

JET PRODUCTION AND RESONANCES

IN

110 GeV/c K^-p INTERACTIONS

By

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Abstract

Differential cross section of single particle and multiparticle systems produced in K^-p interactions at 110 GeV/c are presented. At large values of transverse momentum (P_T) we find the multiparticle cross section to be an order of magnitude larger than that for single particles. This and other features of our data are consistent with results obtained at 200 GeV/c that had been claimed as evidence for hard-scattering behaviour. However, similar features are observed in a K^-p experiment at 16 GeV/c. In addition it was found that the multiparticle cross section strongly depends on the size of the solid angle used for jet analysis. Average values of sphericity $\langle S \rangle$ and $\langle 1-T \rangle$ where T is the thrust, are presented for K^-p interactions at 10, 16 and 110 GeV/c and are compared with those of leptonic data. Similar variation with E_{cm} is observed in the K^-p and lepton interactions. With diffractive events removed, the 110 GeV/c sphericity and thrust distributions are similar to those in the lepton reactions. The values of $\langle P_T \rangle$ and $\langle P_{||} \rangle$ relative to the thrust axis are similar in two different processes. However, the $\langle P_T^2 \rangle$ relative to the beam axis in K^-p data does not rise as fast with E_{cm} as, the $\langle P_T^2 \rangle$ relative to the current direction in νN interactions. Possible reasons for this behaviour are discussed. Results on inclusive $\bar{K}^*(890)^0$, $K^{*-}(890)$ and $\rho(770)^0$ production in K^-p interactions at 110 GeV/c are also presented. The $\bar{K}^{*0}$ (K^{*-}) and ρ^0 inclusive cross sections follow the trends set by K^- data obtained at lower energies; they are slightly rising with beam momenta. A comparison is made with the beam fragmentation and central components of the K^* and ρ^0 production in various experiments using different beam particles and momenta. In all cases the magnitude of the beam fragmentation is found to be independent of the beam momentum; whereas the central component is found to rise rapidly

with beam momenta. Our results are consistent with the predictions of some quark models.

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CHAPTER ONE

HISTORY OF THE EXPERIMENT

1.1 Introduction

This experiment was proposed by the Aachen-Berlin-CERN-Cracow-Imperial College, London-Vienna-Warsaw Collaboration. The experiment was approved in August 1976 by the CERN SPSC and given the code number WA28. The collaboration requested a large statistics (20 events per microbarn) exposure of the Big European Bubble Chamber (BEBC) filled with hydrogen to an R.F separated K^- beam at 110 GeV/c incident momentum. The S3 beam is the highest separated kaon beam in the world. As $\pi^-/K^-/\bar{p}$ separation was not complete at 110 GeV/c the experiment also required a tagging system to identify the kaons. This system consists mainly of two Čerenkov counters and two scintillator hodoscopes. An External Particle Identifier (EPI) was also in operation while taking the data, in order to identify high momentum single tracks emerging from interactions in BEBC into this apparatus.

This chapter describes the history of our experiment. Chapter 2 describes the experimental set up. This contains the R.F separated beam, the tagging system, and a discussion on the beam composition and contamination. BEBC and EPI are briefly described.

Chapter 3 presents the application of beam tagging-data at the scanning, measuring and subsequent processing of the bubble chamber data.

Jet definition and prescriptions used for jet analysis are discussed in chapter 4. In chapter 5 we present hadron production

analysis in the range of high transverse momentum to study the behaviour of single particle and multiparticle distributions. The point is to study if the features of high P_T multiparticle events observed by an FNAL experiment, ref (1.1), which were claimed as evidence for hard scattering jets are also present in low P_T hadron physics. A multiparticle distribution obtained using this beam is also compared with those initiated by non-strange particles to see if strange beam makes any significant difference in the distribution.

Chapter 6 is concerned with the comparison of soft hadron production in this experiment as well as in the lower kaon beam momenta, with quark jet behaviour in leptonic reactions (mainly due to e^+e^- annihilations and deep inelastic neutrino interactions). The aim is essentially to give some insight into the application of Quantum Chromodynamics (QCD) to the soft hadron reactions. Chapter 7 gives a detailed account of inclusive cross sections for the production of $K^*(890)^0$ and $\rho^0(770)$; a method of calculating their mutual reflections is presented. Their Feynman x distributions are also used to account for an analysis of beam fragmentation and central components of these resonances. The overall results are compared with those from the lower kaon beam momenta as well as the results of various experiments with different beam particles and momenta.

1.2 The history of the experiment (1.2, 1.3)

The author joined the experiment in October 1977 when the preliminary stage was already underway. The first data taking run of the experiment was in August 1977. At this time the experiment was running with the wide band ν -hydrogen experiment (WA21) with BEBC

double pulsing each SPS cycle, using the first pulse for hadron data and the second pulse for the ν data. The hadron ejection from the SPS took place when the protons had attained 200 GeV/c in the SPS cycle, ~ 3.6 seconds before the ν ejection at 350 GeV/c, fig (1.1). But data taking for hadrons stopped as there was severe turbulence inside the chamber, while operating in double pulsing, and ν data was taken alone. To have a sample of K^- events the ν taking stopped for a short period, and K^- data was taken. This ended with 3000 frames in a single pulsing mode (Run I). This was the only data from the August run which was usable for physics. While taking the ν pictures the kaon beam was kept running to check the beam tagging system at 110 GeV/c. The turbulence in the chamber during double pulsing was cured by shielding the chamber bottom with a few spring mounted, scotchlite-covered panels. These new panels were mounted on much weaker springs, so that they moved with the liquid and did not cause turbulence when the chamber was filled with hydrogen.

The second run took place in November-December 1977, with the revised panels already fitted in the chamber. This period was scheduled for 10 days, but a few days were lost due to problems with the tuning of the extracted proton beam from the SPS, before the R.F beam target. So the result of the run was only ~ 28000 frames, with ~ 1 event per five frames giving ~ 5600 events (Run II), corresponding to ~ 0.3 events per microbarn. This was less than half of the data anticipated before the run. These films have been completely scanned, measured and processed.

The third run of the experiment was performed in March 1979. This was a good hadron run with a complete use of EPI and with BEBC double

pulsing on two hadron ejections from SPS. Again there were some problems with the SPS extracted proton beam, as in the second run. In addition there was a problem with the first Čerenkov counter in the beam tagging system. It appeared that there was a slow leak in the Counter, which operates at below atmospheric pressure, letting some other gas into the vessel leading to misidentification of the particles. The only solution of this problem was to evacuate the Counter every six hours and refill it with fresh gas. Due to this problem four days of running were lost and the run ended with ~ 80000 frames out of a possible 120000 expected to be taken.

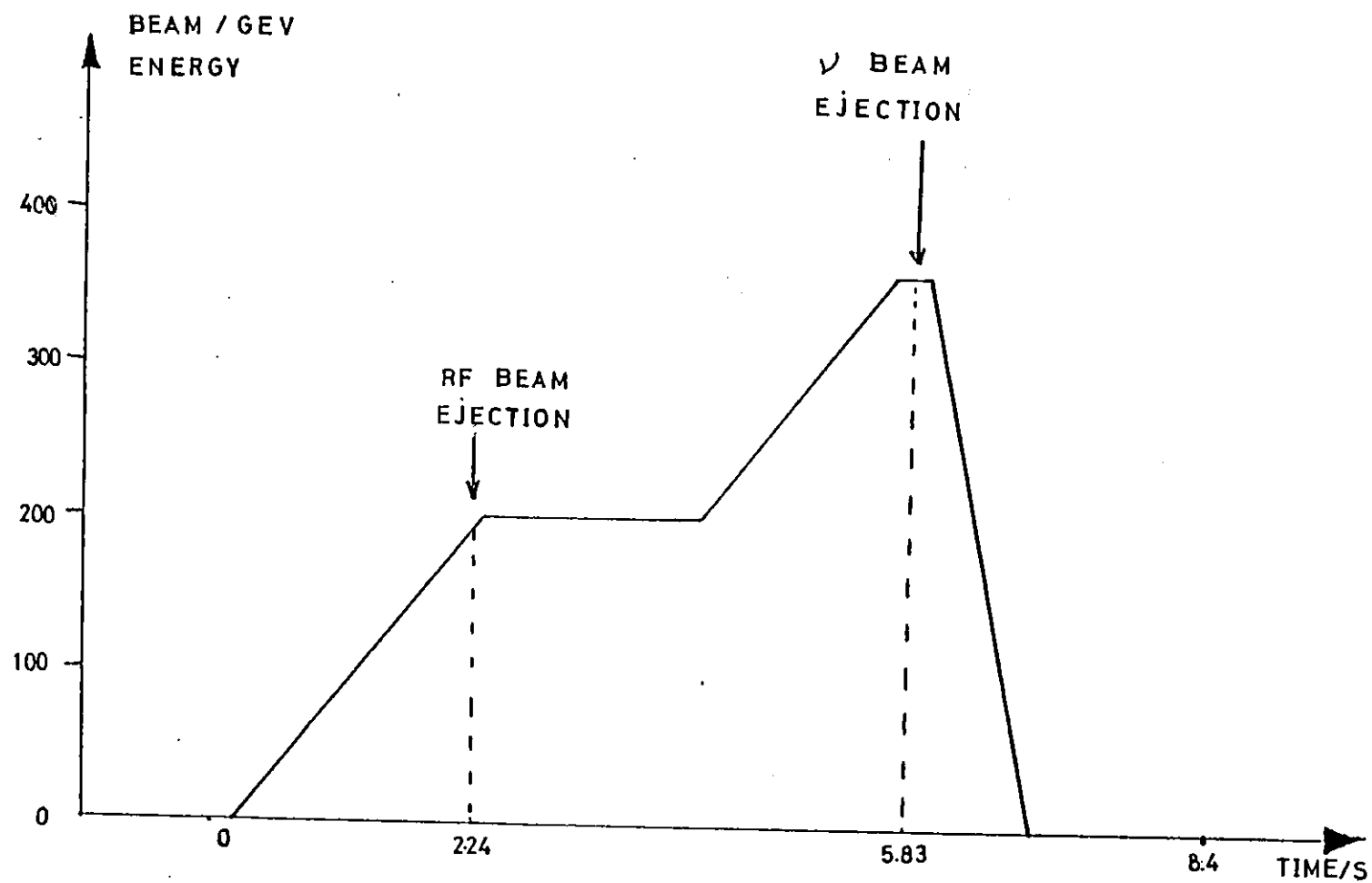
As the beam density was higher than previous runs, an average of 1 event per 4 frames, we expected to obtain 20,000 events (Run III) which corresponded to ~ 1.0 events per microbarn. The analysis of the Imperial College share of this run was the author's responsibility and it has now been completed. A description of the analysis procedure for this data is given in section 3. Most of the results presented in chapters 5, 6 and 7 are based on all three sets of data.

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- 1.1 C. Bromberg et al., Nucl. Phys. B134, 189 (1978)
- 1.2 Addendum to proposal to expose BEBC to a $K^-/\bar{p}$ beam of highest available momentum (~ 110 GeV/c) CERN/SPSC/75-86/ p57
- 1.3 P.R.S. Wright, thesis (Ph.D, 1980), London

Figure Caption

- 1.1 SPS Magnet cycle showing hadron and neutrino beam ejection timing



FIG(1.1.)

CHAPTER TWO

EXPERIMENTAL APPARATUS

A brief description of the apparatus will be given in this chapter explaining only the important stages of the beam line, the tagging system and BEBC itself (plus a description of EPI), because the detailed descriptions exist in the literature.

2.1 The R.F. Separated Beam

The R.F. beam, S3 was used to provide the highest separated kaon particle momentum in the world. The CERN SPS facilities can produce a pure kaon beam up to 75 GeV momentum, but it is also possible to produce a kaon beam momentum up to 110 GeV with about 80-90% purity.

The S3 beam line is designed to transport a maximum momentum of 150 GeV/c (unseparated) from T7 to BEBC, fig (2.1). The target is located in the extracted proton beam tunnel, about 50m from the SPS ejection point. The secondary beam is then bent into the tunnel towards the bubble chamber. These secondary particles will have different momenta. The first step is to provide the required incident beam momentum. This is done by using a single vertical bend together with a pair of collimators.

The next stage is the mass definition of this momentum selected beam. This is done by an R.F. separator. R.F. separation is based on the fact that particles with different masses but with the same momenta

will have different velocities and so will cover the same distance in different times. To explain this in further detail, supposing two different particles such as kaons and pions pass through the first cavity R.F.1. Both kinds of charged particles will be deflected due to electromagnetic field in the cavity. By using vertical and horizontally focussing quadrupoles the particles are focussed into the next cavity R.F.2. The phase difference between the two R.F. deflection fields is adjusted in such a way that the unwanted particles arrive at R.F.2 when the phase is the same as it was in R.F.1, so they are deflected back to the beam axis i.e. no deflection for unwanted particles, which are observed by a downstream collimator (C6). The wanted particles are deflected and can be selected by a suitable opening of this collimator.

It should be noted in general three R.F. cavities are used to separate $K^- - \pi^- - \bar{p}$, but in 110 GeV due to the very high energy, the time of flight differences are so small that we can only separate out one of the particles with the two furthest apart R.F. cavities. Hence both K^- and $\bar{p}$ are deflected. Due to different masses of kaons and protons which consequently give them different velocities, the phase difference between the two R.F. cavities makes antiprotons deflect more than kaons, fig (2.2a). As the figure shows the kaon signal is located between that of pions and antiprotons. Note also that there are pion and antiproton tails under the kaons.

To provide a rather pure sample of K^- beam, a beam stopper would be useful if only the pions were present, with no contamination of antiprotons. Because of this contamination a collimator is used to select one of the two regions which is considerably richer in kaons, fig (2.2a). One of these regions is enough to provide the required kaon flux for

the experiment.

The actual beam composition as measured by the tagging system (to be discussed later) is $\sim 80\% K^-$, $10\% \pi^-/\mu^-$ and $\approx 10\% \bar{p}$. The region where the collimator is set for kaons is very sensitive to the variations in the width or positions of the images at the collimators. One major reason for fluctuations is temperature variations in the phase cable connecting the two R.F. cavities, causing a phase shift of several degrees. Due to this problem a regular phase scan must be made to find the best value of phase difference, i.e. finding the phase difference for which the standard deviation of the pion peak σ_{π^-} is minimum, fig (2.2b)

After this the position and the width of C6 is adjusted for the required flux of kaons.

The third and the last chain of the 895m long beam line, serves to clean and shape the beam before it enters the chamber. It is in this stage that the BEAM-TAGGING system is positioned.

2.2 Beam Tagging System (2.1)

As explained previously it is not possible to obtain a pure beam of K^- at 110 GeV. It is therefore necessary to "tag" the beam particles to separate the kaons from the non kaon beam particles. To this end a beam tagging system is installed in the last section of the S3 beam after the last bending magnet, fig (2.3). The system is required to work in the momentum range 30 - 150 GeV/c with an average of 5 - 10 particles per SPS burst. The system consists of two threshold Čerenkov counters and two scintillator hodoscopes. The Čerenkovs identify beam particles

and the hodoscopes are for positional information.

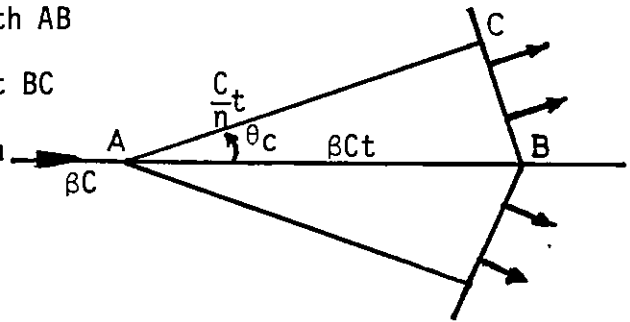
Čerenkov radiation is produced whenever the velocity βc of a charged particle exceeds the velocity of light ($\frac{c}{n}$, where n is the refraction index) in a given medium. As the figure shows the radiation from excited atoms along the path AB

can produce a coherent wavefront BC

at the particular angle θ_c which

can be calculated as (ref 2.2)

$$\cos \theta_c = \frac{c}{n} t / \beta c t = \frac{1}{n\beta}$$



For $\beta c < \frac{c}{n}$ there will be no Čerenkov radiation. There are two sorts of Čerenkov counters, one which is known as a differential counter is based on the fact that θ_c is dependent on the β value of the particle (momentum is fixed). So this angle can be fixed to detect only the wanted particles. This method only works for a parallel beam. As the S3 beam is strongly divergent, differential counters are of no use here.

The other sort of Čerenkov counter which is not dependent on the beam trajectory and so is used in our experiment uses the threshold effect. The main task is to separate pions from kaons from anti-protons. As the β values for these particles are different for the fixed momentum (i.e. 110 GeV/c in our case) the refractive index at the threshold for each particle will be a unique value. To separate pions from kaons a counter with a refractive index at the kaon threshold is needed. This will give a signal for pions but not for kaons, and to separate kaons from antiprotons a counter with a refractive index at the antiproton threshold is needed, giving a signal for kaons (and pions) but not for antiprotons.

The first Čerenkov (C1) which is roughly 21m long with the pressure

of 0.3 atmos. of Helium is a π/K discriminator, and the second Čerenkov (C2) which is about 11m long with a pressure of 0.55 atmos. of neon is used as a $K/\bar{p}$ discriminator. In order to correlate the particle tags obtained from the Čerenkov counters with beam particles seen in BEBC, the trajectory of each particle must also be determined. To achieve this, two scintillator hodoscopes are placed one before the first Čerenkov counter and the other as close to the BEBC as the stray magnetic fields will allow, i.e. ~ 100 Gauss at the chosen position (see fig(2.3)). The first hodoscope covers 16cm horizontally in 64 bins of 0.25cm, the second hodoscope covers 32cm in 64 bins of 0.5cm.

Hodoscopes have vertical fingers so they can only predict horizontal position in BEBC, but the vertical spread is very small. After the beam focussed on the first hodoscope (H1), is diverged by a set of three small quadrupoles (Q27), and then by a large quadrupole (Q28), fig (2.4). This produces an average beam width of 20cm in BEBC. All the scintillator strips in one layer are connected via light guides to a single photomultiplier. A particle transversing any finger in a given layer will give a signal in the associated phototube which will end up to a unique number for each of 64 bins across the hodoscope. 6 multipliers are required to cover 64 bins. A problem appears when two particles arriving too close together in time generating a code number which will result to the wrong position. For this reason the average number of particles should not exceed more than 5-6 per pulse, also the beam spill length has to be kept to at least a few μs .

The electronics which are used to record all information obtained by using the tagging system, are positioned roughly equidistant between the hodoscopes, to minimize the need for delay units necessary to

balance the signals. We assume the presence of signal in the first scintillator to be represented as S_1 , in the first Čerenkov counter as C_1 , and for the second elements as S_2 and C_2 , also the absence of signal to any of these elements to be represented as $\bar{S}_1, \bar{C}_1, \bar{S}_2, \bar{C}_2$. If the first Čerenkov set near kaon threshold and the second near the antiproton threshold, the coincidence $S_1 C_1 C_2 S_2$ indicates a pion, $S_1 \bar{C}_1 C_2 S_2$ a kaon and $S_1 \bar{C}_1 \bar{C}_2 S_2$ an anti-proton. By use of a suitable delay the arrival time of the signals from all the photomultipliers is equalized to facilitate recording of information in each burst. It is thus possible to identify incoming beam particles in a burst and to predict their entry points in BEBC.

To improve the efficiency of tagging system and also to allow for a larger beam spread, some changes were made in the tagging system for data taking in March 1979. C_1 was moved upstream of M39 and C_2 set in the old position of C_1 . This produced space in the last part of the beam line to install several large quadrupoles to increase the horizontal divergence of the beam. The Č tubes were partially lined with the reflecting material to improve light collecting efficiency. H2 was moved upstream towards H1, to accommodate the increased beam spread, fig (2.5). This resulted in a larger error on the extrapolation due to shorter separation and the longer lever arm.

2.3 Big European Bubble Chamber (BEBC) (2.3)

The general lay out of BEBC is shown in figs (2.6a, 6b). The chamber is a vertical cylinder, 4m high and 3.7m in diameter with a hemisphere at the top containing a window for the five cameras. The

expansion piston is at the bottom. The cameras have been equipped with fish eye lenses so that each camera can view the entire useful volume of the chamber. The chamber vessel is surrounded by a cylindrical vacuum tank 3.2m in radius and 9.2m high. The magnetic field is generated by two superconducting magnets cooled by liquid helium. The bubble chamber is also surrounded by an array of multi-wire proportional chambers which serve to identify muons coming from neutrino interactions in the chamber liquid and is known as the External Muon Identifier (EMI), see fig (2.6b). The magnetic field of 3.5 tesla is parallel to the axis of the bubble chamber over the whole useful volume and enables accurate momentum measurements to be made for even very fast tracks up to ~ 100 GeV/c. In our experiment the bubble chamber was filled with hydrogen; as the interaction length for K^- in hydrogen is about 12m, with the size of BEBC one expects one interaction for every four hadrons entering the chamber. Also with this interaction length 5% of beam tracks are expected to interact in the entry window, creating a "wallon". The tracks are visible as black lines over a regular illuminated background, which result in white lines on a black background on the film.

2.4 External Particle Identifier (EPI)

For part of Run II and all of Run III External Particle Identifier was installed behind BEBC. The EPI is a box of 2m x 1m x 8m containing a matrix of single wire proportional chambers of 32 x 128 cells. The purpose is to identify the mass of high momentum single tracks, by sampling the ionization in a large fraction of the 128 cells and using the relativistic rise of ionization.

Two wire chambers are installed one in the entry window and the other in the exit position of EPI to determine the secondary particle trajectories. For the 1977 run as the EPI wire chambers were not yet constructed, the two very forward chambers of EMI were used (25, 52). These chambers allow a good determination of the secondary particle trajectories as they leave BEBC.

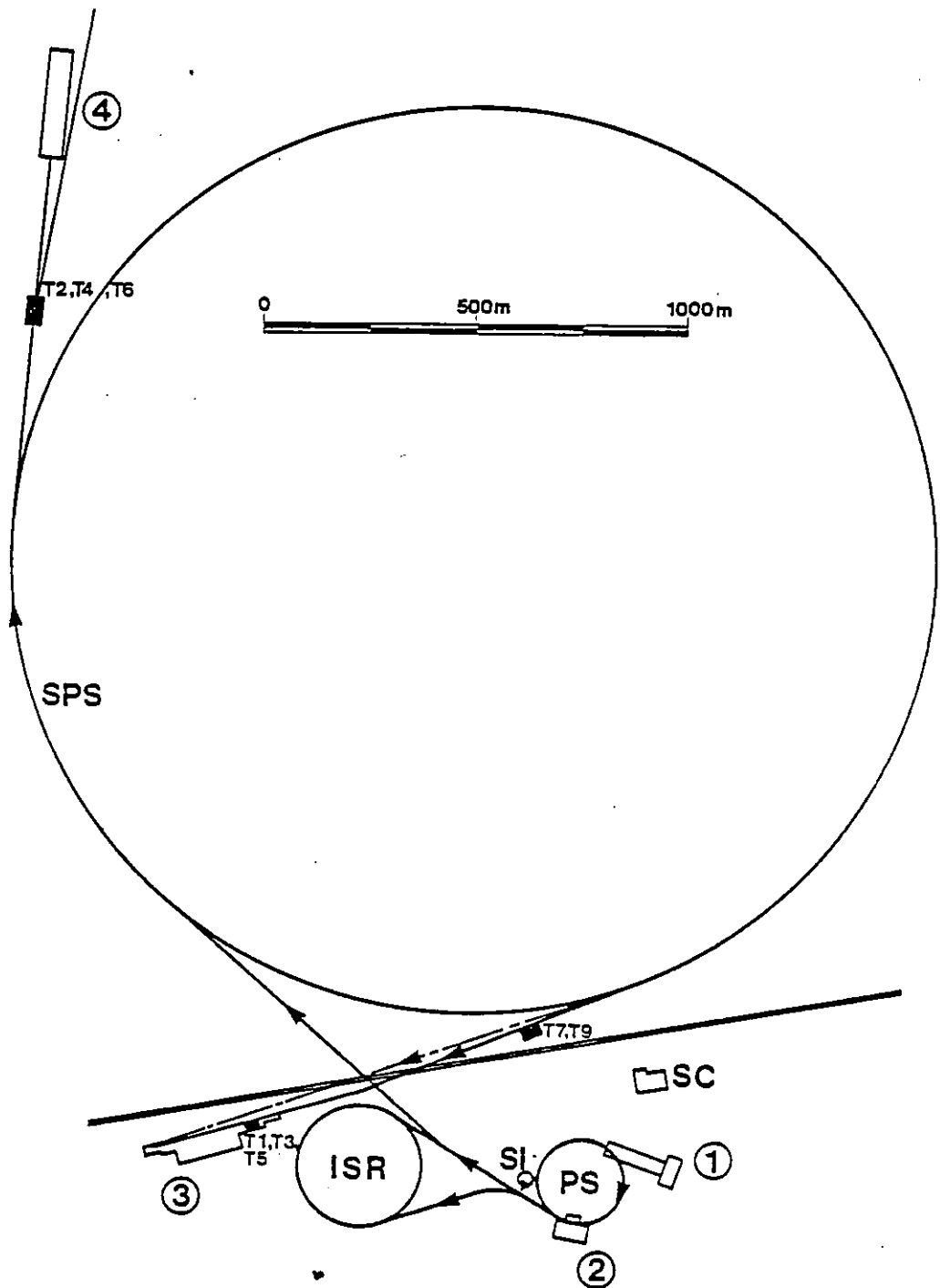
To enable the hadronic particles to leave the chamber and reach EPI, some of the iron shielding blocks in the forward direction had to be removed. Unfortunately not enough blocks were removed and there were a number of secondary interactions in the iron which reached the EPI and caused severe background problems. The EPI is not yet fully calibrated. A full discussion of EPI may be found in ref. (2.4).

References

- 2.1 I. Lehrs. CERN/EF/BEAM 76-3
- 2.2 D.H. Perkins, Addison Wesley (1972)
- 2.3 BEBC Users Handbook
- 2.4 P.R.S. Wright, thesis (Ph.D., 1980), London
- 2.5 E.J.W. West, thesis (Ph.D., 1979), London

Figure Captions

- 2.1 Layout at CERN showing arrangement of SPS and target T7
- 2.2 110 GeV/c K^- separation:
 - a) Beam profile at Wire Chamber 7
 - b) Phase scan results.
- 2.3 Plan view of tagging system (original layout)
- 2.4 Horizontal beam envelope at position of tagging system (old layout)
- 2.5 Modified layout of tagging system
- 2.6 Layout of BEBC
 - a) vertical cross section
 - b) horizontal cross section



FIG(2.1)

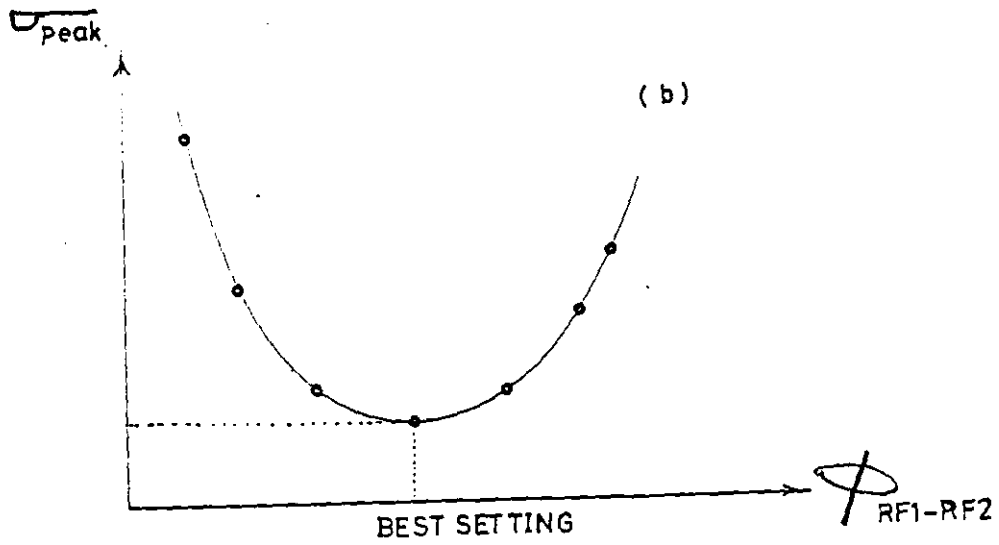
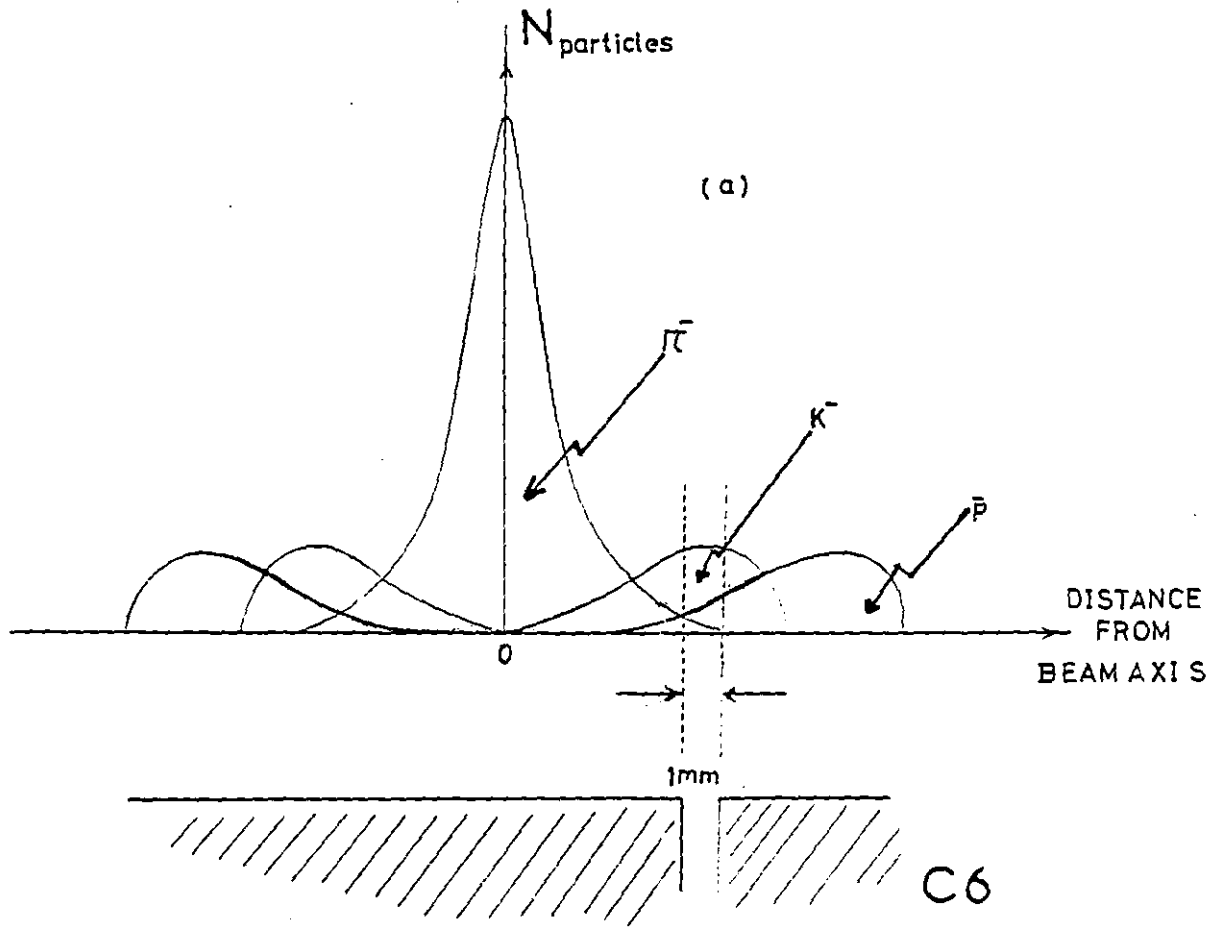


FIG (2.2)

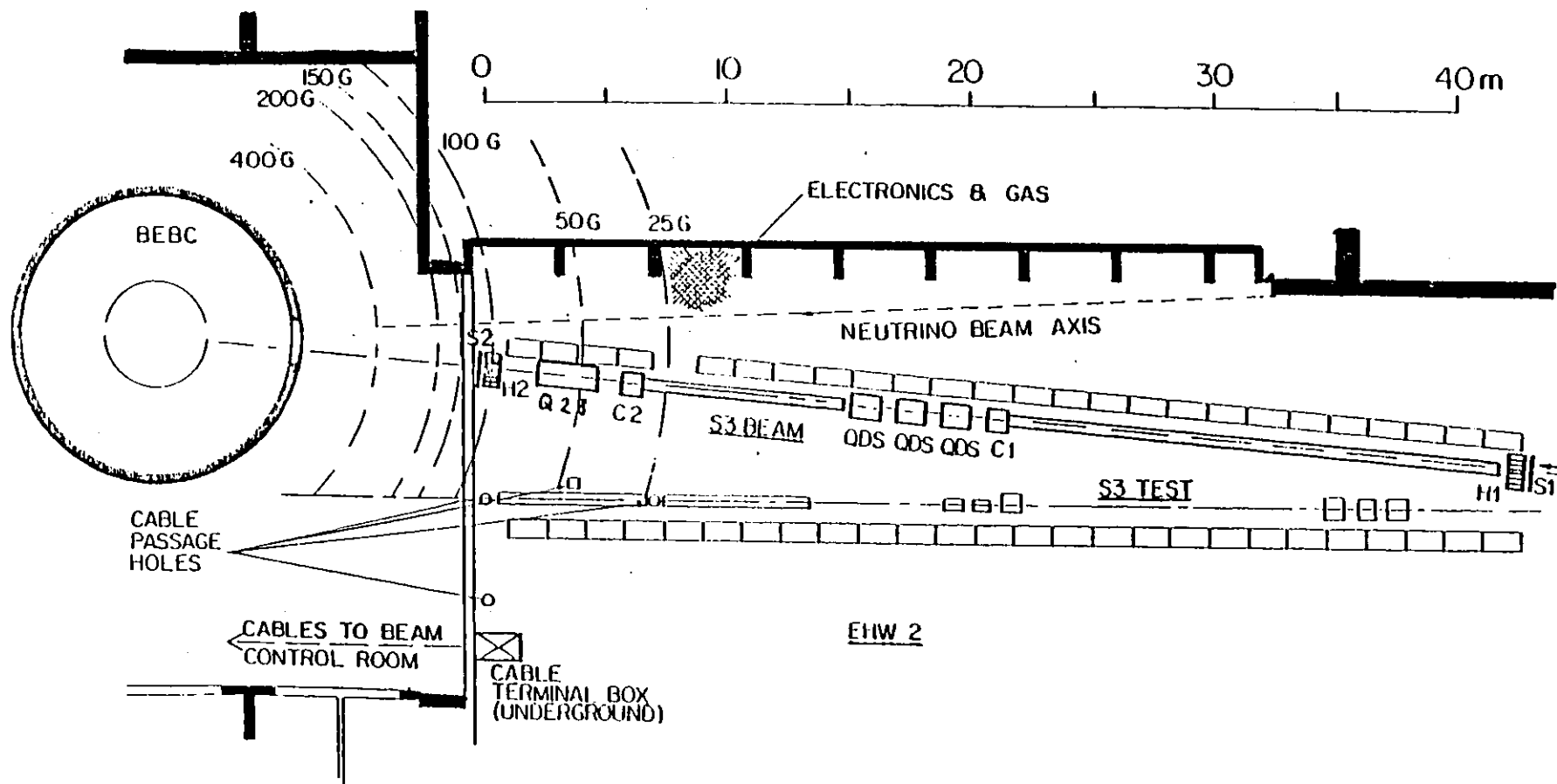
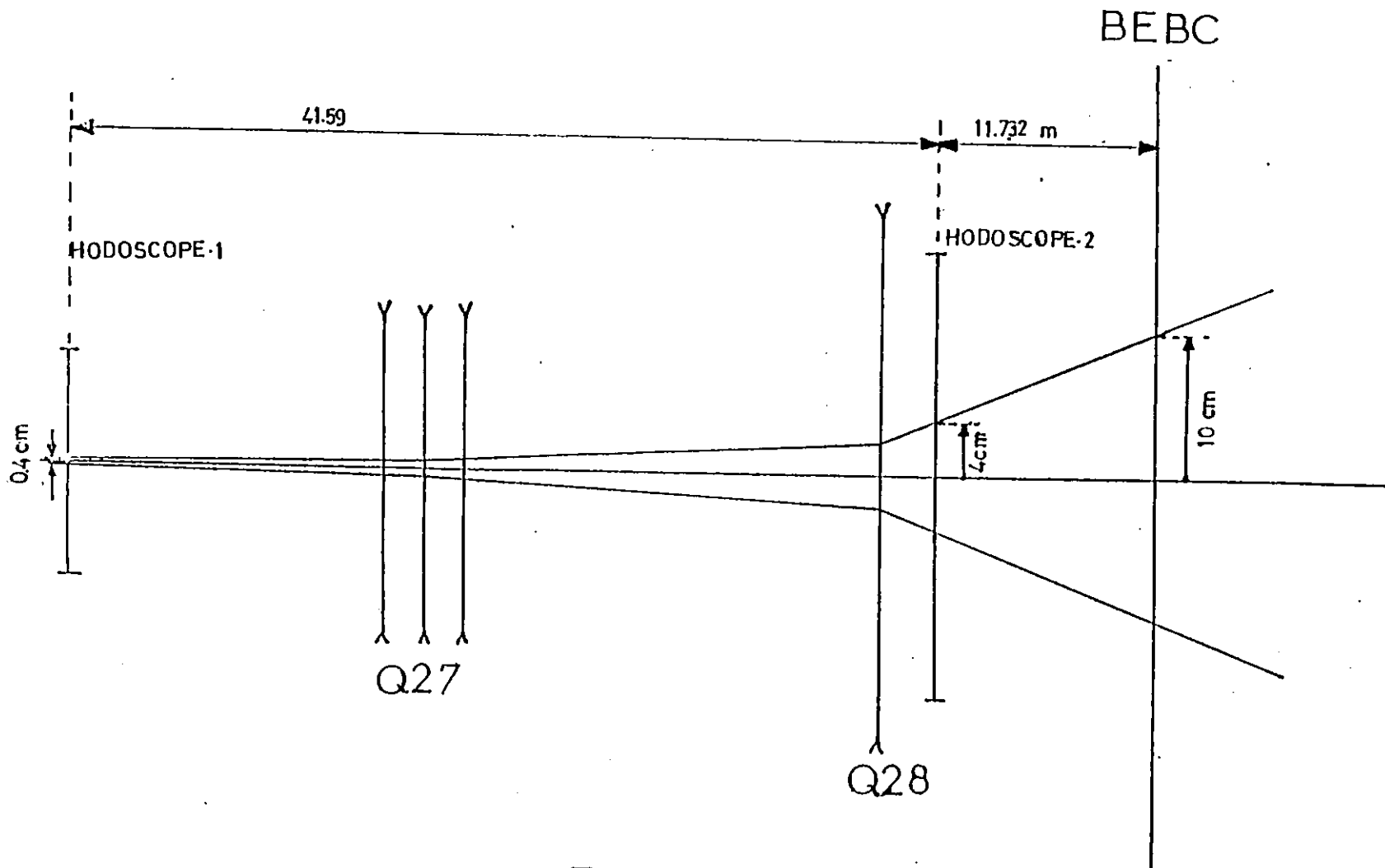


FIG (2.3)



FIG(2.4).

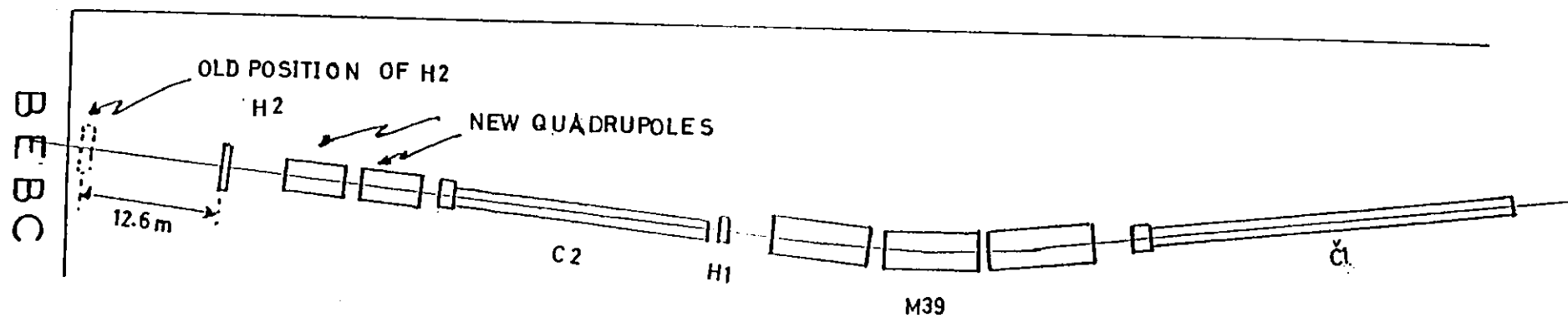


FIG (2.5)

CHAPTER THREE

DATA PROCESSING

3.1 Introduction

This chapter describes the scanning and measuring of the film. The processing of the data is briefly described. The method of associating beam tracks seen at the scanning stage with the corresponding beam tagging data and the selection of a pure sample of K^- interactions is presented. The scanning procedure, and also the calculation of scanning efficiencies for primary vertices, the measuring system and measuring criteria used are briefly described.

3.2 Application of Beam Tagging Data

During BEBC operation, for every frame of film which is taken in BEBC, the information about the corresponding beam tagging data is recorded on a tape. This record contains information on the type and trajectories of the beam particles for the separated beam as described in the previous chapter.

The main problem is to associate this data with the beam tracks seen on the film, to separate the kaon interacting beams from the non-kaon interacting beams. The method used to find a correct matching of the extrapolated beam point in BEBC and the corresponding entry point seen on the scan table is discussed in detail in ref (3.1). Using this information it is possible to find the bin number of each hodoscope through which the beam particle passed. These numbers are necessary

when we calculate the predicted entry point of each beam in BEBC in terms of the template unit, as will now be discussed.

The entry point co-ordinates of some ~ 300 beam tracks are measured on the scan table. In order to make this measurement easier a template was used. Fig (3.1a) shows the beam entry window of BEBC with some typical beam tracks. For Runs I & II there was no vertical beam spread so the template was made by drawing a line between the midpoints between the fiducials A, B and C, D and dividing it into 100 divisions. The template corresponding to fig (3.1a) is shown in fig (3.1b). To use this template on the scan table it is lined-up with the fiducials at the corners of the entry window. Then the position of every beam can be read off and recorded in terms of the template units. This template was devised only for view 2, which was good enough for our purpose.

For Run III, carried out in March 1979, as the position of the γ Cerenkovs as well as the position of two hodoscopes were changed to allow for a better efficiency plus a larger beam spread, another form of template was employed. Again the beam entry window on the scan table was used; an equi-spaced scale from 0-100 was drawn between the midpoints A, C and B, D. The latter pair covers a larger distance than the former pair on the scan table and so, lines drawn from the corresponding elements on the two scales form a "fan" and are not parallel, fig (3.2). The entry points of beams in the chamber (the first bubble) were recorded by using this template, in terms of the template units (Y_s)

The next step is to find a formula to give us the predicted entry point (Y_p) of each beam in BEBC in terms of the template unit. This formula in general can be written in the form of

$$Y_p = a_1 + a_2 H_1 + a_3 H_2 + a_4 (H_1)^2 + a_5 (H_2)^2 + \dots \quad (3.1)$$

where a_i ($i = 1, \dots$) are constant coefficients; H_1 = Hodoscope 1, H_2 = Hodoscope 2. By knowing the information on both hodoscopes and the measured values for every single beam, and also by using the minimum χ^2 method such that $\sum (Y_p - Y_s)^2 = \text{a minimum}$ (sum runs over ~ 300 typical beams for each roll of film under process), the coefficients in equation (3.1) were found. The values of a_4 and a_5 plus the higher orders were consistent with zero. For Runs I & II (using the old template) the value of a_3 was also zero, i.e. a linear relation between H_1 and H_2 . For the run in March 1979 there is a definite improvement of the minimum when $a_3 \neq 0$, i.e. using the information on both hodoscopes.

For the first few films a test of tagging association was carried out on a few hundred beam tracks. This was done by measuring the template position of every beam track to associate them to the predictions. To prevent incorrect sets of measured points on the scan table with the corresponding predicted values, the frames with one (several) beam track(s) predicted and one (several) beam track(s) scanned were used. For every track the difference between the measured position and the predicted position was calculated and plotted. The result is shown in fig (3.3) for view 2. Note that in most cases the difference is considerably less than one template unit which is adequate according to the criteria to be described in the next section.

3.3 Scanning Criteria (3.1, 5, 6)

The scanning criteria can be divided into two major parts. The first part involves the association of the predictions to the observed tracks. Taking into account the results described in the previous section the following rules were devised:

1. For each event, the "beam track template" is used to decide whether the incident track was parallel to some typical beam tracks drawn on the template and hence was, or was not a beam track. If it is not a beam track the event is ignored.
2. The entrance position of each incident interacting beam track is read off the "tagging template" using view 2. If this position agrees within one template unit of a predicted kaon beam track then this is assumed to be a good kaon event.
3. Suppose two tracks lie within $\frac{1}{2}$ template unit of each other and one track contains an event and both agree well with the predicted position (i.e. within 1 template unit), then two situations may happen:
 - a) If both tracks are predicted to be of the same particle type (i.e. kaons) then the interacting beam is assumed as a kaon event.
 - b) If the particle types are different, then the position of all beam tracks on the frame is recorded. This information is used and compared by a physicist with the corresponding predicted values. In this way it was sometimes found to be possible to identify the beam tracks which lie within $\frac{1}{2}$ template unit of each other.

The second part of the scanning criteria consists of the rules used after a primary event is located on a tagged kaon beam track. The fiducial volume for primary events is defined in view 2 as the region between the inner edge of the beam entry window and the outer circle on the far side of the chamber i.e. regions A1 to A6, C; B1 and B6 outside

the beam entry window, fig (3.4). For ν zero, gamma, ν zero/gamma the fiducial volume is the entire visible volume. On this figure is also a typical kaon event with a gamma and a ν zero associated. The primary events in the fiducial volume were scanned and the frame was searched for all ν zeros and gammas that could possibly be associated to the event. A ν zero should have a non-zero opening angle. It may also have one or both tracks which scatter or are heavily ionized. A gamma has always a zero opening angle and at least one track which curls up tightly. However, a ν zero may also appear to have a zero opening angle. When it is not clear if the ν is a ν zero or a gamma it was called ambiguous. At this stage no attempt is made to identify ambiguous ν zeros/gammas, as all hypotheses for ν zeros and gammas are tried in the kinematics program, ref (3.1). Dalitz pairs at the primary vertex which were recognizable either by an e^+e^- pair at the vertex, or by one electron (or positron) seen and an odd number of remaining tracks, were subtracted from the total number of secondary tracks. The complete sample was scanned twice using the above rules for scanning, and a third comparison scan made. The first two scans were done independently and the third scan was done as a check, using the results of the first two scans.

At the third scan stage a drawing of every good primary event as well as associated ν zeros and gammas were carried out to facilitate the measurement as will be explained later. In order to analyse the results of the three scans by computer, they were collected and recorded on punched cards. These cards were useful in calculating the scanning efficiencies and also in preparing lists of events which could help at the measuring stage.

3.4 Scanning Efficiencies

The primary vertex scan efficiency is calculated on the assumption that all primary events are equally visible*. If N_1 is the number of events seen on scan 1, N_2 the number of events seen on scan 2, then the scan efficiency for scan 1 and scan 2 will be

$$E_1 = \frac{N_1}{N_T}, \quad E_2 = \frac{N_2}{N_T} \quad (3.2)$$

where N_T is the total number of events (still not known).

The number seen on both scans is:

$$N_{12} = E_1 E_2 N_T \quad (3.3)$$

solving 3.2 and 3.3 for E_1 , E_2 and N_T we obtain:

$$\begin{aligned} E_1 &= \frac{N_{12}}{N_2} \\ E_2 &= \frac{N_{12}}{N_1} \\ N_T &= \frac{N_1 N_2}{N_{12}} \end{aligned} \quad (3.4)$$

The probability of an event being missed by both scans is $(1 - E_1)(1 - E_2)$ so the two scan efficiency (E) is:

$$\begin{aligned} E &= 1 - (1 - E_1)(1 - E_2) \\ &= E_1 + E_2 - E_1 E_2 \\ E &= \frac{N_{12} (N_1 + N_2 - N_{12})}{N_1 N_2} \end{aligned} \quad (3.5)$$

* This is not true for the two prong events, but it is a good approximation for more than two prong events.

Using this formula the two scan efficiency for > 2 prongs has been computed from the data on the scan cards. This efficiency is greater than 99% for all the labs. The scan efficiency for the two prong events was found to be about 96%. As mentioned earlier these scan efficiencies are calculated on the basis of the assumption that all primary events are equally visible. But this is not true for the 2 prong events. A value of 90% was felt to be more realistic than the value found using this simple formula.

The scanning efficiency for v zero and gamma was found in a similar manner to the primary vertex scan efficiency. Taking the average of all labs the two scan efficiency for v zeros was found to be $90 \pm 5\%$ and for that of gammas was found to be $80 \pm 5\%$. The gammas are harder to see and to associate to the primary vertex than V^0 s, particularly low energy ones.

3.5 Measuring System

In this experiment an "on-line geometry" measuring system was used. This enables the measurements to be checked immediately they are made.

Events are measured on conventional "National" measuring machines ("Willie" and "Bertha"), using on-line control and geometrical reconstruction programs (OLGA). The measuring machines are connected with a PDP-8 computer. This computer accepts the measurements from the measuring machines and reconstructs the fiducial co-ordinates for each point, then transmits them to the control program in the PDP-10. There is one control program for each measuring machine. The control program

communicates with the measurer on a normal teletype (TTY). Both PDP-8 and TTY are interfaced with the PDP-10 through a teletype line distributor (DC-10). This allows several machines to measure on-line simultaneously. OLGA is normally resident on disc, but is "woken up" by the control program when the measurement of track is complete. The whole process is shown schematically in figure (3.5) and further details are given in ref (3.4).

To measure an event, the control program directs the measuring using information given to it by the measurer. To measure a typical frame the control program asks for the BEBC Roll/Frame number, how many primary vertices, gammas, v zeros, are on the frame, and draws up an "item" list which will be processed in order. Then it demands that the fiducials on each of three views be measured.

A track is measured on at least three views; this is done by measuring a number of points on each track. These are transmitted to the control program which then passes them on to the on-line geometry program which reconstructs the track in space. The parameters of the reconstructed tracks are returned to the control program which performs some check to see whether the tracks have been measured well enough for off-line reconstruction, or whether better measurements are required. In the former case the program then asks for the next track to be measured, in the latter case the program asks for a remeasurement of the track.

This process of measurement and reconstruction continues until the program is satisfied that either the measurements are good enough for off-line geometry/kinematics to reconstruct the track, or that subsequent remeasurement will not improve track reconstruction.

3.6 Measuring Criteria

The following criteria are used in this experiment:

1. All K^- tagged primary events, together with all ν zeros and gammas plus ambiguous ν zeros/gammas, associated to the primary vertex, as well as those associated to charged $V^-(V^\pm)$ decays are measured.
2. No non-kaon tagged events are measured.
3. No neutron stars are measured.
4. All leaving points of tracks are measured (this helps the off-line geometry program, and the EPI analysis program, ref (3.1)).
5. All $V^\pm$ (kink) vertices, together with the outgoing tracks are measured.

In Runs I and II outgoing tracks from secondary interactions were also measured if the momentum of interacting track could not be measured. The idea behind this was that by measuring the outgoing tracks from the interaction of an unmeasurable secondary track, an estimate can be made of the momentum of the interacting track. The author wrote a program to find a correction factor (3/2) for such secondaries, ref (3.2). It was done for 16 GeV data, assuming this beam momentum is a good approximation for high energy secondary interaction tracks in 110 GeV. As only $\sim 1.5\%$ of all tracks (including short straight high energy tracks with secondary interactions) had a momentum error of more than 50%, no secondary tracks were measured in the Run III.

Table (3.1) shows a listing of the number of events which have been analysed by each lab for Run I and II and for Run III separately.

The events measured at Imperial College, are taken from 9000 frames out of the complete sample of 30,000 in Run I and II and 15,000 frames out of the complete sample of 80,000 frames in Run III

3.7 Geometry

After the event is measured the information obtained at this stage is returned through the geometry program "off-line" to find the particle momenta. HYDRA geometry was used both "on-line" and "off-line" ref (3.3) This program was developed at CERN, and contains all the tasks needed for geometrical reconstruction. The main idea is to use the film measurements to reconstruct the vertices and tracks in three dimensions so as to determine their position in space and from the curvature of the tracks to calculate the particle momenta. The first stage is the matching of the vertices on different views which are images of the same point in space. In this experiment all vertices are labelled when measuring the event, in order to facilitate the matching of measurements. Given these measurements the position of the point (x_1, x_2, x_3) and associated error matrix $\langle x_i, x_j \rangle$ are estimated.

In general it is not possible to measure exactly the same points on each view, except the point where the track enters (leaves) the chamber wall, or where it decays into other particles, as well as the interaction points. Such points are known as corresponding points. The position of every corresponding point measured is related to the x-y-z co-ordinate system specified by the fiducial positions on the chamber windows. The images of these fiducials on the film are measured (at least on 3 views) at the same time as the measurements are made of the

track images. This relates the co-ordinate system in which the film measurements are made to the bubble chamber co-ordinate system. Then approximate values of (x_1, x_2, x_3) are obtained by choosing the point in space such that the sum of squares of distances from the point to the light rays through the chamber (path of a ray leaving the measured point on the film and passing through the optical centre of the lenses) is a minimum. A least square fit is then made by minimising the sum of squares of the deviations in the film reference planes between the measurements and the projected points. This is felt to give the best estimate of (x_1, x_2, x_3) and the associated error matrix.

The next stage is "track fitting" which is more difficult, because several non-corresponding points on a given track are measured on each view. Corresponding points if present, as well as a set of arbitrary points are measured along the track on different views.

First an approximate trajectory for the track is obtained in space assuming a helical shape and no mass dependent, energy loss corrections. The next stage is to make mass dependent fits with the assumed trajectory projected into the different views. In this case the fits take into account differing energy losses for different particles.

These fits give a set of chi-squared and mean residuals (the mean spread of measurement points along any track about the fitted track on the film) and it is possible to study which particle trajectory best fits that track.

For each track several mass dependent fits may be obtained which for the tracks over 2 GeV momentum are almost indistinguishable. A problem may appear when a too heavy mass is assigned to a track. In this case the track will be recognised as "overstopping" (ref 3.7).

This means that the range calculated for the track from the momentum measured from curvature, assuming a certain mass is shorter than the measured length. In this case the track cannot be that particular assumed mass.

Next a so called "convex fit" is done to improve the vertex measurements. The track fits from each vertex are used to better define the vertex position by using their common points of intersection.

Finally, the completed event is written as a HYDRA data structure, which contains the point-fit (PF), track-fit (TF) and mass-fit (MF) banks linked together.

3.8 Kinematics

The main task of kinematic fitting is to find the track parameters at a given vertex which satisfy energy and momentum conservation, using the measured information on each track and assuming certain mass assignments. The variables used are $(1/p, \lambda, \phi + \text{errors})$. These are deliberately chosen because they have gaussian error distributions.

The components of the four momenta of a track can be found, using these variables. By applying constraints to the vertex, which include momentum and energy conservations

$$\sum \vec{P}_i = 0, \quad \sum (\pm E_i) = 0 \quad (3.6)$$

the parameters of neutral tracks are computed. In general from measured quantities these equations would not be satisfied, instead

$$\sum P_{ik}(x) = F_k(x) \quad \begin{array}{l} i = 1, N \text{ TRACK} \\ k = 1, \dots, 4 \end{array} \quad (3.7)$$

HYDRA kinematics varies the fit values corresponding to the measured and unmeasured track parameters until the χ^2 for the fit is a minimum. The main use for kinematic fitting in our experiment is to find a clean sample of full constraints ν zeros and gammas associated to the primary vertex (i.e. 3C for ν zeros and 4C fit for gammas). A complete description of geometry and kinematics about this experiment can be found in ref (3.1).

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- 3.2 M. Zomorrodian, IC/HENP/PN/78/16
- 3.3 Hydra System Manual, CERN Program Library
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- 3.5 F.A. Triantis, CERN/EP/WA28, 77-3
- 3.6 F.A. Triantis, CERN/EP/WA28, 78-1
- 3.7 Hydra Application Library, CERN Program Library

TABLE 3.1

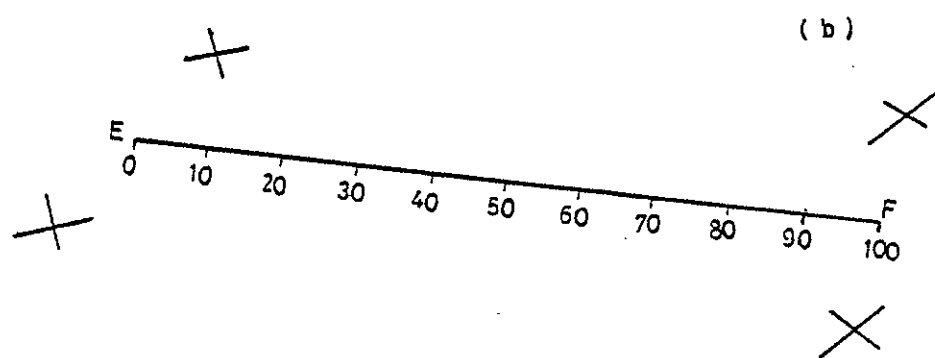
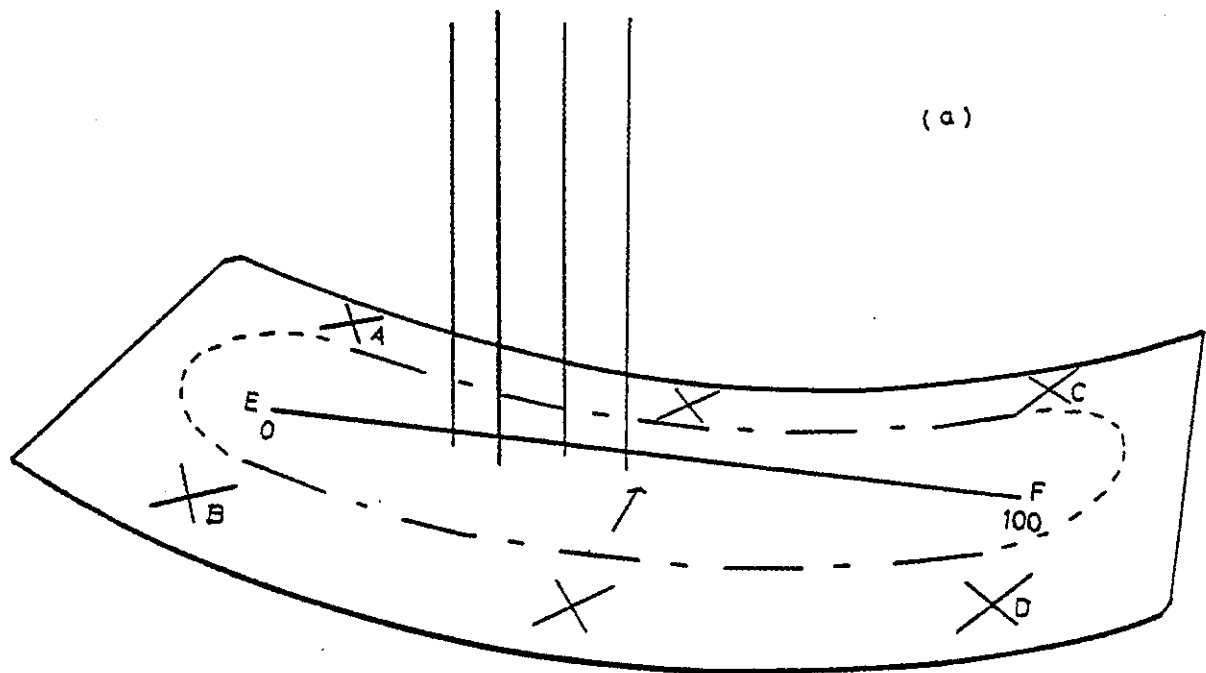
THE NUMBER OF EVENTS ANALYSED BY EACH LAB IN DIFFERENT RUNS

	RUN I+II		RUN III	
	BEFORE BEAM CUTS	AFTER BEAM CUTS	BEFORE BEAM CUTS	AFTER BEAM CUTS
AACHEN	564	500	1842	1666
BERLIN	825	701	-	-
CERN	1274	1116	3256	2960
CRACOW	372	257	1311	937
LONDON	1816	1578	2756	2360
VIENNA	429	357	1623	1307
WARSAW	725	645	1512	1269
TOTAL	6005	5154	12300	10499

GRAND TOTAL OF "GOOD" EVENTS: 15653

Figure Captions

- 3.1 a) Beam entry window as seen on view 2
 b) Corresponding tagging template for the Runs I & II
- 3.2 Beam entry window as seen on view 2 as well as the corresponding tagging template for the Run III.
- 3.3 Histogram of Δ = Beam track entry position (measured) - Beam track entry position (predicted) on view 2
- 3.4 Picture of the BEBC interior on view 2 at the time of this experiment, showing the fiducials and beam entry window, plus a typical event with a v zero and a gamma associated to the primary vertex.
- 3.5 Schematic Diagram of on-line Measuring System



FIG(3.1)

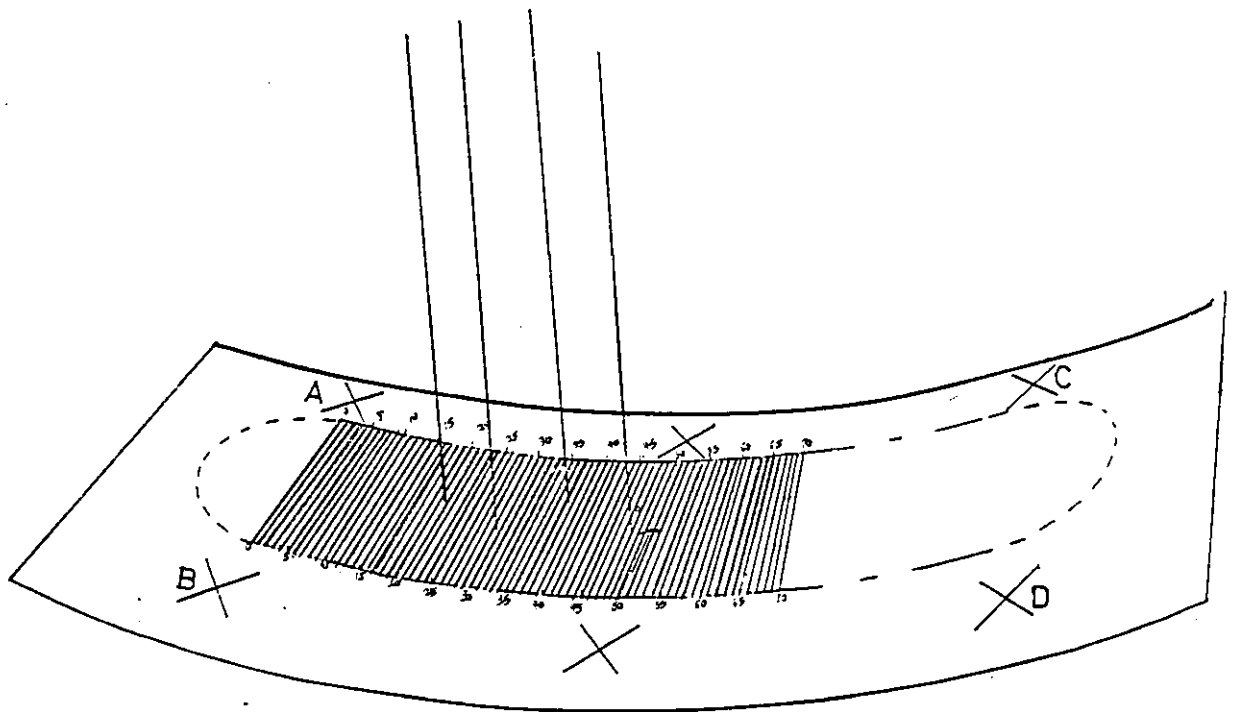


FIG (3.2)

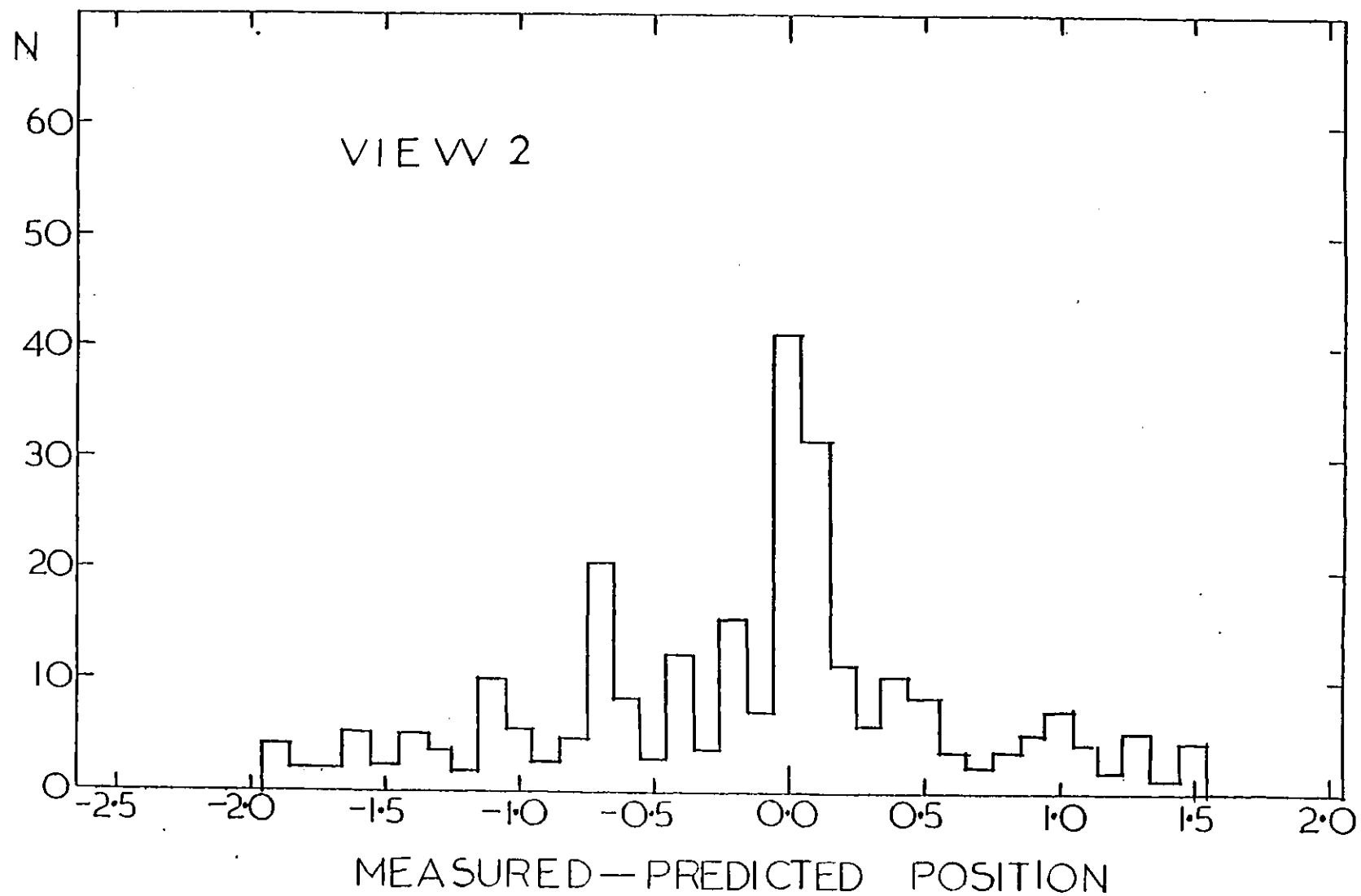
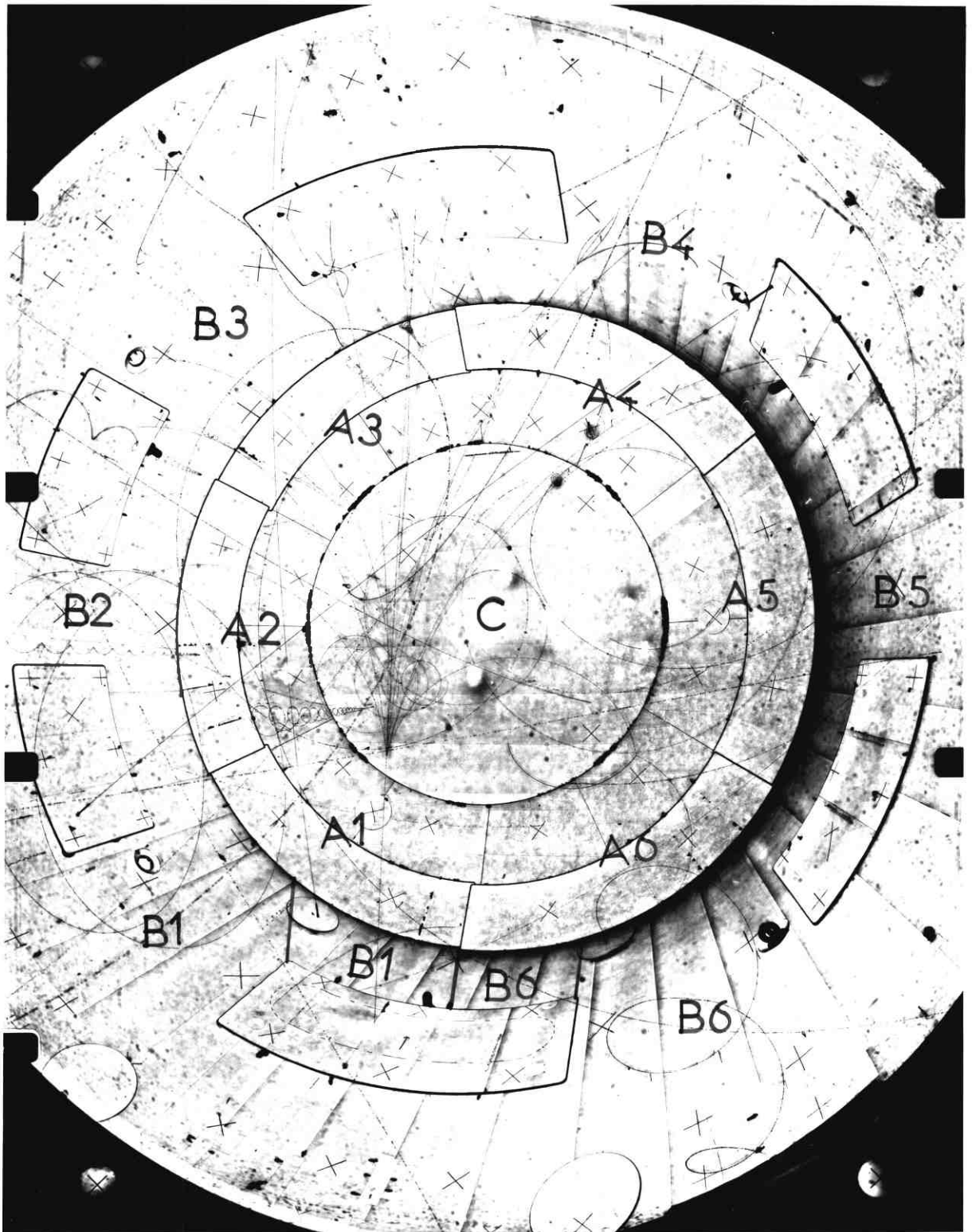


FIG (3 . 3)



FIG(34)

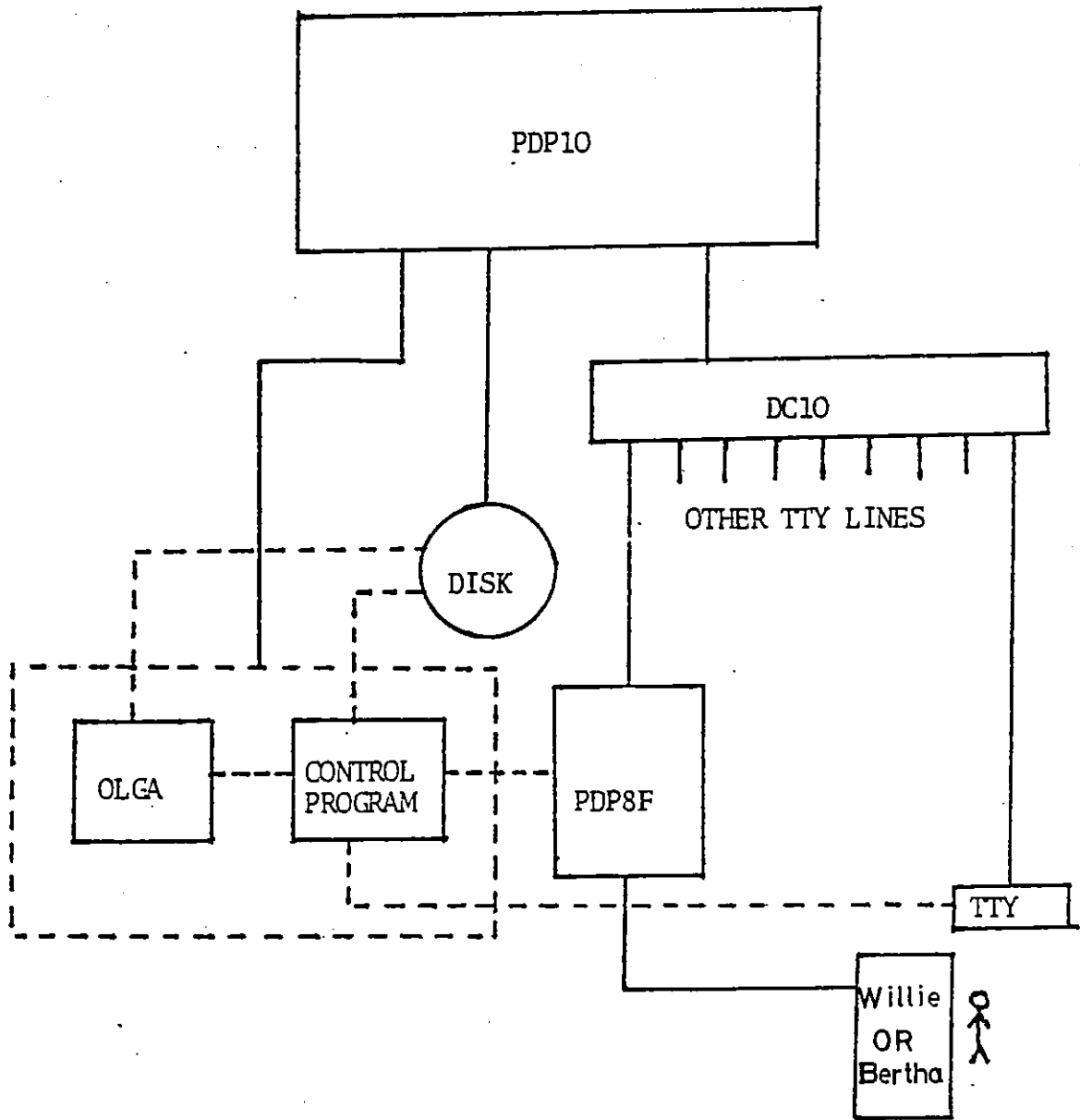


FIG (3.5)

CHAPTER FOUR

JET DEFINITION AND JET PRESCRIPTIONS

4.1 Jet Definition in Momentum Space

A caplanar two jet structure is a common behaviour of nearly all hadron scattering data. A jet being a set of particles, usually pions, all produced in a particular direction. When hadrons collide at high energy, most of the energy appears in many particles moving in the directions of the original momenta with only a small transverse momentum. In fact one of the most persistent features of hadron collisions is that the transverse momenta of all particles produced in the final states are very small compared with the values allowed by phase space and with the longitudinal momenta of these particles. This behaviour is independent of energy over a wide range, starting as low as two or three GeV and above the energies of this experiment.

There are however a few hadrons of unusually high transverse momenta. The typical configuration is shown in fig (4.1a). As the plot shows two jets of hadrons are produced at wide angle, while forward and backward jets are also present, as is usually the case for hadronic reactions. This sort of event arises in a parton model from the hard scattering of point-like constituents. The scattered partons form the trigger and away side jets; the reset of the particles form forward and backward jets.

The experimental support for these wide angle jets which is one of the most significant features of hadronic collisions at very high energies was seen for the first time at CERN, in ISR experiments ref(4.1)

and will be described in the next chapter. The association of these phenomena with the hard scattering and fragmentation of hard constituents, fig (4.1b) has now gained general currency (ref 4.2). The angular correlations implied by a jet structure and a limited mean transverse momentum for jet fragments (relative to jet axis) are believed to be two typical jet properties.

For every jet there is a principal axis which is a characteristic of that jet. The term "principal axis" is a general name used to describe the "jet axis". There are many different definitions of the principal axis, such as the sphericity or the thrust axis. Each definition leads to a completely different method to calculate this axis. However, in practice it turns out for K^+p interactions that these calculations all give very similar directions for this axis. The first definition for principal axis was proposed by Brandt et al (ref 4.3) as follows:

Given the momentum vectors of all secondaries in the C.M. structure of the collision, one puts any straight line through their common region, projects all the momenta onto this line and sums up the absolute values of these projections. The line for which the sum is a maximum is defined as the principal axis of the jet.

At this stage the variables used in jet analysis (in the next two chapters) may be defined. Currently the most common variables are sphericity and thrust which are defined as follows:

4.2 Sphericity

Sphericity is defined as:

$$S = \min_{\hat{n}} S(\hat{n})$$

$$S(\hat{n}) = \frac{3 \sum_{i=1}^N p_{iT}^2}{2 \sum_{i=1}^N p_i^2} \quad (4.2)$$

$\hat{n}$: A unit vector along the jet axis

p_{iT} : transverse momentum component relative to the jet axis

p_i : magnitude of the momentum of i^{th} track.

This definition is equivalent to:

$$S = 3 \frac{\lambda_1}{\lambda_1 + \lambda_2 + \lambda_3} \quad \lambda_1 < \lambda_2 < \lambda_3 \quad (4.3)$$

where λ_1 , λ_2 and λ_3 are the eigenvalues of the tensor:

$$I_{\alpha\beta} = \sum_{i=1}^N (p_i^2 \delta_{\alpha\beta} - p_{i\alpha} p_{i\beta}) \quad (4.4)$$

The sum runs over the charged particles in each event, and α , β are three vector indices. The tensor $I_{\alpha\beta}$ is diagonalized event by event. To every event belongs three eigenvectors with the corresponding eigenvalues λ_1, λ_2 and λ_3 :

$$\lambda_K = \sum (p_{iT} \hat{z}_p^k)^2 \quad k = 1, 2, 3 \quad (4.5)$$

where $\hat{z}_p^k$ is the unit vector. It turns out that if λ_K is the smallest eigenvalue, $\hat{z}_p^k$ is the principal axis defined previously. $\hat{z}_p^k$ is also known as the sphericity axis. The factor 3/2 in definition (4.2)

is the normalization factor, i.e. for a perfectly isotropic event $S \rightarrow 1$, for an ideal jet $S \rightarrow 0$.

In some cases another tensor is used to diagonalize event by event:

$$J_{\alpha\beta} = \sum_{i=1}^N P_{i\alpha} P_{i\beta} \quad (4.6)$$

The transformation between the eigenvalues of this tensor (μ_1, μ_2, μ_3 ; $\mu_1 > \mu_2 > \mu_3$) and the eigenvalues of tensor 4.4 ($\lambda_1, \lambda_2, \lambda_3$; $\lambda_1 < \lambda_2 < \lambda_3$) is:

$$\begin{aligned} \lambda_1 &= \mu_2 + \mu_3 & \mu_1 &= \frac{\lambda_2 + \lambda_3 - \lambda_1}{2} \\ \lambda_2 &= \mu_1 + \mu_3 & \mu_2 &= \frac{\lambda_1 + \lambda_3 - \lambda_2}{2} \\ \lambda_3 &= \mu_1 + \mu_2 & \mu_3 &= \frac{\lambda_1 + \lambda_2 - \lambda_3}{2} \end{aligned} \quad (4.7)$$

we define:

$$S_i = \frac{3\mu_i}{\mu_1 + \mu_2 + \mu_3} \quad (i = 1, 2, 3), \quad S_1 + S_2 + S_3 = 3 \quad (4.8)$$

$$S_1 > S_2 > S_3$$

S_1, S_2 and S_3 describe the shape of events in three dimensional momentum space and will be presented in the next chapter. The connection between the parameters S_1, S_2 and S_3 with sphericity, S (definition 4.2) is

$$\begin{aligned} S_1 &= 3 - 2S & 3 \geq S_1 \geq 1 \\ S_2 + S_3 &= 2S & 0 \leq S_2 \leq 1.5, 0 \leq S_3 \leq 1.5 \end{aligned} \quad (4.9)$$

4.3 Thrust

Thrust is defined as:

$$T = \max T(\hat{n})$$

$$T(\hat{n}) = \frac{\sum_{i=1}^N |\vec{p}_i|}{\sum_{i=1}^N |\vec{p}_i|} = \frac{\sum_{i=1}^N \vec{p}_i \cdot \hat{n}}{\sum_{i=1}^N |\vec{p}_i|} \quad (4.10)$$

$\hat{n}$ is along the direction which maximizes T . In contrast to sphericity it is not possible to find the principal axis for the thrust analytically, as the momentum in the definition appears linearly rather than quadratically, (this turns out to be an advantage for QCD calculations). There are also a number of ways to find this axis. The most efficient method for the events of not very high multiplicity is the Brandt and Dahmen (ref 4.4) method. This finds the largest total momentum of all combinations, that is, by trying all directions defined by the resultant momentum of all possible combinations in the event. So 2^N different combinations must be checked to find the thrust axis for an N prong event. This construction for finding the thrust axis was proposed as far back as 1964 (ref 4.3). This method is good as long as the number of charged tracks in the event is not very large. This method was also checked with another method where all unit vectors covering a range of polar co-ordinates about the beam axis were tried. The result was very similar to the Brandt-Dahmen method but involved much less computing time than the former at the very high multiplicities. There are some advantages on using the thrust to sphericity. Neither sphericity nor thrust is free of degeneracies (more than one minimum or maximum). They occur in particularly symmetric events. The degeneracy of sphericity may be infinite but thrust has finite degeneracies (ref 4.5). Sphericity weighs a

single particle with large momentum higher than a group of particles with the same momentum. This is due to the fact that the momenta appear quadratically in the definition of sphericity. For example consider two events which are identical except that in event 1 one of the jets consists of a single fast hadron with momentum $\vec{p}$ (plus soft particles), while in the event 2 the corresponding jet consists of two fast particles, each with momentum $\frac{1}{2}\vec{p}$ (again neglecting soft particles and also small transverse momenta). The thrust depends only on the total momentum of each jet, while sphericity is distributed among the hadrons. This has two unfortunate consequences for sphericity. Firstly, the nonlinearity of sphericity makes this measure dependent on the history of the decays of the particles originally produced in the interaction into those finally observed. Secondly, the sphericity axis does not, in general, point into the direction of a system of particles. Thus the association of particles with jets is not so well defined by sphericity (ref 4,5). Hence the two main reasons for favouring thrust are:

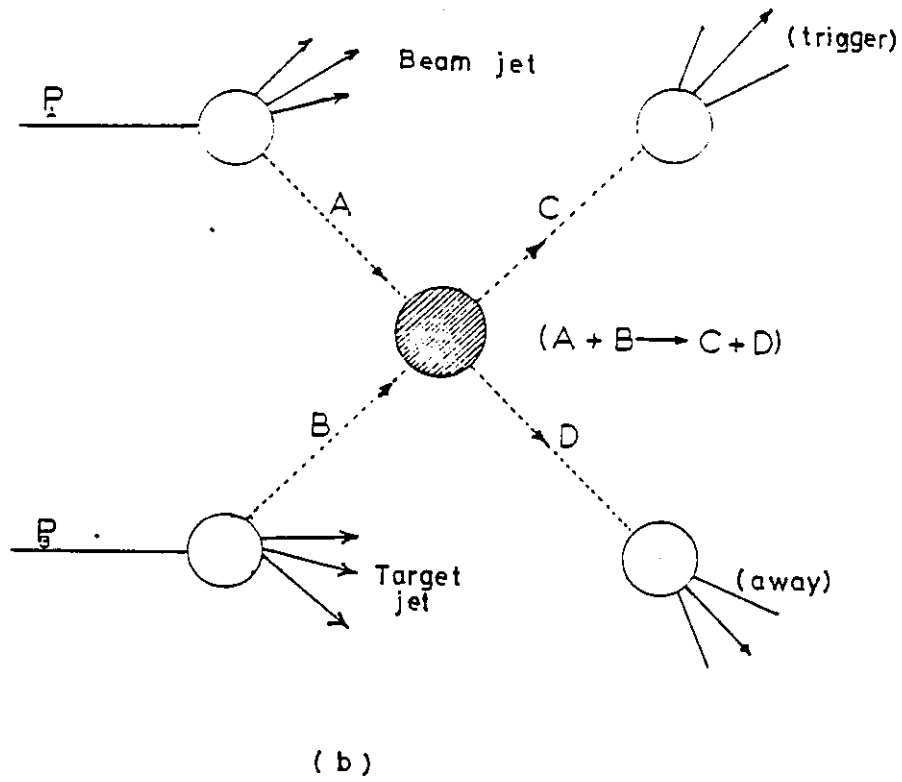
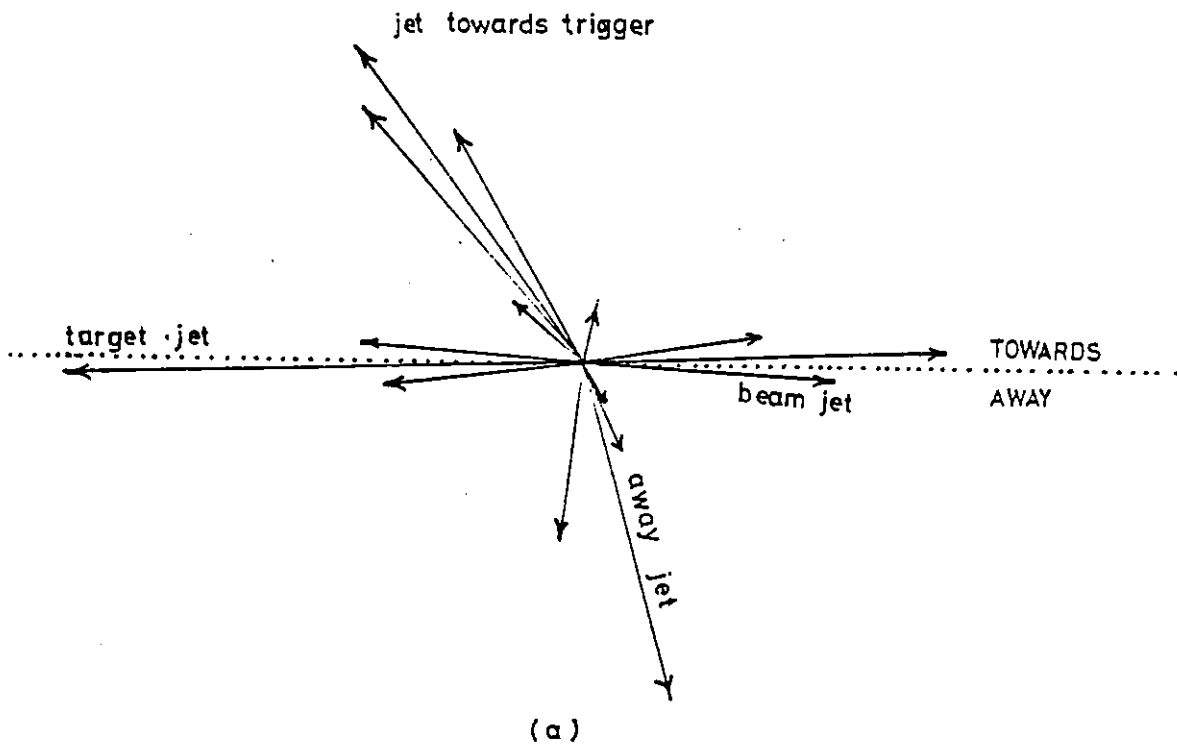
- 1) Thrust points always into the direction of a subset of particles with the largest total momenta. This makes it a good prescription for associating particles with jets.
- 2) As it is a jet measure which is linear in the particle momenta thrust doesn't depend on the history of the sequence of intermediate states.

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- 4.3 Brandt, S., Phyrouch, Sosnowski, R., Wroblewski, A., Phys. Lett. 12 (1964) 57
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- 4.5 S. Brandt and H.D. Dahmen, Particles and Fields 1, 61-79 (1979)

Figure Captions

- 4.1 a) An idealized picture showing the two wide angle jets associated with the fragmentation of the scattered constituents. Also shown are the forward and backward jets typical of hadronic interactions.
- b) The hard scattering approach to high P_T production. Constituents A and B scatter into Constituents C and D. The trigger particle is a fragment of constituent C.



F.I G(4.1)

CHAPTER FIVE

ANALYSIS OF SYSTEMS WITH HIGH P_T

5.1 A Review of Hadron Jets

The study of particle production at large transverse momentum is of great interest. It offers the possibility to understand the short range hadron interactions. This physical picture has led to the prediction that in hadron-hadron interactions, particles with high transverse momentum should be produced with much higher cross section than expected from the extrapolation of the low P_T behaviour.

The subject was born at CERN, ISR in 1972 with the observation of larger than expected π meson production with high transverse momenta with respect to the incident centre of mass direction.

As is mentioned previously in high energy hadron collisions, secondary particles are mostly produced at low transverse momenta with an exponentially falling off distribution. Three groups working independently at the ISR (ref 5.1) reported that at large P_T ($P_T \gtrsim 1$ GeV/c) the distribution is no longer falling as rapidly as at low P_T . This new component in the P_T distribution was interpreted as due to the hard scattering among proton constituents. The experimental work went much beyond the analysis of inclusive studies. Evidence for hadronic jets emerging at large angle from proton-proton collisions has been studied at the ISR. A correlation analysis which established evidence for a jet structure has also been studied at CERN since 1975 (ref 5.2). This means that if the particles produced at

wide angle, organize themselves as jets, any large P_T particle seen at the same time as the trigger particle, should be observed in about the same direction i.e., at similar longitudinal rapidity, Y , and more generally the fragments of the same jet should be close in rapidity. This was indeed observed to be the case (ref 5.2). Furthermore, a large P_T jet should also occur on the away side of the trigger particle with similar features to the trigger jet.

There is some evidence for a typical configuration with these two wide angle jets (trigger and away side jets) with approximately opposite transverse momenta. While some other configuration can not be excluded at this stage, available data are available to justify this balancing of transverse momenta. This behaviour appeared for the first time in p-p collisions in CERN, ISR experiments (ref 5.3, 4) (if high P_T jets correspond to parton-parton scattering, then the P_T of the trigger jet should be approximately balanced by a high P_T jet in the away side jet).

It is thus possible to attempt to reconstruct the actual jet shape from the detected particles, and to estimate with some approximation the centre of mass energy of the two jet-system. One is then in a position to compare jet fragment distributions and multiplicities (integrating over the inclusive fragmentation distribution), to those observed in e^+e^- annihilations and deep inelastic lepton scattering. Such a comparison has been performed in some experiments (i.e. ref 5.4,7). We have also done a similar comparison in our experiment for the forward and backward jets, ref (5.5) and this will be presented in full detail in the next chapter. There are also some results from calorimeter experiments at Fermilab (E260), and many of them are complementary to those from the ISR (ref 5.8). In a

publication from E260 (ref 5.9) it has been shown that multiparticle cross section is 2 orders of magnitude larger than the single particle cross section. It has also been shown that the events show evidence for the coplanar structure and that the momentum distributions of charged particles as well as the other features of their results give strong support to a simple parton-parton scattering model.

We have done a similar analysis in our experiment and in the experiments with lower kaon beam momenta. These results have been compared with those presented by E260. The main idea behind this was to see if the features of high P_T hadronic jets are also present in low P_T K^-p interactions.

The rest of this chapter is devoted to this rather detailed analysis which was published soon after the first publication of Fermilab results (ref 5.10) on preliminary data. This analysis has now been extended in order to study the E260 trigger conditions more carefully using our total statistics.

It should be noted that in a more recent experiment carried out in North Area Calorimeter Experiment at CERN (ref 5.11), a comparable procedure led to different interpretation of the results from the FNAL experiments.

5.2 Analysis of System with Large P_T in K^-p Interactions

We have used in this analysis two different definitions of multiparticle systems. The first definition was used in our early publication (ref 5.10) mainly because of the low statistics of our preliminary data which made it difficult to simulate the experimental conditions of E260 experiment. Therefore a choice was made of a way

to define "jets", and it was found that the single particle (C) and multiparticle (M) distributions (to be defined later) extrapolated to the corresponding distributions in E260 experiment.

Next we use jet definition 2. Our present statistics now make it possible to impose the E260 cuts on our data exactly, so a more direct comparison can be established with the results of FNAL data. We also use the new statistics for jet definition 1, because our new results extend to the higher values of transverse momenta (P_T), this makes it possible to check if the extrapolation method was a reasonable choice in our early publication.

5.2(a) Jet Definition 1

We define a multiparticle system as the group of all charged particles that have the same sign of P_T component along a principal axis in the transverse plane. This axis is obtained by a rotation in the transverse plane about the beam direction such that the sum of the squares of all momentum components along that axis is a maximum. The 4-vector of the multiparticle system is the c.m.s vector sum of its constituents. As we require a multiparticle system to consist of at least two charged particles, we restrict this analysis to events with at least four prongs. For the analysis of single particles we use the c.m.s 4-vector of all charged particles in our data sample.

Fig (5.1) and Fig (5.2) show the single particle (C) and multiparticle (M) P_T distributions at 16 and 110 GeV K^-p respectively. Fig (5.2a) shows our results using the preliminary data, ref (5.10) and fig (5.2b) shows the results with the full statistics. Figs (5.2) also show the results of the E260 calorimeter experiment which was pp and πp at 200 GeV/c (ref 5.9). The fiducial region which was used for jet analysis in E260 experiment lies in the rapidity range of

0.1 to 0.44. Also the calorimeters cover an azimuthal angle of $\pi/2$. As our data is obtained with a 4π detector, we can easily simulate the experimental conditions of E260 data. We do this by requiring the "jet" to be in the rapidity (Y) range of 0.1 to 0.44. However the way we define the multiparticle at this stage does not make it necessary to define an azimuthal angle of $\pi/2$ for multiparticle system.

Note that at 16 and 110 GeV/c both the single and multiparticle systems have similar slopes at high P_T . Also it can be seen that the cross-section for the multibody system is an order of magnitude larger than the cross section for single particle distributions. This latter feature was claimed in ref (5.9) as evidence for quark-quark scattering of the proton constituents. Further, both fig (5.2a) and fig (5.2b) show that if we extrapolate 110 GeV to the P_T values above 3 GeV it joins smoothly to the results of FNAL data. In addition the figure with full statistics extends to the higher values of P_T and shows a better extrapolation to the results of E260 experiment. This confirms that the extrapolation method was a reasonable choice in our early publication (ref 5.10). Furthermore since we do not expect much hard scattering to be present in low P_T 110 GeV data, these features are not unambiguous evidence for hard scattering effects.

It should be noticed that in the original results of our Collaboration (figs (5.2)), to remove the slow protons from our data, all single particles having a rapidity, $Y < -0.5$ were removed. If we neglect this cut, the multi-particle distribution lies significantly above our previous results, as can be seen on fig (5.3). But this effect does not change the basic interpretation of our results when compared with FNAL data. However, as it removes most of the backward tracks from K^-p data, we will remove this cut from our subsequent analysis.

5.2(b) Jet Definition 2

To make a more direct comparison with the E260 experiment, we calculate the jet P_T by summing vectorially the contributions of all particles that enter a solid angle, which is comparable to the size of the calorimeter used in E260 experiment (the E260 calorimeters cover an azimuthal angle of $\pi/2$). In particular we only use events where the "jet" total momentum vector lies in this solid angle, which is the case for the E260 as well.

Fig (5.4) shows the "jet" cross section calculated in this manner for 110 GeV K^-p data. Within statistical errors it joins smoothly to the results of E260. The invariant distribution for single particles added to the figure is very similar to the corresponding distribution shown on fig (5.2). Also in the range of large P_T the results of multiparticle system are very similar to those found by using jet definition 1, in this region. This suggests that the method used in ref (5.10) is justified as similar results are obtained at large P_T with jet definition 2 which is very similar to E260. Furthermore since one does not expect hard scattering effect to dominate at low P_T in K^-p interactions these features again cast doubt on the interpretation of the E260 results as evidence for a large hard scattering constituent.

Next we change the azimuthal angle of the solid angle to check if the experimental cross-section for "jet" production depends on the size of the solid angle subtended by the calorimeter. The point is that if there is a natural size for a jet, one might hope to measure it by using a calorimeter with a variable solid angle trigger acceptance and searching for a concentration of transverse momentum with solid angle or a difference in the behaviour of

$\frac{d\sigma}{dP_T}$ for particles inside and outside the jet region (ref 5.11). This is done in ref (5.11) and we will do a similar analysis using our K^-p data.

Fig (5.5) shows the "jet" cross sections calculated in the way described earlier, for three azimuthal angles of π , $\pi/2$ (this is the azimuthal angle of the E260 calorimeters) and $\pi/4$ respectively. It is clear that at large P_T the cross section decreases significantly as the azimuthal angle cut is reduced. This dependence of cross-section on the solid angle may indicate that the calorimeters used in E260 experiment do not include the total "jet" cross section.

This conclusion is confirmed when we investigate the azimuthal correlations between the particles in near and away-side jets. We have chosen to study this for both single particle triggers and "jet" triggers in the near-side jets, and then we study the azimuthal angles of the particles not in the single or jet trigger. We define the single particle trigger as the highest P_T constituent among the charged particles. The "jet" trigger is defined as the vector sum of the constituents of all charged particles that enter the solid angle equal in size to, and at the position of, the E260 Calorimeter.

Fig (5.6) is the azimuthal distribution of all single particles relative to that at highest P_T (the trigger particle is not included in the figure). The values on the horizontal axis have been scaled in such a way that the range between 0-1 equals 0-180 degrees. Also we have considered the smaller angle of particles with respect to the trigger, so that the range between 180-360 is folded to 0-180.

If no restriction is made on the P_T of the single particle triggers, the distribution is rather flat with an excess to 180 degrees to the trigger due to momentum conservation. As the P_T trigger increases,

there is a tendency for the particles to be mostly produced at 180 degrees relative to trigger. This tendency is clearer in the range of $1.5 < P_T \text{ trigger} < 2.$, which indicates that particles with a high P_T track are more coplanar than those with low P_T .

Fig (5.7) also shows the azimuthal distribution of all single charged particles relative to the jet trigger for various ranges of P_T jet trigger. In all P_T intervals there is a strong tendency of particles to the jet trigger. However, the collimation in the away-side jet is stronger for single particle triggers rather than for multi-particle triggers. The azimuthal angle of $\pi/2$ opposite to the trigger which corresponds to the azimuthal acceptance of the E260 calorimeter, is marked with a dashed line in figures 5.6 and 5.7 (this angle is $\pi/4$ in these figures). Both figures indicate that this angle is not large enough to contain all the tracks in the away-side jet. Hence it is not surprising that jet cross section varies by changing the size of the azimuthal cut as was observed from figure (5.5).

Though it could be that at higher P_T values the jets are more collimated, so that all the charged particles will emerge into the calorimeter, but these figures do not show such evidence (at least for the higher P_T values comparable to those in E260), suggesting that the E260 calorimeter was not including all the jet particles. This result therefore supports that of the North Area Calorimeter Experiment at CERN (ref 5.11), where the solid angle dependence of trigger cross-sections has been investigated by using a large detector solid angle acceptance (full acceptance in azimuth). It was found that the jet cross section strongly depends on the size of solid angle at the transverse momenta comparable to those of E260. They conclude that these features do not produce good evidence in favour of narrow jets, and therefore more detailed analysis is required before ascribing

with confidence to the results of E260 experiment as a hard scattering mechanism.

5.3 The fractional momentum distribution within a multiparticle system

For later comparison the momentum distribution of particles within a multiparticle system has been studied in terms of the function Z_R defined as:

$$Z_R = \frac{\vec{p}_i \cdot \vec{p}_M}{|\vec{p}_M|^2}$$

$\vec{p}_i$ is the momentum of the i^{th} particle in the system

$\vec{p}_M$ is the momentum of the multiparticle system

Z_R is the fraction of momentum carried by this single particle

We have only used jet 1 definition for this analysis, since both definitions give similar results for the $\vec{p}_M$. Fig (5.8) shows the Z_R distribution of charged particles in multiparticle systems with $P_T(M) > 1.4$ GeV/c at both beam momenta. The dashed curve shows the 16 GeV data weighted to give the same topological cross-sections as observed at 110 GeV. The difference in shape of distribution at low values of Z_R for different beam momenta can be understood in terms of the change of multiplicity if we consider the following points:

The integral over all values of Z_R in one multiparticle system is, by definition, equal to one. Also the multiplicity of the multiparticle system is increased when the beam momentum rises from 16 GeV/c

to 110 GeV/c. Hence the mean values of Z_R must decrease and the region of small values of Z_R becomes more densely populated at 110 GeV/c compared to 16 GeV/c. To illustrate our conclusion that the main reason for the difference in shape between 16 and 110 GeV/c is the difference in multiplicity, we show as the broken line in fig (5.8) the 16 GeV/c data weighted by the 110 GeV/c multiplicity. The broken line is in fact in reasonable agreement with the 110 GeV/c data.

Fig (5.9) compares the results of the fractional momentum distributions from some leptonic experiments. Despite the different definitions for Z_R all distributions fall exponentially with similar slopes at large values of Z_R . Also the consistency of these distributions shows that no major influence of the choice of beam particles ($\pi/K/p$) exists on the fragmentation of multiparticle systems at large P_T . A similar feature to these results has been observed in E260 experiment (ref 5.8) where the ratio between kaon and pion induced reactions (i.e. $\frac{K^- p \rightarrow \text{jet} + x}{\pi^- p \rightarrow \text{jet} + x}$) is shown to be compatible with 1. This is also true for both single particle and multiparticle data.

5.4 Search for Jet-Like Events

The final point in this comparison with high P_T jets is the shape of the events in momentum space using the triangle plot.

In fig (5.10) the S_i are the parameters which were defined previously (see chapter 4 section 2). A two jet-like event will be cigar shaped in momentum space i.e. $S_1 \sim 3$, $S_2 \sim S_3 \sim 0$. An event having 2 high P_T jets as well as the beam and target fragmentation jets will be "disc" shaped, $S_1 \sim S_2 \sim 1.5$, and $S_3 = 0$. A no-jet event that is the

events which are spherically symmetric will have $S_1 \sim S_2 \sim S_3 \sim 1$. These regions are shown in fig (5.10a). The corresponding number of disc shaped events in fig (5.10b) is negligible compared to the number of cigar shaped events. Fig (5.10c) shows a similar distribution at 16 GeV data, also it is normalized to the total number of events in 110 GeV to make the comparison easier.

The major difference between fig (5.10b) and fig (5.10c) is in the region of large S_1 , where the number of cigar shaped events in 110 GeV is considerably larger than the corresponding number in 16 GeV. This may be explained by the fact that the longitudinal momenta of the particles are larger in 110 GeV compared to 16 GeV, while their transverse momenta are not significantly different. This allows the shape of events to stretch more along the beam direction, hence producing more elongated (cigar shaped) events. Also the larger cross section of planar events at 16 GeV (region of small S_3) can be explained by taking into account the average multiplicity of events which is lower than at 110 GeV.

The fact that our single particle and multiparticle P_T distributions extrapolate to the E260 data plus the similarity of the Z_R distributions, suggests that if E260 have a large proportion of jets as they claim then we should see a large proportion of disc shaped events (at high P_T) at 110 GeV/c. However, we see only a small number in the "disc" corner of the plot in fig 5.10b when compared with 16GeV, where we do not expect hard scattering events to be present.

5.5 Conclusions

We have calculated the single particle and multiparticle distributions for our data by using different definitions of multiparticle systems. We found that the cross section for the production of multiparticle system at large P_T is an order of magnitude larger than the corresponding cross section of single charged particles in K^+p interactions at 110 GeV/c. In addition the P_T distribution of single charged particles and multiparticle system has the same slope at large P_T . These results are all consistent with those described in ref (5.9). On the other hand since we do not expect much hard scattering to be present in low P_T 110 GeV data, these features are not unambiguous evidence for hard scattering processes.

We also investigated the dependence of multiparticle system on the size of solid angle. We found that, the cross section for the multiparticle system strongly depends on the size of solid angle used for "jet" analysis. The jet cross section increased (decreased) by increasing (decreasing) the size of solid angle. This indicates that the calorimeters of E260 experiment do not contain the full "jet" cross section.

On the other hand the results on large P_T multiparticle systems produced in K^+p interactions at 16 GeV are also consistent with those at 110 GeV. This and the fact that the vast majority of events with a large multi-particle system does not exhibit high P_T jet-like structure, indicates that no hard scattering of hadron constituents is required to explain the main features of our data.

Furthermore, as our 110 GeV data extrapolates well to the E260 data and many of the features of E260 data, this casts doubt on the interpretation of the E260 Collaboration, that these features were

evidence for large hard scattering constituents.

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Figure Captions

- Fig 5.1 P_T distribution of invariant cross-section of single charged particles C and multiparticle M in the rapidity range of $0.1 < Y < 0.44$ for 16 GeV data, using jet definition 1.
- Fig 5.2 a) As Fig 5.1 (jet definition 1) but with the preliminary data from K^-p interactions at 110 GeV/c. In addition all constituents of multiparticle systems in this figure have values $Y > -0.5$. Also drawn are data taken from fig 2 3 in ref (5.9). The dashed lines are a guide to the eye.
b) As fig (5.2a) but with the full statistics of 110 GeV K^-p data (jet definition 1).
- Fig 5.3 P_T distribution of invariant cross section of multi-particle M in the rapidity range $0.1 < Y < 0.44$ for the full statistics in 110 GeV K^-p data; with and without $Y < -0.5$ cuts on the constituents of multiparticle systems (jet definition 1).
- Fig 5.4 P_T distribution of invariant cross section of single charged particles C and multiparticle systems M in the rapidity range $0.1 < Y \leq 0.44$, for 110 GeV K^-p data using jet definition 2.
- Fig 5.5 As fig 5.4, but only for the multiparticle systems, in different sizes of the solid angles (jet definition 2).
- Fig 5.6 Azimuthal distribution of all single particles relative to that at highest P_T (trigger), for different ranges of P_T single particle trigger.
- Fig 5.7 Azimuthal distribution of all single charged particles relative to the jet trigger for various ranges of P_T jet trigger.
- Fig 5.8 The cross section (σ_C) for charged constituents of multiparticle systems with $P_T(M) > 1.4$ GeV/c as a function of the constituents fractional momentum Z_R in K^-p interactions at 16 GeV/c and 110 GeV/c. The distributions are normalized

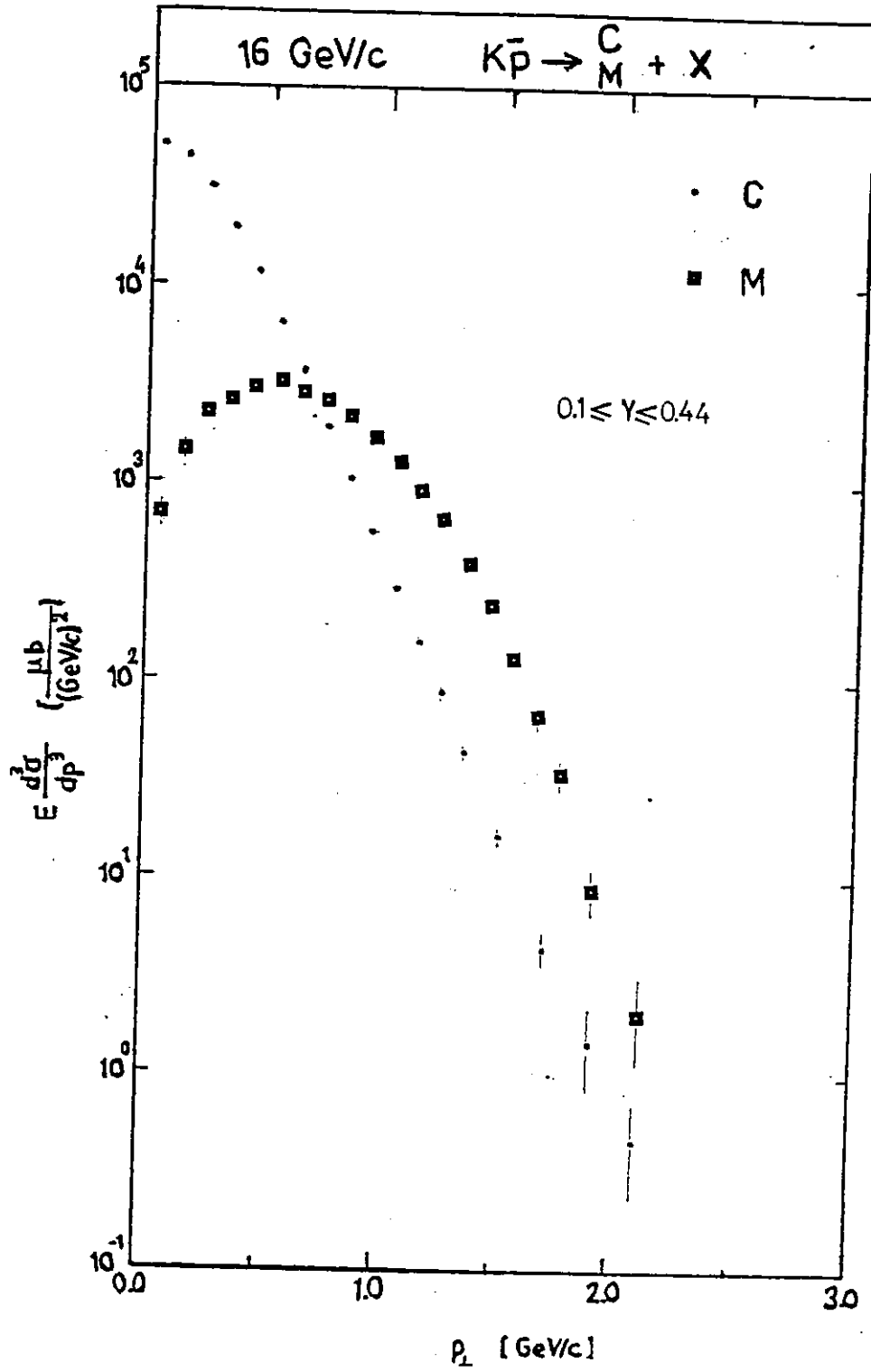
by the cross section (σ_M) for multiparticle systems. The dashed line represents the result of weighting 16 GeV/c data by topological cross sections of 110 GeV/c data.

Fig 5.9 The distribution of transverse momentum fraction Z as taken from ref (5.9) (fig 2 4) and our results at 110 GeV/c from fig (5.8).

Fig 5.10 a) Regions of interest in the variables S_i defined in the text.

b) The population (number of events ≥ 4 prong) in fig (5.10a) for 110 GeV/c K^-p data.

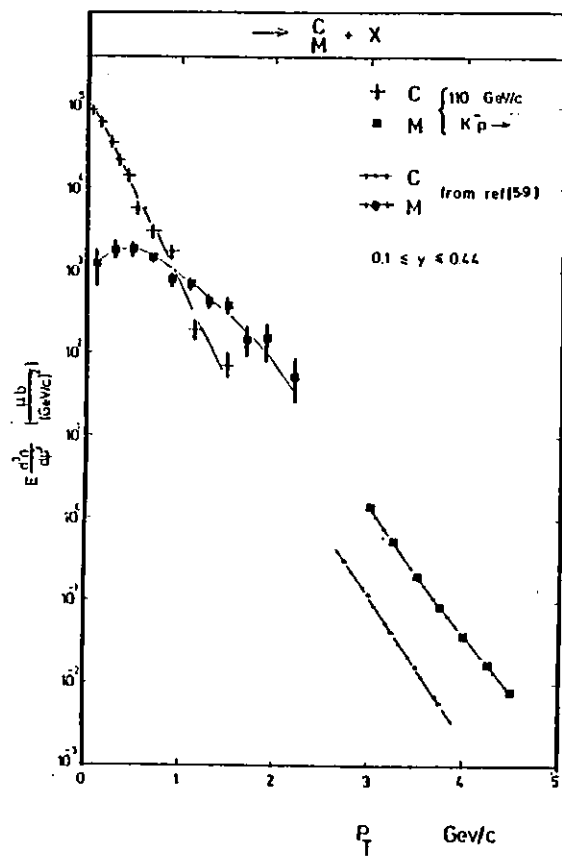
c) The population in fig (5.10a) for 16 GeV/c K^-p data, the number of events is normalized to the total number of events ≥ 4 prong at 110 GeV/c



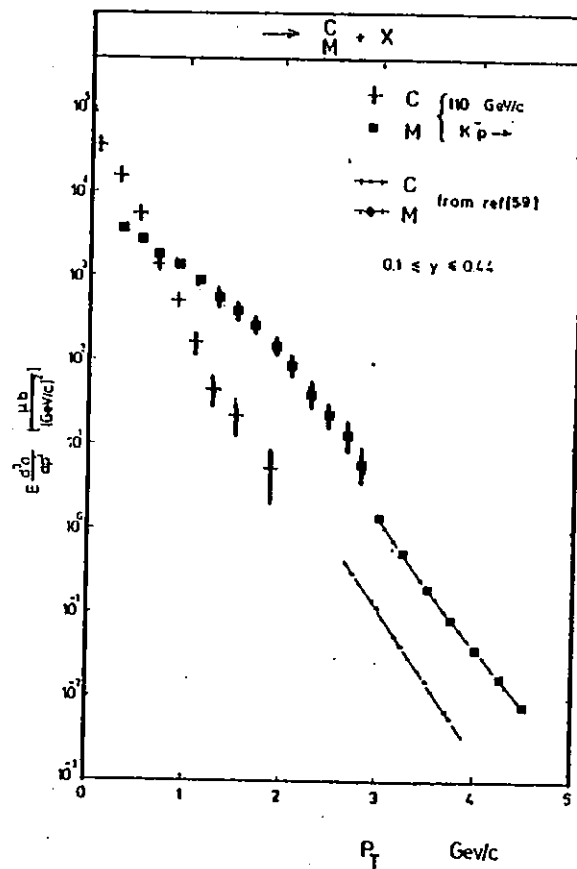
FIG(5.1)

preliminary data

JET DEFENITION 1

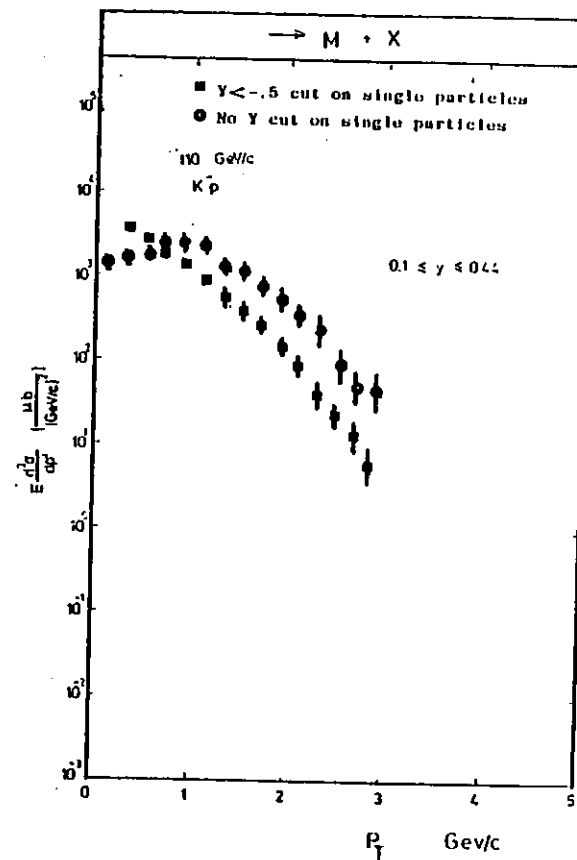


a.



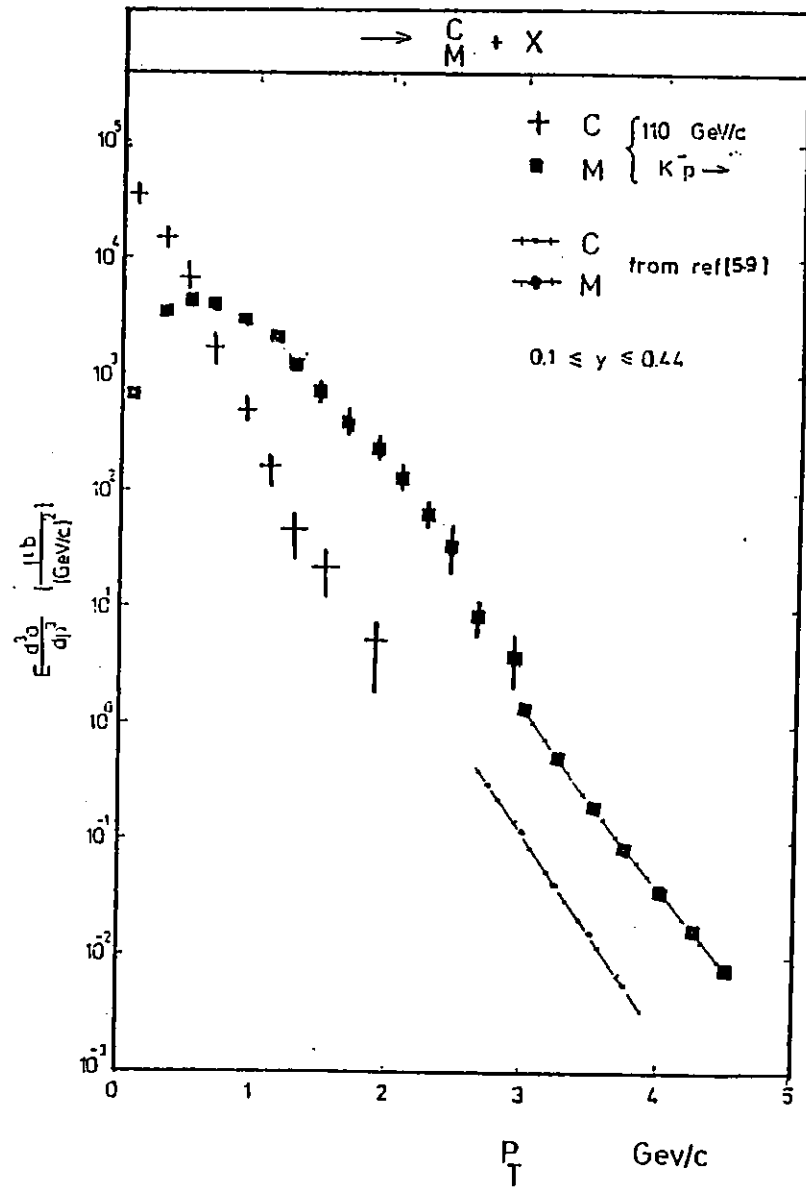
b.

FIG (5.2)

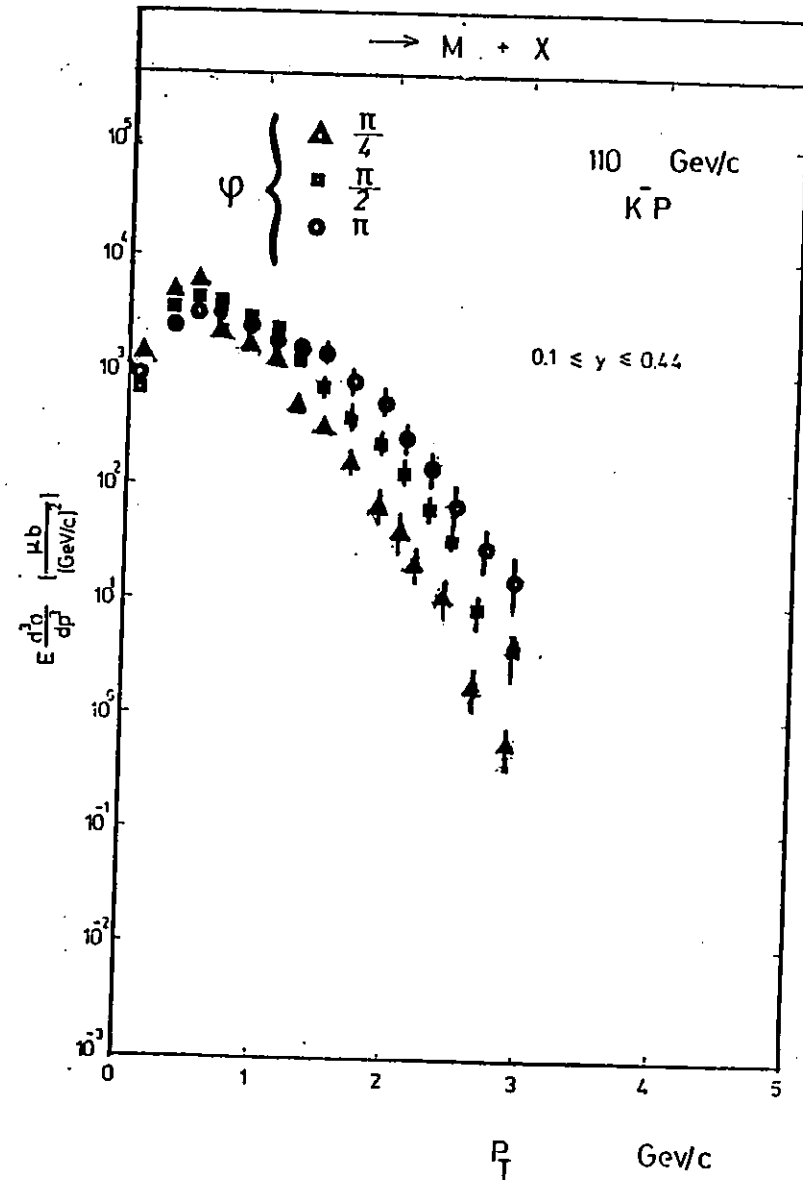


FIG(5.3)

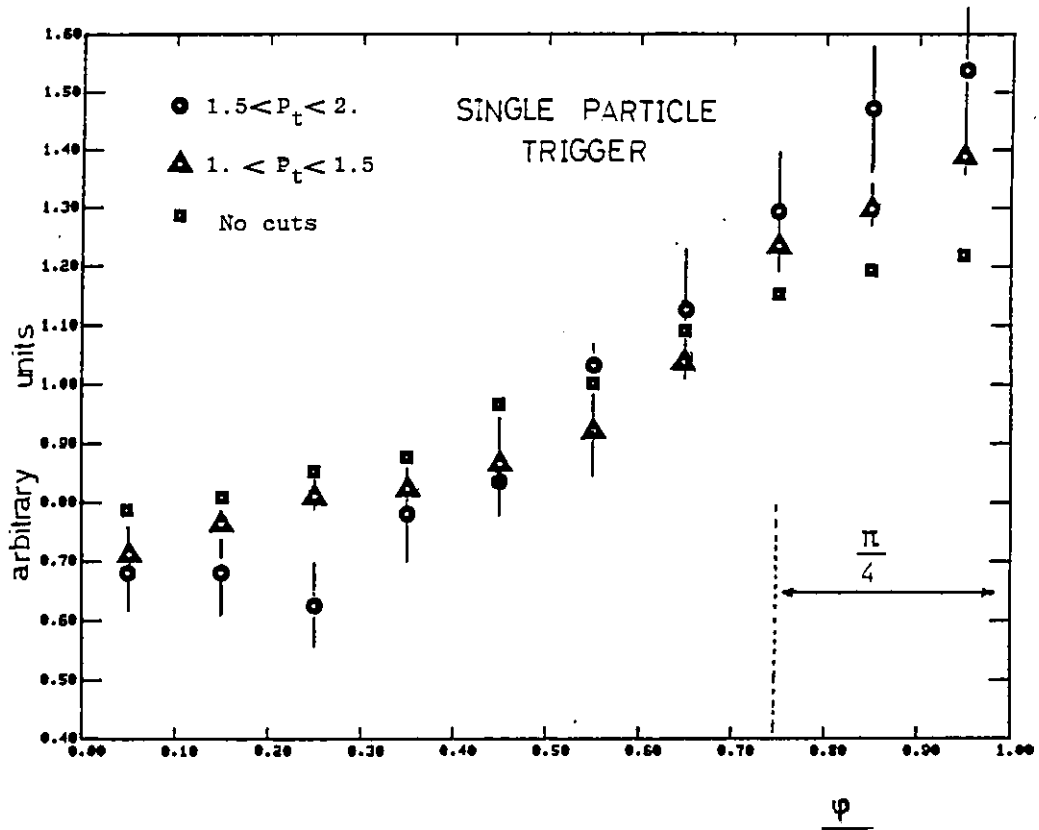
JET DEFINITION 2



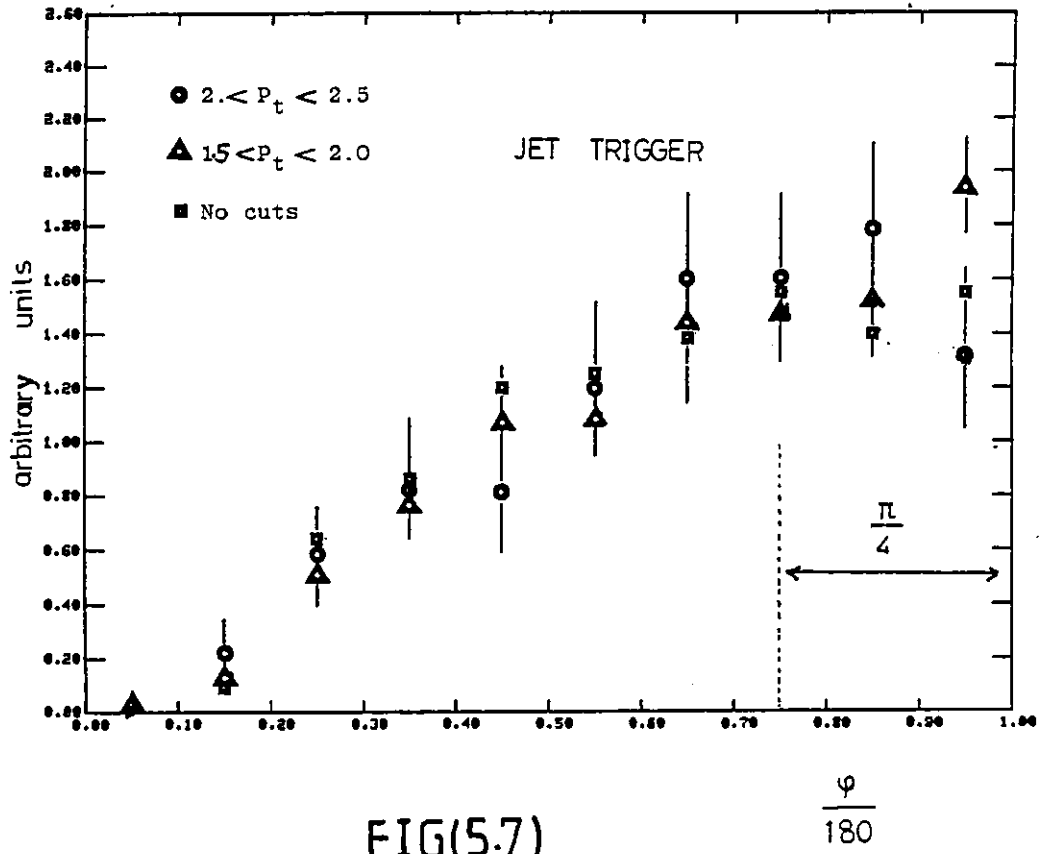
FIG(5.4)



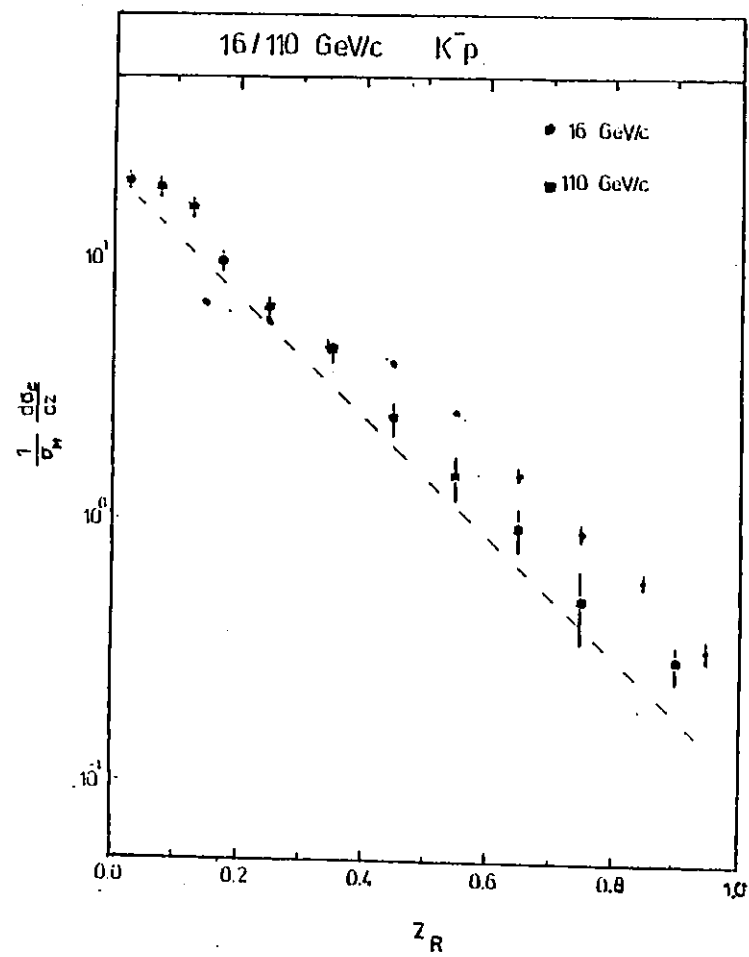
FIG(5.5)



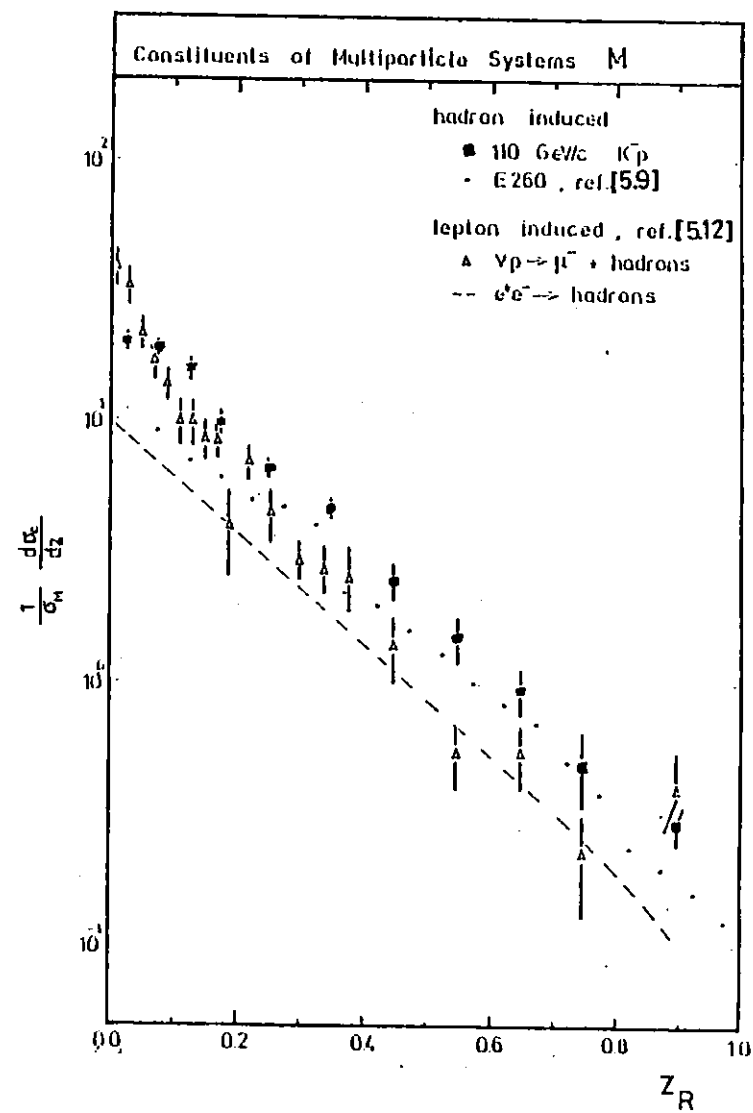
FIG(5.6)



FIG(5.7)

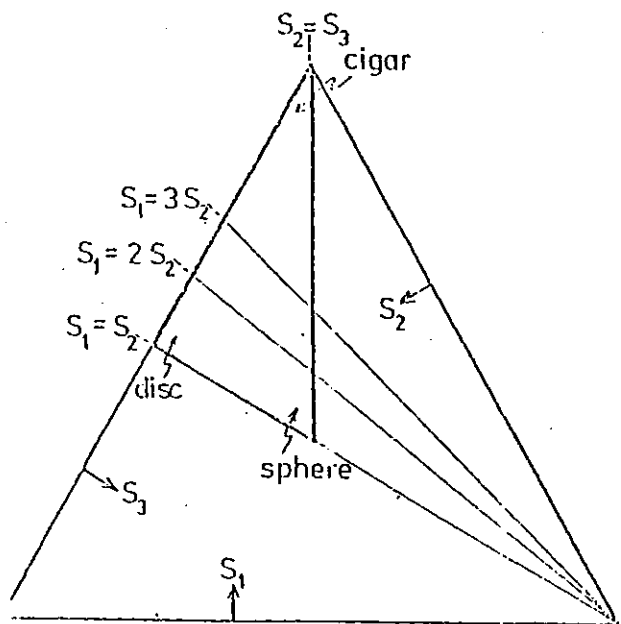


FIG(5.8)



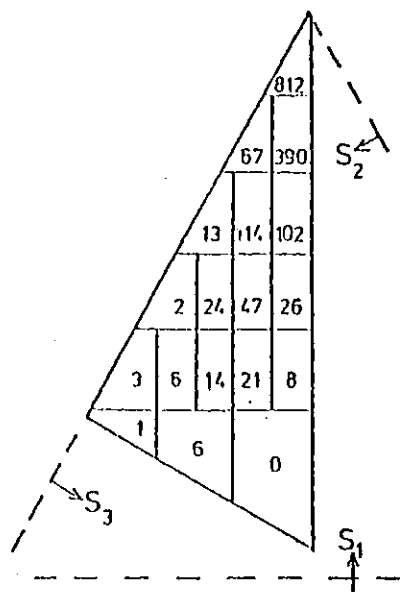
FIG(5.9)

Regions of Interest in S_1



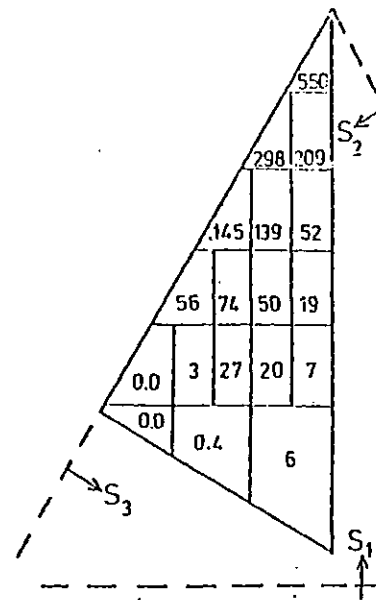
a.

110 GeV/c K^-p



b.

16 GeV/c K^-p



c.

FIG(5.10)

CHAPTER SIX

SOFT HADRON PRODUCTION IN K^-p INTERACTIONS AND COMPARISON WITH JET BEHAVIOUR IN LEPTONIC REACTIONS

6.1 QCD Theory

Quantum Chromodynamics* is presently the best candidate to be the theory of strong interactions. The symmetry group corresponding to this theory is SU(3) and this SU(3) comes from requiring three colours for baryon symmetry (ref 6.1). These colours are necessary for both theoretical and experimental reasons. Introducing 3 colours for each flavour, resolves the spin-statistics problem (ref 6.2) for ground state baryons.

Colour also has indirect experimental support, from the value of $R = \frac{\sigma(\text{hadrons})}{\sigma(\mu^+\mu^-)}$ in e^+e^- annihilation. The experimental values are in much better agreement with $R = 2$ (the result with colour quarks) than with $R = 2/3$ (ref 6.2). Also in the decay rate of neutral pion into two photons: $\pi^0 \rightarrow 2\gamma$, the experimentally observed rate was nine times larger than the quark model prediction. Introducing colour increased the number of intermediate quark states and the corresponding pion decay amplitude by a factor of 3 and hence the rate by 9.

QCD is a Gauge theory based on the group SU(3), and the carriers of the strong force are the 8 gluons of SU(3) which correspond to the 8 generators of the SU(3) group. These gluons are chargeless with spin 1, have small or zero mass and mediate the strong interaction between coloured quarks. In this way gluons are to QCD

* This name was invented by M. Gell-mann

what photons are to Quantum Electrodynamics (QED). However, an extremely important difference is that gluons carry colour and therefore interact strongly among themselves, while photons are electrically neutral and therefore cannot directly interact with one another.

An important property of QCD is asymptotic freedom (ref 6.3, 4). The idea is that at high energies, quarks act as though they were free particles inside hadrons, hence the effective coupling between fields decreases at short distances and consequently we can do perturbation theory. This is known as perturbative QCD which has had some success in predicting the behaviour of structure functions at large four-momentum transfers (ref 6.6).

Using QCD one should eventually be able to calculate hadron masses, the coupling between mesons and baryons, strong interaction cross sections, hadron fragmentation and essentially all strong interaction phenomena. However, there are some problems facing QCD field theories. The most significant problem is the absolute confinement of colour. The idea is as one tries to break a colourless (singlet) hadron (i.e. π , k , p) apart into coloured constituents, the potential energy grows until there is enough energy to create new quark-antiquark pairs and gluons out of the vacuum. In this way the hadron can divide into several colourless hadrons, but quarks, gluons and their colours remain confined (ref 6.2).

The hope is that QCD will eventually be found to explain confinement. However, since perturbation techniques cannot be used in the confinement regime, it is not presently clear how to solve these problems on QCD. This is often called the non-perturbative part of QCD and a theoretical understanding of the way quarks dress themselves up or fragment into the observed hadrons may not be possible until the confinement problem is solved.

6.2 Reasons for Comparison of Hadronic Reactions with Leptonic Data

1) One of the characteristics of high energy interactions is the relative smallness of transverse momentum (P_T) of secondary particles. These features can be described in terms of $\langle P_T^2 \rangle$ versus X_F (Seagull effect), and $\langle P_T^2 \rangle$ versus rapidity (Y), (ref 6.11). X_F is the Feynman x variable $X_F = \frac{P_L}{P_{Lmax}}$ defined in the CM system; Y is defined as $Y = \frac{1}{2} \ln \frac{E + P_L}{E - P_L}$

Fig (6.1a) shows the X_F distributions against $\langle P_T^2 \rangle$ relative to the beam axis for 10, 16 and 110 GeV K^-p interactions respectively. The presence of a seagull dip at $X_F = 0$ in the plot is due to the kinematical effects which are themselves a consequence of P_T limited phase space. The $\langle P_T^2 \rangle$ increases as $|X_F|$ is increased with approximately forward-backward symmetry, and a falling off in the distribution at the high $|X_F|$ which is again due to kinematical effects.

Fig (6.1b) shows $\langle P_T^2 \rangle$ against rapidity for 16 and 110 GeV K^-p data. It shows that $\langle P_T^2 \rangle$ is an almost constant function of rapidity. The change in $\langle P_T^2 \rangle$ in the high values of $|Y|$ is attributed to the kinematical effects, since in this region one simply cannot produce large transverse momenta. The approximately constant value of $\langle P_T^2 \rangle$ in terms of rapidity may be explained by the fact that, for P_T limited phase space one finds a distribution of particles, that to a good approximation factorizes into two functions, one of rapidity and one of P_T . As a consequence $\langle P_T \rangle$ is a rather constant function of rapidity. On changing this into a distribution of X_F and P_T a large range of rapidity around $Y = 0$ at small P_T becomes a small range of X_F at small P_T . Therefore the distribution of particles peaks strongly at small X_F and small P_T , resulting in a small value of P_T at $X_F = 0$, (fig 6.1a).

On the other hand in e^+e^- annihilation as well as in deep inelastic

neutrino scattering the study of transverse momenta is claimed (i.e. ref 6.18 - 23) to be a good way of testing perturbative QCD. Therefore soft hadron physics (where non-perturbative effects probably dominate), is a fairly good means of checking the differences in features between leptonic reactions and the general phenomena of hadron physics, which could indicate the presence of perturbative QCD effects in the former.

2. The second reason for the comparison of hadron-hadron with lepton data is an experimental one. Comprison with minimum bias bubble chamber data may be useful in determining if any jet-like behaviour is due either to the experimental errors or to the problems with the different methods proposed for separating out of the "jets".

In e^+e^- experiment the jet analysis is restricted by the use of sphericity and thrust axes only, because these are the main axes which have been proposed for investigating the "jetiness" of events for this data.

Because of the neutral particles missing in ν data, the jet axis defined by either thrust or sphericity does not in general represent the direction of the struck single quark. Therefore the current axis (direction of virtual boson) is used as a reference axis. However, the current axis will deviate from the single quark axis because of smearing effect due to the primordial transverse momentum of the confined quarks in the nucleon and the small internal motion of nucleons in the heavy targets. But the P_T sum for all particles from such effects should balance between the forward and backward hemispheres (ref 6.21).

In fact the current direction can be found if the magnitude of incident ν energy is known. The most common method which has been proposed in some recent neutrino papers (ref 6.18, 21) is a method

based on transverse momentum balance. By this way the hadronic energy in each event is estimated by applying a suitable correction factor to the measured energy of the observed hadrons. Then the energy of incident ν is taken as the sum of the muon and corrected energies, which helps to calculate the current direction. There are also several methods of finding this correction factor. The method which has been proposed in νD_2 (ref 6.21) of calculating the corrected energy of incident ν is given by:

$$E_{\nu} = p_{\ell}^{\mu} + p_{\ell}^C + p_{\ell}^C \cdot |p_T^{\mu} + p_T^C|/p_T^C$$

where $p_{\ell}^{\mu}(p_T^{\mu})$ and $p_{\ell}^C(p_T^C)$ are the longitudinal (transverse momentum) of the μ^- and the charged hadron system relative to ν direction respectively.

It is also common to use the mean hadron direction (ref 6.22) to analyse the features of ν data, assuming that the missing neutrals are distributed symmetrically about this direction.

In the K^-p data there is no current axis. Instead the mean direction of all final hadrons including both charged and neutral particles is approximated by simply using the beam axis. This direction in the kaon-nucleon CM system for hadron data can then be compared with the current direction in the virtual boson-nucleon CM system, for the ν data.

In e^+e^- annihilation also there is no "natural" axis corresponding to the current direction. As mentioned earlier the only direction which could be used as the current axis can be determined through a minimization or maximization process which gives for example the sphericity or thrust axis. Therefore it would be necessary to check if these different axes suggested for analysing jets are themselves

sensitive to jet behaviour.

6.3 Data Cleaning and Analysis Technique

To improve our data sample we have removed about 2% of the tracks at 110 GeV because of reconstruction problems or unacceptable momentum error ($\frac{\Delta p}{p} > 30\%$). Tracks identified as protons from range, ionization or fitting were treated as protons. All other charged tracks have been taken as pions. As the majority of tracks are pions and there is no method to identify the fast kaons, and also the mass difference between the kaons and pions is not significant at high momenta we believe this is a reasonable assumption for our data sample. We have used the charged tracks to make our distribution, as it is the case for the leptonic data. The e^+e^- experiments trigger on ≥ 3 charged tracks (SPEAR) or ≥ 4 charged tracks (PLUTO), so when we compare our results with these experiments we remove the 2-prong events. It should be noted that acceptance inefficiencies in e^+e^- data were not corrected for. Also in the νN data there is some loss of events because of close in secondary interactions in NeH_2 but this makes a negligible correction on our data.

The 10 and 16 GeV K^-p data come from 350000 and 400,000 events which were taken in the 1.5m British National and 2m CERN bubble chamber respectively. A subsample of 40,000 from each data has been used in our subsequent analysis.

To investigate the jet-like behaviour of our events we have used the same variables as have been employed in e^+e^- . These are sphericity and thrust which were defined previously. We have used Brandt-method to find the thrust axis as it is the case for e^+e^- as well. Also the method to find the sphericity axis in both experiments is similar.

One problem in comparison of soft hadron interactions with leptonic reactions is that in the hadron data there are some diffractive events which are small or completely absent in the leptonic reactions. To find diffractive events in our data we have made a cut on Feynman x to remove the events with at least one fast track which lies within the range of this cut. As fig (6.2) shows $|x_F| > 0.85$ is a reasonable cut for our purpose. It can be seen that this cut removes the diffractive dissociation events while at the same time only removing a very small number of non-diffractive events. In fact this cut doesn't affect the average values of quantities such as sphericity and thrust significantly, but it can't be neglected in the differential distributions, especially in the most jet like events. In general the results will be presented with the diffractives removed. When the effect of diffractive events is significant both distributions will be shown.

6.4 Comparison with Leptonic Data

In this section we mainly compare our results with e^+e^- experiment. So we restrict our analysis by using the sphericity and thrust axes. Also some results from ν experiments relative to these axes will be presented.

Figs (6.3a, b, c) show the sphericity distributions for the 10, 16 and 110 GeV respectively. The shapes of sphericity at 10 and 16 GeV are similar. At 110 GeV the distribution peaks at smaller values when compared to the lower energies. This is due to the more clearly defined forward-backward jets at 110. In soft hadron interactions most of the energies of the particles are longitudinal and the transverse momenta of the particles are small. Figs (6.4a, b, c) show the thrust distributions at 10, 16 and 110 respectively. Again the 10 and 16 GeV

distributions are similar, the 110 GeV distribution peaks at higher values compared to 10 and 16 GeV as expected because low sphericity corresponds to high thrust.

Fig (6.5a, b) shows the average values of sphericity ($\langle S \rangle$) and $\langle 1-T \rangle$ as a function of CM energy. Two prong events have been removed to make our data consistent with e^+e^- data. It is obvious that the 110 K^-p values are in good agreement with the e^+e^- results. The K^-p values at 10 and 16 GeV are higher than 110 GeV but they are not as high as in the e^+e^- case. But at the low energies one should notice that the values of e^+e^- presented by DORIS and SPEAR which come from two different detectors at two different accelerators differ by as much as the K^-p and SPEAR results. These differences between the two sets of data and between the e^+e^- and K^-p data, could be due to problems in finding the jet axis at low energies where the events are fairly isotropic.

On fig (6.5b) are also the results obtained from the ν experiment. E_{cm} for ν data is calculated by finding the corrected CM energy W of the ν reactions (ref 6.17). The shape of variation of $\langle 1-T \rangle$ with respect to CM energy is similar to that of leptonic reactions. It is particularly in good agreement with the ν results.

To study the difference between the thrust and sphericity estimates for jet direction, we show in fig (6.6) the angle between sphericity and thrust axis (θ_{ST}). It is clear that the sphericity axis is very close to the thrust axis in both K^-p at 14.8 GeV and e^+e^- at 9.4 GeV. The small differences that is observed between the two axes, may be due to the difficulties in defining the jet axis discussed above. It can also be seen that the difference for the e^+e^- data is wider than the corresponding angle in K^-p at 110 GeV. This gives us further evidence that the difference between the e^+e^- and K^-p data at low energies could

be due to problems in determining the jet axis direction in rather spherical events. This difference may be also due to the CM energies being significantly different.

To compare the K^-p and leptonic interactions in more detail, we compare the S distribution at 16 GeV K^-p ($E_{cm} = 5.6\text{GeV}$) with the S distribution in e^+e^- at the closest energy at which data has been published. Fig (6.7a) shows that 16 GeV distribution peaks at rather lower values than the SPEAR data at 6.2 GeV. Fig (6.7b) is the S distribution in 110 GeV ($E_{cm} = 14.8$) and S distribution from PLUTO results at 17 GeV (ref 6.12). It shows that both distributions are in good agreement within the errors. The TASSO S distribution at 17 GeV (ref 6.13) is very similar to the PLUTO results at this energy. Fig(6.8) shows that the T distribution at 110 GeV and νN values within the range of $8 < W < 12$ GeV, are very consistent with each other. On these plots the K^-p distributions are shown with and without the diffractive component. In all cases it can be seen that diffractive events contribute to the most jet like events i.e. low S and high T. It is also clear that the leptonic distributions are more consistent with the K^-p distributions after removal of the diffractive component. The only difference between the shapes of lepton and hadron data is the peaking of K^-p at lower S values compared with leptonic data. This may be partly due to problems in finding the sphericity axis at low E_{cm} as explained before.

To discuss the jet like behaviour of our experiment in further detail fig (6.9) shows $\langle P_T \rangle$ and $\langle P_{||} \rangle$ relative to the thrust axis. Again the two prong events have been removed to improve the comparison with the PLUTO results at DORIS and PETRA. It can be seen that the K^-p values at 10, 16 and 110 GeV follow the same trend as the e^+e^- results. On the plot is also $\langle P_{||} \rangle$ with a cut on $|X_{||}| > 0.1$ where X is

defined as $\frac{2P_{||}}{E_{cm}}$. The values in both K^-p and e^+e^- have the same behaviour with the increasing E_{cm} .

We also present some results from νD_2 relative to thrust axis (ref 6.21). Fig (6.10) shows the W dependence of $\langle P_T^2 \rangle$ relative to this axis separately for the forward and backward hemispheres. In order to compare with this data, we have also divided the K^-p data into forward and backward regions relative to the thrust direction and for each region we have calculated $\langle p_T^2 \rangle$ relative to thrust axis.

The most noticeable result from this figure is that $\langle P_T^2 \rangle$ in the two hemispheres have nearly the same magnitude and rise together with W . This is also true for both data. We conclude that, transverse momenta relative to thrust axis show no difference between the leptonic and hadronic data. We will discuss this in further detail in the next section, where we show $\langle P_T^2 \rangle$ relative to the beam direction.

Fig (6.9) also shows that the $\langle P_{||} \rangle$ increases by increasing E_{cm} , whereas $\langle P_T \rangle$ stays small and only rises to a value of ~ 400 MeV at 17 GeV. Both features imply that the events show a more jet structure as the energy increases.

On the other hand the small rise on $\langle P_T \rangle$ at high energies is claimed to give an indication of gluon radiation which broadens one of the two side jets in e^+e^- experiment (ref 6.14).

To study this effect in further detail, fig (6.11) shows the $\langle P_T^2 \rangle$ distributions for e^+e^- against Z for wide jet and thin jet separately (ref 6.14). Here Z is defined as $\frac{P}{P_{beam}}$ where P is the CM momentum of each track and P_{beam} refers to the CM system. Wide and thin jets are calculated by dividing each event into two halves by a plane

perpendicular to the thrust axis, and determining $\langle p_T^2 \rangle$ separately for the two sides namely wide and thin jets.

We have done a similar calculation for the hadron data. The 110 GeV distribution ($E_{cm} = 14.8$ GeV) for the two sides is very similar to the e^+e^- in the comparable energy range of 13-17 GeV. The $q\bar{q}$ model of Feynman and Field (ref 6.7) with $\sigma_q = 0.3$ GeV/c is also plotted on this figure. This model assumes that quarks fragment into observed hadrons with a transverse momentum which is independent of energy. It fits the data rather well at these rather low energies. In the higher energies however this model does not fit the e^+e^- data, where σ_q has to be increased to fit the higher energy data.

Obviously higher hadron energies are needed before reaching a firm conclusion for hadron data. However, in a recent paper (ref 6.16) the planar features of K^-p interactions have been compared with e^+e^- annihilation where it is pointed out that the simple quark model would not describe these hadron data below the present available energies either.

6.5 Transverse Momentum Distributions with Respect to the Current (or Beam) Direction

6.5.1 Deep Inelastic ν Scattering

In this section we mainly compare our K^-p results relative to the beam axis with the ν data relative to the current direction. Some results relative to the mean hadron direction will also be presented.

Fig (6.12a) shows $\langle p_T^2 \rangle$ relative to the current direction against X_F for two ranges of W from the BEBC neutrino-nucleon experiment (ref 6.23, 24). This data came from a mixture of νp and νN charged current interactions from the hydrogen and neon experiments respectively.

The current direction for this data is found by using the transverse momentum balance method. In this figure the seagull effect is clearly visible. Furthermore, at small W a forward-backward symmetry is observed, whereas at large W the Seagull effect becomes asymmetric. In addition the P_T of backward secondaries does not show a strong dependence on W whereas that of forward secondaries increases significantly at high W and high X_F .

Figs (6.12b, c) also compare these distributions with the seagull plots extracted from hadronic data, in the similar range of energies. In Fig (6.12b) to a good approximation the hadron data ($E_{cm} = 5.6$ GeV) show a similar behaviour to the νH_2 data ($4 < W < 6$) in both forward and backward regions, although in some cases the hadron data tend to lie systematically above the ν results. Such small differences between the two sets of data may be attributed to the hadronic centre of mass energies, being larger for K^-p interactions. They may also be related to the fact that we compare $\langle P_T^2 \rangle$ in ν data relative to the current direction with $\langle P_T^2 \rangle$ in K^-p data relative to the beam axis. Our K^-p data at $E_{cm} = 14.8$ GeV also show rather good agreement with the statistically weak, higher energy νH_2 data ($W > 8$ GeV), in the backward and in the central regions. However, for $X_F \gtrsim 0.3$ the νH_2 data show a significantly faster rise compared with the K^-p data. This effect may bring out different features between the leptonic and hadronic results as now will be further described.

Fig (6.13a) shows $\langle P_T^2 \rangle$ of charged particles relative to the beam axis, against the CM energy for K^-p interactions. Also some results from νNe interactions (ref 6.22) have been added to the figure. The $\langle P_T^2 \rangle$ for νNe data has been calculated relative to the resultant direction of the measured hadrons including neutrals. We also calculated the $\langle P_T^2 \rangle$ relative to the resultant direction of the measured hadrons

in our data, but within the statistical errors the results were very similar to $\langle P_T^2 \rangle$ relative to the beam axis. It is clear from the figure that the ν results are very similar to the K^-p results in the lower range of W . However, in the range of larger hadronic CM energies, the ν results are above the hadronic data.

Fig (6.13b) shows $\langle P_T^2 \rangle$ for νNe values with a $Z > 0.2$ cut where Z is defined as $\frac{E_h}{E_{tot}}$ and E_h is the energy of each hadron in lab system. Some results have also been added from the new νNe (ref 6.18). The axis used for this new νNe data was found in a similar manner to that for the old νNe data.

The old νNe data (ref 6.22) is consistent with the QCD theory that is, an increase on $\langle P_T^2 \rangle$ is proportional to a rise with W^2 . The new νNe data (ref 6.18) show that the rise in $\langle P_T^2 \rangle$ is proportional to $\ln S$. The discrepancy between the two νNe data appears to be due to the higher statistics of the new νNe data.

The rise of $\langle P_T^2 \rangle$ in hadron data is also proportional to $\ln S$, but this is not as fast with increasing energy as the νNe results. Such a variation for hadron data has been previously pointed out in a publication over a narrower range of energy (ref 6.9). On this plot we also include some results from that paper, where they have made the cut on Feynman x . They claim that the cut on Z and X_F gives similar results, and we have checked with our data that this is so.

To further study the W dependence of $\langle P_T^2 \rangle$ we present in figs (6.14a, b) and fig (6.15) the $\langle P_T^2 \rangle$ for forward and backward going charged hadrons as a function of W for both hadron and νp and νD_2 data. Now if any difference is observed in P_T^2 between the two regions in ν data, it reflects the difference in the jet properties between the single quark jet and the recoiling diquark system. In the above

analysis, $\langle P_T^2 \rangle$ is calculated relative to the beam axis for K^-p data, and relative to the current direction, for ν data. In addition, the current direction in both sets of ν data has been found by the application of the transverse momentum balance method.

As these figures indicate, the $\langle P_T^2 \rangle$ in K^-p data has a very similar magnitude and rise, as well as little energy dependence, in both forward and backward regions. On the other hand the ν data show that $\langle P_T^2 \rangle$ is fairly constant and similar to that for K^-p data in the backward hemisphere, whereas a significant rise with increasing W is observed in the forward hemisphere. This is the major difference between lepton and soft K^-p interactions.

However, as shown in previous section the jet properties for both hadronic and leptonic data are quite similar when analysed in terms of sphericity or thrust (i.e. fig (6.10)). This is due to the nature of the procedure used to determine the thrust axis being insensitive to the small differences between forward and backward jets.

On the other hand the current direction as mentioned earlier, is only determined approximately in neutrino data. Hence it may not necessarily coincide with the 'true' current direction. Small deviation up or down will cause an apparent fluctuation of transverse momenta of jet fragments. There has been some effort to check the method used for finding this direction, in neutrino experiments by using $\langle P_n^2 \rangle$ defined as the transverse momentum squared perpendicular to the plane containing the incident ν and the outgoing μ^- . The $\langle P_n^2 \rangle$ is less influenced by the deviation of the current axis and is related to $\langle P_T^2 \rangle$ (if correctly measured) according to $\langle P_n^2 \rangle = 0.5 \langle P_T^2 \rangle$ (ref 6.19). In ref(6.19, 21) it was found that the $\langle P_n^2 \rangle$ coincides with $0.5 \langle P_T^2 \rangle$ within errors, indicating that the method is accurate enough for the purpose of jet analysis.

If this way of checking the current axis is correct, then the faster rise of $\langle P_T^2 \rangle$ in ν data compared with the soft hadron data may be related to the QCD predictions that "the forward (struck) quark is strongly accelerated and therefore would be expected to radiate gluons broadening the forward P_T distributions".

6.5.2 Deep Inelastic Muon Scattering

In this section we extend our analysis by using some results from recent μp scattering data from the EMC collaboration (ref 6.20). One of the advantages of this data is that the current direction seems to be well known from the precise kinematic determination of the incident and scattered muons, so that it need not be reconstructed from the observed hadrons (ref. 6.20).

In fig (6.16) we present the W^2 dependence of $\langle P_T^2 \rangle$ relative to the current direction for μp scattering data with a $Z > 0.2$ cut. Z is defined as $\frac{E_h}{E_{tot}}$ and E_h is the energy of each hadron in lab system. The hadrons in the EMC data were only considered if they were produced in the forward hemisphere of the hadronic centre of mass system. Some results from νNe and $K^- p$ data discussed earlier, have also been added to this figure. As the $Z > 0.2$ cut removes the bulk of slow tracks in the backward hemisphere, from the νNe and the hadron data, a direct comparison is possible with the results of μp scattering data. This figure shows that the results for muon data are very similar to those obtained from new νNe data, confirming that the rise in $\langle P_T^2 \rangle$ though proportional to $\ln S$, has a faster rise with increasing W^2 , than the corresponding $K^- p$ data.

In fig (6.17) we also present the W^2 dependence of $\langle P_T^2 \rangle$ for three different ranges of Z for these different data. A remarkable similarity is observed between the ν and muon data, in all three regions. In

addition the K^-p data are similar to the leptonic results in the two lower Z regions. However for $Z > 0.4$ the hadron results lie significantly below the leptonic results.

This behaviour may be further studied in fig (6.18), where $\langle P_T^2 \rangle$ is plotted against Z^2 for μp data in the range of $\langle W^2 \rangle = 210 \text{ GeV}^2$, which is comparable with the value of $W^2 = 220 \text{ GeV}^2$ in $110 \text{ GeV } K^-p$ data. The diffractive events have been removed from our K^-p data. We have also checked that the mean hadron direction gives a similar result to that for the beam axis. The main feature of this figure is that both $\langle P_T^2 \rangle$ have approximately the same magnitude and rise together with Z^2 up to $Z^2 \approx 0.15$, then start deviating from each other for $Z^2 > 0.15$. The K^-p data show a little rise with increasing Z^2 except for the large Z^2 values, which has a falling off distribution due to the kinematical effect. On the other hand the muon data increases more rapidly than the K^-p data, indicating a strong rise in the forward region.

We conclude that μp scattering data show a pronounced widening of the forward P_T distribution relative to the current direction, when compared with the corresponding K^-p distribution relative to the beam axis. Consequently the μp scattering results confirm the results of ν data, being in qualitative agreement with the prediction of QCD.

6.6 Conclusions and Discussion

In conclusion we have observed that variation of $\langle S \rangle$ and $\langle 1-T \rangle$ with E_{cm} in K^-p interaction, is similar to those at e^+e^- annihilation and deep inelastic neutrino interactions. The only differences on these variations are in the lower energy where we observe the K^-p values are lower than the leptonic results, but these differences are comparable

with the difference between the SPEAR and DORIS data. This may be due to the fact that the sphericity axis is not well determined for the high sphericity events.

With diffractive events removed, sphericity and thrust distributions in 110 GeV are in very good agreement with the leptonic data. The $\langle P_T^2 \rangle$ relative to the thrust axis is very similar in both leptonic and hadronic data. These similarities between the two sets of data could be related to the idea that at present energies the non-perturbative effects still dominate. In addition the broadening of the P_T distribution in e^+e^- as the energy reaches above 15 GeV is claimed as evidence that a small proportion of events is subject to single hard gluon radiation at wide angle by one of the quarks. It would therefore be interesting to compare high energy hadron data with the latest high energy e^+e^- data in order to check whether these features of e^+e^- interactions are a unique signal for gluon jets.

On the other hand, there is a major difference between the soft hadron and the lepton data when $\langle P_T^2 \rangle$ is investigated in terms of the current direction in ν data, and in terms of the beam axis in K^-p data. We observe that the K^-p results do not rise as fast as the ν results with increasing energy, in the forward hemisphere. This indicates that e^+e^- and ν data are similar to hadron data when using sphericity and thrust axes, at least up to 14.8 GeV. But K^-p data relative to the beam direction and deep inelastic data relative to the current direction do differ. In other words, using the thrust axis is not a sensitive way to detect small differences between the forward and backward hemispheres. This insensitivity to the thrust or sphericity, could partially explain the strong similarities between the K^-p and lepton data.

Furthermore, the faster rise of $\langle P_T^2 \rangle$ relative to the current direction in the forward region for the ν and μp scattering data, is believed to indicate the presence of an additional contribution to the outgoing single quark, due to gluon emission. This conclusion is strengthened by the observation that the ν and μp scattering data also show a faster rise of $\langle P_T^2 \rangle$ when compared with the soft hadron data. However, this could be partly due to the fact that we have arbitrarily chosen the beam direction for the comparison. There may be some other direction in the hadron case that is the more equivalent to the current direction in lepton interactions. We may therefore conclude that some more detailed analysis of data relative to different axes could further clarify the situation.

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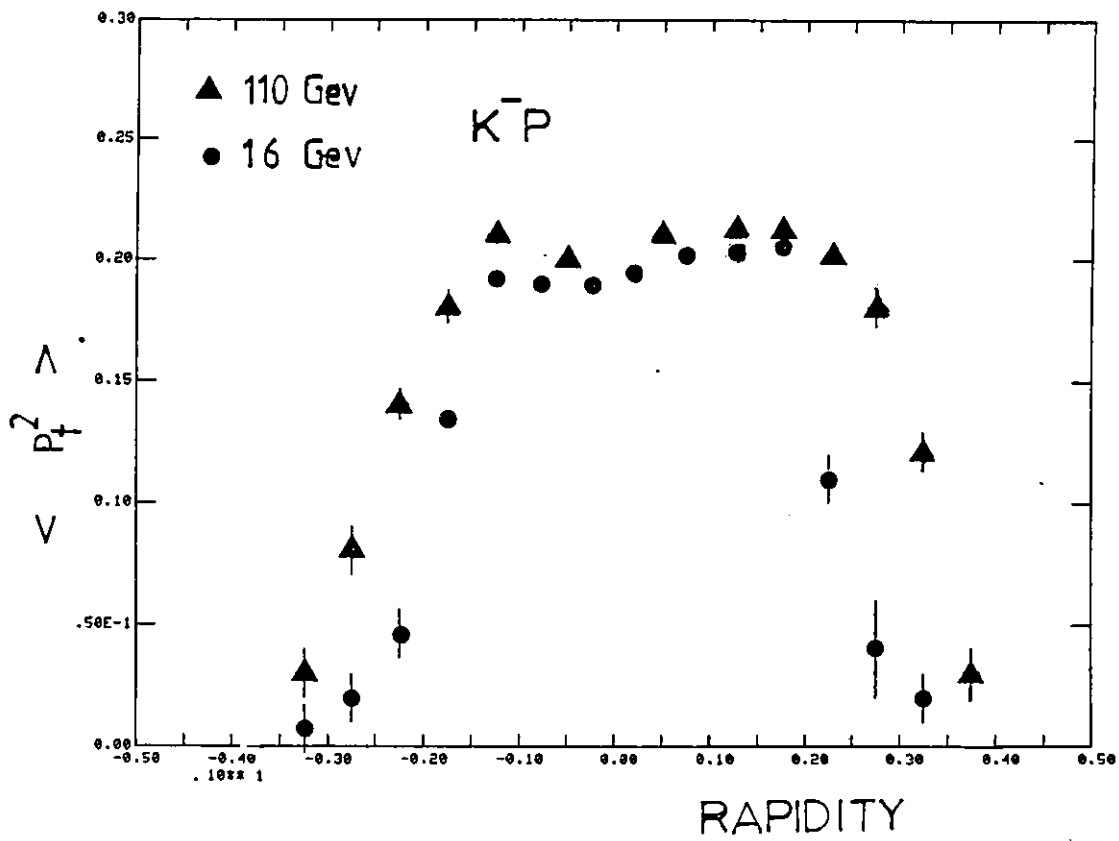
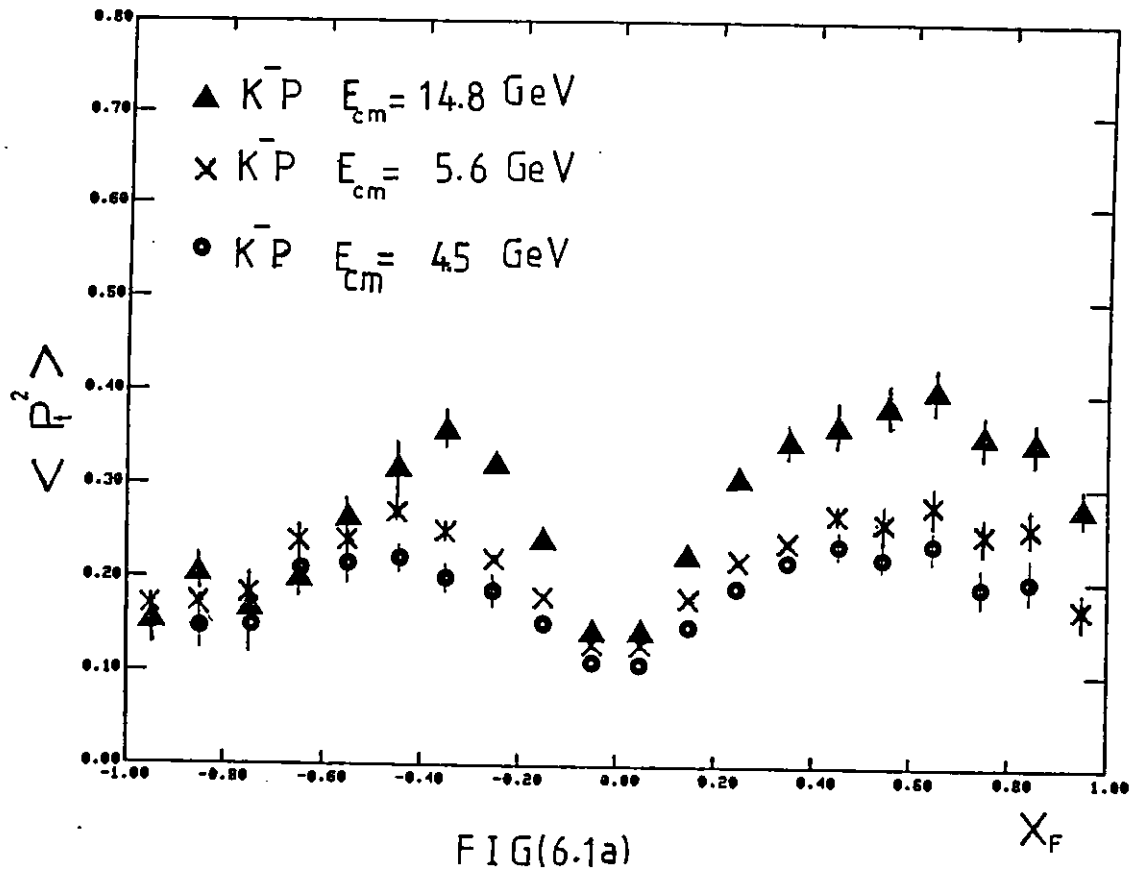
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Figure Captions

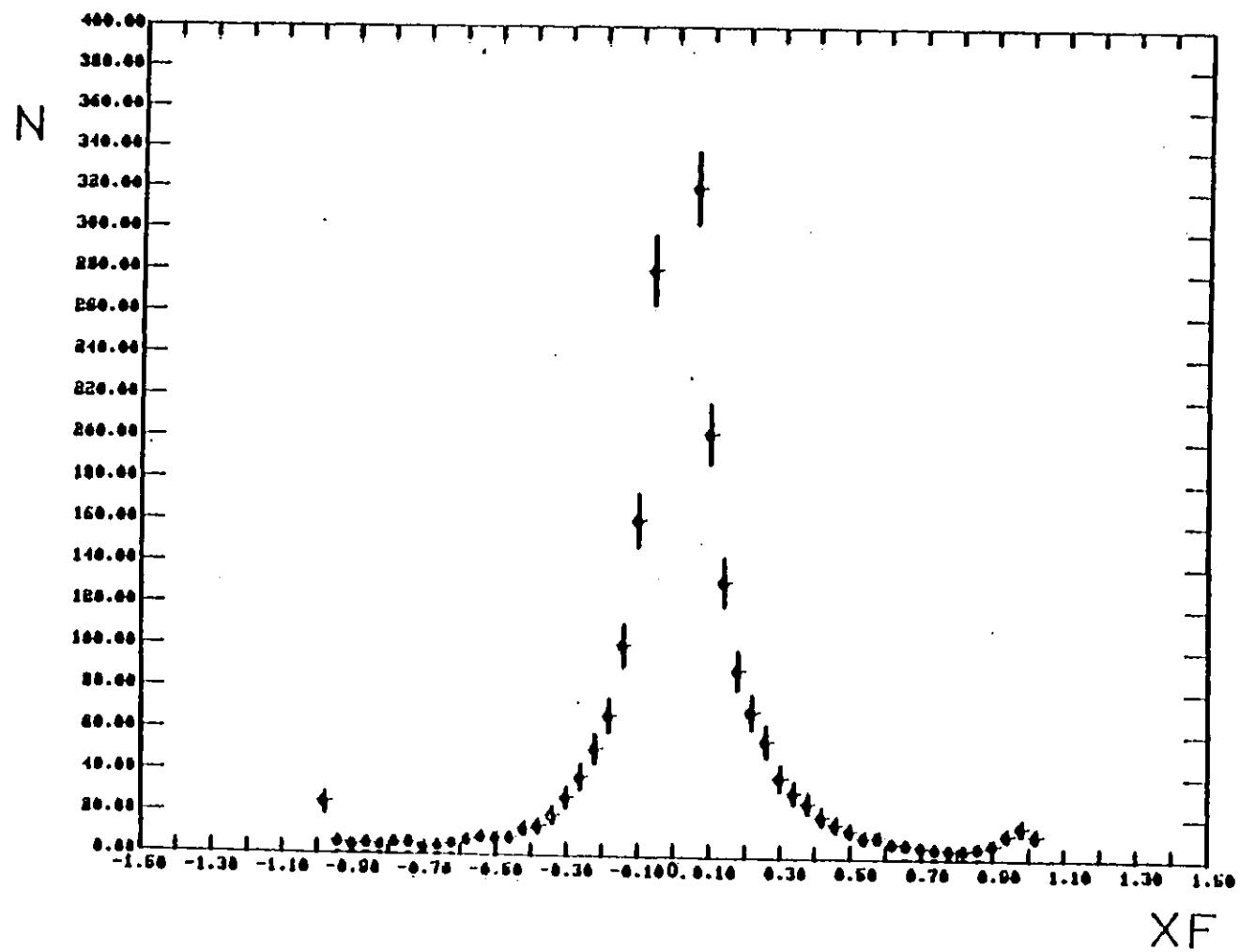
- 6.1 a) P_T^2 versus Feynman X (X_F) for ($\blacktriangle$) K^-p Interactions at 110 GeV ($E_{cm} = 14.8$), (X) K^-p Interactions at 16 GeV ($E_{cm}=5.6$), ($\bullet$) K^-p interactions at 10 GeV ($E_{cm}=4.5$).
- b) P_T^2 versus rapidity for ($\blacktriangle$) K^-p interactions at 110 GeV and ($\bullet$) K^-p interactions at 16 GeV.
- 6.2 Feynman X distribution of single charged particles against the number of events for K^-p Interactions at 110 GeV/c.
- 6.3 Sphericity distribution for K^-p interactions:
- a) 10 GeV
- b) 16 GeV
- c) and 110 GeV.
- 6.4 Thrust distribution for K^-p interactions
- a) 10 GeV
- b) 16 GeV
- c) and 110 GeV
- 6.5 a) $\langle S \rangle$ the average sphericity relative to the sphericity axis for ($\bullet$) K^-p interactions, (X) e^+e^- interaction at SPEAR (∇) e^+e^- interactions at PLUTO and (Δ) e^+e^- interactions at TASSO.
- b) $\langle 1-T \rangle$ where T is thrust for ($\bullet$) K^-p interactions, ($\Delta\nabla$) e^+e^- interactions and ($\square$) νN interaction.
- 6.6 Angle θ_{ST} between sphericity and thrust axes at 110 GeV/c K^-p data ($\bullet$). Values of θ_{ST} in e^+e^- annihilation at $E_{cm} = 9.4$ GeV from ref (6.15) are shown.
- 6.7 a) S distribution relative to sphericity axis for ($\bullet$) K^-p interactions at $E_{cm} = 5.6$ GeV, with diffractive events removed, ($\blacklozenge$) K^-p interactions including diffractives, (X) e^+e^- interactions at SPEAR at $E_{cm} = 6.2$ GeV

- b) S distribution relative to the sphericity axis for (●) K^-p interactions at $E_{cm} = 14.8$ GeV with diffractive component removed, (◆) K^-p interactions including diffractives, (▽) e^+e^- interactions at PETRA at 17 GeV.
- 6.8 T distribution relative to the thrust axis for (●) K^-p interactions at $E_{cm} = 14.8$ GeV with diffractive events removed, (◆) K^-p interactions including diffractives, (□) νN interactions for $8\text{GeV} < W < 12$ GeV.
- 6.9 Average values of various quantities relative to thrust axis:
 $\langle P_T \rangle$ for (●) K^-p and (o) e^+e^- interactions in PLUTO;
 $\langle P_{\parallel} \rangle$ for (■) K^-p and (□) e^+e^- interactions in PLUTO
 $\langle P_{\parallel} \rangle$ with $|X_{\parallel}| > .1$ for (▼) K^-p and (▽) e^+e^- interactions in PLUTO
- 6.10 $\langle P_T^2(T) \rangle$ versus W in the two different hemispheres for, K^-p interactions: (▲) forward, (△) backward and, $\nu D2$ data: (●) current and (X) target regions. $P_T(T)$ is calculated relative to thrust axis
- 6.11 $\langle P_T^2 \rangle$ relative to thrust axis as a function of $Z = \frac{P}{P_{beam}}$ for the wide and narrow jets separately for, K^-p data: (▲) $E_{cm} = 14.8$ GeV, (■) $E_{cm} = 5.6$ GeV, (○) $E_{cm} = 4.5$ GeV, and e^+e^- data: (●) in the range of 13-17 GeV. The curve shows the prediction from the $q\bar{q}$ model with $\sigma_q = 0.30$ GeV/c (ref 6.7)
- 6.12 a) $\langle P_T^2 \rangle$ versus X_F for $\nu H2$ data: (●) $4 < W < 6$ GeV, (○) $W > 8$ GeV.
b) $\langle P_T^2 \rangle$ versus X_F for (●) $\nu H2$ data for $4 < W < 6$ GeV, and (X) K^-p data at $E_{cm} = 5.6$ GeV
c) $\langle P_T^2 \rangle$ versus X_F for (●) $\nu H2$ data for $W > 8$ GeV and (X) K^-p interactions at $E_{cm} = 14.8$ GeV.
- 6.13 a) (●) $\langle P_T^2 \rangle$ relative to the beam axis for K^-p interactions (□) $\langle P_T^2 \rangle$ relative to shower direction for νNe interactions
b) As (a) but with a cut $Z > 0.2$, with extra K^-p data from ref (6.9) and some new νNe data from ref (6.18).

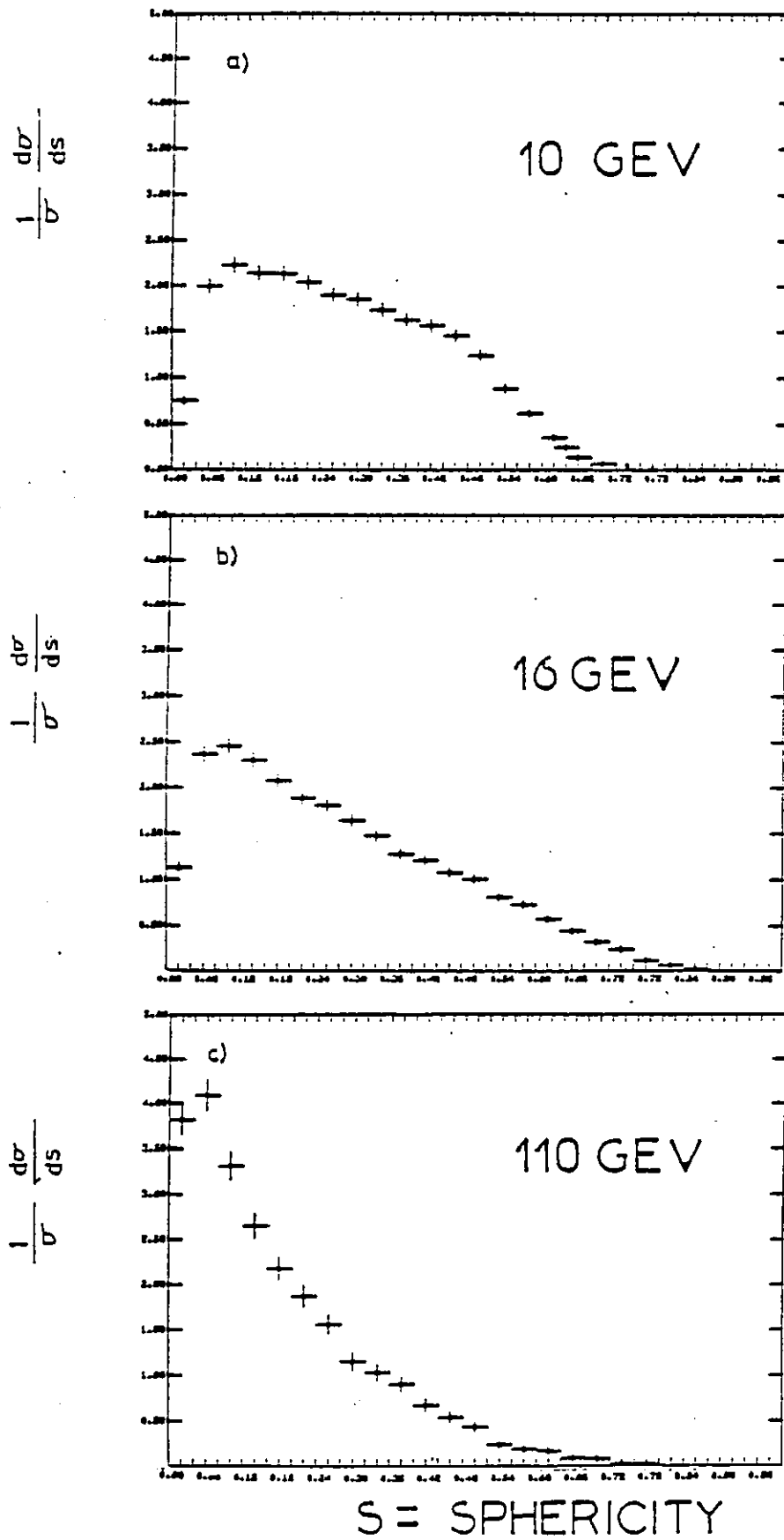
- 6.14 a) $\langle P_T^2 \rangle$ in the forward region of hadronic centre of mass for:
 (●) K^-p interactions relative to beam axis
 (□) νp interactions relative to the current direction
 b) as (a) but for tracks going backward
- 6.15 $\langle P_T^2 \rangle$ versus W in the two different hemispheres for, K^-p interactions: (▲) forward, (△) backward and, $\nu D2$ data: (●) current and (X) target regions. P_T^2 is calculated relative to the beam axis for K^-p data, and relative to the current direction for $\nu D2$ data.
- 6.16 As fig (6.13b), as well as some results from the μp scattering data (ref 6.20).
- 6.17 $\langle P_T^2 \rangle$ of hadrons versus W^2 for $0.1 < Z < 0.2$, $0.2 < Z < 0.4$, $Z < 0.4$ for K^-p , μp scattering and νNe data. P_T^2 is calculated relative to the beam axis for K^-p data, relative to the current direction for μp data and relative to shower direction for νNe data.
- 6.18 $\langle P_T^2 \rangle$ versus Z^2 for (▲) K^-p data at 110 GeV ($W^2 \approx 220 \text{ GeV}^2$) and (●) μp scattering data for $\langle W^2 \rangle = 210 \text{ GeV}^2$. P_T^2 is calculated relative to the beam axis for K^-p data and relative to the current direction for μp scattering data.



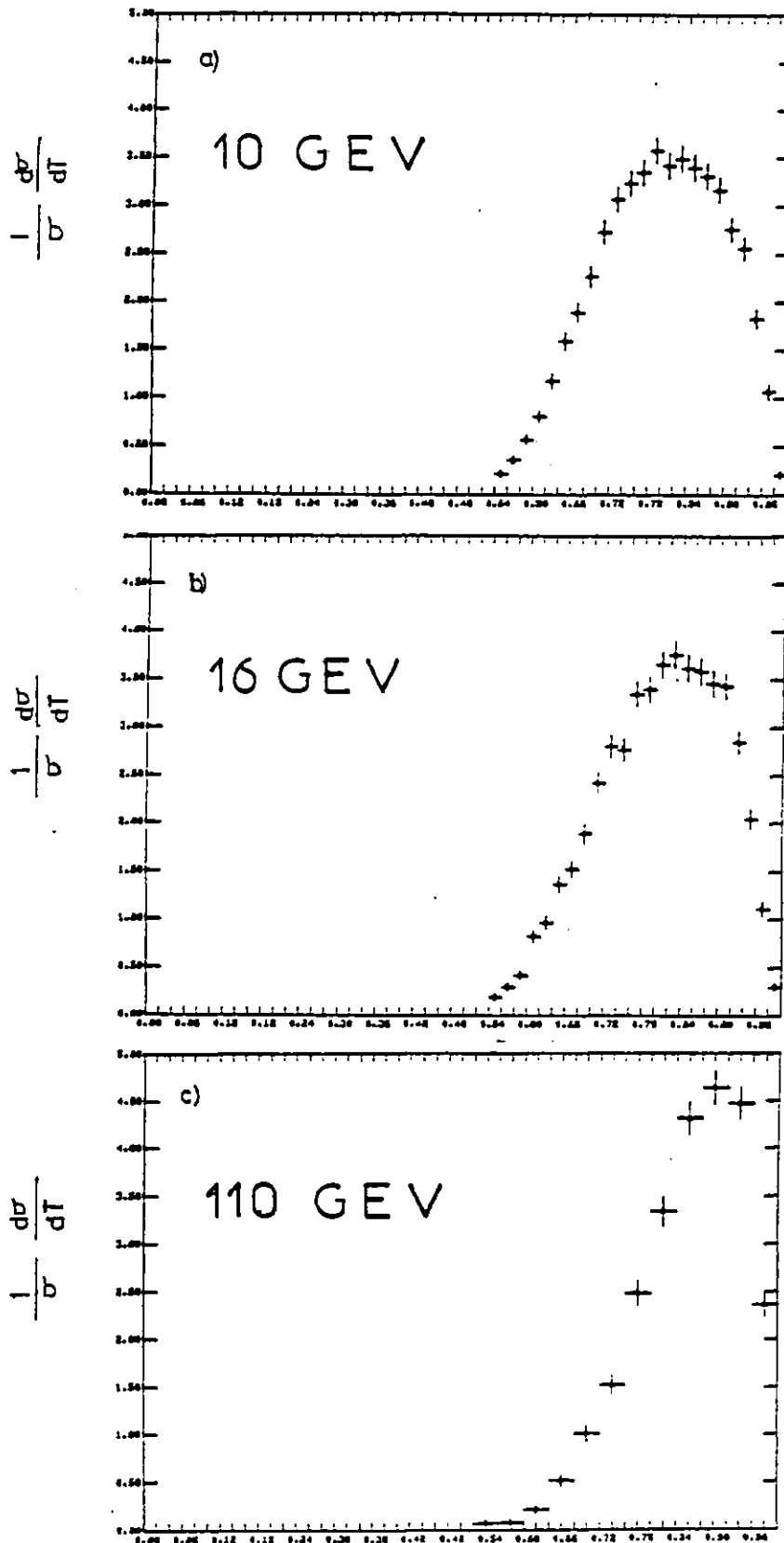
FIG(6.1b)



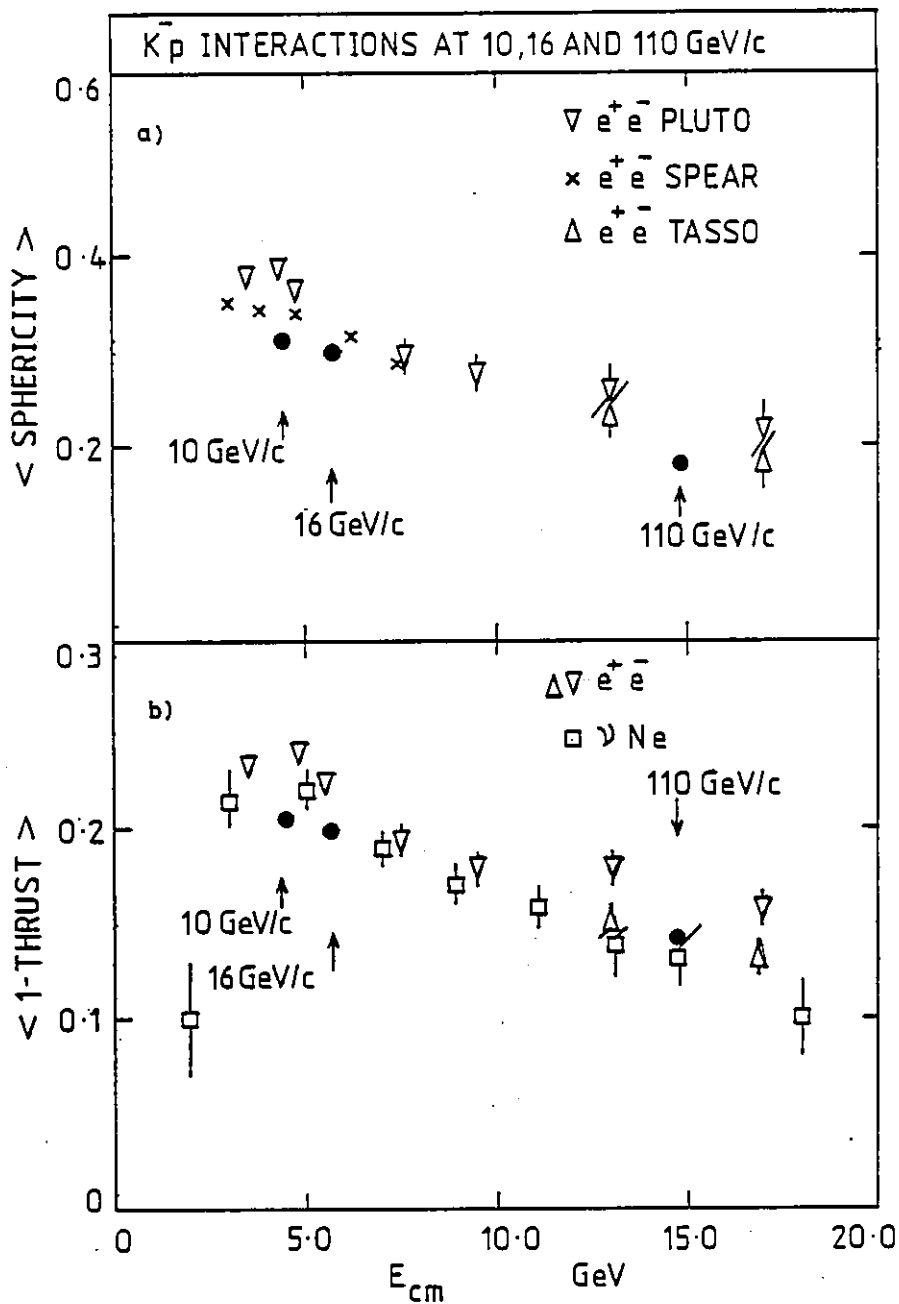
FIG(6.2)



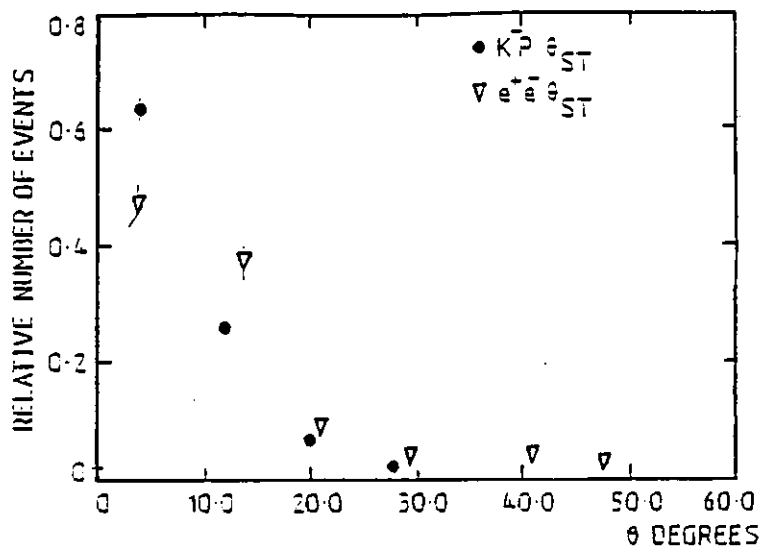
FIG(6.3)



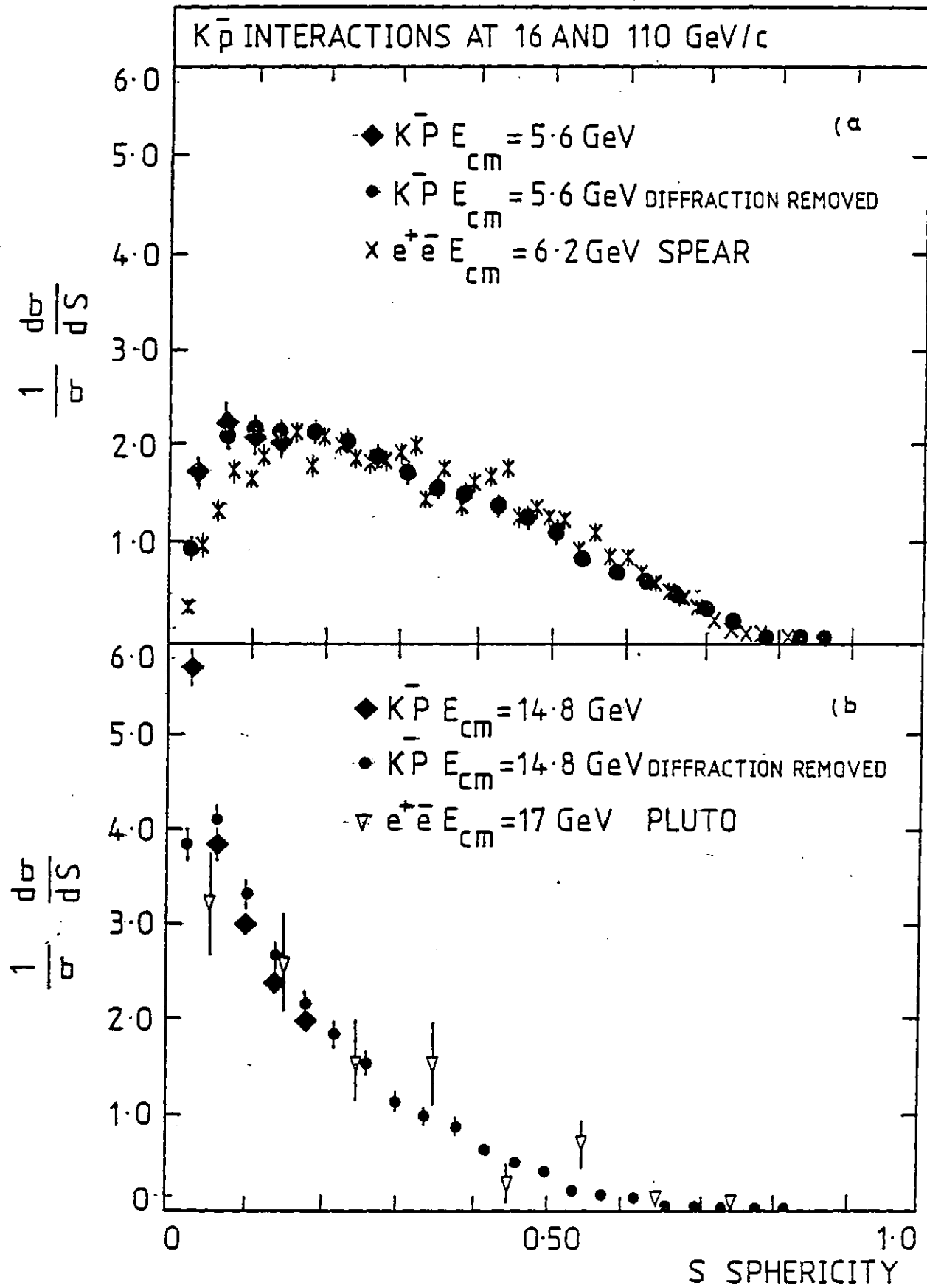
FIG(6.4)

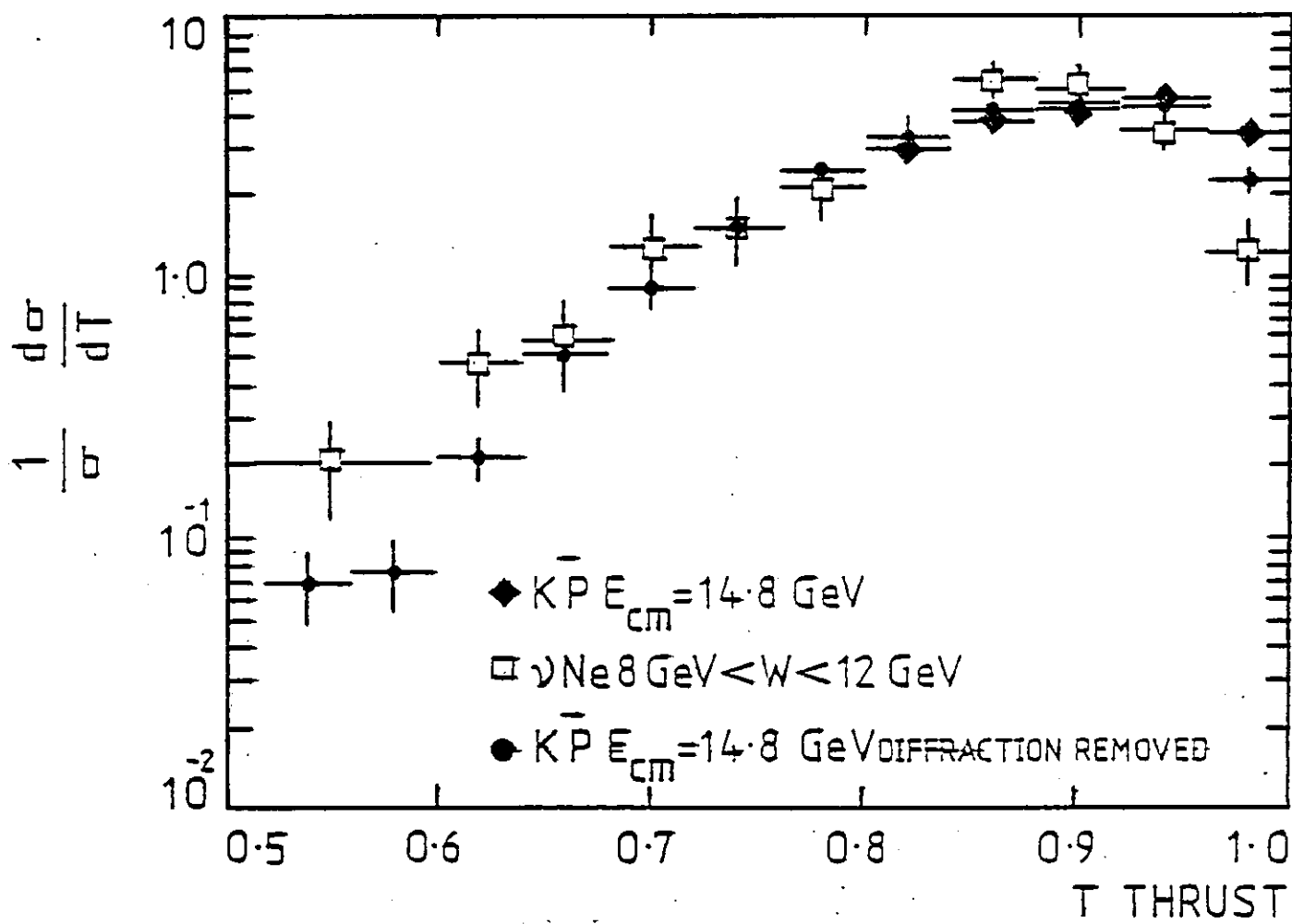


FIG(6.5)

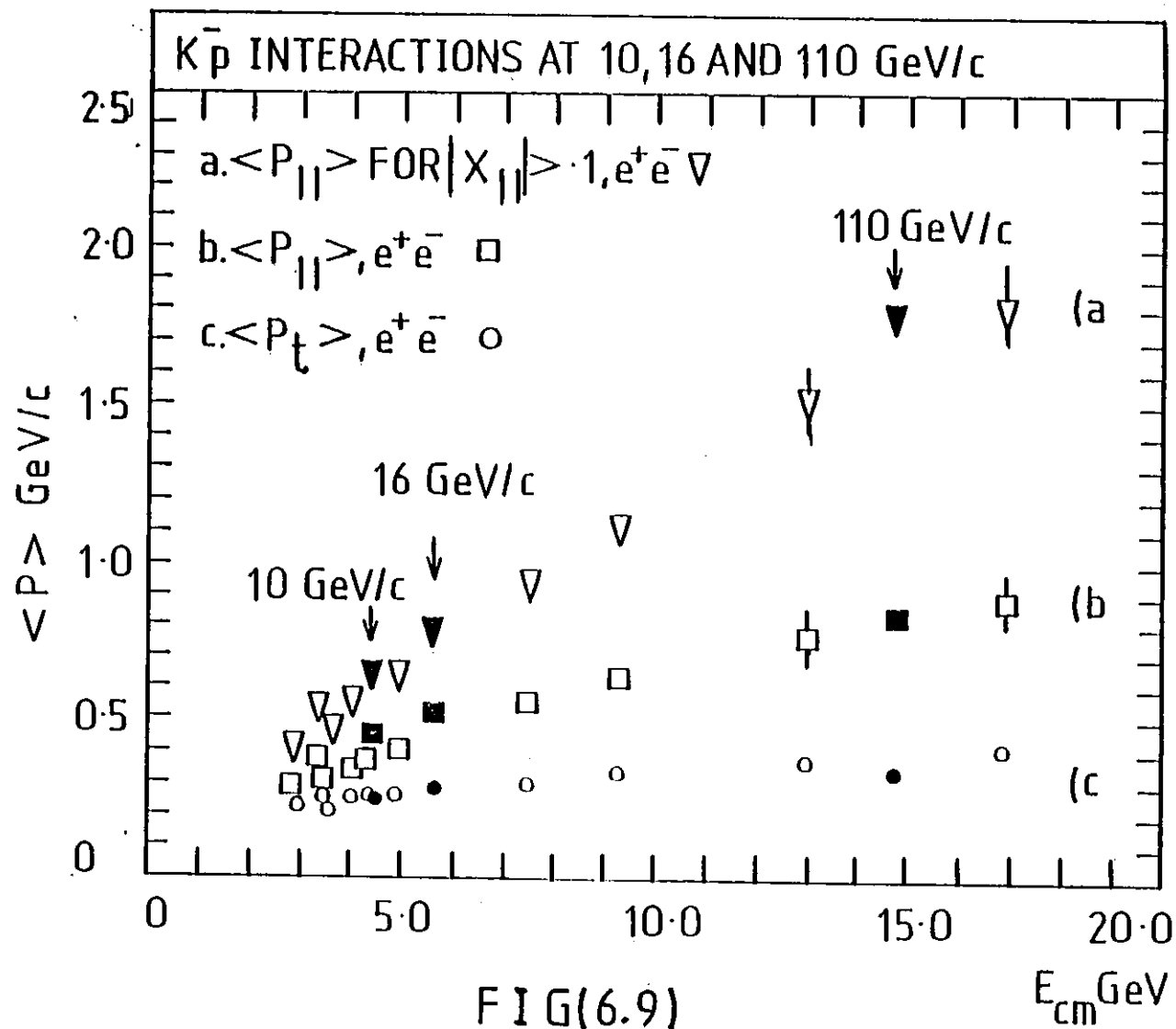


FIG(6.6)

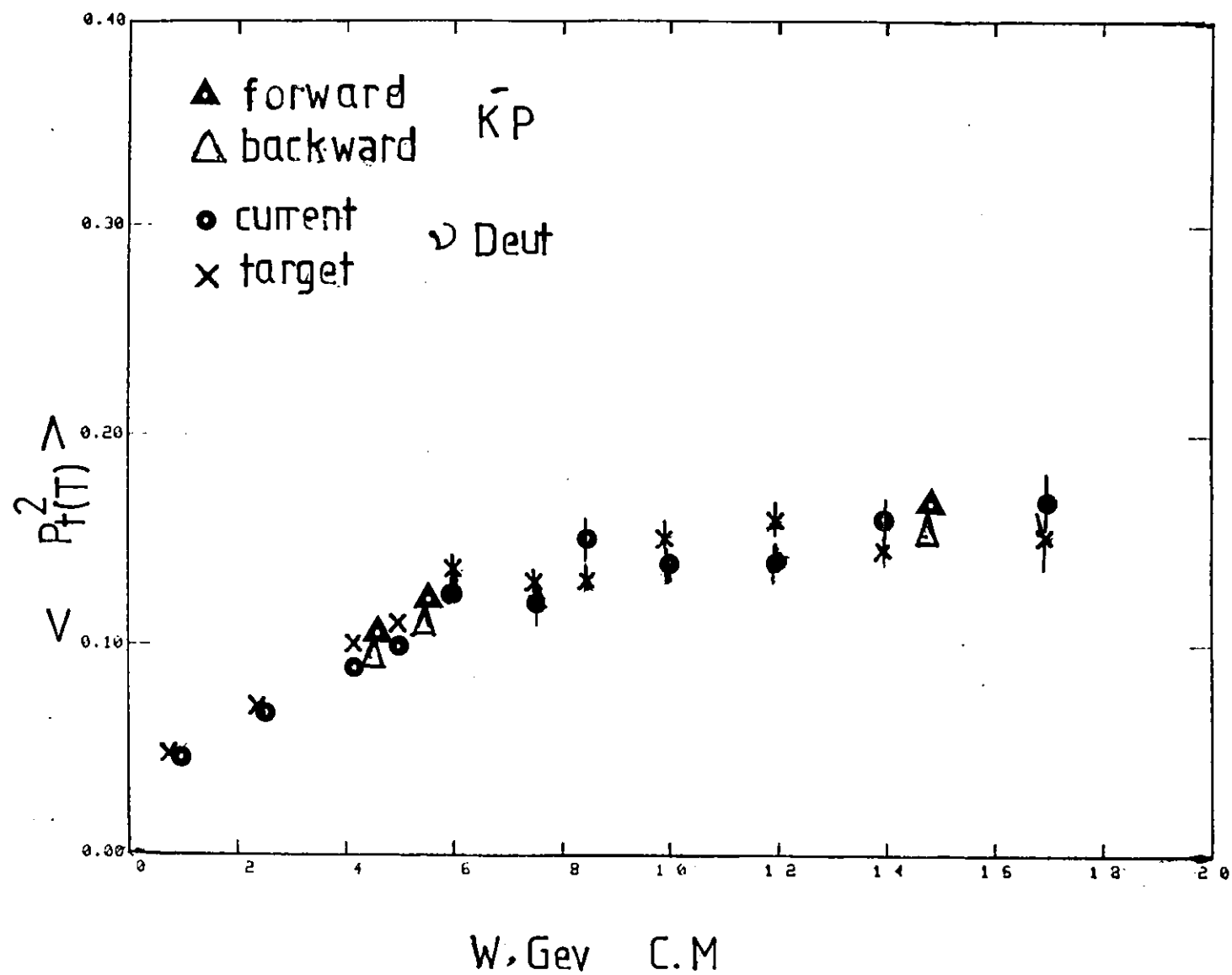




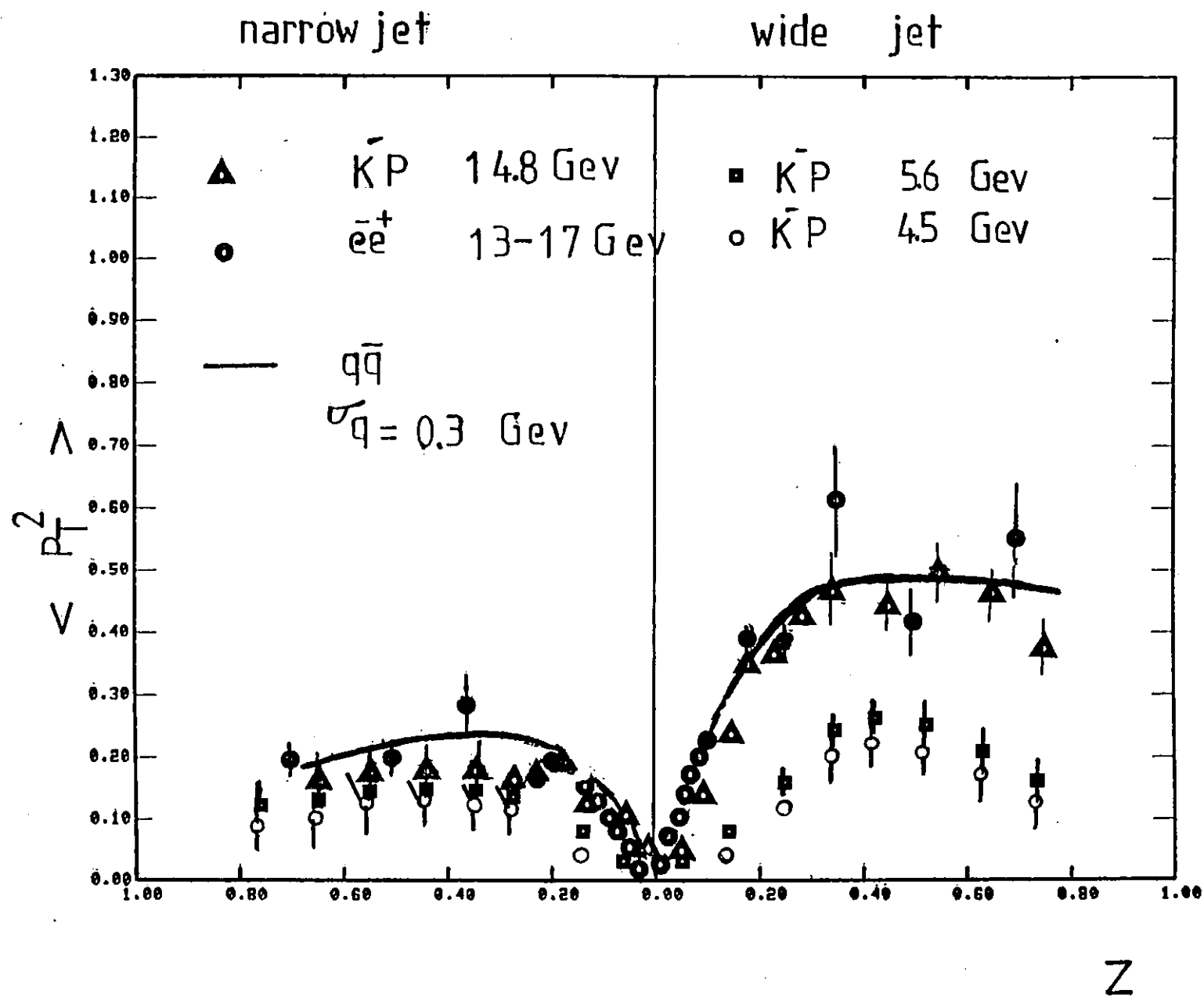
FIG(6.8)



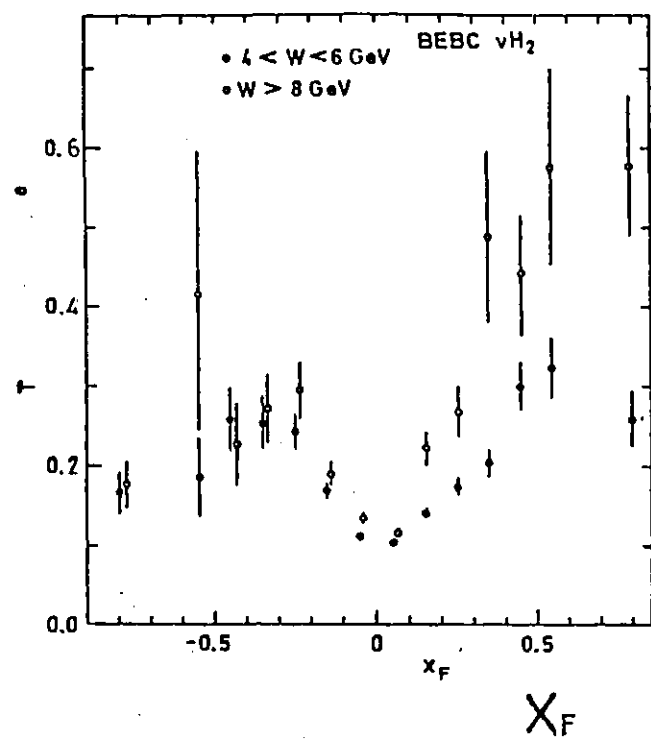
FIG(6.9)



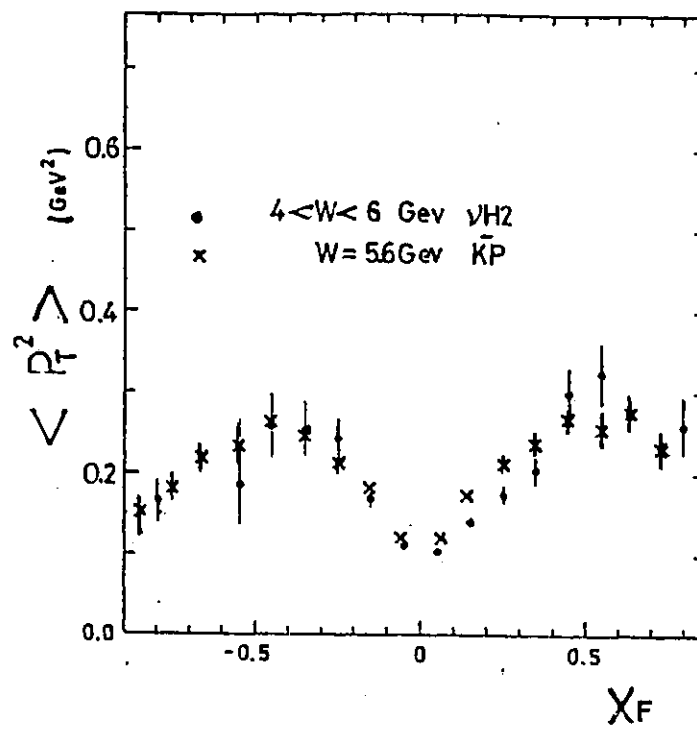
FIG(6.10)



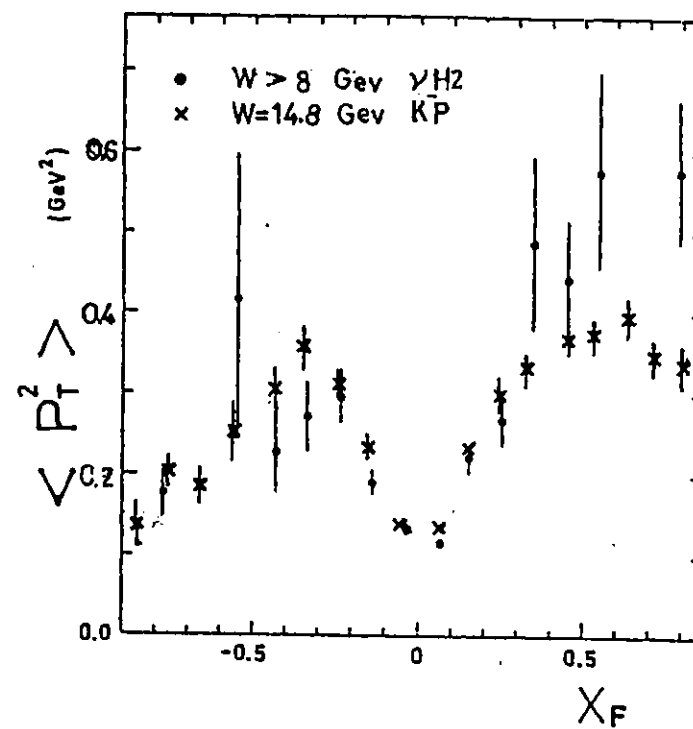
FIG(6.11)



a.



b.



c.

FIG(6.12)

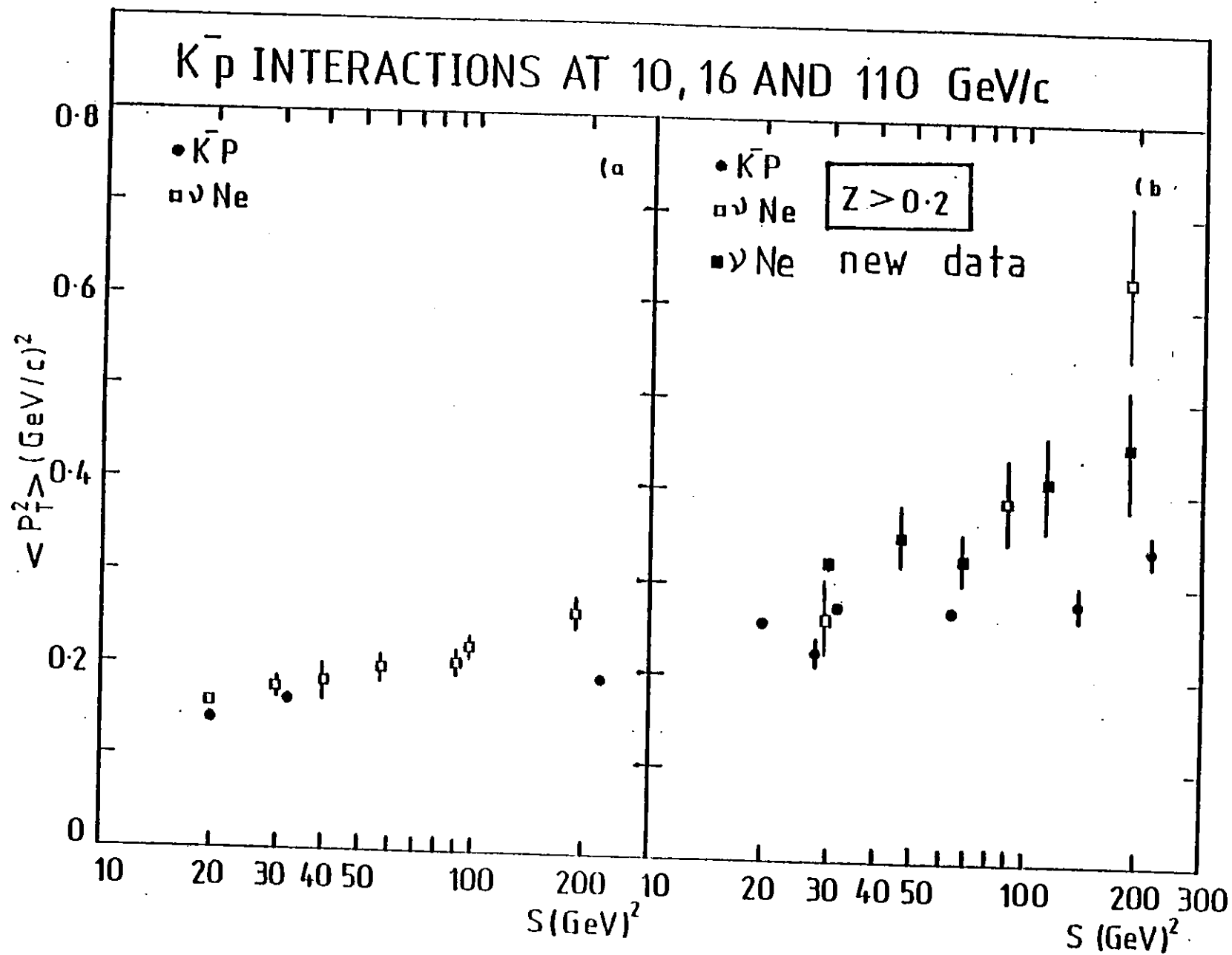
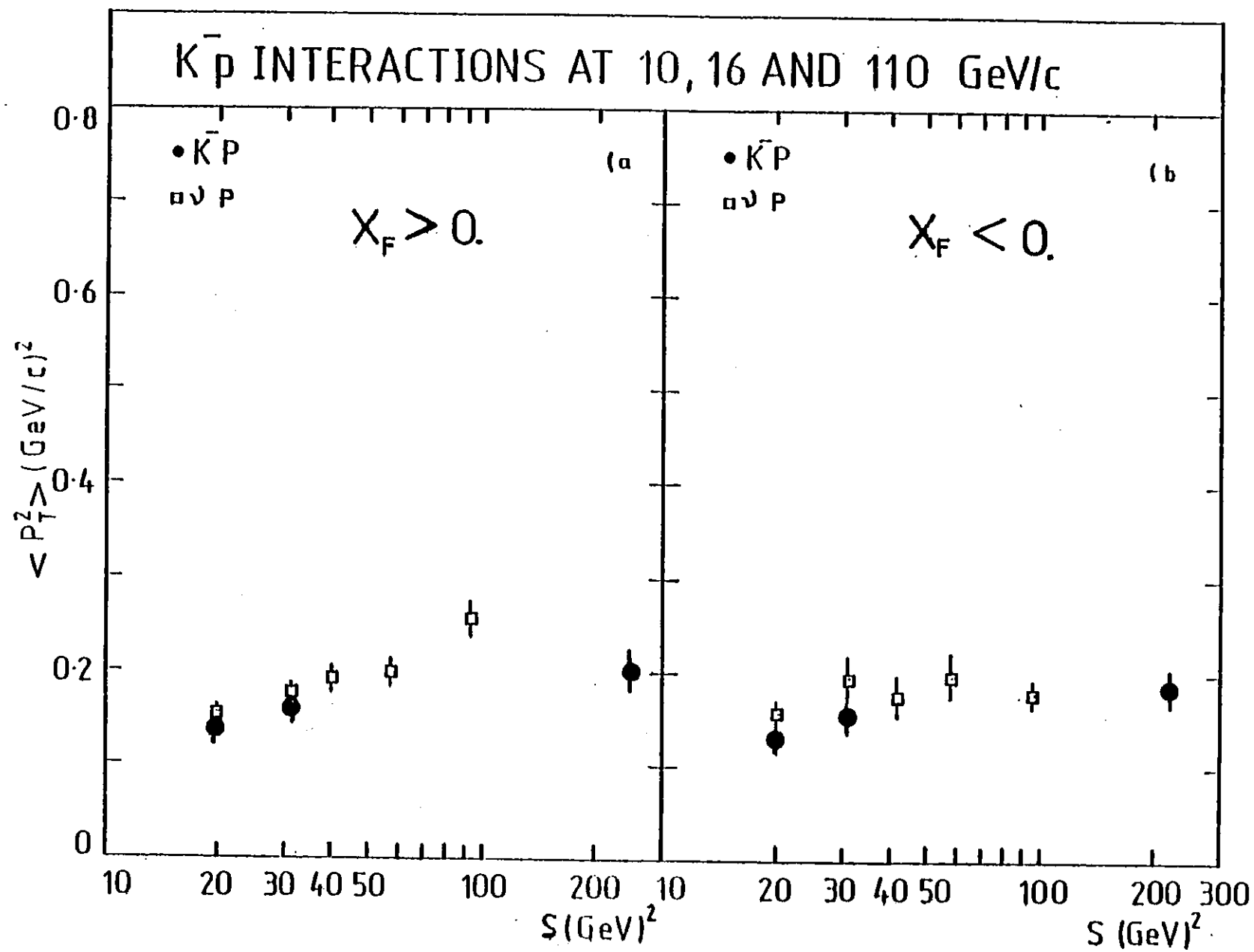
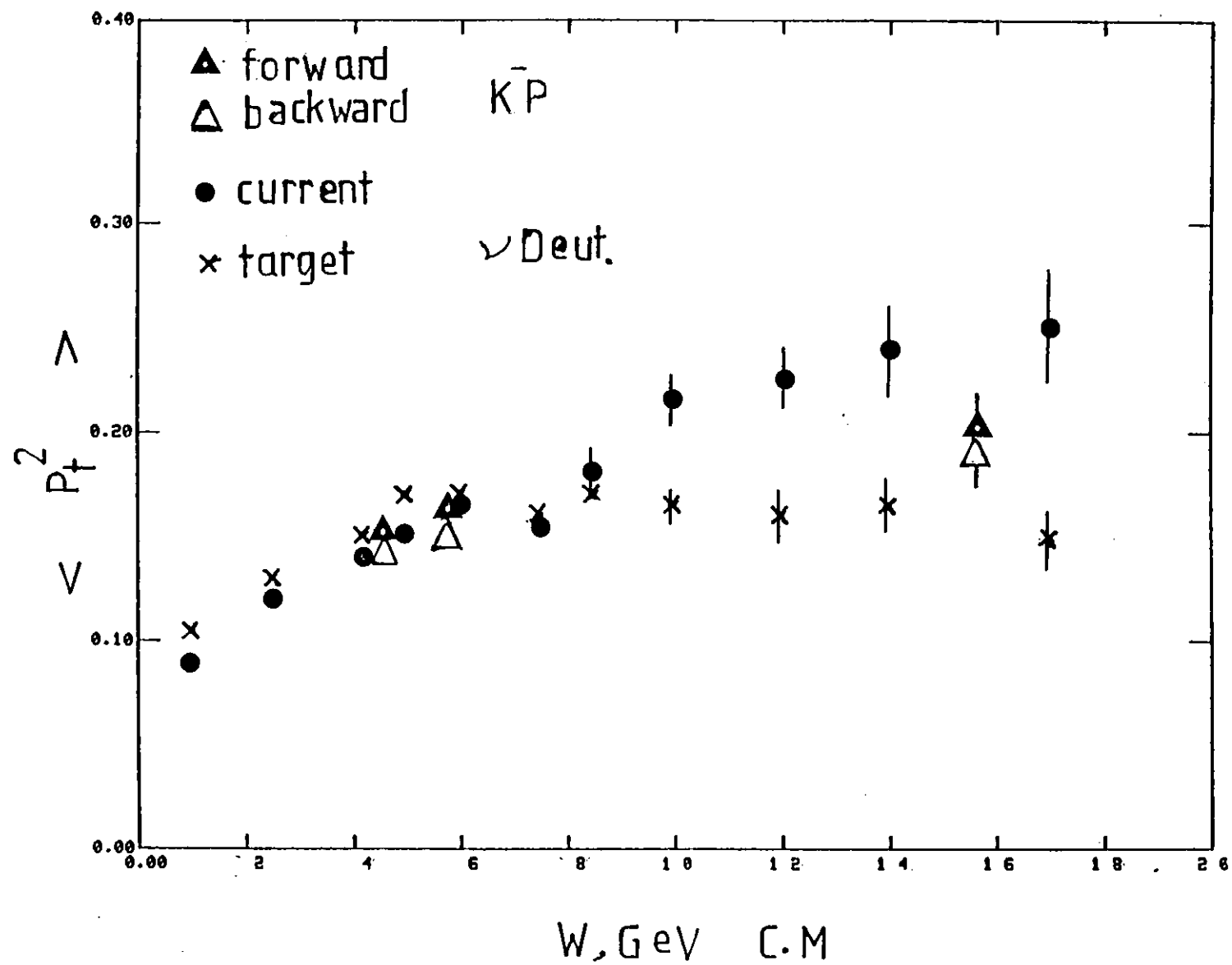


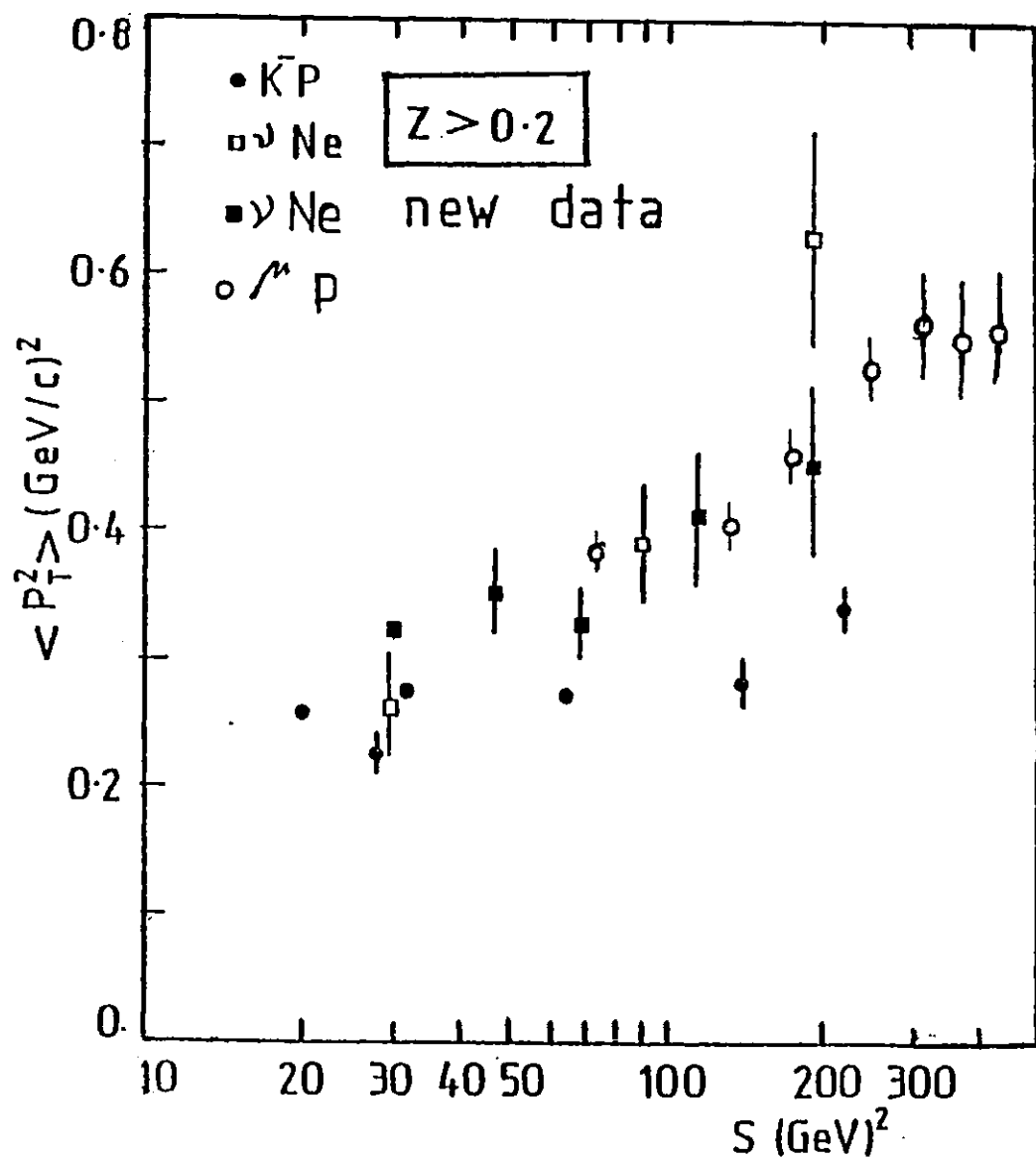
FIG (6.13)



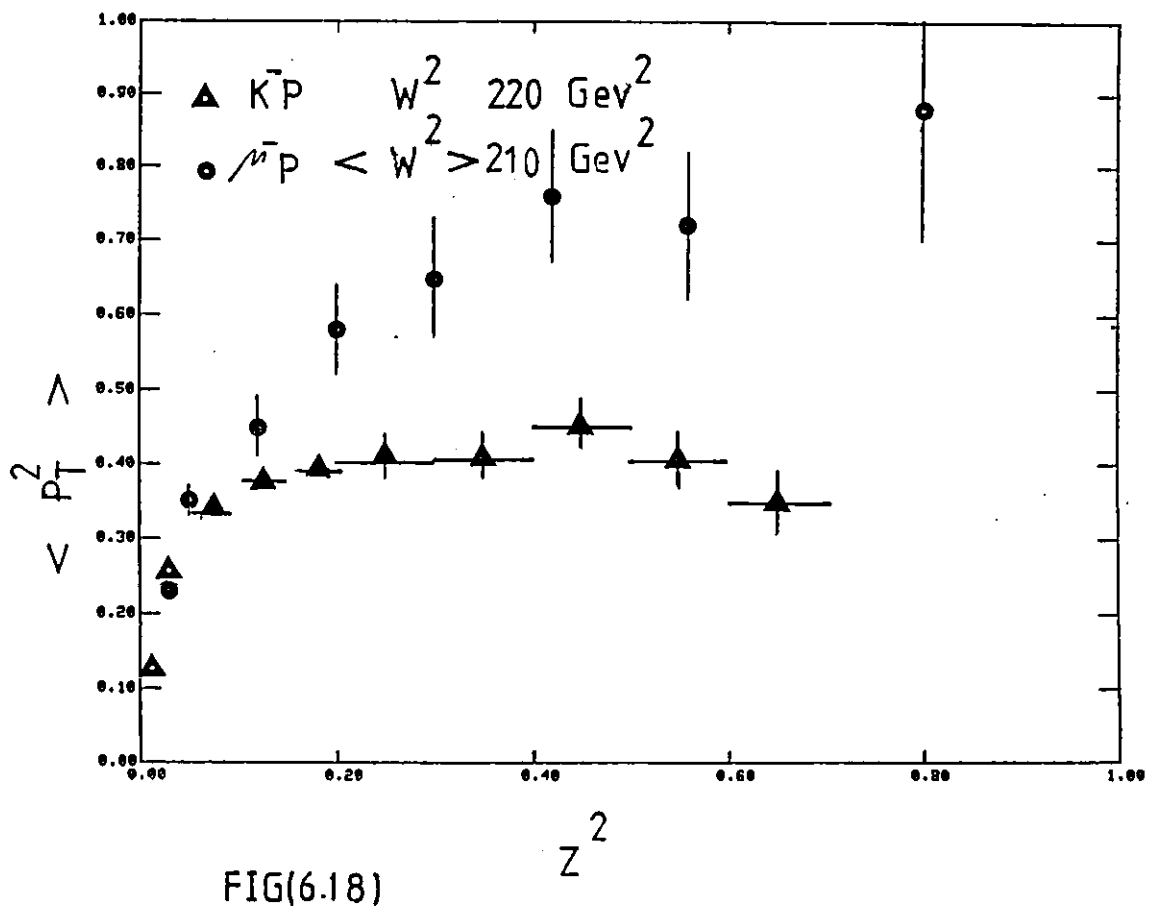
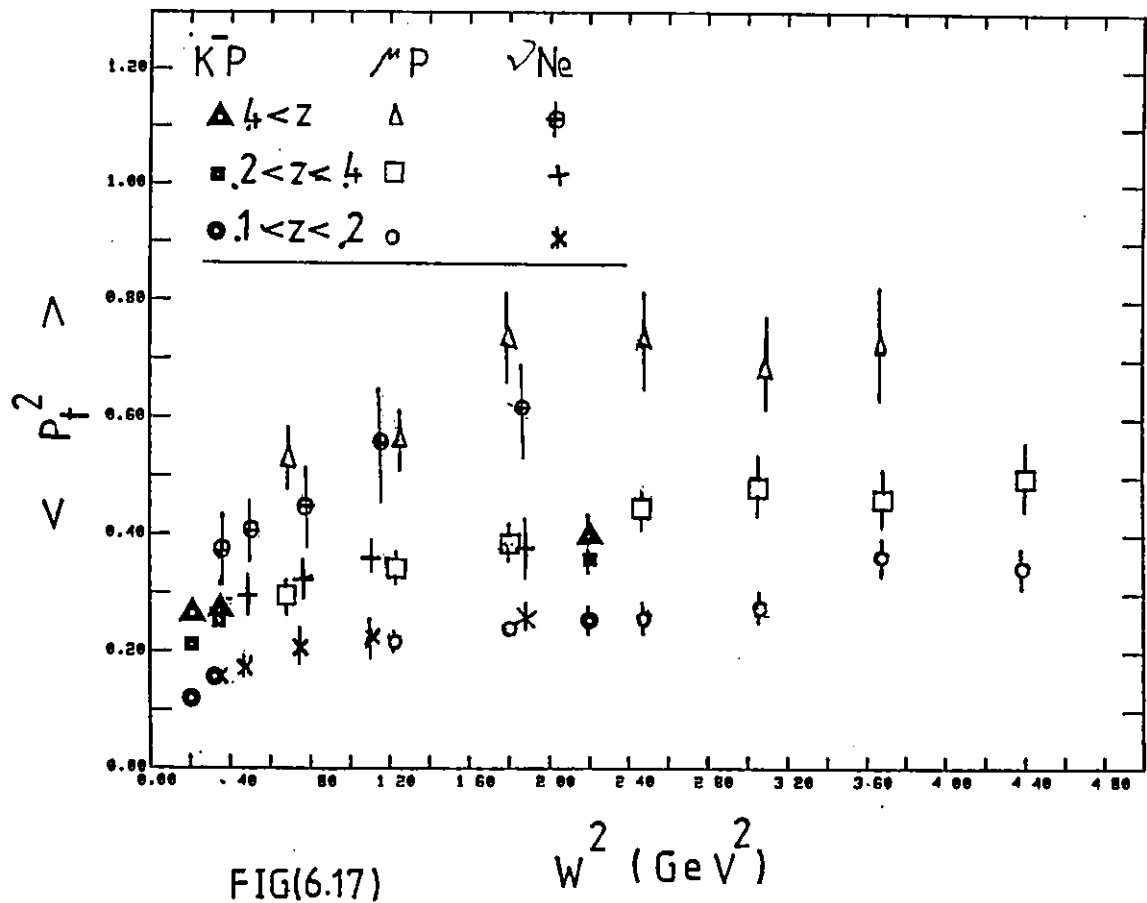
FIG(6.14)



FIG(6.15)



FIG(6.16)



CHAPTER SEVEN

RESONANCES

7.1 Introduction

In this chapter the results on inclusive $\bar{K}^*(890)^0$ and $\rho^0(770)$ production in K^-p interactions at 110 GeV/c beam momentum are presented. A technique to estimate their mutual reflections is described. A comparison is made with the beam fragmentation and central components of the $\bar{K}^{*0}$ and ρ^0 production in the lower kaon beam momenta as well as the results of various experiments with different beam particles and momenta. A study of resonance production at high energy collisions is a subject of interest for a number of reasons.

- 1) Studies of inclusive production often assume that all particles seen in the chamber are directly produced from the primary interaction. But a "contamination" of resonance decays would affect the single particle spectra. So one of the reasons for studying resonance production is that it is useful to know how many of the number of particles seen in the chamber (i.e. π , K, p) are directly produced, rather than as a decay of high mass resonances.
- 2) As has already been mentioned, it is not yet possible to calculate hadron production with QCD. One approach primarily to Field and Feynman ref(7.1) is to introduce fragmentation functions which attempt to describe the way a particular quark fragments into a certain type of final state particle. It is clearly important to try to determine fragmentation functions of quarks into resonances as well

as quarks into π , K, and protons.

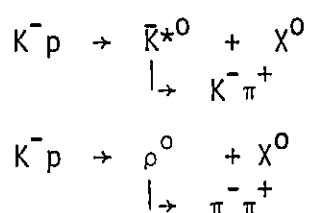
- 3) As there is much interest in direct lepton production at high energies, the substantial cross sections of some resonances (i.e. ρ^0 which has a branching ratio to $\ell^+ \ell^-$ of 0.011) will be responsible for a relatively large lepton background, despite small branching ratio.

Detailed studies of resonance production at the highest available energy on this beam particle are necessary for a better understanding of all these effects.

In general it is difficult to estimate cross section for resonance production, because at these high energies the two body phase space tends to peak at rather low masses; quite often the resonance lies near the background maximum.

In general we do not have π -K-p identification so, because of the high multiplicity of events the number of combinations on each event for finding the resonances is very high. This makes the signal to background ratio very small. Furthermore the reflections of the resonances give enhancements near the masses of other resonances. This causes a major problem on separating the pure resonance from the reflections and the background.

Our 110 GeV/c K^-p cross sections were obtained by investigation of the reactions



As it was mentioned earlier it is difficult to distinguish

between pion and kaon mass fits, though a small fraction of positive tracks has been identified as protons by checking the ionization or fitting.

So our analysis was performed by using the mass spectra containing all the possible combinations of one positive track (except identified protons) with one negative track where the positive tracks were assumed to be pions and the negative tracks were assumed to be pions or kaons according to the process under study. Hence any negative, positive invariant mass plot will contain the relevant resonances and "reflections"* from all other -ve, and +ve resonances.

7.2 The Data Presentation

A few cuts have been imposed on some of the tracks to improve our data. The tracks with a momentum error greater than 50%, which contain 1.5% of the total tracks, were removed from the data. The remaining tracks were weighted to compensate for this loss and loss of tracks through Geometry (1.3%). The positive tracks which were identified as protons were removed from the sample.

The events lost at the scanning stage do not affect the cross section results because we calculated the cross sections by making

* It should be noted that "reflection" does not have the usual meaning here. It refers to the effect of the misidentification of the mass of one of the two mesons that make up a resonance. e.g. the $\bar{K}^*890$ decays to $K^- \pi^+$ with narrow width, if the K^- is called a π^- the " $\pi^- \pi^+$ " effective mass shows an enhancement, known as the reflection of the $\bar{K}^*$ which is in the region of the ρ^0 mass.

a normalization to the total inelastic K^-p cross section at 110 GeV/c, ref (7.2).

7.3 $K^- \pi^+$ and $\pi^- \pi^+$ distributions

Fig (7.1) shows the $\pi^- \pi^+$ invariant mass for -ve, +ve combinations. Similarly fig (7.2) presents the $K^- \pi^+$ invariant mass distribution. In $K^- \pi^+$ distribution there is a broad bump seen at about the mass of the $\bar{K}^{*0}$ resonance. Also in the $\pi^- \pi^+$ distribution there is a broader bump within the range of the ρ^0 mass and width, but in both cases the resonances are not centred on the correct mass. This is due to their mutual reflections as well as the reflections from the other resonances whose masses lie in the vicinity of these resonances.

The bump in the $K^- \pi^+$ figure is identified with a mixture of the $\bar{K}^{*0}$ resonance together with "reflection" of ρ^0 plus the reflections from other resonances. Similarly the $\pi^- \pi^+$ bump contains a pure ρ^0 resonance together with the reflection of $\bar{K}^{*0}$ plus the reflections from other resonances.

7.4 Estimation of the reflection profiles

7.4.1 ρ^0 , $\bar{K}^{*0}$ and K^{*0} reflections

The shape of the reflection of the ρ^0 into the $K^- \pi^+$ channel was calculated by generating a pure ρ^0 sample, then recalculating its -ve, +ve invariant mass but reassigning the mass of the negative track as a kaon.

To explain this in more detail we define:

$$w_i = \frac{1}{\mu_i} \times B(m) \quad (7.1)$$

w_i is the weight for $\pi^- \pi^+$ combinations in i^{th} bin. μ_i is the number of entries in i^{th} bin in fig. (7.1)

B is the Breit Wigner resonance shape

$$B(m) = \frac{(\frac{\Gamma^0}{2})^2}{(m-m_0)^2 + (\frac{\Gamma^0}{2})^2} \quad (7.2)$$

where Γ^0 and m_0 are the width and mass of ρ^0 resonance taken from PDG tables* (ref 7.2). The width Γ^0 has been increased to take into account the experimental resolution. The pure ρ^0 sample was obtained by weighting these $\pi^- \pi^+$ combinations with w_i to give a ρ^0 signal.

The same -ve, +ve combinations were then assigned K, π masses respectively and replotted using the weight calculated above. The result is shown in figure (7.3a). It is clear from the figure that the distribution is not symmetric, and it is not smooth curve either, as it is produced from the experimental data. Also only the shape of this distribution is important, so, the ordinate can have arbitrary units.

Fig (7.3b) shows the reflection of $\bar{K}^{*0}$ into the $\pi^- \pi^+$ channel. It was calculated in a similar manner to that performed for the ρ^0 reflection. The reflection of K^{*0} into $\pi^- \pi^+$ channel has essentially the same shape as the $\bar{K}^{*0}$ reflection, while the reflection of $\bar{K}^{*0}/K^{*0}$ into $K^+ \pi^-/K^- \pi^+$ masses is smooth.

*We have also checked the relativistic Briet-Wigner formula plus mass dependent width, (ref 7.3). The results were similar within the errors, so, we preferred using the simpler formula

It should be noted that this method assumes background dimeson systems with the same mass as the resonance have similar production and decay propoerties to the resonance. A Monte-Carlo method has been used to calculate these reflections for a K^- beam momentum at 70 GeV/c. This method requires some assumptions about the resonances, P_T , Feynman x distribution and the spin density matrix, and so was not used here. Figures (7.4a) and (7.4b) show their results for the reflection of ρ^0 into the $K^- \pi^+$ channel and the reflection of $\bar{K}^{*0}$ into $\pi^- \pi^+$ channel respectively (ref 7.9). Despite the fact that the two methods are completely different, the shape of the distributions is very similar. This suggests that both techniques are acceptable.

7.4.2 ω and ϕ reflections

It is not possible to detect the ω resonance in our experiment because our statistics are not high enough to make $\pi^- \pi^+ \pi^0$ distribution. Instead a Monte-Carlo technique has been used to calculate the ω reflection. Fig (7.5a) shows the $\pi^- \pi^+$ invariant mass distribution of pions which are produced by the decay of ω ; the decay is assumed to be $j^P = 1^-$ and the ω to have a fixed mass and zero width. The ω reflection into the $K^- \pi^+$ channel was calculated in a similar manner to the calculation of the ρ^0 into the $K^- \pi^+$ channel except that instead of using the weight (equation 7.1) for figure (7.1) to reproduce a pure ρ^0 , this weight was used to reproduce fig (7.5a). Fig (7.5b) is the shape of ω reflection into the $K^- \pi^+$ channel.

Fig (7.6a) and fig (7.6b) show the reflection of ϕ into the $\pi^- \pi^+$ and $K^- \pi^+$ channels respectively. These reflections were produced in analogous manner to the mutual reflections of ρ^0 and $\bar{K}^{*0}$ into each other, i.e. by weighting the $K^- K^+$ invariant mass plot to reproduce a pure ϕ .

7.5 Results obtained by fitting the $K^-\pi^+$ and $\pi^-\pi^+$

Initially figures (7.1) and (7.2) were each separately fitted with an expression

$$a(M^b + cM^{-c} \exp(cM)) \exp(-dm - em^2) + fB(m) + gR \quad (7.3)$$

where $M = m - m_0$

$a \rightarrow g$ are free parameters

m is the $K^-\pi^+$ or $\pi^-\pi^+$ invariant mass

m_0 is the relevant threshold mass

The expression $B(m)$ is the Breit-Wigner form, equation (7.2), and the expression R is the number of events in the m mass bin of fig (7.1) and fig (7.2) respectively. The fits were performed by using the minimum χ^2 technique (using 20MeV mass bins).

The first expression in equation 7.3 represents the shape of background which, accounts for a sharp rise at threshold and an exponential fall off behaviour at high masses. This was fitted first to a $\pi^+\pi^+$, fig (7.7a) and a $K^+\pi^+$ (fig 7.7b) invariant mass distributions where no resonances are expected. The value found for the χ^2 per degree of freedom ($\frac{\chi^2}{PDF}$) is close to 1.0 for each fit so that we believe it justifies our assumption for using the shape of background in equation (7.3).

Next we used the full expression in equation (7.3) including resonance and reflection terms, and performed the fitting to the $\pi^-\pi^+$ and $K^-\pi^+$ distributions separately. Fig (7.8) and fig (7.9) show the results of these fits to the $\pi^-\pi^+$ and $K^-\pi^+$ channels respectively.

The values of reflections and resonances are normalized in such

a way that the area under each curve represents the corresponding value of the cross section. For an ideal fit we expect the amount of ρ^0 reflection into $K^-\pi^+$ channel to be equal to the amount of pure ρ^0 resonance in $\pi^-\pi^+$ channel. In a similar manner we expect the amount of $\bar{K}^{*0}$ reflection in $\pi^-\pi^+$ channel to be equal to the amount of pure $\bar{K}^{*0}$ resonance in $K^-\pi^+$ channel. As the figures show the ρ^0 inclusive cross section in both is similar although the $\bar{K}^{*0}$ values differed by a factor 2. Nevertheless the results are compatible because the parameter g has large errors i.e. the reflection signals are very wide compared with the resonance signals and so will give acceptable fits for a larger range of values for the parameter g than the parameter f . At this stage the ω , ϕ and K^{*0} reflections were not used because they also are wide.

As the separate fits had given results compatible with errors it was decided to constrain the fits further by imposing a simultaneous fit on the combined data. The 14 free parameters were reduced to 12 by removing the parameters $f_{\bar{K}^{*0}}$, $g_{\bar{K}^{*0}}$, f_{ρ^0} , g_{ρ^0} and replacing them by a parameter specifying the number of $\bar{K}^{*0}$ s in each histogram and a second parameter to specify the number of ρ^0 .

In this way the size of the $\bar{K}^{*0}$ in the $K^-\pi^+$ histogram is forced to be equal to the $\bar{K}^{*0}$ reflection in the $\pi^-\pi^+$ histogram. The amount of K^{*0} reflection was then introduced as a thirteenth parameter. The remaining 10 parameters ($a_{\bar{K}^{*0}} \rightarrow e_{\bar{K}^{*0}}$, $a_{\rho^0} \rightarrow e_{\rho^0}$) were not changed.

The results are presented in the first column of table 7.1. The ω reflection was then introduced with a fourteenth parameter ($=$ number of ω 's). There are theoretical reasons for suggesting that the ρ^0 and ω cross sections are the same (ref 7.2.4). So two more fits were tried once with the number of ω s equal to the number of ρ^0 s (decay branching ratio having been taken into account) and once with 14 independent variables. These results complete table (7.1). These fits all give

similar values for $\bar{K}^{*0}$ and ρ^0 inclusive cross sections despite the different values for the amount of ω . We introduced a fifteenth parameter for the ϕ for any of the above fits but it didn't significantly affect the results. In every case the ϕ cross section was compatible with zero and the values of ρ^0 and $\bar{K}^{*0}$ cross sections were compatible with those presented in table (7.1).

Figures (7.10), (7.11) and (7.12) show the fitted distributions for the case of no ω , $\sigma_\omega = \sigma_\rho$ and the ω as a free parameter respectively.

We also found the cross section for K^{*0} , where we made a simultaneous fit of $K^+\pi^-$ and $\pi^-\pi^+$ channels, by taking into account all other reflections; fig (7.13). Table (7.2) presents our best estimates for all the cross sections evaluated here plus the charged meson resonances taken from ref (7.9b).

It should be noticed that the amount of $\bar{K}^{*0}$ reflection in the simultaneous fitting of $K^+\pi^-$ and $\pi^+\pi^-$ channels gives a larger cross section than the actual value of $\bar{K}^{*0}$ cross section given on table 7.2. As was mentioned earlier this is due to the fact that the reflection signals are very wide compared with the resonance signals and so will give acceptable fits for a wider range of values, when the resonant contribution is not fitted directly. This is also the case for the amount of K^{*0} reflection into the simultaneous fitting of $K^-\pi^+$ and $\pi^-\pi^+$ channels.

To extend our studies on these resonances, we have calculated the cross section for each Feynman x region ($x_F = \frac{2P_L}{S}$, where P_L is the longitudinal momentum of each pair of combinations in CM system and S is the total centre of mass energy). Due to limited statistics we divided the $\pi^-\pi^+$ and $K^-\pi^+$ Feynman x distributions into just seven regions, and for every region we repeated the whole analysis described earlier. The results are shown in table (7.3).

We believe that our method of finding the total cross section for the ρ^0 and $\bar{K}^{*0}$ is valid for a number of reasons:

- 1) The χ^2 per degree of freedom for each fit and within the vicinity of resonances is close to 1.0.
- 2) We have used different forms of background employing different numbers of parameters. In each case we performed simultaneous fits to $\pi^-\pi^+$ and $K^-\pi^+$ distributions, to calculate the ρ^0 and $\bar{K}^{*0}$ cross sections. The results in all cases agreed within the errors with the results obtained using the parameterization in equation (7.3). These tests of different backgrounds were made with and without ω and ϕ reflections. The amount of ρ^0 and $\bar{K}^{*0}$ agreed with errors for the different backgrounds..
- 3) Using the shape of background on the $\pi^+\pi^+$ or $K^+\pi^+$ distributions give a reasonable χ^2 per degree of freedom, thus, confirming that the form of our background for the fitting is correct. Furthermore on fitting the whole of equation 7.3 to these like-charge particles we obtain negligible cross sections for the " ρ^{++} ", " ρ^{--} ", " K^{*++} " and " K^{*-} " pseudo resonances.
- 4) The sum of the cross sections calculated from each Feynman x regions is consistent with the total cross section calculated from the whole Feynman x range. This is true for both the $\bar{K}^{*0}$ and the ρ^0 cross sections (table 7.3).

7.6 Comparison with results obtained at lower K^-p centre of mass energies

Figs (7.14a, b, c) compare our $\bar{K}^{*0}$, ρ^0 and K^{*-} inclusive cross sections with the values obtained from the other experiments at lower

beam momenta (ref 7.5-9, 7.11). The K^{*-} inclusive cross section at 110 GeV/c has been taken from ref (7.9b). The $\bar{K}^{*0}$ cross section is higher at 110 GeV/c than in the 10-32 GeV/c range. The K^{*-} data also indicate that there is a slight increase of cross section with increasing CM energy. The cross section for ρ^0 production also appears to have a similar trend to that of the other resonances. We conclude that our results are consistent with the trends set by the lower energy data.

We also compare our Feynman x distributions with the distributions of these resonances from the lower energies. Fig (7.15) shows the ρ^0 distribution obtained in 110 GeV. Plotted on this figure is the distribution from 10-16 GeV data (ref. 7.11). Fig (7.16) shows the $\bar{K}^{*0}$ Feynman x distribution obtained in 110 GeV/c together with those from 16 GeV (ref 7.6) and 32 GeV (ref 7.8) K^-p interactions. The weight used in fig (7.15) specifies the ρ^0 density;

$$g(x) = \frac{1}{\sigma_{inel}} \frac{d\sigma}{dx} \quad (7.4)$$

The weight used in fig (7.16) is

$$f(x) = \frac{1}{\pi P_{max}} \int E^* \frac{d^2\sigma}{dx dP_T^2} dP_T^2 \quad (7.5)$$

where $P_{max} = \frac{\sqrt{s}}{2}$ and s is total centre of mass energy. E^* is the average centre of mass energy of each pair of combinations in the range of ρ^0 and $\bar{K}^{*0}$ width and mass. We assume that the background events within the range of resonance width and mass have a similar behaviour to the resonances themselves. The reasons for using different weights in two plots is essentially to facilitate our comparison with the lower energies where the published data were presented in these forms.

Table (7.4) shows the invariant $\bar{K}^{*0}$ cross sections (using definition

7.5) as well as the $\bar{K}^{*0}$ density for each region of Feynman x . Table (7.5) shows a similar table for the ρ^0 for each region of Feynman x .

On fig (7.15) the ρ^0 Feynman x distribution has the same shape at 110 GeV as that at 16 GeV in the forward and backward regions. The data do not show forward or backward peaks. In the central region both distributions contain a symmetric peak around $x_F = 0$, but the 110 GeV results are significantly higher than those at 16 GeV data in this region. We conclude that the shape of distributions for the ρ^0 varies with beam momenta. This also indicates that the total increase of ρ^0 production in 110 GeV K^-p data is due to the rise in the central region.

On the other hand the $\bar{K}^{*0}$ invariant Feynman x distribution shown on fig (7.16), for 32 and 110 GeV are similar within the large errors. The distribution for 16 GeV in the lower Feynman x region is practically the same as 32 and 110 GeV. The strong forward peak which appears at $x_F \geq 0.8$ at 10-16 GeV is probably mainly due to the two body channels as they decrease rapidly in cross section with increasing beam momenta. For completeness we show in fig (7.17) the K^{*-} invariant Feynman x distributions. The noticeable forward peak at 10-16 GeV is again probably due to quasi two body reactions which contribute mostly to the high x_F regions.

But this contribution for $\bar{K}^{*0}$ at 16 GeV shows a different shape and a higher cross section when compared with that for K^{*-} . The latter peaks only in the most forward x_F bin where the main contribution is probably the $K^-p \rightarrow K^{*-}p$ reaction. In the rest of forward region the quasi-two-body channels producing $\bar{K}^{*0}$ have a larger cross section than for the K^{*-} production at low energies. One example of this is the production of the Q meson in the $K\pi\pi$ system (ref 7.31) which has a branching ratio of 2:1 for decaying into $\bar{K}^{*0}$ and K^{*-} respectively.

Figs (7.18) show the fitted distributions for $\bar{K}^{*0}$ and ρ^0 in

different Feynman x regions.

7.7 Separation of $\sigma_{\text{inclusive}}$ into central and beam fragmentation components and comparison with results from other reactions

7.7.1 Determination of central and beam fragmentation cross sections

In order to separate the inclusive cross sections for $\bar{K}^{*0}$ and ρ^0 into central and beam fragmentation regions we have used a method which is proposed in ref (7.30). This method assumes that target fragmentation region for $K^-p \rightarrow \bar{K}^{*0}$ and $K^-p \rightarrow \rho^0$ inclusive has zero cross sections. There are a number of reasons to believe that this is a reasonable assumption:-

- 1) On fig (7.16) the target fragmentation region may be approximated by the region of $x_F < -0.3$. The figure indicates that the cross section in this region for all beam momenta is very small.
- 2) Fig (7.19) shows $\sigma_{\text{inclusive}}$ for reactions

$$pp \rightarrow K^{*+} + X \quad (7.6a)$$

$$pp \rightarrow K^{*-} + X \quad (7.6b)$$

One would expect the central production to have the same cross section in reactions (7.6a) and (7.6b), as well as equal amounts of forward and backward cross sections. Similarly we expect the amount of fragmentation for reaction 7.6b to be very small. Therefore the difference between the total cross sections of these two reactions is a measure of fragmentation components for reaction (7.6a) being $\sim 0.4\text{mb}$. This implies that the target fragmentation for reaction (7.6a) is less than 0.2mb .

3. In all pp and $\bar{p}p$ data (e.g. ref 7.24, 26) the Feynman x for inclusive

ρ^0 production shows a narrow central peak, with a very small fraction for $|x_F| > 0.5$. So we conclude that for all ρ^0 and K^* contributions the target fragmentation cross sections are very small i.e. $\lesssim 0.5\text{mb}$ and their omission will not cause a major contradiction to this assumption.

The central component (σ_c) in this method is defined to be symmetric around $x_F = 0$, and the whole of fragmentation component (σ_b) is defined to be confined to the $x_F > 0$ region. Thus one obtains.

$$\sigma_c = 2 \times \sigma_{x_F < 0} \quad (7.7a)$$

$$\begin{aligned} \sigma_b &= \sigma_{x_F > 0} - \sigma_{x_F < 0} \\ &= \sigma_{\text{total}} - \sigma_c \end{aligned} \quad (7.7b)$$

Table (7.6) shows the values of ρ^0 and $\bar{K}^{*0}$ plus K^{*0} cross sections in our experiment by fitting our data in the corresponding Feynman x regions. This table also gives σ_c and σ_b values extracted from these results using equations (7.7a) and (7.7b).

7.7.2 Comparison with other kaon data

The simple definitions σ_c (7.7a) and, σ_b (7.7b) have the advantage that they can be used for any kind of reaction whose target fragmentation is negligible and the minimum information of the forward and backward cross sections are given. Figs (7.20a, b, c) show the P_{lab} distribution for central and forward components from our experiment and from the all available published data for ρ^0 , $\bar{K}^{*0}$ and K^{*-} respectively. The errors in the total cross sections are as given in the published data. We did not attempt to estimate the errors on σ_b and σ_c as these cannot be calculated accurately from the published Feynman x distributions. However, the errors

are estimated to be not more than about ± 0.5 to ± 1.0 mb (except for the beam momenta greater than 100 GeV when the errors could be as high as ± 2.0 mb). Where these figures contain data from 32 GeV for $K^+p \rightarrow \rho^0, K^{*0}, K^{*+}$ inclusive the K^+ and K^- data are compatible.

The most noticeable result extracted from these figures is that the beam fragmentation components in all data are rather constant and independent of beam momenta; ~ 1 mb for ρ^0 , ~ 2.5 mb for $\bar{K}^{*0}$ and ~ 3 mb for K^{*-} . These figures also indicate that the central production shows an increase with P_{lab} in all these reactions. The rise in the total cross sections seen above ~ 30 GeV/c is compatible with being due entirely to the rise in the central production for all these resonances.

It should be noticed that in fig (7.16) we observed that the shape of the beam fragmentation component for $K^-p \rightarrow \bar{K}^{*0}$ varies with P_{beam} , although from fig (7.20b):

$$\sigma_b = \int_{x_F > 0} \frac{d\sigma_b}{dx_F} dx_F \quad (7.8)$$

remains constant. This is due to quasi two body cross sections which contribute the most to the high x_F region; this contribution to the inclusive cross section decreases rapidly with increasing beam momentum. However, this effect does not change the basic interpretation of our results, the beam fragmentation component is independent of beam momenta.

To clarify further the situation, we show in figure 7.21a($\bar{K}^{*0}$) and figure 7.21b(K^{*-}) the distribution of $\frac{d\sigma}{dx}$ (non invariant) for 16 and 110 GeV data. The value of σ in 16 GeV is calculated from the published invariant distribution by estimating the mean value of E^* for each Feynman x bin, (we have chosen an approximate value of 0.35 GeV for the amount of transverse momentum in each Feynman x bin, but this effect is negligible compared with the resonance mass and its longitudinal momentum).

In contrast to the invariant distributions in fig (7.16) and fig (7.17)

the area under the curves in fig (7.21) represents an absolute measure of the total resonance cross section. Again taking $x_F \gtrsim 0.3$ as an estimate for σ_b , we see from fig (7.21) that although at 110 GeV the quasi two body cross section has fallen at high Feynman x region, the area under the curve for $x_F \gtrsim 0.3$ is approximately equal to the corresponding value at 16 GeV. This behaviour is clearer in fig (7.21a) and within the large statistical errors it is also clear in fig (7.21b).

7.7.3 Comparison with other beam particles

There is unfortunately no data available on K^{*0} production in p, $\bar{p}$, π^+ nor π^- proton experiments. There is however, some data available on inclusive ρ^0 production on these experiments over a range of energy up to 400 GeV/c (ref. 7.21, 29). The beam fragmentation and central component of $\pi^+p \rightarrow \rho^0$ (ref 7.12-20) inclusive cross sections were calculated in the same manner as explained earlier (e.g. $\sigma_b = \sigma_{x_F>0} - \sigma_{x_F<0}$ for all available data). Fig (7.22) shows the values. Despite the fact that the total cross section rises with increasing energy, we observe that the beam fragmentation component is again independent of the beam momenta. This component is about 2.4mb, a very similar value to the forward $\bar{K}^{*0}$ production in K^- interactions. Also the increase in total cross section appears to be entirely due to a rise to the central production. Furthermore, in the comparable energies, this central component for a π^+ beam has almost the same magnitude and rise to that for a K^- beam in this region (see figure 7.20a).

The formulae (7.7a) and (7.7b) are not applicable in the inclusive reactions $pp \rightarrow \rho^0 x$ and $\bar{p}p \rightarrow \rho^0 x$ because of the beam target symmetry. However, the x_F distributions in all these reactions peak at about $x_F \approx 0$ and contain a negligible cross section for the region $|x_F| > 0.7$. So we conclude that the ρ^0 production in pp and $\bar{p}p$ reactions are produced

strongly in the central region with a constant cross section in the fragmentation regions which is compatible with zero. This latter result is consistent with the assumption of negligible backward ρ^0 production in Kp and πp interactions. Table 7.7a summarizes the inclusive production of beam fragmentation component for different beam types together with the results of 110 GeV K^-p data. We will use this table in the next section when we test some predictions of a quark model.

7.7.4 Comparison with quark models

In this section we compare our results with some predictions of the quark models. These are mainly the quark model of ref (7.30) and the quark model of Anisovich and Shekhter (ref 7.4). The first model predicts the absolute cross section of different resonances for different beam particles in the central and beam fragmentation regions, while the second model predicts the relative probability of resonance production for different beam particles and momenta in these regions. In addition the ratio of vector to pseudo-scalar meson production in the former case is 1:1 (observed ratio), whereas this ratio in the latter one is 3:1 (theoretical ratio). The parameterization in these two models is also slightly different. The parameter which characterizes the suppression of strange quark production (λ) is ~ 0.25 for the former and ~ 0.33 for the latter. Admittedly this is due to the recent utilization of higher energy data which is claimed by ref (7.30) to give a more accurate value for this parameter.

The quark model of ref (7.30) predicts for a $K^-(K^+)$ beam a production value of 1.1 mb for ρ^0 , 2.2 mb for $\bar{K}^{*0}(K^{*0})$ and 2.8 mb for $K^{*-}(K^{*+})$ in the beam fragmentation region for all beam momenta. This model also yields for a $\pi^\pm$ beam a production of 2.2mb for the ρ^0 in the beam fragmentation region again for all beam momenta. These results are

justified by the values shown on table 7.7a. The table also shows that within statistical errors our K^-p results at 110 GeV are compatible with this model. This model also predicts cross sections for the central region. These vary with the centre of mass energies, but at high energies do not depend on the beam and target particle types. Fig (7.23) reproduces fig 4 from ref (7.30b), and summarises the predicted central components. As we have a strange beam, the addition of on average 0.5 strange quarks to the central region is claimed (ref 7.30) to enhance about 2.5 mb in each case to the central $\bar{K}^{*0}$ and K^{*-} production. Also the K^{*+} and K^{*0} do not share a common quark with the beam K^- , hence their production is expected to be purely central. Table 7.7b compares our results in 110 GeV with the predicted values obtained from fig (7.23). The table shows that, within one or two standard deviations our results are consistent with the predicted values.

Table 7.8 gives the comparison of the vector meson production rates in our experiment with the quark model of Anisovich and Shekhter (ref 7.4). Again we see that within one or two standard deviations our results are compatible with the predicted values.

7.8 Conclusion

We have determined the inclusive cross sections for $\bar{K}^{*0}$ and ρ^0 production in K^-p interactions at 110 GeV/c as 5.6 ± 0.8 and 4.6 ± 0.8 respectively. These were obtained by simultaneously fitting the $K^-\pi^+$ and $\pi^-\pi^+$ invariant mass distributions by taking into account their mutual reflections and the reflections from some other resonances. The $\bar{K}^{*0}$ and ρ^0 inclusive cross sections follow the trend set by K^- data obtained at lower energies; both are rising with beam momenta. The K^{*-} cross section at 110 GeV taken from ref (7.9b) shows a similar behaviour to these resonances.

Their Feynman x distributions are also presented and compared with the corresponding distributions in the lower kaon energy data. We found that the non invariant ρ^0 Feynman x distribution shows a symmetric centrally produced signal which is larger at 110 GeV than at 16 GeV. The invariant $\bar{K}^{*0}(K^{*-})$ Feynman x distribution has a similar shape to that at 32 GeV; but it does not show the strong forward peak seen in 16 GeV data.

We have used a method to separate the inclusive ρ^0 and $\bar{K}^{*0}(K^{*-})$ cross sections into central and beam fragmentation components, and have investigated how both components vary with beam type and momentum. The central components rise rapidly with P_{beam} ; however the beam fragmentation components are found to be independent of the beam momentum. The total increase of cross section above 30 GeV was found to be due entirely to the rise in central region. Our results are also consistent with the predictions of the Anisovich and Shekhter Quark model and the Quark model of ref (7.30)

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TABLE 7.1

COMBINED FIT RESULTS

Parameters	no ω	$\sigma_{\omega} = \sigma_{\rho^0}$	σ_{ω} free parameter
No. of $\bar{K}_S^{*0} \rightarrow K^- \pi^+$	2617 ± 381	2588 ± 335	2708 ± 387
No. of $\rho_S^0 \rightarrow \pi^- \pi^+$	1711 ± 642	2745 ± 578	3332 ± 579
No. of $\omega_S \rightarrow \pi^- \pi^+ \pi^0$	0	2471 ± 455	8200 ± 5000
b_{K^*}	0.712	0.721	0.764
c_{K^*}	0.013	0.013	0.013
d_{K^*}	4.569	4.523	4.447
e_{K^*}	-1.040	-1.021	-0.969
b_{ρ}	0.745	0.802	0.838
c_{ρ}	0.027	0.031	0.037
d_{ρ}	3.970	4.024	3.772
e_{ρ}	-0.690	-0.698	-0.579
χ^2 per degree of freedom	1.381	1.270	1.136
$\bar{K}^{*0}$ σ inclusive	5.5 ± 0.8	5.4 ± 0.7	5.6 ± 0.8
ρ^0 σ inclusive	2.4 ± 0.9	3.8 ± 0.8	4.6 ± 0.8

TABLE 7.2

Resonance	Total Cross sections (mb)
$\bar{K}^{*0}(890)$	5.6 ± 0.8
$K^{*0}(890)$	1.4 ± 0.6
$K^{*-}(890)$	$4.7 \pm 0.5^*$
$K^{*+}(890)$	$2.2 \pm 0.6^*$
$\rho^0(770)$	4.6 ± 0.8

* From Ref (7.9b)

TABLE 7.3

FEYNMAN x RESULTS OF THE INCLUSIVE CROSS SECTIONS

	$\sigma_{K^{*0}} \text{ mb}$	$\sigma_{\rho^0} \text{ mb}$
$x_F < -0.4$	0.05 ± 0.1	0.38 ± 0.03
$-0.4 \leq x_F < 0$	1.41 ± 0.42	1.86 ± 0.45
$0 \leq x_F < 0.2$	1.38 ± 0.19	1.10 ± 0.43
$0.2 \leq x_F < 0.4$	0.89 ± 0.20	0.99 ± 0.22
$0.4 \leq x_F < 0.6$	0.92 ± 0.12	0.36 ± 0.09
$0.6 \leq x_F < 0.8$	0.56 ± 0.07	0.01 ± 0.05
$0.8 \leq x_F$	0.20 ± 0.05	0.17 ± 0.04
sum of the above	5.41 ± 0.53	4.87 ± 0.67
inclusive (overall range)	5.65 ± 0.80	4.65 ± 0.8

TABLE 7.4

TABLE $\bar{K}^{*0}$ INVARIANT CROSS SECTION ($f(x)$) AS WELL AS THE
 $\bar{K}^{*0}$ DENSITY ($g(x)$) USING DEFINITIONS 7.4 AND 7.5

x range	$f(x)$	$g(x)$
$-1.0 \leq x_F < -0.4$	0.02 ± 0.03	0.005 ± 0.01
$-0.4 \leq x_F < 0$	0.24 ± 0.07	0.19 ± 0.06
$0 \leq x_F < 0.2$	0.38 ± 0.05	0.37 ± 0.05
$0.2 \leq x_F < 0.4$	0.45 ± 0.10	0.24 ± 0.06
$0.4 \leq x_F < 0.6$	0.75 ± 0.10	0.25 ± 0.03
$0.6 \leq x_F < 0.8$	0.63 ± 0.08	0.15 ± 0.02
$0.8 \leq x_F$	0.28 ± 0.07	0.05 ± 0.01

TABLE 7.5

THE ρ^0 INVARIANT CROSS SECTION ($f(x)$) AS WELL AS THE
 ρ^0 DENSITY ($g(x)$) USING DEFINITIONS 7.4 AND 7.5

x range	$f(x)$	$g(x)$
$-1.0 \leq x_F < -0.4$	0.08 ± 0.01	0.033 ± 0.002
$-0.4 \leq x_F < 0$	0.27 ± 0.06	0.25 ± 0.06
$0 \leq x_F < 0.2$	0.28 ± 0.11	0.30 ± 0.12
$0.2 \leq x_F < 0.4$	0.52 ± 0.12	0.27 ± 0.06
$0.4 \leq x_F < 0.6$	0.29 ± 0.07	0.10 ± 0.02
$0.6 \leq x_F < 0.8$	0.006 ± 0.03	0.002 ± 0.01
$0.8 \leq x_F$	0.14 ± 0.03	0.05 ± 0.01

TABLE 7.6

INCLUSIVE CROSS SECTIONS
PRODUCED IN 110 GeV/c K^-p EXPERIMENT

	$\bar{K}^{*0}$	K^{*-}	ρ^0
σ_{total}	5.6 ± 0.8	4.7 ± 0.5	4.6 ± 0.8
$\sigma_{x_F < 0}$	1.4 ± 0.5	0.9 ± 0.3	2.3 ± 0.6
$\sigma_{x_F \geq 0}$	4.3 ± 0.6	3.8 ± 0.6	2.1 ± 0.6
$\sigma_{\text{beam frag.}}$	2.9 ± 0.8	2.9 ± 0.7	$0. \pm 0.9$
σ_{central}	2.7 ± 0.9	1.8 ± 0.8	4.6 ± 0.8

TABLE 7.7(a)

INCLUSIVE PRODUCTION OF BEAM FRAGMENTATION COMPONENT
USING THE SEPARATION METHOD DESCRIBED IN THE TEXT*

Inclusive production	beam particle	beam fragmentation component	110 GeV K^-p results
$\bar{K}^{*0}$	K^-	~ 2.5 mb	2.9 ± 0.8 mb
K^{*-}	K^-	~ 3.0 mb	2.9 ± 0.7 mb
K^{*0}	K^+	~ 2.5 mb	
ρ^0	K^+, K^-	~ 1.0 mb	0 ± 0.9 mb
ρ^0	π^+, π^-	~ 2.4 mb	
ρ^0	$p, \bar{p}$	~ 0 mb	

* the errors on each is about ± 0.5 mb

TABLE 7.7(b)

COMPARISON OF EXPERIMENTAL INCLUSIVE CROSS SECTIONS FOR VECTOR MESONS
WITH THE QUARK MODEL OF REF (7.30) IN THE CENTRAL REGION

Resonance Type	Experimental Value	Quark model prediction
$\bar{K}^{*0}(890)$	2.7 ± 0.9	3.5
$K^{*-}(890)$	1.8 ± 0.8	3.5
$K^{*0}(890)$	1.4 ± 0.6	1.0
$K^{*+}(890)$	2.2 ± 0.6	1.0
$\rho^0(770)$	4.6 ± 0.8	4.2

TABLE 7.8

COMPARISON OF EXPERIMENTAL INCLUSIVE CROSS SECTIONS RATIOS FOR VECTOR MESONS WITH QUARK MODEL PREDICTIONS (REF 7.4) IN DIFFERENT KINEMATICAL REGIONS

Resonance cross section ratios	Kinematical production regions	Experimental values	Quark Model prediction
$\frac{\bar{K}^{*0}(890)}{K^{*-}(890)}$	beam fragmentation	1.0 ± 0.4	.75
$\frac{\rho^0(770)}{K^{*-}(890)}$	beam fragmentation	0 ± 0.3	.375
$\frac{\rho^0}{\bar{K}^{*0}(890)}$	beam fragmentation	0 ± 0.3	.5
$\frac{\bar{K}^{*0}(890)}{K^{*-}(890)}$	central	1.5 ± 0.8	1
$\frac{\rho^0(770)}{K^{*-}(890)}$	central	2.6 ± 1.2	3
$\frac{\rho^0(770)}{\bar{K}^{*0}(890)}$	central	1.7 ± 0.7	3

FIGURE CAPTIONS

Fig 7.1 The $\pi^-\pi^+$ effective mass distribution for all -ve, +ve particle combinations consistent with a π^- and a π^+ mass fit respectively. A small enhancement near 0.7 GeV containing the ρ^0 and the $\bar{K}^{*0}$ reflection can just be distinguished.

Fig 7.2 The $K^-\pi^+$ effective mass distribution for all -ve, +ve particle combinations consistent with a kaon and pion mass fit respectively. A small enhancement near 0.9 GeV containing the $\bar{K}^{*0}$ and ρ^0 reflection can be distinguished.

Fig 7.3 a) The shape of the "reflection" of ρ^0 into the $K^-\pi^+$ channel, the absolute normalization of the vertical axis is unimportant. The shape is obtained by generating a pure ρ^0 from the experimental $\pi^-\pi^+$ distribution then reflecting the -ve, +ve combinations into the $K^-\pi^+$ channel.

b) The shape of the "reflection" of $\bar{K}^{*0}$ into the $\pi^-\pi^+$ channel, the absolute normalization of the vertical axis is unimportant. The shape is obtained by generating a pure $\bar{K}^{*0}$ from the experimental $K^-\pi^+$ distribution, then reflecting the -ve, +ve combinations into the $\pi^-\pi^+$ channel.

Fig 7.4 a) & b) The reflections of the ρ^0 and $\bar{K}^{*0}$ into the $K^-\pi^+$ and $\pi^-\pi^+$ channels respectively, as calculated by the 70 GeV K^-p collaboration (a copy of figure 1 of ref (7.9)). It is seen that these profiles are very similar to figures 7.3a and 7.3b.

Fig 7.5 a) The reflection of the ω into the $\pi^-\pi^+$ channel. This reflection shape was calculated assuming the particle data group(ref 7.2) values for the mass, spin and parity of the ω .

Fig 7.5 b) The reflection of ω into $K^-\pi^+$ channel. This profile was obtained by weighting figure 7.1 to copy figure 7.5a, then reassigning the particle masses as $K^-\pi^+$ and calculating their invariant mass.

Fig 7.6 a) The reflection of ϕ into the $\pi^-\pi^+$ channel, the normalization of the vertical axis is unimportant.

b) The reflection of the ϕ into the $K^-\pi^+$ channel, the normalization of the vertical axis is unimportant.

Fig 7.7 a) The $\pi^+\pi^+$ effective mass distribution for all possible combinations.

b). The $K^+\pi^+$ effective mass distribution for all possible combinations.

Fig 7.8 Results of the separate fit to the $\pi^-\pi^+$ channel.

solid histogram	experimental data
xxxxxxxxx	best fit
-----	background contribution
-.-.-.-.-	ρ^0 resonance contribution
+ + + + +	K^{*0} reflection contribution

Fig 7.9 Results of the separate fit to the $K^-\pi^+$ channel.

solid histogram	experimental data
xxxxxxxxx	best fit
-----	background contribution
-.-.-.-.-	$\bar{K}^{*0}$ resonance contribution
+ + + + +	ρ^0 reflection contribution

Fig 7.10 a) Results of the best combined fit to the $\pi^-\pi^+$ channel,
removing the ω reflection profile

The symbols are similar to those explained in figure 7.8.

b) Results of the best combined fit to the $K^-\pi^+$ channel,
removing the ω reflection profile.

The symbols are similar to those explained in figure 7.9

Fig 7.11 a) Result of the best combined fit to the $\pi^-\pi^+$ channel,
putting the amount of ω equal to the amount of the ρ^0 .

The symbols are similar to those explained in figure 7.8

plus: lower " " " " " " " for the ω reflection distribution.

b) Results of the best combined fit to the $K^-\pi^+$ channel,
putting the amount of the ω equal to the amount of the ρ^0 .

The symbols are similar to those explained in figure 7.9

plus: lower " " " " " " " for the ω reflection distribution.

Fig 7.12 a) Similar to 7.11a except that the fitted ω distribution has
been made by putting the ω as a free parameter.

b) Similar to 7.11b except that the fitted ω distribution has
been made by putting the ω as a free parameter.

Fig 7.13 Results of the best combined fit for K^{*0} by making a
simultaneous fit of $K^+\pi^-$ and $\pi^+\pi^-$, similar to the simultaneous
fit of $K^-\pi^+$ and $\pi^-\pi^+$ channels taking into accounts all other
reflections.

solid histogram

experimental data

xxxxxxxxxxxxxxxx

best fit

background contribution

.....

K^{*0} resonance contribution

+++++	ρ^0 reflection contribution
" " " " " "	ω reflection contribution

Fig 7.14 a) The inclusive $K^-p \rightarrow \bar{K}^{*0}x^0$ cross section as a function of beam momentum. The $\bar{K}^{*0}$ cross section is higher at 110 GeV/c than in the 10-32 GeV/c range.

b) The inclusive $K^-p \rightarrow \rho^0x^0$ cross section as a function of beam momentum. The ρ^0 cross section at 110 GeV shows a similar trend to that for $\bar{K}^{*0}$.

c) The inclusive $K^-p \rightarrow K^{*-}x$ cross section as a function of beam momentum. The 110 GeV/c result has been taken from ref (7.9b). The K^{*-} data also indicate that there is a slight increase of cross section with increasing CM energy.

Fig 7.15 The Feynman x distribution for the inclusive reactions $K^-p \rightarrow \rho^0x^0$ at GeV/c and at 110 GeV/c. It is clear from the figure that the shape of distribution varies with beam momenta.

Fig 7.16 The invariant Feynman x distribution for the inclusive reactions $K^-p \rightarrow \bar{K}^{*0}x^0$ at various beam momenta. The strong forward peak which appears at $x_F \gtrsim 0.8$ at 10-16 GeV is probably mainly due to the two body channels as they decrease rapidly with increasing beam momenta.

Fig 7.17 The invariant Feynman x distribution for the inclusive cross sections $K^-p \rightarrow K^{*-}x$ at various beam momenta. The noticeable forward peak at 10-16 GeV is again probably due to quasi two body reactions which contribute the most to the high x_F region.

Fig 7.18 Results of best combined fits to the $\pi^-\pi^+$ channel and $K^-\pi^+$ channel for different Feynman x regions by putting the ω as a free parameter. The symbols are similar to those explained earlier.

Fig 7.19 Total cross-sections for the inclusive interactions $pp \rightarrow K^{*+}x$ and $pp \rightarrow K^{*-}x$ (ref 7.25, 28, 29). An estimation of the $p \rightarrow K^*$ fragmentation is obtained from the difference between the K^{*+}

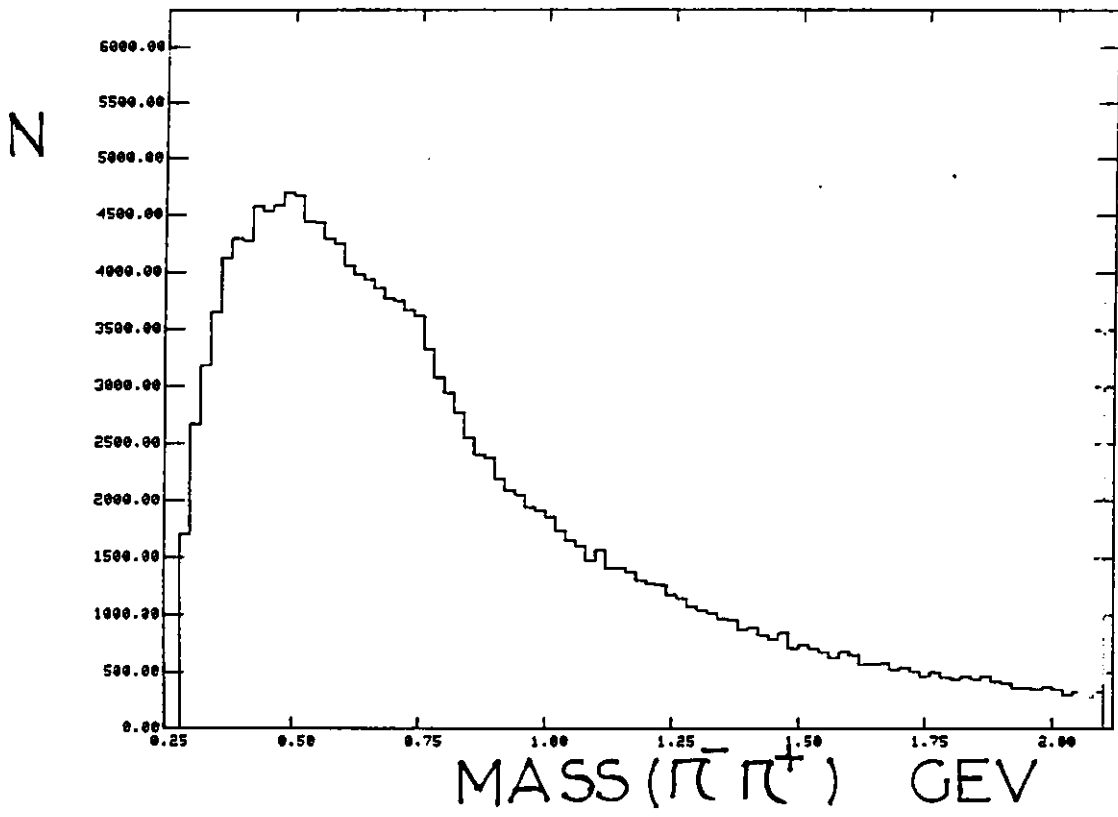
K^{*-} values.

- Fig 7.20 a) The total beam fragmentation and central components (using the definitions of 7.7a, b) of the inclusive interactions $K^{\pm}p \rightarrow \rho^0 x$ (ref 7.8-11). Our data at 110 GeV/c confirms the trend of rising central production but constant beam fragmentation production of the ρ^0 . The straight line is an "eye-ball" fit to the σ_b component.
- b) The total beam fragmentation and central components (using the definitions 7.7a, b,) of the inclusive interactions $K^{\pm}p \rightarrow K^{*0} x$ (ref 7.5-10). Our data at 110 GeV again confirms the trend of rising central production but constant beam fragmentation production of the $\bar{K}^{*0}$. "Eye-ball" fits have been added to the figure.
- c) The total beam fragmentation and central components (using the definitions 7.7a, b,) of the inclusive interactions $K^{\pm}p \rightarrow K^{*\pm} x$ (ref 7.5-10). Our data at 110 GeV taken from ref (7.9b) confirms the trend of rising central production but constant beam fragmentation production of the K^{*-} . "Eye-ball" fits have also been added to the figure.

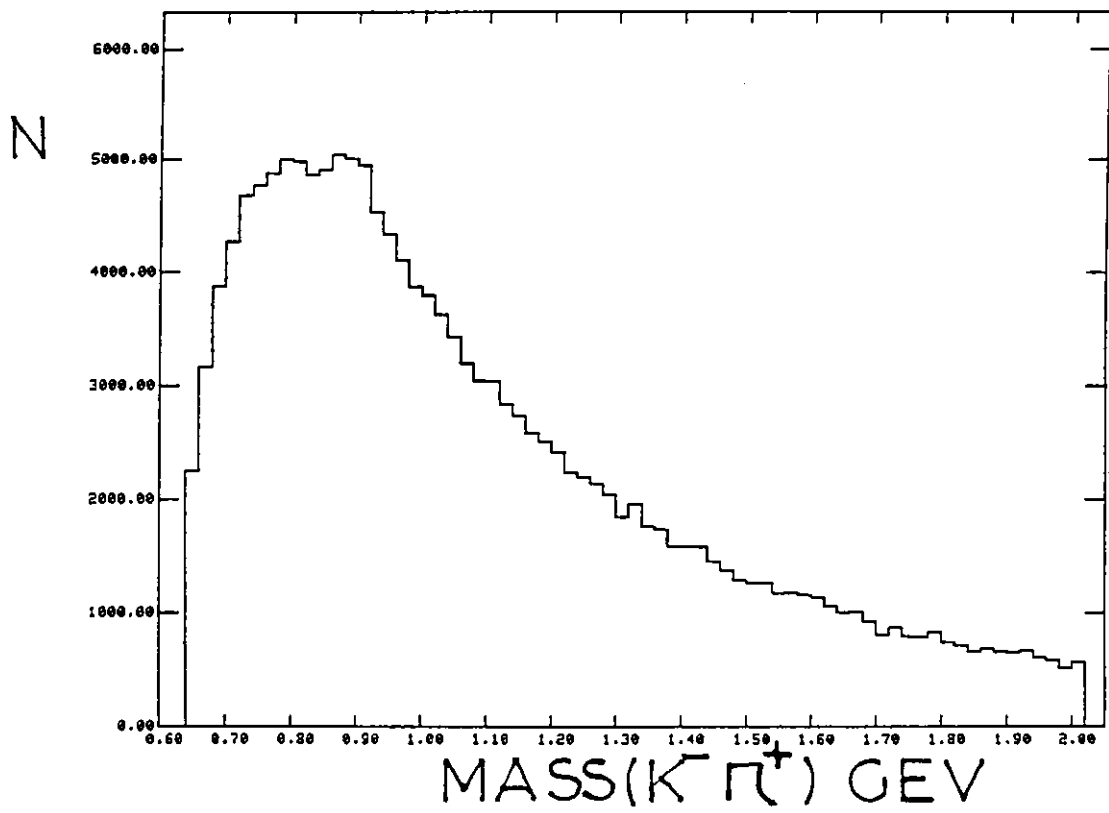
- Fig 7.21 a) Feynman x distribution $\frac{d\sigma}{dx}$ (non invariant) for the inclusive reactions $K^-p \rightarrow \bar{K}^{*0} x$ at 16 and 110 GeV/c K^-p data. The value of σ in 16 GeV is calculated from the published invariant distribution (fig 7.16). Taking $x_F \gtrsim 0.3$ as an estimate for σ_b the area under the curve for $x_F \gtrsim 0.3$ is approximately equal in both energies.
- b) As fig (7.21a) but for the inclusive reactions $K^-p \rightarrow K^{*-} x$ at 16 and 110 GeV/c K^-p data. A similar conclusion to fig (7.21a) can be obtained from this figure for K^{*-} in the $x_F \gtrsim 0.3$ region.

Fig 7.22 The total beam fragmentation and central components of the inclusive interactions $\pi^\pm p \rightarrow \rho^0 x$ (ref 7.12, 14, 16-20). σ_b is seen to be constant over the whole range of P_{beam} , and has the same value for both π^+ and π^- data. "Eye-ball" fits have again been added to the figure.

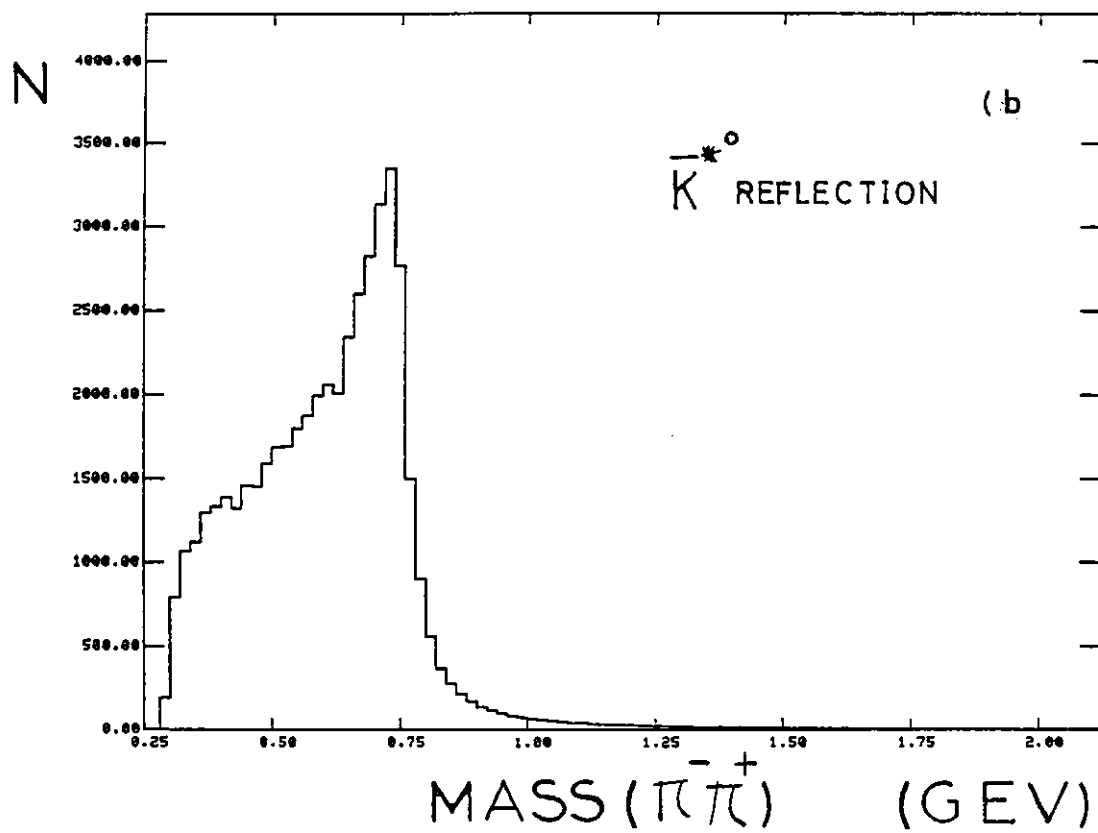
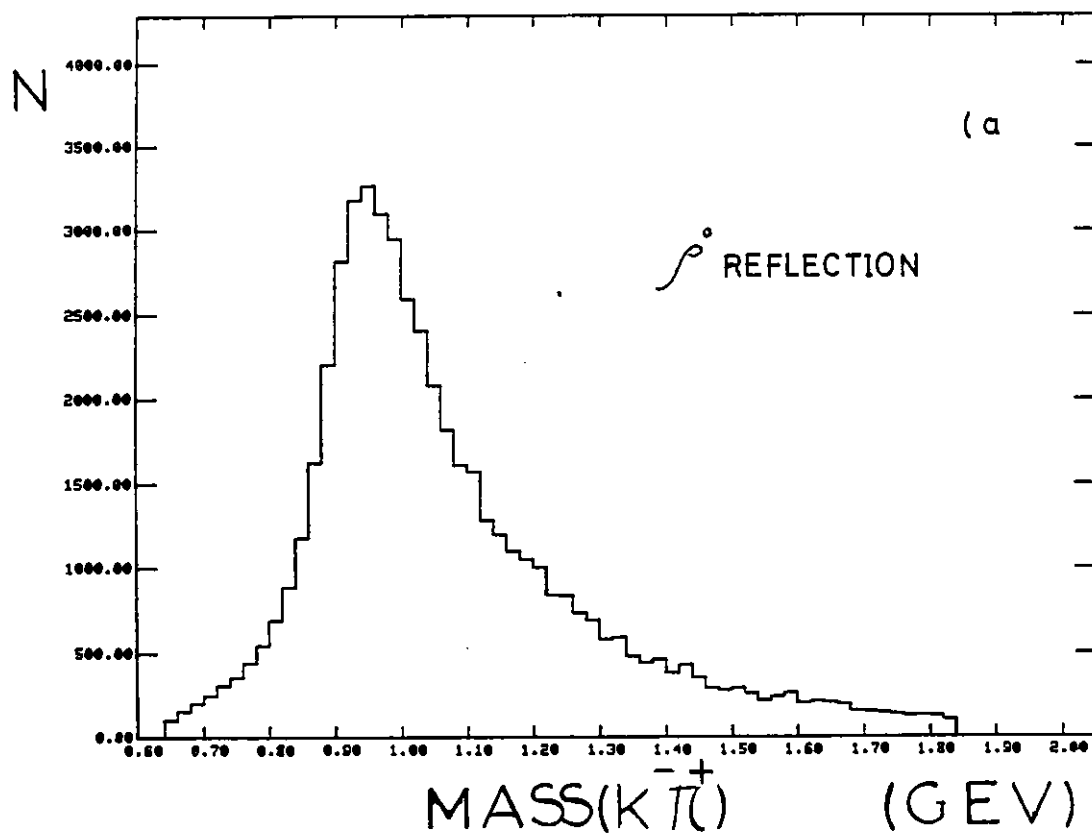
Fig 7.23 The central component of various inclusive reactions as a function of $\sqrt{s}$. This figure is a copy of figure 4, of ref (7.30b) As we have a strange beam, the addition of on average 0.5 strange quarks to the central region is claimed (ref 7.30) to enhance about 2.5mb in each case to the central $\bar{K}^{*0}$ and K^{*-} production.



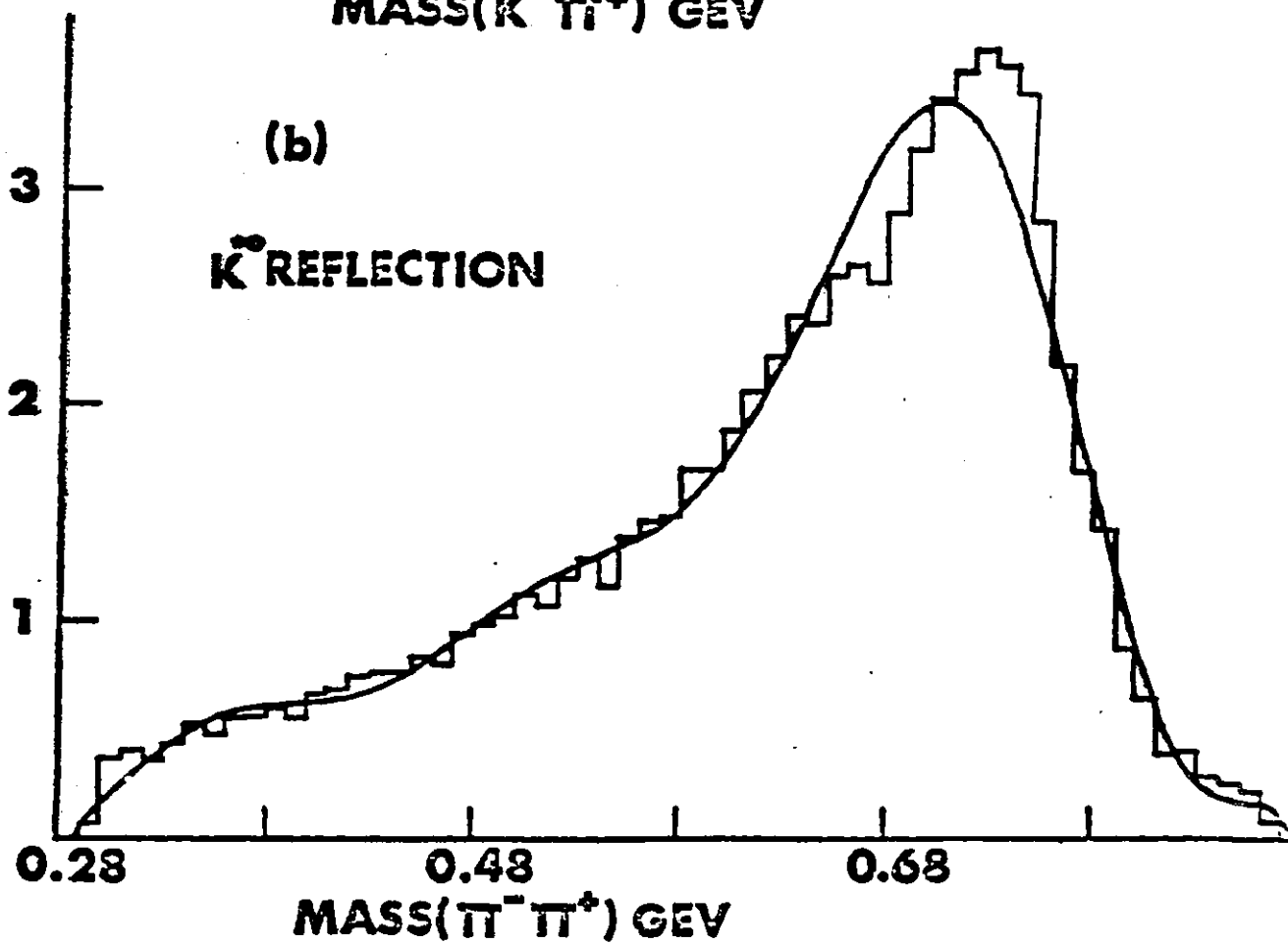
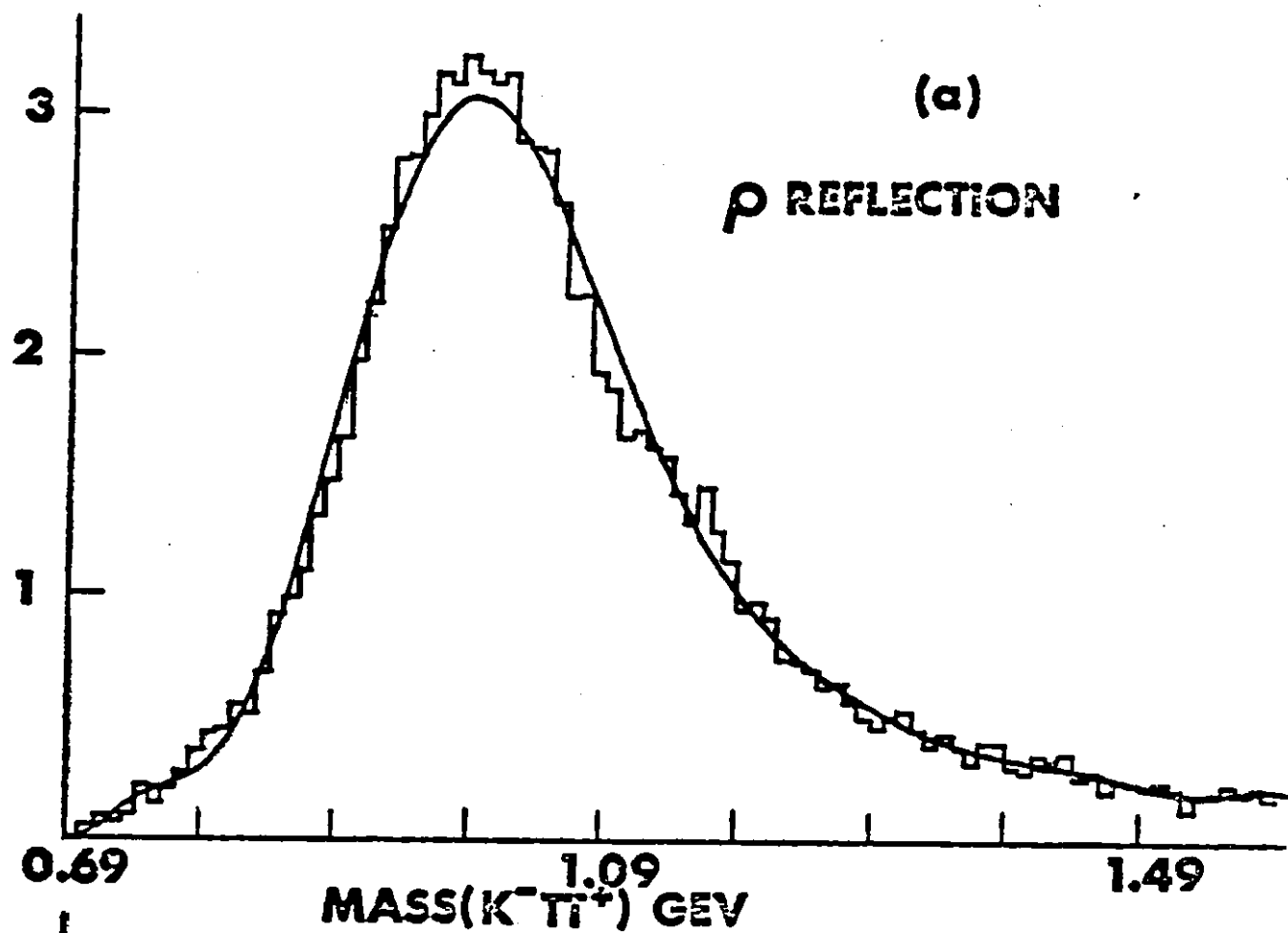
FIG(7.1)



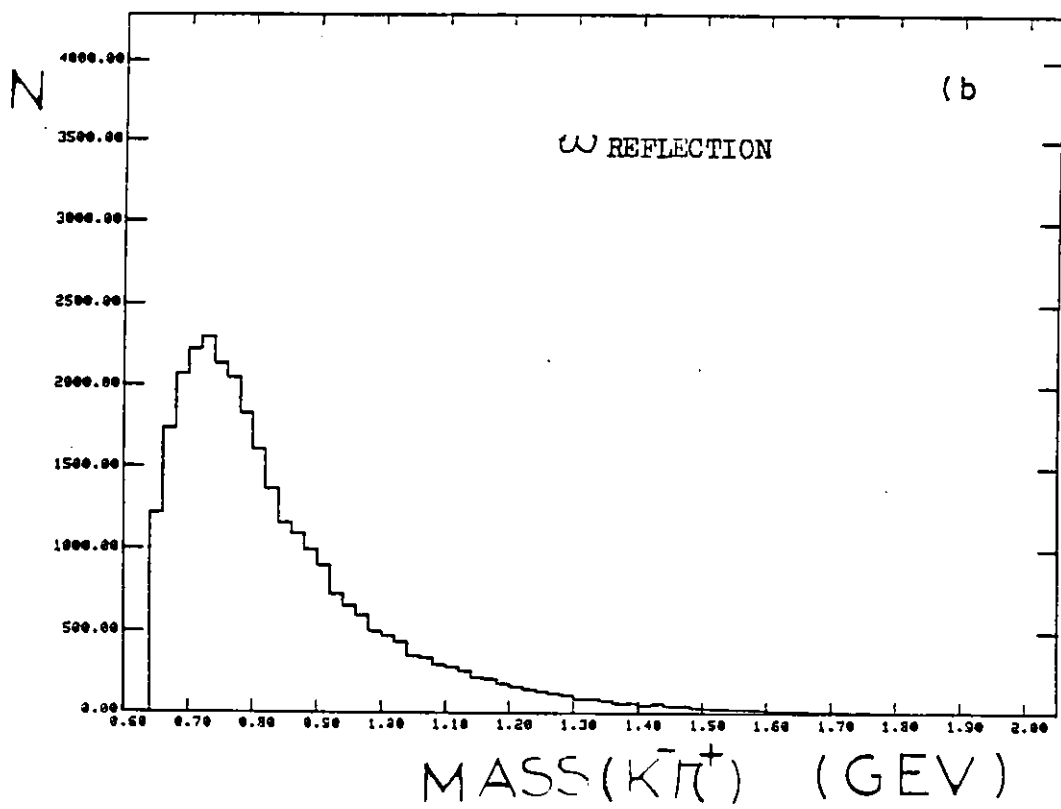
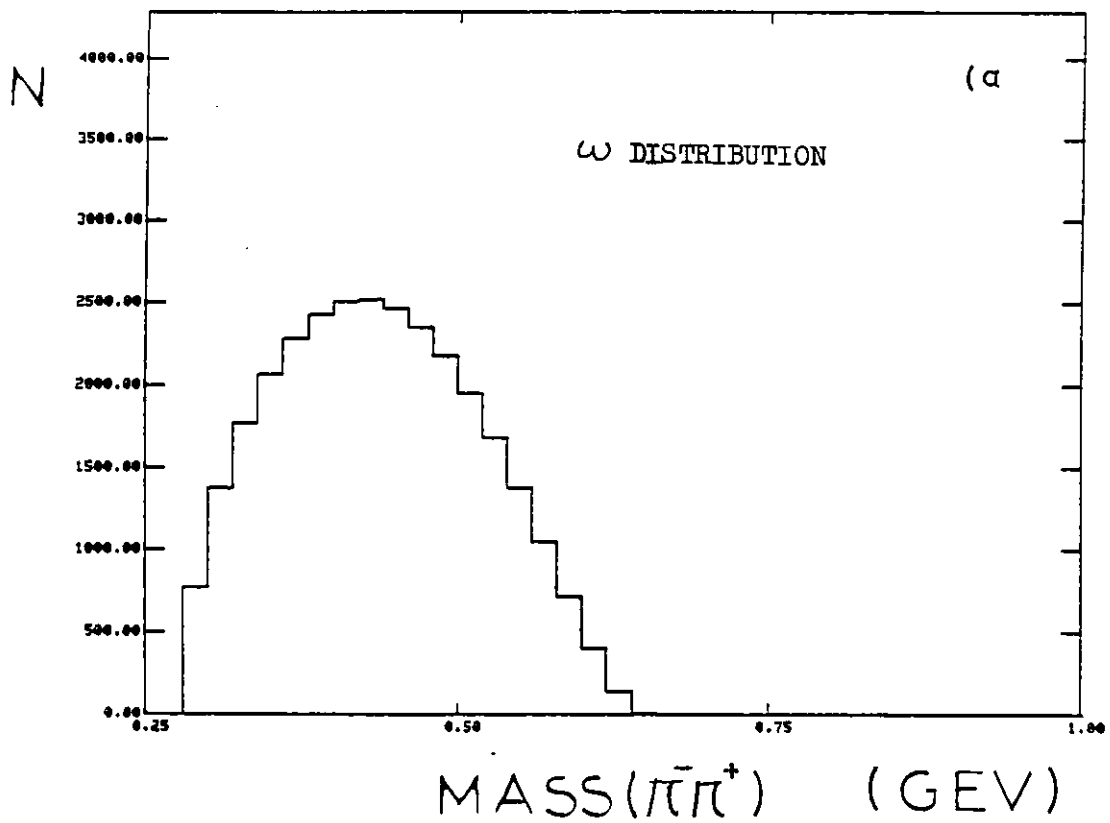
FIG(7.2)



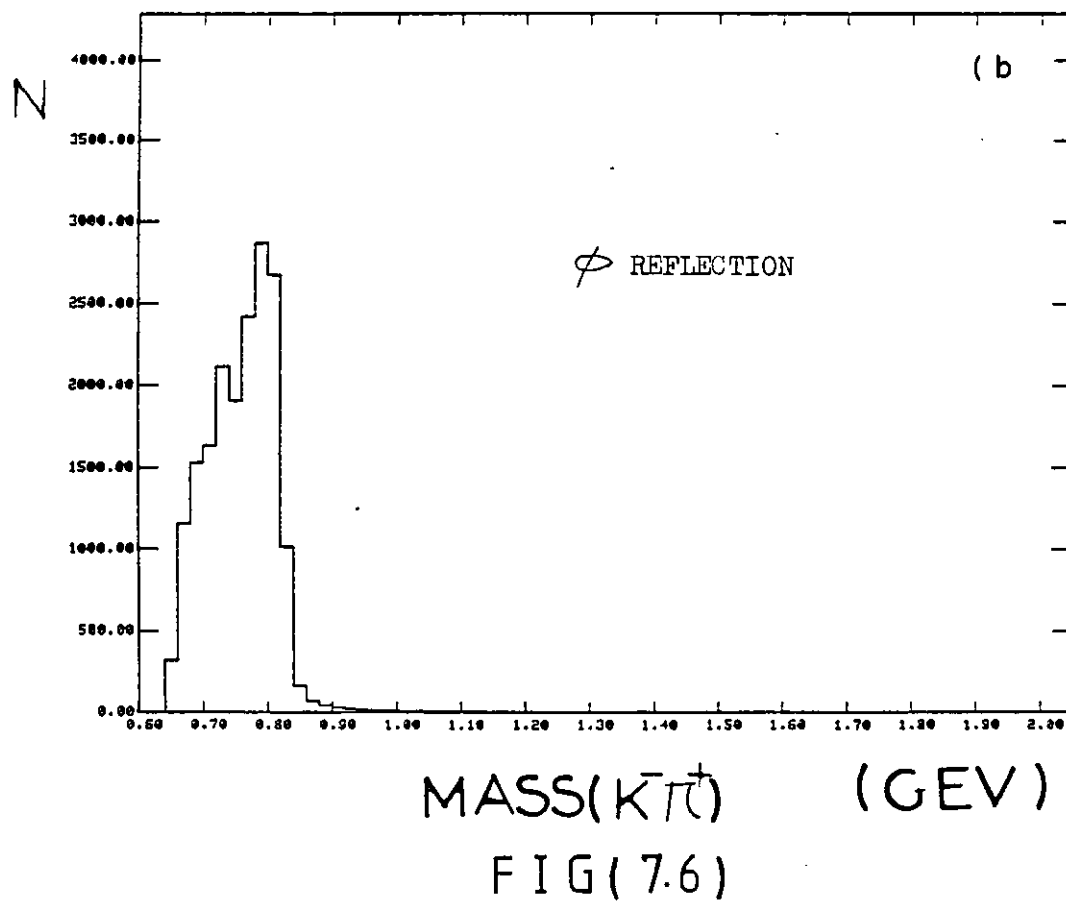
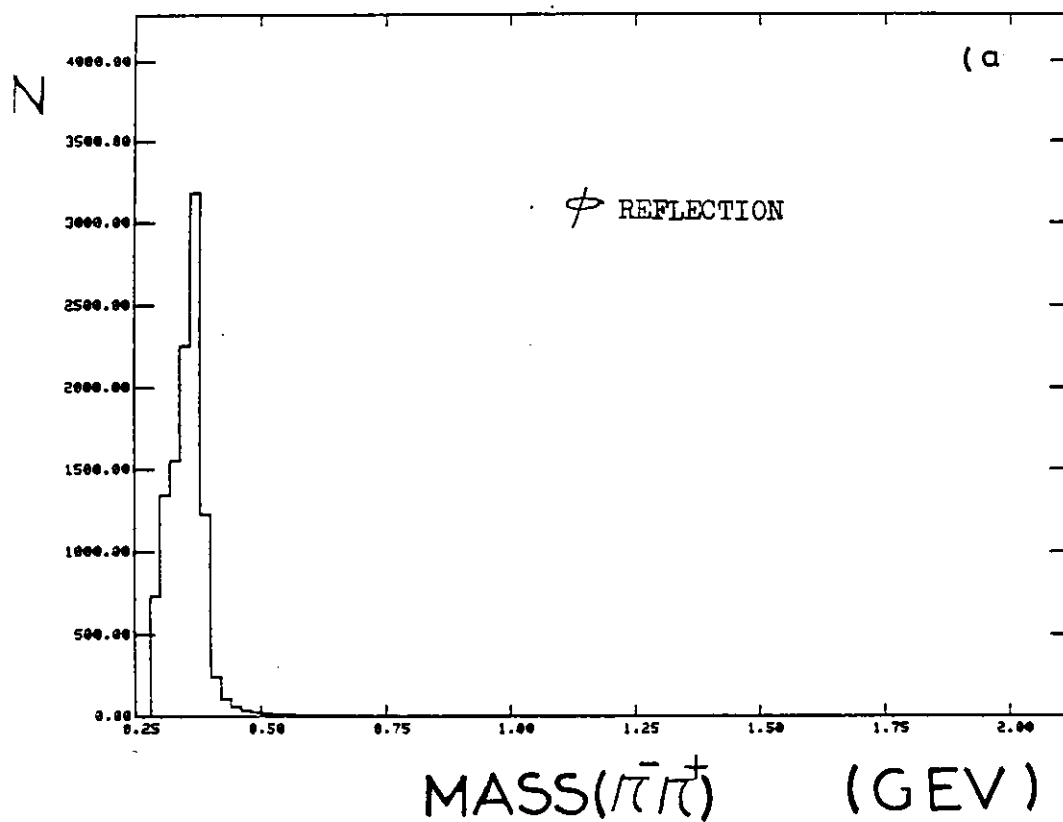
FIG(7.3)

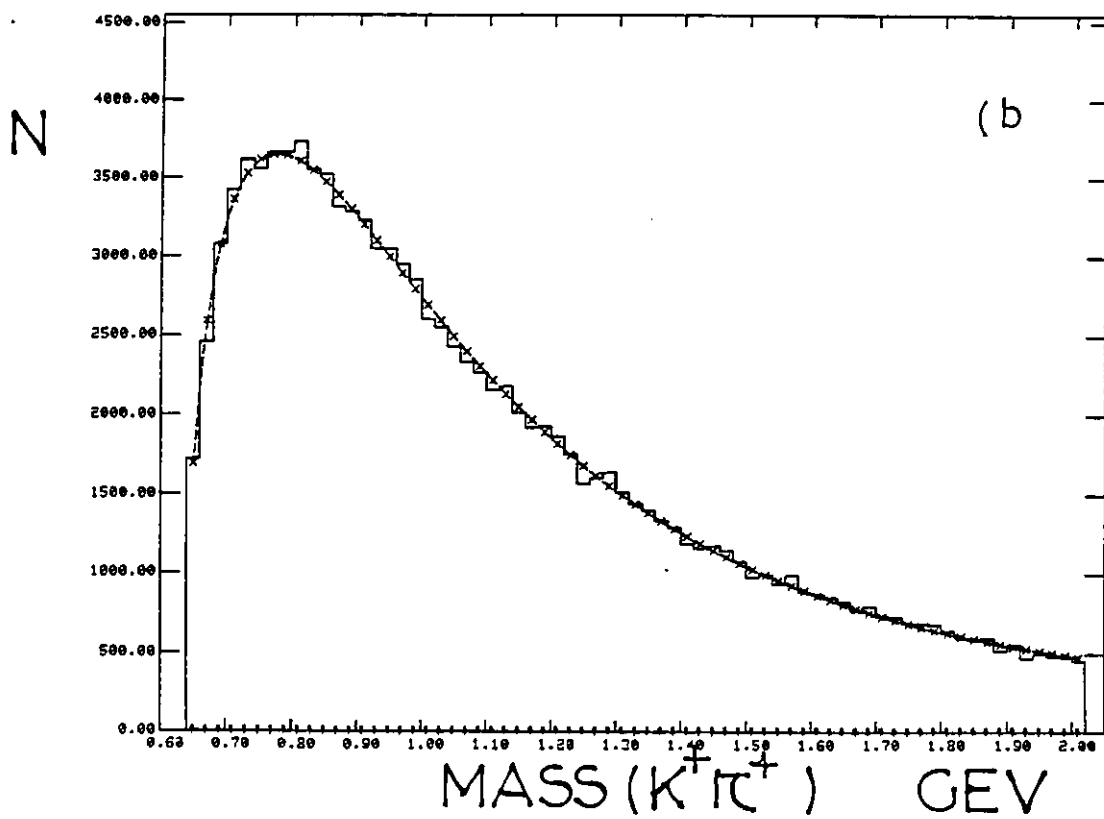
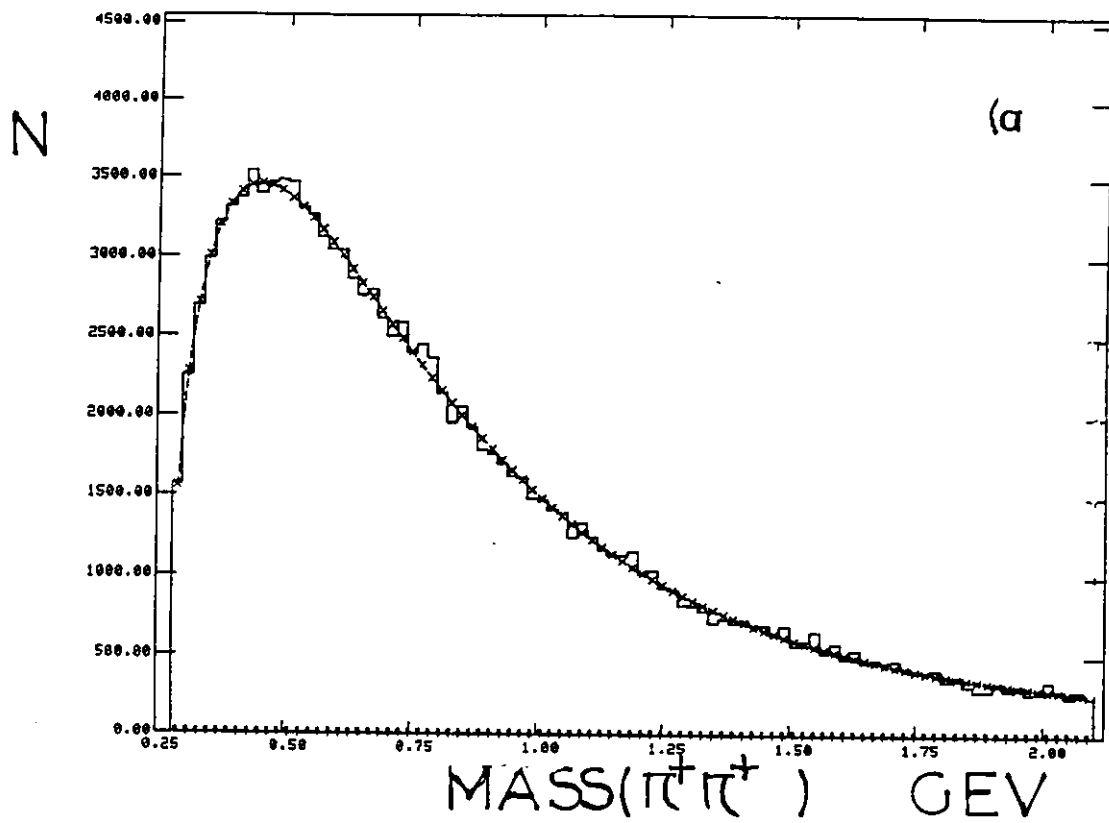


FIG(7.4)

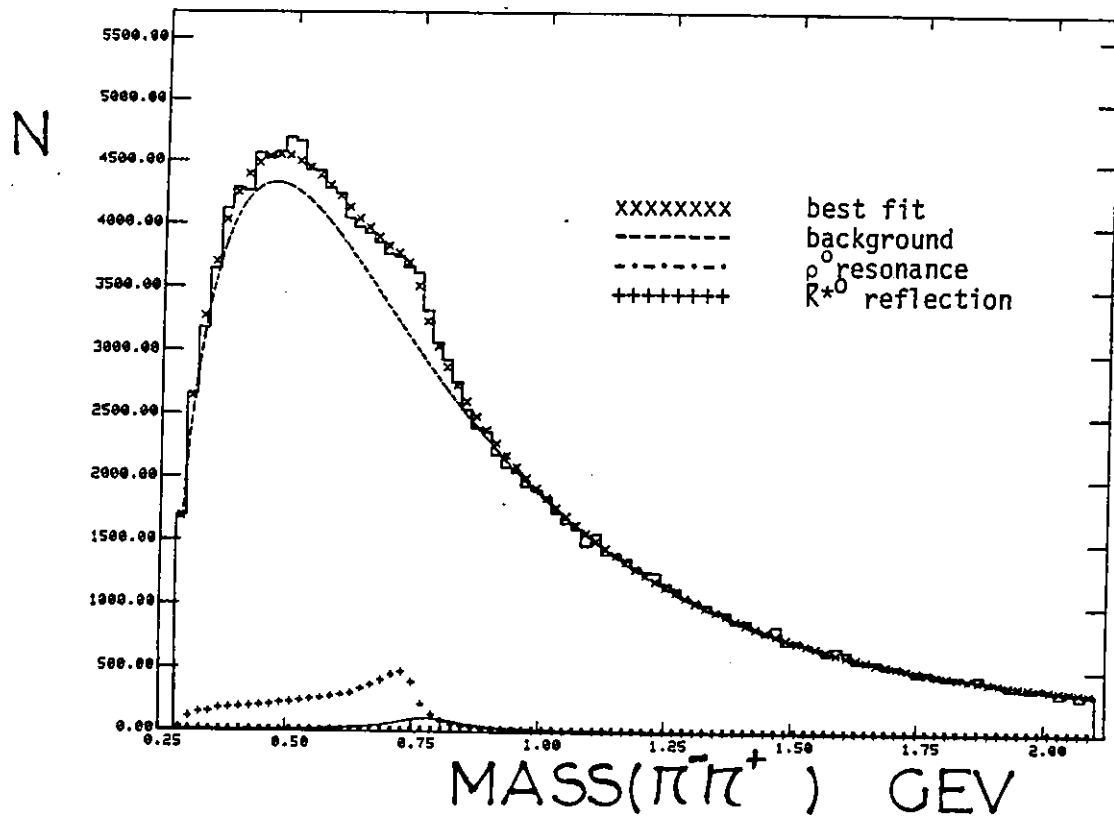


FIG(7.5)

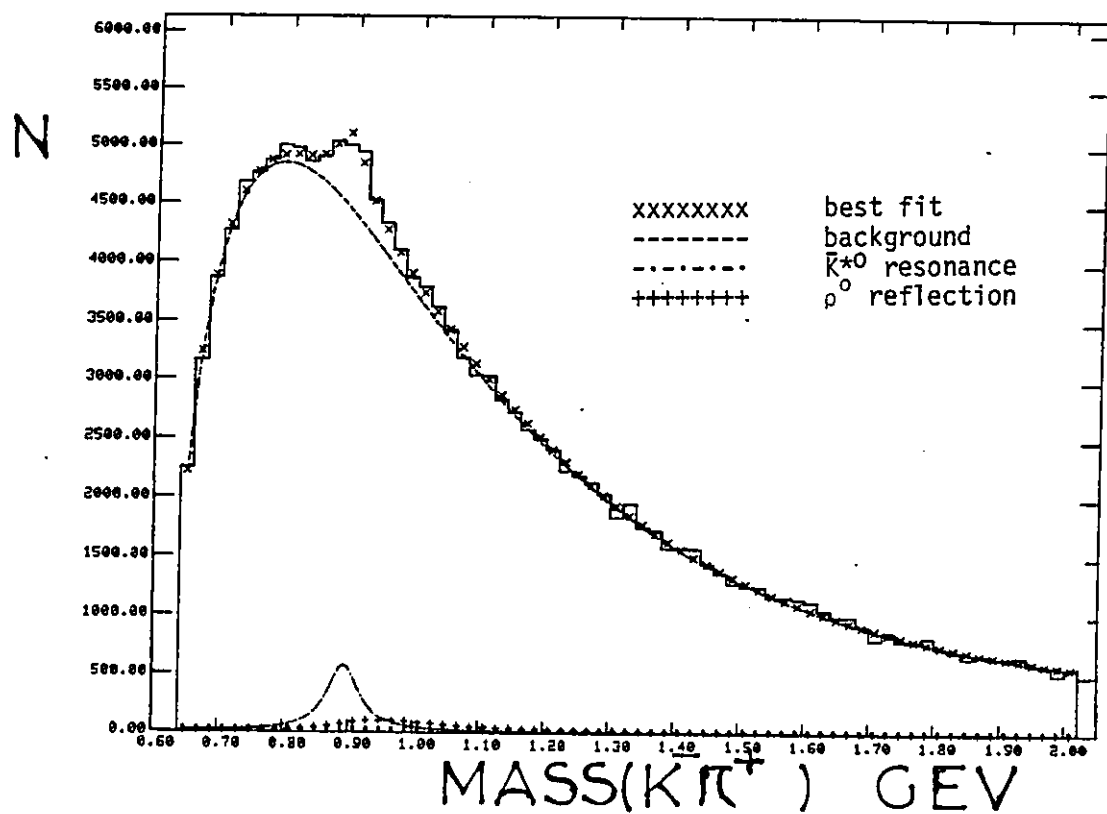




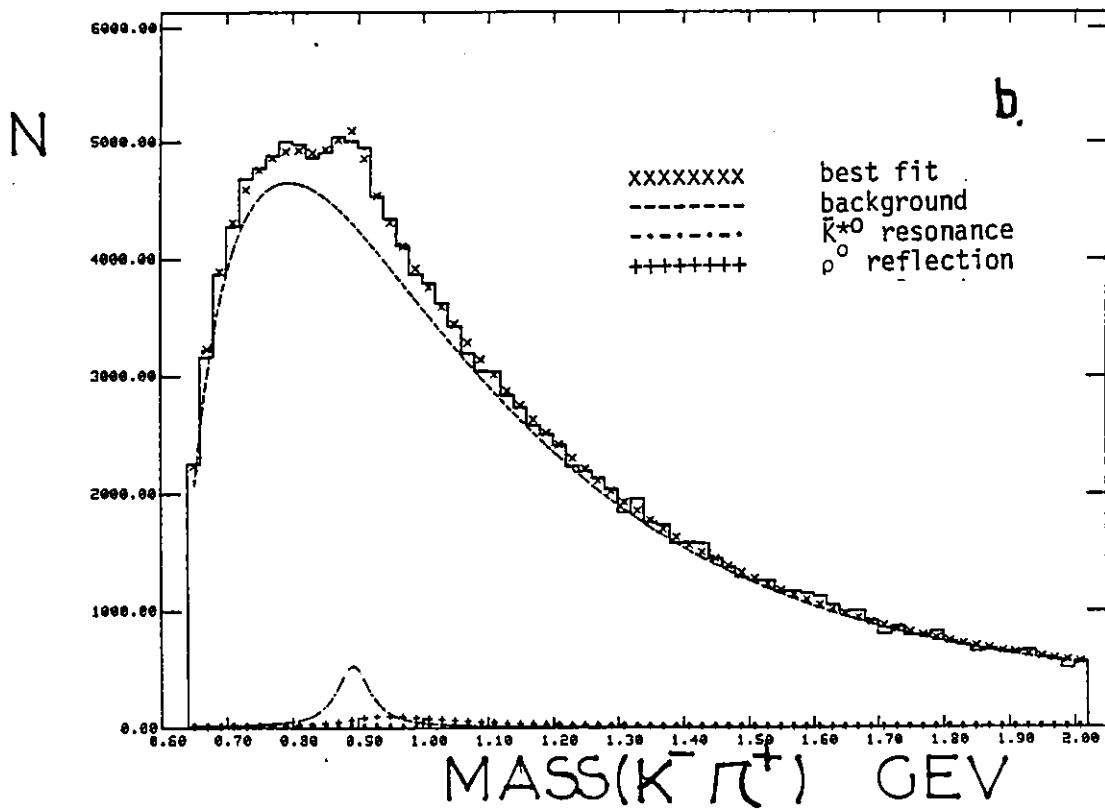
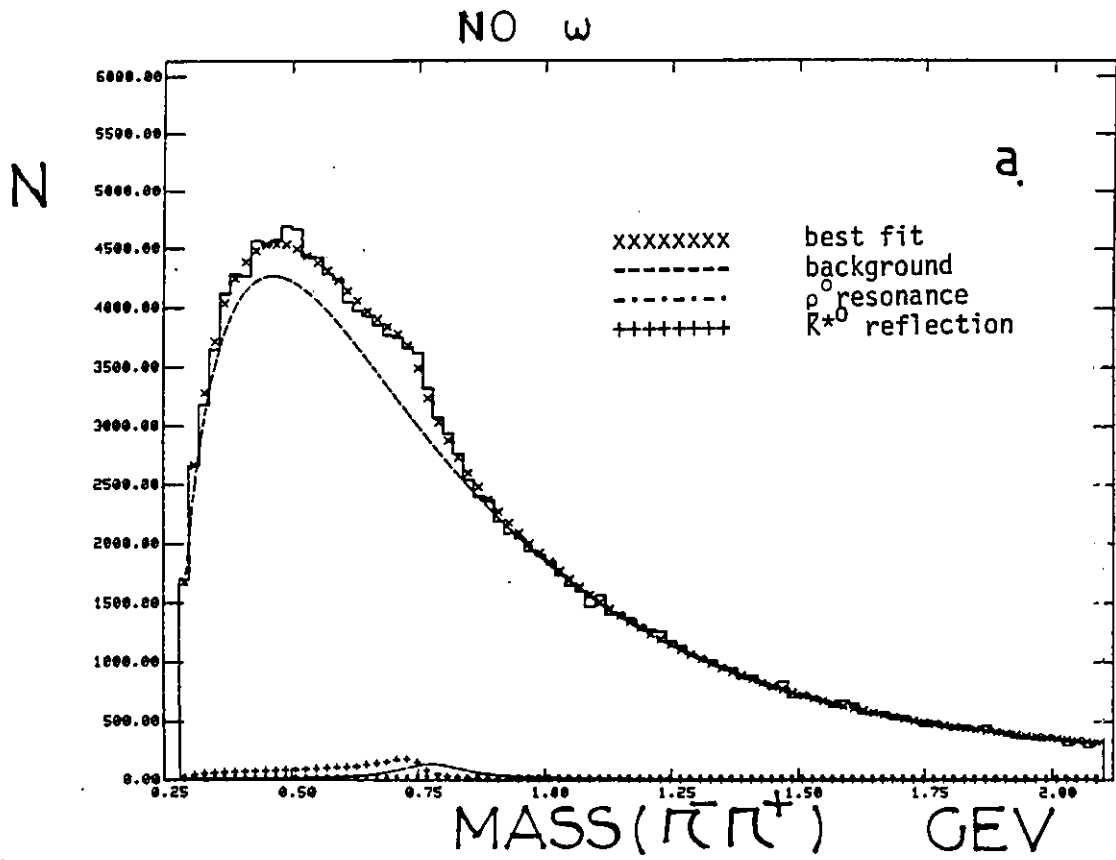
FIG(7.7)



FIG(7.8)

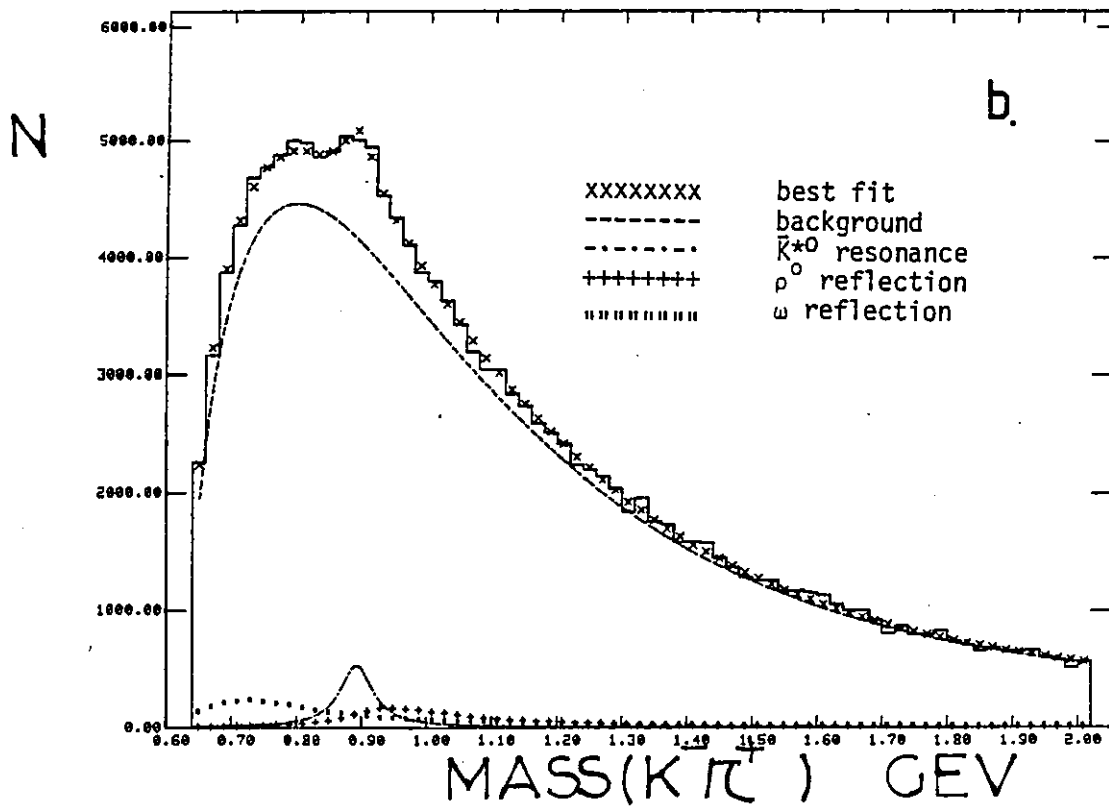
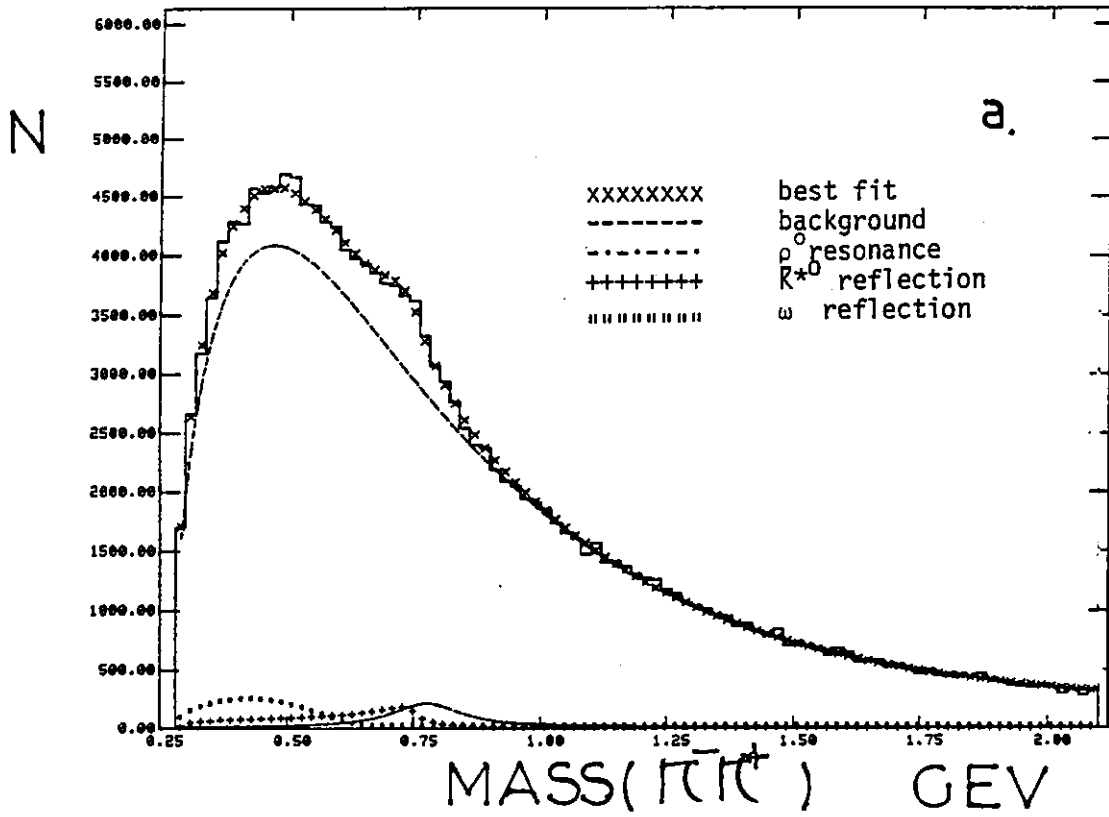


FIG(7.9)

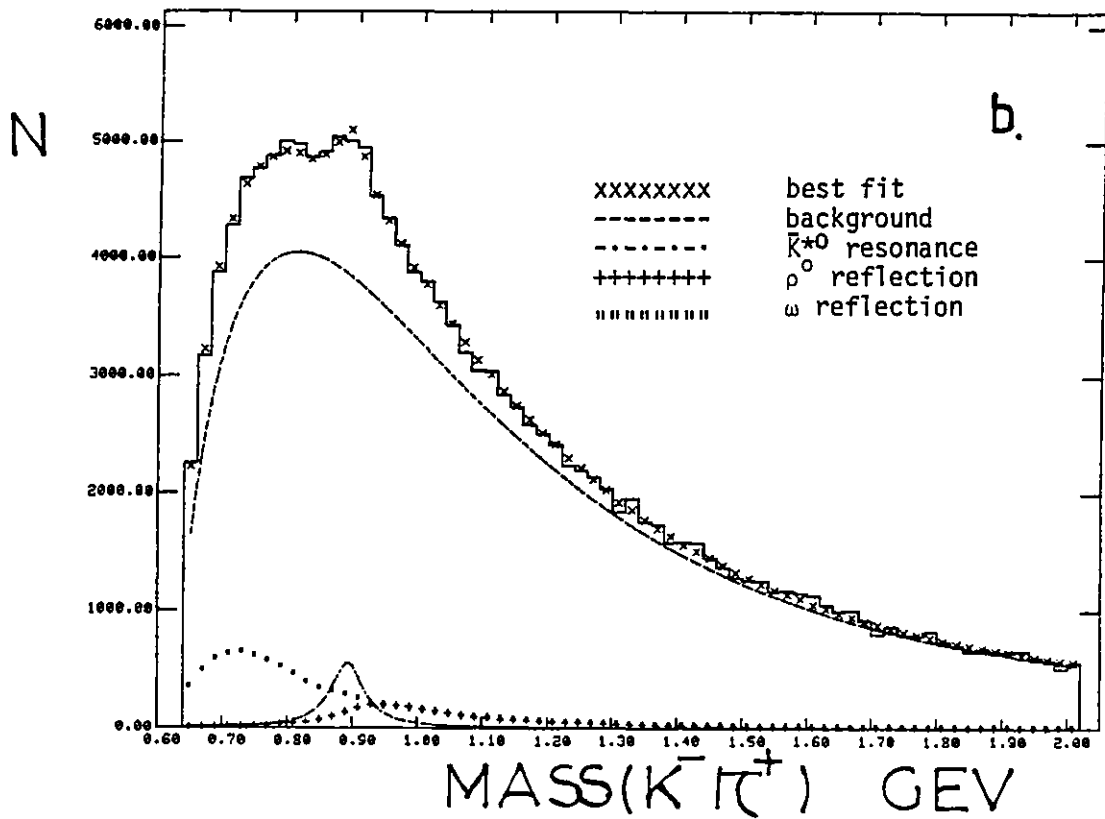
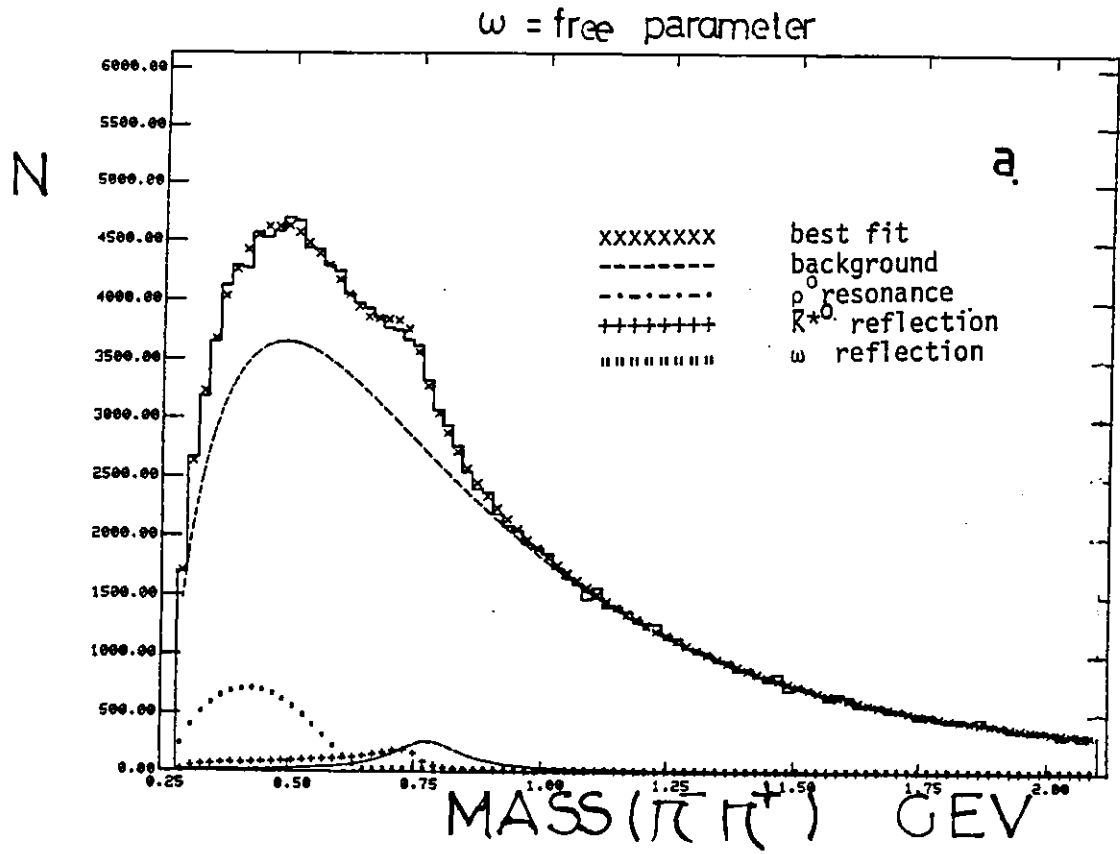


FIG(7.10)

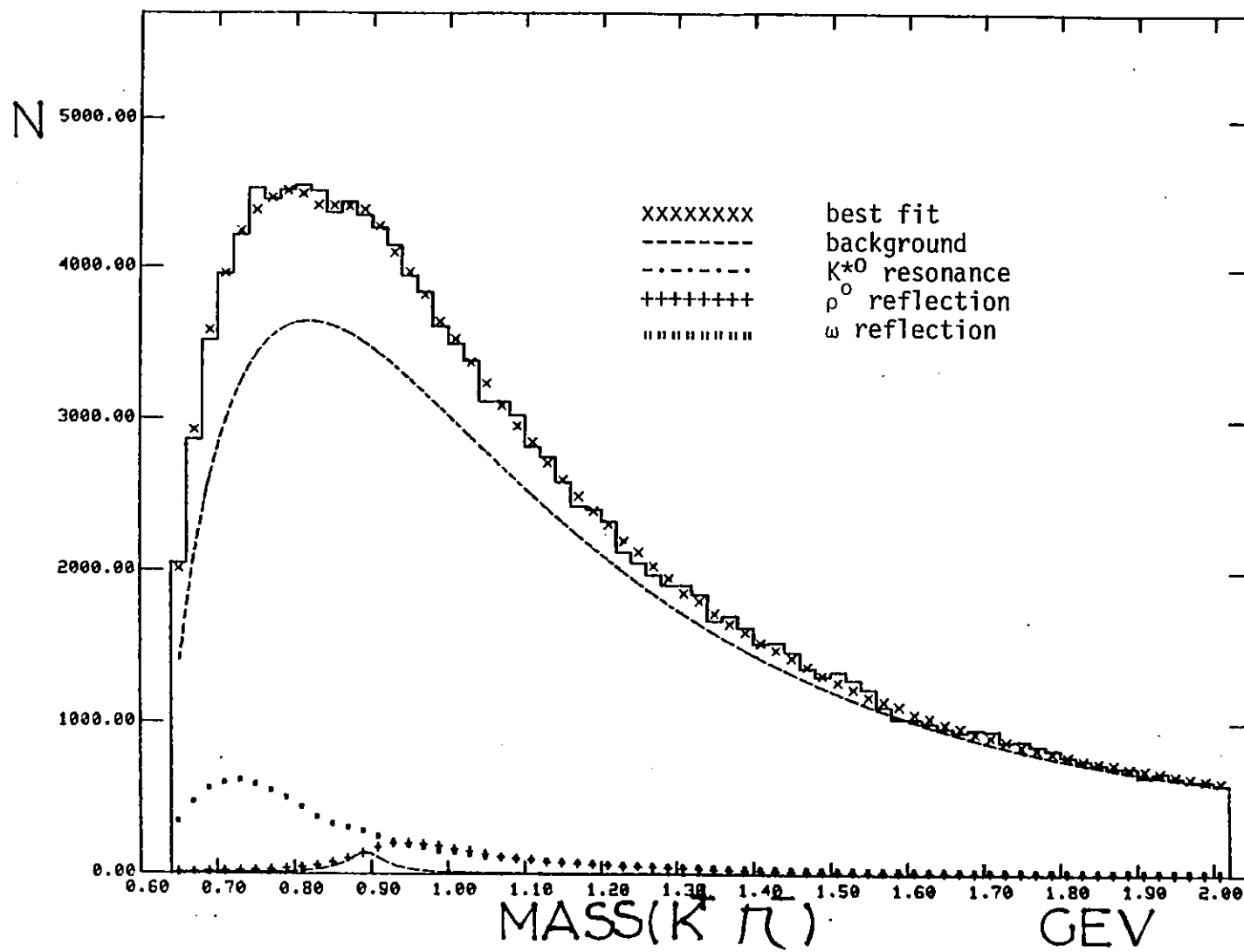
$$\omega = \rho$$



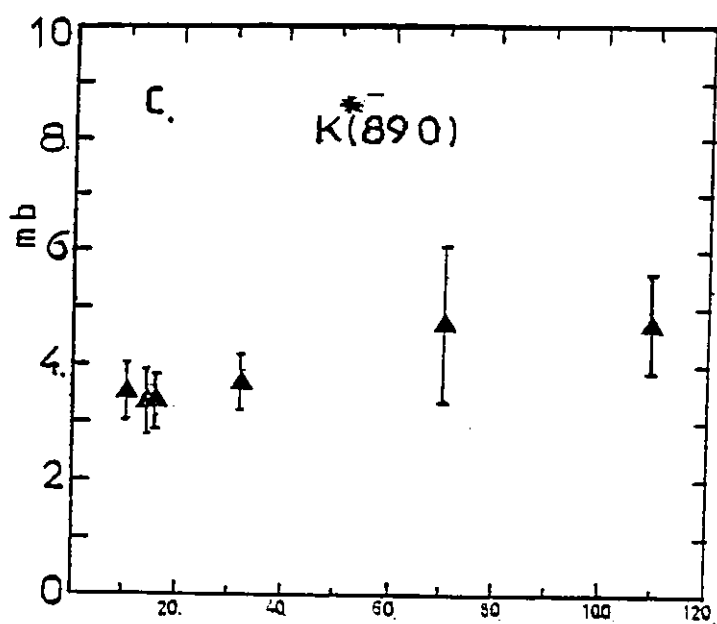
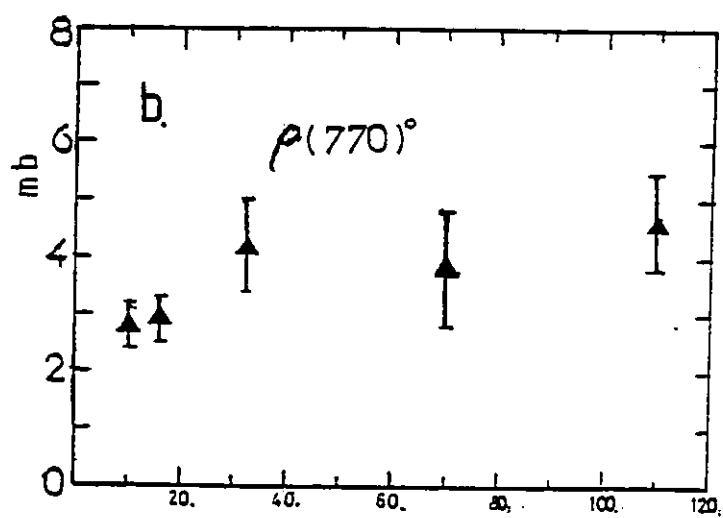
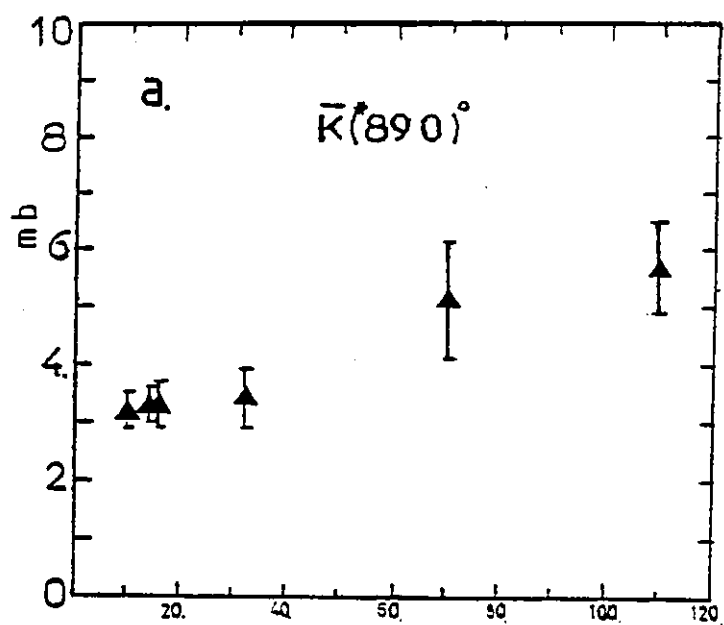
FIG(7.11)



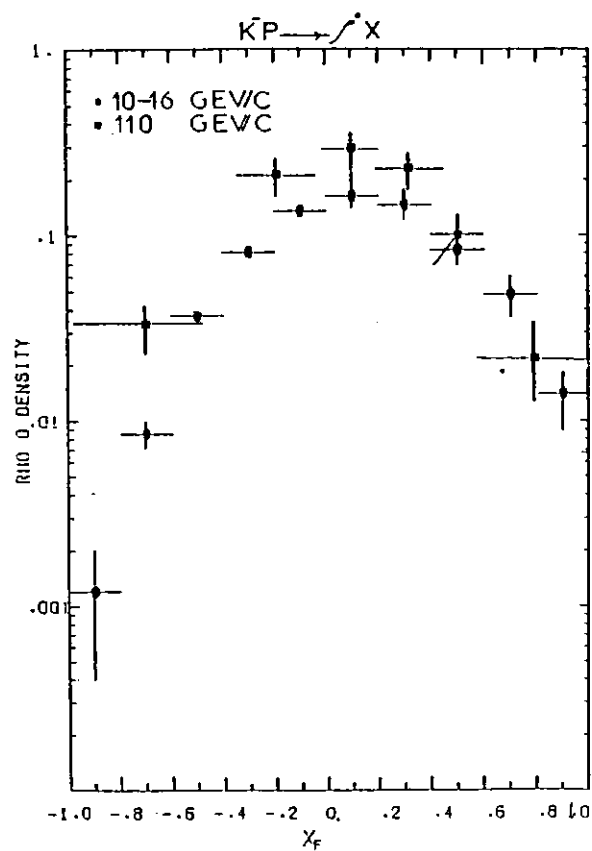
FIG(7.12)



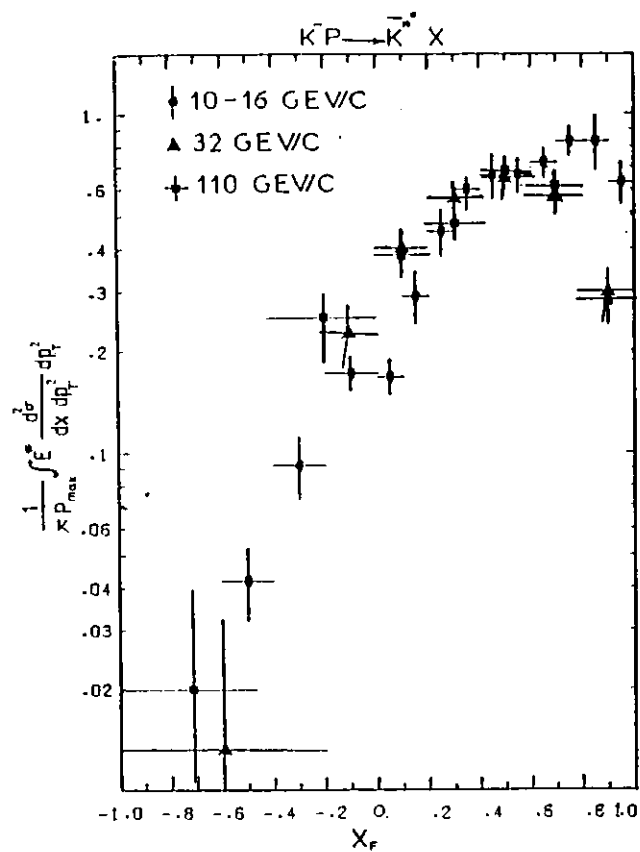
FIG(7.13)



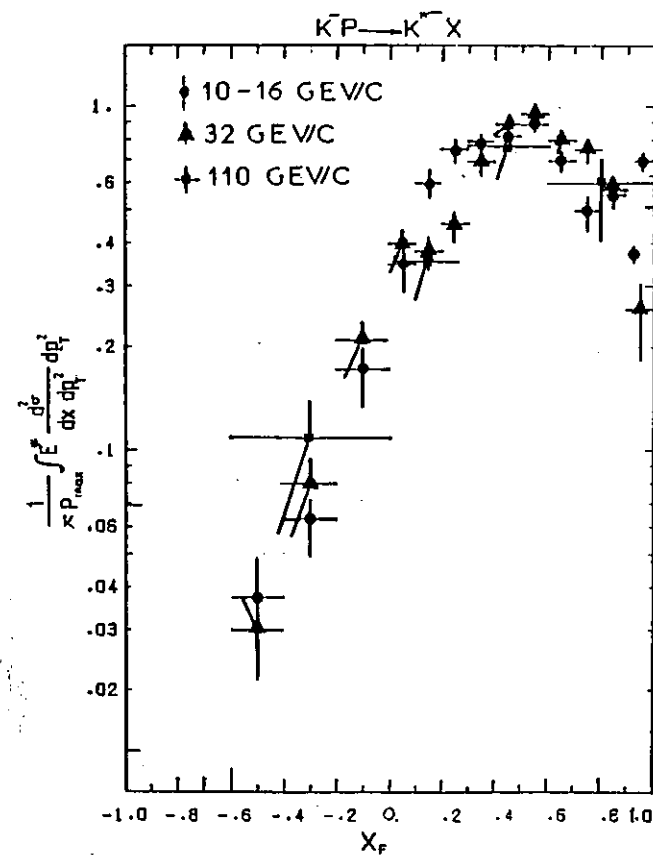
$p_{\text{lab}}^{\text{beam}}$



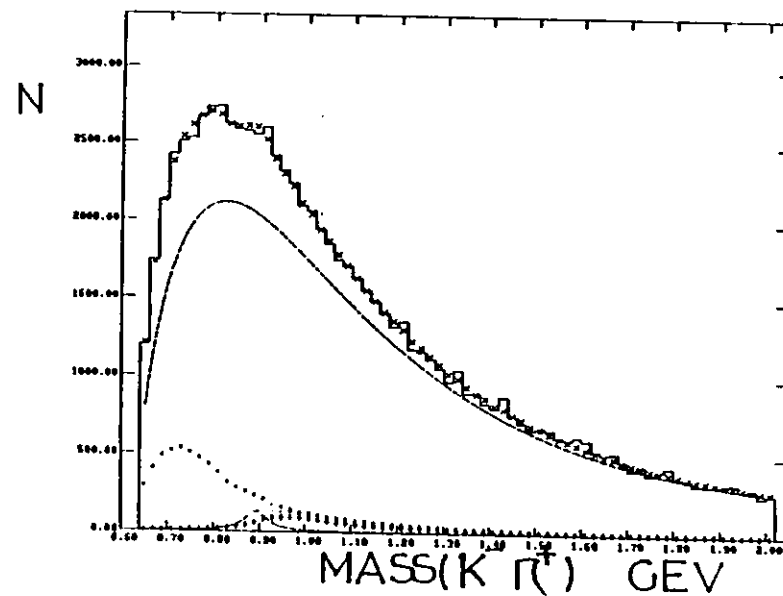
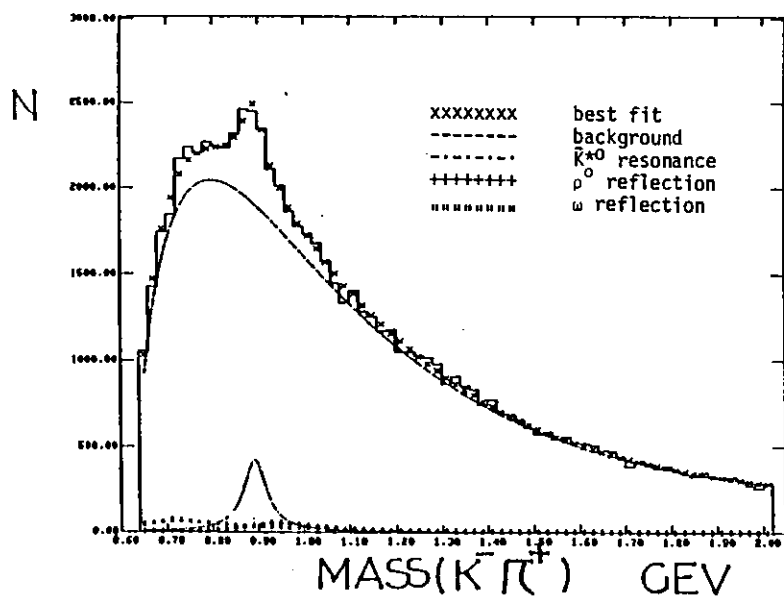
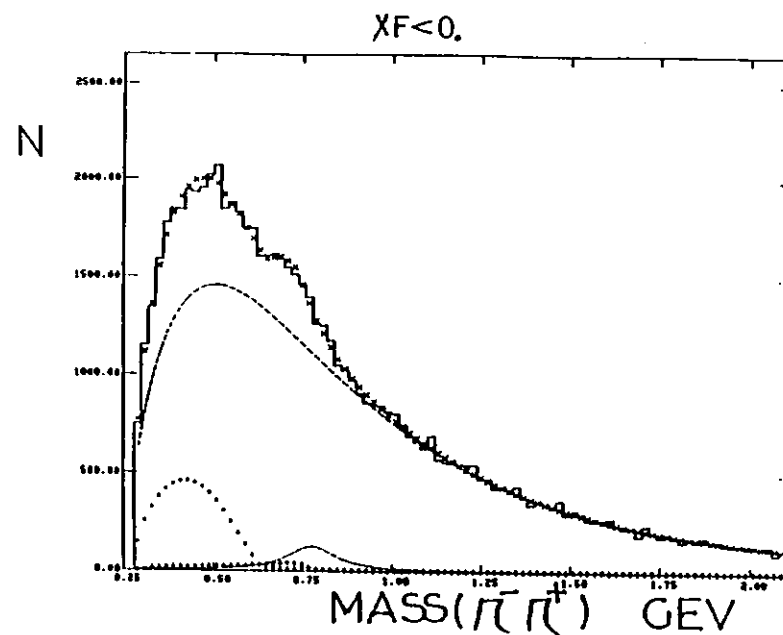
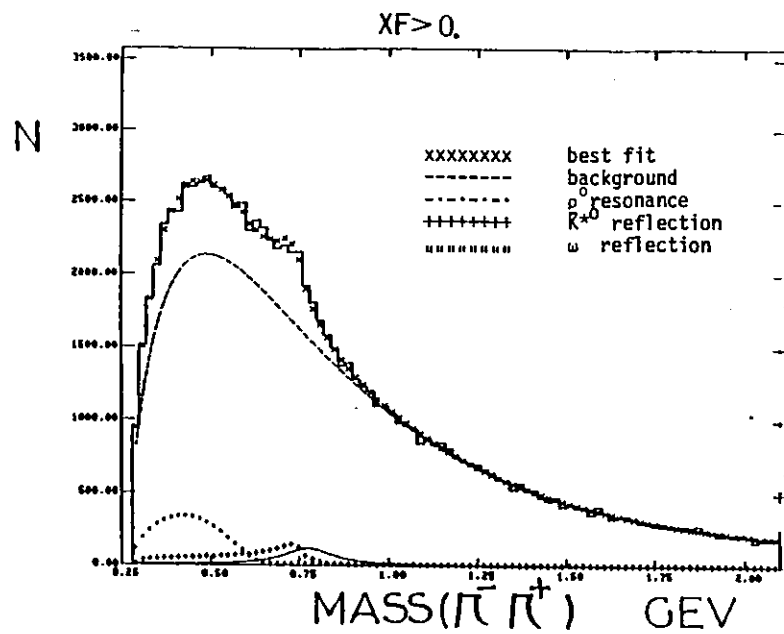
FIG(7.15)



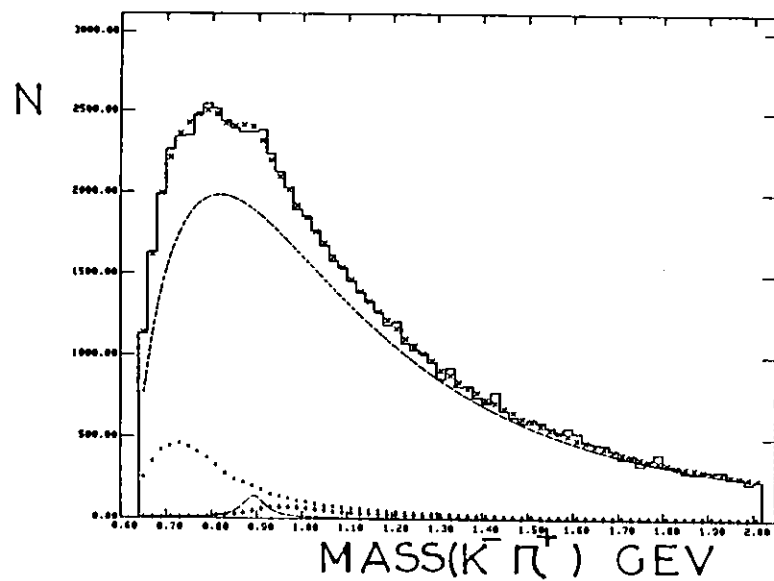
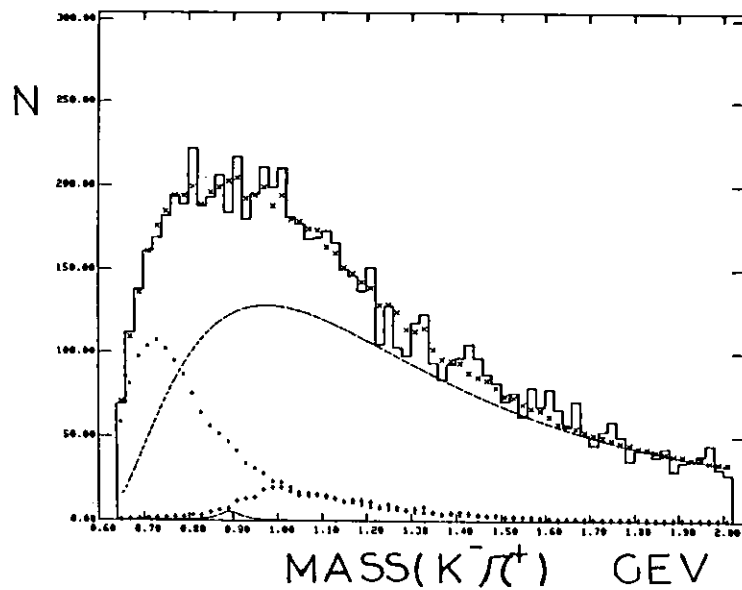
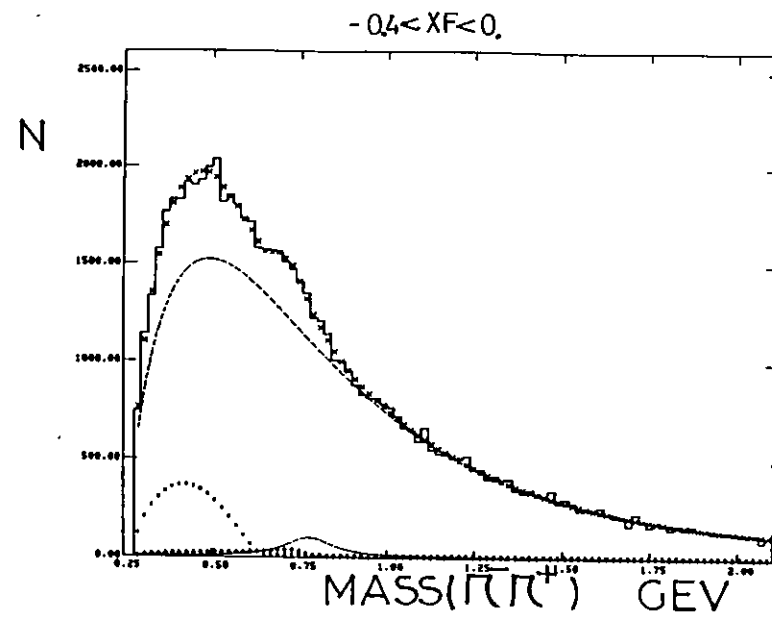
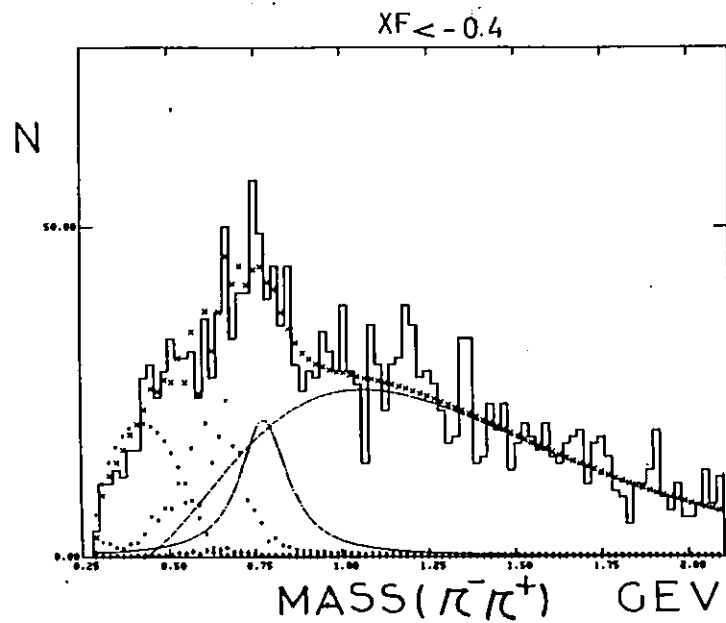
FIG(7.16)



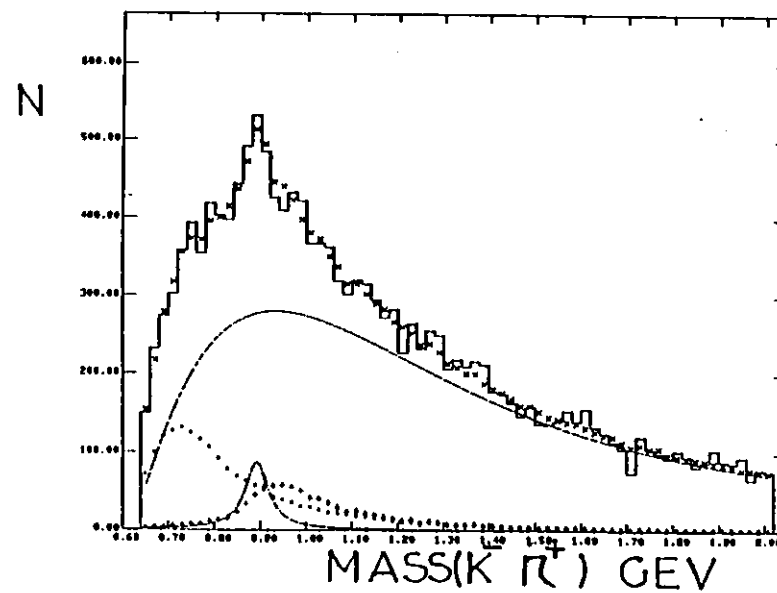
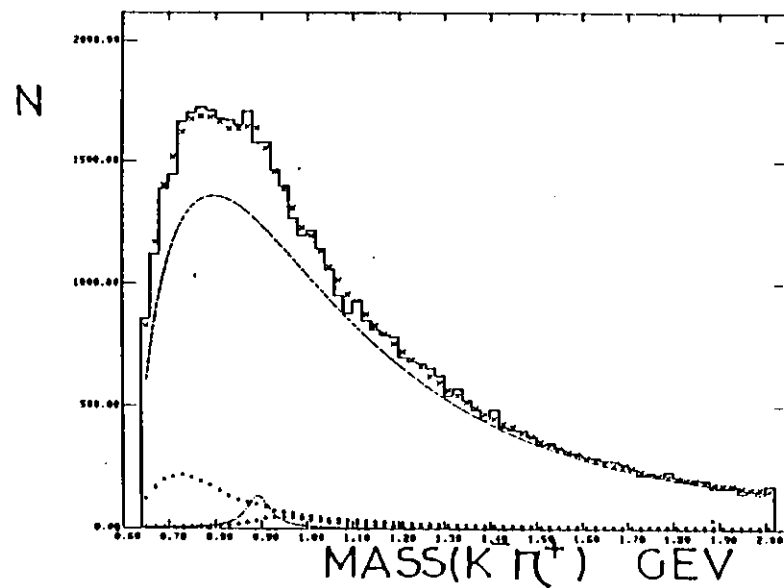
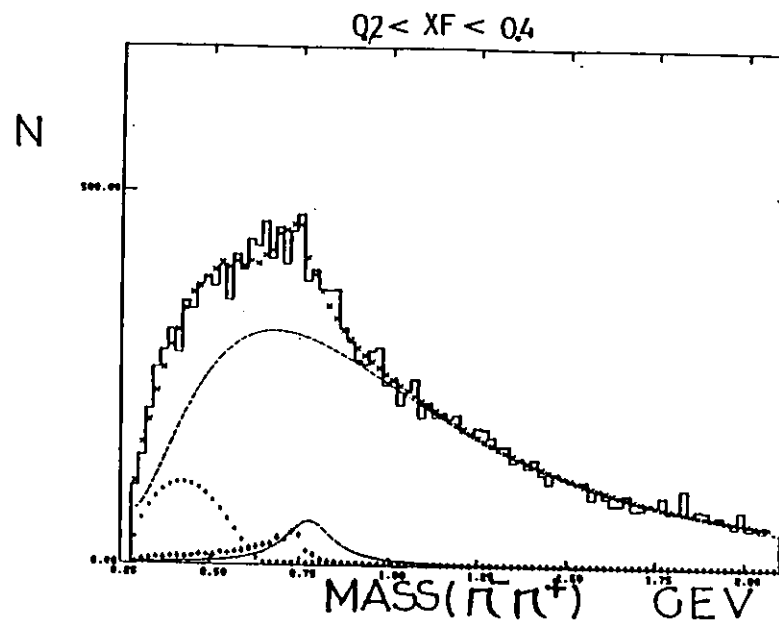
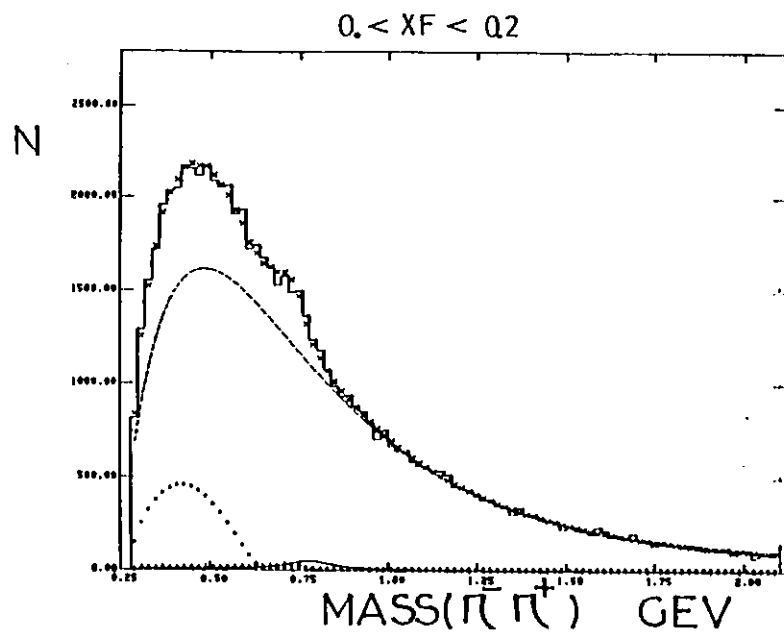
FIG(7.17)



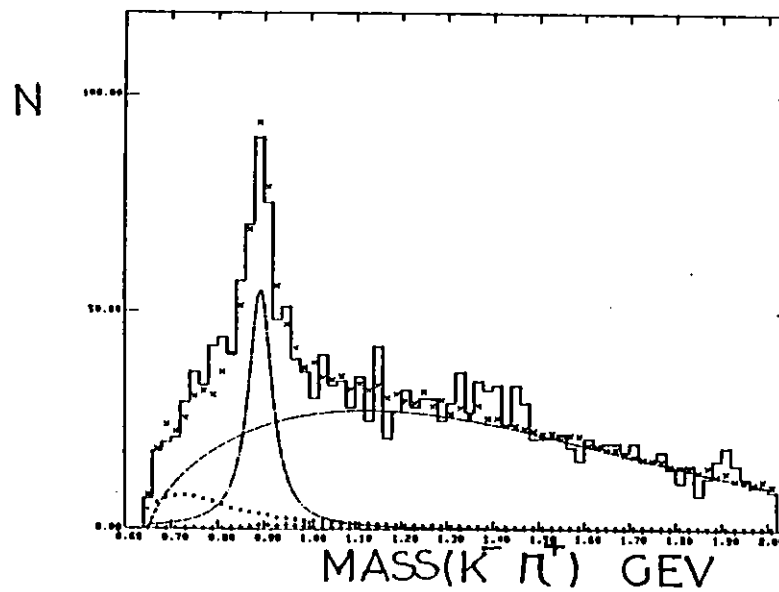
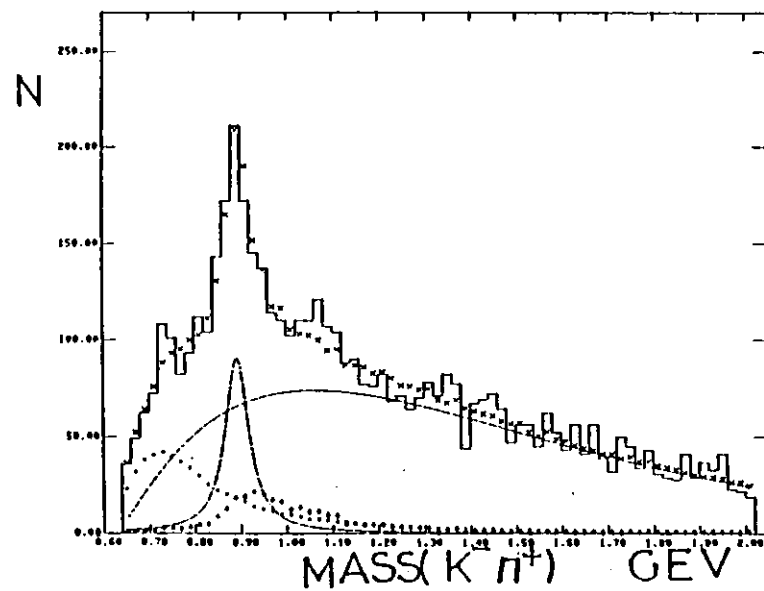
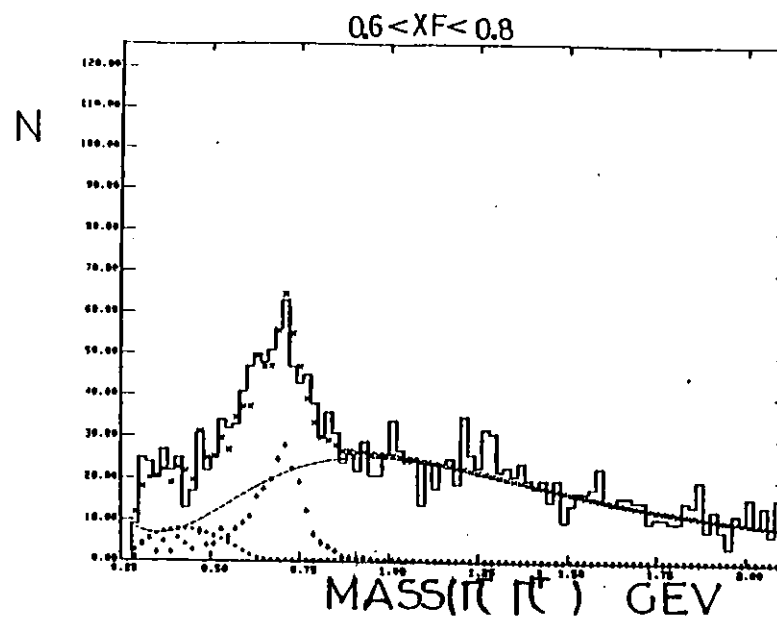
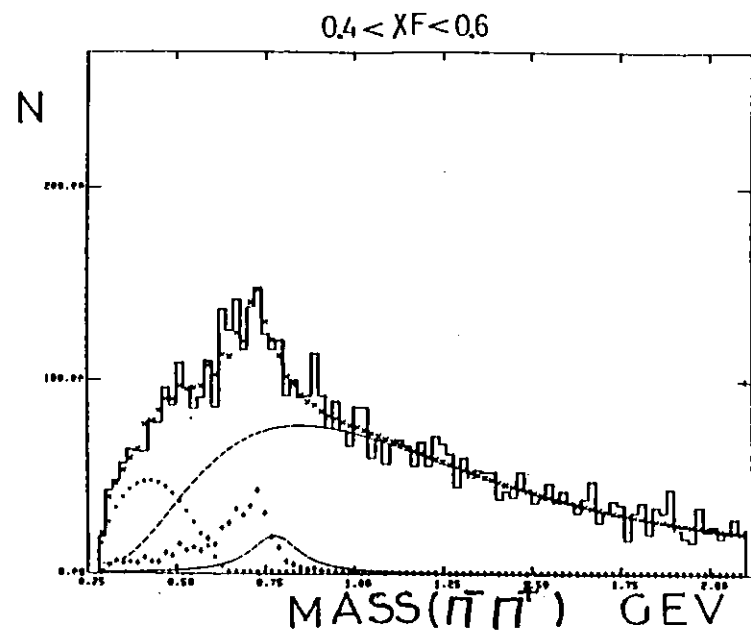
FIG(7.18)



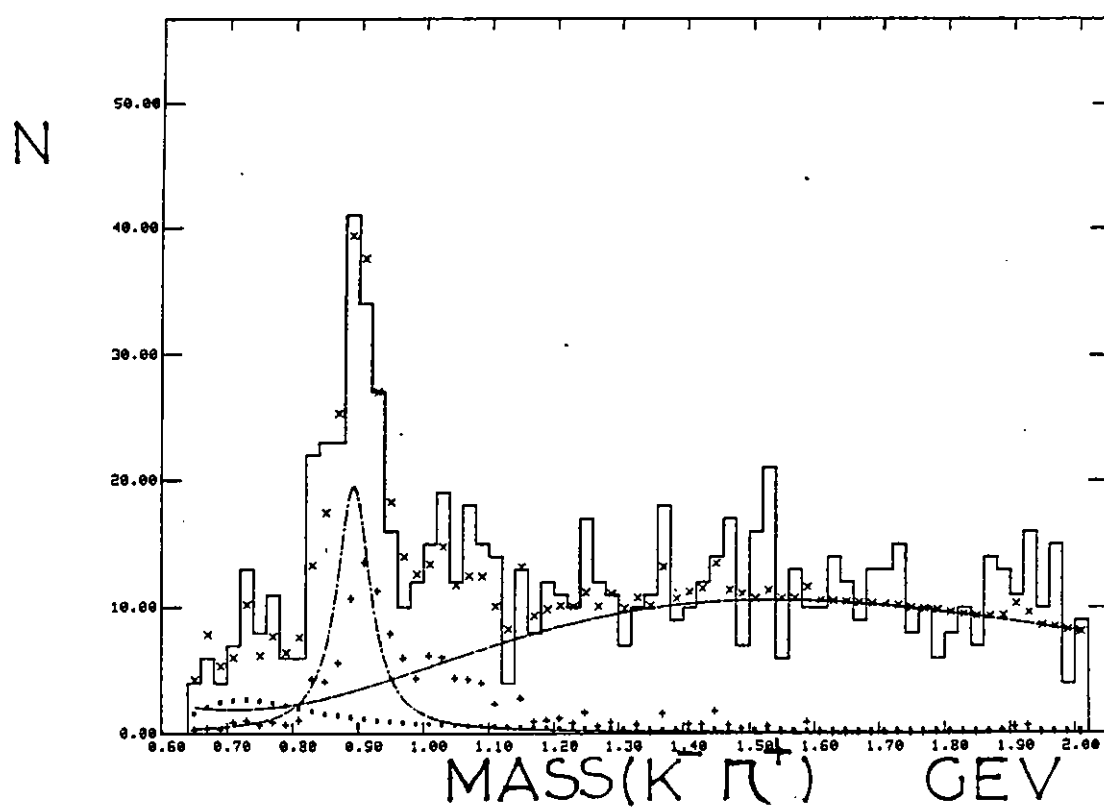
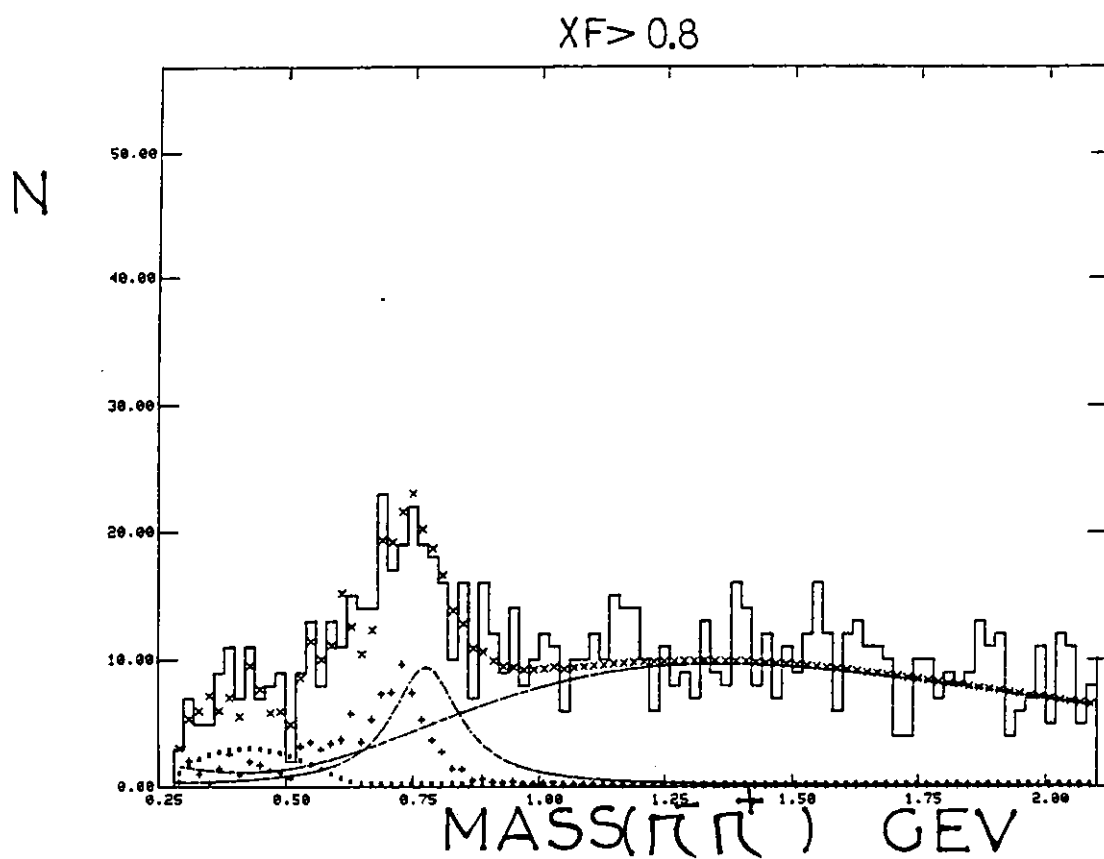
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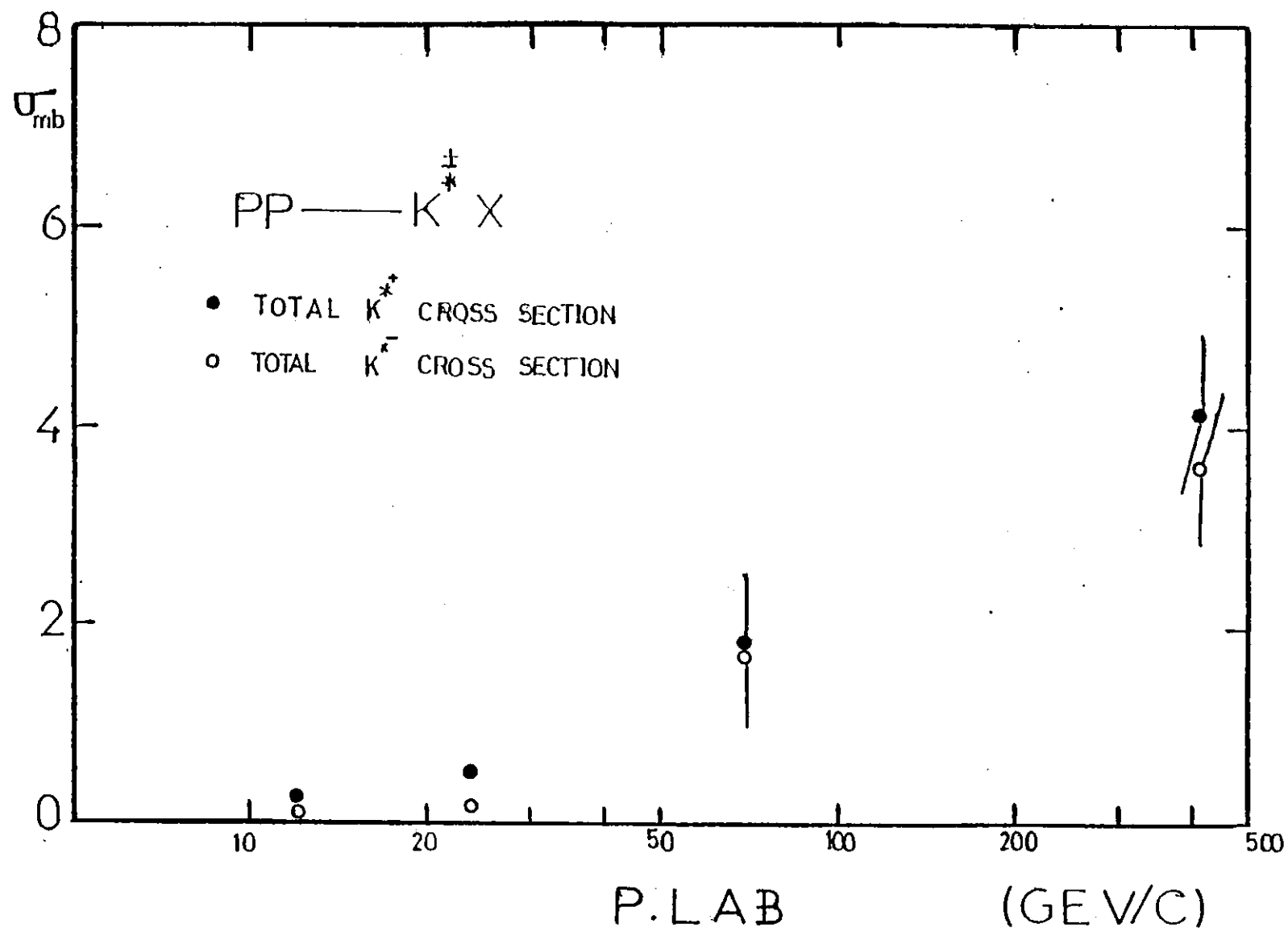
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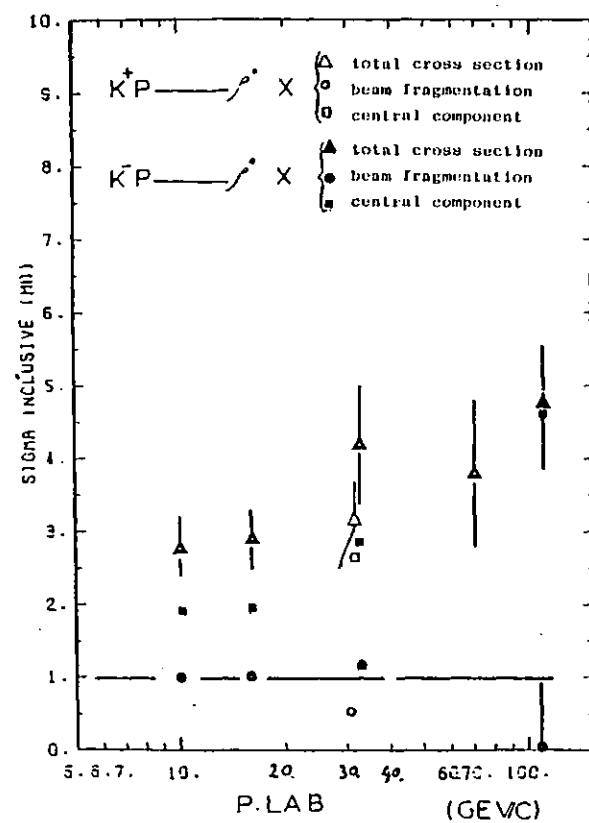
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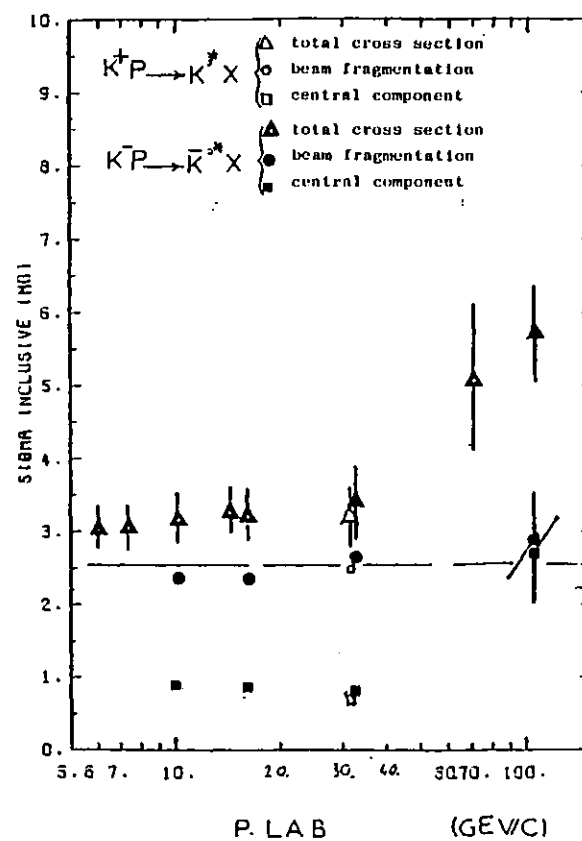
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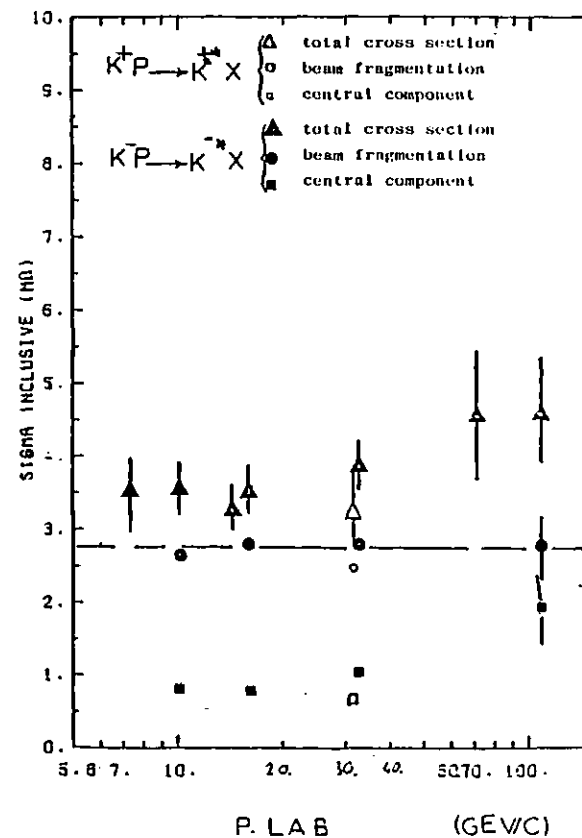
FIG(7.19)



a.

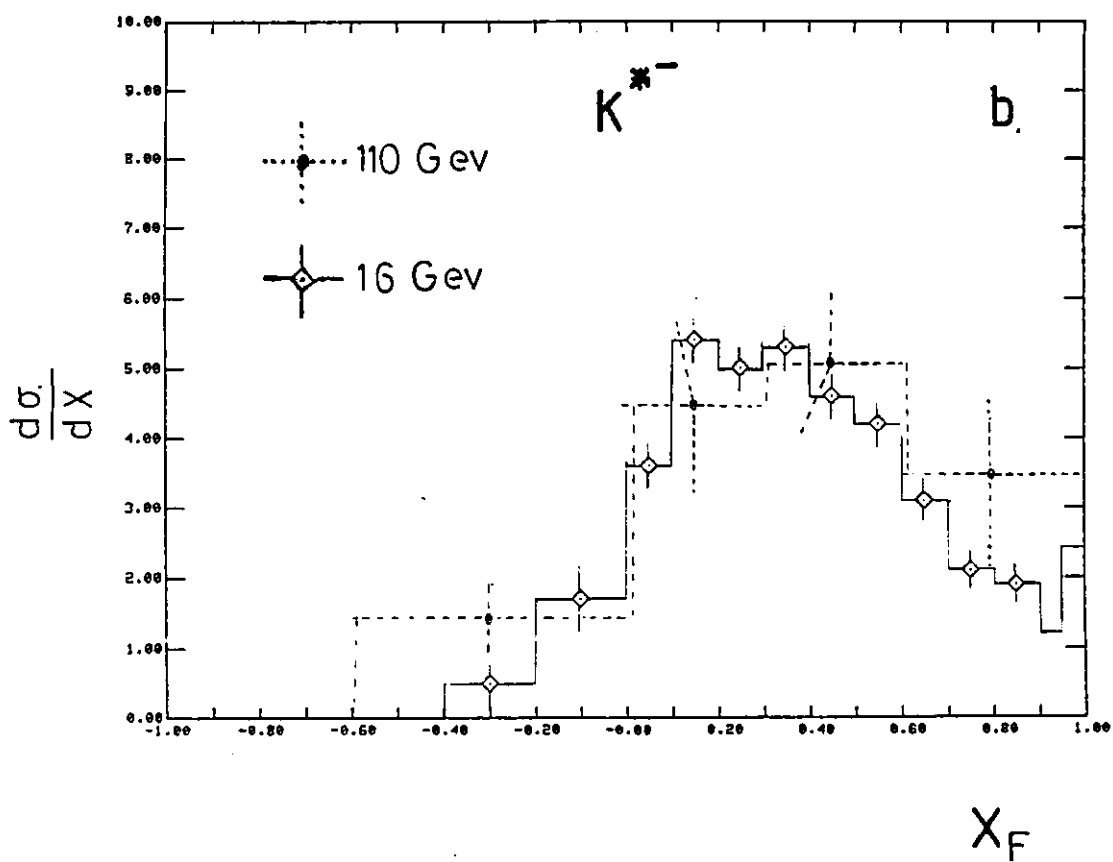
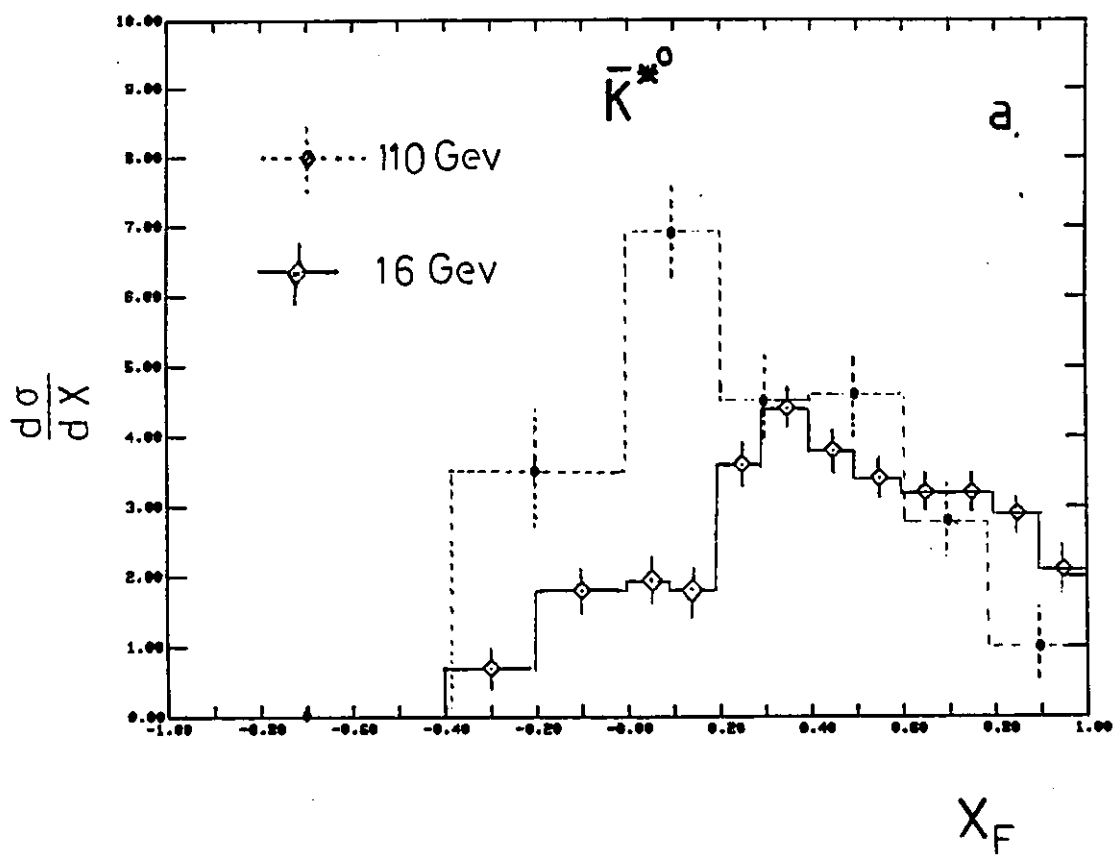


b.

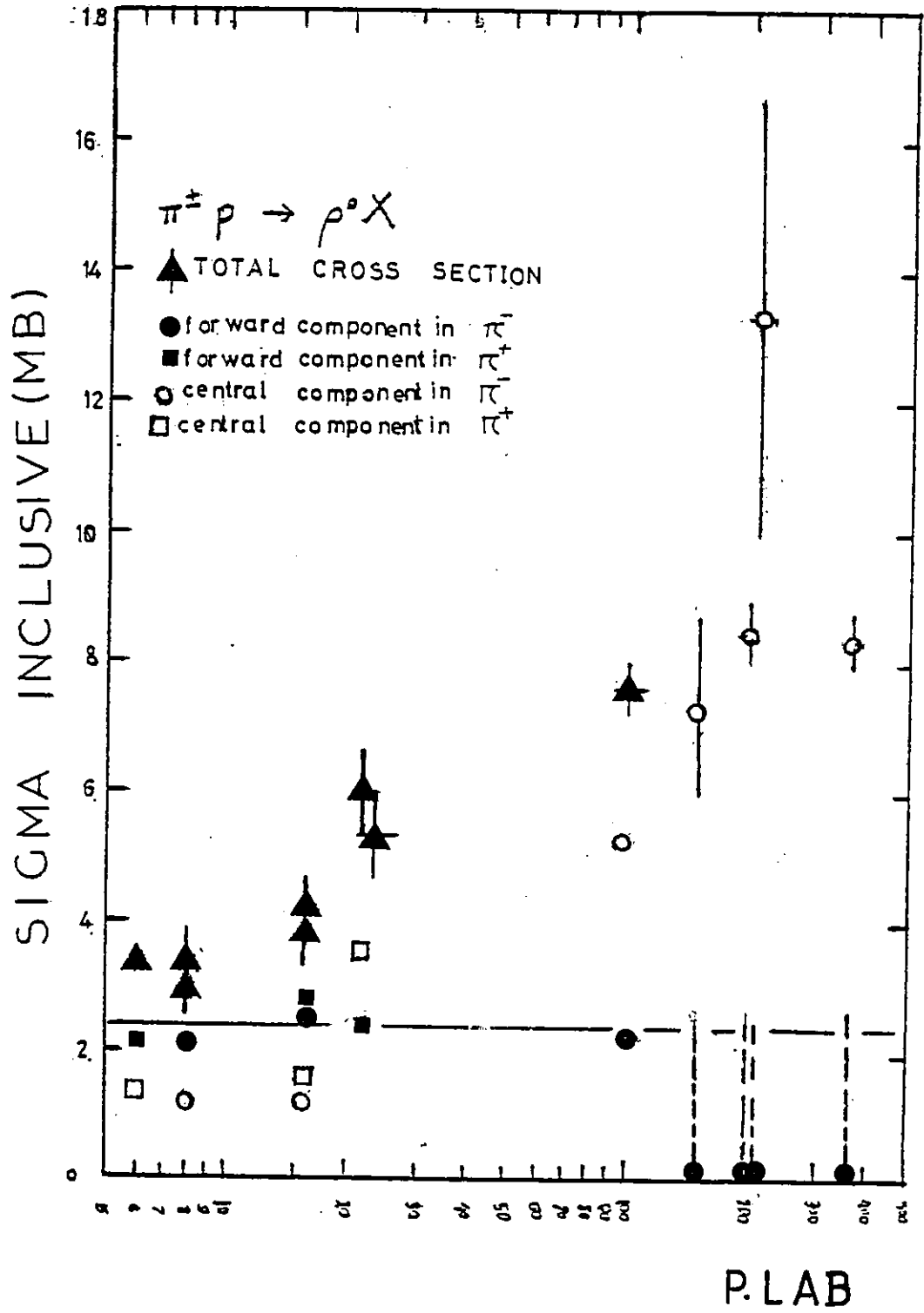


c.

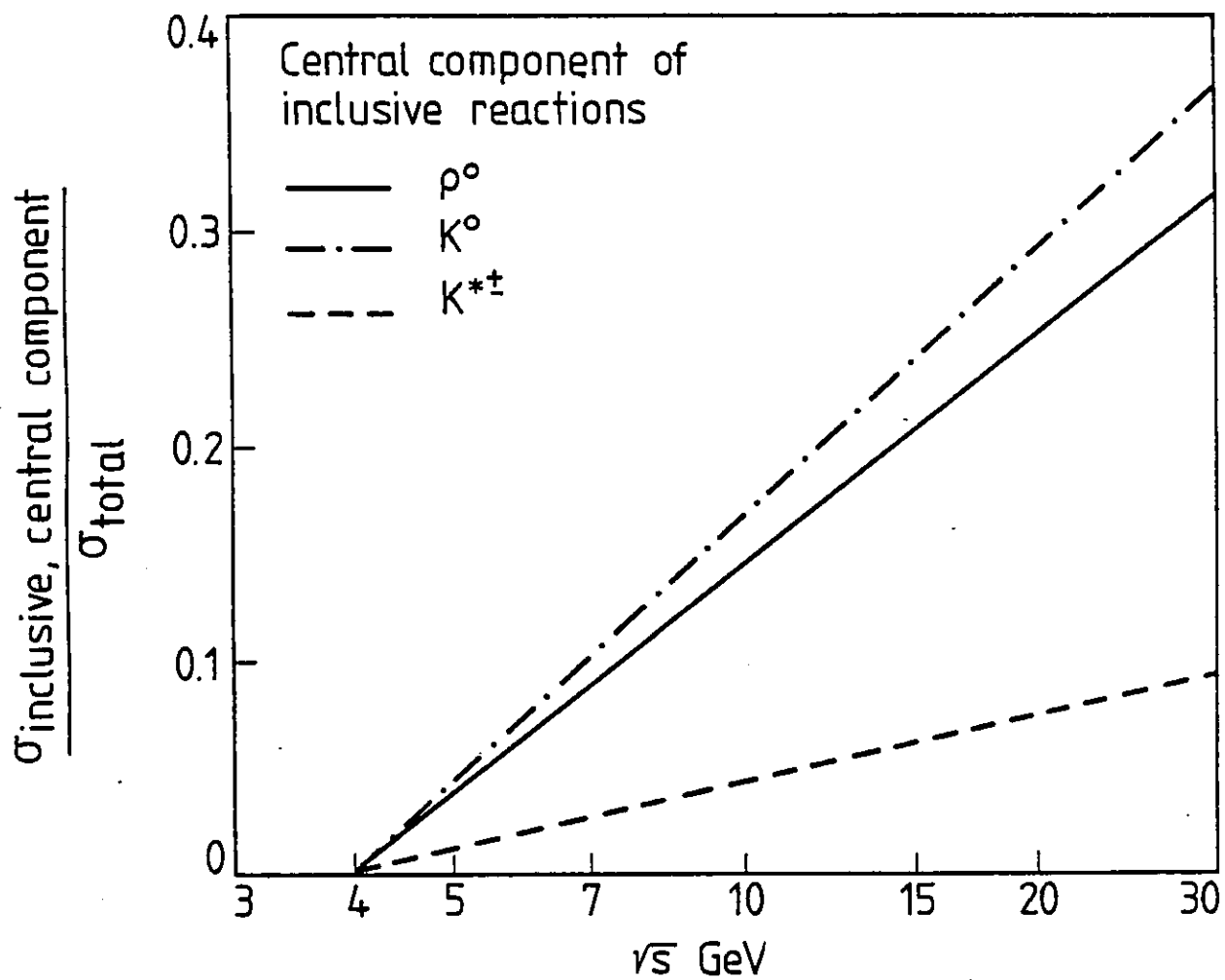
FIG(7.20)



FIG(7.21)



FIG(7.22)



FIG(7.23)

Acknowledgements

I would like to express my thanks to Professor I. Butterworth for giving me the opportunity of working in the H.E.N.P. Group at Imperial College. It gives me pleasure to acknowledge the assistance of my supervisor, Dr. K.W.J. Barnham, who has offered much valuable advice on all aspects of the subject. Thanks also to P. Wright, E. Clayton, of Imperial College, and J. Wells of Oxford for their assistance during the past four years.

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