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Evidence for new states produced in the central region in the reaction $pp \to p_f (\pi^+\pi^-\pi^+\pi^-) p_s$ at 300 GeV/c

WA76 Collaboration

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Abstract

The reaction $pp \to p_f(\pi^+\pi^-\pi^+\pi^-)p_s$, where the $\pi^+\pi^-\pi^+\pi^-$ system is centrally produced, has been studied at 300 GeV/c in an experiment designed to search for gluonic states. The $\pi^+\pi^-\pi^+\pi^-$ mass spectrum shows evidence for the $f_1(1285)$ with a mass of 1281 ± 1 MeV and a width of 31 ± 5 MeV. In addition there is evidence for two new enhancements at masses of 1449 ± 4 and 1901 ± 13 MeV with widths of 78 ± 18 and 312 ± 61 MeV respectively. An analysis of the state at 1.45 GeV indicates that it is not a $\pi^+\pi^-\pi^+\pi^-$ decay mode of the $f_1(1420)$ or $\iota/\eta(1440)$.

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In recent years the 4π channel has been studied using several different production mechanisms. In two photon physics a broad enhancement is observed near threshold in $\rho^0\rho^0$ which is produced with a four times larger cross section than $\rho^+\rho^-$ [1]. It has been suggested that this suppression of $\rho^+\rho^-$ could be due to the presence of a four quark state [2]. In radiative J/ψ decays the 4π spectrum is dominated by pseudoscalar $\rho\rho$ production. No $\rho^+\rho^-$ suppression is observed but two enhancements are observed in the mass region between 1.5 and 1.8 GeV with $J^{PC} = 0^{-+}$ decaying to $\rho\rho$ [3] [4]. The $4\pi^0$ channel has been studied in peripheral π^-p interactions [5] where the production mechanism is assumed to be dominated by one pion exchange. This means that the $4\pi^0$ system is restricted to $J^{PC} = (\text{even})^{++}$ and also decays involving ρ's are not possible; an analysis of this data provides evidence for two new states in the mass range 1.5 to 1.8 GeV.

This paper studies the centrally produced exclusive final states formed in the reaction

$$pp \rightarrow p_f\,(\pi^+\pi^-\pi^+\pi^-)\,p_s \qquad (1)$$

at 300 GeV/c, where the subscripts f and s indicate the fastest and slowest particles in the laboratory respectively. It has been suggested that such a kinematic region could be a source of gluonic states [6], the search for which is one of the motivations behind the present experiment.

The data come from experiment WA76 which has been performed using the CERN Omega Spectrometer. Details of the layout of the apparatus, the trigger conditions and the data processing have been given in a previous publication [7].

Reaction (1) has been isolated from the sample of events having six outgoing tracks by first imposing the following cuts on the components of missing momentum: $|\text{missing } P_x| < 20.0$ GeV/c, $|\text{missing } P_y| < 0.16$ GeV/c, $|\text{missing } P_z| < 0.06$ GeV/c, where the x axis is along the beam direction. A pulse-height momentum correlation obtained from a system of scintillation counters was used to ensure that the slow particle was a proton.

The central particles are required, if passing through the Cerenkov system, to have a mass consistent with being a pion. The Delta function defined as :-

$$\Delta = MM^2(p_f\,p_s) - M^2(\pi^+\pi^-\pi^+\pi^-)$$

is then calculated for each event and a cut of $|\Delta| \leq 3.0$ (GeV)^2 is used to select the $\pi^+\pi^-\pi^+\pi^-$ channel (67034 events).

Fig. 1a shows the $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum; a clear peak is seen at 1.28 GeV which is probably due to the $f_1(1285)$. It is also difficult to ignore the enhancement in the 1.45 GeV region. In order to try to describe the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum it was initially fitted with a single Breit-Wigner, representing the peak in the 1.28 GeV region, 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.[1] The χ^2/NDF obtained was 283/142 indicating a bad fit. The major contributions to the χ^2 come from the 1.45 and 1.9 GeV regions. A Breit-Wigner was then introduced to take account of the enhancement at 1.45 GeV which resulted in a χ^2/NDF of 233/139. If a third Breit-Wigner is introduced to describe the excess of events in the 1.9 GeV region the fit has a χ^2/NDF of 137/136 indicating a statistical significance of 5σ for the excess at 1.9 GeV. If now the Breit-Wigner describing the 1.45 GeV enhancement is omitted the χ^2/NDF increases to 231/139 indicating a statistical significance of 5σ for this enhancement.

Thus the data require the introduction of two Breit-Wigners, in addition to the one to describe the peak at 1.28 GeV, to account for the excess of events at 1.45 GeV and 1.9 GeV. From now on these enhancements are referred to as X(1450) and X(1900). The masses and widths determined from the fit[2] are given in table 1.

Fig. 1b shows the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum when no γ's are detected in the gamma calorimeter. The η' and $f_1(1285)$ reflections are reduced but the $f_1(1285)$, X(1450) and X(1900) signals are enhanced, indicating that they are not themselves reflections from a channel involving a π^0 which falls within the missing momentum cuts.

Fig. 2a shows the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum when a cut of $|t| < 0.15$ GeV^2 has been placed on the four momentum transfer squared at both the fast and slow vertices. The spectrum is fitted using three Breit-Wigners, with masses and widths fixed to the values given in table 1, and a background as described above (χ^2/NDF = 67/65). Fig. 2b shows a fit to the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum when both

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[1] 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 these reflections have been included in the fit as two histograms.

[2] In order to calculate the errors on the fit parameters many different mass distributions have been generated from the original by varying the number of events in each bin according to a Poisson distribution. These spectra have then been refitted and the variation in values obtained from these fits has been used to calculate the errors quoted.

the slow and fast vertices have $|t| > 0.15$ GeV^2. Since there is only evidence for the $f_1(1285)$ and X(1450) the fit uses only two Breit-Wigners, with fixed masses and widths and has a χ^2/NDF of 61/66. It thus appears that the X(1900) is produced predominantly at low $|t|$.

A possible explanation of the X(1450) is that it is the $f_1(1420)$ observed in the $K^0{}_S K^{\pm}\pi^{\mp}$ channel. The selection of the channel $K^0{}_S K^{\pm}\pi^{\mp}$ has been described in a previous publication [8] and shows enhancements which have been identified as the $f_1(1285)$ and $f_1(1420)$. The mass and width of the peak observed in the $\pi^+\pi^-\pi^+\pi^-$ spectrum at 1.28 GeV (1281$\pm$1, 31$\pm$5 MeV) is consistent with that found for the $f_1(1285)$ in the $K^0{}_S K^{\pm}\pi^{\mp}$ spectrum (1278$\pm$2, 25$\pm$4 MeV). In contrast, the peak at 1.45 GeV in the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum has a mass of 1449$\pm$4 MeV which differs from the mass of 1429$\pm$3 MeV found for the mass of the $f_1(1420)$ in the $K^0{}_S K^{\pm}\pi^{\mp}$ spectrum by 4σ. In addition, to test whether the peak seen at 1.45 GeV in the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum is a new decay mode of the $f_1(1420)$, the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum has been fitted using the mass and width determined for the $f_1(1420)$ from a fit to the $K^0{}_S K^{\pm}\pi^{\mp}$ spectrum. The χ^2/NDF increases from 137/136, with a free mass and width of the X(1450), to 169/138 when the parameters are fixed.

A study has been made of the branching ratios of the 1.28 and 1.45 GeV enhancements to $K^0{}_S K^{\pm}\pi^{\mp}$ and $\pi^+\pi^-\pi^+\pi^-$ for $|t(slow)| < 0.2$ GeV^2 and $|t(slow)| > 0.2$ GeV^2 which divides the data into two equal samples. If the enhancements seen in the two channels are the same the branching ratios should be constant with $|t|$. The geometrical acceptances for the $\pi^+\pi^-\pi^+\pi^-$ and $K^0{}_S K^{\pm}\pi^{\mp}$ systems are found to be smoothly varying with effective mass. The acceptance corrected effective mass spectra have been fitted in the two $|t|$ regions and the number of events in the resonance peaks for each channel and in each $|t|$ region has been determined. Defining R to be the number of events in the $\pi^+\pi^-\pi^+\pi^-$ peak divided by the number in the $K^0{}_S K^{\pm}\pi^{\mp}$ peak results in the following values for the 1.28 GeV enhancement

$$R = 6.4 \pm 0.9 \text{ at low } |t| \text{ and}$$

$$R = 6.3 \pm 0.7 \text{ at high } |t|.$$

This, together with the fact that the masses and widths are found to be consistent in the two channels indicates that they are two decay modes of the same resonance which has been determined to be the $f_1(1285)$ from a spin parity analysis of the $K^0{}_S K^{\pm}\pi^{\mp}$ channel.

In contrast, however, in the 1.45 GeV region

$$R = 2.8 \pm 0.4 \text{ at low } |t| \text{ and}$$

$$R = 1.3 \pm 0.2 \text{ at high } |t|.$$

Hence there is a 3σ change with $|t|$. This change in R together with the fact that the mass of the $\pi^+\pi^-\pi^+\pi^-$ enhancement (1449±4 MeV) is inconsistent with the mass of the $f_1(1420)$ in the $K^0{}_S K^\pm \pi^\mp$ channel (1429±3 MeV) suggests that the resonance observed in the $\pi^+\pi^-\pi^+\pi^-$ channel is not due to a $\pi^+\pi^-\pi^+\pi^-$ decay mode of the $f_1(1420)$.

If the X(1450) is not the $f_1(1420)$ then another possibility is that it could be a $\pi^+\pi^-\pi^+\pi^-$ decay mode of the $J^{PC} = 0^{-+}$ $\iota/\eta(1440)$ observed in radiative J/ψ decays to $K\bar{K}\pi$ with a mass of 1454 ± 3 MeV and a width of 98 ± 7 MeV [9]. However this state is not observed in the $K^0{}_S K^\pm \pi^\mp$ channel of the present experiment [8], thus ruling out this hypothesis.

In order to determine the different reactions that contribute to the observed final states a channel likelihood fit [10] using a modified version of CHAFIT [11] has been used. The program performs a maximum likelihood fit of different overlapping amplitudes and has been used as described in ref. [12]. The results of the fit to the total $\pi^+\pi^-\pi^+\pi^-$ mass spectrum are shown in table 2. The main results can be summarised as follows :

1. The $f_1(1285)$ and X(1450) decay dominantly to $\rho^0\pi^+\pi^-$.

2. The X(1900) is found to decay equally to $f_2(1270)\pi\pi$ and $a_2\pi$.

3. There is 3.0 ± 0.4 % $\rho^0\rho^0$ production.

A spin-parity analysis of the $\pi^+\pi^-\pi^+\pi^-$ channel has been performed, assuming that the resonances are isoscalar. The $\rho^0\pi^+\pi^-$ decay modes of the $f_1(1285)$ and X(1450) have been parameterised in terms of quasi two-body final states corresponding to $\rho\ (\pi\pi)$ and $(\rho\pi)\ \pi$. For the $\rho\ (\pi\pi)$ case an angular analysis of the $\rho\ (\pi\pi)$ system has been performed in the $f_1(1285)$ and X(1450) regions, using a modified version of the formalism of Chang and Nelson [13] and Trueman [14], assuming that they are both I = 0 objects. This assumption implies that the internal angular momentum (ℓ) of the $\pi^+\pi^-$

pair opposite the ρ^0 must be odd. Assuming $\ell = 1$, the system can be described as decaying through an intermediate state of two vector particles. Two angles have to be considered: the azimuthal angle χ between the ρ^0 decay plane and the $\pi^+\pi^-$ decay plane, and the polar angle θ of the π^+ decay in the ρ^0 rest frame relative to the ρ^0 momentum in the $\rho^0\pi^+\pi^-$ rest frame.

The $\rho^0\pi^+\pi^-$ mass spectra have been fitted as a function of χ and $\cos\theta$. The numbers of $f_1(1285)$ and X(1450) events have been calculated from these fits and the resulting acceptance corrected angular distributions are shown in fig. 3. Curves corresponding to the distributions expected for states with different J^P, including ρ combinatorial effects, have been computed by Monte Carlo and superimposed on the data. All spins up to J = 2 have been considered.

In the $f_1(1285)$ region (fig. 3a,b) curves corresponding to states with $J^P = 0^-$, $1^\pm$ and 2^+ are shown. The $J^P = 1^\pm$ hypothesis gives the best description of the data (χ^2/NDF = 4/13). In the X(1450) region (fig. 3c,d) the $J^P = 0^-$ hypothesis can be excluded (χ^2/NDF = 50/13); the $J^P = 1^\pm$ (χ^2/NDF = 13/13) and 2^+ (χ^2/NDF = 9/13) hypotheses all give acceptable descriptions of the data.

For the $(\rho\pi)\,\pi$ case, since a spin-parity analysis of the $\rho\pi$ subsystem from the $\pi^+\pi^-\pi^+\pi^-$ channel at 85 GeV/c showed that it was dominated by the 1^+ S wave [12], a spin-parity analysis of the $(\rho\pi)\,\pi$ case has been performed, using Zemach tensors [15], assuming that the decay proceeds via a pseudo $a_1(1260)$ isobar, describing the 1^+ S wave where the fit is not found to be sensitive to the a_1 parameters used [16].

In this case the angles found to contain information are the polar angle θ_1 between the π^+ coming from the decay of the ρ^0 relative to the ρ^0 momentum, and the polar angle θ_2 of the π^+ from the $\pi^+\pi^-$ pair not in the ρ^0 relative to the ρ^0 momentum in the $\rho^0\pi^+\pi^-$ rest frame.

The experimental angular distributions are obtained as described above for the $\rho\,(\pi\pi)$ case and are shown for the X(1450) region in fig. 4a,b. The curves corresponding to spin-parities $J^P = 1^-, 0^+, 1^+$ and 2^+ are superimposed on the data. It can be seen that $J^P = 0^+$ can be excluded (χ^2/NDF = 238/15), $J^P = 1^+$ is disfavoured (χ^2/NDF = 22/15) and $J^P = 1^-$ (χ^2/NDF = 11/15) or 2^+ (χ^2/NDF = 8/15) both give an acceptable description of the data.

For the $f_1(1285)$ region the $a_1\pi$ $J^P = 1^+$ hypothesis (not shown) gives a poor description of the data, suggesting a $\rho^0\,(\pi^+\pi^-)$ decay, in agreement with what has been observed in radiative J/ψ decays

[4]. Thus, the peak at 1.28 GeV is found to be consistent with a state having $J^P = 1^+$ decaying through a ρ^0 $(\pi^+\pi^-)$ system. For the X(1450), assumed to be isoscalar, $J^P = 1^{\pm}$ or 2^+ give good descriptions of the data.

In order to study the energy dependence of the production of the $f_1(1285)$ and X(1450) their cross sections have been calculated at 85 and 300 GeV/c, under our trigger conditions, taking into account losses due to detector inefficiencies, geometrical acceptance and tails of cuts. The cross sections have been calculated for $|x_F| < 0.2$ where the two experiments have a good acceptance. The values found are

$$\sigma(f_1(1285)\rightarrow\pi^+\pi^-\pi^+\pi^-) = 530 \pm 70 \text{ nb} \quad \text{at 85 GeV/c and}$$
$$\sigma(f_1(1285)\rightarrow\pi^+\pi^-\pi^+\pi^-) = 335 \pm 60 \text{ nb} \quad \text{at 300 GeV/c.}$$

Since there is no evidence for the X(1450) in the 85 GeV/c data [12] only an upper limit on its cross section can be calculated. The values are

$$\sigma(X(1450)\rightarrow\pi^+\pi^-\pi^+\pi^-) < 145 \text{ nb (95 \% c.l.)} \quad \text{at 85 GeV/c and}$$
$$\sigma(X(1450)\rightarrow\pi^+\pi^-\pi^+\pi^-) = 290 \pm 60 \text{ nb} \quad \text{at 300 GeV/c.}$$

Thus the cross section for the X(1450) increases with energy. In contrast, in the $K^0_S K^{\pm}\pi^{\mp}$ channel the cross section for the $f_1(1420)$ remains constant with energy ($\sigma(f_1(1420)) = 400\pm120$ nb at 85 GeV/c and $\sigma(f_1(1420)) = 400\pm110$ nb at 300 GeV/c) [8].

The branching ratio of the $f_1(1285)$ to 4π and $K\bar{K}\pi$ has been calculated to be[3]

$$(f_1(1285)\rightarrow K\bar{K}\pi)/(f_1(1285)\rightarrow 4\pi) = 0.28 \pm 0.05 .$$

In conclusion, an analysis of the centrally produced $\pi^+\pi^-\pi^+\pi^-$ channel at 300 GeV/c shows evidence for two new structures in addition to the well known $f_1(1285)$. The structure at 1.45 GeV is found to decay to $\rho^0\pi^+\pi^-$, and that at 1.9 GeV is found to decay equally to $a_2\pi$ and $f_2\pi\pi$. An analysis of the state at 1.45 GeV indicates that it is not a $\pi^+\pi^-\pi^+\pi^-$ decay mode of the $f_1(1420)$ or the $\iota/\eta(1440)$.

[3] The branching ratio has been calculated assuming $\rho\pi\pi$ and $a_0(980)\pi$ intermediate states and all unseen decay modes have been corrected for.

The cross section for the centrally produced $f_1(1285)$ decreases with energy. In contrast, as there was no evidence for the X(1450) at 85 GeV/c its cross section must rise with energy; this behaviour is consistent with a double Pomeron exchange mechanism, which is predicted to be a source of gluonic states. It is interesting to note that this state has not been observed in any other production mechanism.

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1. Tables

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

$f_1(1285)$	Mass	1281	±	1	MeV
	Γ	31	±	5	MeV
X(1450)	Mass	1449	±	4	MeV
	Γ	78	±	18	MeV
X(1900)	Mass	1901	±	13	MeV
	Γ	312	±	61	MeV

Table 2: Results from CHAFIT.

Channel	Percentage
$p_f(f_1(1285) \to \rho^0\pi^+\pi^-)p_s$	3.1 ± 0.1
$p_f(X(1450) \to \rho^0\pi^+\pi^-)p_s$	2.7 ± 0.2
$p_f(X(1900) \to f_2\pi^+\pi^-)p_s$	2.3 ± 0.2
$p_f(X(1900) \to a_2\pi)p_s$	2.5 ± 0.4
$p_f(\rho^0\pi^+\pi^-)p_s$	40.0 ± 1.0
$p_f(f_2\pi^+\pi^-)p_s$	3.8 ± 0.3
$p_f(a_2\pi)p_s$	5.0 ± 0.6
$p_f(\rho^0\rho^0)p_s$	3.0 ± 0.4
$(\Delta^{++} \to p_f\pi^+)(\pi^+\pi^-\pi^-)p_s$	8.7 ± 0.2
$(\Delta^0 \to p_f\pi^-)(\pi^+\pi^-\pi^+)p_s$	1.5 ± 0.1
K^0_S contamination	1.4 ± 0.1
η' reflection	0.8 ± 0.1
$f_1(1285)$ reflection	2.9 ± 0.1
Phase Space	21.8 ± 0.8

2. Figures

Fig. 1 The $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum with fit using 3 Breit-Wigners:

a) total spectrum and

b) requiring no γ's detected in the gamma calorimeter.

Fig. 2 The $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum, with fit described in the text, for

a) $|t(slow)| < 0.15\ (GeV)^2$ and $|t(fast)| < 0.15\ (GeV)^2$ and

b) $|t(slow)| > 0.15\ (GeV)^2$ and $|t(fast)| > 0.15\ (GeV)^2$.

Fig. 3 The χ and $\cos\theta$ distributions for

a),b) the $f_1(1285)$ region and

c),d) the X(1450) region.

The superimposed curves represent different spin parities for the ρ $(\pi\pi)$ hypothesis.

Fig. 4 The a) $\cos\theta_1$ and b) $\cos\theta_2$ distributions for the X(1450) region.

The superimposed curves are described in the text for the $(\rho\pi)$ π hypothesis.

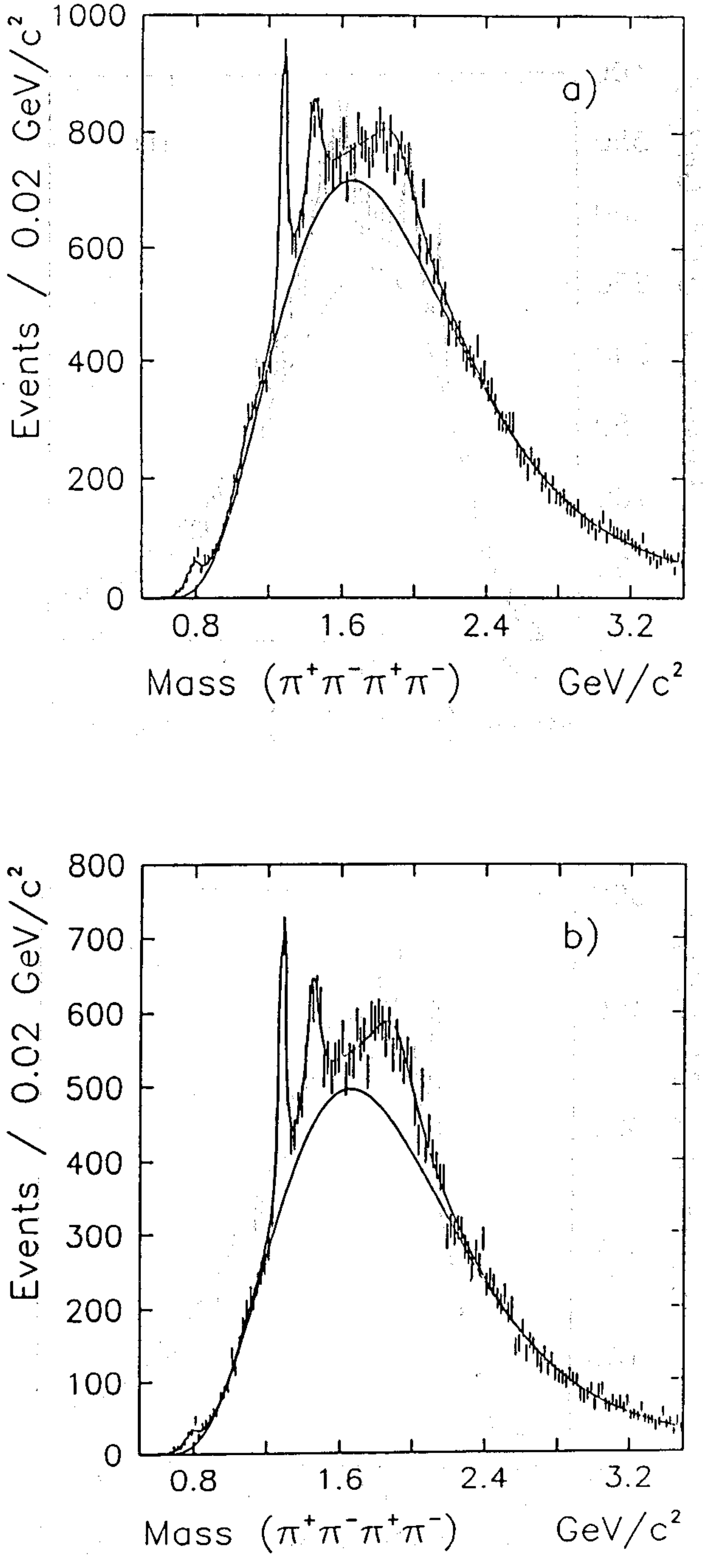

a)
Events / 0.02 GeV/c²
1000
800
600
400
200
0
0.8
1.6
2.4
3.2
Mass (π⁺π⁻π⁺π⁻) GeV/c²
b)
Events / 0.02 GeV/c²
800
700
600
500
400
300
200
100
0
0.8
1.6
2.4
3.2
Mass (π⁺π⁻π⁺π⁻) GeV/c²

Fig. 1

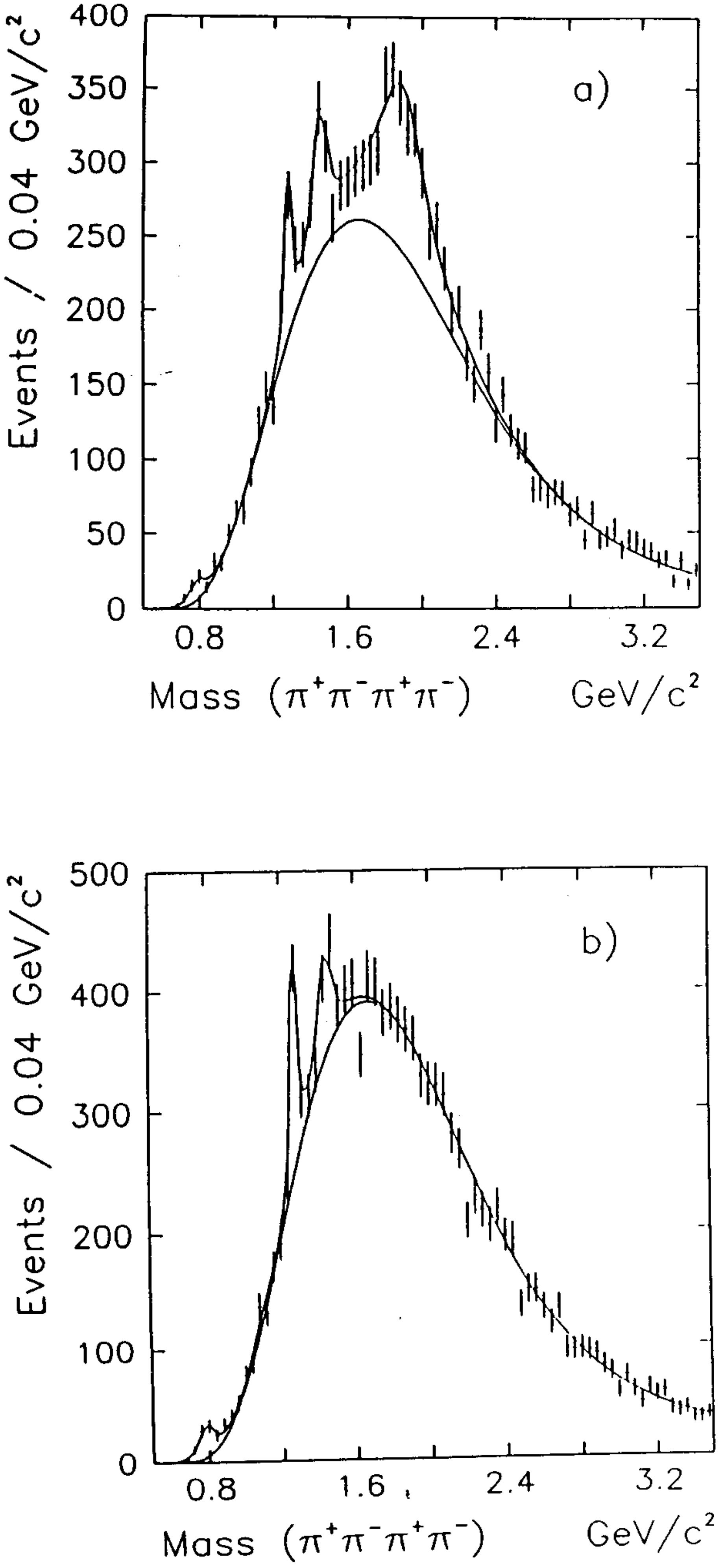

a)
Events / 0.04 GeV/c²
400
350
300
250
200
150
100
50
0
0.8
1.6
2.4
3.2
Mass (π⁺π⁻π⁺π⁻)
GeV/c²
b)
Events / 0.04 GeV/c²
500
400
300
200
100
0
0.8
1.6
2.4
3.2
Mass (π⁺π⁻π⁺π⁻)
GeV/c²

Fig. 2

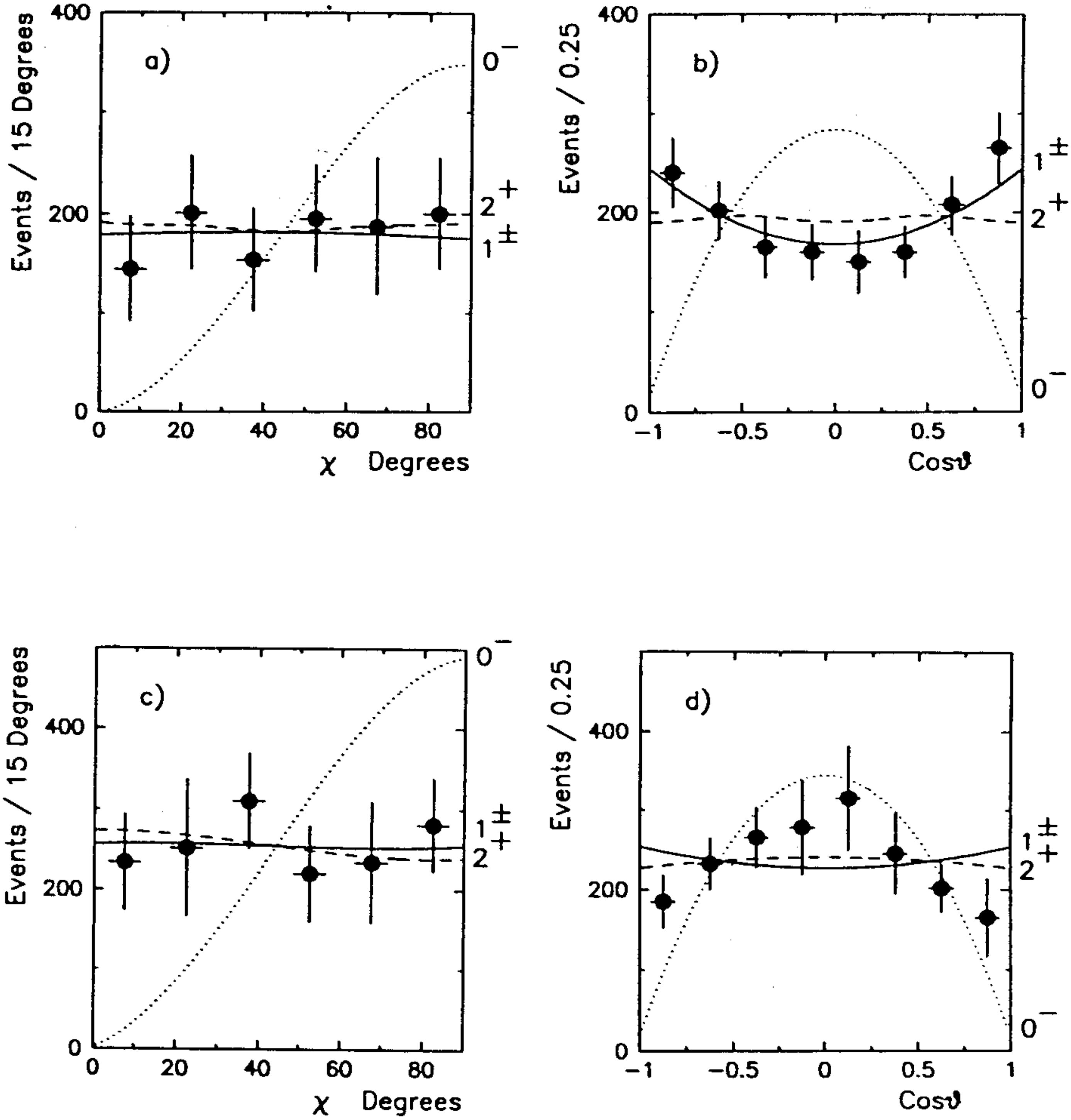
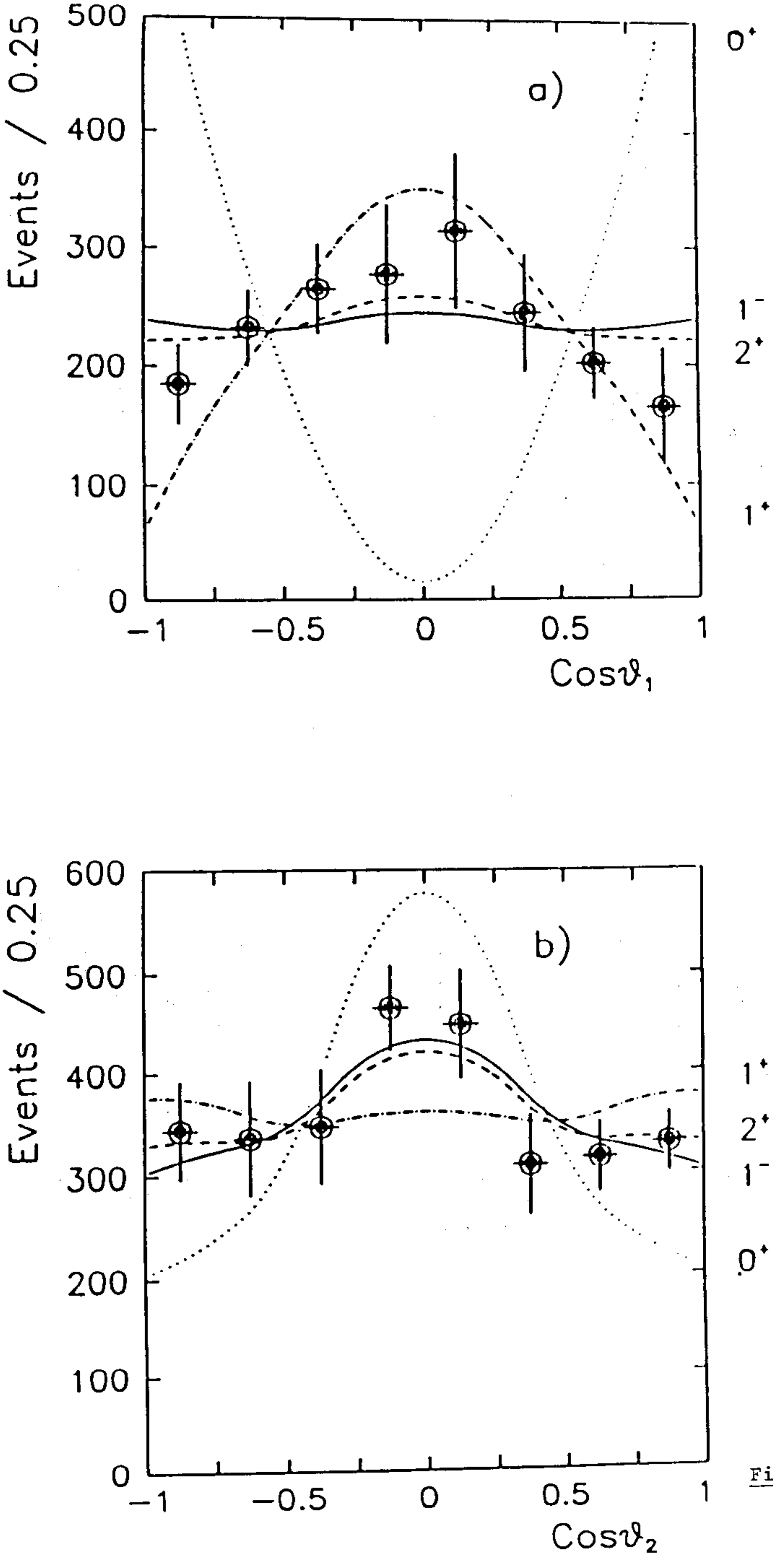

a)
Events / 15 Degrees
400
200
0
0
20
40
60
80
χ Degrees
0⁻
2⁺
1±
b)
Events / 0.25
−1
−0.5
0.5
1
Cosϑ
c)
d)

Fig. 3



a)
Events / 0.25
500
400
300
200
100
0
−1
−0.5
0
0.5
1
Cosϑ₁
0⁺
1⁻
2⁺
1⁺
b)
Events / 0.25
600
500
400
300
200
100
0
−1
−0.5
0
0.5
1
Cosϑ₂
1⁺
2⁺
1⁻
0⁺

Fig. 4