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A study of the centrally produced $\phi\phi$ system in pp interactions at 450 GeV/c

The WA102 Collaboration

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Abstract

The reaction $pp \rightarrow p_f p_s (K^+K^-K^+K^-)$ in which the $K^+K^-K^+K^-$ system is centrally produced has been studied at 450 GeV/c. $\phi\phi$ production has been found to dominate this reaction and is compatible with being produced by double Pomeron exchange. An angular analysis of the $\phi\phi$ system favours $J^{PC} = 2^{++}$ and its dP_T dependence is similar to that observed for glueball candidates.

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Experiment WA102 is designed to study exclusive final states formed in the reaction

$$pp \to p_f(X^0)p_s \tag{1}$$

at 450 GeV/c. The subscripts f and s indicate the fastest and slowest particles in the laboratory respectively and X^0 represents the central system that is presumed to be produced by double exchange processes. The experiment has been performed using the CERN Omega Spectrometer the layout of which is described in ref. [1] In previous analyses of other channels 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 [1, 2], all the undisputed $q\overline{q}$ states are suppressed at small dP_T in contrast to glueball candidates. In addition, it has recently been suggested [3, 4] that this effect could be due to the fact that the production mechanism is through the fusion of two vector particles. It is therefore interesting to make a study of the dP_T dependence of systems decaying to two vectors. One such system is the $\phi\phi$ final state which has the added interest that the observation of glueball candidates has been claimed in this channel [5].

This paper presents a study of the $\phi\phi$ system decaying to $K^+K^-K^+K^-$ produced in central pp interactions and represents a factor ten increase over previously published data samples [6, 7]. Events corresponding to the reaction

$$pp \to p_f(K^+K^-K^+K^-)p_s \tag{2}$$

have been isolated from the sample of events having six outgoing charged tracks by first imposing the following cuts on the components of the missing momentum: $|$missing $P_x| < 14.0$ GeV/c, $|$missing $P_y| < 0.12$ GeV/c and $|$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.

In order to select the $K^+K^-K^+K^-$ system, information from the Čerenkov counter was used. Two data samples were selected: Sample A in which three of the centrally produced particles were identified as ambiguous kaons/protons and sample B in which one of the centrally produced particles was identified as an ambiguous kaon/proton and none of the other particles was positively identified as a pion.

The method of Ehrlich et al. [8] , modified for four tracks, has been used to compute the mass squared of the four central particles (assumed to be equal). The resulting distribution for sample A is shown in fig. 1a) where a clear peak can be seen at the kaon mass squared. This distribution has been fitted with three Gaussians to represent the contributions from the $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ channels. From this fit the number of $K^+K^-K^+K^-$ events in sample A is estimated to be 305 ± 30. A cut on the mass squared of $0.16 \leq M^2 \leq 0.36$ GeV^2 has been used to select a sample of $K^+K^-K^+K^-$ events. The mass of one K^+K^- pair is plotted against the mass of the other K^+K^- pair in fig. 1c) and shows a strong $\phi\phi$ signal.

As can be seen from fig. 1b) the Ehrlich mass distribution for sample B is dominated by a peak at the pion mass squared. However, if the same cut used for sample A is applied then, as can be seen from fig. 1d), the $\phi\phi$ channel can clearly be selected.

The four possible K^+K^- mass combinations are plotted in fig. 2a) and b) for samples A and B respectively. A clear ϕ signal can be seen. A fit has been performed to these spectra where the ϕ is described by a spin 1 relativistic Breit-Wigner convoluted with a Gaussian to represent the experimental resolution, and a background of the form $(m - m_{th})^a exp(-bm - cm^2)$ where m is the K^+K^- mass, m_{th} is the threshold mass and a,b and c are fit parameters. The width of the Breit-Wigner has been fixed to the PDG value of 4.43 MeV [9]. The result of the fit to the two spectra are compatible and give $m(\phi) = 1019.5 \pm 0.4$ MeV and $\sigma(Gaussian) = 3.3 \pm 0.5$ MeV. By selecting one K^+K^- mass to lie within a band around the ϕ mass (from 1.01 - 1.03 GeV) and plotting the effective mass of the other pair, the spectra of fig. 2c) and d) were produced for samples A and B respectively. The large ϕ signal with little background confirms the presence of a strong $\phi\phi$ signal. The background beneath the ϕ signal is similar in both samples.

The number of events in nine regions around the $\phi\phi$ position in the K^+K^- scatter plot are shown in fig. 2e) and f) for samples A and B respectively; no event has more than one entry in this region. From these numbers and applying a correction for the tails of the ϕ, the total number of $\phi\phi$ events is found to be 110 $\pm$ 18 (sample A) and 409 $\pm$ 33 events (sample B).

In order to compare the production rates for ϕK^+K^- and $\phi\phi$, the number of ϕK^+K^- events has been estimated. This was done by subtracting twice the number of $\phi\phi$ events from the total number of ϕs observed in fig. 2a) and b), and this gives 187 $\pm$ 47 ϕK^+K^- events for sample A and 600 $\pm$ 84 ϕK^+K^- events for sample B. A possible source of contamination could come from $\phi\pi^+\pi^-$ events where a π was misidentified as a K. However, it has been shown previously [10] that the $\phi\pi^+\pi^-$ channel is very weak and after the selections applied in this analysis its contribution to this channel is found to be negligible.

The geometrical acceptance has been found to be similar for $\phi\phi$ and ϕK^+K^- production. After correcting for unseen decay modes of the ϕ, the ratio of cross sections is estimated to be $\sigma(\phi K^+K^-)/\sigma(\phi\phi) = 0.83 \pm 0.21$ (sample A) and 0.72 ± 0.07 (sample B). For sample A we can also calculate the number of $K^+K^-K^+K^-$ events that do not include a ϕ using the fit to fig. 1a) which gives 7 $\pm$ 50 $K^+K^-K^+K^-$ events. The results obtained for samples A and B are similar and since the statistics are greater in sample B for the rest of the results presented in this paper we shall use sample B only. This dominance of the $\phi\phi$ channel over the ϕK^+K^- and $K^+K^-K^+K^-$ channels is similar to what has been observed by the JETSET experiment [11].

The $\phi\phi$ final state is selected by requiring that both K^+K^- mass combinations fall within $1.01 \leq m(K^+K^-) \leq 1.03$ GeV. The $\phi\phi$ effective mass spectrum is shown in fig. 3a) and as can be seen shows a broad distribution with a maximum around 2.35 GeV.

The angular distributions of the $K^+K^-K^+K^-$ system can be used to determine the spin-parity of the intermediate $\phi\phi$ state using a method formulated by Chang and Nelson [12] and Trueman [13]. Three angles have to be considered: the azimuthal angle χ, between the two ϕ decay planes and the two polar angles θ_1 and θ_2 of the K^+s in their respective ϕ rest frames relative to the ϕ momenta in the $\phi\phi$ rest frame.

For a $\phi\phi$ sample of unique spin-parity and free of background the distribution of χ takes the form $dN/d\chi = 1 + \beta cos(2\chi)$ where β is a constant which depends only on the spin-parity of the $\phi\phi$ system and is independent of its polarisation. Similarly $dN/dcos\theta = 1 + (\zeta/2)(3cos^2\theta - 1)$. Values of β and ζ for different spin-parity states are given in table 1 [14]. Fig. 3b) and c) shows the χ and $cos\theta$ distributions. A chi-squared fit has been performed to these spectra using the distributions expected for a single state with a given value of J^{PC}. The results of the fit are given in table 1 and as can be seen the lowest chi-squared is for a fit using $J^P = 2^+$ (L=0, S=2) with β=1/15 and ζ=0. As can be seen the $J^{PC} = 0^{++}$ and 0^{-+} hypotheses can be clearly ruled out. A free fit to the distributions has been performed and gives $\beta = 0.0 \pm 0.1$ and $\zeta = 0.1 \pm 0.1$. The spin analysis has been repeated in three slices in mass of the $\phi\phi$ system. The results found are similar to that for the total sample.

The Feynman x_F distributions for the slow particle, the $\phi\phi$ system and the fast particle are shown in fig. 4a). As can be seen the $\phi\phi$ system lies within $|x_F| \leq 0.2$. After correcting for geometrical acceptances, detector efficiencies and losses due to cuts and charged kaon decay, the cross-section for $\phi\phi$ production at $\sqrt{s}$ = 29.1 GeV in the x_F interval $|x_F| \leq 0.2$ is $\sigma(\phi\phi) = 41.0 \pm 3.7$ nb. This can be compared with the cross-sections found in the same interval at $\sqrt{s}$ = 12.7 [6] and 23.8 GeV [7] of 42 $\pm$ 9 nb and 36 $\pm$ 6 nb respectively. This effectively constant cross-section as a function of energy is consistent with the $\phi\phi$ system being produced by a Double Pomeron Exchange (DPE) mechanism.

A study of the $\phi\phi$ system as a function of the parameter dP_T, which is the difference in the transverse momentum vectors of the two exchanged particles [1, 2], has been performed. The acceptance corrected dP_T dependence of the $\phi\phi$ system is shown in fig. 4b). The fraction of $\phi\phi$ 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 0.22 $\pm$ 0.05, 0.51 $\pm$ 0.04 and 0.27 $\pm$ 0.04 respectively. This results in a ratio of production at small dP_T to large dP_T of 0.81 $\pm$ 0.22. This ratio is much higher than what has been observed for the undisputed $q\overline{q}$ states which typically have a value for this ratio of 0.1 [15].

Fig. 4c) shows the four momentum transferred from one of the proton vertices for the $\phi\phi$ system. The distribution has been fitted with a single exponential of the form $exp(-b|t|)$ and yields b = 6.3 $\pm$ 0.6 GeV which is consistent with what is expected from DPE [16]. The azimuthal angle (ϕ) between the p_T vectors of the two protons is shown in fig. 4d). This distribution differs significantly from that observed for the π^0, η, η' [17] and ω [18].

In conclusion, a study of the reaction $pp \rightarrow p_f p_s(K^+K^-K^+K^-)$ shows that the production of $\phi\phi$ is the dominant process and that there is effectively no $K^+K^-K^+K^-$ production not involving one or more ϕ mesons. The $\phi\phi$ mass spectrum shows a broad distribution with a maximum around 2.35 GeV and an angular analysis shows that it is compatible with having $J^{PC} = 2^{++}$. The behaviour of the cross-section as a function of centre of mass energy and the four momentum transferred dependence are compatible with what would be expected if the $\phi\phi$ system was produced via double Pomeron exchange which has been predicted to be a source of glueballs [19]. In addition, the dP_T behaviour is different to that observed for all undisputed $q\overline{q}$ states.

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Table 1: The β, ζ and chi-squared values for different spins of the $\phi\phi$ system

J^P	L	S	β	ζ	chi-squared
0^+	0	0	2/3	0	124
0^+	2	2	1/3	1	202
0^-	1	1	-1	-1	356
1^-	1	1	0	1/2	69
1^+	2	2	0	1/2	69
2^+	0	2	1/15	0	36
2^+	2	0	2/3	0	124
2^+	2	2	2/21	3/14	44
2^-	1	1	-2/5	-1/10	61
2^-	3	1	-31/5	-2/3	162

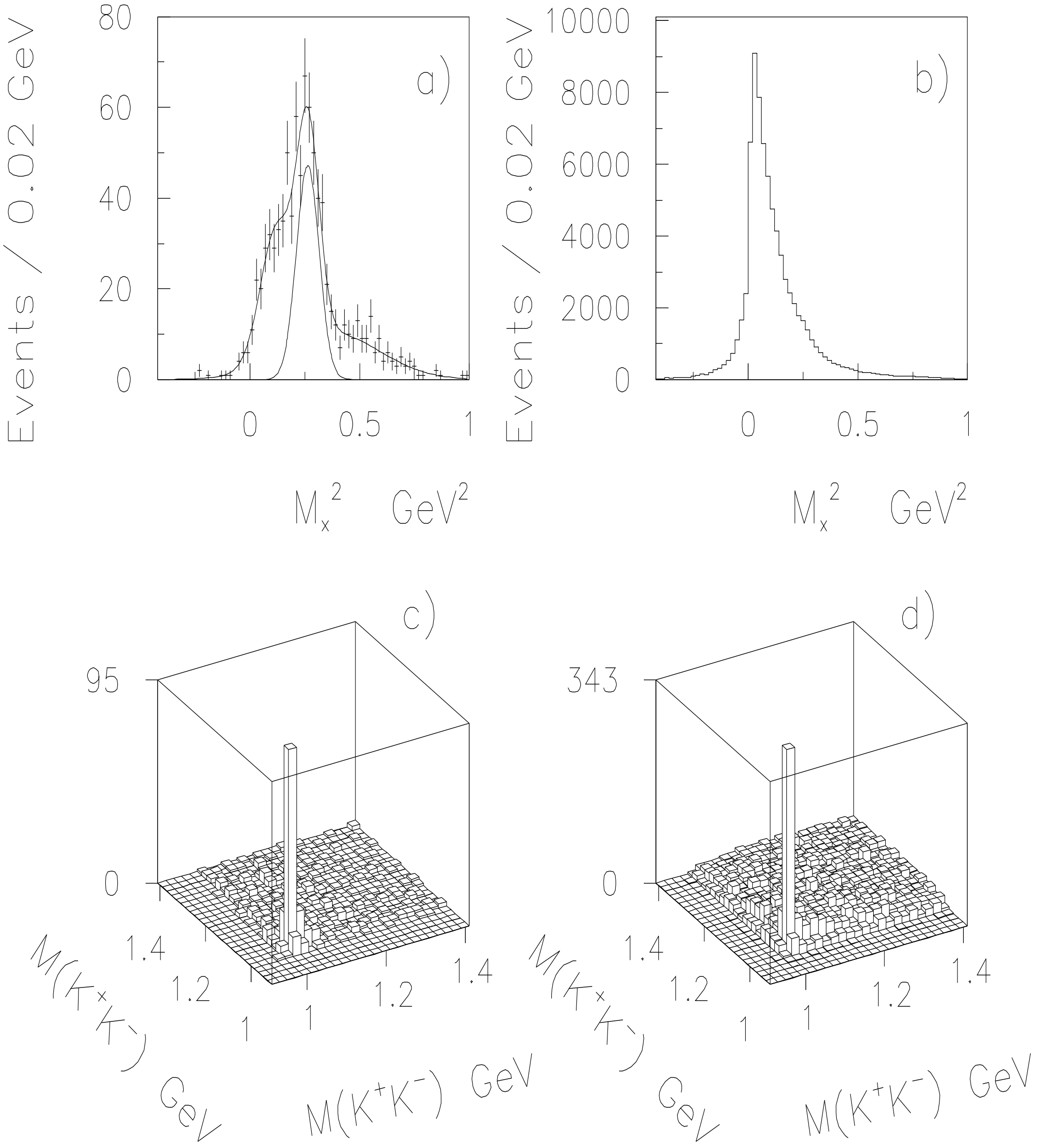
Figures

Figure 1: The Ehrlich mass squared distribution for a) sample A and b) sample B. The lego Plot of one K^+K^- mass against the other (two entries per event) for c) sample A and d) sample B.

Figure 2: a) and b) The K^+K^- mass spectrum (four combinations per event), c) and d) the K^+K^- effective mass of one K^+K^- combination after selecting the other to lie in the ϕ mass band and e) and f) a scatter table of one K^+K^- mass against the other in the $\phi\phi$ region. a), c) and e) for sample A b), d) and f) for sample B.

Figure 3: a) The $\phi\phi$ effective mass spectrum, b) and c) the χ and $cos\theta$ distributions (the superimposed curve represents the 2^+ (L=0, S=2) wave).

Figure 4: a) The x_F distribution for the slow particle, the $\phi\phi$ system and the fast particle. b) The dP_T spectrum, c) the four momentum transfer squared ($|t|$) from one of the proton vertices and d) the azimuthal angle (ϕ) between the two outgoing protons for the $\phi\phi$ system.



a)
b)
c)
d)
Events / 0.02 GeV
Events / 0.02 GeV
M_x^2 GeV^2
M_x^2 GeV^2
M(K^+K^-) GeV
M(K^+K^-) GeV
M(K^+K^-) GeV
M(K^+K^-) GeV

Figure 1

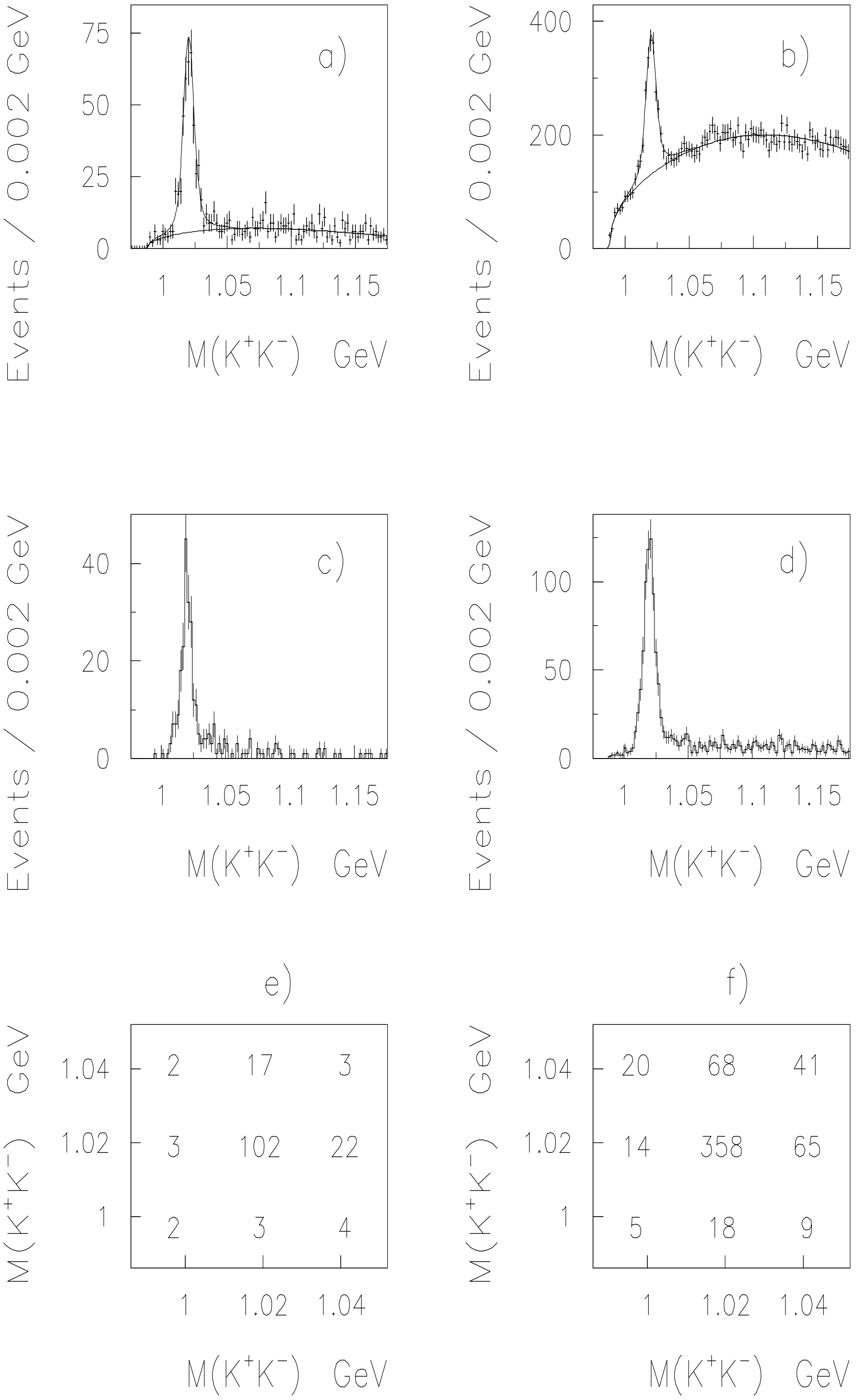

a)
b)
c)
d)
e)
f)
Events / 0.002 GeV
M(K+K−) GeV
1.04
1.02
1
2 17 3
3 102 22
2 3 4
20 68 41
14 358 65
5 18 9

Figure 2

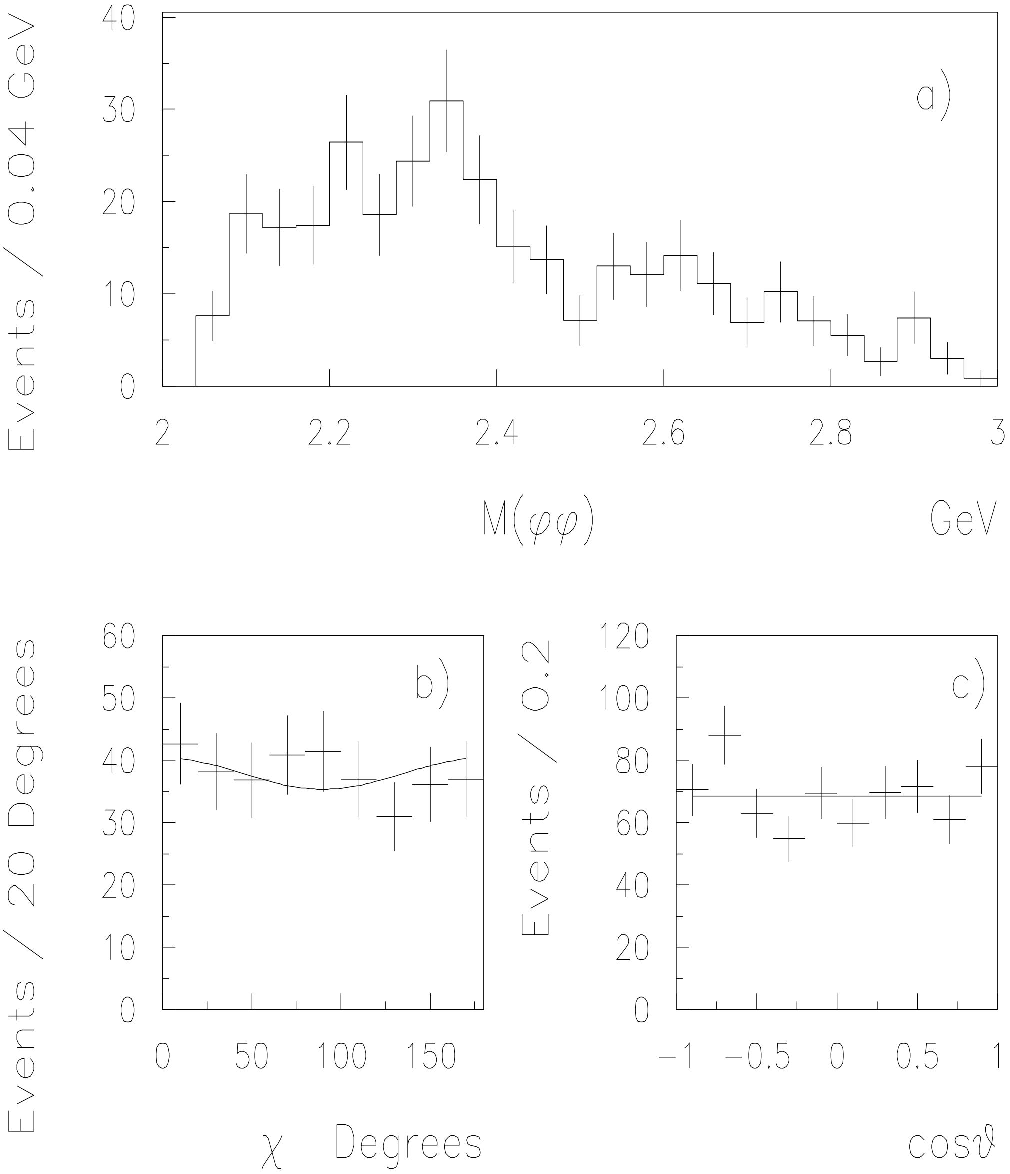
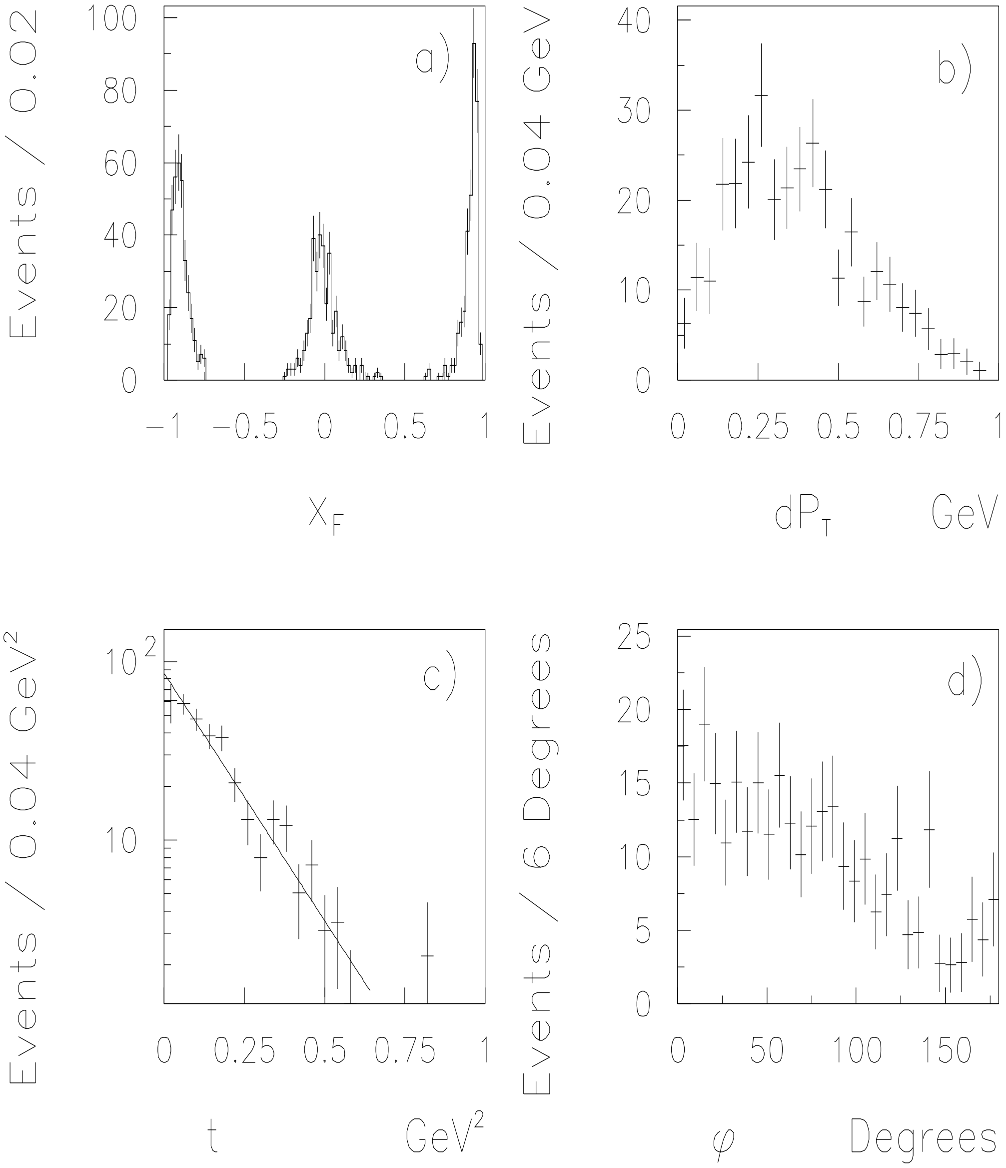

Events / 0.04 GeV
40
30
20
10
0
a)
2
2.2
2.4
2.6
2.8
3
M(φφ)
GeV
Events / 20 Degrees
60
50
40
30
20
10
0
b)
0
50
100
150
χ Degrees
Events / 0.2
120
100
80
60
40
20
0
c)
−1
−0.5
0
0.5
1
cosϑ

Figure 3



Events / 0.02
a)
X_F
Events / 0.04 GeV
b)
dP_T
GeV
Events / 0.04 GeV²
c)
t
GeV²
Events / 6 Degrees
d)
φ
Degrees

Figure 4