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A Study of K_S Production with a Microvertex Detector
at the CERN Proton-Antiproton Collider

by
Irwin R. Sheer

A dissertation submitted in partial satisfaction
of the requirements for the degree of

DOCTOR OF PHILOSOPHY
in
PHYSICS



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MARCH 1988

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March 1988

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March 1988

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I dedicate this dissertation to my parents Edward and Barbara and to my sisters Marci and Robin.

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ABSTRACT OF THE DISSERTATION

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by
Irwin R. Sheer
March 1988

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, March 1988
Professor Anne Kernan, Chairperson

The design, and construction of the UA1 Microvertex Detector, a small pressurized drift chamber, is described. The chamber provided 16 radial measurements of particle trajectories between 3 and 8 cm from the axis of the CERN Super Proton-Antiproton Synchrotron. The performance of the chamber in a test beam and in the proton-antiproton collider are discussed.

Using the Microvertex Detector in conjunction with the UA1 apparatus, the production of inclusive K_S in $\bar{p}p$ collisions with a center of mass energy of 630 GeV has been studied. The mean transverse momentum is estimated to be $\langle P_t \rangle = 0.473 \pm 0.089$
 $+0.055$ _{-0.032} GeV/c. The rapidity distribution is found to be flat in the region $|y| < 2$ and the central rapidity density is estimated to be 0.177 ± 0.063
 $+0.028$ _{-0.033}. The inclusive inelastic K_S production

cross-section is estimated at $56. \pm 21. \pm 13.$ mb. The mean K_S multiplicity is estimated to be $1.20 \pm 0.44 \pm 0.23$. (Systematic errors have been given in *Italics*.) Upper limits on lambda production are also estimated.

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CHAPTER I

INTRODUCTION

1.1 Outline

The principle focus of this dissertation is two fold: 1) The design, construction, and performance of a small pressurized drift chamber, the UA1 Microvertex Detector (MVD), will be described and; 2) The results of a measurement of the inclusive K_S production cross-section utilizing this detector will be presented. The Microvertex Detector was designed to be a high resolution tracking chamber capable of studying short lived particles. The measurement of the K_S production cross-section is a direct outcome of the first tests the Microvertex Detector in the CERN Super Proton-Antiproton Synchrotron.

This chapter describes the discovery of strange particles, the role they played in the development of the "Standard Model", the CERN Super Proton-Antiproton Synchrotron, and the UA1 Experiment.

Chapter II deals with the Microvertex Detector. The motivation for adding the Microvertex Detector to the UA1 Experiment, its design and construction are related. The performance of the detector in a test beam and in the collider are described.

Chapter III describes the data sample, the conditions under which the data were taken, and the event reconstruction procedure used for the Microvertex Detector including matching of Microvertex Detector tracks to Central Detector tracks.

Chapter IV describes the technique by which neutral strange particle decays (K_S and λ) were identified. The Monte Carlo studies needed to correct the data are summarized and results on the inclusive production of K_S and λ are given.

The general features of strange particle production from threshold to Super Proton-Antiproton Synchrotron energies is discussed in Chapter V.

In Chapter VI a summary of conclusions is presented.

1.1 Historical Review

The very first observation of a strange particle occurred in a 1947 cosmic ray experiment conducted by Rochester and Butler [1.1]. In two of the photographs taken of their cloud chamber, forked tracks were observed. The forked tracks, they conjectured, were decay products of a new type of heavy unstable particle. Subsequent analysis has shown that the forked tracks in one of the pictures was caused by the decay of a K_S into two oppositely charged pions.

The discovery of Rochester and Butler was soon confirmed by other experimenters and a second " V_0 " particle, the Λ , was

observed [1.2-1.3]. The relatively high production rates of these particles, about 1% of the pion rate, implied a strong production mechanism. The long lives of these particles, 10^{-8} - 10^{-10} s, indicated a weak decay. Because these particles appeared to be produced strongly and decay weakly, the particles were labeled "strange".

The underlying cause of this behavior was proposed by Pais in 1952 through the concept of "Associated Production" [1.4]. He suggested that strange particles could be produced strongly in pairs; whereas they could decay individually through weak interactions. To formalize this concept a quantum number, strangeness, was introduced which was conserved in strong but not weak interactions.

With the discovery of strange particles it became increasingly apparent that these and other strongly interacting particles (hadrons) were probably composite particles. (Leptons, which are particles that do not strongly interact, are still considered to be fundamental.) In 1964 Gell-Mann [1.5] and Zweig [1.6] independently put forth a scheme whereby all hadrons could be constructed from three new fundamental objects. Gell-Mann dubbed these objects quarks and gave them three flavors: up, down, and strange. By combining quarks (antiquarks) in triplets or in quark-antiquark pairs all hadrons could be created. A charged pion (π^-) for example could be constructed from an $\bar{u}d$ quark combination, a proton (p) from an uud quark combination and a

neutral kaon (K^0) from a $\bar{d}s$ quark combination. (A K_S is formed through the weak mixing of K^0 and $\bar{K}^0$.)

This quark model, with three additional quark flavors, is today accepted as a fundamental part of the "Standard Model". Figure 1.1 shows what has become known as the "Periodic Table of Elementary Particles". All of the known universe, matter and energy, can be divided into two categories: constituents and forces through which constituents interact. Four forces are known, these are (in order of strength): Strong, Electromagnetic, Weak, and Gravitational. Interactions between constituents occurs through the exchange of mediators. The respective mediators of the Strong, Electromagnetic, Weak, and Gravitational forces are: gluons, photons, intermediate vector bosons, and gravitons.

Proton-antiproton collisions at high energies can be divided into two categories depending on the amount of momentum that is exchanged between the constituents of proton and antiproton. Large momentum transfer processes, which make up only a small fraction of the inelastic proton-antiproton cross-section, can be calculated through perturbative QCD. (Quantum Chromo-Dynamics is a field theory which describes strong interactions.) Small momentum transfer process ("soft" collisions) cannot be calculated since the QCD coupling constant (α_s) increases as the momentum transfer (Q^2) decreases, becoming too large for perturbative techniques. Insight into soft processes has been obtained through modeling. In Chapter V a more detailed discussion of these models

will be presented.

1.3 Experimental Overview

This work was made possible through the superbly coordinated efforts of two very large and complex machines, the CERN Super Proton-Antiproton Synchrotron and the UA1 Experiment. A brief description of these devices is presented below.

1.31 The Super Proton-Antiproton Synchrotron

The Super Proton-Antiproton Synchrotron (SPPS) is located at CERN, the European Laboratory for Particle Physics, near Geneva, Switzerland (Figure 1.2). It is a large machine, 7 km in circumference, that is used to accelerate counter-rotating beams of protons and antiprotons to very high energies and then collide them.

The Super Proton Antiproton Synchrotron began as the Super Proton Synchrotron (SPS) which was proposed in 1971 as a 300 GeV/c fixed target machine [1.7]. In a fixed target machine protons are accelerated and then extracted so that they can collide with stationary targets. In 1976 it began operation at 400 GeV/c reaching its peak of 500 GeV/c in 1978. The energy available for creation of new particles in this type of collision is roughly $\sqrt{(2EM)}$; where E is the energy of the incident particle and M is the

mass of the target particle. At these high energies collisions take place between quarks so that the energy of interest is that which is typically carried by a quark. Normally half the momentum of a proton is carried by gluons leaving the remaining momentum to be split between the three valence quarks; hence, any one of them typically carries only a sixth of the proton's momentum. The SPS at its energy of 400 GeV/c was thus able to produce particles with masses up to about $4.5 \text{ GeV}/c^2$.

This was unfortunately more than an order of magnitude short of the energy needed to create the intermediate vector bosons predicted by the Electroweak Theory of Weinberg [1.8], Glashow [1.9], and Salam [1.10]. According to the Electroweak Theory the mediators of the Electromagnetic and Weak forces were formed from the mediators of the Electroweak force early in the history of the universe as it began to cool. The mediators of the Electroweak are massless particles which give rise to the massless photon and massive intermediate vector bosons as symmetry is spontaneously broken through a mechanism that involves a particle known as the Higgs (not shown in Figure 1.1). The theory, which unified the Weak and Electromagnetic forces and captured a Nobel prize for the creators in 1979, urgently needed verification. Verification could come through the discovery of the intermediate vector bosons which were predicted by the theory to have masses of about $100 \text{ GeV}/c^2$.

In 1976, Carlo Rubbia, Peter McIntyre, and David Cline put

forth the idea that antiprotons could be collected and put in the same ring as protons where the magnetic field would cause them to be accelerated in the opposite direction as the protons, and make head-on collisions possible [1.11]. The energy available for creation of new particles in a head-on collision is $2E$; taking into account the fraction of the energy carried by a quark enabling the creation of particles with masses up to about $90 \text{ GeV}/c^2$ for beams of $270 \text{ GeV}/c$ and put physicists in striking range of the intermediate vector bosons. The only problems with this scheme was that nobody knew how to collect the number of antiprotons needed or if the collider idea would work.

At CERN, Rubbia became the standard bearer for the collider idea. One of the many crucial contributions he made to the project was realizing that the solution to the problem of collecting antiprotons was a technique that had been developed earlier, by Simon van der Meer, called Stochastic Cooling. Through the brilliant partnership of Rubbia and van der Meer the collider idea became a reality at CERN.

In July 1981 the Super Proton Synchrotron became the Super Proton-Antiproton Synchrotron by colliding for the first time protons and antiprotons at a center of mass energy of 540 GeV . Since that time, collisions have been observed at energies that range all the way up to 900 GeV in the center of mass. (The Super Proton-Antiproton is also referred to as the $\bar{p}p$ Collider.)

1.32 The UA1 Experiment

The UA1 Experiment derives its name from its location - Underground Area 1 which is 20 m underground in the long straight section 5 of the Super Proton-Antiproton Synchrotron. The experiment was proposed in 1978 as an experiment "well suited to the study of large P_t jets and the the search for the W mesons" [1.12]. This goal was achieved in November of 1982 with the discovery of the W [1.13] and subsequently in May of 1983 with the discovery of the Z^0 [1.14]. In December of 1984 Carlo Rubbia and Simon van der Meer were awarded the Nobel Prize in Physics for "their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction".

Constructed in a modular fashion, the experiment is the size of a small house; it is over 10 m high, weighs over 1000 tons and it is designed to cover the largest possible solid angle around the interaction region. The detectors that together form the UA1 Experiment are of two basic types: tracking chambers, and sampling calorimeters (Figures 1.3-1.4). A tracking chamber records the trajectory of charged particles whereas a sampling calorimeter is used to measure particle energies. In order to measure momentum the experiment includes a 0.7 T dipole magnet with dimension 7 x 3.5 x 3.5 m.

A tracking chamber consists basically of a gaseous volume

and an ensemble of wires at different potentials which create an electric field. As a charged particle traverses the gaseous volume of the detector it ionizes the molecules of the gas, freeing electrons. Free electrons acted upon by the electric field begin to drift towards anode (sense) wires. As an electron approaches a sense wire it rapidly gains kinetic energy that it subsequently loses in collisions with other gas molecules that free additional electrons. The end result is an avalanche of electrons, anywhere from 10^4 - 10^8 electrons per primary electron will arrive at the sense wire. A large number of electrons arriving at the sense wire induces an electronic pulse which is used to stop a clock which was started at some fixed time relative to the original collision. Knowing the electric field and the drift properties of the gas it is then possible to reconstruct a point (or points) in the plane perpendicular to the wires axis through which the particle must (may) have passed. Determination of the longitudinal coordinate of the pulse can be achieved by comparing the charge collected on each end of the sense wire, a procedure known as charge division, or through various other means.

The heart of the UA1 Experiment is the Central Detector, a large, 25 m^3 , cylindrical drift chamber with 22,800 wires. It has been described in detail elsewhere [1.15]; however, since this piece of the apparatus is crucial to this analysis a brief summary will be given here. The Central Detector is a self-supporting cylinder 5.8 m long and 2.3 m in diameter (Figure 1.5). It is constructed from

six half-cylindrical modules each of which is composed of several drift volumes. The orientation of the drift volumes, vertical for central modules and horizontal for forward modules, was chosen to maximize the number of points per track while keeping a constant density of points, one per cm, over the whole detector volume. Figure 1.6 shows a typical Central Detector Drift Volume. The chamber is filled with a 60:40 argon/ethane gas mixture and the drift field is 1.5 kV/cm, giving a saturated drift velocity of 53 $\mu\text{m}/\text{ns}$. Sense wires are read out on both ends by flash ADCs which record drift time, charge division, and energy loss [1.16]. The detector has an overall spacial resolution per point in the drift plane of 280 μm and a resolution of 1.7% of the wire length in the charge division coordinate [1.17].

Inside the Central Detector as close as possible to the interaction region is another, much smaller, cylindrical tracking chamber. This chamber, which is a major topic of this dissertation, is called the Microvertex Detector and it will be described in detail in the next chapter. Other parts of the UA1 Experiment, not used in this analysis, are described in references [1.17-1.20].

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Figure 1.1
The Periodic Table of Elementary Particles

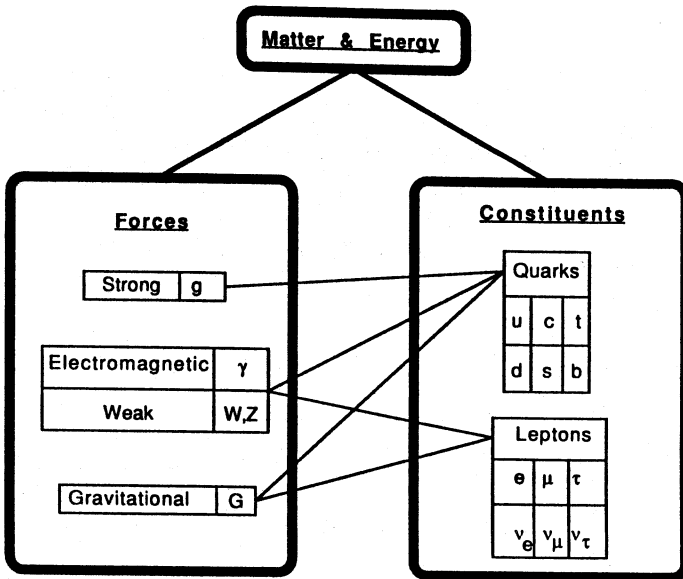


Figure 1.2
The CERN Super Proton-Antiproton Synchrotron

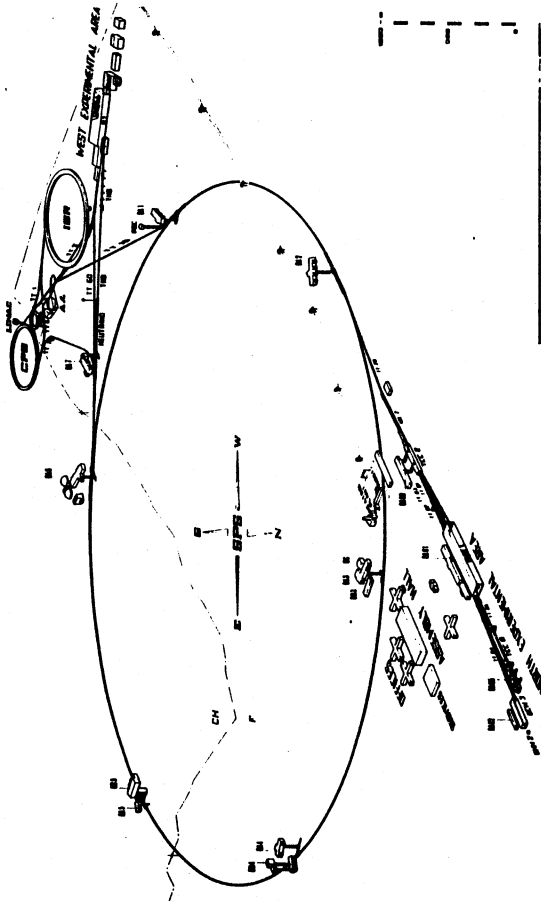


Figure 1.3
The UA1 Experiment

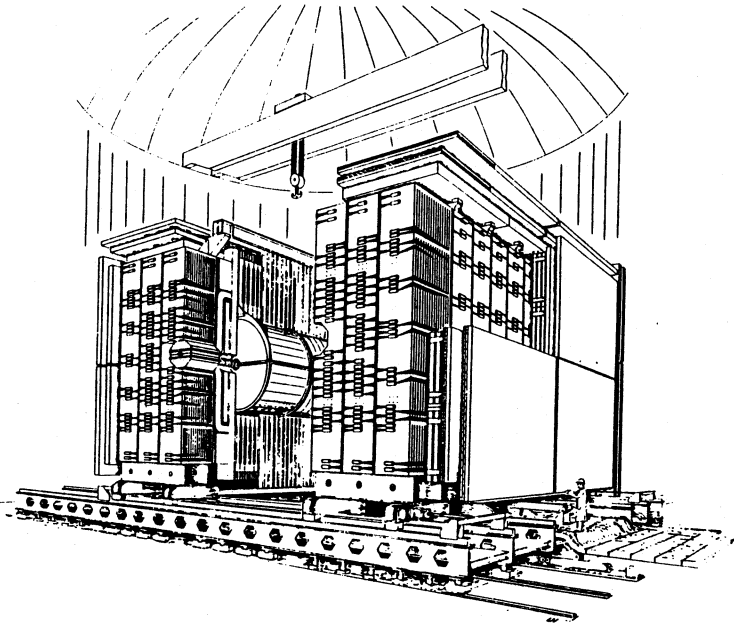
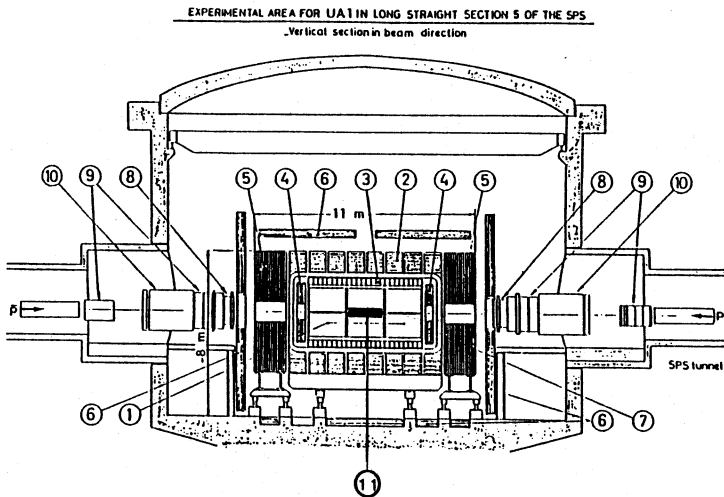


Figure 1.4
A Side View of the UA1 Experiment



- (1) Central Detector, (2) hadron calorimeter C's, (3) electromagnetic calorimeter Gondolas, (4) electromagnetic calorimeter Bouchons, (5) hadron calorimeter I's, (6) muon chambers, (7) magnet coil, (8) forward chambers, (9) forward calorimeters, (10) compensating magnets, (11) Microvertex Detector

Figure 1.5
The UA1 Central Detector

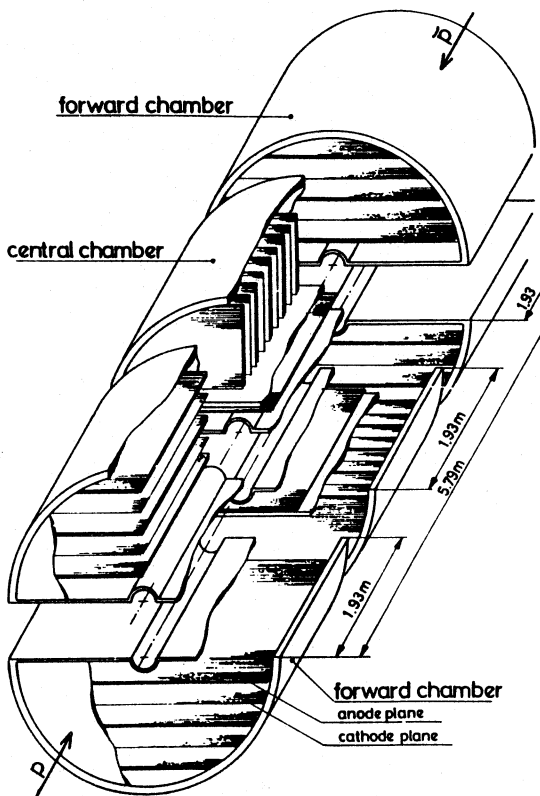
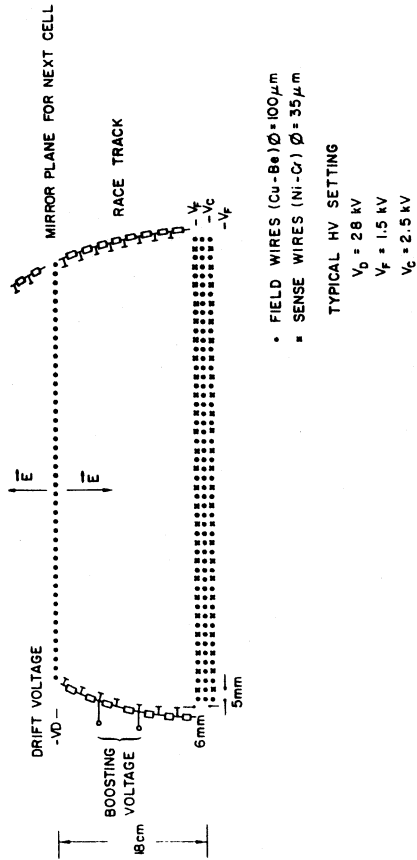


Figure 1.6**A Central Detector Drift Volume**

CHAPTER II

THE MICROVERTEX DETECTOR

2.1 Introduction

In 1983, a proposal was put forward to upgrade the UA1 Experiment and expand its physics program through the addition of a Microvertex Detector [2.1]. The Microvertex Detector was to be a compact - high resolution tracking device which would allow detailed pictures of the interaction and its decay vertices to be created. This chapter describes the design, construction, and performance of the Microvertex Detector.

2.11 Physics Motivation and Resolution Requirements

The principle motivation for the addition of the Microvertex Detector to the UA1 Experiment was that it would enable decays of long lived particles to be observed. Mesons which contain charm or bottom quarks are relatively long lived with mean lifetimes ($\langle\tau\rangle$) of about 10^{-12} s. Decays of these long-lived particles can be observed indirectly by identifying tracks that do not extrapolate back to the interaction's primary vertex or directly by reconstructing the decay vertex.

The accuracy with which tracks can be extrapolated back to

the interaction's primary vertex is determined by the detector's impact parameter resolution (σ_{ip}); where the impact parameter is defined as the minimum distance between a track and the primary vertex. A rough estimate of the mean impact parameter ($\langle b \rangle$) of tracks that come from the decay of a long lived particle, $\langle \tau \rangle = 10^{-12}$ s, is given by:

$$\langle b \rangle \approx \langle c\tau \rangle \approx 300 \mu\text{m}.$$

A good vertex detector, one capable of effectively separating decay vertices from the primary vertex, will have an impact parameter spatial resolution given by:

$$\sigma_{ip} \leq \langle c\tau \rangle / 4 \approx 75 \mu\text{m}$$

or a projected impact parameter resolution (σ_{pip}) of:

$$\sigma_{pip} \leq \langle c\tau \rangle / (4\sqrt{2}) \approx 50 \mu\text{m}.$$

The projection of the impact parameter into a plane is most relevant since most detectors are capable of measuring particle trajectories to a high degree of accuracy in only one plane.

2.12 The Choice of Detector Technology

The choice of detector technology to be used in the construction of the Microvertex Detector was straight forward since only two possible technologies existed which could achieve the desired projected impact parameter resolution. The two possibilities were: 1) silicon strip technology such as that used by the NA11 fixed target experiment which achieved $\sigma_{pip} = 20 \mu\text{m}$

[2.2]; or 2) high pressure drift chamber technology such as that used by the Mark II [2.3] and TASSO [2.4] e^+e^- collider experiments which achieved $\sigma_{\text{pip}} \approx 100 \mu\text{m}$. The obvious choice in terms of physics potential was (1). However, it was estimated that several years of technological development, particularly in the area of readout, would be required before such a detector could be successfully operated in a collider environment. Option (2) could be completed in a more reasonable time scale and detectors of this type had proven themselves reliable in a collider environment. The desire to have the detector completed and taking data as soon as possible and a belief that there was still room for improvements in results obtained from option (2) inevitably led to the choice of high pressure drift chamber technology for the Microvertex Detector.

The Mark II and TASSO vertex detectors had a great deal of influence on the design of the Microvertex Detector. These detectors optimized impact parameter resolution through: 1) high spatial accuracies, less than $90 \mu\text{m}$ single wire resolutions, 2) jet style geometries [2.5], wires running parallel to the beam, and 3) minimal multiple coulomb scattering as particles traversed the detectors.

High spatial accuracies (1) were obtained in these detectors principally through accurate placement of sense wires, $\approx 15 \mu\text{m}$, and high pressure (p) operation which increased spatial accuracy (σ_s) by reducing diffusion in the gas; σ_s and p are related by:

$$\sigma_s \sim 1/\sqrt{p} \text{ (atm)}.$$

Jet style geometries (2) optimized impact parameter resolution by minimizing the extrapolation length of a track back to the primary vertex and maximizing the angular resolution of the detector since first and last measurements are separated maximally in the radial direction.

Multiple coulomb scattering (3) was minimized by designing the beam tube to double as the chambers inner wall and then constructing it out of beryllium which has an exceptionally large radiation length (35.3 cm).

2.2 Chamber Design

The Microvertex Detector was a cylindrical - high pressure - jet style drift chamber. The detector was mounted on a 1 mm thick x 5 cm inner diameter beryllium beam tube that doubled as the inner wall of the detector's pressure vessel. The outer diameter of the detector was 17.8 cm and the length of the chamber's sensitive volume was 80 cm. (Figure 2.1 shows a cross-section of the Microvertex Detector.) The chamber was divided into 16 identical wedge shaped cells each of which provided 16 radial measurements (Figure 2.2). The chamber provided full coverage in azimuth, each cell spanning 22.5° . A particle produced normal to the beam direction traversed 0.56% of a radiation length before entering the sensitive volume of the detector. A summary of detector parameters is presented in Table 2.1.

2.21 Cell Geometry

Figure 2.3 shows the wire pattern for a single cell. The central plane of wires in each cell contained 16 sense wires which alternated with 17 field wires. Sense wires were staggered by $\pm 100 \mu\text{m}$ from the field wire plane so that the inherent left-right ambiguity of the cell could be resolved. Cathode planes were separated azimuthally from sense-field wire planes by 11.25° and were composed of 33 wires each. Wires along each plane were spaced 1.58 mm apart. The first sense wire was located 33 mm from the chamber's axis.

Cylindrical printed circuits (racetracks) with lines that ran parallel to the wires were used to close the field on the external radii of the cell with minimal distortions. The outer racetrack had 15 surface and 14 subsurface lines per cell while the inner racetrack had 6 and 5 respectively.

Voltages were stepped on the racetracks and cathode wires so that lines of equal potential ran parallel to the sense-field plane. Figure 2.4 shows lines of equal potential and Figure 2.5 shows trajectories of drifting electrons for a typical cell.

2.22 Mechanical Aspects

Chamber wires were strung between two annular end-plates made from fiberglass in epoxy resin [2.6]. Wires were positioned

and held in place by pins in the end-plates. End-plates were supported externally from the outer racetrack, via fiberglass straps. The chamber was enclosed in an external pressure vessel that had an aluminum outer wall and beryllium inner wall, the inner wall doubled as the beam tube.

The inner diameter of the beryllium tube, 5 cm, was determined from beam profiles and from the vertical displacement of the beam when the UA1 dipole magnet was at full strength [2.1]. The outer diameter of the detector, 17.8 cm, was determined from the inner diameter of the Central Detector, 18 cm. The length of the chamber, 80 cm, was chosen so that the acceptance of the chamber in pseudorapidity (η) nearly matched that of the Central Detector. Pseudorapidity is defined by:

$$\eta = \log(\tan(\theta/2));$$

where θ is the polar angle measured with respect to the beam's axis.

2.221 Wires

The chamber's sense wires were made from Nicotin, a Ni-Co-Cr-Mb-Fe alloy, chosen for its: 1) strength, 2) resistivity, and 3) high surface quality [2.7]. The strength (1) of the wire allowed sense wires to be strung with a tension of 77 ± 4 g which was as close to the wire's elastic limit as was considered safe. The resistivity (2) of the wire, 2.2 K Ω /m, allowed longitudinal

measurements through charge division. The diameter of the wire, 23 μm , was chosen because it optimized gain without compromising wire stability.

Field and cathode wires were made from Cu-Be and strung at a tension of 300 ± 20 g [2.7]. The wires were gold-plated and had a diameter of 160 μm . The diameter was chosen because it minimized the electric field on the surface preventing field emission effects.

2.222 Pins

Sense wires were held in place by a three-part pin (Figure 2.6). The inner part of the pin, which positioned the sense wire, was made from a cylindrical piece of gold alloy that was polished round at the tip and had a vee shaped notch cut longitudinally in it. The notch was cut such that the sense wire while resting in it would be offset from the cylinder's axis by 100 μm . Staggering of sense wires was achieved by aligning, under a microscope, alternate vee pins so that neighboring pins were rotated by 180° relative to each other. The other two parts of the pin, a brass tube and cone, were used to hold the wire in place. The sense wire was passed through the tube and then the cone was driven into the tube wedging the sense wire in place. A drop of glue was used to prevent slippage. The three-part sense wire pin was estimated to have a placement accuracy of ≈ 25 μm .

Field and cathode wires were held in place by a crimped copper tube (Figure 2.6). Placement accuracy with these pins was approximately the same as that of the vee pins.

2.223 End-plates

Figure 2.7 shows a mechanical drawing of one of the chamber end-plates. The end-plates were annular in shape and made from 12 mm thick Stesalite™ (fiberglass in epoxy resin). Holes for the pins which fixed the wires were drilled into the plate with an estimated accuracy of $\approx 10 \mu\text{m}$; two different hole profiles were used depending on which of the two different pins was to be used. Larger holes were also provided so that the chamber gas could freely pass through them. On the back side of each plate 32 Stesalite™ ribs were added to increase the plate's stiffness and to provide additional insulation between connectors. The plates were notched on their inner radii so that the inner racetrack could be easily aligned. On the end-plate's exterior radii dovetails were cut to receive the ends of fiberglass straps which were used to suspend the end-plates inside the outer racetrack.

2.224 Racetracks

The chamber's inner and outer racetrack were cylindrical printed circuit whose principle functions were to close the drift

field on the inner radius of the chamber and degrade the high voltages inside the sensitive volume of the chamber to ground [2.8]. The racetracks were laminates of: 1) Kapton™ sheets with double-sided printed circuits of gold-plated copper, 2) Kapton™ insulating layers, and 3) a ground plane (Figure 2.8). Printed circuits were designed such that lines of 400 μm width and 13 μm thickness ran parallel to the chamber's wires. Lines were spaced by 717 μm and arranged so that lines on one side of the circuit corresponded to gaps on the other side.

To minimize the multiple scattering that particles underwent as they traversed the inner racetrack, it was constructed using a minimum amount of material. A particle traversing the inner racetrack perpendicular to its axis would have passed through about 0.28% of a radiation length.

The outer racetrack was reinforced with fiberglass so that it could support the end-plates and with them the 260 kg wire load. A particle crossing the outer racetrack perpendicular to its axis would have traversed nearly 1% of a radiation length.

Resistor divider chains (Figure 2.9 and 2.10) were soldered directly on the racetracks. The racetracks were segmented with respect to high voltage because they stored energy in the form of capacitance, which could damage the chamber in the event of a discharge. The outer racetrack was segmented into 16 parts while the inner racetrack was segmented into only 4 parts because of spatial constraints. Voltages were supplied to the individual

resistor chains via bus rings.

2.3 Detector Construction

The assembly of the Microvertex Detector can be described in four sequential stages: 1) wiring, 2) connecting, 3) transfer and alignment, and 4) final mounting in the pressure vessel.

2.31 Wiring

To facilitate wiring of the detector a special jig was constructed (Figure 2.11A). The jig supported the end-plates from their outer radii on bearings which allowed the end-plates to be rotated about their axis. A prestress was applied at the center of the plates to compensate for deformations of the plates under the wire load [2.9].

The chamber was wired from the inner radius outward completing each ring before beginning the next. To prevent wire damage caused by pulling the whole length of the wire through a pin the following wiring technique was used: 1) a piece of wire was cut from the spool, 2) the wire was threaded, on each end, through a hole in the end-plate and then through the pin, 3) the wire was fixed in place on one end, 4) the proper tension was applied to the wire with an appropriate weight, and 5) the wire was fixed on the other end. Wire tension was monitored after each

ring was wired using a permanent magnet and a system of feed back amplifiers, which forced wires to vibrate in their fundamental mode [2.10]. The frequency of vibration (f) is related to the wire's tension (T) through the relation:

$$f = (1/2L)\sqrt{(T/m)};$$

where m is the mass per unit length of the wire and L its length. If the vibrational frequency of a wire was out of specification it was replaced.

After the chamber was wired a final tension check of all wires revealed larger plate distortions than anticipated. The results showed a reduction of 4 g for the sense wires nearest the inner radius of the detector. The cause of this discrepancy was thought to be a misapplied or miscalculated prestress.

2.32 Connecting

Special connectors were designed for use on the end-plates of the Microvertex Detector. The connectors were of two varieties: 1) sense-field connectors and 2) cathode connectors. The sense-field connector supplied voltages to the field wires and accepted signals from the sense wires for one cell. The cathode connector supplied a pair of cathode planes with high voltage (Figure 2.12). All exposed conductors on these connectors were insulated with mylar tape.

The sense-field connector (Figure 2.12A) was actually two

connectors in one. On one side of the connector sense wire springs were soldered to a ribbon cable which then made its way to the pressure vessel feed-throughs via a 16 pin Scotchflex™ connector. On the other side of the connector field wire springs were soldered to a metal bus which was soldered to a high voltage cable which made its way to the pressure vessel feed-throughs via a high voltage connector. The high voltage connector was made from a Burndy™ pin and a Delrin™ insulator. The field wire bus was interrupted with two 500 M Ω series resistors between field wires 2-3 and 15-16 to prevent any current draw on the external field wires.

Two varieties of cathode connectors (Figure 2.12B) were needed because of severe space constraints. On one side of the detector inner cathode wires (1-17) were connected while outer cathode wires (17-33) were connected on the other side. Cathode connectors supplied voltage to two planes of wires at the same time via a flexible printed circuit which was soldered at both ends to cathode wire spring contacts. The circuit at its center was soldered to a West Electric™ 17 pin connector.

All sense-field connectors were installed followed by one type of cathode connectors and then the other. After each set of connectors was installed, connections were tested for electrical continuity. Any missing contacts were promptly fixed so that all wires were properly connected.

Cathode connectors were then connected to the cathode

resistor divider rings (Figure 2.13). The cathode resistor divider chain was split into two identical halves. Each half was made in the shape of a ring so that cathode connectors could plug directly into them.

2.33 Transfer and Alignment

The transfer procedure was the process by which the support of the wire load was passed from the wiring jig to the outer racetrack. The procedure required two steps; the wire load was passed from the wiring jig to a transfer jig and then, from the transfer jig to the outer racetrack. The transfer jig consisted of a precision steel rod which supported the end-plates via "spiders" near either end (Figure 2.11B). The spider was an eight legged device which attached to the rod at its center and to an end-plate near its periphery. Spider legs were rods that threaded into the backs of the end-plates.

Passing the wire load from the wiring jig to the transfer jig was straight forward. Spiders were mounted on the precision rod which was already in place having been used to apply the prestress during wiring. The legs of the spiders were attached to the end-plates and the wire load was passed to the transfer jig by turning a screw which pushed against the end of the rod and pulled the spiders apart. When the transfer jig had fully taken up the wire load the wiring jig was dismantled and removed.

To prepare for the transfer to the outer racetrack the fiberglass straps which support each end-plate were fitted into their respective dovetails on the outer edges of the end-plates. A prealignment of the end-plates was done on a rectified marble table using a height gauge. Then, the chamber was fixed vertically and aligned with a theodolite. Fiduciary marks on the chamber were copied to the transfer jig to facilitate alignment of the outer racetrack with respect to the chamber and the wires were given a final cleaning with isopropyl alcohol.

The transfer process commenced by lowering the outer racetrack into place. Once in place, a prestress to compensate for distortions under the wire load was applied to the racetrack, via an external compression cage. The racetrack was aligned with the chamber and aluminum head pieces were attached to the fiberglass straps which fixed them in place on the edge of the racetrack. As the prestress on the racetrack was removed the wire load was taken up by the racetrack.

The chamber was removed from the transfer jig and returned to the marble table for final alignment. Final alignment was done by displacing the fiberglass straps which held the end-plates inside the outer racetrack until a fiduciary mark on the outer racetrack was correctly positioned relative to small gas holes on the face of the end-plates. Measurement of their relative alignment was made using a theodolite. The accuracy of alignment was estimated to be $\sim 100 \mu\text{m}$ at the outer radius of the detector

($\approx 0.06^\circ$). The end-plates were kept aligned through the insertion of wedges between the end-plates and the outer racetrack.

The inner racetrack was then slid into place and glued. Its alignment made trivial by a keyway on the inner radius of an end-plate.

2.34 Final Mounting

Placement of the chamber into the pressure vessel began by sliding the chamber onto a surrogate beam tube which would later be exchanged for the beryllium beam tube. The pressure vessel end-plates (pressure-plates), 12 mm thick annular plates, were then fixed into place. The seal between the pressure-plates and the beam tube was made by an O-ring.

The pressure-plates each contained 24 Fisher™ high pressure - radiation resistant - aluminum feed-throughs and a passage for gas. Sixteen of the feed-throughs were 16-pin signal feed-throughs that each carried all of the signals for one cell. The remaining eight were a mixture of single and five-pin high voltage connectors.

All connections to feed-throughs were made and verified. Then, the outer wall of the pressure vessel, a 1 mm thick aluminum cylinder, was slid into place and welded to the pressure-plates. The chamber's assembly was then completed by the replacement of the surrogate beam tube with the beryllium

beam tube.

2.4 The High Voltage System

The Microvertex Detector high voltage system was modeled after the Central Detector high voltage system [2.11]. The high voltage system can be subdivided into two parts: 1) drift voltage and 2) field voltage. Part (1) provided voltage for cathode wires and the racetracks which created the drift field, while part (2) provided voltage for the field wires which promoted gain on the sense wires. Control and monitoring of the high voltage system were accomplished via a dedicated microcomputer and an oscilloscope. Figure 2.14 shows a block diagram of the high voltage system.

The determination of voltages for a given set of operating conditions was achieved through computer modeling. A typical cell was modeled as an ensemble of wires [2.12] and then the electrostatic properties of the cell for a given voltage configuration was calculated [2.13]. Calculations were repeated in an iterative fashion until a satisfactory voltage parameterization was found.

Six degrees of freedom were utilized in the voltage parameterization. Three of these corresponded to maximum and two to minimum voltages on the cathode and racetrack divider chains (the inner and outer racetrack had the same minimum

voltage). The sixth was reserved for the field voltage. For a voltage parameterization to be satisfactory the chamber had to have: 1) a uniform electric field over most of the cell, 2) large surface fields on the sense wires so that gain would be sufficient, and 3) minimal surface fields on cathode wires so that field emission effects could be avoided. Requirement (1) was measured at the 1% level since that was the limit at which drift voltages were controllable. The surface fields required on the sense wires (2) were dependent on the pressure while surface fields on the cathode wires (3) were required to be below 40 kV/cm.

The magnitude of the drift field was dependent on the drift properties of the gas used and the operating pressure.

2.41 Drift Voltage

The drift voltage system began with a digitally controlled 30 kV Bertan™ power supply. Digital control of the Bertan™ was provided by the microcomputer via a SEN 20R 251 output register. The power supply was connected to an Active Divider [2.14] via a relay that could be tripped within a few milliseconds of a current surge.

The Active Divider degraded the input voltage producing 12 different low impedance output voltages (taps). These voltages were then connected to the cathode and racetrack divider chains. The output voltages were allocated among the chains as follows: 7

taps for the cathode, 4 for the outer racetrack, and 3 for the inner racetrack (the inner and outer racetracks shared 2 taps). Several taps were used on each resistor chain to avoid variation of potentials along the chain due to ionization current.

Current draw on each tap was measured inside the Active Divider and then converted to a frequency which was read out via CAMAC by a UA1 built scalar that was gated with a SEN RTC 2078 real time clock [2.14]. The amplitude of the signal was used to measure current surges. A surge of 150 μA on any tap caused an alarm condition which forced open the drift relay.

The voltage on each tap was monitored via simple 0.5 : 1000 M Ω dividers which scaled down the high voltage by a factor of 2000 so that it could be read out via CAMAC by a LeCroy™ LRS 2232A ADC.

Capacitive spies, high voltage capacitors plus resistors to ground, were placed on the largest output tap of each divider chain so that activity on high voltage lines could be monitored directly with an oscilloscope.

2.42 Field Voltage

Each of the sixteen field channels was powered independently by a modified LeCroy™ 4032A power supply. As with the drift voltage each high voltage line passed through a relay, which could be tripped within a few hundred microseconds of a current surge.

Two General Processor Micro Controllers [2.15] were used to ramp voltages, monitor voltages and currents, and trip relays if current surges of more than 50 μA occurred. To further insure security an interlock system was created so that a drift voltage trip would force all field voltage relays open [2.16].

A capacitive spy was placed on each field channel so that high voltage activity could be monitored in each cell.

2.43 High Voltage Control and Monitoring

A dedicated Super Caviar Microcomputer was used to control and monitor the High Voltage System. The program allowed the user: 1) to open and close relays, 2) ramp voltages up and down, and 3) to quickly turn off the high voltage in case of emergency. While idling the program continuously monitored the status of all relays, currents, and voltages. A color display allowed voltages and currents that strayed too far from their nominal settings to be highlighted. If a high voltage trip occurred, the program alerted the user and attempted to diagnose the cause of the trip.

2.5 Readout Electronics

The readout chain for the Microvertex Detector [2.17] began with preamplifiers mounted directly on the end-plates of the pressure vessel. Signals were then split and sent along two

different chains for processing (Figure 2.15). The first chain was used to determine the drift time; right and left signals were summed, clipped, discriminated, split again, and finally sent to time to digital convertors (TDC). The second chain was used to determine the longitudinal coordinate of the hit through charge division; right and left signals were sent via delay electronics to charge and time digitizers (CTD). Since this analysis does not utilize charge division measurements, no further description of this second chain will be given.

2.51 Preamplifiers

To reduce attenuation and noise, preamplifiers were placed as close to the Microvertex Detector as possible. The preamplifiers were thus mounted directly onto the end-plates of pressure vessel. Because of their low noise, high gain, fast rise time, small dimensions, and low power consumption, the Laben™ VV35 preamplifier was used. This preamplifier's specifications are listed in Table 2.2. To match impedance with the sense wires, the preamplifiers were connected via a $270\ \Omega$ series resistor and a $4.7\ \text{k}\Omega$ resistor at the AC coupled preamplifier input, was used to define the sense wire potential and permit test pulses to be injected. Preamplifiers were mounted on cards in groups of 8 and the cards were mounted in pairs so that each preamplifier sandwich could read out one cell. Cross talk between channels

inside the preamplifier card was measured to be as low as 0.5%. Cooling for the preamplifiers was provided by pressurized air. Power to the preamplifiers was interlocked with cooling and temperature sensors.

2.52 Discriminator Electronics

The closest location to the Microvertex Detector for the discriminator electronics was 13.5 m away from the preamplifiers under the UA1 dipole magnet. The cables that connected the preamplifiers and discriminators were 50 Ω coax cables. These cables affected the rise time of a typical pulse by 5 ns and its amplitude by -6 db.

The right and left signals from one wire were first received by a Summing Transceiver Baby Card. The baby card had two functions: 1) it converted the input pulse into a differential output, 2) and it summed left and right inputs clipping the pulse tail. Clipping was achieved by sending the summed signal to a 4 ns delay line shorted at its end. The length of the delay line was equal to the pulse's rise time; hence, an edge differentiation was made. This technique allowed discrimination between two superposed pulses with a separation of only 20 ns, thus the Microvertex Detector had an effective two hit resolution of about 1 mm.

Eight baby cards were mounted on a Discriminator Mother

Board. On the mother board LeCroy™ MVL 407's discriminated the clipped analog sum provided by each baby card. The mother board also contained electronics to create test pulses for injection into the right and left channels of a preamplifier board so that relative gains could be monitored.

Thresholds were independently set for each discriminator via a GPMC-RAC which was programmed to monitor them so that they remained constant, independent of time and temperature. The GPMC-RAC outputs voltages in the range of ± 2.5 V with an accuracy of 8 bits. By passing these voltages through a 1 : 45 divider, threshold voltages up to 55 mV in steps of 0.44 mV could be set.

Discriminator output was sent via video twisted pairs to ECL splitters which had three outputs, one available for a fast trigger, and two for TDCs.

2.53 Time to Digital Convertors

Because of their multi-hit capabilities LeCroy™ 1879 Fastbus TDCs were used to digitize discriminator outputs. The 1879 can store the input status of 96 ECL channels with an accuracy of 2 ns during 1 μ s. To improve resolution each channel was digitized by two TDCs driven by cables which differed in length by 1 ns. Combining the information present in the two TDCs thus gave an effective accuracy of 1 ns. Six 1879 modules were needed to read out the Microvertex Detector. All six modules and a LeCroy™ 1821

Segment Manager, which served as controller, were mounted in a Fastbus crate. The crate was read out by the UA1 VME Readout System via a Fastbus/VME/VMX interface card designed and built within the UA1 collaboration [2.18].

2.6 Test Beam Results

Construction of the Microvertex Detector was completed in the spring of 1985. Prior to its installation in the UA1 Experiment the detector was tested in a 10 GeV/c pion beam at the CERN Proton Synchrotron. In the test beam nominal operating conditions were established and the detector's single wire resolution was measured.

2.61 Operating Conditions

Stable operating conditions were achieved in the test beam with a drift field (E) of 5.55 kV/cm and a gas pressure (p) of 3 atm. The gas used was a 53 : 47 argon-ethane mixture which saturated well below the 1.85 kV/cm/Atm operating point (Figure 2.16) giving a drift velocity of 51 $\mu\text{m/ns}$. Voltages required to obtain the drift field are listed in Table 2.3. Surface fields on the sense, field and cathode wires were respectively 442, 6.0, and 34.8 kV/cm.

The mean pulse height for a minimum ionizing particle which

traversed the chamber normal to its axis was measured at 80 mV, such a pulse corresponded to the collection of about 28 primary electrons by the sense wire. Integration of pulses to determine the total charge collected gave an estimated gain per primary electron of 4.6×10^4 . Discriminator thresholds during data taking were set to 5 mV, effectively the 2nd primary electron to arrive at the sense wire.

LeCroy™ 2228A TDCs with 250 ps precision were used to record drift times. These were used in place of the detector's Fastbus electronics (Section 2.53) since the latter were not yet operational.

2.62 Results

To determine the chamber's single wire resolution the chamber was oriented so that beam particles would traverse the detector perpendicular to its axis at the chamber's center. Since no magnetic field was present, tracks were fit to straight lines. Residuals from track fits were histogrammed as a function of the drift distance, the widths of these distributions were then used to calculate the average single wire resolution as a function of the drift distance. Figure 2.17 shows the square of the single wire resolution as a function of the drift distance.

The single wire resolution (σ_{swr}) of the detector can be expressed as:

$$\sigma_{\text{swr}} = \sqrt{(\sigma_0^2 + \sigma_{\text{dif}}^2)};$$

where σ_0 is the detector's intrinsic single wire resolution, and σ_{dif} is the contribution to the resolution from diffusion in the gas. The intrinsic resolution of the detector is a function of: 1) primary ionization statistics, 2) electronic noise, and 3) the accuracy to which the position of the sense wires are known. The contribution to the resolution from diffusion in the gas is related to the drift distance (x) by:

$$\sigma_{\text{dif}} \sim \sqrt{x}.$$

The expected linear relation between the square of the single wire resolution and the drift distance is evident in Figure 2.17, extrapolation to $x = 0$ gives an intrinsic single wire resolution of 36 μm for the detector.

2.7 Collider Experience

The Microvertex Detector was operated in the Super Proton-Antiproton Synchrotron during the Fall 1985 and Spring 1986 runs. During the Fall run the detector operated stably at luminosities up to $2 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ where a total ionization current of 120 μA was measured. During the Spring run no useful data was collected because of problems with the beam tube.

2.71 The Fall 1985 Run

As the Fall run began the Microvertex Detector slowly made its way to full voltage. Once there, small diagnostic samples of data were taken to determine optimum running conditions for the collider environment. The differences between running the detector in a test beam and a collider quickly became obvious. Problems with external electronic noise and ionization current which were virtually non-existent in the test beam plagued the detector in the collider environment.

Noise picked up from the beam as proton bunches traversed the detector caused phantom hits to appear on a large fraction of the chamber's wires. In order to operate the detector with this background the detector's sensitivity had to be reduced. Discriminator thresholds were forced upward from 5 to 32 mV, effectively from the 2nd primary electron to the 11th.

Ionization current in the detector was nearly an order of magnitude larger than had been anticipated when the chamber's resistor divider chains were designed. Figure 2.18 shows the total ionization current as a function of the luminosity that was observed; the non-zero intercept indicates that beam halo was at least partly responsible for the higher than expected chamber currents. To keep electric field distortions caused by ionization current at a reasonable level as the collider reached luminosities of $3.4 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$, it was decided to operate the chamber at

95% of its nominal voltage, which corresponded to roughly 50% of its nominal gain.

With these running conditions established, data was taken for the calibration and alignment of the detector. This data, which will be discussed in the next chapter, was unfortunately also the last data that the detector would take. The Fall run, for the Microvertex Detector, was abruptly truncated after three weeks because the failure of a key detector component, the outer racetracks's high voltage bus ring, prevented high voltage operation of the chamber.

2.72 The Spring 1986 Run

After the outer racetrack bus ring failed, the detector was taken out of the collider so that a redesigned bus ring could be installed and modifications to the detector for the Spring run begun. During the Fall run problems had been observed in the Central Detector which were traced to the Microvertex Detector's pressure-plates, preamplifiers, and parts of the beam tube assembly. Large numbers of photons were converting while traversing these massive objects, producing low energy electrons and positrons which were being swept, by the experiment's dipole magnet, into the Central Detector. These particles then spiraled in the Central Detector until they ran out of energy, creating an immense number of hits which clouded the chamber to the point

where pattern recognition was impossible. To correct this situation for the Spring run, the pressure vessel and beam tube assembly were redesigned out of much less massive carbon fiber and the preamplifiers were moved outward by 4.5 m so that they were outside of the magnet.

When these modifications were completed the detector was reinstalled in the UA1 Experiment and the experiment was pushed into the SPPS for a dedicated Microvertex Detector run. Two faults in the redesigned beam tube prevented this from occurring. The first fault, inadequate radio-frequency shielding in the beam tube, prevented useful data from being taken with the detector. The second fault, an irreparable leak in the beam tube, caused the cancellation of the run before any attempt to fix the first problem could be attempted.

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- [2.17] P. Cennini, UA1 Technical Note, UA1/TN 86-87 (1986).
- [2.18] A. Schwartz and J. Rohlf, UA1 Technical Note, UA1/TN 85-73 (1985).

Table 2.1**Parameters for the Microvertex Detector**

inner radius	25 mm
outer radius	89 mm
wire length	80 cm
maximum drift distance	16 mm
number of cells	16
sense wires per cell	16
wire pitch	1.58 mm
sense wire staggering	100 μ m
total number of sense wires	256
total number of field wires	272
total number of cathode wires	528
first radial measurement	
33 mm	
last radial measurement	80 mm
inner wall thickness in radiation lengths	0.58 %

Table 2.2**Laben Preamplifier Specifications**

model	VV53
RMS noise	2100 electrons
gain	4.7 mV/ μ A
rise time	1.8 ns
power consumption	35 mW

Table 2.3**Nominal Voltages for the Microvertex Detector**

electric field (E):	5.55 kV/cm
pressure (P):	3 Atm
E/P:	1.85 kV/cm/Atm

	<u>minimum</u>	<u>maximum</u>	<u>step</u>
sense wires:	ground	ground	0
field wires:	-2.15 kV	-2.15 kV	0
cathode wires:	-11.05 kV	-5.60 kV	165 V
inner racetrack:	-4.85 kV	-1.33 kV	320 V
outer racetrack:	-11.20 kV	-1.33 kV	340 V

Figure 2.1
Microvertex Detector Cross-section

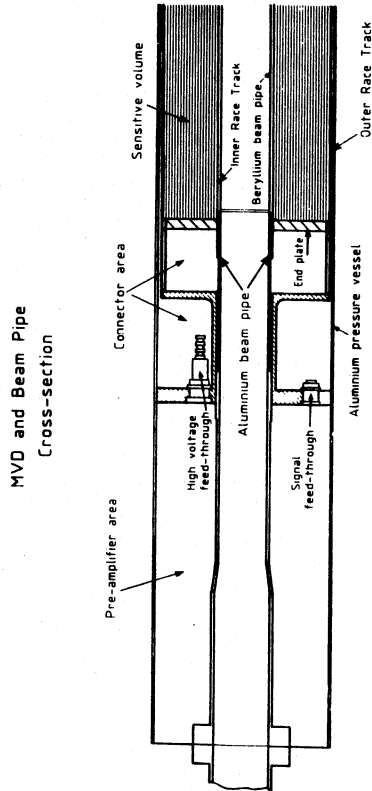


Figure 2.2
Microvertex Detector Cell Arrangement

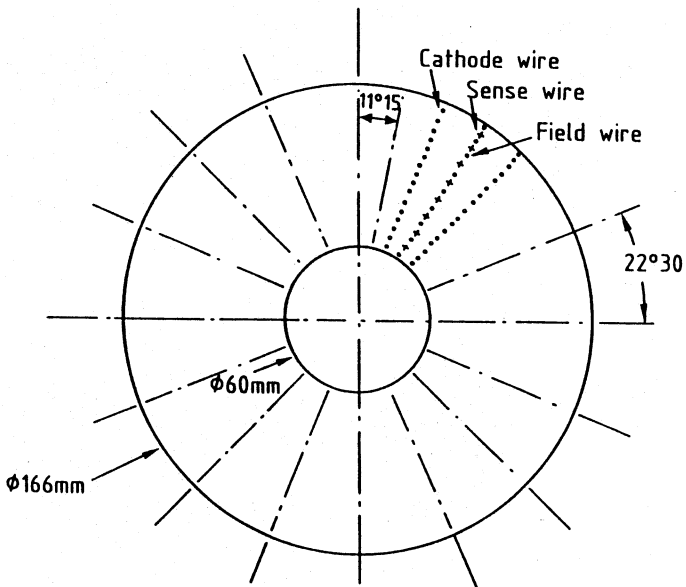


Figure 2.3
Microvertex Detector Wire Pattern

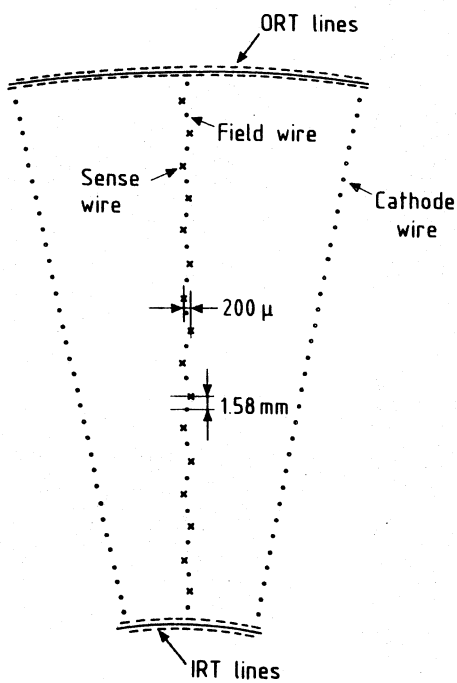


Figure 2.4
Equipotential Map of a Microvertex Detector Cell

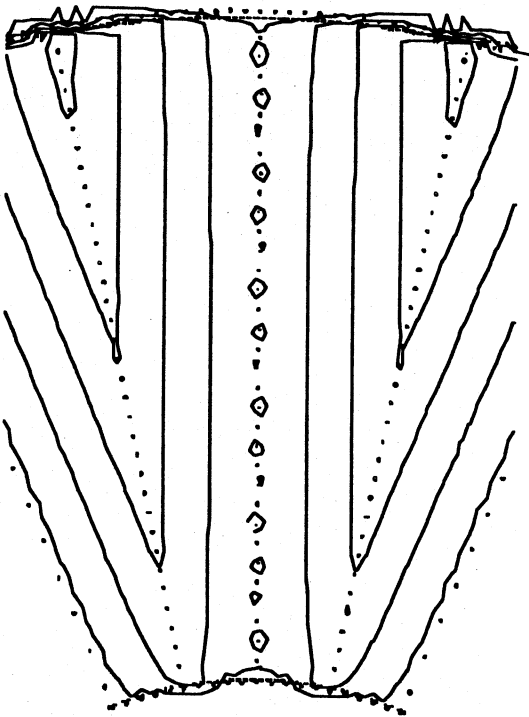


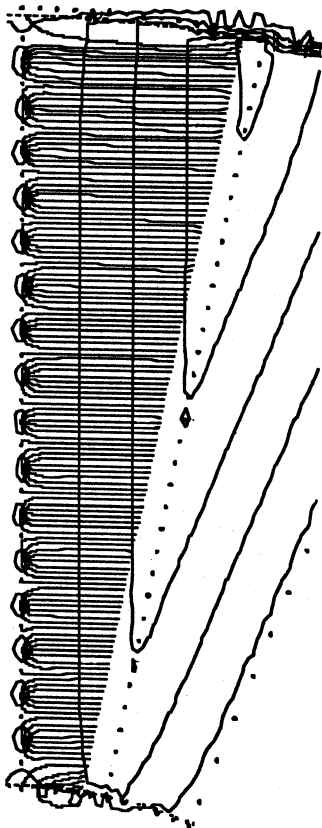
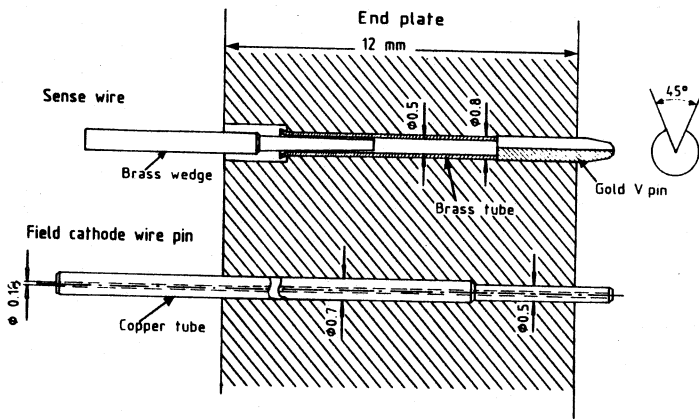
Figure 2.5**Drift Map for a Microvertex Detector Cell**

Figure 2.6
Microvertex Detector Sense and Cathode-Field Wire Pins



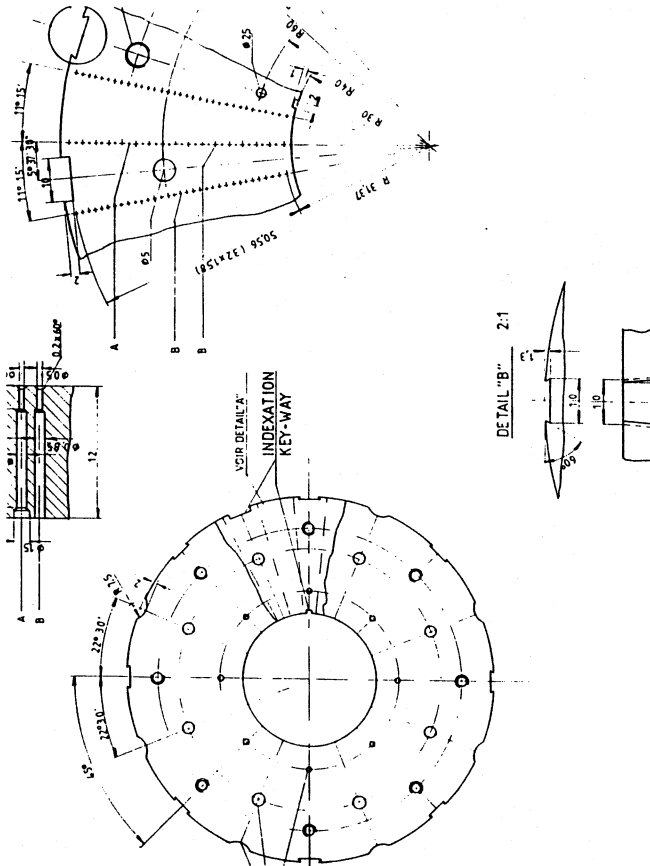
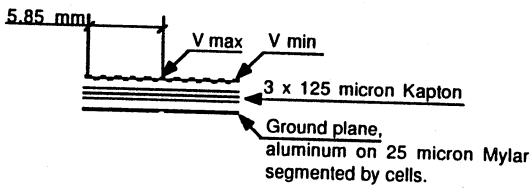


Figure 2.8
Microvertex Detector Inner and Outer Racetrack
Cross-sections

A) Inner Racetrack



B) Outer Racetrack

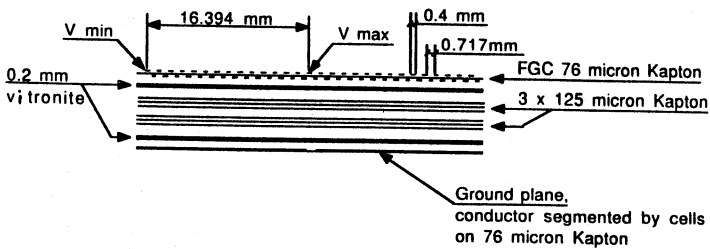
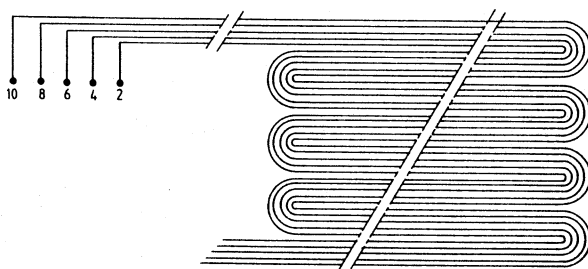


Figure 2.9

Microvertex Detector Inner Racetrack

INNER RACETRACK OUTSIDE DRIFT VOLUME
GROUP OF 4 CELLS



INNER RACETRACK INSIDE DRIFT VOLUME
GROUP OF 4 CELLS

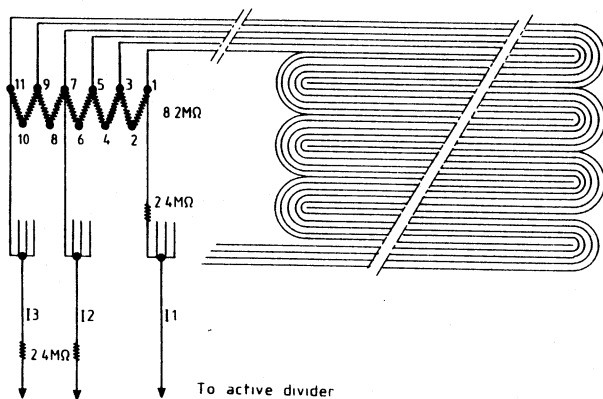
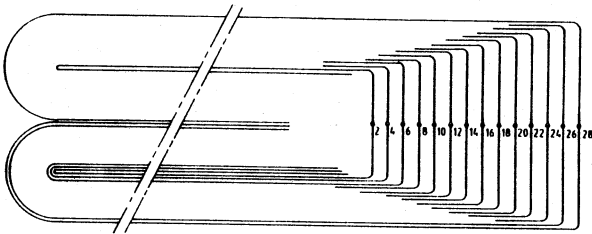


Figure 2.10
Microvertex Detector Outer Racetrack

OUTER RACETRACK OUTSIDE DRIFT VOLUME
 GROUP OF 2 CELLS



OUTER RACETRACK INSIDE DRIFT VOLUME
 16 INDEPENDENT CELLS WITH TWO TYPES OF CONNECTIONS,
 CORRESPONDING TO A AND B AS DRAWN

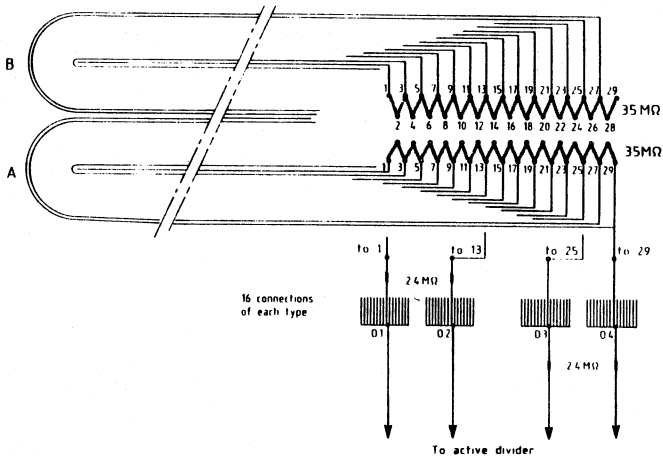


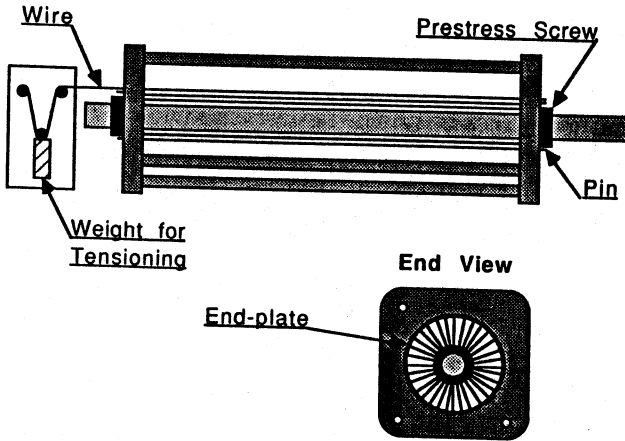
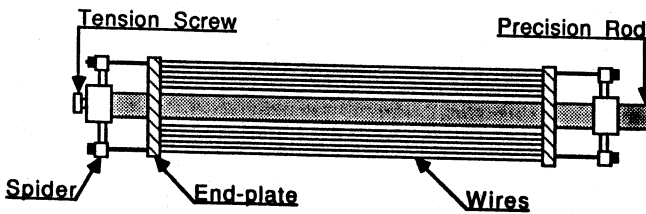
Figure 2.11**Jigs Used in the Construction of the Microvertex Detector****A) Wiring Jig****B) Transfer Jig**

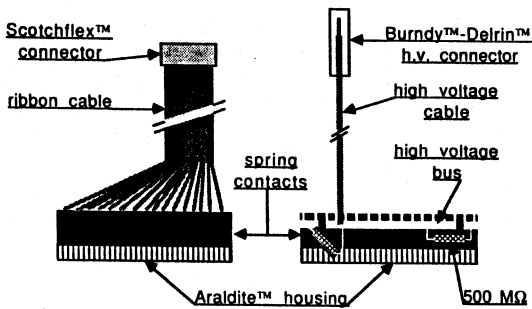
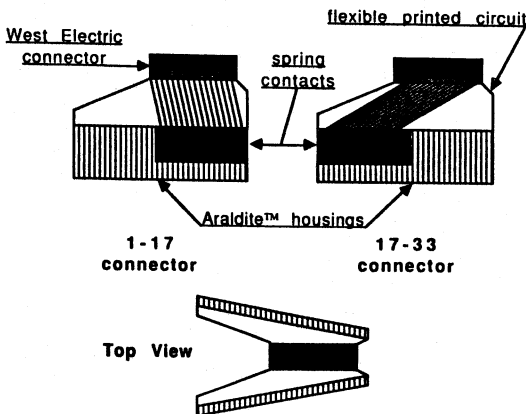
Figure 2.12**Microvertex Detector End-plate Connectors****A) Both Sides of a Sense-Field Connector****B) Both types of Cathode Connectors**

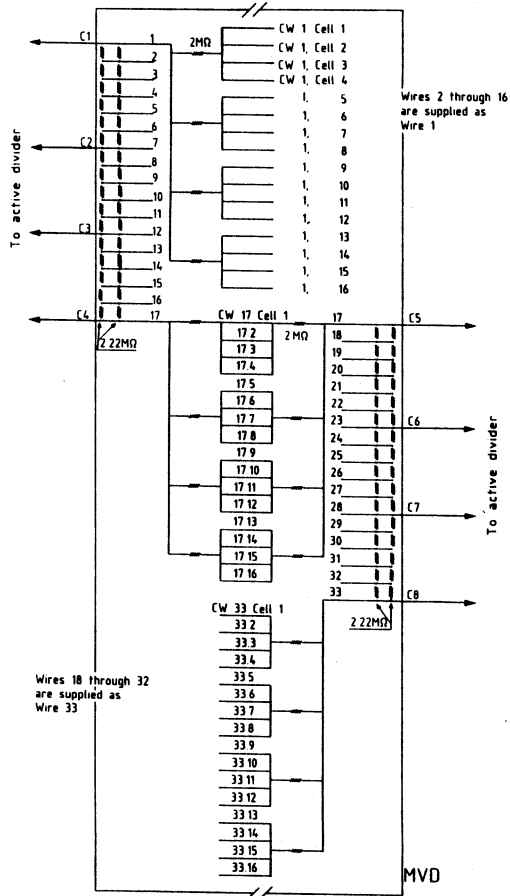
Figure 2.13**Microvertex Detector Cathode Divider Chain**

Figure 2.14
Block Diagram of the Microvertex Detector High Voltage
System

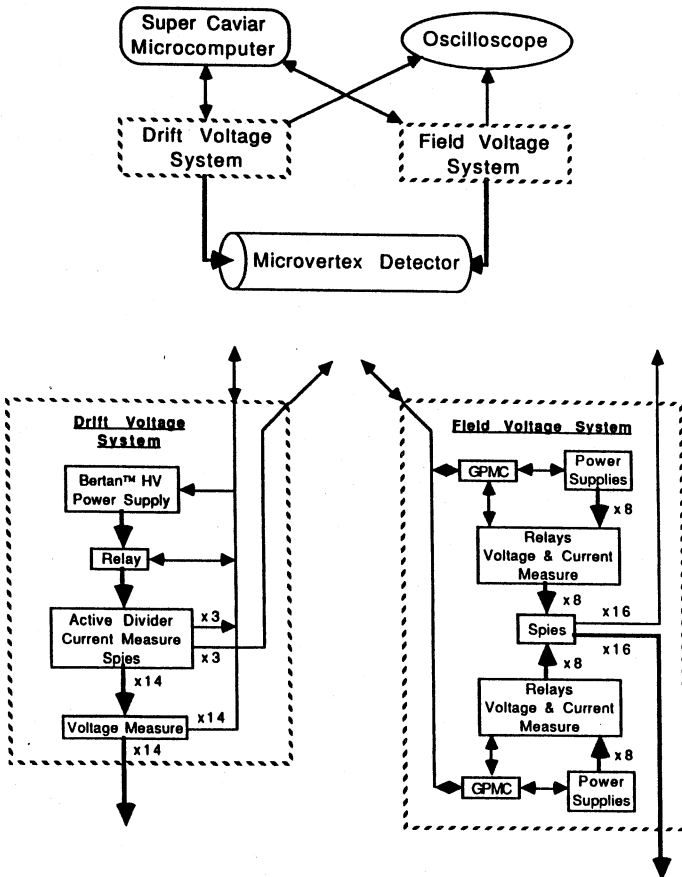


Figure 2.15
Block Diagram of the Microvertex Detector Readout
Electronics

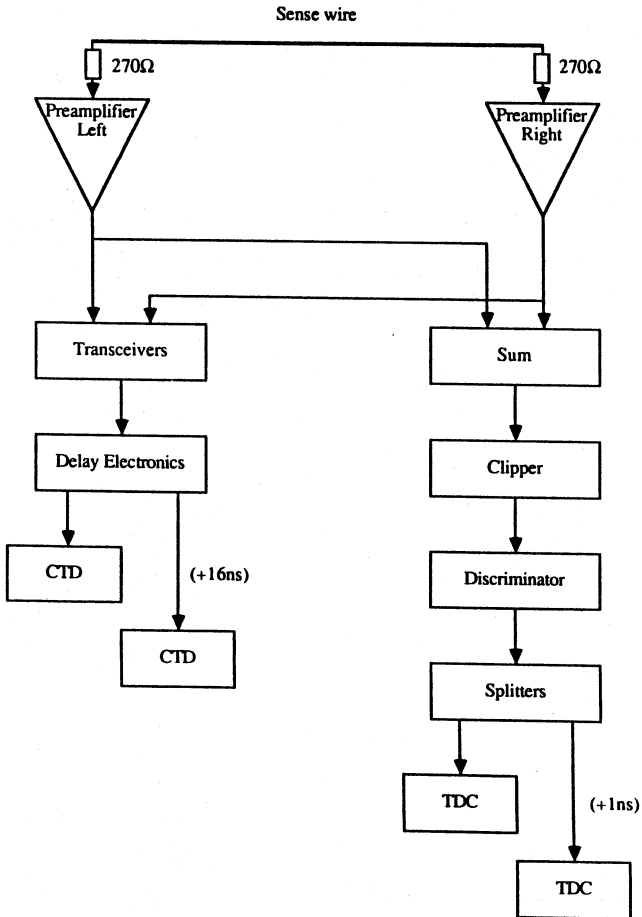
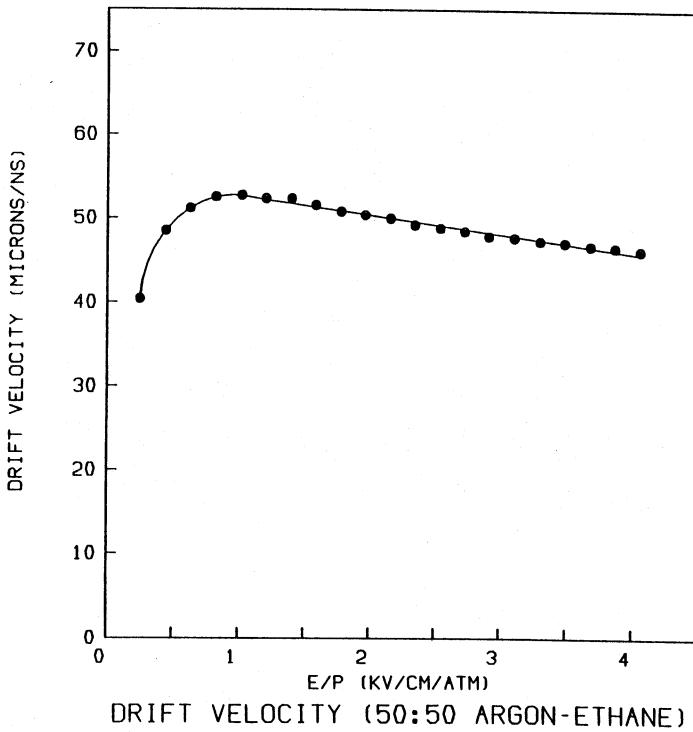


Figure 2.16

**Drift Velocity of Argon-Ethane Gas Mixtures as a Function
of the Electric Field Strength**



(data from B. Jean-Marie et al., Nucl. Instr. Meth. 159 (1979) 213.)

Figure 2.17
Microvertex Detector Single Wire Resolution as a
Function of the Drift Distance

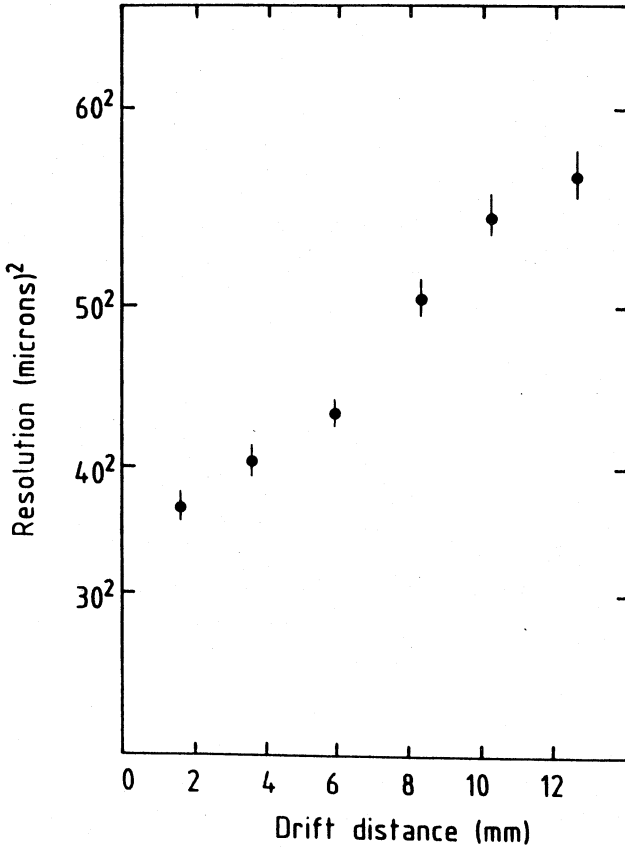
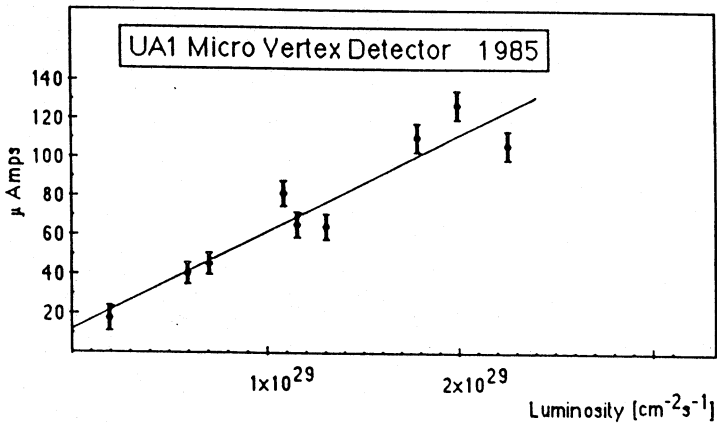


Figure 2.18
Microvertex Detector Ionization Current as a Function of
the Luminosity



CHAPTER III

EVENT RECONSTRUCTION

3.1 Introduction

As described in the previous chapter the Microvertex Detector operated stably in the collider and data was collected. In this chapter the running conditions under which that data was collected will be described as well as the process by which the data was transformed into computer images of the collisions.

3.2 The Data Sample

In the Fall of 1985 a data sample of 5460 $\bar{p}p$ collisions at a center of mass energy of 630 GeV was recorded. This data sample, which corresponded to an integrated luminosity of $140 \pm 21 \text{ mb}^{-1}$, comprised the largest sample of data collected by the Microvertex Detector. Table 3.1 summarizes the running conditions during data taking. A discussion of how these running conditions were chosen was presented in Section 2.7.1.

The data was collected with a "minimum bias" trigger which was designed to accept all inelastic $\bar{p}p$ collisions with the exclusion of single diffractive events which account for 10 - 15% of the inelastic cross-section [3.1]. (A single diffractive event is

a collision in which the proton or antiproton escapes intact.) Two independent pairs of hodoscopes triggered the events. They were used in tightly timed coincidence to select preferentially beam-beam events. The first pair were ± 6.6 m from the crossing point and covered the angular range ~ 12 to ~ 56 mrad while the second pair were at ± 2.9 m with angular coverage from ~ 68 to ~ 400 mrad. The OR of the two triggers was estimated to be more than 95% efficient in the selection of non-single diffractive inelastic collisions.

During data taking the magnet current was set at $1/20$ of its nominal value, reducing the strength of the magnetic field to 350 G, so that the Central Detector would be free of the spiraling electrons described in Section 2.72.

3.3 Event Reconstruction

Event reconstruction is the process by which the raw data collected by the experiment is transformed into a computer image of the collision. A description of this process for the Microvertex Detector is presented below, the corresponding process for the Central Detector has been described in reference [3.2].

The process of event reconstruction in the Microvertex Detector can be broken down into five steps: 1) initial calibration, 2) track finding, 3) track fitting and final calibration, 4) vertex finding and fitting, and 5) matching of Microvertex and Central

Detector tracks (Figure 3.1A).

3.31 Initial Calibration

Initial calibration is the process that converts the digital output of the Microvertex Detector's TDC's into wire numbers, drift times, and pulse widths. Each TDC hit consists of two 16-bit words in which the FASTBUS crate controlled has encoded the following information: 1) the TDC module and channel number, 2) the time at which discriminator first fired - the leading edge time, and 3) the time at which the discriminator stopped firing - the trailing edge time [3.3]. (The discriminator fires as the input pulse height exceeds the discriminator's threshold.) The leading and trailing edge times are determined relative to the last time that the TDC's shift register was reset which occurred at a fixed time before the bunch crossing.

The wire number and pulse width can be readily extracted from the TDC information. The wire (and cell) number is determined from a wiring diagram while the pulse width is calculated directly as the difference between trailing and leading edge times. The drift time differs from the leading edge time by a constant known as the t_0 . The t_0 is the elapsed time between collision and TDC reset plus the time it takes the signal to propagate from the chamber to the TDC.

To determine the t_0 for a given channel, a histogram of all

leading edge times for the channel is made. The spectrum of drift times is fit to a function composed of a plateau with a gaussian leading edge. The leading edge was taken as gaussian since this gave the best fit to test beam data. (Recall that high resolution, 250 ps, TDC's were used in the test beam.) The t_0 is taken as the half height of the gaussian leading edge. The width of the leading edge was typically less than the TDC bin width of 2ns, thus the width of the leading edge was estimated from the number of hits that preceded the start of the plateau.

The LeCroy™ TDC's have an accuracy of 2 ns. To improve the accuracy of the drift time measurement each Microvertex Detector sense wire is read out with two TDC channels driven in parallel by cables that differ in length by 1 ns.

3.32 Track Finding

Track finding is the procedure by which wire numbers, drift times, and pulse lengths are converted into space points and then associated together to form tracks. Space points in the detector's drift plane can be calculated from the drift times, sense wire locations, and the drift velocity in the gas. Sense wires can collect electrons from either side of the cell (Figure 2.3), thus it is impossible to tell from the drift time alone on which side of the cell a given track has passed. For each hit, two points must be generated only one of which is real. The fake point is referred to

as a "ghost" points. Figure 3.2A shows all of the real and ghost points for a typical event. (The points in Figure 3.2 appear as lines to indicate the length of the pulse.) To find tracks all these points must be sorted to determine which points are real and which not, and to which track each real point belongs.

The track finding process is summarized in Figure 3.1B. It is an iterative process that is based on a limited "road search" pattern recognition algorithm. The road search is a powerful yet simple technique for finding points associated with tracks. Track projections into the drift plane of the detector can be closely approximated by straight lines (Section 3.331) thus tracks are found by searching for groups of points which resided inside of a road. A road is two parallel lines which defined the limits of tolerance of points associated with a possible track. Ghost tracks are distinguishable from real tracks since the staggering of the sense wires, with respect to the central axis of the cell, forces the points associated with a ghost track to zigzag in an obvious fashion.

Before describing the track finding algorithm it is helpful to establish the following three points (listed in order of importance):

- 1) Road searches are limited to two adjacent Microvertex Detector half cells at a time. The detector is divided into 32 non-distinct regions for track finding (i.e. half cells: 1 & 2, 2

& 3, 3 & 4, ... , 32 & 1).

- 2) Tracks with the largest numbers of hits are found first. A track with 15 hits is always found before a track with 10 hits and so forth.
- 3) Tracks which point back to the nominal beam position are found first.

The track finding algorithm is based on two nested loops. The outer loop is the track selection requirement loop while the inner loop controls the region of the detector to be searched.

Track selection requirements are two-fold: 1) a minimum number of wires with hits inside of a road (N) is required and 2) a maximum number of absent wires (i.e. holes in the track) is permitted. Requirement (1) can be quantified by:

$$N \geq N_{\min};$$

where $N_{\min}$ is set to 16 for the first pass and then decreased by 1 each pass until $N_{\min}$ is 6. If a wire has more than one hit in a road the one nearest the center of the road is chosen. Requirement (2) can be quantified by:

$$\epsilon = N/(n_o - n_i + 1) \geq \epsilon_{\min};$$

where n_i and n_o are respectively the wire numbers of the inner and outer most wires hit, $\epsilon_{\min}$ is taken as 0.75. (The efficiency, per wire, of the chamber was estimated to be about 90%. This

estimate was made by relaxing $\epsilon_{\min}$ to zero and then calculating the ratio:

$$\epsilon_i^w = N_o/N_{\theta};$$

where ϵ_i^w is the efficiency of the wire in the i th radial position, N_{θ} is the number of times a hit was expected on wire i , and N_o is the number of hits that were observed on wire i . A hit was expected on wire i if both wires $i-1$ and $i+1$ were hit. To prevent a biased efficiency estimate, observed hits were not counted unless both wires $i-1$ and $i+1$ were hit as well.)

The actual road search is the process by which combinations of initiators, points that define the center of a road, are examined. The choice of initiators is not arbitrary since it is desirable to have them as far apart as possible. One initiator is typically chosen near the inner radius of the detector and the other near the outer radius. The choice of the first inner initiator is always the nominal beam position. (A value of 1 is assigned to n_i for this initiator).

The road width (w_r) was carefully chosen. It had to be small enough so that a ghost track would not fit inside and it had to be big enough to allow for systematic detector effects and detector resolution. To partially offset systematic effect a temporary drift time correction (Δt) was added to all drift times. Best results were obtained with the road width and temporary drift time correction that are given in Table 3.2. (Drift time corrections will be described in greater detail in Section 3.332.)

Track finding parameters are summarized in Table 3.2. Figure 3.2B show the points that were associated with tracks while Figure 3.2C shows unused points and their ghosts for a typical event. The distribution of the percent of hits that were used in track finding per event is shown in Figure 3.3A. An average of 70.8% of the hits in a given event were associated to tracks. Unused points can be attributed partly to unreconstructable tracks and partly to noise in the data. Figure 3.3B shows the distribution of the number of tracks that were found per event. The average number of tracks per event, 19.5, corresponds well with what one would expect from the chambers acceptance, ~ 5 units of pseudorapidity, and the central pseudorapidity density for charged particles, ~ 4 per unit of pseudorapidity. Figure 3.3C shows the distribution of hits per track found. Tracks were permitted a minimum of 6 and a maximum of 16 hits, the average number of hits per track was 11.4.

3.33 Track Fitting and Final Calibration

Tracks found through the process described above were fit to straight lines. Concurrent with fitting, a final calibration was applied to drift times. This section is divided up into three parts: Section 3.331 discusses the choice of track parameterization - straight lines, Section 3.332 discusses the drift time corrections that are applied to the data as a final calibration, and Section

3.333 discusses the track fitting procedure.

3.331 Track Parameterization

Before any track fitting could be done the proper mathematical parameterization for a track projection into the drift plane of the Microvertex Detector had to be chosen. A charged particle traveling through a magnetic field experiences a force perpendicular to its velocity vector and to the direction of the magnetic field. The trajectory of the particle in a vacuum is thus a helix. Choosing a coordinate system such that the magnetic field is parallel to the Z axis allows the parametric equations for a helix to be written:

$$x = x_0 + R[\cos(\phi) - \cos(\phi_0)];$$

$$y = y_0 + R[\sin(\phi) - \sin(\phi_0)];$$

$$z = z_0 + \sin(\lambda)s;$$

where:

$$\phi = \phi_0 + \cos(\lambda)s/R;$$

$$\lambda = \sin^{-1}(P_Z/P);$$

$$R = \cos(\lambda)P/0.3qB;$$

$(x,y,z)_0$ is a point on the helix, ϕ_0 is the azimuthal angle of the point with respect to the axis of the helix at $(x,y,z)_0$, λ is the pitch (or dip) angle of the helix, R is the radius of the helix, P is the momentum of the particle in units of GeV/c, q is the charge of the particle in units of eV, B is the magnitude of the magnetic field in

units of T , and s is the length along the helix from $(x,y,z)_0$ to (x,y,z) .

Since the projection of the helix into the transverse plane (YZ) is of principle interest for the Microvertex Detector, one can solve for ϕ in terms of z and substitute the result into the expression for y above to get:

$$y = y_0 + R[\sin((z-z_0)/R\tan(\lambda) + \phi_0) - \sin(\phi_0)].$$

Using the trigonometric identity:

$$\sin(a+b) = \sin(a)\cos(b) + \cos(a)\sin(b)$$

and defining:

$$\zeta = (z-z_0)/R\tan(\lambda),$$

the above expression for y then becomes:

$$y = y_0 + R[\sin(\phi_0)(\cos(\zeta)-1) + \sin(\zeta)\cos(\phi_0)].$$

Expanding $\sin(\zeta)$ and $\cos(\zeta)$ in a Taylor series gives:

$$y = y_0 + R[\sin(\phi_0)\{-\zeta^2/2! + \zeta^4/4! + \dots\} + \cos(\phi_0)\{\zeta - \zeta^3/3! + \dots\}].$$

If terms of order ζ^2 are dropped the resulting equation is simply that of a straight line:

$$y = y_0 + R\cos(\phi_0)\zeta = y_0 + (z-z_0)\cos(\phi_0)/\tan(\lambda).$$

The error in this approximation can be estimated from the lowest order term dropped:

$$|\Delta y| = R\sin(\phi_0)\zeta^2/2! = \sin(\phi_0)(z-z_0)^2/2R\tan^2(\lambda);$$

where $|\Delta y|$ can be identified as the extrapolation error (i.e. the error in extrapolating a track a distance $(z-z_0)$). If an extrapolation error of $|\Delta y|_{\max}$ is tolerable then the maximum extrapolation length, $(z-z_0)_{\max}$, is given by:

$$(z-z_0)_{\max} = \sqrt{(2|\Delta y|_{\max} R \tan^2(\lambda) / \sin(\phi_0))}.$$

If one then takes $|\Delta y|_{\max} = 100 \mu\text{m}$, $B = 0.035 \text{ T}$, $\sin(\phi_0) = 0.5$, using Monte Carlo data described in the next chapter, one finds that over 96% of the tracks that will pass through the Microvertex Detector have maximum acceptable extrapolation length of greater than what is necessary to extrapolate the track back to the primary vertex. Clearly under these circumstances a straight line track model is quite adequate.

3.332 Drift Time Corrections

Five corrections, apart from t_0 subtraction are applied to drift times (t_i) in order to optimize resolution by correcting for systematic detector effects. These systematic effects are due to: 1) sense wire displacement, 2) the slope of the track with respect to the sense-field plane, 3) discriminator time slewing, 4) time of flight and 5) time of propagation.

- 1) The largest drift time correction is due to displacements of the sense wire in the electric field. The necessary correction is calculated by approximating the shape of the displaced wire by a parabola. (The shape of a displaced wire is actually hyperbolic, however, the difference between catenary and parabola is negligible when compared to the accuracy required here.) The correction is given by:

$$\Delta t_i = (d_{\max}/v_d)[1 - (2x_i/L)^2];$$

where $d_{\max}$ is the maximum sagitta of the wire, v_d is the drift velocity of the gas, x_i is the longitudinal coordinate of the the hit, and L is the length of the wire. The values of $d_{\max}$ and v_d have been determined from calibration and are given in Table 3.3. The maximum drift time correction due to wire displacement is given by:

$$(\Delta t_i)_{\max} = d_{\max}/v_d = 5.64 \text{ ns.}$$

- 2) Each sense wire in the Microvertex Detector collects electrons, liberated by the passage of a charged particles, in a specific region of the detector. In the transverse plane (YZ) this region is trapezoidal with a width ($w = 3.16 \text{ mm}$) that is twice the wire spacing. Under normal conditions the first few electrons that arrive at the sense wire will induce sufficient voltage on the wire to cause the discriminator to fire. These electrons will come from different parts of the collection region depending on the angle (γ) of the track with respect to the sense wire plane (Figure 2.5). Since the drift distance is defined with respect to the center of the collection region a correction of the form:

$$\Delta t_i = [1/\cos(\gamma) - 1]t;$$

where

$$\begin{aligned} t &= t_i; \text{ for } t_i > w/v_d, \\ &= w/v_d; \text{ for } t_i \leq w/v_d. \end{aligned}$$

is applied to the drift time. If γ was greater than 30° no correction of this type was attempted (this happened in only very rare cases none of which had any hope of surviving the track fitting procedure which will be described later). The largest correction that could be applied is given by:

$$(\Delta t)_{\max} = [1/\cos(\gamma_{\max}) - 1] t_{\max} = 50.3 \text{ ns};$$

where $t_{\max}$ has been taken as 325 ns.

- 3) Pulses induced on the sense wire can assume various shapes, each of which will fire the discriminator at slightly different times. This effect is known as time slewing and is due to the discriminator needing only a voltage above a predefined threshold to fire. Compensation for time slewing is made by applying a correction of the form:

$$\Delta t_i = a + bP_i;$$

where P_i is the pulse width, a and b are constants. The values of a and b have been determined through calibration and are given in Table 3.3. Time slewing correction ranged from 0.26 ns for the shortest pulses (4 ns) to -5.5 ns for the longest pulses (100 ns). The mean pulse length was 20 ns which produced a correction of -0.7 ns.

- 4,5) Particles originating at the interaction vertex traveling perpendicular to the wires will arrive in the collection region of the sense wire sooner than those which traveled along the

wire, and pulses induced at the center of the wire will be propagated along a greater length of wire than those which arrive at the ends. To compensate for the time of flight (t_f) of the particle and the time of propagation (t_p) of the pulse, a correction of the form:

$$\Delta t_i = t_f + t_p - t_c$$

is used; where t_c is a constant. The time of flight is approximated by:

$$t_f = |r_i - r_v|/c;$$

where r_i and r_v were respectively the coordinates of the hit and the interaction vertex, and c is the speed of light. The time of propagation is approximated by:

$$t_p = (L/2 - |x_i|)/v_p;$$

where v_p was the velocity of propagation of a pulse along the wire estimated at 70% of the speed of light. The constant term is approximated by:

$$t_c = \sqrt{(L^2/4 + r_w^2)}/c;$$

where r_w is the radial distance of the wire from the axis of the Microvertex Detector. The time of flight and propagation correction was the smallest of the corrections. The maximum correction was less than 1 ns, thus errors introduced by assuming a particle velocity of c are effectively negligible.

Three of the above corrections (1,4,5) depend on the longitudinal coordinate of the hit (x_i) which is unfortunately

unknown so that these corrections have to be determined in conjunction with track fitting. Calibration constants are summarized in Table 3.3.

3.333 Track Fitting

The track fitting procedure is summarized in Figure 3.1C. The process is composed of two principle steps: final calibration and a final track fit. All track fits are to straight lines of the form:

$$y = mz + b$$

using a linear least squares method that minimizes the sum of squares of residuals to the fit. The residual of the i th data point, $(y, z)_i$, is defined by:

$$r_i = y_i - mz_i - b;$$

where m and b are fit parameters. Fits are performed in a reference frame rotated so that the drift direction of the majority of the hits on the track is parallel to the Y axis.

Final calibration consists of applying the drift time corrections described in the last section to the data. This was difficult because three of the corrections depend on the longitudinal coordinate (x_i) of the hit which is unknown. To get an estimate of these coordinates two assumptions are made: 1) the track passes through the longitudinal coordinate of the primary vertex as determined by the Central Detector and 2) the projection of the track is a straight line in the plane that contains the track

and the beam. These assumptions reduced the problem of estimating N longitudinal coordinates to the more manageable problem of estimating a single angle (θ), the angle of the track with respect to the transverse plane (YZ). During the matching process (Section 3.35) tracks which match to Central Detector tracks are refit using longitudinal coordinates obtained from extrapolation of Central Detector tracks.

Determination of θ was achieved by minimizing the chi square of the track fit with respect to θ . This is possible since the chi square of the track fit is ultimately a function of the drift time corrections which are functions of θ . Minimization of the chi square of the track fit was achieved through a Golden Section Search [3.4].

The final track fit was done in an iterative fashion so that points with exceptionally large residuals could be excluded from the fit. Points with residuals greater than 3 times the nominal setting error were excluded from the final fit. The setting error, 110 μm , was determined iteratively from the width of the residual distribution. If after excluding points with exceptionally large residuals too few points remained for a fit (i.e. < 3) or the resulting chi square per degree of freedom of the fit was greater than 5, the fit was considered a failure and the track discarded.

Figure 3.2D shows fits of points associated to Microvertex Detector tracks. The distribution of percentages of hits that were used per track fit is shown in Figure 3.4A. On average 87.5% of the

hits associated to the track were used in the final track fit. Figure 3.4B shows the distribution of chi square per degree of freedom obtained from track fits. Figure 3.4C shows the distribution of residuals obtained from all tracks and drift distances. The full width at half maximum of this distribution gave a working resolution of 110 μm . This result which is at least a factor of 2 worse than what was obtained in the test beam (for the largest drift distances) can readily be understood because: 1) the chamber was operated at ~50% of nominal gain to reduce ionization current, 2) the discriminator thresholds were a factor of 6.4 higher due to beam noise, 3) most tracks were not perpendicular to the chamber's wires as in the test beam, 4) distortions due to overlapping tracks and ionization current were present, and 5) the resolution of the FASTBUS TDC's were a factor of 8 worse than those used in the test beam.

3.34 Vertex Finding and Fitting

Vertex finding and fitting is combined into a single procedure. The vertex fitting algorithm is summarized in Figure 3.1D. Vertex fitting is done by minimizing, via a least squares method, the sum of squared projected impact parameters of tracks on a point in the transverse (YZ) plane. The square of the projected impact parameter of the i th track is given by:

$$d_i^2 = (b_i - y_v + z_v m_i)^2 / (1 + m_i^2);$$

where m_i and b_i are respectively the track slope and intercept in the transverse plane and $(y,z)_v$ are the coordinates of the vertex, the fit parameters.

Vertex fitting is done in an iterative fashion so that tracks with exceptionally large projected impact parameters, which are likely to be unassociated to the vertex, can be excluded from the fit. If a track has a projected impact parameter of greater than 3 times the nominal setting error, the track is considered to be unassociated with the vertex and excluded from the fit. The setting error, 380 μm , was determined iteratively from the half width of the projected impact parameter distribution. If after excluding tracks with exceptionally large projected impact parameters too few tracks remain for a fit (i.e. < 3) or the resulting chi square per degree of freedom of the fit is greater than 5, the fit is considered a failure and the vertex discarded.

The first vertex found is taken as the primary vertex, invariably this has the most tracks associated with it. Secondary vertices are found by repeating the same technique on unassociated tracks.

Figure 3.2E shows the resulting vertex extrapolations for a typical event. Figure 3.5A-C shows the distributions for the number of tracks per primary vertex, tracks per secondary vertex, and unassociated tracks per event. The respective means of these distributions are 13.2, 4.4, and 4.9. The ratio of secondary to primary vertices was found to be 0.53. Figure 3.6 shows the

distribution of chi square per degree of freedom obtained from vertex fits.

Figure 3.7A-B shows the projected impact parameter of all tracks on the primary vertex and nominal beam position. The nominal beam position was determined from the means of the primary vertex coordinates. Through this method, the beam spot was determined with an accuracy of $250\text{ }\mu\text{m}$ in both the Y and Z directions (the nominal size of the beam spot is $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$). The working projected impact parameter resolution for minimum bias events, $380\text{ }\mu\text{m}$, was calculated from the half width at half maximum of either of the projected impact parameter distributions. This result is dominated by the low transverse momentum tracks that have undergone multiple coulomb scattering as they traversed the inner wall of the detector.

The momentum of tracks is not measurable in the Microvertex Detector; therefore, a direct measurement of the intrinsic projected impact parameter resolution by separating out high large momentum tracks, for which multiple coulomb scattering is negligible, is not possible. However, Monte Carlo studies indicate that one can infer an intrinsic projected impact parameter resolution of $110\text{ }\mu\text{m}$ under collider conditions. This comes out to be the same as the single wire resolution because of the chamber and beam pipe geometry.

3.35 Track Matching

The Microvertex Detector was designed to give accurate trajectory information in the transverse plane. To obtain trajectory information in three dimensions Microvertex Detector tracks are matched to Central Detector tracks.

Figure 3.1E summarizes the matching algorithm that was used. The matching process is factorized into two parts: 1) best matches are found for each Microvertex Detector track and 2) matching ambiguities are isolated and resolved. (A matching ambiguity is when two tracks in one detector match to the same track in the other detector.)

The best matching Central Detector track for a Microvertex Detector track is found by identifying the tracks that represented possible matches and then choosing the best of these. The angle of intersection of the track with the outer radius of the Microvertex Detector (α) and its tangent at the intersection (β) in the transverse plane have been chosen as matching angles (Figure 3.8A). Figure 3.8B-C shows distributions of $\Delta\alpha$ and $\Delta\beta$ for all pairs of Microvertex and Central Detector tracks; where:

$$\Delta\alpha = |\alpha_{MVD} - \alpha_{CD}|$$

and

$$\Delta\beta = |\beta_{MVD} - \beta_{CD}|.$$

If a pair of tracks had a $\Delta\alpha < 6^\circ$ and a $\Delta\beta < 6^\circ$ the pair are considered a possible match.

The best of possible matches is found by refitting Microvertex Detector tracks, as in Section 3.333, with the longitudinal coordinates of Microvertex Detector hits estimated from an extrapolation of the Central Detector track. The Central Detector track which resulted in the fit with the smallest chi square per degree of freedom is taken as the matching track.

In this process it is possible for two Microvertex Detector tracks to match to the same Central Detector track. The resolution of this ambiguity is made on the basis of matching angles. The pair with the smallest value of δ , where $\delta = \sqrt{(\Delta\alpha^2 + \Delta\beta^2)}$, is chosen as the true match.

Figure 3.2F shows the matches found in a typical event. Figure 3.9 shows a distribution of the percentage of Microvertex Detector tracks matched per event. On average 52.3% of the Microvertex Detector tracks in a given event were matched.

References

- [3.1] G. Alner et al., Z. Phys. **32C** (1986) 153.
- [3.2] M. Pimia, "Track Finding in the UA1 Central Detector at the CERN ppbar Collider", Ph.D. Dissertation, University of Helsinki (1985)
- [3.3] J. Rohlf and A. Schwartz, UA1/TN 85-65 (1985).
- [3.4] F. James, "Function Minimization", Proceedings of the 1972 CERN Computing and Data Processing School, Pertisau, Austria (1972).

Table 3.1**Run Conditions for Data Sample**

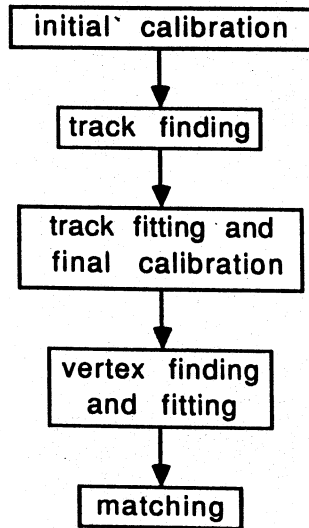
pressure	3 Atm
discriminator threshold	32 mV
MVD high voltage	95%
CD high voltage	100%
magnetic field strength	350 G
trigger	minimum bias

Table 3.2**Track Finding Parameters**

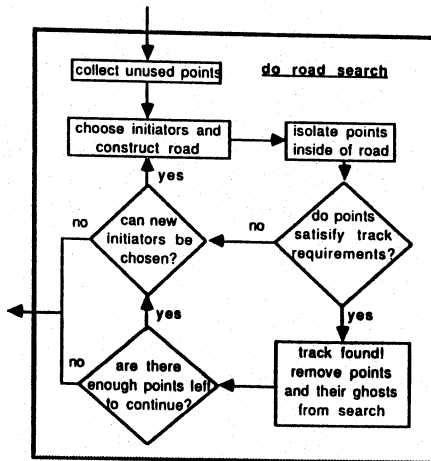
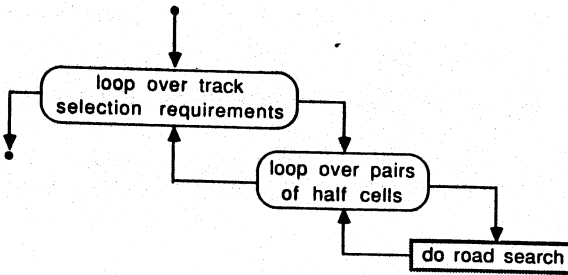
$N_{\min}$:	
first pass	16
last pass	6
decrement/pass	-1
$\epsilon_{\min}$	0.75
w_r	1.25 mm
Δt	6.1 ns

Table 3.3
Calibration Constants

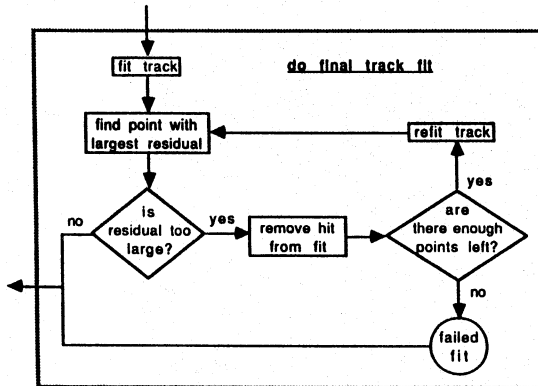
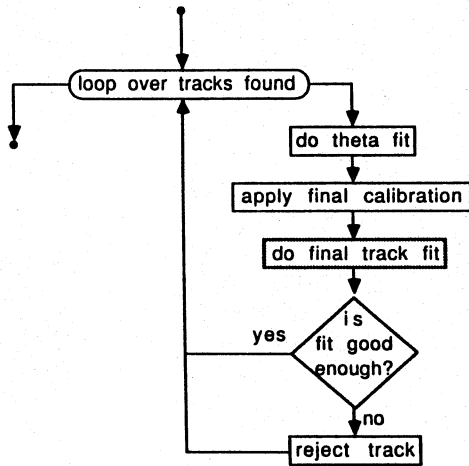
$d_{\max}$	275 μm
v_d	48.75 $\mu\text{m/ns}$
w	1.5 mm
a	0.50
b	-0.06
v_p	0.7c

Figure 3.1**Flow Charts of the Event Reconstruction Process****A) Event Reconstruction**

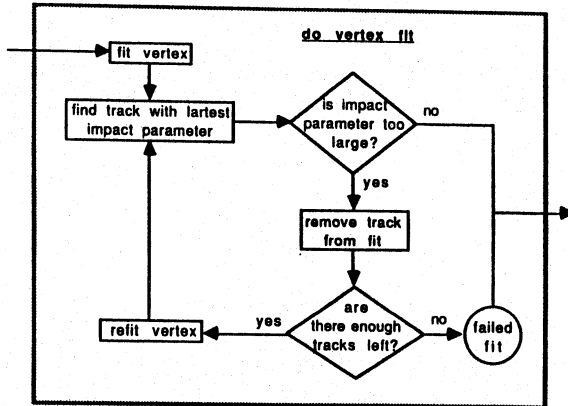
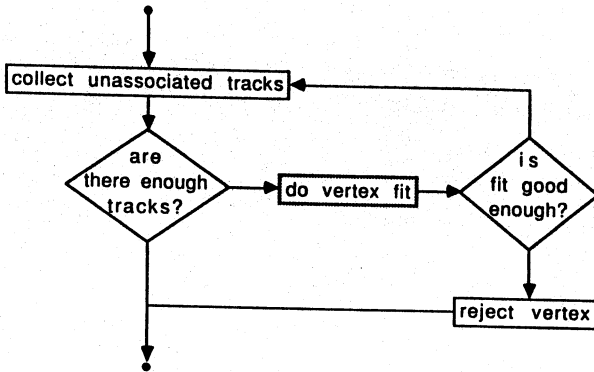
B) Track Finding



C) Track Fitting



D) Vertex Finding and Fitting



E) Matching

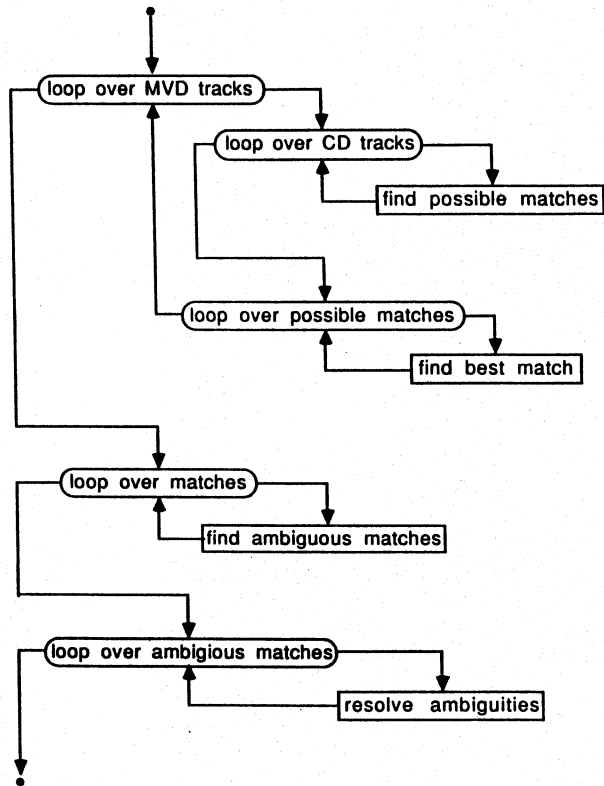
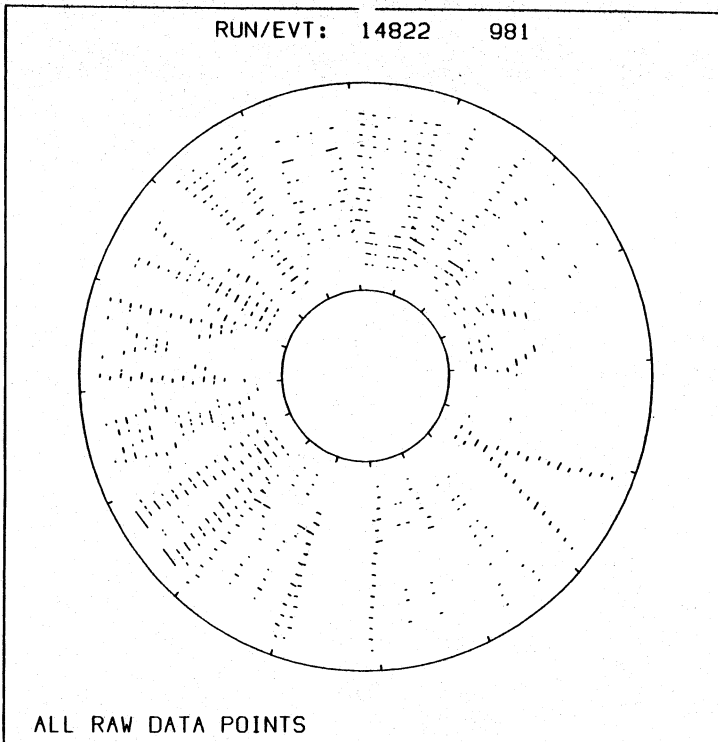
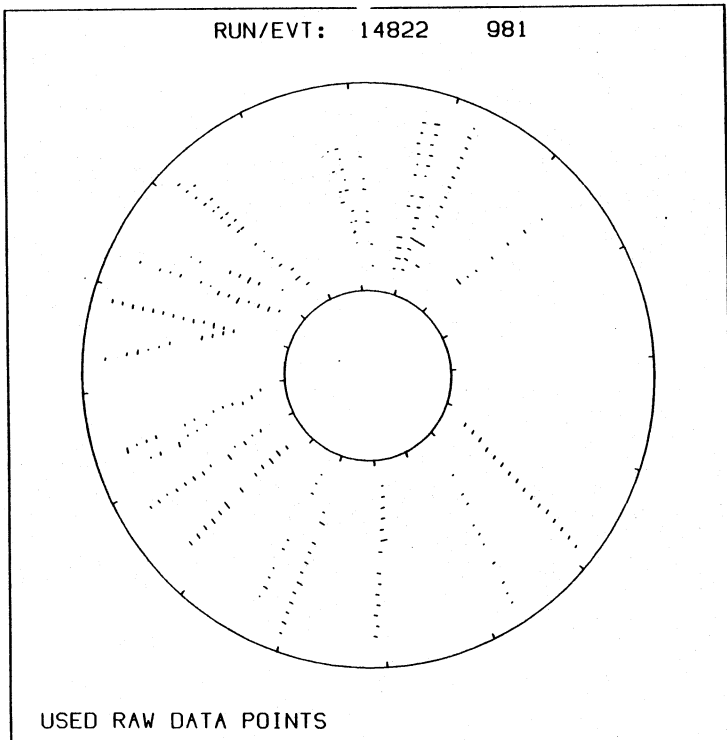


Figure 3.2
Various Stages of Reconstruction for a Typical Event

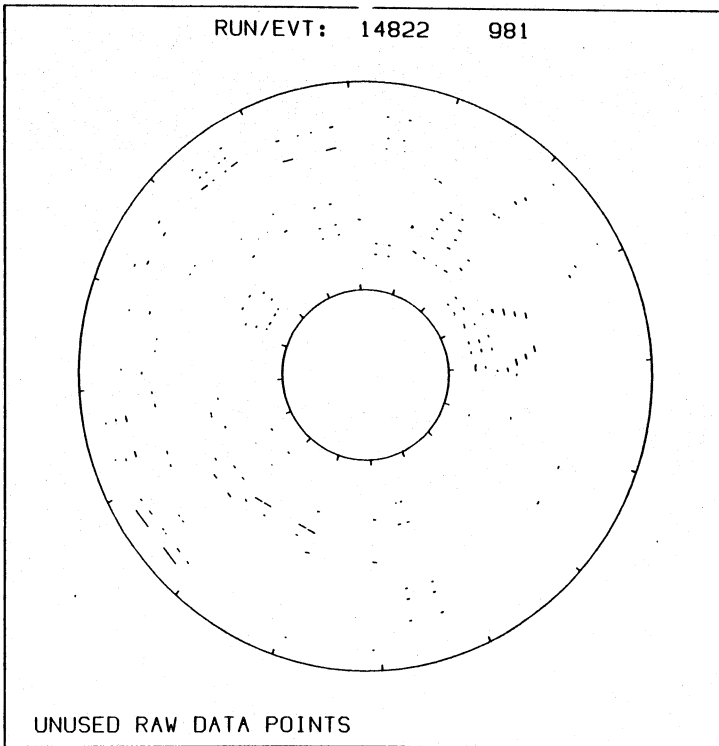
A) Raw Hits and their Ghost Points



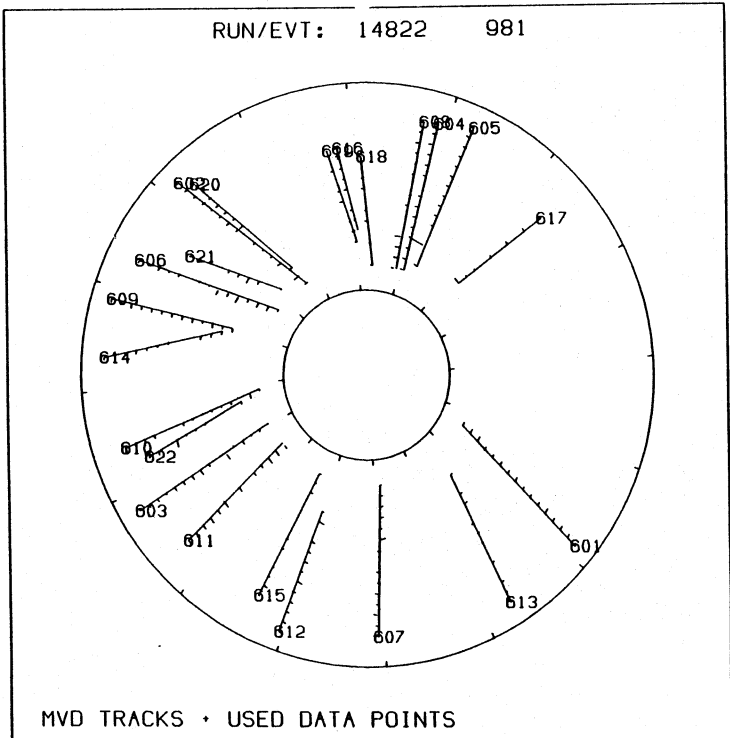
B) Hits that have been Associated to Tracks



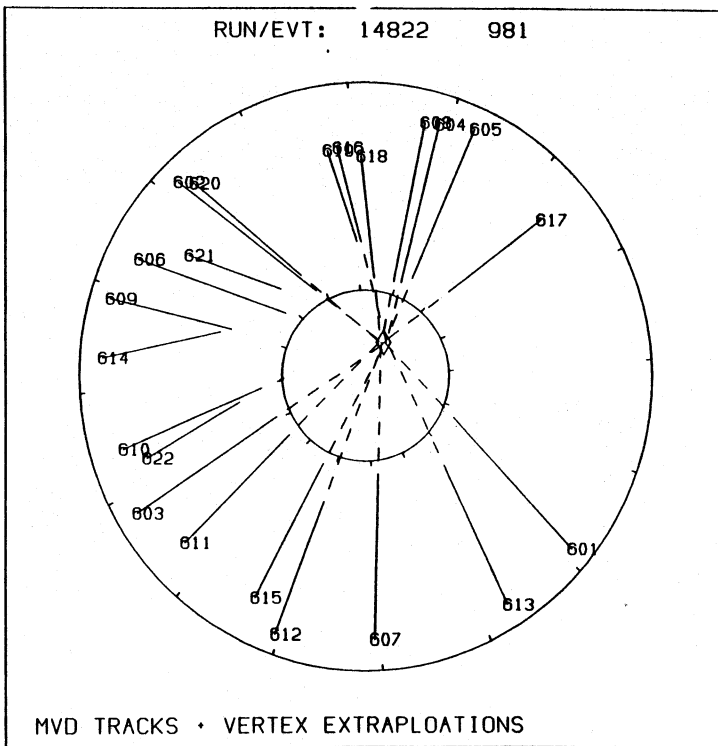
C) Hits that have not been Associated to Tracks and their Ghost
Points



D) Fits to Points Associated with Tracks



E) Extrapolations of Microvertex Detector Tracks



F) Central Detector Matches to Microvertex Detector Tracks Vertex

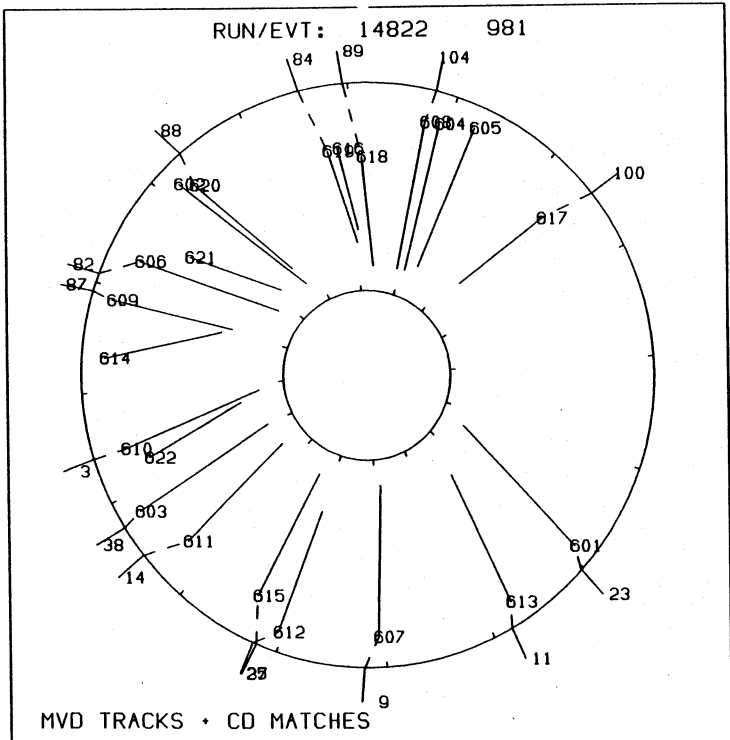
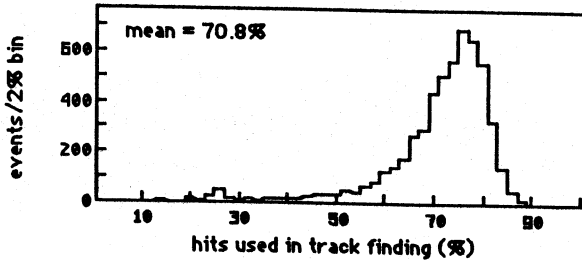
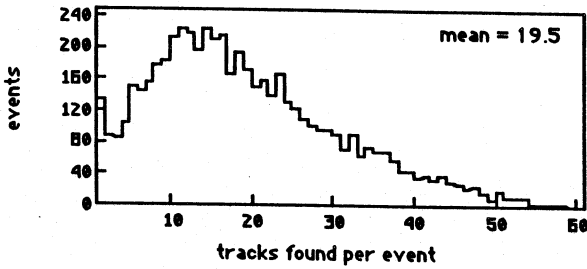


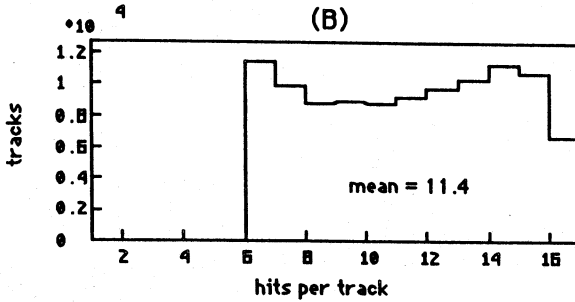
Figure 3.3
Track Finding Results



(A)



(B)



(C)

Figure 3.4
Track Fitting Results

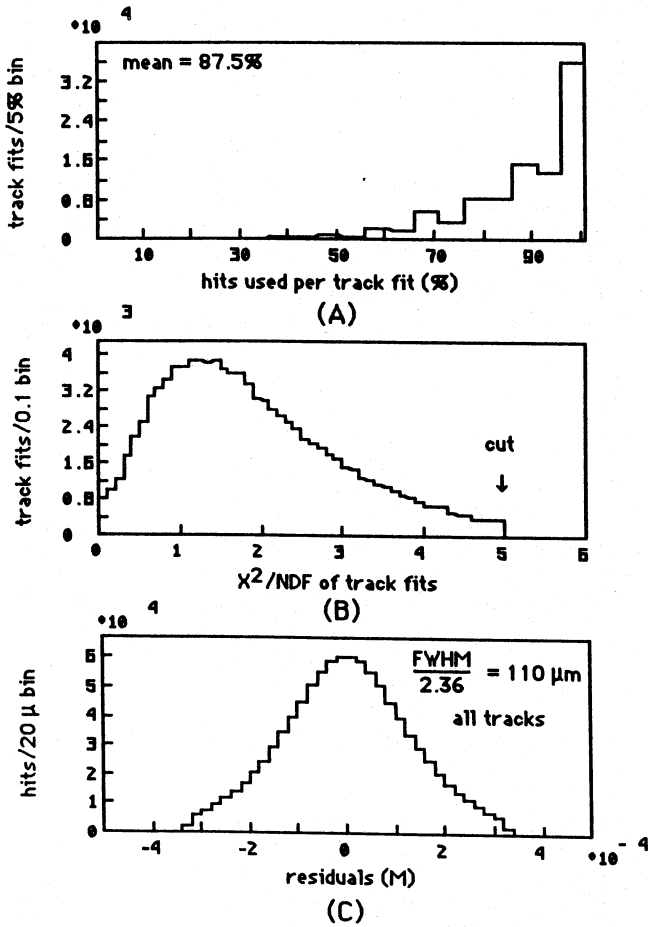
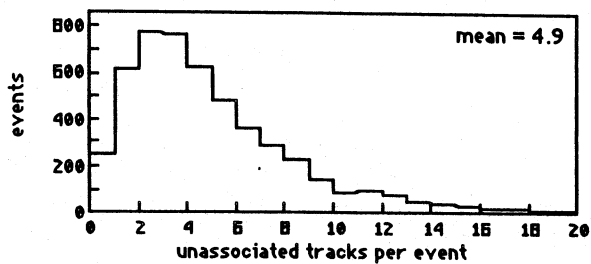
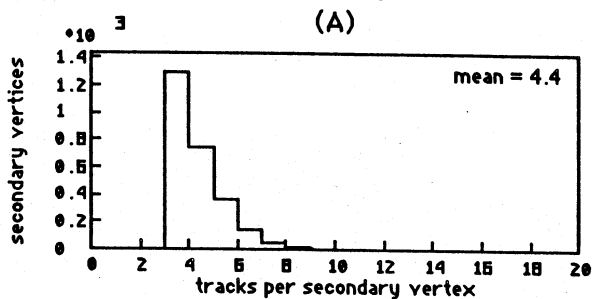
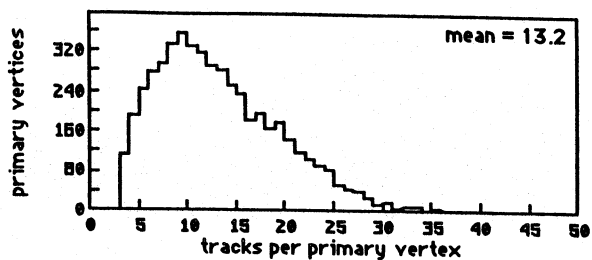


Figure 3.5

**Tracks per Primary Vertex, Tracks per Secondary Vertex,
and Unassociated Tracks per Event**



(C)

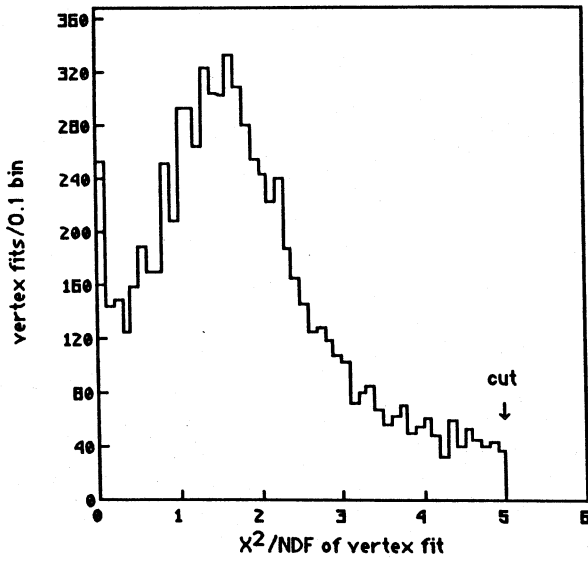
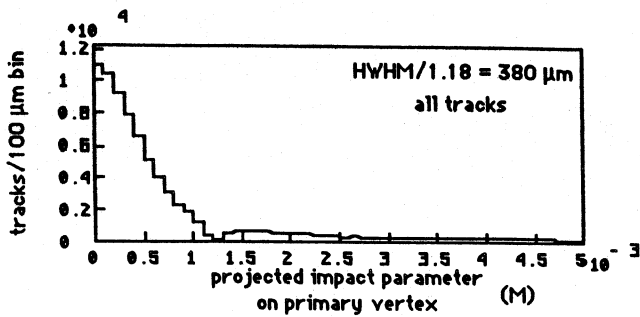
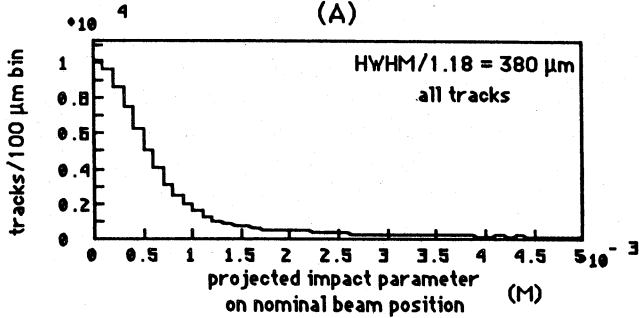
Figure 3.6**Chi Square per Degree of Freedom of Vertex Fits**

Figure 3.7**Projected Impact Parameters of all Tracks**

(A)



(B)

Figure 3.8
Angular Correspondence of Microvertex and Central
Detector Tracks

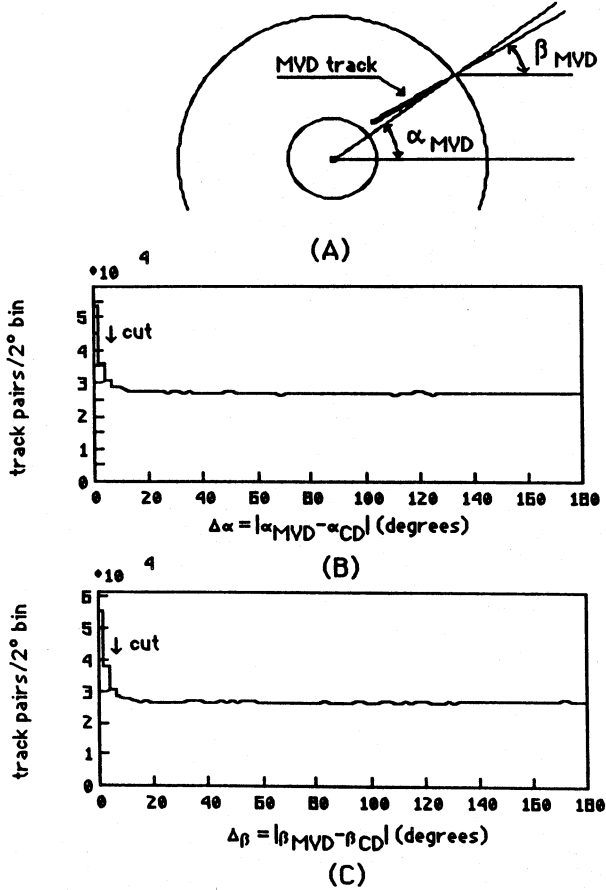
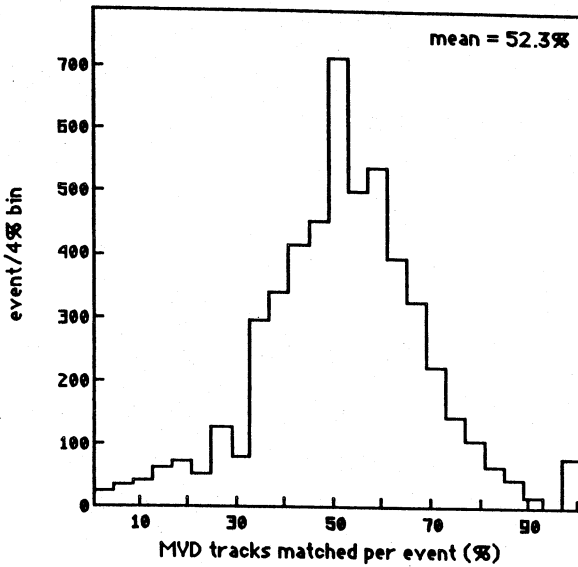


Figure 3.9
Percentage of Tracks Matched per Event



CHAPTER IV

K_S FINDING AND RESULTS

4.1 Introduction

The Microvertex Detector was designed to identify large projected impact parameter tracks and to reconstruct secondary vertices from which they originated. Ultimately the Microvertex Detector was to be used to find decays of heavy quarks, however, with the limited amount of data that was collected this was not possible.

The most copiously produced secondary vertex in $\bar{p}p$ collisions comes from the decays of V_0 particles. (A V_0 particle is a neutral particle, such as a γ , K_S , Λ , or $\bar{\Lambda}$, which decays or is converted into a pair of charged tracks.) Using data collected in the Fall of 1985 a search for V_0 decays has been performed. The end result of this search is a measurement of the inclusive K_S production cross-section in $\bar{p}p$ collision with a center of mass energy of 630 GeV. Measurements of the mean K_S multiplicity as well as K_S transverse momentum and rapidity distributions are also presented. An upper limit to the inclusive lambda production cross-section and mean lambda multiplicity has also been obtained.

4.2 K_S Finding

The mean lifetime (τ) of the K_S is 89.23 ± 0.22 ps and its principle decay mode, which has a branching fraction of 0.6861 ± 0.0024 [4.1], is given by:

$$K_S \rightarrow \pi^+ \pi^-.$$

The mean transverse decay path ($\langle d_t \rangle$), the projection of the decay path into the transverse plane, of the K_S is given by:

$$\langle d_t \rangle = (P_t/M_K) c \tau;$$

where P_t is the transverse momentum and M_K is the mass of the K_S . For P_t in units of GeV/c this becomes:

$$\langle d_t \rangle = P_t \cdot 5.37 \text{ cm};$$

thus virtually all K_S in the data with a $P_t < 1$ GeV and $|\eta| < 2$ will have decayed before exiting the Microvertex Detector.

4.21 K_S Selection

Since two track vertices cannot be found through the vertex finding algorithm described in Section 3.33, a special selection process was developed to find K_S decays. This procedure is summarized below and in Figure 4.1.

All pairs of Microvertex Detector tracks were surveyed to determine if they (and/or their Central Detector counterparts) satisfied the following requirements:

- 1) The projected impact parameter of both tracks on all vertices in the event had to be greater than 1.14 mm. This was three times the working projected impact parameter resolution (σ_{pip}). (See Section 3.34 for a description of how σ_{pip} was estimated.)
- 2) Both Microvertex Detector tracks were required to match Central Detector tracks so that full spatial information regarding the two tracks was available.
- 3) The vee formed by the two unassociated Microvertex Detector tracks was required to be causal with the primary vertex in the transverse plane (Figure 4.2). (This was insured by requiring that the crossing point of the two tracks resided in the triangular region of the transverse plane defined by the primary vertex and the start points of the two tracks. The crossing point of the tracks in this plane (Y_0, Z_0) was then taken as the transverse coordinates of the decay vertex.)
- 4) The Central Detector tracks were required to have opposite charge. (If the tracks had the same sign they were processed in a parallel "same sign" stream so that later the background due to misassociated tracks in the final K_S sample could be estimated.)

- 5) The longitudinal coordinate (X_0) of the decay vertex was required to reside inside of the Microvertex Detector. (Determination of the longitudinal coordinate of the decay vertex was made by refitting the Central Detector tracks without any vertex constraint and then finding their crossing point in the bending plane (XY). The X_0 distributions obtained are presented in Figure 4.3A.)
- 6) The Central Detector tracks were required to meet in space. (This was done by calculating the difference in the Z coordinates (ΔZ) of the tracks at their crossing point in the bending plane. Tracks were assumed to meet in space if ΔZ was less than ΔZ_{max} ($= 30$ cm). The ΔZ distributions obtained are presented in Figure 4.3B.)
- 7) The invariant mass of the two tracks was required to be similar to the K_S mass. (This was done by assigning pion masses to both Central Detector tracks and then calculating their invariant mass. The difference between the K_S mass ($M_K = 497.7 \text{ MeV}/c^2$ [4.1]) and the invariant mass (ΔM) was required to be less than ΔM_{max} ($= 300 \text{ MeV}$). Figure 4.3C shows the invariant mass distributions that were obtained.)
- 8) The vee was required to be causal with the primary vertex in the plane of the vee. (This was enforced by refitting the

Central Detector tracks using the hypothetical decay point as a constraint. The plane of the vee was calculated from the decay vertex and the track tangents at the decay vertex. Causality was insured by requiring that the vee straddle the line connecting the primary vertex and decay vertex and that the primary vertex be on the vee's convex side. Because of finite detector resolution the primary vertex does not always reside in the plane of the vee so in those cases the nearest point in the plane was used.)

- 9) The vee was required to be unique. (A check was made to insure that no two vees shared the same track. If such an ambiguity was found the candidate with the invariant mass closest to the K_S mass was chosen. Of the candidates that survived requirement (8) about 12% had ambiguities which were subsequently resolved in this fashion.)

If a pair of tracks satisfied all of the above requirements it was considered a K_S decay candidate. Table 4.1 summarizes some of the cuts that were used in the K_S selection procedure.

4.22 Selection Results

The K_S selection process was applied to the full data sample described in Section 3.1. The process was carried out in two steps:

first, a loose selection was performed to reduce the volume of data to a workable level and then the tight selection described above. The loose selection differed from the tight selection in that only the criteria 1-3 and 8 were imposed.

The loose selection reduced the number of events that needed to be processed by slightly more than a factor of 20. The resulting tight selection contained 108 K_S decay candidates. A typical K_S decay candidate is presented in Figure 4.4. A break down of the data reduction for the tight selection is presented in Table 4.2.

The parallel selection of the same sign data (see requirement 4 in Section 4.21) indicates that the background due to misassociated tracks can be estimated at 66 of the 108 K_S decay candidates. To estimate the level of background due to lambdas ($\bar{\Lambda}+\Lambda$), γ 's, and K_l 's in the sample a Monte Carlo study was needed.

4.3 Monte Carlo Studies

In order to estimate the efficiency of the selection procedure for finding K_S decays and to estimate the number of lambdas, γ 's, and K_l 's contaminating the K_S sample, a Monte Carlo study was performed.

Antiproton-proton collisions at a center of mass energy of 630 GeV/c were generated using the ISAJET 5.2 [4.2] Monte Carlo program. A total of 15,000 events, roughly three times the number of events in the real data sample, were generated. The ISAJET

Monte Carlo generates minimum bias events using an algorithm that is based on a proposal of Abramovskii, Kanchelli, and Gribov (AKG) [4.3]. The algorithm used in generating minimum bias events in the ISAJET Monte Carlo is perhaps best summarized by its authors:

"A simplified version of the AKG scheme modified to take account of leading particles has been implemented in ISAJET. A number of cut Pomerons is selected. For the left and right sides of the event an x_0 for the leading baryon and an x_i for each Pomeron are generated uniformly between 0 and 1, and the sum $x_1 + \dots + x_K$ is rescaled to $1 - x_0$. Then each cut Pomeron is hadronized in its own center of mass using a modified independent fragmentation model. The probabilities for the different flavors are taken to be $u : d : s = .46 : .46 : .08$ to reproduce the observed fraction of K mesons. To incorporate the observed increase in dn/dy the splitting function is made energy dependent:

$$f(x) = 1 - a + a(b(s) + 1)(1 - x)^{b(s)},$$

$$b(s) = b_0 + b_1 \ln(s).$$

The probabilities P_K for K cut Pomerons are taken to be independent of energy and are adjusted to fit the experimental data." [4.2]

The events generated by ISAJET were then processed through a simulation of the Microvertex and Central Detectors which created raw detector digitizations. These digitizations were then reconstructed in the same fashion as real data and the K_S selection procedure described in Section 4.21 was performed. (This selection will be referred to as the "Monte Carlo K_S selection" or "Monte Carlo selection" for short.)

4.31 Background Estimates

As discussed in Section 4.21 real data can be used to determining the level of background in the K_S sample due to misassociated tracks, however, real data cannot be used to determine the level of background due to lambdas, γ 's, and K_L 's, for this one must rely on the Monte Carlo. The results of the Monte Carlo study indicate that after subtracting off background due to misassociated tracks, one is left with a sample of 226 K_S decay candidates. These breakdown into 173 K_S , 26 Λ , 25 $\bar{\Lambda}$, 1 γ , and 1 K_L decays. Compared to lambdas, γ 's and K_L 's represent a negligible source of background and will henceforth be ignored. The data reduction for the Monte Carlo tight selection is summarized in Table 4.3.

The expected number of K_S in the selection after background subtraction (N_K) can be estimated using the following relation:

$$N_K = (N_C - N_b) F_K;$$

where N_C (= 108) is the number of K_S decay candidates in the selection, N_b (= 66) is the estimated background from misassociated tracks, and F_K is the fraction of the remainder which are K_S decays. (It is assumed that the fraction of lambda remaining is $1 - F_K$.)

The K_S sample is assumed to be composed of the sum of three components: misassociated tracks, K_S , and lambdas. The contribution due to misassociated tracks is easily determined

using the data from the same sign selection. To determine F_K , the fraction of the remainder which are K_S , the following technique has been used:

- 1) Invariant proton-pion mass distributions, where the particle with the largest momentum is taken as the proton, of the following data sets were made: i) all K_S decays candidates, ii) all same sign track pairs that survived the parallel selection, iii) all K_S that survived the Monte Carlo selection, and, iv) all lambdas that survived the Monte Carlo selection. The above four distributions will be referred to as: $M(p,\pi)_C$, $M(p,\pi)_D$, $M(p,\pi)_{K^{mc}}$, and, $M(p,\pi)_{\bar{\Lambda}+\Lambda}^{mc}$ respectively. Figure 4.5A shows $M(p,\pi)_C$ and $M(p,\pi)_D$ while Figures 4.5B and 4.5C show respectively $M(p,\pi)_{K^{mc}}$ and $M(p,\pi)_{\bar{\Lambda}+\Lambda}^{mc}$. ($M(p,\pi)_{K^{mc}}$ and $M(p,\pi)_{\bar{\Lambda}+\Lambda}^{mc}$ have been renormalized - see (3) below.)
- 2) The difference between distributions $M(p,\pi)_C$ and $M(p,\pi)_D$ was taken. The resulting distribution shall be referred to as $M(p,\pi)_{K+\bar{\Lambda}+\Lambda}$ and it is shown in Figure 4.5D. This effectively gives the proton-pion mass distribution of K_S and lambdas in the real data selection.
- 3) Distributions $M(p,\pi)_{K^{mc}}$ and $M(p,\pi)_{\bar{\Lambda}+\Lambda}^{mc}$ were renormalized so that they had the same area as $M(p,\pi)_{K+\bar{\Lambda}+\Lambda}$.

- 4) The value of F_K was determined by fitting the $M(p,\pi)_{K^+ \bar{\Lambda}+\Lambda}$ distribution to the sum of the $M(p,\pi)_K^{mc}$ and $M(p,\pi)_{\bar{\Lambda}+\Lambda}^{mc}$ distributions using the following relation:

$$M(p,\pi)_{K^+ \bar{\Lambda}+\Lambda} = F_K \cdot M(p,\pi)_K^{mc} + (1-F_K) \cdot M(p,\pi)_{\bar{\Lambda}+\Lambda}^{mc}.$$

The results of the fit gave:

$$F_K = 0.85 \pm 0.15,$$

with a chi squared per degree of freedom of 24/6. This result is consistent with expectations since one expects a higher production rate of K_S and selection requirements are likely to reject lambdas at a higher rate (especially requirements (1), (7), and (9) described in Section 4.21). The invariant proton-pion mass distribution was used to estimate F_K in lieu of the invariant pion-pion mass distribution because it permitted a greater differentiation between lambdas and K_S 's.

A consistency check on the value of F_K can be made using the relationship:

$$F_K = N_K^{mc} / (N_K^{mc} + N_{\bar{\Lambda}+\Lambda}^{mc});$$

where N_K^{mc} (=173) is the number of K_S decays and $N_{\bar{\Lambda}+\Lambda}^{mc}$ (=51) is the number of lambda decays found in the Monte Carlo selection. Using values of N_K^{mc} , and $N_{\bar{\Lambda}+\Lambda}^{mc}$ presented above gives:

$$F_K = 0.77 \pm 0.08$$

which is consistent with the value for F_K quoted above. (The latter value of F_K depends on the K_S and lambda production cross-sections assumed by the Monte Carlo thus it is used only as a

consistency check.)

Now that N_C , N_B , and F_K have been determined, the number of K_S decays remaining in the selection after background subtraction can be calculated. The results of the calculation give:

$$N_K = 36 \pm 12.$$

The corresponding number of lambda decays remaining in the selection after background subtraction can be calculated from the relation:

$$N_{\bar{\Lambda}+\Lambda} = (N_C - N_B) \cdot (1 - F_K)$$

yielding:

$$N_{\bar{\Lambda}+\Lambda} = 6.3 \pm 5.4$$

or

$$N_{\bar{\Lambda}+\Lambda} < 17$$

at a confidence level of 95%.

4.32 Efficiency Estimates

Monte Carlo data was needed to estimate what fraction of the K_S decays could be found through the selection process described in Section 4.21. By comparing the number of K_S decays that were generated in the Monte Carlo production and the number of K_S decays that were actually found via the K_S selection process an estimate of the efficiency for K_S detection could be made.

The overall efficiency of K_S finding (ϵ_K) can be expressed as:

$$\epsilon_K = R^2(N_K^{mc}/\beta G_K^{mc});$$

where N_K^{mc} (= 173) is as above the number of K_S decays found in the Monte Carlo selection, G_K^{mc} (= 10,354) is the number of $K_S \rightarrow \pi^+ \pi^-$ decays generated in the Monte Carlo production, β and R are correction factors.

The correction factor, R , is needed because the rate of matching of Microvertex Detector tracks to Central Detector tracks in real data differs from that observed in Monte Carlo data. (R is squared because two tracks must be matched for every K_S decay.) The correction factor can be estimated from:

$$R = P_m / P_m^{mc};$$

where P_m is the matching probability observed in real data and P_m^{mc} is the matching probability observed in Monte Carlo data. The matching probability is the ratio of tracks matched to total tracks and it has been calculated using two different sets of tracks: 1) all Microvertex Detector tracks, and 2) Central Detector tracks that are sure to have passed through the Microvertex Detector. (To insure that a Central Detector track passed through the Microvertex Detector the track was required to be associated to the event's primary vertex and have $|\eta| < 2$.) Combining the results for these calculation leads to:

$$R = 0.623 \pm 0.016 \pm 0.069.$$

The correction factor, β , is needed to compensate for the K_S rapidity distribution assumed by the ISAJET Monte Carlo. To estimate β , ISAJET predictions for the pseudorapidity distribution of charged particles at $\sqrt{s} = 540$ GeV was compared to UA1 data

[4.4]. The results of the comparison indicate that ISAJET overestimates the tails ($|\eta| > 2$) of the pseudorapidity distribution by slightly more than 20%. Assuming that ISAJET likewise overestimates the tail of the K_S rapidity distribution, β has been taken as:

$$\beta = 0.955 \pm 0.021 \pm 0.085$$

Calculating the overall efficiency for K_S finding using the above results gives:

$$\epsilon_K = (0.68 \pm 0.06 \pm 0.12) \cdot 10^{-2}.$$

A corresponding calculation can be carried out for the overall lambda finding efficiency yielding:

$$\epsilon_{\bar{\Lambda}+\Lambda} = (0.368 \pm 0.054 \pm 0.066) \cdot 10^{-2}.$$

4.4 Results

From the results of the K_S selection, same sign selection, and the Monte Carlo studies, estimates of the inclusive K_S and lambda production cross-sections can be obtained. Mean K_S and lambda multiplicities as well as K_S distributions with respect to lifetime, transverse momentum, and rapidity will be presented. Combining mean K_S and lambda multiplicity results enables an estimate of the lambda to K_S ratio to be made.

4.41 Inclusive K_S Production Cross-Section and Mean K_S Multiplicity

The non-single diffractive $\bar{p}p$ cross-section (σ_{nsd}) can be estimated from:

$$\sigma_{nsd} = N_{evts}/\epsilon_t L;$$

where N_{evts} is the number of event in the data set, and ϵ_t is the trigger efficiency (values of N_{evts} and ϵ_t can be found in Section 3.2). Assuming a systematic error of ± 0.05 for the trigger efficiency gives:

$$\sigma_{nsd} = 41.1 \pm 0.6 \pm 6.5 \text{ mb.}$$

The inclusive K_S production cross-section in non-single diffractive $\bar{p}p$ collisions is given by:

$$\begin{aligned} \sigma_{nsd}(\bar{p}p \rightarrow K_S x) &= (N_K/\epsilon_K L)/BR(K_S \rightarrow \pi^+ \pi^-) \\ &= 55. \pm 19. \pm 13. \text{ mb;} \end{aligned}$$

where N_K is the number of K_S decay candidates remaining in selection after background subtraction, ϵ_K is the overall K_S finding efficiency, L is the integrated luminosity of the data sample and $BR(K_S \rightarrow \pi^+ \pi^-)$ is the branching ratio for the observed decay mode. (The values of N_K , ϵ_K , L , and $BR(K_S \rightarrow \pi^+ \pi^-)$ have been presented in Sections 4.31, 4.32, 3.2, and 4.2 respectively.)

The mean K_S multiplicity in non-single diffractive events can be calculated from the relationship:

$$\begin{aligned}
\langle n(K_S) \rangle_{\text{nsd}} &= \sigma_{\text{nsd}}(\bar{p}p \rightarrow K_S x) / \sigma_{\text{nsd}} \\
&= [(N_K / e_K) / \text{BR}(K_S \rightarrow \pi^+ \pi^-)] / [N_{\text{ev}} / \epsilon_t] \\
&= 1.34 \pm 0.46 \pm 0.25.
\end{aligned}$$

To determine the inclusive inelastic K_S production cross-section, an estimate of the ratio $\sigma_{\text{nsd}}(\bar{p}p \rightarrow K_S x) / \sigma(\bar{p}p \rightarrow K_S x)$ is needed. This ratio can be estimated from UA5 results [4.5] to be 0.98 ± 0.14 at $\sqrt{s} = 540$ GeV. Assuming that this ratio changes little from 540 GeV to 630 GeV the inclusive inelastic K_S production cross-section is:

$$\sigma(\bar{p}p \rightarrow K_S x) = 56. \pm 21. \pm 13. \text{ mb.}$$

The mean K_S multiplicity for inelastic collisions can be estimated by recalling that the non-single diffractive cross-section comprises 85-90% of the inelastic cross-section (Section 3.2), thus:

$$\sigma_{\text{inel}} = 46.9 \pm 2.6 \pm 7.2 \text{ mb.}$$

and

$$\begin{aligned}
\langle n(K_S) \rangle &= \sigma(\bar{p}p \rightarrow K_S x) / \sigma_{\text{inel}} \\
&= 1.20 \pm 0.44 \pm 0.23.
\end{aligned}$$

4.42 Differential K_S Production Cross-Sections

In order to calculate differential cross-section for K_S production with respect to lifetime, transverse momentum, and rapidity, the momenta (P_K) of the K_S 's must be known. If this can be measured then it is possible to calculate their proper lifetimes

(t), transverse momenta (P_t), and rapidities (y).

4.421 K_S Momentum Determination

The momentum of a candidate K_S can be determined using the measured directions in space of the daughter pions, the K_S line of flight, and conservation of energy and momentum. In principle the K_S momentum can be determined by using the measured pion momenta to perform a 3C fit. However, Monte Carlo studies have shown that a better estimate of the K_S momentum can be obtained by ignoring the measured pion momenta and using a 1C fit; where the momenta of the K_S and the two pion are taken as free parameters. (This is because the pion momenta have been poorly measured due to the low magnetic field.) The fit is done using a single parameter variation algorithm [4.6] to minimize the function:

$$\phi = \Delta P_x^2 + \Delta P_y^2 + \Delta P_z^2 + \Delta E^2;$$

where

$$\Delta P_x = P_K \cos(\lambda_K) \cos(\phi_K) - P_1 \cos(\lambda_1) \cos(\phi_1) - P_2 \cos(\lambda_2) \cos(\phi_2),$$

$$\Delta P_y = P_K \cos(\lambda_K) \sin(\phi_K) - P_1 \cos(\lambda_1) \sin(\phi_1) - P_2 \cos(\lambda_2) \sin(\phi_2),$$

$$\Delta P_z = P_K \sin(\lambda_K) - P_1 \sin(\lambda_1) - P_2 \sin(\lambda_2),$$

and

$$\Delta E = \sqrt{(P_K^2 + M_K^2)} - \sqrt{(P_1^2 + M_\pi^2)} - \sqrt{(P_2^2 + M_\pi^2)}.$$

The angles λ and ϕ are respectively track dip and azimuthal angles, λ_K and ϕ_K are determined from the position of the primary and

decay vertices while $\lambda_{1,2}$ and $\phi_{1,2}$ are determined from individual track fits.

4.422 Uncorrected Distributions

The uncorrected (or raw) lifetime, transverse momentum, and rapidity distributions for the K_S candidates are shown in Figures 4.6A-C. The lifetime has been plotted as a function of the measured lifetime (t) divided by the mean K_S lifetime (τ). The rapidity distribution has been folded about rapidity zero.

4.423 Background and Efficiency

The estimated background due to misassociated tracks and lambdas is shown as a solid line in Figures 4.6A-C. The background was determined by summing the distributions obtained from measured same sign tracks and Monte Carlo lambdas. (The Monte Carlo lambda distributions were renormalized to the expected number of $\bar{\Lambda} + \Lambda$ in the K_S selection.)

The efficiency as a function of the lifetime, transverse momentum, and rapidity, can be estimated from Monte Carlo data. The data points in Figure 4.7A-C show the efficiency as a function of the aforementioned quantities. (Efficiency in each bin has been calculated in roughly the same fashion as in Section 4.32.) The data, to first order, indicates that the efficiency is independent of

the K_S lifetime and transverse momentum (in the observed range) while it is linearly dependent on the rapidity. The linear dependence of the efficiency on the rapidity is expected since the probability of a track escaping unreconstructed increases with the rapidity. The independence of the efficiency with respect to lifetime and transverse momentum can best be understood from the expected efficiency dependence on the transverse decay path:

$$d_t = (P_t/M_K)ct.$$

The efficiency as a function of d_t is expected to be negligible near the vertex and beyond the chamber's mid-radius, in between the efficiency is expected to be finite and constant. One would expect that the efficiency would depend on the lifetime and transverse momentum in a similar fashion. Deviations from flat near the limits of the observed lifetime and transverse momentum efficiency distributions are minimized by the large binning that was used.

Fits to the efficiency distributions are summarized in Table 4.4. In order to compensate for any bias introduced by the assumed efficiency parameterizations, calculations will be carried out both with and without the results of the fits. (When fit results are not used, the efficiency is simply taken as measured.) Discrepancies in the results will be used in determining systematic errors.

4.424 Corrected Distributions

Fully corrected K_S lifetime, transverse, momentum, and rapidity distributions are shown in Figure 4.8A-C. Fits to the distributions are summarized in Table 4.4.

The fully corrected lifetime distribution (Figure 4.8A) provides a consistency check on the data and the correction procedures. If the data is representative of K_S decays the distribution should be exponential in t/τ with a slope of -1. The data in Figure 4.8A indicates that this is indeed the case. (The line drawn in Figure 4.8A represents the expected slope.)

The corrected transverse momentum distribution is shown in Figure 4.8B. The data has been fit using two functional forms: 1) an exponential in P_t , $\exp[-P_t/T]$, and 2) an exponential in M_t , $\exp[-M_t/T]$; where T is a fit parameter and M_t is the transverse mass (or energy) which is given by:

$$M_t = \sqrt{(M_K^2 + P_t^2)}.$$

Both hypotheses give excellent fits to the data.

Hagedorn [4.7] has argued, on statistical grounds, that the inclusive transverse momentum spectra should nearly follow a Boltzman distribution and thus form (2) is expected to give a much better approximation. From the statistical view point, an antiproton-proton collision is visualized as a compression and subsequent expansion of hadronic matter. The parameter T indicates the ambient temperature of the hadron gas or quark-gluon

plasma (if the temperature is great enough) that is formed under compression. (A further discussion of temperature will be presented in Section 5.4.)

The mean K_S transverse momentum can be calculated from the K_S mass and the value of T obtained from fit (2) using the relation:

$$\begin{aligned}\langle P_t \rangle &= \int P_t e^{-M_t/T} dP_t / \int e^{-M_t/T} dP_t \\ &= \sqrt{(\pi M_K T/2)} \cdot [K_2(M_K/T)/K_{3/2}(M_K/T)];\end{aligned}$$

where $K_n(x)$ is a modified Bessel Function of the second kind. Hagedorn has suggested that this approximation underestimates the true value of $\langle P_t \rangle$ by 4-7%. To compensate for this the results of the above calculation have been scaled by 1.055 ± 0.015 yielding:

$$\langle P_t \rangle = 0.473 \pm 0.089 + 0.055_{-0.032} \text{ GeV/c.}$$

The result includes estimates of systematic error due to the choice of binning in P_t and the assumed efficiency parameterization.

If one assumes that the exponential in P_t is the correct form, then the mean transverse momentum can be calculated from the value of T obtained through fit (1) using the relation:

$$\begin{aligned}\langle P_t \rangle &= \int P_t e^{-P_t/T} dP_t / \int e^{-P_t/T} dP_t \\ &= 2T.\end{aligned}$$

The results of this second calculation give a mean transverse momentum of 0.45 ± 0.12 GeV/c which is consistent with the other measurement.

The final rapidity distribution is shown in Figure 4.8C. The distribution is consistent with flat (over the observed region) as

would be expected from phase space arguments. The non-single diffractive central rapidity density is given by:

$$(1/\sigma_{\text{nsd}})d\sigma_K/dy|_{y=0} = 0.202 \pm 0.072 +0.032_{-0.037}$$

From the ratio $\sigma_{\text{nsd}}/\sigma_{\text{inel}}$ the central rapidity density in all inelastic collisions can be calculated yielding:

$$(1/\sigma_{\text{inel}})d\sigma_K/dy|_{y=0} = 0.177 \pm 0.063 +0.028_{-0.033}$$

The results includes estimates of systematic error due to the choice of binning in y and the assumed efficiency parameterization.

4.43 Inclusive Lambda Production Cross-Section and Mean Lambda Multiplicity

The inclusive lambda production cross-section in non-single diffractive $\bar{p}p$ collisions is given by:

$$\sigma(\bar{p}p \rightarrow \Lambda x) + \sigma(\bar{p}p \rightarrow \bar{\Lambda} x) = (N_{\bar{\Lambda}+\Lambda} / \epsilon_{\bar{\Lambda}+\Lambda} L) / \text{BR}(\Lambda \rightarrow p\pi^-)$$

$< 54 \text{ mb};$

where $N_{\bar{\Lambda}+\Lambda}$ is the number of lambda decay candidates remaining in selection after background subtraction, $\epsilon_{\bar{\Lambda}+\Lambda}$ is the overall lambda finding efficiency, L is the integrated luminosity of the data sample and $\text{BR}(\Lambda \rightarrow p\pi^-)$ ($= 0.642 \pm 0.05$ [4.1]) is the branching ratio for the observed decay mode. The upper limit has been calculated at a confidence level of 95%. (The values of $N_{\bar{\Lambda}+\Lambda}$, $\epsilon_{\bar{\Lambda}+\Lambda}$, and L have been presented in Sections 4.31, 4.32, and 3.2 respectively. For clarity, nsd subscripts have been suppressed.) Assuming that $\sigma(\bar{p}p \rightarrow \Lambda x) = \sigma(\bar{p}p \rightarrow \bar{\Lambda} x)$ the result:

$$\sigma(\bar{p}p \rightarrow \Lambda x) = \sigma(\bar{p}p \rightarrow \bar{\Lambda} x) < 27 \text{ mb}$$

is obtained.

The mean lambda multiplicity in non-single diffractive events can be calculated from the relationship:

$$\begin{aligned} \langle n(\bar{\Lambda} + \Lambda) \rangle &= [\sigma(\bar{p}p \rightarrow \Lambda x) + \sigma(\bar{p}p \rightarrow \bar{\Lambda} x)] / \sigma_{\text{nsd}} \\ &= [(N_{\bar{\Lambda} + \Lambda} / \epsilon_{\bar{\Lambda} + \Lambda}) / \text{BR}(\Lambda \rightarrow p\pi^-)] / [N_{\text{evt}} / \epsilon_t]. \end{aligned}$$

The mean lambda multiplicity in non-single diffractive $\bar{p}p$ collisions is given by:

$$\langle n(\bar{\Lambda} + \Lambda) \rangle < 1.3$$

or

$$\langle n(\Lambda) \rangle = \langle n(\bar{\Lambda}) \rangle < 0.64$$

at a confidence level of 95%.

4.44 Lambda to K_S Ratio

From the mean multiplicity measurements summarized in Sections 4.42 and 4.43 an upper limit to the Lambda to K_S ratio for non-single diffractive collisions can be set at:

$$\langle n(\Lambda / \bar{\Lambda}) \rangle / \langle n(K_S) \rangle < 0.49;$$

at a confidence level of 95% (where $\Lambda / \bar{\Lambda}$ denotes either Λ or $\bar{\Lambda}$).

This calculation has been done using the following relationship:

$$\begin{aligned} \langle n(\Lambda / \bar{\Lambda}) \rangle / \langle n(K_S) \rangle &< [(N_{\bar{\Lambda} + \Lambda} / 2) / \{(N_{\bar{\Lambda} + \Lambda}^{\text{mc}} / G_{\bar{\Lambda} + \Lambda}^{\text{mc}}) \text{BR}(\Lambda \rightarrow p\pi^-)\} / \\ &[N_K / \{(N_K^{\text{mc}} / G_K^{\text{mc}}) \text{BR}(K_S \rightarrow \pi^+ \pi^-)\}]] \end{aligned}$$

in order to exclude unnecessary sources of systematic error.

References

- [4.1] M. Aguilar-Benitez et al., Phys. Lett. 170B (1986) 1.
- [4.2] F. Paige and S. Protopopescu, BNL - 37271 (1985).
- [4.3] V. Abramovskii, et al., XVI International Conf. on High Energy Physics (Batavia, IL, 1973), 1 (1973) 389.
- [4.4] G. Arnison et al., Phys. Lett. 118B (1982) 167.
- [4.5] G. Alner et al., Nucl. Phys. 258B (1985) 505.
- [4.6] F. James, "Function Minimization", Proceedings of the 1972 CERN Computing and Data Processing School, Pertisau, Austria (1972).
- [4.7] R. Hagedorn, Riv. Nuovo Cim. 6 no. 10 (1983) 1.

Table 4.1
Cuts Used in K_S Finding

<u>requirement</u> *	<u>cut</u>	<u>value</u>
1	$3\sigma_{pip}$	1.14 mm
6	ΔZ_{max}	30 cm
7	ΔM_{max}	300 MeV

* see Section 4.21.

Table 4.2
Data Reduction for Tight Selection

<u>requirement</u>	<u>K_S Selection</u>	<u>same sign</u>
1) association	14653	-
2) matching	2146	-
3) causality (YZ)	606	-
4) charge	334	272
5) $ x_0 < L/2$	305	252
6) $\Delta Z < \Delta Z_{max}$	252	208
7) $\Delta M < \Delta M_{max}$	149	101
8) causality (V-plane)	115	72
9) uniqueness	108	66

Table 4.3**Data Reduction for Monte Carlo Tight Selection**

<u>requirement</u>	<u>K_s</u>	<u>Δ</u>
1) association	-	-
2) matching	234	68
3) causality (YZ)	234	65
4) charge	219	63
5) $ x_0 < L/2$	218	62
6) $\Delta Z < \Delta Z_{\max}$	218	61
7) $\Delta M < \Delta M_{\max}$	184	52
8) causality (V-plane)	177	51
9) uniqueness	173	51

Table 4.4**Fit Results**

<u>fig</u>	<u>fit results</u>	<u>χ^2/dof</u>
4.7A	$\epsilon_K(v\tau) = (0.709 \pm 0.058) \cdot 10^{-2}$	4.7/3
4.7B	$\epsilon_K(P_T) = (0.622 \pm 0.049) \cdot 10^{-2}$	8.6/3
4.7C	$\epsilon_K(y) = [(2.22 \pm 0.24) - (1.06 \pm 0.19) y] \cdot 10^{-2}$	0.9/2
4.8A	$dN/d(vt) = \exp[(8.97 \pm 0.30) - vt]$	2.0/3
4.8B	$d\sigma/dP_T^2/\sigma_{\text{nsd}} = \exp[(2.76 \pm 0.65) - P_T/(0.227 \pm 0.060)]$	0.1/2
4.8B	$d\sigma/dP_T^2/\sigma_{\text{nsd}} = \exp[(5.4 \pm 1.3) - M_T/(0.160 \pm 0.043)]$	0.6/2
4.8C	$d\sigma/d y /\sigma_{\text{nsd}} = 0.40 \pm 0.14$	1.5/3

Figure 4.1
 K_S Selection Requirements

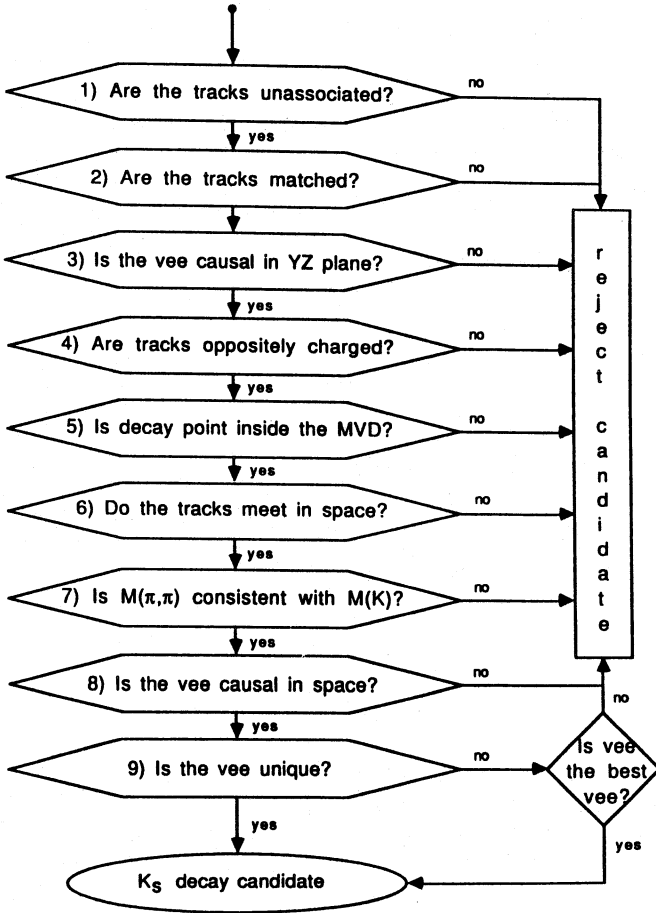
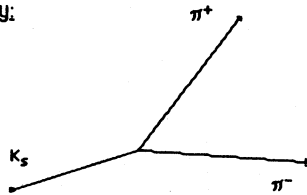


Figure 4.2
Causal and Non-causal K_S Decays

Causal Decay:



Non-causal Decays:

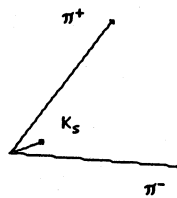
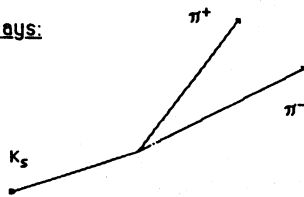


Figure 4.3
Distributions of X_0 , ΔZ , and $M(\pi, \pi)$

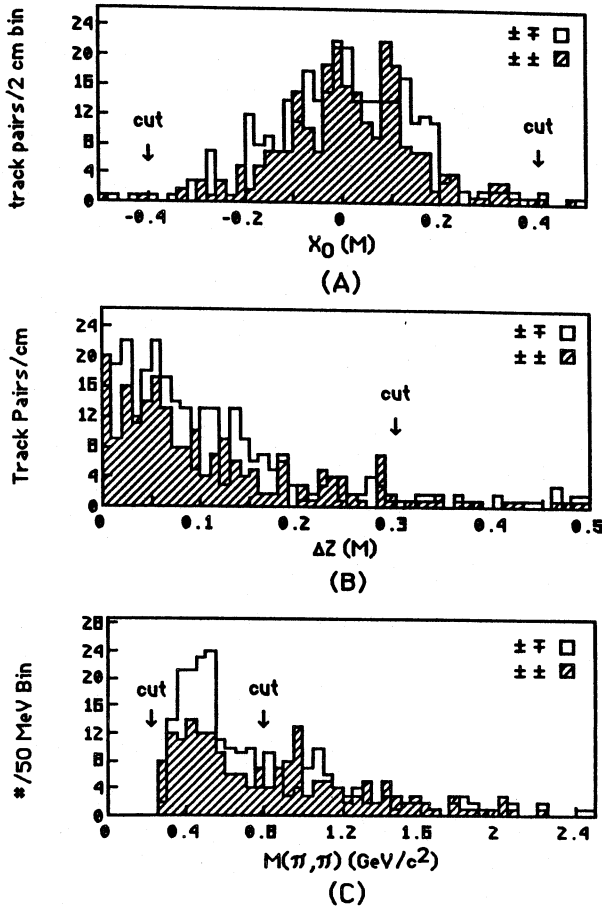


Figure 4.4
A Typical K_s Decay Candidate

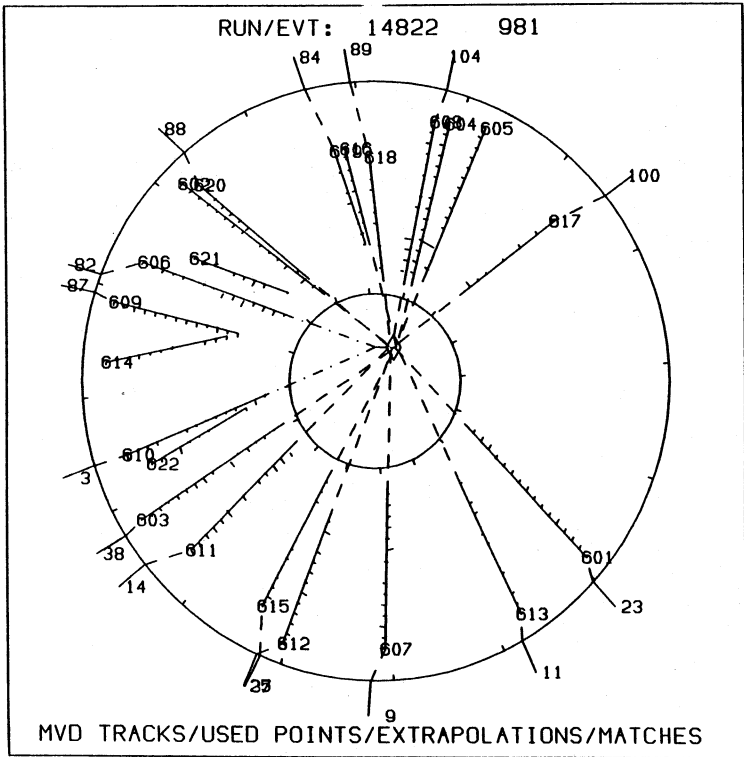
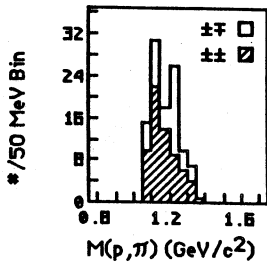
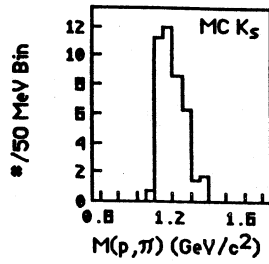


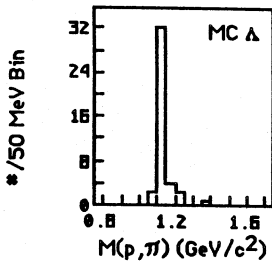
Figure 4.5
 $M(p,\pi)$ Distributions



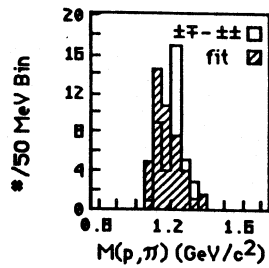
(A)



(B)

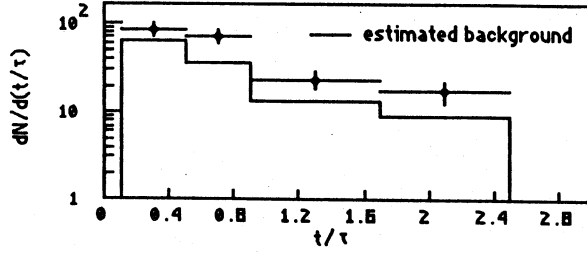


(C)

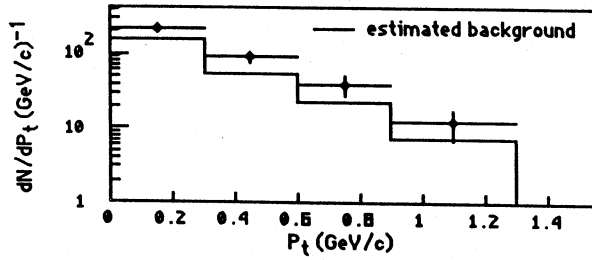


(D)

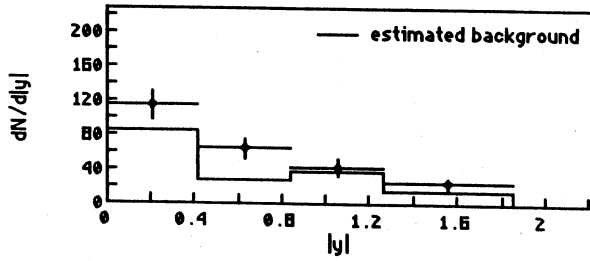
Figure 4.6
Uncorrected Lifetime, Transverse Momentum and Rapidity
Distributions



(A)



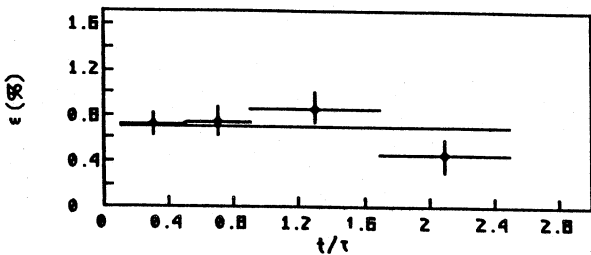
(B)



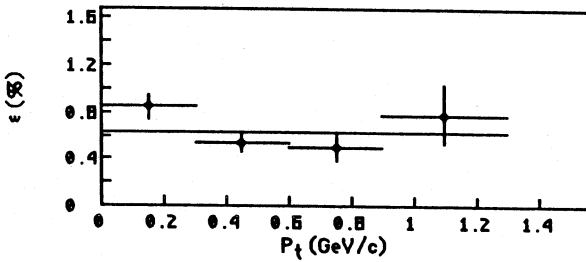
(C)

Figure 4.7

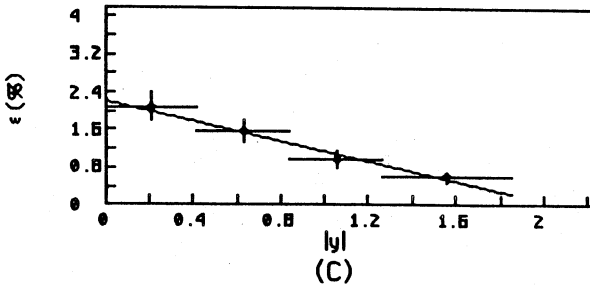
Efficiency as a Function of the K_S Lifetime, Transverse Momentum, and Rapidity



(A)

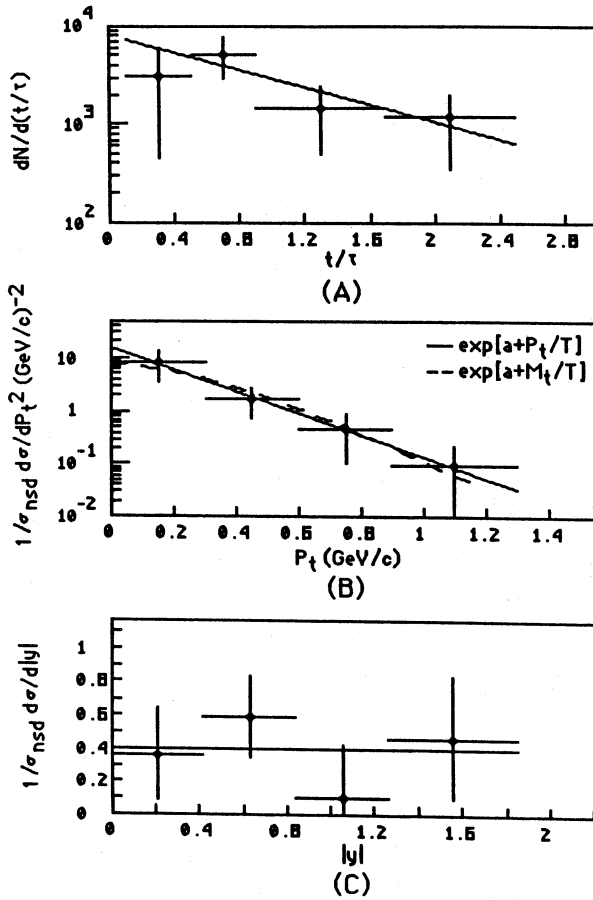


(B)



(C)

Figure 4.8
Fully Corrected K_S Lifetime, Transverse Momentum, and
Rapidity Distributions



CHAPTER V

DISCUSSION

5.1 Introduction

Strange particle production has been studied in $\bar{p}p$ and pp collision with center of mass energies ranging from 2 GeV to 900 GeV for the former [5.1-5.18] and 4 GeV to 63 GeV for the latter [5.7, 5.19-5.37]. A compilation of results that have been obtained from these experiments is presented in Tables 5.1-5.2. Figures 5.4-5.10 graphically depict the data giving the general features of strange particle production in $\bar{p}p$ and pp collisions as a function of the center of mass energy. In the remainder of this chapter phenomenological fits to these distributions and a comparison of the data to ISAJET Monte Carlo predictions will be discussed. In all cases the results of this experiment were found to be consistent with the results already published by UA5 and with the assumed phenomenological forms. Fit results are presented in Table 5.3. The ISAJET Monte Carlo was found to describe the data reasonably well for medium and higher energies.

5.2 Strangeness Particle Production

As stated in Chapter I strangeness production occurs through

soft hadronic processes which unfortunately cannot be calculated via perturbative QCD; however, it is possible, at least in a qualitative sense, through modeling, to gain insight regarding strange particles production in hadronic interactions.

Hadronic interactions are perhaps difficult to understand because of the hadron's rather complex nature. In the Standard Model, and as evidenced by results of numerous experiments, a hadron is composed of valence quarks (antiquarks) sea quarks (antiquarks) and gluons (Figure 5.1A). Valence quarks are the quarks which give hadrons their attributes (i.e. in the case of a proton these are uud). Within the constraints of the Uncertainty Principle it is possible for $\bar{q}q$ pairs to be excited from the vacuum, these quarks (antiquarks) are referred to as sea quarks.

The Strong force is also known as the color force, this is because quarks are presumed to carry a "color" quantum number that is conserved in Strong interactions. Color in strong interactions has nothing to do with the visible electromagnetic spectrum, in effect it plays an analogous role to charge in Electromagnetic interactions. Quarks (antiquarks) come in three varieties of color: red (antired), blue (antiblue), and green (antigreen). Hadrons are composed only of color neutral combinations of quarks (i.e. red-blue-green, red-antired, antired-antiblue-antigreen, etc.). Gluons, the mediators of the color force, carry both a color and an anticolor and come in eight varieties (i.e. red-antigreen, blue-antired, etc.).

Much that has been learned about the structure of hadrons comes from the study of deep inelastic lepton-hadron interactions. The structure of nucleons has been studied in great detail through high energy ep , eN , vp , vN , $\bar{v}p$, and $\bar{v}N$ interactions. In a deep inelastic lepton-hadron interaction the lepton probes the hadron by exchanging a virtual photon or intermediate vector boson with a quark inside of the hadron. This exchange will impart momentum to the quark and forces it to be ejected from the hadron, if the momentum imparted is great enough. When this happens the gluons which bind the quark inside of the hadron are stretched until they break. As a gluon breaks, color neutrality is preserved through the appearance of an appropriately colored $\bar{q}q$ pair at the discontinuity. Quarks and antiquarks then recombine to form color neutral hadrons. These hadrons will all be moving in roughly the same direction as the original quark forming a "jet" of particles. The quark content of the hadron can be deduced through studies of inclusive production cross-sections for various hadrons in deep inelastic scattering experiments. Figure 5.1B-C illustrates the quark (antiquark) content of the proton as a function of the fraction of the proton's momentum that is carried by a given quark. Only half of the protons momentum is carried by quarks the remainder is carried by gluons.

Presently, there exists two models, the Dual Parton Model (DPM) [5.38] and the Lund Model [5.39], that have been reasonably successful at describing the general features of multiparticle

production in hadron-hadron interactions in terms of quarks and gluons. In the Dual Parton Model an inelastic hadron-hadron interaction gives rise to color separation inside of the interacting hadron and the subsequent formation of gluon strings linking the colored fragments of one hadron to the other. The dominant process in inelastic interactions is one where two strings linking valence quarks are formed (Figure 5.2A), in Regge language this corresponds to a single exchange of a cut Pomeron. The strings that link the two hadrons must conserve baryon number so that in $\bar{p}p$ interactions one string connects a quark and an antiquark while the other connects a diquark and an antidiquark.

Higher order processes, which are interpreted as multiple inelastic collisions, give rise to additional pairs of strings linking sea quarks (Figure 5.2B). Diffractive processes, where one of the interacting hadrons escapes intact, are interpreted in the framework of the DPM as a color separation in one hadron which forms two strings linking valence and sea quarks (Figure 5.2C).

The momentum of the quarks on the ends of the strings are determined from measured structure functions and the fragmentation of the strings is assumed to occur in a analogous fashion to deep inelastic scattering or e^+e^- interactions with hadronic final states. Apart from the DPM dependence on measured structure functions and fragmentation models the model has no free parameters since the relative weights of higher order processes are determined through Reggeon Calculus [5.40].

The DPM and Lund Model share a similar topology. In the latter, soft events are also assumed to consist of two strings. The Lund Model, however, includes: 1) "semi-hard" interactions, which extend large momentum transfer processes into the small momentum transfer regime and 2) impact parameter structure to account for the finite size of the hadrons.

Within the framework of the DPM or Lund Model, strangeness production in non-diffractive interactions occurs at the level of string fragmentation. Several fragmentation models exist (Lund, Webber, Field and Feynman, etc.) that well describe the available experimental data [5.41-5.43]. The Independent Fragmentation Model of Field and Feynman is one of the simplest. In this model quark jets are assumed to fragment independently (i.e. as quark and antiquark are pulled apart the fragmentation of the quark jet is unaffected by the fragmentation of the antiquark jet and visa versa).

The ansatz assumed in the Independent Fragmentation Model is that a quark (q_0) moving in a given direction with a given momentum creates a color field in which a new quark-antiquark pair ($\bar{q}_1 q_1$) is produced. The original quark then combines with the antiquark from the sea to form the meson ($\bar{q}_1 q_0$) which carries away a finite fraction of the original quarks momentum. The remaining quark then creates a field in which a new quark-antiquark ($\bar{q}_2 q_2$) pair is produced, and so forth (see Figure 5.3A). The leftover quark from the quark jet is combined with the

leftover antiquark from the antiquark jet in order to preserve color neutrality. Through this scheme the structure of a quark jet is completely determined by specifying: 1) the probability in which up, down, and strange quark-antiquark pairs are created, 2) the probability that the mesons created are pseudoscalar, vector, or unstable higher spin resonances; 3) the transverse momenta of the mesons; and 4) the probability that the meson leaves behind a given fraction of the momentum to the remaining cascade.

Two major flaws exist in the Independent Fragmentation Model: energy is not conserved in the quark cascade, and baryon production is not accounted for. (The LUND fragmentation scheme by contrast conserves energy and momentum at every step.) Baryon production has been incorporated into the model by assuming that diquark-antidiquark pairs are produced in the fragmentation of the string as well as quark-antiquark pairs.

The Webber Model approaches fragmentation from a slightly different perspective. In this model the initial quark-antiquark pair give rise to a gluon cascade as they separate. Gluons formed in the cascade then split into quark-antiquark pairs. Quarks (and antiquarks) then combine into colorless hadronic clusters which decay into observable particles (Figure 5.3B).

The ISAJET Monte Carlo combines DPM and Independent Fragmentation Model principles, thus comparisons of the data to the Monte Carlo is useful for gaining physics insight. The widespread use of ISAJET for the simulation of hadron-hadron

collisions at present and future energies underscores the necessity for such comparisons.

5.3 Inclusive K_s Production Cross-Section and Mean K_s Multiplicity

Figure 5.4 shows the inclusive inelastic K_s production cross-section in $\bar{p}p$ and pp collision as a function of the center of mass energy. At low center of mass energies, less than ~ 6 GeV the $\bar{p}p$ cross-section is relatively flat. This has been attributed to annihilation processes (see Figure 5.1D). Above ~ 6 GeV the $\bar{p}p$ and pp cross-section become virtually indistinguishable because the annihilation contribution to the inclusive cross-section becomes less and less significant. The increase in the inclusive cross-section with $\ln(\sqrt{s})$ can be parameterized as a quadratic in $\ln(\sqrt{s})$. A $\ln^2(\sqrt{s})$ rise in the cross-section is a direct consequence of a rapidity plateau that is expanding and rising linearly with $\ln(\sqrt{s})$. The expanding plateau is simply due to an increase in the available phase space as the center of mass energy increases. (The rise in the central rapidity density will be discussed later in Section 5.5)

The dashed curve in Figure 5.4 is a fit to the $\sqrt{s} > 6$ GeV combined $\bar{p}p$ and pp data. (In order to obtain a reasonable fit chi square, systematic errors of 10% have been added in quadrature with quoted statistical errors.) The solid curve in Figure 5.4 is the

ISAJET prediction for the inclusive inelastic K_S production cross-section in $\bar{p}p$ collisions. One is not surprised to find out that ISAJET disagrees with the data at low energies since no attempt is made in the Monte Carlo to simulate $\bar{p}p$ annihilation. At medium and high energies reasonable agreement with the data is obtained.

The mean K_S multiplicity in inelastic collision is shown in Figure 5.5. As above, the dashed curve is a fit to the $\sqrt{s} > 6$ GeV combined $\bar{p}p$ and pp data and the solid curve represents the predictions of the ISAJET Monte Carlo for $\bar{p}p$ collisions. The resemblance in shape of the mean K_S multiplicity and inclusive K_S production cross-section as a function of the center of mass energy is due to the former being the ratio of the latter and the inelastic cross-section which is relatively flat over much of the energy range. Impressive agreement with medium and higher energy data has been obtained by ISAJET through tuning of the quark mixture assumed in independent fragmentation; the $u : d : s$ mixture assumed by ISAJET is 0.46 : 0.46 : 0.08. It is interesting to note that the original model of Field and Feynman assumed 0.4 : 0.4 : 0.2 for the same ratio. Strange quark production is suppressed relative to up and down quark production because of the strange quark's larger mass.

5.4 Mean K_S Transverse Momentum

Figure 5.6 shows the mean transverse momentum of K_S as a function of the center of mass energy. The phenomenological fit results and ISAJET predictions are once again respectively given by the dashed and solid lines. A rise in the $\langle P_t \rangle$ is consistent with earlier UA1 results [5.44] which showed that the $\langle P_t \rangle$ for charged tracks (which are mostly pions) had increased by 18% from $\sqrt{s} = 63$ GeV to $\sqrt{s} = 540$ GeV. The fit shown in Figure 5.6 has been made assuming that the $\langle P_t \rangle$ rises linearly with $\ln(\sqrt{s})$. (In order to obtain a reasonable fit chi square, systematic errors of 5% were added in quadrature with the quoted statistical errors. Because of its extremely large chi square and obvious disagreement with the rest of the data, the $\langle P_t \rangle$ estimated in reference [5.26] has been excluded from the fit.)

A linear rise in $\langle P_t \rangle$ is expected from the statistical point of view since $\langle P_t \rangle$ is proportional to the temperature of the hadron gas and the temperature should increase with the energy of the collision. Hagedorn [5.45] has suggested that the $\langle P_t \rangle$ will tend to a finite limit as the temperature of the hadron gas approaches the quark-gluon plasma phase transition temperature. This transition temperature is expected to be between 150 and 200 MeV.

From the fit to the transverse momentum distribution described in Section 4.424 (exponential in M_t) the mean temperature for a $\bar{p}p$ collision at $\sqrt{s} = 630$ GeV in which a K_S was

produced can be estimated. The results of the fit give:

$$T = 160 \pm 43 \text{ MeV.}$$

Since this temperature is near the expected transition temperature it is interesting to look to the data to see if indications of a phase transition can be seen. From the data presented in Figure 5.6 it is difficult to reach any conclusion as per the trend of the $\langle P_T \rangle$ at high energies due to the relatively few high energy measurements that have been made and the large experimental errors associated with those measurements. Perhaps a more definitive statement will come in the near future from $\bar{p}p$ collider experiments at Fermilab where collisions are taking place at a center of mass energy of 2 TeV.

The Independent Fragmentation Model in assuming a $\langle P_T \rangle$ distribution which become flat at medium and higher energies underestimate the $\langle P_T \rangle$ over virtually the whole energy range.

5.5 Central K_S Rapidity Density

Estimates of the inclusive K_S central rapidity density in pp collisions have been compiled by UA5 [5.17]. This data along with UA5 data [5.15, 5.18] and data from this experiment have been plotted in Figure 5.7. The dashed line is a fit to the $\sqrt{s} > 6 \text{ GeV}$ combined $\bar{p}p$ and pp data while the solid curve is the prediction of the ISAJET Monte Carlo for $\bar{p}p$ collisions. The fit assumes a linear rise in the central rapidity density with $\ln(\sqrt{s})$. A linear

rise in the central rapidity density is consistent with earlier UA1 results [5.46] which compared the central pseudorapidity density for charged tracks at $\sqrt{s} = 540$ GeV to results obtained by other experiments over a broad range of $\sqrt{s}$.

The rapidity plateau, in the framework of the DPM, is built up by superposing the rapidity distributions from each particle chain. In $\bar{p}p$ collisions chains have small longitudinal momentum and will thus give rise to distributions which are balanced in rapidity. The $\bar{q}q$ chain will carry, on average, less momentum than the $\bar{q}q$ -qq chain and will thus be shorter. The superposition of the rapidity distributions from the two chains plus contributions from additional chains formed when multiple inelastic collisions occurs forms the rapidity plateau. It is easy to see that the central rapidity density will rise as the number of multiple inelastic collisions increases. In pp collisions the situation is similar except for the valence strings are equal in length and of the q -qq variety; which because the diquark will carry, on average, more momentum than the quark are given a boost in rapidity.

The predictions of the ISAJET Monte Carlo, while consistent with the experimental data, appears to rise at a slightly slower rate than the data implies. (Further indication of this is the overestimation, by ISAJET, of the tails of the pseudorapidity rapidity distribution for charged particles (Section 4.32) while at the same time correctly estimating the mean K_S multiplicity.)

5.6 Inclusive Lambda Production Cross-Section and Mean Lambda Multiplicity

The inclusive inelastic lambda production cross-section as a function of the center of mass energy is presented in Figure 5.8. Because of CP invariance the Λ and $\bar{\Lambda}$ production cross-section in $\bar{p}p$ collisions are expected to be the same, thus in Figure 5.8 the average of the Λ and $\bar{\Lambda}$ cross-sections has been plotted. The dashed line represents a fit to the $\sqrt{s} > 6$ GeV $\bar{p}p$ data and the solid line represents the ISAJET prediction for $\bar{p}p$ collision. As in the case of K_S discussed earlier, the rise of the inclusive cross-section has been parameterized as quadratically increasing function of $\ln(\sqrt{s})$.

Data from pp collisions is shown in Figure 5.8 for comparison. Lambda production in $\bar{p}p$ collisions can be attributed to three sources: 1) annihilation (Figure 5.1E), 2) diffraction (Figure 5.1C), and 3) central production (Figures 5.1A-B). In pp collisions Λ production occurs through (2) and (3); while $\bar{\Lambda}$ production occurs only through (3). From the comparison of $\bar{p}p$ and pp data it is apparent that diffractive production of lambdas plays a much more significant role than with K_S . The contrast between Λ and $\bar{\Lambda}$ production in pp collisions thus gives the relative significance of processes (2) and (3). The importance of annihilation in lambda ($\Lambda + \bar{\Lambda}$) production for $\bar{p}p$ collisions can be observed by contrasting lambda production in $\bar{p}p$ collisions with lambda production in pp

collisions.

In predicting the inclusive inelastic production cross-section ISAJET seem to have grossly overestimated the inclusive cross-section at low energies while perhaps slightly overestimating it at high energies.

The mean lambda multiplicity as a function of the center of mass energy is presented in Figure 5.9. The ISAJET prediction and fit results are shown with solid and dashed lines respectively. Again data from pp collision is shown for comparison. As above, ISAJET overestimates at both low and high energies. Baryon production in ISAJET is achieved by assuming diquark-antidiquark and quark-antiquark pairs are created with a relative probability of 0.08 : 0.92.

5.7 Lambda to K_S Ratio

By using data from experiments that have measured both lambda and K_S mean multiplicities (or lambda and K_S inclusive production cross-sections) the lambda to K_S ratio ($\langle n(\Lambda / \bar{\Lambda}) \rangle / \langle n(K_S) \rangle$) can be estimated. Results of these calculations are shown in Figure 5.10. The solid line represents the predictions of the ISAJET Monte Carlo. No fit has been attempted since it is unclear what a reasonable parameterization of the expected distribution would be.

Data from pp collisions is shown in Figure 5.10 for

comparison. The differences between $\bar{p}p$ and pp data is striking at low energies because of the elevated K_S production cross-section in $\bar{p}p$ collisions caused by annihilation. At higher energies the Λ to K_S ratio in pp and $\bar{p}p$ collisions tend toward one another as one would expect. The large difference between the $\bar{\Lambda}$ to K_S ratio in $\bar{p}p$ and pp collisions once again underscores the significance of the role of diffraction with respect to Λ production.

The Λ to K_S ratio appears to approach a finite value at high energies. This perhaps indicates that the ratio of the probability of producing a $\bar{s}s$ pair to the probability of producing a $\bar{s}q$ - sq pair approaches a constant at high energy; where q is used here to denote u or d quark.

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Table 5.1
Data from $\bar{p}p$ Collisions

$\sqrt{s}$ (GeV)	$\sigma(K_S)$ (mb)	$\langle n(K_S) \rangle$	$\langle P_T \rangle$ (MeV/c)	$\sigma(\Lambda/\bar{\Lambda})$ (mb)	$\langle n(\Lambda/\bar{\Lambda}) \rangle$	ref.
2.0	2.64 ± 0.04	0.031 ± 0.001	$343. \pm 10.$	-	-	[5.1]
2.158	2.075 ± 0.110	-	-	-	-	[5.2]
2.169	2.041 ± 0.098	-	-	-	-	[5.2]
2.179	2.051 ± 0.121	-	-	-	-	[5.2]
2.188	2.040 ± 0.092	-	-	-	-	[5.2]
2.201	2.131 ± 0.097	-	-	-	-	[5.2]
2.8	2.00 ± 0.10	-	-	0.345 ± 0.065^a	-	[5.3]
2.9	2.00 ± 0.10	-	-	0.44 ± 0.09^a	-	[5.3]
2.96	2.06 ± 0.12	-	$364. \pm 1.$	0.485 ± 0.045^a	-	[5.4]
3.1	1.90 ± 0.07	-	-	0.505 ± 0.075^a	-	[5.3]
3.2	1.85 ± 0.08	-	-	0.53 ± 0.07^a	-	[5.3]
3.3	2.3 ± 0.1	0.050 ± 0.002	-	0.75 ± 0.05	0.020 ± 0.002	[5.5]
3.9	2.00 ± 0.10	0.045 ± 0.003	$368. \pm 4.$	0.920 ± 0.070^a	0.020 ± 0.002^b	[5.6]
4.3	2.03 ± 0.10	0.047 ± 0.002^c	$383. \pm 8.$	0.93 ± 0.05	0.021 ± 0.001^d	[5.7]
4.4	2.1 ± 0.1	0.05 ± 0.01	-	1.1 ± 0.1	0.03 ± 0.01	[5.5]
4.9	2.14 ± 0.19	-	$449. \pm 4.$	-	-	[5.8]
4.9	2.15 ± 0.20	0.053 ± 0.005^d	$440. \pm 34.^e$	1.075 ± 0.175^a	0.027 ± 0.004^d	[5.9]
5.431	2.08 ± 0.18	-	$400. \pm 20.$	0.84 ± 0.22^a	-	[5.10]
6.62	2.26 ± 0.06	0.058 ± 0.002	$413. \pm 6.$	1.17 ± 0.20^a	0.034 ± 0.001	[5.11]
7.88	3.10 ± 0.05	0.083 ± 0.003	$431. \pm 3.$	1.55 ± 0.35^a	0.042 ± 0.004	[5.12]
12.	4.95 ± 0.21	0.14 ± 0.01	$428. \pm 15.^e$	2.21 ± 0.30^a	0.054 ± 0.014^f	[5.13]
13.8	5.2 ± 0.3	0.15 ± 0.01	$460. \pm 13.$	2.4 ± 0.2	0.070 ± 0.005	[5.14]
200.	36.7 ± 6.4^g	0.90 ± 0.36^h	$514. \pm 85.^{h,i}$	-	-	[5.15]
540.	$49. \pm 5.$	1.0 ± 0.1	$570. \pm 30.$	17.2 ± 6.0^j	0.35 ± 0.10^k	[5.16, 5.17]
630.	$56. \pm 25.^l$	1.20 ± 0.50^l	$480. \pm 100.$	$<27.^m$	$<1.3^m$	this exp.
900.	$57. \pm 9.$	1.3 ± 0.2	$620. \pm 60.$	19.7 ± 4.9^j	0.45 ± 0.05	[5.18, 5.15]

^a average of $\sigma(\Lambda)$ and $\sigma(\bar{\Lambda})$

^b average of $\langle n(\Lambda) \rangle$ and $\langle n(\bar{\Lambda}) \rangle$

^c estimated from $\sigma(K_S)/\sigma_{inel}$

^d estimated from $\sigma(\Lambda/\bar{\Lambda})/\sigma_{inel}$

^e estimated from fit results

^f estimated from $\langle n(K_S) \rangle \cdot \sigma(\Lambda/\bar{\Lambda})/\sigma(K_S)$

^g estimated from $\sigma(K_S)_{nsd}/(0.98 \pm 0.14)$

^h $|\eta| < 3.5$

ⁱ measurement with asymmetric error has been transformed to measurement with symmetric error

^j estimated from $\sigma(K_S) \cdot \langle n(\Lambda/\bar{\Lambda}) \rangle / \langle n(K_S) \rangle$

^k $|\eta| < 3.$

^l systematic error included

^m at 95% confidence level

Table 5.2
Data from pp Collisions

$\sqrt{s}$ (GeV)	$\sigma(K_S^0)$ (mb)	$\langle n(K_S^0) \rangle$	$\langle P_T \rangle$ (MeV/c)	$\sigma(\Delta)$ (mb) $\sigma(\bar{\Delta})$ (mb)	$\langle n(\Delta) \rangle$ $\langle n(\bar{\Delta}) \rangle$	ref.
4.	0.320 ± 0.020	-	-	0.200 ± 0.020	-	[5.29]
4.3	0.42 ± 0.04	0.014 ± 0.001	$375. \pm 14.$	0.84 ± 0.06	0.028 ± 0.002	[5.7]
4.9	0.600 ± 0.012	-	-	1.154 ± 0.020	-	[5.20]
5.01	0.685 ± 0.080^a	0.023 ± 0.002^a	$415. \pm 16.$	1.07 ± 0.11	0.036 ± 0.004	[5.21, 5.22]
6.1	1.270 ± 0.040	-	$402. \pm 3.$	1.855 ± 0.060	-	[5.23]
6.8	1.514 ± 0.017	-	-	2.011 ± 0.023	-	[5.20]
6.91	1.370 ± 0.125	-	$373. \pm 33.$	1.13 ± 0.20	-	[5.24]
11.	3.43 ± 0.23	0.109 ± 0.007	$456. \pm 18.$	3.44 ± 0.20 0.16 ± 0.03	0.109 ± 0.006 0.005 ± 0.001	[5.25]
13.8	3.8 ± 0.3	-	$230. \pm 30.$	3.5 ± 0.4 0.24 ± 0.07	-	[5.26]
13.9	4.58 ± 0.46	0.141 ± 0.014	$424. \pm 43.$	3.22 ± 0.37	0.099 ± 0.012	[5.27]
16.7	5.0 ± 0.2	0.15 ± 0.01	$452. \pm 51.^b$	4.2 ± 0.2 0.8 ± 0.2	0.07 ± 0.01 0.024 ± 0.006^c	[5.28]
19.7	5.79 ± 0.40	0.181 ± 0.014	$412. \pm 14.$	3.33 ± 0.33 0.41 ± 0.13^d	0.103 ± 0.011 0.013 ± 0.004^c	[5.22]
23.8	7.34 ± 0.59	0.224 ± 0.018	$480. \pm 40.$	3.61 ± 0.35	0.11 ± 0.01	[5.29]
23.8	6.9 ± 0.8	0.220 ± 0.025	$500. \pm 8.$	3.6 ± 0.5 0.65 ± 0.14	0.11 ± 0.02 0.021 ± 0.004	[5.30]
23.9	9.8 ± 1.3	0.31 ± 0.04	-	4.2 ± 1.0	0.133 ± 0.025^c	[5.31]
26.0	8.55 ± 0.51	0.26 ± 0.01	-	4.08 ± 0.40 0.43 ± 0.12	0.12 ± 0.02 0.013 ± 0.004	[5.32]
27.4	6.61 ± 0.73	0.20 ± 0.02	-	3.97 ± 0.54 0.42 ± 0.16	0.12 ± 0.011 0.013 ± 0.003	[5.33]
27.6	7.43 ± 0.45	0.232 ± 0.011	-	4.01 ± 0.35 0.63 ± 0.12	0.125 ± 0.008 0.020 ± 0.004	[5.34]
52.5	11.5 ± 2.5	-	-	-	-	[5.35]

$\sqrt{s}$ (GeV)	$\sigma(K_S)$ (mb)	$\langle n(K_S) \rangle$	$\langle P_T \rangle$ (MeV/c)	$\sigma(\Lambda)$ (mb) $\sigma(\bar{\Lambda})$ (mb)	$\langle n(\Lambda) \rangle$ $\langle n(\bar{\Lambda}) \rangle$	ref.
53.	-	-	-	4.4 ± 0.2 1.2 ± 0.4	-	[5.36]
62.	-	-	-	4.7 ± 0.2 1.3 ± 0.5	-	[5.36]
63.	25.5 ± 1.4	-	429 ± 6 ^b	7.8 ± 1.2	-	[5.37]

^a systematic errors included

^b estimated from fit results

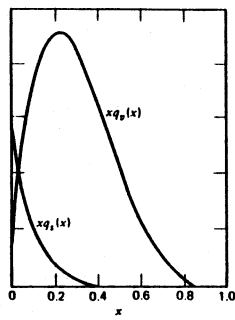
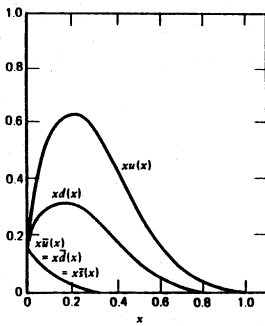
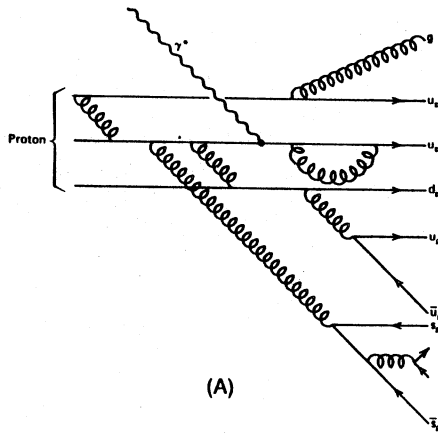
^c estimated from $\sigma(\bar{\Lambda}) \cdot \langle n(\Lambda) \rangle / \sigma(\Lambda)$

^d measurement with antisymmetric error has been transformed to measurement with symmetric error

Table 5.3
Fit Results

figure	fit	χ^2/ndf
5.4	$\sigma(K_S) = (2.9 \pm 1.7) + (-3.9 \pm 1.4) \cdot \ln(\sqrt{s}) + (1.67 \pm 0.27) \cdot \ln^2(\sqrt{s})$	55/20
5.5	$\langle n_K \rangle = [(-2.3 \pm 3.3) + (0.6 \pm 2.7) \cdot \ln(\sqrt{s}) + (2.64 \pm 0.51) \cdot \ln^2(\sqrt{s})] \cdot 10^{-2}$	31/15
5.6	$\langle P_T \rangle = (0.359 \pm 0.020) \text{ GeV}/c + (0.0286 \pm 0.0066) \cdot \ln(\sqrt{s}) \cdot c^{-1}$	16/15
5.7	$(1/\sigma_{\text{inel}}) d\sigma_K/dy _{y=0} = [(-2.87 \pm 0.47) + (2.76 \pm 0.22) \cdot \ln(\sqrt{s})] \cdot 10^{-2}$	22/13
5.8	$\sigma(\Lambda/\bar{\Lambda}) = (0.5 \pm 1.6) + (-0.6 \pm 1.2) \cdot \ln(\sqrt{s}) + (0.50 \pm 0.22) \cdot \ln^2(\sqrt{s})$	0.2/3
5.9	$\langle n(\Lambda/\bar{\Lambda}) \rangle = [(-1.5 \pm 2.3) + (1.0 \pm 1.7) \cdot \ln(\sqrt{s}) + (0.85 \pm 0.27) \cdot \ln^2(\sqrt{s})]$	0.5/3

Figure 5.1
The Structure of the Proton



(from F. Halzen and A. Martin, "Quarks & Leptons: An Introductory Course in Modern Physics", Wiley, New York (1984))

Figure 5.2
Production Diagrams

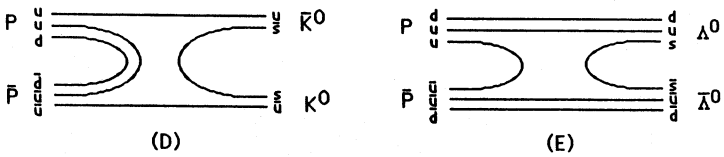
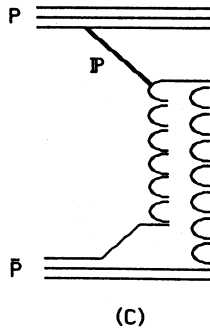
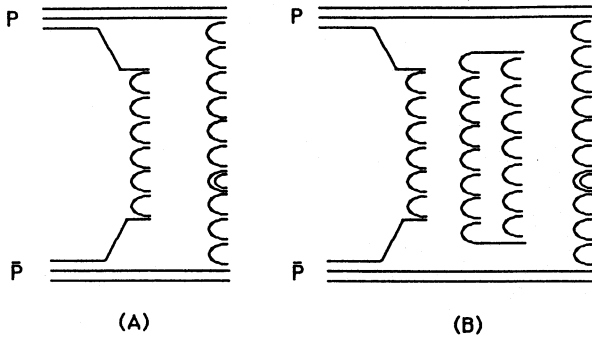
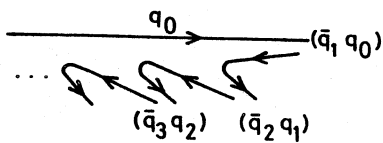
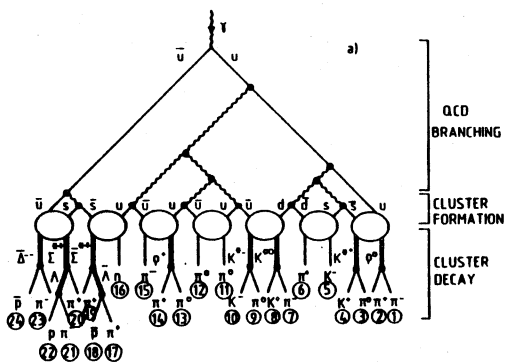


Figure 5.3
Fragmentation Diagrams



(from V. Barger and R. Phillips, "Collider Physics", Addison-Weseley, Redwood City (1987))



(from [5.42])

Figure 5.4
Inclusive Inelastic K_S Production Cross-section as a
Function of the Center of Mass Energy

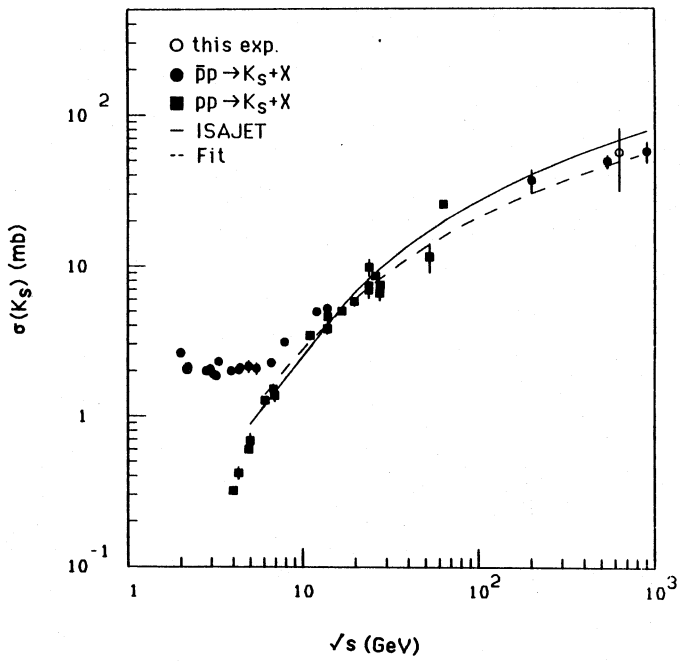


Figure 5.5
Mean K_S Multiplicity per Inelastic Event as a Function of
the Center of Mass Energy

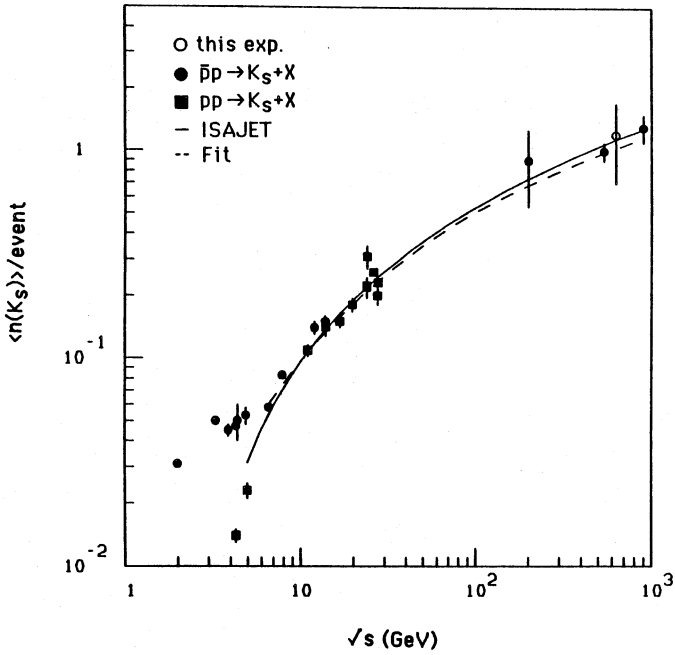


Figure 5.6

Mean K_S Transverse Momentum as a Function of the Center of Mass Energy

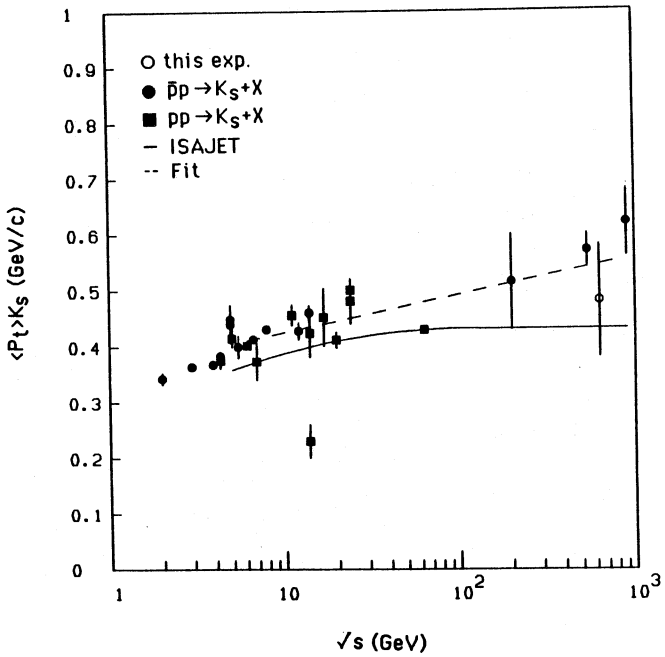


Figure 5.7
Central Rapidity Density for K_S Production as a Function
of the Center of Mass Energy

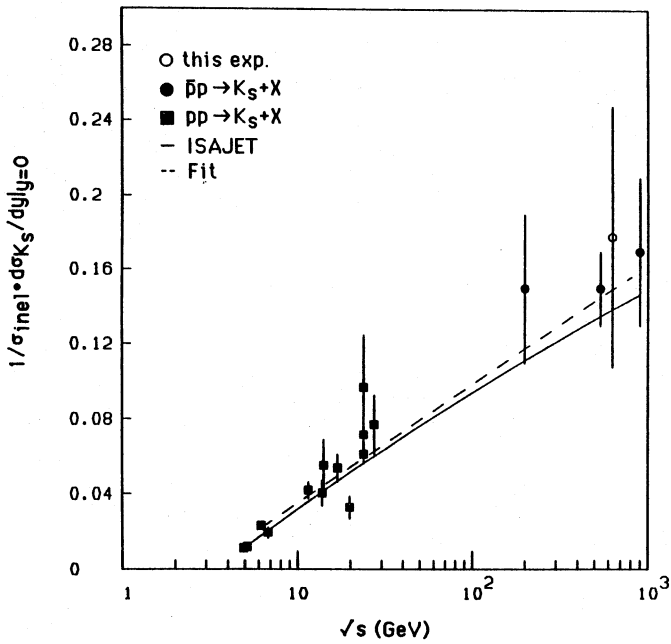


Figure 5.8
Inclusive Lambda Production Cross-section as a Function
of the Center of Mass Energy

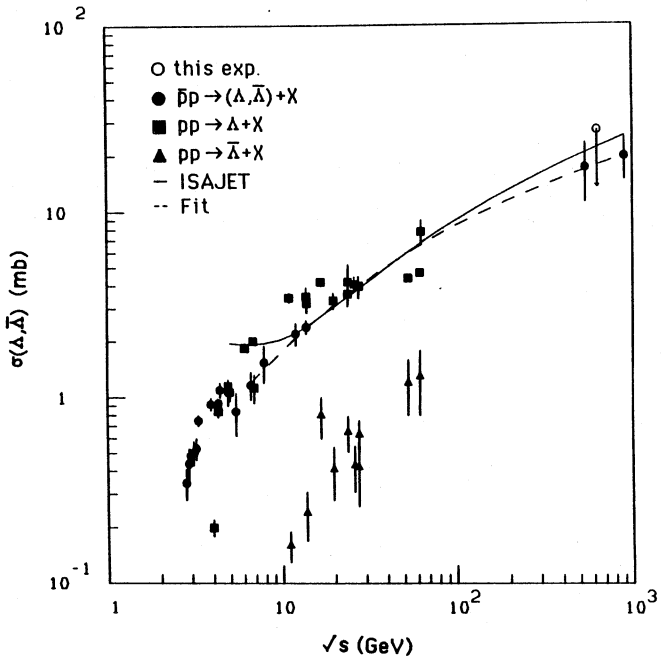


Figure 5.9
Mean Lambda Multiplicity as a Function of the Center of
Mass Energy

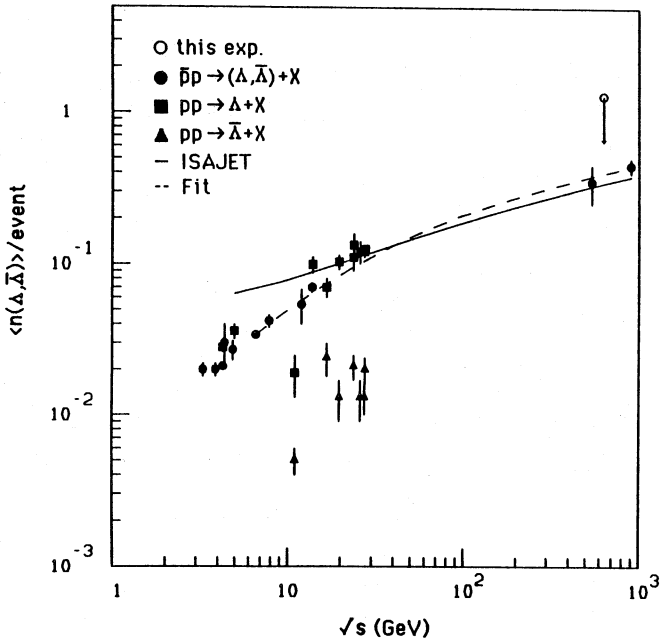
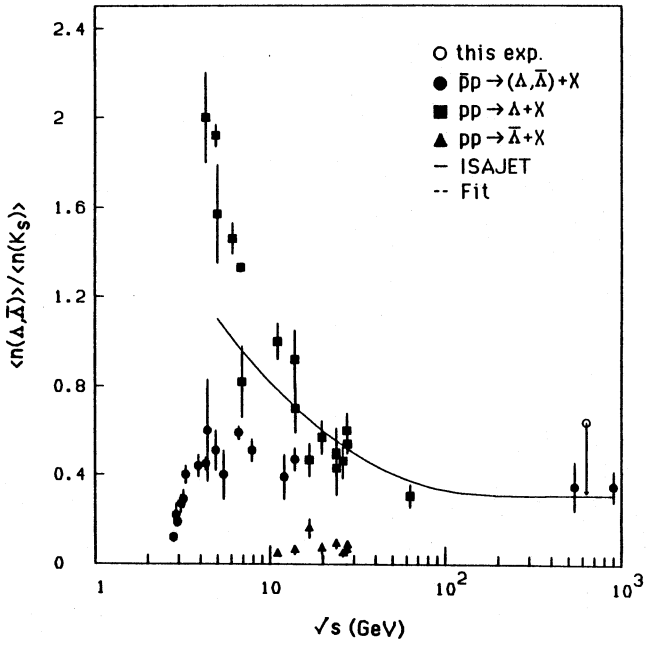


Figure 5.10

Lambda to K_S Ratio as a Function of the Center of Mass Energy



CHAPTER VI

CONCLUSIONS

The UA1 Microvertex Detector, a small high-pressure (3 Atm) cylindrical jet-style drift chamber with a 1.58 mm wire pitch was successfully operated in both a 10 GeV/c pion beam and in CERN $\bar{p}p$ Collider. With respect to detector performance the following information has been obtained:

- The detector achieved an intrinsic single wire resolution of less than 40 μm in a test beam of 10 GeV/c pions.
- The detector was operated successfully less than 2.5 cm from the circulating beams of the CERN $\bar{p}p$ Collider at luminosities up to $2 \times 10^{-29} \text{ cm}^{-2}\text{s}^{-1}$.
- Current in the chamber was observed at about 3 times the rate expected from ionization. This is ascribed to beam halo.
- In the collider, the Microvertex Detector achieved a single wire and projected impact parameter resolution of 110 μm . This degradation of the chamber's performance is due mainly to pick-up noise from the circulating beams and large currents in the chamber.

Inclusive production of K_S in non-single diffractive $\bar{p}p$ collisions with $\sqrt{s} = 630$ GeV was studied yielding the following results (systematic errors are denoted in *italics*.):

- The inclusive production cross-section is:

$$\sigma_{\text{nsd}}(\bar{p}p \rightarrow K_S x) = 55. \pm 19. \pm 13. \text{ mb},$$

and the inelastic production cross-section is:

$$\sigma(\bar{p}p \rightarrow K_S x) = 56. \pm 21. \pm 13 \text{ mb}.$$

- The mean K_S multiplicity per $\bar{p}p$ collision is:

$$\langle n(K_S) \rangle_{\text{nsd}} = 1.34 \pm 0.46 \pm 0.25,$$

and the mean K_S multiplicity per inelastic $\bar{p}p$ collision is:

$$\langle n(K_S) \rangle = 1.20 \pm 0.44 \pm 0.23.$$

- The inclusive K_S differential cross-section $d\sigma_K/dP_t^2$ is well described by an exponential in M_t (or P_t). The mean K_S transverse momentum is estimated to be:

$$\langle P_t \rangle = 0.473 \pm 0.089 \text{ }^{+0.055}_{-0.032} \text{ GeV}/c.$$

- The inclusive K_S differential cross-section $d\sigma_K/d|y|$ is consistent with a flat distribution in the region $|y| < 2$. The central rapidity density is given by:

$$1/\sigma \cdot d\sigma_K/dy|_{y=0} = 0.177 \pm 0.063 \text{ }^{+0.028}_{-0.033}.$$

Upper limits, at a confidence level of 95%, have been set with respect to Λ production in non-single diffractive $\bar{p}p$ collisions at $\sqrt{s} = 630$ GeV. These limits are respectively given by:

$$\sigma_{\text{nsd}}(\bar{p}p \rightarrow \Lambda \bar{\Lambda} X) < 27 \text{ mb};$$

$$\langle n(\Lambda \bar{\Lambda}) \rangle_{\text{nsd}} < 0.64;$$

and

$$[\langle n(\Lambda \bar{\Lambda}) \rangle / \langle n(K_S) \rangle]_{\text{nsd}} < 0.49.$$