

OPERATION OF A SILICON VERTEX DETECTOR IN A 100 GeV PHOTON BEAM

by

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ABSTRACT

This thesis is divided into two parts. The first part concerns the NA14 Silicon Vertex Detector, which was designed to detect the decay of states containing a quark of heavy flavour. A description of the construction, the testing and first operation of the Silicon Vertex Detector in a 100 GeV photon beam is given. Algorithms for heavy flavour enrichment are described and the degradation implied by multiplexing is evaluated. Emphasis is placed on the testing and simulation of the silicon microstrip detectors, in particular the problem of 'charge sharing', a factor that can degrade the performance of such devices. Finally, problems with finding tracks in the microstrips and matching them to those found in the rest of the spectrometer are briefly discussed.

The second part contains a comparison of interactions using γ and π^- beams, in order to obtain an estimate of the strangeness content of the photon. The inelastic ϕ photoproduction cross section

$$\sigma_{inel}(\phi) = 1038 \pm 130 \pm 24\% \text{ nb}$$

is also obtained, which is in agreement with values found by other experiments.

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Chapter I

HEAVY FLAVOUR SEARCHES

1.1 BACKGROUND

The experiment discussed in this thesis is motivated by the proposal and subsequent discovery of the charm quark and the obvious wish to study its interactions. In the 1960's theorists proposed three types of quark, up, down and strange, (u , d , s) to explain the classification of hadron spectrum observed at that time. Applying this substructure to a description of weak decays led to an expectation of strangeness changing neutral currents (eg $K^0 \rightarrow \mu^+ \mu^-$). Experimentally these currents were not found, and to explain their non-occurrence, a fourth quark, charm, was proposed in 1970 by Glashow, Iliopoulos and Maiani (GIM)[1]. In 1974 evidence for the existence of charm was found by Aubert et al.[2] and Augustin et al. [3] with the discovery of the J/ψ (3100 MeV), a $c\bar{c}$ state. Subsequently further $c\bar{c}$ states (excitations of the J/ψ) and 'open' charm states have been found.

In 1977 the T (9460 MeV) or $T(1S)$ state was found by Herb et al. [4] and Innes et al.[5]. This was interpreted as evidence for a fifth quark known as 'bottom' or 'beauty', $T(9460)$ being a $b\bar{b}$ bound state. Subsequently open beauty states have been found.

With the discovery of new quark flavours and of the τ lepton, a pattern of 'generations' can be seen in both the quark and

lepton families, each generation being heavier than the last.

Our present knowledge suggests these generations are:-

1 st generation	2 nd generation	3 rd generation
$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$

The aim of particle physics is to understand why these generations exist and how they interact with each other.

Estimates of the mass of these new quarks can be made from the lowest lying $Q\bar{Q}$ state which is J/ψ for charm and $T(1S)$ for beauty, giving $\text{mass}(\text{charm}) \sim 1.5 \text{ GeV}$ and $\text{mass}(\text{beauty}) \sim 5.0 \text{ GeV}$. Using these values and the fact that these quarks decay weakly, estimates of the lifetimes of the charm and beauty quarks can be made by comparison with the muon lifetime [6].

$$\tau_Q = 0.2 \tau_\mu \left(\frac{m_\mu}{m_Q} \right)^5 \frac{1}{|V_{bc}|^2}$$

where Q is charm, beauty etc

and τ is the lifetime.

$0.2 = 1/5$, where 5 is the number of available fermion decay channels.

V_{bc} is the mixing value between Q and lower mass quarks and is an element in the Kobayashi-Maskawa (K-M) matrix [7]. The K-M matrix, whose elements have to be measured experimentally, is an expression of our knowledge of the mixing of flavours in weak decays. Charm decays to strange and beauty decays to charm, and

since this latter process is across generations (3rd to 2nd) the element V_{bc} is expected to be small. This is indeed what is found, as early results from decays of charm and beauty particles indicate that they have similar lifetimes of between 10^{-13} - 10^{-12} s, despite the higher mass of the b quark. This means that equipment designed to look for charm decays is capable of looking at beauty decays as well.

The production of these heavy flavours has been investigated in various ways. Both fixed target and colliding beam configurations have been used, utilizing electrons, photons, neutrinos and hadron beams. The following results show the ratio of heavy flavour to light flavour production found experimentally for various different interactions.

		heavy/light hadrons
lepton + lepton	$e^+e^- \rightarrow Q\bar{Q}$	~ 0.5
lepton + hadron	$\nu N \rightarrow \mu QX$	~ 0.1
photon + hadron	$\gamma N \rightarrow Q\bar{Q}X$	~ 0.01
hadron + hadron	$h h \rightarrow Q\bar{Q}X$	~ 0.001

The above figures indicate the signal to noise ratio for charm that can be expected in a particular interaction and shows, for example, the high content of charm in lepton-lepton interactions as compared with hadron-hadron interactions. The particular experiment, NA14, described in this thesis studies photon hadron interactions.

The NA14 experimental rig, a fixed target experiment performed in the North Area of the CERN SPS, was designed to explore those properties of real photons which distinguish them from ordinary

hadrons, in particular photon hard scattering. In 1984 the emphasis was changed towards heavy flavour photoproduction exploiting the larger fraction of final states containing heavy quarks than is observed using incident hadrons. A method therefore had to be adopted to find the decays of these heavy flavours.

1.2 METHODS OF FINDING CHARM

There are two methods of finding charm. Firstly 'bump hunting' in which the invariant mass combinations of final state particles are examined for enhancements indicative of a decay. The second method involves detecting and measuring the distance between the primary and secondary (decay) vertices; this is done either visually, ie can be viewed directly by eye, as is the case with bubble chambers and emulsions, or by computer reconstruction as is the case with electronic counters. This second method must be used when lifetime measurements $> 10^{-13}$ seconds are required, as a necessary part of the calculation is the distance between primary and secondary vertices. A combination of the two methods can be used to increase the signal to noise ratio, this process is described and used in Chapter 5.

Due to the comparatively short lifetimes of charm ($\sim 10^{-13}$ s), high precision equipment is necessary to detect secondary vertices. In charm decays the resulting decay particles have trajectories that are offset from the primary vertex, when extrapolated back, and it is the existence of these offset tracks that indicate a secondary vertex may be found. The typical

flight path of a charm particle, ie the separation of primary and secondary vertices is

$$d \sim \gamma c \tau$$

where τ is the lifetime of the particle.

which increases with the energy. This Lorentz boost given to the charm particle aids in its detection and is the advantage of high energy fixed target experiments. The impact parameter δ is given by

$$\delta \sim \gamma c \tau \times \theta$$

where θ is a typical decay angle $\sim m/p \sim 1/\gamma$

hence

$$\delta \sim c \tau$$

Given the lifetime of charm this requires equipment with a precision of $\sim 30 \mu\text{m}$ and better. Such equipment is described below.

1.2.1 Bubble Chambers

Probably the best known visual detection method is the ionization trail left by a charged particle in a bubble chamber. For studying decays of heavy flavours small liquid hydrogen filled bubble chambers ($\leq 1\text{m}$ diameter) have been used. These bubble chambers are small so they can be pulsed faster eg 15Hz compared to the Big European Bubble Chamber (BEBC) which was pulsed once every 12 secs or so [8]. These smaller bubble chambers are operated at a higher temperature eg the SLAC chamber was run at 29 K compared to BEBC which was run at 26 K. Running at a higher temperature slows down the rate of bubble growth ($50 \mu\text{m}$ after

150 μ s) and also leads to a higher density of bubbles (70 bubbles/cm) [9]. These small and high density bubbles aid in the detection of secondary vertices from charm decays. The same principle applies to the use of heavier liquids run at 300 K.

1.2.2 Emulsions

Emulsions are very similar to bubble chambers in that the tracks and the primary and secondary vertices are actually seen. A number of experiments such as WA57 and WA75 [10] (both at CERN) use this particular method when searching for heavy flavours.

The usual method is to have a stack of emulsion sheets and move them at regular intervals and regular distances on high precision devices such as milling machines during the exposure time. The intervals are recorded by computer so vertices in one part of the stack can be related to events recorded by the spectrometer. The position of the vertices in the emulsion stack is usually found with the aid of silicon microstrip detectors to localise the region requiring scanning with microscopes.

1.2.3 Silicon Detectors

Unlike bubble chamber film and developed emulsions which can be viewed by eye (though not directly in the case of emulsions) silicon detectors require the use of algorithms and computers to reconstruct tracks from the information they supply.

There are at present two types of silicon detector used for high precision tracking in heavy flavour searches, Charged Coupled Devices (CCDs) and Microstrip Detectors (MSDs).

The structure of a CCD is described in reference [11]. Their advantage is that being two dimensional arrays they give (y,z) coordinates ie a unique space point, given that the array plane is at a known x coordinate. Their disadvantage is that they are slow to read out- ~ 40 ms to read out a device 4 cm^2 as the pixels are read serially. Work is progressing on reducing this readout time. The accuracy of CCDs comes from the area of their pixels which are $\sim 20 \times 20 (\mu\text{m})^2$ in area and means there are approximately 2.5×10^5 pixels per cm^2 .

Microstrips are one dimensional arrays of diodes which are manufactured on the same silicon crystal. The fact that there are many diodes in close proximity to one another means that cross talk can occur between them and this is discussed in Chapter 3. Detectors with various diode pitches of between 20 to 200 μm have been built and have been used in experiments. The smaller pitch gives the greater precision. Being one dimensional devices they can only read a y or z coordinate but not both. To locate a space point three planes, each measuring a different projection (eg y, z and $u = y \cos\theta + z \sin\theta$) are needed and a stack of such planes is necessary for tracking.

1.3 EXPERIMENTS USING MICROSTRIPS

Apart from the experiments where microstrips are used in conjunction with emulsion stacks there are a number which use microstrips alone as vertex detectors in heavy flavour searches, examples of which are NA32, E691 and NA14.

NA32 is a CERN experiment using a 200 GeV π^- beam on to a Be target. Two stacks or telescopes of silicon microstrips are used, one of 7 planes to measure the trajectory of the incoming beam and the second of 8 planes (20 μm pitch) to detect the secondaries from the π -Be interaction. Two CCDs are used in conjunction with the 8 plane telescope to help find the vertices [10].

E691 is a Fermilab experiment using a tagged photon beam of ~ 180 GeV. The photons interact in a 5 cm long Be target and a stack of 9 microstrip detectors (50 μm pitch) are employed to find tracks.

Both experiments have been successful in using their microstrips to measure the decay lengths of charmed particles they have found [12,13].

1.4 STRUCTURE OF THIS THESIS

With the development of new devices there are always teething troubles and unfortunately NA14 has not been without them ! Due to problems encountered during the prototype run in 1984 (see Chapter 4), the physics of charmed states could only follow from the successful run in 1985. So although the first part of this thesis describes the development of the silicon vertex detector, especially the microstrip stack used by NA14, the second part is a study of processes involving the photoproduction of strange quark states in particular the Kaon to Pion ratio and the inelastic ϕ cross section.

Chapter II

EXPERIMENTAL DETAILS OF NA14

2.1 OVERVIEW

The spectrometer used in the NA14 experiment is shown in figure 1. A brief outline of the spectrometer is given here with a more detailed description later in this chapter. The Silicon Vertex Detector is described in Chapter 4.

Photons are incident on a silicon target which is located in the magnetic field of the AEG, the smaller of the two magnets used. The low energy electromagnetic pairs produced in large numbers are of no interest and are swept away by the magnetic field of the AEG.

Situated downstream of the AEG is an array of Multi-Wire Proportional Chambers (MWPCs), which is referred to as Stack One: this is used to track the charged particles.

An electromagnetic calorimeter, known as CROWN, follows. This measures photons and electrons in the backward hemisphere of the centre of mass system.

The charged particles with momenta exceeding a few GeV then pass through the Goliath magnet (3.1 Tm) to a Cathode Pad Detector. This large chamber gives coarse two dimensional measurements in the plane transverse to the beam, and is used to "trigger" on high Pt hadrons.

The momenta of charged particles are measured using Stack Two

of MWPCs and the magnetic bending of Goliath. In a limited momentum range they are identified by a Cerenkov counter (a second Cerenkov counter now under construction will be placed in the Goliath magnet to extend the range of momenta over which identification can be provided.)

Following the Cerenkov are two more electromagnetic calorimeters, ILSA and OLGA, and Stack Three of MWPCs.

Finally, approximately 20 m downstream of the silicon target, an iron wall and scintillator hodoscope arrays serve as a muon detector.

NA14

Chapter 2

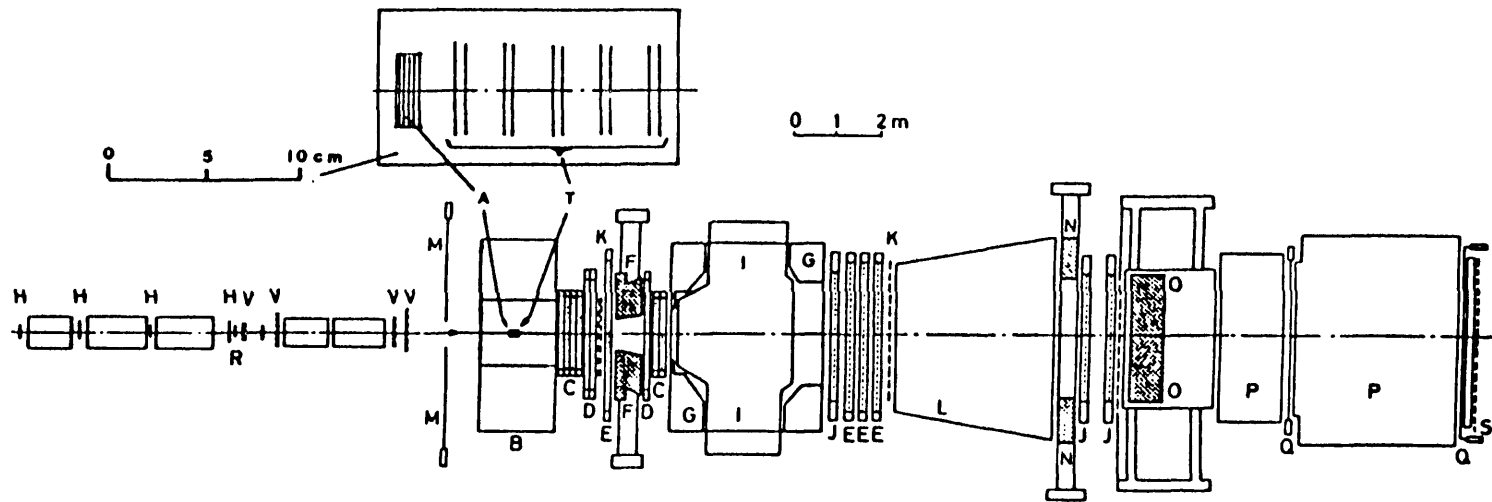


Figure caption:

H, V	tagging hodoscopes	F	"crown" lead glass calorimeter	R	Radiator,
M	muon veto	G	Goliath Magnet	O	Olga-Penelope Calorimeter
A	Si active target	I, L	Čerenkov Counters	P	iron filter
B	AEG vertex magnet	K	trigger hodoscopes	Q, S	μ hodoscopes
C, D, E, J	MWPC's	N	Imperial College Calorimeter		
T	Si microstrip detector				

Figure 1: NA14 Spectrometer

Experimental Details

2.2 THE PHOTON BEAM

The NA14 experiment uses a Broadband Electron and Gamma beam (BEG) [14], (figure 2). This beam is designed to yield a high flux of high energy photons with a very low hadron contamination.

The beam is produced in the following way. Protons, from the CERN SPS with a 400 GeV energy, are incident on a 0.5 m long Beryllium (Be) target. Each SPS burst produces about 2×10^{12} protons, of which approximately 70% interact in this target. Among the interaction products are neutral pions that decay to produce a primary photon beam. The choice of target material is a compromise between the two conflicting requirements: efficient use of the incident protons and the loss of photons due to e^+e^- conversion. The best choice would have a high ratio of radiation length (X_0) to nuclear interaction length, implying a low atomic number. Beryllium was chosen.

The secondaries and non interacting protons pass through a magnetic field that deflects the unwanted charged particles into a 4 m thick iron wall. This leaves the photons and neutral hadrons to strike a 4 mm thick lead (Pb) converter, positioned 14 m downstream of the Be target. Here the photons convert to electrons and positrons. The design of the converter is a compromise between the flux of the resulting pairs and the contamination by charged particles produced by the interaction of the neutral hadrons. We require the photons to convert while letting the neutrals and pairs pass through without interacting. Hence lead is used as it has a low ratio of radiation length to

nuclear interaction length.

Approximately 40% of the photons convert in the lead converter. The electrons were selected from the resulting electron positron pairs via sweeping magnets and passed through a chicane by three bending and two focusing magnets. The electrons so selected had a mean energy of 140 GeV. The neutral and positive particles were dumped into a 4 m iron wall. Electrons rather than positrons were selected to reduce the contamination due to positive muons (μ^+), which result from π decays between the Be target and the 4 m iron wall. The ratio of μ^+ to μ^- is approximately 2.

The electrons then pass through a 0.5 mm lead sheet (the radiator), in which bremsstrahlung occurs. About 10% of the electrons in this sheet radiate a single high energy photon, forming the beam used by NA14. A greater yield of photons could be produced if the sheet was thicker but this would increase the probability of multiple bremsstrahlung. The beam parameters are summarised in table 1.

Primary proton beam	intensity energy	2×10^{12} 400-450 GeV
Electron beam	intensity/burst energy range mean energy	10^8 120-250 GeV 140 GeV
Photon Beam (γ energy cut 40 GeV)	intensity mean energy	5×10^6 80 GeV
Beam size	Horizontal F.W.H.M Vertical F.W.H.M	34 mm 22 mm
Hadron contamination		$< 10^{-4}$

TABLE 1

NA14 Gamma Beam Parameters

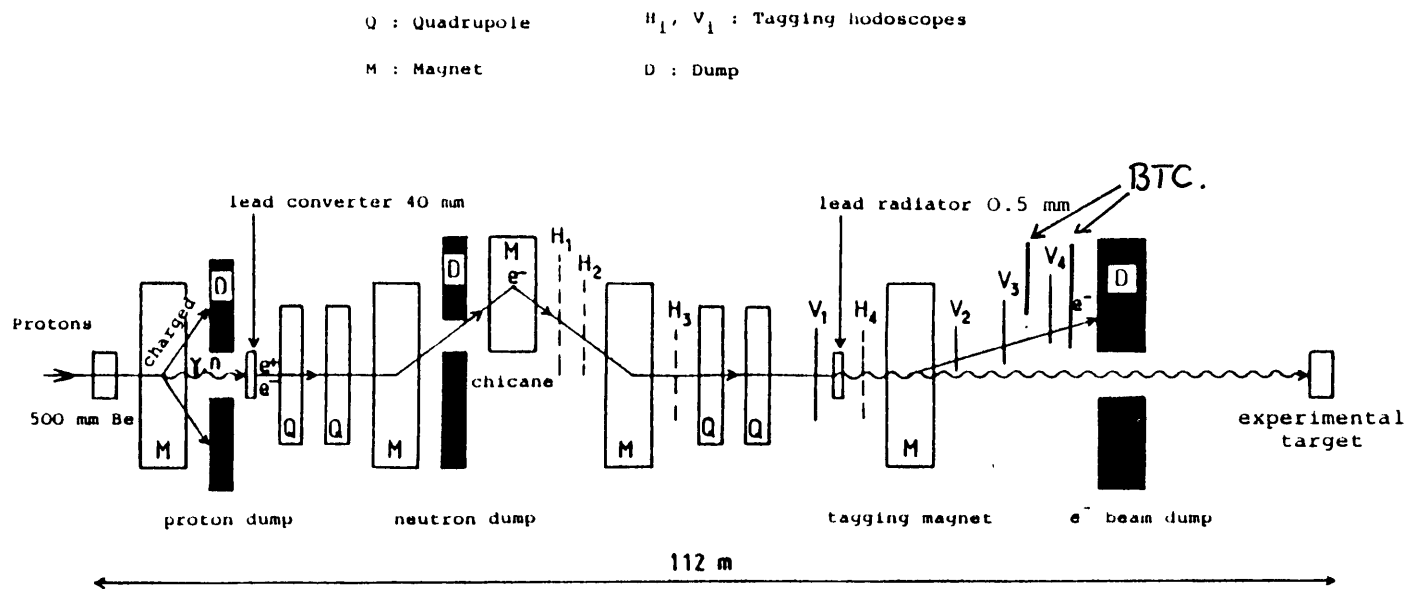


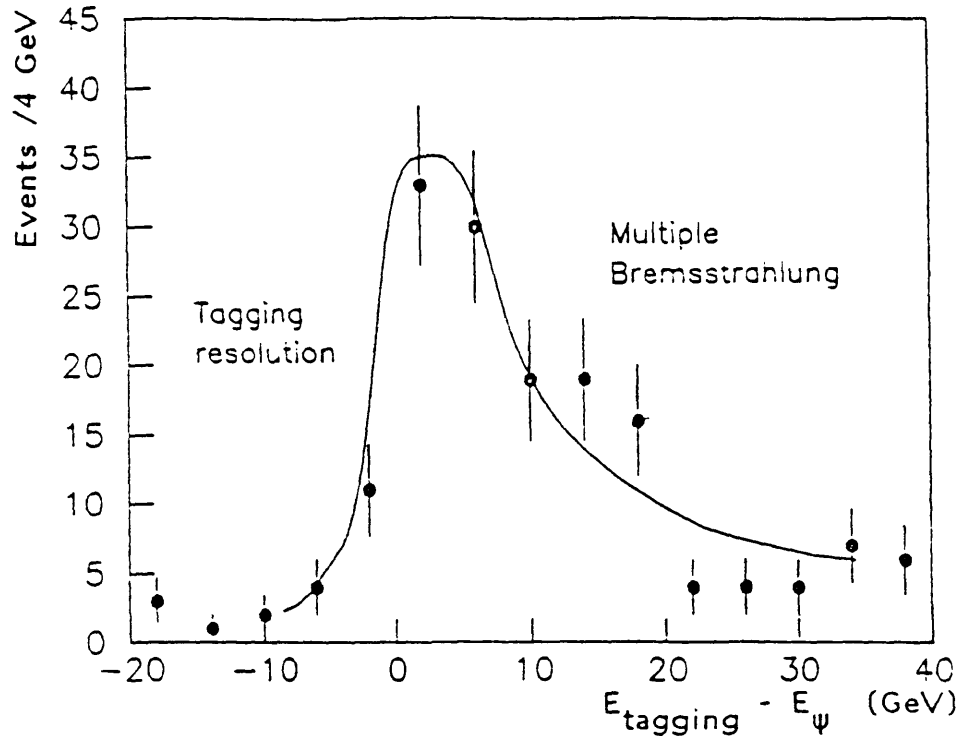
Figure 2: Photon Beam Production

2.3 THE TAGGING

The photon's energy is tagged by measuring the momentum of the electron, upstream and downstream of the radiator. Each upstream electron is detected by the scintillator hodoscopes H1, H2, H3 and H4 (see figure 2). Each downstream electron is detected by V1, V2, V3, V4 and the Back Tagging Counter, BTC (which is also part of the pretrigger) [16].

The tagging counters were scintillator hodoscopes, used in preference to MWPCs because of the intensity of the electron beam. MWPCs do not react fast enough to cope with the 10^8 electron s^{-1} beam flux. The scintillator hodoscopes were connected to fast photomultipliers and TDCs, which provided a timing resolution of about 1 ns. The timing information from the up and downstream detectors was used to associate an upstream electron with a downstream electron. With this information a solution for the energy of the photon can be obtained.

The energy resolution of the tagging is demonstrated in figure 3, which shows the difference between the tagging energy and the energy of the elastic J/ψ (measured in the MWPCs in the $\mu^+\mu^-$ channel). The long positive tail is due to multiple bremsstrahlung.

Figure 3: Elastically produced J/ψ

2.4 THE PION BEAM

A π^- beam was used to compare hadro- to photo-production. By removing the 4 mm lead converter and switching off the magnets directly upstream of the proton dump, all the charged particles were allowed to pass through, see figure 2. Due to the difference in the interaction cross section for hadroproduction compared to photoproduction, the intensity of the primary proton beam is reduced by a factor of 100, thereby reducing the experimental beam flux by the same factor. Negative particles were selected in the same way as the electrons, via the chicane, and were delivered to the experiment by turning off the tagging magnet and removing the 0.5 mm lead radiator. The beam is

referred to as the π^- beam, since π^- dominates the K^- and $\bar{p}$, and has an energy of 90 ± 6 GeV. The spread in momenta is determined by the aperture size of the neutral particle dump. The central value is chosen to correspond to the mean photon energy.

2.5 THE SPECTROMETER MAGNETS

The AEG magnet, where the Silicon Vertex Detector is located, sweeps out the e^+e^- pairs with energies < 100 MeV, and gives a coarse momentum measurement for backward tracks (as measured in the centre of mass frame). The Goliath magnet is used to measure the momentum of energetic particles (> 1.5 GeV). The important details of the magnets are given in tables 2 and 3.

Magnetic Field	$B = 1.4\text{T}$
Vertical Opening	50cm ($z = \pm 25\text{cm}$)
Horizontal Opening	130cm ($y = \pm 65\text{cm}$)
Integrated Field	$\int B dl = 1.3\text{Tm}$

TABLE 2

AEG Magnet Parameters

Magnetic Field	$B = 1.3\text{T}$
Vertical Opening	120cm ($z = \pm 60\text{cm}$)
Horizontal Opening	240cm ($y = \pm 120\text{cm}$)
Position along the beam line from target	$4.36\text{m} \leq x \leq 6.64\text{m}$
Integrated Field	$\int B dl = 3.1\text{Tm}$

TABLE 3

Goliath Magnet Parameters

2.6 MULTI-WIRE PROPORTIONAL CHAMBERS (MWPCS)

In order to track the charged particles there are three stacks of MWPCs, located as shown in figure 1. Proportional chambers are used rather than drift chambers owing to the very high flux of particles. They are placed as far as possible in field free regions to avoid problems produced by spiralling electrons and because there are difficulties in finding a fast-tracking algorithm to work in high magnetic fields.

Table 4 gives the parameters of the various wire chambers used in the experiment.

Stack One, immediately downstream of the AEG, consists of 4 small but fast chambers, 2 Orsay chambers and 6 CPK chambers. Each chamber has a "beam killer" at its centre (as shown in figure 4). The larger chambers also have moustaches (also shown in figure 4) to render the central horizontal plane inactive. These prevent the chamber being swamped by the large number of e^+e^-

Chamber type	Number	Number of Planes	Angle of wires w.r.t. horizontal	Number of wires	Pitch of the wires
CPK Chamber	6	4 VO V H HO	76° 0° 90° 104°	766 896 576 368	2mm
Saclay CPK Large Area	3	4 H V VO HO	0° 90° 104° 76°	1024 704 1024 896	3mm
Orsay Chamber	4	4 X1 U V X2	90° 120° 60° 90°	1792 1792 1792 1792	2mm
Fast chamber	4	2 V VO	90° 120°	256 256	1mm
Hexagonal Chamber	3	3 L1 L2 L3	0° 120° 60°	616 616 616	3mm

TABLE 4

Wire Chamber Parameters

pairs. The smaller fast chambers have no need of moustaches due to their small area (5x4 cm²) and shorter gate time 50 ns cf 100 ns of the larger chambers. The fast chambers are placed inside the AEG to provide track information close to the target.

Stack Two has 5 chambers which contain 20 planes^{of wires}. Six planes have large area (6m²), and are intended to track particles which travel at large angles to the beamline emerging from Goliath.

Stack 3 consists of 3 hexagonal chambers of 3 planes each. Stacks 1 and 2 are used for pattern recognition while Stack 3 is used to give a more precise momentum measurement on the high

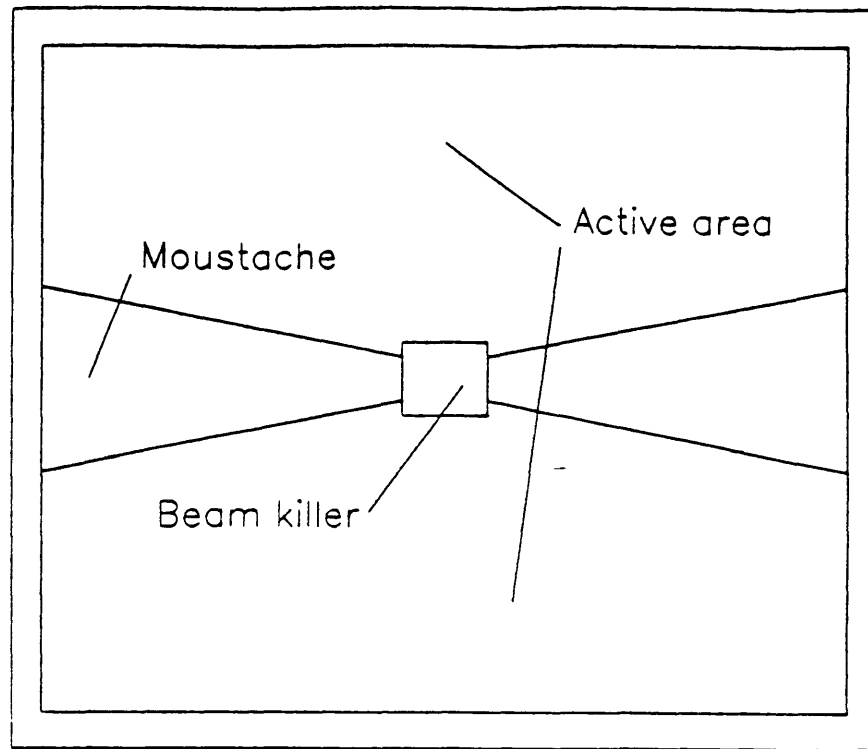


Figure 4: Beam Killer and Moustache

momentum tracks.

2.7 THE CERENKOV

To facilitate particle identification there is a segmented threshold Cerenkov Counter [15]. Basically this is a 3.1m long sealed box containing dry air. An array of 48 mirrors reflects the Cerenkov light received on to 8 photomultiplier tubes. (see figure 5 for the mirror pattern)

Note the gap between the second and third rows of the mirrors: like the MWPCs this region is desensitized to avoid problems due to e^+e^- pairs. The Cerenkov was used in analysis as a threshold device. The theoretical thresholds for light production are

5.73 GeV/c and 20.27 GeV/c for pions and kaons respectively. The observed values, which are not well defined, can be seen in figure 6.

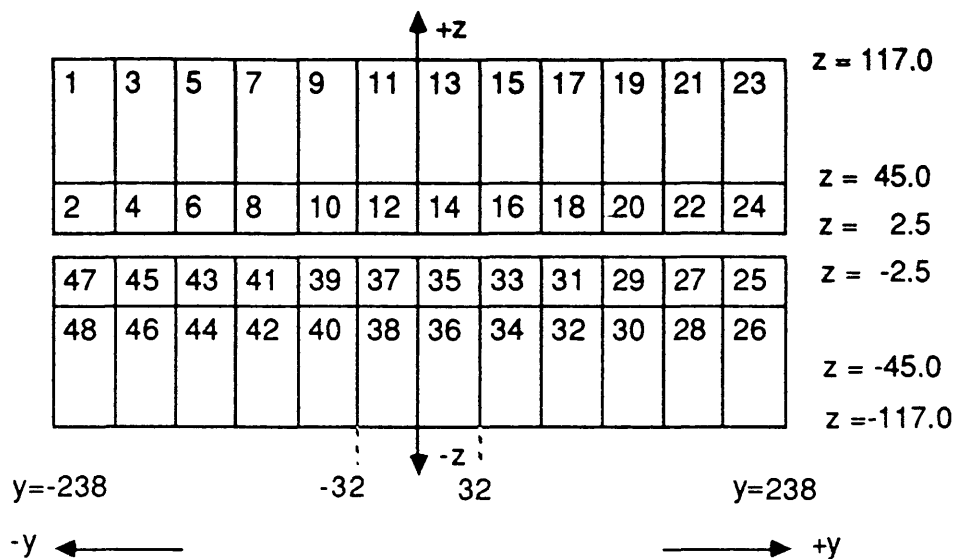


Figure 5: Mirror pattern of the Cerenkov Counter

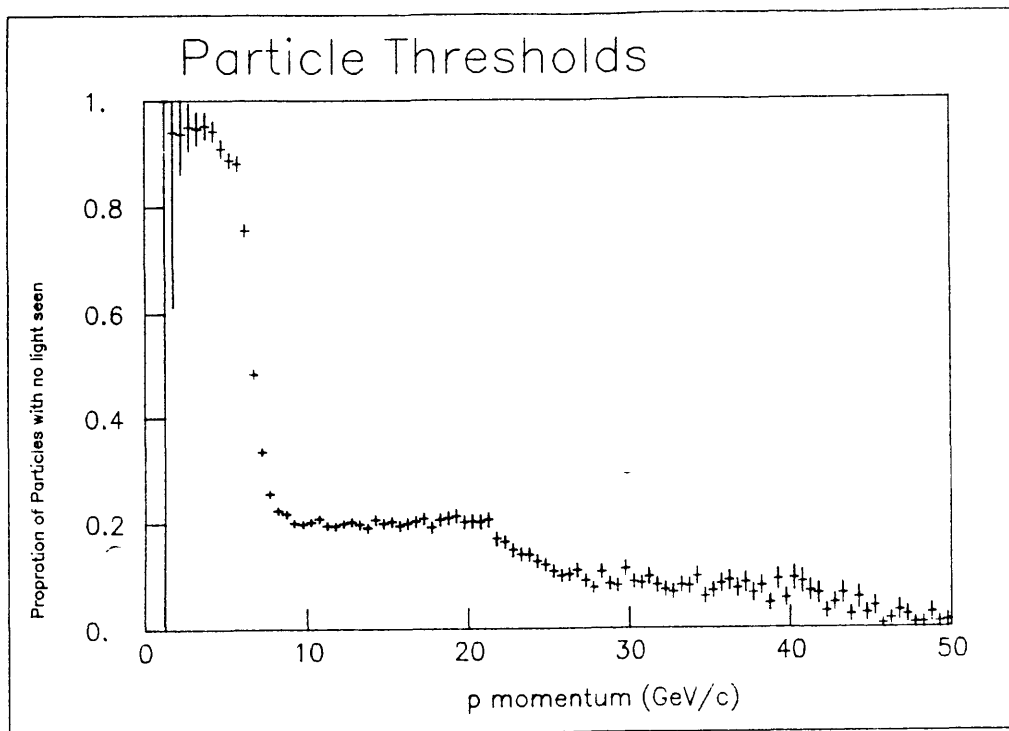


Figure 6: Threshold of light output for Cerenkov

2.8 SCINTILLATOR HODOSCOPE ARRAYS

There are three scintillator hodoscope arrays. The purpose of these detectors is to trigger on a hadronic event. The detectors are:-

1. G1 lies 1.85 m downstream of the target in Stack One. It consists of 80 vertical scintillators each with an area of 55 cm x 5.4 cm arranged in four planes of twenty, two above the beam and two below. The back plane in each pair is displaced by 2.7cm relative to the front plane. The gap between top and bottom planes is 5cm.
2. G2H lying 7.5 m downstream of the target, consists of 32 elements 120 x 7cm² horizontally arranged and placed

downstream of Goliath. The elements overlap and again there is a 5cm gap between elements in the central horizontal plane.

3. G2V is 0.8 m downstream of G2H and consists of 24 vertical scintillators measuring 75x20cm² each. They are arranged in 2 arrays of 12, one above, one below the beam axis, separated by 6cm.

All three hodoscopes can be considered to be in two halves, one below and one above the beam line.

2.9 THE MUON FILTER

At the end of the spectrometer there is an iron wall, 20 m downstream of the target and 5 m thick. Two metres into the iron there is a scintillator hodoscope, H1H, followed at 5m depth by hodoscopes H3H, H3L and H3V. The horizontal scintillators H1H and H3H are arranged with a geometry which points to the target thus distinguishing μ 's produced there from the halo muons, which are essentially parallel to the beam. A particle satisfying the coincidence condition in these hodoscopes is interpreted as a muon.

2.10 THE ELECTROMAGNETIC CALORIMETERS

In order to detect electrons and photons over wide angles, there are three electromagnetic (EM) calorimeters. The forward region is covered by OLGA; the intermediate region is covered by ILSA; and for the backward hemisphere of particles in the centre of mass system, there is CROWN.

The coverage of the EM calorimeters, as seen by the approaching beam, is shown in figure 7 where the angular acceptance in the laboratory system is defined.

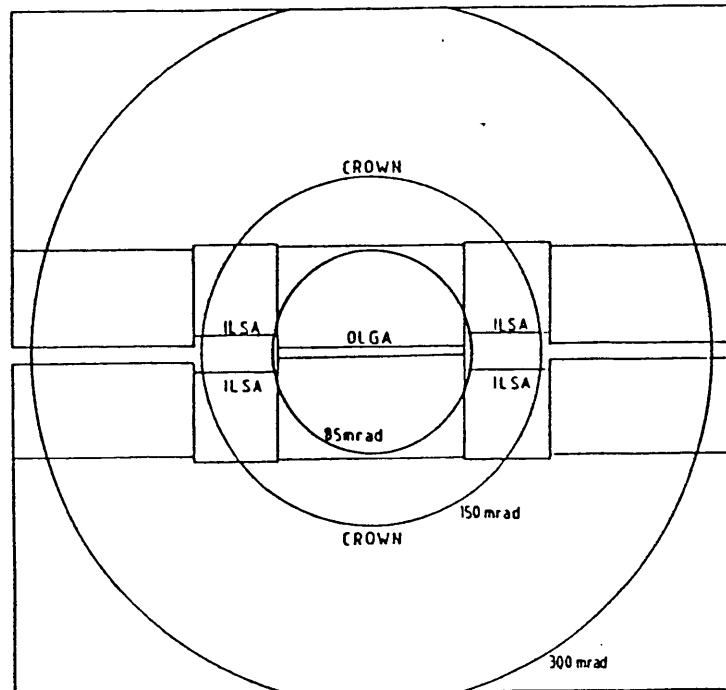


Figure 7: Photon's eye view of the spectrometer

The CROWN (see F figure 1) is situated 2.5 m from the experimental target. Its function is to detect electrons and photons emitted backwards in the centre of mass, hence the necessity for a wide angular acceptance and its proximity to the target. The lead glass blocks in this calorimeter are $9 \times 9 \text{ cm}^2$. The photon position detector in front of CROWN, known as Kali, is an orthogonal scintillator array with finger widths of 8 mm. Due to the proximity of the target the showers from π^0 decays are not

well separated. For this reason the converter in front of Kali consists of 5 radiation lengths of inactive lead in preference to lead glass, thus minimizing the lateral extent of the showers.

OLGA (see O figure 1) is very similar to CROWN in construction. It is further away from the experimental target (~ 15 m) so its components are larger. OLGA is made from 344 lead glass blocks, each block being 18.5 radiation lengths deep and presenting an area of $14 \times 14 \text{ cm}^2$ to the on coming particles. As with the other detectors described in this chapter the central horizontal region is not covered, as the high flux of e^+e^- pairs would darken the glass through radiation damage. In front of the blocks are two orthogonal planes of scintillator fingers 1.5 cm wide. This array is used as a position detector and is known as Penelope. In front of Penelope there are 3 radiation lengths of active lead glass converter and an array of charge veto counters, used to distinguish γ 's and e 's. One cell of OLGA is shown in figure 8. *(Note 20% of γ 's simulate electrons due to back scattering of the electromagnetic shower).*

ILSA (see N figure 1) is a lead scintillator sandwich calorimeter placed 13.5 m downstream of the silicon experimental target. It consists of 4 quadrants positioned as shown in figure 9. Each quadrant consists of 4 layers of calorimeter modules A, B, C and D, four cells to a layer each cell measuring $25 \text{ cm} \times 100 \text{ cm}$ and aligned alternately vertically and horizontally. Thus a $25 \times 25 \text{ cm}^2$ crossing area is formed, which is covered in front by a $27 \times 27 \text{ cm}^2$ scintillator array acting as a charge particle veto. The modules are composed of layers, 6 layers in A and B, and 9 layers in C and D, each layer being built up from

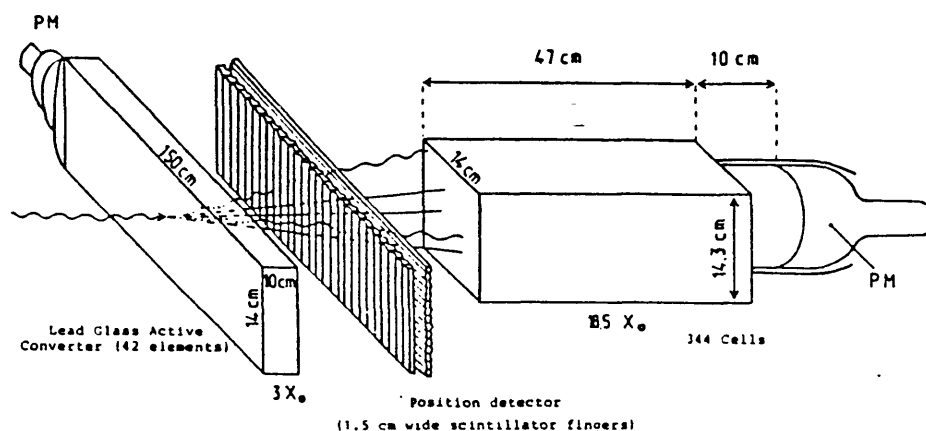


Figure 8: OLGA cell

5 mm thick sheets of plexipop scintillator sandwiched between 3 mm sheets of lead. This means that the A and B modules are approximately $3.5 X_0$ and the C and D modules about $5.5 X_0$. In front of the modules is a $1X_0$ sheet of lead, to enhance conversion before the position detector. The position detector, known as Ariadne, consists of 1.5m long strips of scintillator arranged in two orthogonal arrays at a depth of $4.5 X_0$ behind the first module layer A. There are also 2 additional scintillator counters S and T, one in front and one behind the B module. These counters are used to trigger the calorimeter.

The calorimeters receive only a brief description as they play a minor role in the physics analysis presented in this thesis.

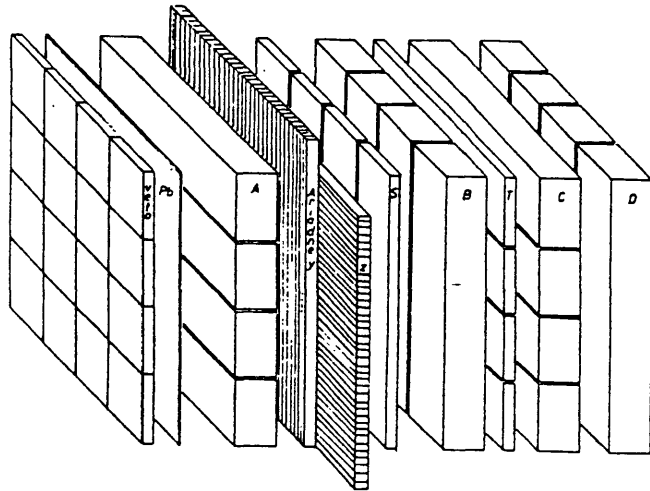


Figure 9: ILSA plan

They are used to measure the effect of electron contamination in K/π ratios.

2.11 THE PRETRIGGER PT1

All the triggers for the NA14 data acquisition are strobed by a pretrigger which provides an unbiased sample of hadronic photon interactions. The timing signal for the experiment is derived from the beam tagging counters. The pretrigger demands that:

1. An electron from the radiator must have energy of less than 80 GeV. The energy is determined by the trajectory downstream of the second tagging magnet. This corresponds to there being a photon of > 60 GeV.

2. There must be a signal of less than 2 Minimum Ionizing Particles (MinI) in the charge veto which lies upstream of the target. This provides protection against showers from electrons which strike the last collimator of the beam.
3. The following conditions must be fulfilled:-
 - a) A 'hit' in each of the scintillator hodoscopes G1,G2H,G2V upper halves or the lower halves.
 - b) ≥ 1 hit in G2H in the opposite half to a).
 - c) There must be no hit in the muon veto in the same half (up or down) as the scintillator hodoscope hits.
4. The silicon active target must show evidence for an interaction in its central region ($\sim 1 \text{ cm}^2$).

Events taken with this pre-trigger have a 50% probability of being hadronic.

Chapter III

SILICON DETECTORS

3.1 INTRODUCTION

Semiconductor detectors have been used for many years in Nuclear Physics, but it is only in the 1980's that they began to be widely used in Particle Physics. This arose from a need for accurate measurements of tracks near the vertex of events containing short lived particles, and the available technology whereby solid state devices with the necessary high spatial resolution and compact read out electronics could be built.

The advantages of the solid state detector are a high energy resolution, a relatively simple structure and fast signal collection. For counter experiments, eg NA14, the fast output is particularly important because of the high counting rates involved to match the high interaction rates which can be accommodated by a detector based on MWPCs. There are naturally some disadvantages: for example their small size limits their applications in collider experiments and after long exposure to radiation their performance is degraded.

3.2 SEMICONDUCTORS

A semiconductor is a substance with a small energy difference (~ 1 eV) between its valence and conduction bands. This energy difference is known as the Energy Band Gap. Many materials from conductors through to insulators have a crystalline structure, which gives rise to the energy band structure of the electrons. These crystals are formed by covalent bonds, which are produced via the valence electrons. The difference in energy between these valence band and conduction band electrons determines the electrical properties of the material. In a metal or other conductor the valence and the conduction bands overlap. In an insulator there is a large energy gap between the valence and conduction bands (>5 eV), and in a semiconductor there is a small energy gap ≈ 1 eV.

In a semiconductor, when an electron is excited into the conduction band, a 'hole' is left behind in the valence band. The electrons and holes behave in a similar manner, for example their mobilities are of the same order, which means their drift time in an electric field is also similar.

The two main semiconductors used as detectors are Germanium and Silicon. Their energy band gaps are 0.66 eV and 1.12 eV respectively at 300 K. Silicon is preferred as it can more easily be used at room temperature. Germanium detectors, because of the smaller energy band gap, have a larger leakage current, and they may have to be cooled. Although in the following sections silicon (Si) detectors are described, many of the arguments apply equally to germanium.

Although the energy band gap in silicon is 1.12eV, the energy required to form an electron hole pair (e/h) via ionization from a charged particle is 3.62eV. The increase in energy is due to the interactions of the electrons with the crystal lattice resulting in lattice vibrations. Even so, the energy resolution is much better than the 30eV per ion/electron for gases and the 300 eV/photoelectron in a scintillator.

In intrinsic (ie pure) semiconductors, in the absence of ionizing radiation, all the electrons in the conduction band and all the holes in the valence band are there as a result of thermal excitations. The number of electrons and holes therefore balance one another.

$$n_i = p_i$$

n_i = number of conduction electrons per unit volume.

p_i = number of holes per unit volume.

It is not possible to obtain absolutely pure semiconductors, some impurities will always remain. Even the small traces of impurities found after purification can dominate the electrical properties of the material. To get the desired properties from a semiconductor small quantities of impurities are added deliberately. The effect of these impurities is described in the following section.

3.2.1 n-type and p-type Semiconductors

Silicon, in its normal crystalline structure, is tetravalent. An atom forms covalent bonds with its four nearest neighbours. If a small concentration of pentavalent material, eg phosphorus, is introduced the same structure is formed. As there are 5 valence electrons in the impurity atom, one is left over after all the covalent bonds have been formed, therefore this extra electron is only very lightly bound to the original impurity site and very little energy is needed to excite it into the conduction band. A hole is not created as all covalent bonds are intact. This type of impurity with 5 valence electrons is known as a donor or n-type impurity, as it donates electrons to the conduction band.

The concentration of donor impurities added is such that the conduction band electrons are almost entirely from the impurities, i.e.

$$n \approx N_d$$

where n = N° of electrons per unit volume $\gg n_i$

N_d = N° of donor atoms.

The added concentrations of electrons in the conduction band increase the rate of recombination, hence fewer holes exist. In equilibrium conditions the product of n and p is the same as for the intrinsic material

$$np = n_i p_i$$

where p = N° of holes per unit volume $\ll p_i$

In n-type silicon the electrons are called the majority carriers and the holes are the minority carriers.

In a p-type semiconductor a trivalent impurity such as boron

is introduced to the silicon lattice. Since there are fewer valence electrons than needed for the covalent bonds to the surrounding silicon atoms, a hole is formed, but no electron is put into the conduction band. Normal thermal excitation in the crystal ensures that there will always be electrons to fill these vacancies in the lattice. Since the electrons come from other normal covalent bonds the holes appear to move. The materials that yield p-type semiconductors are called acceptor impurities.

In an analogous way to the electrons in the n-type, the concentration of holes in p-type is dominated by the impurities

$$p \approx N_a$$

where N_a = The number of acceptor atoms per unit volume.

In this case the holes are the majority carriers and the electrons are the minority carriers.

3.2.2 Resistivity

The doping concentration of a semiconductor determines the resistivity ρ ,

$$\rho = \frac{1}{\sigma} = \frac{1}{q(\mu_e n + \mu_h p)}$$

where μ_e and μ_h are the mobilities of the electron and

holes respectively and q is the charge on the electron.

The highest resistivity readily achievable in silicon is 20 k Ω cm, corresponding to a doping of $\approx 10^{11}$ atoms per cm³. (In germanium doping levels of 10^9 atoms per cm³ can be obtained.)

A high resistivity is important for detectors, and this aspect

will be considered in more detail later.

3.2.3 Trapping and Recombination

Metallic impurities in the silicon can form what are known as 'deep impurities'; they sit in the middle of the energy band gap. These impurities can act as metastable traps for electrons and holes, and are called 'recombination centres'. These centres release the carriers after a time, but the time delay is often long enough to prevent a carrier from contributing to the measured pulse from a detector. Recombination centres may also capture both electrons and holes, which annihilate resulting in a loss of carriers

3.3 OPERATION OF A SEMICONDUCTOR JUNCTION DETECTOR

The passage of an ionizing particle through a semiconductor detector produces electron hole pairs. To collect these pairs, an electric field is applied across the detector. This field causes a leakage current to flow, due to the finite resistivity of the semiconductor. The leakage current is a source of noise (to be discussed later) and so in order to see the small signal produced by the passage of a particle, it needs to be as small as possible. This cannot be achieved at room temperature with intrinsic silicon, as the leakage current is too high. A p-n junction diode structure, when used in the reverse bias mode, overcomes the leakage current problem as described below.

When a p-n junction is formed, electrons from the n region diffuse into the p region; likewise holes from the p region

diffuse into the n region. This establishes a space charge region due to the crystal ions which have become depleted of free charge carriers. If the diode is reverse-biased (i.e. the n-type is biased positive with respect to the p-type silicon), the depleted zone is extended. With a sufficiently high voltage the diode can be totally depleted. Any current that flows must come therefore from minority carriers. Hence the use of a p-n junction reverse biased diode as detectors of ionizing particles. The leakage currents are then sufficiently small to allow the signal to be detected.

To collect as much signal charge as possible from a traversing particle a fully depleted solid state detector is needed. If the detectors are not totally depleted not all the charge is collected due to recombination in the field free undepleted region.

The relationship between depletion depth, W , and applied voltage, V , follows from Poisson's equation and is given by [17,18,19],

$$W = \sqrt{(2\epsilon_s V \mu_h \rho)}$$

where $\rho = 1/q\mu N_b$ $1/N_b = 1/N_n + 1/N_p$

and μ is the mobility of the minority carriers.

Hence for silicon of a given resistivity, the voltage to deplete totally can be evaluated. If the field is too high the silicon will break down, so to achieve total depletion without breakdown, high resistivity silicon is used (Breakdown field for Si $\sim 3 \times 10^5$ V/cm). Silicon used in the manufacture of integrated

circuits is a few Ωcm , that of silicon used in Particle Physics is $\sim 5000\Omega\text{cm}$ where the required depletion depths are $\sim 300\text{--}400\ \mu\text{m}$.

3.4 P-N JUNCTION CONSTRUCTION

There are three established techniques of making p-n junctions, namely, Diffusion, Surface Barrier and Ion Implantation. It is the Ion Implantation technique developed by the micro-electronic industry for producing high resolution structures on silicon which is employed in the NA14 detectors.

3.4.1 Ion Implantation

An ion implanted junction detector is made using the standard techniques developed by the micro-electronic industry, passivisation, photolithography and doping. The essential processing steps are shown in figure 10 [23]; a more detailed description of the NA14 detectors' construction follows.

A crystal of n-type silicon with a resistivity of between $3000\text{--}6000\ \Omega\text{cm}$ was sawn along the (1,1,1) axis into wafers of ~ 350 or $450\ \mu\text{m}$ thickness, depending on the thickness of detectors required. One side of the wafer was polished, to form the front surface, and the other was etched to form the back surface of the device. The back surface was then gettered by spraying it with $25\ \mu\text{m}$ diameter aluminium oxide particles from an air gun. The gettering process helps to remove the heavy ion and oxygen impurities that form trapping centres in silicon. The wafer was then heated to 1030°C and exposed to a stream of oxygen

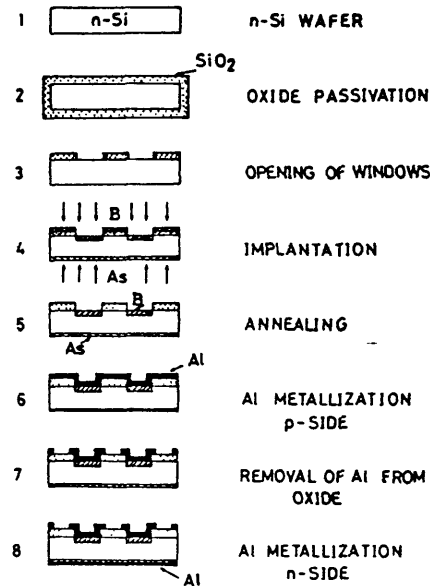


Figure 10: Processes in Semiconductor Diode Construction

and water vapour so that a layer of SiO₂, 0.8 μm thick, is formed on the surface. The controlled production of the oxide layer, which contains far fewer impurities than if produced naturally, stops the formation of high electric fields between the front surface and the sides and helps to protect the bulk of the silicon from contamination. This process is called passivisation.

The next stage was photolithography, the basic steps of which are shown in figure 11 [23]. Photoresist was applied to the front surface of the wafer and a mask that contained the pattern of the diodes aligned on the surface. The wafer was then irradiated with ultraviolet light, thus hardening the photoresist

in the exposed areas not covered by the mask. This was followed by treating with developer whereby the unexposed photoresist was removed. The exposed areas of SiO_2 were removed in hydrofluoric acid (HF) and the hardened photoresist by nitric acid. The wafer was then irradiated by boron ions, at 20 keV, to produce the p-type layer implant of $\sim 0.25 \mu\text{m}$. The ion implantation causes damage to the crystalline structure so following the implantation process the wafer was annealed at $\sim 600^\circ\text{C}$. The metal contacts were then applied, aluminium on the back surface and gold on the front surface in thin films using electron beam evaporation. On the front surface photolithography was again used to remove the unwanted metal from the oxide areas. All these processes were carried out in the laboratories of Micron Semiconductor Ltd., where the cleanest conditions are maintained in order to reduce the danger of contamination with impurities that would ruin the devices.

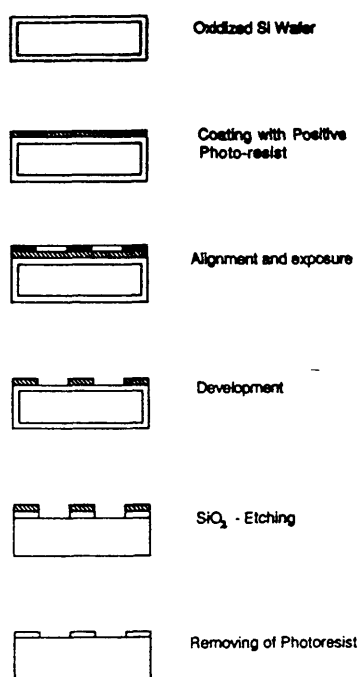


Figure 11: Processes of Photolithography

3.5 CHARGED PARTICLE DETECTION

The object of the semiconductor detector and associated electronics is to monitor the passage of a charged particle and pass the information gained to a computer to be recorded; usually on magnetic tape. The process of charged particle detection can be described in three stages. Formation of the signal, Collection of the signal and Signal processing. These stages are described in the final three sections of this chapter.

3.6 FORMATION OF SIGNAL IN SILICON DETECTORS

The charge collection from a silicon detector has two contributors, the signal from an ionizing particle and the leakage current inherent in all semiconductor devices.

3.6.1 Energy Loss in Silicon Detectors

The signal from an ionizing particle is derived from the energy loss process. Given that the silicon is $\sim 400 \mu\text{m}$ the energy loss is that of a thin absorber as treated by Landau, Vavilov et al. [24,25,26]. The signal size has a Landau Distribution and as such is subject to large fluctuations. The mean (Δ) and the most probable energy loss can be calculated but not the loss in any single interaction. Given a particular value of the Landau distribution parameter λ the energy loss Δ can be calculated using

$$\lambda = \frac{\Delta - \bar{\Delta}}{\xi} - (1 - \beta^2 - C) - \ln(K)$$

Choosing a random value from the Landau distribution and calculating the resulting energy loss is used in Chapter 4 in the microstrip detector simulation. An explanation of the symbols is given in Appendix A along with a brief account of the contributions of Landau, Vavilov, Bichsel et al. to the subject. An account is also given, in Appendix A, of the 'broadening effect', which is due to electrons being in a material and not free as assumed by Landau et al.. This effect becomes more

significant as the wafer thickness decreases.

The observed signal from a detector is the sum of the energy loss and the effect of the amplifier noise.

3.6.2 Leakage Currents

The diode structure stops the migration of the majority carriers, but this only reduces the leakage current. Two sources remain, one from the bulk of the material, the other from its surface. The contribution from the bulk can in turn be split into two different types. The first is diffusion of minority carriers across the junction due to the electric field, a minor source of the current. Secondly, electrons and holes are generated by traps or faults in the silicon. The rate at which these trapping centres generate e/h pairs is proportional to their cross-section and the density of such centres, and depends on their position in the energy band gap. The number of such centres that contribute to the leakage current is proportional to the depleted volume. Hence the current generated from this source increases with the voltage as $\sqrt{V}$.

The sources of the surface currents are not well understood, but the currents depend on temperature, time, humidity and the environment in general. To reduce surface leakage currents encapsulation techniques are sometimes used. An example of one such technique is applying Silicon nitride (Si_3N_4) to the surface of the detector. This though has the disadvantage of introducing a dead layer through which the particle will have to travel.

a) Radiation Damage

There are two major sources of radiation damage, the Frenkel defect and surface effects. The operation of any semiconductor detector depends on the near perfection of its crystal lattice. This is to ensure that defects do not trap the carriers and cause incomplete charge collection. Frenkel defects are produced by the displacement of an atom in the semiconductor from the normal lattice site. The vacancy in the lattice and the atom now in an interstitial position, constitute trapping sites for the carriers. The surface effects are due to ionizing radiation causing a build up of +ve charges in the SiO_2 and in the Si/SiO_2 interface. The charges build up after the passage of a charged particle due to the high mobility of the electrons in SiO_2 and the relative immobility of the holes. These charges on the surface result in higher leakage currents. All of these effects lead to a worsening of the signal to noise ratio.

3.7 COLLECTION OF THE SIGNAL

In collecting the signal there are two important considerations, the collection time of the signal, and the effect of the diodes being in close proximity to one another, as is the case with microstrips.

3.7.1 Collection Time

The charge deposited in a silicon detector by an ionizing particle has to be collected. The collection takes a finite time known as the 'collection time'. This period is measured from the production of the charge until the arrival of the e/h at the anode/cathode of the diode.

For a single carrier the collection time depends on the time required for the carrier to travel from its production point, to its collection point. The time to cross the device is then

$$t = \int ds / \mu E$$

where ds is the infinitesimal distance travelled in the detector,
 μ is the mobility of the carriers and
 E = local electric field.

A higher electric field therefore reduces the collection time, but at high fields ($>10^3$ V/cm) the mobility of the electrons and holes decreases, since the mean free path of the carriers decreases with their increased energy. The collection time is calculated using the 'abrupt approximation' [18] and the solution of the electric field in the depleted diodes. The resulting collection time is :-

$$t = \frac{-d^2}{2V_D\mu} \left[\ln\left(\frac{V-V_D}{x} + \frac{2V_D}{d}\right) - \ln\left(\frac{V-V_D}{d} + \frac{2V_D}{d^2}x\right) \right]$$

V = total voltage applied across the diode.
 V_D = voltage needed to totally deplete the diode.
 d is the depleted depth of the diode (= thickness of diode)
 x is direction of electric field $0 \leq x \leq d$.

Typical collection times when measured are of the order 10 - 20ns in 300 μ m of silicon.

3.7.2 Charge Sharing

So far the discussion has involved the general characteristics of a single diode detector. The detectors used in Particle Physics are, for the most part, arrays of such diodes. The diodes forming a microstrip array are on the same crystal and cross-talk between them is possible. The cross-talk in this case is where energy that was released in a diode is detected in neighbouring diodes. This phenomenon has two main causes - diffusion and δ -rays - and because the transfer of charges is involved, it is known as 'charge sharing'.

a) Diffusion

The ionizing particle produces electrons and holes (e/h) in a narrow tube around its path. After production the e/h pairs drift in the electric field towards the appropriate electrode. During their drift diffusion occurs consequently the charge distribution at the readout point is enlarged. The magnitude of the increase can be found from solving the diffusion equation

$$\nabla^2 C = \frac{1}{\alpha^2} \frac{dC}{dt}$$

where C is the charge density and α is the diffusion constant.

and making the following assumptions:-

1. The incident particle traverses the Detector at time $t = 0$.
2. The path of the particle is along $y = z = 0$
3. A unit charge is deposited.

The solution is then

$$C(x, y, z, t) = \frac{1}{4\pi D_h t d} \exp[-(y^2 + z^2)/(4D_h t)] \quad \text{for } 0 \leq x \leq d$$

where D_h is the diffusion constant of holes in silicon and x is the direction of the electric field (figure 12).

This means the resulting charge distribution has an R.M.S. of $\sqrt{(2 \cdot D_h \cdot t)}$, where t is the time it takes a hole or electron produced at point x_0 to reach the collection point (see 3.7.1).

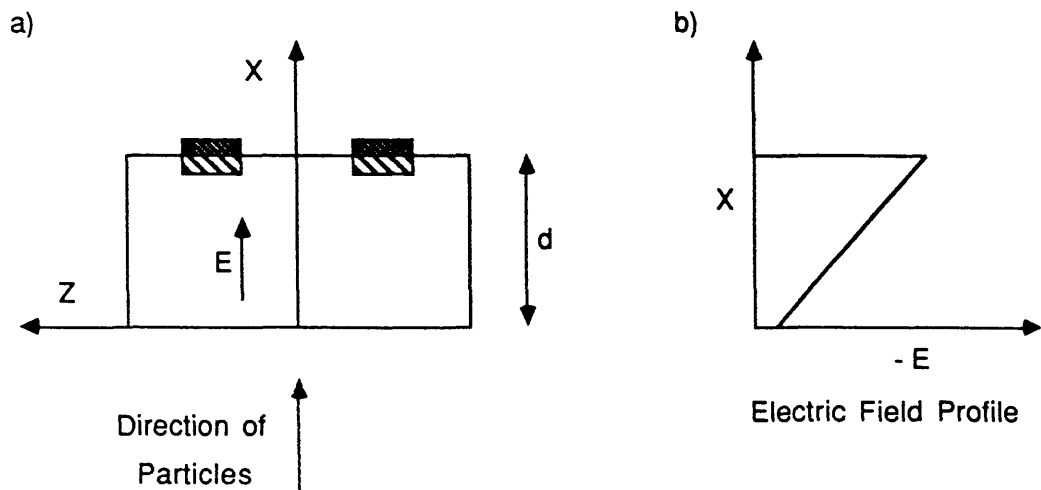


Figure 12: Electric field direction and Profile in a Diode

Hence knowing the drift time, the charge distribution at the

readout is calculated and the amount of charge sharing between diodes due to diffusion can be estimated.

b) δ -Rays

The other process that results in the sharing of charge is the production of δ -rays. The name δ -ray is given to an ionised electron that has enough energy to become a secondary ionizing particle. The distance travelled by δ -rays is dependant of their initial energy, which is lost relatively rapidly. Given enough energy and depending on the direction, a δ -ray can pass through two or more diodes. The number of diodes transversed is also a function of the diode pitch. Energy can therefore be transferred from one diode to another by δ -rays.

Due to multiple scattering it is difficult to estimate the distance a δ -ray will actually travel, but a practical or effective range can be found. For the simulation described in Chapter 4 two methods for the effective range were used. The first was derived by K.H.Weber [20] who gave an expression for the practical range vs kinetic energy

$$R = AT[1 - B/(1+CT)]$$

where $A = 0.55 \text{ mg cm}^{-2}$

$B = 0.9841$

$C = 0.003 \text{ keV}$

$T = \text{kinetic energy}$

$R = \text{distance travelled}$

The second method uses the results of M.J.Berger and S.M.Seltzer (NASA) [21] who examined the stopping powers of electrons and positrons in various materials including silicon. The two methods produce very similar results. From these results

it can be seen that δ -rays of energy 100 keV have a range of $\sim 58 \mu\text{m}$ in silicon, which is enough enable the δ -ray to pass into neighbouring strips and possibly be detected.

3.8 SIGNAL PROCESSING

To make use of the signal produced by the detector it first has to be amplified. After amplification the signal is superimposed on a background noise that is produced by the amplifier and in the detector itself. The reason for the noise from the amplifier and detector, plus some discussion on amplifier configurations used, are discussed below.

3.8.1 Detector and Amplifier Noise

The small signal currents ($\sim 40 \text{ nA}$ for $100 \mu\text{m}$) that are generated from a silicon particle detector tend to be obscured by noise. The objective therefore is to reduce the noise as much as possible.

The physical origins of noise are due to three main sources- Thermal or Johnson noise, Shot noise and Flicker or Modulation noise [22]. The causes of each are briefly dealt with in this section.

Thermal noise is due to fluctuations in the spatial distribution of the carriers, which arise from thermal diffusion. The magnitude of the thermal noise does not depend on the voltage or the dark or bulk current and is present even in the absence of an applied field. The equivalent current generated is given by

$$i^2 = 4kT\sigma\Delta f$$

k = Boltzmann constant,
 T = absolute temperature,
 σ = conductivity,
 Δf = bandwidth.

This thermal noise is negligible in high resistivity silicon and so is ignored in detectors used in Particle Physics.

Current or Shot noise in semiconductors is due to random fluctuations in the number of carriers. This leads to a change in conductivity and the noise power is proportional to the current flowing. The mean square noise current is given by

$$i^2 = 2qI\Delta f$$

where I = dark/bulk current

Finally there is the Excess, Flicker or Modulation noise which is a frequency dependent phenomenon: the mean square current is

$$i^2 \approx 1/f^n$$

where n is almost independent of temperature ($n \approx 1$)

Excess noise originates in the surface of the material and depends on the condition of the surface. The noise arises from two sources, firstly recombination of carriers in the surface traps, and secondly migration of e/h pairs in the surface layer material. In high resistance material the recombination is negligible. Migration dominates, and is reduced if the surface is clean and dry. The overall noise from the detector or amplifier is then

$$(\Delta E)^2 = (\Delta E_{\text{shot}})^2 + (\Delta E_{\text{flicker}})^2 + (\Delta E_{\text{johnson}})^2$$

For detectors ΔE represents the broadening of the energy loss distribution for minimum ionizing particles.

In conclusion the dominant noise sources for the detector are a combination of Shot plus Excess noise, while for the combined

detector amplifier system Johnson noise is dominant due to the high capacity.

3.8.2 Electronics

The small signals produced by the detectors have to be amplified. In many experiments two amplifiers are used, a head amplifier, as close as possible to the detector, followed by a main amplifier. These amplifiers must be able to handle the high count rates produced by high intensity beams (10^6 interactions per second is typical). They must also be small and have a low power consumption as many channels have to be used to read an array of detectors, and the amplifiers have to be packed as densely as possible.

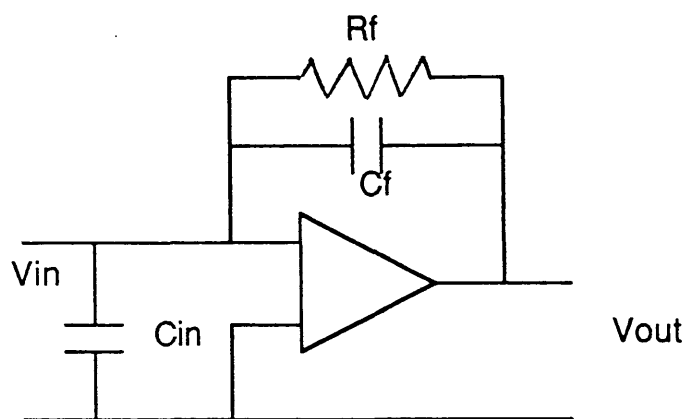
In the design of the head or pre-amplifier much effort has been directed at reducing the noise generated. They must also be simple and cheap to construct. Three basic designs of low noise amplifier are used in conjunction with silicon detectors. They are shown in figure 13 [27]. In all three types the input stage is responsible for the majority of the noise generated. Due to the high counting rates and therefore the high frequencies used in particle physics, the pre-amplifiers have to produce short width pulses at their output. At high frequencies bipolar transistors can compete with Field Effect Transistors (JFETs) on noise production, so are often used on the input stages of these amplifiers.

The question: 'Which is the best preamplifier to use?', is difficult to answer. The special requirements and circumstances

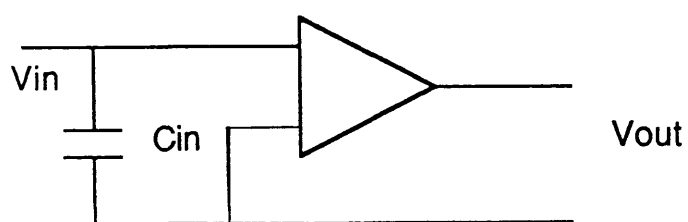
of the experiment and what is available determines the device used [27]. For NA14 a current sensitive pre-amplifier, the MSD2, was chosen because it had few components and was therefore low in cost and in power consumption. It was also fast enough to handle the counting rates of the experiment.

For use with ADCs and discriminators the current sensitive amplifier has the advantage of not requiring a special CR circuit to stop 'undershooting', as is required by the two other designs. Their disadvantage is that they are noisier than the charge sensitive design by at least a factor of 2. As an example, the MSD2 in normal running conditions has a equivalent noise charge of $\sim 2000e$ while a charge sensitive amplifier would have $\sim 1000e$.

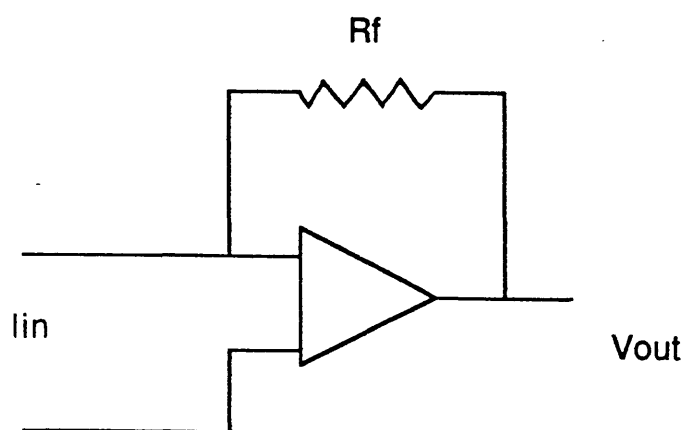
The main amplifier has a wide band frequency acceptance and is used to get shaping and extra amplification so the signal can be fed into an ADC or discriminator.



Charge Sensitive $V_{out} = -Q/C_f$



Voltage Sensitive $V_{out} = -Q/C_{in}$



Current Sensitive $V_{out} = -R_f I_{in}$

Figure 13: Pre-amplifier Configurations

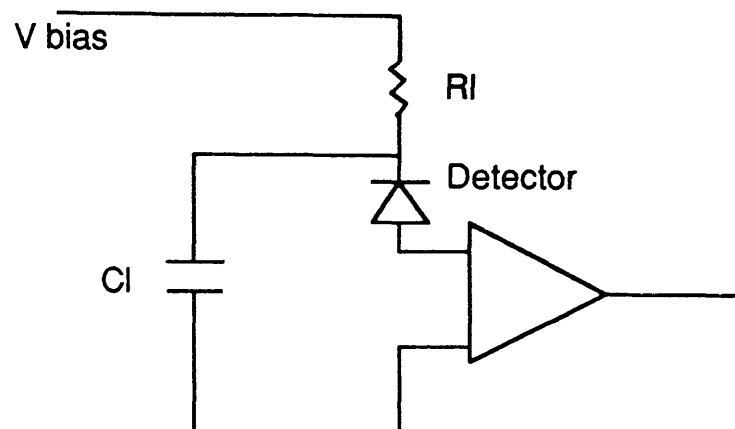


Figure 14: Detector-Amplifier circuit

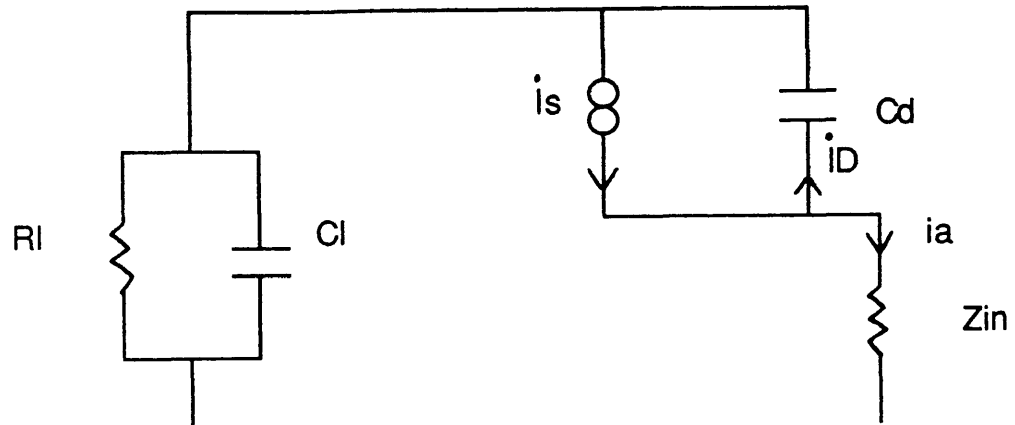


Figure 15: Detector-Amplifier equivalent circuit

3.8.3 Effect of Electronics on Charge Collection

In tests of the microstrips detectors (see Chapter 4) not all the charge deposited by a minimum ionizing particle was collected by the amplifier. An explanation as to why this occurred is given here. The typical circuit for detector and electronics is shown in figure 14 while the equivalent circuit is shown in figure 15, where the detector is displayed as a current generator in parallel with a capacitance [28]. In figures 14 and 15 R_1 is the bias resistor that ensures the detector does not draw too much current (ie $< 10 \mu A$) and C_1 is the isolating capacitor which provides the AC return to ground.

The total source current i_s is (terms explained in figure 15)

$$i_s = i_d + i_a$$

The voltage across the amplifier and across the detector and bias resistor are equal :-

$$i_a Z_{in} = i_d [1/(j\omega C_d) + Z_1]$$

$$\text{where } Z_1 = R_1 + 1/(j\omega C_1)$$

This enables i_a to be found in terms of i_s from

$$i_a + i_a Z_{in} / [1/(j\omega C_d) + Z_1] = i_s$$

$$i_a = \frac{i_s}{1 + \frac{Z_{in}}{[1/(j\omega C_d) + Z_1]}} \leq i_s$$

To short out the thermal noise of R_1 to ground, C_1 is made as large as possible, if this was not done the noise would go through the amplifier, which is undesirable. Since $Z_1 \ll 1\Omega$ if $C_1 \rightarrow \infty$

$$i_a = i_s / (1 + Z_{in} j\omega C_d)$$

(typically values for $Z_{in} \sim 100 \Omega$).

Therefore at a specific frequency $\dot{I}_a < \dot{I}_s$.

The charge/current input to the amplifier approximates to a δ function, which obeys :-

$$\int_{-\infty}^{\infty} \delta(t) \exp(-i\omega t) dt = 1$$

This implies I_s is uniformly distributed over all ω (hence $I_s(\omega) = \text{constant}$). Assuming the amplifier has a constant gain then for all frequencies

$$Q(\text{observed}) = \int i_a(\omega) d\omega$$

$$Q(\text{signal}) = \int i_s(\omega) d\omega$$

Given that $\dot{I}_a < \dot{I}_s$ it is easily seen that the observed charge is less than that deposited as some finds its way to earth via the detector. This effect in the NA14 electronic system is responsible for a 20% loss in charge collection.

Chapter IV

THE SILICON VERTEX DETECTOR

This chapter describes the Silicon Vertex Detector used in the NA14 experiment. Its position in the spectrometer is in the AEG magnet as shown in figure 1. The general aim of this piece of apparatus as its position may indicate is to enable tracks to be reconstructed as near to the vertex as possible, in order to detect heavy flavour decays.

This chapter is split into three parts. Firstly the mechanical and electrical construction of the detector, secondly the way in which the detector is used in charm searches, and finally some test results of the detector. This final part will deal in particular with the amount of charge sharing found on detector planes.

4.1 OVERVIEW OF THE VERTEX DETECTOR

The Vertex Detector can be split into two separate pieces of equipment, the Active Target and the Microstrip Stack. The Active Target consists of 32 planes of silicon diodes; the signal from each diode is amplified and fed into an Analogue to Digital Converter (ADC). The function of the target is to indicate the position of the vertex of the interaction along the beam direction, to an accuracy of 500 μ m. This piece of equipment was built at the Saclay Laboratory. The Microstrip Stack consists of

10 planes of silicon diodes, and its purpose is to track particles with great accuracy in the plane transverse to the beam. The accuracy achieved is $16\text{ }\mu\text{m}$ on a single measurement. It was designed, constructed and tested at Imperial College, hence the emphasis applied to it in this Chapter.

4.2 ACTIVE TARGET

The Active Target is composed of 32 wafers of thin silicon diodes, all of the same overall dimensions. The first 30 sheets contain 24 vertical diodes of width 2.0 mm with separations of 0.1 mm, the last two sheets having 21 horizontal diodes, with the same width and spacing. The overall dimensions of each sheet are 50.3 mm (horizontal) by 44.0 mm (vertical). The active area of each sheet is approximately 20 cm^2 . Each sheet is $300\text{ }\mu\text{m}$ thick, separated from its neighbours by $200\text{ }\mu\text{m}$ [29]. The overall length in the direction of the beam is 1.58 mm.

The Active Target is primarily designed to locate the X (beam direction) coordinate of an interaction: however, as the sheets are subdivided to enable them to withstand the very high fluxes, with reduced likelihood of signal pile-up, ^{course values of} the Y and Z coordinates can be obtained.

The diodes for the Active Target were constructed by the Enertec (Schlumberger) company. The original wafers, of n-type silicon, were of resistivity $\sim 6000\text{ }\Omega\text{cm}$. A p-type ion-implant (phosphorus) was used to produce the diodes.

The amount of silicon in the target gives it a radiation length of some 10% and a nuclear interaction length of

approximately 3.2%.

4.2.1 Active Target Electronics

Each of the 768 diodes of the Active Target is read out by the sequence shown in figure 16.

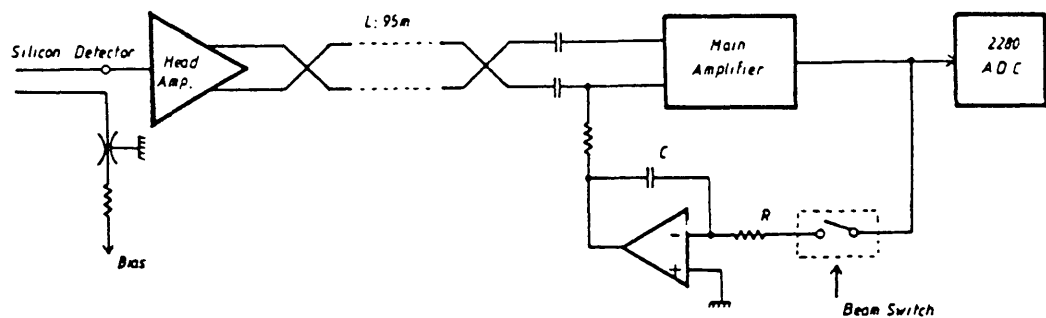


Figure 16: Active Target Readout Chain

The amplification chain is a two stage process - a head amplifier is attached as close to the diodes as possible and a main amplifier 95m away, along a twisted pair cable. The figure shows the AC coupling mode of the equipment. It is possible to run the system in the DC coupled mode [29], but during tests on the Active Target it was found that the AC coupling gave a better signal to noise ratio. Treating the noise as gaussian the standard deviations were 17.7 keV and 20.7 keV for the AC and DC couplings respectively. 17.7 keV is equivalent to 4900 electron/hole pairs.

Following the amplification stages the signal is fed into a charge-sensing ADC (LeCroy 2282), using a gate time of 70ns.

4.2.2 Performance of the Active Target

The target was tested at the CERN PS, using 10 GeV pions with a flux of $10^6/\text{sec}$. At the start and end of each run, the target was calibrated using a muon beam, with the object of assessing the long term stability after exposure to radiation. It was found that the noise pedestal shifted by ≈ 2 ADC channels a month. The most probable energy loss is about 150 ADC channels (equivalent to 85 keV), so that the pedestal variations affect the energy scale calibration by about 1% [29].

The standard deviation of the noise gaussian (mean ~ 25 keV) varies by about 7.5%. Each strip of the target was examined for 2 or more relativistic particles (>170 keV). Therefore the fluctuation in the noise is negligible compared with the required signal.

Overall the leakage current was found to average 54 nA per strip, which provides a negligible contribution to the noise charge.

4.3 MICROSTRIPS

During the development of the Microstrip Stack a number of changes to the original design have been found necessary. These changes have been necessary for mechanical and physical reasons. The largest change was the introduction of an extra pair of planes. This was found necessary in order to be able to reconstruct tracks, for reasons that will be discussed later. Dimensions quoted will be for both the Prototype and Final Detectors.

The physical dimensions of the Prototype are shown in figure 17. The positions of the 8 planes can be seen, as well as their relation to the Active Target. Figure 18 shows the corresponding positions of the Final or Main Detector with its 10 planes.

The microstrip silicon plane is $5 \times 5 \text{ cm}^2$ and contains 1000 p-n diodes, each being $50 \mu\text{m} \times 5 \text{ cm}$. The p-type implant is $\sim 30 \mu\text{m}$ wide with a $20 \mu\text{m}$ spacing. For the prototype detector the thickness of the planes was $350 \mu\text{m}$, but experience indicated thicker silicon would give a better performance, hence $450 \mu\text{m}$ thick silicon was used in the Final detector.

The silicon planes were glued (using epoxy resin) to Printed Circuit Boards (PCB). Each PCB ($384 \times 384 \text{ mm}$) acts as a fan out and enables twenty 50-way ribbon cable connectors to be attached around the periphery. The PCBs were 1.6 mm thick (the only thickness available) and required some stiffening. Electrically, each diode is connected via aluminium bonds attached to the metallisation (gold) on the diodes and the gold tracks of the PCB. The delicate ($25 \mu\text{m}$ diameter) bonds are connected via a localized ultrasonic bonding process that heats the bond and the gold. Some channels were lost due to poor bonding, or bonds touching each other, which reduces slightly the resolution of the detector.

The PCBs need to be supported securely to avoid undue stress on the silicon wafer and the bonds. For high precision equipment there is also a need to ensure that the planes are static relative to one another. This security was achieved using 4 symmetrically placed dowels, indicated by the 3 vertical hatched

PROTO-TYPE PLANE LAYOUT.

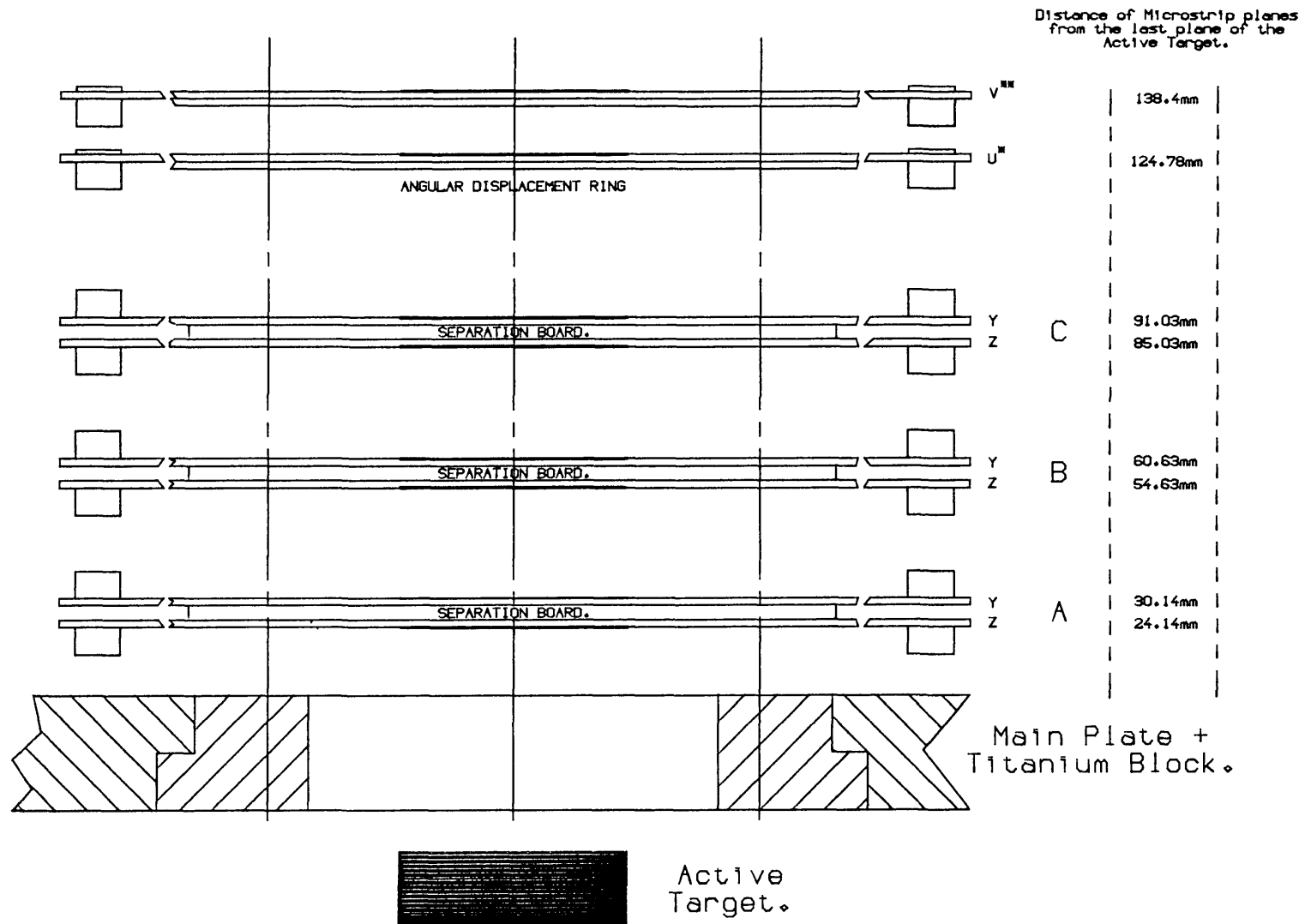
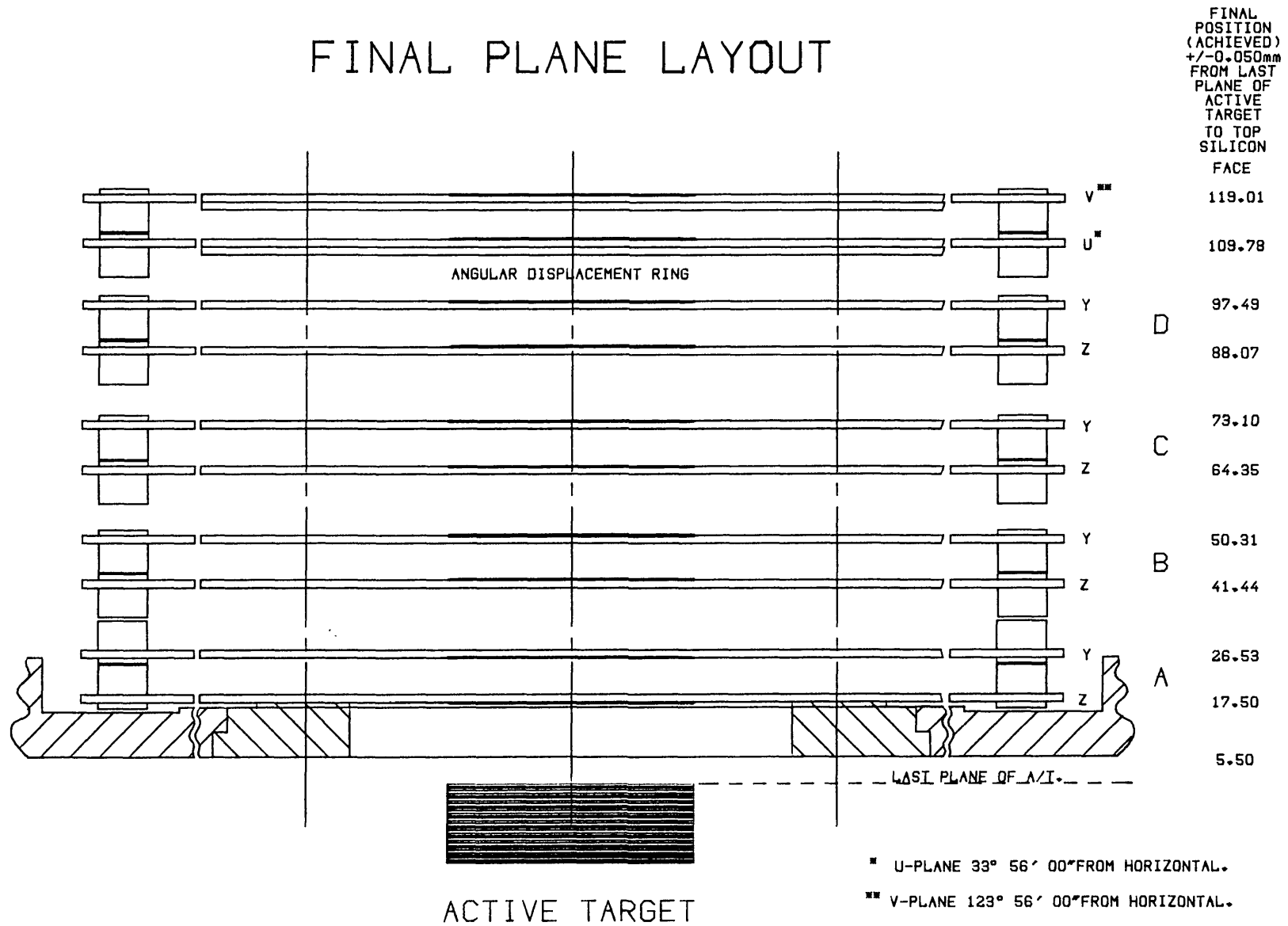


Figure 17: Prototype Microstrip Stack

FINAL PLANE LAYOUT

Figure 18: Final Microstrip Stack



lines as shown in figures 17 and 18; the central hatched line, due to the drawing projection, marking the position of 2 dowels. The planes and the pre-amplifiers are on the same chassis, so cables connecting diodes to amplifiers do not exert undue stress, which would otherwise happen during transportation and movement.

In figures 17 and 18 it can be seen that the planes are placed in doublets, due to the fact a wafer can only measure one coordinate. All the wafers are in the YZ plane, but the last doublet (UV) is rotated by 32.5° with respect to the others. The pairs of YZ and UV measurements can then be used to reconstruct tracks. Technically and structurally the UV planes were the most difficult because the original PCBs used for the YZ planes had to be specially cut and extra boards fitted. These added boards were bonded to the original PCB using the same ultrasonic bonding as mentioned previously.

Accurate alignment of the microstrip stack is very important; in particular the parallelism and orthogonality of the strips. This was achieved using the bed of a jig borer and travelling microscope as described below.

The construction of the Prototype and Main detectors differed slightly due to the different attachment of the 50 way connectors on the PCB. The Prototype detectors were aligned in pairs: note the reversal of the silicon surface in figure 17. One plane would be aligned using the travelling microscope, which was sighted on the silicon strips. Cross hairs were then attached to the PCB and the plane reversed. The second plane was then aligned, with its strips lying perpendicular to the strips in the

first. The three YZ planes were assembled this way. The UV planes were placed on a specially made support ring that was rotated 32.5° relative to the YZ plane. The silicon surfaces for these planes faced the same way.

The Main detector was assembled much more as a single unit, rather than a pair at a time. Note how the silicon surfaces are facing the same direction, in planes 3 - 10. Planes 1 and 2 face the opposite way, in order to reduce the distance between the Active Target and the first plane. The U and V planes were assembled in the same manner as for the Prototype.

Throughout both constructions, great care was taken to ensure that the boards did not move relative to one another once they were in place. In the alignment of the strips an accuracy of $4\text{ }\mu\text{m}$ in 5cm was achieved i.e. 0.08 mrad.

Figure 19 shows the Final Detector during assembly. In the picture the silicon, the PCB and the cables can be seen. The supporting dowels can also be seen clearly.

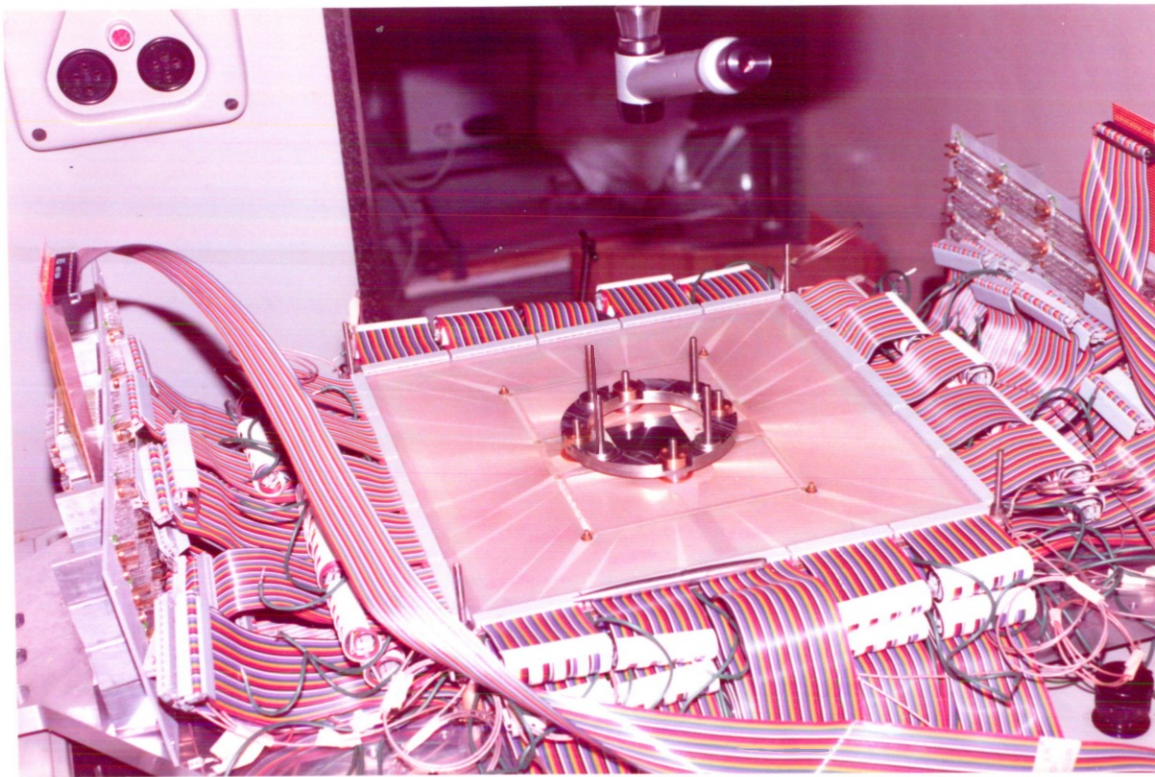


Figure 19: Assembly of the Microstrip Stack

4.3.1 Cable Lengths and Capacitance

During construction of both the Prototype and Final Detectors care was taken to keep the cable lengths to a minimum. This was particularly so in the length of cable between PCBs and pre-amplifiers, owing to the degradation in noise characteristics of the pre-amplifiers with increased input capacitance. Altogether the PCB and 20 cm of cable gave an input capacitance of ≈ 30 pF.

4.4 ELECTRONICS FOR THE MICROSTRIPS

As with the Active Target, the signals from the microstrips diodes have to be amplified. The amplification chain is again a two stage process. The electronics chain is shown in figure 20. The signals are first taken through a short cable to the pre-amplifier (MSD2) and then to the MSD3 containing an amplifier and a discriminator. The output of the MSD3 is fed to an 'ORgate' and then to a Proportional Counter Operating System (PCOS) Latch to be read by computer. The PCOS and the term ORgate are explained later.

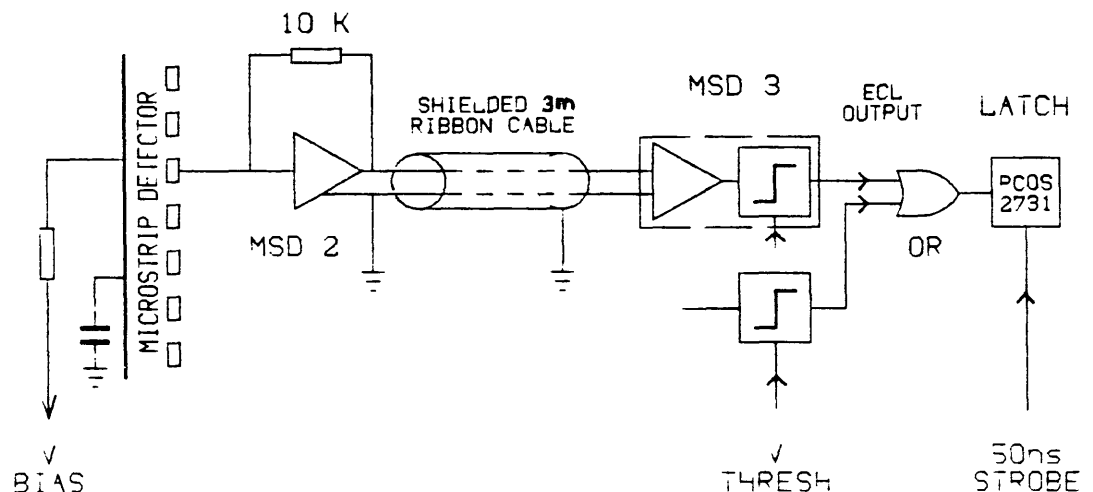


Figure 20: Electronic Readout Chain for Microstrips

4.4.1 The Pre-Amplifier (MSD2)

The MSD2 is a fast current sensitive pre-amplifier designed to be used in conjunction with silicon microstrip detectors [30]. The characteristics of the MSD2 are those described in section 3.8.2 for current sensitive pre-amplifiers. Table 5 gives some of the major features of the MSD2.

Input Characteristics	Single Ended. Z_{in} 120 Ω . DC connected
Output Characteristics	Single Ended. Z_{out} 300 Ω . AC connected
Overall Characteristics	Transresistance Gain 10 - 40 mV/μA dependent on output load. Rise Time 2 - 5 ns, dependent on input capacitance and collector current of the first transistor. Power consumption 15 mW/channel Density 4 channels/inch² + 40 channels/inch³. Crosstalk ~ 4% between adjacent channels.

TABLE 5

MSD2 Characteristics

4.4.2 Amplifier/Discriminator MSD3

The MSD3 circuit, like the MSD2, is placed on a ceramic tile PCB, with 4 channels per board. Again this is to enable high density packing of these amplifiers.

The MSD3 is centred around an Operational Amplifier giving a gain ~ 50, and a discriminator whose threshold is controlled by PCOS. The threshold voltage of the discriminator can be varied by applying a voltage (V_t) between 0 - 7 V. The applied voltage, which comes from PCOS, is related to the threshold voltage in an indirect way. Each MSD3, whose gain and offset are variable, has a separate relationship between applied and threshold voltages that depends on the gain and offset. The MSD3s were 'tuned' so that the discriminator had a 30 mV threshold when an applied

voltage of 1.6 V was used. The value of 30 mV is the expected output of the amplifiers for an energy deposit corresponding to 40% of a minimum ionizing particle. The MSD3 delivers an ECL output when the signal is greater than the threshold voltage.

The MSD3s were mounted on boards that were named 'Plancher'. The input to the Plancher was in the form of 2 sets of 25 MSD2 channels. The output was 48 channels via the ORgate to the PCOS, with the 2 remaining channels fed into separate Orgate PCOS units.

During development work on the Prototype detector many problems were encountered, the major one being oscillation in the MSD2-MSD3 amplification system, which necessitated alterations to the plancher and the MSD3 outputs. Originally the MSD3 output delivered a pseudo ECL output, but this was found to cause much of the oscillation due to pick up, hence a change to true ECL was made, with the introduction of a small circuit on the plancher. Improvements in the grounding of the MSD2 mountings were also necessary.

Further reductions in the oscillations were obtained by varying the V_t so it was $\sim 2.0V$ for an SPS burst and $7.0V$ at other times during the 12s cycle of the SPS. In principle each block of 48 MSD3 channels could have had a separate V_t supplied from their PCOS unit. Due to the stepping in the voltage necessary to stop oscillation it was found there simply was not enough computing power (computer used was a PDP 11/45) available to do this, hence a global V_t was adopted and in fact worked satisfactorily.

Finally figure 21 shows the combined MSD2-MSD3 noise vs input capacitance [30]. Although this combination is well matched to deal with the large input capacitance when compared with other systems in current use it is clearly advantageous to keep the input capacity down to 20 - 30 pF.

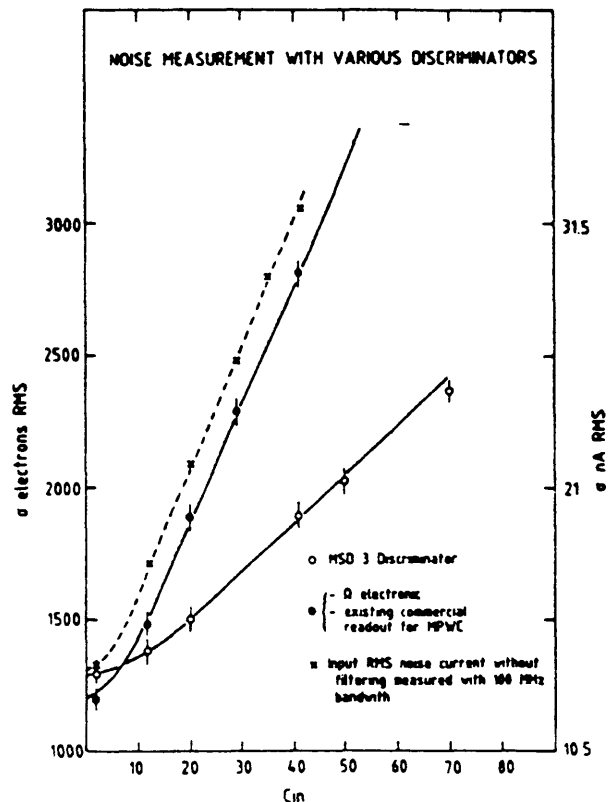


Figure 21: Noise vs Input Capacitance for the MSD2-MSD3 system

4.4.3 ORgating

The number of PCOS units possessed by NA14 was 5000, when the Prototype Detector was being tested only 2800 channels were used. However, with the Final Detector, 10000 channels were needed, it therefore became necessary to feed 2 channels of detector into 1 of PCOS. This was called 'ORgating'.

Care had to be taken in the arrangement of the ORgating to reduce problems with pattern recognition which are due to extra tracks being generated. As far as possible channels were 'ORgated' together in such a way as to minimise the production of ghost tracks, but there were also the physical problems arising from cabling which defined groups of channels that had to be ORed together.

A number of different ORgate patterns were tried using Monte Carlo Methods, on the Prototype plane configuration, the best of these being extended to 10 planes when it was known an increase in planes was required. The comparisons between patterns were made in the following manner:- two sets of data were generated, one containing all charm events, the other containing no charm events. These were passed through a reconstruction program (to be described later) and the charm enrichment found using the following expression.

$$E = \frac{\% \text{ of Charm events in which a Secondary Vertex is found}}{\% \text{ of Non-charm events in which a Secondary Vertex is found}}$$

The results of the ORgate patterns were compared to those results where no ORgate was employed (each channel separate) by the ratio

$$\frac{E \text{ ORgate (Eor)}}{E \text{ no ORgate (Enor)}}$$

Values of this ratio varied from 50-80%.

The ORgate pattern with the best results, and used by the experiment, is shown in figure 22. Eor in this case is 80% of Enor. The philosophy behind the ORgate pattern used was to pair together channels from orthogonal planes and change the

arrangement of ORgating from one pair of planes to another. Doing this arranges the 'mirror' hits so that the reconstruction program does not produce large numbers of 'ghost tracks'. Figure 22 shows 4 pairs of planes, the actual planes represented are shown at the sides (AZ, Ay etc). Within each pair the plane measuring the $z(u)$ coordinate is ORed to the plane measuring the $y(v)$ coordinate. Numbers at the edge of a plane define regions within that plane. The numbers at the centre of a region in a given plane, define the area in the orthogonal plane to which that region is ORed.

Chapter 4

Ay V

11	(5)
10	(5,7)
9	(4,8)
8	(3,9)
7	(2,10)
6	(1,11)
5	(2,10)
4	(3,9)
3	(4,8)
2	(5,7)
1	(5)

By

11	(5)
10	(4,6)
9	(3,7)
8	(2,8)
7	(1,9)
6	(2,10)
5	(3,11)
4	(4,10)
3	(5,9)
2	(6,8)
1	(7)

Cy

11	(7)
10	(6,8)
9	(5,9)
8	(4,10)
7	(3,11)
6	(2,10)
5	(1,9)
4	(2,8)
3	(3,7)
2	(4,6)
1	(5)

Dy

11	(7)
10	(6,8)
9	(5,9)
8	(4,10)
7	(3,11)
6	(2,10)
5	(1,9)
4	(2,8)
3	(3,7)
2	(4,6)
1	(5)

Vertex Detector

Az U

11	(5)
10	(5,7)
9	(4,8)
8	(3,9)
7	(2,10)
6	(1,11)
5	(2,10)
4	(3,9)
3	(4,8)
2	(5,7)
1	(5)

Dz

11	(5)
10	(4,6)
9	(3,7)
8	(2,8)
7	(1,9)
6	(2,10)
5	(3,11)
4	(4,10)
3	(5,9)
2	(6,8)
1	(7)

Cz

11	(7)
10	(6,8)
9	(5,9)
8	(4,10)
7	(3,11)
6	(2,10)
5	(1,9)
4	(2,8)
3	(3,7)
2	(4,6)
1	(5)

Bz

11	(7)
10	(6,8)
9	(5,9)
8	(4,10)
7	(3,11)
6	(2,10)
5	(1,9)
4	(2,8)
3	(3,7)
2	(4,6)
1	(5)

Figure 22: ORgate pattern used by NA14 experiment

4.4.4 Proportional Counter Operating System (PCOS)

PCOS stands for Proportional Counter Operating System, and is a Multiplexing Device which reads many channels (5000 in this case) in parallel and writes the results serially to a computer.

PCOS was chosen for the experiment because it has a programmable delay. A delay of $\approx 450\text{ns}$ is necessary in the signals from the microstrip detector to allow strobing derived from signals generated by the trigger counters of NA14. An interesting fact is that without PCOS 1200km of cable would be needed, which would be expensive and lead to attenuation of the signals.

4.5 OPERATION OF THE SILICON VERTEX DETECTOR

The early part of this Chapter dealt with the construction of the Vertex Detector; this part deals with the possible use of the detector as a filter for heavy flavour particles.

Each part of the Vertex Detector, i.e. the Active Target and the Microstrips stack, can be used independently as a filter. These filters have been tested using Monte Carlo methods similar to those described in the section on ORgates to estimate their efficiency.

4.6 THE ACTIVE TARGET FILTER

The basis of the Active Target charm filter is its ability to detect jumps in the multiplicity of the secondary particles as they traverse successive planes. The filter devised using this ability is only effective for events which are not complicated by the presence of highly ionizing target fragments, i.e. it favours coherently produced charm events where the nucleus recoils intact and is absorbed within the same silicon plane as the interaction.

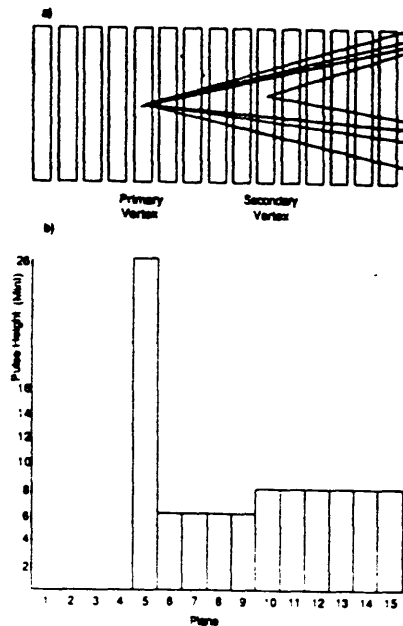


Figure 23: Active Target filter, diagrammatical description

Each strip of the target is calibrated, so for a given ADC count the mean number of relativistic particles passing through that strip can be estimated. To detect tracks of interest ≥ 3 relativistic particles must be found in the corresponding strips for ≥ 4 consecutive planes. This reduces the likelihood of picking e^+e^- pairs. To select an event both, a primary and a secondary vertex need to be found as shown in figure 23 a). The

primary vertex is found where tracks appear ie a jump in multiplicity in the strip. The secondary vertex is found by a second jump in multiplicity see figure 23 b).

The preceding method is limited by the following efficiencies:-

1. Due to the finite longitudinal spacing of the silicon layers and the statistical Landau fluctuations, only 50% of coherent events and 30% of incoherent events are accepted by the filter criteria in the Monte Carlo simulation [31].
2. The disintegration of the target nucleus produces nuclear fragments that spoil the visibility of the vertices. Averaging the various forms of break up of the nucleus the efficiencies are 100% for coherent events and 20% for incoherent events [31].

Assuming 3% of charm events are coherent, this would mean :-

$$\epsilon_c = (.03 \times .5 \times 1.) + (.97 \times .3 \times .2) = 7.5\% \text{ of charm events}$$

coherent incoherent

would be seen by the Active Target [31].

Non-charm events can simulate jumps in multiplicity e.g. pair production by γ originating from π^0 decay. Estimates of these effects gives 20% of non-charm producing jumps in multiplicity. Hence assuming non-charm events have the same visibility factor (20%) we retain

$$\epsilon_n = 20\% \times 20\% = 4\%$$

of non charm events [31]. This gives an enrichment $E \approx 2$ which is marginal.

Recently, during the examination of 1984 data, it was found

that the nuclear break up fragments are not as much of a problem as was once thought. The tracks can be used to determine the primary vertex of the events in the beam (x) direction even more accurately than the microstrips. This method employs the wide angle tracks of the break up.

4.7 THE MICROSTRIP STACK FILTER

The information obtained from the Microstrips is in the form of a 'hit' or 'no hit' for each strip. These hits then have to be turned into particle tracks. The accuracy with which the microstrip stack performs, enables the primary, and some secondary, vertices to be found in most events (monte carlo result). The track and vertex finding algorithms developed for this purpose are described briefly in the following sections.

4.7.1 Reconstruction of the Tracks

In order to find a track there is a prerequisite of at least 3 hits per projection satisfying certain conditions, which will be described briefly. Three points are needed to fit a straight line, hence the 3 hit requirement. The need for 3 hits is also the reason for 10 planes in the Final Detector. Any inefficiencies mean the possibility of losing a hit, which in an eight plane detector, means too high a risk of losing a track.

The microstrip stack examines four coordinates y,z,u and v. The four Y planes and the four Z planes enable the track reconstruction algorithm to calculate the y and z projections of the tracks. The U and V planes provide information to help

remove ambiguities between tracks with similar z coordinates and different y coordinates and vice versa. The track reconstruction algorithm uses the information supplied by the microstrips in the following manner.

1. Each hit is taken in turn on the first plane of the z projection. A line is drawn between it and every hit on the last plane of the z projection. Every line will have a gradient or slope given by

$$\text{slope} = (Z_{Nj} - Z_{1i}) / (X_{Nj} - X_{1i})$$

$1 \leq i \leq n$ hits on first plane

$1 \leq j \leq m$ hits on last plane

N = number of planes in the projection.

2. A maximum gradient of the slope is imposed of

$$\text{slope} \leq 0.3 \text{ radians}$$

The value of 0.3 radians is derived from the maximum acceptance of the stack which is ~ 0.3 radians. Tracks with slopes greater than 0.3 are rejected.

3. Using the remaining lines, predictions for their intersection with the intermediate planes are made. If an actual 'hit' is found within $100\mu\text{m}$ (z projection) on one of the intermediate planes a track is registered.
4. The hits on the tracks are then subjected to a linear fit, hence a parameterisation of the track is obtained.
5. Tracks that cross other tracks are removed. This process is done by removing the tracks with the highest number of crossings first and proceeding downwards.

6. Steps 1-5 are then repeated for the y projection. For the y projection a parabolic fit is used to parameterise the track as the magnetic field acts in the y direction.
7. Tracks in projection are matched in the following way.
 - a) Pair each track in the z projection with every track in the y projection.
 - b) Each pair of tracks is weighted according to the distance to the nearest hit in the U or V planes. The maximum distance allowed is 80 μm .
 - c) An assignment matrix is then used to find the most probable tracks, (essentially a minimization problem). The assignment matrix is then solved by Monkres algorithm [32]. The problem itself is the solution of an $n \times n$ matrix (a_{ij}) of real numbers. The solution is the permutation of $k(1), k(2) \dots k(n)$ of integers $1, 2, \dots, n$ that minimizes

$$\sum a(i, k(i))$$

After this procedure the tracks are known in both the z and y projections.

4.7.2 Finding The Primary Vertex

Once the tracks are found an attempt is made to find the primary vertex. This proceeds as follows.

1. All combinations of pairs of space tracks are taken.
2. The point (x, y, z) of closest approach for a pair is checked to ensure it is inside the Active Target.

3. The mean point (X,Y,Z) of closest approach of all the combinations is found.
4. The pair of tracks, whose closest approach is furthest from (X,Y,Z) is rejected if it does not satisfy

$$\sqrt{(0.0025(X-x')^2 + 0.25(Y-y')^2 + (Z-z')^2)} \leq 60\mu\text{m}$$
 (weights are explained later in section 4.7.4)
5. Steps 3 and 4 are repeated, until no more tracks are rejected.

A primary vertex can be found for 98% of Monte Carlo events.

4.7.3 Secondary Vertex

Finally the Secondary Vertex, if one exists, has to be found.

The algorithm for this is as follows:-

1. All tracks that have an impact parameter, relative to the primary vertex (X,Y,Z) , between $80-300\mu\text{m}$ are found. The impact parameter is again a weighted quantity, the values of the weights used are given in the next section.
2. One or more offset tracks are taken to form a secondary vertex. Depending on how selective a sample of events is required, 2 methods are used.
 - a) One offset track combined with any other track.
 - b) Two offset tracks are taken and combined.
3. The Secondary vertex if found must satisfy the following.
 - a) Must be contained in the Active Target.
 - b) The 2 tracks must pass within $100\mu\text{m}$ in space of one another.

- c) The minimum distance the secondary vertex can be from the primary vertex in the transverse plane to the beam is $135\mu\text{m}$.
- d) The secondary vertex must be downstream of the Primary vertex.

Hence our charm candidate must have a primary and secondary vertex.

4.7.4 Weighting and Results of Monte Carlos

The distances of tracks and vertices from one another are expressed in a weighted form. This arises from the accuracy of the measurements possible in the various directions when tracks are extrapolated back to the vertex. Monte Carlo studies using the above algorithm give the following extrapolation errors from which the weights are derived.

$\sigma_x = 450\mu\text{m}$	weight = 0.0025
$\sigma_y = 40\mu\text{m}$	weight = 0.25
$\sigma_z = 20\mu\text{m}$	weight = 1.00

The parameters and cuts quoted in the description of the algorithm have been chosen empirically to optimise the charm enrichment factor while maintaining a high efficiency for charm decays using monte carlo data. For most of the real data these tolerances are increased by a factor of ~ 1.5 in order to find more tracks. However one parameter, the maximum distance between primary and secondary vertices is decreased by a factor of ~ 1.5 .

Table 6 shows the results of the Microstrip Filter on 100

Charm events and 500 non-charm events. It can be seen that as the limits are made tighter ie, $1 \rightarrow 2$ offset tracks, the enrichment increases. The disadvantage is that fewer actual charm events are found. The effect of the OR gate is also shown.

The values of the charm particle lifetimes used in the Monte Carlo were taken from the Particle Data Book 1982. The Monte Carlo also incorporates inefficiencies expected in the microstrips, such as dead strips (5%) and charge sharing.

Criteria	Charm Data Set % secondary vertices found	Non-Charm Data Set % secondary vertices found	Enrichment
1 offset track $\geq 80\mu\text{m}$ No orgate	40.0	10.6	3.8
1 offset track $\geq 80\mu\text{m}$ Orgate	41.0	11.6	3.5
1 offset track $\geq 100\mu\text{m}$ No orgate	37.0	8.0	4.6
1 offset track $\geq 100\mu\text{m}$ Orgate	35.0	9.8	3.6
2 offset track $\geq 80\mu\text{m}$ No orgate	22.0	2.8	7.9
2 offset track $\geq 80\mu\text{m}$ Orgate	21.0	3.8	5.5
2 offset track $\geq 100\mu\text{m}$ No orgate	17.0	2.0	8.5
2 offset track $\geq 100\mu\text{m}$ Orgate	19.0	2.2	8.6

TABLE 6

Charm enrichment for various secondary vertex criteria

4.8 EXPERIMENTAL TESTS OF THE MICROSTRIPS

Before and during the operation of both Microstrip stacks, various tests were performed. The aim was to measure the charge collection and more importantly the charge sharing of the strips. The charge collection is important from the view point of seeing particles, i.e. is enough charge collected to fire the discriminators. The charge sharing is important because charge spreading from one strip to another can give rise to two hits rather than one, and this can reduce the resolution of the detector. Development of the detector meant the examination of three thicknesses of silicon, using a wide range of test particles from radioactive sources to the CERN SPS.

4.8.1 Charge Collection

The first study of the microstrips was to measure their charge collection. The first experimental technique used for this purpose is shown in figure 24. A Rh β^- emitting source was used to irradiate the detector and the resulting energy deposited in the detector by the relativistic β particles was then collected in the form of charge by the ADC. Through the same circuit a test pulse (produced by a 0.99pF capacitor, a resistor and a 0.7 V square wave pulse attenuated by 44db) which delivered approximately the same charge as that produced by a Mini particle in that thickness of silicon (270 μm), was passed. A comparison was made between the charge collected when the pulses from the test pulse and the detector were used. The results showed that $80 \pm 5\%$ of the charge deposited by a Mini particle was collected

by the detector.

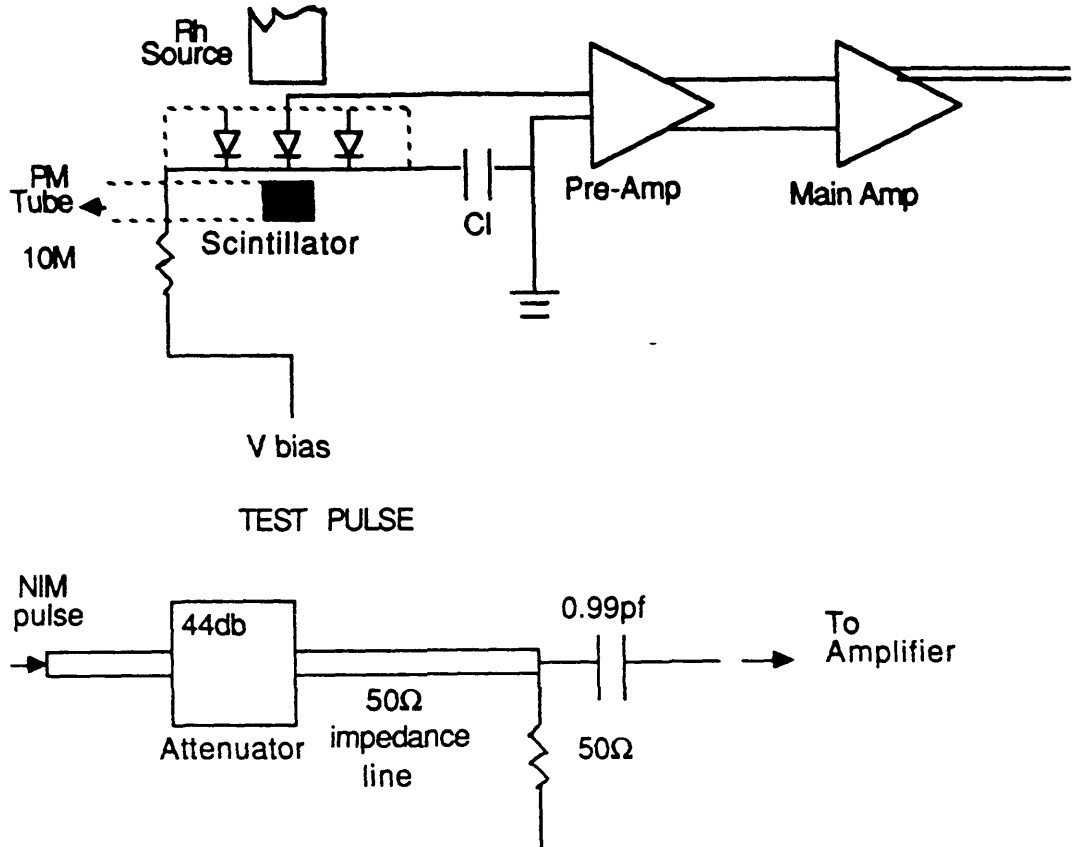


Figure 24: Test Circuits for Charge Collection: Bench Test

The problem with using β sources is that electrons or positrons in their passage through the material are multiply scattered e.g. the r.m.s deflection is $70\mu\text{m}$, in $300\mu\text{m}$ of silicon hence the β particles do not stay in one strip, given that the strips used had a pitch of $50\mu\text{m}$.

Repeating the preceding study, this time in a $3.5\text{ GeV}/c\ \pi^-$ beam from the CERN PS, gave the same figure of $80\pm 5\%$ for charge collection.

In section 3.8.3, the effect of the electronics in charge

collection was discussed. It is believed that this is the reason for the incomplete charge collection. Fortunately the value of $80 \pm 5\%$ charge collection is quite sufficient to fire the discriminators.

4.8.2 Charge Sharing in the Microstrips

The processes that cause much of the charge sharing were discussed in Chapter 3, diffusion and delta-rays. In order to investigate the charge sharing a variable had to be devised which was the ratio of :-

(N° of Pulse heights > threshold in an Adjacent Strip, given a Pulse height > threshold in The Trigger Strip.)

and

(N° of Pulse heights > threshold in The Trigger Strip.)

The Trigger Strip is simply the strip chosen for study. This definition is used throughout as a measure of charge sharing.

The results of the charge sharing tests in the three different thicknesses of silicon are now described. In each case the amplification system was comprised of the MSD2 and the main amplifiers used by the Active Target. The resulting signal was fed into ADCs.

4.8.3 270 μ m Thick Silicon

The objective of the tests performed on the 270 μ m thick silicon was to measure the effects of varying the bias voltage and altering the angle of incidence of the incident particles on charge sharing. A single plane of 270 μ m thick silicon, with

only 16 of its 1000 channels correctly biased, was placed in the CERN PS test beam and irradiated with 3.5 GeV/c π^- .

Six channels, including one in the trigger, were fully equipped with the readout system. One channel was used in the trigger, to increase the quantity of useful data taken. Data were taken at various voltages between 80-200 V (at a fixed angle 0°) and at various angles (at fixed voltage 80V) between -0.3 and $+0.3$ radians. The angles were measured from the normal to silicon plane. The results of these tests are shown in figure 25 and figure 26.

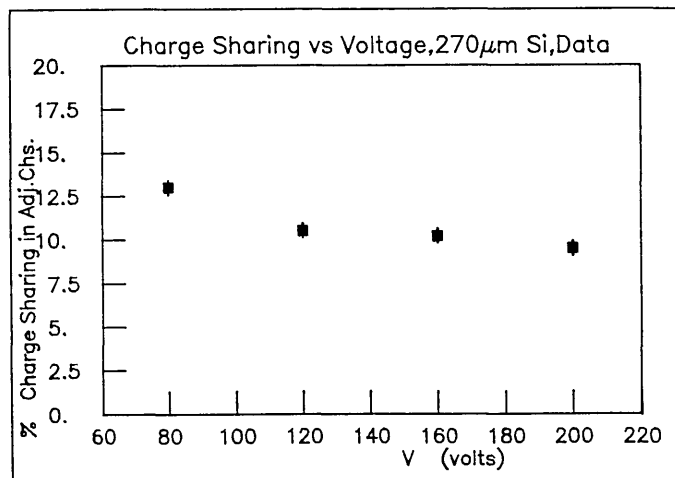


Figure 25: Voltage vs Charge Sharing

Increasing the bias voltage decreased the charge sharing, which was expected because an increase in the electric field decreases the collection time and hence decreases the rms of the charge distribution at the collection point. The increase of charge sharing with angle was explained geometrically. The

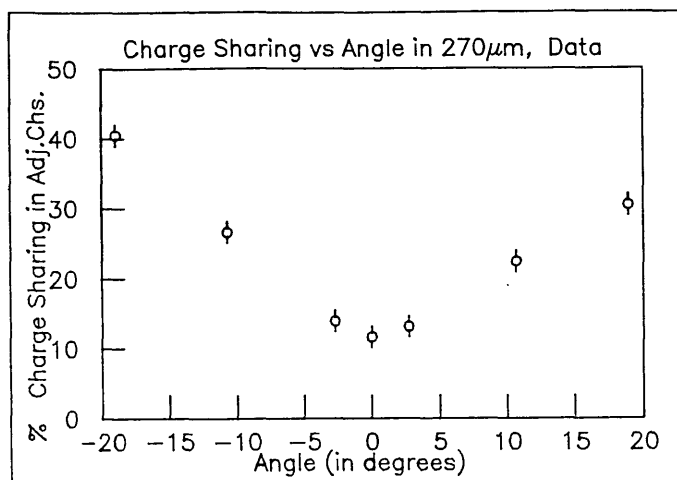


Figure 26: Angle vs Charge Sharing

angular variation was also useful in that it demonstrated that particles were detectable up to the full acceptance of the Microstrip Stack. In these studies the following software thresholds were used:-

Threshold on adjacent strip = 40% MinI in 270 μ m of Si

Threshold on trigger strip = 50% MinI in 270 μ m of Si

Another important measurement taken during these tests was the amount of noise, which for the 270 μ m detector was 10.5 keV r.m.s equivalent to 2900 electrons.

4.8.4 350 μ m Thick Silicon

The aim of the tests on the 350 and 450 μ m silicon planes was to assess the threshold chosen for the experiment i.e. for 40% MinI threshold cut was there an unacceptable amount of charge sharing resulting in cluster sizes > 1. The 350 μ m thick planes were those of the Prototype Stack. The beam tests were performed in

the NA14 experimental zone using ~ 200 GeV/c muons. Of the 8000 channels in the stack, 240 (the central strips of each plane being used) were connected to ADC's. The same configuration was used for the alignment of the microstrips (see section 5.2) and finding the amount of charge sharing.

Tracks were fitted to 'hits' using the criteria for track reconstruction. The hits on the tracks were then used to study charge sharing, by examining the hit strip and those either side. Data were only written to tape if they were above 120 ADC channels ($\sim 20\%$ MinI). This causes the plateau seen between 0-20% MinI in figure 27.

Figure 27 shows the variation of charge sharing as a function of threshold expressed in terms of 1 MinI in $350\ \mu\text{m}$. For the selected threshold cut of 40% MinI (1 MinI = 102 keV) the amount of charge sharing was $\sim 5.5\%$, which is acceptable for detector resolution. The electronic noise for this run was found to be ~ 10 keV.

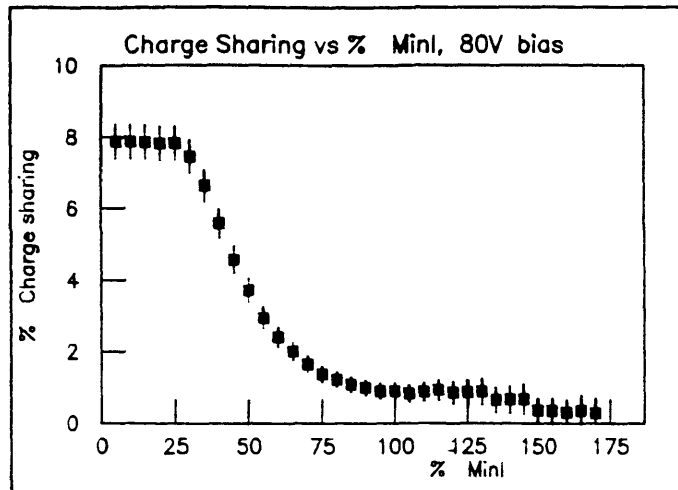


Figure 27: Threshold vs Charge Sharing (1 MinI = 102keV)

4.8.5 450 μ m Thick Silicon

Using the same test procedures on the Final Detector as used on the Prototype, the amount of charge sharing for 450 μ m thick silicon was obtained. The variation of charge sharing vs threshold is shown in Figure 28. There is no plateau in the 450 μ m data as all ADC values, not just those above 120 channels, were written to tape in this run. At 40% MinI (1 MinI = 130 keV in 450 μ m Si) the amount of charge sharing was $\sim 8\%$. Again this value of charge sharing at 40% MinI threshold is acceptable for detector resolution. The performance of the amplification system in this case was a signal to noise ratio of ~ 14 , which indicates an electronic noise of ~ 8 keV.

Test runs were performed with the magnet field on and off to search for any signs of the Hall Effect. In the data taken with high energy muons no sign of the Hall effect could be detected, which is excellent news for the tracking procedure.

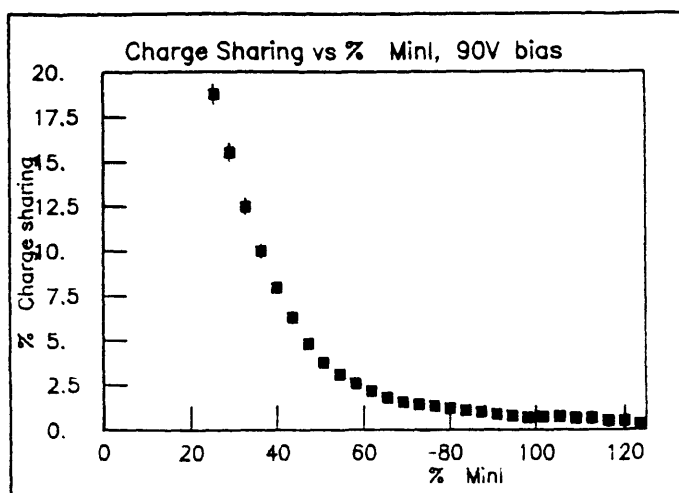


Figure 28: Threshold vs Charge Sharing (1 Mini = 130keV)

4.9 MONTÉ CARLO STUDY OF THE CHARGE SHARING

A Monte Carlo was written to simulate the charge sharing in the three thicknesses of silicon, using the models and methods of chapter 3. The aim of the Monte Carlo was to see if charge sharing was understood in terms of diffusion and δ -rays. The simulation was also used in determining the efficiency of the planes to detect particles incident at various angles, the results of which were used in the development of the track reconstruction program (see section 4.7). The results of the angular efficiencies are presented in section 4.10. The Monte Carlo calculated the quantity of charge sharing from diffusion and δ -rays produced by the incident particle using the following assumptions:-

1. The incident particle always had the same energy.
2. Energy was deposited at a single point.

3. Perfect silicon, no trapping centres.
4. Energy deposited by δ -rays was proportional to path length.

The basic steps of the monte carlo were as follows :-

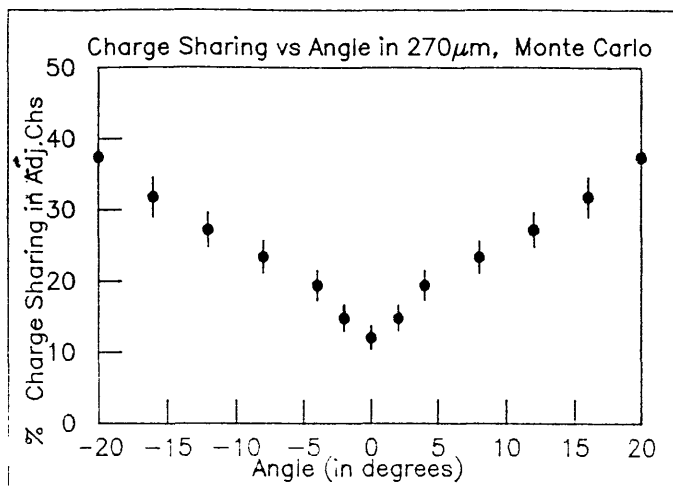
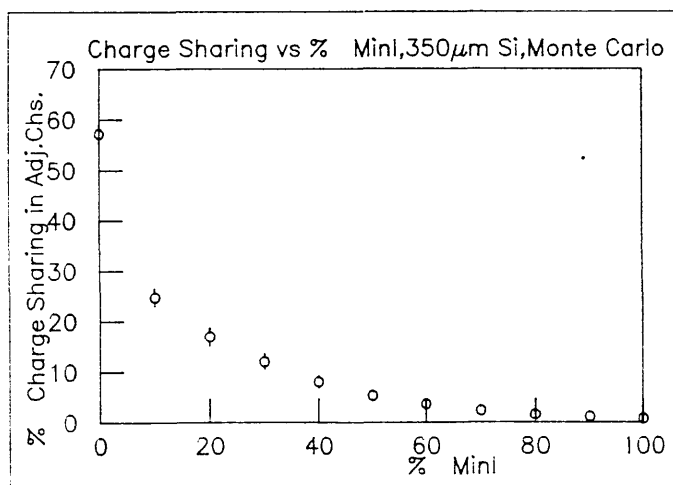
1. Calculate the path length of the incident particle in each strip it traverses.
2. Calculate the energy loss in each strip using equation stated in section 3.6.1, where λ is chosen at random using an approximation, by Findlay and Dusautay [33], of the Landau distribution.
3. The point at which the charge (energy) was deposited in the strip is chosen at random, along the path of the incident particle.
4. From the solution of the diffusion equation ie the movement of holes in the detector under the influence of an electric field, the r.m.s. of the charge distribution at the collection point can be calculated from $\sigma = \sqrt{(2Dh.t)}$, where σ is the r.m.s. of the resulting charge distribution at the collection point, Dh the diffusion constant of the holes and t the collection time.
5. Given the σ of the distribution, the fraction of energy that was deposited into a strip and into adjacent strips was obtained.
6. The electronic noise and the broadening effect due to long distance collisions are added in quadrature. The electronic noise was obtained by random selection from a gaussian distribution. The broadening effect was found in

a similar way, this time from a gaussian of variance $x\delta$, (see appendix A).

7. The number and energy of the δ -rays produced was calculated from reference [20]. The range of these rays has been described by two means, the first in reference [20] and the second by [21]. The results were approximately the same. From these results the energy deposited in each strip by δ -rays was calculated.
8. The components from the diffusion, δ -rays and electronics were then summed and a pulse height (ie what would be seen in an ADC) was calculated for each strip.
9. To obtain the amount of charge sharing the same definition of it was used as for the data.

The simulation performed for charge sharing vs angle (270 μm Si) is shown in figures 29, while the variation of charge sharing vs threshold for 350 and 450 μm thick Si are shown in figures 30 and 31.

The outcome of these simulations shows that although the general trends of the data are followed there are discrepancies. For the 270 μm and 450 μm thicknesses of silicon, the simulated data approximates well the actual data, see figures 26,29,28 and 31. However for the 350 μm silicon the simulated data was too high (compare figures 27 and 30). The reason for this difference is not known.

Figure 29: Monte Carlo of charge sharing in 270 μ m SiliconFigure 30: Monte Carlo of Charge Sharing in 350 μ m Silicon

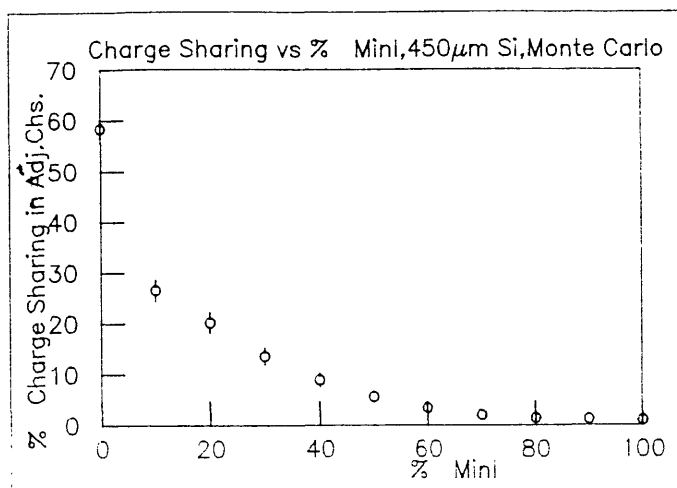


Figure 31: Monte Carlo of Charge Sharing in 450 μm Silicon

4.10 PLANE THICKNESS

It has previously been mentioned that the number of planes employed was increased in order to 'see' tracks. The same reasoning was behind the increase in thickness of the planes from 350 μm to 450 μm .

Monte Carlo studies of a single 350 μm thick Si detector subjected to particles incident at angles between -0.3 and 0.3 radians were performed and the efficiency with which the detector sees particles in a plane was plotted vs the angle, as shown in figure 32.

At angles > 0.2 radians the percentage of particles seen becomes disastrously low, given that to find a track ≥ 7 hits are needed in the stack. Since the experiment uses a threshold device, which gives problems with oscillation if the threshold is too low, the only way to increase efficiency of detection was to increase the signal, hence the need for thicker silicon. Figure

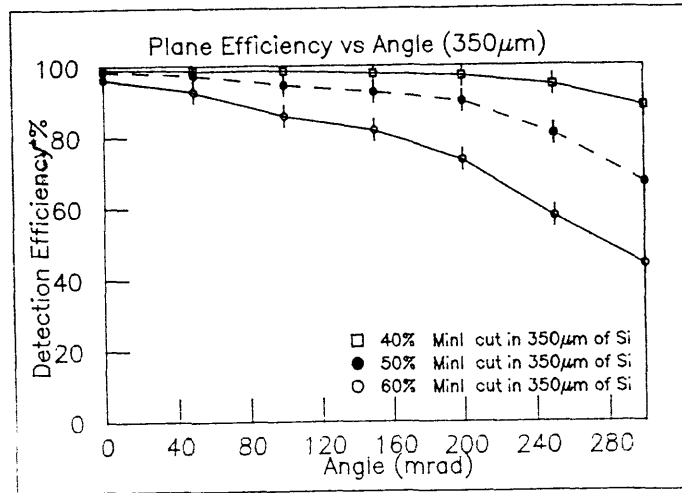


Figure 32: Plane efficiency for 350 μm silicon

33 shows the corresponding efficiency for 460 μm of silicon, with the same cuts imposed as were applied to the 350 μm silicon.

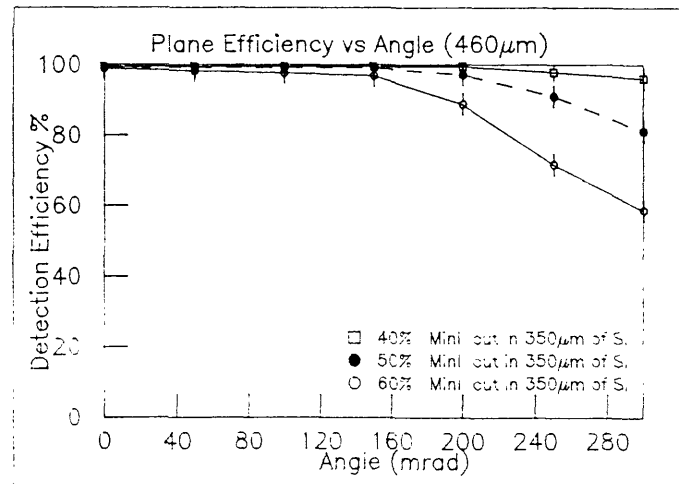


Figure 33: Plane efficiency for 460 μm silicon

Increasing the silicon thickness means more tracks will be found at large angles, and the larger number of planes means that

there is some redundancy. The need for this redundancy became evident when comparisons were made between tracks found in the 1984 microstrip data and the tracks found in the wire chambers. Wire chamber tracks are called Trident tracks after the reconstruction program that finds them (see Chapter 7). When the angles of the microstrip and Trident tracks were compared a correlation could be seen and by manipulation of the Trident tracks to the hits in the microstrips it was seen that 'hits' were missing, hence the need for a redundancy in the number of planes.

4.11 CONCLUSIONS

The tests performed on the various silicon thicknesses have shown that it is possible to see tracks up to the full acceptance of the stack and that the amount of charge sharing (cluster size > 1) is small enough ($\sim 10\%$) so as not to interfere drastically with the track reconstruction at the level of cut ($\sim 40\%$ MinI) imposed by the discriminator. The simulation of the charge sharing enabled the experimental results to at least be partially understood and predictions made for the efficiency of the planes, which had a direct bearing on their thickness.

Chapter V

FIRST RESULTS FROM THE MICROSTRIPS

5.1 INTRODUCTION

This chapter deals with two main areas. Firstly getting the alignment, the spatial precision and the efficiency of the microstrips, and secondly a search for a charm decay. All the data used in this chapter comes from the 1985 Final Detector run using muon and photon beams.

5.2 ALIGNMENT, SPATIAL PRECISION AND EFFICIENCY

The alignment, the spatial precision and the efficiency to register a hit were found using similar techniques. The alignment was done using high energy muons which traversed the detector planes. A 'line' was drawn between each hit in the first plane, of a projection, to every hit in the last plane of that projection. These 'lines' were then compared to the hits in the intermediate planes and the residuals plotted. The displacements of these intermediate planes were found by the position of the peaks of the residual plots. Typical displacements were $\sim 200 \mu\text{m}$. A similar method was used to find the displacements of the U and V planes.

After the displacements were corrected for, plots such as figure 34 were obtained using high multiplicity photon interactions. Figure 34, which is for a typical plane, is a

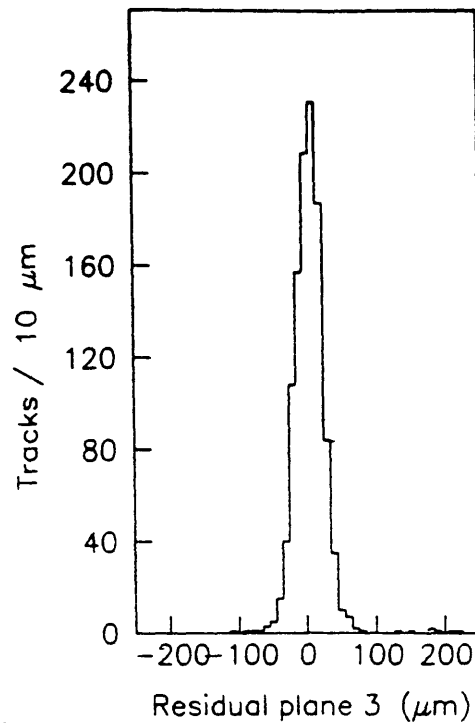


Figure 34: Typical Residual Plot

residual plot this time showing the displacement of the closest hit to a straight line fit through points from the three other planes in that projection (no magnetic bending). From the width (F.W.H.M) of this distribution the spatial precision of $16 \mu\text{m}$ was calculated, which is close to the theoretical value of $50/\sqrt{12} \mu\text{m}$.

Using the same technique the efficiency to register a hit was estimated from the number of times a 4th hit on a track was found when three hits had already been found. Averaged over all planes an efficiency of 98.7% is estimated. No fall in efficiency is observed for track angles up to 150 mrad.

5.3 THE CHARM SEARCH

The rest of this chapter is devoted to the techniques used in a search for heavy flavours. The original data set used in this search consisted of 100k events. Events were written to tape using a trigger which selected hadronic photon interactions.

This search is divided into 3 parts. The first part deals with how events were selected and processed for possible D^0 candidates. The second part shows how for these special events the tracks from the microstrips and the tracks obtained from the MWPCs relate to one another. The final part presents the most promising of the candidates.

Before embarking on this description it is worth noting that preliminary estimates of the number of D^0 's to be found in the sample, after branching ratios, acceptances and other efficiencies were accounted for, gave a value of ~ 1 .

5.4 FILTERING OF THE DATA SAMPLE

5.4.1 TYPHON

The original data sample was 100k events. These events were then passed through a program known as Typhon, which reconstructed tracks using a simplified model of the magnetic fields together with space points from the MWPCs. From this information track momenta can be obtained with a precision of order 20% and the Cerenkov cell through which the track passed can be identified. The full 100k data sample was processed and events containing kaon candidates (26k) were selected for further analysis.

5.4.2 Microstrip Filter

Using the method described in Chapter 4, the 26k events were examined for a possible secondary vertex. The requirement was an identified primary vertex in the Active Target and an offset track, reconstructed by the microstrips, which forms a secondary vertex with another track in the event. This filter reduced the number of events to 3.2k.

5.4.3 Trident

The full track reconstruction program TRIDENT is described in Chapter 7 where the different categories of tracks are defined. The 3.2k events were analysed using Trident and the momenta and direction of all tracks determined with a much improved precision compared with that obtained using the faster but cruder methods of Typhon. Kaons and pions were identified using the Cerenkov counter (see Chapter 7) and invariant mass combinations were obtained for all events containing at least a kaon and pion of opposite charge. This reduced the sample to 2k events. The difference between the 3.2k events, selected by Typhon, and the 2k events selected by Trident, is due to the poor momentum estimate by Typhon which requires a more generous definition of a kaon.

D^0 candidates were filtered off by selecting events with a $K\pi$ invariant mass in the range 1.76-1.96 GeV. This range is derived from the $\pm 3\sigma$ error on the D^0 mass due to track reconstruction errors. The final sample of 31 events thus have a $K\pi$ mass in the D^0 region and evidence for a secondary vertex as found in the

microstrips.

5.5 MATCHING SPECTROMETER AND MICROSTRIP TRACKS

To ascertain if any of the 31 events in this final sample actually contained a charm event, the K and π found by the MWPCs have to be matched in angle to the tracks found by the microstrips. Trident tracks must be associated to microstrip tracks in order to identify particles coming from secondary vertices. This is done by matching in angle because Trident tracks have an accuracy of only ± 1 mm at the vertex in the plane transverse to the beam, and this precision is insufficient for spatial identification; the tracks separation is typically 0.5 mm in the microstrips. The angular precision from both microstrips and MWPCs is about ± 1 mrad and this allows tracks to be identified.

5.5.1 UV Matching

Using the microstrips filter to search for secondary vertices only tracks which had 4 points in each projection and were matched in the U or V planes were used. These tracks were matched to the Trident flag types 2 and 4 (see chapter 7 for details on these tracks). Tracks found by the microstrips were considered to be the same track as found by Trident if

$$\text{For Flag 2 } |\text{Angle microstrip} - \text{Angle Trident}| \leq 0.005 \text{ rad}$$

$$\text{For Flag 4 } |\text{Angle microstrip} - \text{Angle Trident}| \leq 0.0025 \text{ rad}$$

differences,

The above angular Δ were obtained from studies on a large sample of reconstructed tracks. Examples of the angular correlations between microstrips and Trident tracks are shown in figure 35.

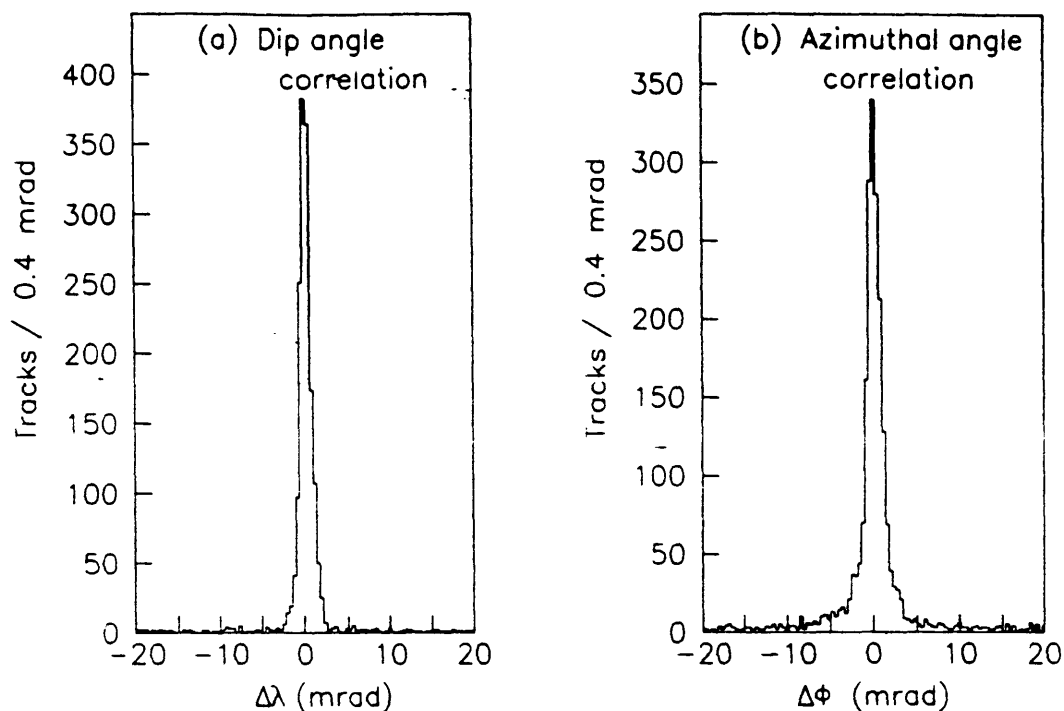


Figure 35: Angular Correlations between Microstrips and Trident

Following this procedure none of the 31 $D^0 \rightarrow K\pi$ candidates, identified by Trident was matched to a secondary vertex in the microstrips.

Results from a systematic study of the track matching are summarised by figures 36 and 37. These show a reasonable success ($> 70\%$) in matching Trident to microstrip tracks in projection. But when the projections are combined using the U and V planes the matching efficiency is poor ($< 30\%$). Since the U and V plane efficiencies to record a hit are $\sim 97\%$ the cause of this poor matching efficiency probably lies in the algorithm used to assign tracks in projection and drop 'ghosts'.

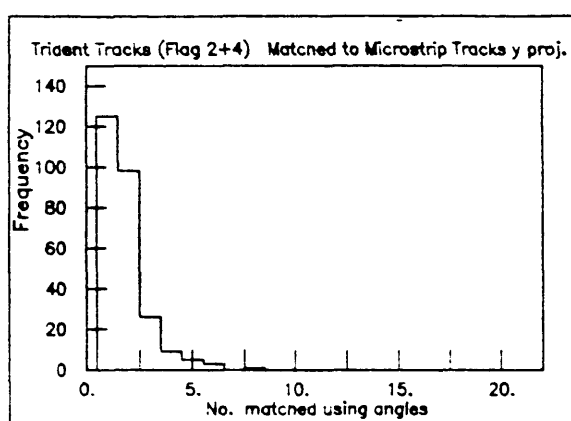
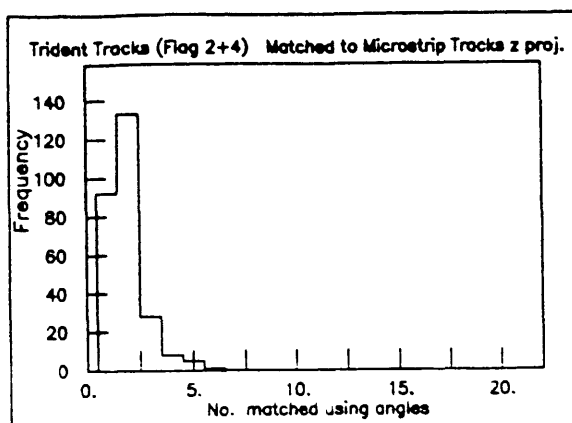


Figure 36: Trident Matched to Microstrip Tracks in projection using angles

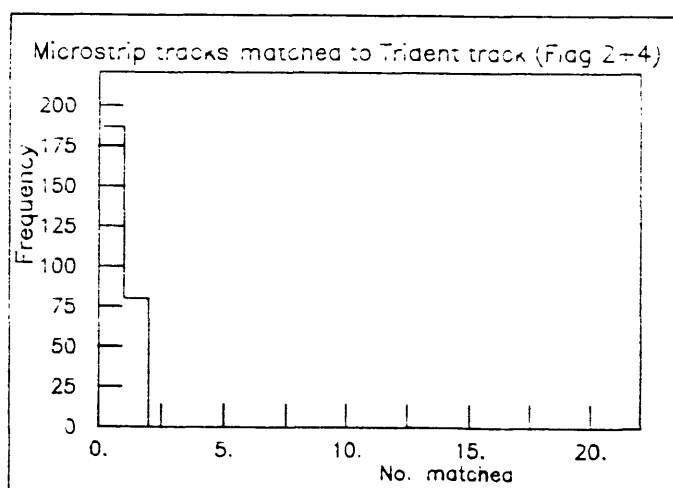


Figure 37: Trident Matched to Microstrip Tracks in Space using angles

5.5.2 Trident Matching

Since only 30% of the tracks were found in space but 70% in projection, a different method of matching the projection tracks was tried. This involved using Trident to match the microstrip projection tracks, in the following way.

1. The dip and azimuthal angles of each projected microstrip track were found: for the purposes of this exercise they were taken at plane 5 see (figure 18) of the microstrips.
2. The angle of the Trident tracks were found in both projections. In the x-y projection the track is curved by the AEG magnetic field so the angle is defined at the intersection of the track with plane 5 of the microstrips.
3. Each Trident track was compared with the angles of all microstrip tracks in projection using the cuts stated in section 5.4.1.
4. Projections that matched a Trident track were associated to form a microstrip track in space. This track was extrapolated to the U and V planes to see if there was a 'hit' in these planes. This process was performed to validate the tracks and reduce the possibility of projections being associated incorrectly.
5. The search for primary and secondary vertices then proceeded as described in Chapter 4

Proceeding as described the percentage of Trident tracks found in the microstrips increases to 46% which is a significantly greater than the 30% found by the previous method. The actual number of tracks found using this Trident matching method is shown in

figure 38.

The disadvantage of this procedure is that many microstrip tracks are matched to the same Trident track (see figure 39). The same process was repeated using 3 point tracks i.e. 3 hits out of 4 in a projection, but the only effect of this was to increase the multiple matchings without increasing the number of new tracks found.

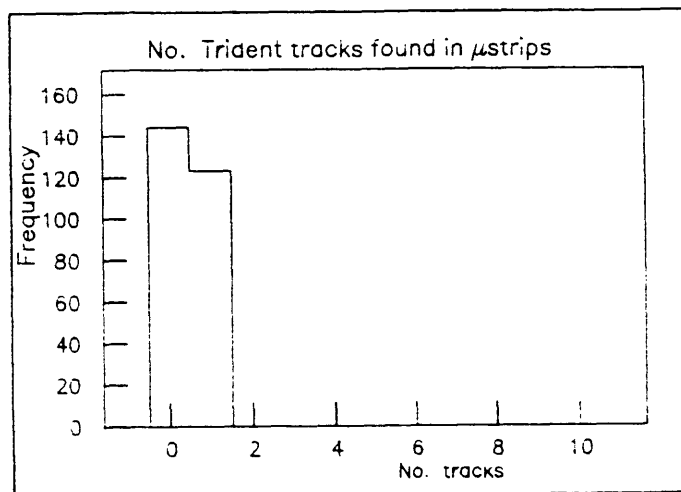


Figure 38: Trident used to Match 4-point Tracks

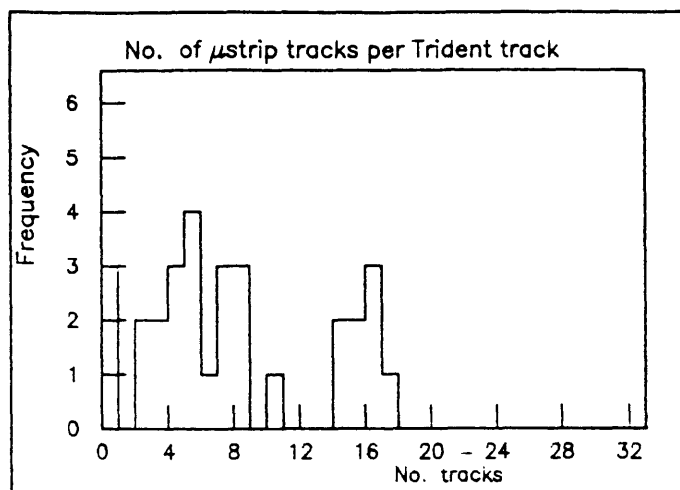


Figure 39: Multiplicity of 4-point μ -strip tracks matched using Trident

5.6 POSSIBLE CANDIDATE

Using the Trident matching techniques an event was found, where both the K and π that formed a D^0 mass were seen in the microstrips and which together formed a secondary vertex; this event is shown in figure 40. In figure 40 the solid lines represent tracks that are fitted to a primary vertex while the hatched lines represent tracks that are offset from this vertex. The primary vertex itself is shown as an open square and the secondary vertices are shown as open circles. The secondary vertex of interest in this event is marked by an arrow. The numbers at the bottom of both the y and z projections label tracks. Reading from left to right they correspond to microstrip tracks that intersect the right hand side of figure 40 from bottom to top. Unfortunately it is not a terribly convincing event as although a primary vertex can be seen in the z projection, the y vertex is diffuse. This could mean that tracks

in the y projection, simply because they have the desired angle, are being associated with the wrong Trident tracks.

The $K\pi$ invariant mass combination of this event is 1.84 ± 0.01 GeV, which means it is within 2.5 σ of the D^0 mass stated in the Particle Data Book. Other relevant details are given in Table 7.

This event has many properties required of a charmed particle decay but to be more convincing a much better y projection vertex is required. Work to find such an event is continuing and hopefully much clearer events will be found when more data is processed, and the microstrip and Trident tracking are integrated.

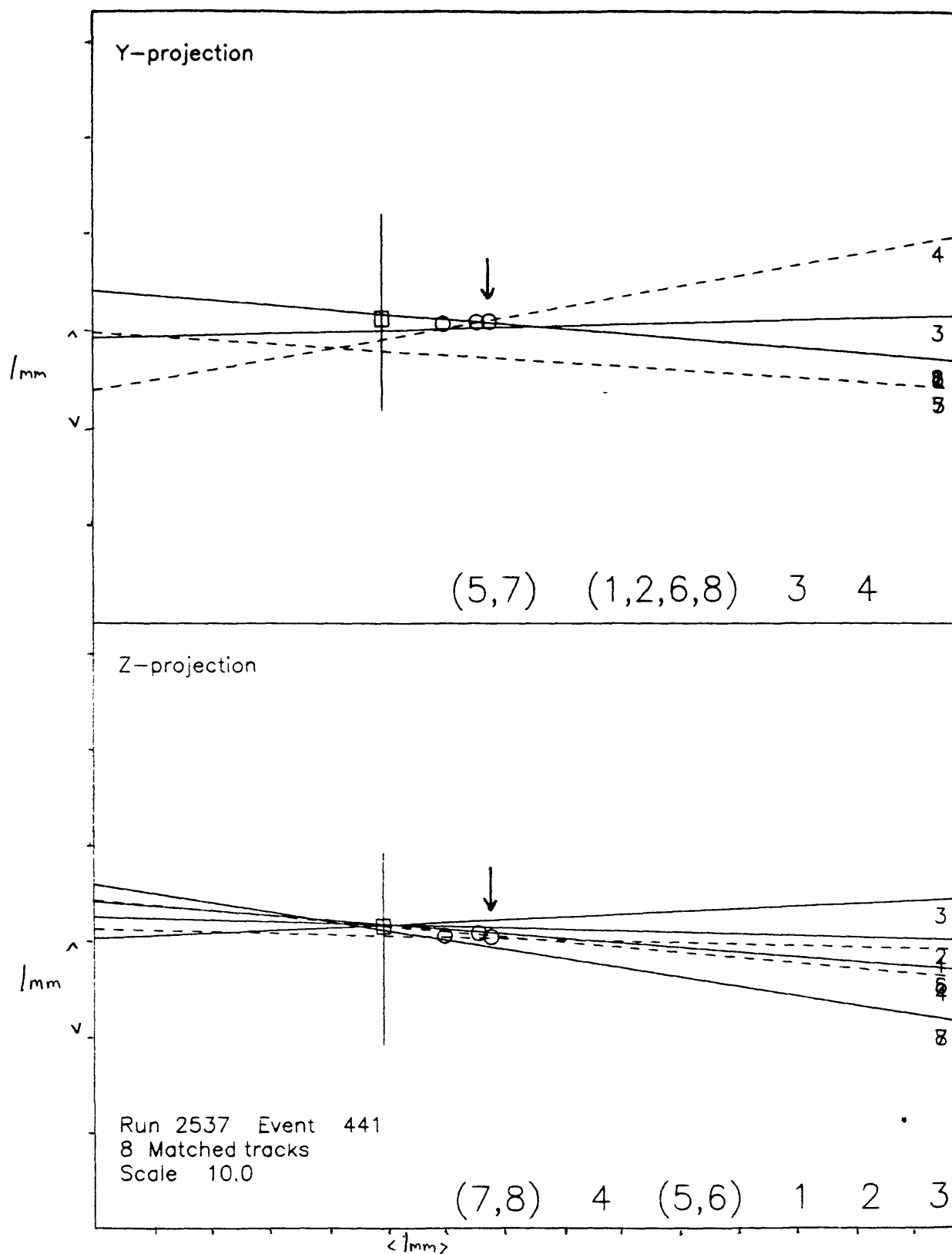


Figure 40: Candidate Event in Both X-Y and X-Z Projections

Momentum of K +ve Momentum of π -ve	14.65 GeV Track #6 in figure 40 13.45 GeV Track #4 in figure 40
Primary Vertex	x = -30.3182cm y = -1.0086cm z = -0.2555cm
Secondary Vertex	x = -30.1201cm y = -1.0124cm z = -0.2628cm
Distance between vertices or Flight path (unweighted)	f = 1983.0 μ m
Distance between vertices (weighted)	s = 124.5 μ m
Distance between tracks forming secondary vertex.	d = 28.5 μ m

TABLE 7

Details of possible candidate

Chapter VI

PHOTOPRODUCTION

This chapter provides the link between the two parts of this thesis. Models for photon production of heavy flavours are discussed and expressed in such a way that the results can be applied to strange quark production. The term heavy flavour is not usually considered applicable to strange quarks. Heavy is to be compared with the scale parameter of the strong interaction, $\Lambda \sim 200$ MeV, above which perturbative QCD calculations are expected to be valid. The strange quark mass, usually taken to be ~ 500 MeV, barely satisfies this requirement.

6.1 PHOTON STRUCTURE

The photon appears to have two interaction properties. Firstly the point-like interaction with quarks and leptons. This process is responsible for phenomena such as QED and QCD Compton scattering. Secondly the photon can interact as if it was a hadron, more specifically a vector meson, this property is known as the hadronic interaction.

To reflect these differing interaction properties the structure function for real photons is split into two parts, point-like and hadronic. The photon structure function has been explored in e^+e^- storage rings in the process [34]

$$e^+e^- \rightarrow \gamma\gamma \rightarrow X$$

known as two photon processes.

The point-like interaction is calculable while the hadronic interaction is not. Only estimates of the hadronic interaction can be made. The major contribution ($\sim 99\%$) of the photon's hadronic cross section can be described by the hadronic component. The remaining 1% is described by the point-like component [35]. The hadronic component is also found to dominate at low P_t while at high P_t ($\geq 2.0 \text{ GeV}/c$) the point like component becomes dominant.

6.2 PRODUCTION MECHANISMS

The two different interaction properties of the photon have been used to model the particle production in photon interactions. Recently a lot of interest has been paid to the problem of heavy flavours production in photon interactions; this interest has led to three different models, Vector Meson Dominance (VMD), Quark-Quark fusion (qq) and Gamma-gluon fusion (γg). In principle these models can be used to predict the cross section for light flavour production, but the difficulty arises from perturbation theory when α_s is not small. α_s becomes large when Λ is comparable with the mass of the quark. As α_s increases higher order corrections to the models become increasingly more important.

The three models are briefly described in the following sections.

6.3 VECTOR MESON DOMINANCE

Vector Meson Dominance uses the assumption that the photon is a superposition of vector meson states

$$|\gamma\rangle = \sum_V \frac{4\pi}{\gamma_V^2} |V\rangle$$

where V is the vector meson.

Each of the vector mesons is coupled to the photon by $4\pi/\gamma_V^2$, which is related to the electric charge on the quarks in the meson.

An expression for the heavy flavour photoproduction cross section using the VMD model is not given here (one can be found in reference [36]) as it is not applicable to work elsewhere in this thesis. However for the second part of this thesis, the relative coupling strengths of the vector mesons to the photon are important. Their importance comes when estimating the K/π ratio in photoproduction. For the ρ , ω , ϕ , and J/ψ vector mesons the relative couplings strengths are 9:1:2:8. These values can be calculated from the simple quark model (see reference [39]). Using these values and a naive model in which ρ and $\omega \rightarrow \pi^+\pi^-$ and ϕ and $\psi \rightarrow K^+K^-$ (ie charm $\rightarrow$ strange) a value for the K/π ratio of $\rightarrow 100\%$ is obtained. This model can be improved by taking into account the suppression of high mass vector mesons. The amount of suppression that occurs is a function of M_V^2 , where M_V is the mass of the vector meson. Assuming that the three lowest lying vector mesons are not suppressed and only the masses are

considered it would be expected that the $\sigma(\psi)/\sigma(\phi) \simeq 1/9$ given $m(\psi) \simeq 3m(\phi)$. Combining this result with the 9:1:2:8 couplings of the vector mesons to the photon a K/ π ratio of $\sim 30\%$ is obtained.

Two further refinements can be made. Firstly assuming that $\psi \rightarrow$ strange and non strange particles in equal fractions and secondly using the suppression factors of 0.7 and 0.3 respectively for ϕ and ψ calculated by Sivers [36]. These refinements produce a K/ π ratio of $\sim 25\%$ a value not drastically different than the previously calculated value of 30%.

In conclusion using the coupling strengths of the vector mesons to the photon a K/ π ratio of between 25-30% is anticipated.

6.4 GAMMA-GLUON FUSION

Gamma-gluon fusion involves the point-like interaction of the photon as shown in figure 41. One method of calculating this process in first order is as follows:

referring to figure 41

$$\gamma p \rightarrow q \bar{q} X$$

which is related to

$$\gamma \gamma \rightarrow q \bar{q}$$

and this is calculable in QED. The difference between the two processes is the γq vertex involves an a while the gq vertex involves an as and the introduction of a 1/2 factor from colour averaging over the gluons. Thus

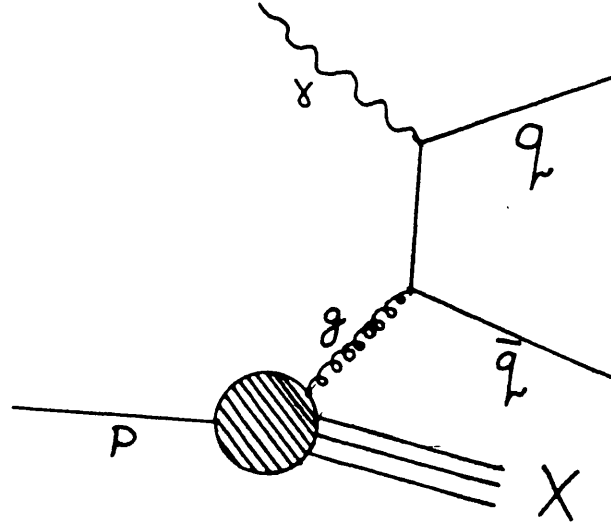


Figure 41: Gamma Gluon Fusion

$$\sigma(\gamma p \rightarrow q\bar{q}) = 0.5 Q_i^2 (\alpha_s/\alpha) \sigma(\gamma\gamma \rightarrow q\bar{q})$$

where Q_i is the charge on the quark q .

To calculate the total cross section for this process, the gluon momentum fraction of the proton is required and integration is necessary.

$$\sigma(\gamma p \rightarrow q\bar{q}X) = \int_{x_1}^1 dx G(x) \sigma(\gamma g \rightarrow q\bar{q})$$

In the above expression $G(x)$ is the gluon momentum distribution in the proton, the fraction of momentum carried by the gluons in the proton. The integration is performed between x_1 , where $x_1 = s'/s$ (s' is the invariant mass of the $q\bar{q}$ system and s is the invariant mass of the γp system), and 1. The x_1 value expresses the fact that there is a minimum energy required for $q\bar{q}$ production. There is no definite rule as to the definition of this threshold and various gamma-gluon fusion models use s' in

the range

$$4m_q^2 < s' < 4m_M^2$$

where m_q = mass of quark q

and M_M = mass of meson containing quark q

The final step is the QED calculation of $\gamma\gamma \rightarrow q\bar{q}$

$$\sigma(\gamma\gamma \rightarrow q\bar{q}) = \frac{(4\pi\alpha^2)}{s} \left[(1+\delta-0.5\delta^2) \ln \left| \frac{1+\sqrt{(1-\delta)}}{1-\sqrt{(1-\delta)}} \right| - (1+\delta)\sqrt{(1-\delta)} \right]$$

where $\delta = 4m_q^2/s'$

and hence $\sigma(\gamma p \rightarrow q\bar{q}X)$ is obtained.

There are however a number of difficulties, which concern the knowledge of the form and size of the following quantities in the model

1. α_s , running coupling constant
2. m_q , mass of the quark
3. $G(x)$, gluon distribution function.

6.4.1 Running Coupling Constant α_s

The α_s parameter is defined as

$$\alpha_s(\mu^2) = \frac{12\pi}{(33 - 2f) \ln(\mu^2/\Lambda^2)}$$

f is defined as the number of active quarks and Λ is the mass scale at which α_s becomes small enough to perform perturbative

QCD. The favoured values for Λ^2 are between $(0.1-0.5 \text{ GeV})^2$. μ^2 is again dependent on keeping α_s small to allow perturbative QCD. The generally adopted method is to set μ^2 equal to s' . Therefore

$$\alpha_s(s') = \frac{12\pi}{25 \ln(s/\Lambda^2)}$$

with $s' > 4m_q^2$.

The Monte Carlo, used in Chapter 4 in order to access the charm enrichment of a particular 'ORgate', generated charm events using a gamma-gluon model to produce cc pairs. The cc pairs were then fragmented using the Lund method. The s' used in the Monte Carlo was

$$s' = 4 [m_q^2 + p_t^2 / (1 - \cos^2 \theta)]$$

where p_t is the transverse momentum of the $q\bar{q}$ system and θ the angle between the direction of the outward going quarks and the direction of the γ and g in the C.M frame. The major problem with performing this calculation with quarks of light flavour is that their mass is $\sim \Lambda$, which means α_s is large and hence perturbative Q.C.D. is unreliable.

6.4.2 Gluon Momentum Distribution Function $G(x)$

The most favoured form for this function is

$$G(x) = \frac{(n+1)(1-x)^n}{2x}$$

where $n = 5$

and satisfies the condition

$$\int xG(x)dx = 1/2$$

ie half the momentum of the proton is carried by the gluons. The above form is motivated from deep inelastic scattering results [41] and constituent particle counting rules [42].

6.4.3 Mass of Quark

The quark mass is a very difficult quantity to ascertain and in fact only estimates of it can be made. Changing the mass of the quark has a sizeable effect on the magnitude of the cross section but not the form. Figures 42 and 43 both show a set of cross sections vs beam energy. The 11 curves on both diagrams were produced by ~~varying~~ the mass of the quark (either u or d and s) between 0.1 - 0.6 GeV in steps of 0.05 GeV. The result is, as the quark mass increases the cross section decreases for all beam energies.

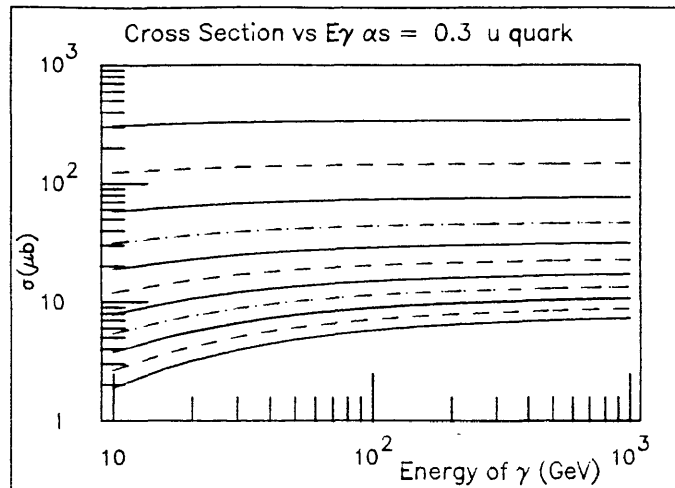


Figure 42: Cross-section for varying mass of u quark

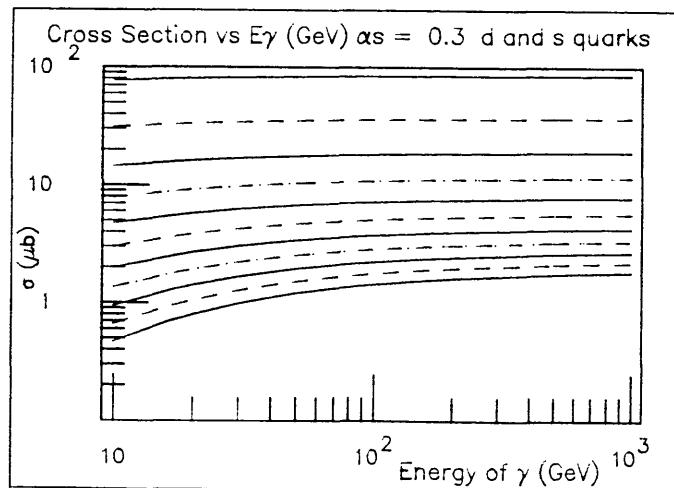
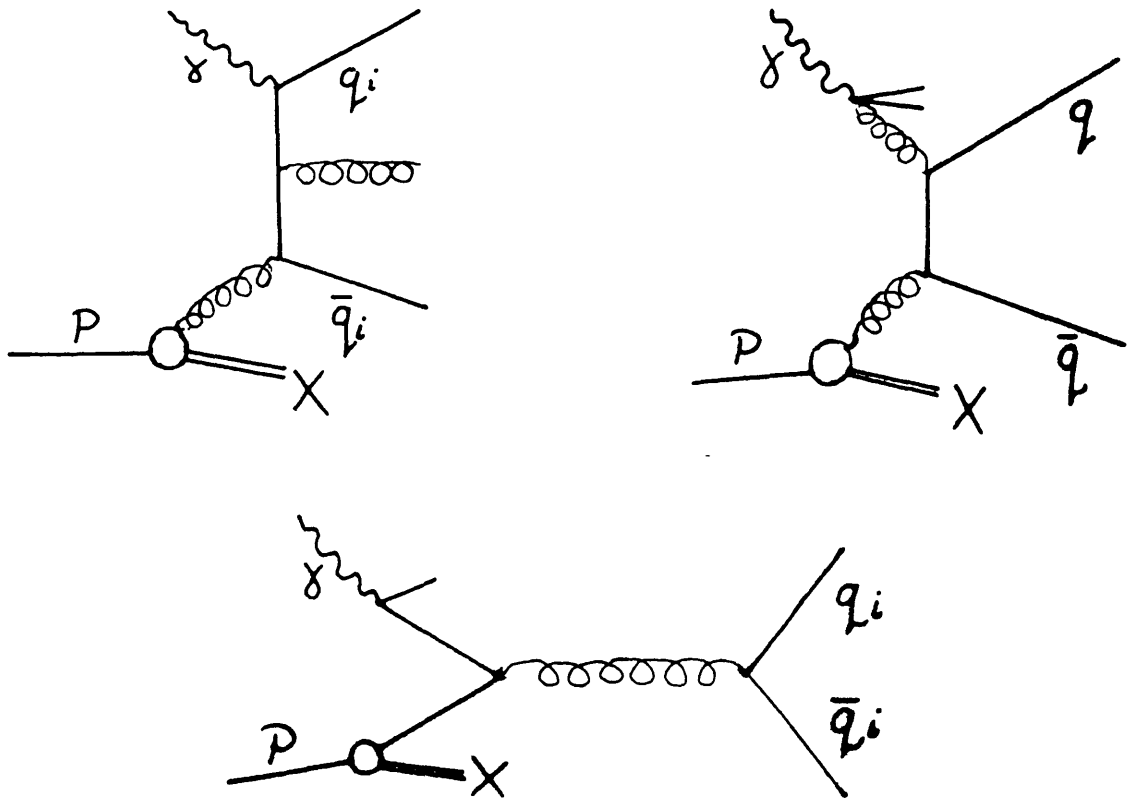


Figure 43: Cross-section for varying mass of d and s quarks

6.4.4 Higher Order Processes

Higher order processes such as those shown in Figure 44 are not important for heavy flavours [40] but for lighter flavours u, d, and s their effects may well be very significant because of the large value of αs .

Figure 44: Higher order γg processes

6.5 QUARK-QUARK FUSION

The quark quark fusion model is really an extension of the Drell-Yan [43] process shown in figure 45 where two quarks annihilate to produce a virtual γ which decays to a lepton pair. The structure function $f(x)$ expresses the probability of finding a quark, with a particular momentum fraction, inside the hadron. Using the structure functions of hadrons h_1 and h_2 the cross-section for $h_1 h_2 \rightarrow l^+ l^- X$ is :-

$$\sigma(h_1 h_2 \rightarrow l^+ l^- X) =$$

$$(1/3) \int \int dx_1 dx_2 \sum_i \{ f_i^{h_1}(x_1) \bar{f}_i^{h_2}(x_2) + \bar{f}_i^{h_1}(x_1) f_i^{h_2}(x_2) \}$$

$$\sigma(q_i \bar{q}_i \rightarrow l^+ l^-) \delta(x_1 x_2 s - M^2)$$

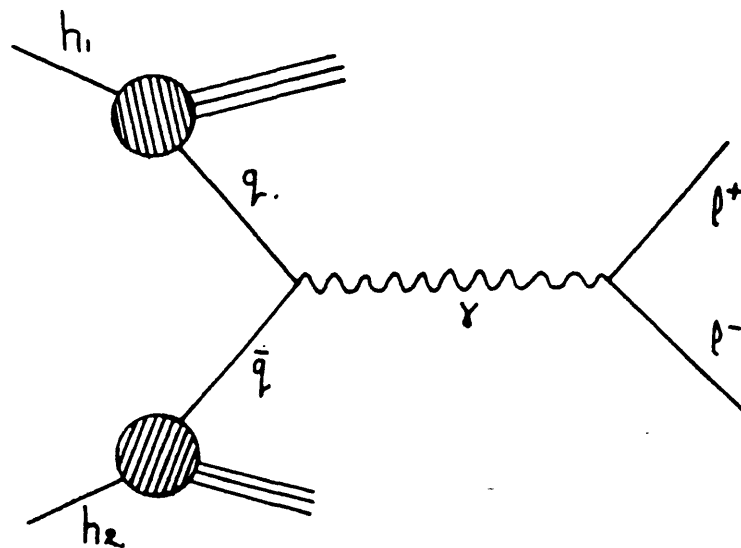


Figure 45: Drell Yan Process

In the preceding expression M is the invariant mass of the final lepton system, x_1 and x_2 are the momentum fractions of quarks in h_1 and h_2 and i indicates a sum over flavours. The cross section $\sigma(q\bar{q} \rightarrow l^+l^-)$ is a QED process and can be calculated to give

$$\sigma(q_i\bar{q}_i \rightarrow l^+l^-) = \frac{4\pi\alpha^2}{3M^2}$$

The Drell-Yan process can be extended to that shown in figure 46 for open flavour production. In this process the electromagnetic annihilation is no longer necessary and rather than the $q\bar{q}\gamma$ vertex there is now a $q\bar{q}H$. At the $q\bar{q}H$ vertex α is the coupling strength so replaces one α in the Drell Yan expression. The resulting expression is

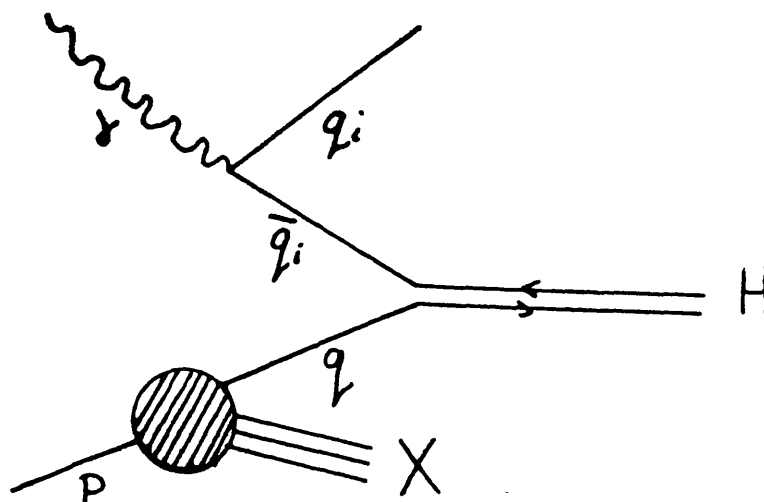


Figure 46: Quark-Quark Fusion Producing Quarks of Flavour f

$$\sigma(\gamma p \rightarrow HX) = \frac{4\pi\alpha\alpha_s}{9M^2}.$$

$$\iint dx_1 dx_2 \sum_i \{ f_i^{h1}(x_1) \bar{f}_j^{h2}(x_2) + \bar{f}_i^{h1}(x_1) f_j^{h2}(x_2) \} \delta(x_1 x_2 s - M^2)$$

This can be reexpressed as :-

$$\sigma(\gamma p \rightarrow HX) = \frac{\sqrt{s} 4\pi\alpha\alpha_s}{E \ 9M^2} \int dx_F \sum_i \{f_i^{h1}(x_1) \bar{f}_j^{h2}(x_2) + \bar{f}_i^{h1}(x_1) f_j^{h2}(x_2)\}$$

where $x_1 - x_2 = xf$, $x_1 x_2 = M^2/s$, and $x_1 + x_2 = 2E/\sqrt{s}$

E = energy of the meson M produced.

This is a more useful expression for experimentalists since x_f can be measured. The difficulties with this model are the values of a_s to use and the quark structure functions for the photon which are not known precisely.

6.6 USES OF THE HEAVY FLAVOUR MODELS

As mentioned previously the γg model was used to generate events that were used to test the efficiencies of the microstrips. In chapter 8 the VMD and γg fusion models, are used to estimate the K/π ratio. A comparison with data is made which shows the VMD model gives the better description of this ratio. The γg and $q\bar{q}$ fusion models are also used to calculate the inelastic ϕ photoproduction cross section.

Chapter VII

DATA PROCESSING AND REDUCTION

7.1 AIMS

Photoproduction of strange quarks leads to strange particles in the final state. The charged K mesons, having lifetimes $\sim 10^{-8}$ sec are observed as charged tracks which traverse the NA14 apparatus with a small decay probability. Some explanation of the identification of charged tracks and particle types is necessary. This chapter describes briefly how this was achieved.

7.2 TRACK RECONSTRUCTION

To reconstruct the charged tracks, information from the MWPCs and of the magnet fields was fed into a computer program known as TRIDENT. This was originally developed for track and vertex identification in the Omega particle detector system; the TRIDENT used by NA14 is very similar to that used in Omega experiments, apart from the obvious changes from one spectrometer to the other.

A summary of Trident's operation is given below, a more detailed description is given in reference [44].

The philosophy of TRIDENT is to calculate the position and momentum of a particle anywhere along its trajectory, without having to solve the equations of motion. The quantities required to define a track at a particular x coordinate are px, py, pz,

y and z. The trajectory of a track passes through a number of planes of MWPCs giving hits on the wires. A linear relationship can be found between coordinates of hits from the same track in different MWPC planes and the required quantity (ie px, py, pz, y and z). For each quantity there is a separate relationship. The coefficients of these relationships are obtained via the use of Monte Carlo events, which are passed through a simulation of the spectrometer and incorporates the exact positions of the MWPCs. Using the following expression,

$$U_j = \sum A_i.V_{ij}$$

j = 1,m where m = number of tracks
 A_i = unknown coefficients
 n = number of observations
 U_j = track #j
 V_{ij} = observation of a track,

the exact trajectories of a set of tracks and a least squares minimisation technique, the coefficients A are found.

Once the coefficients have been found real data can be passed through and the actual particle tracks obtained, this time solving for U.

Once the position and momenta of the tracks are found a vertex can be obtained provided the tracks pass close enough to one another. In fact TRIDENT produces two classes of tracks: those that can be fitted to a vertex, known as 'Fitted Tracks', and those that cannot be fitted to a vertex, known as 'Extra Tracks'. These extra tracks are mostly due to beam halo muons which can occur within the strobe time of the MWPCs though some result from genuine secondary tracks which have been badly reconstructed.

7.3 TYPES OF TRACKS

The major classes of tracks - Fitted and Extra - are each subdivided into six Flag types. These Flags, as numbered in the following four subsections, indicate how well the tracks are determined and their location in the spectrometer.

7.3.1 Flag 2

Flag 2 tracks are found in the Stack 1 MWPCs only, between the AEG and Goliath. They have experienced only the bending power of the AEG hence their momenta are not well determined. Furthermore the momentum determination must assume the trajectory passes through the vertex. For this reason vertices formed solely from flag 2 tracks are of doubtful precision.

7.3.2 Flag 3

Flag 3 tracks are found in Stack 2, downstream of the Goliath magnet, but no track segment is visible in the upstream chambers. These can be due to secondary interactions or, more commonly, due to random e^+e^- pairs which traverse the desensitized regions close to the beam in the upstream chambers.

7.3.3 Flag 4

Flag 4 tracks are the best measured tracks of all, being seen in both Stack 1 and Stack 2. The vast majority of tracks used in the analysis were of this flag type.

7.3.4 Flags 12,13, and 14

The other three types of track have flags 12,13 and 14 assigned: these are the same as flags 2, 3 and 4 but the quality of the track fit is poorer than expected from the precision of the MWPCs. They might indicate a scattering track or a misassociation of track segments. They were ignored in analysis.

7.3.5 Ratio of Flag Types

Figure 47 shows the relative proportions of the track types according to their flag.

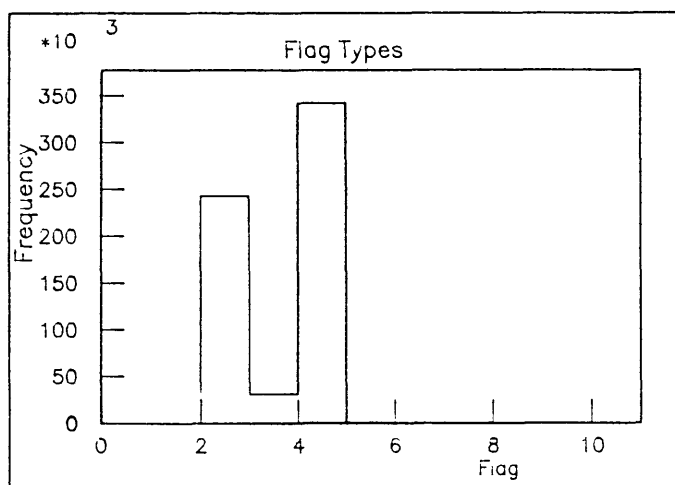
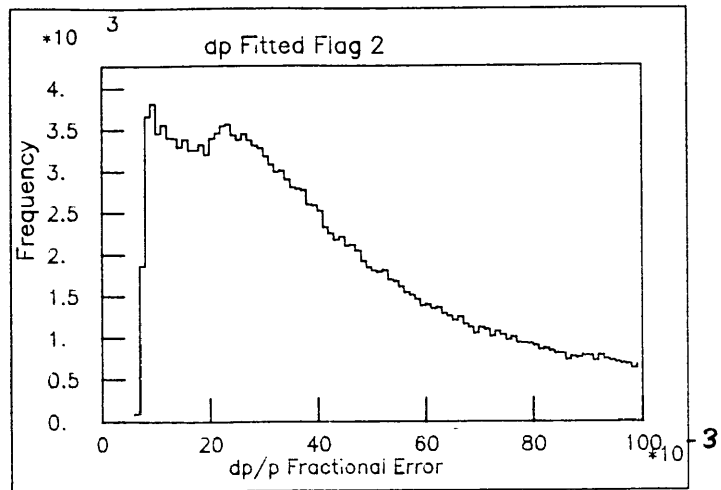
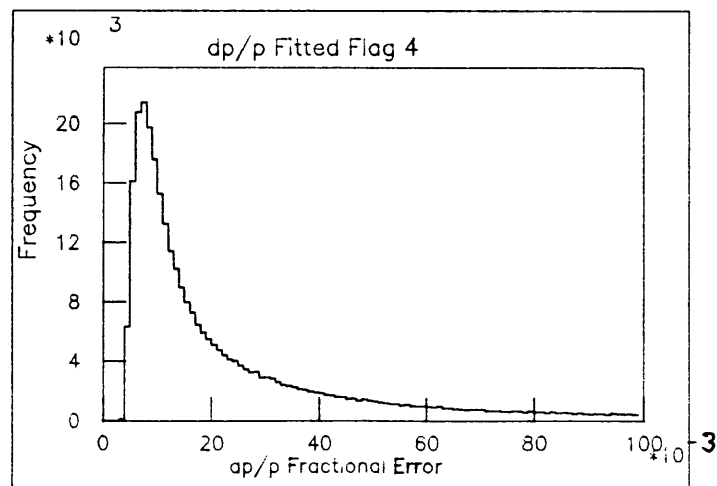


Figure 47: Proportion of Flag type relative to one another

7.3.6 Momentum Error

Figures 48 and 49 shows the fractional momentum error dp/p for fitted flag 2 and flag 4 tracks respectively. Note the error on the flag 4 tracks which is smaller than for flag 2. This reflects the much greater bending power used in the momentum determination for flag 4 tracks.

Figure 48: dp/p for Flag 2 fitted tracksFigure 49: dp/p for Flag 4 fitted tracks

7.4 VERTEX AND TRACK CUTS

The decision as to whether or not a track or vertex was 'good' could not be left entirely in the hands of TRIDENT. Using the track and vertex errors supplied by TRIDENT, the following criteria had to be met before a track and vertex were accepted.

1. A check was made on whether a vertex was found. Of the events recorded with the interaction trigger $\sim 55\%$ were found to have a vertex consistent with a hadronic interaction.
2. A check was made to ensure that the vertex was within $\pm 3\sigma$, where σ refers to the reconstruction error of the vertex, of the target.
3. Tracks were tested to ensure they were within the expected energy range for their flag type and that their errors were not too large.
(Flag 2 $1 < p < 40$ GeV, $dp/p < 0.1p$: Flag 4 $p < 100$, $dp/p < 0.15$)
4. Trident sometimes finds two tracks where only one should have been seen. This occurred mainly with flag 2 and flag 4 tracks. To remove the spurious track a test was made to see if the two tracks were more than 2 mrad apart in one or both of the measured angles. If a pair of tracks (flag 2 and 4) failed this test, the flag 2 was dropped and the flag 4 kept.

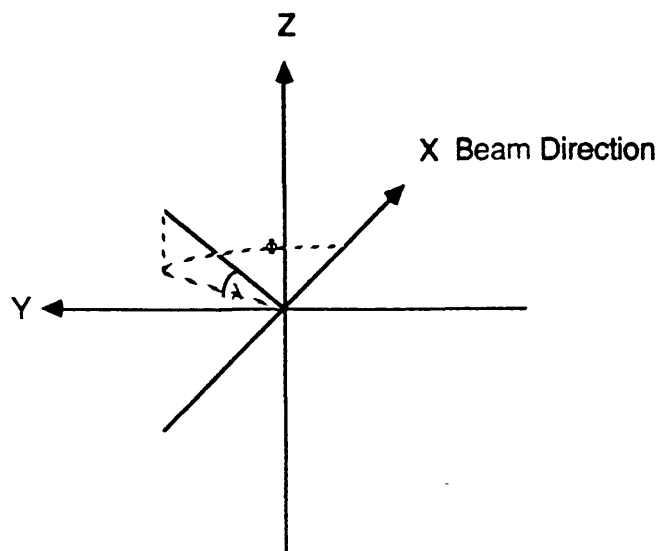


Figure 50: Diagram to explain Coordinate System

7.5 TRACK RECONSTRUCTION ERRORS

For each track, Trident produces 3 parameters $1/p$, ϕ and λ (see figure 50) which define the track. The Trident program gives errors on each parameter and the correlated errors between them in the form of an error matrix.

After the tracks have been identified (to be described in the next section) the energy of the track can be calculated from the momentum. Invariant masses can be formed by subtracting the combined momentum from the combined energy of two or more particles. An error on this invariant mass can be obtained by combining the reconstruction errors on the particle tracks. To indicate how accurately the experiment can determine particle masses, the error on the invariant mass for the following resonances are given :-

in the ρ mass region the error on $m(\pi^+\pi^-) = 20.0$ MeV

in the ϕ mass region the error on $m(K^+K^-) = 5.3$ MeV

in the K^* mass region the error on $m(K\pi) = 13.7$ MeV

in the D^0 mass region the error on $m(K\pi) = 33.6$ MeV

These errors were calculated using real photon interaction data.

7.6 PARTICLE IDENTIFICATION

Having described the method by which the tracks and vertex were found there follows a discussion on how particles were identified.

7.6.1 Cerenkov

Much of the work in the next chapter relies on the identification of pions, kaons and protons using the Cerenkov counter. Due to the position of the Cerenkov the tracks that passed through it were flag 3 and 4, predominantly flag 4, hence the particle tracks identified by it were well reconstructed. Unfortunately NA14 had only one working Cerenkov, which meant the momentum range over which particles could be identified was rather restricted. To avoid ambiguity particles were not identified when more than one track could emit light in the direction of a single Cerenkov mirror (cell). In theory, the pion/kaon threshold is 6 GeV/c, and the kaon/proton threshold is 21 GeV/c. However, examining figure 6, it can be seen that, due to the slope of the curve in the region 6-8 GeV/c, a more realistic figure for the pion/kaon threshold is 8 GeV/c. The upper limit of this 'window' should be reduced to 18 GeV/c to allow for momentum errors. Note also that the kaon/proton threshold is moved to 28 GeV/c for the same reason. (The threshold at which protons emit light in air

is 38 GeV/c). In the next chapter, a momentum window of 8-18 GeV/c is used for work on phi photoproduction, while the range 10-20 GeV/c is used for work on kaon/pion ratios for comparison with data obtained in the same experiment but using a data sample of high transverse momentum triggers [15].

In the momentum band 8-20 GeV/c electrons, muons and pions can produce light in the Cerenkov counter. For the purposes of this analysis the electrons and muons are considered as a contamination of the pions and their contribution is estimated in later sections. A further problem encountered with the Cerenkov was inefficiency due to a phototube not registering when light from a particle is incident upon it. The size of this inefficiency was estimated from examining the region above 43 GeV/c in figure 6 where all particles should give light. This gives a figure of approximately 2%, which agrees with a more detailed analysis (reference [15]).

7.6.2 Muon Contamination

Muons were identified using the Muon Filter, the contents and positions of which were described in Section 2.9. Using the information supplied by the muon detectors a program calculated a χ^2 probability for each track seen to be a muon. This was based on the requirement that a particle traversed 5 m of steel with a multiple coulomb scattering consistent with the particle's momentum. A track was accepted as a muon if this probability was ≥ 0.1 .

To test the efficiency of the muon detectors and the muon

detection program, J/ψ events which decayed via the $\mu^+\mu^-$ channel were used. Using the cut of ≥ 0.1 in χ^2 probability, as explained above, it was found that only 0.76 of the muons were found rather than the 0.9 that were expected. This error was corrected for in calculating the fraction of muons observed for both γ and π^- beams.

The contamination of muons in the momentum range 10-20 GeV/c was found for both the γ and π^- beams. The results were :

γ beam $1.1 \pm 0.2\%$

π^- beam $0.2 \pm 0.04\%$

and independent of the Pt of the particle.

In all this work, flag 4 tracks were used with the same kinematic cuts applied to muon tracks as to other particle types. One potential difficulty arises due to the acceptance of the muon filter, which is less than that of the Cerenkov. Since the spatial distribution of muons in the Cerenkov was similar to that of other particles it was assumed that the observed muon contamination, measured within the acceptance of the muon filter, could be applied across the full Cerenkov acceptance.

7.6.3 Electron Contamination

To estimate the contamination due to electrons in the range 10-20 GeV/c, the electromagnetic calorimeters were used. As the tracks were all forward in the C.M. frame OLGA and ILSA were used.

To identify charged tracks as electrons each track was extrapolated to a calorimeter. By examining the detectors in the

calorimeter for an electromagnetic shower, at the position indicated by the extrapolation, a track could be identified as an electron or positron.

The combined acceptance of OLGA and ILSA is approximately that of the Cerenkov. Hence the measured contamination of electrons is across the full Cerenkov acceptance.

The electron contamination in the γ and π^- beams was found to be:-

γ beam $1.1 \pm 0.06\%$

π^- beam $0.9 \pm 0.03\%$

The distribution was approximately flat in Pt, the above values being an average for all Pt, and used in all Pt ranges.

7.7 OBTAINING RAW PARTICLE YIELDS

For the work in the next chapter, it was necessary to find the number of pions, kaons and protons produced in both γ and π^- beams.

The way in which the proportion of various particles was obtained is explained with the aid of figure 51. In the momentum range 25-38 GeV/c the proportion of protons was found by subtracting the phototube inefficiency from the proportion of particles not giving light in this momentum range ie B - A. The proportion of kaons and protons was found from the momentum range 10-20 GeV/c in a similar manner. Assuming that the proton content is a constant over the momentum range concerned, then the proportion of kaons seen is simply

$$C - B - A$$

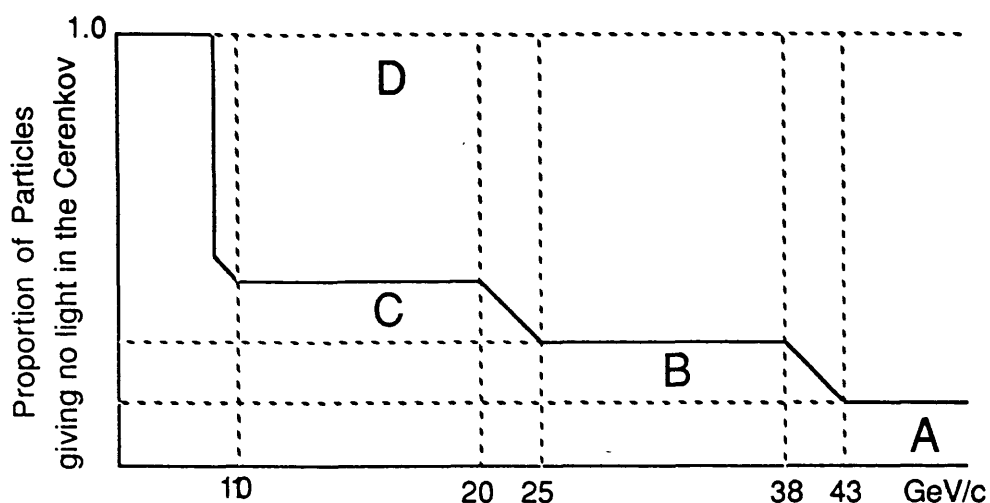


Figure 51: Diagram to explain Cerenkov Analysis

The proportion of pions was then found by assuming all the particles that gave light in the momentum region 10-20 GeV/c (ie area D) were pions. This was then corrected by subtracting the muon and electron contamination as previously calculated and adding the inefficiency, on the assumption that the majority of particles that did not trigger the Cerenkov were pions, since these are the most abundant particles.

7.8 TAGGING

In Chapter 2 mention was made of the tagging system that can be used to determine the energy of the incident photons. Unfortunately in only 50% of the cases could an energy for the photon be obtained by interrogating the tagging counters. This figure dropped to 35% when a well timed solution was required. Well timed means there is an unambiguous solution for the photon energy, ie a photon is associated in time to an in- and out-

going electron. Another unfortunate problem with the tagging was the large processing time required to pass events through the software that interrogates the tagging counters and produces the measured photon energies. For this reason only the ϕ candidates were processed in order to determine the elastic or inelastic nature of the production process.

Chapter VIII

STRANGE PARTICLE PRODUCTION IN A PHOTON BEAM

This chapter presents results relating to the production of strange quarks in a high energy γ beam. Two subjects are examined. Firstly a comparison of the K/π production ratio as observed in both γ and π^- beams. The results of these ratios are used to estimate the strangeness content of the photon. Secondly, the production of the phi meson is studied and the inelastic photoproduction cross-section is compared with simple quark model predictions.

8.1 ACCEPTANCE AND PARTICLE RATIOS

The results for the particle yields π^{+-} , K^{+-} , p^{+-} are presented as ratios. The objective of taking ratios is based on the assumption that with the use of limited momentum and transverse momentum regions, where unless the cross section varies rapidly over the kinematic region, the acceptances are the same and hence cancel. This has the advantage of reducing systematic errors relating to the acceptance of the spectrometer and the Cerenkov counter.

8.2 RESULTS

The various particle ratios obtained from the analysis are shown in figures 52 to 55 for both γ and π^- beams. A comparison is also made of the relative production in the two beams. The figures present two separate data sets. The data at $P_t < 1.1$ GeV/c were obtained from the interaction trigger as described in Chapter 7, while the $P_t > 1.1$ GeV/c were obtained for both γ and π^- beams using a special high P_t trigger. This trigger (described in more detail in reference [15]) required correlated hits in the first wire chamber of Stack 2 and the OLGA veto counters. This correlation, when combined with the bending power of the Goliath magnetic field, was used to write events to tape only if the P_t exceeded 1.5 GeV/c. The object of including the high P_t in the particle ratios was to see if the trends in the low P_t data were continued into the higher P_t region: this did occur with certain exceptions.

The results shown in figures 52 to 55 suffer from large errors whose main contribution comes from an estimate of the number of protons in the data. These errors unfortunately tend to obscure the trends being sought.

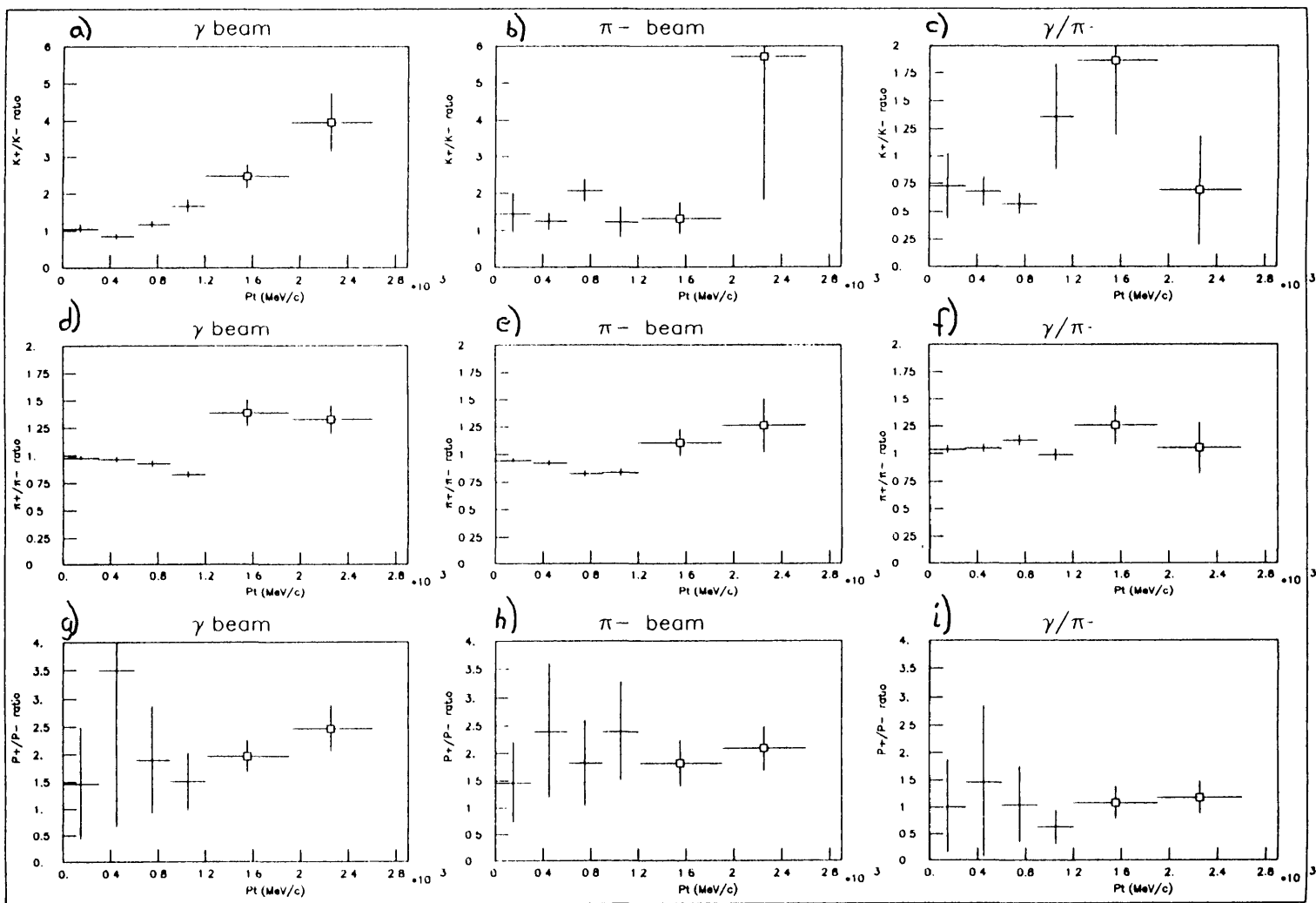


Figure 52: Particle Anti-particle ratios

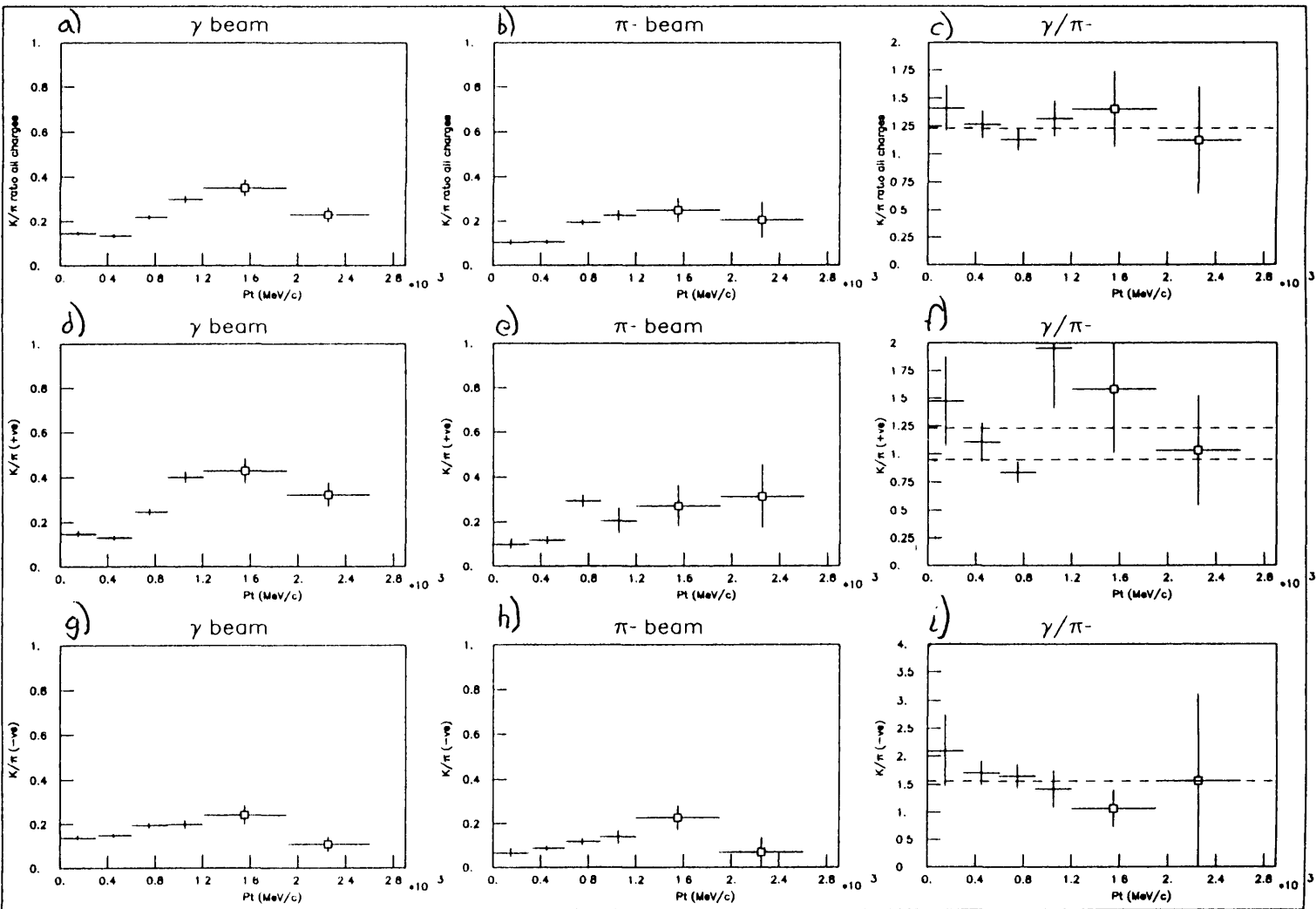


Figure 53: Kaon to Pion ratios

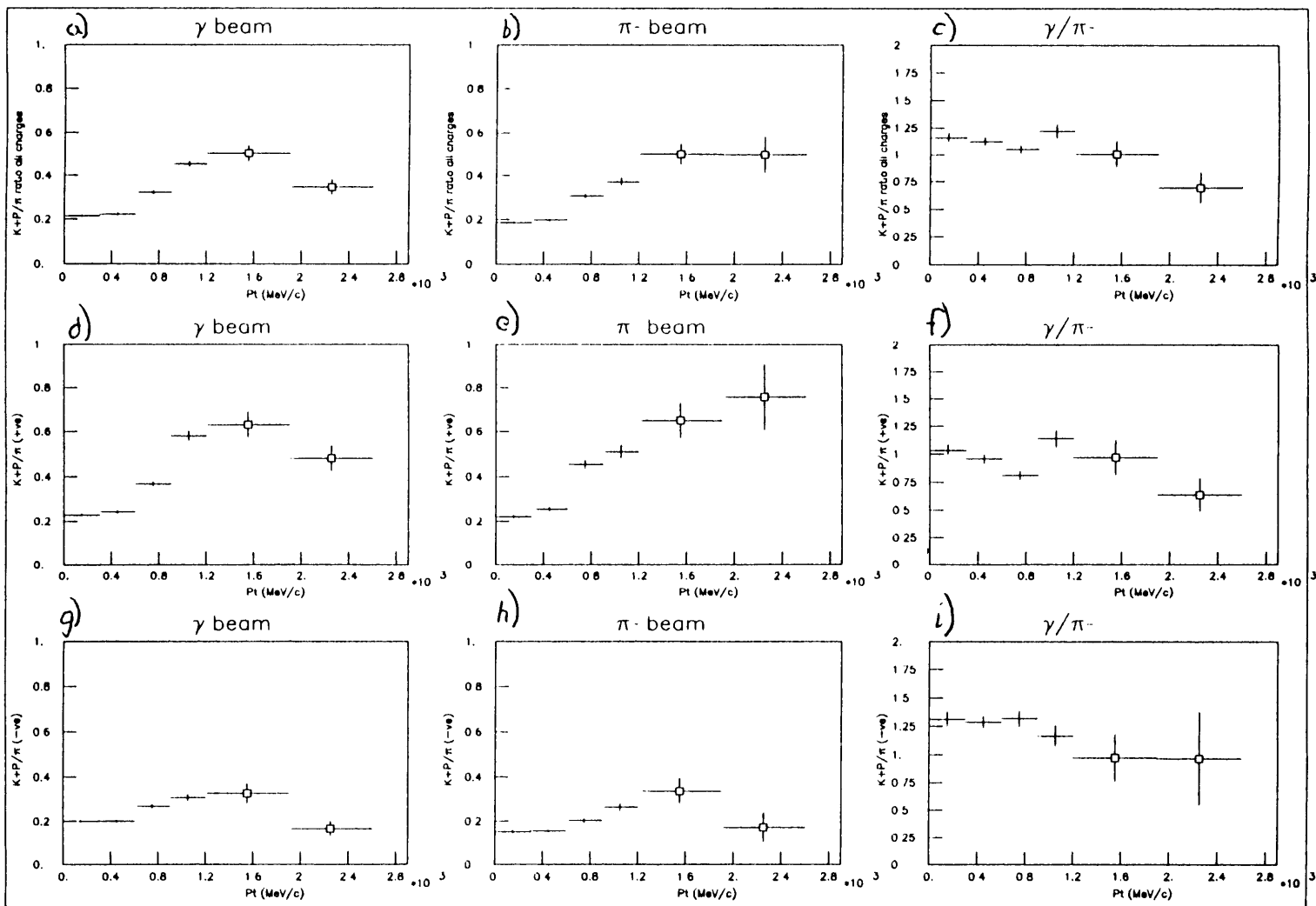


Figure 54: Kaon+Proton to Pion ratios

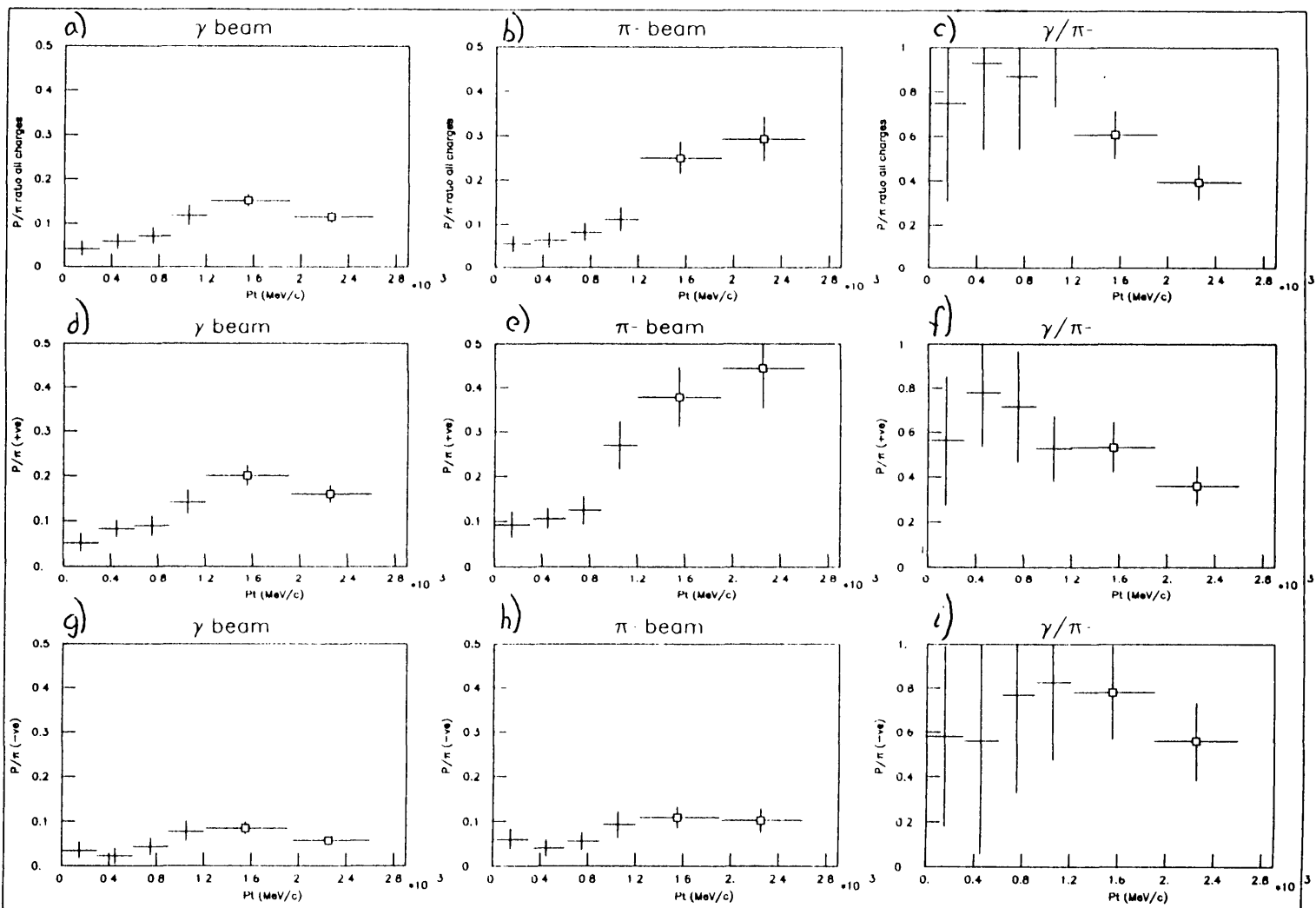


Figure 55: Proton to Pion ratios

8.3 PARTICLE ANTI-PARTICLE RATIOS

Although not the main objective of this analysis the particle anti-particle ratios for π , K and p are presented as they provide a useful comparison with values found by other experiments.

The results for the ratios of K^+/K^- and p/p^- were found to be similar to those published by Frisch et. al. [45] (π^- beam) and Boyarski et. al. [46] (γ beam). The K^+/K^- ratio is > 1 in both γ and π^- beams. This can be explained due to the presence of a valence u quark in the nucleon which is a necessary component of the K^+ . The Pt distribution of the K^+/K^- ratio in the γ beam is steeper than the corresponding ratio in the π^- beam. A possible answer to this is the following three part argument. Firstly at values of $xf = Q^2/2M \geq 0.2$ valence quarks are probed in preference to sea quarks. Secondly the presence of the u quark in the nucleon (as explained previously) and finally the greater the probing momentum the larger the possible Pt. Therefore the steeper rise with Pt in the γ beam of the K^+/K^- ratio could be due to u valence quarks being selected in high momentum γq interactions which result in K^+ having a higher Pt.

The results for the π^+/π^- ratio are not consistent with previous experiments, and the low and high pt data samples are not self consistent. Figures 52 d) and e) show a π^+/π^- ratio < 1 at low Pt in γ and π^- beams and a ratio > 1 at high Pt. The low Pt data in the π^- beam agree with those of Frisch et al. and are as expected from π^-p interactions, where a result of $\pi^+/\pi^- < 1$ can be explained because the initial π^- clearly has the right

ingredients to make another π^- , whether by a valence quark scattering process, or processes involving more than two quarks. For the low Pt γ beam data the results are not so easily explained. By charge conservation it is expected that γp interactions would have a π^+/π^- ratio slightly greater than 1, and γn interactions would have a π^+/π^- ratio equal to 1. The silicon target has approximately equal number of protons and neutrons so the expectation is a π^+/π^- ratio of ~ 1 . The ratio $\pi^+/\pi^- < 1$ observed in the low Pt data set is therefore not understood. The combined high and low Pt results do however give the expected result of ~ 1 .

In conclusion the particle/anti-particle ratios are for the most part consistent with those of the previous experiments of Frisch et al. and Boyarski et al., and the general trends of these ratios can be explained using simple quark counting rules.

8.4 K/ π RATIO RESULTS

The experimental results for the K/ π ratios, for both γ and π^- beams, are presented in figure 53 for 1) particles irrespective of charge, (figure 53 a) - c)) 2) +ve particles (figure 53 d) - f)) and 3) -ve particles (figure 53 g) - i)). A comparison of production in the γ and π^- beams is also given.

In both γ and π^- beams the trend for the K^+/π^+ ratios shows a rise with Pt, with the possible indication of a leveling off at high Pt. In the π^- beam data there is an anomalous point centred on Pt = 750 MeV/c, which is shifted by $\sim 3\sigma$ upward from the position that would be expected by interpolation from the

surrounding data points. The only explanation for this occurrence is that it is a statistical fluctuation.

Other features observable in figure 53 are a flatter P_t distribution for the K^-/π^- compared with the K^+/π^+ and the excess K^-/π^- produced in the γ beam compared with the π^- beam is larger than for K^+/π^+ .

These results for the K/π ratios confirm the findings of previous experimenters. [45, 46].

8.4.1 Implication of the K/π Ratio

Both the K^+ and π^+ contain a u quark, and since the particle obtained depends on whether the u quark picks up a d or s antiquark, the K^+/π^+ ratio reflects the s/d ratio. Since it is not one the ratio in some way is a measure of the $SU(3)$ symmetry breaking, and is a result of the mass difference between the d and s antiquarks. The asymptotic (high P_t) value of 0.5 found in previous analyses [45, 47]. and the values $\sim 0.4 - 0.5$ measured here imply a s/d ratio of ~ 0.5 or greater in the sea. A lower bound is set as the observed K/π ratio reflects not only the primary s/d suppression but also the secondary suppression due to resonance decay. The flatter P_t distribution of the K^-/π^- ratio in the π^- beam is explained by the presence of the valence u antiquark, necessary for both the K^- and π^- , in the initial state. The flatter P_t distribution of the K^-/π^- ratio in the gamma beam is more difficult to explain. Why does it not show the same variation with P_t as the K^+/π^+ ? A possible answer relates to the original K^+/K^- and π^+/π^- P_t distributions in both

γ and π^- beams. In the γ beam K^+/K^- distribution rises with P_t while in the π^- beam it is flat. The π^+/π^- distribution in both beams are ~ 1 and are very similar. Hence the shape of the K^+/π^+ compared with the K^-/π^- in the γ beam.

8.4.2 Excess of Strangeness Production in Gamma Beam

An excess of strangeness production in the γ beam compared with the π^- beam can be seen in figures 53 c), f) and i). A value for this excess was obtained from a one parameter fit to the P_t distributions (ie assuming that the relative γ/π^- production yields are independent of P_t as indicated by the data). The values found were :-

Ratio γ/π

$$K/\pi \rightarrow 1.23 \pm 0.06$$

$$K^+/\pi^+ \rightarrow 0.95 \pm 0.08$$

$$K^+/\pi^- \rightarrow 1.23 \pm 0.14$$

$$K^-/\pi^- \rightarrow 1.56 \pm 0.12$$

The K^+/π^+ data were fitted twice. In the second fit the ratio obtained at $P_t = 750\text{MeV}/c$ was not included due to the anomalous result in the π^- beam (fig 53 e)).

Predictions of the K/π ratio can be made using VMD and $\gamma\gamma$ fusion models of photoproduction. As stated in chapter 6, VMD predicts a K/π ratio of $\sim 30\%$. For the $\gamma\gamma$ fusion process the calculation yields an energy dependence for the production cross section of quarks of various flavours. Using the quark masses given below and performing first order $\gamma\gamma$ model calculations the following results were obtained assuming the interaction of a

100 GeV photon :-

Mass	Cross-section (μb)
c quark 1.4 GeV	0.538
u quark 0.3 GeV	28.755
d quark 0.3 GeV	7.188
s quark 0.5 GeV	2.233
total	= 38.7

For these calculations a gluon momentum function for the target nucleon

$$G(x) = 3(1-x)^5/x$$

was used (the most popular form for this function). This follows from the simple counting rule model, normalized to yield a 50% contribution to the nucleon momentum. The sum of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ and $c\bar{c}$ cross sections is $38.7 \mu\text{b}$, which is not unreasonable given the total photoproduction cross-section is $\sim 100 \mu\text{b}$ and that only first order calculations were involved. Although no 2nd order calculations were attempted the result is not expected to be small since the u, d, s masses are comparable with Λ the scale parameter of QCD. Over the range of γ energies used in the experiment (20 - 140 GeV) the predicted strange/non-strange ratio varies between 4.9 - 6.4%.

To compare the strangeness content of the photon predicted by the two models, simple VMD and $\gamma\gamma$ fusion a comparison with data was necessary. The strangeness content of the photon can be estimated from the data using the quark quark fusion model, provided a quark structure for the photon can be devised. For the purposes of the calculation the photon was assumed to be a

superposition of a π^+ and π^- plus a s and $\bar{s}$ contribution. The structure functions for the pion and nucleons were taken from Donnachie and Moore [48]. The s and $\bar{s}$ contribution took the form of the following structure function.

$$a(1-x)^b$$

The actual calculation took the form of minimizing the following expression

$$\frac{\sigma_K^\gamma / \sigma_\pi^\gamma}{\sigma_K^{\pi^-} / \sigma_\pi^{\pi^-}} - (\text{Ratio } \gamma/\pi)$$

by altering the values of a and b in the strangeness contribution. The expression itself involves the calculation of the K and π cross sections in both γ and π^- beams using the quark quark fusion model. (Ratio γ/π are the values shown on page 157). To account for the energy spectrum in the γ beam the expression was averaged over 100 events of varying beam energies chosen at random from the distribution shown in figure 56. The distribution shown in figure 56 simulates the relative proportions of beam energies in the NA14 beam and has the advantage of being quick and simple to use. The pion beam energy was assumed constant at 90 GeV. The fit was only performed for the parameter ' a ', while the quantity ' b ' was fixed for each minimisation run ($b = 0, 1, 2, 3, 4$). Only a single parameter fit was possible as Ratio γ/π is a constant for each charge type (ie

i) all charges ii) +ve charges and iii) -ve charges). The values of b chosen are around those expected for valence quarks see reference [48]. A value for 'a' was obtained for each value of 'b' and the four values of Ratio γ/π . The functions $a(1-x)^b$ obtained were then normalized using the expression for normalizing valence quarks

$$\int_0^1 \frac{V(x)}{x} dx$$

to obtain the strangeness content of the photon. The results did show some rise in strangeness content with increasing b values ie $b = 0 - 4$ strangeness content $0.30 - 0.42$, but given the errors involved and the approximations made, means the significance of this can not be weighted too highly. The mean value for the strangeness content is found to be

$$0.34 \pm 0.04$$

In conclusion it is found that the excess of strangeness in the photon beam is due to the photon containing s and $\bar{s}$ valence quarks. The value for the strangeness content, 0.34 , would indicate that the γg fusion model gives too low a value for the K/π and that there must be more strangeness in the sea ^{of the photon}. The VMD model includes the sea contribution and therefore fits the data better. This confirms the Vector Dominance Model of the photon at low Pt.

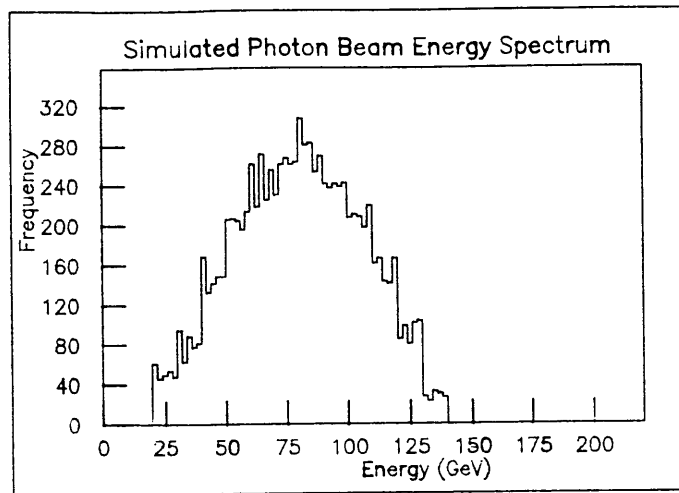


Figure 56: Simulated Beam Spectrum

8.5 PHI PHOTOPRODUCTION

8.5.1 General Characteristics

The data obtained in the August 1984 run of NA14 using a photon interaction trigger were analysed and where possible charged particles were identified using the Cerenkov counter as described in Chapter 7. Using the events containing an identified Kaon, invariant mass combinations were studied. The most striking signal observed was the phi (ϕ) signal seen in the K^+K^- channel (figure 57). Although the ϕ , possessing the same quantum numbers as the incident photon, is expected to be produced 'diffractively' it was considered unlikely that these would be detectable with any reasonable efficiency in the MWPCs due to the beam killers and the moustaches which render the forward horizontal region insensitive. Subsequent examination of the kinematics of the observed ϕ s indeed indicates that their origin is 'inelastic' production.

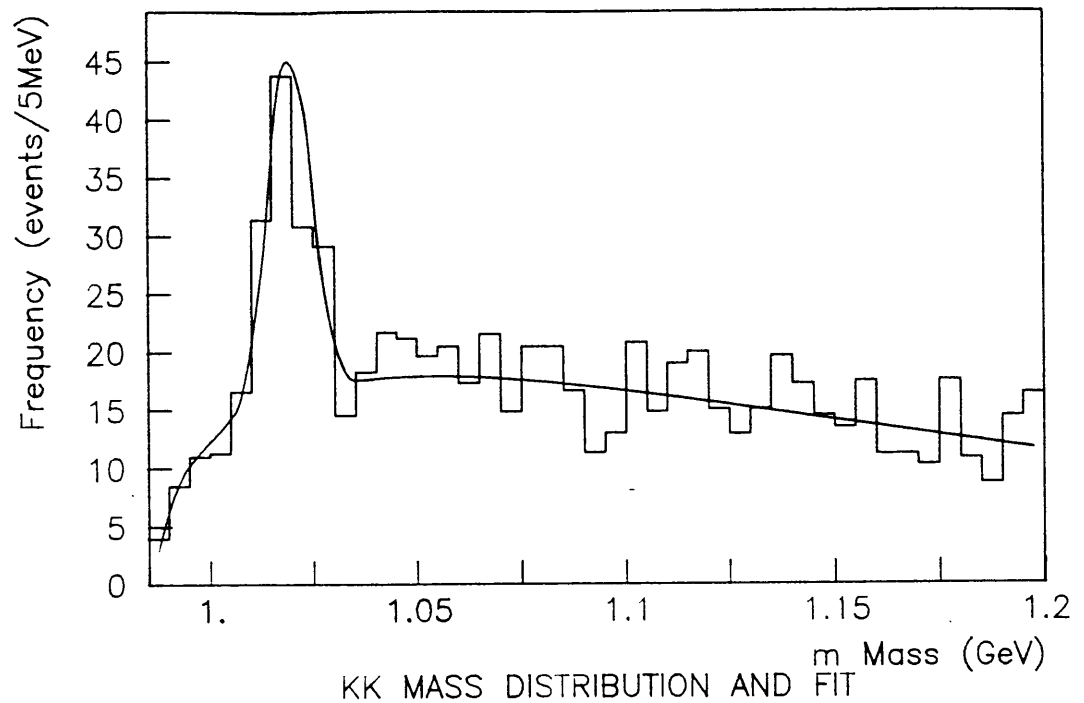


Figure 57: K^+K^- mass plot showing Φ signal

A K^+K^- combination with an invariant mass between 1.00-1.04 GeV was defined as a ϕ .

In figures 58 and 59 the general production characteristics are given in P_L and P_t . The P_L distribution is restricted to the range 16-36 GeV/c due to the requirement that both kaons be identified in the Cerenkov momentum window 8 - 18 GeV/c. An attempt to observe the ϕ using just one identified kaon was unsuccessful due to the large background.

To determine the elastic or inelastic nature of the ϕ production the relative energy of the KK combination compared with the total energy of the charged tracks was measured. This ratio is shown in figure 60. It can be seen for all but a few events the ϕ energy is less than 90% of the observed charged particle energy. When the neutral particles energy is included it

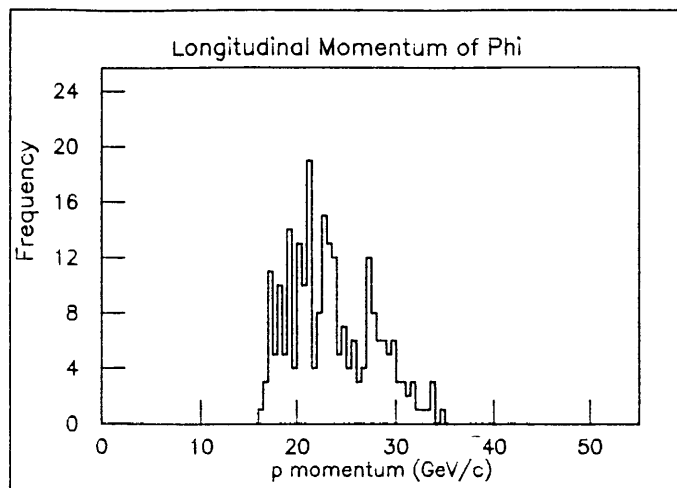


Figure 58: Phi P1 Distribution

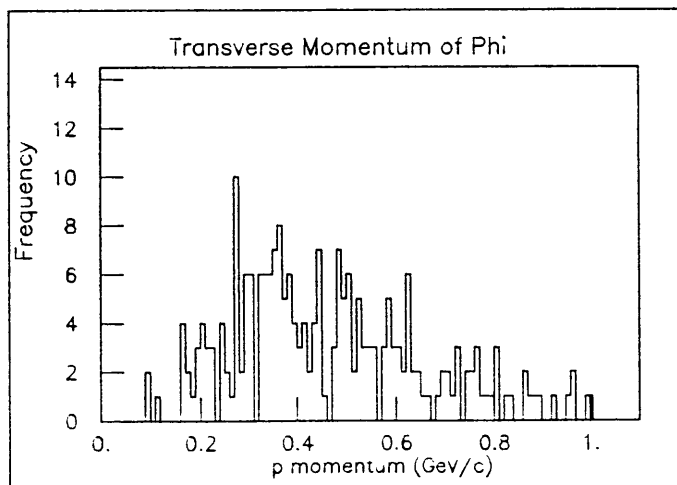
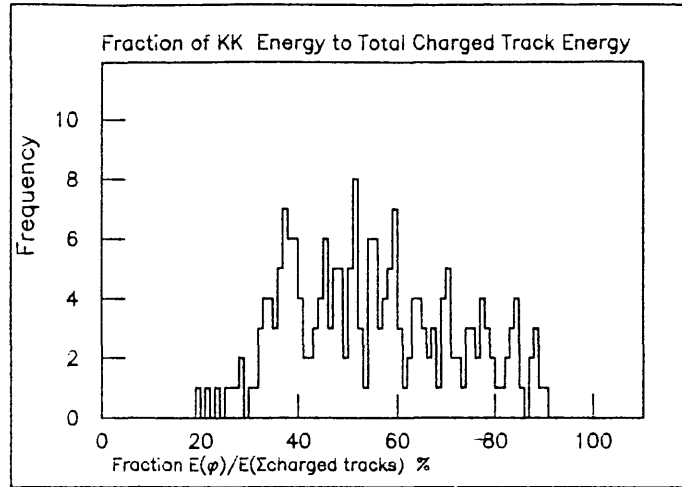


Figure 59: Phi Pt Distribution

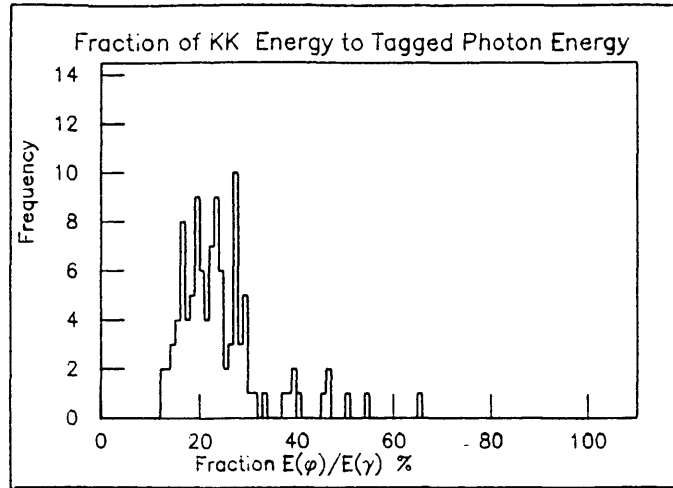
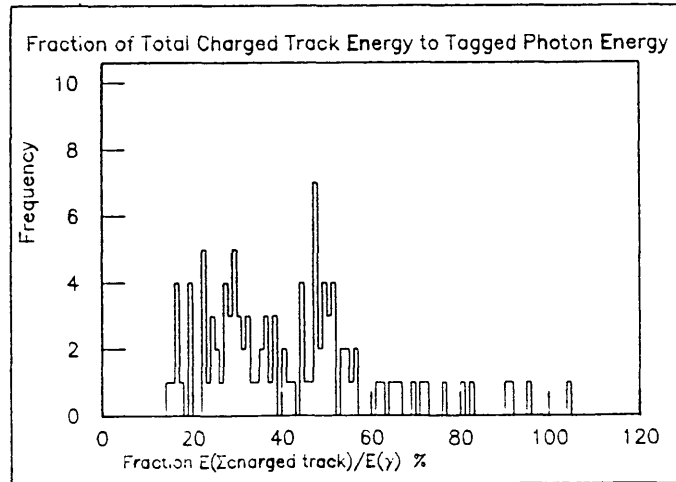
is clear that the ϕ sample is not produced elastically.

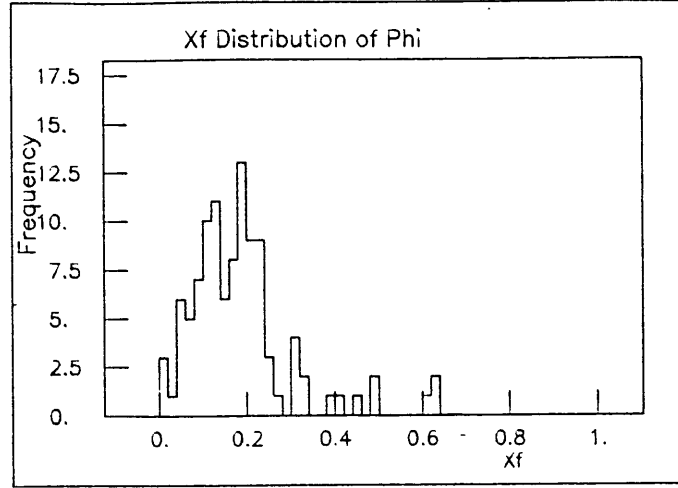
The photon energy tagging provides an independent measure of the elastic/inelastic ϕ production. Due to the high γ flux the tagging provides unambiguous energy in only 50% of the events. In figure 61 the ratio $E(\phi)/E(\gamma)$ is shown which confirms the

Figure 60: $E(\phi)/E(\text{charged tracks})$

inelastic production mechanism.

Finally in figure 62 the measured energy of the charged tracks is compared with the tagged photons energy. This indicates that on average only 40% of the photons energy is observed in the charge particles detected. A further 30% is observed on average by the electromagnetic calorimeters and the missing 30% could be due to a number of sources including non interaction neutrals, detector inefficiencies and over estimating the mean photon energy due to double bremsstrahlung in the radiator.

Figure 61: $E(\phi)/E(\gamma)$ Figure 62: $E(\text{charged tracks})/E(\gamma)$

Figure 63: Xf Distribution of ϕ s

8.6 INELASTIC PHI CROSS SECTION

To determine the inelastic phi cross-section three numbers are required; the number of observed ϕ 's, (see figure 57), the acceptance of the NA14 spectrometer to inelastic ϕ 's and finally the sensitivity of the experiment (ie the number of incident photons) The calculation of these quantities is described in the following sections.

8.6.1 Phi Signal

The ϕ signal in figure 57 has to be measured in the presence of background: the mass plot was fitted using a least squares method to the following parameterisation:-

$$a(m - m_{th})^b \exp(cm + dm^2) + A \exp\{-(m - \bar{m})^2 / 2\sigma^2\}$$

In total there are seven parameters to fit: a, b, c, and d refer to the background fit, which is of empirical form. The threshold

mass $m_{\pi\pi}$ in this case $2m(K)$. The signal is fitted using a gaussian with parameters A , $\bar{m}$ and σ (which is a measure of the experimental precision). The fit was performed using several initial values of the parameters. In this way the systematic errors were found. The best fit values of the parameters were: -

$$\begin{aligned} a &= 1094600. \pm 12. & A &= 30.0 \pm 0.8 \\ b &= 0.46 \pm 0.03 & \bar{m} &= 1.0191 \pm 0.0005 \text{ GeV} \\ c &= -11.6 \pm 0.1 & \sigma &= (0.51 \pm 0.02) \times 10^{-2} \text{ GeV}^{-1} \\ d &= 2.2 \pm 0.1 \end{aligned}$$

The value of m is in good agreement with the ϕ mass. Using the above values the number of ϕ 's in the signal was obtained:

$$72.55 \pm 8.52 \pm 0.57 \text{ } \phi\text{'s}$$

The quoted statistical error (± 8.52) was obtained by taking the square root of the signal, and ± 0.57 is the systematic error.

8.6.2 Acceptance for Inelastic Phi

The acceptance of the NA14 spectrometer was calculated by simulating ϕ events in the detector and comparing the number found by the analysis programs with the number generated.

The acceptance calculation involved the following procedures:

1. The Monte Carlo generation of inelastic ϕ 's.
2. The simulation of the NA14 detectors.
3. Processing the results of the simulation through TRIDENT.
4. Imposing the trigger conditions.

a) Monte Carlo Generation Of Φ s

The Monte Carlo program used to generate the inelastic Φ s was the same as that used to generate charm events previously described. It used a $\gamma\gamma$ fusion model with the charm quark characteristics replaced by those of the strange quark.

A total of 3000 Φ events were generated with photon energies selected at random from the beam energy distribution of figure 56. The distribution shown in figure 56 has its difficulties in that it stops at 140 GeV, while the real beam does not, but considering x_f values (obtained from tagging) show no real Φ was found produced by a photon with an energy ≥ 140 GeV it is a safe approximation. Variations were made in the gluon momentum function used in the generation model, but the resulting number of Φ found after processing was not sensitive to these changes. The variations were performed in order to estimate the error on the value found for the acceptance.

b) Detector Simulation

The equipment simulated included the Active Target, the trigger scintillator hodoscopes and the MWPC's. The program used to simulate these devices was GEANT [49], a CERN library facility designed for this purpose.

c) Trident

The simulated data were presented in the same format as real data and so could be passed through the standard charged track reconstruction program TRIDENT.

8.6.2.4 Trigger Conditions

All events were processed, not only those that satisfied the trigger conditions. The effect of the trigger, the scintillator hodoscopes and the Active Target were treated in turn.

8.6.2.5 Result

The acceptance was calculated after determining which events satisfied the trigger conditions, which tracks passed the track and vertex cuts applied in Trident and the number of pions that could be reconstructed using kaons identified by the Cerenkov counter in the 8-18 GeV/c momentum window.

The final result from the Monte Carlo simulation show that both P_T and P_L distributions (figures 64 and 65). are very similar to those of the real data (figures 58 and 59). The integrated acceptance is

$$0.026 \pm 0.0005 \pm 0.003$$

The statistical error (± 0.0005) was derived from the fractional error on the 3000 simulated events, while the systematic error (± 0.003) was derived by varying the gluon structure function.

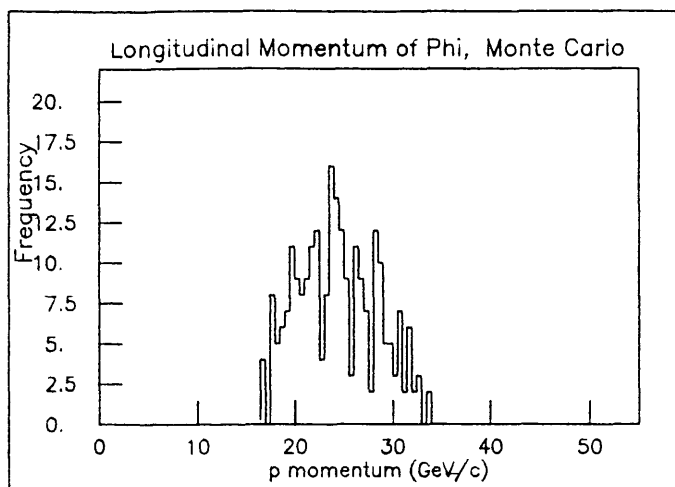


Figure 64: Monte Carlo Phi P1 Distribution

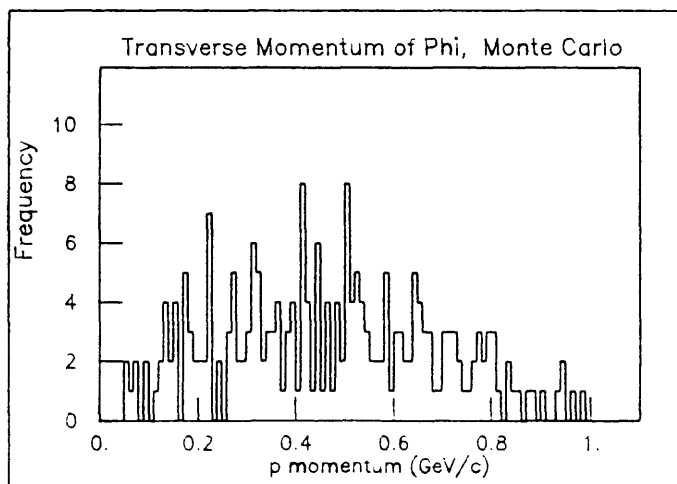


Figure 65: Monte Carlo Phi Pt Distribution

8.6.3 Sensitivity

The sensitivity of the experiment can be expressed in terms of the number of events of a given type expected for a given cross section (events/nb). Work performed by other members of the NA14 collaboration has used a so called 'Double Arm Trigger' (DARMT)

to estimate the sensitivity. This trigger condition demands at least one hit in each half of the scintillator hodoscopes G1, G2H and G2V: ie tracks are required both up and down to traverse G1 and G2, a more stringent requirement than imposed by the pre-trigger (see Chapter 2) from these hodoscopes. The sensitivity can then be calculated using the formula [50].

$$s = \frac{\Sigma(\text{DARMT}) p}{\sigma_{\text{eff}}} \frac{1}{\int a(E_b) n dE_b}$$

The symbols will be explained and values given or calculated for each in following text.

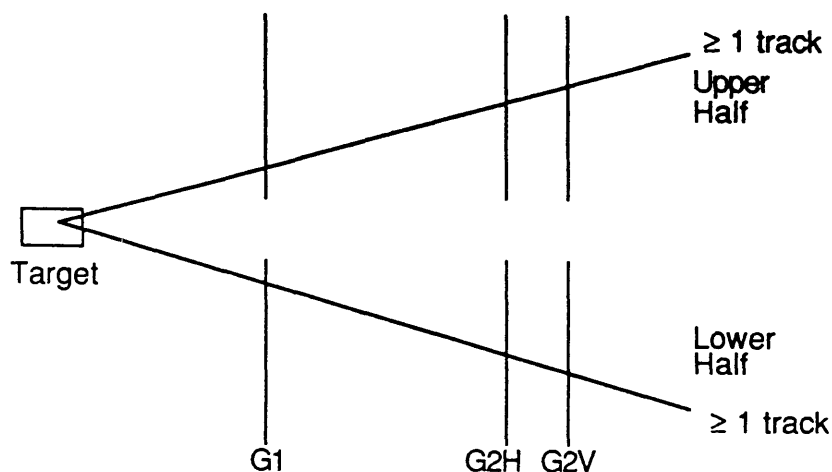


Figure 66: Conditions for the Double Arm Trigger

a) $\Sigma(\text{DARMT})$

The conditions required by the DARMT are shown in figure 66. For each raw data event the signals from the hodoscopes were written to tape so a software cut was applied to the data to determine the number of events satisfying this trigger. However the data on tape includes only events for which the Active Target trigger requirements were satisfied and another Monte Carlo simulation was run to evaluate the effect of the target condition on ΣDARMT . The result obtained was

$$0.485 \pm 0.02 \pm 0.033 \text{ DARMTs}$$

satisfy the target conditions.

The statistical error (± 0.02) results from the number of events generated and the systematical error (± 0.033) reflects the variation in this fraction over the beam energy spectrum.

From 220k events on tape, 97k were found to satisfy the DARMT condition: correcting for the effect of the Active Target suggests that

$$200104 \pm 8000 \pm 13609$$

would have been seen by the DARMT.

b) p : Hadronic Probability

p is the probability that an event which satisfies the DARMT condition was a hadronic interaction in the target. This was evaluated from a study of reconstructed event and found to be 0.75 ± 0.1 [50] for the photon beam.

c) $a(E)$ and $n.dE$

$a(E)$ is the acceptance of DARMT to inelastic hadronic events which has been calculated as a function of energy, using Monte Carlo techniques.

$n.dE$ describes the photon beam energy spectrum. This is shown in figure 67 a). The points marked in figure 67 b) represents an estimate of the beam energy spectrum after unfolding the acceptance and cross section. The solid line or curve in figure 67 b) was produced by a monte carlo also used to obtain $n.dE$. The agreement between the two is reasonable.

Integrating the acceptance over the beam energy distribution the value obtained is:-

$$\int a(E)n.dE = 0.40 \pm 0.05$$

d) The Effective Cross-Section $\sigma_{eff}(Si)$

The total hadronic cross section has been measured at $\sim 115 \mu b$ for 100 GeV photons [51], (UCSB collaboration). If the elastic ρ , ω and ϕ cross sections are subtracted the inelastic cross-section is

$$\sigma(\text{inelastic}) \sim 100 \mu b.$$

Nucleons when bound in a nucleus produce a phenomenon whereby the effective number of nucleons in a nucleus of mass number A may be lower than A . This is called shadowing which can be estimated from the results of UCSB experiment [51] in which various nuclear targets were used. Interpolation of the graph shown in figure 68 gives a value of $A_{eff}/A \sim 0.8$ for the silicon nucleus. This results in an effective inelastic photoproduction

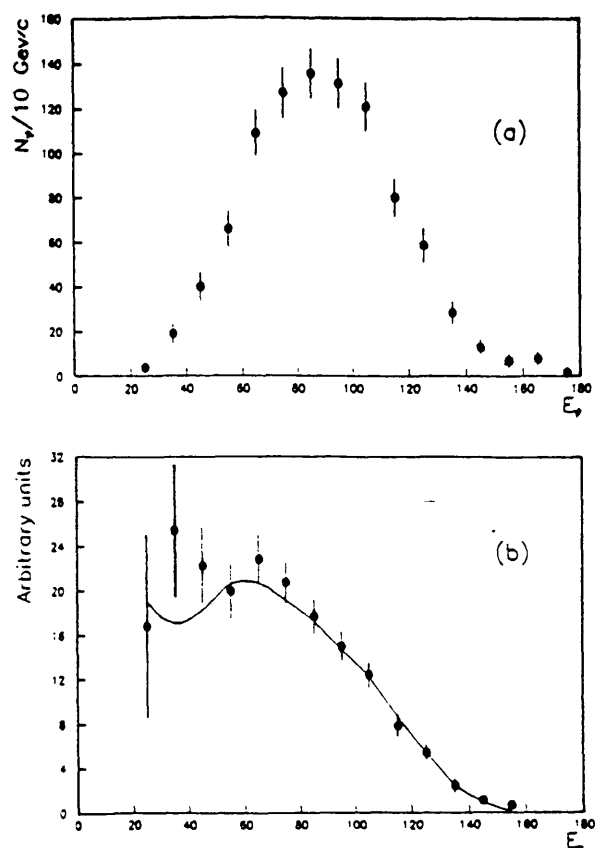


Figure 67: Evaluated Spectrum of Gamma Beam
from elastic J/ψ .

cross-section for silicon of

$$\sigma_{\text{eff}}(\text{Si}) = 80 \pm 4 \mu\text{b.}$$

e) Sensitivity per 10^6 DARMT

For a data sample in which 10^6 DARMT are recorded the substitution of the above numbers yields a sensitivity of

$$s = 4.69 \pm 0.19 \pm 0.07 \text{ events/nb}$$

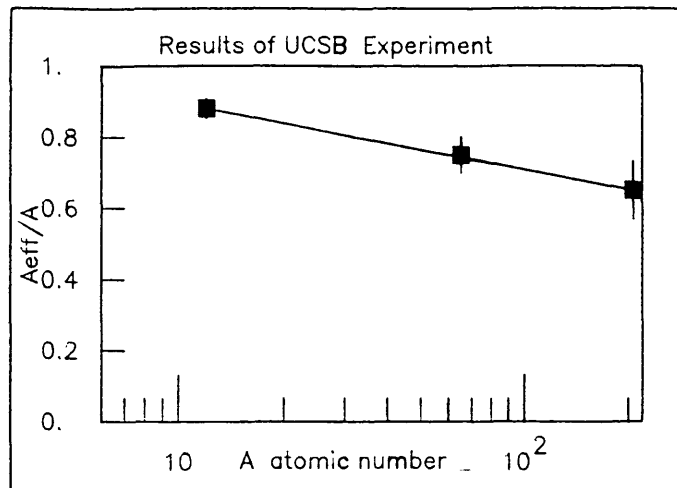


Figure 68: Results of the UCSB experiment

8.6.4 Calculation of ϕ Cross-Section

To complete the cross section calculation for inelastic ϕ production, two further components are required. Firstly the branching ratio $\phi \rightarrow K^+K^-$, which is taken from the Particle Data Book, and secondly the effect of requiring a DARMT on events containing the phi signal. An examination of the ϕ data showed that 86% satisfied the DARMT condition, hence the number of ϕ 's was reduced by 0.86 to obtain the cross section from

$$\sigma_{inel} = \frac{\text{Observed number of Phis}}{\text{Acceptance} \cdot \text{Branching Ratio} \cdot \text{Sensitivity}}$$

$$\sigma_{inel}(\phi) = 1038 \pm 130 \pm 211 \text{ nb.}$$

8.6.5 Production Mechanisms for Inelastic Φ

Popular production mechanisms based on the photon subprocesses quark-quark fusion and photon-gluon fusion have been described in Chapter 6. Using the equations given there a value was obtained from both models for the inelastic ϕ cross-section. The results of these first order calculations are shown below.

$$qq \text{ fusion } \sigma_{inel}(\gamma P \rightarrow \phi X) = 2.5 \text{ } \mu\text{b at } 100 \text{ GeV}$$

$$\gamma g \text{ fusion } \sigma_{inel}(\gamma P \rightarrow \phi X) = 157 \text{ nb at } 100 \text{ GeV}$$

The main theoretical uncertainties involve the strange quark mass to which the result is very sensitive and secondly the fact that since this quark mass is not significantly greater than Λ the scale parameter of QCD the results of the first order perturbation calculations cannot be reliable.

Given these uncertainties it is not clear which of these two mechanisms can best describe the data. If quark quark fusion is playing a role then it appears that a strange quark mass higher than that used in the calculation ($m(s) = 0.5$) is required. If on the other hand γg fusion is the dominant mechanism then either a lower quark mass or very large higher order effects are required.

A more sensitive test could be provided by the x_F distribution of the produced ϕ 's which differs for the two models. However the limited Cerenkov acceptance does not allow this distinction to be made. The addition of the second Cerenkov counter will significantly extend the range of momenta over which K 's can be identified and the discriminating power of subsequent data should be improved in this respect.

8.6.6 Discussion and Comparison with Other Data

Using the tagging procedure, the γ beam energy was calculated and hence the Feynman variable x_f evaluated for each event in the ϕ region. The resulting distribution is shown in figure 63. It should be noted that the limited Cerenkov acceptance limits the observation of high x_f ϕ 's. The raw data used in the cross section calculation has x_f values ranging from 0.1 - 0.66.

Values for the inelastic ϕ photoproduction cross section have been found by two other experiments. Firstly in the Omega experiment WA57 [52], using a 20-70 GeV photon beam, the values they obtained were :-

$$\text{for } 0.1 \leq x_f \leq 0.95: \sigma_{\text{inel}}(\gamma P \rightarrow \phi X) = 1.499 \pm 0.074 \pm 0.15 \mu\text{b}$$

$$\text{for } 0.2 \leq x_f \leq 0.80: \sigma_{\text{inel}}(\gamma P \rightarrow \phi X) = 0.907 \pm 0.037 \pm 0.09 \mu\text{b}$$

Using a slightly different energy range 25-70 GeV photon beam in the same experiment a value of

$$\text{for } 0.2 \leq x_f \leq 0.80: \sigma_{\text{inel}}(\gamma P \rightarrow \phi X) = 0.621 \pm 0.033 \pm 0.19 \mu\text{b}$$

was obtained. Secondly in the SLAC BC75 experiment, where a 20 GeV photon beam was used, a value of

$$\sigma_{\text{inel}}(\gamma P \rightarrow \phi X) = 0.731 \pm 0.105 \pm 0.120 \mu\text{b}$$

was found [53].

These results are, within errors, in agreement with the result found in NA14 and there is no evidence for a strong energy dependence in the range 20 - 100 GeV photon energy.

Appendix A

ENERGY LOSS IN THIN ABORBERS IE SILION DETECTORS

In Particle Physics, silicon detectors are used to sample the energy of energetic particles, hence this account of the energy loss in thin absorbers is appended.

Landau [24] made the first significant contribution to this field and hence his name is used to describe the distribution observed. Landau considered the energy loss Δ , by summing the many single losses occurring in collision between the individual atomic electrons and the incident particle. The ionization resulting from these collisions is subject to considerable fluctuations and can be expressed as the distribution function, $f(x, \Delta)$, where x is the thickness of the absorber. The distribution can be derived from solving the following transport equation

$$\frac{df(x, \Delta)}{dx} = \int_0^{\infty} w(E) [f(x, \Delta-E) - f(x, \Delta)] dE \quad \text{Eq. 1)}$$

which expresses the difference in the number of particles which acquire a given energy Δ , due to ionization losses along dx , and the number of particles which leave the given energy interval dE . Solving this equation with a Laplace transform method, results in

$$f(x, \Delta) = \frac{1}{2\pi i} \int_{C-i\infty}^{C+i\infty} \exp(l) dp \quad \text{Eq. 2)}$$

where

$$l = p\Delta - x \int_0^{\infty} w(E) [1 - \exp(-pE)] dE \quad \text{Eq. 3)}$$

The function $w(E)$, the atomic electron collision cross section, is not generally known. Landau approximated with the free electron cross-section to obtain the approximate solution:

$$w(E) = \frac{\xi}{x} \cdot \frac{1}{E^2} \quad \text{Eq. 4)}$$

$$\frac{\xi}{x} = \frac{2\pi e^4}{mc^2 \beta^2} \frac{\rho Z N_0}{A} \approx \frac{1.78 \times 10^{-2}}{\beta^2} \quad \text{Eq. 5)}$$

The incident particle and the electron are assumed to have the same absolute charge, Z and A are the atomic number and weight of the material, ρ is the density of the material, m is the mass of the electron, and βc is the velocity of the incident particle.

Landau had assumed an infinite energy transfer was possible, but in 1957 Vavilov [25] derived an improved solution by taking into account the kinematic constraint on the energy transfer E . The maximum transfer of energy from an incident particle to an atomic electron is given by :-

$$E_{\max} = \frac{2mc^2\beta^2\gamma^2}{(1 + 2\gamma m/M)} \quad \text{Eq. 6)}$$

where M = mass of the incident particle.

Vavilov also used a slightly different cross-section which takes into account the spin of the particle. This cross section has the form:-

$$w(E) = \frac{\xi}{x} \cdot \frac{1}{E^2} (1 - \beta^2 E/E_{\max}) \quad \text{Eq. 7)}$$

Using these improvements he also solved Eq 1). The solution can be obtained analytically by expanding the integrand in Eq 3) as a Taylor series.

$$I = p(\Delta - \Delta) - x \int_0^{E_{\max}} w(E) [1 - \exp(-pE) - pE] dE \quad \text{Eq.8)}$$

Vavilov also showed that his solution and Landau's coincided for $K < 0.01$ where $K = \xi/E_{\max}$ and the result can then be written as

$$f_L(x, \Delta) = \frac{1}{\xi} \phi(\lambda) \quad \text{Eq. 9)}$$

where λ is the only variable of the universal function $\phi(\lambda)$, which can be expressed as

$$\phi(\lambda) = \frac{1}{\pi} \int_0^{\infty} \exp(-\pi y/2) \cos(y \ln(y) + \lambda y) dy \quad \text{Eq. 10)}$$

and λ is :-

$$\lambda = \frac{\Delta - \bar{\Delta}}{\xi} - (1 - \beta^2 - C) - \ln(K) \quad \text{Eq. 11)}$$

where $C = \text{Euler's constant} = 0.5772$

The Landau distribution $f(x, \Delta)$ is asymmetric with a tail extending to $E_{\max}$. In units of λ , $f(x, \Delta)$ has a Full Width Half Maximum (F.W.H.M) of 4.02 and a peak at $\lambda = -0.223$

The mean energy loss Δ of an incident particle can be calculated from the Bethe-Block formula

$$\bar{\Delta} = 2\xi \left[\ln(2mc^2\beta^2\gamma^2/I_{\text{eff}}) - \beta^2 - \delta/2 \right] \quad \text{Eq. 12)}$$

where I_{eff} is the effective ionization potential of the absorber medium (172eV in Si), and δ is a correction factor due to the shielding produced by the polarisation of the atoms in the material in response to the electric field of the incident particle [54].

The distribution described so far produces too narrow a peak to explain accurately the experimental data from thin absorbers. Hence further corrections were needed to the Landau distribution: these were attempted by Blunck and Leisegang [55], Shulak et. al. [56] and Bichsel [57] who took into account that the electrons in the material are not free, as had been assumed so far. This problem can be solved by expanding Eq 3) to the next order in p and replace the function I of Eq 2) by $I' = I + \delta I$ where

$$\delta I = -x \int_0^{E_{\max}} [w'(E) - w(E)] (1 - \exp(-pE) - pE) dE \quad \text{Eq. 13)}$$

$$\delta I = 0.5xp^2 \int_0^{E_{\max}} [w'(E) - w(E)] E^2 dE$$

$$= 0.5 \times p^2 \delta_2$$

where $w(E)$ is the assumed cross-section and $w'(E)$ is the actual cross-section. A solution for $f'(x, \Delta)$ is obtained by using the region where the Landau and Vavilov solutions coincide ($K \leq 0.01$) and the convolution properties of the Laplace transform giving

$$f(x, \Delta) = \frac{1}{\sqrt{2\pi x \delta_2}} \int_{-\infty}^{\infty} f_L(\Delta - y) \exp(-y^2/2x\delta_2) dy \quad \text{Eq. 14)}$$

which means that the experimentally observed spectrum of the energy loss can be calculated by convolving the Landau distribution with a normal/gaussian distribution of variance $x\delta_2$.

The next problem is to calculate this broadening, which means we need to know the form of δ_2 . A form for this was proposed by Shulak et. al. [56] which is

$$\delta_2 = \frac{8}{3} \times \sum_i I_i f_i \ln \left(\frac{2mc^2 \beta^2}{I_i} \right) \quad \text{Eq. 15)}$$

where I_i is the effective ionization potential of the i th shell and f_i is the fraction of electrons in that shell. For Silicon this formula yields

$$\delta_2 \approx 1.8 \times 10^3 \text{ keV cm}^{-1} \text{ for } \beta \approx 1$$

Bichsel [58] has shown that using higher orders of the expansion of Eq. 3) does not contribute greatly to the broadening so they can be neglected.

Hence the distribution widths of energy loss in thin Silicon absorbers (detectors) can be calculated.

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