a) the $\omega\omega$ channel and b) for the $f_2(1910)$.

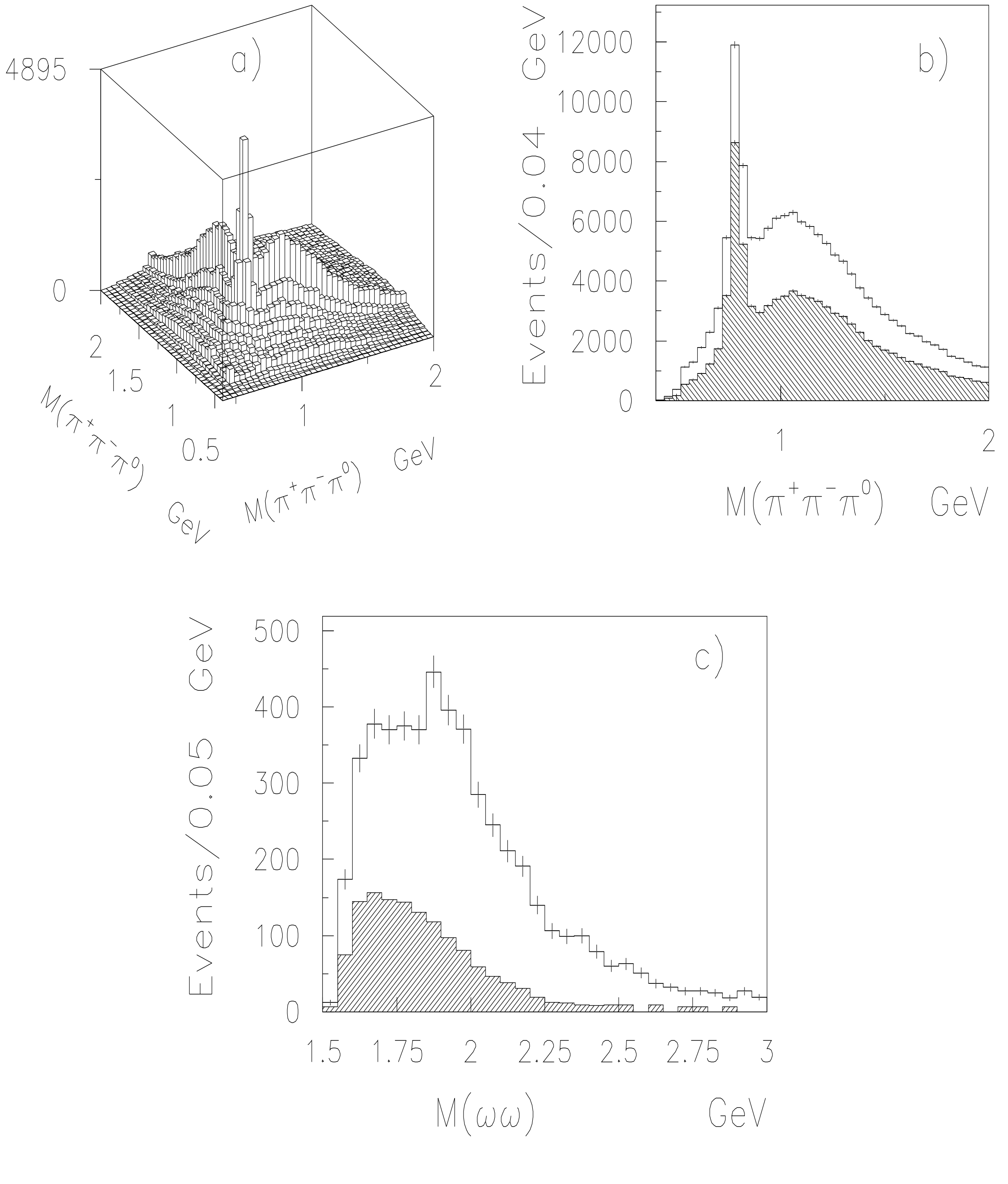
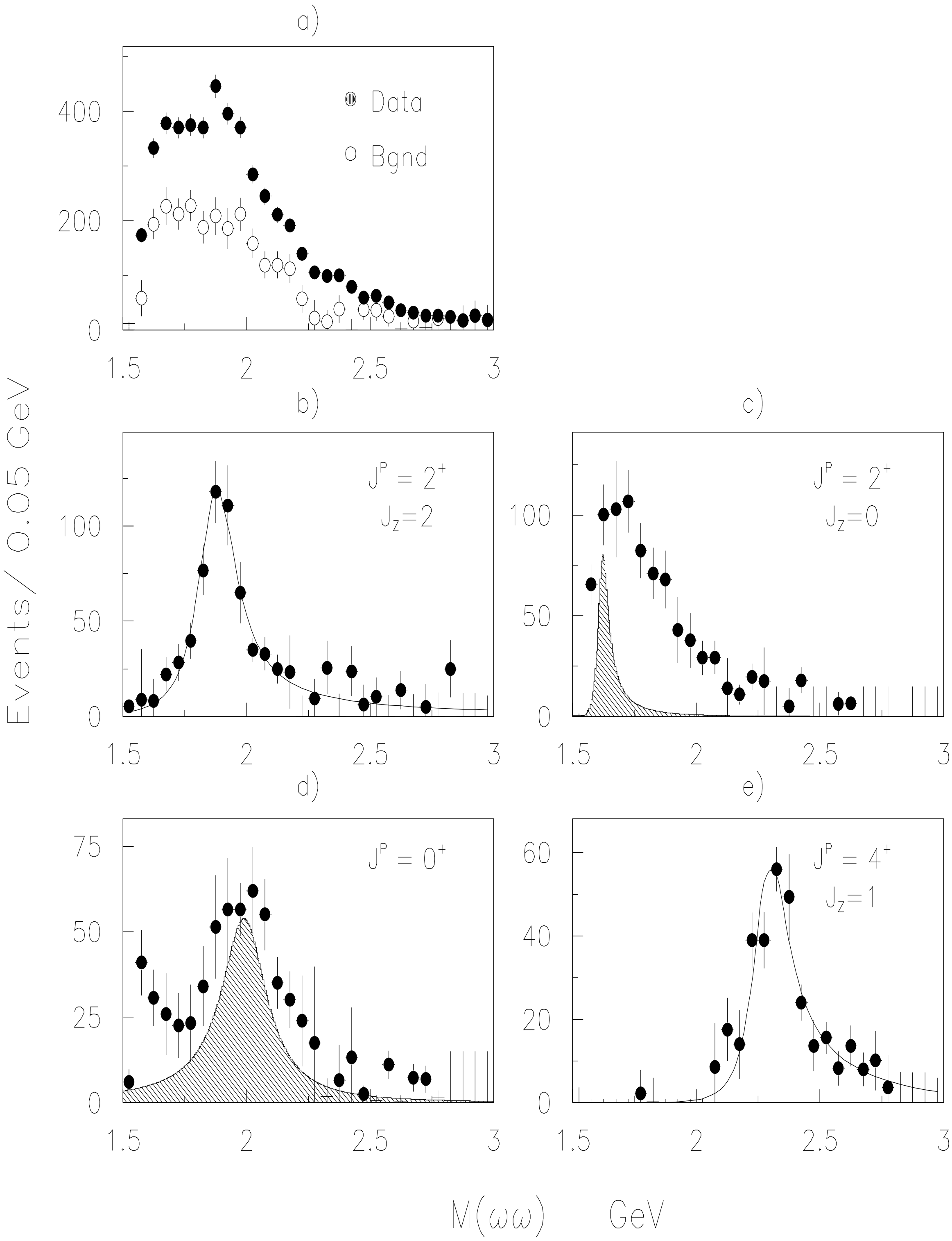

a)
4895
0
2
1.5
1
0.5
1
2
M(π⁺π⁻π⁰) GeV
M(π⁺π⁻π⁰) GeV
b)
Events/0.04 GeV
12000
10000
8000
6000
4000
2000
0
1
2
M(π⁺π⁻π⁰) GeV
c)
Events/0.05 GeV
500
400
300
200
100
0
1.5
1.75
2
2.25
2.5
2.75
3
M(ωω) GeV

Figure 1



a)
Data
Bgnd
b)
$J^P = 2^+$
$J_z=2$
c)
$J^P = 2^+$
$J_z=0$
d)
$J^P = 0^+$
e)
$J^P = 4^+$
$J_z=1$
Events/ 0.05 GeV
$M(\omega\omega)$ GeV

Figure 2

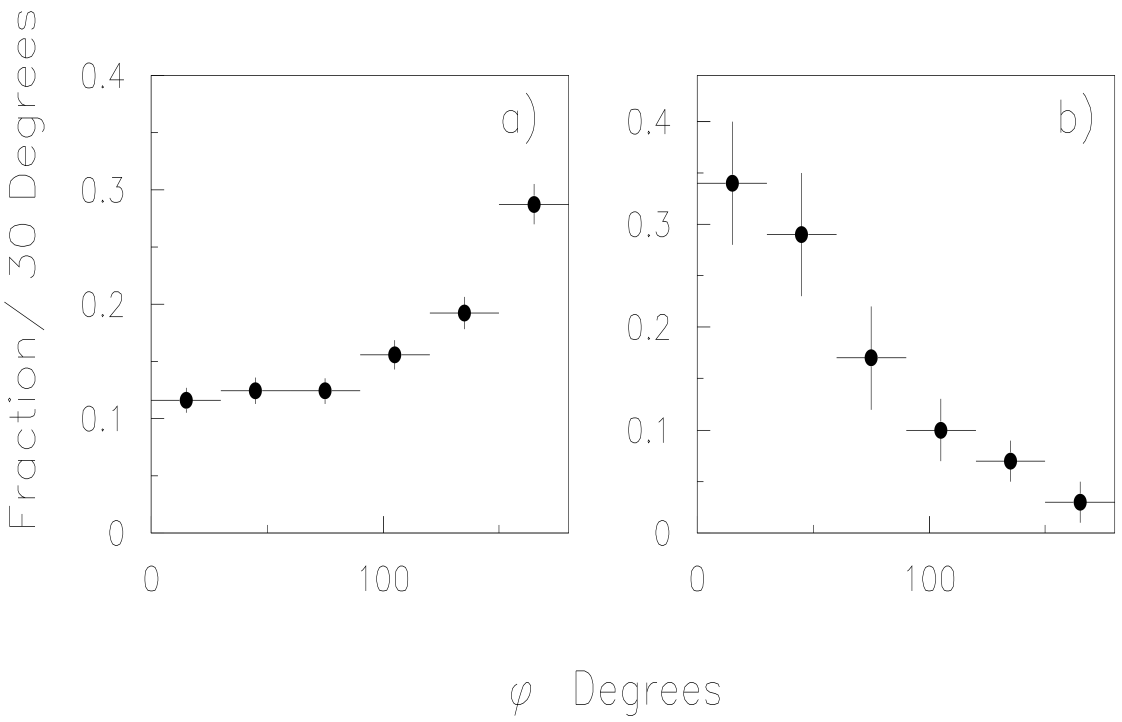

Fraction/ 30 Degrees
0.4
0.3
0.2
0.1
0
a)
0
100
0.4
0.3
0.2
0.1
0
b)
0
100
φ Degrees

Figure 3