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Experimental evidence for a vector-like behaviour of Pomeron exchange

The WA102 Collaboration

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Abstract

Evidence is presented that the Pomeron act as a non-conserved vector current. A study has been made of the azimuthal angle ϕ, which is defined as the angle between the p_T vectors of the two outgoing protons, in the reaction $pp \to pp(X^0)$ for those resonances (X^0) which are compatible with being produced by double Pomeron exchange. These distributions have been compared with a model which describes the Pomeron as a non-conserved vector current and a qualitative agreement is found. In addition, when one of the particles exchanged is known to have spin 0, namely π-Pomeron exchange, the ϕ distribution is flat.

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

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

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: in particular Double Pomeron Exchange (DPE). The experiment has been performed using the CERN Omega Spectrometer, the layout of which is described in ref. [1]. 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 [1, 2], 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 [3].

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. Historically it has been assumed that the Pomeron, with "vacuum quantum numbers", transforms as a scalar and hence that the ϕ distribution would be flat for resonances produced by DPE. The ϕ dependences observed [4, 5, 6, 7, 8] are clearly not flat and considerable variation is observed among the resonances produced.

Several theoretical papers have been published on these effects [9, 10]. All agree that the exchanged particle must have J > 0 and that J = 1 is the simplest explanation for the observed ϕ distributions. Close and Schuler [10] have calculated the ϕ dependences for the production of resonances with different J^{PC} for the case where the exchanged particle is a Pomeron that transforms like a non-conserved vector current. In order to try to get some insight into the nature of the particles exchanged in central pp interactions we will compare the predictions of this model with the data for resonances with different J^{PC} observed in the WA102 experiment.

The simplest situation is for the production of $J^{PC} = 0^{-+}$ states where the model of Close and Schuler [10] predicts

$$\frac{d^3\sigma}{d\phi dt_1 dt_2} \propto t_1 t_2 \sin^2\phi \tag{2}$$

where t_1 and t_2 are the four momentum transfer at the beam-fast and target-slow vertices respectively. Fig. 1a) and b) show the experimental ϕ distributions for the η and η'. They have been fitted to the form $\alpha \sin^2\phi$ which describes the data well. It has also been found experimentally that $d\sigma/dt$ is proportional to t [5] (where t is t_1 or t_2) as predicted from equation (2).

The fact that both the η and η' signals are suppressed at small four-momentum transfers, where Double Pomeron Exchange (DPE) is believed to be dominant, was assumed to imply that the 0^{-+} states do not couple to DPE [11]. However, from equation (2) it can be seen that if DPE is mediated via Pomerons transforming as vector particles then the production of 0^{-+} resonances will be suppressed at small t. Equation (2) is general to all vector vector exchange processes, so to investigate if the η and η' are produced by DPE we have attempted to determine their cross sections as a function of energy. To do so we have calculated the ratio of the cross sections measured by the WA76 experiment, at 85 GeV/c ($\sqrt{s}$ = 12.7 GeV), to those measured by the WA102 experiment at 450 GeV/c ($\sqrt{s}$ = 29.1 GeV).

Up to now the determination of this ratio has been limited to resonances that decay to final states containing only charged particles due to the fact that there was no calorimeter in the 85 GeV/c run of the WA76 experiment. However, the WA76 experiment was able to reconstruct the $\eta\pi^+\pi^-$ mass spectrum using the decay $\eta \rightarrow \pi^+\pi^-(\pi^0)_{missing}$ [12]. In this mass spectrum the η' and $f_1(1285)$ are seen. The cross section of the $f_1(1285)$ at 85 GeV/c has been well measured through its all charged particle decay mode and hence can be used to determine the cross section of the η' after taking into account the different acceptance and combinatorial effects and gives

$$\frac{\sigma_{450}(\eta')}{\sigma_{85}(\eta')} = 0.72 \pm 0.16 \tag{3}$$

For Pomeron-Pomeron exchange we would expect a value of ≈ 1.0, while for ρ-ρ exchange the value would be ≈ 0.2. Due to charge conjugation the η' can not be produced by ω-Pomeron exchange and Isospin forbids ρ-Pomeron exchange. Therefore, it would appear that DPE is dominant in η' production. For the η there is no possibility of determining the ratio because in the $\pi^+\pi^-\pi^0$ channel there is no suitable reference signal.

The cross section as a function of energy for the $J^{PC} = 1^{++}$ $f_1(1285)$ and $f_1(1420)$ has been found to be constant [6]. Hence both the $f_1(1285)$ and $f_1(1420)$ are consistent with being produced by DPE [6]. For the $J^{PC} = 1^{++}$ states the model of Close and Schuler predicts that $J_Z = \pm 1$ should dominate, which has been found experimentally to be correct [6], and in addition that

$$\frac{d^3\sigma}{d\phi dt_1 dt_2} \propto (\sqrt{t_2} - \sqrt{t_1})^2 + 4\sqrt{t_1 t_2}\sin^2\phi/2 \tag{4}$$

Fig. 1c) and d) shows the the ϕ distributions for the $f_1(1285)$ and $f_1(1420)$. The distributions have been fitted to the form $\alpha + \beta\sin^2\phi/2$, which describes the data well. Equation (4) also predicts that when $|t_2 - t_1|$ is small $d\sigma/d\phi$ should be proportional to $\sin^2\phi/2$ while when $|t_2 - t_1|$ is large $d\sigma/d\phi$ should be constant. Fig. 1e) and f) show the ϕ distributions for the $f_1(1285)$ for $|t_1 - t_2| \leq 0.2$ GeV^2 and $|t_1 - t_2| \geq 0.4$ GeV^2 respectively; as can be seen from the figures the expected trend is observed in the data.

The $f_0(980)$, $f_0(1500)$ and $f_2(1270)$ are other states for which the cross section as a function of energy has been found to be constant [7] and hence are consistent with being produced by DPE. For the scalar states and for the tensor states with $J_Z = 0$ Close and Schuler have predicted that

$$\frac{d\sigma}{d\phi} \propto (R - \cos\phi)^2 \tag{5}$$

where R is predicted from ref. [10] to be a function of $t_1 t_2$ and can be negative or positive. In order to compare the data with the model we have studied the ϕ dependences for the $f_0(980)$, $f_0(1500)$ and $f_2(1270)$ by studying their decays to $\pi^+\pi^-$.

In ref. [7] a Partial Wave Analysis (PWA) was performed in six bins of ϕ in order to determine the ϕ dependences of the above resonances. It has not been possible to perform a PWA as a function of ϕ and $t_1 t_2$. Therefore in order to determine the ϕ dependences in intervals of $t_1 t_2$ we have performed a fit to the total mass spectrum in each interval using the method described in ref. [13]. A PWA has been performed in each $t_1 t_2$ interval discussed below, integrated over ϕ, to determine the amount of $f_2(1270)$ produced with $J_Z = 0$ compared to $J_Z = \pm 1$. The amount of $J_Z = \pm 1$ is found to be ≈ 10 % of the $J_Z = 0$ contribution irrespective of the $t_1 t_2$ interval. The $J_Z = \pm 2$ contribution is consistent with zero.

Fig. 2a), d) and g) show the ϕ distributions, for the $f_0(980)$, $f_0(1500)$ and $f_2(1270)$ respectively, for all the data. These distributions are similar to those found from a fit to the PWA amplitudes [7]. The ϕ distributions have been fitted to the form given in equation (5). The values of R determined from the fit are given in table 1. Since R is predicted to be a function of t_1t_2 the ϕ distributions have been analysed in two different intervals of t_1t_2, the corresponding values of R are given in table 1. Fig. 2b), e) and h) show the ϕ distributions, for the $f_0(980)$, $f_0(1500)$ and $f_2(1270)$ respectively for $|t_1t_2| \leq 0.01$ GeV^4. Fig. 2c), f) and i) show the corresponding ϕ distributions for $|t_1t_2| \geq 0.08$ GeV^4.

For the resonances studied to date, in the WA102 experiment, the model of Close and Schuler [10] is in qualitative agreement with the data. *Hence the data are consistent with the hypothesis that the Pomeron transforms as a non-conserved vector current.*

In order to understand what happens if a different particle is exchanged a study has been made of the reactions

$$pp \rightarrow \Delta_f^{++}(\pi^-)p_s \tag{6}$$

and

$$pp \rightarrow \Delta_f^{++}(\rho^-)p_s \tag{7}$$

In this case a particle with $I = 1$ has to be exchanged from the p-Δ^{++} vertex and hence we are no longer studying reactions which are DPE. In the case of central π^- production the most likely production mechanism is π-Pomeron exchange. For the ρ^- production the most likely production mechanisms are ρ-Pomeron and π-π exchange.

To select reaction (6) a study has been made of the reaction

$$pp \rightarrow p_f(\pi^+\pi^-)p_s \tag{8}$$

at 450 GeV/c. The isolation of reaction (8) has been described in ref. [14]. Fig 3a) shows the $p_f\pi^+$ effective mass spectrum where a clear peak corresponding to the $\Delta^{++}(1232)$ can be observed. In order to separate reaction (6) from the reaction

$$pp \rightarrow N_f^* p_s \tag{9}$$

where $N_f^* \rightarrow \Delta_f^{++}\pi^-$, the rapidity gap between the π^- and the $p_f\pi^+$ system has been required to be greater than 2.0 units. The resulting $p_f\pi^+$ effective mass spectrum is shown in fig. 3b). Reaction (6) has been selected by requiring $M(p_f\pi^+) \leq 1.4$ GeV. The remaining $p_f\pi^+\pi^-$ and $\pi^+\pi^-$ mass spectra have no resonance contributions.

The four momentum transfer ($|t_{fast}|$) at the beam-Δ^{++} vertex is shown in fig. 3c) and has been fitted to the form

$$\frac{d\sigma}{dt} = \frac{\alpha|t|}{(|t| + m_\pi^2)^2} e^{-2\beta(|t|+m_\pi^2)} \tag{10}$$

which is the standard expression used to describe π exchange [15]. The first bin in the distributions has been excluded from the fit due to the fact that the uncertainties in the acceptance correction are greatest in this bin. The fit describes the data well, and yields $\beta = 2.4 \pm 0.2$ GeV^{-2}, consistent with π exchange [15].

The four momentum transfer ($|t_{slow}|$) at the target-slow vertex is shown in fig. 3d) and has been fitted to the form e^{-bt}. The data with $|t| \leq 0.1$ GeV^2 has been excluded from the fit due to the poor acceptance for the slow proton in this range. The fit yields a value of $b = 6.2 \pm 0.1$ GeV^{-2} which is compatible with Pomeron exchange being the dominant contribution [16].

In this case the azimuthal angle ϕ is defined as the angle between the p_T vectors of the slow proton and the Δ^{++} and is shown in fig. 3e). The ϕ distribution is consistent with being flat as would be expected if the process was dominated by the exchange of a particle with spin 0, as in π exchange.

To select reaction (7) a study has then been made of the reaction

$$pp \rightarrow p_f(\pi^+\pi^-\pi^0)p_s \tag{11}$$

the isolation of which has been described in ref. [8]. Fig 4a) shows the $p_f\pi^+$ effective mass spectrum where a clear peak corresponding to the $\Delta^{++}(1232)$ can be observed which has been selected by requiring $M(p_f\pi^+) \leq 1.4$ GeV in order to select the reaction

$$pp \rightarrow \Delta_f^{++}(\pi^-\pi^0)p_s \tag{12}$$

A rapidity gap of 2.0 units is required between the Δ^{++} and the $\pi^-\pi^0$ system.

Fig. 4b) shows the $\pi^-\pi^0$ effective mass spectrum where a clear peak corresponding to the $\rho^-(770)$ can be observed. The mass spectrum has been fitted using two Breit-Wigners, representing the $\rho^-(770)$ and the broad enhancement in the 1.65 GeV region, plus a background of the form $a(m - m_{th})^b exp(-cm - dm^2)$, where m is the $\pi^-\pi^0$ mass, m_{th} is the $\pi^-\pi^0$ threshold mass and a, b, c, d are fit parameters. The fit yields for the $\rho^-(770)$ M = 771 $\pm$ 3 MeV, Γ = 160 $\pm$ 15 MeV and for the 1.65 GeV region M = 1660 $\pm$ 9 MeV, Γ = 240 $\pm$ 25 MeV, which could be due to the $\rho_3(1690)$ or the $\rho(1700)$.

In order to determine the four momentum transfer ($|t|$) at the beam-Δ^{++} vertex for ρ^- production the $\pi^-\pi^0$ mass spectrum has been fitted in 0.05 GeV^2 bins of t with the parameters of the resonances fixed to those obtained from the fits to the total data. The resulting distribution is shown in fig. 4c). In this case it can not be fitted with the π exchange formula and instead has been fitted to the form e^{-bt}. The first bin in the distributions has been excluded from the fit due to the fact that the uncertainties in the acceptance correction are greatest in this bin. The fit yields a value of $b = 4.7 \pm 0.1$ GeV^{-2} which is compatible with ρ exchange being the dominant contribution [17].

The four momentum transfer ($|t_{slow}|$) at the target-slow vertex is shown in fig. 3d) and has been fitted to the form e^{-bt}. 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 fit yields a value of $b = 6.1 \pm 0.1$ GeV^{-2} which is compatible with Pomeron exchange being the dominant contribution [16].

In order to determine the azimuthal angle ϕ between the p_T vectors of the slow proton and the Δ^{++} for ρ^- production the $\pi^-\pi^0$ mass spectrum has been fitted in 30 degree bins of ϕ with the parameters of the resonances fixed to those obtained from the fits to the total data. The resulting distribution is shown in fig. 4e). The ϕ distribution is clearly not flat in this case. Hence the ρ^- is consistent with being produced by particles that carry spin, for example ρ-Pomeron exchange with the Pomeron transforming like a non-conserved vector current.

In summary, for the resonances studied to date which are compatible with being produced by DPE, the model of Close and Schuler [10] is in qualitative agreement with the data and hence is consistent with the Pomeron transforming like a non-conserved vector current. When one of the particles exchanged is known to have spin 0, namely π-Pomeron exchange, the ϕ distribution is flat. When ρ-Pomeron exchange is the dominant contribution the ϕ distribution is not flat.

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Table 1: Determination of R from fits to the ϕ distributions.

	All data	$\lvert t_1 t_2 \rvert \leq 0.01$ GeV^4	$\lvert t_1 t_2 \rvert \geq 0.08$ GeV^4
$f_0(980)$	-1.9 $\pm$ 0.1	-2.3 $\pm$ 0.3	0.01 $\pm$ 0.03
$f_0(1500)$	-1.6 $\pm$ 0.2	-1.7 $\pm$ 0.2	0.16 $\pm$ 0.06
$f_2(1270)$	2.5 $\pm$ 0.1	2.1 $\pm$ 0.2	3.8 $\pm$ 0.4

Figures

Figure 1: The azimuthal angle ϕ between the fast and slow protons for a) the η, b) the η', c) the $f_1(1285)$ and d) the $f_1(1420)$. The ϕ distribution for the $f_1(1285)$ for e) $|t_1 - t_2| \leq 0.2$ GeV^2 and f) $|t_1 - t_2| \geq 0.4$ GeV^2. The fits to the distributions are described in the text.

Figure 2: The azimuthal angle ϕ between the fast and slow protons. The first column is for all the events, the second for events with $|t_1 t_2| \leq 0.01$ GeV^4 and the last for those with $|t_1 t_2| \geq 0.08$ GeV^4 for the $f_0(970)$ (a, b and c), the $f_0(1500)$ (d, e and f) and for the $f_2(1270)$ (g, h and i) respectively. The fits to the distributions are described in the text.

Figure 3: The selection of the reaction $pp \to \Delta_f^{++}(\pi^-)p_s$. The $p_f\pi^+$ effective mass spectrum for a) all the data and b) for events with a rapidity gap greater than 2.0 units between the π^- and $p_f\pi^+$ system. c) The four momentum transfer distribution at the beam-Δ^{++} vertex with a fit to π exchange described in the text. d) The four momentum transfer distribution at the target-slow vertex with a fit described in the text. e) The azimuthal angle ϕ between the p_T vectors of the slow proton and the Δ^{++}.

Figure 4: The selection of the reaction $pp \to \Delta_f^{++}(\pi^-\pi^0)p_s$. a) The $p_f\pi^+$ effective mass spectrum. b) The $\pi^-\pi^0$ effective mass spectrum with fit described in the text. c) The four momentum transfer distribution at the beam-Δ^{++} vertex for ρ^- production with a fit described in the text. d) The four momentum transfer distribution at the target-slow vertex for ρ^- production with a fit described in the text. e) The azimuthal angle ϕ between the p_T vectors of the slow proton and the Δ^{++} for ρ^- production.

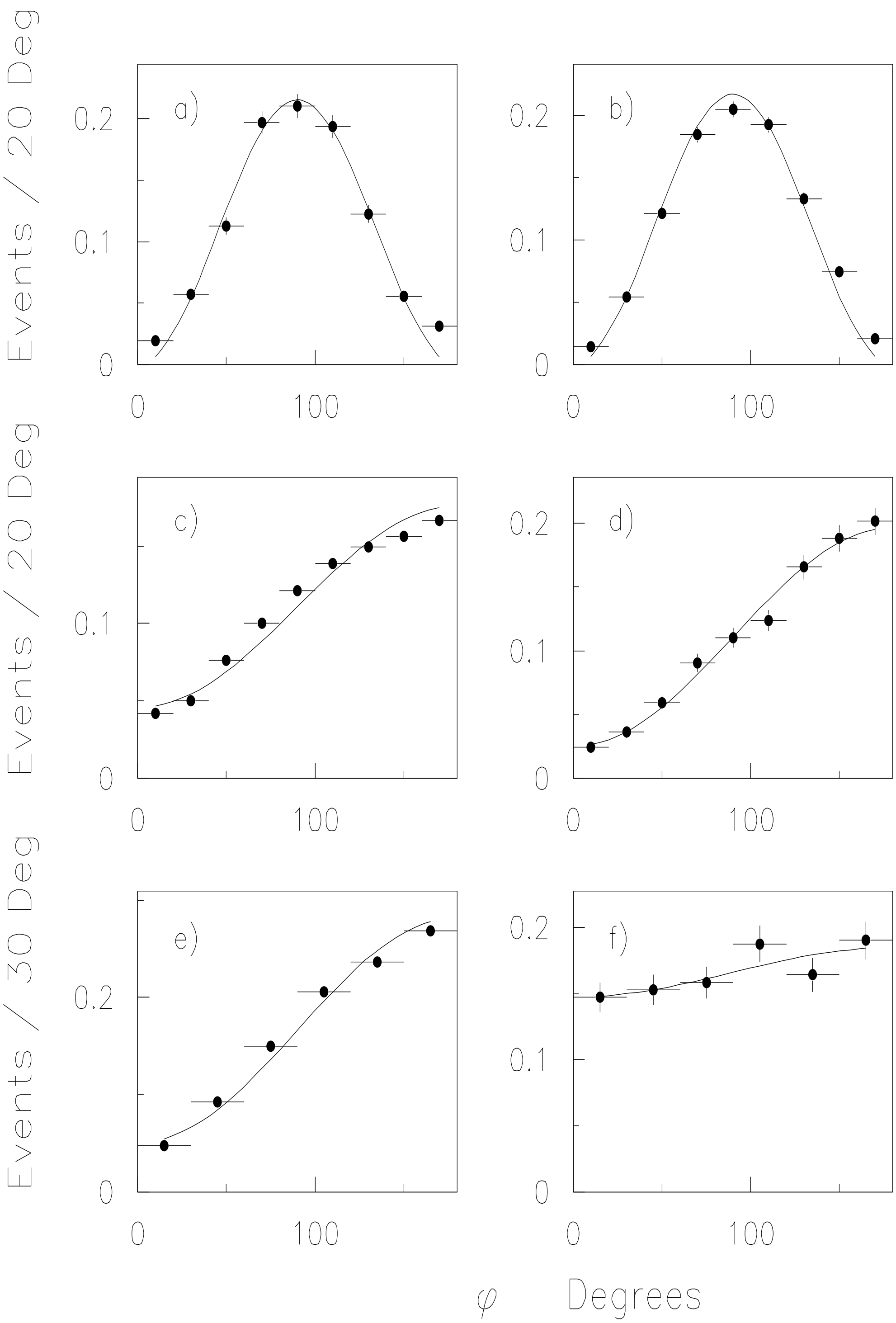

Events / 20 Deg
Events / 20 Deg
Events / 30 Deg
a)
b)
c)
d)
e)
f)
0.2
0.1
0
0
100
φ Degrees

Figure 1

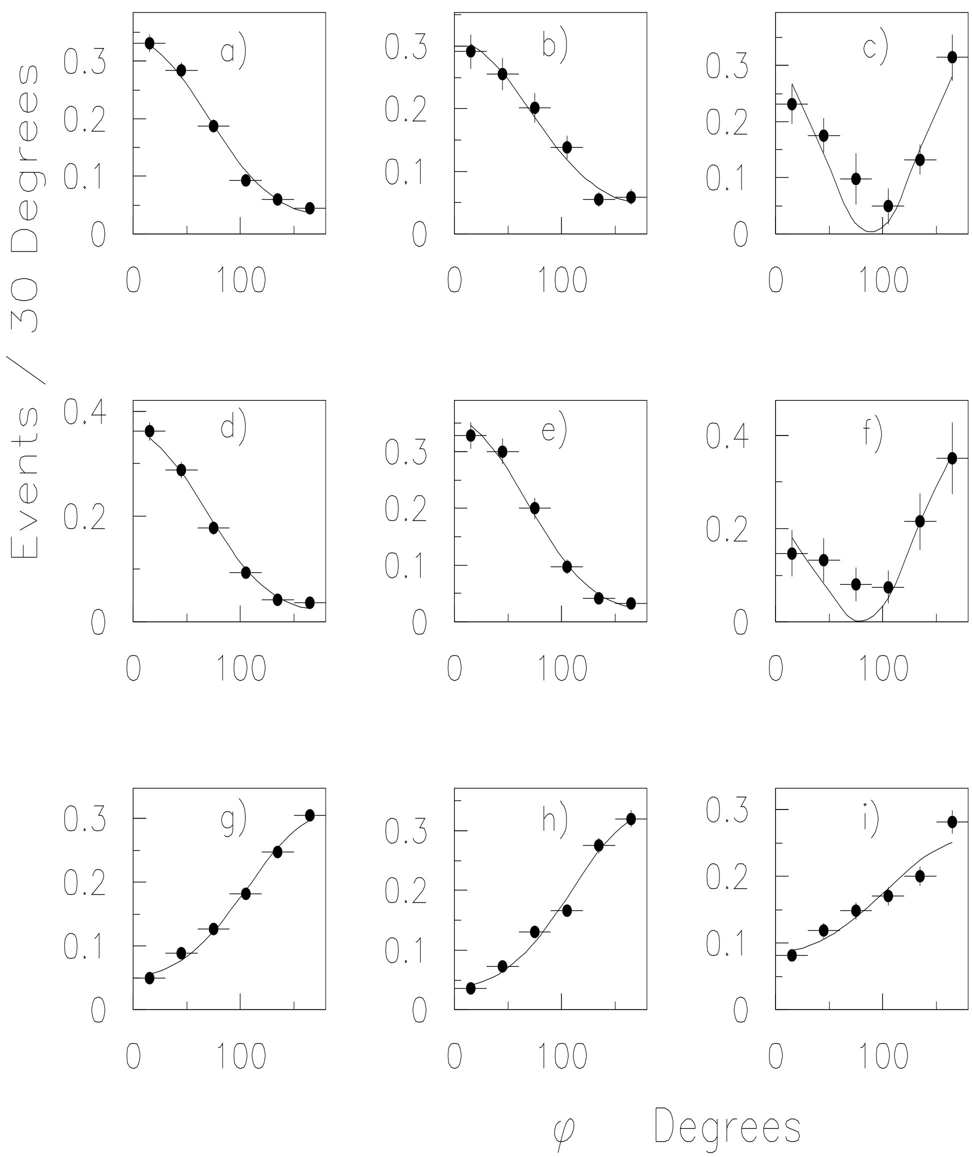
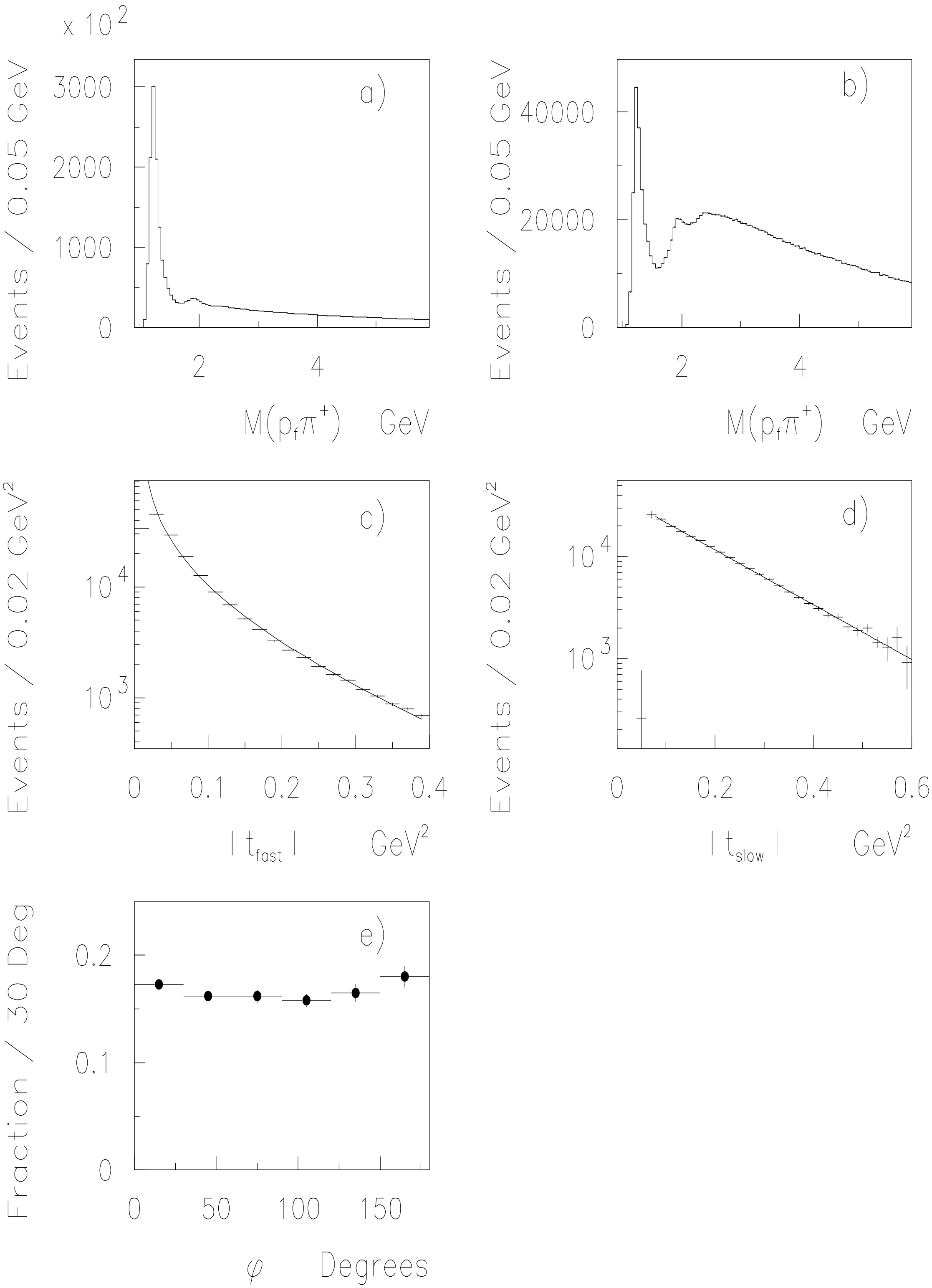


Figure 2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Events / 0.05 GeV
3000
2000
1000
0
a)
2
4
M(p_f π^+) GeV
Events / 0.05 GeV
40000
20000
0
b)
2
4
M(p_f π^+) GeV
Events / 0.02 GeV^2
10^4
10^3
c)
0
0.1
0.2
0.3
0.4
| t_fast | GeV^2
Events / 0.02 GeV^2
10^4
10^3
d)
0
0.2
0.4
0.6
| t_slow | GeV^2
Fraction / 30 Deg
0.2
0.1
0
e)
0
50
100
150
φ Degrees

Figure 3

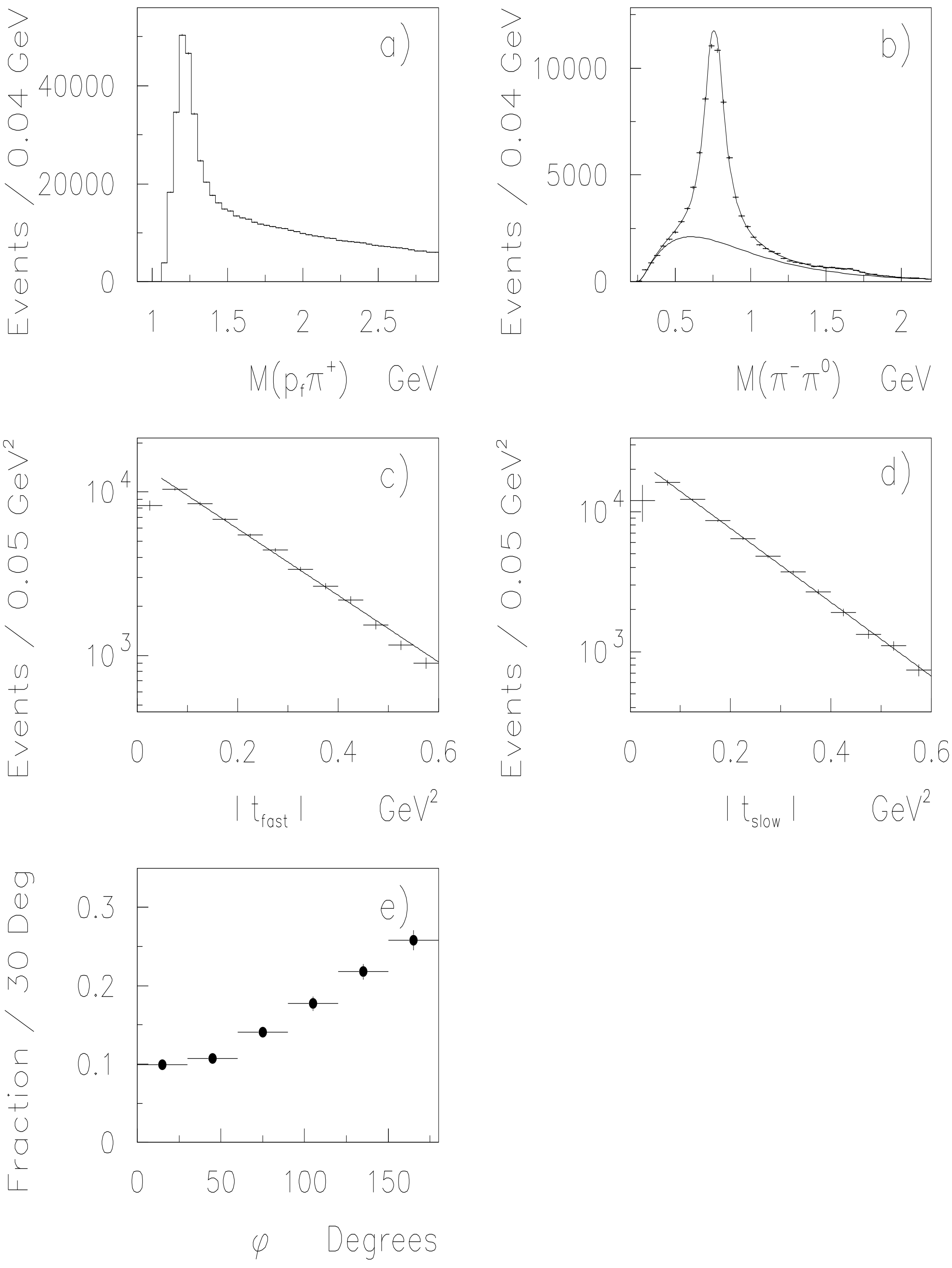
a)
Events / 0.04 GeV
0
20000
40000
1
1.5
2
2.5
M(p_f π^+) GeV
b)
Events / 0.04 GeV
0
5000
10000
0.5
1
1.5
2
M(π^- π^0) GeV
c)
Events / 0.05 GeV^2
10^3
10^4
0
0.2
0.4
0.6
| t_fast | GeV^2
d)
Events / 0.05 GeV^2
10^3
10^4
0
0.2
0.4
0.6
| t_slow | GeV^2
e)
Fraction / 30 Deg
0
0.1
0.2
0.3
0
50
100
150
φ Degrees

Figure 4