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A study of the centrally produced $\eta\pi^0$ and $\eta\pi^-$ systems in pp interactions at 450 GeV/c

The WA102 Collaboration

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Abstract

A partial wave analysis of the centrally produced $\eta\pi^0$ and $\eta\pi^-$ channels has been performed in pp collisions using an incident beam momentum of 450 GeV/c. Clear $a_0(980)$ and $a_2(1320)$ signals have been observed in S and D_+ waves respectively. The dP_T, ϕ and $|t|$ distributions of these resonances are presented.

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The $\eta\pi$ system has been studied in several experiments in the search for exotic states [1, 2]. The interest in this system is mainly caused by the fact that P-wave in the $\eta\pi$ system carries exotic quantum numbers $J^{PC} = 1^{-+}$.

In addition to the well-known $a_0(980)$ and $a_2(1320)$, two new $q\bar{q}$ states were observed recently in the $\eta\pi$ system. In 1994 the Crystal Barrel collaboration claimed a new $I^G J^{PC} = 1^- 0^{++}$ state, the $a_0(1450)$ [3], which they then confirmed in different channels [4, 5, 6]. This resonance could be considered as the isovector member of the ground state scalar multiplet instead of the $a_0(980)$, which is a peculiar object in meson spectroscopy and whose nature is still not completely clear, see for example ref. [7]. In addition, the Crystal Barrel collaboration observed a new isovector tensor state, the $a_2(1660)$, decaying to $\eta\pi^0$ [8].

In a previous analysis of the centrally produced $\eta\pi^0$ system by the NA12/2 collaboration [9] clear $a_0(980)$ and $a_2(1320)$ signals were observed but no evidence for a $J^{PC} = 1^{-+}$ state was found. An interesting feature of that analysis was the ratio of the $a_0(980)$ to $a_2(1320)$ which was found to be much bigger than had been observed in $\pi^- p$ interactions [2].

This paper presents a study of the centrally produced $\eta\pi$ final state. Firstly the reaction

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

has been studied at 450 GeV/c, where the η is observed decaying to 2γs . 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. [10]. The GAMS-4000 multiphoton spectrometer has been used to detect γs .

Reaction (1) has been isolated from the sample of events having two outgoing charged tracks and four γs 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. 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 separation of events belonging to reaction (1) has been performed on the basis of a kinematical analysis (6C fit, four-momentum conservation being used and the masses of the two mesons being fixed). There is evidence for a small $\Delta^+(1232)$ signal in the $p_f\pi^0$ mass spectrum which has been removed by requiring M $(p_f\pi^0) > 1.3$ GeV. Detector acceptances and efficiencies have been calculated using a Monte-Carlo simulation taking into account the geometry of the set up, detector resolutions, event selection criteria and the kinematical fitting procedure. The resulting centrally produced $\eta\pi^0$ effective mass distribution corrected for efficiency and rescaled to the total number of observed events is shown in fig. 1a) and consists of 6045 events. There is clear evidence for the $a_0(980)$ and $a_2(1320)$. As can be seen from the $\gamma\gamma$ mass spectrum shown as an inset (fig 1b)) there is approximately 30 % background below the η signal. To investigate the effects of this background the side bands around the η signal have been studied. Superimposed on the mass spectrum as a shaded histogram is the estimate of the background. Fig. 1c) shows the background subtracted mass spectrum.

To determine the parameters of the resonances produced in reaction (1) a fit to the efficiency corrected mass spectrum has been performed using a parametrisation of the form

$$dN/dm\ (m) = BG(m) + a_1|BW_{a_0(980)}(m,0)|^2 + a_2|BW_{a_2(1320)}(m,2)|^2$$

where

$$BG(m) = (m - m_{thr})^{\alpha} e^{-\beta m - \gamma m^2}$$

represents the background. m is the $\eta\pi$ mass, m_{thr} is the $\eta\pi$ threshold mass and a_n, α, β and γ are parameters to be determined from the fit. Relativistic Breit-Wigner functions $BW_i(m, J)$, where J is the spin of the resonance, have been convoluted with a Gaussian to account for the experimental mass resolution. The Breit-Wigner used to describe the $a_0(980)$ uses the Flatté formula [11]. In order to describe the centrally produced $\eta\pi$ mass spectra the differential cross section has been multiplied by the kinematical factor $(M_{\eta\pi} - 4m_{thr}^2)^{1/2}/M_{\eta\pi}^3$ [12]. The fit is shown in fig. 1c) and gives $M(a_0(980)) = 975 \pm 7$ MeV, $\Gamma(a_0(980)) = 72 \pm 16$ MeV and $M(a_2(1320) = 1308 \pm 9$ MeV, $\Gamma(a_2(1320)) = 115 \pm 20$ MeV. The parameters found for the $a_0(980)$ and $a_2(1320)$ are consistent with those from the PDG [13].

A PWA has been performed in the mass interval from 670 to 2000 MeV for the $\eta\pi^0$ final state in 60 MeV mass bins. The PWA of the centrally produced $\eta\pi$ system has been made assuming that the $\eta\pi$ 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 $\eta\pi$ centre of mass. The y axis is defined by the cross product of the momentum vectors 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 $(\theta,\phi)=\Omega$ of the π in the $\eta\pi$ centre of mass relative to the coordinate system described above. The amplitudes used for the PWA are defined in the reflectivity basis [14]. In this basis the angular distribution $I(\Omega)$ is given by a sum of two non-interfering terms corresponding to negative and positive values of reflectivity ϵ. The waves used were of the form J_0 ($m\epsilon = 0-$), J_- ($m\epsilon = 1-$) and J_+ ($m\epsilon = 1+$). Only S, P and D waves (corresponding to $J = 0, 1, 2$) have been used in the PWA with $m = 0, 1$. It has been determined from a study of the moments that the contributions of higher waves are negligible in the mass region under study. Finally, 12 parameters have to be determined from the fit to the angular distributions. In this model of the PWA the number of non-trivial solutions in each mass interval can be less than or equal to 8 due to the ambiguities problem [14, 15]. In each mass bin an event-by-event maximum Likelihood method has been used. The PWA analysis has been performed by extending the likelihood function to include the background subtraction, namely the function

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

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, t_{LM} are the moments of the angular distribution and N_{bg} is the number of background events.

All solutions for S, P and D waves have been found for each interval. In the mass region above 1.2 GeV, because the D-wave is the dominant contribution, the solutions are not affected by ambiguities and the 8 solutions are effectively identical. The threshold region does suffer from ambiguities, however, we have picked the solution in which the known $a_0(980)$ is in the S-wave.

The physical solution for the $\eta\pi^0$ system is shown in fig. 1d). As can be seen the D_+ wave dominates above 1.2 GeV. The fit of the D_+ wave amplitude squared with a Breit-Wigner function gives parameters for $a_2(1320)$ meson similar to the ones from the fit to the efficiency corrected mass spectrum. A fit to the S wave amplitude squared gives parameters for $a_0(980)$ similar to those from a fit to the mass spectrum. There is no evidence for an $a_0(1450)$ nor an $a_2(1660)$. As can be seen there is no evidence for other significant structures in any other wave.

In previous analyses we have observed that I = 1 mesons are suppressed in the reaction $pp \to ppX^0$ but are enhanced in the reaction $pp \to \Delta^{++}pX^-$ [16]. Therefore, the reaction

$$pp \to p_s(\eta\pi^-)\Delta^{++} \tag{2}$$

with the Δ^{++} observed decaying to $p_f\pi^+$, has been studied at 450 GeV/c. The η is observed decaying to 2γs . Reaction (2) has been isolated from the sample of events having four outgoing charged tracks and two γs by imposing the cuts on the components of missing momentum used for reaction (1). Events have been separated by a kinematical analysis (5C fit). The events with a $\Delta^{++}(1232)$ in the final state have been selected by requiring M $(p_f\pi^+) < 1.4$ GeV. The background process $pp \to p_s(\eta\pi^+\pi^-)p_f$ gives the biggest background below the Δ^{++} peak. By requiring M $(\eta\pi^+\pi^-) > 1.5$ GeV the signal to background in the Δ^{++} region is greater than 10 (fig 2b)). The resulting acceptance corrected $\eta\pi^-$ mass spectrum rescaled to the total number of observed events is shown in fig. 2a) and consists of 8027 events. The mass spectrum is similar to that observed in the $\eta\pi^0$ final state but the ratio a_0/a_2 is different. In the $\gamma\gamma$ mass spectrum (not shown) there is approximately 30 % background below the η signal. To investigate the effects of this background the side bands around the η signal have been studied. Superimposed on the mass spectrum as a shaded histogram is the estimate of the background.

A fit to the centrally produced background subtracted $\eta\pi^-$ system is shown in fig 2c). The fit yields $M(a_0(980)) = 988 \pm 8$ MeV, $\Gamma(a_0(980)) = 61 \pm 19$ MeV and $M(a_2(1320) = 1316 \pm 9$ MeV, $\Gamma(a_2(1320)) = 112 \pm 14$ MeV.

A PWA has been performed in the mass interval from 670 to 2000 MeV for the $\eta\pi^-$ final state in 60 MeV mass bins using the method described above. The physical solution for the $\eta\pi^-$ system is shown in fig. 2d). As can be seen the D_+ wave dominates above 1.2 GeV, the fit of the D_+ wave amplitude squared with a Breit-Wigner function gives the parameters for $a_2(1320)$ meson similar to the ones from the fit to the efficiency corrected mass spectrum. A fit to the S wave amplitude squared gives the same parameters for $a_0(980)$ similar to those from the fit to the mass spectrum. Again there is no evidence for an $a_0(1450)$ nor an $a_2(1660)$. As can be seen there is no evidence for other significant structures in any other wave.

The fits to $\eta\pi^0$ and $\eta\pi^-$ mass spectra, give the following values for the production ratio of the $a_0(980)$ and $a_2(1320)$ decaying to $\eta\pi$:

$$\frac{\sigma(pp \to pp[a_0(980) \to \eta\pi])}{\sigma(pp \to pp[a_2(1320) \to \eta\pi])} = 2.0 \pm 0.3$$

for reaction (1) and

$$\frac{\sigma(pp \to p\Delta^{++}[a_0(980) \to \eta\pi])}{\sigma(pp \to p\Delta^{++}[a_2(1320) \to \eta\pi])} = 0.8 \pm 0.2$$

for reaction (2). In the charge exchange reaction ($\pi^-p \to \eta\pi^0 n$), where the $a_2(1320)$ meson dominates the $\eta\pi^0$ mass spectrum [2]:

$$\frac{\sigma(\pi^-p \to [a_0(980) \to \eta\pi]n)}{\sigma(\pi^-p \to [a_2(1320) \to \eta\pi]n)} \approx 0.15$$

at 38 GeV/c beam momentum.

In previous WA102 analyses it has been observed that centrally produced states have different dP_T dependencies, where dP_T is the difference in the transverse momentum vectors of the two exchange particles [17]. The ratio of the production cross section for $dP_T < 0.2$ GeV to $dP_T > 0.5$ GeV is significantly different for $q\bar{q}$ states and for the glueball candidates. It has been observed that all undisputed $q\bar{q}$ states which can be produced by DPE have very small values for this ratio (≤ 0.1). States which cannot be produced by DPE (with negative G parity, for example) have slightly higher values (≈ 0.25). And all non-$q\bar{q}$ candidates $f_0(980)$, $f_0(1500)$, $f_0(1710)$ and $f_2(1950)$ have values of this ratio about 1. A study of the $\eta\pi^0$ and $\eta\pi^-$ systems, which can not be produced by DPE, has been made as a function of dP_T. The results are given in table 1.

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 [16]. In order to determine the azimuthal angle ϕ for the $a_0(980)$ and $a_2(1320)$ the $\eta\pi^0$ and $\eta\pi^-$ mass spectra have been fitted in 30 degree bins of ϕ with the parameters of the resonances fixed to those obtained from the fit to the total data. The resulting distributions for the $a_0^0(980)$ and $a_2^0(1320)$ are shown in fig. 3 a) and b) respectively. The distributions for the $a_0^-(980)$ and $a_2^-(1320)$ are shown in fig. 4 a) and b) respectively.

In order to determine the four momentum transfer dependence (t) of the resonances observed, the $\eta\pi^0$ mass spectrum has 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. 3c) and d) shows the four momentum transfer from one of the proton vertices for the $a_0^0(980)$ and $a_2^0(1320)$ respectively. The distributions have been fitted with a single exponential of the form $exp(-b|t|)$ and the values of b found are $b = 6.2 \pm 0.8$ for the $a_0^0(980)$ and $b = 8.8 \pm 0.4$ for the $a_2^0(1320)$.

In order to determine the four momentum transfer ($|t|$) at the beam-Δ^{++} vertex for the $a_0^-(980)$ and $a_2^-(1320)$ the $\eta\pi^-$ mass spectrum has been fitted as described above. The resulting distributions are shown in fig. 4c) and d) for the $a_0^-(980)$ and $a_2^-(1320)$ respectively. The distributions have been fitted with a single exponential of the form $exp(-b|t|)$ and the values of b found are $b = 4.0 \pm 0.3$ for the $a_0^-(980)$ and $b = 5.9 \pm 0.5$ for the $a_2^-(1320)$.

The four momentum transfer ($|t_{slow}|$) distributions at the target-slow vertex are shown in fig. 4e) and f) for the $a_0^-(980)$ and $a_2^-(1320)$ respectively. The data for $|t| \leq 0.1$ GeV^2 has been excluded from the fit due to the poor acceptance for the slow proton in this range. The distributions have been fitted with a single exponential of the form $exp(-b|t|)$ and the values of b found are $b = 7.5 \pm 0.4$ for the $a_0^-(980)$ and $b = 7.9 \pm 0.6$ for the $a_2^-(1320)$.

In summary, a partial wave analysis of the centrally produced $\eta\pi^0$ and $\eta\pi^-$ channels has been performed in the mass region $670 - 2000$ MeV. Clear $a_0(980)$ and $a_2(1320)$ signals are seen in the S and D_+ waves respectively. No evidence is found for any significant structures in other waves. In particular, there is no evidence for the $a_0(1450)$ nor the $a_2(1660)$. The ratio of the $a_0(980)$ to $a_2(1320)$ is found to depend on the production mechanism.

Acknowledgements

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References

[1] D.Alde *et al.,* Phys. Lett. **B205** (1988) 397;
H.Aoyagi *et al.,* Phys. Lett. **B205** (1988) 397;
G.M.Beladidze *et al.,* Phys. Lett. **B313** (1993) 276;
D.R. Thompson *et al.,* Phys. Rev. Lett. **79** (1997) 1630;
A.Abele *et al.,* Phys. Lett. **B423** (1998) 175;
A.Abele *et al.,* Phys. Lett. **B446** (1999) 275.

[2] D.Alde *et al.,* Phys. Atom. Nucl. **62** (1999) 421, Yad. Phys. **62** (1999) 462.

[3] C. Amsler *et al.,* Phys. Lett. **B333** (1994) 277.

[4] C. Amsler *et al.,* Phys. Lett. **B446** (1999) 275.

[5] C. Amsler *et al.,* Phys. Lett. **B355** (1995) 425.

[6] A.Abele *et al.,* Phys. Lett. **B404** (1997) 179.

[7] R.L.Jaffe, Phys. Rev. **D15** (1977) 267.
L.Montanet, Rep. Prog. Phys. **46** (1983) 337.
N.N.Achasov *et al.,* Usp.Fys.Nauk **142** (1984) 361.
F.E.Close, Rep. Prog. Phys. **51** (1988) 833.
J.Weinstein and N.Isgur, Phys. Rev. **D41** (1990) 2236.
S.Ishida *et al.,* KEK Preprint 95-167, Talk at HADRON'95, Manchester, (1995) 454.

[8] A.Abele *et al.,* Eur. Phys.J. **C8** (1999) 67.

[9] D.Alde *et al.,* KEK Preprint 95-160, Talk at HADRON'95, Manchester, (1995) 448.

[10] D. Barberis *et al.,* Phys. Lett. **B397** (1997) 339.

[11] S. Flatté *et al.,* Phys. Lett. **B63** (1976) 224.

[12] K.L. Au, D. Morgan and M.R. Pennington, Phys. Rev. **D35** (1987) 1633.

[13] Particle Data Group, Eur. Phys.J. **C3** (1998) 1.

[14] S.U.Chung, Phys. Rev. **D56** (1997) 7299.

[15] S.A.Sadovsky, Preprint IHEP 91-71, Protvino, 1991.

[16] D.Barberis *et al.,* Phys. Lett. **B467** (1999) 165.

[17] D.Barberis *et al.,* Phys. Lett. **B397** (1997) 339.

Table 1: 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.

Resonance	$dP_T \leq 0.2$ GeV	$0.2 \leq dP_T \leq 0.5$ GeV	$dP_T \geq 0.5$ GeV	$R = \frac{dP_T \leq 0.2 GeV}{dP_T \geq 0.5 GeV}$
$a_0^0(980)$	25±3	33±5	42±4	0.57 ± 0.09
$a_0^-(980)$	14±3	37±2	49±2	0.29 ± 0.06
$a_2^0(1320)$	10±2	38±2	52±3	0.19 ± 0.04
$a_2^-(1320)$	9±3	39±2	52±2	0.17 ± 0.06

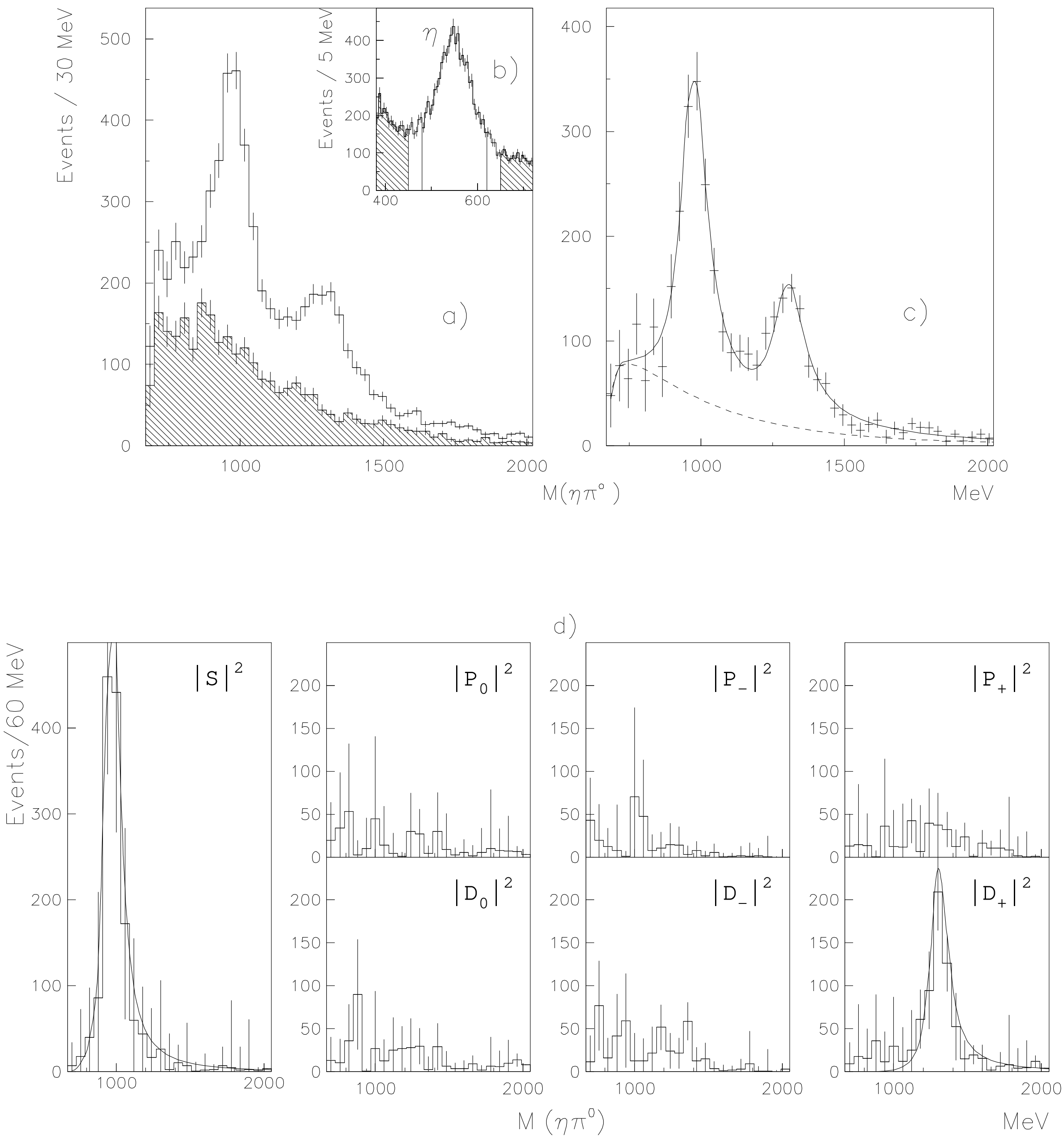
Figures

Figure 1: a) The efficiency corrected mass spectrum for the centrally produced $\eta\pi^0$ events. Superimposed as a shaded histogram is an estimation of the background contribution. Inset b) the $\gamma\gamma$ mass spectrum. c) The efficiency corrected background subtracted mass spectrum for the centrally produced $\eta\pi^0$ events. The curve is the result of the fit described in the text. d) The physical solutions from the PWA of the $\eta\pi^0$ events.

Figure 2: a) The efficiency corrected mass spectra of centrally produced $\eta\pi^-$ events. Inset b) presents the distribution to the $p_f\pi^+$ invariant masses. c) The efficiency corrected background subtracted mass spectrum for the centrally produced $\eta\pi^-$ events. The curve is the result of the fit described in the text. d) The physical solutions from the PWA of the $\eta\pi^-$ events.

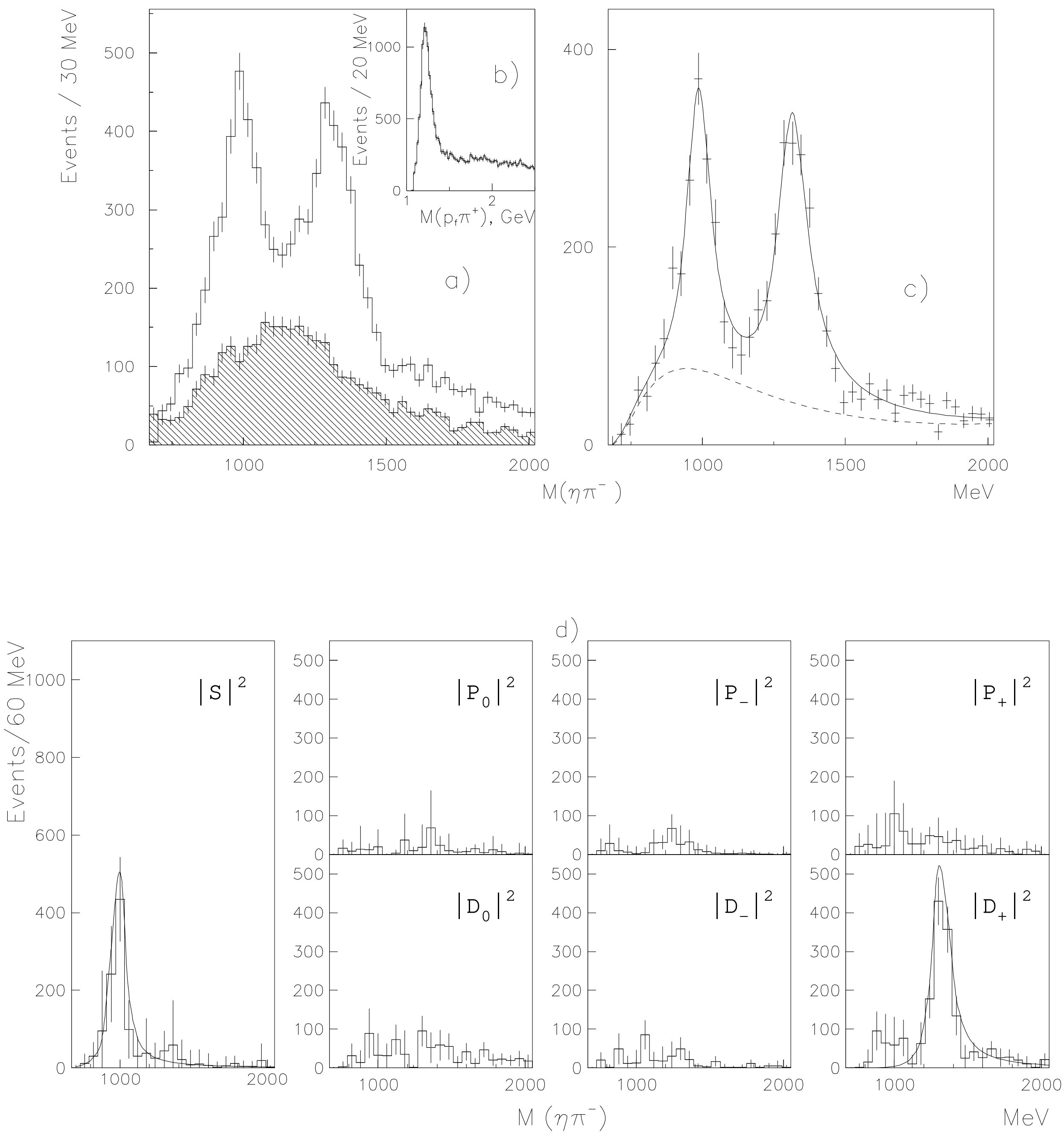
Figure 3: The azimuthal angle ϕ between the p_T vectors of the slow and fast protons for a) the $a_0^0(980)$ and b) the $a_2^0(1320)$. The four momentum transfer distributions for c) the $a_0^0(980)$ and d) the $a_2^0(1320)$, with the fits to the form $e^{-b|t|}$.

Figure 4: The azimuthal angle ϕ between the p_T vectors of the slow proton and fast Δ^{++} for a) the $a_0^-(980)$ and b) the $a_2^-(1320)$. The four momentum transfer distributions from the beam-fast vertex for c) the $a_0^-(980)$ and d) the $a_2^-(1320)$ and for the target-slow vertex e) the $a_0^-(980)$ and f) the $a_2^-(1320)$, with the fits to the form $e^{-b|t|}$.



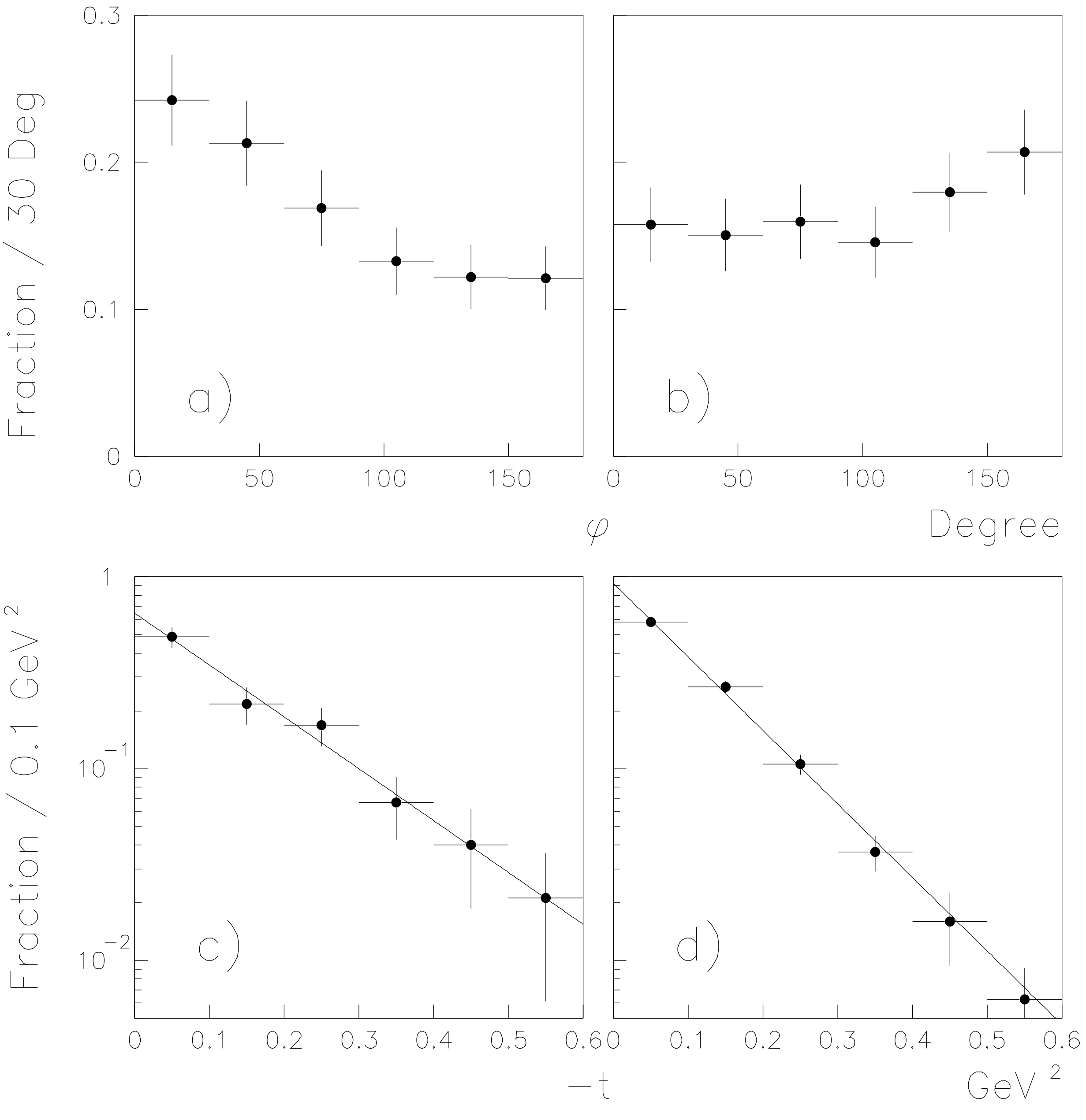
Events / 30 MeV
Events / 5 MeV
η
b)
a)
c)
M($\eta\pi^0$)
MeV
d)
Events/60 MeV
$|S|^2$
$|P_0|^2$
$|P_-|^2$
$|P_+|^2$
$|D_0|^2$
$|D_-|^2$
$|D_+|^2$
M ($\eta\pi^0$)
MeV

Figure 1:



Events / 30 MeV
Events / 20 MeV
b)
M(p_f π^+), GeV
a)
c)
M(ηπ^-)
MeV
d)
Events/60 MeV
|S|^2
|P_0|^2
|P_-|^2
|P_+|^2
|D_0|^2
|D_-|^2
|D_+|^2
M (ηπ^-)
MeV

Figure 2:



0.3
0.2
0.1
0
Fraction / 30 Deg
a)
b)
0
50
100
150
φ
Degree
1
10^{-1}
10^{-2}
Fraction / 0.1 GeV ^{2}
c)
d)
0
0.1
0.2
0.3
0.4
0.5
0.6
$-t$
GeV ^{2}

Figure 3:

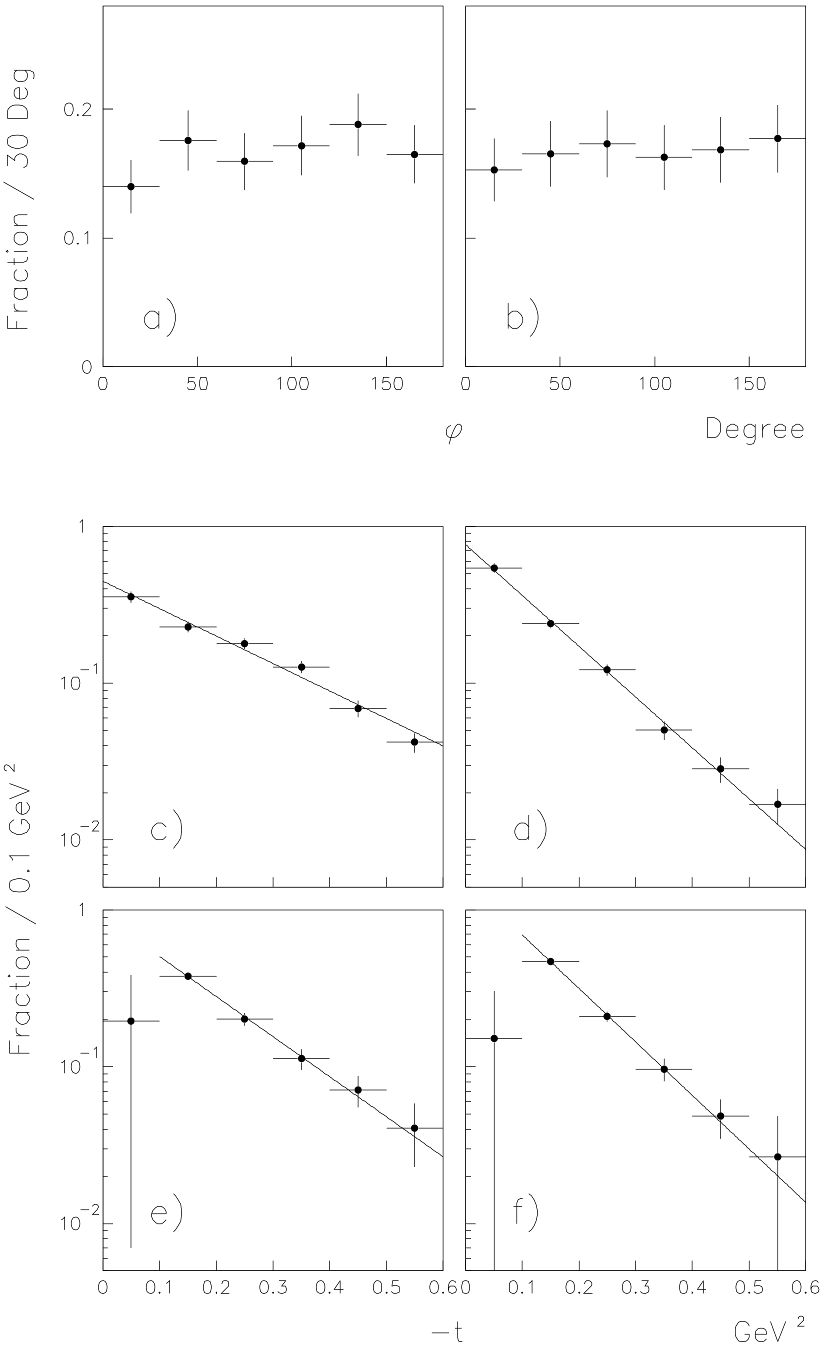

Fraction / 30 Deg
0.2
0.1
0
a)
b)
0
50
100
150
φ
Degree
Fraction / 0.1 GeV 2
1
10−1
10−2
c)
d)
e)
f)
0
0.1
0.2
0.3
0.4
0.5
0.6
−t
GeV 2

Figure 4: