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ANTIPROTON-PROTON INTERACTIONS

AT 7.3 GeV/c

G.D. PATEL

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of the University of Liverpool for the
degree of Doctor in Philosophy

by

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ABSTRACT

This thesis describes the processing and partial analysis of a high statistics $\bar{p}p$ experiment at 7.3 GeV/c. An absolute determination of the total and topological $\bar{p}p$ cross sections is made and compared with other data. Charged particle ambiguities are treated and non-strange exclusive channel cross sections calculated.

Inclusive total, topological and differential cross sections for neutral strange particles (K_s , Λ , $\bar{\Lambda}$) and γ 's are presented after a description of the corrections made to the sample. Inclusive two strange particle cross sections are used to consider strange particle production in $\bar{p}p$ annihilations.

Inclusive charged particle (p , π) cross sections are calculated and compared with an independent determination using a statistical technique on the same data. The separated sample is used to study inclusive π^+ , π^- production in annihilations and non-annihilations and comparisons with simple quark recombination ideas made.

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Chapter I

INTRODUCTION

This thesis describes the processing and partial analysis of a high statistics antiproton-proton bubble chamber experiment at 7.3 GeV/c carried out at CERN (the European Centre for Nuclear Research), Geneva. The experiment was performed in collaboration with groups from Amsterdam, Athens and Vienna [1.1]. A total of 1.1 million pictures were taken in the 2m Hydrogen Bubble Chamber (HBC) in two separate exposures in November 1975 and May/June 1976, of which approximately 300000 pictures came to Liverpool.

This experiment was one of a long series of $\bar{p}p$ experiments undertaken by Liverpool, in collaboration with various groups, aimed primarily at studying the annihilation process over a range of energies [1.2-1.12]. The two earliest of these were low energy formation experiments in the incident $\bar{p}$ momentum range 1.2-2.0 GeV/c. After these, intermediate energy experiments at 2.5, 4.6 and 9.1 GeV/c were performed, followed by experiments at 3.6 and 12 GeV/c and the high statistics experiment at 7.3 GeV/c described in this thesis. More recently a very high energy $\bar{p}d$ experiment at 100 GeV/c in the 30" chamber at FNAL (Fermi National Accelerator Laboratory), and a 70 GeV/c $\bar{p}p$ TST (Track Sensitive Target) experiment in BEBC (Big European Bubble Chamber) studying direct lepton production have been

performed and currently experiments in the range 200-400 GeV/c using a streamer chamber detection system are running at CERN.

There are three distinct stages in a bubble chamber experiment: (i) exposure of the film, (ii) extraction of data from the film and (iii) analysis of the data. Whilst the first stage is short, typically a few weeks, the second and third stages usually extend over several years. After a brief description of the experimental runs at CERN, during which the film was taken in Chapter 2, an account of the data production system in Liverpool is given in Chapter 3. This describes the extraction of data from the bubble chamber film, through measurement and reconstruction of events, to the preparation of a DST (data summary tape) containing information about the events in a form suitable for analysis.

Chapter 4 describes the determination of absolute values of total and topological cross sections from the scanning data and the various correction factors applied, the largest being for the loss of two prong elastics in the small four-momentum transfer region ($|t| < 0.04 \text{ (GeV/c)}^2$). An independent determination of the total cross section by fitting the x distribution of primary vertices of a sample of measured events is then given and the results compared with the trend of existing data.

Before exclusive channel cross sections can be calculated it is necessary to resolve charged particle ambiguities

which arise because of the difficulty of identifying particles at high laboratory momenta. The method employed is described and in particular the identification of annihilation events considered. Annihilations form a substantial part ($\approx 36\%$) of the total inelastic cross section at this energy and such a separation is feasible as it was previously performed in the 9.1 GeV/c experiment [4.7]. A recent $\bar{p}p$ experiment at 8.9 GeV/c in the SLAC Hybrid Facility [1.13] employing downstream detectors to identify non-annihilation events has confirmed the separation results of [4.7]. In higher energy $\bar{p}p$ experiments no such separation is possible and $(\bar{p}p - pp)$ differences have to be used. [1.13] also have pp data taken in the same experiment and have been able to compare direct annihilation measurements with $(\bar{p}p - pp)$ differences [6.10]

In the 4.6 and 9.1 GeV/c $\bar{p}p$ experiments V^0 events and γ 's were not originally measured. A sample of V^0 's and γ 's were subsequently processed and results, with rather low statistics, were published [5.4]. In this experiment all event types were measured from the outset and the kinematic fitting made as general as possible. The V^0, γ statistics are therefore rather better than in the earlier experiments.

In Chapter 5 the procedures use to obtain an inclusive, unambiguous sample of V^0 's and γ 's are described and inclusive and semi-inclusive cross sections calculated after corrections for losses. The longitudinal and transverse differential properties of production, $F(x)$ and $d\sigma/dp_t^2$ are

calculated and found to be in agreement with results at 4.6, 9.1 and 12.0 GeV/c. The K_s sample is separated and found to be 80% annihilation compared to 96%, 70% and 55% at the energies mentioned previously. Inclusive two strange particle cross sections, where at least one is a V^0 , are calculated. Strange particle production in $\bar{p}p$ annihilations is considered using the two strange particle cross sections.

There exists a statistical technique, originally used in pp reactions [6.1, 6.2], which allows inclusive charged particle distributions to be determined making use only of the momentum and charge measurements and neglecting any information on particle identification. The original method for pp reactions relied on the fact that charged particle spectra should be forward-backward symmetric in the centre of mass system (CMS) and assumes that the final states only contained two types of charged particles (p, π to first approximation). The method has been extended to $\bar{p}p$ interactions using their charge conjugation symmetry in place of the forward-backward symmetry of pp interactions by Karimaki [6.3]. In Chapter 6 this method has been used to find the inclusive charged particle cross sections and the results compared with the values obtained from the separated data of Chapter 4.

There is good agreement in the results of the two methods and the separated sample is further used to study inclusive pion production in annihilations and non-annihilations. The $(1-x)^n$ dependence of the π^+, π^- invariant cross sections are

determined and comparisons made with the simple quark counting prescription of Brodsky and Gunion [6.5]. Particle ratios, or more strictly ratios of particle invariant cross sections, $F(x)$, are given and found to be in agreement with simple constituent quark expectations.

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- 1.1 (a) Zeeman Laboratory, Amsterdam.
 (b) Nuclear Research Centre 'Demokritos', Athens.
 (c) University of Athens, Athens.
 (d) Institute of High Energy Physics, Vienna.
- 1.2 1.2-1.6 GeV/c T129
 CERN - College de France - Lausanne -
 Liverpool - Neuchatel - Oslo - Padova
 - IPN/Paris - LPNHE/Paris - RHEL.
- 1.3 1.5-2.0 GeV/c T144
 CERN - College de France - Liverpool -
 IPN/Paris - Rome - Saclay.
- 1.4 2.5 GeV/c T89
 Athens - CERN - Demokritos - Liverpool
 - EP/Paris - IPN/Paris - Stockholm.
- 1.5 4.6 GeV/c T145
 Athens - Liverpool - Stockholm.
- 1.6 9.1 GeV/c T184
 Liverpool - Stockholm
- 1.7 3.6 GeV/c T80
 CERN - Paris - Liverpool.
- 1.8 12.0 GeV/c T226
 Amsterdam - Helsinki - Liverpool -
 Stockholm.
- 1.9 7.3 GeV/c T237
 Amsterdam - Athens - Demokritos -
 Liverpool - Vienna.
- 1.10 100 GeV/c FNAL
 Liverpool - Vanderbilt - Stockholm.
- 1.11 70 GeV/c BEBC
 Brussels - Mons - Helsinki - Stockholm
 - Liverpool.
- 1.12 200-400 GeV/c NA5
 Bari - Krakow - Liverpool - Munich
- 1.13 Exclusive Annihilation Processes in 8.9 GeV/c $\bar{p}p$
 Interactions and Comparisons Between $\bar{p}p$
 Non-Annihilations and pp Interactions. D.R.Ward et al.
 Cambridge HEP 80/2.

Chapter II

FILM ACQUISITION - CERN

2.1 INTRODUCTION

It is an unavoidable feature of experimental High Energy Physics that large and complex equipment is required for the investigation of the fundamental forces of nature. That the installation and maintenance of the necessary accelerators and experimental facilities would be beyond the financial resources of the individual European nations was apparent by the late 1940s. Thus it was that CERN (the European Centre for Nuclear Research) came into existence 26 years ago. Located near Meyrin, Geneva it has successfully provided the facilities and expertise for the home institutes of all the member nations.

Permanent CERN staff maintain and operate the accelerators and, in the case of a bubble chamber experiment, the initial beam tuning and the operation of the bubble chamber is also performed by resident experts. Consequently the visiting physicists who will subsequently extract and analyse the data from the film played a relatively minor role in the experimental run, performing routine monitoring of the beam and quality checks on the film being taken. Accordingly, only a brief description of this stage of the experiment is given.

2.2 THE ANTIPROTON BEAM

The CERN proton synchrotron (PS) [2.1] was fed with 50 MeV/c protons by a two stage pre-acceleration system consisting of electrostatic and linear accelerators. In the synchrotron 20 bunches of protons were accelerated to the maximum PS momentum of 28 GeV/c in a cycle time of approximately 2.4 seconds. One bunch was then ejected onto the external metal target of the high energy, radio frequency (RF) separated U5 beam.(Figure 2.1)

From the secondary particles produced at the target, the beam line selected antiprotons of the required momentum and transported them to the bubble chamber.(Figure 2.2). Initial momentum selection of particles of the correct charge was achieved by a system of bending magnets and collimators. Two RF cavities (RF1 & RF2 on Figure 2.2) performed the mass definition, deflecting only particles of the required mass past the beam stopper [2.2]. Final momentum selection was performed by another bending magnet and collimator in order to further reduce contamination, due principally to muons coming from the decay of pions and kaons. Throughout the line, the beam shape was controlled by a series of quadrupole magnets and final optics produced a beam which was centrally positioned in the horizontal plane and well spread in the vertical plane at the bubble chamber.

2.3 THE BUBBLE CHAMBER

The CERN 2m Hydrogen Bubble Chamber (HBC), [2.3], served as both the target and the detector in this experiment. It had dimensions of 200 x 50 x 50 cm. and was filled with liquid hydrogen at a pressure of 6 atmospheres and a temperature of 27 K, see Figures 2.3 a-c.

The chamber was triggered by a signal from the PS indicating the imminent arrival of a burst, when it was expanded to a pressure of 2 atmospheres converting the liquid hydrogen to a superheated state. Any charged particle traversing the liquid ionised atoms along its path, forming potential nucleation centres on which local boiling of the superheated liquid was liable to occur. After a few milliseconds the bubbles forming on these centres had grown to a photographable size and three flash tubes were fired simultaneously, illuminating the chamber. This was photographed in stereo by three cameras recording any interactions which might have occurred. The chamber was then recompressed, destroying the bubbles, in preparation for the next burst in a cycle time of about one second. Figure 2.4 shows schematically the chamber conditions through one cycle.

The whole chamber was set in a large electromagnet providing a uniform 1.7 tesla field aligned along the z-axis, this curves all charged tracks in the x-y plane and allows their charge and momenta to be determined. See Figure 2.3(b) for a definition of the chamber co-ordinate

system. In order to relate the information on the three stereoscopic views there were fiducial marks etched on three of the glass faces and their positions relative to the cameras were accurately measured.

Also appearing on each photograph (Figure 2.5) was a data box recording the date of exposure, camera number, beam particle and momentum, and roll and frame numbers (in both decimal and binary form). Brenner marks appear at the beginning of each frame and are used by automatic measuring machines (such as the F.S.D. - see 3.4) to locate and position the frame correctly before measuring.

2.4 THE EXPERIMENTAL RUNS

The film for this experiment was taken in two separate exposures in November 1975 and May/June 1976 respectively. Throughout these runs the experimental conditions were constantly monitored by groups of visiting physicists from all the laboratories involved in the collaboration. We were responsible for maintaining the optimum beam conditions set by the CERN specialists during the beam tuning at the beginning of the runs and also for ensuring that the film being taken was of the desired quality.

The monitoring of the beam was greatly facilitated by a PDP9 computer, situated in the beam control room. [2.4] This logged all quadrupole and bending magnet currents, collimator settings, and RF separator phase settings on request, indicating any which had deviated seriously from

their preset values in the printout. The computer was also capable of performing a phase scan of the RF separators, a great help as a manual scan could be very time consuming. These phase scans were a necessary part of the routine and were performed periodically to determine the correct phase setting for the RF separators which varied slowly because of external conditions, such as the temperature for example.

As each roll of about 3200 frames was completed, a short strip of roughly 20 frames cut from the end was developed immediately and delivered to the physicists on shift. It was their responsibility to scan these test-strips and ensure that the quality of the pictures was of the required standards. The film advance, uniformity of flash illumination, visibility of fiducial marks, focus and contrast, and legibility and accuracy of the data box information were all checked.

Each frame was then scanned and the number and spread (distribution in y) of the incoming beam tracks was recorded as was the number and topology of any interactions found. In addition a check was performed on the depth in the chamber of the beam tracks, ideally this should be central at $z = -25$ cm. Finally the bubble density of minimum ionizing (beam) tracks was checked using a small microscope with a graduated scale. Earlier experience of scanning and measuring 2m HBC film had shown that 14 bubbles/cm. on film was an optimum value, this value was achieved and maintained by variation of the pressure change and temperature as the

bubble density depends on the degree of superheating of the liquid.

From the scanning information, plots of number of beam tracks per frame (ideally 9), interactions per frame, and tracks per interaction as a function of roll number were made. This information was used to estimate the beam contamination (assumed to be entirely muons, see Appendix A) for each roll and was a useful check as large increases in the estimated contamination could often be rectified by the PS control room crew redirecting the primary PS beam onto the external metal target at the beginning of the U5 beam. The first two hundred frames of every fifth roll was taken with the 'RF off' for a more accurate evaluation of the beam contamination at a later stage (4.2.2).

In order to achieve the high statistics required for this experiment double pulsing was employed on the second run. This meant that two bunches were delivered to the U5 beam on each PS cycle thus doubling the picture taking rate. The two bunches were of course sufficiently well separated in time so as to allow for the recycling of the bubble chamber.

The sensitivity of the beam stopper transmission to the phase conditions of the RF separators provided an accurate method of determining the beam momentum [2.2]. This was found to be 7.235 ± 0.030 and 7.220 ± 0.030 at the entrance to the chamber ($x = -70.0$ cm.) for the first and second runs respectively.

Approximately 1.1 million pictures were taken during the two exposures. The first batch was divided equally between the four groups University of Athens; Nuclear Research Centre "Demokritos"; Liverpool and Vienna. Amsterdam joined the collaboration at a later date and received 100000 pictures of the second batch, the remainder again being divided equally between the above four groups.

2.5 REFERENCES

- 2.1 "Proton synchrotron of 28 GeV/c". CERN Technical Notebook No. 2
- 2.2 "Particle separation with two and three RF separators at CERN". CERN Yellow Report 68-29
- 2.3 CERN 2m HBC Handbook.
- 2.4 "Computer aided control of separated bubble chamber beams". CERN Yellow Report 74-1.

2.6 FIGURES

2.1 General layout of bubble chamber beams in the East Hall.

2.2 Layout of the RF separated high energy U5 beam.

2.3 a) The 2m HBC.

b) Orientation of chamber co-ordinate system and camera positions for 2m HBC.

c) Vertical and horizontal sections of 2m HBC.

2.4 A schematic graph of one complete bubble chamber cycle.

2.5 A typical bubble chamber photograph taken during the first run.

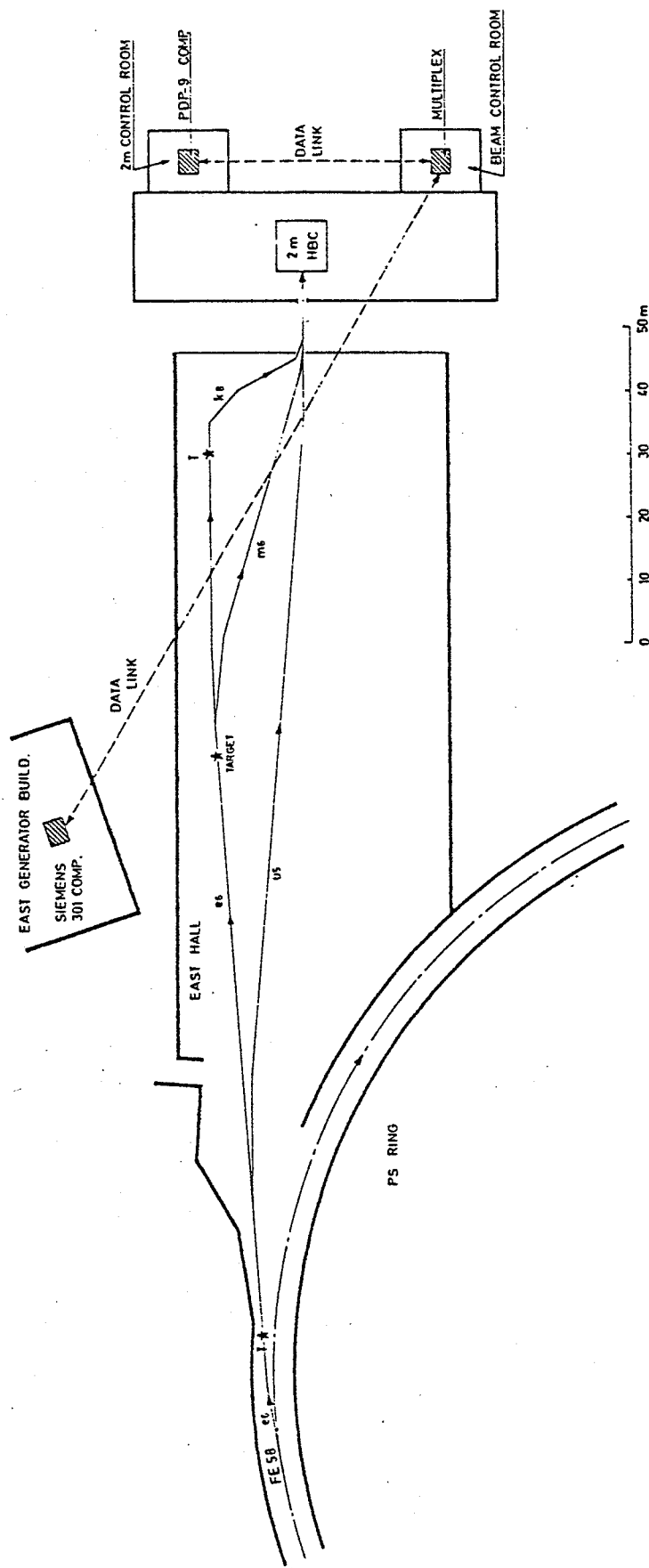


Fig. 2.1 General layout of the bubble chamber beams in the East Hall.

101, 101, 101, 101

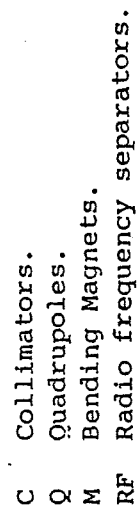


Fig.2.2.2 Layout of the RF separated high energy U5 beam.

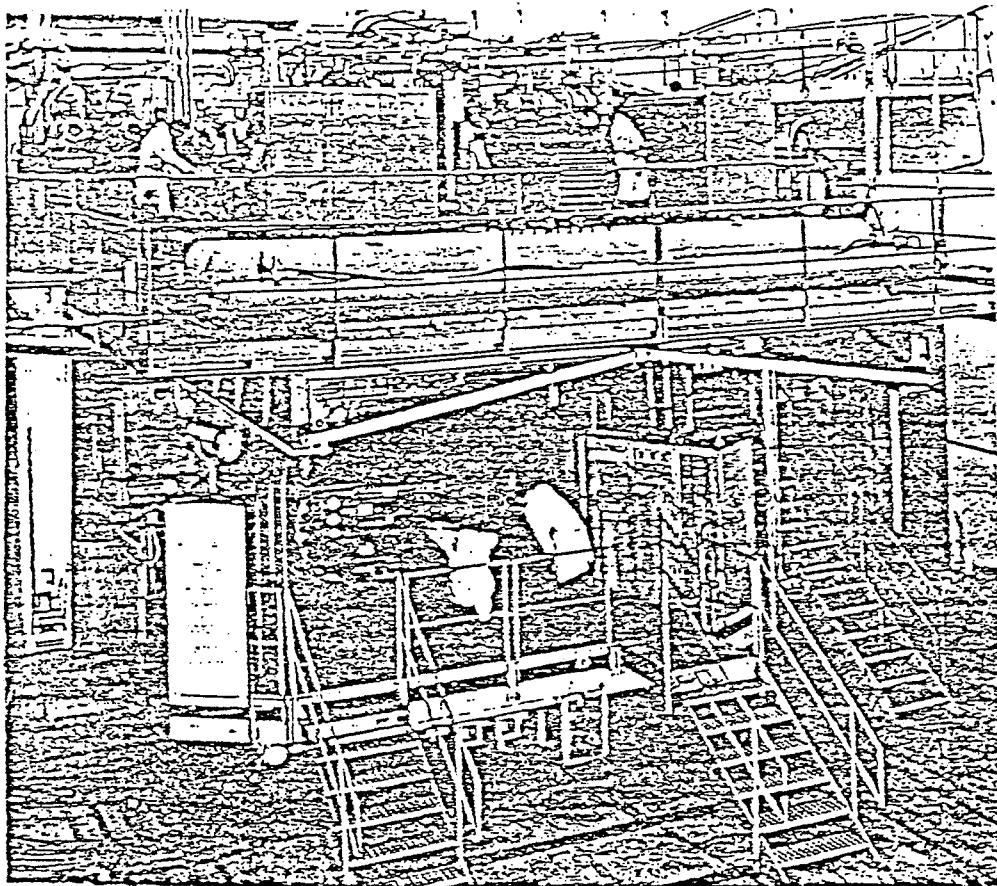


Figure 2.3a The 2m HBC.

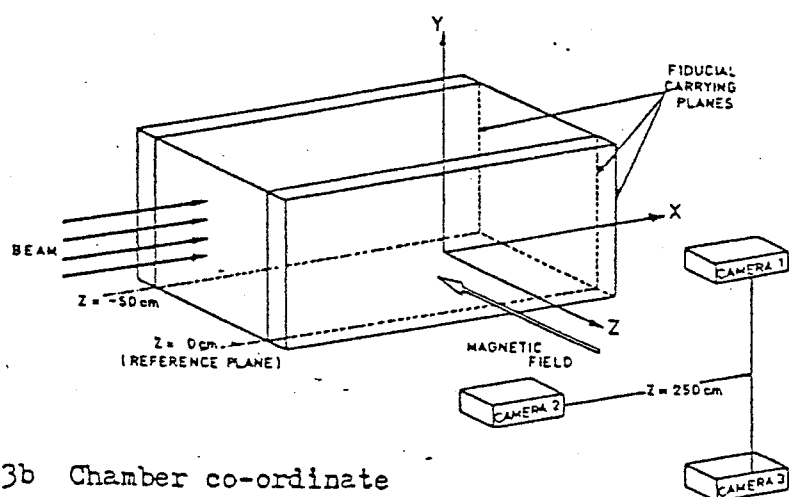


Figure 2.3b Chamber co-ordinate system and camera positions.

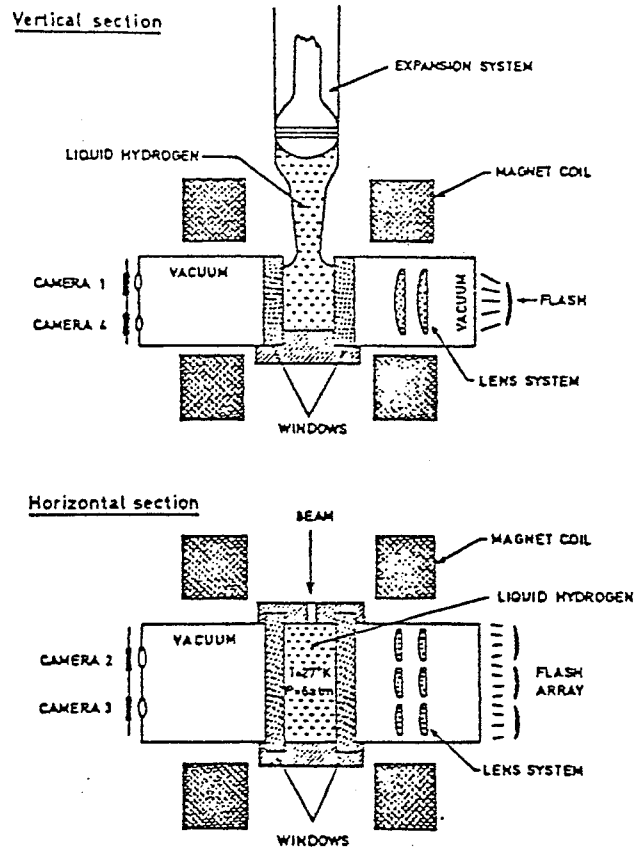


Figure 2.3c Vertical and horizontal cross sections of the 2m HBC.

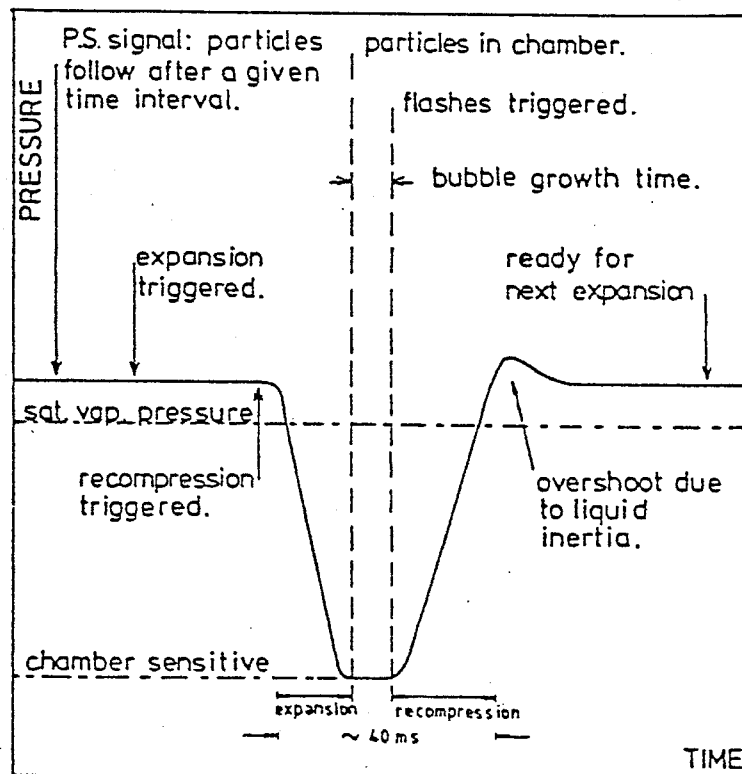
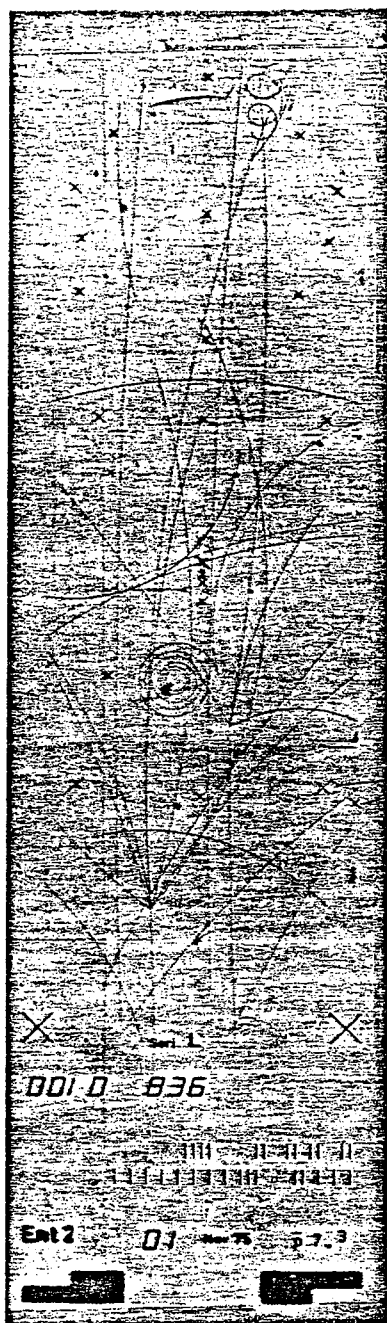


Figure 2.4 A schematic graph of one bubble chamber cycle.



Fiducial marks

Beam in

Frame and roll number (decimal)

Roll number (binary)

Frame number (binary)

View number, date, beam type and momentum

Brenner marks

- ✕ Front glass fiducials
- ✕ Front liquid/glass fiducials
- ✕ Back liquid/glass fiducials

Figure 2.5 A typical bubble chamber photograph: roll 836, frame 10, view 2.

Chapter III

DATA ACQUISITION - LIVERPOOL

3.1 INTRODUCTION

All the 1.1 million pictures for this experiment were taken in the relatively short time of six weeks. The process of extracting the information and recording it in a form suitable for analysis is by contrast a task which takes many years to complete.

The data production chain is long and complex, a flow chart representation of it is given in Figure 3.1, there are however three major stages in the process -

1. Examination (scanning) of the film for the location and identification of events of interest.
2. Measurement and geometrical reconstruction of these events in three dimensional space.
3. Particle identification and production of a data summary tape (DST).

3.2 SCANNING

It was for the physicist to define the criteria by which the film was to be scanned and the "events of interest" to be recorded. As this was to be a high statistics experiment we wanted to categorise as many event types as possible and record the rarer configurations (for example events with decaying track and V^0 's) which had been neglected in earlier experiments.

Successful reconstruction of an event requires the measurement of sufficient track length for accurate momentum determination (most especially fast tracks), a scanning region was defined by certain fiducials on view 2 (Figure 3.2), and those primary events outside this region, and hence near the edge of the film, were ignored. However associated secondary features such as V^0 's, secondary interactions, charged track decays and neutron stars were always noted irrespective of their position on the frame provided only that the primary vertex lay within the scanning region.

Any interactions produced by non-beam tracks (i.e. incoming tracks which were not strictly parallel to the other beam tracks) were ignored. (Though later analysis will show that not all events in this category could be rejected at the scanning stage). N prong events in which two of the tracks were unambiguously identified as an electron pair were recorded as (N-2) prongs; a note of the Dalitz pair being made. The electron-positron tracks were subsequently ignored at the measuring stage.

Basically six different classes of event were to be recorded. (See Figures 3.3 a-f for examples) -

1. 'Ordinary' events with no kind of associated secondary feature.
2. Events with associated V^0 's. (including γ 's).
3. Events with one or more tracks undergoing a secondary interaction of any multiplicity.
4. Events with one or more decaying tracks.

5. Events with an associated neutron star.

6. Events with a stopping track.

These classes and some combinations of them were given unique scan type numbers as shown in Table 3.1. However some event configurations occurred for which no scan type number was defined, for example an event with a secondary interaction, stopping track and a V^0 . In such cases the event was reduced to one of the categories given in Table 3.1 according to the following hierarchy -

1. All V^0 's must be noted.
2. Then decays (1 or 2) together with V^0 's (0,1 or 2)
3. Then all neutron stars.
4. Then all secondary interactions.
5. Then all stopping tracks.

Thus the example would be recorded as an event with a secondary interaction and a V^0 , though the 'missing' information (i.e. the presence of the stopping track) would be noted as a comment.

The scanning region was divided into three section (1-3), which were further sub-divided into left and right parts (Figure 3.2). This grid allowed the approximate position of the primary interaction vertex to be recorded. Each event was therefore uniquely defined by its roll, frame, event number, scan type number and approximate position on the frame.

Scanning was performed by two trained operators, viewing the projection of a roughly life-size image of a frame onto

a white topped table, two views being projected side by side. The use of two views provided an immediate cross check and aided in the classification of 'difficult' events, such as those with a steeply dipping track. Views 1 and 2 were used on the first scan and views 3 and 2 on the second, independent, scan. (View 2 being the master view, was always used.) Two independent scans and a third merge scan, to resolve any differences, are required for the calculation of scanning efficiencies. However, because of the large quantity of film to be processed in this experiment, only every tenth roll was double scanned to provide a sample from which scanning efficiencies would be calculated. In order to maintain a high single scan efficiency a count of both incoming and outgoing beams was performed on every frame and this had to correspond to the number of observed events.

Each scanning table was equipped with a display linked into the online scanning program [3.1] running on the IBM 360/65 in the Oliver Lodge Laboratory. The scanning results were immediately typed in through these displays and stored temporarily on disc and then transferred to scan master tapes each night. Thus all the scanning information was stored on magnetic tape which greatly facilitated the production of lists and summaries.

At a later stage in this experiment it was decided that only those events with associated V^0 's (excluding unambiguously identified gammas) should be processed. Summaries of all the events scanned in Liverpool before and

after this decision are given in Tables 3.2 and 3.3 respectively.

3.3 PREDIGITISING

The measuring system in Liverpool was based on an HPD Mark 2 (Hough-Powell Device) flying-spot digitiser (FSD), operated under full, or road, guidance. The FSD therefore had to be provided with the approximate positions of the tracks to be measured. This information was provided by predigitising the events on the RITA (Rapid Instrument for Track Analysis) image plane digitisers, designed and built in Liverpool by Dr. W.H. Evans. It should be noted that the RITAs were originally designed and used for full manual measurement of events and their effective measuring accuracy of 15 microns on film was well beyond the requirements of the FSD.

The RITAs operated interactively with the measuring program which runs on the IBM 1130. Two specified fiducials were measured first on each frame to define the co-ordinate transformation between the RITA and FSD systems. For each event on the measure list the operator supplied the roll, frame, event number, the scan type number and also some additional information on unambiguously identified gammas and the multiplicity of associated secondary interactions, which could not be included at the scanning stage, for permanent storage on the INDEX.

The scan type number was a pointer into a table which informed the measuring program about the number and order in

which to expect the vertices and tracks and the labels to be assigned to them. The labelling conventions are shown in Figure 3.4. All vertices were measured first and then the tracks were digitised with three well spread points per track on each of the three views. The program performed several consistency checks including a circle fit for each track on each view, a red light indicating the track had failed and needed remeasuring.

The length of track measured by the FSD was defined by the furthest predigitised point as the road ended at this point. Since the measuring error on the momentum is proportional to $1/l^2$, where l is the length of track on the table, it was important that the predigitisings were well spread along the maximum possible length of track.

The data from the RITAs was stored temporarily on the IBM 1130 disc pack and then transmitted to the IBM 360/65 each evening. The program PLANT then reformatted the data, labelled all tracks and vertices, and stored the events on disc in the correct data bank for the experiment.

The events were then sorted according to their roll, frame, event numbers and combined with previously sorted events to produce a master tape of rough digitisings by the programs SORT and MERGE.

3.4 THE FSD

The FSD [3.2] was a highly sophisticated machine designed to automatically measure bubble chamber film to a high degree of precision by scanning the photograph with a spot of laser light about $15\text{ }\mu\text{m}$ in diameter.

The laser beam was split so that whilst one spot scanned the film the other simultaneously scanned a precision picket fence grating. The film was firmly held in a gate mounted on the film stage which was driven horizontally at a constant speed past the scanning spot which swept out a fixed vertical line. Any image, such as a bubble, on the film modulated the light transmitted to the photomultiplier behind the film and the resulting signal triggered the picket fence grating counter to record the y co-ordinate of the centre of the image. The x co-ordinate was calculated from this and a knowledge of the stage position as given by a second grating system mounted between the stage and the bed of the machine.

When the angle between a track and the scanlines is less than 30° the measurement quality deteriorates and it is necessary to perform an abnormal scan (abscan) perpendicular to the normal direction.

The FSD was equipped with a rapid film transport system, the passing frames being counted by photocells, which detected the Brenner marks (Figure 2.5) and positioned the required frame in the gate.

3.5 THE FSD SOFTWARE

As previously mentioned the FSD was operated in road guidance mode, this meant that of the large numbers of digitisings produced for each frame, only those within the roads (≈ 2 mm. wide centred on the predigitised track) and around the fiducials were recorded, greatly reducing the computer storage space required.

The program SETUP prepared a batch of events, usually about 300, for measurement on the FSD. With the predigitisings master tape for input it created the roads, merged all the events on a given frame (so that they could all be measured in a single scan), and decided if an abscan was necessary, storing this information on a disc-file. If the events were being measured for the first time SETUP created a six-word record for each event in the experiment's INDEX for the frame and event information from the scan lists. (The role of the INDEX is fully described in section 3.9)

The FSD measurement of the film was controlled, on-line to the IBM 360/65 computer, by the program FUGOS (Full Guidance On-line System), which accessed the information in the SETUP disc-file and output the required digitisings to disc.

The geometrical reconstruction program THRESH cannot cope with the large numbers of digitisings produced by the FSD. The pattern recognition program HAZE [3.4] attempted to filter out the 'true' track digitisings from background

signals in the roads, which can arise from crossing tracks for example. HAZE divided each road into sections of 16 or 32 scanlines, depending on the track curvature, and averaged the 'selected' digitisings which constitute the track to produce a master point. These master points together with the angle of the track in each section and a value of the relative ionization of the track, determined from the numbers of scanline "hits" and "misses", were stored on disc. The HAZE output data-banks were transferred to tape by the program PRING.

The next stage was to reconstruct the events in space. However, due to the difficulties involved in track filtering, about 40 % of the events contained tracks which failed to reconstruct. It is obviously advantageous to try to rescue some of these events, rather than returning all of them to the predigitising stage for remeasurement. Consequently the HAZE output was run through a short mass independent version of THRESH which produced a list of all the failed tracks on tape. The program EXTRACT then copied, to tape, the road digitisings from the FSD measurements disc and the HAZE master points of these failed tracks, the program PATCH subsequently displayed them on the IBM 2250 visual display unit. Using a light-pen any incorrect master points were then removed and/or new master points added manually by the PATCH operator. This rescue system reduced the THRESH failure rate to about 25 %, though an unfortunate side effect was that the ionization information from HAZE was lost for the PATCHed tracks. The program GRAFT then

merged the corrected tracks with the data on the PRING tape to produce a new THRESH input data set.

3.6 GEOMETRICAL RECONSTRUCTION

Geometrical reconstruction of the events in space was performed by a mass-dependent version of the CERN program THRESH [3.5]. The master points and fiducial measurements, together with a set of constants required for the reconstruction calculations, formed the input to THRESH. The constants (called the THRESH TITLE) described the positions and focal lengths of the cameras, the refractive indices and thicknesses of the relevant media, optical distortion coefficients, the precise fiducial co-ordinates and the magnetic field in the chamber. The optical parameters listed above may in principle be obtained by direct measurement, in practice however, the results are not sufficiently accurate and the constants used were generated by the CERN program PYTHON [3.6].

A linear transformation brought the measured points to the chamber reference system shown in Figure 2.3(b). For each event, the vertex co-ordinates in space were first determined using light rays from two views and taking into account all the optical corrections contained in the THRESH TITLE. Individual track points were reconstructed in a similar manner, however in general, the master points along the tracks on different views did not correspond to the same points in space. Therefore a principle view, on which the measured points were most nearly orthogonal to the camera,

was chosen, together with a second view which gave the best stereoscopic conditions with the former. Points corresponding to the principle view master points were then calculated for the second view by interpolation between the nearest master points on that view, and the track space points then calculated.

Energy losses and magnetic field variations were initially neglected for an approximate determination of the track parameters (radius of curvature, dip and azimuthal angles) from a least-squares fit of a helix through the set of reconstructed track points in space, the deviations of the master points on all three views from the projected helix being minimised. The mass dependent energy losses due to ionisation and magnetic field variations were then included and a decaying helix fit for pion, kaon or proton masses performed, starting with the approximate track parameters previously determined. The final track parameters, vertex co-ordinates and associated fitting errors were recorded onto the THRESH output tape, ready for input into GRIND.

The program BDTHPLOT was run immediately after THRESH and produced histograms of measured beam momentum, track residuals and other variables of interest from the output tape, for routine checking of measurement quality. (See Figure 3.4 for examples.)

3.7 EVENT IDENTIFICATION

Geometrical reconstruction provides the spatial characteristics of each track in an event separately, the final stage is the physical interpretation of the event as a whole. The kinematical fitting program GRIND [3.7] was used to test a given set of particle mass hypotheses with the constraints of energy-momentum conservation at the interaction vertex. For those hypotheses which obtained a successful kinematic fit, the predicted ionisations for each track were tested against those provided by HAZE. Where ionisation information was unavailable (e.g. patched tracks), the test of predicted against actual ionisation had to be performed visually by the physicist at a scanning table. The hypotheses satisfying both kinematic and ionisation constraints were accepted for inclusion on the DST (Data Summary Tape).

The input to GRIND consisted of experiment dependent information, the GRIND TITLES, and the geometry output from THRESH. The TITLES contained several blocks of data the magnetic field map, range-momentum tables for determining the momenta of stopping tracks, convergence criteria for the kinematic fits, beam information, the labelling scheme for tracks and vertices and finally the list of particle mass hypotheses to be tested for each event type. The beam information contained the beam momentum determined during the runs (see section 2.4) which was far more accurate than could be obtained by measurement. The beam momentum used in the fitting process was a weighted mean of the TITLE value

and the measured momentum from THRESH, the weights depending on the relative errors. However, if the measured beam momentum was significantly different from the TITLE value, the event was rejected and flagged for remeasure.

For each event GRIND attempted single vertex fits to associated neutral decays (V^0 's and γ 's), then charged decays, passing the results of these secondary vertex fits through for incorporation in the primary vertex fit performed last. The correct hypothesis block for a given vertex was selected by constructing a type number uniquely defining the vertex topology as follows

$$\begin{aligned} \text{Type Number} = & 50000 * (1 - \text{Target charge}) \\ & + 10000 * \text{No of positive decay tracks} \\ & + 1000 * \text{No of non-decaying positive tracks} \\ & + 100 * \text{No of negative decay tracks} \\ & + 10 * \text{No of non-decaying negative tracks} \\ & + \text{No of } V^0\text{'s} \end{aligned}$$

e.g. Simple 4 prong = 2020 ; 6 prong with a positive decay and a V^0 = 12031 ; V^0 = 51010 etc.

Each hypothesis in that block was then attempted and identified by its position within the block (its hypothesis number).

For this experiment it was decided that we should be as general as possible about the hypotheses included and they were generated by the following rules -

1. Sum of charges = 0
2. Sum of strangeness = 0
3. Sum of baryon number = 0
4. Sum of the rest-masses of the secondary particles less than the centre of mass energy minus the number of secondary particles * 0.1

5. Number of baryons/antibaryons $\ll 1$
6. Number of strange particles equals number of seen strange particles unless this is odd in which case we add a K_s as an unseen strange particle.

The 'true' values of the particle momenta necessarily satisfy energy-momentum conservation. However, in general, the reconstructed track parameters from THRESH do not satisfy the conservation laws due to measurement error, multiple Coulomb scattering, and the possibility of one or more unseen neutral particles occurring in the final state. Indeed, in the latter case, energy-momentum conservation could never hold when applied to the measured track parameters alone.

Consequently GRIND performed an iterative fit for each hypothesis in the relevant block, "pulling" the measured values to satisfy energy-momentum conservation whilst minimising the χ^2 defined by -

$$\chi^2 = \sum_i \frac{(m_i - f_i)^2}{\sigma_i^2}$$

where for the i th. variable m_i, f_i and σ_i were the measured value, fitted value and measurement error respectively. The likelihood of a particular hypothesis being 'correct' was related to the amount by which the measured quantities had to be "pulled" from their initial values. This was quantified by the χ^2 defined above, which was minimised for each fit and could be converted into a fit probability given the number of constraints (fitp(4C) or fitp(1C)).

If only charged particles were produced in an event, then the parameters of all the tracks had been measured and these had to satisfy the four equations of constraint provided by energy-momentum conservation. Thus a four constraint (4C) fit was possible for such an event. However, if one unseen neutral particle of given mass was also produced then three of the four constraint equations were needed to determine the momentum of the undetected neutral particle, leaving only one equation of constraint and only a 1C fit was possible for these events. When two or more neutral particles were produced, there were no remaining constraints on the event and no fit was possible. These 0C events were treated as though there was only one neutral particle of unknown momentum and mass (the "missing mass"), which were calculated directly from the measured quantities using the four constraint equations. Such 0C "fits" were only accepted by GRIND if the calculated missing mass was compatible with being above threshold for the particular mass hypothesis being considered.

Kinematic fitting as a means of particle identification has severe limitations at high energies because of the small contribution of a particle's rest-mass to its energy, the measuring errors on the momenta, and the large fraction of 0C events (see section 4.2). Consequently there were often several hypotheses obtaining successful kinematic fits for a given event. The ambiguities were of two kinds, ambiguities between hypotheses involving the same charged particles but zero, one or several neutral particles, and ambiguities

involving different charged particles ,i.e. different physical hypotheses. Ambiguities of the first kind were resolved on kinematic grounds, the most constrained fit generally being preferred, more details are given in the next section. In an attempt to resolve the second type of ambiguity, between different charged particle assignments, GRIND used the ionisation information from HAZE.

The ionisation (bubble density) of a charged particle track is inversely proportional to the square of its velocity and can therefore be used to distinguish between particles of different mass with the same momentum:

$$\text{ionisation} \propto \frac{1}{v^2} = \frac{p^2 + m^2}{p^2}$$

where the particle of mass m has momentum p and velocity v . Figure 3.6 shows that the resolving power of ionisation is limited, being capable of distinguishing π/K up to 0.9 GeV/c and π/p up to 1.7 GeV/c, since it is possible to just differentiate between ionisations of 1.3 and 1.0 by eye. However, within these limits, the reliability of a track's mass assignment could be tested by comparing the predicted ionisation, corresponding to the fitted momentum, with the actual as measured by HAZE or estimated by eye. Further details are given in the section following.

3.8 HYPOTHESIS SELECTION CRITERIA

As already outlined in the previous section, ambiguities had to be resolved on kinematic and/or ionisation grounds. Obviously the final data sample for analysis should be as

"clean" (unbiased) as possible but at the same time the number of events processed automatically had to be maximised, as it would have been prohibitively time consuming for every single event to be 'decided' manually by a physicist.

For the first few rolls of film to pass through the production chain every event output by GRIND was in fact examined in detail on the table to ensure that the data being produced by the system was compatible with the observed events. This experience was used to optimise the automatic selection routines within GRIND so that we could accept the subsequent 35% of automatic decisions with confidence. The final set of criteria used, separated into the two classes kinematic and ionisation, are given below.

3.8.1 A) Kinematic Decisions

1. Any event with a decay, V^0 or γ was NOT AUTOMATIC.
2. If any constraints had been lost (e.g. momentum of one track failed to reconstruct), any 3C or 2C fits were NOT-AUTOMATIC. However if no 3C or 2C fits were obtained then the event was AUTOMATICALLY flagged for remeasure.
3. Any positively charged track which stopped in the chamber and did not decay, had to have this track as a proton in the fitted hypotheses, all hypotheses not satisfying this requirement being rejected AUTOMATICALLY.
4. If any event has a 4C fit whose predicted ionisations were comparable with the measured ionisations of all the tracks, then it was accepted automatically provided that the kinematic fit probability: $\text{fitp}(4C) > 10\%$.
Two prong elastic scatters were an exception and were accepted automatically with $\text{fitp}(4C) > 5\%$, unless the positive track was identified as a proton, either by ionisation or criteria 3, in which case the elastic fit was accepted AUTOMATICALLY regardless of fit probability.

5. If for a single hypothesis both:

a) 4C and 1C fits were present, then the following fits were accepted AUTOMATICALLY :-

i) 4C fit : if $\text{fitp}(4C) > 1\%$ AND $10 \cdot \text{fitp}(1C) < \text{fitp}(4C)$

ii) 1C fit : if $\text{fitp}(4C) < 1\%$ AND $\text{fitp}(1C) > 5 \cdot \text{fitp}(4C)$

Otherwise the decision was NON-AUTOMATIC.

b) 1C and 0C fits were present, then we AUTOMATICALLY kept :-

i) 1C fit : if $\text{fitp}(1C) > 5\%$

ii) 0C fit : if $\text{fitp}(1C) < 5\%$

3.8.2 B) Ionisation Decisions

The predicted ionisations of the fitted tracks were calculated for every hypothesis which achieved a successful fit in GRIND. These values were compared track by track with the measured ionisations on all three views, for pairs of hypotheses [3.8]. Those tracks having a common mass assignment in both hypotheses were used to normalise the measured and predicted ionisations and then the tracks with different mass assignments were used in the comparison. If one hypothesis was sufficiently worse than the other, it was rejected automatically.

In addition to the relative ionisation tests an absolute ionisation check was performed on the final set of 'acceptable' hypotheses as follows; if the ionisation

measurement indicated that a track was NOT a certain type (π, K, p), then if ANY of the final set of hypotheses had that track identified as the particle type disallowed by the measured ionisation, the decision for that event was NOT-AUTOMATIC.

If there were more than three hypotheses remaining in the final set or if the measured ionisation of a track had not been good enough to decide between two predicted values thought to be resolvable by eye (i.e. difference in predictions > 0.3) then the decision for the event was again NON-AUTOMATIC.

3.9 INSPECTION OF EVENTS ON TABLE

For each event GRIND recorded the type number and selected hypotheses, if any, on the INDEX and output the geometry and fit information on to the GRIND library tape. It was then for the physicist to inspect all the non-automatic events at the scanning table and supply a decision for these, using the observed ionisation and any other clues to the nature of the event.

To facilitate the physicist's task a summary of the GRIND library tape data was written onto a disc file and accessed by the GRIND DISPLAY program [3.9] which presented it in a convenient format on a "Prowest" VDU at the scanning table. The physicist's decision was entered via the interactive VDU and initially stored on the disc file. The following decisions could be entered through the VDU :-

event not measurable; event does not exist (e.g. bad beam);
 remeasure the event; accept the NON-AUTOMATIC GRIND
 decision; accept the specified hypotheses (maximum of 6);
 primary vertex fits failed but accept the specified V^0 fits;
 event has a track identified by ionisation as a kaon but no
 fits, set kaon flag.

After inspection the LOAD/UNLOAD program [3.9] was run
 to read the physicist decision off the disc file and update
 the INDEX and then reload with the next batch of
 non-automatic events to be inspected.

NOTE: It was possible to specify in the load program which
 events were to be loaded and further automation was
 introduced at this step after further experience.
 Some deselection was also performed and all "bad beam"
 events were loaded for inspection even though they
 were flagged for AUTOMATIC remeasure in GRIND. After
 25 rolls only events with associated V^0 's and γ 's and
 non-automatic 4C fits were loaded for inspection.
 Later still only events with one or more strange V^0 's
 were scanned, measured and processed.

3.10 THE DATA SUMMARY TAPE (DST)

Once a roll of film had passed through the sequence of
 decision making the program GLADYS [3.10] accessed the GRIND
 library tape and, utilising the decisions stored on the
 INDEX, extracted the information relevant to the particular
 hypotheses selected and wrote this on magnetic tape in a

format agreed by the collaboration. These event records were to be those used in the physical analysis of the experiment and so contained all the event details that may be necessary for this later use.

The events which failed to reach the DST could be identified from the INDEX and, apart from events deleted or flagged immeasurable by the physicist, these had to be remeasured in the hope that they would succeed on a second pass. All the failed events of the first 25 rolls were remeasured, manually on the RITA's with 8 points per track because of lack of time on the FSD, and then passed through THRESH and GRIND and examined to give an overall pass rate of 83 % for this inclusive sample from 25 rolls.

3.11 THE INDEX

The INDEX has been mentioned at various points in the earlier sections, it was a direct access data set on disc with one six-word record per event created and initialised to zero by SETUP. A full description of the information subsequently stored on the INDEX is given below:

WORD 1 The x,y co-ordinates of the primary vertex packed in two half words, filled in by GRIND.

WORD 2 Scan type number and information on secondary interaction and neutron star topologies supplied at predigitising from scan lists.

WORDS 3,4 Selected primary fits - up to six ambiguous hypotheses packed base 1000, filled in by GRIND and/or GRIND DISPLAY. For V^0 only fits - V^0 label + up to two ambiguous V^0 hypotheses.

WORD 5

Physicist ID (as used by GRIND DISPLAY) * 100000
+ GRIND type number, filled in by GRIND or GRIND
DISPLAY.

WORD 6

The progress flag - a nine digit integer, each
digit being assigned to a particular program or
step in the production chain and taking values
0-9 as set out below.

<u>Digit</u>	<u>Step</u>	<u>Value & Meaning</u>
1	General	(1) Event not measurable (2) Event does not exist (3) Bypassed by LOAD program (4) Accepted in LOAD program
2	PLANT	(1) failed in PLANT
3	SETUP	(1) failed in SETUP
4,5	free	
6	GRIND	(1) AUTOMATIC decision (2) no decision (3) REMEASURE decision (4) NON-AUTOMATIC decision
7	Physicist	(1) Event not measurable (2) does not exist (3) remeasure (4) accept GRIND decision (5) decision by physicist (6) Primary failed but V_0 fit accepted (7) Kaon flag-event has a track which is Kaon by ionisation, remeasure (8) As (6) but remeasure (9) Remeasure with new scan type number
8	GLADYS	(1) Event on DST with primary fit(s) (2) Event on DST with only V_0 fits
9	Measure No	(1) Value supplied by SETUP

3.12 REFERENCES

- 3.1 O.L.S. and utilities writeup. Dr. R. Matthews, Liverpool.
- 3.2 PLANT writeup. R. White, Liverpool.
- 3.3 "The HPD Mark 2 Flying-spot Digitiser at CERN", M. Benot et. al. CERN Yellow Report 68-4
- 3.4 HAZE, J.M. Gerard et. al., CERN FSD bubble chamber programs manual.
- 3.5 THRESH, F. Bruyant, CERN Program Library, long writeup, X201.
- 3.6 PYTHON, J. Zoll, CERN Program Library, long writeup, X200.
- 3.7 GRIND, F. Beck et. al., CERN Program Library, long writeup, X601.
- 3.8 P.S. Gregory, PhD Thesis, Liverpool (1975).
- 3.9 GRIND DISPLAY, Dr. A. Moreton, Liverpool.
- 3.10 GLADYS, Dr. R. Matthews, Liverpool.

3.13 TABLES

3.1 Allowed scan type numbers for this experiment.

3.2 Summary of all events from 'inclusive' scanning.

3.3 Summary of all events from V^0 scanning.

TABLE 3.1 Allowed Scan Type Numbers

	<u>Prong Number</u>							
	0	2	4	6	8	10	12	14
'Simple'	68	221	42	45	153	96	100	210
V ⁰	1	3	5	150	154	101	207	
2V ⁰	2	4	6	151	200	102		
3V ⁰	69	176	181	182	201			
4V ⁰	70	204	205	206				
Decay		48	49	50	155	208	209	
Decay + V ⁰		7	8	189	202	203		
Decay + 2V ⁰		212	213	214	215			
2 Decays		218	219	220	224	225	228	
2 Decays + V ⁰		234	235	236	237	238		
2 Decays + 2V ⁰		244	245	246	247			
S		46	80	84	114			
2S		47	81	85	115			
N	250	71	82	98				
2N	41	72	83	103				
Stop		227	59	57	170			
S + V ⁰		73	86	105	116			
S + 2V ⁰		74	87	106	117			
2S + V ⁰		75	88	107	122			
S + Stop		76	89	109	123			
N + S		77	90	110				
N + V ⁰	124	78	94	112				
N + 2V ⁰	44	79	95	113				
Unassociated Neutron star	125							

S = Secondary interaction

N = Neutron star

V⁰ = Strange neutral particle decay or γ

TABLE 3.2 Results of Inclusive Scanning

Category	0P	2P	4P	6P	8P	10P	12P	TOTAL
'Simple'	4900	35601	30491	12301	2521	455	15	86284
V ⁰	1086	4807	4797	2027	343	42	4	13106
2V ⁰	349	732	588	200	32	4		1905
3V ⁰	41	69	56	15	2			183
4V ⁰	4	9	2	1				16
Decay		1422	2188	1243	322	44	2	5219
Decay + V ⁰		403	355	200	44	5		1007
Decay + 2V ⁰		48	43	15	4			110
2 Decays		42	80	47	16	3	2	190
2 Decays + V ⁰		13	17	6	5			41
2 Decays + 2V ⁰		1	4	1				6
S		7983	10802	5362	1350			25497
2S		406	1570	1221	377			3574
N	701	2209	994	264				4168
2N	28	85	33	7				153
Stop		29325	4698	1201	254			35478
S + V ⁰		966	1555	825	181			3527
S + 2V ⁰		116	201	92	14			423
2S + V ⁰		41	187	171	46			445
S + Stop		4619	1485	467	143			6714
N + S		352	345	121				818
N + V ⁰	154	303	164	63				684
N + 2V ⁰	40	41	23	2				106
Total	7303	89593	60678	25850	5654	553	23	189654

Number of beams-in = 1116240
 Number of beams-out = 926586
 Number of frames scanned = 117129

TABLE 3.3 Results of V^0 only Scanning

Category	0P	2P	4P	6P	8P	10P	TOTAL
V^0	952	3419	2612	783	98	6	7870
$2V^0$	469	819	476	116	6	3	1889
$3V^0$	58	73	51	13	1		196
$4V^0$	2	4	2	1			9
Decay + V^0		483	284	60	5		832
Decay + $2V^0$		44	49	14	2		109
2 Decays + V^0		8	6	2			16
2 Decays + $2V^0$		2	2				4
$S + V^0$		573	718	317	51		1659
$S + 2V^0$		113	166	57	12		348
$2S + V^0$		23	86	48	6		163
$N + V^0$	96	123	78	26			323
$N + 2V^0$	24	28	14	2			68
Total	1601	5712	4544	1439	181	9	13486

Number of frames scanned = 156800

3.14 FIGURES

3.1 Flow chart of the data production chain.

3.2 "Scanning region for this experiment", defined on view 2.

All events within regions 1, 2, 3 were recorded.

3.3 "The six basic scan types".

- a) Simple 6 prong.
- b) Associated V^0 .
- c) Secondary interaction.
- d) Associated neutron star.
- e) Charged track decay.
- f) Stopping track.

3.4 Track and vertex labelling conventions.

3.5 BDTHPLOT output.

- a) Track residuals.
- b) Beam momentum.

3.6 Variation of bubble density with momentum for p, π and K masses. The dotted line shows the limit of visual distinguishability from minimum ionisation.

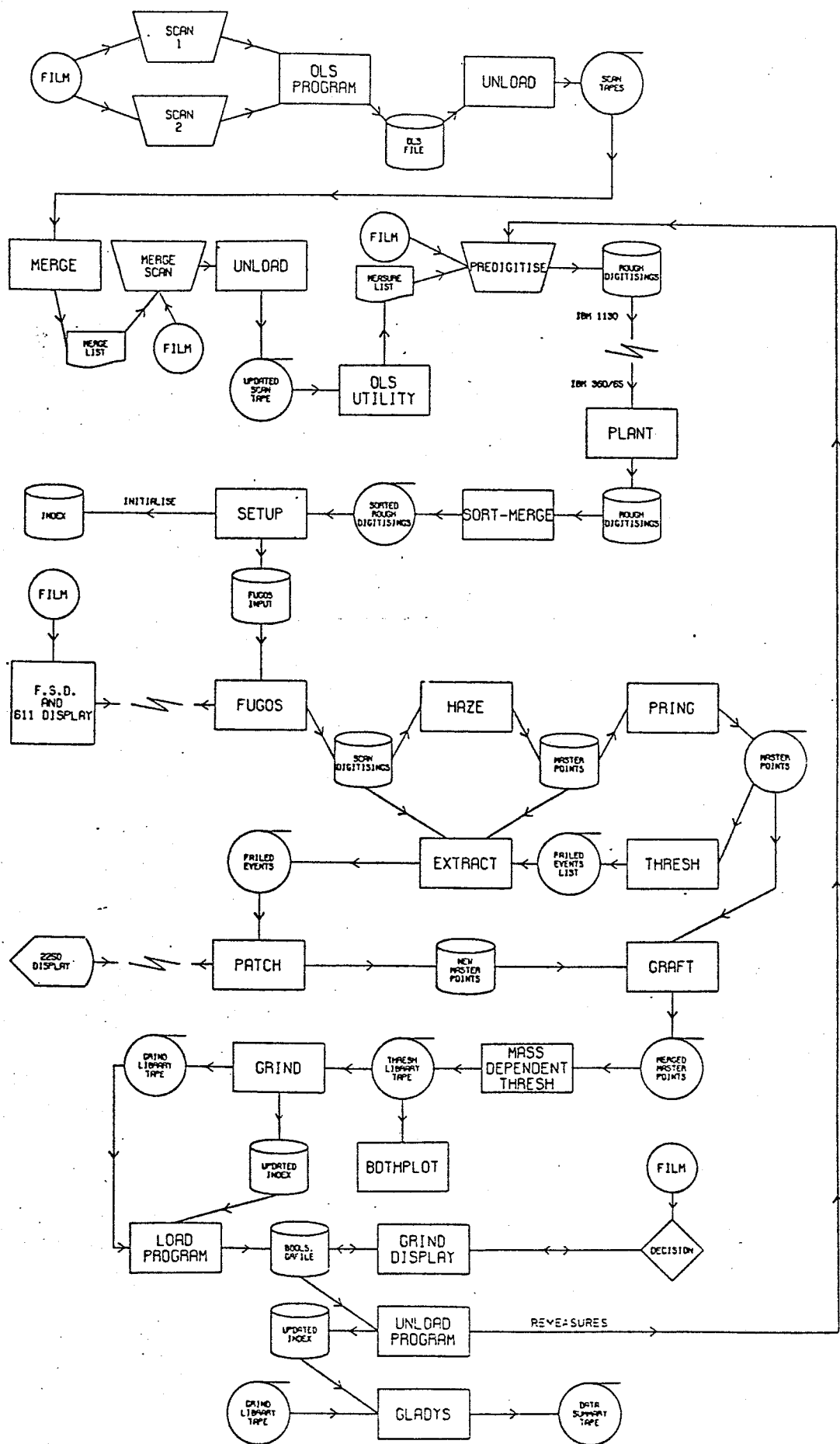


Figure 3.1 Flow Chart of the Data Production Chain

Figure 3.2 Scanning region

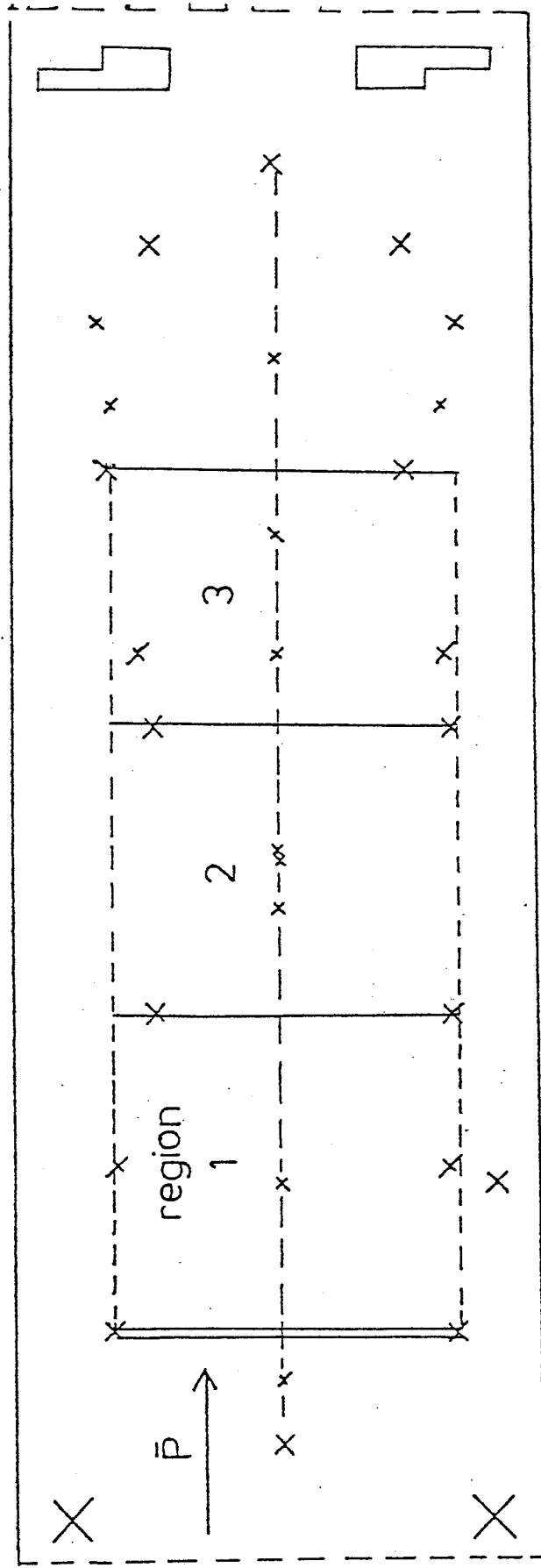
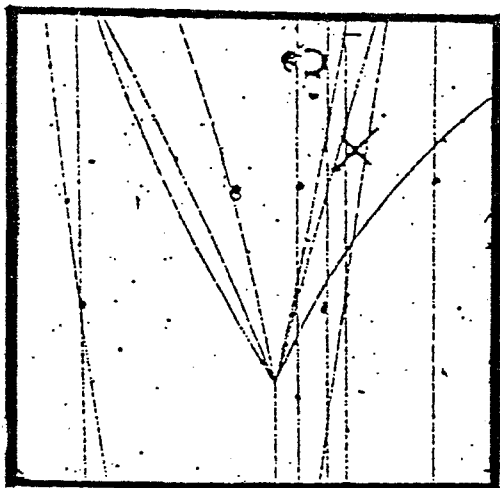
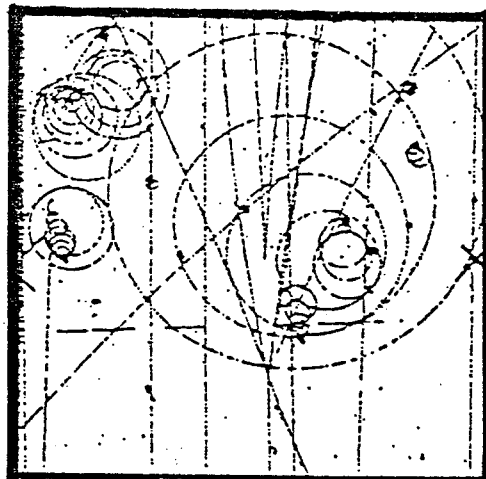


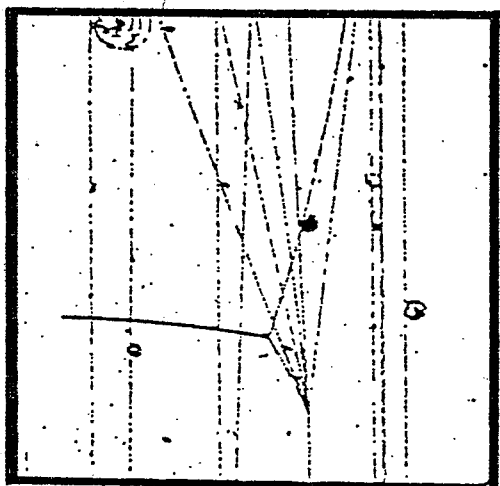
Figure 3.3 The six basic scan types



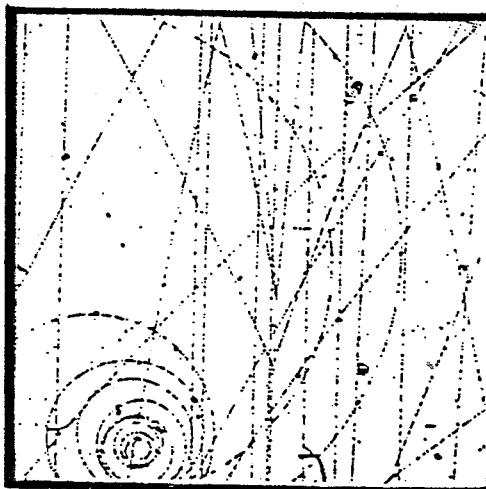
a) 45



b) 150



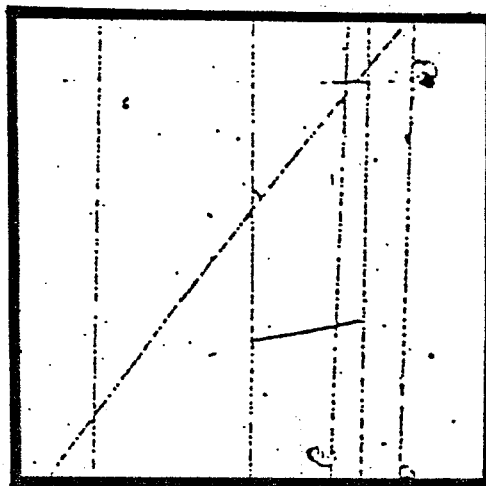
c) 84



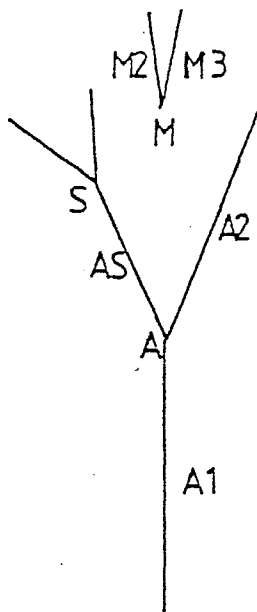
d) 71



e) 49



f) 227



IBM1130 TYPE =73

MEASURE ORDER IS

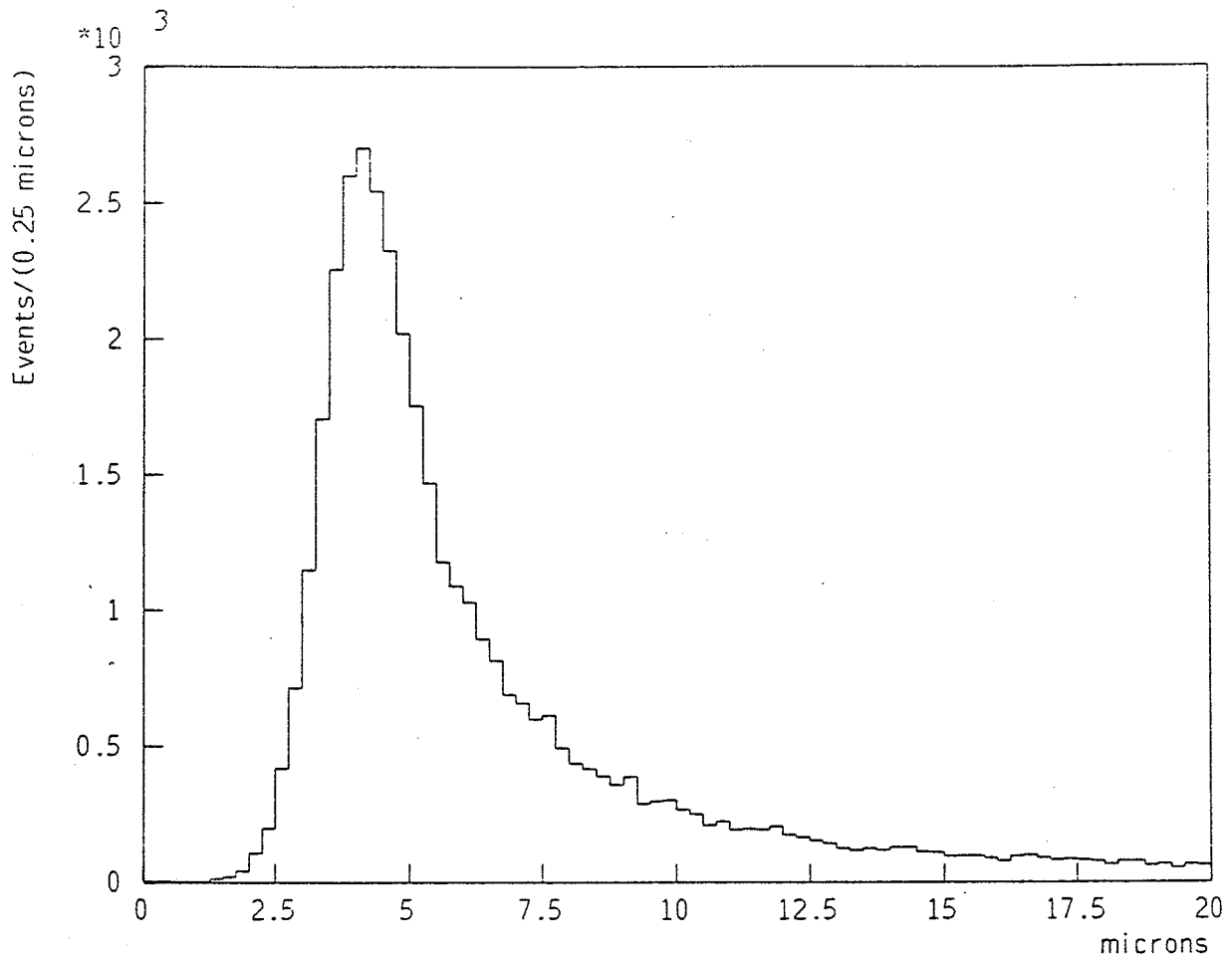
ASMA1A2ASM2M3

VERTEX LABELS

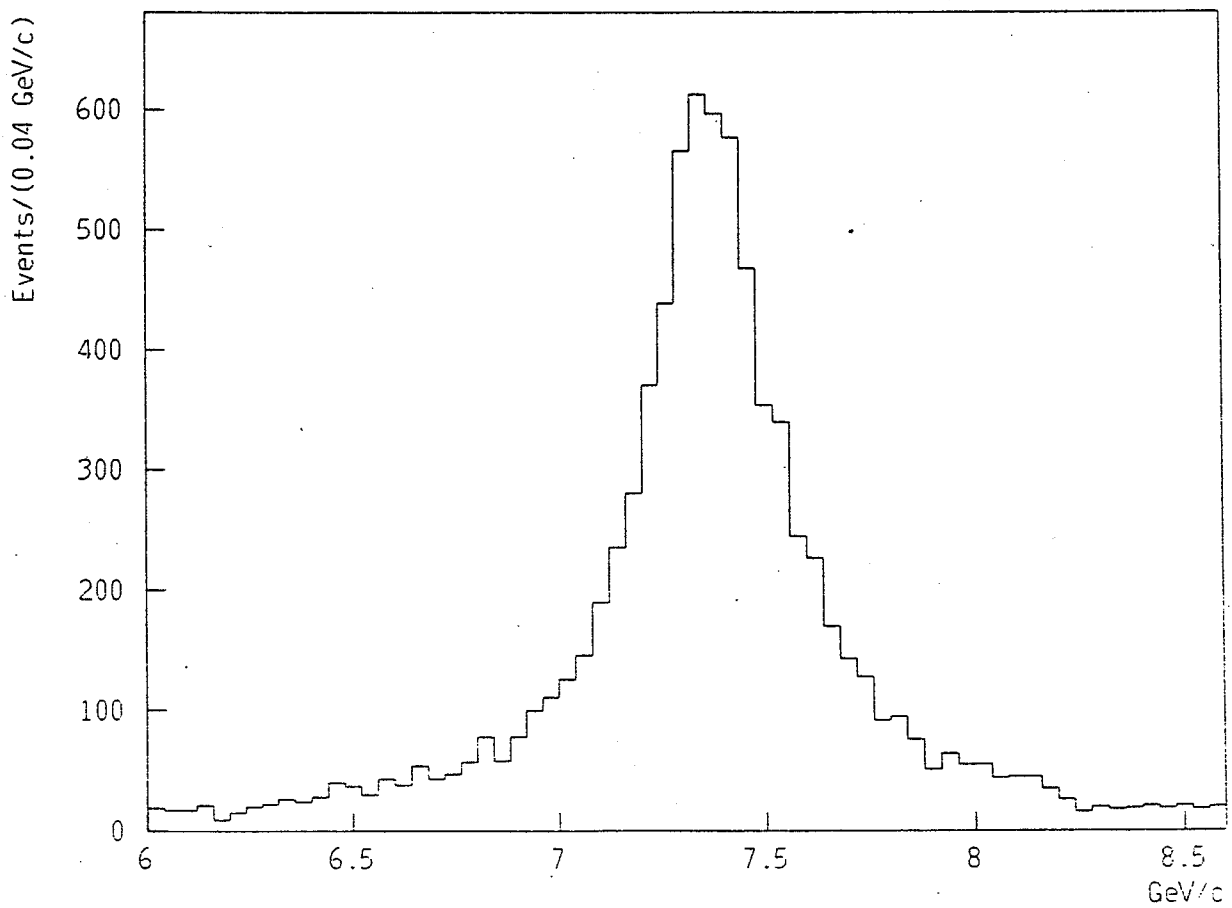
A	PRIMARY VERTEX
B	NEUTRON STAR
L,M,N,O	V^0 's
P,Q	$V^{\pm}$
S,T	SECONDARY
X	STOPPING

FIGURE 3-4 LABELLING CONVENTIONS

Figure 3.5 BDTHPLOT Output



(a) Residuals



(b) Beam Momentum

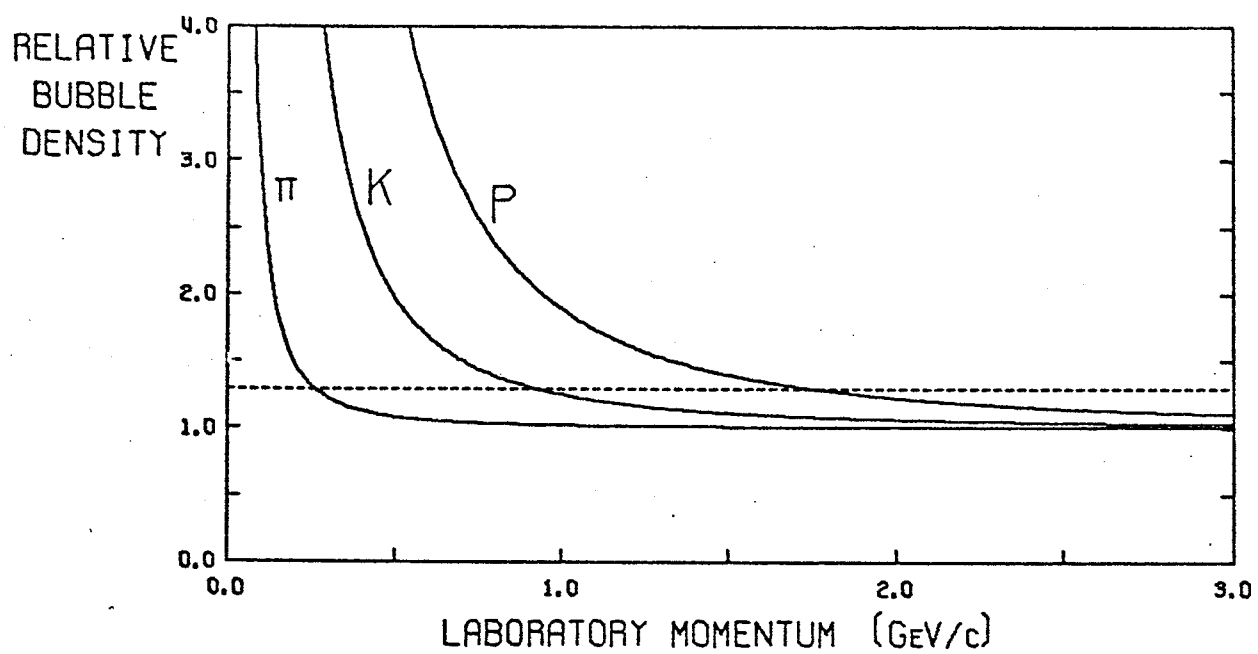


Figure 3.6 Variation of Bubble Density with Momentum

Chapter IV

TOTAL , TOPOLOGICAL AND EXCLUSIVE CHANNEL CROSS SECTIONS

4.1 INTRODUCTION

In this and the succeeding chapter the basic results of the experiment are presented, namely the cross sections. The total and topological cross sections are first calculated from the scanning results after various corrections described below. A second independent determination of the total cross section is then given and the results of the two methods compared. Since many final states are highly ambiguous the problem of resolution of charged particle ambiguities is discussed before the non-strange exclusive channel cross sections are determined. An estimate of the contribution of non-annihilation processes to the $\alpha(\pi^+\pi^-)MM$ channels, $\alpha=1,2,\dots$, is made in an attempt to obtain an annihilation sample for later analysis and the corresponding annihilation cross sections in each topology are given.

4.2 TOTAL AND TOPOLOGICAL CROSS SECTIONS

4.2.1 Introduction

The film was scanned for all topologies of events and a beam count was made on every frame. Thus, provided certain corrections are performed, we may make an absolute determination of the total and topological cross sections from the scanning data.

The total cross section is given by:-

$$\sigma_{tot}(\bar{p}p) = \frac{N}{N_h N_b L_b} \quad (1)$$

where N = total number of $\bar{p}$ interactions.

N_h = number of target hydrogen atoms/unit volume.

N_b = total number of $\bar{p}$ beam tracks entering the scanning region.

L_b = average length of a beam track in the scanning region.

However:

$$L_b = \int \exp[-L/\lambda] dL = \lambda(1 - \exp[-L_r/\lambda]) \quad (2)$$

where

L_r = length of scanning region.

λ = interaction length of $\bar{p}$ in liquid hydrogen.

The latter is of course related to the cross section σ by:

$$\sigma = 1/N_h \lambda \quad (3)$$

From equations (1), (2) and (3) we obtain the result:

$$\sigma_{tot}(\bar{p}p) = \frac{\ln\{N_b/(N_b - N)\}}{N_h L_r} \quad (4)$$

4.2.2 Beam Contamination

The beam is not purely $\bar{p}$, being contaminated by μ^- and π^- particles. During the experimental runs the first 200 frames of every fifth roll of film were exposed with the RF separators 'out of beam'. This meant that the antiprotons were no longer deflected around, but hit, the beam-stopper and only μ^- and π^- contamination entered the chamber. The contamination may therefore be calculated by analysis of the 'RF off' frames on the assumption that the numbers of μ^- and

π^- tracks entering the chamber were independent of whether the RF was on or 'off'.

All the 'RF off' frames for the first run were in the Liverpool share of the film and these were scanned for 'beam' tracks and interactions. In order to identify the tracks on these frames that would have been mistaken for $\bar{p}$ beams, tracks were traced onto a template from normal (RF on) frames and used for comparison. The results were:

$$N_f = \text{number of 'RF off' frames scanned} = 4765$$

$$N_t = \text{number of contamination tracks found} = 4365$$

$$N_i = \text{number of contamination interactions found} = 24$$

Total fraction of contamination beams ($\mu^- + \pi^-$) = $N_t/N_f N_n = 9.7\%$, where N_n is the average number of beams/frame on normal film = 9.46 from scanning results. Since the μ^- is not strongly interacting we may assume that all the N_i interactions observed were π^- induced. Using equation (4):

$$\text{Number of } \pi^- \text{ beams} = N_{pi} = N_i / (1 - \exp[-\sigma N_n L_r]) = 240 \pm 40$$

where $\sigma = \sigma(\pi^- p) = \text{total cross section for } \pi^- p \text{ interactions at } 7.3 \text{ GeV/c} \approx 27.6 \text{ mb. from [4.1]}. \text{ Thus:}$

$$\text{fraction of } \pi^- \text{ contamination} = N_{pi}/N_f N_n = 0.54 \pm 0.10 \%$$

$$\text{fraction of } \mu^- \text{ contamination} = (N_t - N_{pi})/N_f N_n = 9.15 \pm 0.10 \%$$

This may be compared with an estimated 15% contamination calculated from test-strip data during the run. (Appendix A).

The beam composition was therefore:

$$\bar{p} : \mu^- : \pi^- = 0.9031 : 0.0915 : 0.0054$$

Corrections for this beam contamination had to be applied in two places:

- (i) The total contamination was subtracted from the beam count information to give the 'true' number of $\bar{p}$ beams.
- (ii) There was a small correction to the numbers of events scanned due to π^- induced interactions.

In the data sample used we would expect about 800 such contaminating π^- events and these were distributed amongst the various topologies according to the topological π^-p cross sections interpolated from [4.1]. See Table 4.5.

4.2.3 Scanning Losses

The majority of our film was only scanned once in order to achieve a faster rate of processing. A beam-in and beam-out count was performed on every frame so as to maintain a high single scan efficiency, especially for zero prongs and short elastic scatters which can easily be missed. Even so not all events are seen in the single scan and consequently a sample (every tenth roll) was independently scanned a second time and then a third combined scan performed to check the differences between the two scans. The scanning efficiencies were then calculated from this sample as follows:

Let n_1, n_2, n be the number of events of type i found on scans 1, 2 and the combined scan respectively.

n_{12} the number of events common to scans 1 and 2.

N the 'true' number of events on the film.

$\varepsilon_1, \varepsilon_2, \varepsilon$ the scanning efficiencies for scans 1, 2 and combined scan respectively.

We have the relations, $n_1 = \varepsilon_1 N : n_2 = \varepsilon_2 N : n_{12} = \varepsilon_1 \varepsilon_2 N$.

From which $\varepsilon_1 = n_{12}/n_2 : \varepsilon_2 = n_{12}/n_1 : \varepsilon = n/N = nn_{12}/n_1 n_2$

The scanning efficiencies for various topologies of events are given in Table 4.1.

NOTE: Since the majority of film was single scanned, the scanned numbers of events were corrected by the average single scan efficiencies $\epsilon_a = \epsilon_{12}(n_1+n_2)/2n_1n_2$ also given in Table 4.1

4.2.4 Fiducial Volume Cuts and Bad Beams

The scanning volume was defined by two sets of fiducial marks at -60 and +40 cm. in x on view 2. However, due to differences in depth of the events and a tendency to accept events 'near' the boundaries, not all the events accepted at scanning lie in the defined fiducial range $-60 < x < 40$ cm. For about half of the scanned events we had a measured value of the x co-ordinate stored on the INDEX and so the fraction of events lying outside the fiducial volume was calculated for each topology from this information. The overall number was 4.80 ± 0.02 % of the events, see Figure 4.1, and the full results are given in Table 4.2. The scanned numbers were corrected accordingly.

The beam parameters were contained in the GRIND TITLE (section 3.7) and if the measured p, λ, ϕ of the beam track disagreed severely the event was flagged 'BBM' (bad beam) by GRIND and processing was discontinued. For the first 25 rolls examined by physicists all 'BBM' events were examined and it was found that a fraction of them were genuinely non-beam and so had to be rejected completely. These were

either visibly non-parallel, and therefore accepted accidentally, or the dip was too large, a factor which is not easily 'seen' till after measurement as they may appear parallel in projection. The percentages of events rejected by the physicists as non-beam in each topology are given in Table 4.3 and these were applied to the full sample of scanned events.

Overall 3.33 ± 0.12 % of the events from the 25 rolls fully examined were rejected as non-beam and a corresponding correction has also been applied to the total number of beams-out on the assumption that a similar proportion of the through beam tracks will also have been non-beam.

4.2.5 Two Prong Elastic Events

Due to the visual characteristics of a large fraction of elastic events, losses occur at the scanning stage for elastic events with small four-momentum transfer (t) and also for certain azimuthal angles. Corrections must therefore be made to the scanned numbers of two prongs before cross sections can be derived. A sample of 3631 4C elastic events on DST were used to calculate the correction factors as given in the following two subsections.

a) Loss of elastic events due to azimuthal angle

The azimuthal angle (ϕ) referred to above is defined as the angle between the normal to the scattering plane and the vector perpendicular to the beam in the x-y plane. Since the choice of an x-y plane is arbitrary the ϕ distribution of the sample of events should be flat.

However, as can be seen from Figure 4.2, losses occur for events with $|\varphi| < 30^\circ$ and $|\varphi| > 150^\circ$. This may be understood by considering the visual nature of elastics on film, many elastics have a short straight recoil proton track with a fast outgoing $\bar{p}$ track which has little deviation from the original beam direction. As one rotates such an event about the beam axis the apparent proton track length decreases until at $\varphi = 0^\circ$ or 180° , when the recoil proton is travelling towards/away from the cameras, no proton track can be seen and the event is virtually indistinguishable from a non-interacting beam. In order to obtain an unbiased sample events with $|\varphi| < 30^\circ$ or $|\varphi| > 150^\circ$ were removed and the results on the rest scaled up by 3/2 to allow for these cuts.

b) Losses of elastics with small four-momentum transfer.

The four-momentum transfer, t , is defined as:

$$t = (P_a - P_b)^2$$

where P_a and P_b are initial and final four-momenta respectively of the proton. The t -distribution of the restricted (φ cut) sample of 2681 elastics is given in Figure 4.3 and it is clear from this that large losses occur for $|t| > 0.04 \text{ (GeV/c)}^2$. These would correspond to events with very short recoil proton stubs. The fraction of missed events may be calculated by extrapolating a parametrisation of the t -distribution to $t=0$. For small values of t , the distribution is roughly exponential and it is customary to fit this region with $d\sigma/dt = A \exp[-bt]$, [4.2]. A minimum χ^2 fit [4.3] with A and b as free parameters was made over the

interval $-0.32 < t < -0.05 \text{ (GeV/c)}^2$ and the fit is shown in Figure 4.3. The fit parameters are given in Table 4.4. These may be compared with the optical theorem prediction for the forward elastic scattering cross section $(d\sigma/dt)|_{t=0}$. The optical theorem predicts :

$$\begin{aligned} \left. \frac{d\sigma}{dt} \right|_{t=0} &\simeq \frac{\sigma_{tot}^2}{4(hc)^2/\pi} \\ &= 171.9 \pm 2.3 \text{ mb(Gev/c)}^{-2} \end{aligned}$$

using the total cross section results of Table 4.5.

The value of the intercept obtained from the fit gives:

$$(d\sigma/dt)|_{t=0} = 173.3 \pm 9.5 \text{ mb(Gev/c)}^{-2}$$

in good agreement with the optical theorem prediction.

The overall correction factor for unseen elastics was found to be 1.43 ± 0.04 . This correction has been determined from a subsample of the scanned events actually on DST and applies strictly only to the elastics on DST. In order to apply the correction to the scanned two prongs we need to know the fraction of them that were elastics and assume that no systematic differences exist between them and the sample on DST. Again using the two prong sample on DST, we find that the ratio of two prong elastics to total number of two prongs on the DST was $3631/9708 = 37.4 \pm 0.7 \%$. The same ratio will hold for the scanned two prongs on the assumption that the failure rate for both elastic and inelastic two prongs through the data production system to DST was the same.

4.2.6 The Cross Sections

All the corrections which have to be made have now been described and using the scanning results of Table 3.2, Table 4.5 gives the numbers of events in each topology and the corrected numbers after application of the factors detailed in Tables 4.1 - 4.5. The corrected total number of $\bar{p}$ interactions is 191074 ± 1700 . The total number of beams seen entering the scanning region was $1116240 (=N_t)$, this however is not the number of antiprotons, being:

$$N_t = N(\bar{p}) + N(\mu^-) + N(\pi^-) + N_{bbm}(\bar{p}, \mu^-, \pi^-)$$

where N_{bbm} = bad beams as defined in section 4.2.4 and was 3.33 ± 0.12 % of the non-interacting beams. The numbers of μ^- and π^- are then given by the contamination results of section 4.2.2, leaving $N(\bar{p}) = 975515 \pm 2640$. The fiducial volume as defined in section 4.2.4 was of length 1m, i.e. $L_r = 1m$ and finally we require:

$$N_h = \rho_h N_a / M_h$$

where N_a = Avogadro's number.

M_h = Atomic weight of hydrogen.

ρ_h = density of liquid hydrogen in the bubble chamber.

The latter quantity was measured by CERN staff after each roll during the run and the average of those measurements was quoted as, $\rho_h = 0.06258 \pm 0.00002$ gm/cm³. Substitution of the above values in equation (4) then gives:

$$\sigma_{tot}(\bar{p}p) = 58.3 \pm 1.3 \text{ mb.}$$

This together with the corresponding results for the topological cross sections are given in Table 4.6. These values are seen to be in good agreement with the general trend of the data as a function of laboratory momentum as seen in Figure 4.4. The mean charged particle multiplicity, $\langle n \rangle$, was found to be 3.59 ± 0.17 for the inelastic sample.

4.3 $\bar{p}$ ATTENUATION IN LIQUID HYDROGEN

An independent evaluation of the total cross section for this experiment was made by considering the distribution in x of the primary vertices of a subsample of 66388 events. These were events which had been measured and reconstructed and whose x - y co-ordinates were stored on the INDEX.

Given N_0 $\bar{p}$ beams at some reference point $x = x_0$ we know that the number of beams remaining at a point x_1 is given by:

$$N(x) = N_0 \exp[-\sigma(\bar{p}p)\kappa(x_1-x_0)]$$

where $\kappa = N_h$. The number of $\bar{p}$ interactions in an interval (x_1, x_2) is thus:

$$N(x_1, x_2) = N_0 \exp[-\sigma(\bar{p}p)\kappa(x_1-x_0)] * \{1 - \exp[-\sigma(\bar{p}p)\kappa(x_2-x_1)]\}$$

However in addition to $\bar{p}$ interactions there were also π^- interactions due to some fraction β of π^- contamination, thus if $\sigma(\pi^-p)$ is the total π^-p cross section then the total number of events observed in the interval (x_1, x_2) should have been:

$$\begin{aligned}
N(x_1, x_2) = & N_0 \{ \exp[-\sigma(\bar{p}p)\kappa(x_1-x_0)] * (1 - \exp[-\sigma(\bar{p}p)\kappa(x_2-x_1)]) \\
& + \beta \exp[-\sigma(\pi^-p)\kappa(x_1-x_0)] * (1 - \exp[-\sigma(\pi^-p)\kappa(x_2-x_1)]) \\
& * \exp[-\sigma_d\kappa(x_2-x_0)] \}
\end{aligned}$$

where the final factor is a small correction for loss of π^- through decay due to its finite lifetime and $\sigma_d = 0.65$ mb.

Using the observed distribution of the events, similar to Figure 4.1, a series of minimum χ^2 fits in which the difference between predicted and observed numbers of events in 1 cm. intervals of x over different ranges of x were performed. There were four free parameters in the fit, namely $\sigma(\bar{p}p)$, $\sigma(\pi^-p)$, N_0 and β . The results of the fits were remarkably stable over the different ranges of x over which the fits were attempted. The average values of these fitted parameters were:-

$$\sigma(\bar{p}p) = 60.5 \pm 1.9 \text{ mb.}$$

$$\sigma(\pi^-p) = 25.8 \pm 1.3 \text{ mb.}$$

$$N_0 = (291.0 \pm 2.1) 10^3 \text{ } \bar{p} \text{ tracks (at } x_0 = -60 \text{ cm.)}$$

$$\beta = (0.94 \pm 0.21) \% \pi^- \text{ tracks.}$$

We see that $\sigma(\bar{p}p)$ is in reasonable agreement with the result obtained from the scanning data in the previous section. It is really rather surprising, considering the small fraction of π^- contamination, that the $\sigma(\pi^-p)$ cross section from the fitting is also consistent with other data, being 1.5 standard deviations below the more accurate determination of [4.1] at 7.38 GeV/c.

The fits also provide us with the figure of $(291.0 \pm 2.1) \cdot 10^3$ $\bar{p}$ tracks corresponding to the 66388 interactions observed. The scanned number of tracks corresponding to the same number of interactions was $(352.0 \pm 5.0) \cdot 10^3$ beams (after correction for bad beams). The difference between the fitted value of N_0 and the scanned number of tracks correspond to the beam contamination. The above numbers yield μ^- contamination of 16.6 ± 2.0 % and π^- contamination of 0.78 ± 0.21 %. There is however a further correction which could explain the high value of the μ^- contamination found above compared with the 'RF off' value of section 4.2.2. The 66388 events used did not contain any of the 'missed' elastics, which we know exist, and the fitted number of N_0 $\bar{p}$ tracks is thus lower than would have been obtained had the 'missed' elastics been observed and included in the calculation. The values of the cross sections obtained are independent of the missed elastics since the missed sample will have been from the whole range of x and so not change the form of the distribution only the magnitude N_0 . We may make an estimate of the correction to N_0 by using the results of section 4.2.5 together with the number of two prongs in the subsample of 66388 events used. We estimate that in addition to the 66388 events there would have been 5028 'missed' elastics, the corrected number of $\bar{p}$ beams is then $(313.0)10^3$. This leads to values for the contamination of:

$$\mu^- \text{ contamination} = 10.2 \pm 1.5 \%$$

$$\pi^- \text{ contamination} = 0.8 \pm 0.2 \%$$

The results of the two methods are therefore self consistent and this second evaluation provides a useful check on the previous results.

4.4 EXCLUSIVE CHANNEL CROSS SECTIONS

In order to calculate exclusive channel cross sections we have to resolve fit ambiguities existing in the data on the DST and find the numbers of events in each channel. About 26% of the events suffer from ambiguities in the mass assignments of the particles in the final state, i.e. more than one hypothesis is kinematically possible and compatible with the observed ionization of the charged tracks.[See Sections 3.7 & 3.8]

Where a constrained fit was ambiguous the resolution was performed on the basis of fit probabilities and number of constraints. A breakdown of the numbers of unique and remaining ambiguous fits in each channel is given in Table 4.7 for the Liverpool and Amsterdam data samples separately. The two samples show very similar features and subsequently will be treated together, though separate monitoring was performed throughout the analysis. (The Amsterdam two prong data sample was incomplete and so not used.)

4.4.1 The Problem of Ambiguities

The charged track ambiguities which occur are of the type p/π^+ and $\bar{p}/\pi^-$, the latter being predominant as final state $\bar{p}$'s are generally fast (and so indistinguishable from π^- , see Figure 3.6) and final state protons slow, in the laboratory.

In order to resolve these ambiguities we have followed a procedure originally formulated by Gregory [4.4] and later modified slightly by Warren [4.5]. It relies on the different dynamic properties of annihilation and non-annihilation processes, more specifically on the highly peripheral nature of non-annihilation events. The strong constraints imposed by CP invariance in the $\bar{p}p$ interaction, namely :

1. particle distribution equals reflected antiparticle distribution

2. spatial symmetry of self conjugate particles

provide a means of testing the separation.

4.4.2 p/ π^+ Ambiguities

Nearly all protons with $P_{lab} < 1.7$ GeV/c are uniquely identified and backwards in the CMS. The ambiguous protons however are predominantly forward in the centre of mass system (CMS), see Figure 4.5 (a-b). The antiproton CMS angular distributions, Figure 4.5 (c-d), shows that there are very few backward antiprotons and these are almost all uniquely determined as they are slow in the laboratory.

By CP invariance of the proton and antiproton distributions it is clear that the majority of the ambiguous positive tracks must be pions. It was therefore decided that for all events containing a p/ π^+ ambiguous track, the resolution would be in favour of the π^+ . This procedure leaves a small number of protons misidentified as pions. The contamination of the π^+ sample however is negligible.

4.4.3 $\bar{p}/\pi^-$ Ambiguities

Having resolved the positive particle ambiguities the remaining ambiguous events are those in which :

i) $\pi^+\pi^-\alpha(\pi^+\pi^-)(\pi^0/MM)$ is ambiguous with $(n/MM)\bar{p}\pi^+\alpha(\pi^+\pi^-)$

ii) $\bar{p}p\alpha(\pi^+\pi^-)(\pi^0/MM)$ is ambiguous with $(\bar{n}/MM)p\pi^-\alpha(\pi^+\pi^-)$

where $\alpha = 1, 2, 3, \dots$

i) This is the largest and most difficult class of ambiguity to resolve. Examination of the charge conjugate channel $(\bar{n}/MM)p\pi^-\alpha(\pi^+\pi^-)$, where the events are mostly unique, shows that the proton and antineutron-like neutral system are very peripheral. Thus an ambiguous event of this class in which the ambiguous negative particle goes strongly forward and the neutral (n/MM) system goes simultaneously strongly backward in the CMS is more likely to be a genuine $(n/MM)\bar{p}\pi^+\alpha(\pi^+\pi^-)$ event. Gregory employed a simple cut on the $\cos\theta^*$ of the $(\bar{p}/\pi^-)$ and (n/MM) tracks such that reasonable CP invariance in the π^+ , π^- and (π^0/MM) distributions of the $\pi^+\pi^-\alpha(\pi^+\pi^-)(\pi^0/MM)$ channels was achieved. Whilst a cut is satisfactory for determining cross sections, it leads to distortions in the particle distributions in the region of the cut. To avoid this problem we have followed Warren and sought a weight for these ambiguous events such that events with a high degree of peripherality make a large contribution to the $(n/MM)\bar{p}\pi^+\alpha(\pi^+\pi^-)$ samples and a correspondingly small contribution to the $\pi^+\pi^-\alpha(\pi^+\pi^-)(\pi^0/MM)$ samples. The weights which best satisfied CP invariance were found to be :

$$W = \exp[\sqrt{\cos\theta^*}(\bar{p})].\exp[\sqrt{\cos\theta^*}(n/MM)].\exp[-2.0]$$

for the $(n/MM)\bar{p}\pi^+\alpha(\pi^+\pi^-)$ samples and $(1.0 - W)$ for the $\pi^+\pi^-\alpha(\pi^+\pi^-)(\pi^0/MM)$ samples, but where $W = 0.0$ if $\cos\vartheta^*(\bar{p}) < 0.0$ or $\cos\vartheta^*(n/MM) > 0.0$.

The $\cos\vartheta^*$ distributions of the unique and unique+ambiguous $2\pi+2\pi$ -MM events, before weighting are shown in Figure 4.6, CP invariance is not satisfied by either sample.

The $\cos\vartheta^*$ distributions of the final weighted samples of $2\pi+2\pi$ -MM and $3\pi+3\pi$ -MM events are shown in Figure 4.7 and reasonable CP invariance has been achieved.

ii) For the first class of event we were able to construct a weight requiring the $\bar{p}$ and the (n/MM) system to occupy the extreme angular regions simultaneously. For the second class of ambiguity however the behaviour of the negative ambiguous particle is compatible with either hypothesis and so we have relied on the strong forward production of the neutral $(\bar{n}/MM)$ system alone. The weight chosen to satisfy CP invariance was :

$$W = \exp[\sqrt{\cos\vartheta^*(\bar{n}/MM)}].\exp[-1.0]$$

for the $(\bar{n}/MM)p\pi^-\alpha(\pi^+\pi^-)$ samples and $(1.0 - W)$ for the $\bar{p}p\alpha(\pi^+\pi^-)(\pi^0/MM)$ samples, but where $W = 0.0$ if $\cos\vartheta^*(\bar{n}/MM) < 0.0$.

The resulting $\cos\vartheta^*$ distributions of the baryon/antibaryon systems in the $p\pi^-\bar{n}/MM$, $p\pi+2\pi^-\bar{n}/MM$ and charge conjugate channels are seen to satisfy CP invariance in Figure 4.8.

4.4.4 Neutral Particle Contamination

Charged particle ambiguities having been resolved, there remains the possibility of neutral particle contamination in the constrained channels. Any such contamination may be observed in the measured missing-mass-squared (MM^2) distributions of the constrained channels.

There is no noticeable contamination in the 4C samples from events with a missing neutral system, as would be indicated by an excess of events on the positive MM^2 side of the distributions. These are shown in Figure 4.9 (a-f).

The MM^2 distributions for the 1C are rather broader and not all are symmetric about the square of the mass of the missing neutral particle, indicating contamination by multineutral events. The contamination was found in the following channels $2\pi+2\pi-\pi^0$ (19.5%), $3\pi+3\pi-\pi^0$ (6.0%), and $\bar{p}\pi+n$ (13.0%). The corresponding MM^2 distributions are shown in Figure 4.10 (a-c). The uncontaminated symmetric 4 and 6 prong MM^2 distributions are shown in Figure 4.11 (a-f).

A correction for this asymmetry in the MM^2 distributions has been applied when calculating the channel cross sections, the contamination being 'removed' into the corresponding 0C channels.

4.4.5 The Channel Cross Sections

The final numbers of events in each channel obtained after resolution of the charged particle ambiguities and correction of those 1C channels which appeared contaminated

are given in Table 4.8. Using the topological cross sections of Table 4.7, microbarn equivalents were calculated for each topology for the event sample on DST and the non-strange channel cross sections are presented in Table 4.9. Results of the 9.1 GeV/c $\bar{p}p$ experiment are also given in this Table for comparison.

The results were compared with existing data and found to be in good general agreement with the trends. The cross sections of those channels for which there is significant data are shown as a function of laboratory momentum in Figure 4.12.

4.5 THE ANNIHILATION SAMPLE

Once charged particle ambiguities have been resolved the annihilation candidates are well defined. The 4C and 1C annihilation pion channels are 'pure', the 0C, $\pi^+\pi^-$ MM and $2\pi^+2\pi^-$ MM channels, however have a non-annihilation contribution through the presence of $n\bar{n}$ in the missing mass. There is no way of differentiating $n\bar{n}$ type events from true annihilation events in a bubble chamber experiment without additional downstream detectors. This is unfortunate as it makes it very difficult to obtain a complete sample of annihilation events for subsequent analysis.

Attempts have been made to find the $n\bar{n}$ contribution to the pionic MM channels by fitting the observed MM^2 distributions with generated $2\pi^0$, $3\pi^0$, $4\pi^0$, $n\bar{n}$ and $n\bar{n}\pi^0$ effective mass distributions [4.6,4.7,4.8]. Such fits are

very difficult to perform and have large errors, none the less using these results it is estimated that approximately 80% of the $\pi^+\pi^-$ -MM and 20% of the $2\pi+2\pi$ -MM events would be non-annihilation, (i.e. $n\bar{n}$). Consequently the annihilation sample was obtained by applying cuts on the missing mass in these two channels such that 80% and 20% of the events respectively were removed. The cuts employed were 5.5 and 4.9 $(\text{GeV}/c^2)^2$ for the $\pi^+\pi^-$ -MM and $2\pi+2\pi$ -MM channels respectively.

Besides annihilation into the pion channels discussed above, there are also annihilation channels containing charged and neutral kaons. Charged particle ambiguities in these kaonic channels were resolved using techniques similar to those already described.

The annihilation cross sections corresponding to this annihilation sample are summarised in Table 4.10 and compared with other data in Figure 4.13. Also given in Table 4.10 are the corresponding non-annihilation cross sections, pp results at 6.6 GeV/c the nearest available energy [4.9], and the mean charged particle multiplicity in each case. Clearly $\langle n \rangle$ is significantly larger for annihilations, 4.96 ± 0.17 compared with 2.78 ± 0.17 for non-annihilations. This is not too surprising as there are no baryons in the annihilation final states, resulting in more available energy for meson production.

4.6 REFERENCES

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4.7 TABLES

- 4.1 Scanning efficiencies.
- 4.2 Fiducial volume corrections.
- 4.3 Bad beam corrections.
- 4.4 Elastic t-distribution fit results.
- 4.5 Scanned events and final corrected numbers of events.
- 4.6 Total and Topological Cross Sections.
- 4.7 Numbers of unique and ambiguous events by channel for
Liverpool and Amsterdam data samples separately.
- 4.8 Final numbers of events in each channel after ambiguity
resolution.
- 4.9 Non-strange Exclusive Channel Cross Sections.
- 4.10 Topological Annihilation and Non-annihilation Cross
Sections.

TABLE 4.1 Scanning Efficiencies

Topology	n_1	n_2	n_{12}	ϵ_1	ϵ_2	ϵ_{12}	ϵ_a
0	526	509	461	0.906	0.876	0.988	0.891
2	6249	6287	6150	0.978	0.984	1.0	0.981
4	4134	4100	4066	0.992	0.984	1.0	0.988
6	1778	1779	1762	0.990	0.991	1.0	0.991
8	387	390	382	0.979	0.987	1.0	0.983
10	45	45	45	1.0	1.0	1.0	1.0
Total	13119	13110	12866	0.981	0.981	1.0	0.981
V^0	1699	1709	1684	0.985	0.991	1.0	0.988

TABLE 4.2Fiducial Volume Correction

Topology	Fraction in $-60 < x < 40$
0	0.950 ± 0.010
2	0.954 ± 0.002
4	0.955 ± 0.003
6	0.960 ± 0.004
8	0.949 ± 0.010
10	0.933 ± 0.040
Total	0.955 ± 0.002

TABLE 4.3Bad Beam Correction

Topology	Fraction Bad Beam
0	0.920 ± 0.010
2	0.965 ± 0.002
4	0.970 ± 0.002
6	0.978 ± 0.002
8	0.974 ± 0.006
10	0.987 ± 0.010
Total	0.967 ± 0.002

TABLE 4.4 Elastic t-distribution Parameters

Fit to form : $dN/dt = A \exp[-bt]$ over interval :
$-0.32 < t < -0.05 \text{ (GeV/c)}^2$
$A = 447 \pm 10 \text{ events/0.01 (GeV/c)}^2$
$b = 12.8 \pm 0.2 \text{ (GeV/c)}^{-2}$
$\chi^2/ND = 23.9/27$

TABLE 4.5 Scanned Events and Final Corrected Numbers

Topology	Events Scanned	π^-p Events	Corrected No Events	Elastic Corrected
0	7303	23 $\pm$ 5	7139 $\pm$ 180	7139 $\pm$ 180
(elas)				44735 $\pm$ 1500
2	89593	430 $\pm$ 85	83644 $\pm$ 460	52361 $\pm$ 610
(inel)				
4	60678	315 $\pm$ 63	56588 $\pm$ 390	56588 $\pm$ 390
6	25850	86 $\pm$ 16	24407 $\pm$ 200	24407 $\pm$ 200
8	5654	4 $\pm$ 2	5311 $\pm$ 100	5311 $\pm$ 100
10	553		510 $\pm$ 30	510 $\pm$ 30
12	23		23 $\pm$ 5	23 $\pm$ 5
Total	189654	858 $\pm$ 170	177622 $\pm$ 670	191074 $\pm$ 1700

TABLE 4.6 Total and Topological Cross Sections

Topology	σ (mb)
0	2.18 $\pm$ 0.08
2 inelastic	15.98 $\pm$ 0.43
4	17.27 $\pm$ 0.43
6	7.45 $\pm$ 0.19
8	1.62 $\pm$ 0.05
10	0.156 $\pm$ 0.010
12	0.007 $\pm$ 0.002
Total inelastic	44.65 $\pm$ 1.10
2 elastic	13.65 $\pm$ 0.56
TOTAL	58.3 $\pm$ 1.3

$$\langle n \rangle_{\text{inelastic}} = 3.59 \pm 0.17$$

TABLE 4.7 Numbers of Unique and Ambiguous Events

(a) Liverpool Data.

Final State	2 Prong		4 Prong		6 Prong	
	UNIQ	AMB	UNIQ	AMB	UNIQ	AMB
1) $\pi^+\pi^-\alpha(\pi^+\pi^-)$			27		56	
2) $\pi^+\pi^-\alpha(\pi^+\pi^-)\pi^0$	51	282	269	64	389	8
3) $\pi^+\pi^-\alpha(\pi^+\pi^-)MM$	1257	1630	1587	1235	1566	194
4) $\bar{p}p\alpha(\pi^+\pi^-)$	3571		1088	35	104	12
5) $\bar{p}p\alpha(\pi^+\pi^-)\pi^0$	480	233	667	211	71	23
6) $\bar{p}p\alpha(\pi^+\pi^-)MM$	109	550	142	253	17	14
7) $n\bar{p}\pi^+\alpha(\pi^+\pi^+)$	86	640	81	303	10	37
8) $MM\bar{p}\pi^+\alpha(\pi^+\pi^-)$	92	1066	68	623	10	80
9) $\bar{n}p\pi^-\alpha(\pi^+\pi^-)$	427	357	177	173	15	24
10) $MMp\pi^-\alpha(\pi^+\pi^-)$	655	622	220	439	13	44
TOTAL	6278	2690	4326	1668	2251	218
Fraction of total	0.70	0.30	0.72	0.28	0.91	0.09

TABLE 4.7 continued. (b) Amsterdam Data.

Final State	2 Prong		4 Prong		6 Prong	
	UNIQ	AMB	UNIQ	AMB	UNIQ	AMB
1) $\pi^+\pi^-\alpha(\pi^+\pi^-)$			79	2	205	5
2) $\pi^+\pi^-\alpha(\pi^+\pi^-)\pi^0$			1017	163	1525	48
3) $\pi^+\pi^-\alpha(\pi^+\pi^-)MM$			5129	4572	4654	786
4) $\bar{p}p\alpha(\pi^+\pi^-)$			2923	187	277	55
5) $\bar{p}p\alpha(\pi^+\pi^-)\pi^0$			1702	683	171	113
6) $\bar{p}p\alpha(\pi^+\pi^-)MM$			398	841	48	49
7) $n\bar{p}\pi^+\alpha(\pi^+\pi^-)$			221	820	22	146
8) $MM\bar{p}\pi^+\alpha(\pi^+\pi^-)$			255	2254	20	261
9) $\bar{n}p\pi^-\alpha(\pi^+\pi^-)$			609	534	335	123
10) $MMp\pi^-\alpha(\pi^+\pi^-)$			562	1508	27	166
TOTAL			12902	5782	6984	876
Fraction of Total			0.69	0.31	0.89	0.11

TABLE 4.8 Numbers of Events after Ambiguity Resolution

Final State	2	4	6	8	10	12
1) $\pi^+\pi^-\alpha(\pi^+\pi^-)$		113	269	154	21	
2) $\pi^+\pi^-\alpha(\pi^+\pi^-)\pi^0$	102	1145	1877	620	68	1
3) $\pi^+\pi^-\alpha(\pi^+\pi^-)MM$	1855	9870	6984	1359	99	3
4) $\bar{p}p\alpha(\pi^+\pi^-)$	3571 ^a	4684	472	9		
5) $\bar{p}p\alpha(\pi^+\pi^-)\pi^0$	660	3179	376	5		
6) $\bar{p}p\alpha(\pi^+\pi^-)MM$	357	1019	90			
7) $n\bar{p}\pi^+\alpha(\pi^+\pi^-)$	600	1372	198	5		
8) $MM\bar{p}\pi^+\alpha(\pi^+\pi^-)$	815	1594	134	2		
9) $\bar{n}p\pi^-\alpha(\pi^+\pi^-)$	633	1420	196	3		
10) $MMp\pi^-\alpha(\pi^+\pi^-)$	828	1561	99	1		

^a Number before correction for missed elastics.

TABLE 4.9 Non-Strange Exclusive Channel Cross Sections

(a) 2 Prongs.

Final State	7.3 GeV/c σ (mb)	9.1 GeV/c σ (mb)
$\pi^+\pi^-$		
$\pi^+\pi^-\pi^0$	0.26 ± 0.03	0.02 ± 0.01
$\pi^+\pi^-MM$	4.79 ± 0.17	4.83 ± 0.08
$\bar{p}p$	13.65 ± 0.56	11.75 ± 0.23
$\bar{p}p\pi^0$	1.71 ± 0.08	1.31 ± 0.03
$\bar{p}pMM$	0.92 ± 0.06	1.03 ± 0.03
$n\bar{p}\pi^+$	1.55 ± 0.08	1.40 ± 0.03
$MM\bar{p}\pi^+$	2.11 ± 0.09	1.91 ± 0.04
$\bar{n}p\pi^-$	1.64 ± 0.08	1.40 ± 0.04
$MMp\pi^-$	2.14 ± 0.09	1.91 ± 0.05

(b) 4 Prongs

Final State	7.3 GeV/c σ (mb)	9.1 GeV/c σ (mb)
$2\pi^+2\pi^+$	0.072 ± 0.007	0.048 ± 0.006
$2\pi^+2\pi^-\pi^0$	0.73 ± 0.03	0.53 ± 0.02
$2\pi^+\pi^-MM$	6.28 ± 0.17	5.63 ± 0.08
$\bar{p}p\pi^+\pi^-$	2.98 ± 0.09	2.60 ± 0.05
$\bar{p}p\pi^+\pi^-\pi^0$	2.02 ± 0.06	2.04 ± 0.04
$\bar{p}p\pi^+\pi^-MM$	0.65 ± 0.03	0.98 ± 0.03
$n\bar{p}2\pi^+\pi^-$	0.87 ± 0.03	0.98 ± 0.03
$MM\bar{p}2\pi^+\pi^-$	1.02 ± 0.04	1.06 ± 0.03
$\bar{n}p\pi^+2\pi^-$	0.90 ± 0.03	0.98 ± 0.03
$MMp\pi^+2\pi^-$	0.99 ± 0.04	1.06 ± 0.03

(c) 6 Prongs

Final State	7.3 GeV/c σ (mb)	9.1 GeV/c σ (mb)
$3\pi^+3\pi^-$	0.180 ± 0.013	0.16 ± 0.01
$3\pi^+3\pi^-\pi^0$	1.26 ± 0.06	0.94 ± 0.03
$3\pi^+3\pi^-MM$	4.68 ± 0.19	4.23 ± 0.08
$\bar{p}p2\pi^+2\pi^-$	0.32 ± 0.02	0.48 ± 0.02
$\bar{p}p2\pi^+2\pi^-\pi^0$	0.25 ± 0.02	0.48 ± 0.02
$\bar{p}p2\pi^+2\pi^-MM$	0.060 ± 0.007	0.17 ± 0.01
$n\bar{p}3\pi^+2\pi^-$	0.133 ± 0.011	0.19 ± 0.01
$MM\bar{p}3\pi^+2\pi^-$	0.090 ± 0.008	0.26 ± 0.02
$\bar{n}p2\pi^+3\pi^-$	0.131 ± 0.011	0.19 ± 0.01
$MMp2\pi^+3\pi^-$	0.066 ± 0.007	0.26 ± 0.02

(d) 8 Prongs

Final State	7.3 GeV/c σ (mb)	9.1 GeV/c σ (mb)
$4\pi^+4\pi^-$	0.114 ± 0.010	0.09 ± 0.01
$4\pi^+4\pi^-\pi^0$	0.46 ± 0.02	0.48 ± 0.03
$4\pi^+4\pi^-MM$	1.01 ± 0.04	1.31 ± 0.05
$\bar{p}p3\pi^+3\pi^-$	0.007 ± 0.002	0.02 ± 0.005
$\bar{p}p3\pi^+3\pi^-\pi^0$	0.004 ± 0.002	0.02 ± 0.005
$\bar{p}p3\pi^+3\pi^-MM$		
$n\bar{p}4\pi^+3\pi^-$	0.004 ± 0.002	0.01 ± 0.004
$MM\bar{p}4\pi^+3\pi^-$	0.002 ± 0.001	
$\bar{n}p3\pi^+4\pi^-$	0.002 ± 0.001	0.01 ± 0.004
$MMp3\pi^+4\pi^-$	0.001 ± 0.001	

(e) 10 Prongs

Final State	7.3 GeV/c σ (mb)	9.1 GeV/c σ (mb)
$5\pi+5\pi^-$	0.017 ± 0.004	
$5\pi+5\pi-\pi^0$	0.057 ± 0.008	
$5\pi+5\pi$ -MM	0.082 ± 0.010	

(f) 12 Prongs

Final State	7.3 GeV/c σ p(mb)	9.1 GeV/c σ (mb)
$6\pi+6\pi^-$		
$6\pi+6\pi-\pi^0$	0.002 ± 0.002	
$6\pi+6\pi$ -MM	0.005 ± 0.003	

TABLE 4.10 Topological Annihilation Cross Sections

Topology	$\sigma(\text{ann})$ (mb.)	$\sigma(\text{non-ann})$ (mb.)	$\sigma(\text{pp})$ [4.9] (mb.)
0	—	2.18 $\pm$ 0.08	—
2 inel	1.55 $\pm$ 0.10	14.43 $\pm$ 0.42	16.83 $\pm$ 0.70
4	6.37 $\pm$ 0.17	10.90 $\pm$ 0.39	10.50 $\pm$ 0.46
6	6.36 $\pm$ 0.17	1.09 $\pm$ 0.08	0.73 $\pm$ 0.09
8	1.59 $\pm$ 0.04	0.03 $\pm$ 0.03	0.022 $\pm$ 0.008
10	0.156 $\pm$ 0.010		0.009 $\pm$ 0.005
Total	16.03 $\pm$ 0.26	28.6 $\pm$ 1.0	28.09 $\pm$ 0.84
$\langle n \rangle$	4.96 $\pm$ 0.17	2.78 $\pm$ 0.17	2.86 $\pm$ 0.16

4.8 FIGURES

- 4.1 Distribution of the primary vertex in x for the Liverpool DST sample.
- 4.2 Distribution of azimuthal angle φ for elastic events on DST.
- 4.3 t -distribution of the restricted sample of elastics.
- 4.4 $\bar{p}p$ topological cross sections vs. laboratory momentum.
- 4.5 $\cos\theta^*$ distributions of unique and ambiguous protons and antiprotons.
- 4.6 $\cos\theta^*$ distributions for π^+ , π^- and MM for unique and unique+ambiguous samples of $2\pi+2\pi$ -MM events.
- 4.7 $\cos\theta^*$ distributions for π^+ , π^- and MM for final samples, after resolution and weighting of ambiguous events, of $2\pi+2\pi$ -MM and $3\pi+3\pi$ -MM channels.
- 4.8 $\cos\theta^*$ distributions of $p, \bar{n}/MM$ and $\bar{p}, n/MM$ for final weighted samples in the 2 and 4 prong channels.
- 4.9 MM^2 distributions in the 4C channels.
- 4.10 MM^2 distributions of some uncontaminated 1C channels.
- 4.11 MM^2 distributions of the contaminated 1C channels showing asymmetry.
- 4.12 Channel cross sections vs. laboratory momentum.
- 4.13 $\bar{p}p$ topological annihilation cross sections vs. laboratory momentum.

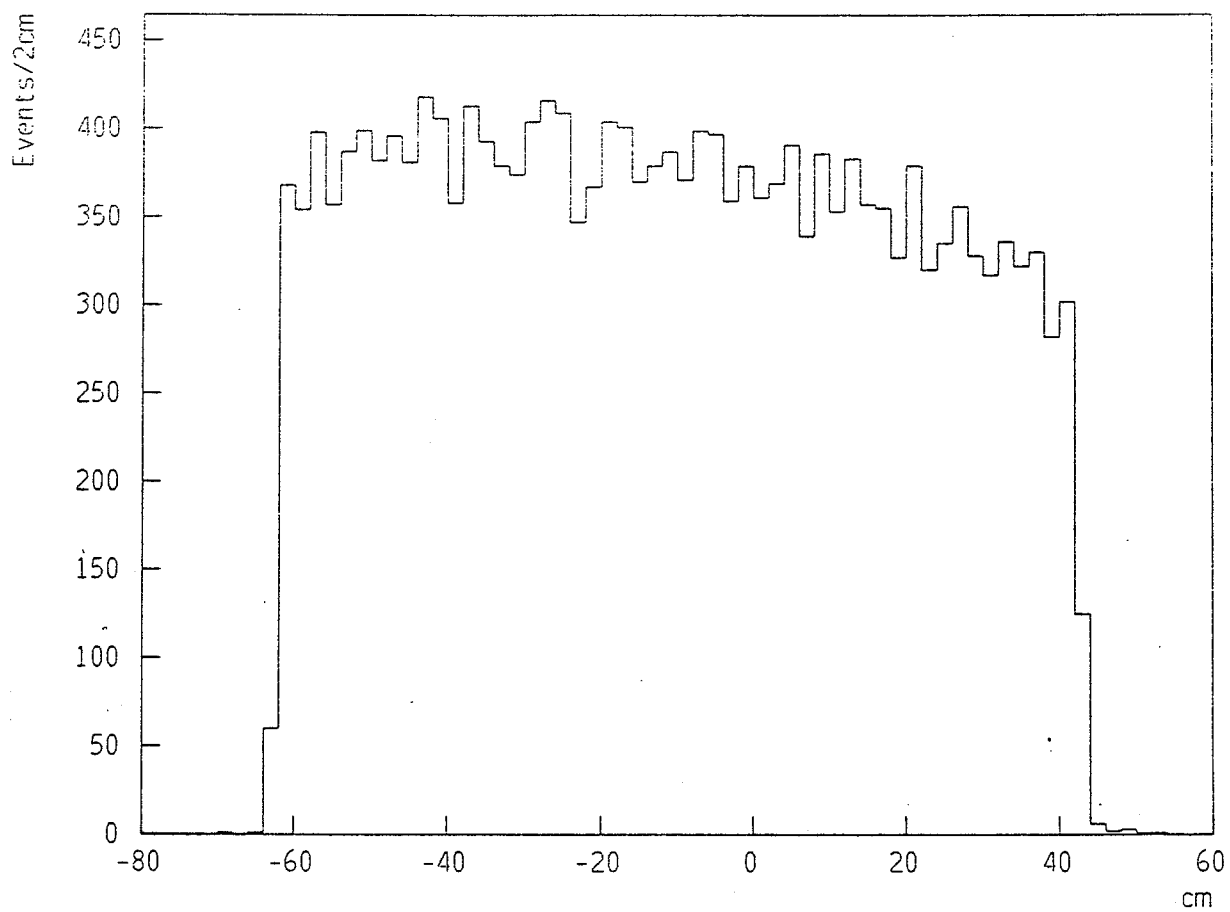


Figure 4.1 x Co-ordinate of Primary Vertex

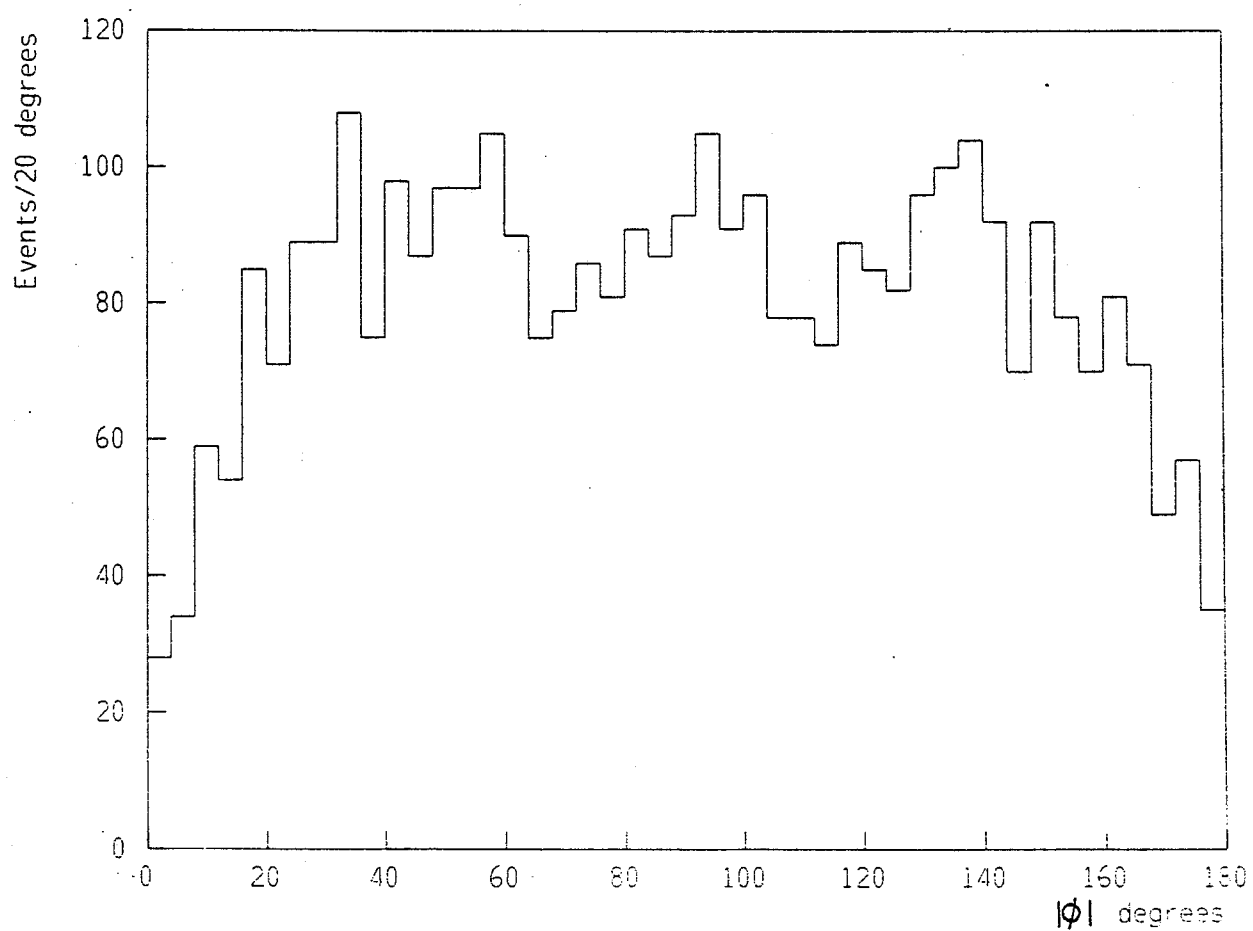


Figure 4.2 Azimuthal Angle for Elastic Events

Figure 4.3

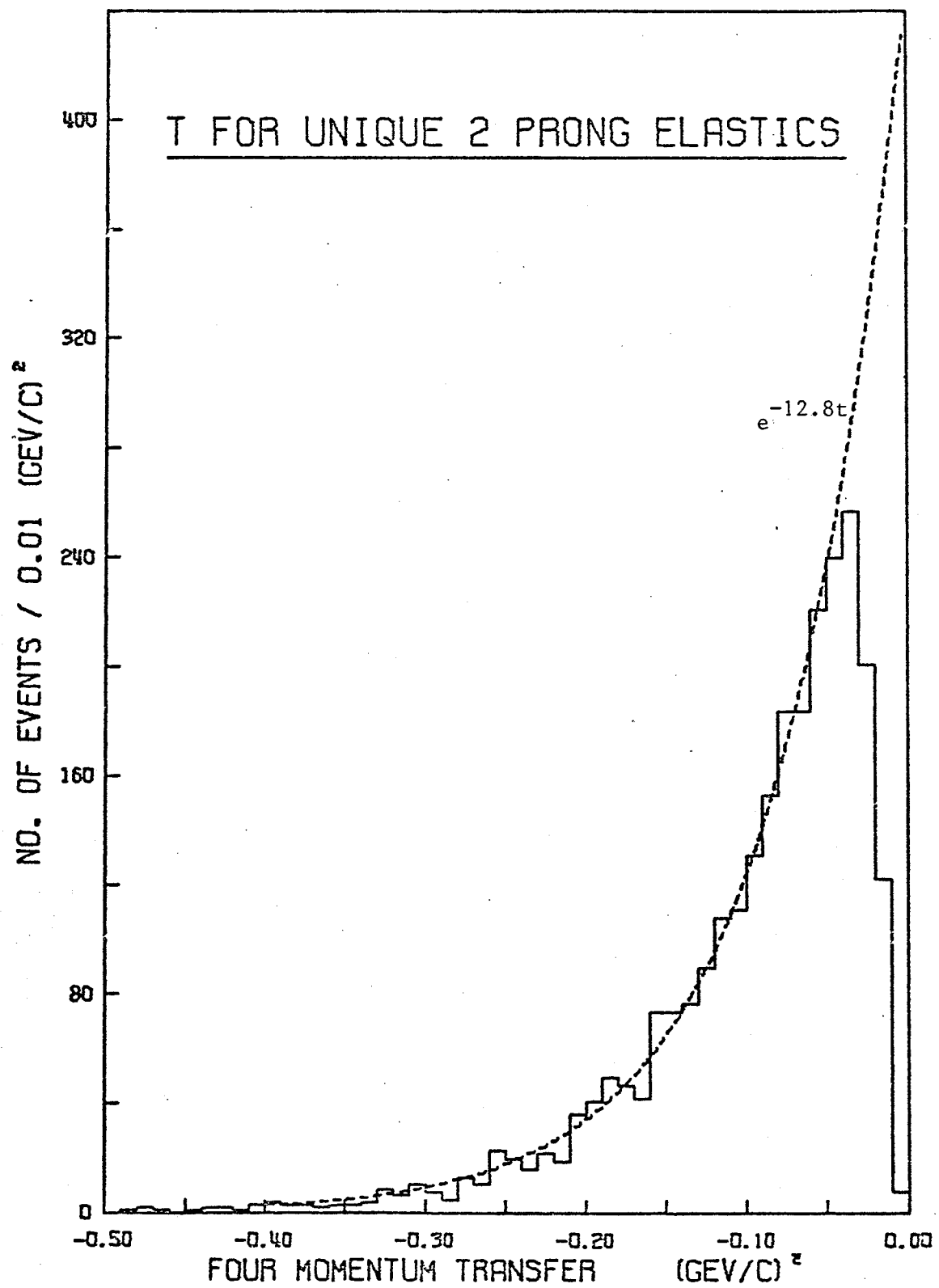


Figure 4.4 $\bar{p}p$ Topological Cross Sections vs P_{LAB}

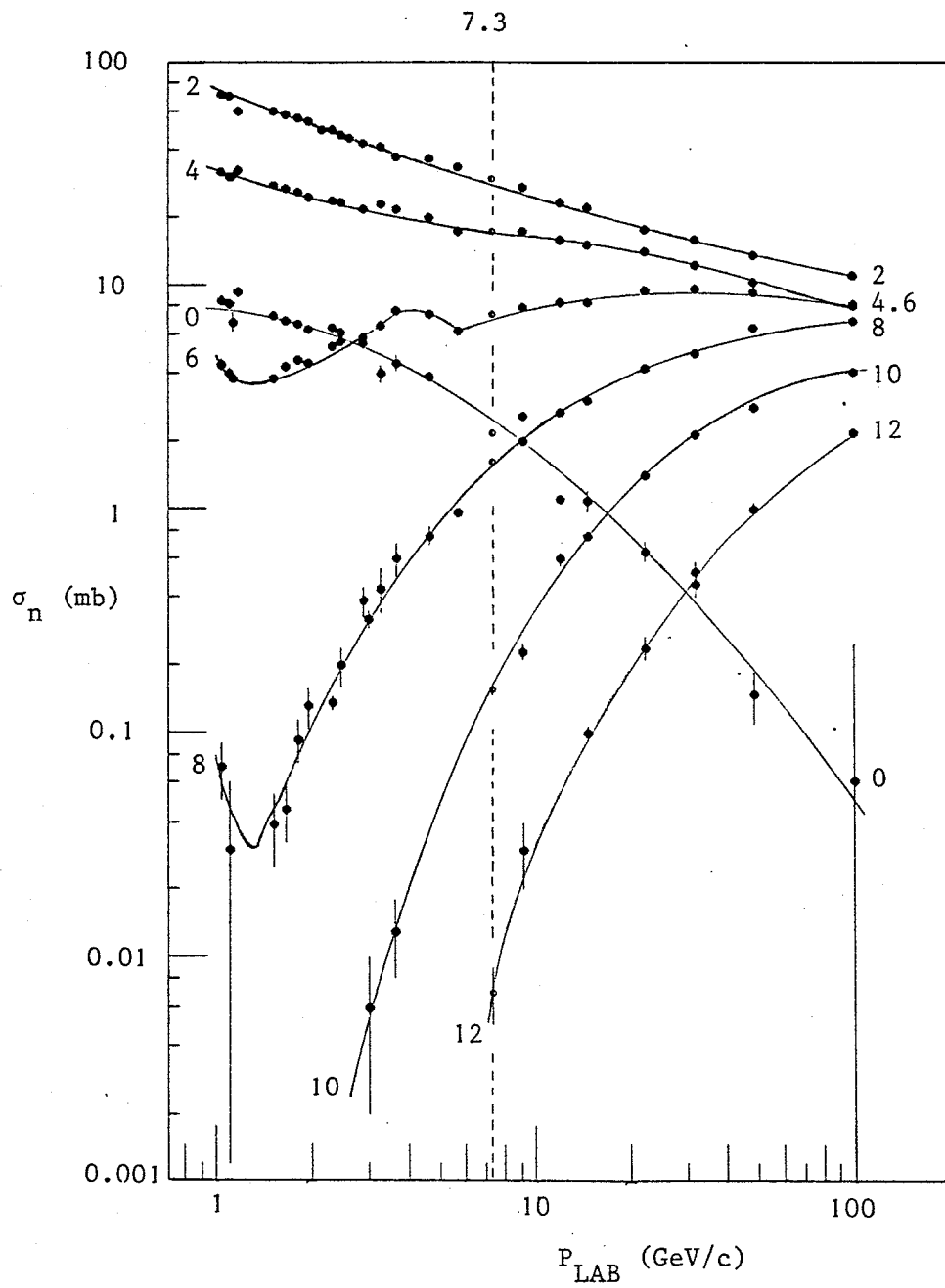


Figure 4.5 $\cos\theta^*$ for Unique, Ambiguous $p, \bar{p}$

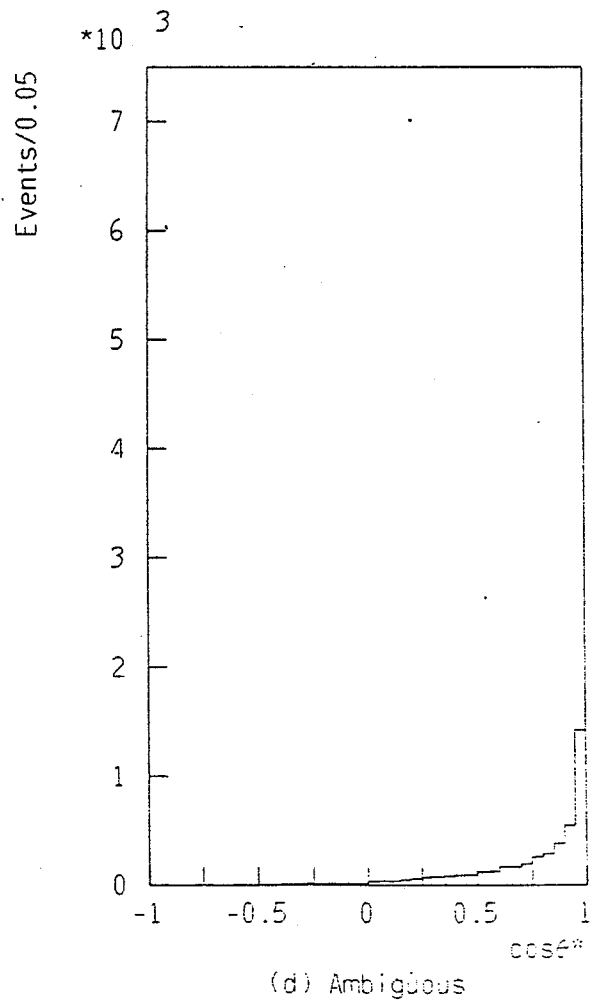
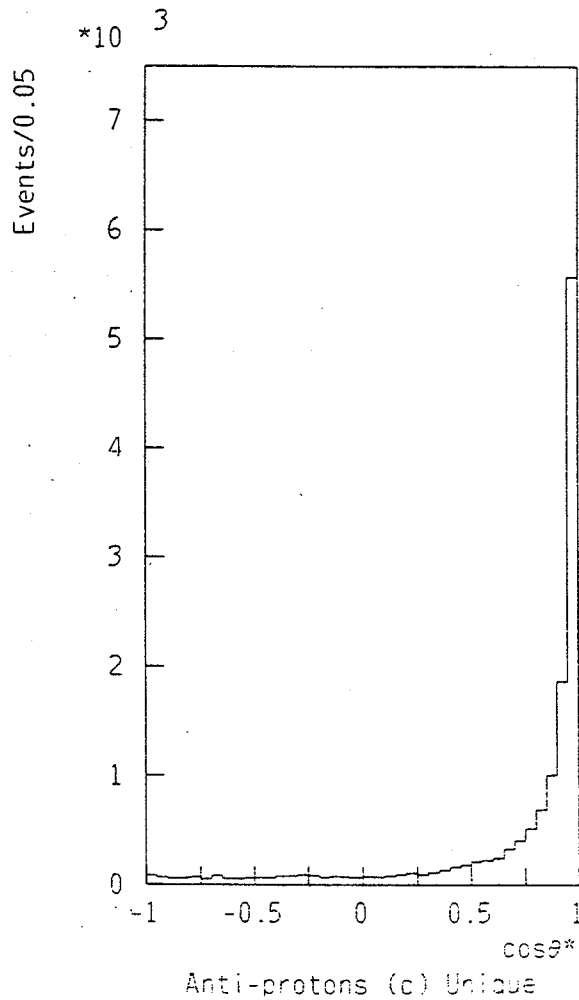
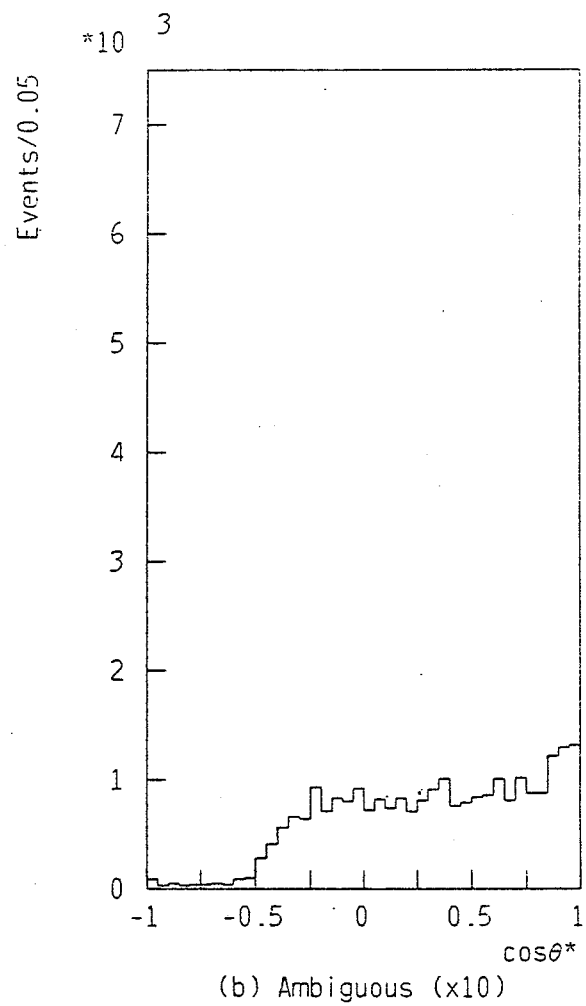
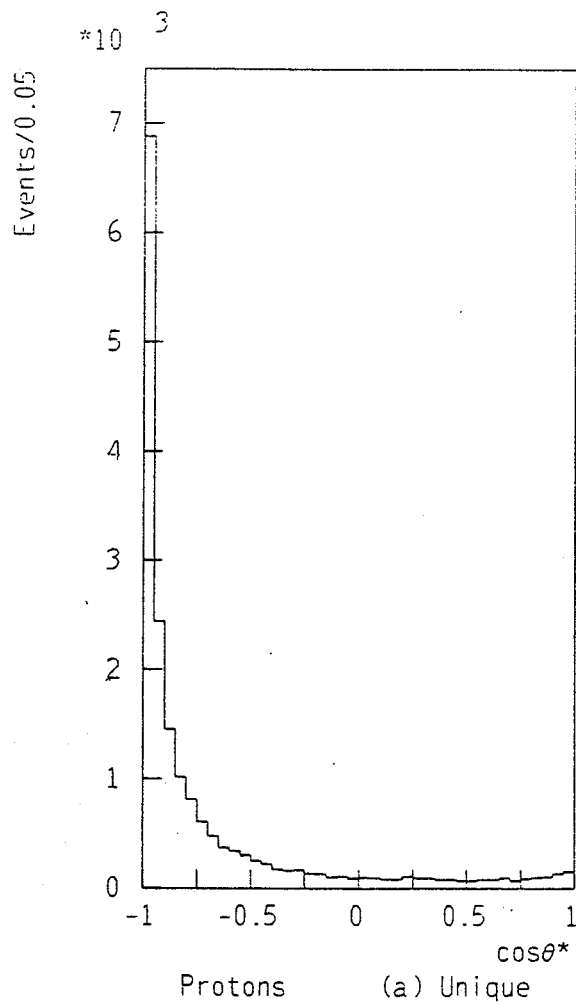


Figure 4.6 $\cos\theta^*$ Distributions in $2\pi^+2\pi^-$ MM Samples

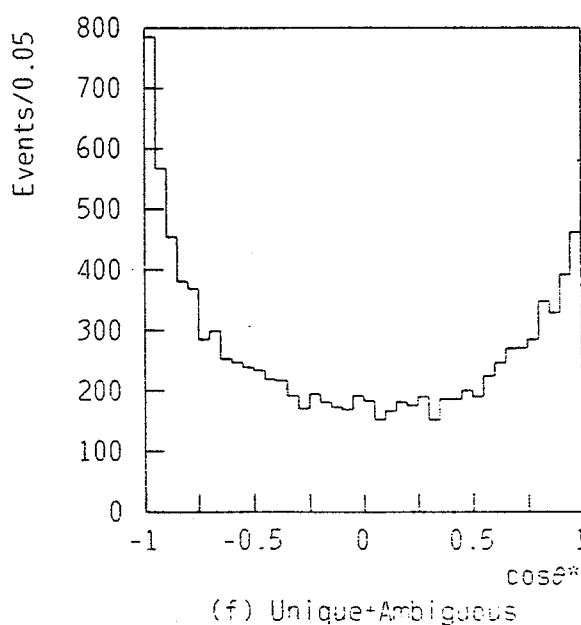
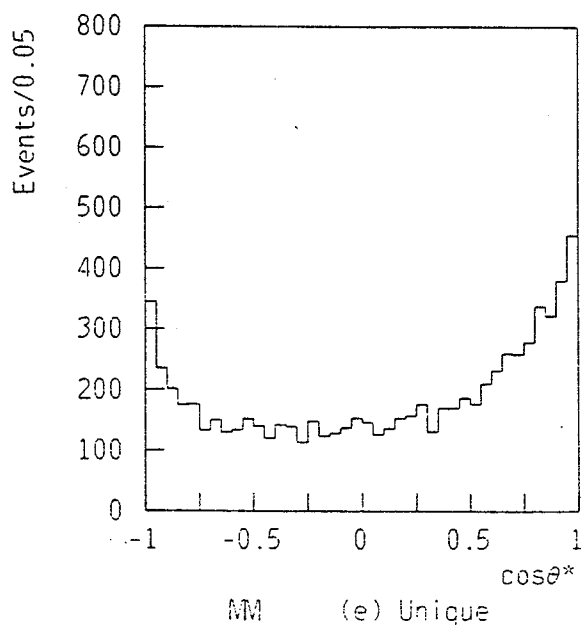
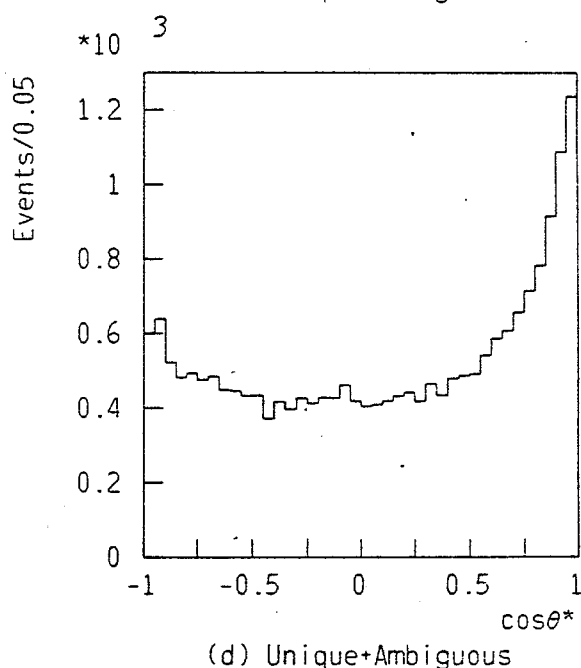
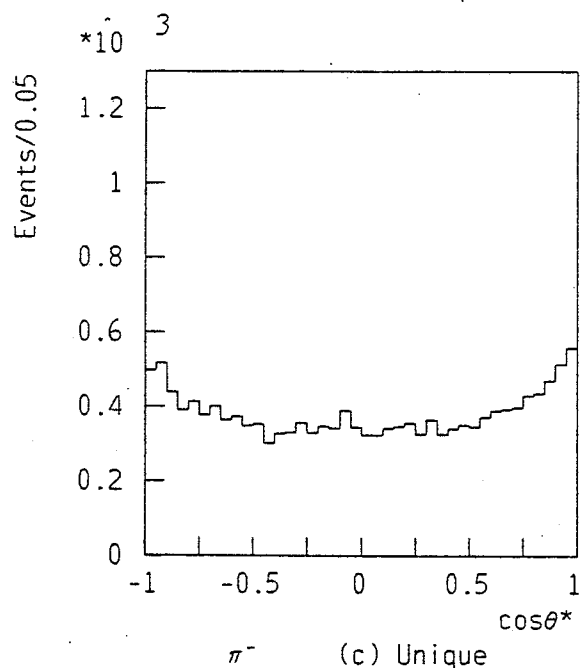
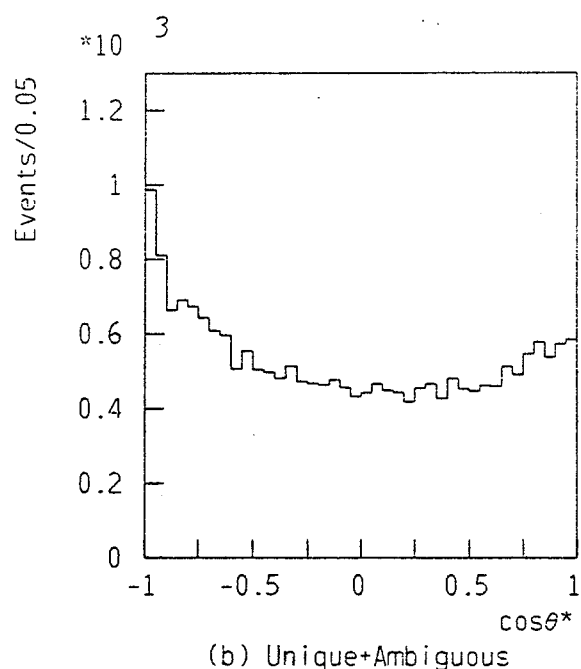
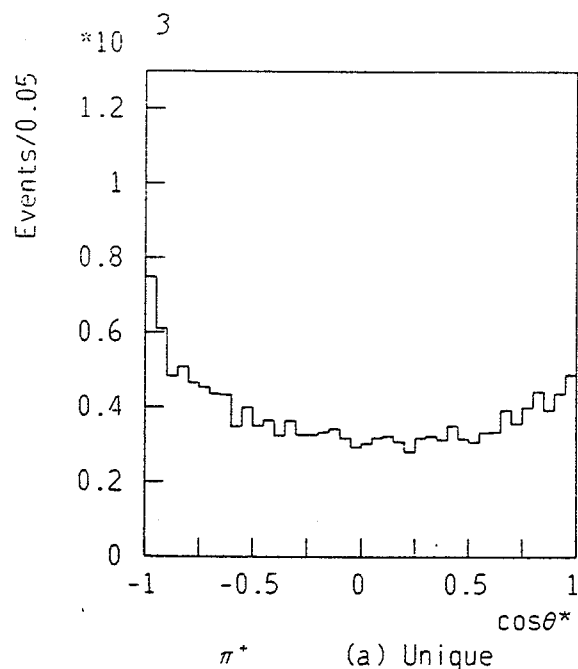


Figure 4.7 $\cos\theta^*$ Distributions in Final Weighted

$2\pi^+2\pi^-MM$

and

$3\pi^+3\pi^-MM$

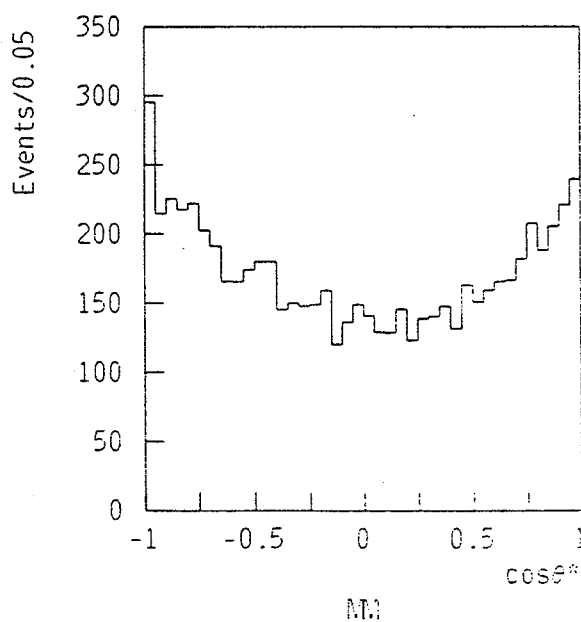
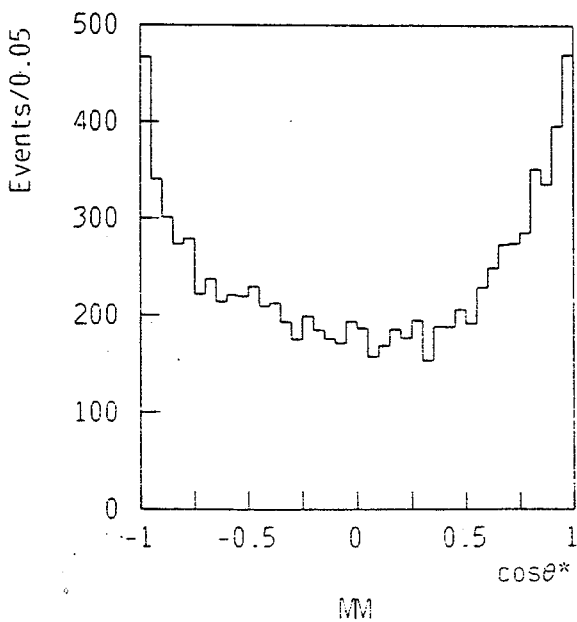
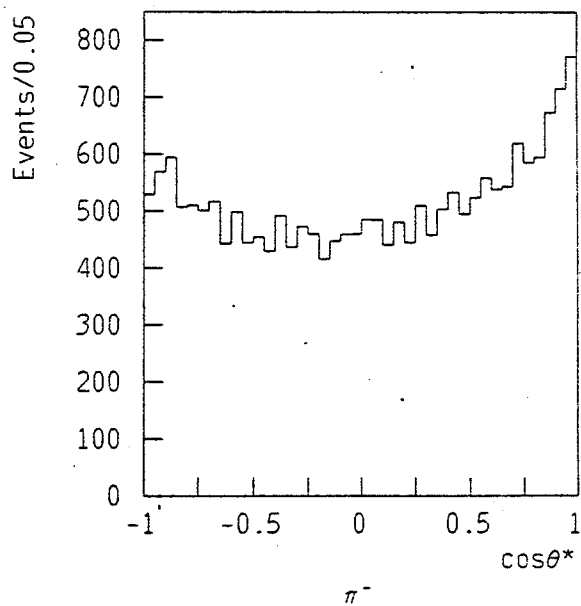
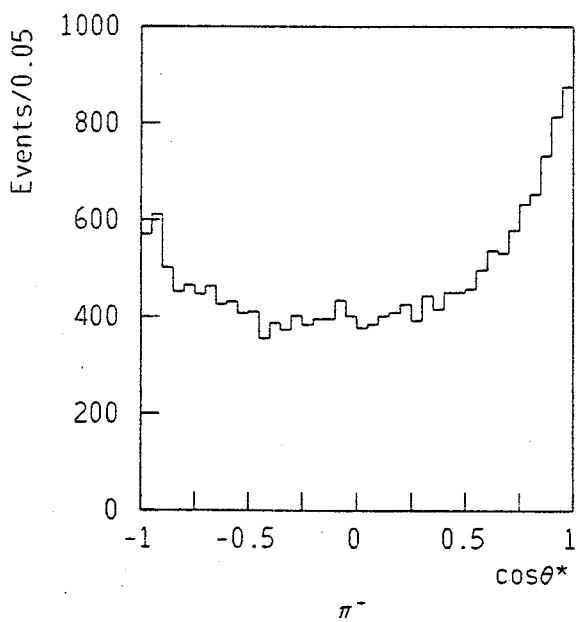
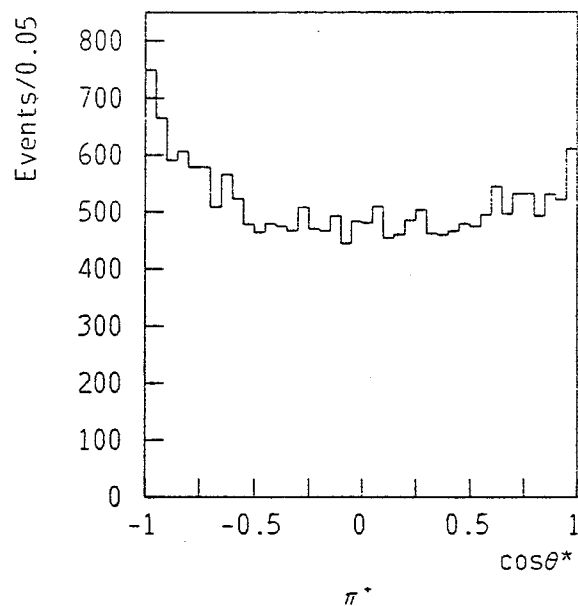
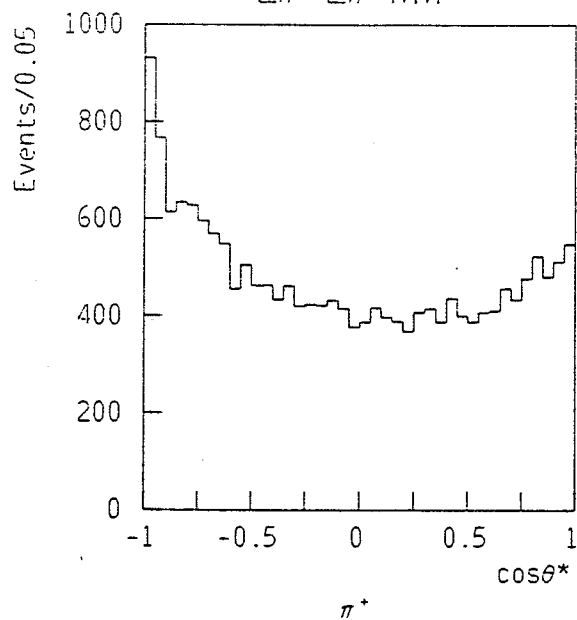


Figure 4.8 $\cos\theta^*$ Distributions in Final Weighted
 $(p, \bar{n}/MM)$ and $(\bar{p}, n/MM)$ Samples

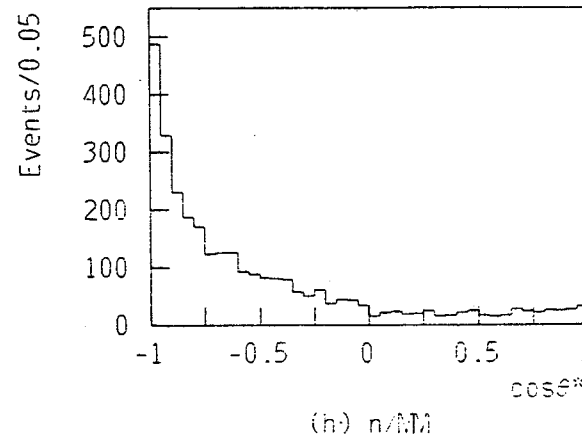
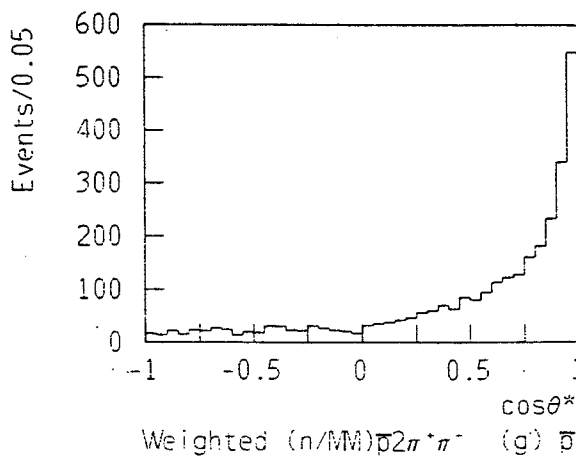
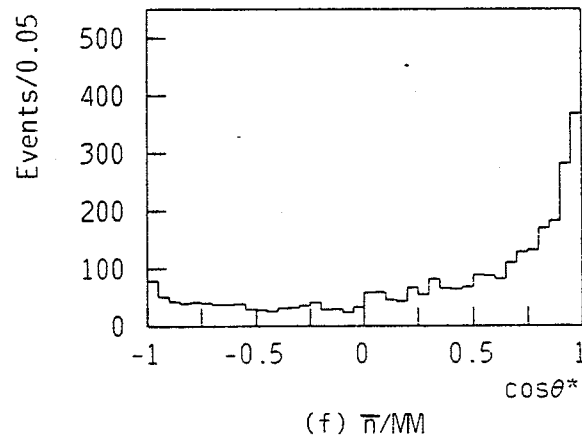
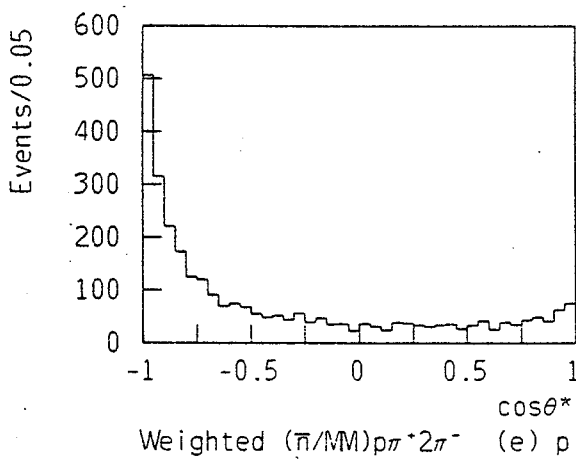
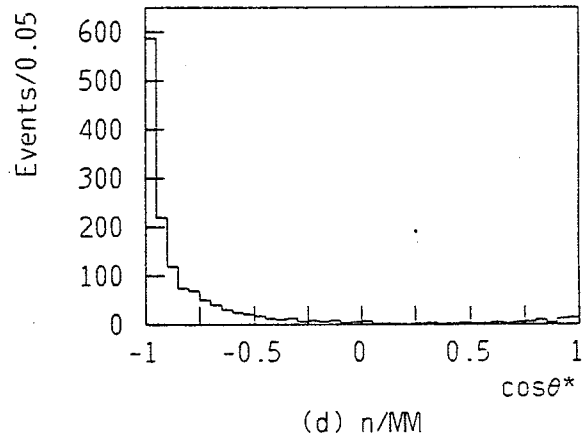
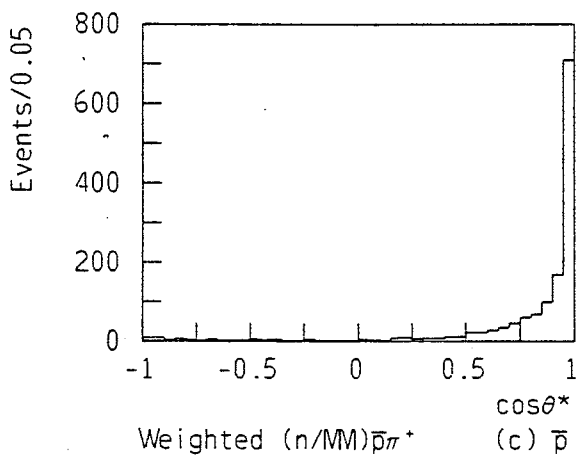
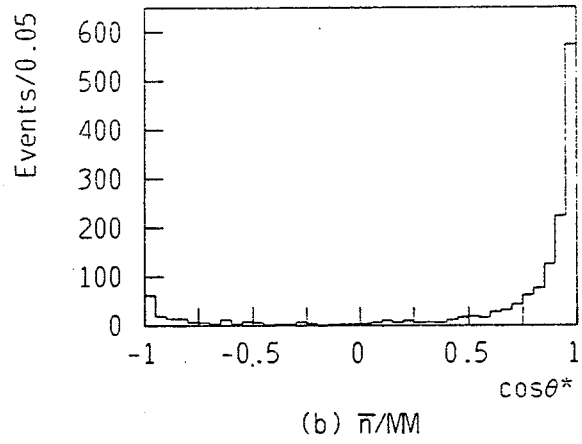
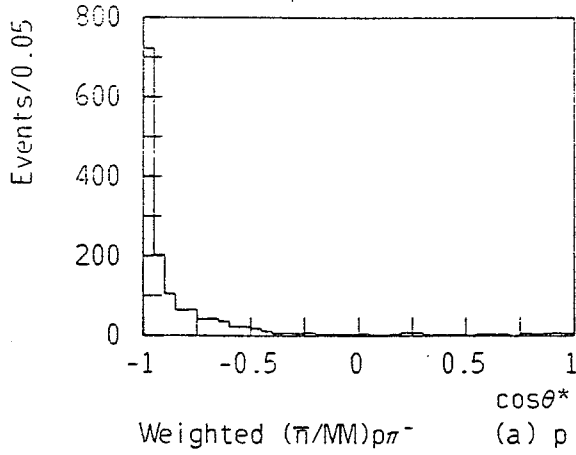


Figure 4.9 4C MM^2 Distributions

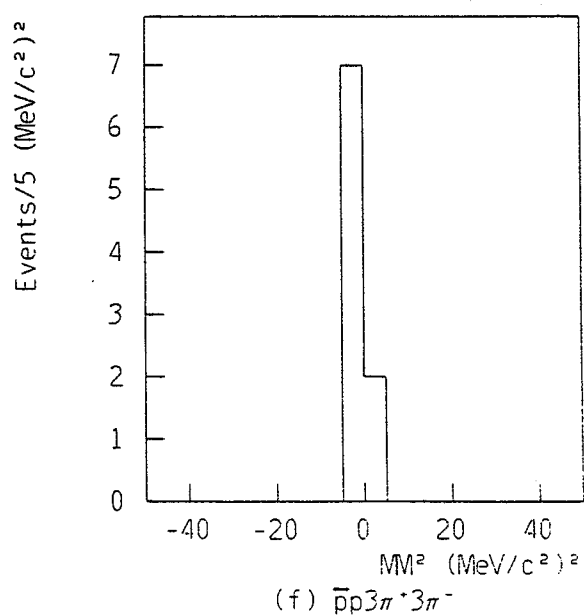
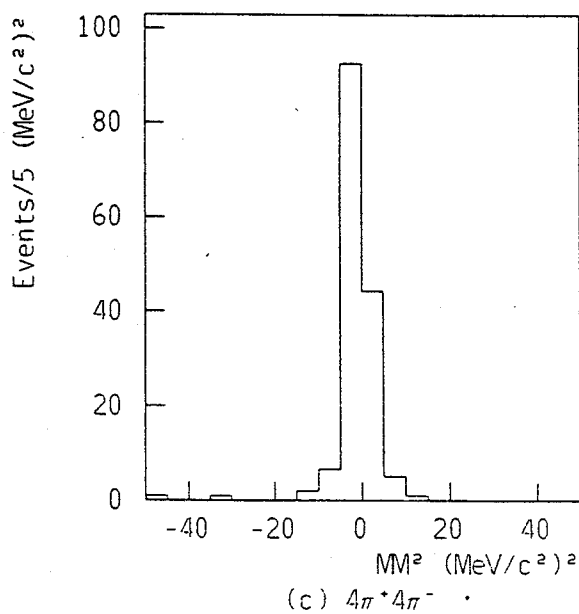
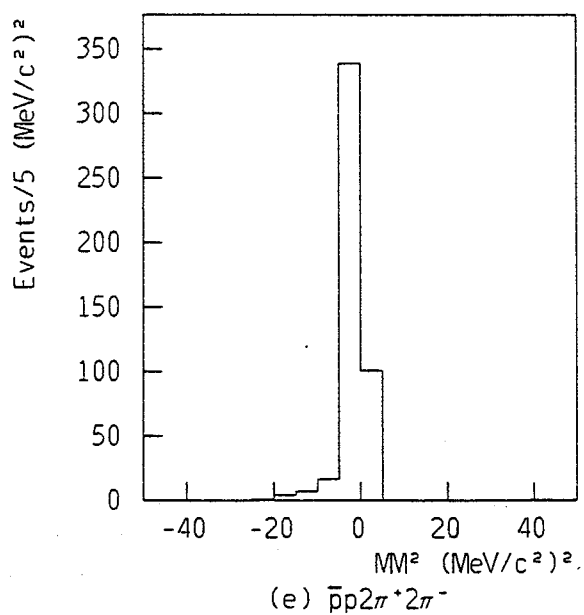
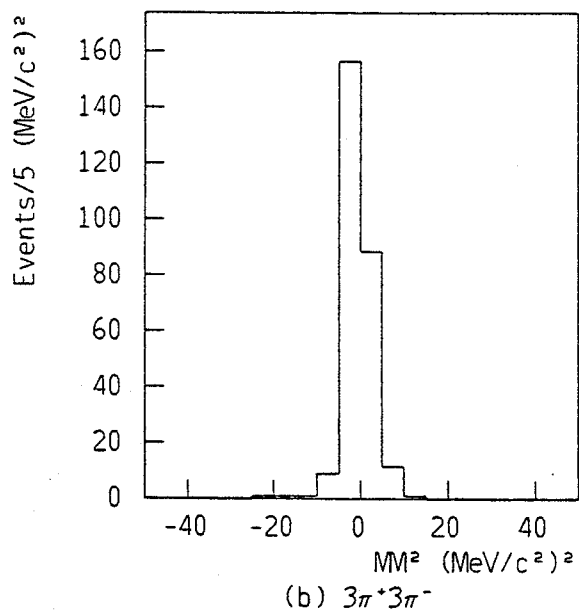
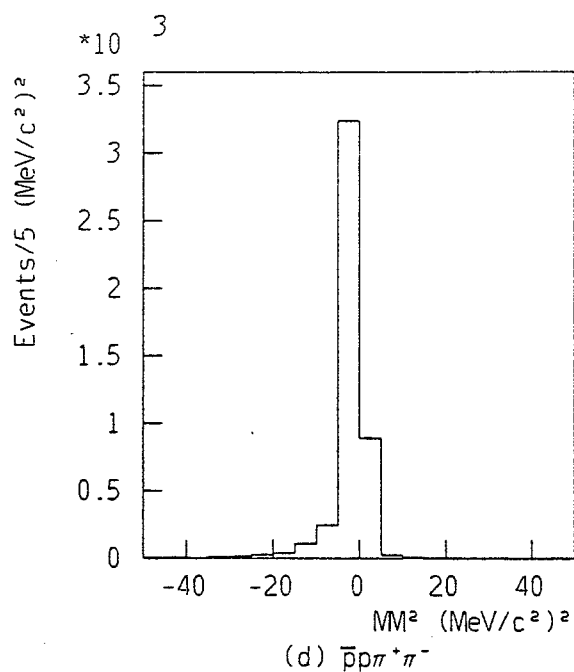
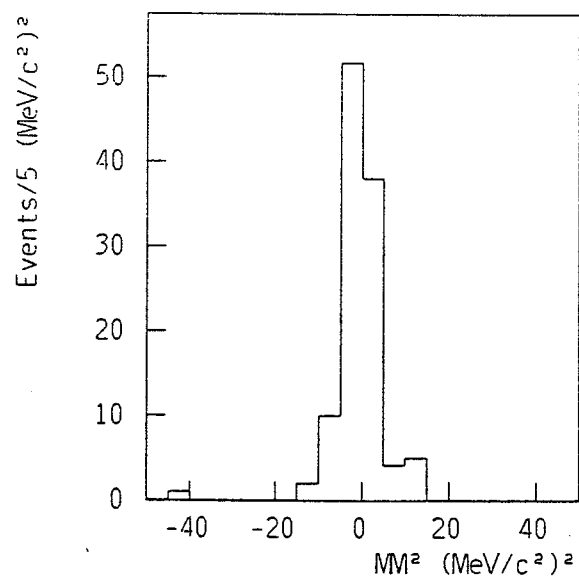


Figure 4.10 1C Uncontaminated MM^2 Distributions

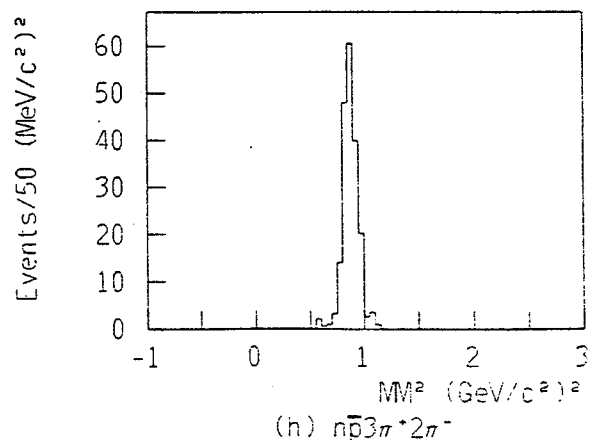
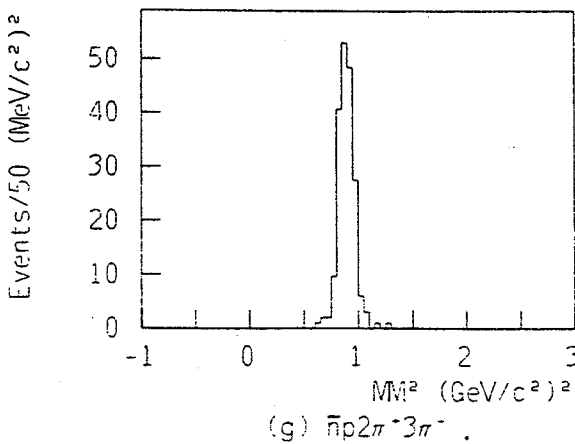
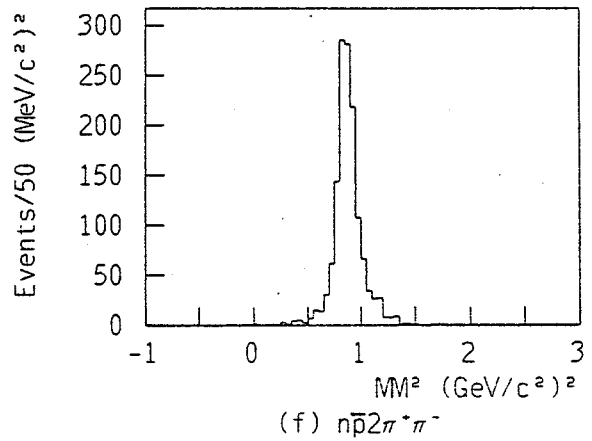
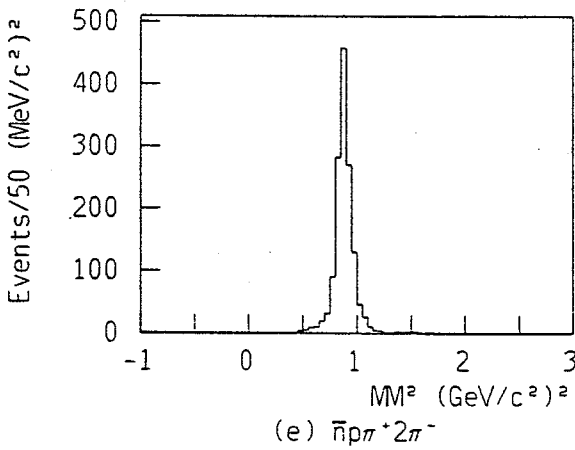
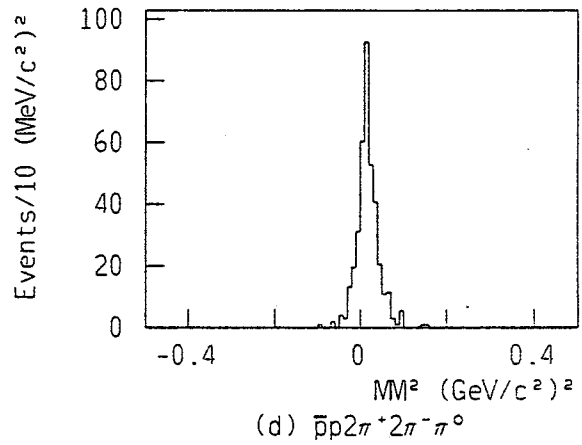
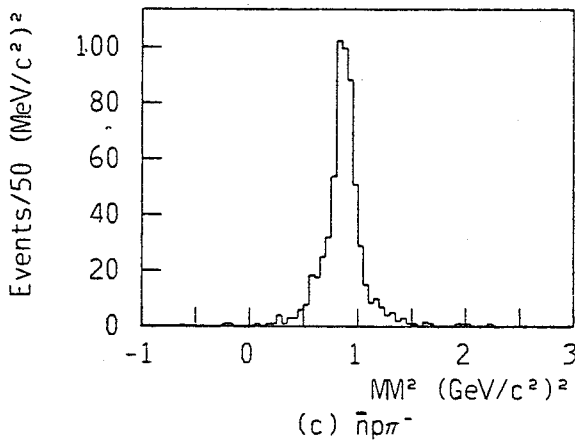
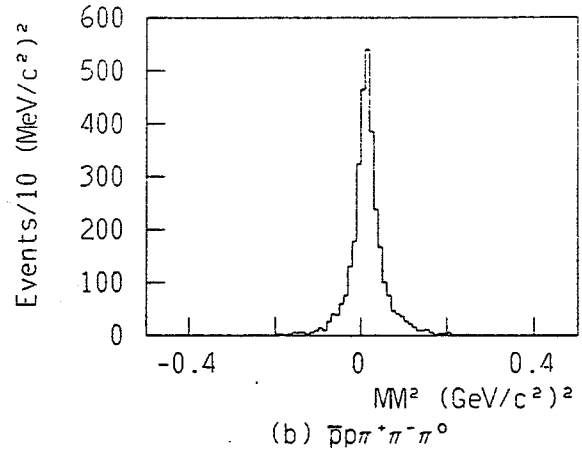
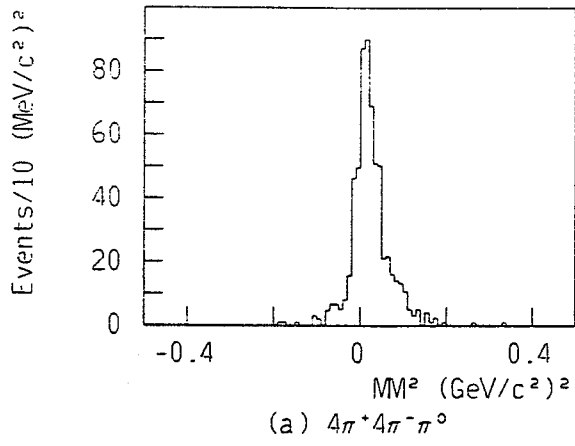
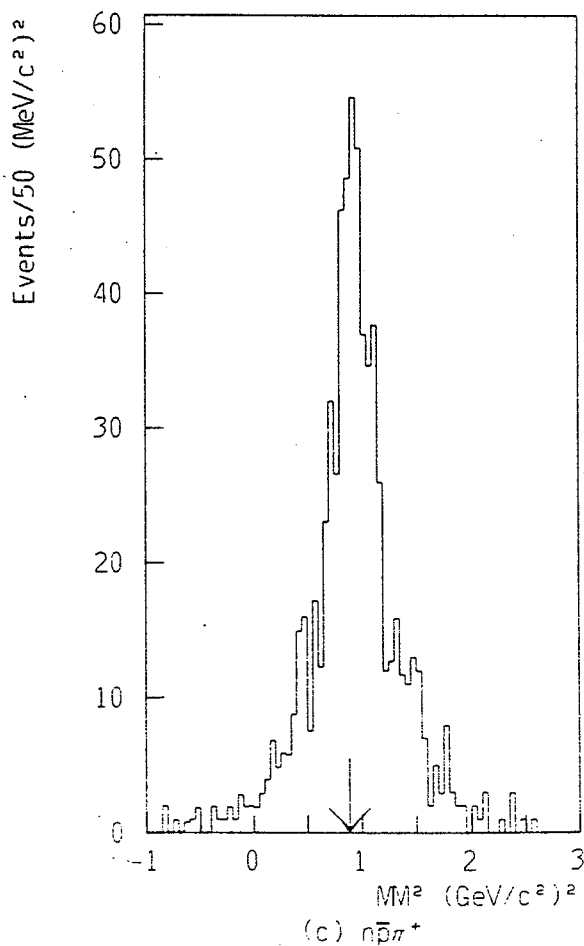
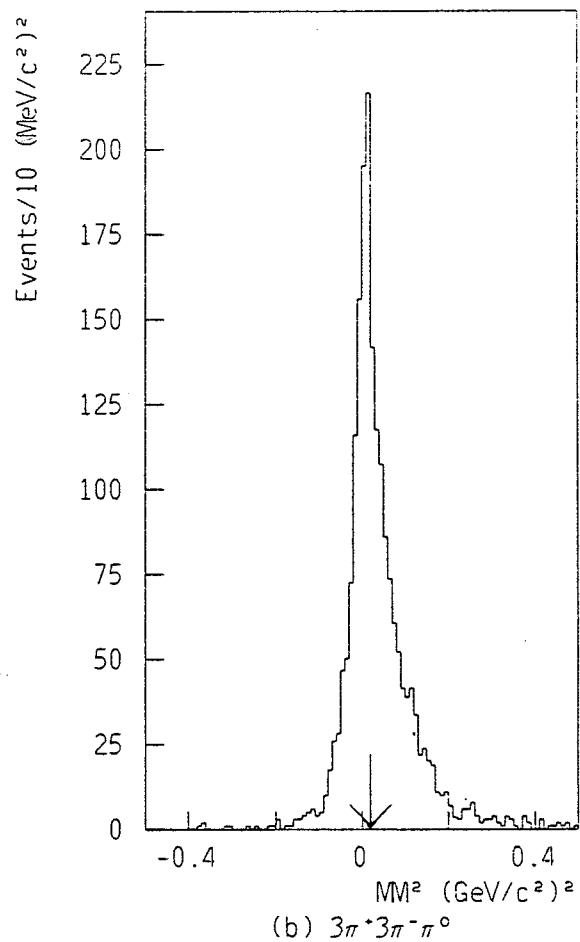
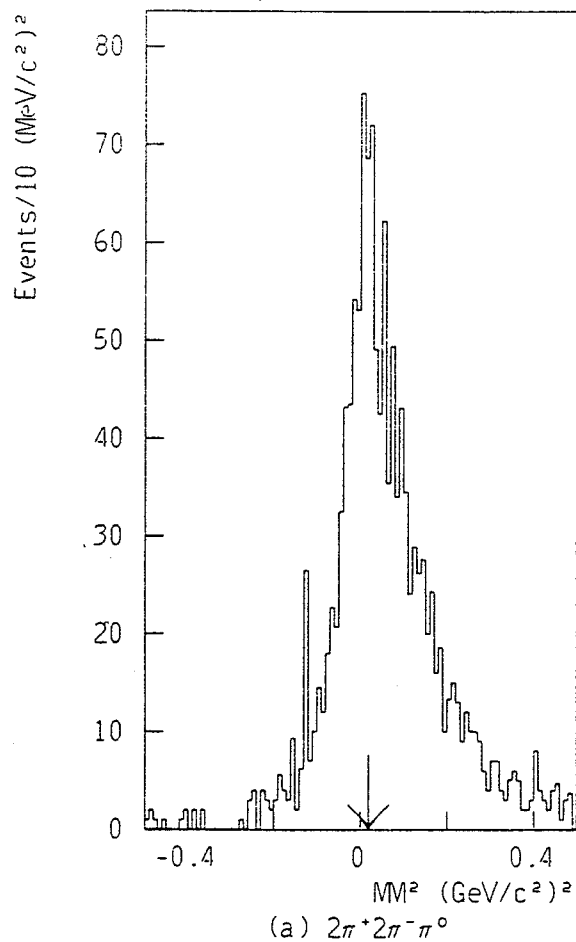


Figure 4.11 10 Contaminated MM^2 Distributions



↓ Indicates -
 $M(\pi^0)^2$ in (a) and (b)
 $M(n)^2$ in (c)

Figure 4.12 Channel Cross Sections vs. P_{Lab}

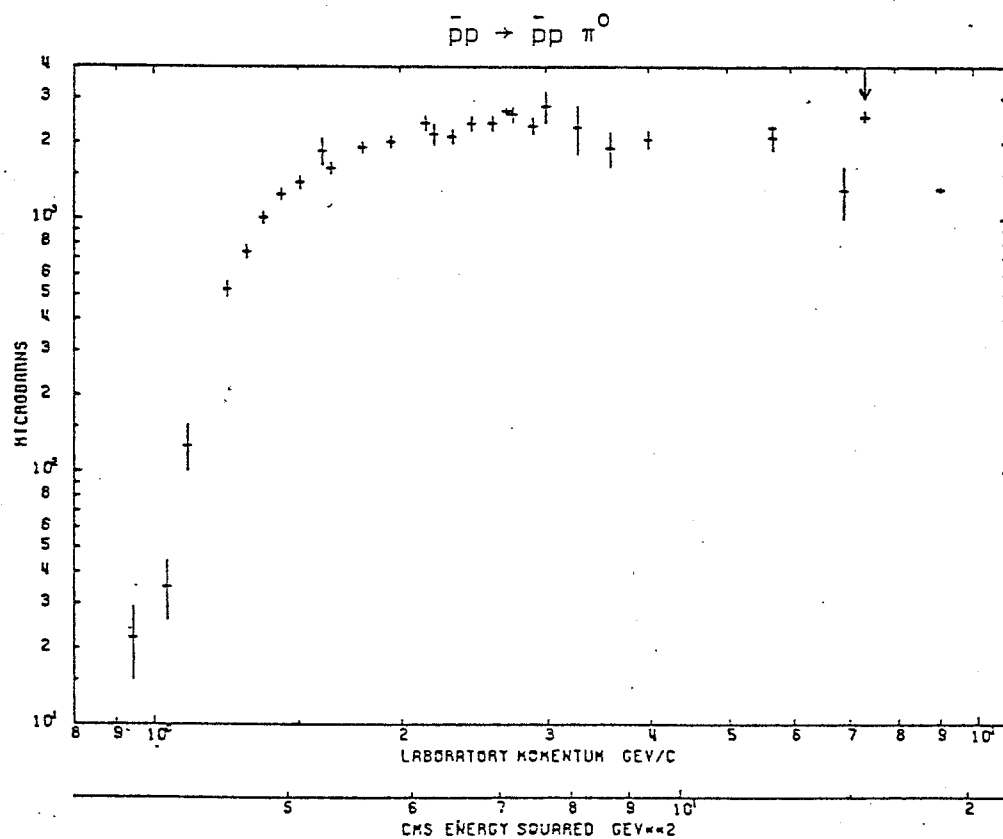
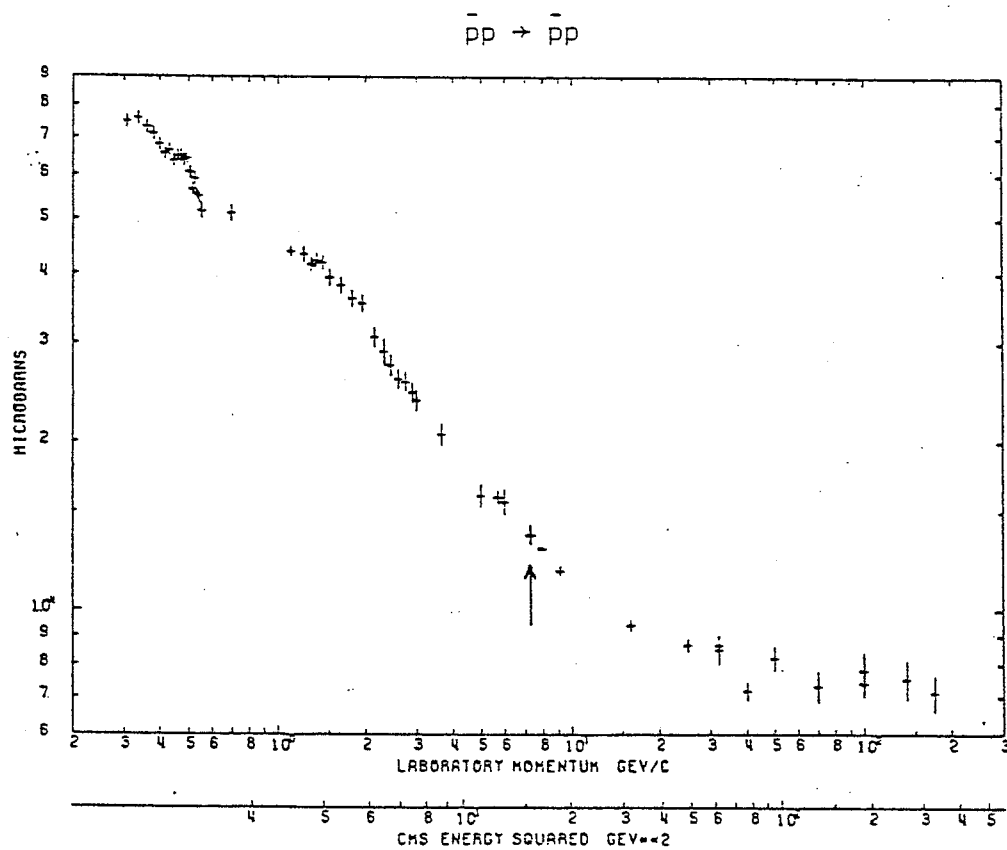


Figure 4.12 cont.

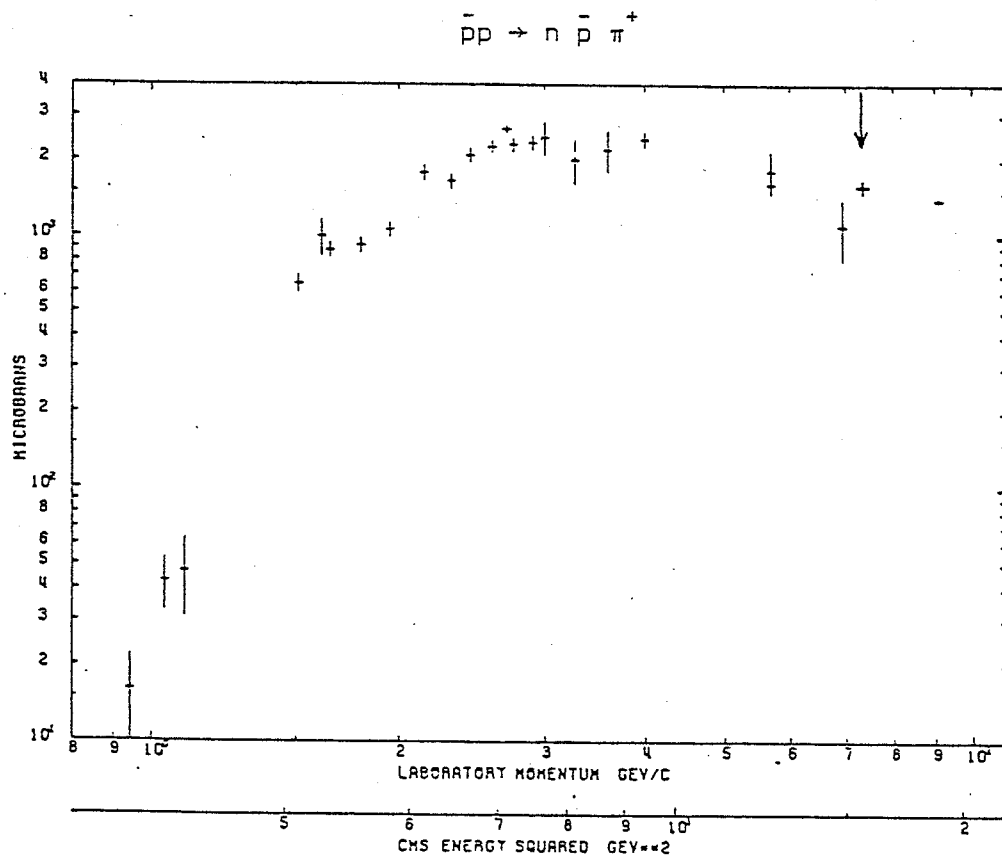
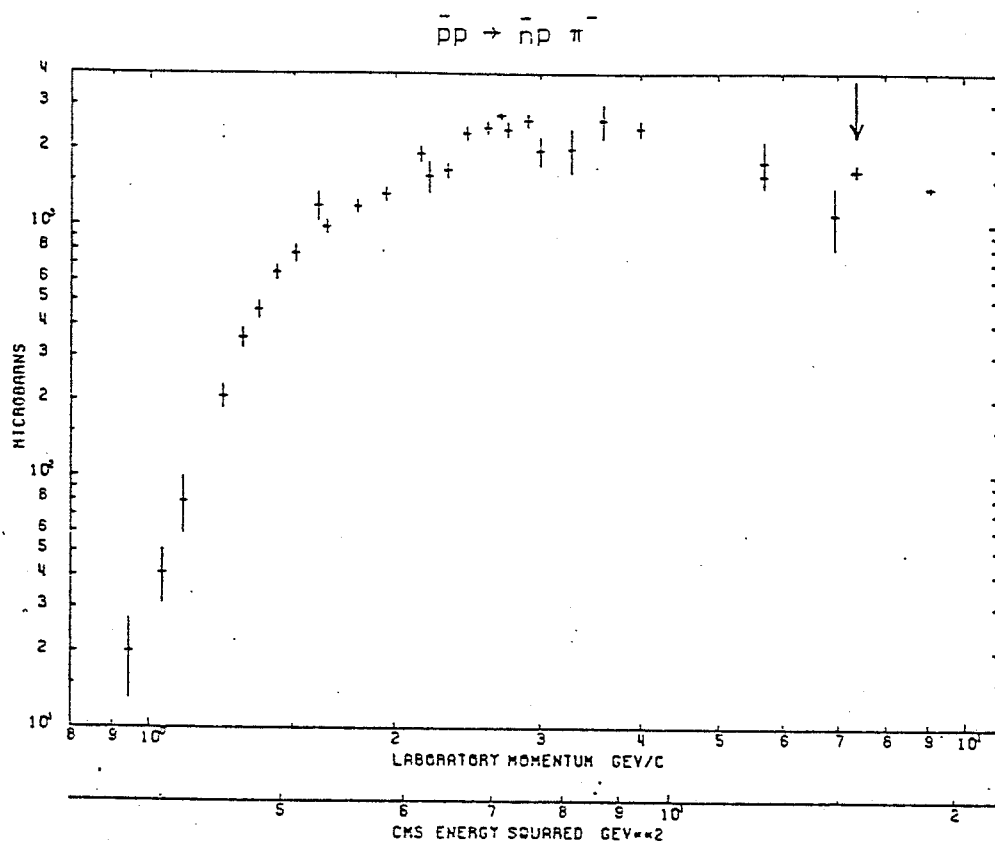


Figure 4.12 cont.

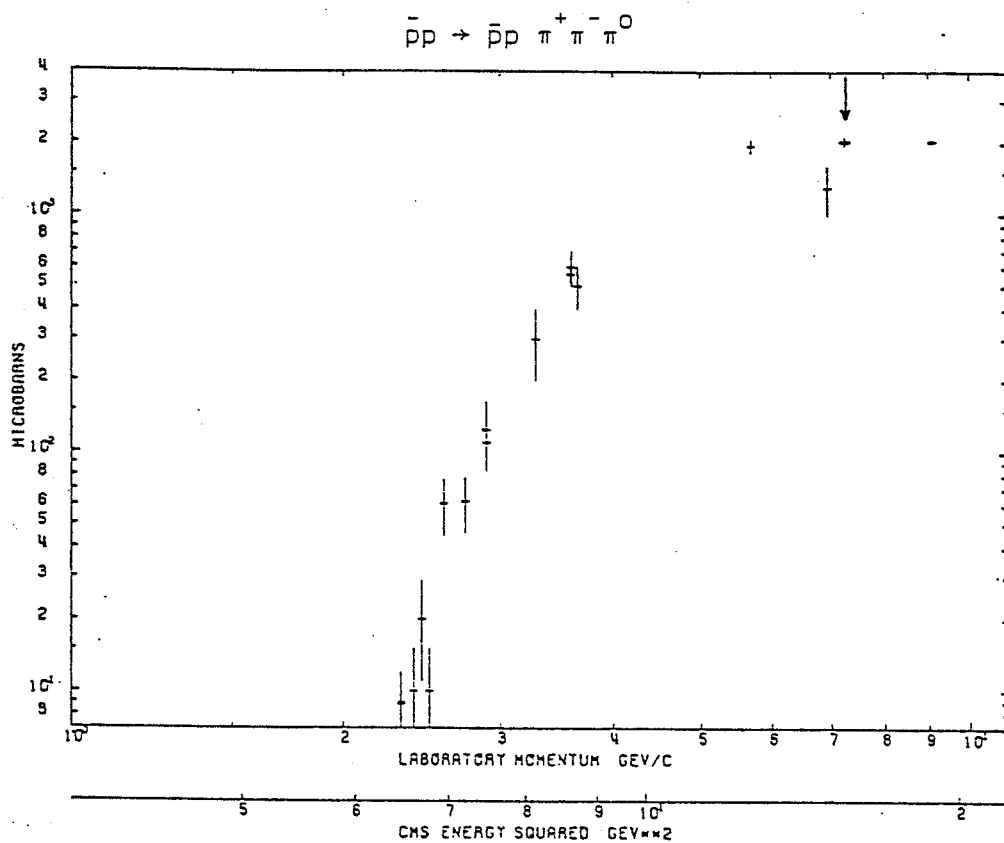
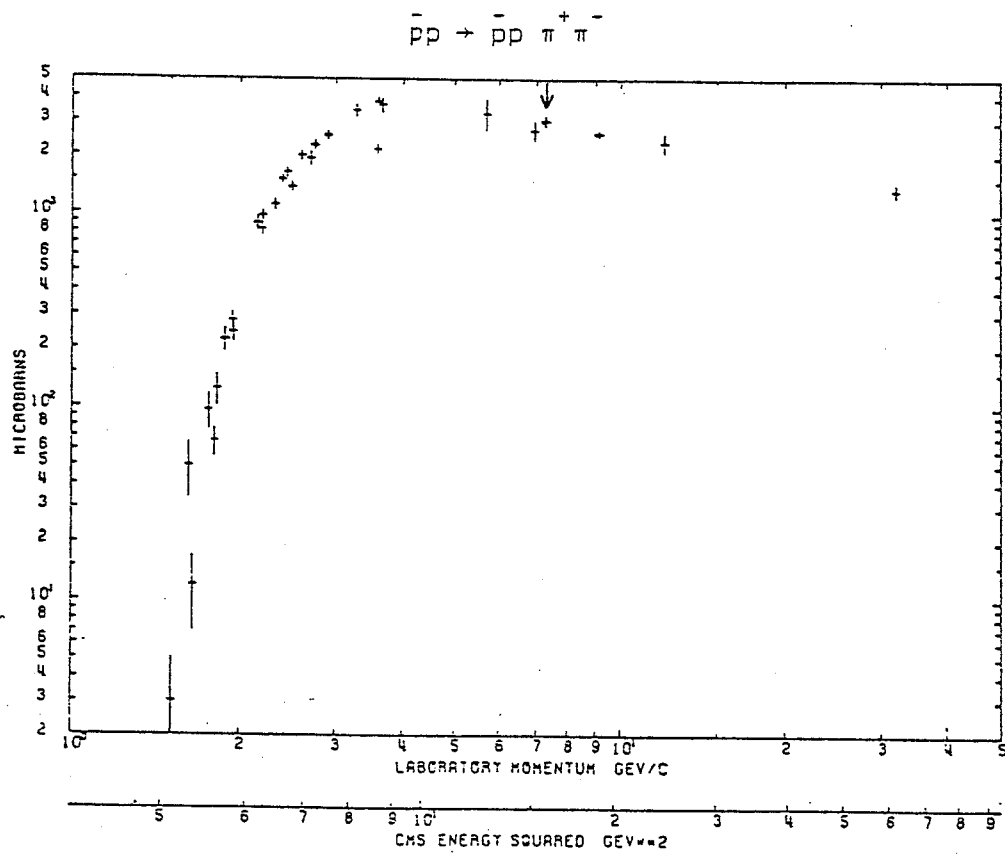


Figure 4.12 cont.

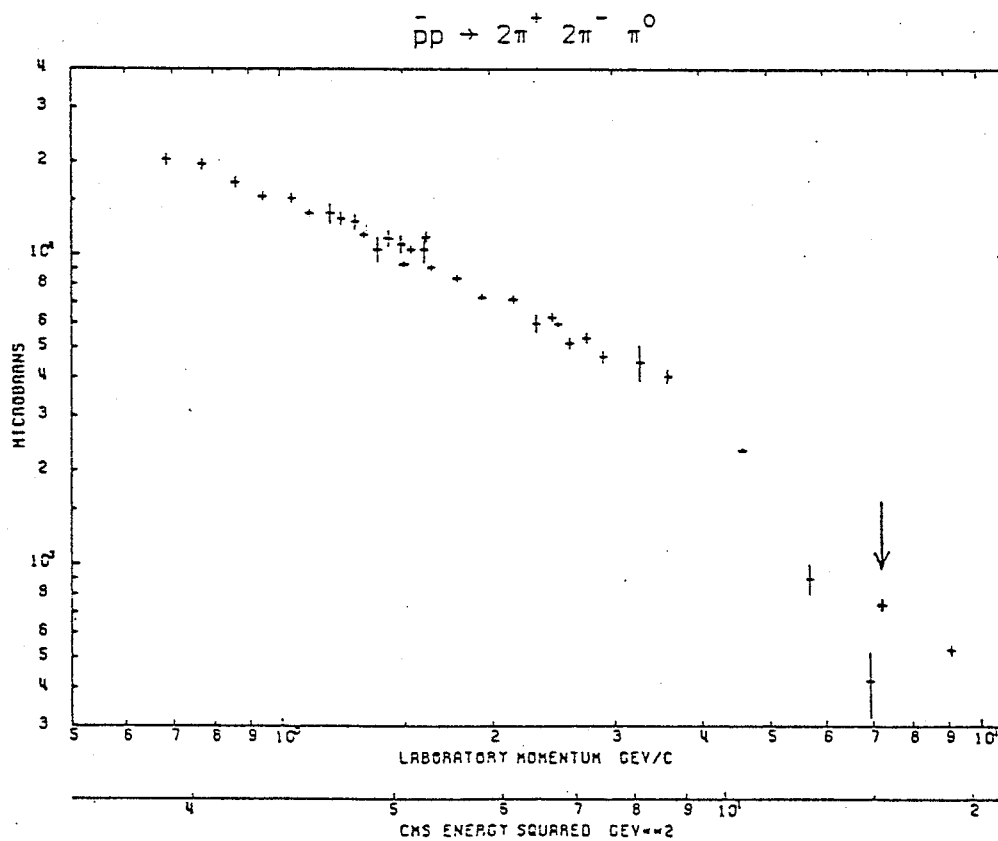
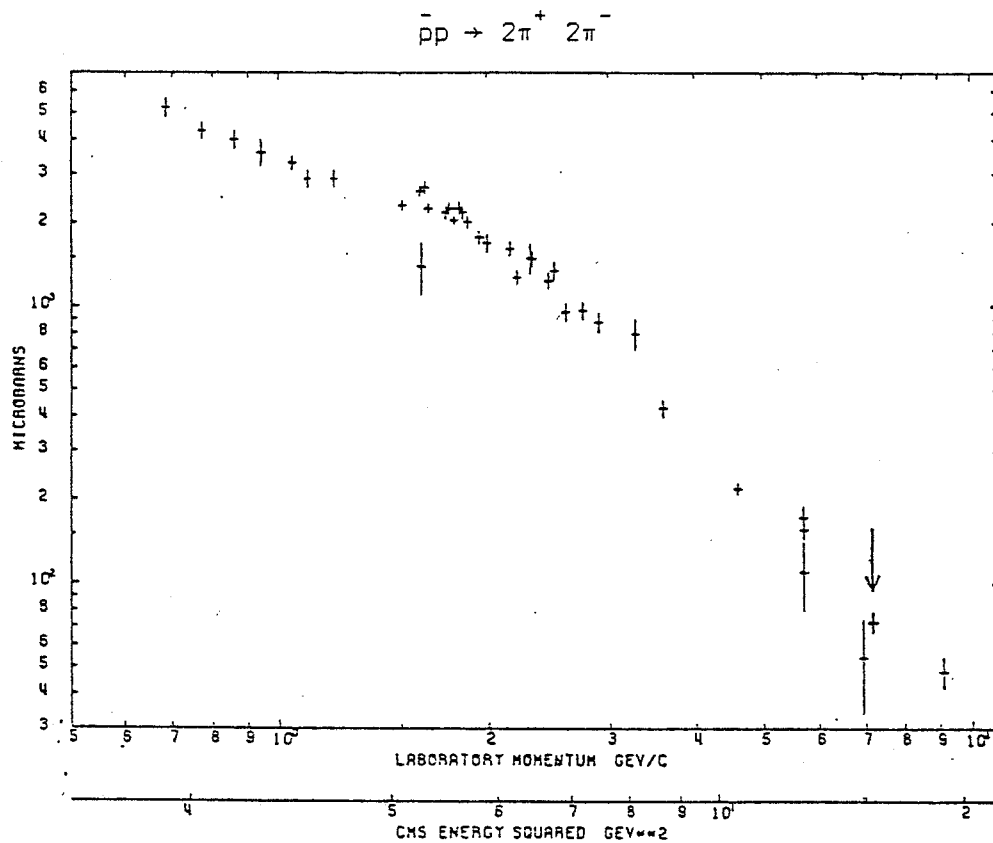


Figure 4.12 cont.

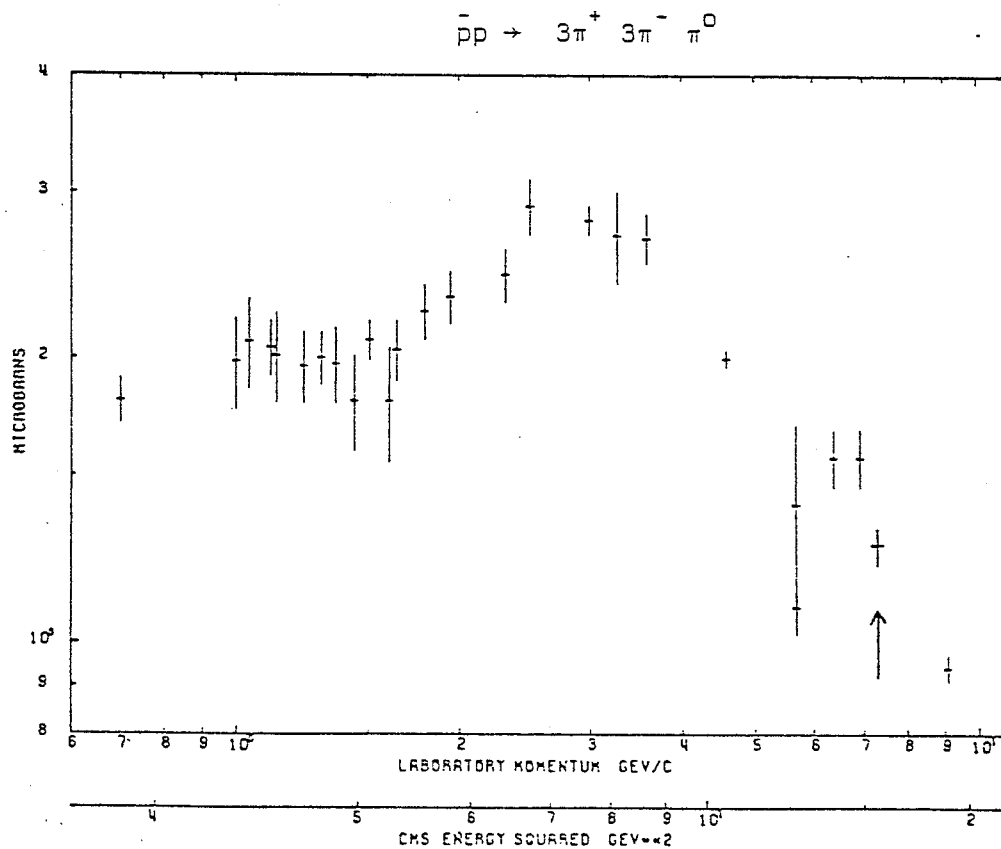
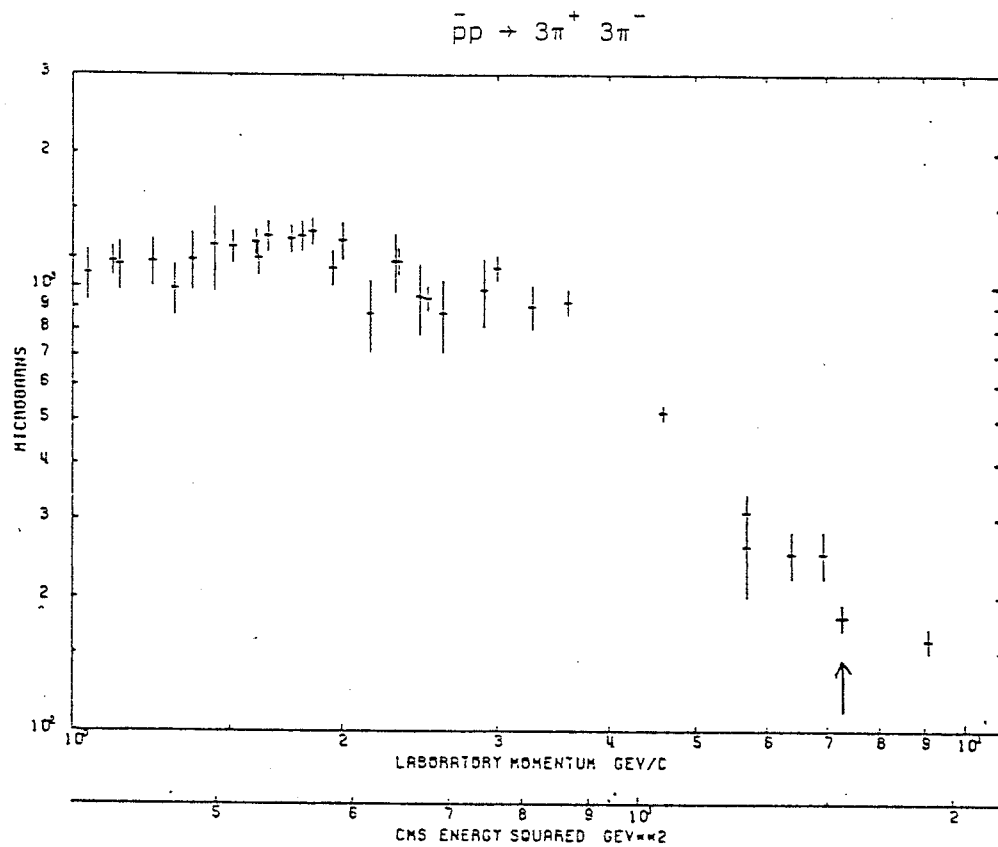


Figure 4.12 cont.

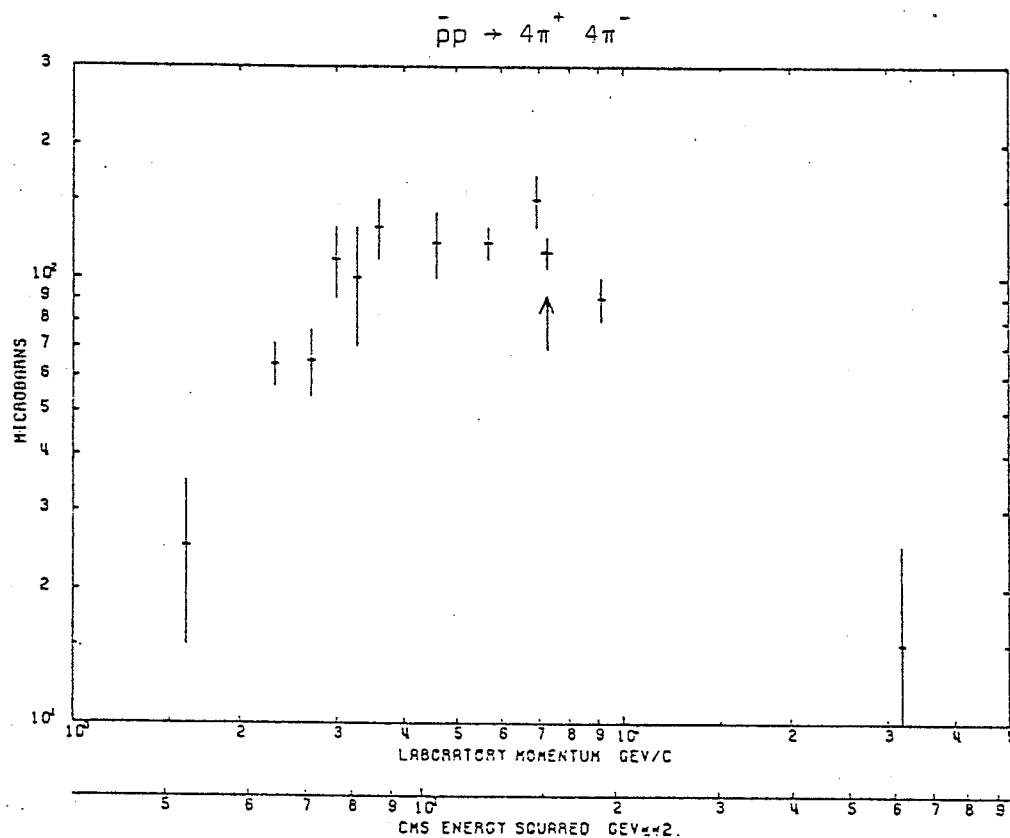
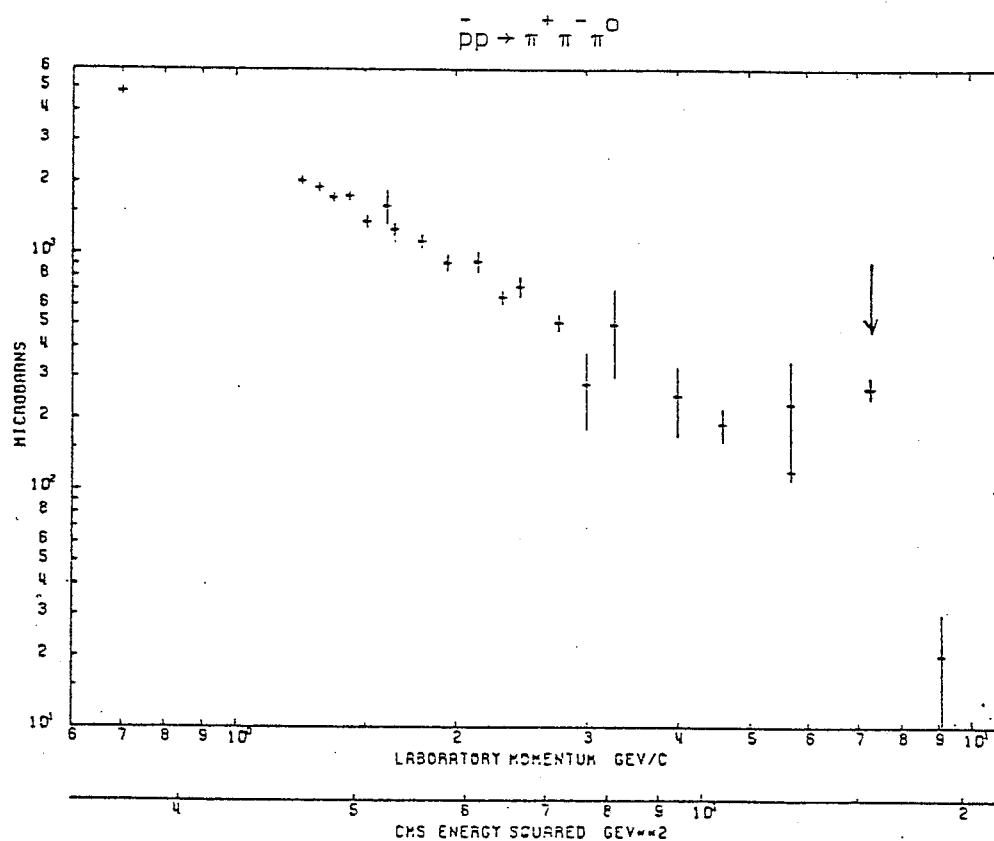
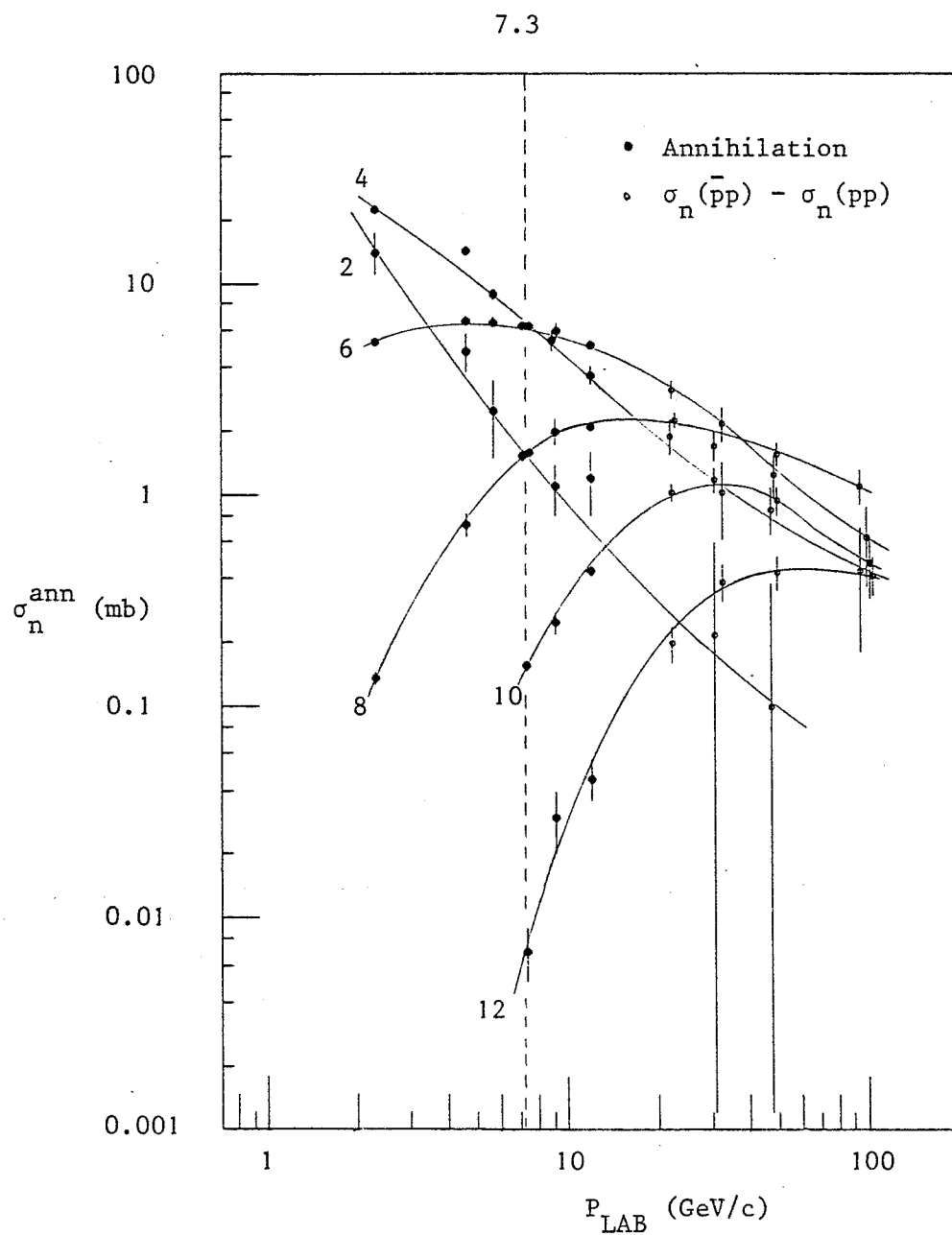


Figure 4.13 $\bar{p}p$ Topological Annihilation Cross Sections vs P_{LAB}



Chapter V

INCLUSIVE V^0 AND γ PRODUCTION

5.1 INTRODUCTION

In the previous chapter only the non-strange channels were considered. This chapter will deal with inclusive neutral strange particle and γ production. The procedure used to obtain a clean, unambiguous sample of V^0 's and γ 's for analysis is first described. The various correction factors are then discussed and inclusive total and topological V^0 and γ cross sections derived. The differential properties of production are investigated and K_s and γ samples are studied after separation into annihilation and non-annihilation components. Finally some inclusive double strange particle production cross sections are calculated and strange particle production in annihilations considered.

NOTATION K^0 -short and K^0 -long will appear as K_s and K_L respectively.

5.2 THE DATA SAMPLE

The V^0 's and γ 's on DST consist of four distinct subsamples. Three of these are Liverpool data from different stages of processing of this experiment (see note Section 3.9) and the fourth is data from our collaborators in Amsterdam.

The Liverpool data consists of a primary sample of 25 rolls of film in which all failed events were remeasured and processed through to DST, a secondary sample from 44 rolls and a third sample which comes from 69 rolls on which only V^0 (not γ) events were processed. Since all these subsamples should be representative and unbiased they will be treated together and all the data used in the final distributions. There are however certain differences (failure rates and normalisations for example) and consequently the inclusive and semi-inclusive V^0 and γ cross sections will be calculated from the Liverpool primary and secondary samples only.

5.2.1 Resolution of V^0 Ambiguities

A small fraction of the V^0 's could not be uniquely identified as K_s , Λ or $\bar{\Lambda}$ either by ionisation of the decay tracks or by kinematic fitting of the V^0 and/or primary vertices. The ambiguity matrix is given in Table 5.1.

Figure 5.1 (a-f) shows the distributions of $\cos\vartheta$, where ϑ is the angle between the positive decay track and the V^0 line of flight in the rest frame of the V^0 , for the unique and unique + ambiguous K_s , Λ , $\bar{\Lambda}$ samples. The K_s , being a spinless particle, will decay isotropically in its rest frame and the $K_s \cos\vartheta$ distribution should be flat. The $\cos\vartheta$ distributions for Λ , $\bar{\Lambda}$ should also be flat, even though they are spin 1/2. This is a consequence of parity conservation in the strong interaction which requires the $\Lambda/\bar{\Lambda}$ spin to be transverse to the production plane [5.1].

Figure 5.1 b clearly shows that the ambiguous K_s 's constitute an excess in two well defined regions of the $\cos\theta$ distribution. The K_s/Λ ambiguities falling near $\cos\theta = +1$ and the $K_s/\bar{\Lambda}$ near $\cos\theta = -1$. The unique K_s 's alone have a flat $\cos\theta$ distribution, but the unique Λ 's and $\bar{\Lambda}$'s show serious depletions. The requirement of flat $\cos\theta$ distributions for all V^0 's is thus best satisfied by resolving all (K_s/Λ) and $(K_s/\bar{\Lambda})$ ambiguities as Λ and $\bar{\Lambda}$ respectively. (The two $(\Lambda/\bar{\Lambda})$ ambiguities of Table 5.1 were resolved using fit probabilities.)

5.2.2 V^0 Mass Resolution

Examination of the V^0 and γ mass resolution plots of Figure 5.2 (a-d) gives masses of 0.4970, 1.115 and 1.116 GeV/c^2 with full widths at half maximum (FWHM's) of 12, 5 and 5 MeV/c^2 for K_s , Λ and $\bar{\Lambda}$ respectively, in good agreement with the published values of 0.49767 and 1.11560 GeV/c^2 respectively [5.2].

A small fraction of the V^0 's and γ 's however are observed to have 'measured' masses well out in the tails of the mass plots. In order to ensure a clean unbiased sample of V^0 's and γ 's a mass cut, as defined in Table 5.2, was employed. The events removed by these cuts are the badly measured ones with large errors on the measured momenta and are a possible source of bias. The remaining events were given additional weight, defined in Table 5.3, to correct for the events removed by the mass cuts.

5.2.3 Fiducial Volume

Fast V^0 's and γ 's decaying close to the chamber walls and thus leaving only short decay tracks are difficult to measure and more likely to fail in reconstruction. In order to make the geometric weight correction (described below) it is necessary to have a sample with an unbiased momentum distribution. Consequently a fiducial volume cut was employed which would ensure that the decay tracks would be at least 10 cm long. The primary and V^0 , γ fiducial cuts used are given in Table 5.4.

5.2.4 Purity of the Final V^0 Sample

The isotropic decay which leads to a flat $\cos\theta$ distribution also requires that, p_t , the momentum of one of the V^0 decay tracks transverse to the V^0 line of flight should take the form:-

$$dN = \frac{p_t dp_t}{p^* \sqrt{(p^{*2} - p_t^2)}}$$

where dN is the fraction of the total tracks with p_t in the range p_t to $p_t + dp_t$ and p^* is the magnitude of the momentum of the decay tracks in the decay rest frame. p^* is equal to 100.4 MeV/c for Λ and $\bar{\Lambda}$ decays and 206.0 MeV/c for K_s decays.

Figure 5.3 (a-c) shows these p_t distributions for the final K_s , Λ , $\bar{\Lambda}$ samples together with the above predicted form as a solid line. The K_s sample has 14.1% with $p_t < 100$ MeV/c compared with the 14.0% predicted by the decay

kinematics. This therefore confirms that no K_s 's were lost in resolving all ambiguities as $\Lambda/\bar{\Lambda}$.

As a further check on the V^0 sample an estimate of the of the lifetime was made. Figure 5.4 (a-c) shows N , the number of events, vs. l/η , where $\eta = p/m$ and p is the laboratory momentum of the V^0 of mass m which travels a distance l before decay. For V^0 decay $N = N_0 \exp[-l/\eta c\tau]$, where N_0 is the initial number at $l=0$, and τ the V^0 lifetime. The inverse of the slopes of the distributions shown therefore give a measure of $c\tau$ the lifetime. The fitted lines are shown in the figure and correspond to values of $c\tau$ of 2.5 ± 0.2 , 7.6 ± 0.4 and 5.9 ± 0.5 for K_s , Λ and $\bar{\Lambda}$ respectively. The K_s and Λ are in agreement with the values in [5.2]. The problem with the $\bar{\Lambda}$ is thought to be due to their much higher laboratory momentum, shown in Figure 5.5.

The average laboratory momenta are 1.60, 1.33, 4.17 and 0.82 GeV/c for K_s , Λ , $\bar{\Lambda}$ and γ respectively. Thus for a Λ with $l/\eta = 25$ cm the average value of l is approximately 30 cm but for $\bar{\Lambda}$ the corresponding value of l is about 94 cm. Consequently there are losses of $\bar{\Lambda}$ due to the finite size of the chamber and the limited statistics. To try and allow for the higher laboratory momentum of the $\bar{\Lambda}$'s a fit with $l/\eta < 10$ cm was made, this gave $c\tau = 6.8 \pm 0.8$, which is better though still rather poor.

The final numbers of V^0 's and γ 's to be used in the subsequent analysis are given in Table 5.5.

5.3 CORRECTING FOR LOSSES

Before the primary and secondary Liverpool subsamples can be used to calculate the inclusive V^0 and γ cross sections weights must be assigned to each event to correct for various losses. One set of weights has already been discussed (Table 5.3), the others are as follows.

5.3.1 Scanning Losses and Minimum Length Cut

The average single scan efficiency for the detection of neutral verticies (V^0 's and γ 's) was 98.8% (see Table 4.1). The events were therefore weighted by the inverse of the efficiency to allow for scanning losses.

For V^0 's and γ 's which decay close to the primary vertex there is a possibility of the decay vertex being missed and the decay tracks being incorrectly associated with the primary vertex. Such losses have been found to be large in very high energy experiments where large numbers of particles may be produced in a 'confused' forward cone. In this experiment, with a mean charged particle multiplicity ≈ 3.6 , there should be little confusion and such losses small. Nevertheless there are losses of both V^0 's and γ 's close to the primary vertex as shown by studying the distribution of the function η defined as:

$$\eta = \frac{\exp[-l/l_0] - \exp[-l_{\max}/l_0]}{\exp[-l_{\min}/l_0] - \exp[-l_{\max}/l_0]}$$

where l = observed path length of neutral.

$l_{\max}$ = maximum potential length of flight of neutral.

$l_{\min}$ = minimum length cut.

l_0 = decay length of V^0 or conversion length of γ .

For the V^0 's $l_0 = p\tau/m$, where m and τ are the V^0 mass and lifetime and p the measured laboratory momentum. For γ 's l_0 is the conversion length in liquid hydrogen for a γ of given momentum and was calculated using the cross sections of Knasel [5.3].

If the secondary vertices are detected with equal efficiency at all distances from the primary vertex then η should be uniformly distributed between 0 and 1. Figure 5.6 (a-h) shows the distributions in η for $K_s, \Lambda, \bar{\Lambda}$ and γ with and without an $l_{\min}$ cut. There is a clear loss near $\eta = 1$ in all cases, corresponding to decays with l small. As $l_{\min}$ is increased the η distribution improves and is uniform with $l_{\min} = 1.0$ cm for K_s, Λ and $\bar{\Lambda}$. For γ 's however an $l_{\min}$ of 3.0 cm was required to give a flat η distribution.

The above results imply that there are losses of V^0 's up to 1.0 cm and γ 's up to 3.0 cm from the primary vertex. Since scanning losses close to the primary vertex should be small, as previously noted, there must be some other factor responsible. The most probable factor is reconstruction losses. There are two reasons why V^0 's and γ 's close to the primary vertex should fail to reconstruct preferentially. One is that there is a greater probability of the decay vertex and/or decay tracks overlying the primary vertex tracks, making them more difficult to measure accurately. The second is due to a lack of sophistication in the version of GRIND kinematics used. This did not take into account the error on the V^0/γ direction as determined from the

vertex measurements. As a consequence V^0 's and γ 's close to the primary vertex are more likely to give an unassociated (1C) fit than those further away which may be 'pulled' in to give 3C fits. The same problems hold to an even greater degree for γ 's where the exact 'decay' point is more easily misjudged because of the zero opening angle.

5.3.2 The Geometric Weight

The geometric (or 'escape') weight accounts for events removed by the $l_{\min}$ cut and for those decaying outside the accepted fiducial volume (i.e. $l > l_{\max}$). This is done by assigning each of the remaining events (with $l_{\min} < l < l_{\max}$) a weight which is the inverse of the probability of decay (or conversion) inside the fiducial volume with $l > l_{\min}$, i.e.

$$\text{Geometric Weight} = \frac{1}{\exp[-l_{\min}/l_0] - \exp[-l_{\max}/l_0]}$$

where the quantities are as previously defined. The mean values of the escape weights were 1.225 for K_s , 1.224 for Λ , 1.258 for $\bar{\Lambda}$ and 31.39 for forward hemisphere γ 's.

5.3.3 Measuring and Reconstruction Losses

As stated previously the scanning efficiency was 98.8%, unfortunately losses from this sample occur during the geometry and kinematics stages and those events reaching the DST have to be weighted to correct for these losses.

Some γ 's can be identified at the scanning stage but the V^0 's in general cannot. In order to calculate the failure rates separately for $K_s, \bar{\Lambda}, \Lambda$ and γ it is therefore necessary to try and identify the failed events. Since all V^0/γ events were examined after kinematics, a careful note was made of the status of every single failed V^0 or γ for the first 21 rolls of film processed. Of the failed events 14.8% had a V^0 or γ which did not really associate and these were deleted. Of the remainder, which were considered to associate but for which no fits were obtained, there were three categories:

- a) Could be identified as $K_s, \Lambda, \bar{\Lambda}$ or γ by available ionisation.
- b) Identified as V^0 NOT γ .
- c) Unidentified. (V^0 OR γ)

In order to calculate the failure rates for each particle type those in categories (b) and (c) had to be reallocated. This was done by assuming that the unidentified failed V^0/γ were in the same proportion as the identified fitted ones. The breakdown of failed events is given in Table 5.6.

It has been previously noted that the loss of V^0/γ close to the primary vertex was thought to be primarily a reconstruction loss, and a correction for this has already been applied through the $l_{\min}$ cut and geometric weight. Care must therefore be exercised in calculating the reconstruction loss weights so as to avoid over-correcting

for these events. An estimate of the numbers of $K_s, \Lambda, \bar{\Lambda}$ and γ 'retrieved' by the geometric weight was made from the observed depletions in the η distributions near $\eta = 1$ (Figure 5.4 a-d) and these were taken away from the failed events samples before failure rates were calculated.

For the Liverpool primary sample there were 3049 V^0/γ scanned, of these 1455 fitted after the first measurement, the remaining 1594 failed events were apportioned according to Table 5.6. The correction for geometric 'retrieval' discussed above was applied to these and the failure rate weight factor for the remaining sample was defined to be $(\text{fitted} + \text{failed})/\text{fitted}$. The failed events of the Liverpool primary sample were remeasured and the failure rate weight factor for the combined first and second measure sample was calculated by taking:

$$N_1 W_{r1} = N_{12} W_{r12} \quad \text{for each particle type}$$

where N_1 = Number on DST after first measure.

N_{12} = Combined number on DST after first and second measure.

W_{r1}, W_{r12} = first and combined measure failure rate weight factors respectively.

These results are summarised in Table 5.7. The same procedure was used for the secondary Liverpool sample, except there was only a single measure so only a first measure failure rate correction factor was required. The results for this sample are given in Table 5.8.

5.3.4 Biases in the Reconstruction Loss

The failure rate correction factors calculated above are an average over the samples with $l > l_{\min}$. It is therefore necessary to see if any further biases exist before these average weights can be applied. The check was performed by examination of the CMS angular distributions shown in Figure 5.6 (a-d), these should be CP symmetric after correction by geometric weighting.

The $\Lambda/\bar{\Lambda}$ distributions are found to be CP symmetric within the errors and uniform failure rates will be assumed. Figure 5.6 a for the K_s 's shows a loss in the backward hemisphere, the asymmetry amounting to a 6% difference between backward and forward K_s 's.

There is no clear explanation for this loss, however study of the K_s data sample indicates an almost total loss of low laboratory momentum (< 300 MeV/c) K_s 's with $l > 2-4$ cm. Reconstruction losses for the reasons already discussed seem to be the most likely cause of this.

For the purposes of obtaining the total K_s cross section an average reconstruction failure weight is sufficient and the values given in Table 5.7 & 5.8 are used to evaluate the total K_s cross section. For the purposes of analysis however an average failure weight is not satisfactory, consequently backward K_s ($\cos\theta^* < -0.6$) were given an additional reconstruction weight such that reasonable CP symmetry of the $\cos\theta^*$ distribution was achieved and this weighted sample was renormalised to the total cross section.

5.3.5 Loss of Low Momentum γ 's

Finally for the γ 's Figure 5.6 d clearly shows a substantial loss in the backward hemisphere. These correspond to γ 's with low laboratory momentum, and as these are very distinctive at scanning, the loss once again must be due to biased reconstruction losses. For the γ 's however the bias is more readily understood as many of the lost events will have slow rapidly spiralling electron tracks which are extremely difficult to measure.

With approximately 30% of the CMS backward γ 's lost, the full γ sample is clearly biased, nor is there much scope for correcting by weighting of the observed backward events as was done for the K_s 's. Consequently only the forward γ 's will be used in the analysis and CP symmetry assumed.

The failure rates calculated previously, given in Tables 5.7 & 5.8, were average failure rates over the full sample. The forward γ failure rate must clearly be smaller than this since the backward γ 's have been found to fail preferentially. The failure rate correction factor for forward γ 's was therefore recalculated as follows:

Let F = Average failure rate for full sample

F_f, F_b = Forward and backward hemisphere failure rates

N_f, N_b = Numbers of forward and backward γ 's

G_f, G_b = Average forward and backward geometric weights

Then $F(N_f + N_b) = F_f N_f + F_b N_b$

and from CP symmetry $F_f G_f N_f = F_b G_b N_b$

F has already been calculated, N_f , N_b and G_f , G_b were calculated from the DST and the two equations solved for F_f and F_b . The results are given in Table 5.9 and only the forward γ 's with failure weight F_f will be used in the subsequent analysis.

5.3.6 Branching Ratios

The V^0 's were observed through their charged decays.

$$K_s \longrightarrow \pi^+\pi^-$$

$$\Lambda \longrightarrow p\pi^-$$

$$\bar{\Lambda} \longrightarrow \bar{p}\pi^+$$

In obtaining inclusive V^0 cross sections it is necessary to correct for the unseen neutral decay modes. This was done by weighting the observed events by the inverse of the charged decay mode branching ratios, giving weights of 1.456 for K_s and 1.558 for $\Lambda/\bar{\Lambda}$.

5.3.7 Normalisation

Separate normalisations for the primary and secondary Liverpool samples were calculated from the numbers of events originally scanned in those samples. The primary and secondary samples came from 24291 and 51179 events scanned respectively. Applying corrections to these numbers as detailed in Chapter 4 then yields the numbers of events in each sample which correspond to the total cross section of 58.3 mb. This gave microbarn equivalents of 2.383 and 1.132 $\mu\text{b}/\text{event}$ for the primary and secondary samples respectively.

5.4 INCLUSIVE V^0 AND γ CROSS SECTIONS

To summarise the following corrections have been considered

W_i = Mass cut weights.

GW = Geometric weights.

F_r = Reconstruction failure rates.

BR = Branching ratios.

SE = Scanning efficiency.

μb = microbarn equivalents.

The total inclusive cross sections are then given by

$$\sigma = W_i \cdot F_r \cdot \mu b / BR / SE \cdot \sum_{i=1}^N GW_i$$

where N = number of $K_s, \Lambda, \bar{\Lambda}$ or γ after l_{min} cuts.

As already stated only the Liverpool primary and secondary samples were used in the total cross section calculations as the failure rates and normalisations are known for these. The inclusive and semi-inclusive cross sections based on these samples are given in Table 5.10. The inclusive π^0 cross sections is half the γ cross section given assuming that all γ 's come from π^0 decay.

These results are compared with other data in Figures 5.8 (a-c). The total K_s cross section shown in Figure 5.8 is seen to be remarkably constant out to 20 GeV/c at which point it starts to rise matching the pp data also shown in the figure for comparison. The π^0 cross section is not strongly dependent upon laboratory momentum either and is substantially higher than pp data at energies up to about 20 GeV/c. These large differences in K_s and π^0 production in

$\bar{p}p$ and pp up to 20 GeV/c can be attributed to the annihilation processes in $\bar{p}p$. The $\Lambda/\bar{\Lambda}$ also agree with the trend of the data which is rising in a manner similar to pp , though $(\sigma(\Lambda) + \sigma(\bar{\Lambda}))$ is higher in $\bar{p}p$ because of $Y\bar{Y}x$ channels (Y being a hyperon) unavailable in pp .

The mean multiplicities are given in Table 5.11, being defined as $\sigma_i(n)/\sigma(n)$, where $\sigma_i(n)$ is the n -prong cross section for particle i ($K_s, \Lambda, \bar{\Lambda}, \gamma$) and $\sigma(n)$ is the topological cross section as given in Table 4.10. The $\Lambda/\bar{\Lambda}$ production is seen to be predominantly in the lower topologies and forms a significant fraction of the zero prong events. K_s and π^0 however are more evenly spread and extend to the 6/8 prongs. The latter is a consequence of annihilation processes as seen from Table 5.12 discussed in the next section. These features have also been seen in experiments at 4.6 and 9.1 GeV/c [5.4].

For the subsequent analysis the full data sample will be used and normalised to the above cross sections.

5.5 ANNIHILATION K_s AND γ CROSS SECTIONS

Using the techniques described in the previous chapter, primary vertex fit ambiguities were resolved and an annihilation sample of K_s and γ events obtained. Annihilation cross sections were calculated for this sample using the topological microbarn equivalents mentioned above. It should be noted that no separation is possible for zero prong events, however their contribution will be small. The

cross sections are given in Table 5.12. Also given is the fraction of annihilation to total in each topology for K_s and π^0 production.

The annihilation process is clearly dominant in K_s production, 80% of all K_s and $\approx 100\%$ for topologies ≥ 4 prongs being produced in annihilation reactions. The annihilation cross section is compared with other data in Figure 5.9. ($\bar{p}p$ -pp) differences have been used at the higher energies, but direct evaluation of the annihilation component is shown when available. This shows that $\sigma(K_s)_{\text{ann}}$ is falling with P_{lab} . Also shown on the same Figure is the total annihilation cross section σ_{ann} , ($\bar{p}p$ -pp) differences again being used at high energies. The solid line is an extrapolation of the fit to low energy data points taken from the 1973 CERN-HERA compilations

$$\sigma_{\text{ann}} = (61.76 \pm 2.32) P_{\text{lab}}^{-0.61 \pm 0.05}$$

and is seen to be in reasonable agreement with the high energy differences. By comparison $\sigma(K_s)_{\text{ann}}$ does not appear to fall so rapidly as σ_{ann} (the exponent of P_{lab} is only about -0.2, shown as dashed line), and thus $2\sigma(K_s)_{\text{ann}}/\sigma_{\text{ann}}$ rises with P_{lab} as shown in Figure 5.10. Strange particle production in $\bar{p}p$ annihilations is thus rising significantly with P_{lab} and at 100 GeV/c [5.5] the figure of 0.6 neutral kaons per annihilation event implies that about 60% of the annihilation events contain a $K\bar{K}$ pair on average.

To keep things in perspective $\sigma(K_s)_{\text{ann}}/\sigma(K_s)$, the fraction of all K_s 's which are produced in annihilations is

also shown in Figure 5.10. This starts at 1.0, since below the non-annihilation threshold all K_s are annihilation products, it however falls rapidly over the intermediate energy range and by 100 GeV/c only 20% of all K_s 's are produced in annihilations.

For π^0 's the fraction produced in annihilations is rather less than for K_s , being about 50% of the total. For topologies ≥ 6 prongs the π^0 production is almost entirely through annihilations, this may be compared with K_s where the annihilation process dominates for ≥ 4 prongs.

The mean multiplicities (no. of K_s or π^0 per annihilation event) are given in Table 5.13. The mean number of π^0 's in annihilations is seen to be greater than was the case for the total sample and is fairly constant up to about the 6 prong topology. Overall there are about 2 π^0 's per annihilation event on average.

The K_s annihilation mean multiplicities show rather different features from the total sample, there being proportionally greater K_s production in the lower topologies. Indeed 1/3 of all 2 prong annihilations contain a K_s . Overall 10% of the annihilation events contain a K_s .

5.6 DIFFERENTIAL V^0 AND γ DISTRIBUTIONS

The Lorentz invariant differential cross section for a single particle inclusive reaction is -

$$f(x, p_t, s) = \frac{2E^* d^2\sigma}{\pi\sqrt{s} dx dp_t^2}$$

where $\sqrt{s}$ = total CMS energy

E^* = energy of particle in CMS

p_t = transverse momentum of particle

x = Feynman variable defined by $x = 2p_L/\sqrt{s}$

p_L = CMS longitudinal momentum of particle

Integrating over all p_t^2 gives the function $F(x)$ where

$$F(x) = \frac{2}{\pi\sqrt{s}} \int \frac{E^* d^2\sigma}{dx dp_t^2} dp_t^2$$

This is shown for K_s , Λ , $\bar{\Lambda}$ and γ in Figure 5.11. (Only forward hemisphere γ 's have been used and these have been reflected about $x = 0$.)

The K_s mesons and γ -rays show predominantly central production, whilst the Λ , $\bar{\Lambda}$ peak at $x \approx -0.5$ and $x \approx +0.5$ respectively. The peripheral $\Lambda/\bar{\Lambda}$ production may be understood in terms of simple quark recombination model ideas. The Λ quark content is (sud), whilst the proton is (uud), the Λ can therefore be made from 2 valence quarks from the proton with an s quark from the sea. Assuming the s quark to be 'wee' i.e. carrying only a small fraction of the proton momentum and the valence (ud) diquark system carrying an average $2/3$ of the proton momentum then the resulting Λ would be expected to have $x \approx -0.67$. Similar arguments hold for a $\bar{\Lambda}$ forming from the $\bar{p}$ with $x \approx +0.67$. In practice the valence quarks are known to carry only about $1/2$ the proton momentum, the rest being carried by the gluon, $q\bar{q}$ sea, consequently the exact x of the $\Lambda/\bar{\Lambda}$ will depend upon how much of the $p/\bar{p}$ sea is taken along with the valence diquark system. However the peripheral nature of $\Lambda/\bar{\Lambda}$ production is easily understandable in this picture. It

is satisfying to note the Λ , $\bar{\Lambda}$ are CP symmetric as earlier experiments [5.4,5.7] have reported difficulties with detection and processing of $\bar{\Lambda}$'s.

The forward hemisphere γ 's were fitted to the parametrisation $F(x) = A \exp[bx]$, as the distribution appeared to be of this form, and gave $A = 21.57 \pm 0.82$, $b = -7.48 \pm 0.25$ with a $\chi^2/ND = 12.4/12$. The fit is shown in Figure 5.11 (b). The value of b obtained can be compared with $b = -7.7 \pm 0.2$ and $b = -7.1 \pm 0.2$ at 4.6 and 9.1 GeV/c respectively [5.6].

The transverse momentum distributions, $d\sigma/dp_t^2$, for K_s , Λ , $\bar{\Lambda}$ and γ are shown in Figure 5.12. The V^0 distributions were fitted to the exponential form $A \exp[-bp_t^2]$. The K_s distribution however did not fit satisfactorily over the whole range and appears to show a two component structure with a break at $p_t^2 \simeq 0.15 \text{ (GeV/c)}^2$. Consequently it was fitted independently over the two regions. The fits appear as solid lines superimposed on the data in Figure 5.12 and the parameters are listed in Table 5.14.

The Λ and $\bar{\Lambda}$ are equal, as they should be, and the slopes are comparable with values at 9.1 and 12.0 GeV/c [5.6,5.7]. The K_s p_t^2 distributions at 9.1 and 12.0 GeV/c were fitted with a single exponential over the whole range. The former had limited statistics and no break is discernable, there are however indications in the 12.0 GeV/c data for a break. This change in slope for small values of p_t^2 may be attributed to indirectly produced K_s , i.e. those coming from

data, and a fit over the range $0.0 < p_t^2 < 0.5 \text{ (GeV/c)}^2$ gave $A = 3.04 \pm 0.20$, $b = -6.87 \pm 0.35$ with a χ^2/ND of 27.7/18. If the speculation that the break is due to resonance production of K_s is correct then one would not expect a break in the non-annihilation data because the resonance contribution is consistent with zero [5.9].

The $F(x)$ distributions for γ 's in annihilations and non-annihilations are comparable, (a consequence of the equality of the cross sections in the two samples). A fit of the form $A \exp[-bx]$ was made for the separated samples and the results are rather similar.

	A	b	χ^2/ND
Annihilation	10.9 ± 0.6	7.86 ± 0.39	7.5/8
Non-annihilation	12.4 ± 0.6	7.40 ± 0.33	8.1/9
Total	21.6 ± 0.8	7.48 ± 0.25	12.4/12

Within the errors the annihilation and non-annihilation slopes are the same. However comparison with the 4.6 and 9.1 GeV/c [5.6] results shows the annihilation to be systematically higher than the non-annihilation by a small amount. The annihilation slopes also appear to be constant over the range 4.6 to 9.1 GeV/c, being 7.9 ± 0.2 and 8.0 ± 0.3 respectively at those energies.

5.8 INCLUSIVE TWO STRANGE PARTICLE CROSS SECTIONS

Inclusive two strange particle cross sections have been calculated using events where both particles were observed. Two V^0 events have been corrected for the branching ratios

data, and a fit over the range $0.0 < p_t^2 < 0.5 \text{ (GeV/c)}^2$ gave $A = 3.04 \pm 0.20$, $b = -6.87 \pm 0.35$ with a χ^2/ND of 27.7/18. If the speculation that the break is due to resonance production of K_s is correct then one would not expect a break in the non-annihilation data because the resonance contribution is consistent with zero [5.9].

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5.8 INCLUSIVE TWO STRANGE PARTICLE CROSS SECTIONS

Inclusive two strange particle cross sections have been calculated using events where both particles were observed. Two V^0 events have been corrected for the branching ratios

of both V^0 's and the CP invariance of inclusive K^+ , K^- distributions was used in resolving events with ambiguous charged kaons. The event samples and total inclusive cross sections are given in Table 5.17. For completeness the topological breakdown of these totals is given in Table 5.18.

CP invariance requirements on the total inclusive cross sections :-

$\sigma(K_s K^+ x) = \sigma(K_s K^- x)$, $\sigma(\Lambda K^+ x) = \sigma(\bar{\Lambda} K^- x)$ and $\sigma(\Lambda K_s x) = \sigma(\bar{\Lambda} K_s x)$ are satisfied within the statistical errors given.

There is evidence that $[\Lambda K]$ processes appear to be preferentially through the charged K modes, with

$$\frac{\sigma(\Lambda K^+ x) + \sigma(\bar{\Lambda} K^- x)}{2[\sigma(\Lambda K_s x) + \sigma(\bar{\Lambda} K_s x)]} = 1.6 \pm 0.3$$

This result is to be expected since $\Lambda/\bar{\Lambda}$ production is predominantly through $p/\bar{p}$ fragmentation in which $\Lambda K^+/\bar{\Lambda} K^-$ are produced as shown in Figure 5.15 (a), but not $\Lambda \bar{K}^0/\bar{\Lambda} K^0$ which require additional sea quarks as shown in Figure 5.15 (b).

5.9 STRANGE PARTICLE PRODUCTION IN $\bar{p}p$ ANNIHILATIONS

An annihilation reaction is one which contains no final state baryons. Strange particle production therefore occurs entirely through processes of the type $\bar{p}p \rightarrow K\bar{K}x$. In addition to direct production there is also resonance production through $\bar{p}p \rightarrow K^*\bar{K}x$, $K\bar{K}^*x$ and $K^*\bar{K}^*x$. This is by no means a negligible proportion of the total, 30-36% of all K_s coming from K^* decay in $\bar{p}p$ annihilations [5.10].

In what guise should the $K\bar{K}$ pairs produced in $\bar{p}p$ annihilations be observed experimentally? The naive assumption has always been that all possible $K\bar{K}$ pair combinations are equally probable, i.e.

$$K+K^- = K+\bar{K}^0 = K^0K^- = K^0\bar{K}^0.$$

This is equivalent to assuming $\sigma(K^+) = \sigma(K^-) = \sigma(K_s) = \sigma(K_L)$. The assumption is represented schematically in Figure 5.16.

The only requirements of strong interaction physics are -

- 1) $\sigma(K^+) = \sigma(K^-)$
- 2) $\sigma(K^0) = \sigma(\bar{K}^0)$
- 3) $\sigma(K+\bar{K}^0) = \sigma(K^0K^-)$

these being necessary from CP invariance in $\bar{p}p$ interactions.

An annihilation K_s sample provides a key for probing some of these assumptions. The two strange particle cross sections given in the previous section were for the total sample. The inclusive two kaon cross sections were also calculated for the annihilation sample and are given in Table 5.19. From Figure 5.16 it is clear that the only source of annihilation K_s not measured by these two kaon cross sections is $\sigma(K_s K_L x)$. However since the total $\sigma(K_s)_{\text{ann}}$ has been measured the $K_s K_L$ component can be calculated as:-

$$\sigma(K_s K_L x) = \sigma(K_s)_{\text{ann}} - \sigma(K_s K^+ x) - \sigma(K_s K^- x) - 2\sigma(K_s K_s x)$$

The results of this calculation are also given in Table 5.19. Even though the errors for the $K_s K_L$ component are large it can still be said the $\sigma(K_s K_L x) = 148 \pm 106 \mu\text{b}$ is

different from the 'predicted' value of $2\sigma(K_s K_{sx}) = 480 \pm 40 \mu\text{b}$. The conclusion appears to be that $K^0 \bar{K}^0$ does not give equal amounts of $K_s K_s$, $K_s K_L$, $K_L K_s$ and $K_L K_L$ as was depicted in Figure 5.16. This may be due to resonance production of $K^0 \bar{K}^0$, though a $(K_s K_s)$ effective mass plot showed no significant resonance signals, Figure 5.17.

Assuming $\sigma(K_L K_L) = \sigma(K_s K_s)$ then -

$$\sigma(K^0 \bar{K}^0) = 2\sigma(K_s K_s) + \sigma(K_s K_L) = 0.63 \pm 0.15$$

$$\sigma(K^+ \bar{K}^0) = 2\sigma(K_s K^+) = 0.95 \pm 0.04$$

$$\sigma(K^0 K^-) = 2\sigma(K_s K^-) = 1.00 \pm 0.04$$

The assumption that $\sigma(K^+ \bar{K}^0) = \sigma(K^0 K^-) = \sigma(K^0 \bar{K}^0)$ therefore is seen not to hold by about 2 standard deviations. Unfortunately there is no measure of $\sigma(K^+ K^-)$ to complete the picture. The fact that the assumed equality does not hold could be due to over-simplification of the picture in Figure 5.16. The actual situation is certainly more complicated than that depicted there by the existence of resonance production which is known to be substantial [5.10].

In an earlier report of this work [5.11], before $\sigma(K_s K^+)$ and $\sigma(K_s K^-)$ had been calculated, the ratio $[\sigma(K_s K_s)/\sigma(K_s)]_{\text{ann}}$ was considered. On the basis of Figure 5.16 this would be expected to be $1/8$ and was found to be systematically higher at all energies up to 100 GeV/c . However the value of $1/8$ is only expected on the assumption of equality and having seen it may not hold, no great significance can be given to this observation.

5.10 REFERENCES

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(b) 36% at 3.6 GeV/c S. Bannerjee et al.,
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- 5.11 Strange Particle Production in $\bar{p}p$ Annihilations. G.D. Patel, Proceeding of V European Symposium on Baryon-Antibaryon Interactions, Bressanone, 1980.

5.11 TABLES

- 5.1 V^0 , γ Fit ambiguity matrix.
- 5.2 V^0 , γ Mass cut definitions.
- 5.3 Mass cut compensation weights.
- 5.4 Primary and V^0 vertex fiducial volumes.
- 5.5 Numbers of V^0 's and γ 's in the final sample.
- 5.6 Breakdown of the sample of failed events.
- 5.7 Primary sample reconstruction failure rates.
- 5.8 Secondary sample reconstruction failure rates.
- 5.9 Forward/Backward γ reconstruction failure rates.
- 5.10 Inclusive V^0 , γ and π^0 cross sections.
- 5.11 Mean multiplicities. Average numbers of V^0 , γ per inelastic event.
- 5.12 Inclusive and semi-inclusive K_s , γ and π^0 annihilation cross sections.
- 5.13 Mean multiplicities. Average numbers of K_s , γ per annihilation event.
- 5.14 Results of fits to $d\sigma/dp_t^2 = A \exp[-bp_t^2]$ for V^0 's.
- 5.15 Mean values, $\langle p_t \rangle$ and $\langle p_t^2 \rangle$, for V^0 's and γ 's.
- 5.16 Results of fits to $d\sigma/dp_t^2 = A \exp[-bp_t^2]$ for separated K_s .
- 5.17 Two strange particle samples and inclusive cross sections.
- 5.18 Topological two strange particle cross sections.
- 5.19 Two strange particle cross sections in $\bar{p}p$ annihilations.

TABLE 5.1 V^0 , γ Ambiguity Matrix

	K_s	Λ	$\bar{\Lambda}$	γ
K_s	3679	46	216	
Λ		1457	2	
$\bar{\Lambda}$			1128	
γ				6017

TABLE 5.2 V^0 , γ Mass Cuts

Type	Cut (GeV)
K_s	$0.47 < M(K_s) < 0.52$
Λ	$1.106 < M(\Lambda) < 1.124$
$\bar{\Lambda}$	$1.106 < M(\Lambda) < 1.124$
γ	$< M(\gamma) < 0.025$

TABLE 5.3 Mass Cut Weights

Type	Primary Sample	Secondary Sample
K_s	1.022	1.033
Λ	1.074	1.026
$\bar{\Lambda}$	1.153	1.075
γ	1.083	1.091

TABLE 5.4 Fiducial Volume Definitions

Vertex	x	y	z
Primary	$-60 < x < 40$	$-18 < y < 18$	$-38 < z < -12$
V^0 , γ	$-62 < x < 58$	$-15 < y < 15$	$-40 < z < 10$

TABLE 5.5 Numbers of V^0 's, γ 's in Final Sample

Topology	K_s	Λ	$\bar{\Lambda}$	γ
0	257	447	377	301
2	1279	835	704	1630
4	1599	162	145	2418
6	469	10	2	1233
8	16		1	196
10	1			6
Total	3621	1454	1229	5784

TABLE 5.6 Breakdown of Failed Events

K_s	Λ	$\bar{\Lambda}$	γ	Deleted
14.5%	6.8%	4.7%	59.2%	14.8%

TABLE 5.7 Primary Sample Failure Rates

Type	Fitted N_1	Failed	W_{r1}	Fitted N_{12}	W_{r12}	After η Correction
K_s	346	231	1.668	474	1.217	1.147
Λ	153	108	1.706	202	1.292	1.249
$\bar{\Lambda}$	160	75	1.469	188	1.250	1.218
γ	796	944	2.186	1310	1.328	1.301
Bad		236				
Total	1455	1594				

TABLE 5.8 Secondary Sample Failure Rates

Type	Fitted N_1	Failed	W_{r1}	After η Correction
K_s	753	550	1.730	1.630
Λ	272	258	1.948	1.88
$\bar{\Lambda}$	285	178	1.625	1.590
γ	1472	2245	2.525	2.474
Bad		561		
Total	2782	3792		

TABLE 5.9 Forward/Backward γ Failure Rates

	F	F_f	F_b
Primary Sample	1.30	1.27	1.41
Secondary Sample	2.47	2.29	3.31

TABLE 5.10 Inclusive V^0 , γ Cross Sections

Prong	$\sigma(K_s)$ mb.	$\sigma(\Lambda)$ mb.	$\sigma(\bar{\Lambda})$ mb.	$\sigma(\gamma)$ mb.
0	0.13 $\pm$ 0.02	0.28 $\pm$ 0.03	0.26 $\pm$ 0.03	7.8 $\pm$ 1.0
2	0.78 $\pm$ 0.04	0.54 $\pm$ 0.04	0.55 $\pm$ 0.04	37.5 $\pm$ 2.2
4	0.83 $\pm$ 0.04	0.11 $\pm$ 0.02	0.09 $\pm$ 0.02	55.1 $\pm$ 3.0
6	0.26 $\pm$ 0.02	0.007 $\pm$ 0.004	0.003 $\pm$ 0.003	29.0 $\pm$ 2.1
8	0.006 $\pm$ 0.003			4.0 $\pm$ 0.7
10				0.2 $\pm$ 0.2
Total	2.00 $\pm$ 0.10	0.94 $\pm$ 0.05	0.90 $\pm$ 0.05	134 $\pm$ 5

TABLE 5.11 Mean Multiplicities (particles/inelastic event)

Prong	$\langle K_s \rangle$	$\langle \Lambda \rangle$	$\langle \bar{\Lambda} \rangle$	$\langle \gamma \rangle$
0	0.060 ± 0.009	0.128 ± 0.014	0.119 ± 0.014	3.58 ± 0.48
2	0.049 ± 0.003	0.034 ± 0.003	0.034 ± 0.003	2.35 ± 0.15
4	0.048 ± 0.003	0.006 ± 0.001	0.005 ± 0.001	3.19 ± 0.19
6	0.035 ± 0.003	0.001 ± 0.001		3.89 ± 0.30
8	0.004 ± 0.002			2.47 ± 0.44
10				1.28 ± 1.28
Total	0.045 ± 0.003	0.021 ± 0.001	0.020 ± 0.001	3.00 ± 0.13

TABLE 5.12 Inclusive K_s , γ Annihilation Cross Sections

Prong	$\sigma(K_s)$ mb.	% of all K_s	$\sigma(\gamma)$ mb.	$\sigma(\pi^0)$ mb.	% of all π^0
2	0.52 ± 0.03	67	7.0 ± 1.0	3.5 ± 0.5	19
4	0.81 ± 0.04	98	29.3 ± 1.9	14.6 ± 1.0	53
6	0.26 ± 0.02	100	26.2 ± 1.7	13.1 ± 0.9	98
8	0.006 ± 0.003	100	4.0 ± 0.7	2.0 ± 0.4	100
10			0.2 ± 0.2	0.1 ± 0.1	100
Total	1.60 ± 0.10	80	66.7 ± 3.0	33.4 ± 1.5	50

TABLE 5.13 Mean Multiplicities in Annihilations

Prong	$\langle K_s \rangle$	$\langle \gamma \rangle$	$\langle \pi^0 \rangle$
2	0.335 ± 0.029	4.52 ± 0.71	2.26 ± 0.35
4	0.127 ± 0.007	4.60 ± 0.32	2.30 ± 0.16
6	0.041 ± 0.003	4.12 ± 0.29	2.06 ± 0.15
8	0.004 ± 0.002	2.52 ± 0.45	1.26 ± 0.23
10		1.28 ± 1.2	0.64 ± 0.64
Total	0.100 ± 0.006	4.16 ± 0.20	2.08 ± 0.10

TABLE 5.14 Results of Fits to $A \exp[-bp_t^2]$ for V^0 's

Type	Range	A	b	χ^2/ND
K_s	$p_t^2 < 0.15$	12.80 ± 0.61	7.70 ± 0.63	2.2/4
	$p_t^2 > 0.15$	8.92 ± 0.68	5.00 ± 0.23	17.6/18
Λ	Full	4.22 ± 0.18	4.44 ± 0.15	27/18
$\bar{\Lambda}$	Full	3.91 ± 0.18	4.32 ± 0.16	12.6/18

TABLE 5.15 Mean Values $\langle p_t \rangle$ and $\langle p_t^2 \rangle$

(a) Total	$\langle p_t \rangle$ (GeV/c)	$\langle p_t^2 \rangle$ (GeV/c) ²
K_s	0.386 ± 0.004	0.184 ± 0.004
Λ	0.413 ± 0.007	0.210 ± 0.006
$\bar{\Lambda}$	0.402 ± 0.007	0.209 ± 0.007
γ	0.185 ± 0.003	0.036 ± 0.001
(b) Separated		
K_s (ann)	0.394 ± 0.004	0.193 ± 0.004
K_s (non-ann)	0.336 ± 0.004	0.147 ± 0.004
γ (ann)	0.185 ± 0.004	0.037 ± 0.001
γ (non-ann)	0.186 ± 0.003	0.036 ± 0.001

TABLE 5.16 Results of Fits to $A \exp[-bp_t^2]$ for Separated K_s

Type Range	A	b	χ^2/ND
K_s $p_t^2 < 0.15$	9.43 ± 0.50	7.17 ± 0.70	3.3/4
K_s (ann) $p_t^2 > 0.15$	6.99 ± 0.56	4.81 ± 0.24	35/18
K_s $p_t^2 < 0.15$	3.84 ± 0.36	10.6 ± 1.3	3.3/4
K_s (non-ann) $p_t^2 > 0.15$	1.83 ± 0.33	5.12 ± 0.55	19.1/18

TABLE 5.17 Inclusive Two Strange Particle Cross Sections

Class	No. of Events	σ (mb.)
$K_s K^+ x$	682	0.51 ± 0.02
$K_s K^- x$	720	0.54 ± 0.02
$K_s K_s x$	181	0.27 ± 0.02
$\Lambda K^+ x$	292	0.28 ± 0.02
$\Lambda K_s x$	138	0.09 ± 0.01
$\bar{\Lambda} K^- x$	278	0.24 ± 0.02
$\bar{\Lambda} K_s x$	118	0.07 ± 0.01
$\bar{\Lambda} \Lambda x$	210	0.35 ± 0.03

TABLE 5.18 Topological Two Strange Particle Cross Sections

Class	0	2	4	6	8	Total
$K_s K^+ x$		146 ± 11	259 ± 14	100 ± 9	2 ± 1	507 ± 20
$K_s K^- x$		165 ± 12	266 ± 14	104 ± 9	3 ± 1	538 ± 20
$K_s K_s x$	13 ± 4	133 ± 16	109 ± 14	13 ± 4		268 ± 22
$\Lambda K^+ x$		190 ± 14	78 ± 9	7 ± 4		275 ± 17
$\Lambda K_s x$	52 ± 7	39 ± 6				90 ± 9
$\bar{\Lambda} K^- x$		182 ± 13	52 ± 7	3 ± 3		237 ± 16
$\bar{\Lambda} K_s x$	40 ± 6	30 ± 6	1 ± 1			71 ± 8
$\bar{\Lambda} \Lambda x$	150 ± 17	180 ± 19	15 ± 6			345 ± 26

TABLE 5.19 Two Strange Particle Production in Annihilations

Class	0	2	4	6	8	Total
$K_s K^+ x$		116 ± 10	255 ± 14	100 ± 9	2 ± 1	474 ± 20
$K_s K^- x$		131 ± 10	261 ± 14	104 ± 9	3 ± 1	498 ± 20
$K_s K_s x$		131 ± 15	109 ± 14	13 ± 4		240 ± 20
$\sigma(K_s)_{ann}$		520 ± 30	810 ± 40	260 ± 20	6 ± 3	1600 ± 100
$(K_s K_L)$		37 ± 36	76 ± 47	30 ± 24	1 ± 3	148 ± 106

5.12 FIGURES

- 5.1 $\cos\theta$ distribution of unique and unique+ambiguous samples of K_s , Λ and $\bar{\Lambda}$. (See text for details.)
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- 5.3 V^0 Transverse decay momentum distributions with expected form shown as solid line.
- 5.4 V^0 Lifetime determination. $1/\eta$ distributions.
- 5.5 V^0 , γ laboratory momentum distributions.
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- 5.8 (a) Inclusive K_s cross sections in $\bar{p}p$ and pp vs. laboratory momentum.
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- 5.15 Quark diagrams for proton fragmentation to ΛK .
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- 5.17 $K_s K_s$ Effective Mass Distribution.

Figure 5.1 V^0 Ambiguity Resolution

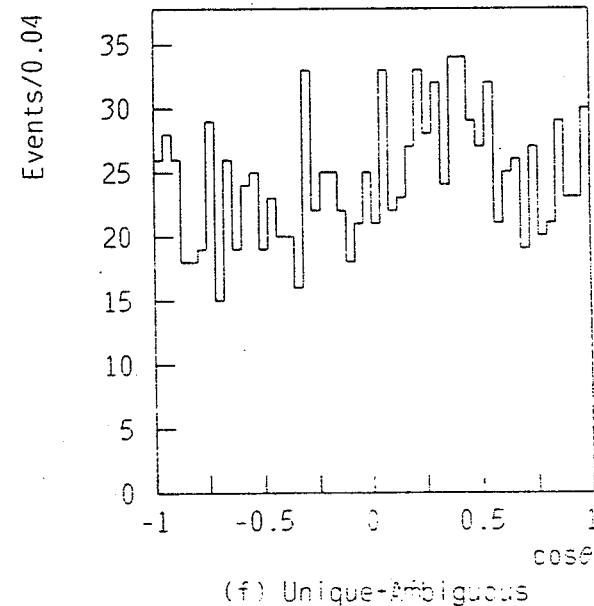
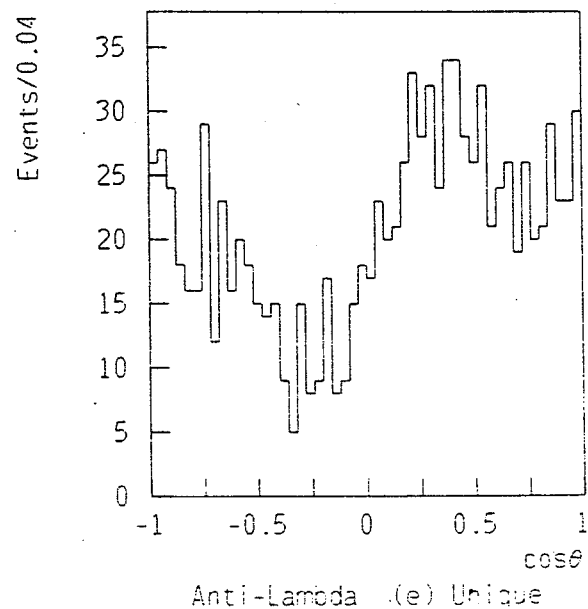
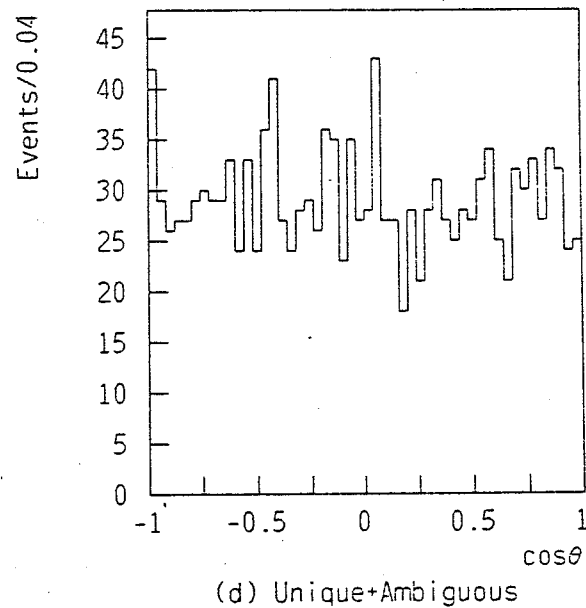
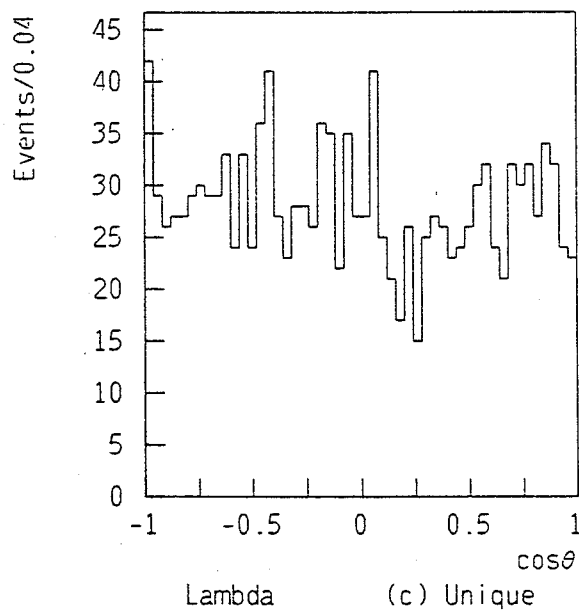
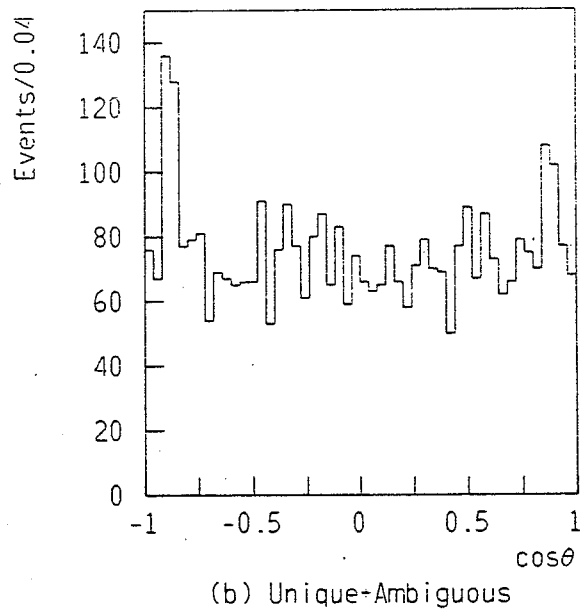
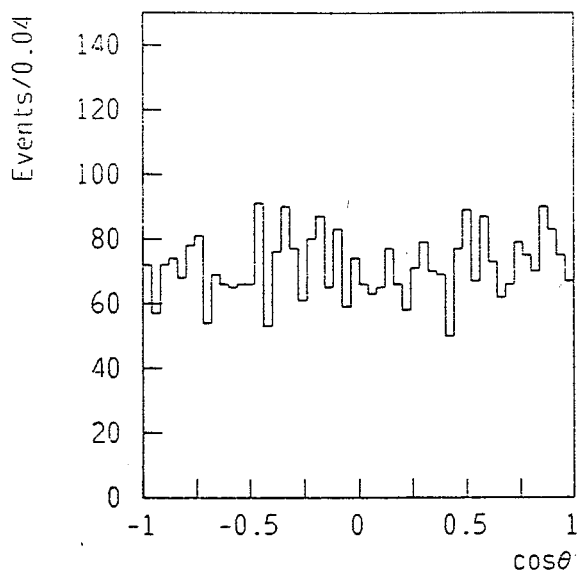
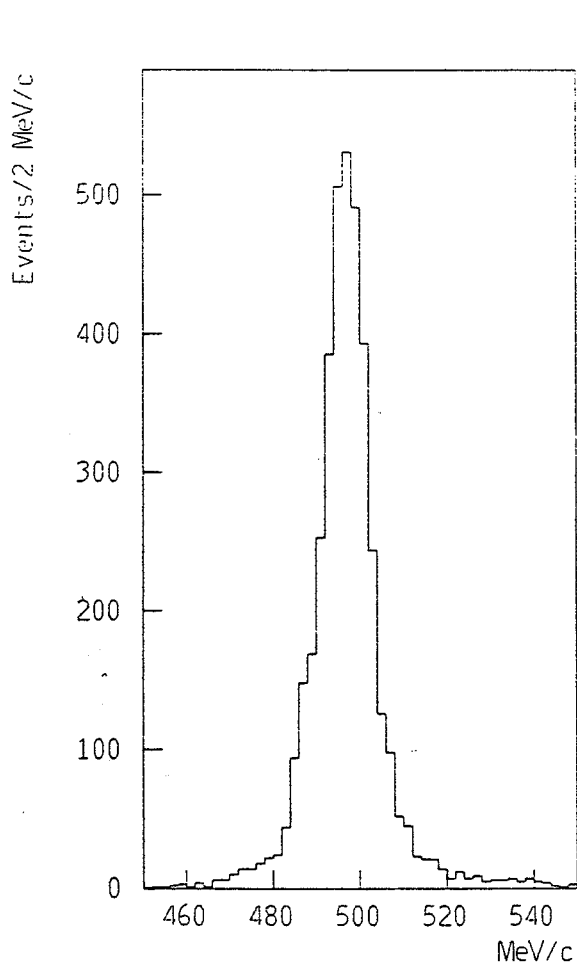
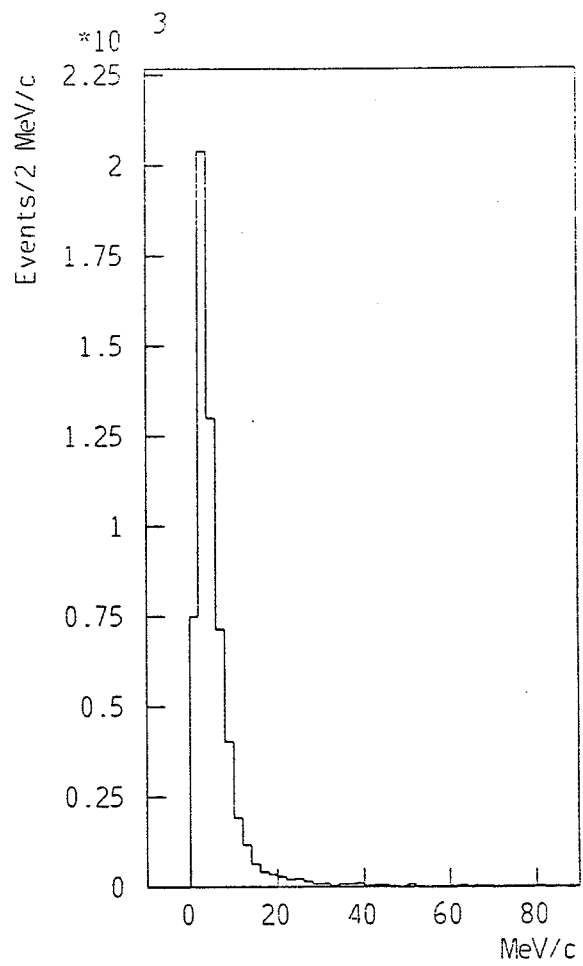


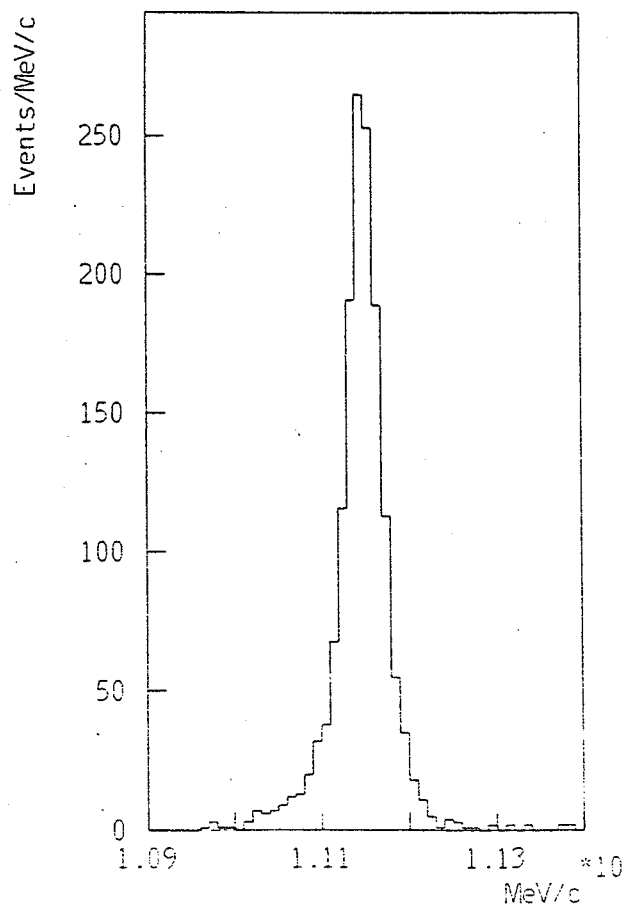
Figure 5.2 V^0, γ Mass Resolution



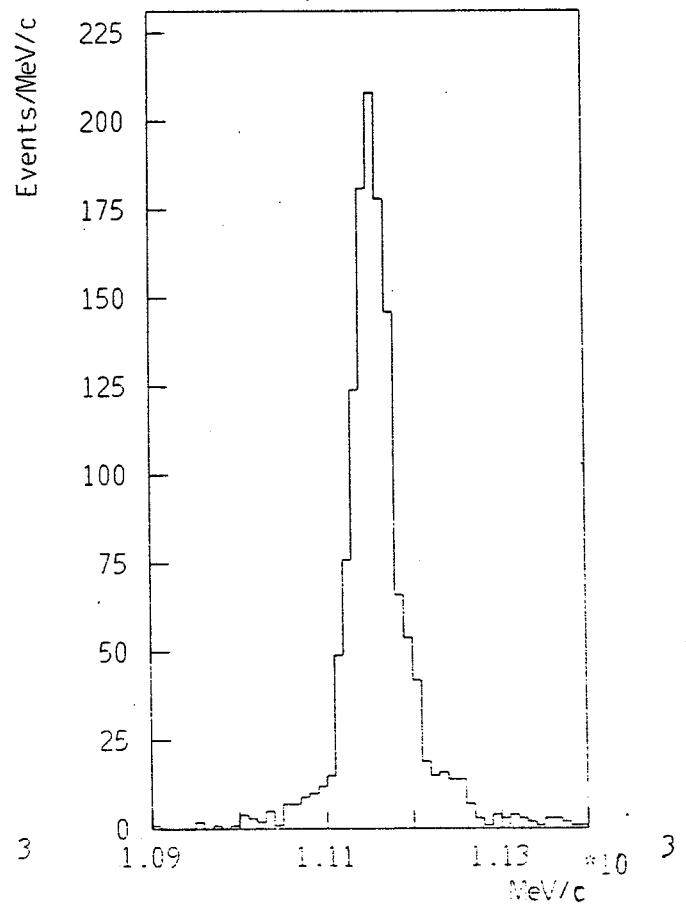
(a) K^0 -short



(b) Gamma

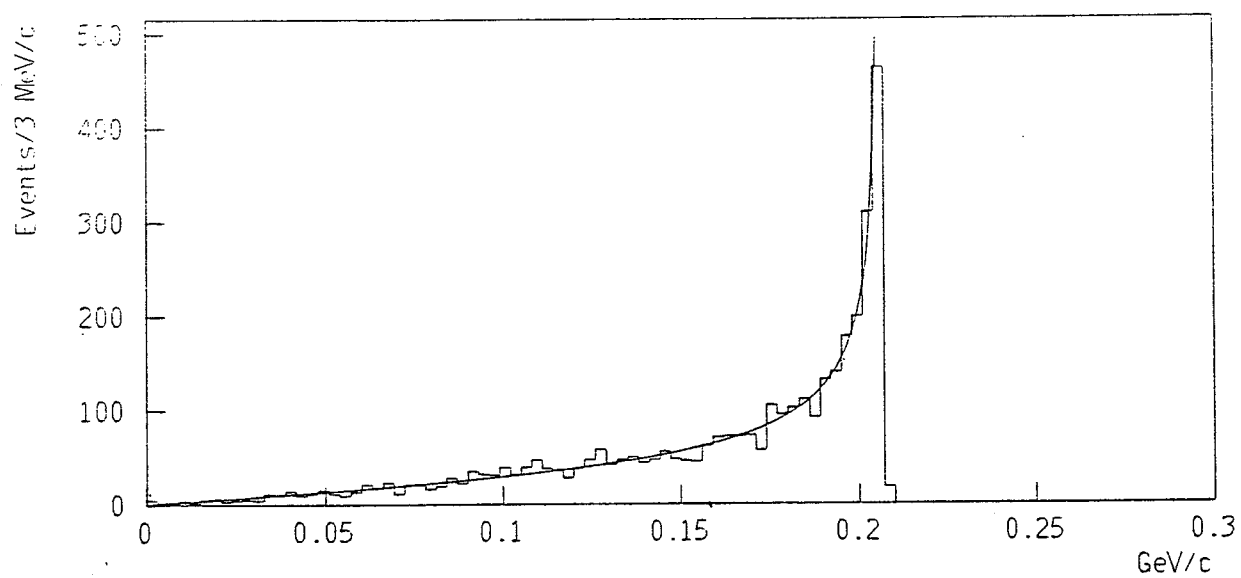


(c) Lambda

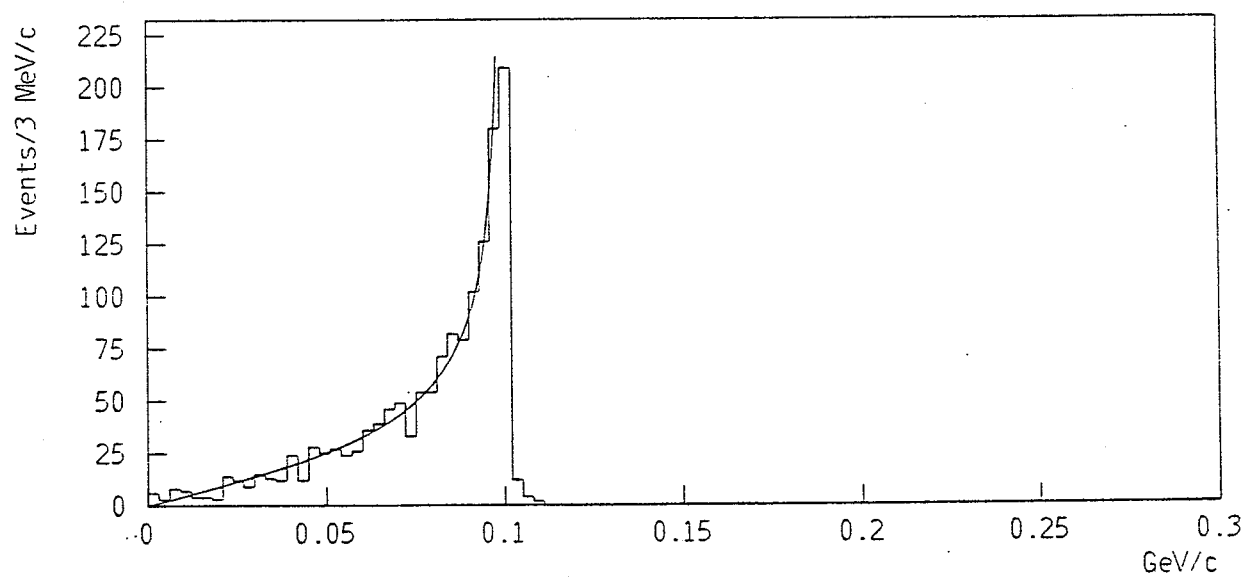


(d) Anti-Lambda

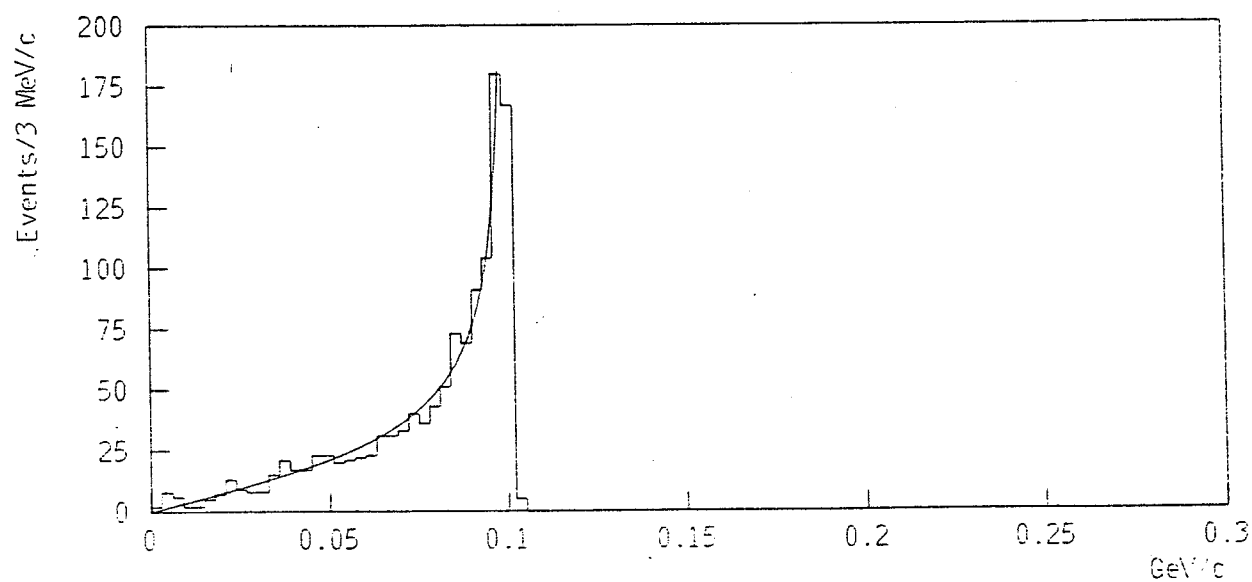
Figure 5.3 V^0 Transverse Decay Momentum



(a) K^0 -short

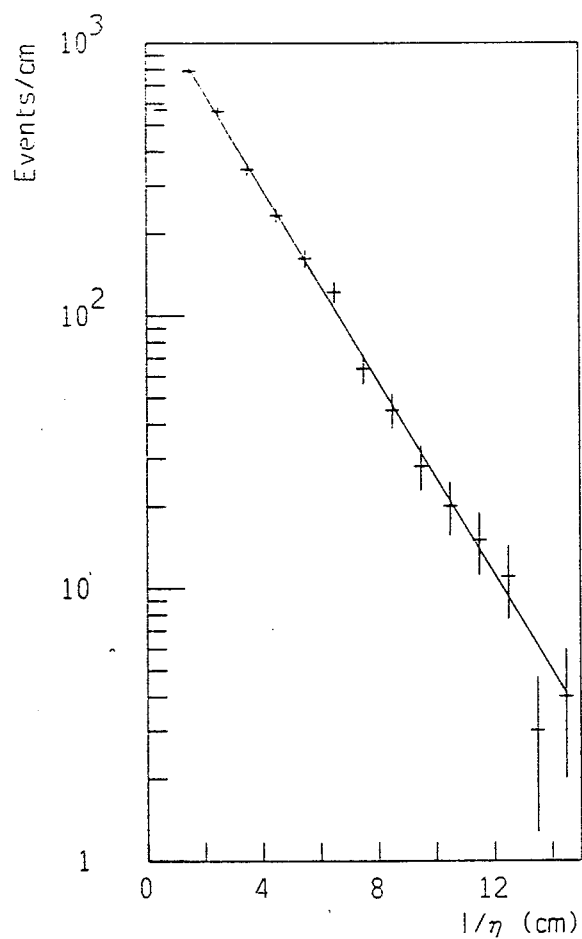


(b) Λ

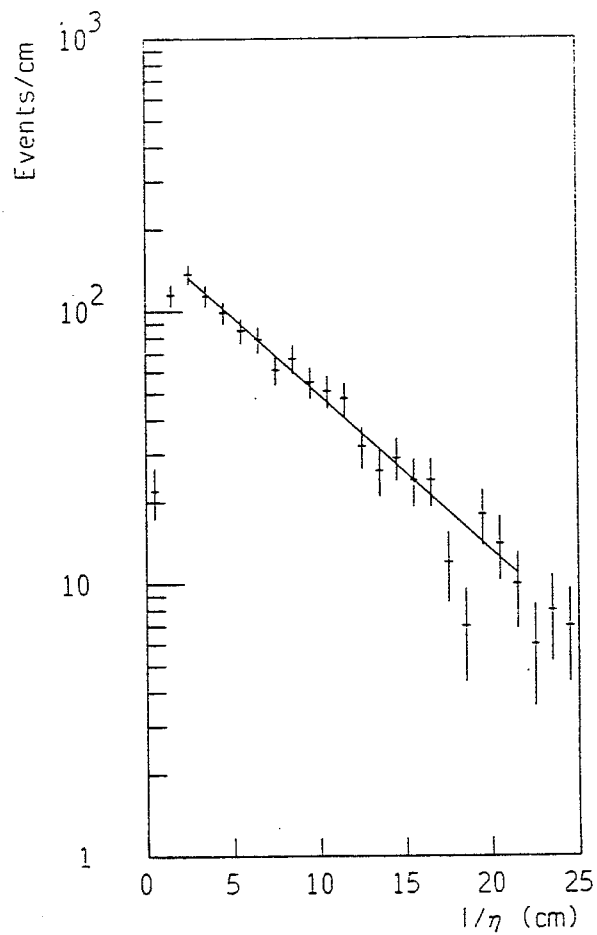


(c) $\bar{\Lambda}$

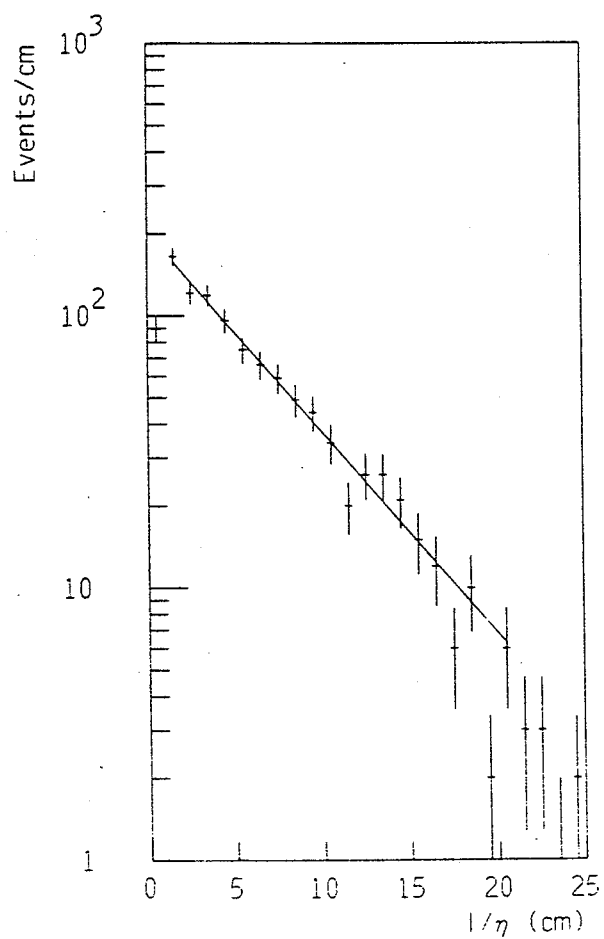
Figure 5.4 V^0 Lifetime, $1/\eta$ Distributions



(a) K^0 -short

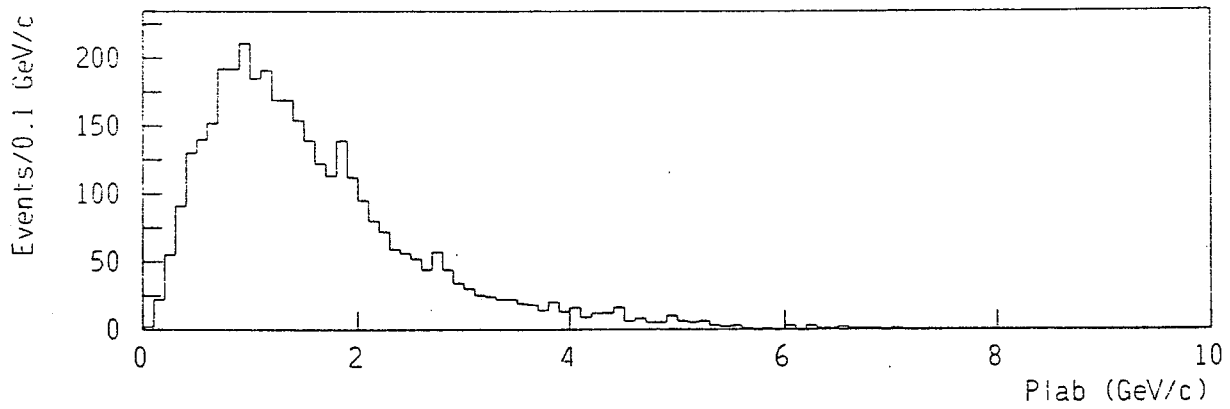


(b) Λ

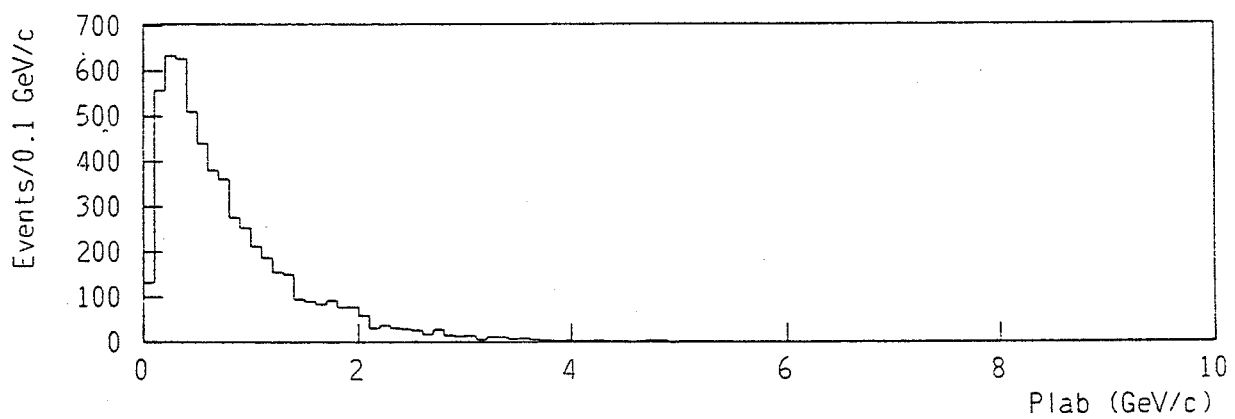


(c) $\bar{\Lambda}$

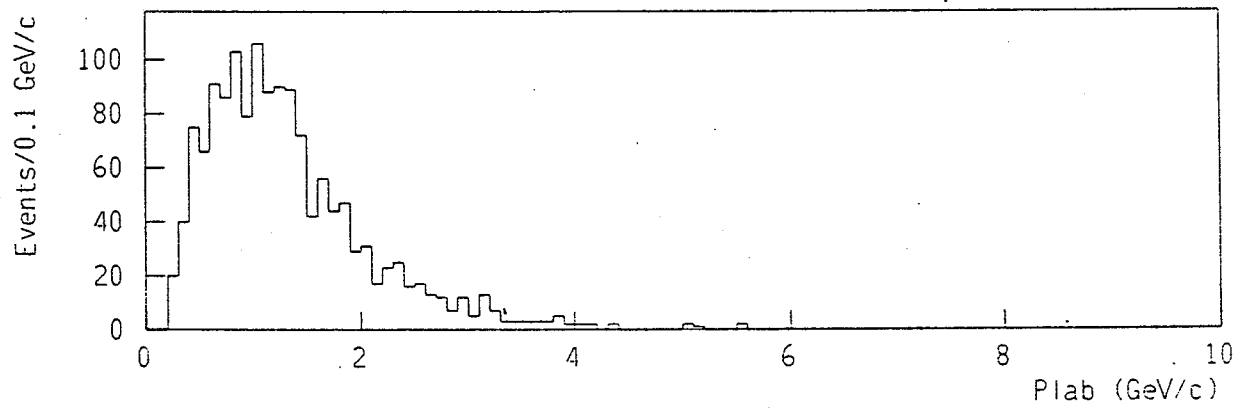
Figure 5.5 V^0, γ Laboratory Momentum



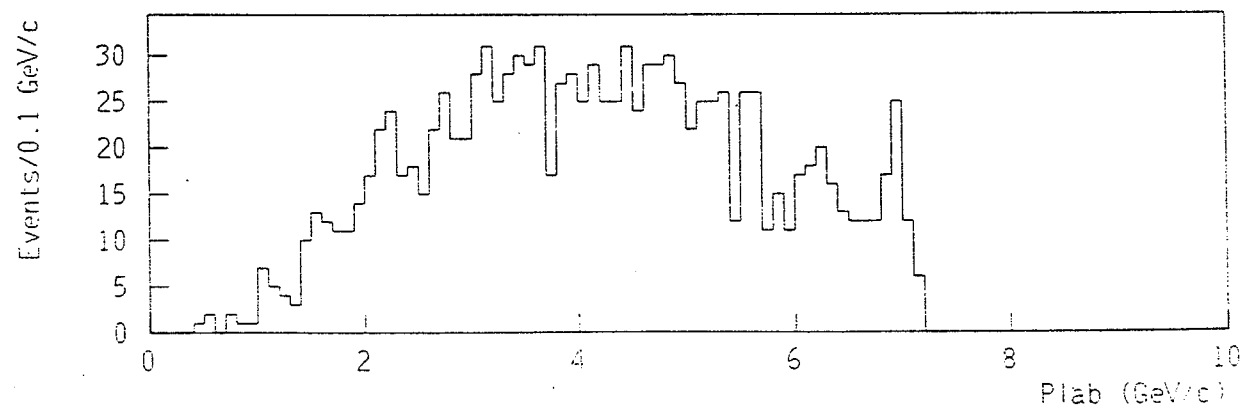
(a) K^0 -short



(b) Gamma



(c) Lambda



(d) Anti-Lambda

Figure 5.6 Effect of Lmin on η Distributions

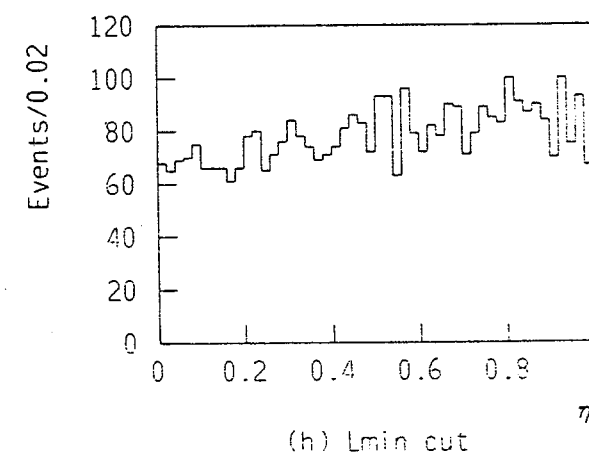
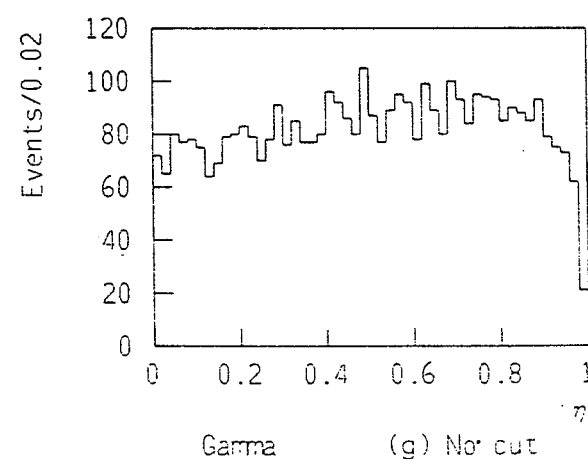
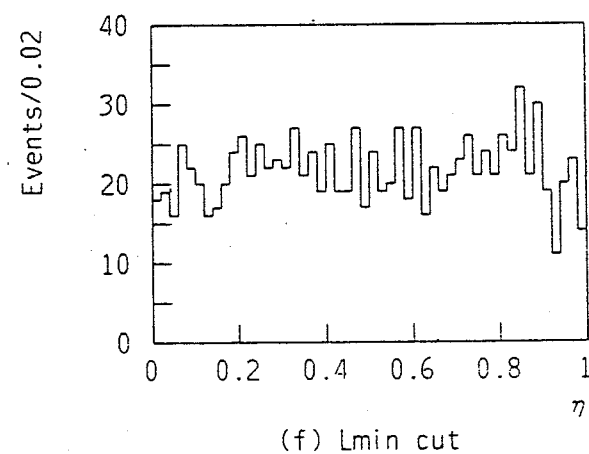
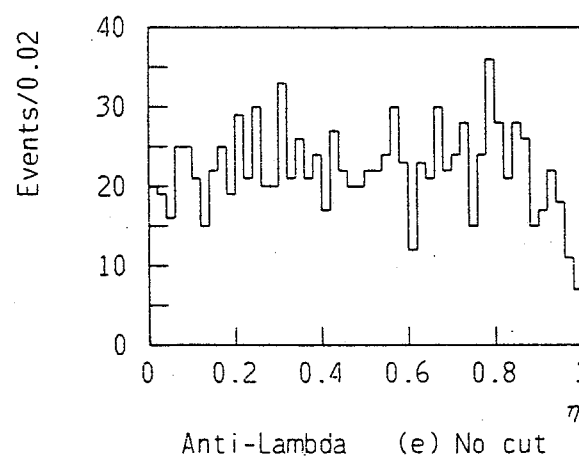
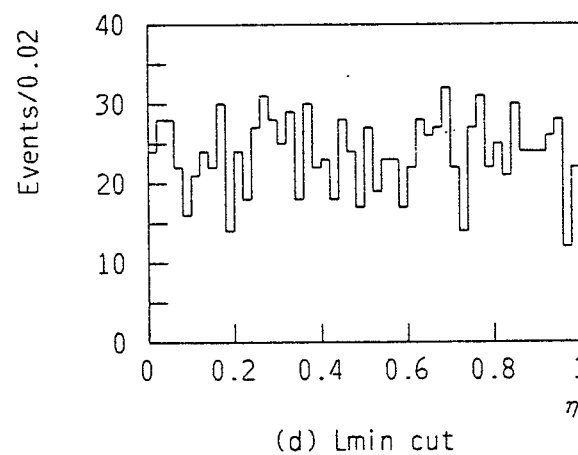
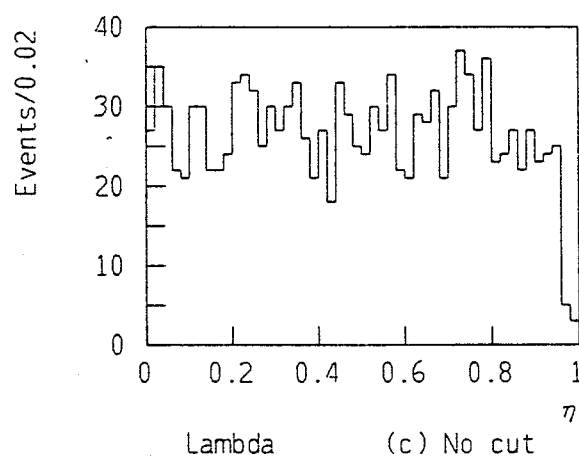
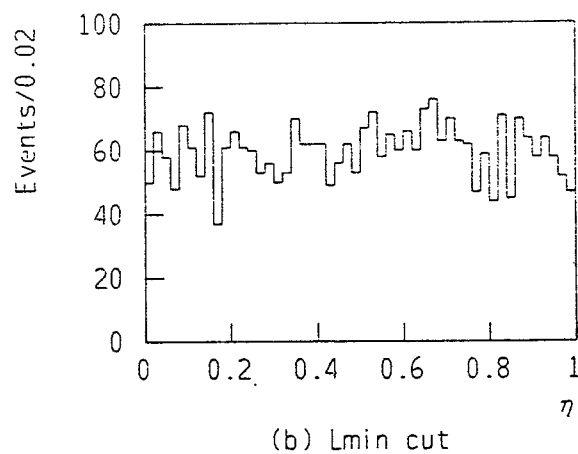
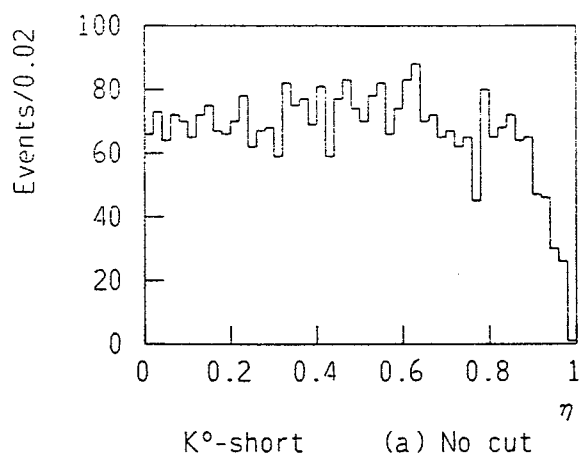


Figure 5.7 V^0, γ CMS $\cos\theta$ Distributions

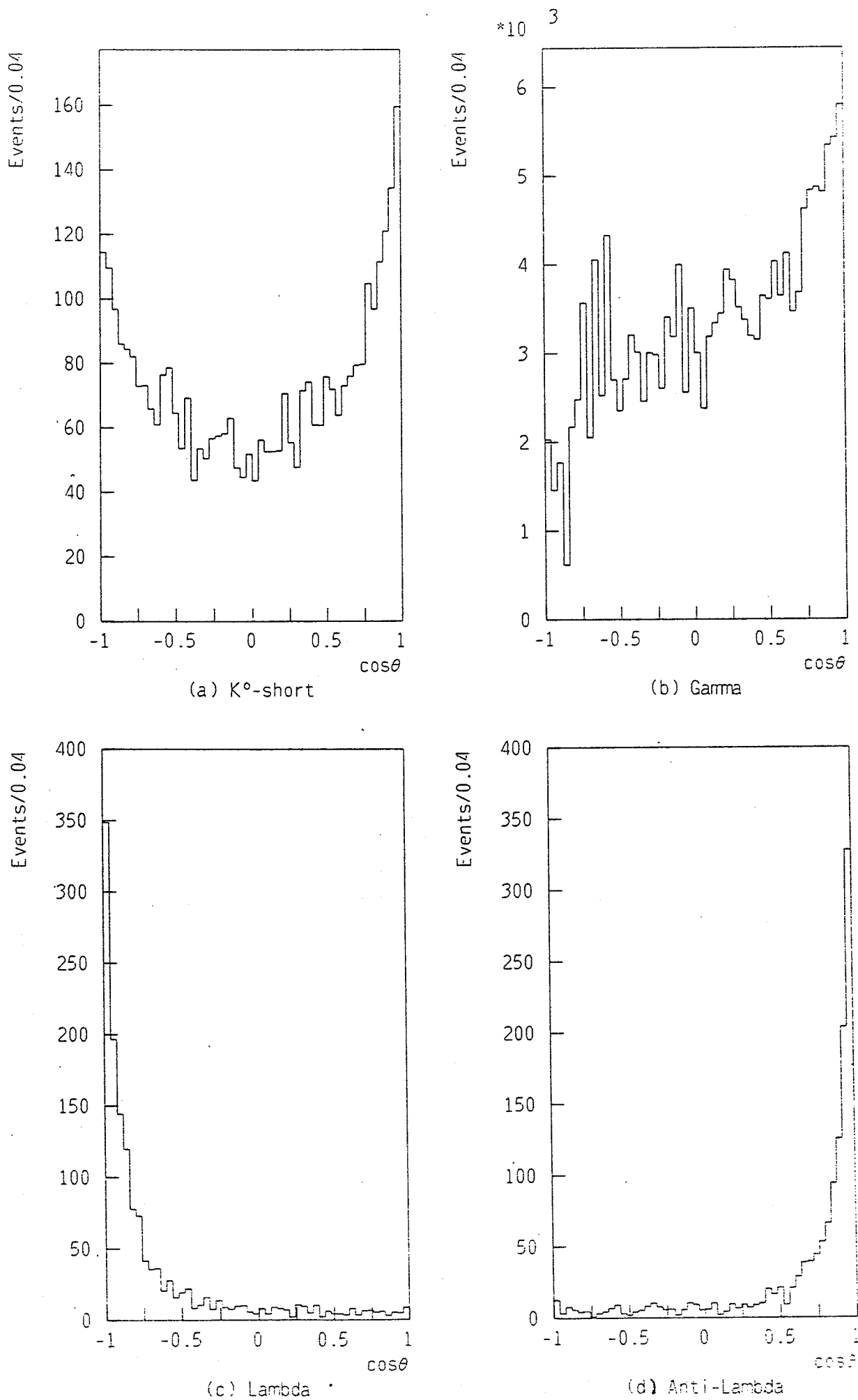


Figure 5.8 a) $\sigma(\bar{p}p \rightarrow K_S^0 X)$ vs P_{LAB}

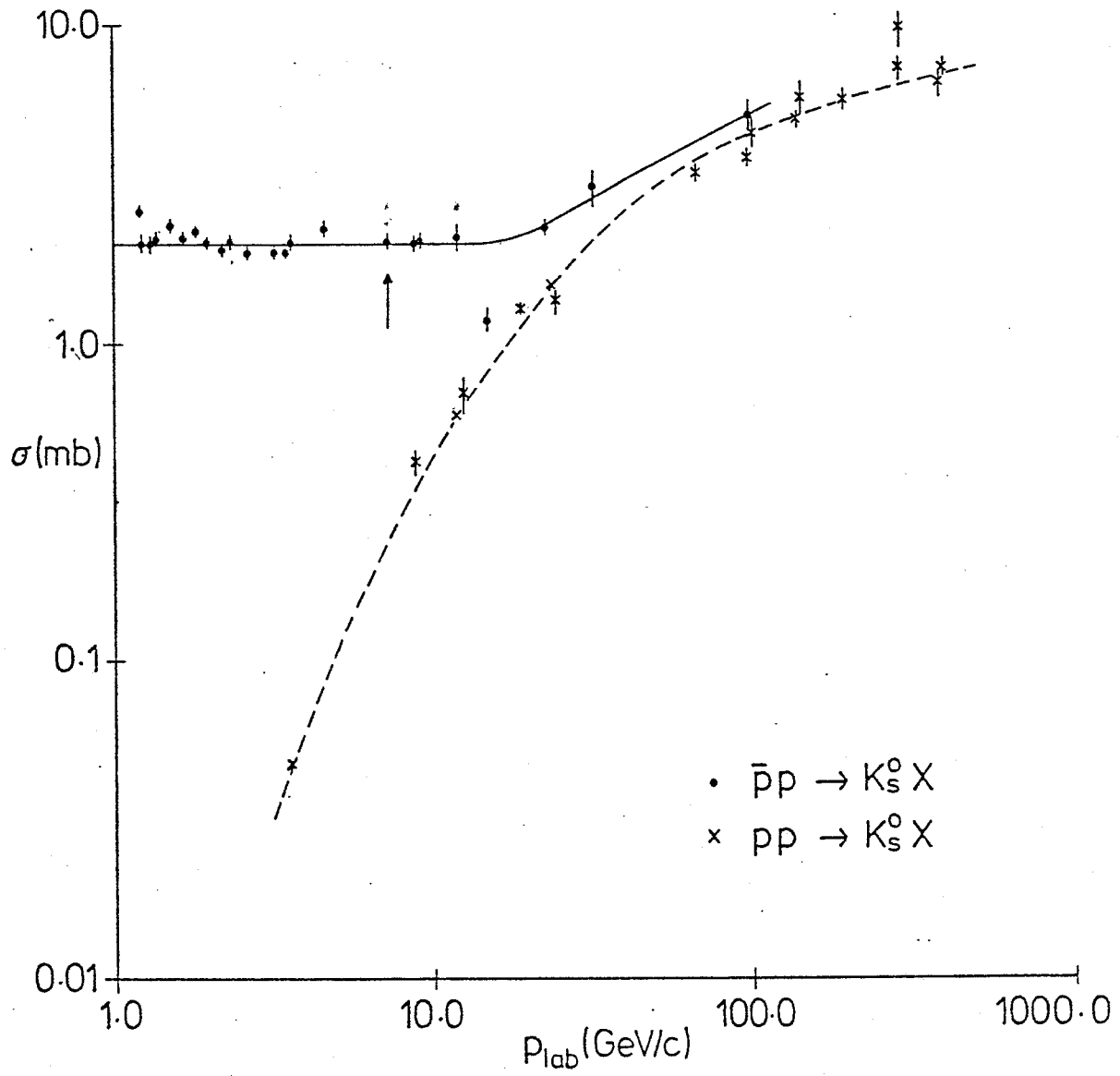


Figure 5.8 cont.

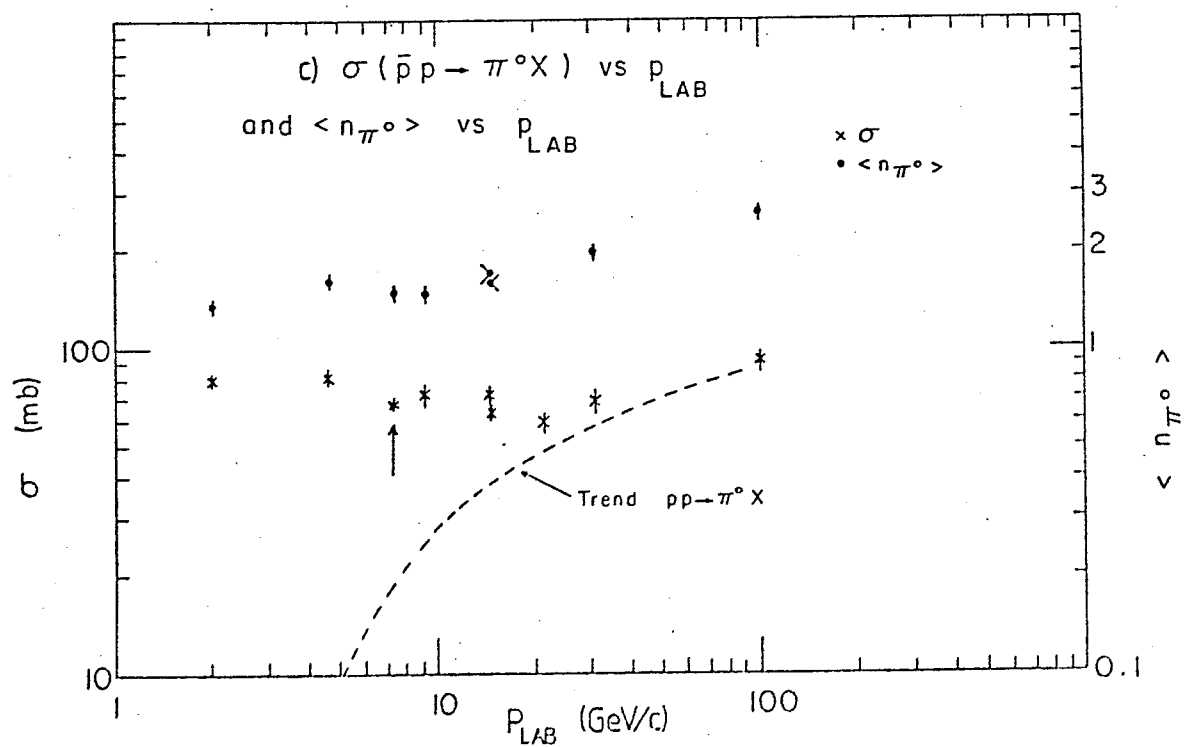
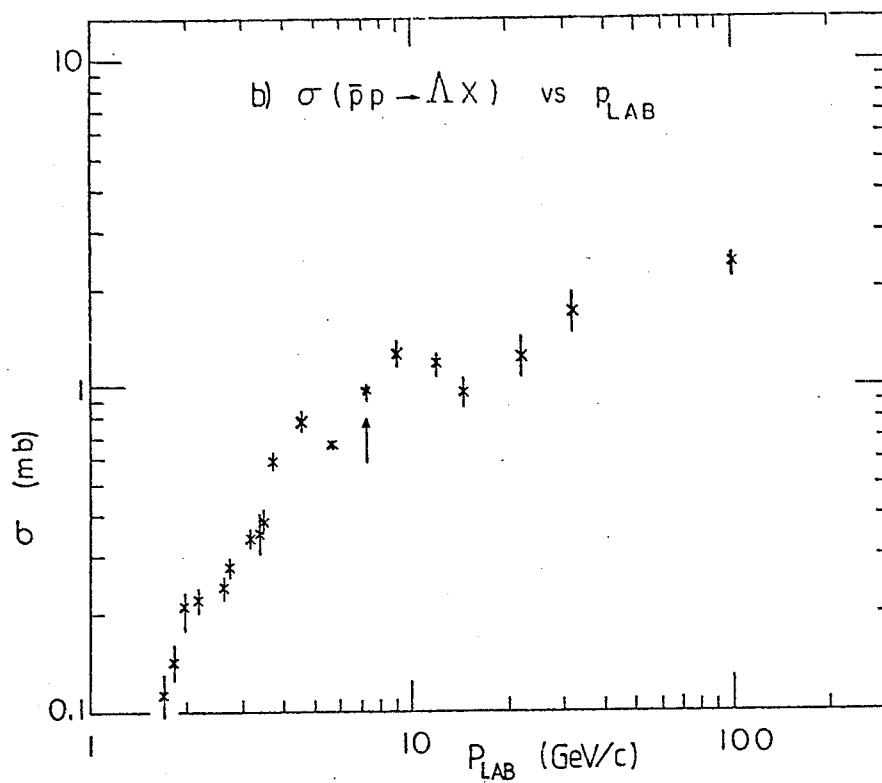


Figure 5.9 Annihilation $\sigma(K_s^0)$ vs P_{lab}

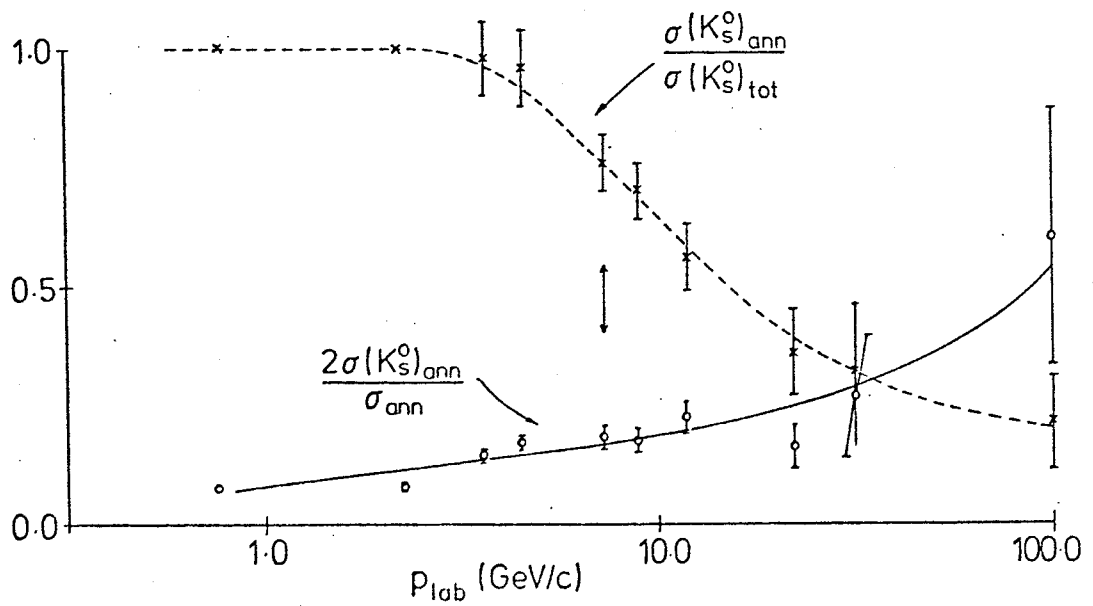
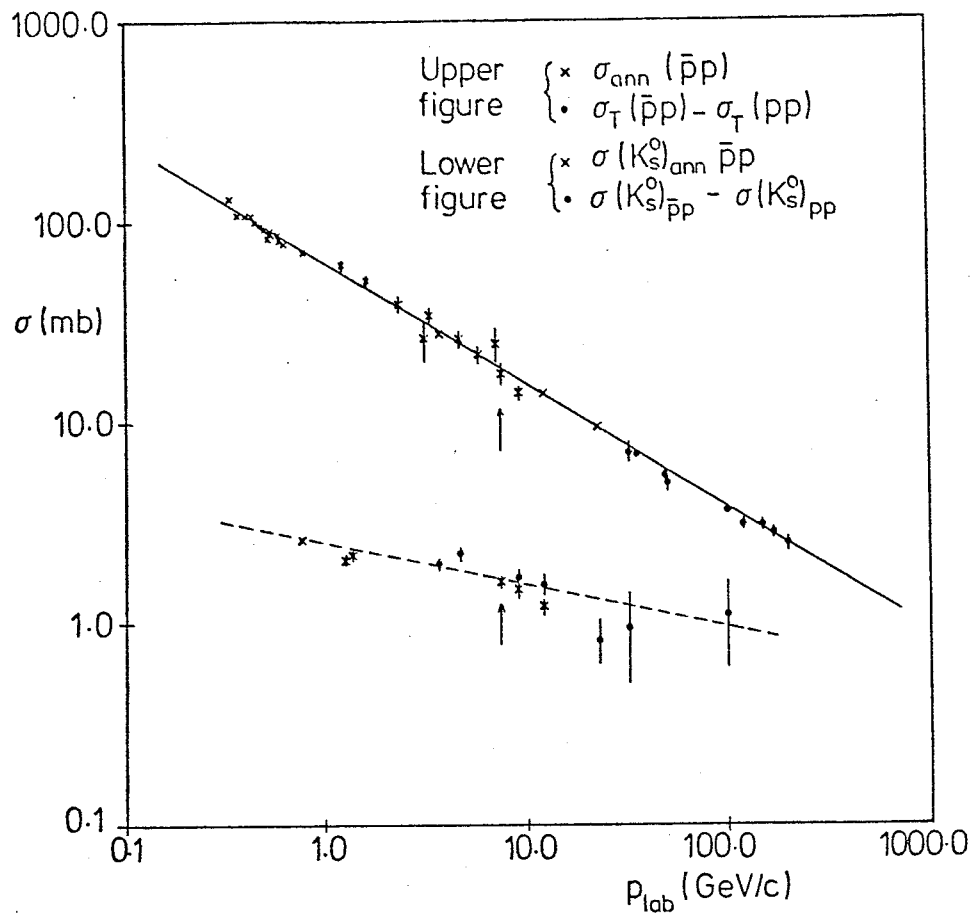
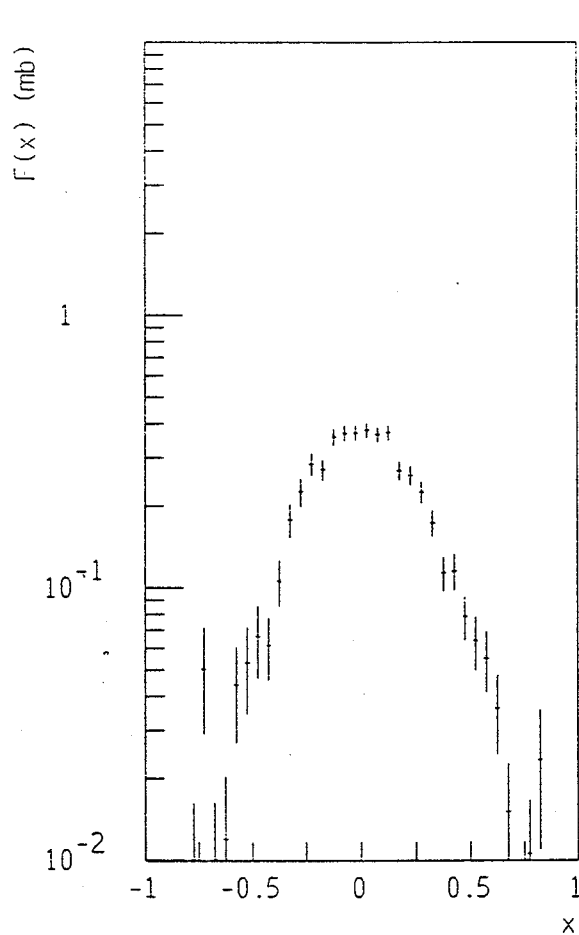
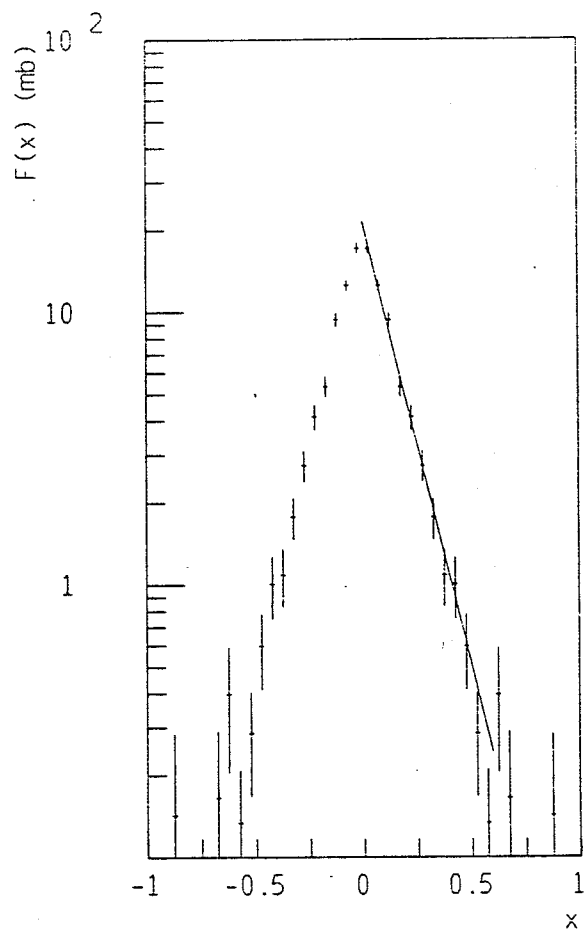


Figure 5.10 Ratios vs P_{lab}

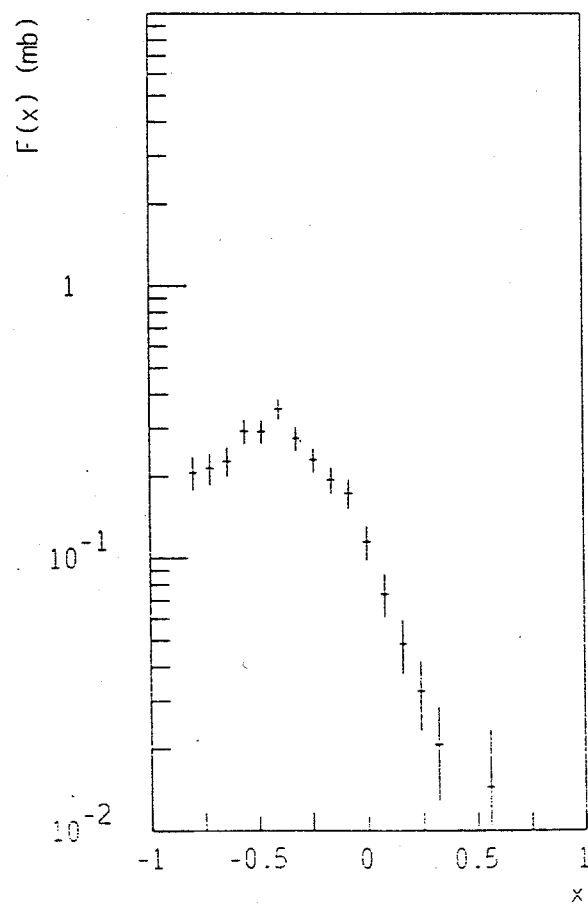
Figure 5.11 V^0, γ $F(x)$ Distributions



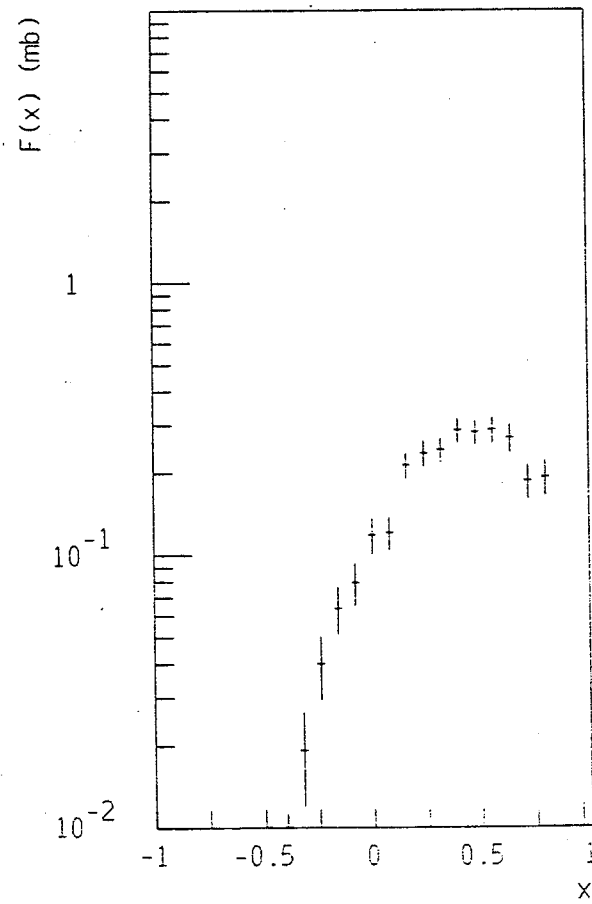
(a) K^0 -short



(b) Gamma



(c) Lambda



(d) Anti-Lambda

Figure 5.12 V^0, γ $d\sigma/dp_T^2$ Distributions

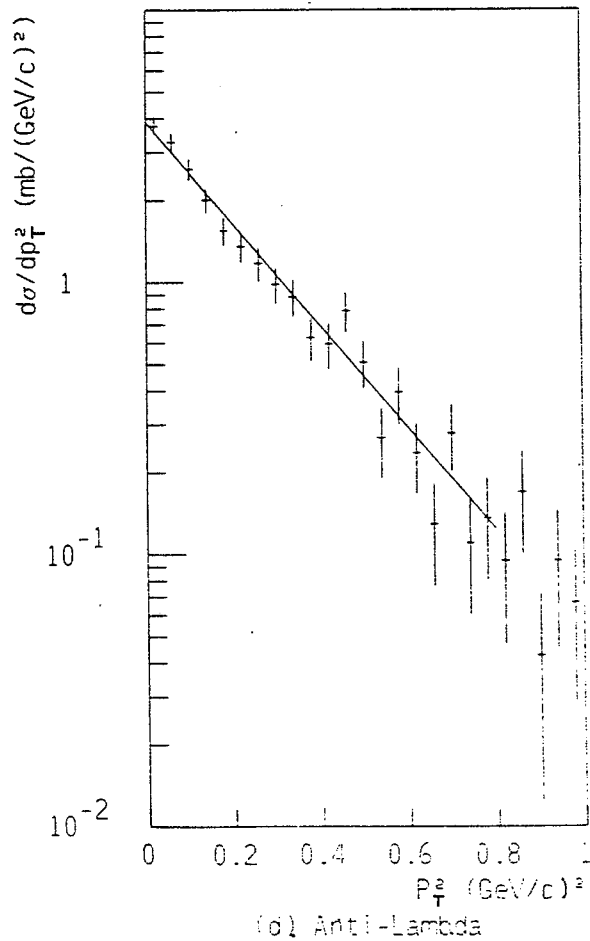
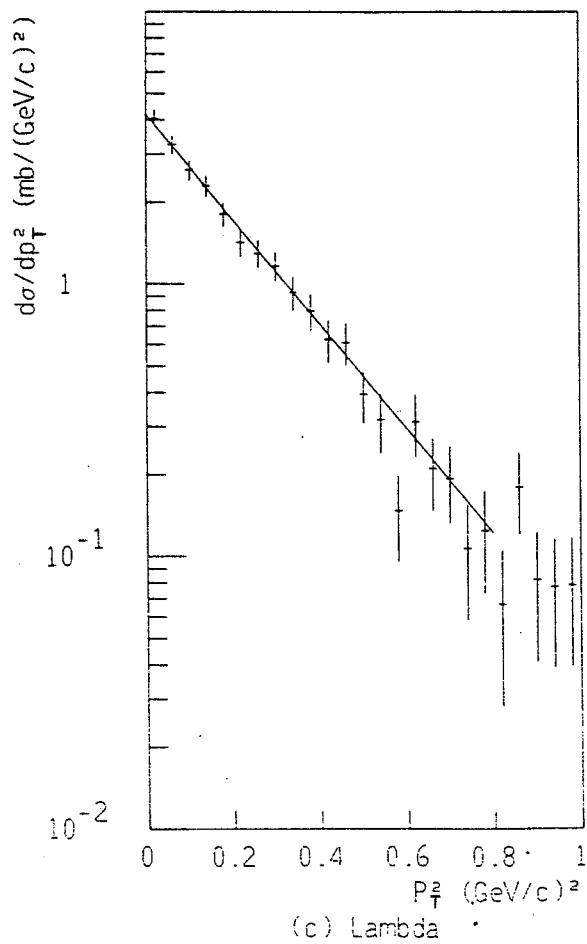
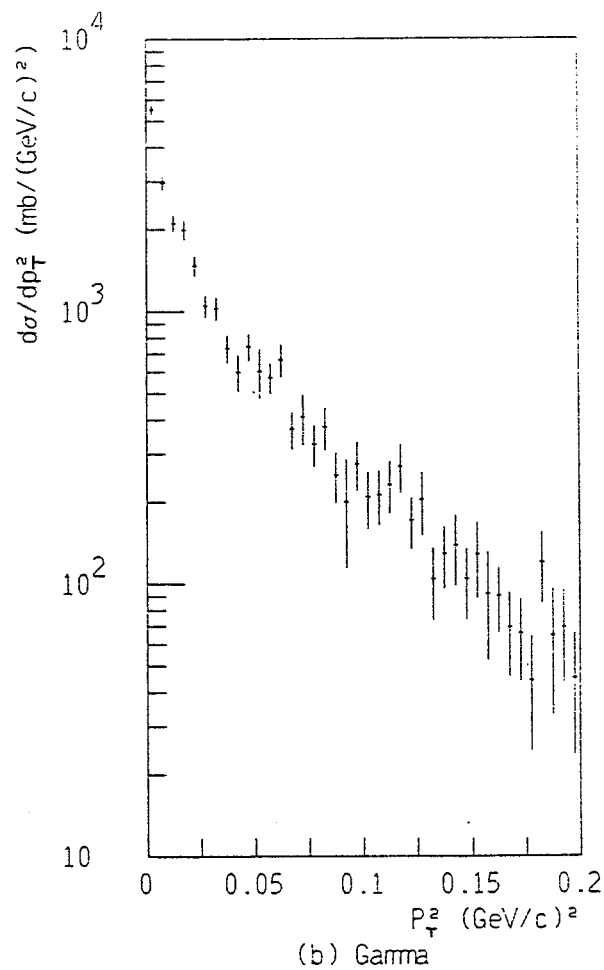
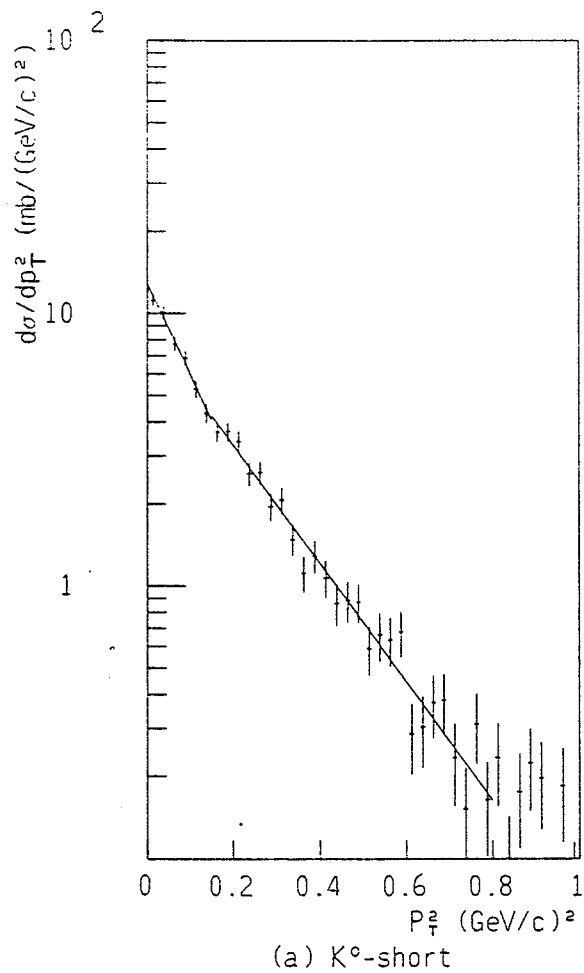


Figure 5.13 Annihilation $d\sigma/dp_T^2$ and $F(x)$

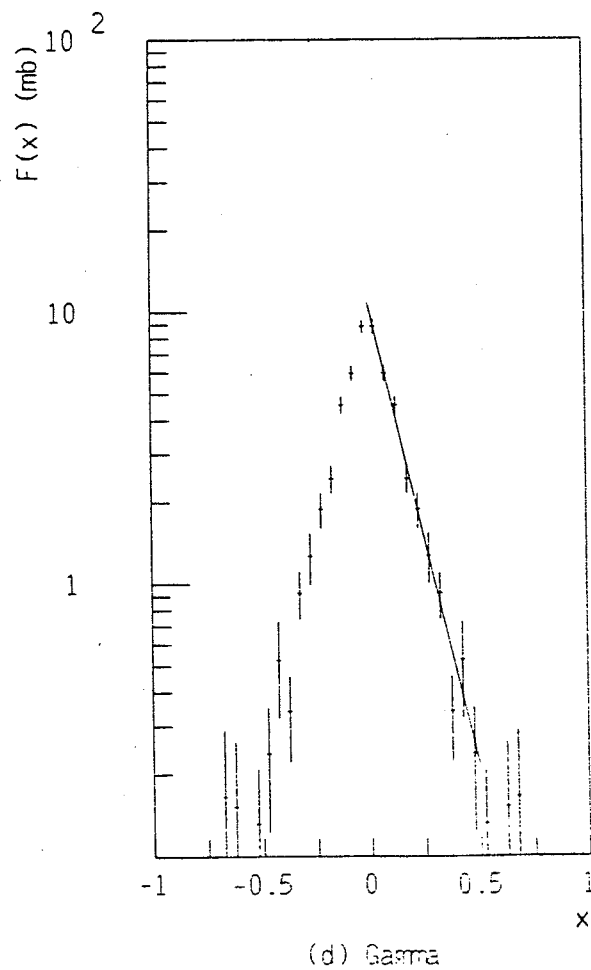
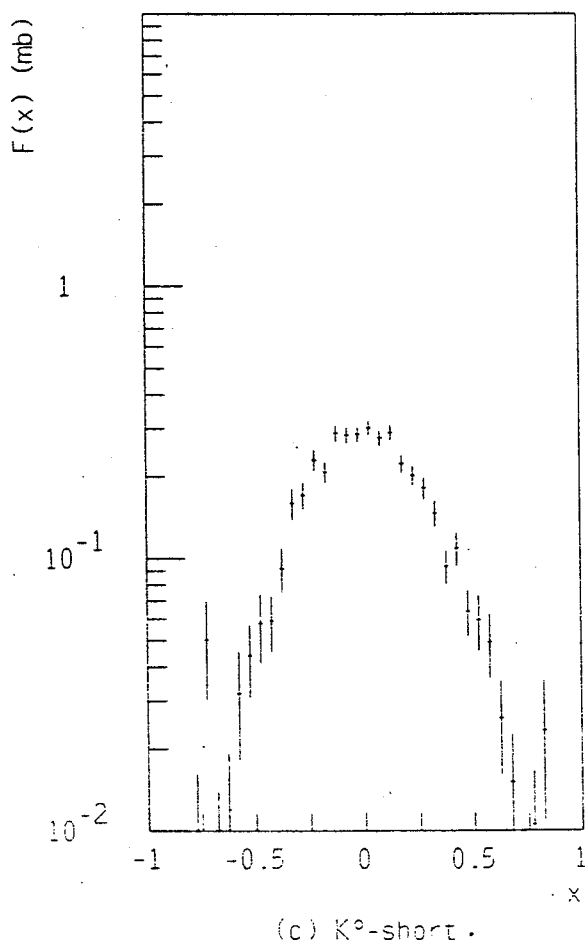
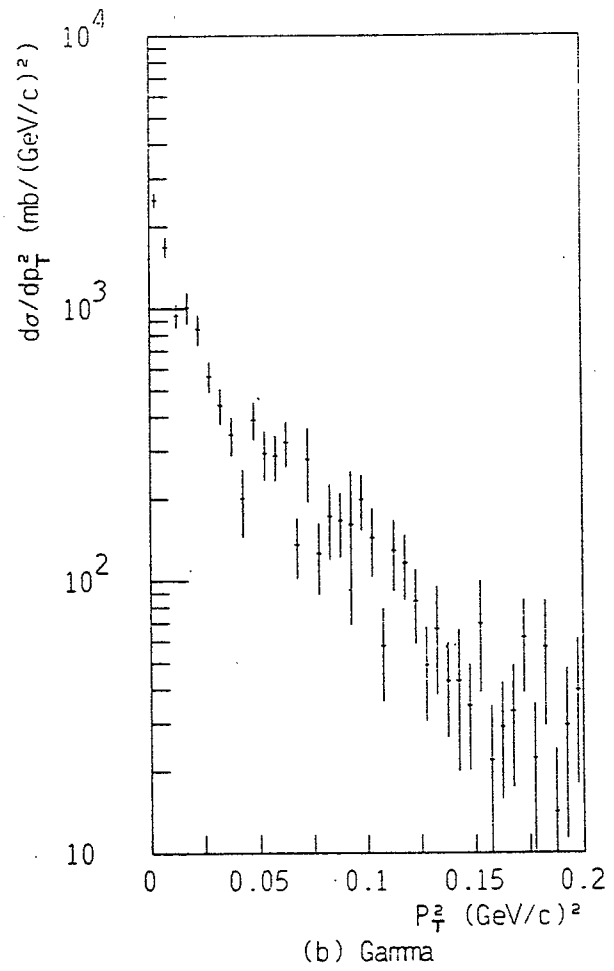
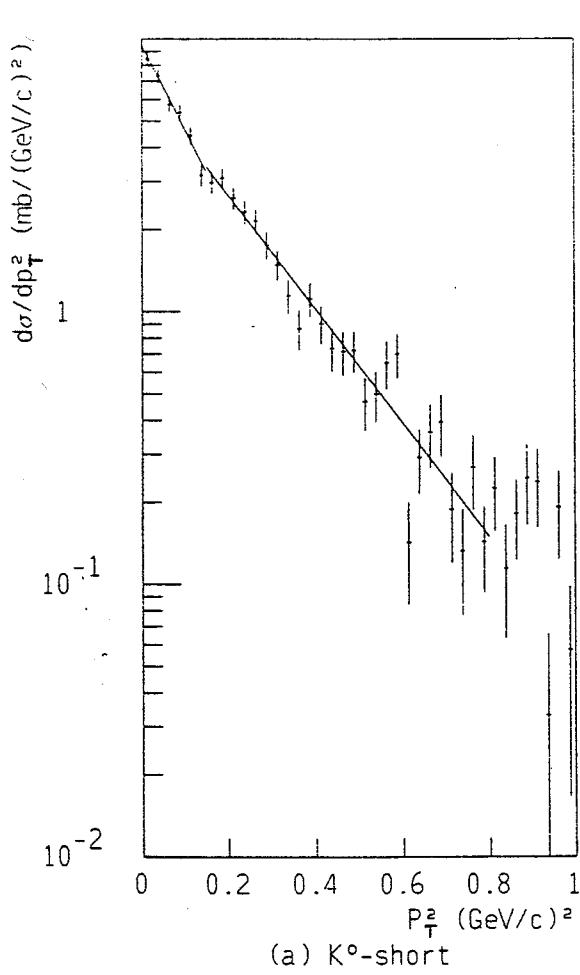


Figure 5.14 Non-Annihilation $d\sigma/dp_T^2$ and $F(x)$

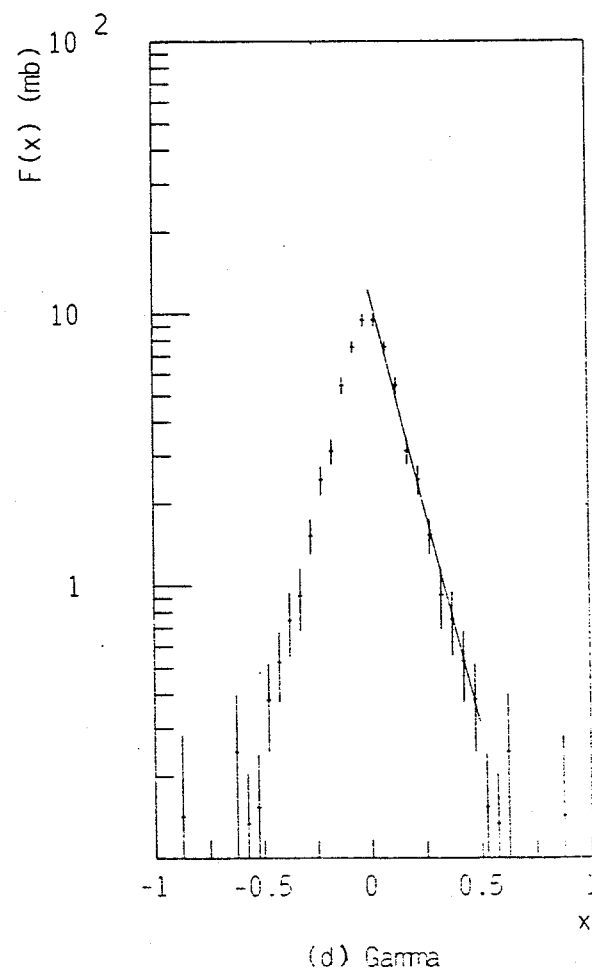
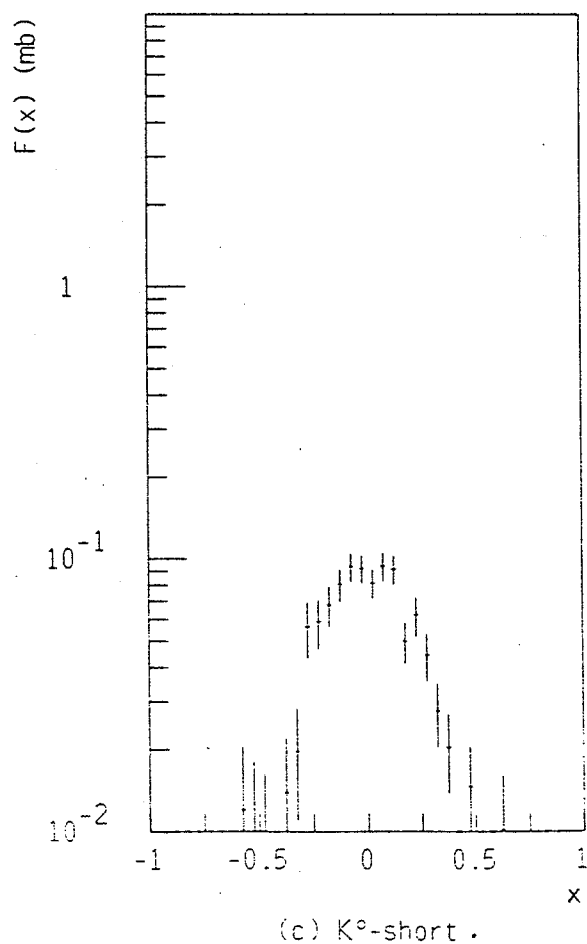
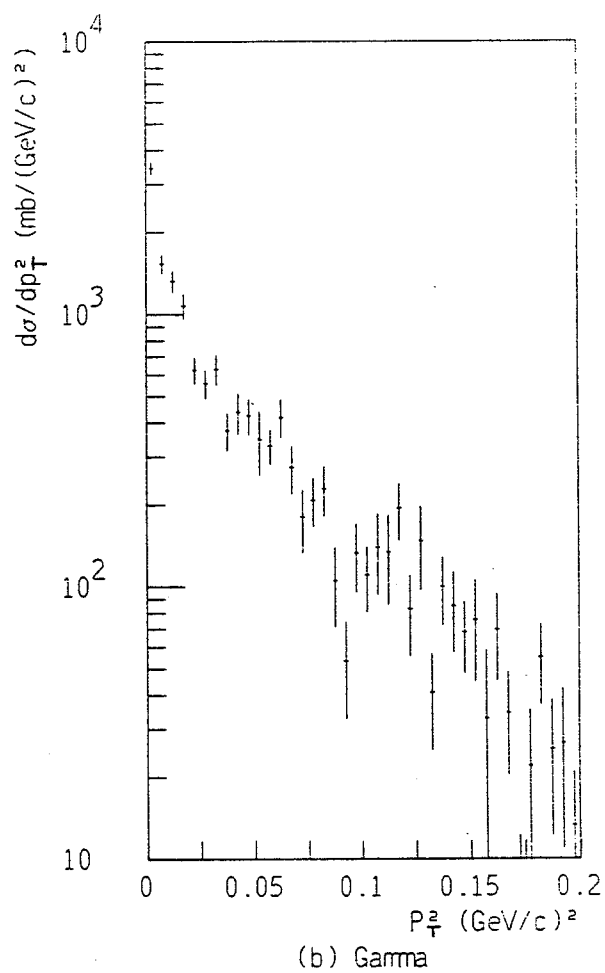
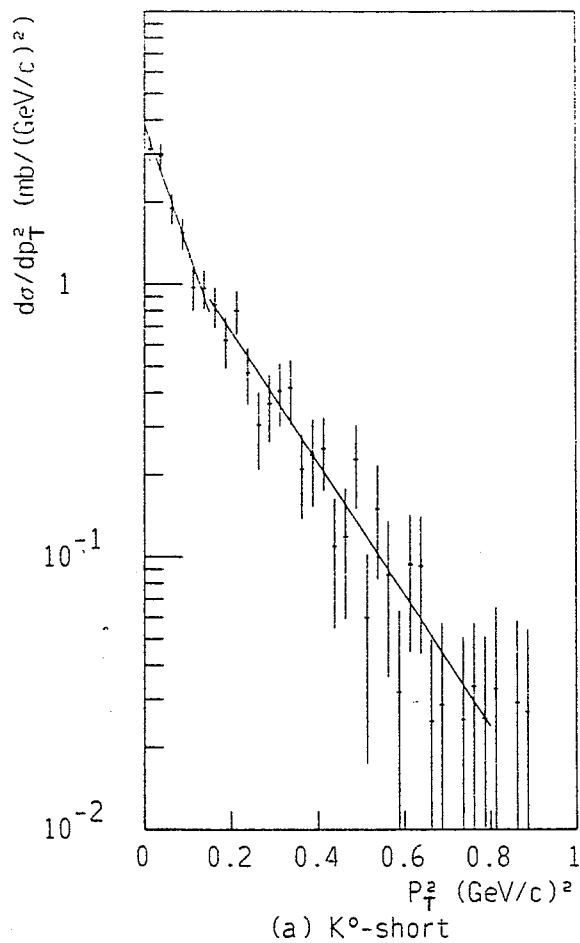
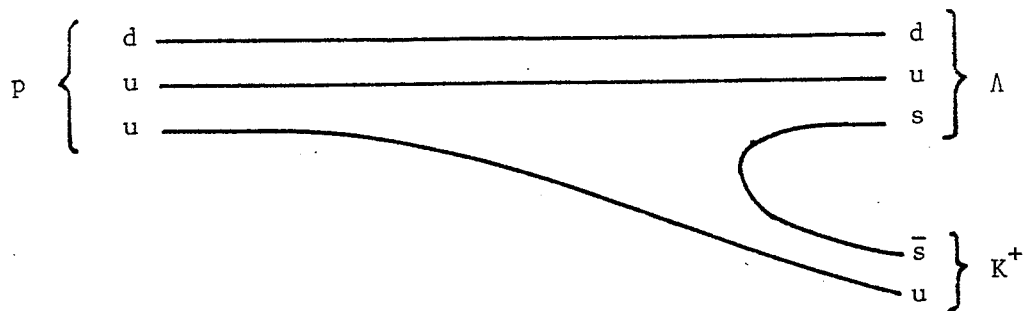
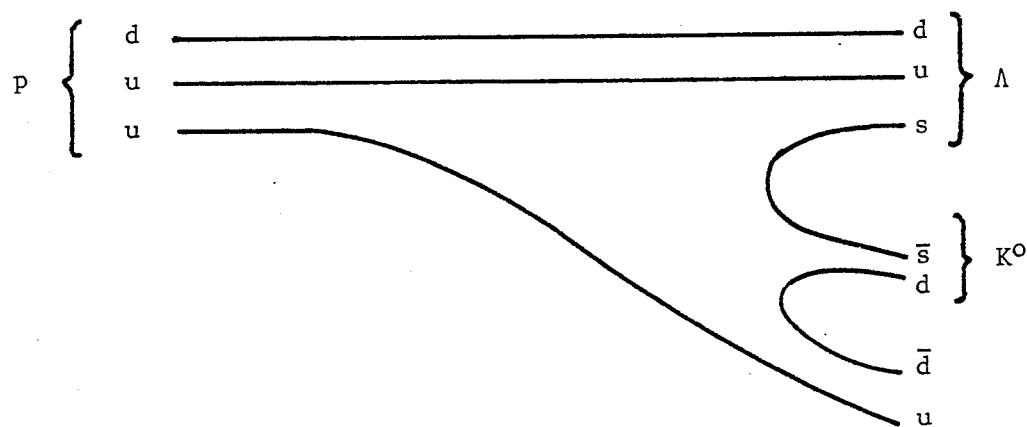


Figure 5.15 Proton Fragmentation to ΛK

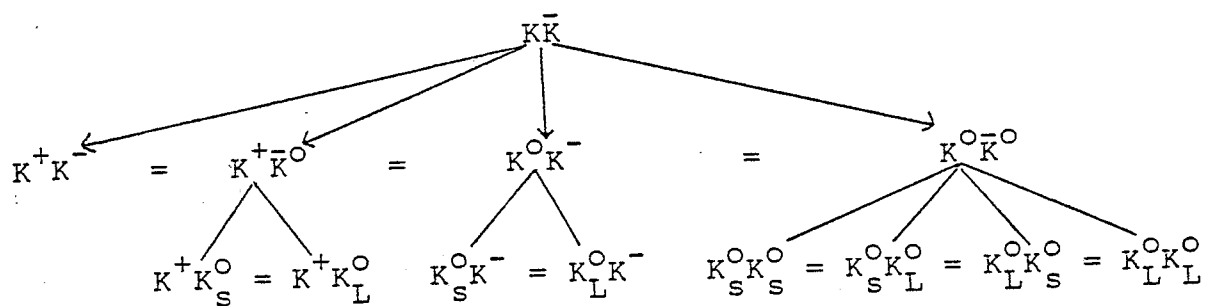


a) $p \rightarrow \Lambda K^+$



b) $p \rightarrow \Lambda K^0$

Figure 5.16 Schematic of $K\bar{K}$ Production in $\bar{p}p$ Annihilations



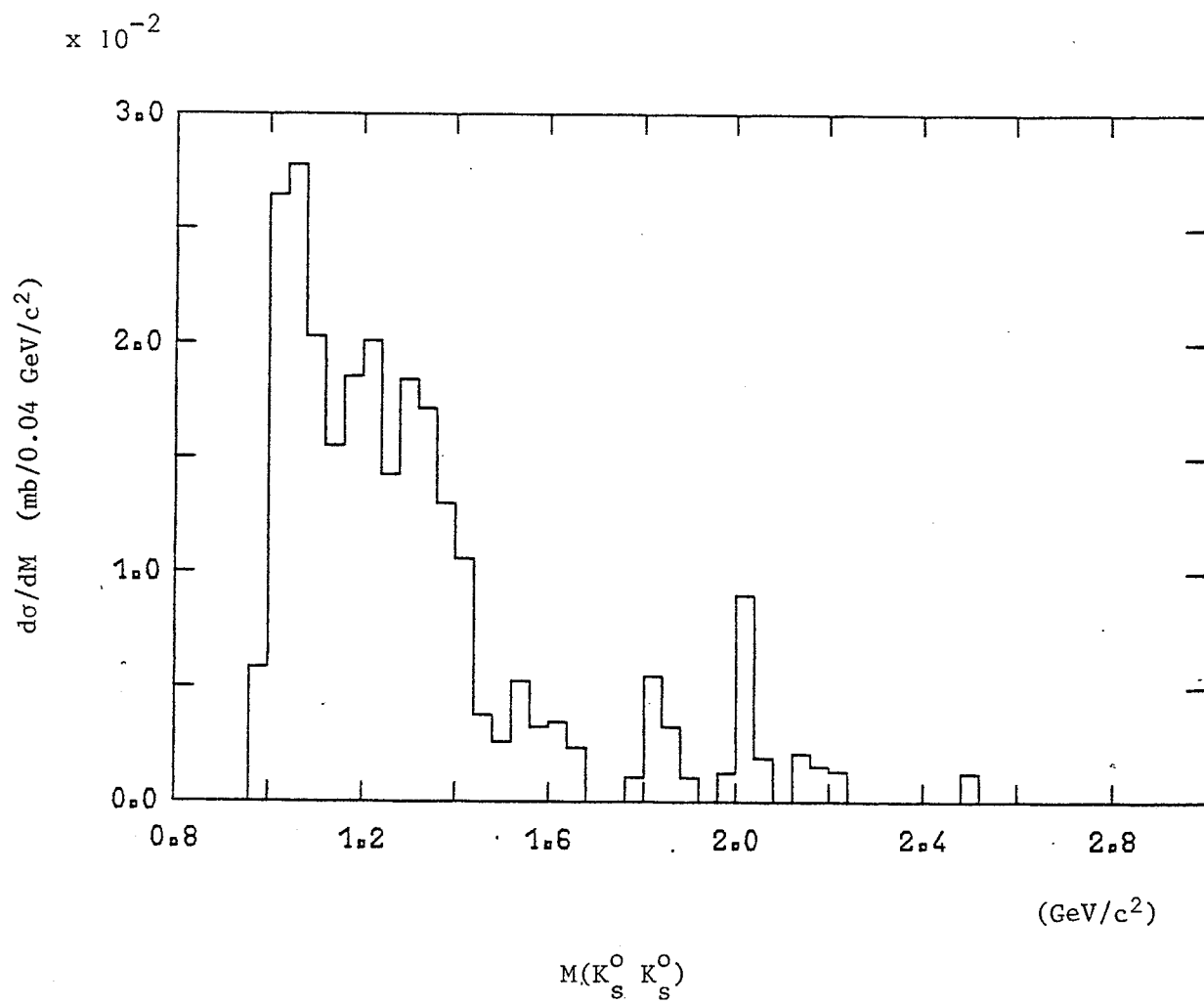


Figure 5.17 $K_S^0 K_S^0$ Effective Mass Distribution

Chapter VI

INCLUSIVE PROTON AND PION PRODUCTION

6.1 INTRODUCTION

The method used to resolve charged particle ambiguities (Gregory/Warren) was described in Chapter 4. There exists, however, an iterative technique for two-particle separation, referred to as the 'Boost' method, and this is described below in some detail. Inclusive charged particle ($p, \bar{p}, \pi^+, \pi^-$) cross sections and distributions have been calculated from the resolved data of Chapter 4 and are compared with the results of the 'Boost' separation.

The two sets of results are found to be in good agreement and so the separation of an annihilation sample in Chapter 4 may be considered as reliable.

Inclusive π^+/π^- production in annihilation and non-annihilation processes is studied using the separated data.

Finally the possibility of obtaining inclusive charged kaon cross sections in annihilations is discussed.

6.2 P/ π SEPARATION BY THE BOOST METHOD

This technique was originally used in pp reactions [6.1,6.2], and allows inclusive charged particle distributions to be determined making use only of the

momentum and charge measurements and neglecting any information on particle identification. For pp reactions the method relied on the forward-backward symmetry of charged particle spectra in the CMS and assumed that the final state contained only two types of charged particle (p/π to first approximation). The method has been modified for $\bar{p}p$ interactions [6.3] using charge conjugation symmetry in place of the forward-backward symmetry of pp interactions.

6.2.1 Details of the Method

Let the longitudinal and transverse momentum components of a particle in the laboratory frame be q and r . The following operators are defined to act on the longitudinal momentum q

R_p This operator is a Lorentz boost from the target (laboratory) frame to the beam (anti-laboratory) frame, assuming the particle has the proton mass, followed by a reflection along the longitudinal momentum axis.

R_{pi} This is an identical Lorentz boost and reflection, but assuming the pion mass for the particle.

Thus

$$R_p q = -\gamma q + \eta(q^2 + r^2 + m_p^2)$$

$$R_{pi} q = -\gamma q + \eta(q^2 + r^2 + m_{pi}^2)$$

where $\gamma = E_{beam}/m_p$ and $\eta = P_{beam}/m_p$ are Lorentz transformation factors. These operators are subdivided into two parts, one acting only on positive tracks and the other only on negative ones, which are denoted

$$R_p(+), R_p(-), R_{pi}(+), R_{pi}(-)$$

From the above definitions and the CP invariance of $\bar{p}p$ interactions it follows that

$$R_p(+)\mathrm{d}\sigma(-) = R_p(-)\mathrm{d}\sigma(+) = R_{pi}(+)\mathrm{d}\sigma(-) = R_{pi}(-)\mathrm{d}\sigma(+) \equiv 0$$

$$R_p(+)\mathrm{d}\sigma(p) = \mathrm{d}\sigma(\bar{p}) \quad \text{and} \quad R_p(-)\mathrm{d}\sigma(\bar{p}) = \mathrm{d}\sigma(p)$$

$$R_{pi}(+)\mathrm{d}\sigma(\pi^+) = \mathrm{d}\sigma(\pi^-) \quad \text{and} \quad R_{pi}(-)\mathrm{d}\sigma(\pi^-) = \mathrm{d}\sigma(\pi^+)$$

where the $\mathrm{d}\sigma$'s represent the inclusive single particle spectrum of the particle in question. The identity operators are defined as

$$I(+)\mathrm{d}\sigma(+) = \mathrm{d}\sigma(+), \quad I(-)\mathrm{d}\sigma(-) = \mathrm{d}\sigma(-)$$

$$\text{and} \quad I(-)\mathrm{d}\sigma(+) = I(+)\mathrm{d}\sigma(-) \equiv 0$$

Using these operators it is then possible to extract the individual single particle spectra $\mathrm{d}\sigma(p)$, $\mathrm{d}\sigma(\bar{p})$, $\mathrm{d}\sigma(\pi^+)$ and $\mathrm{d}\sigma(\pi^-)$ from the observed total spectrum $\mathrm{d}\sigma$, where

$$\mathrm{d}\sigma = \mathrm{d}\sigma(p + \bar{p} + \pi^+ + \pi^-) = \mathrm{d}\sigma(p) + \mathrm{d}\sigma(\bar{p}) + \mathrm{d}\sigma(\pi^+) + \mathrm{d}\sigma(\pi^-)$$

by the application of the following operator series

$$P_p(+) = I(+) - R_{pi}(-) + R_{pi}(-)R_p(+) - R_{pi}(-)R_p(+)R_{pi}(-) \dots$$

$$P_p(-) = I(-) - R_{pi}(+) + R_{pi}(+)R_p(-) - R_{pi}(+)R_p(-)R_{pi}(+) \dots$$

$$P_{pi}(+) = I(+) - R_p(-) + R_p(-)R_{pi}(+) - R_p(-)R_{pi}(+)R_p(-) \dots$$

$$P_{pi}(-) = I(-) - R_p(+) + R_p(+)R_{pi}(-) - R_p(+)R_{pi}(-)R_p(+) \dots$$

Application of these operator series to the total observed charged particle spectrum yields -

$$P_p(+)\mathrm{d}\sigma = \mathrm{d}\sigma(p)$$

$$P_p(-)\mathrm{d}\sigma = \mathrm{d}\sigma(\bar{p})$$

$$P_{pi}(+)\mathrm{d}\sigma = \mathrm{d}\sigma(\pi^+)$$

$$P_{pi}(-)\mathrm{d}\sigma = \mathrm{d}\sigma(\pi^-)$$

For example consider the operator series $P_p(+)$ operating on $\mathrm{d}\sigma$

$$P_p(+)\mathrm{d}\sigma = P_p(+)\mathrm{d}\sigma(p + \bar{p} + \pi^+ + \pi^-)$$

$$= P_p(+)\mathrm{d}\sigma(p+\bar{p}) + P_p(+)\mathrm{d}\sigma(\pi^+\pi^-)$$

The first term gives the required proton spectrum, $\mathrm{d}\sigma(p)$, since in the series expansion the 2nd/3rd, 4th/5th and all subsequent pairs cancel. The second term contributes zero since in the expansion all the terms cancel in pairs, 1st/2nd, 3rd/4th etc. Thus $P_p(+)$ does indeed generate $\mathrm{d}\sigma(p)$ and similarly the other operators are generators of $\mathrm{d}\sigma(\bar{p})$, $\mathrm{d}\sigma(\pi^+)$ and $\mathrm{d}\sigma(\pi^-)$.

The operator series $P_p(+)$, $P_p(-)$, $P_{pi}(+)$, $P_{pi}(-)$ do not represent unique solutions, since the alternative set

$$P_p^1(+)=R_p(-)P_p(-)$$

$$P_p^1(-)=R_p(+)P_p(+)$$

$$P_{pi}^1(+)=R_{pi}(-)P_{pi}(-)$$

$$P_{pi}^1(-)=R_{pi}(+)P_{pi}(+)$$

will also generate the same single particle spectra. A weighted combination of these two solutions was used as this gives a statistically more accurate result.

6.2.2 Practical Implementation of the Method

Given a 'complete' sample of data (i.e. satisfying CP invariance), it is necessary to calculate for each measured track with momentum components (q,r) the results of operating on q with the operators

$$A_n = R_{pi}, R_p R_{pi}, R_{pi} R_p R_{pi} \dots$$

$$\text{and } B_n = R_p, R_{pi} R_p, R_p R_{pi} R_p \dots \quad n = 1, 2, 3 \dots$$

Each of these terms must then be added to the appropriate distributions with the appropriate sign from the series. For example, a positive track would contribute to $\sigma(p)$

through the terms $I(+)$, B_2 , B_4, to $\sigma(\bar{p})$ through $-A_1$, $-A_3$, $-A_5$, to $\sigma(\pi^+)$ through $I(+)$, $-B_1$, $-B_3$, and to $\sigma(\pi^-)$ through A_2 , A_4 , A_6

For each of the series A_n , B_n it is found in practice that all terms, for n larger than some cutoff value, lie outside the kinematically allowed region. It is therefore only necessary to calculate the first few terms in each series for each track. For p/π separation about 5 terms in each series had to be computed on average. Using the transformed q values, $q_n = A_n q$, further quantities, Feynman x , y^* etc., can be calculated and fully inclusive distributions of all these variables may be derived as well as the total integrated cross sections.

6.2.3 Monte Carlo Tests

The method (and the program to implement it) was tested for p/π separation using a sample of 4C $\bar{p}p\pi^+\pi^-$ events generated with the GO package [6.4]. The cross sections and inclusive distributions obtained for the generated sample were in good agreement with the actual 'raw' input data. The statistical errors on the cross sections were low, being only about twice those which would be expected if all particles were uniquely identified. (As they are for the generated test events.)

6.3 INCLUSIVE CHARGED PARTICLE CROSS SECTIONS

Fully inclusive and semi-inclusive p , $\bar{p}$, π^+ and π^- cross sections were calculated using the resolved data sample of Chapter 4. Identified kaons were excluded in this analysis. For the Boost separation, however, the full data sample (including kaons and any other strange charged particles) was used and treated as consisting of entirely $(p/\bar{p})$ and (π^+/π^-) . The identified kaons were not removed since the full sample is already contaminated by unidentified kaons taken as pions in OC events and CP symmetry is better maintained by retaining all the tracks. It is however necessary to bear in mind that this kaon contamination will tend to increase the overall cross sections from the Boost method.

The results for the inclusive charged particle cross sections by the two independent procedures are compared for protons and pions in Table 6.1 (a,b). Only the statistical errors are given. For the separated data $\sigma(p) = \sigma(\bar{p})$ and $\sigma(\pi^+) = \sigma(\pi^-)$ for each topology and so also for the total, within these statistical errors. The systematic errors are rather more difficult to estimate. There is good general agreement with the results of the Boost separation, though the proton cross sections obtained by the Boost method are systematically higher. To some degree this is to be expected because of the known kaon contamination, which must appear somewhere.

Overall, considering the radically different approaches by which these results have been derived, the agreement can be said to be good. (The mean inclusive charged pion cross section of 64mb may be compared with the value of 67 ± 3 mb derived for the total inclusive π^0 cross section in Chapter 5. These are expected to be of the same order).

In addition to the inclusive and semi-inclusive cross sections, various distributions were also derived by the two methods. The following distributions, $d\sigma/dp_t$, $d\sigma/dp_t^2$, $F(x)$, y^* and $\cos\theta^*$ for p , $\bar{p}$, π^+ and π^- from the separated sample are shown in Figures 6.1 to 6.5. Superimposed on these as solid curves are the results of the Boost method. The statistical errors in the Boost method are of the same order as those on the actual data points, so that these curves are not theoretical predictions but have errors at least as large as those shown for the data points. These figures show that there is substantial agreement in the distributions as well as in the overall integrated cross sections.

The mean values $\langle p_t \rangle$ and $\langle p_t^2 \rangle$ for protons and pions are compared in Table 6.2. The agreement for pions is very good, for protons the Boost method values are slightly higher.

Semi-inclusive $F(x)$ distributions for p , $\bar{p}$, π^+ and π^- in 2, 4, 6 and ≥ 8 prongs from the separated sample are shown in Figures 6.6 and 6.7. The 2 prong π^- is seen to be contaminated in the forward hemisphere. This is due to fast

$\bar{p}$'s ambiguous with π^- which have not been removed completely by the resolution procedure used. Subsequent analysis shows that the separation technique used in Chapter 4 is fairly reliable for obtaining overall cross sections. The limitations of the procedure, however, are seen when more detailed examination of the data, such as inclusive $\pi^- F(x)$ distributions, is made. It may be noted that the $F(x)$ distributions become narrower and more limited in x for pions as the topology increases. This is to be expected as more particles share the same amount of energy with increasing topology. The $p/\bar{p}$ $F(x)$ distributions are observed to become less peripheral in the higher topologies.

6.4 π^+/π^- IN ANNIHILATION, NON-ANNIHILATION PROCESSES

The inclusive and semi-inclusive π^+ , π^- cross sections in annihilations and non-annihilations calculated from the separated data are given in Table 6.3. The overall inclusive cross sections $[\sigma(\pi^+) + \sigma(\pi^-)]$ are 80.2 ± 0.3 and 48.3 ± 0.3 in annihilations and non-annihilations respectively. Only the statistical errors are given, the systematic errors due to the separation technique are estimated to be about 5% and are significantly more than the errors given.

The means, $\langle p_t \rangle$ and $\langle p_t^2 \rangle$, for π^+ , π^- in the separated data are given Table 6.4. The annihilation $\langle p_t \rangle$'s are seen to be higher by about 60 MeV/c. A similar difference is seen in the separated K_s $\langle p_t \rangle$'s given in Table 5.15, though the K_s $\langle p_t \rangle$ is significantly higher than the pions in both cases.

6.4.1 $(1-x)^n$ Dependence of the Invariant Cross Section

Having separated the total data sample it is of interest to compare inclusive features in the two distinct processes taking place in $\bar{p}p$ interactions. The invariant cross section $F(x)$ has already been given for π^+ , π^- in the total sample (Figure 6.3), the distributions in the separated data samples are given in Figure 6.8.

There has been much interest in recent years in hadronic fragmentation as a means of studying the underlying quark dynamics. In particular the $(1-x)^n$ dependence of inclusive single particle distributions, $F(x)$, in the fragmentation region have been considered.

Brodsky and Gunion give a simple quark counting prescription for computing the power law exponent [6.5], namely $n = 2n_s - 1$ where n_s is the number of spectator quarks in the fragmentation process $a \rightarrow b$. (Strictly speaking, their prediction gives lower limits for n .) In particular there are different predictions depending upon the underlying mechanism involved in the fragmentation process. There are two different mechanisms which could characterize proton fragmentation to π^+ and these are (a) gluon exchange and (b) quark annihilation/exchange as illustrated in Figure 6.11. The number of spectator quarks in these two processes are 3 and 2 leading to power law exponents of 5 and 3 for processes (a) and (b) respectively. Naively it could be said the quark annihilation/exchange mechanism may play a major role in $\bar{p}p$ annihilations, it

should however be remembered that process (b) is not restricted to annihilation final states but also applies in non-annihilation processes.

Using the results shown in Figure 6.3 and 6.8, the pion $F(x)$ distributions were fitted to the parametrisation $A(1-x)^n$ for $|x| > 0.3$, in the forward and backward hemispheres separately. The results for the exponent n obtained in these fits are summarised in Table 6.5 and the distributions with the fits superimposed are given in Figure 6.9. It was not possible to fit the π^- in the forward hemisphere with this parametrisation, the fits giving unacceptable χ^2/ND . Examination of the π^- $F(x)$ distributions shows the forward hemisphere to be distorted and this is due to $\bar{p}$ contamination remaining in spite of the 'successful' separation. The backward hemisphere π^+ however provides a measure of the same quantity, and the forward π^+ /backward π^- are not incompatible.

The results for the total sample appear to favour a value of n near 3 rather than 5. The separated samples, however, have significantly different dependences. $F(x)$ for π^+ , π^- in $\bar{p}p$ annihilations are characterised by $(1-x)^n$ distributions with n lower than in non-annihilations. This difference in annihilation, non-annihilation results has previously been reported in 12 GeV/c $\bar{p}p$ [6.6] where $n = 4.5 \pm .5$ for $\bar{p}p \rightarrow \pi^+$ in non-annihilations and $2.1 \pm .4$ for $\bar{p}p \rightarrow \pi^+$ averaged with π^- in annihilations. These are compatible with the results given in Table 6.5. Comparing

the results for the separated sample with the quark counting expectations it is seen that the non-annihilation results favour $n = 5$, whilst the annihilation favour $n = 3$. The separated K_s data of Chapter 5 was folded about $x = 0$ and fitted with the same parametrisation giving $n = 2.46 \pm 0.18$ and $n = 3.55 \pm 0.82$ for the annihilation and non-annihilation data respectively. The folded data and fits are shown in Figure 6.10. These values again show a difference of about 1 unit and are comparable with the results for the pion fits. However it is not clear how much significance, if any, can be given to this apparent favouring of the two different mechanisms (a) and (b) in the non-annihilation and annihilation processes respectively.

One reason for this is that the quark counting rule should really only be applied to directly produced mesons. The pion samples used here include indirect production through resonances, and this is especially true for the annihilation sample. In addition, $\bar{p}p$ results at higher energies, 100 and 175 GeV/c [6.7], where non-annihilation processes will dominate, have shown that the quark annihilation/exchange processes is the dominant mechanism.

6.4.2 Particle Ratios

In addition to the $(1-x)^n$ dependence there has been interest in particle ratios in single particle inclusive production. Most of this work has not been in $\bar{p}p$ and much of it has been at high energies [6.8]. The ratios of the invariant cross sections for π^+/π^- , π^+/K_s and π^-/K_s in the backward

hemisphere for the total and separated data samples are presented in Figure 6.12 (a-c). It is clear that the large x region $|x| > 0.6$ is almost totally dominated by the annihilation process at this level of statistics.

The π^+/π^- ratio rises and is ≈ 2 for $x < -0.5$ in the total sample. This is also the case for the annihilation which dominates in the large x region. A ratio of 2 is what might be expected from simple valence quark counting. A proton consists of (uud) , π^+ is $(u\bar{d})$ and π^- $(\bar{u}d)$. Thus in terms of recombination model ideas, where the π^+ , π^- would be expected to contain one valence quark from the proton, the ratios for large x will tend to 2. Reflecting the fact that the proton contains 2 u quarks and only one d quark.

The non-annihilation has a rather different behaviour, rising to about 2 but rather more quickly. It subsequently appears to drop, though this could be due to systematic errors in the separation technique. The limited statistics available for $x < -0.6$ shows a subsequent rise. However both the annihilation and non-annihilation results are in good agreement with those reported by Ward [6.10] at 8.9 GeV/c. The non-annihilation results of [6.10] shows the π^+/π^- ratio rising again for $x < -0.6$, though a similar drop is seen between $-0.6 < x < -0.3$.

The π^+/K_s and π^-/K_s ratios start around 20-25 at $x = 0$. The former is not very strongly dependent on x within the rather large errors for $x < -0.4$. The π^-/K_s , however, falls steadily from about 20 at $x = 0$ to 3.05 ± 1.70 at $x = -0.85$ in

both the total and annihilation samples. The ratios are significantly higher, about twice, in the non-annihilation sample, though the trends are similar.

Duke and Taylor [6.11] have used the recombination model of Das and Hwa [6.12] to calculate sea-quark x distributions in the proton and predict π^+/π^- , π^+/K_s for pp interactions. The model of [6.12] explains meson production at low transverse momentum in the fragmentation region in terms of the recombination of a valence quark with an antiquark from the sea of the same particle. [6.11] finds that π^+/K_s starts at about 10 and rises to almost 30 by $x = -0.8$. In terms of quark constituents π^+/K_s is like $[u\bar{d}]/[d\bar{s}+\bar{d}s]$, which should reduce to $[u\bar{d}]/[d\bar{s}]$ in the proton fragmentation region. Considering only the valence quarks, (u/d) , this is the same as expected for π^+/π^- and is predicted to rise. The difference in magnitude arises from the sea quark content, the strange quark being suppressed.

The π^-/K_s ratio also starts around 10 but then falls slowly as $x \rightarrow -1$. The ratio would be expected to behave as $[d\bar{u}]/[d\bar{s}+\bar{d}s]$ or $[d\bar{u}]/[d\bar{s}]$ in the proton fragmentation region. Consequently for large x the behaviour is governed by the sea quarks, $(\bar{u}/\bar{s})$. The sea quark distribution functions of [6.11] show a relative increase in strange over non-strange sea quarks as x increases, hence this ratio is predicted to fall with K_s production becoming relatively easier compared to the production of π^- .

Although the calculations of [6.11] were for pp , the model does not in fact differentiate between pp and $\bar{p}p$ in the proton fragmentation region. The predictions however do not really agree with the $\bar{p}p$ data presented here. The π^+/K_s is observed to be fairly constant and certainly does not rise by a factor of 3 as predicted. The π^-/K_s falls, but more rapidly than predicted by [6.11], approaching 1 for $x = -1$ and implying comparable K, π production at large x . Indeed Muirhead has speculated that at higher energies K, π production in exclusive channels (e.g. $2K2\pi/4\pi$) becomes comparable and that kaon suppression at lower energies may only be due to lack of phase space. The disagreement is not too surprising since annihilations are known to be important in K_s production and as the recombination model does not differentiate between pp and $\bar{p}p$, no real account of annihilation mechanisms has been taken.

No really satisfactory models for $\bar{p}p$ annihilations are presently available. A variation on quark recombination is the quark fusion model in which a quark from one particle combines with an antiquark from the other particle. This model does predict some differences between pp and $\bar{p}p$. It has been applied with some success to ρ^0 production in 12 GeV/c $\bar{p}p$ [6.9], but has limitations as it fails completely for $K^*(890)$ in $\bar{p}p$ [5.9].

One final ratio is presented in Figure 6.13, this is $p/\bar{p}$ in the backward hemisphere. This shows an almost exponential rise, certainly for $-0.5 < x < 0.0$.

Unfortunately the exponential behaviour is not presently understood though p would be expected to dominate over $\bar{p}$ for $x \rightarrow -1$. In terms of recombination, the production of a $\bar{p}$ in the proton fragmentation region requires three sea antiquarks ($\bar{u}\bar{u}\bar{d}$), since no valence antiquarks exist in the proton, and such a process is strongly suppressed.

6.5 THE BOOST METHOD APPLIED TO ANNIHILATIONS

Theoretically the Boost method is sound, given its basic assumptions. It was applied to the total data sample assuming only protons and pions were present. If one can successfully extract an annihilation sample, by the method described in Chapter 4 for example, then it is reasonable to assume that only pions and kaons are present in the sample. The boost method will work just as well in separating K/π as in separating p/π . All that is required is a replacement of the operator R_p by R_k (ie acting with the kaon mass) and substitution throughout.

One consequence of trying K/π separation is a substantial increase in the average number of terms required for each track to about 10, because of the smaller mass difference between the particle types. Monte-Carlo tests with a mixture of 4π and $2\pi 2K$ events shows the method can successfully extract the kaon cross section even when less than 10% of the total. However the greatest difficulty is in the $p/\bar{p}$ contamination of the annihilation sample.

Tests in which $p/\bar{p}$ contamination was introduced are very discouraging since the effect on the derived kaon cross

sections was to increase them by an amount greater than the $p/\bar{p}$ present i.e the pion cross section is also affected and lowered below its true value. Since $\sigma(K^+) = \sigma(K^-)$ in annihilations is only expected to be about 2mb at 7.3 GeV/c, compared with $\sigma(\pi^+) = \sigma(\pi^-) \approx 40\text{mb}$, it is clear that only a small proportion of $p/\bar{p}$ events contaminating the annihilation sample will make it impossible to derive reliable charged kaon results.

Although the separation of Chapter 4 appears to be sound, reasonable CP symmetry of distributions and equality of charge-conjugate channels having been achieved, the contamination is still present. This is clearly indicated in the results of the previous section where it proved impossible to fit the $\pi^- F(x)$ in the forward hemisphere due to $\bar{p}$ contamination. Consequently the derivation of inclusive charged kaon cross sections in $\bar{p}p$ annihilations, although it appears possible in principle, requires a purer sample than is presently available.

An interesting possibility is the application of K/π separation by the Boost method to low energy $\bar{p}p$ data. For example 0.76 GeV/c is a possibility [6.14]. The annihilation cross section at this energy is large and furthermore, non-annihilation events are fairly easily identified, a large proportion being elastics. Reliable inclusive charged kaon data in annihilations would be of great interest for comparison with neutral kaon production in annihilations discussed in section 5.9.

6.6 REFERENCES

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6.7 TABLES

- 6.1 Inclusive and semi-inclusive p , $\bar{p}$, π^+ and π^- cross sections compared with p/π results from the Boost method.
- 6.2 Mean values, $\langle p_t \rangle$ and $\langle p_t^2 \rangle$ for $p, \bar{p}, \pi^+$ and π^- compared with results from the Boost method. Errors are typically 1-4 MeV/c.
- 6.3 Inclusive and semi-inclusive π^+ , π^- cross sections in annihilations and non-annihilations from the separated data.
- 6.4 Mean values, $\langle p_t \rangle$ and $\langle p_t^2 \rangle$, for π^+ , π^- in annihilations and non-annihilations. Errors are typically 1-4 MeV/c.
- 6.5 Fitted values of n in the parametrisation $(1-x)^n$ for π^+ , π^- , K , $F(x)$ distributions in backward and forward hemispheres.

TABLE 6.1 Inclusive p/π Cross Sections(a) $p/\bar{p}$ Results.

Topology	Separated Data		Boost $\sigma(p/\bar{p})$ mb
	$\sigma(p)$ mb	$\sigma(\bar{p})$ mb	
2	6.52 $\pm$ 0.13	6.37 $\pm$ 0.12	6.87 $\pm$ 0.18
4	7.61 $\pm$ 0.08	7.62 $\pm$ 0.08	7.91 $\pm$ 0.12
6	0.83 $\pm$ 0.03	0.86 $\pm$ 0.03	0.94 $\pm$ 0.07
8	0.013 $\pm$ 0.003	0.016 $\pm$ 0.003	0.03 $\pm$ 0.03
Total	14.97 $\pm$ 0.15	14.87 $\pm$ 0.15	15.75 $\pm$ 0.23

(b) π^+/π^- Results.

Topology	Separated Data		Boost $\sigma(\pi^+/\pi^-)$ mb
	$\sigma(\pi^+)$ mb	$\sigma(\pi^-)$ mb	
2	9.20 $\pm$ 0.15	9.37 $\pm$ 0.15	9.78 $\pm$ 0.19
4	26.31 $\pm$ 0.13	26.35 $\pm$ 0.13	26.51 $\pm$ 0.13
6	21.17 $\pm$ 0.12	21.12 $\pm$ 0.12	21.36 $\pm$ 0.10
8	6.44 $\pm$ 0.07	6.43 $\pm$ 0.07	6.44 $\pm$ 0.06
10	0.78 $\pm$ 0.03	0.78 $\pm$ 0.03	0.78 $\pm$ 0.02
12	0.042 $\pm$ 0.009	0.042 $\pm$ 0.009	0.042 $\pm$ 0.006
Total	63.94 $\pm$ 0.25	64.09 $\pm$ 0.24	63.92 $\pm$ 0.26

TABLE 6.2 Mean Values $\langle p_t \rangle$ and $\langle p_t^2 \rangle$ GeV/c

Prong	p		$\bar{p}$		π^+		π^-	
	$\langle p_t \rangle$	$\langle p_t^2 \rangle$	$\langle p_t \rangle$	$\langle p_t^2 \rangle$	$\langle p_t \rangle$	$\langle p_t^2 \rangle$	$\langle p_t \rangle$	$\langle p_t^2 \rangle$
2	0.389	0.205	0.388	0.210	0.344	0.167	0.350	0.174
4	0.389	0.203	0.388	0.203	0.325	0.151	0.322	0.148
6	0.387	0.193	0.364	0.178	0.310	0.134	0.312	0.137
≥ 8	0.299	0.105	0.276	0.102	0.269	0.101	0.271	0.103
Total	0.389	0.203	0.387	0.204	0.316	0.142	0.317	0.143
Boost	0.392	0.218	0.394	0.218	0.315	0.141	0.315	0.141

TABLE 6.3 Inclusive π^+, π^- Cross Sections(a) Annihilation π^+/π^- Results.

Topology	Separated Data	
	$\sigma(\pi^+) \text{ mb}$	$\sigma(\pi^-) \text{ mb}$
2	1.46 ± 0.06	1.49 ± 0.06
4	12.55 ± 0.09	12.56 ± 0.09
6	18.89 ± 0.12	18.87 ± 0.12
8	6.38 ± 0.07	6.37 ± 0.07
10	0.78 ± 0.03	0.78 ± 0.03
12	0.042 ± 0.009	0.042 ± 0.009
Total	40.10 ± 0.18	40.11 ± 0.18

(a) Non-Annihilation π^+/π^- Results.

Topology	Separated Data	
	$\sigma(\pi^+) \text{ mb}$	$\sigma(\pi^-) \text{ mb}$
2	7.74 ± 0.14	7.74 ± 0.14
4	13.94 ± 0.10	13.95 ± 0.10
6	2.34 ± 0.04	2.31 ± 0.04
8	0.062 ± 0.007	0.059 ± 0.007
Total	24.08 ± 0.17	24.20 ± 0.17

TABLE 6.4 Mean Values $\langle p_t \rangle$ and $\langle p_t^2 \rangle$ GeV/c

Prong	Annihilation				Non-annihilation			
	π^+ $\langle p_t \rangle$	π^+ $\langle p_t^2 \rangle$	π^- $\langle p_t \rangle$	π^- $\langle p_t^2 \rangle$	π^+ $\langle p_t \rangle$	π^+ $\langle p_t^2 \rangle$	π^- $\langle p_t \rangle$	π^- $\langle p_t^2 \rangle$
2	0.501	0.328	0.505	0.336	0.314	0.136	0.320	0.143
4	0.388	0.206	0.385	0.203	0.268	0.101	0.266	0.099
6	0.319	0.141	0.322	0.144	0.234	0.076	0.230	0.074
≥ 8	0.270	0.102	0.272	0.104	0.172	0.045	0.185	0.056
Total	0.339	0.161	0.340	0.162	0.279	0.110	0.280	0.111

TABLE 6.5 Results of n in $(1-x)^n$ Fits

		Forward Hemisphere	Backward Hemisphere
Total	π^+	3.37 ± 0.11	2.83 ± 0.07
	π^-		3.13 ± 0.09
Annihilation	π^+	3.12 ± 0.10	2.34 ± 0.07
	π^-		2.78 ± 0.09
Non-annihilation	π^+	4.28 ± 0.37	4.68 ± 0.25
	π^-		4.35 ± 0.40
Annihilation	K_s	2.46 ± 0.18	
Non-annihilation	K_s	3.55 ± 0.82	

6.8 FIGURES

6.1 $d\sigma/dp_t$

6.2 $d\sigma/dp_t^2$

6.3 $F(x)$

6.4 y^*

6.5 $\cos\vartheta^*$

The above distributions are shown for p , $\bar{p}$, π^+ and π^- from the separated data, with results from the Boost method superimposed as solid curves.

6.6 Semi-inclusive $F(x)$ distributions for p and $\bar{p}$.

6.7 Semi-inclusive $F(x)$ distributions for π^+ and π^- .

6.8 $F(x)$ distributions for π^+ , π^- in annihilations and non-annihilations.

6.9 π^+ , π^- $F(x)$ distributions in total, annihilation and non-annihilation samples with fits of $A(1-x)^n$ superimposed.

6.10 K_s $F(x)$ distributions in annihilations and non-annihilations, with fits to $A(1-x)^n$ superimposed.

6.11 Quark diagrams for proton fragmentation to π^+ via

(a) Gluon Exchange.

(b) Quark Annihilation/Exchange.

6.12 Particle ratios, π^+/π^- , π^+/K_s and π^-/K_s for total, annihilation and non-annihilation samples in the backward hemisphere.

6.13 $p/\bar{p}$ ratio in the backward hemisphere.

Figure 6.1 $d\sigma/dp_T$ Distributions

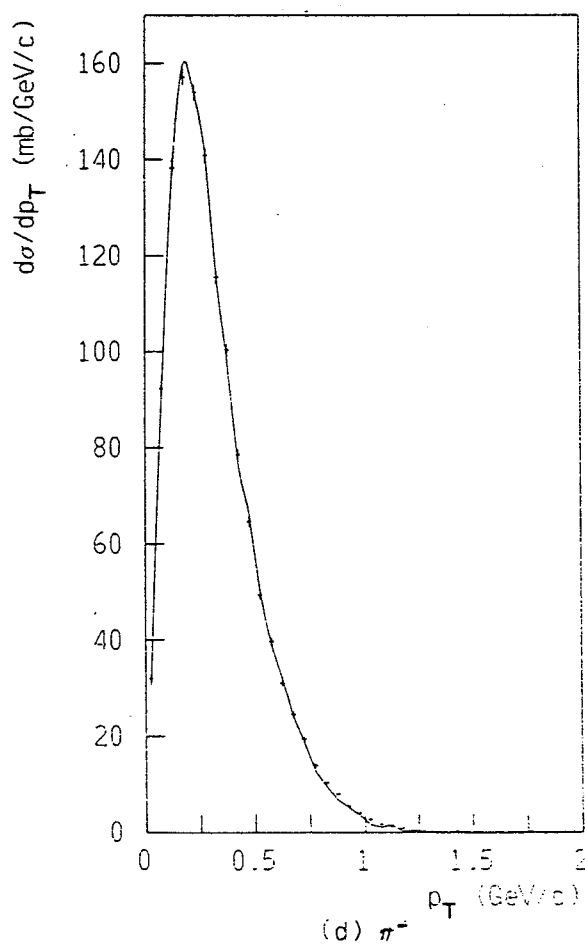
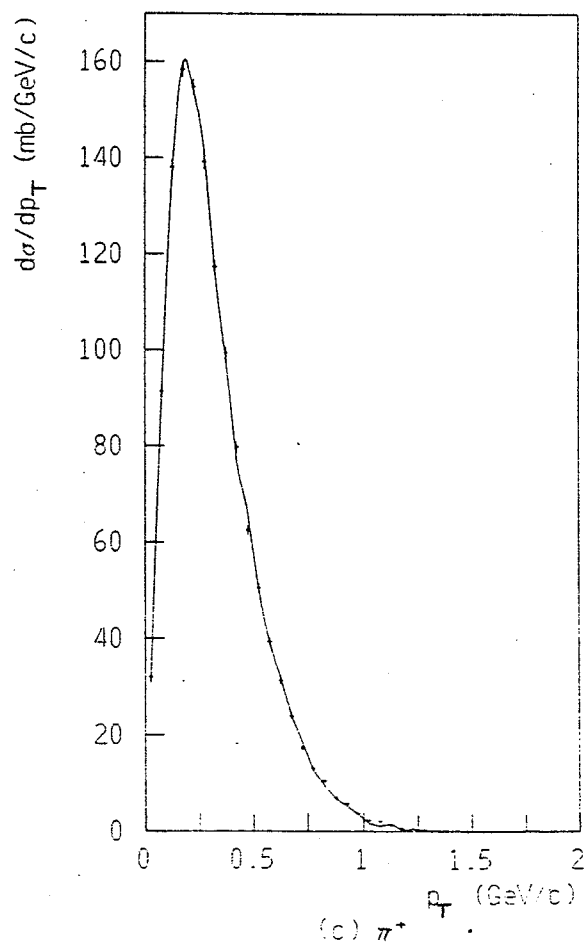
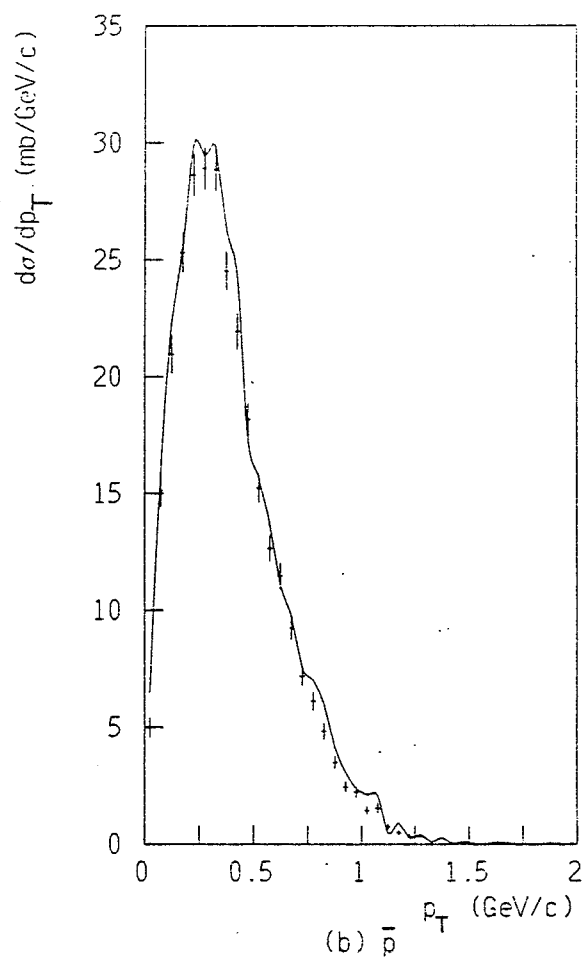
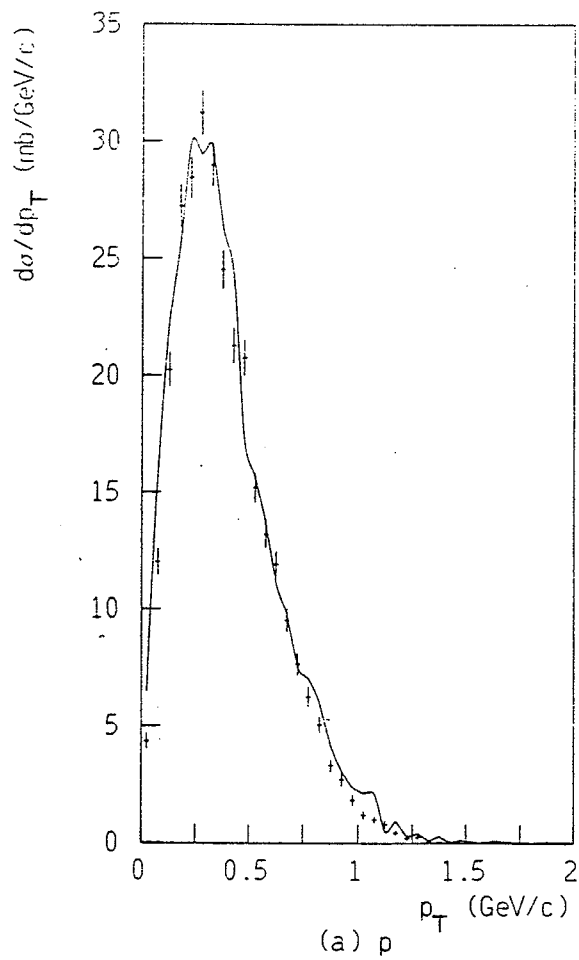


Figure 6.2 $d\sigma/dp_T^2$ Distributions

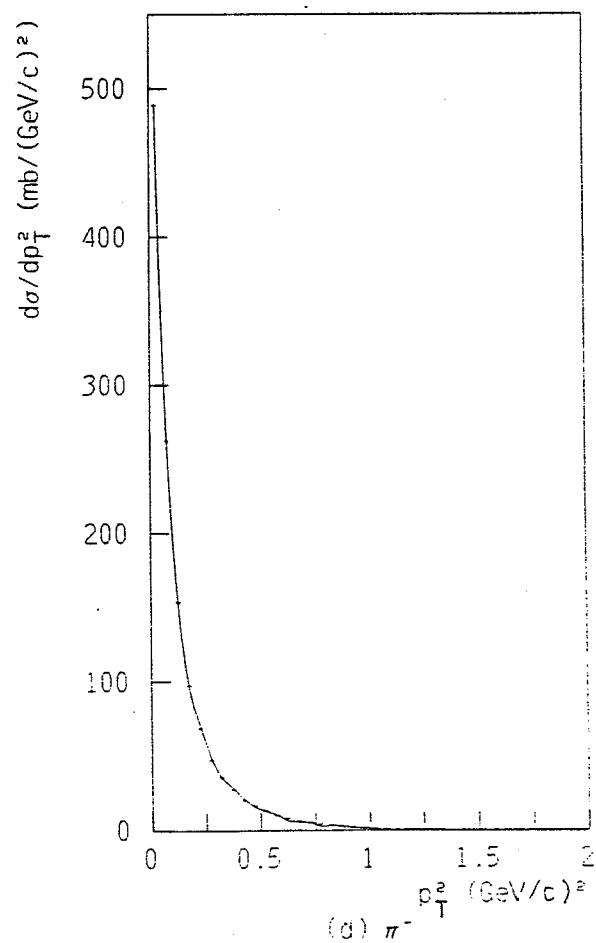
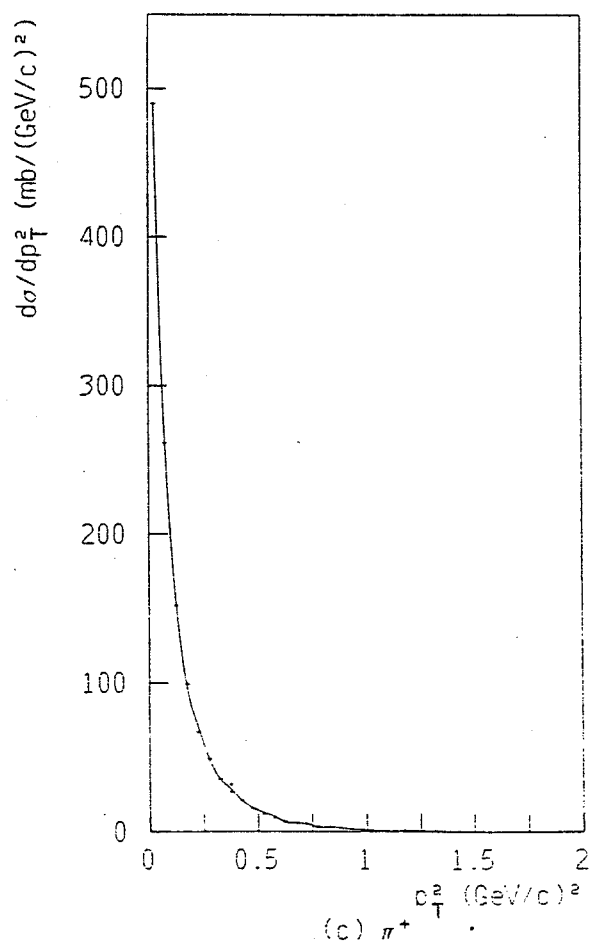
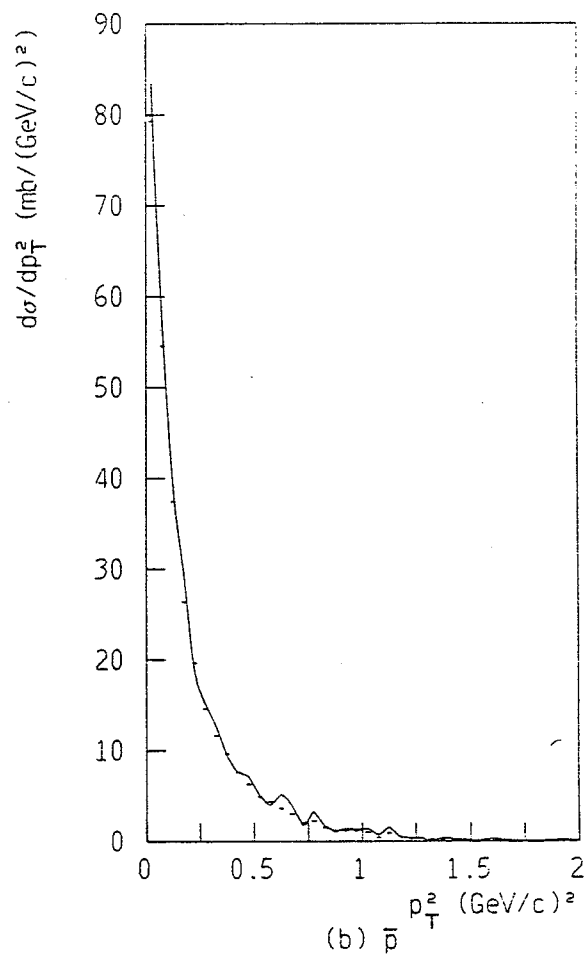
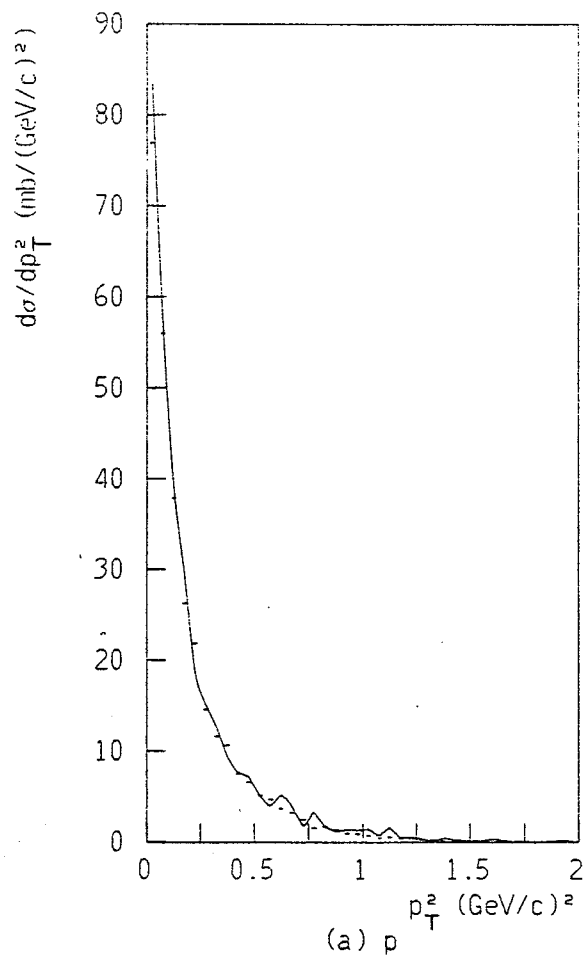
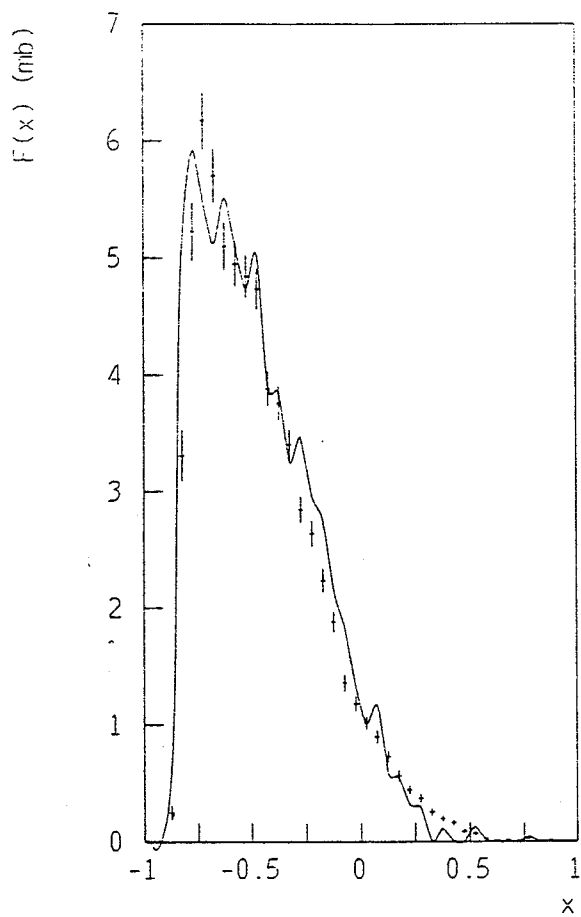
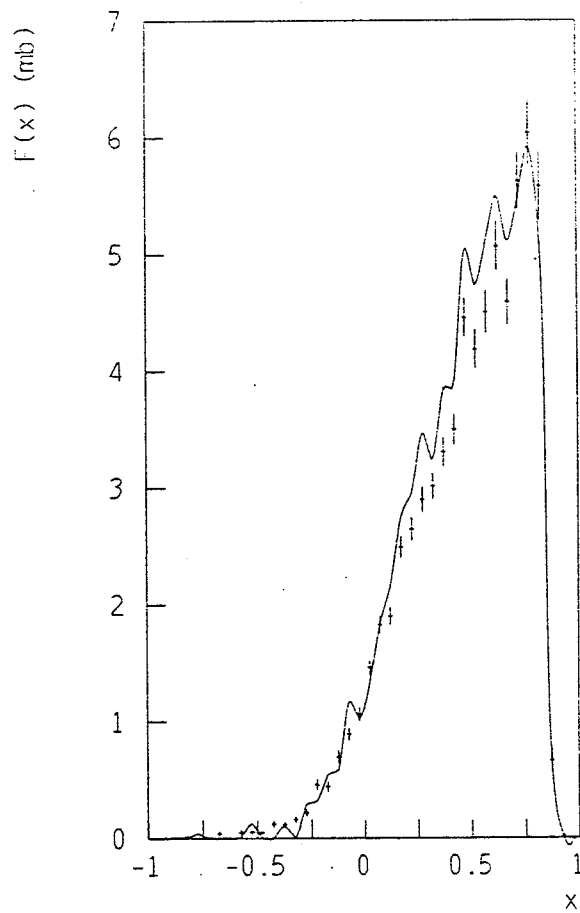


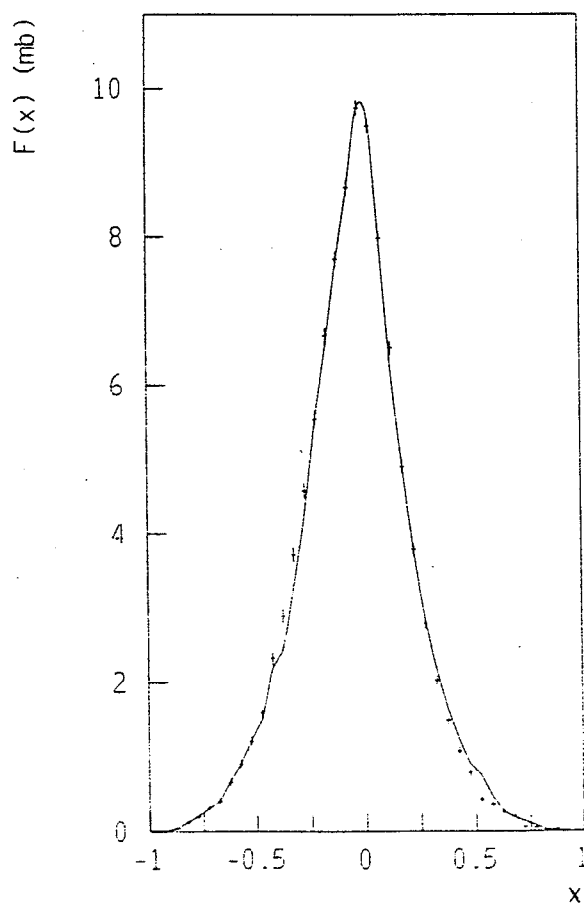
Figure 6.3 $F(x)$ Distributions



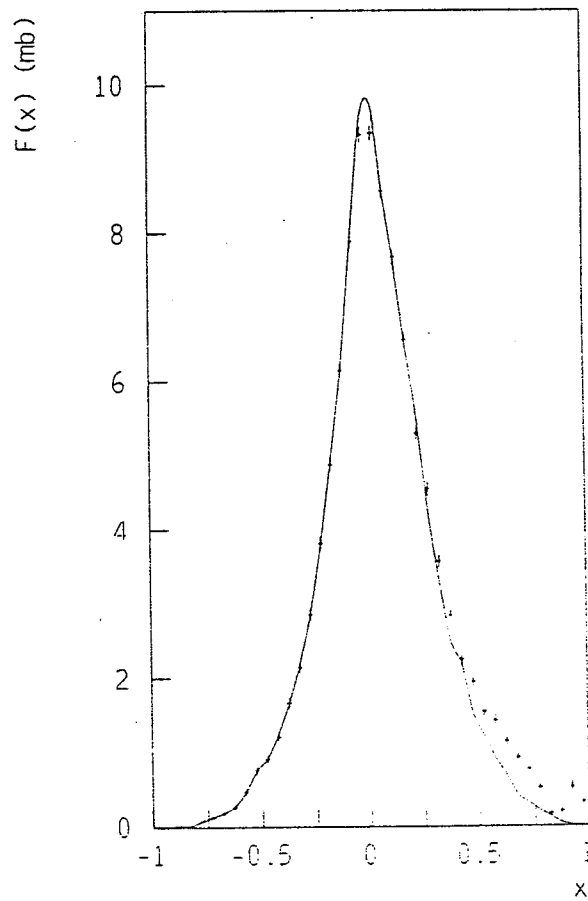
(a) p



(b) $\bar{p}$



(c) π^+



(d) π^-

Figure 6.4 y^* Distributions

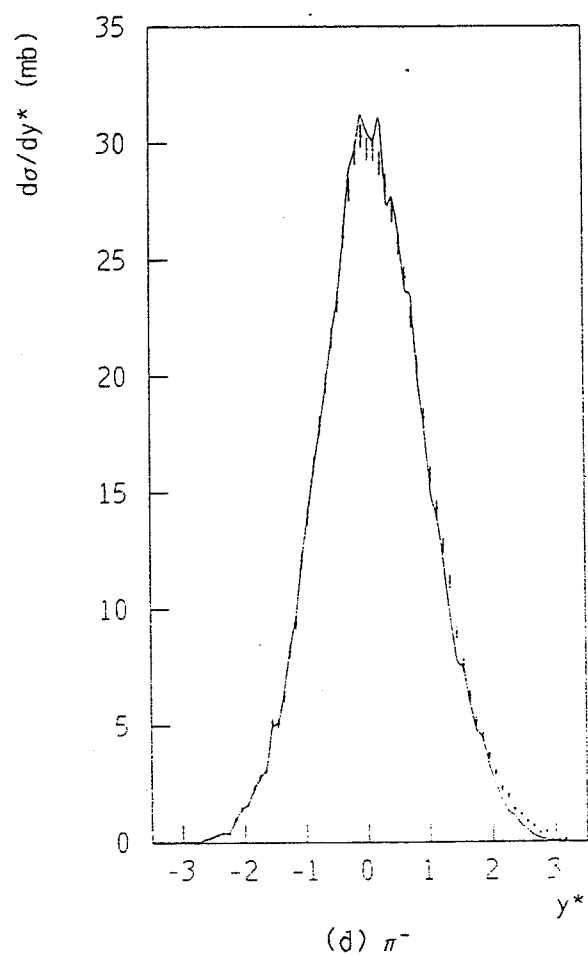
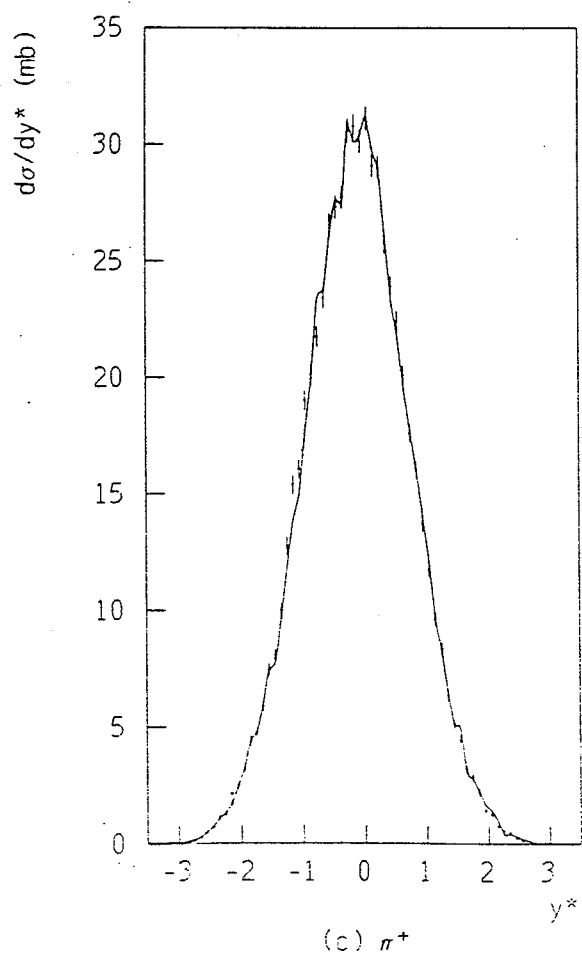
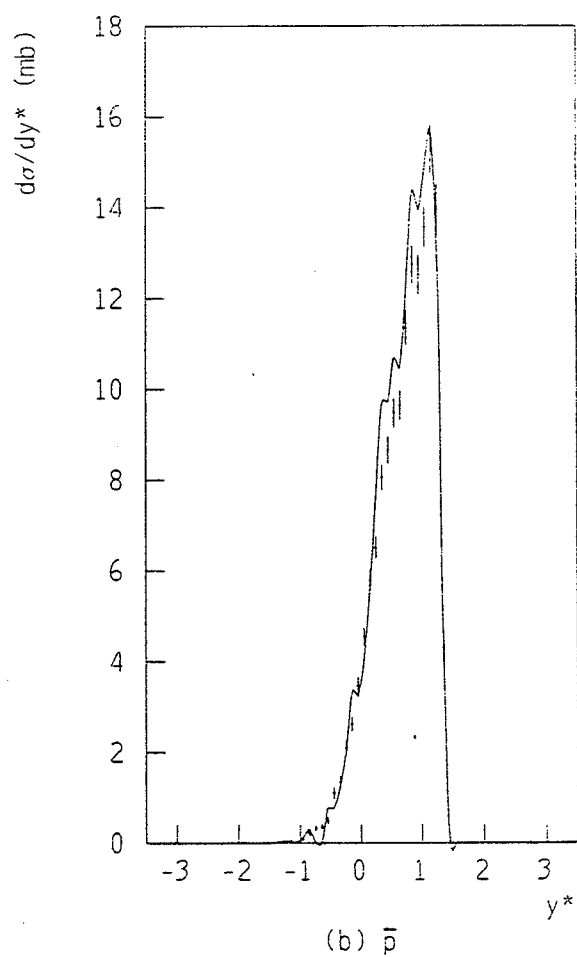
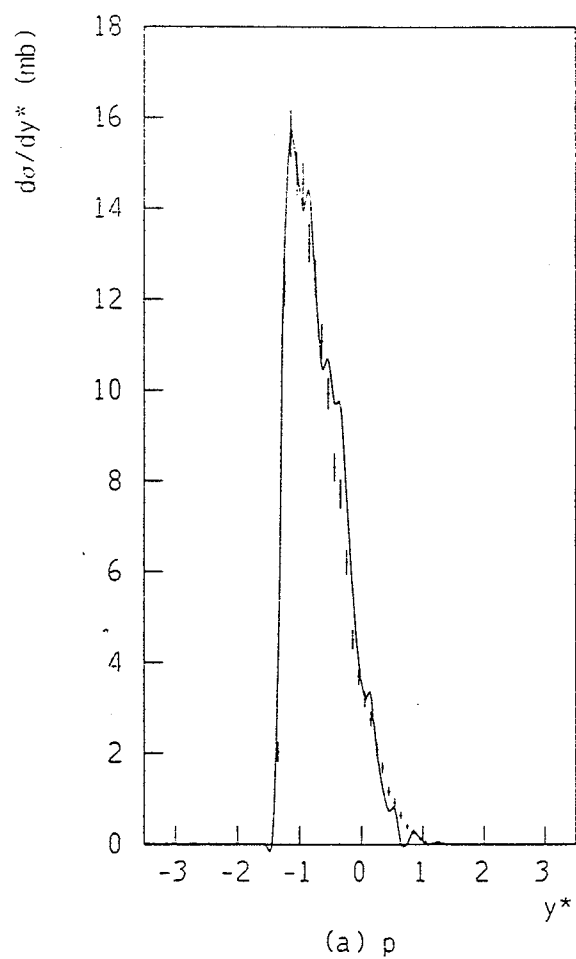
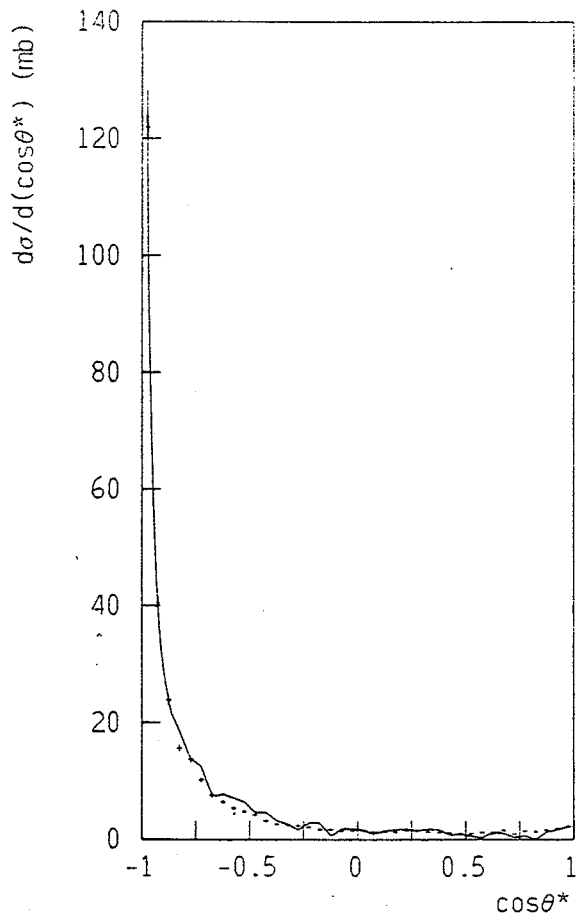
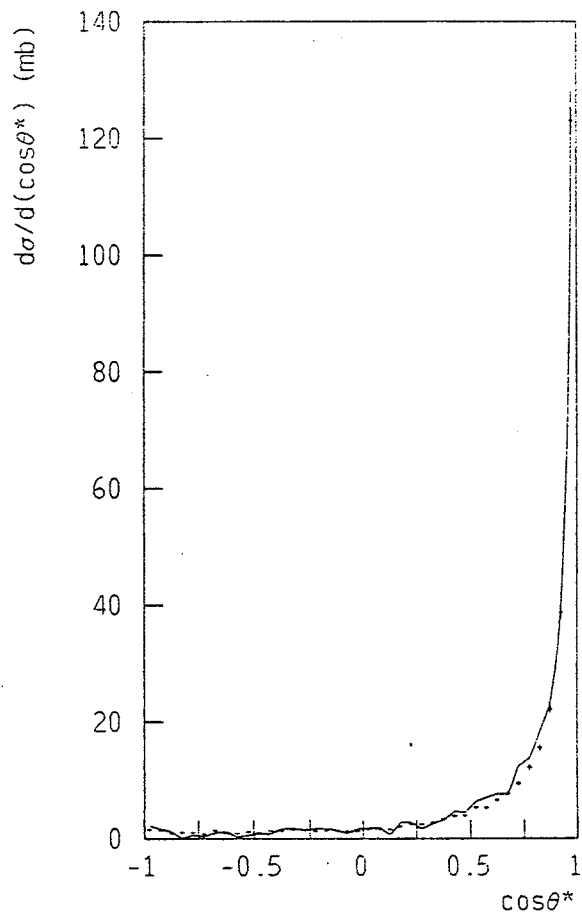


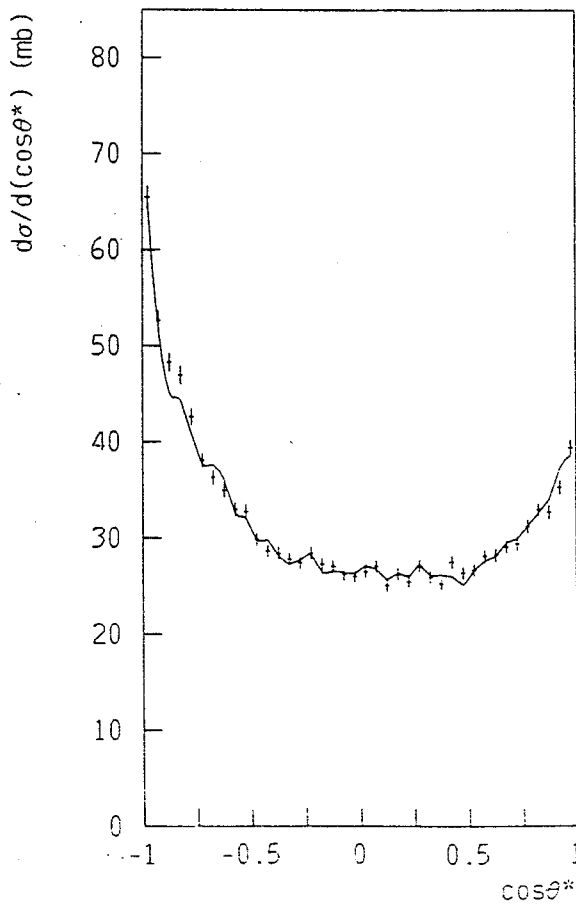
Figure 6.5 $\cos\theta^*$ Distributions



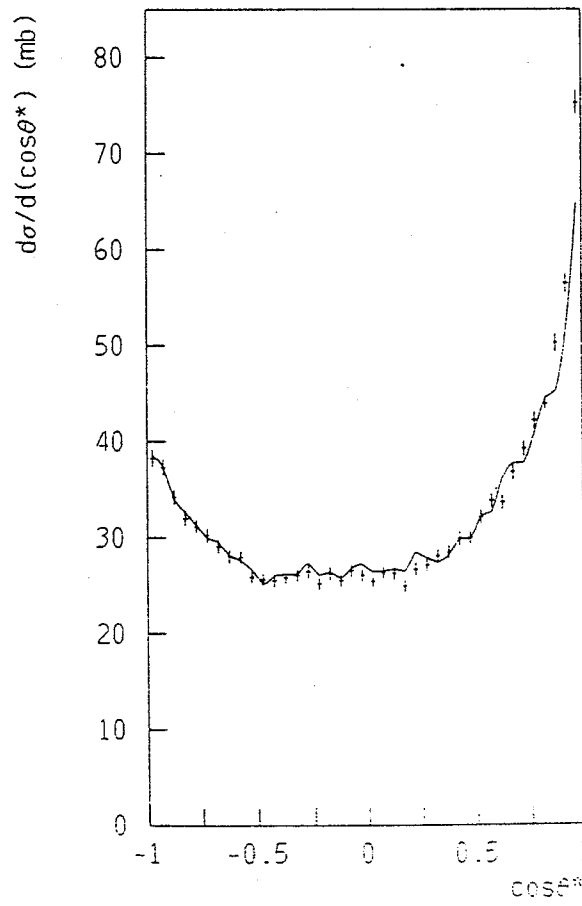
(a) p



(b) $\bar{p}$

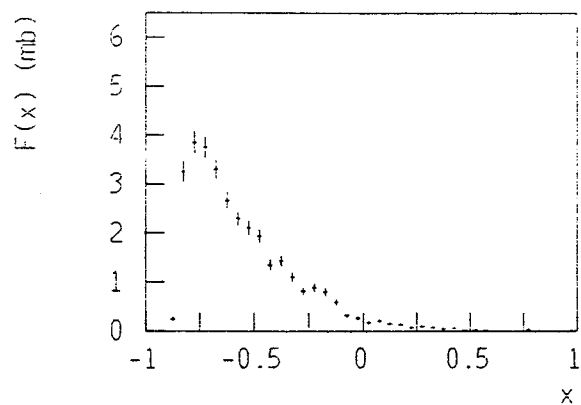


(c) π^+

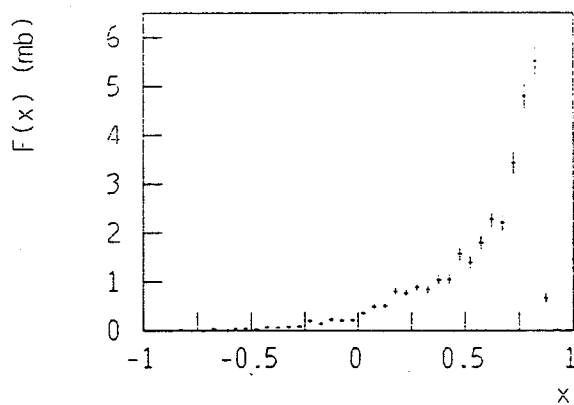


(d) π^-

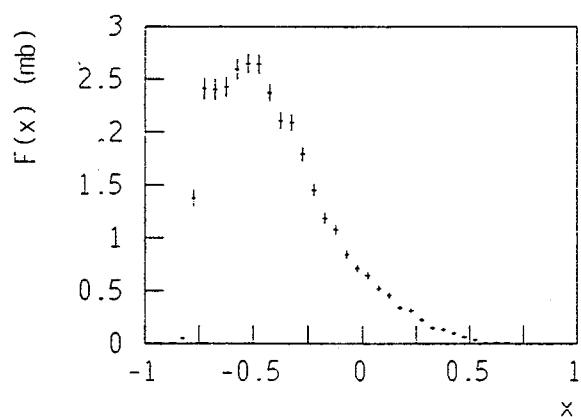
Figure 6.6 Semi-Inclusive $F(x)$ for $p, \bar{p}$



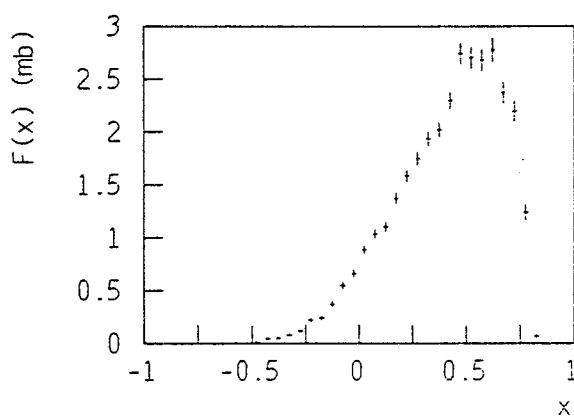
2 Prongs (a) p



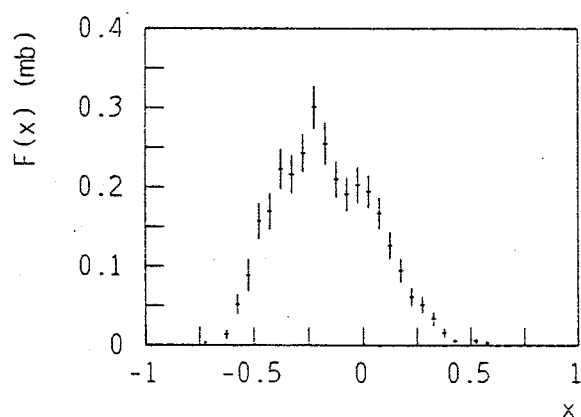
2 Prongs (b) $\bar{p}$



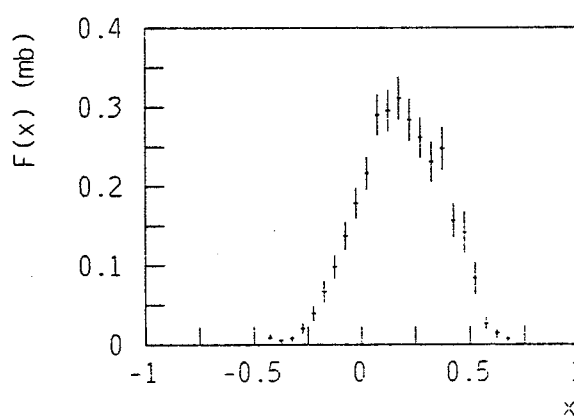
4 Prongs (c) p



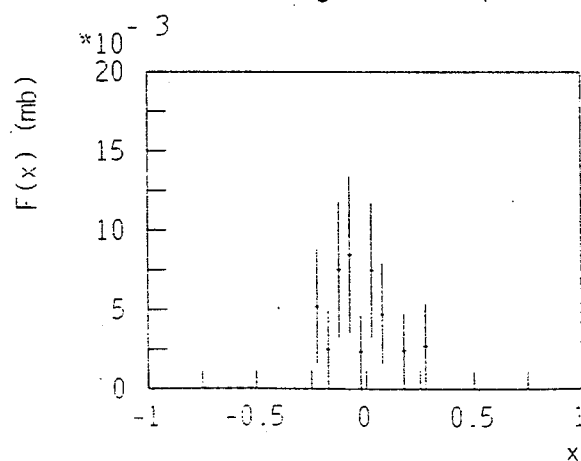
4 Prongs (d) $\bar{p}$



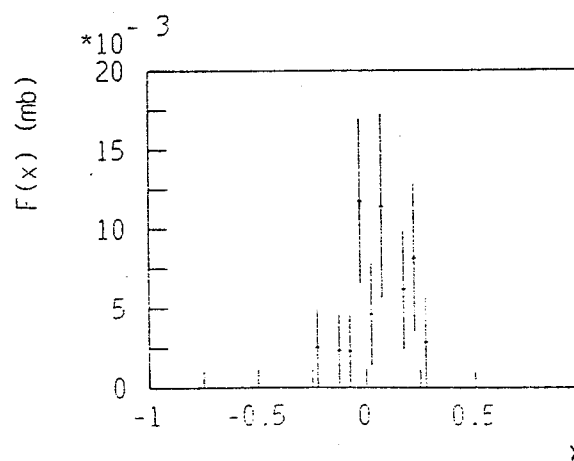
6 Prongs (e) p



6 Prongs (f) $\bar{p}$



>6 Prongs (g) p



>6 Prongs (h) $\bar{p}$

Figure 6.7 Semi-inclusive $F(x)$ for π^+, π^-

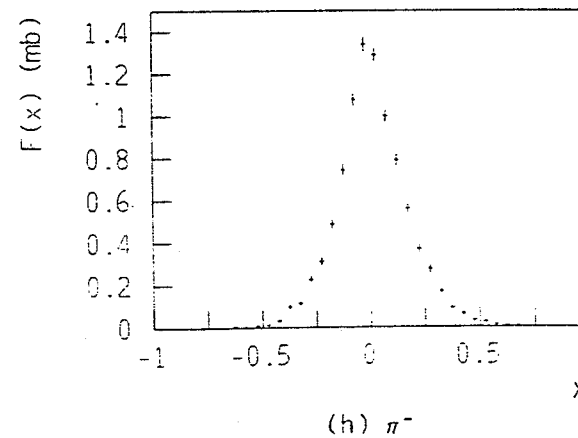
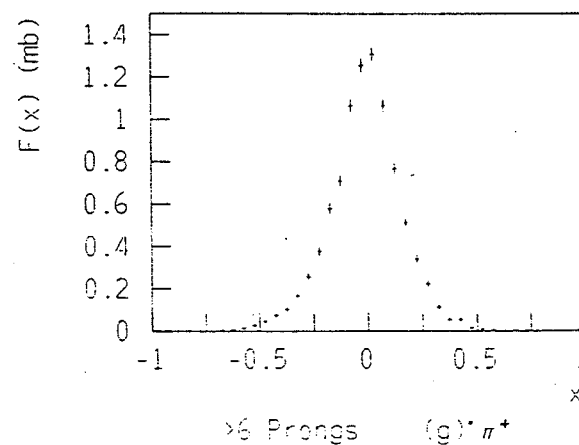
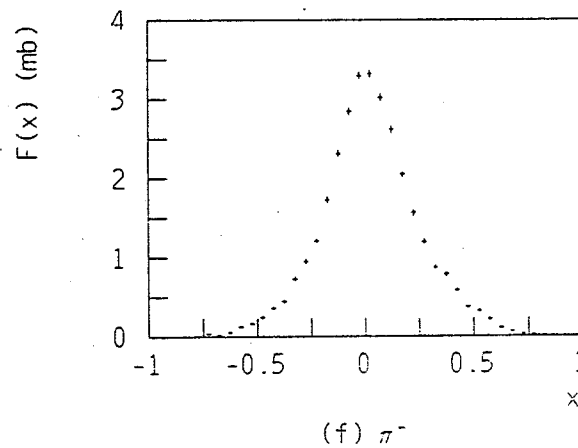
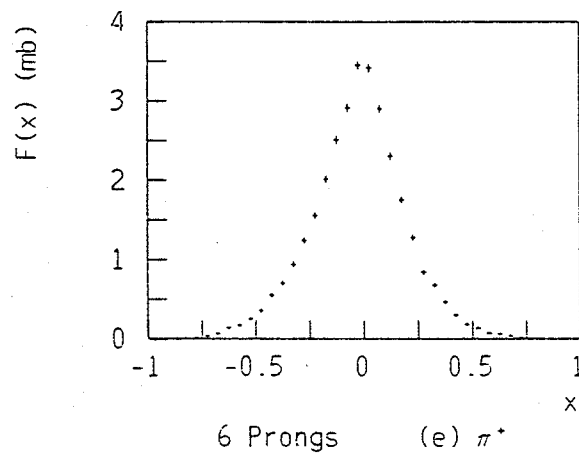
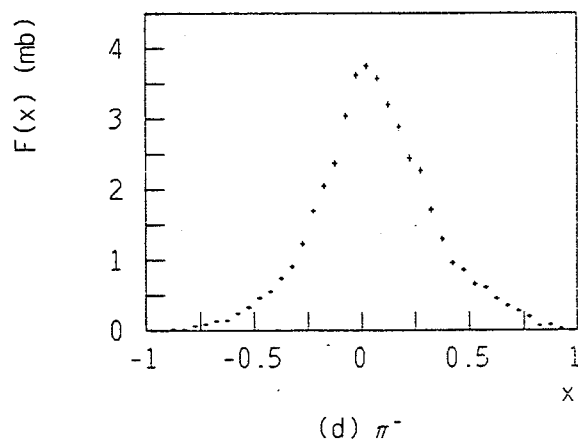
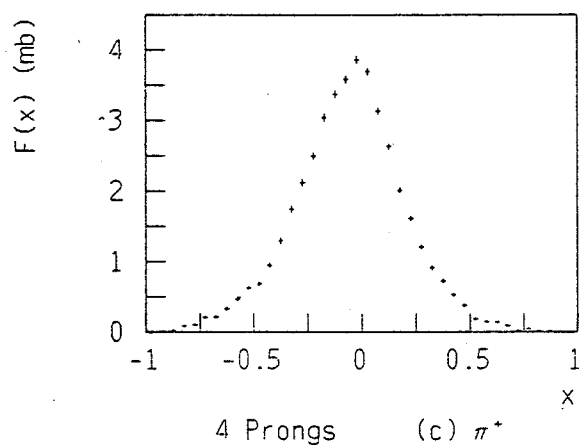
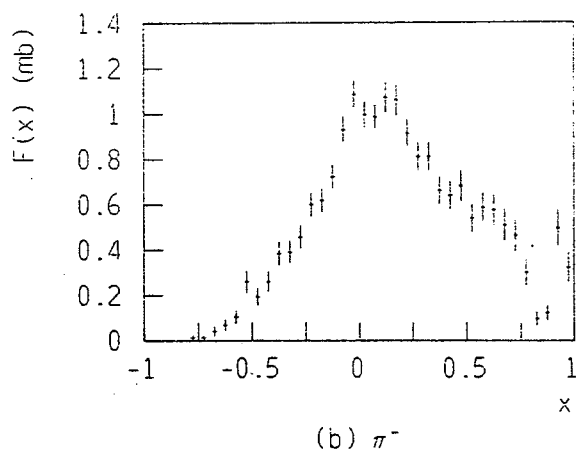
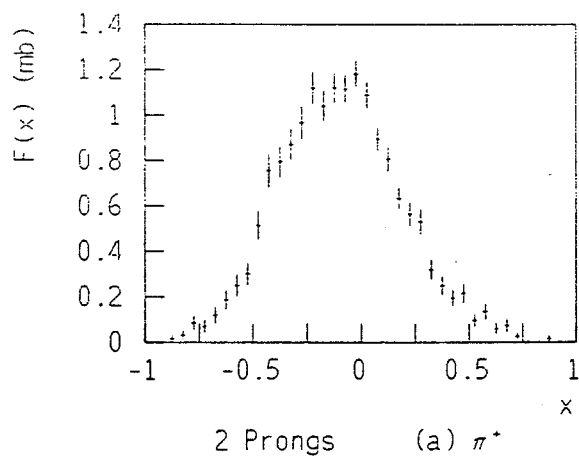


Figure 6.8 Separated $F(x)$ Distributions for π^+, π^-

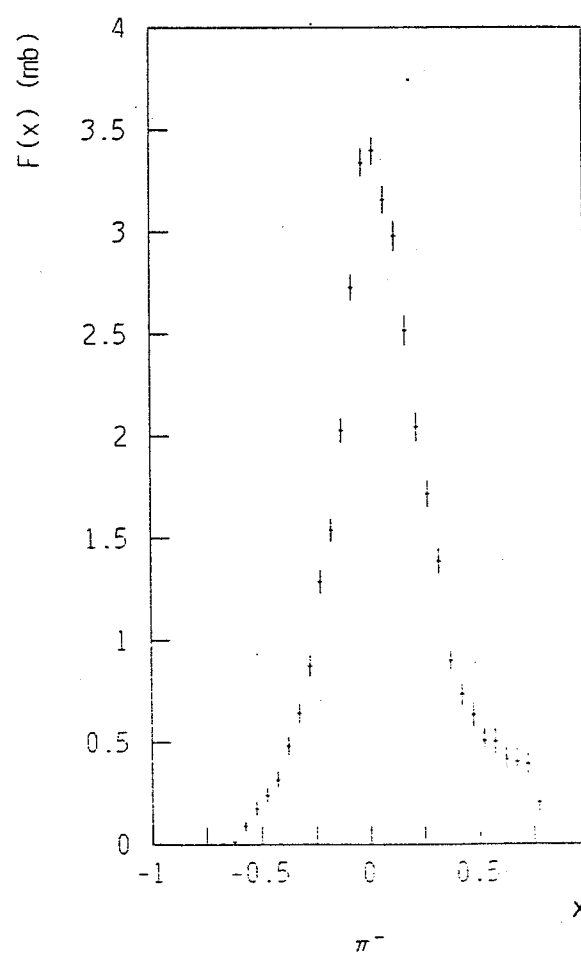
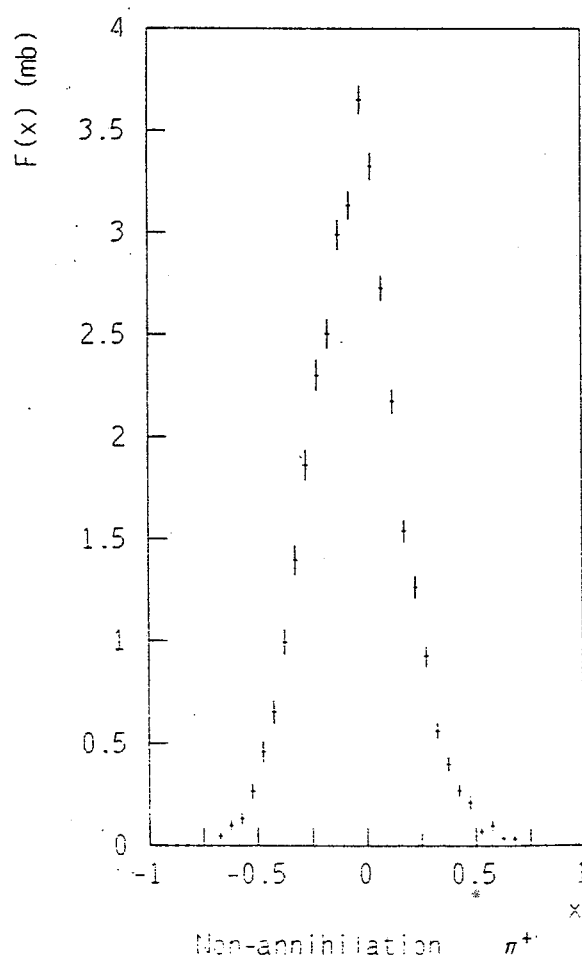
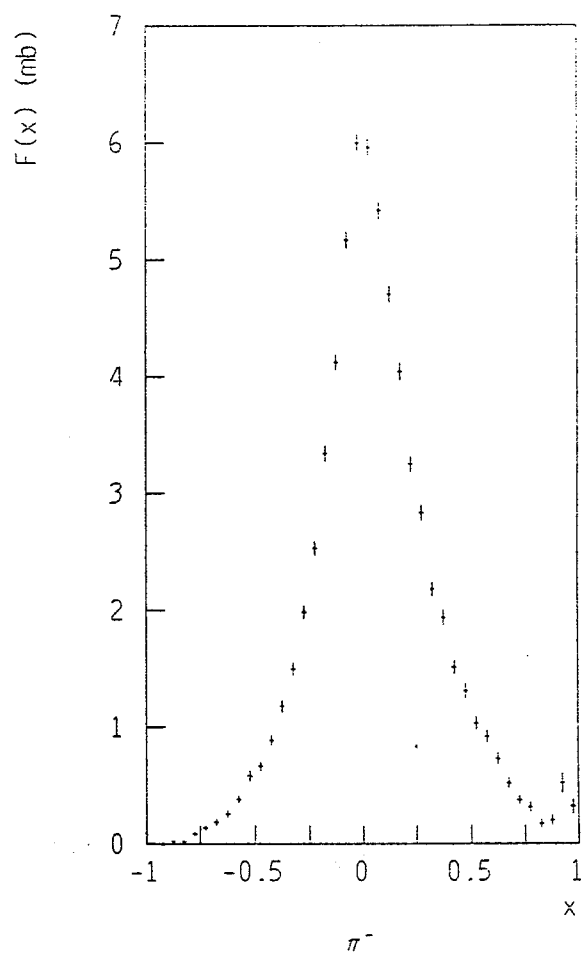
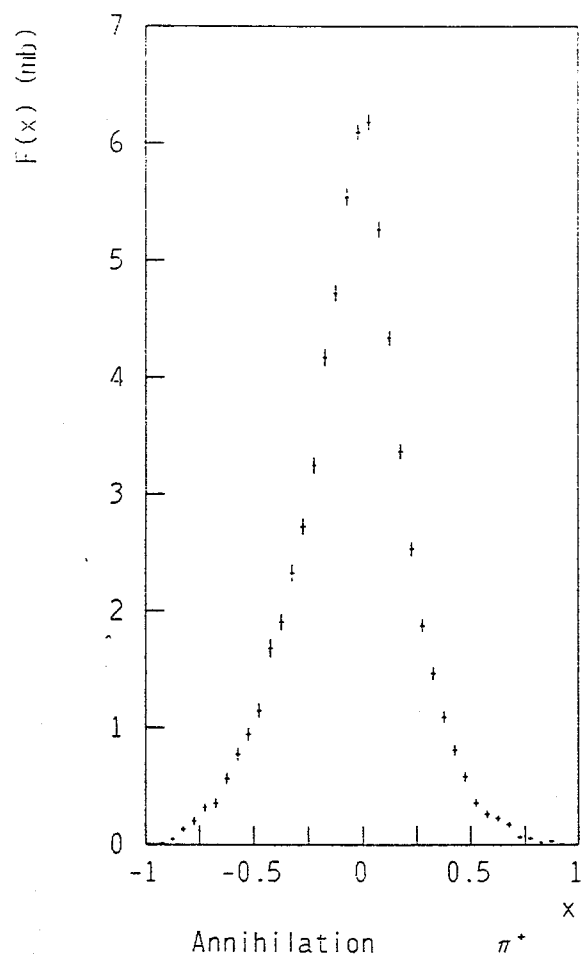


Figure 6.9 $F(x)$ Distributions with $(1-x)^n$ fits

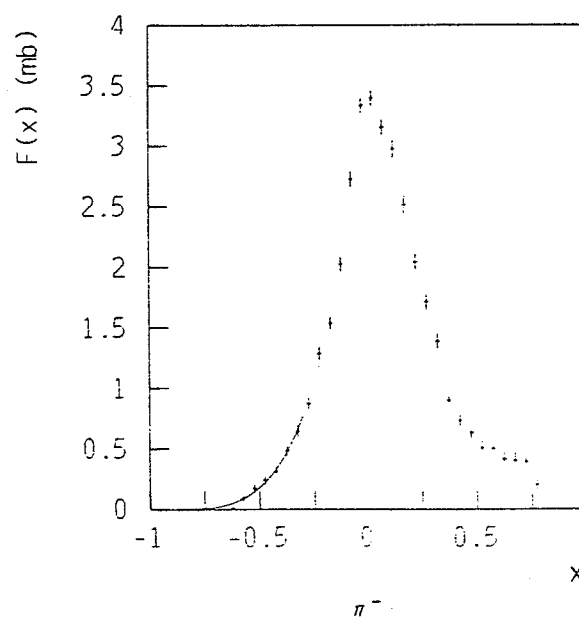
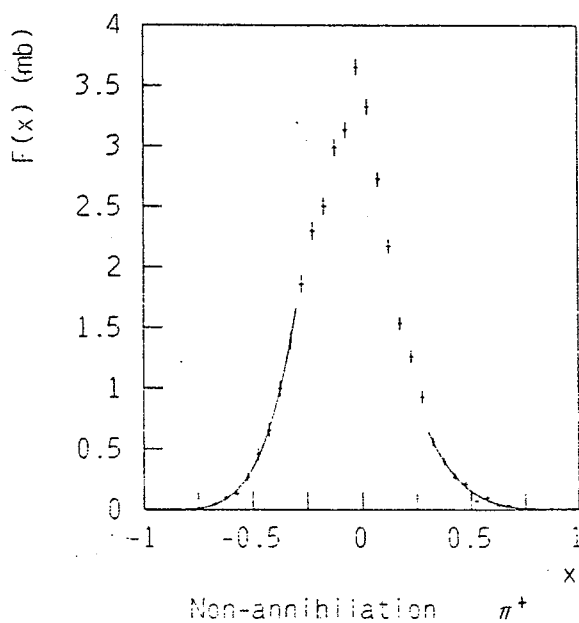
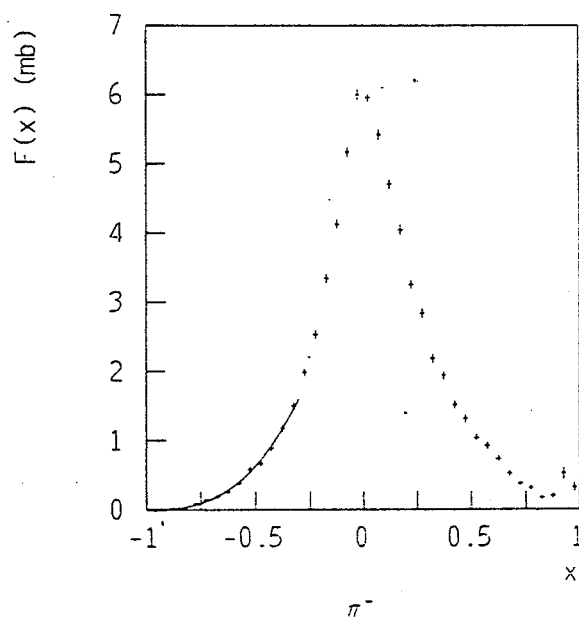
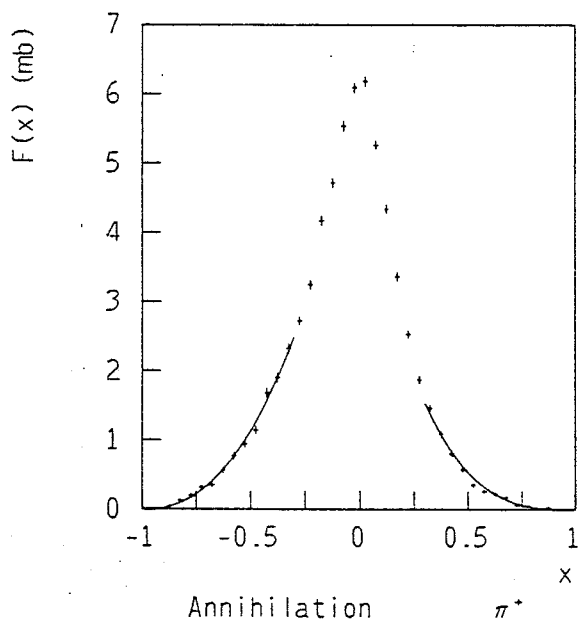
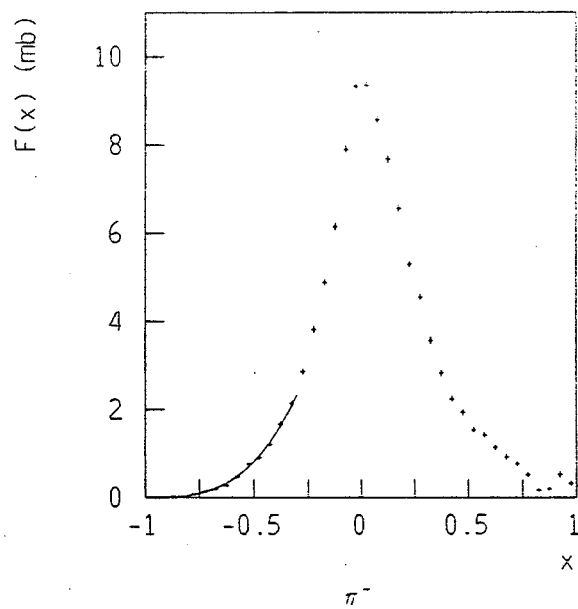
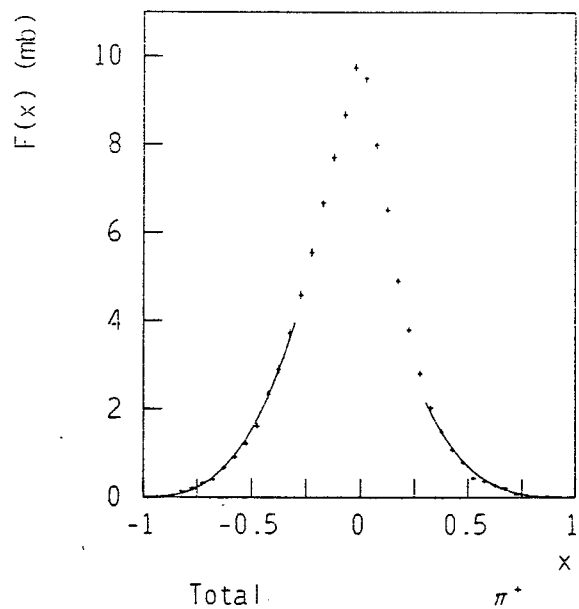


Figure 6.10 Separated K_s^0 $F(x)$ Distributions

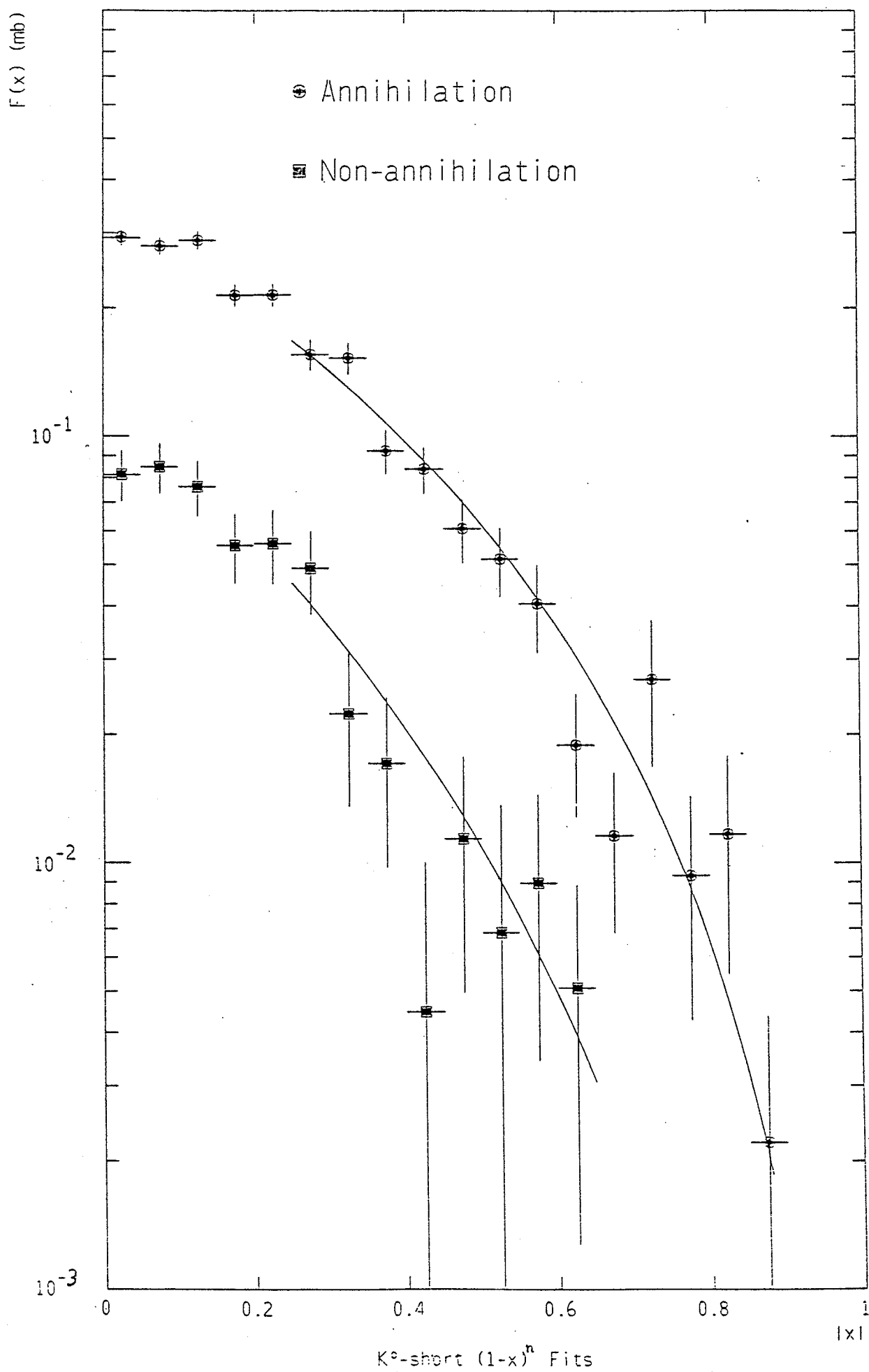
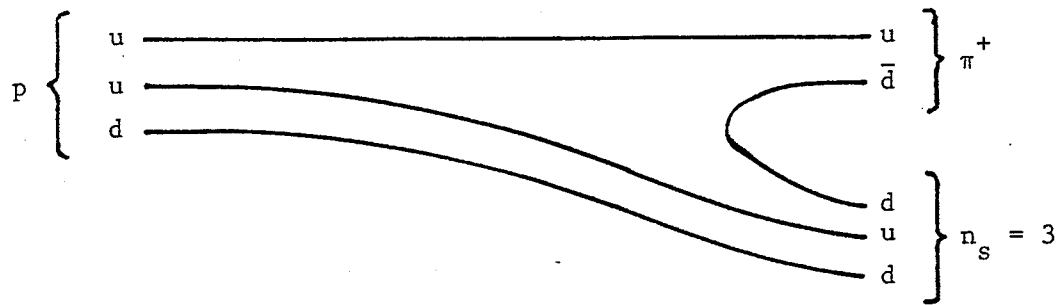
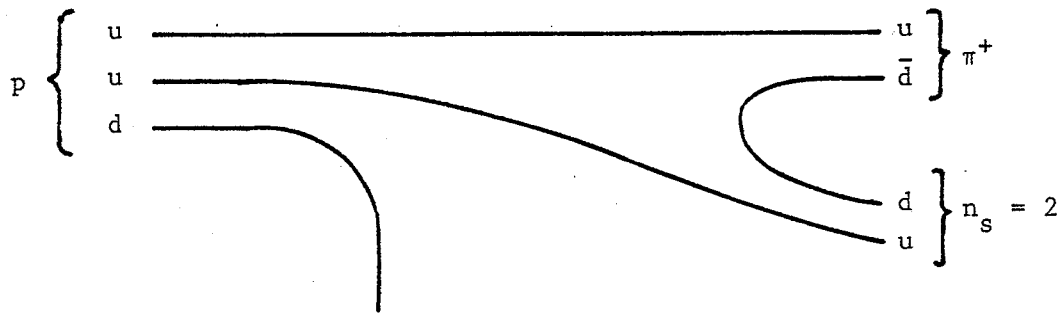


Figure 6.11 Quark Counting in Proton Fragmentation to π^+

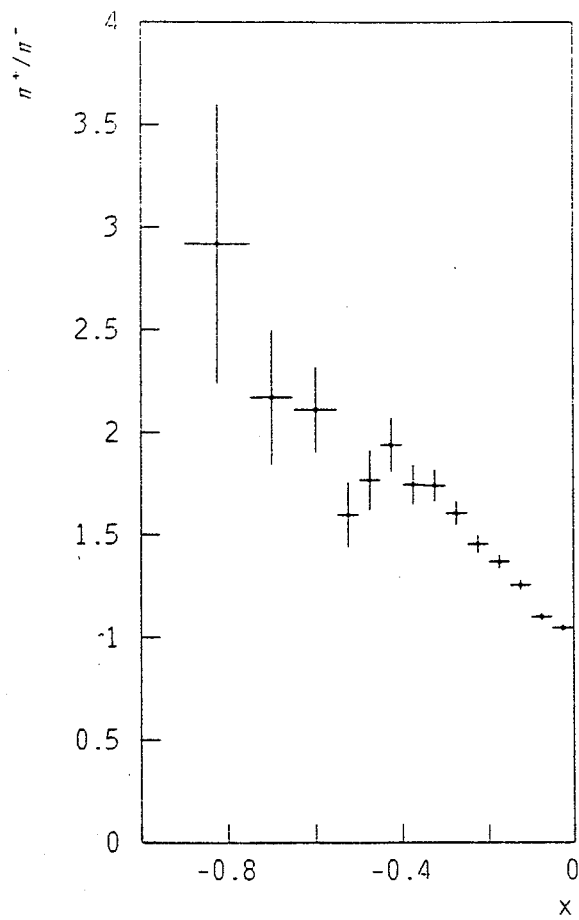


a) Gluon Exchange

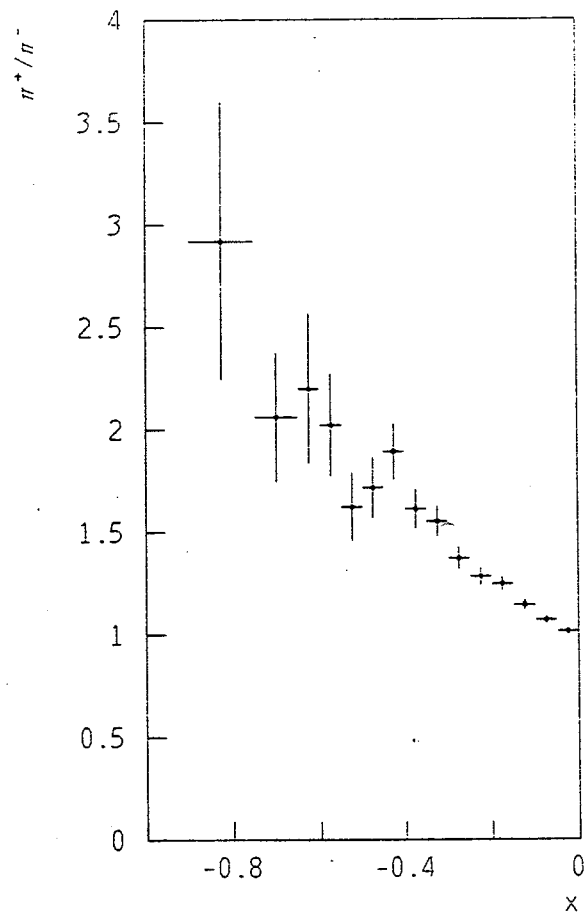


b) Quark Annihilation/Exchange

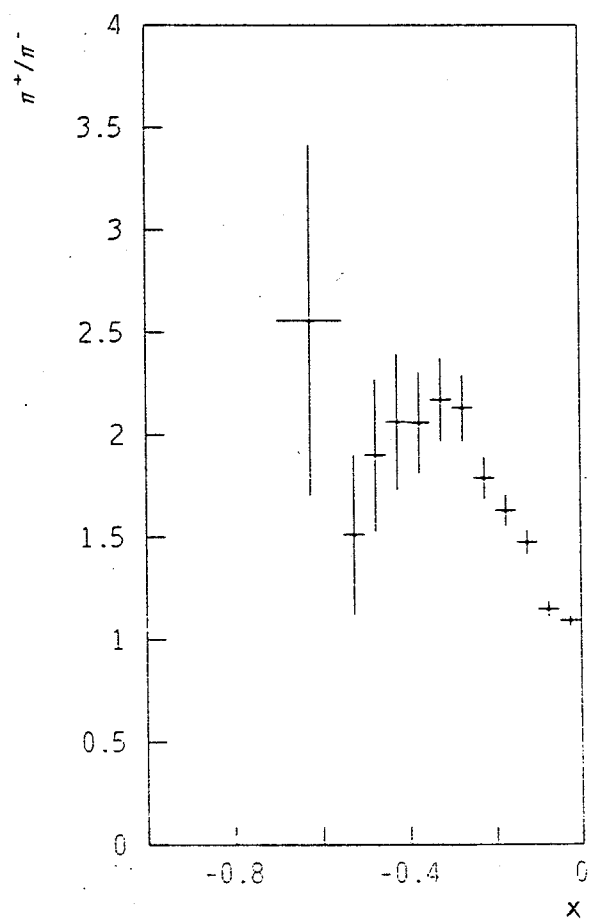
Figure 6.12 (a) π^+/π^- Ratio



(1) Total

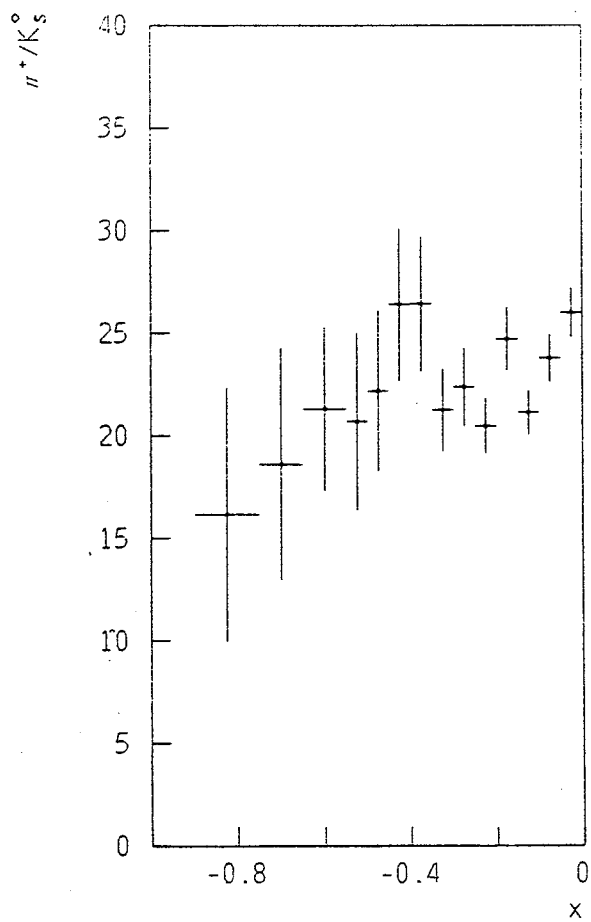


(2) Annihilation

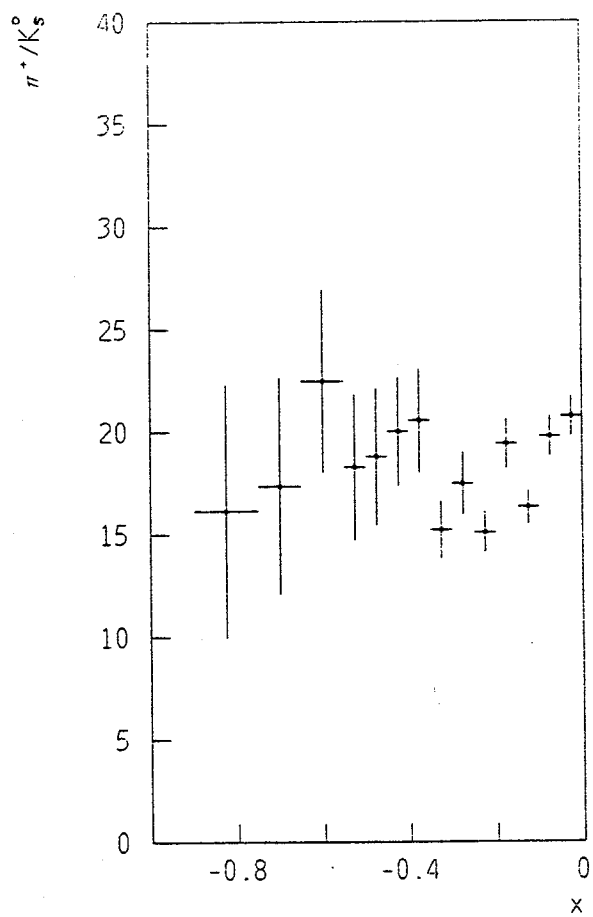


(3) Non-annihilation

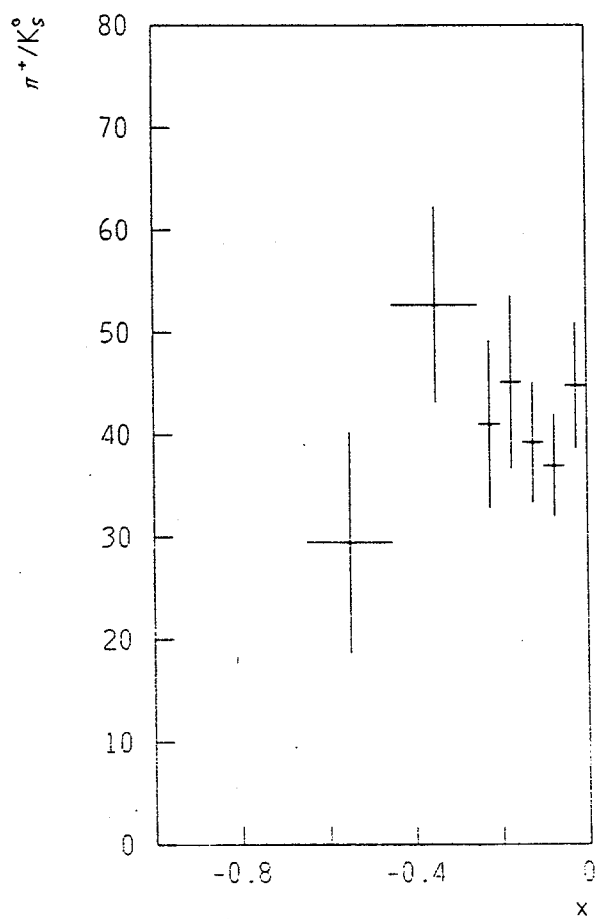
Figure 6.12 (b) π^+/K_S^0 Ratio



(1) Total

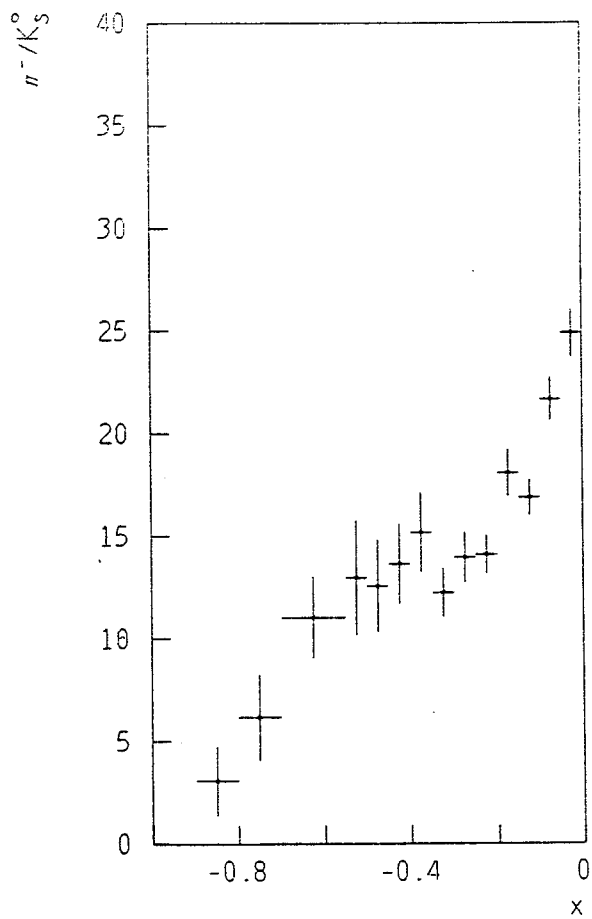


(2) Annihilation

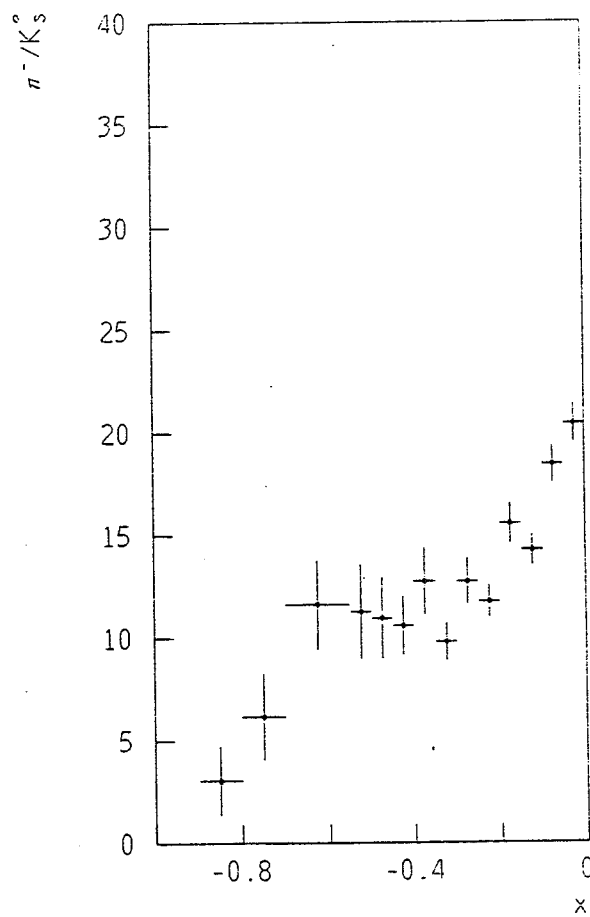


(3) Non-annihilation

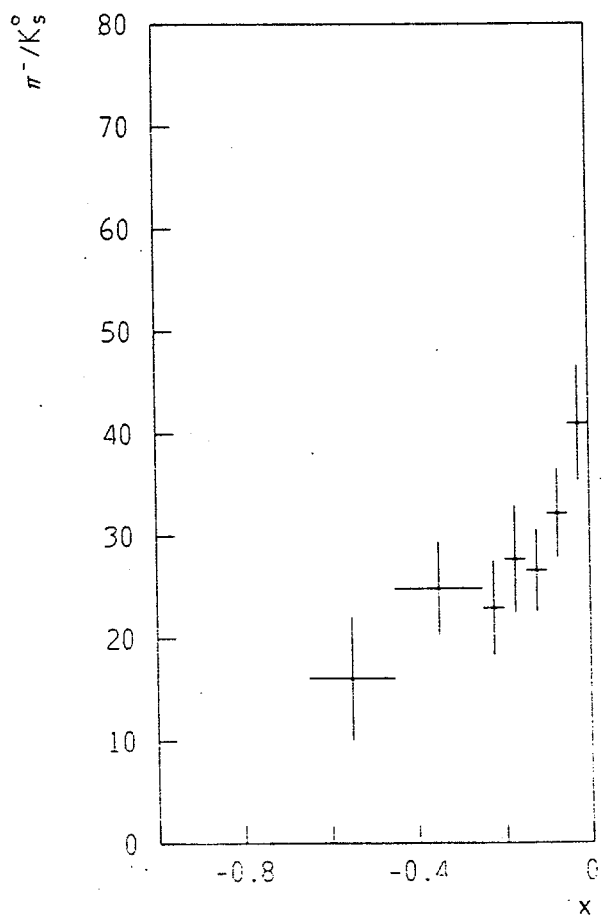
Figure 6.12 (c) π^-/K_S^0 Ratio



(1) Total

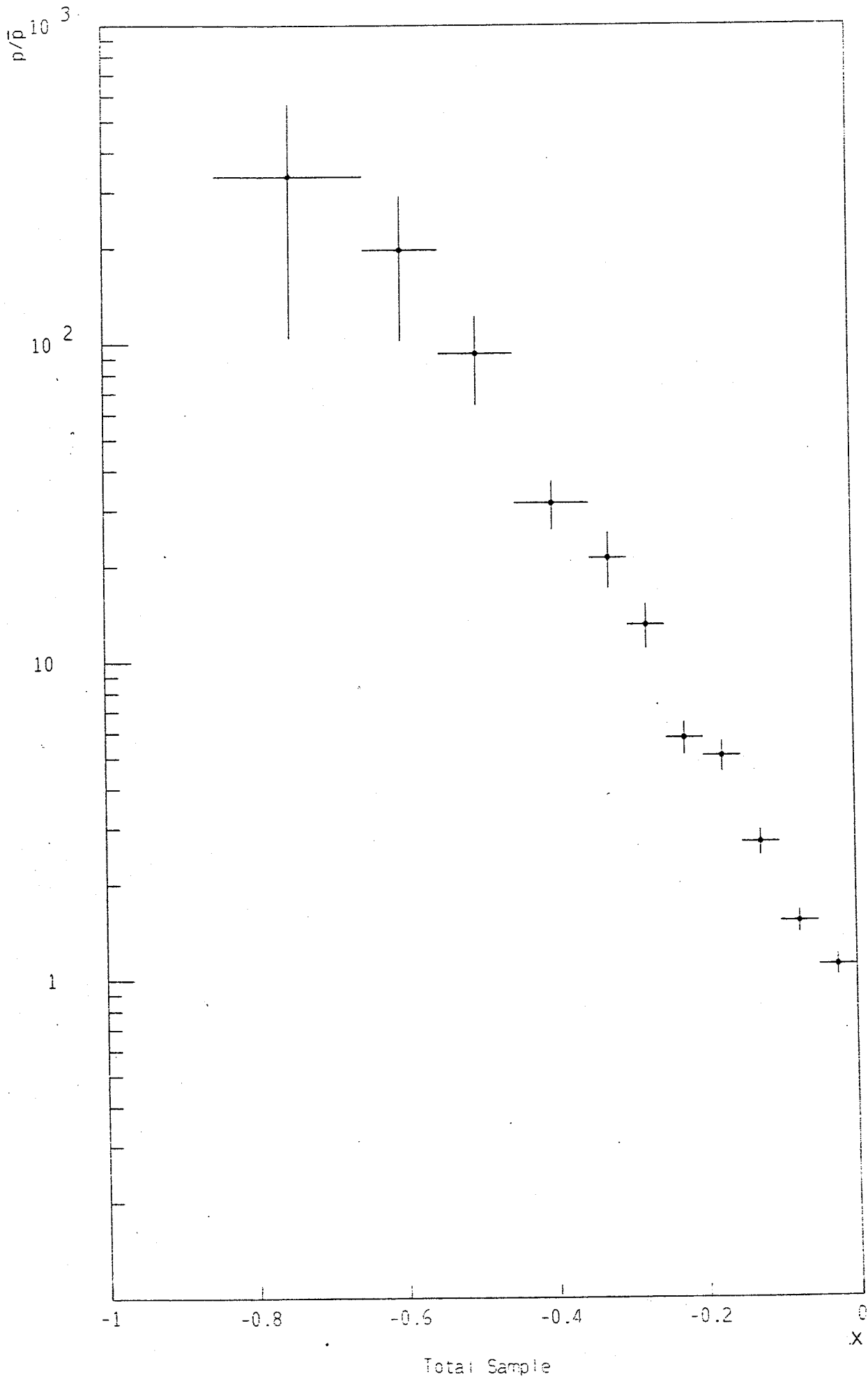


(2) Annihilation



(3) Non-annihilation

Figure 6.13 $p/\bar{p}$ Ratio in Backward Hemisphere



Chapter VII

CONCLUSIONS

Absolute cross sections have been determined and are in good agreement with other data as shown in Figures 4.4 and 5.8. Charged particle ambiguities were resolved by techniques based on those of Gregory and Warren [4.5,4.6,4.8]. The resulting channel cross sections and topological annihilation cross sections are in reasonable agreement with other data as seen in Figures 4.12 and 4.13.

Inclusive V^0 and γ production was studied in terms of the longitudinal and transverse single particle distributions $F(x)$ and $d\sigma/dp_t^2$ respectively. Certain general features, such as the $\Lambda/\bar{\Lambda}$ $F(x)$ distributions which peak at $x \approx -0.5$ and $x \approx +0.5$, can be understood with simple quark recombination ideas. The $\Lambda/\bar{\Lambda}$ p_t^2 distributions were found to fit a simple $A \exp[-bp_t^2]$ parametrisation. The K_s however, exhibits a break at $p_t^2 \approx 0.15 \text{ (GeV/c)}^2$ and gave different values for the slope parameter b in the two regions. The sharper rise for $p_t^2 < 0.15$ is conjectured to be due to indirect K_s production through resonance decay. The separated data shows that K_s production is predominantly through annihilation processes. Two strange particle cross sections have been calculated and provide a useful probe for strange particle production in $\bar{p}p$ annihilations.

Inclusive charged particle production was studied using the ambiguity resolved data of Chapter 4. For comparison inclusive charged particle distributions were derived independently using a statistical technique which generates single particle spectra on the assumption of only two particle types in the sample. The two methods compare well for the total inclusive cross sections and in most of the differential distributions.

The $(1-x)^n$ dependence of π^+ and π^- invariant cross sections for $|x| > 0.3$ has been calculated and compared with the simple quark counting predictions of [6.5]. The results show n to be lower in annihilations than non-annihilations. Particle ratios have been calculated and general features are shown to be in agreement with simple constituent quark and recombination model ideas.

The original high statistics aims of this experiment have not been achieved and the analysis presented here has been with the Liverpool and Amsterdam data presently available.

ERRATA

Appendix A

This appendix gives a brief description of the method used to estimate the contamination of the beam by non-interacting μ^- during the course of the run. The results were more of a guide to variations in contamination between rolls rather than an absolute determination.

From chapter 4, equation (4), the number of interactions per beam:

$$\frac{N_i}{N_b} = 1 - \exp \left[-\sigma_{tst} N_h L_r \right]$$

Using an interpolated $\sigma_{tst} = 60$ mb and a test-strip scanning region with $L_r = 1.20$ m, $N_i/N_b = 0.237$. If N_t is the observed number of tracks for N_i interactions on the test-strip and the non-interacting contamination is a fraction x , then:

$$\frac{N_i}{N_b} = \frac{N_i}{N_t(1-x)} = 0.237$$

$$\therefore x = 1 - \frac{N_i}{0.237N_t}$$

The average value for this contamination from all the test-strips scanned was 15%, however fluctuations were large ranging between -34% and +60%.

