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

The WA102 Collaboration

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Abstract

The reaction $pp \to p_f(\eta\pi^+\pi^-)p_s$ has been studied at 450 GeV/c. There is clear evidence for an $a_2(1320)\pi$ decay mode of the $\eta_2(1645)$ and $\eta_2(1870)$. In addition, there is evidence for an $a_0(980)\pi$ decay mode of both resonances and an $f_2(1270)\eta$ decay mode of the $\eta_2(1870)$. No evidence is found for a $J^{PC} = 2^{++}$ $a_2(1320)\pi$ wave.

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In an analysis of the $\pi^+\pi^-\pi^+\pi^-$ final state the WA102 collaboration observed three peaks in the mass spectrum [1]. A spin analysis showed that the peak at 1.28 GeV was due to the $f_1(1285)$, the peak at 1.45 GeV could be interpreted as being due to interference between the $f_0(1370)$ and $f_0(1500)$ and the peak at 1.9 GeV, called the $f_2(1950)$, was found to have $I^G J^{PC} = 0^+2^{++}$ and decay to $f_2(1270)\pi\pi$ and $a_2(1320)\pi$ [1]. However, it was not possible to determine whether the $f_2(1950)$ was one resonance with two decay modes, or two resonances, or if one of the decay modes was spurious.

One of the major problems of studying the $\pi^+\pi^-\pi^+\pi^-$ final state is the number of possible isobar decay modes that are present. Therefore in this paper, in order to study the $a_2(1320)\pi$ final state, an analysis is presented of the $\eta\pi^+\pi^-$ channel. In addition, the spin analysis of the $\pi^+\pi^-\pi^+\pi^-$ channel showed evidence in the $J^{PC} = 2^{-+}$ $a_2(1320)\pi$ wave for the $\eta_2(1645)$ and $\eta_2(1870)$. There has been previous evidence [2] that the $\eta_2(1645)$ and $\eta_2(1870)$ may decay to $a_0(980)\pi$ and $f_2(1270)\eta$. These two decay modes will be searched for in the present analysis.

The data come from the WA102 experiment which has been performed using the CERN Omega Spectrometer, the layout of which is described in ref. [3]. The selection of the reaction

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

where the subscripts f and s indicate the fastest and slowest particles in the laboratory respectively, has been described in ref. [4]. The η has been observed decaying to $\gamma\gamma$ and $\pi^+\pi^-\pi^0$. Fig. 1a) and 1b) show the $\eta\pi^+\pi^-$ mass spectra for the decays $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ respectively. The mass spectra are dominated by the η' and $f_1(1285)$.

In this current paper a spin-parity analysis of the $\eta\pi^+\pi^-$ channel is presented for the mass interval 1.0 to 2.0 GeV using an isobar model [5]. Assuming that only angular momenta up to 2 contribute, the intermediate states considered are $a_0(980)\pi$, $\sigma\eta$, $f_0(980)\pi$, $a_2(1320)\pi$, and $f_2(1270)\eta$. σ stands for the low mass $\pi\pi$ S-wave amplitude squared [6]. 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 $\eta\pi^+\pi^-$ mass bins from 1.0 to 2.0 GeV. The incoherent sum of various event fractions a_j is calculated so as to include more than one wave in the fit, using the form:

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

where the term $(1 - \sum_j a_j)$ represents the phase space background. This background term is used to account for the background below the η (which is 10 % for the $\gamma\gamma$ decay mode and 15 % for the $\pi^+\pi^-\pi^0$ decay mode), $\eta\pi^+\pi^-$ three body decays and decay modes not parameterised in the fit. The negative Log Likelihood function ($-\mathcal{L}$) is then minimised using MINUIT [7]. Different combinations of waves and isobars have been tried and insignificant contributions have been removed from the final fit.

The spin analysis has been performed independently for the two η decay modes. As was shown in the previous analysis [4], for both decay modes and for M($\eta\pi^+\pi^-$) $\leq$ 1.5 GeV the only wave required in the fit is the $J^{PC} = 1^{++}$ $a_0(980)\pi$ wave with spin projection $|J_Z| = 1$. No $J^{PC} = 0^{-+}$ $a_0(980)\pi$ or any $\sigma\eta$ waves are required in the fit. Fig. 2a) and 3a) show the $J^{PC} = 1^{++}$ $a_0(980)\pi$ wave where the $f_1(1285)$ and a shoulder at 1.4 GeV can be seen.

Superimposed on the waves is the result of the fit used in ref. [4] which uses a K matrix formalism including poles to describe the interference between the $f_1(1285)$ and the $f_1(1420)$. As can be seen from fig. 2a) and 3a) the parameterisation describes well the $J^{PC} = 1^{++}$ $a_0(980)\pi$ wave.

For M($\eta\pi^+\pi^-$) $\geq$ 1.5 GeV only waves with $J^{PC} = 2^{-+}$ and $|J_Z| = 1$ are required in the fit. In contrast to what was found in the analysis of the $\pi^+\pi^-\pi^+\pi^-$ final state [1] there is no evidence for any $J^{PC} = 2^{++}$ $a_2(1320)\pi$ wave. The largest change in Log Likelihood comes from the addition of the $J^{PC} = 2^{-+}$ $a_2(1320)\pi$ wave with $|J_Z| = 1$ which yields a Likelihood difference $\Delta\mathcal{L} = 562$ and 203 for the $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ decays respectively and are shown in fig. 2b) and 3b).

As was observed in the case of the $\pi^+\pi^-\pi^+\pi^-$ channel [1], the $J^{PC} = 2^{-+}$ $a_2(1320)\pi$ wave is consistent with being due to two resonances, the $\eta_2(1645)$ and the $\eta_2(1870)$. Superimposed on figs. 2b) and 3b) is the result of a fit using a single channel K matrix formalism [9] with two resonances to describe the $\eta_2(1645)$ and $\eta_2(1870)$. The masses and widths determined for each resonance and each η decay mode are given in table 1. The parameters found are consistent for the two decay modes and with the PDG [8] values for these resonances. An alternative fit has been performed using two interfering Breit-Wigners. The parameters presented include not only the statistical error but also the systematic error, added in quadrature, representing the difference in the two fits.

The addition of the $J^{PC} = 2^{-+}$ $a_0(980)\pi$ wave with $|J_Z| = 1$ yields a Likelihood difference $\Delta\mathcal{L} = 66$ and 23 for the two η decay modes respectively and the waves are shown in figs. 2c) and 3c). Superimposed is the result of a fit using the parameters for the $\eta_2(1645)$ and the $\eta_2(1870)$ determined from the fit to the $a_2(1320)\pi$ final state. A good description of the data is found. The branching ratio of the $\eta_2(1645)$ and $\eta_2(1870)$ to $a_2(1320)\pi/a_0(980)\pi$ in the $\eta\pi\pi$ final state can be determined. Neglecting unseen decay modes the branching ratio of $\eta_2(1645)$ to $a_2(1320)\pi/a_0(980)\pi = 2.3 \pm 0.4$ and 2.1 ± 0.5 for the decays $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ respectively. The branching ratio of $\eta_2(1870)$ to $a_2(1320)\pi/a_0(980)\pi = 5.0 \pm 1.6$ and 6.0 ± 1.9 respectively.

Correcting for the unseen $a_2(1320)$ decay modes using the PDG [8] branching ratio and using the branching ratio for the $a_0(980)$ to $\eta\pi$ determined by this experiment [4] of 0.86 ± 0.10 and taking the average of the two η decay modes the branching ratio to $a_2(1320)\pi/a_0(980)\pi$ for the $\eta_2(1645)$ is 13.0 ± 2.7 and for the $\eta_2(1870)$ is 32.6 ± 12.6.

The addition of the $J^{PC} = 2^{-+}$ $f_2(1270)\eta$ wave with $|J_Z| = 1$ yields a Likelihood difference $\Delta\mathcal{L} = 42$ and 12 and the waves are shown in figs. 2d) and 3d). The $f_2(1270)\eta$ wave shows little evidence for the $\eta_2(1645)$. Superimposed is the result of a fit using the parameters for the $\eta_2(1870)$ determined from the fit to the $a_2(1320)\pi$ final state. A satisfactory description of the data is found. Correcting for the unseen $a_2(1320)$ and $f_2(1270)$ decay modes the branching ratio of the $\eta_2(1870)$ to $a_2(1320)\pi/f_2(1270)\eta$ has been determined to be 38.5 ± 14.4 and 56.0 ± 33.4 for the two η decay modes. The addition of the $J^{PC} = 2^{-+}$ $f_0(980)\eta$ or $J^{PC} = 2^{-+}$ $\sigma\eta$ waves produces no significant change in the Likelihood and hence they have been excluded from the fit. The resulting background term is found to be smooth and structureless and corresponds to ≈ 40 % of the channel.

In previous analyses it has been observed that when the centrally produced system has been analysed as a function of the parameter dP_T, which is the difference in the transverse momentum vectors of the two exchange particles [3, 10], all the undisputed $q\overline{q}$ states (i.e. η, η', $f_1(1285)$ etc.) are suppressed as dP_T goes to zero, whereas the glueball candidates $f_0(1500)$, $f_0(1710)$ and $f_2(1950)$ are prominent [11]. In order to calculate the contribution of each resonance as a function of dP_T, the waves have been fitted in three dP_T intervals with the parameters of the resonances fixed to those obtained from the fits to the total data. Table 2 gives the percentage of each resonance in three dP_T intervals together with the ratio of the number of events for dP_T $<$ 0.2 GeV to the number of events for $dP_T >$ 0.5 GeV for each resonance considered. These distributions are similar to what have been observed for other $q\overline{q}$ states [11].

In addition, an interesting effect has been observed in the azimuthal angle ϕ which is defined as the angle between the p_T vectors of the two outgoing protons. For the resonances studied to date which are compatible with being produced by DPE, the data [12]. are consistent with the Pomeron transforming like a non-conserved vector current [13]. In order to determine the ϕ dependence for the resonances observed, a spin analysis has been performed in the $\eta\pi^+\pi^-$ channel in four different ϕ intervals each of 45 degrees. The results are shown in fig. 4a) and b) for the $\eta_2(1645)$ and $\eta_2(1870)$ respectively.

In order to determine the four momentum transfer dependence ($|t|$) of the resonances observed in the $\eta\pi^+\pi^-$ channel the waves have been fitted in 0.1 GeV^2 bins of $|t|$ with the parameters of the resonances fixed to those obtained from the fits to the total data. Fig. 4c) and d) show the four momentum transfer from one of the proton vertices for the $\eta_2(1645)$ and $\eta_2(1870)$ respectively. The distributions cannot be fitted with a single exponential. Instead they have been fitted to the form

$$\frac{d\sigma}{dt} = \alpha e^{-b_1 t} + \beta t e^{-b_2 t}$$

The parameters resulting from the fit are given in table 3.

After correcting for geometrical acceptances, detector efficiencies, losses due to cuts, and unseen decay modes of the $a_2(1320)$, the cross-section for the $\eta_2(1645)$ and $\eta_2(1870)$ decaying to $a_2(1320)\pi$ at $\sqrt{s}$ = 29.1 GeV in the x_F interval $|x_F| \leq 0.2$ has been determined to be $\sigma(\eta_2(1645))$ = 1664 $\pm$ 149 nb, and $\sigma(\eta_2(1870))$ = 1845 $\pm$ 183 nb.

A Monte Carlo simulation has been performed for the production of a $J^{PC} = 2^{-+}$ state with spin projection $|J_Z|$ =1 via the exchange of two non-conserved vector currents using the model of Close and Schuler [13] discussed in ref. [12]. The prediction of this model is found to be in qualitative agreement with the observed ϕ, dP_T and t distributions of the $\eta_2(1645)$ and $\eta_2(1870)$. This will be presented in a later publication.

In summary, there is evidence for an $a_2(1320)\pi$ decay mode of the $\eta_2(1645)$ and $\eta_2(1870)$ in the $\eta\pi^+\pi^-$ final state. In addition, there is evidence for an $a_0(980)\pi$ decay mode of both resonances and possibly a $f_2(1270)\eta$ decay mode of the $\eta_2(1870)$. There is no evidence for any $J^{PC} = 2^{++}$ $a_2(1320)\pi$ wave, in particular no evidence for the decay $f_2(1950) \rightarrow a_2(1320)\pi$.

Acknowledgements

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Tables

Table 1: Parameters of the $\eta_2(1645)$ and $\eta_2(1870)$

Resonance	Final state	Mass (MeV)	Width (MeV)
$\eta_2(1645)$	$\eta\pi\pi$ $\eta \to \gamma\gamma$	1605 ± 12	188 ± 22
$\eta_2(1645)$	$\eta\pi\pi$ $\eta \to \pi^+\pi^-\pi^0$	1619 ± 11	179 ± 28
$\eta_2(1870)$	$\eta\pi\pi$ $\eta \to \gamma\gamma$	1841 ± 18	249 ± 30
$\eta_2(1870)$	$\eta\pi\pi$ $\eta \to \pi^+\pi^-\pi^0$	1831 ± 16	219 ± 33

Table 2: Production of the resonances as a function of dP_T expressed as a percentage of their total contribution and the ratio (R) of events produced at $dP_T \leq 0.2$ GeV to the events produced at $dP_T \geq 0.5$ GeV.

	$dP_T \leq 0.2$ GeV	$0.2 \leq dP_T \leq 0.5$ GeV	$dP_T \geq 0.5$ GeV	$R = \frac{dP_T \leq 0.2 GeV}{dP_T \geq 0.5 GeV}$
$\eta_2(1645)$	8.9 ± 1.1	32.2 ± 3.0	58.9 ± 5.2	0.15 ± 0.02
$\eta_2(1870)$	8.2 ± 1.0	28.6 ± 2.8	63.2 ± 5.6	0.13 ± 0.02

Table 3: The slope parameters from a fit to the $|t|$ distributions of the form $\frac{d\sigma}{dt} = \alpha e^{-b_1 t} + \beta t e^{-b_2 t}$.

	α	b_1 GeV^{-2}	β	b_2 GeV^{-2}
$\eta_2(1645)$	0.4 ± 0.1	6.4 ± 2.0	2.6 ± 0.9	7.3 ± 1.3
$\eta_2(1870)$	0.3 ± 0.1	5.9 ± 3.5	4.3 ± 1.5	8.3 ± 2.0

Figures

Figure 1: The $\eta\pi^+\pi^-$ mass spectrum for a) $\eta \to \gamma\gamma$ and b) $\eta \to \pi^+\pi^-\pi^0$.

Figure 2: The $\eta\pi^+\pi^-$ mass spectrum for the decay $\eta \to \gamma\gamma$. a) The $J^{PC} = 1^{++}$ $a_0(980)\pi$ wave, b) the $J^{PC} = 2^{-+}$ $a_2(1320)\pi$ wave, c) the $J^{PC} = 2^{-+}$ $a_0(980)\pi$ wave and d) the $J^{PC} = 2^{-+}$ $f_2(1270)\pi$ wave.

Figure 3: The $\eta\pi^+\pi^-$ mass spectrum for the decay $\eta \to \pi^+\pi^-\pi^0$. a) The $J^{PC} = 1^{++}$ $a_0(980)\pi$ wave, b) the $J^{PC} = 2^{-+}$ $a_2(1320)\pi$ wave, c) the $J^{PC} = 2^{-+}$ $a_0(980)\pi$ wave and d) the $J^{PC} = 2^{-+}$ $f_2(1270)\pi$ wave.

Figure 4: The azimuthal angle (ϕ) between the two outgoing protons for a) the $\eta_2(1645)$ and d) the $\eta_2(1870)$. The four momentum transfer squared ($|t|$) from one of the proton vertices for c) the $\eta_2(1645)$ and d) the $\eta_2(1870)$ with fits described in the text.

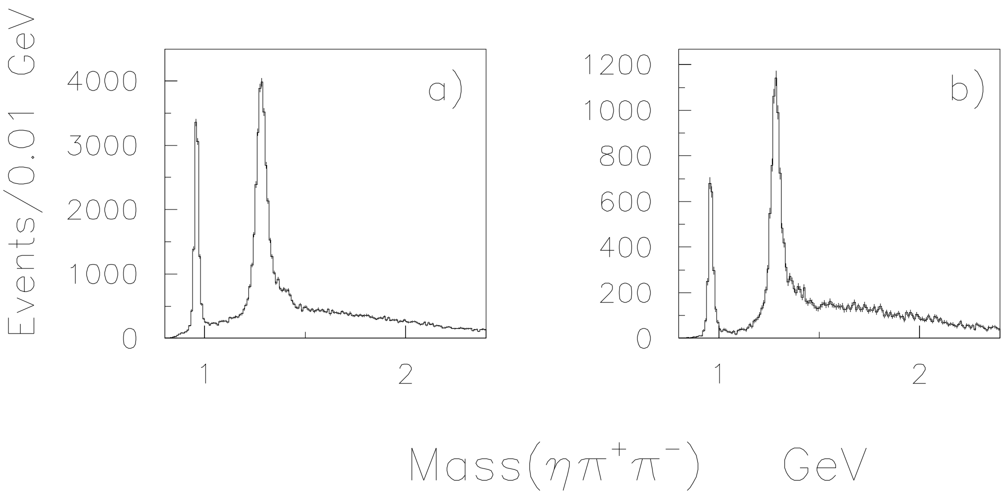
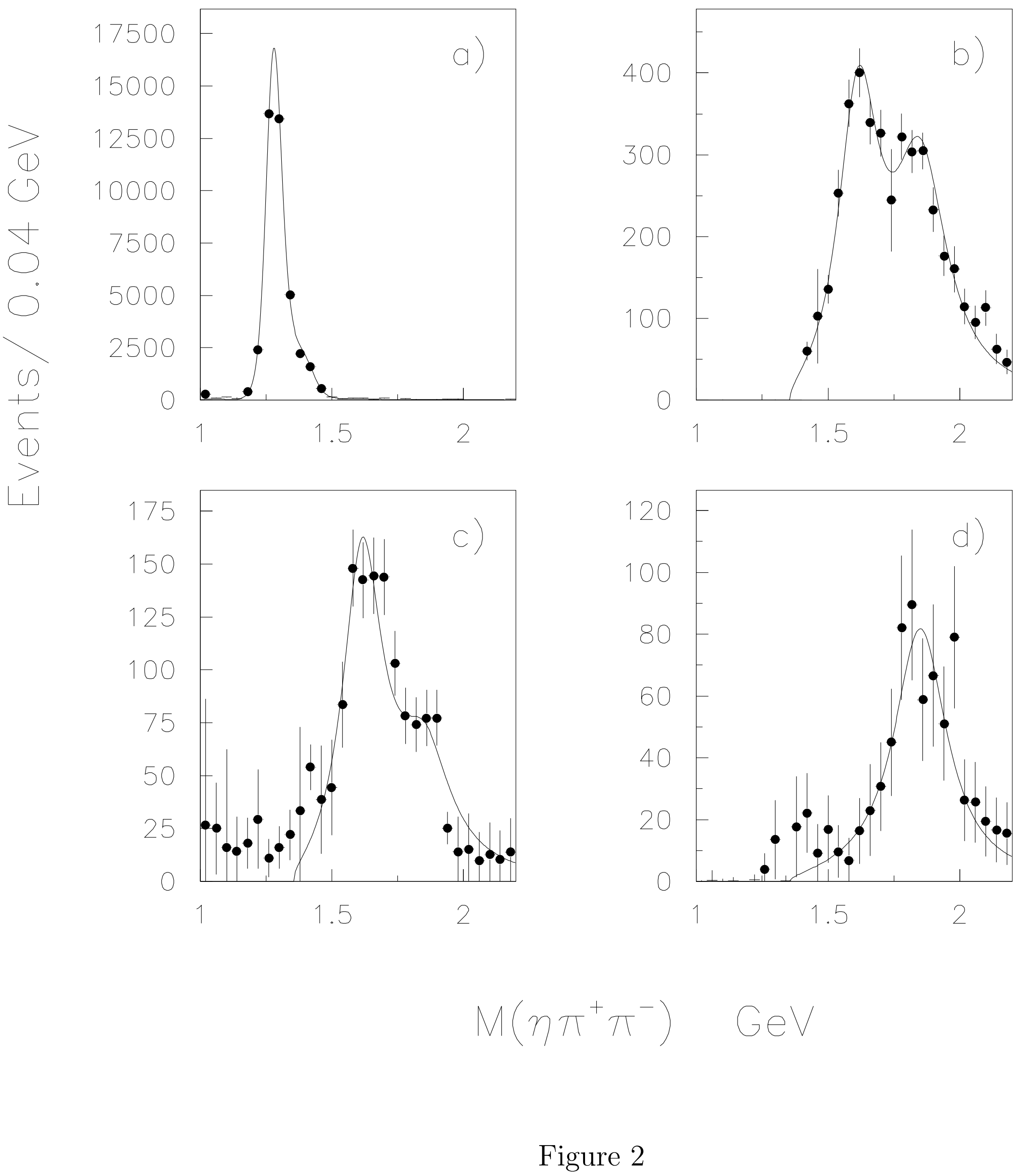

Events/0.01 GeV
4000
3000
2000
1000
0
a)
1
2
1200
1000
800
600
400
200
0
b)
1
2
Mass($\eta\pi^+\pi^-$) GeV

Figure 1



Events/ 0.04 GeV
a)
b)
c)
d)
17500
15000
12500
10000
7500
5000
2500
0
400
300
200
100
175
150
125
100
75
50
25
120
80
60
40
20
1
1.5
2
M(ηπ⁺π⁻) GeV

Figure 2

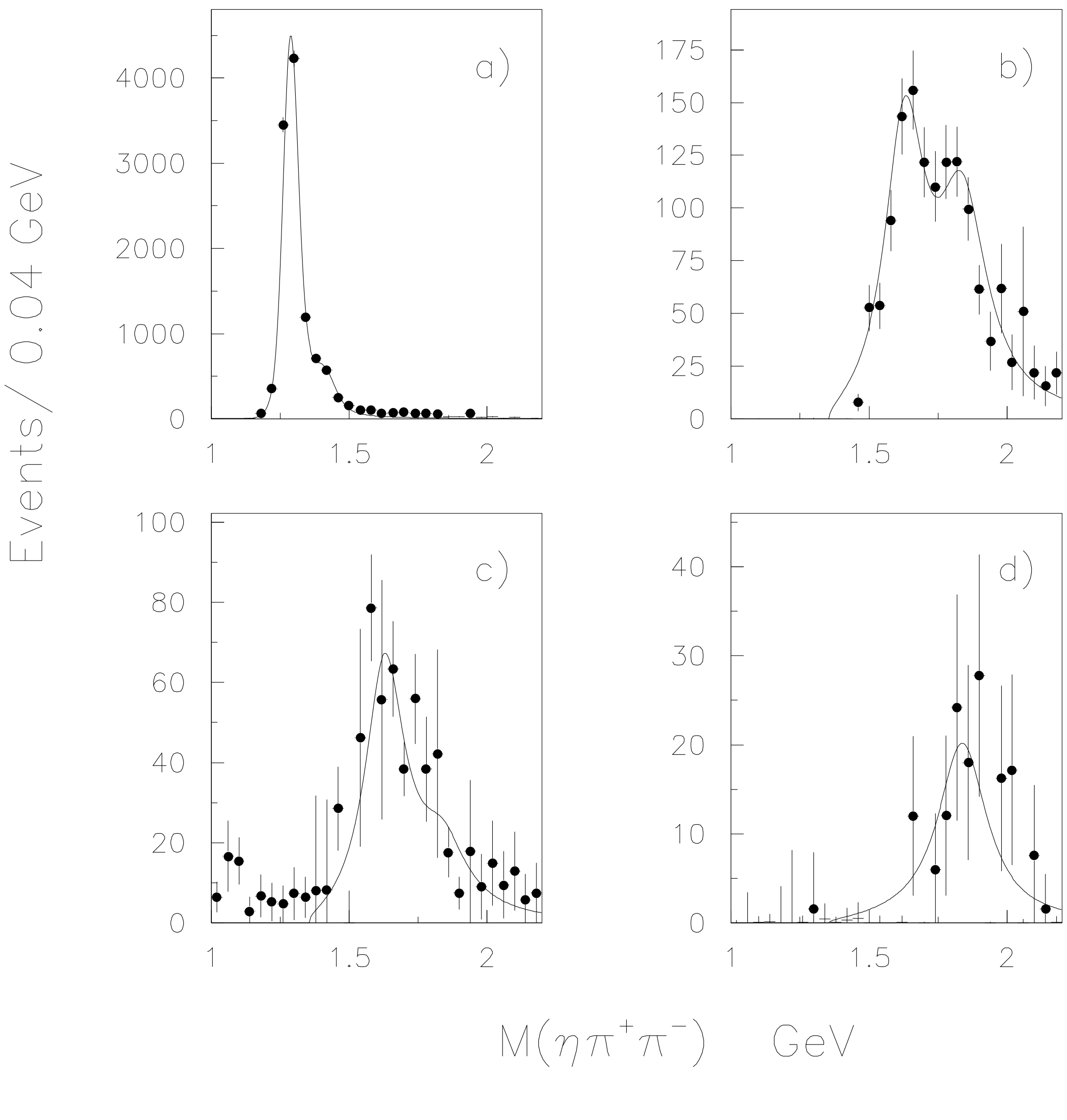
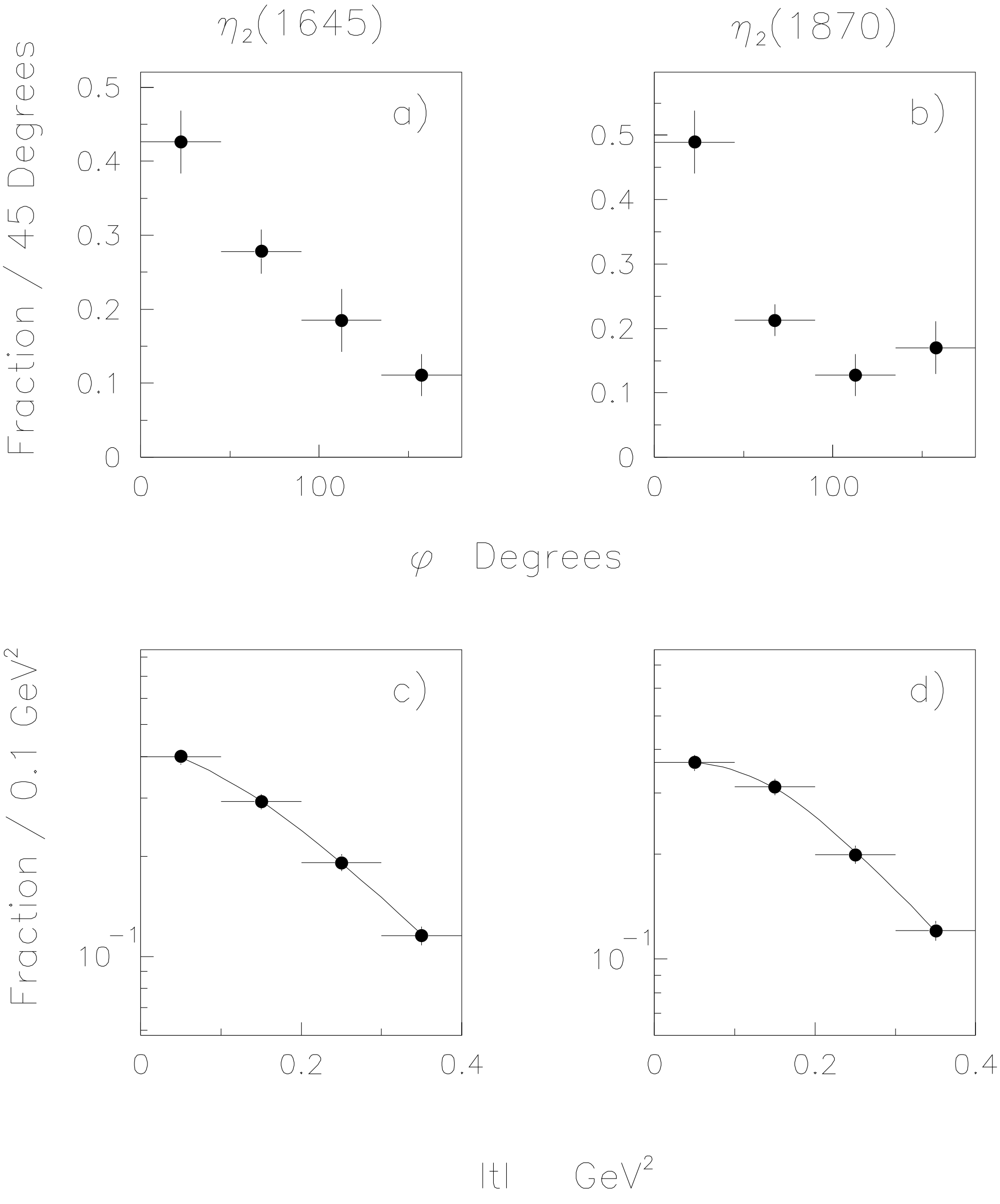


Figure 3



η2(1645)
η2(1870)
a)
b)
c)
d)
Fraction / 45 Degrees
Fraction / 0.1 GeV2
φ Degrees
|t| GeV2
0
0.1
0.2
0.3
0.4
0.5
100
10−1
0.2
0.4

Figure 4