UNIVERSITY OF CALIFORNIA
RIVERSIDE

Search for Charmed Particle Production in Proton-
Proton Collisions at the CERN-ISR

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

Doctor of Philosophy

in

Physics

by

William Leigh Marsh

June, 1977

MASTER

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Dissertation Committee:

Professor Anne Kernan, Chairman

Professor Bipin R. Desai

Professor Benjamin C. Shen

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ABSTRACT OF THE DISSERTATION

Search for Charmed Particle Production in Proton-Proton Collisions at the CERN-ISR

by

William Leigh Marsh

Doctor of Philosophy, Graduate Program in Physics

University of California, Riverside, June 1977

Professor Anne Kernan, Chairman

Experimental results on a search for charmed particle production in proton-proton collisions at the center of mass energy ($\sqrt{s}$) of 53 GeV are presented here. We have searched for evidence of electron-strange particle coincidences, a signature of charmed particle production.

The inclusive e/π ratio was measured with a magnetic spectrometer located at 32° from Beam 1 of Intersection I6 of the CERN Intersecting Storage Rings (ISR). The e/π ratio from direct (unknown) sources was found to rise from 1.06×10^{-4} at $p_\perp = 1.5$ GeV/c to 5.53×10^{-4} at $p_\perp = 0.25$ GeV/c. One possible source for this signal is the semi-leptonic decay of charmed particles (e.g. $D \rightarrow K^0 e \nu$). If so, then electron-strange particle (e.g. Λ^0, K^0) coincidences are expected.

The charged decay products of Λ^0 and K^0 were detected in a multiparticle spectrometer surrounding Beam 1 downstream of the intersection. To determine if there is an electron-

strange particle correlation, the number of Λ^0 's (K^0 's) in coincidence with an electron in the 32° spectrometer was compared with the number of Λ^0 's (K^0 's) in coincidence with a hadron in the same kinematic range.

No evidence for an enhanced production of strange particles with electrons relative to hadrons was found. However, given the acceptance of the apparatus, the absence of a signal is consistent with current models of charmed particle production and decay.

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CHAPTER I

INTRODUCTION

This dissertation describes an experiment to search for evidence of charmed particle production in strong interactions. Specifically, I describe here the portion of the experiment which searched for evidence of electron-strange particle coincidences. The experiment was performed at the CERN-ISR at the center of mass energy ($\sqrt{s}$) of 52.8 GeV.

In August 1974, when the experiment was proposed, direct production of electrons and muons had been observed at high $p_{\perp}$ ($p_{\perp} > 1$ GeV/c) in proton-proton collisions at high energy ($\sqrt{s} > 10$ GeV)¹. The rate of production of both electrons and muons was found to be 10^{-4} times the pion production rate, a surprisingly high value. Furthermore, both the ratio of electron rate to pion rate (e/π) and the ratio of muon rate to pion rate (μ/π) were approximately constant over the experimentally measured regions of $p_{\perp}$ and $\sqrt{s}$ ($1.5 < p_{\perp} < 5$ GeV/c, $7 < \sqrt{s} < 53$ GeV).

This phenomenon appeared as an anomaly and could not be easily explained in terms of the existing conventional models of lepton production². Quark-anti quark models predicted lepton production about one-tenth of what was observed. It also appeared to be unlikely that the signal

could be explained by leptonic decays of the vector mesons ρ , ω , and ϕ .

However, a model which might explain the anomaly was the strong production of pairs of particles C and $\bar{C}$ which possess a new quantum number, charm, conserved in strong and electromagnetic interactions. Eventually, C and $\bar{C}$ were expected to decay via the weak interaction into $\mu^\pm + \nu + \text{hadrons}$, $e^\pm + \nu + \text{hadrons}$, or hadrons alone.

This model, first proposed in 1964 by Bjorken and Glashow³, received renewed interest in 1974 not only because of the anomalous lepton production but also because of the recent discovery of weak neutral currents.⁴ The charm model explained the suppression of strangeness changing weak neutral currents while providing for the existence of strangeness conserving weak neutral currents. It also provided an explanation for the production of two muons (dimons) in neutrino interactions which had been observed at FNAL⁵.

Later, in November 1974, the J/ψ and ψ' particles were discovered. Since the charm model provided a natural explanation for them, the physics motivation of the experiment was further enhanced.

A. Charm Model

There have been many excellent reviews of charmed particle models.⁶ Only a brief description of the simple charm model as it pertains to the experiment will be given here.

This simple model assumes the addition of a fourth quark with the new additive charm quantum number to the simple three quark model (Table I-1). The mathematical symmetry group changes from SU_3 to SU_4 and results in the particles given in Figure I-1 for mesons ($q\bar{q}$ combinations) and Figure I-2 for baryons (qqq combinations).

Charm is assumed to be conserved in strong and electromagnetic interactions. Thus, particles carrying the charm quantum number must be produced in pairs in p-p collisions similar to the associated production of strange particles. These particles may then decay strongly into other charmed particles plus non-charmed hadrons thereby conserving the charm quantum number. Eventually, however, the lightest charmed meson or baryon in the chain decays weakly, violating charm.

This weak charmed particle decay may take the following forms:

- (1) $C \rightarrow \text{hadrons},$
- (2) $C \rightarrow \mu + \nu_e + \text{hadrons},$ and
- (3) $C \rightarrow e + \nu_e + \text{hadrons}.$

TABLE I-1
Quark Quantum Numbers

Quark	Strangeness	Charge	Isospin I	I_z	Charm C
n	0	$-1/3$	$1/2$	$-1/2$	0
p	0	$2/3$	$1/2$	$1/2$	0
λ	-1	$-1/3$	0	0	0
c	0	$2/3$	0	0	-1

Figure I-1

Figure 1-2

Moreover, the model predicts that about 95% of the decays should involve a strange hadron. This prediction follows from the absence of strangeness changing neutral currents as discussed below.

The weak interaction, shown schematically in Figure I-3, is well described by a weak current-current interaction patterned after quantum electrodynamics. Lepton conservation in the weak interaction corresponds to charge conservation in the electromagnetic interaction. Furthermore, just as the electromagnetic interaction is mediated by the photon, the weak interaction is thought to be mediated by the intermediate vector boson W . However, unlike the electromagnetic interaction, the weak interaction has two types of currents, a current of hadrons and a current of leptons.

Until 1974 only charged currents had been observed implying that the W boson was either positive or negative but not neutral. Furthermore, this charged current was found to have a component which changed the strangeness of the hadrons involved and one which did not. The relative amplitude of these two components was found to be related by an angle θ (12.4°) called the Cabbibo angle. The hadronic weak current in the three quark model was found to be given by

$$W^+ = \bar{p}(n\cos\theta + \lambda\sin\theta).$$

Electromagnetic Interaction

Weak Charged Current
Interaction

However, Weinberg and Salam had constructed a more fundamental theory of the weak interaction.⁷ In their model which unites the weak and electromagnetic interactions, neutral as well as charged currents are expected. The neutral current has both strangeness changing and strangeness conserving parts. The amplitude of the strangeness conserving part is of the same order of magnitude as the amplitude of the strangeness conserving charged current. The amplitude of the strangeness changing part is of the same order as the amplitude of the strangeness changing charged current.

In 1974 reactions such as $\nu_\mu + N \rightarrow \nu_\mu + \text{hadrons}$ which implied the existence of a weak neutral current were discovered. However, other evidence, such as the ratio for $(\mu^+ \rightarrow \pi^+ e^+ e^-) / (K^+ \rightarrow \pi^0 e^+ \nu) \sim 10^{-5}$, the suppression of $K_L \rightarrow \mu^+ \mu^-$ relative to $K_L \rightarrow \gamma\gamma$, and the $K_L K_S$ mass difference, showed that the strangeness changing neutral current is suppressed--contrary to what the theory implied.

This apparent contradiction can be resolved by introducing the charmed quark into the weak interaction in such a manner that the strangeness changing neutral current is cancelled out. This requires that the charged weak current of the charmed quark be of the form

$$W^+ = \bar{c}(\lambda \cos\theta - n \sin\theta).$$

Therefore, ninety-five percent ($\cos^2\theta$) of the time the charmed quark will decay into the strange (λ) quark

($c \rightarrow \lambda$, $\bar{c} \rightarrow \bar{\lambda}$). Thus ninety-five percent of weak charmed particle decays are expected to give rise to a strange particle.

B. Physics Aims of the Experiment

Since charmed particles are produced in pairs in hadronic collisions, two possible signatures for their production are an $e^{\pm}-\mu^{\mp}$ correlation and an $e^{\pm}$ -strange particle correlation. Furthermore, since charmed particles may decay into hadrons alone, they might appear as narrow peaks, (Γ = mass resolution), in hadronic effective mass spectra.

Theorists were predicting the mass of the charmed D meson to be about $2 \text{ GeV}/c^2$. The expected semi-leptonic decay mode was the three body decay $D \rightarrow K e \nu$. Assuming a V-A interaction, the average electron momentum in the rest frame of the D is expected to be about 470 MeV. Assuming the D is produced with small $p_{\perp}$ similar to the known hadronic average of 340 MeV/c, the $p_{\perp}$ of the electron is expected to be less than 1 GeV/c. Thus, one might be more sensitive to charmed particle production by detecting low $p_{\perp}$ electrons ($<1 \text{ GeV}/c$) rather than the high $p_{\perp}$ electrons ($>1 \text{ GeV}/c$) previously studied.

Therefore, the experiment was proposed to

- (1) measure the direct electron signal (e/π ratio) at low $p_{\perp}$,

- (2) search for an $e^{\pm}-\mu^{\mp}$ correlation,
- (3) search for an $e^{\pm}$ -strange particle correlation, and
- (4) search for narrow peaks in hadronic mass spectra.

C. Experimental Setup

The experiment was carried out at Intersection I6 of the Intersecting Storage Rings (ISR) of the CERN Laboratory in Geneva, Switzerland. The ISR (Figure I-4) was constructed in order to achieve very high center of mass energies by colliding two protons head-on. Proton beams, accelerated at the Proton Synchrotron (PS) to momenta in the range 10 to 28 GeV/c, are injected into the ISR rings through two channels, TT1 and TT2, with opposite circulating directions. The beams intersect each other at eight positions around the ISR at a crossing angle of about 15° thereby providing the "head-on" collisions.

The experimental setup (Figure I-5) consisted by a single particle spectrometer at 32° from the Arm 1 beam and a multiparticle spectrometer in the forward direction along Arm 1. The single particle spectrometer was used to measure the flux of single electrons and therefore is called the "electron arm" or the "electron telescope". The forward multiparticle spectrometer was used to detect muons and the charged decay products from the strange particles Λ^0 and K^0 .

The electron arm and electron identification is discussed in Chapter II. Chapter III covers the e/π ratio. More

CERN

Figure I-4

13

Figure I-5

detailed discussions of these subjects are given in the Diploma theses of Rudiger Voss⁸ and Joachim Irion⁹ with the results being published in Physics Letters¹⁰. The forward spectrometer and electron-strange particle coincidences are described in Chapter IV. The on-line computer data acquisition system is discussed in Appendix I.

CHAPTER II

ELECTRON DETECTION--ELECTRON-HADRON SEPARATION

To achieve the physics goals of measuring the e/π ratio at low $p_{\perp}$ and of searching for electron-muon and electron-strange particle coincidences, electrons must be detected and identified. Since the e/π ratio at high $p_{\perp}$ is 10^{-4} and flat in $p_{\perp}$, the e/π ratio at small $p_{\perp}$ can be expected to also be on the order of 10^{-4} . Thus, the electron arm must be able to reject hadrons to a level of at least 10^{-5} to 10^{-6} .

Furthermore, there are known background sources of electrons which must be considered. These are:

- (1) pair production (γ -conversion, $\gamma N \rightarrow e^+ e^- N$) in the material before the electron arm,
- (2) Dalitz pairs from π^0 and η^0 decay ($\pi^0, \eta^0 \rightarrow e^+ e^- \gamma$).
- (3) Compton electrons from γ -scattering on atomic electrons in the material before the electron arm, and
- (4) semi-leptonic decay of kaons ($K^0 \rightarrow e^+ \pi^- \bar{\nu}_e, K^+ \rightarrow e^+ \pi^0 \nu_e$).

The γ 's are mostly produced through electromagnetic decay of hadrons ($\pi^0, \eta^0 \rightarrow \gamma\gamma$).

The background due to $e^+ e^-$ pairs from γ -conversion and Dalitz decays can be suppressed by insisting that only one particle transverses the electron arm. However, because of multiple scattering and large angle Dalitz pairs, not

all of the pairs can be eliminated in this manner. Furthermore, electrons from Compton scattering and kaon decay are single and therefore cannot be distinguished from the direct electrons.

Thus, although it is possible to estimate this background, it is impossible to tell on an event by event basis which electrons are "direct" and which are from background. So since the above mentioned backgrounds are derived mostly from hadronic interactions, the electron-strange particle correlation study will be done by comparing electron-strange particle coincidences with hadron-strange particle coincidences.

A. The Electron Arm

The electron arm (Figure II-1) consisted of a magnetic spectrometer for momentum determination, a gas Cerenkov counter and lead glass Cerenkov counter matrix for electron-hadron separation, trigger counters, and a system of anti-counters (Figure II-2) for vetoing e^+e^- pairs.

Sixteen drift chamber planes of 2.84 cm cell width and a magnet of $\int B dl$ of 0.6 T m formed the magnetic spectrometer of the electron arm. Each plane was paired with another of the same drift direction to form eight modules. Within each module the planes were displaced by $1/2$ cell length to solve the left-right drift ambiguity problem. There are two x-modules of horizontal drift and three y-modules of vertical drift before the magnet and

TABLE II-1
Electron Arm Parameters

Angle from Beam 1	31.6°
Horizontal acceptance	$\pm 4.5^\circ$
Vertical acceptance	$\pm 2.8^\circ$
Solid Angle	$0.0012 \times 4\pi$ steradians
Magnet	$\int B dl = 0.6 \text{ T m}$
Momentum Resolution	$\Delta p/p = 0.012p$
Scintillation counters	
Trigger counters	4 in front of magnet 2 behind magnet
Anti-counters	6 before magnet 2 inside magnet
Track Reconstruction	16 drift chambers 5 x-modules 3 y-modules
Electron identification	
Gas Cerenkov counter	
gas	CO ₂ under atmospheric pressure
radiator length	1.1 meter
π threshold	4 GeV/c
Lead Glass $\checkmark$ counter	15 blocks in 5x3 matrix 1 block 150 x 150 x 350 mm ³ 15 radiation lengths

Figure II-1

Scintillation counter system

Figure II-2.

two x-modules and one y-module behind the magnet. The magnetic field was predominantly in the y-direction.

The 1.1 meter long gas Cerenkov counter was situated inside the magnet and filled with CO_2 gas under atmospheric pressure. Cerenkov light was focused onto two UV sensitive photomultiplier tubes by two parabolic mirrors. The thresholds for e, π , K, and p were 0.015, 4.0, 14, and 27 GeV/c respectively.

The lead glass Cerenkov counter was situated behind the last drift chamber of the spectrometer. It consisted of 15 blocks arranged in a 5x3 matrix. Each block had a rectangular cross sectional area of $150 \times 150 \text{ mm}^2$ and was 350 mm long (15 radiation lengths). A photomultiplier tube at the end of each block detected the Cerenkov light.

The system of scintillation counters of the electron arm is illustrated in Figures II-2 and II-3. The pulse-height of each of the counters was recorded for each event.

The vacuum chamber surrounding the interaction region is shown in Figure II-4. It consisted of corrugated stainless steel of thicknesses 0.2 mm and 0.7 mm as shown in the figure. In addition there is a window in the forward direction for the forward spectrometer. Particles incident on the electron arm therefore may go through either the "thick" 0.7 mm section or the "thin" 0.2 mm section. This is an important consideration since the electron background processes

Figure II-3

Figure II-4

of pair production and Compton effect depend on material thicknesses.

A single electron transversing the electron telescope would have its momentum determined by the spectrometer, give a pulse in the gas Cerenkov counter, and deposit all of its energy in the lead glass matrix giving a signal proportional to the energy. On the other hand, a hadron transversing the spectrometer would not give a gas Cerenkov pulse if below threshold (4 GeV/c for pions) and would only give a minimum signal in the lead glass matrix. A e^+e^- pair coming into the spectrometer would be detected by either the counter hit pattern or a double particle pulseheight in one of the counters. Single electrons, e^+e^- pairs, and hadrons can thus be distinguished.

B. Trigger

Two types of triggers differing in electron arm requirements were used. These were (1) an "electron" trigger in which events were biased to enhance the electron signal and (2) a "hadron" trigger in which the only electron arm requirement was that there be a particle in the electron arm in front and behind the magnet. The purpose of the hadron trigger was to provide an unbiased sample for the measurement of the e/π ratio and so that the hadron background in the electron sample could be studied.

The electron arm requirements for the electron trigger were:

- (1) a particle in the electron arm in front and behind the magnet,
- (2) a pulse ($>1/2$ photoelectron) in the gas Cerenkov counter to help veto hadrons, and
- (3) more than 0.2 GeV energy deposition in the whole lead gas matrix to help veto hadrons.

Each of the two types of triggers required that:

- (1) a particle hit one of the two front supermodules of the forward spectrometer (see Chapter IV), and
- (2) a particle transverse a system of counters placed downstream of the intersection around the beam opposite the forward spectrometer (Beam 2).

The purpose of this last requirement was to reduce background from accidental triggers and beam-gas interactions. Furthermore, for both types of triggers the magnetic field of the electron arm magnet was periodically reversed to ensure equal detection efficiency of positive and negative particles.

The electron trigger condition, however, does not veto all hadrons. Nor does it attempt to veto e^+e^- pairs. The trigger thresholds of both the Cerenkov counter and lead glass matrix were set low so as to catch as many electrons as possible and so that the background could be studied.

Through such mechanisms as (i) creation of delta rays in the gas Cerenkov counter, (ii) an accompanying γ -ray causing an electromagnetic shower in the lead glass, or (iii) a high energy hadron creating gas Cerenkov light, it is possible for a hadron to satisfy the trigger condition. However, more detailed off-line analysis can lead to the separation of single electrons, hadrons, and e^+e^- pairs.

C. Electron Definition

The separation of electrons from the hadron background is achieved by requiring:

- (1) the energy deposited in the lead glass be equal to the momentum of the track in the spectrometer,
- (2) the energy so deposited in the lead glass be confined to a small area of at most a four block cluster which is compatible with the position on the lead glass of the extrapolated track, and
- (3) the CO_2 gas Cerenkov counter give greater than two photoelectrons.

The electrons so defined have about 6% background due to hadrons.

The separation of single electrons from pairs is achieved by requiring:

- (1) a counter hit pattern consistent with a single particle,
- (2) a single particle pulseheight in the counters that are hit,
- (3) only 1 track in the x and y projections of the spectrometer, and
- (4) only 1 pair of matching hits in each of the drift chamber modules before the magnet.

These requirements are very effective in eliminating pairs in which both particles enter the sensitive area of the arm. However, scattering within the vacuum chamber walls and wide angle pairs can give pairs in which one particle misses the arm. These events cannot be separated from true singles. They can only be estimated.

D. Hadron Identification

A particle is considered a hadron if it is reconstructed through the spectrometer, gives a gas Cerenkov signal of less than 1 photoelectron, and is a single particle as defined above. Since, as will be seen, e/π is on the order of 10^{-4} , the background due to electrons is negligible. Also, the loss of hadrons due to the Cerenkov cut is estimated to be on the order of 10^{-4} and is therefore neglected.

E. Counter Cuts

Figures II-2 and II-3 show the trigger and anti-counter setup. To eliminate small opening angle pairs from γ -conversion and Dalitz decay, the hit pattern and pulseheight of the counter setup is required to be consistent with a single minimum ionizing particle. This condition is also applied to hadron trigger events.

The raw pulseheight spectra of the front trigger counters for electron and hadron triggers are shown in Figure II-5. The two particle peak of e^+e^- pairs is clearly apparent in the electron trigger events. To eliminate these the indicated cut in Figure II-6 is made.

The same cut on trigger counter pulseheight was used for both electron and hadron events. Figure II-5 shows that the pulseheight spectrum for electron and hadron trigger are the same for the initial single particle peak. It is

Figure II-5

Figure II-6

therefore not unreasonable to assume that the spectrum for single electrons is the same as that for minimum ionizing hadrons. Thus, there is no relative loss of electrons over hadrons due to this cut.

F. Spectrometer Track Reconstruction

Particle tracks are reconstructed through use of the drift chamber coordinates. The direction of the momentum is determined by making χ^2 fits to the coordinates obtained from the front chambers. The magnitude of the momentum is determined by the bending that occurs in the magnetic field as determined by the chambers behind the magnet.

In order to eliminate any pairs that sneak through the counter cuts, only 1 track in the x and y projections is allowed. Furthermore, only one pair of matching hits is permitted in the drift chamber modules in front of the magnet.

A more detailed description is given in Appendix II.

G. Losses Due to Event Reconstruction

Intense scrutiny of events leads to the conclusion that the reconstruction efficiency for electrons is about 26% less for electrons than for hadrons. One principle reason for this is that electron trigger events have a greater multiplicity of hits in the front drift chambers most of which do not form coordinate pairs. This is not

unexpected since electrons may interact in the drift chambers or scintillation counters forming cascade showers. Events are lost in this way because they fail to meet the single track requirement. Furthermore, the cascade shower in the lead glass for electrons sometimes produces backscattering of particles into the back drift chambers leading to a greater multiplicity of hits and therefore a loss of efficiency. This backscattering accounts for about 7% of the 26% difference.

H. The Lead Glass

Electrons and photons of high energy incident on the lead glass interact through bremsstrahlung and pair production to create a cascade shower. A parent electron radiates in the lead glass and the resulting photons convert to electron-positron pairs, which in turn radiate. Furthermore, the total track length of all charged particles (e^+e^-) in the shower is proportional to the energy of the incident electron or photon. Thus, since the electron Cerenkov threshold in the lead glass is 0.4 MeV, the intensity of the Cerenkov light produced by the shower is approximately proportional to the incident energy.

Hadrons, on the other hand, do not have this chain reaction mechanism for creating showers, but mostly lose energy through the ionization mechanism. The Cerenkov thresholds for π , K, and p in the lead glass are 104, 369

and 701 MeV, respectively. Some Cerenkov light is thus expected. But lacking the chain reaction mechanism the intensity of the light is less and is not directly proportional to the incident energy. A highly relativistic muon or non-interacting hadron gives the same light as a 366 MeV electron.¹¹

I. Lead Glass Reconstruction

Since the diameter of an electron cascade shower of several GeV is not bigger than several centimeters in diameter,¹² a shower from an electron must be contained in at most four adjacent blocks. Thus, the energy E_{cl} deposited in each of all possible combinations of four adjoining blocks (clusters) is calculated. The cluster with the highest energy is selected for further consideration. In order to eliminate background from multiphoton events the requirement

$$E_{tot} - E_{cl} < \begin{cases} 1/3 E_{tot}, E_{tot} > 300 \text{ MeV} \\ 100 \text{ MeV}, E_{tot} < 300 \text{ MeV} \end{cases}$$

E_{tot} = energy in entire matrix

E_{cl} = energy in the selected cluster

is imposed. The coordinate of the shower (x_c, y_c) is then calculated by taking the energy-weighted average of the midpoints of the blocks. To ensure that the shower was

caused by the particle reconstructed in the spectrometer, the requirement, defining (x_s, y_s) as the hit point of the extrapolated track on the lead glass,

$$|x_c - x_s| < 90 \text{ mm}$$

$$|y_c - y_s| < 90 \text{ mm}$$

must be satisfied.

By examining events without these lead glass cuts, it is estimated that the imposition of these cuts eliminates 2.5% more electrons than hadrons.

J. Energy-Momentum Check

Since electrons of $p > 400 \text{ MeV}/c$ are extremely relativistic and since the resulting electron cascade shower in the lead glass should be completely contained, the momentum p_{sp} of an electron measured by the spectrometer should be equal to the energy E_{lg} measured in the lead glass. In contrast, the energy of an incident hadron E_h is much greater than the energy E_{lg} measured in the lead glass. Thus, for hadrons, p_{sp} is much greater than E_{lg} .

Figure II-7 is a scatter plot of E_{lg} vs. p_{sp} for events obtained with the hadron trigger. Figure II-8 is the scatter plot for events obtained with the electron trigger. The vertical band in both figures can be associated with hadrons while the diagonal band in Figure II-8 can be associated with electrons. To be classified as an

Figure II-7

Figure II-8

electron an event is required to be in the "electron band" defined by the two lines:

$$P_1(E) = 0.55E_{lg}$$

$$P_2(E) = 1.16E_{lg} + 150 \text{ MeV.}$$

The number of electrons lost due to this requirement can be estimated by fitting the lead glass pulseheight spectrum for various momentum intervals with a Gaussian of the form

$$\exp \left\{ - \frac{(E - p - \delta(p))^2}{2\sigma^2(p)} \right\}$$

An average loss of 0.5% is obtained.

K. Cerenkov Cut

Figures II-9 and II-10 show the pulseheight spectra of the gas Cerenkov counter for events in the electron band and in the hadron band respectively. As expected those in the electron band have a larger pulseheight than those in the hadron band. To be classified as an electron an event is required to have a pulseheight greater than two photoelectrons.

The number of electrons which fall below the gas Cerenkov cut can be estimated by fitting the pulseheight spectrum above the cut with the summation of Gaussian photoelectron peaks whose heights obey the expected Poisson distribution. A loss factor of about 10.5% is obtained.

Figure II-9

Figure II-10

It is important to note here that in the pulseheight plot for the hadron band (Figure II-10), most of the events are actually in the pedestal which is not shown. The rejection power of the Cerenkov cut (number above the cut divided by the total number) is actually about 4×10^{-3} .

L. Hadron Contamination in Electron Band

It can be seen from the scatter plot of E_{lg} vs p_{sp} for hadron trigger data (Figure II-8) that there is a background of hadron events which satisfy the criteria of an electron. To obtain a quantitative estimate of this background, the quantity $r = (E_{lg} - p_{sp}) / (p_{sp} \sqrt{2})$ is plotted in Figure II-11 for both electron and hadron trigger events. Normalizing so that the hadron peaks of both plots have equal number of events, it is found that the contamination C , defined as the number in the electron band for hadron trigger divided by the number in the band for electron trigger, is, on the average, 0.059. Table II-2 gives C as a function of p_L .

M. Hadron Composition at 30° in the ISR

The equipment of the experiment does not allow for the separation of π 's from other hadrons. However, all that is needed to calculate the e/π ratio is the pion to hadron ratio (π/h). This must be obtained from other experiments.

Figure II-11

TABLE II-2

Hadron Contamination in the Electron Band Whose Track
Extrapolates to the Thin and Thick Sections of the Vacuum
Chamber.

P_1 (GeV/c)	C Thin Bicone	C Thick Bicone
.2 - .3	.130	.067
.3 - .4	.063	.049
.4 - .5	.052	.030
.5 - .6	.053	.033
.6 - .7	.057	.059
.7 - 1.0	.056	.085
1.0 - 2.0	.132	.145

Specifically, two groups have measured the inclusive cross sections of π^+ , K^+ , p , and $\bar{p}$ at $\sqrt{s} = 52.8$ GeV, the energy of the experiment.¹³ Extrapolating their data to the x and $p_{\perp}$ range covered by electron arm, Figure II-12 is obtained. However, in reconstructing hadron events, a pulse-height consistent with minimum ionization in the front trigger counter was required. Since nonrelativistic protons and kaons are more heavily ionizing than pions of the same $p_{\perp}$, this cut preferentially rejects protons and kaons. Hadron losses due to this ionization requirement have been calculated using the well known energy loss formulas. Table II-3 gives the results and Figures II-13 and II-14 are plots of the experimental momentum spectra for positive and negative hadrons with the relative contributions of π , K , and p .

N. Event Losses

For the purpose of normalization it is important to know the losses of events due to selection criteria, absorption, instrumentaall and data processing inefficiencies, etc. However, since in this experiment the main thrust is to look for differences between electron and hadron events, and the measurement of the e/π ratio, a knowledge of the relative loss factors of electrons and hadrons will suffice.

The relative losses from all the major sources have already been discussed in this chapter. These were:

Figure II-12

TABLE II-3

Composition and Efficiency of Detection of Electron Arm Hadrons

	$p_{\perp}$ GeV/c	.2-.3	.3-.4	.4-.5	.5-.6	.6-.7	.7-1.0	1.0-2.0
Extrapolated Ratio	p/π^+	0.072	0.093	0.110	0.124	0.135	0.149	0.172
	K^+/π^+	0.045	0.067	0.095	0.128	0.164	0.219	0.372
	$\bar{p}/\pi^-$	0.053	0.066	0.079	0.089	0.099	0.113	0.150
	K^-/π^-	0.023	0.038	0.055	0.072	0.090	0.117	0.186
Monte Carlo efficiencies	$\epsilon_p/\epsilon_{\pi}$	0.0	0.004	0.109	0.358	0.681	0.996	1.329
	$\epsilon_K/\epsilon_{\pi}$	0.106	0.541	0.859	0.944	1.118	1.199	1.306
Effective π/h	π^+/h	0.992	0.952	0.913	0.855	0.792	0.716	0.582
	π^-/h	0.944	0.965	0.931	0.898	0.853	0.799	0.693

Figure II-13

Figure II-14

- (1) a 26% loss of electrons relative to hadrons in event reconstruction,
- (2) a 0.5% loss of electrons relative to hadrons from the electron band cut,
- (3) a 2.5% loss of electrons relative to hadrons from the lead glass cluster cuts, and
- (4) a 10.5% loss of electrons relative to hadrons from the gas Cerenkov counter pulseheight cut.

Combining the above determined relative losses into relative efficiencies of detection one obtains:

$$\begin{aligned}
 \frac{\epsilon_e}{\epsilon_h} &= \left(\frac{\epsilon_e}{\epsilon_h} \text{ reconstruction} \right) \left(\frac{\epsilon_e}{\epsilon_h} \text{ C} \right) \left(\frac{\epsilon_e}{\epsilon_h} \text{ Band} \right) \left(\frac{\epsilon_e}{\epsilon_h} \text{ lead glass} \right) \\
 &= (.74) (.895) (.995) (.975) \\
 &= 0.64
 \end{aligned}$$

CHAPTER III

THE INCLUSIVE DIRECT ELECTRON SIGNAL--THE "e/ π " RATIO

Since electrons have now been separated from hadrons and that since the hadronic composition and the relative efficiency of detecting electrons and hadrons have been estimated, the inclusive direct electron yield, in the form of the ratio of electrons to pions as a function of $p_{\perp}$, can now be determined.

A. The Measured e/ π Ratio

The e/ π ratio measured in the electron arm irrespective of the source can be determined by dividing the number of electrons by the number of hadrons from hadron trigger events, normalizing to equal livetime, correcting for the relative loss of electrons ($\epsilon_e/\epsilon_h = 0.64$), and correcting for hadrons other than pions. The resulting e^-/π and e^+/π ratios ($\pi = \frac{1}{2}(\pi^+ + \pi^-)$) as a function of $p_{\perp}$ are given in Table III-1 and plotted in Figures III-1 and III-2.

B. Background Sources

There are a number of known sources of electrons which must be considered when measuring the direct electron signal. The electrons from these sources are not considered as part of the direct electron signal and therefore must be eliminated. These sources are:

TABLE III-1

The Measured e/π Ratio as a Function of $p_{\perp}$ for Events Whose Track Extrapolates to the Thin and Thick Sections of the Vacuum Chamber.

$p_{\perp}$ GeV/c	.2-.3	.3-.4	.4-.5	.5-.6	.6-.7	.7-1.0	1.0-2.0
THIN Vacuum Chamber							
$\frac{e^+}{\pi}(10^{-4})$	9.72 ± 1.30	6.05 ± 0.80	4.76 ± 0.58	3.28 ± 0.51	2.68 ± 0.53	2.54 ± 0.44	1.27 ± 0.41
$\frac{e^-}{\pi}(10^{-4})$	12.01 ± 1.48	7.78 ± 0.96	5.13 ± 0.62	4.15 ± 0.59	3.48 ± 0.62	3.37 ± 0.52	1.42 ± 0.41
THICK Vacuum Chamber							
$\frac{e^+}{\pi}(10^{-4})$	20.33 ± 2.83	13.05 ± 1.64	8.78 ± 1.04	6.06 ± 0.90	4.06 ± 0.87	3.43 ± 0.61	2.76 ± 0.82
$\frac{e^-}{\pi}(10^{-4})$	26.93 ± 3.56	15.99 ± 1.90	12.02 ± 1.28	8.71 ± 1.14	8.74 ± 1.35	4.94 ± 0.77	2.29 ± 0.66

Figure III-1

Figure III-2

- (1) pair production in the vacuum chamber where one particle misses the spectrometer through multiple scattering,
- (2) Compton electrons produced in the vacuum chamber,
- (3) Dalitz pairs from π^0 and η^0 where one particle misses the spectrometer either through multiple scattering in the vacuum chamber or through wide opening angle of the pair, and
- (4) electrons from the semi-leptonic decay of kaons.

These processes are illustrated in Figure III-3. Electrons from any source other than the above listed background sources are considered to be "direct" electrons.

It is important to note that the first background processes depend on the vacuum chamber thickness D . The production cross section of the first two depends linearly on D . Furthermore, the multiple scattering in γ -conversion gives an extra factor of $D^{1/2}$ resulting in a total dependence of $D^{3/2}$ for this process. The third process, Dalitz pairs, has a component which does not depend on this thickness (wide angle pairs) in addition to the multiple scattering component which has a $D^{1/2}$ dependence.

It is therefore expected that thick vacuum chamber events have a higher raw e/π ratio than do thin vacuum chamber events. The data shows that this is indeed the case. Thus, in order to be as background independent as possible, thick

Figure III-3

vacuum chamber events will only be used to help estimate the background while thin vacuum chamber events will be used to determine the e/π ratio.

Background due to pair production and Compton effect can be estimated by Monte Carlo calculation. The production mechanisms of these two electromagnetic processes are known. The multiple scattering of the particles is modeled in the computer by doing a random walk whose overall distributions obey the multiple scattering laws. It is assumed that the γ 's are from π^0 decays, so that the μ production distribution is generated by modeling π^0 production and decay using the measured inclusive pion cross sections.

Furthermore, the Monte Carlo calculations for these two processes can be checked against the experimental data. First, the data from thin and thick sections of the vacuum chamber can be compared. Subtracting the e^+ contribution of each section from the corresponding e^- contribution gives an experimental measurement of the Compton background. Subtracting the e^+ contribution of the thin section from the e^+ contribution of the thick section gives an estimate of the pair background.

The background due to γ -conversion and Compton electrons can be experimentally measured by placing next to the vacuum chamber extra conversion material with veto counters in front and trigger counters behind (Figure III-4). Electrons not coming from γ -conversion and Compton effect can therefore

Figure III-4

be vetoed. The material is identical to the actual vacuum chamber material. In this case the e^+ contribution gives the pair background and e^-e^+ gives the Compton background.

The resulting contributions from Compton electrons and pair production to the raw e/π contribution are given in Table III-2 and compared with the data in Figure III-5a. These results come from the Monte Carlo calculation. Because of limited statistics the experimental background measurement was used only to check the Monte Carlo results.

As can be seen in Table III-2 after Compton electrons are taken into account, the data is consistent with no charge assymetry to within 1 standard deviation in all $p_{\perp}$ bins. Therefore, the e^- and e^+ data are averaged to form a total e/π rate.

The background from π^0 and η^0 Dalitz and K decays is calculated with a Monte Carlo. The pion and kaon inclusive cross sections are known through experimental measurements.¹³ The η/π ratio has been measured for $p_{\perp} > 1.5$ GeV/c.¹⁴ For $p_{\perp} < 1.5$ GeV/c the η/π ratio is assumed to follow the same form as the K/π ratio. The resulting e/π ratios from these sources are given in Table III-2 and compared with the data in Figures III-5a and III-5b.

C. The Final e/π Ratio

The e/π ratio with these backgrounds subtracted as a function of $p_{\perp}$ is listed in Table III-3 and plotted in

TABLE III-2

The Background Contribution to e/π as a Function of $p_{\perp}$

$p_{\perp}$ GeV/c	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-1.0	1.0-2.0
Raw e^{-}/π	12.01±1.40	7.78±0.96	5.13±0.62	4.15±0.59	3.48±0.62	3.37±0.52	1.42±0.43
Compton	1.95±0.09	1.17±0.05	0.75±0.04	0.46±0.03	0.38±0.04	0.22±0.01	0.12±0.02
$K^{-} \rightarrow e^{-} \pi^{0} \nu$	0.19±0.06	0.27±0.06	0.25±0.06	0.20±0.10	0.17±0.07	0.10±0.05	0.12±0.08
$e^{-}/\pi -$ Compton- K^{-}	9.87±1.40	6.34±0.96	4.13±0.62	3.49±0.60	2.93±0.63	3.05±0.52	1.18±0.44
Raw e^{+}/π	9.72±1.30	6.05±0.80	4.76±0.58	3.28±0.51	2.68±0.53	2.54±0.44	1.27±0.41
$K^{+} \rightarrow e^{+} \pi^{0} \nu$	0.25±0.07	0.38±0.08	0.28±0.07	0.25±0.09	0.22±0.09	0.14±0.06	0.13±0.10
$e^{+}/\pi - K^{+}$	9.47±1.30	5.67±0.80	4.48±0.58	3.03±0.52	2.46±0.54	2.40±0.44	1.14±0.42
γ -conversion	1.45±0.28	1.19±0.24	0.74±0.18	0.54±0.27	0.38±0.22	0.23±0.12	0.10±0.05
π Dalitz	1.97±0.26	1.00±0.17	0.62±0.13	0.38±0.07	0.28±0.12	0.18±0.08	0.0 ±0.08
η Dalitz	0.51±0.08	0.32±0.04	0.15±0.03	0.12±0.03	0.03±0.01	0.03±0.02	0.0 ±0.02
$K^{0} \rightarrow e^{\pm} \pi^{\mp} \nu$	0.20±0.10	0.25±0.12	0.20±0.10	0.17±0.10	0.10±0.09	0.07±0.07	0.0 ±0.07
Σ	4.13±0.40	2.76±0.32	1.71±0.25	1.21±0.30	0.79±0.27	0.51±0.16	0.10±0.12
$e^{-}/\pi - \Sigma$	5.74±1.46	3.58±1.01	2.42±0.67	2.28±0.67	2.14±0.69	2.54±0.54	1.08±0.46
$e^{+}/\pi - \Sigma$	5.34±1.36	2.91±0.86	2.77±0.63	1.82±0.60	1.67±0.60	1.89±0.47	1.04±0.44
$e^{\pm}/\pi$	5.53±1.00	3.19±0.65	2.61±0.46	2.02±0.45	1.87±0.45	2.17±0.35	1.06±0.32

TABLE III-3

The "Direct" e/π Ratio at 30° in the Center of Mass as a Function
of $p_\perp$

$p_\perp$ GeV/c	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-1.0	1.0-2.0
e^-/π (10^{-4})	5.74 ± 1.46	3.58 ± 1.01	2.42 ± 0.67	2.28 ± 0.67	2.14 ± 0.69	2.54 ± 0.54	1.08 ± 0.46
e^+/π (10^{-4})	5.34 ± 1.36	2.91 ± 0.86	2.77 ± 0.63	1.82 ± 0.60	1.67 ± 0.60	1.89 ± 0.47	1.04 ± 0.44
$e^\pm/\pi$ (10^{-4})	5.53 ± 1.00	3.19 ± 0.65	2.61 ± 0.46	2.02 ± 0.45	1.87 ± 0.45	2.17 ± 0.35	1.06 ± 0.32

Figure III-5a,b,c

Figure III-5c. The most striking features are:

- (1) There is a sizable unexplained source of electrons,
- (2) The ratio rises from the canonical 10^{-4} at $p_{\perp} = 1.5 \text{ GeV/c}$ to 6×10^{-4} at $p_{\perp} = 0.25 \text{ GeV/c}$.

It thus appears as if the high $p_{\perp}$ behavior is different than the low $p_{\perp}$ behavior.

Figure III-6 gives a comparison of this data with the data obtained by the CCRS group¹⁵ at the same ISR energy. The flat behavior at high $p_{\perp}$ can clearly be seen in their data. However, there appears to be a small (1.5 standard deviation) discrepancy between our data and the CCRS data in the overlap region between the two experiments. This could easily be due to differences in background subtraction. Furthermore, the CCRS group measured the e/π at 90° in the center of mass.

D. Possible Sources

There have been a number of suggested sources for the excess electrons. These are excellently discussed in a review article by Lederman.¹⁶ They can be broken down into three main categories:

- (1) electrons from Vector meson decay($\rho, \omega, J/\Psi$).
- (2) electrons from the decay of new particles (i.e. charmed particles), and
- (3) virtual photon continuum models.

Each of these will be briefly discussed.

Figure III-6

D.1 Electrons from Vector Meson Decay

The vector mesons ρ , ω , and ϕ are produced with hadronic cross sections and have leptonic branching ratios ($\sim 10^{-4}$ - 10^{-5}) and therefore might be expected to be a source. Furthermore, even though J/ψ is produced with a low cross section at the ISR ($3 \times 10^{-3} \text{ cm}^2$),¹⁷ the branching ratio into e^+e^- is a high 7%.¹⁶ It too can be expected to contribute especially for $p_{\perp}$ greater than about 2 GeV/c.

Using their phenomenological model,¹⁷ Bourquin and Gaillard (See Chapter IV-J.5) have calculated the expected contribution of known vector mesons to the e/π ratio at 90° . Their results are compared to the data in Figure III-7. The contribution approaches 10^{-4} at high $p_{\perp}$ but falls far below at low $p_{\perp}$. Calculations by other theorists give similar results.

D.2 Electrons from Decay of Charmed Particles

As mentioned in the introduction, one possible source of electrons is from semi-leptonic decay of charmed particles. However, as outlined below, it is difficult to explain the rise with low $p_{\perp}$. Theoretical estimates for charmed particle production in p-p collisions are in the range 1-100 μb .¹⁹ Electron decay branching ratios are expected to be 10% to 20%. Thus, the absolute limit for σ_B is about 20 μb .

One model for associated production of the charmed particles D and $\bar{D}$ has been developed by Bourquin and

Figure III-7

Gaillard¹⁷. However, with $M_D = 2.2 \text{ GeV}/c^2$ they need $\sigma_B(D \rightarrow K e \nu)$ to be $3.6 \times 10^{-30} \text{ cm}^2$ to fit the CCRS data after the vector meson contribution has been subtracted (Figure III-8). Clearly, the decay $D \rightarrow K e \nu$ cannot be responsible for the bulk of our electron signal.

An attempt to explain the low $p_\perp$ data has been made by Hinchliffe and Llewellyn-Smith²⁰ by assuming the decay $D \rightarrow K^*(890) e \nu$. Figure III-9 compares our data with their calculation for $M_D = 1.8 \text{ GeV}/c^2$ and $\sigma_B = 30 \times 10^{-30} \text{ cm}^2$. It fits the data to $p_\perp = 0.4 \text{ GeV}/c$, but falls rapidly after that.

Another critical problem for the charm model explanation is the apparent lack of an energy threshold in the production of prompt electrons. The Penn-Stony Brook group at BNL has observed an e/π ratio of the order 10^{-4} at $\sqrt{s} = 4.5 \text{ GeV}$, below the threshold energy for $D\bar{D}$ production.²¹

D.3 Photon Continuum Model

There have been a number of processes suggested which produce electrons through decay of virtual photons emerging from the hadronic blob. With the addition of electrons from vector meson decays Farrar and Frautschi have been able to explain the large $p_\perp 10^{-4}$ ratio with a large $p_\perp$ virtual bremsstrahlung model.²² With a modified Drell-Yang

Figure III-8

Figure III-9

parton annihilation model M. Duong-Van has also been able to explain the e/π ratio at large $p_{\perp}$.²³ However, neither of these models attempt to predict the low $p_{\perp}$ behavior.

Using a soft virtual bremsstrahlung model R. Ruckl has obtained an e/π ratio which rises with low $p_{\perp}$ of approximately the right order of magnitude.²⁴ However, since his calculation includes small opening angle e^+e^- pairs while our experimental setup rejects pairs with opening angle less than about 600 mrad, a direct comparison of theory and experiment is not possible.

A Gurtu, D. S. Narayan and K. Sarma have applied the hadronic cluster model to lepton production by assuming a small branching ratio to leptons.²⁵ Low mass "central" hadronic clusters are assumed to be produced with small momenta in the center of mass system. The clusters then decay into e^+e^- , $\mu^+\mu^-$ and $\pi^+\pi^-$ such that the inclusive pion distribution is reproduced for small $p_{\perp}$ and p_L and such that the e^+e^- branching ratio of the cluster with the ρ mass is the e^+e^- branching ratio of the ρ meson (4.3×10^{-5}). The results of their model are compared with our data in Figure III-10. Although the agreement is good for low $p_{\perp}$, the model does not predict high $p_{\perp}$ behavior.

Figure III-10

CHAPTER IV

ELECTRON-STRANGE PARTICLE COINCIDENCES

Now that electrons and hadrons have been reconstructed and separated in the electron arm, we can turn to the forward spectrometer to isolate strange particle events to determine if there is an electron-strange particle coincidence, a signature of charmed particle production. Although there are many strange particles, only Λ^0 's and K^0 's will be considered because they can be readily identified on the basis of the momentum measurement alone.

The three strange particles Λ^0 , K_S^0 , and K_L^0 have relatively long lifetimes of 2.6×10^{-10} , 0.9×10^{-10} , and 5.2×10^{-8} second respectively. The average decay lengths for a particle with a momentum of 1 GeV/c are thus 6.9, 5.4, and 3120 cm respectively. Therefore, since the predominant charged decay modes are $\Lambda^0 \rightarrow p\pi^-$, $K_S^0 \rightarrow \pi^+\pi^-$, and $K_L^0 \rightarrow \pi^+\pi^-\pi^0$, $\pi^\pm e^\mp \nu$, $\pi^\pm \mu^\mp \nu$, a characteristic topology of these particles is two charged tracks materializing at a point downstream of the interaction point forming a "V" (see Figure IV-1). Furthermore, Λ^0 and K_S^0 are further identifiable by the unique four momentum ("effective mass") of the measureable charged tracks of the V.

Λ^0 's, K_S^0 's, and V's are identified by this method in the spectrometer. Then the number of these particles

Topology of strange particle detected by the apparatus.

Figure IV-1

associated with an electron is compared with those associated with a hadron in the electron arm to determine if there is any correlation.

A. The Forward Spectrometer

The forward spectrometer (Figures II-2 and IV-2) was used to detect strange particles and muons. A variant of it²⁶ was used in earlier experiments²⁷ to study diffractive dissociation.

Two septum magnets, each with aperture $62 \times 30 \text{ cm}^2$ and $\int Bdl$ of $4.7 \text{ kG} \times 2.6 \text{ meters}$, were placed 4.69 meters downstream of the intersection along Beam 1. Two multiwire proportional chamber supermodules, 0.83 meter apart, were placed in front of each magnet 2.75 meters from the intersection. Each supermodule (Figure IV-3) consisted of four planes: x, y planes with 2 mm wire spacing and u, v planes with $2\sqrt{2} \text{ mm}$ spacing orientated 0° , 90° , $+45^\circ$, and -45° from the vertical respectively. The upstream half of each magnet contained a four element gas Cerenkov counter filled with Freon 22 at atmospheric pressure (Figure IV-4). The thresholds for π , K , and p were 3.6 , 12.7 , and 24.1 GeV/c respectively. A supermodule was placed just downstream of the Cerenkov counter at the center of each magnet. The downstream half of each magnet was filled with concrete for use as a muon filter. Two supermodules with iron in between were placed behind each magnet to identify muons.

TABLE IV-1
Forward Spectrometer Parameters.

Two septum magnets	62 x 80 cm ² aperture	
$\int Bdl$ through magnet chambers (hadron)	4.7x1.3 kG.m	
$\int Bdl$ through entire system (μ)	4.7x2.6 kG.m	
Solid angle		
Through magnet chamber	0.0018x4 π	
Through front chambers	0.0024x4 π	
Angular Range		
horizontal	± 60 mrad	
vertical	$\pm (20-100)$ mrad	
MWPC Modules	2 in front 2 after 1 inside	} each magnet
	- each consists of 4 planes	
	x,y : 2mm spacing	
	u,v : 2 $\sqrt{2}$ mm spacing	
Cerenkov Counter	4 cells in each magnet	
Gas	1 atmosphere Freon 22	
Thresholds	π - 3.6 GeV/c K - 12.7 GeV/c p - 24.1 GeV/c	
Absorber	0.8m steel between the back MWPC supermodule	
	1.5 meter concrete behind magnet MWPC inside magnet

FORWARD ARM SPECTROMETER SIDE VIEW

Figure IV-2

Figure IV-3

Figure IV-4

Thus, only the first half of the spectrometer can be used to detect the hadrons from strange particle decays. The supermodules in front of the magnet are used to determine hadron trajectories. The momentum of a hadron is calculated from the bending in the magnetic field as determined by the supermodule at the center of the magnet before the concrete muon filter

B. Coordinate System

The coordinate system as shown in Figure IV-2 was used in the forward arm track reconstruction and analysis. The origin of the system is the ISR intersection point. The z axis is along the axis of the forward spectrometer (Beam 1). The y axis is vertical and points in the direction of the magnetic field. The x axis points inward toward the center of the ISR ring.

C. Track Reconstruction

The purpose of this analysis is to see if there is an excess of Λ 's or K^0 's in events with an identified electron over those with a hadron in the electron arm. It is therefore only necessary to find events with two tracks in the forward spectrometer which meet in a vertex.

The track finding method is described in detail in Appendix III. Simply, it consists of three major steps:

- (1) points are found in each supermodule,
- (2) lines are formed between the two modules in front of the magnet, and
- (3) tracks are formed by matching this line with a point in the magnet chamber.

The momentum distribution of the resulting tracks as given in Figure IV-5.

D. Momentum Resolution

As derived in Appendix IV, an approximate expression for the momentum resolution is

$$\Delta p = (0.02)p^2 \quad (p \text{ in GeV})$$

Thus by 5 GeV an error of 12% results.

However, due to the quantization of the proportional wire chamber coordinates, this distribution is not truly Gaussian. The resulting quantization of the momentum resolution distribution can be seen in the Monte Carlo calculated Δp distributions of Figure AIV-3 (see Appendix IV). As momentum increases a tail develops and is clearly visible by 4 GeV (Figure AIV-4). The calculated momentum of particles in this tail is higher than the true momentum. This tail is the result of the nonlinear dependence of the momentum on the entry and exit points of the particle in the magnetic field. An error in these points toward higher momentum results in a much higher momentum error than an equal error in the points toward lower momentum.

MOMENTUM OF TRACK
HADRON COINCIDENCE

Figure IV-5

E. Vertex Reconstruction

Particle tracks originating from the same point (the vertex) do not normally meet at this point after reconstruction due to experimental measurement error. Their closest distance of approach (CDA) depends upon the measurement error. The CDA distribution of all pairs of tracks as given in Figure IV-6. Those pairs in the peak at low CDA (< 20 mm) are presumed to be pairs whose tracks "meet" in a vertex. The vertex is assumed to be the midpoint of the line connecting the two tracks at the closest distance of approach.

The problem of vertex reconstruction of three or more tracks whose particles had originated from the same point is similar. The point which minimizes the sum of the squares of the distances to each of the respective tracks (SSQ^2) is found. Figure IV-7 is a plot of the SSQ distribution for three tracks two of which transverse the forward spectrometer while the other transverses the electron arm. Those with $SSQ < 20$ mm are presumed to be events whose three tracks originate from the same point.

F. Vertex Resolution

The fact that tracks of particles originating from the same point do not experimentally meet at this point implies that there is a minimum experimentally resolvable separation distance $L_{\min}$ between a V from Λ^0 or K^0 decay and

HADRON COINCIDENCE-NO SSQ CUT

Figure IV-6

HADRON COINCIDENCE-NO SSQ CUT

Figure IV-7

the primary interaction vertex. When the decay distance is less than this minimum distance, then the V appears to form a multitrack vertex event with the other tracks from the interaction.

$L_{\min}$ is not constant but depends upon the angles between the tracks involved. Specifically, in this paper we are concerned with a topology where the two tracks from the strange particle decay transverse the forward arm while a third track transverses the electron arm (Figure IV-1). The forward arm track directions vary between 20 and 120 milliradian from the beam while the electron arm track varies between 470 and 650 milliradian (27-37 degrees). The angular resolutions of both spectrometers is about 1 milliradian. The angle between the electron arm track and either of the forward arm tracks is thus well determined compared to the angle between the forward arm tracks. It is thus the opening angle of the V on which the minimum separation distance depends.

As this opening angle decreases, a fluctuation in the angle of one of the tracks causes an increasing change in the position of the vertex. Thus, the uncertainty of the position of the vertex becomes worse with smaller opening angle. The minimum separation distance $L_{\min}$ resolvable by the equipment also becomes greater.

One way of determining $L_{\min}$ is to find the maximum separation distance between the vertex of a V and the interaction vertex for events whose V is unresolvable (events where experimentally the V forms part of the interaction vertex). Figure IV-8 is a scatter plot of the distance between the two track vertex of the forward arm tracks ($CDA < 20$ mm) and the three track vertex ($SSQ < 20$ mm). The maximum distance is about 200 mm for the larger angles. However, at about 60 milliradians a tail begins to develop so that by 10 milliradians the maximum is greater than one meter. Fortunately, the average opening angle is 74 milliradians.

Another way of determining $L_{\min}$ is to use V's whose effective mass corresponds to a Λ (1.095-1.135 GeV). Figure IV-9 is a scatter plot of the SSQ of the three tracks and the distance between the vertex of the forward arm V and the primary interaction vertex. The primary interaction vertex is calculated from the " Λ " and the electron arm tracks (see next section). Some of these events have small opening angle so that there are some events with large distance and small SSQ. However, the absolute minimum distance which can be resolved by the equipment ($SSQ > 20$ mm) is again about 200 mm. (Events with $SSQ < 20$ mm form a "good" vertex).

SSQ VS DISTANCE
HADRON COINCIDENCE

Figure IV-8

SSQ VS. DISTANCE
LAMBDA EVENTS

Figure IV-9

Thus, for V's whose opening angle is above about 50 milliradian the minimum decay path resolvable by the spectrometers is about 200 mm. For small opening angle V's this distance becomes increasingly greater.

G. Identification of Λ^0

The Λ^0 particle decays weakly with a lifetime of 2.6×10^{-10} second. A 10 GeV Λ^0 has an average decay path of 70 cm. Therefore, an excellent method of isolating Λ^0 events is to require that the vertex of the V caused by the Λ^0 decay ($\Lambda^0 \rightarrow p\pi$) be a minimum distance from the production vertex.

This can be accomplished in the following manner:

- (1) The total vector momentum $\vec{p}_t$ of each two tracks of zero net charge is calculated ($\vec{p}_t = \vec{p}_1 + \vec{p}_2$) forming a possible trajectory of the Λ^0 .
- (2) This trajectory is required to form a vertex (CDA < 20 mm) with the track of the particle from the electron arm. This vertex is required to be in the ISR diamond. The vertex of the V and of the interaction are known so that the requirement of minimum separation distance can be enforced.
- (3) The positive track is assumed to be a proton and the negative a pion. The resulting effective mass is then calculated.

Figure IV-10 a, b, c, and d are plots of the resulting $p\pi^-$ mass spectrum for minimum separation distances of the V from the interaction vertex of 0, 100, 200, and 300 mm. A clear signal at the Λ^0 mass ($1.115 \text{ GeV}/c^2$) with a width (FWHM) of less than $30 \text{ MeV}/c^2$ develops. A plot of the total momentum p_t of the $p\pi^-$ events between 1.095 and $1.135 \text{ GeV}/c^2$ with a minimum separation distance of 100 mm, Figure IV-11, shows that the average momentum is about $10 \text{ GeV}/c$ with a spread of $16 \text{ GeV}/c$. In Appendix IV the mass resolution (FWHM) of Λ^0 is calculated to vary between $6 \text{ MeV}/c^2$ at $p_{\Lambda^0} = 2 \text{ GeV}/c$ to $20 \text{ MeV}/c^2$ at $p_{\Lambda^0} = 15 \text{ GeV}/c$. Thus, the width of this peak at the Λ^0 mass is compatible with the Monte Carlo calculated mass resolution of the Λ^0 .

The integrated proper lifetime spectrum of events with a mass between 1.10 and $1.14 \text{ GeV}/c^2$ is given in Figure IV-12. For each point the number of events is the number with lifetime greater than the given value. The data gives a fitted lifetime of $2.2 \pm 0.2 \times 10^{-10}$ second. Considering the statistics and background, this is quite compatible with the known lifetime of the Λ^0 , 2.6×10^{-10} second.

The $p\pi^-$ effective mass plots show that even for the higher separation distance plots there are events which are not in the Λ^0 peak. The mass resolution studies of Appendix IV show that some of the events at higher masses may be Λ^0 's which reconstruct with a large error. Another

NO DISTANCE CUT

DISTANCE CUT OF 100 MM

DISTANCE CUT OF 200 MM

DISTANCE CUT OF 300 MM

MASS OF P PI- FOR HADRON COINCIDENCE

Figure IV-10

Figure IV-11

Figure IV-12

source of background is misidentified K^0 's which would give a recognizable V. Furthermore, since the resolution of the equipment requires at least 200 mm between the interaction vertex and the V vertex in order to identify a V, most of the large background seen in the lower distance plots is due to non-V events. Since some of these events have small opening angle (Figure IV-13) for which the minimum distance is even greater, non-V events may form background events even for the larger distance plots.

H. Λ -e Coincidences

To determine if there are more Λ^0 's associated with an electron than with a charged hadron in the electron arm, the ratio of the number of electron associated Λ^0 's to the total number of electrons ($R_e = N_{e\Lambda} / N_e$) is compared to the ratio of the number of hadron associated Λ^0 's to the total number of hadrons ($R_h = N_{h\Lambda} / N_h$). To keep the background due to non-direct electrons as low as possible, only electrons from the thin section of the vacuum chamber are used in this study. Even for these events about 40% of the electrons are not direct. To equalize acceptance the hadrons are also restricted to the thin section.

The background in the Λ^0 peak for hadronic associated events can be estimated by extrapolating the spectrum at high mass into the Λ peak as shown in Figure IV-14. The number of Λ^0 's ($N_{h\Lambda}$) associated with a hadron in the

Figure IV-13

NO DISTANCE CUT

DISTANCE CUT OF 100 MM

DISTANCE CUT OF 200 MM

DISTANCE CUT OF 300 MM

MASS OF P π^- FOR HADRON COINCIDENCE THIN BICONE

Figure IV-14

electron arm is then obtained by subtracting this background from the total number of events (N_{ht}) between 1.09 and 1.14 GeV/c^2 .

Since there are only 5147 thin bicone electrons there are too few electron associated events to make a good background estimate. This background is assumed to be at the same level as in the case of the hadron associated events.

The results are given in Table IV-2. There is no evidence of a coincidence signal. However, the statistics are poor. There would have to be about twice as many Λ^0 's associated with electrons than with hadrons to give a four standard deviation effect.

I. K_S^0 Identification

The problem of isolating the K_S^0 signal is similar to but more difficult than Λ^0 identification. The K_S^0 lifetime, 0.866×10^{-10} second, is one-third the lifetime of the Λ^0 . If, for example, the Λ^0 and K^0 momenta were the same, then a decay path distance of 300 mm for Λ^0 would be equivalent to 200 mm for K_S^0 . This implies that a greater fraction of the K_S^0 's be unresolvable than in the case of the Λ^0 's. Furthermore, the mass resolution (FWHM) of K_S^0 , as calculated in Appendix IV, varies between $30 \text{ MeV}/c^2$ at $p_K = 4 \text{ GeV}/c$ to $70 \text{ MeV}/c^2$ at $p_K = 10 \text{ GeV}/c$. This is much worse than the 7 to $13 \text{ MeV}/c^2$ range of the Λ^0 . Thus, the K_S^0 signal at a specified minimum separation distance is not

TABLE IV-2

Comparison of the number of Λ 's associated with an electron and the number of Λ 's associated with a hadron in the same kinematic range. The total number of electrons (N_e) is 5147. The total number of hadrons (N_h) is 63430.

Minimum Distance (mm)	Hadron Coincidence Events			Electron Coincidence Events		Ratio Comparison	
	$N_{ht} =$ Total Events 1.09-1.14 GeV/c ²	$N_{h\Lambda} =$ N_{hE} back-ground	$S = \frac{N_{h\Lambda}}{N_{ht}}$	$N_{et} =$ total events 1.09-1.14 GeV/c ²	$N_{e\Lambda} =$ $\frac{N_{e\Lambda}}{N_{et}}$	$R_{h\Lambda} =$ $\frac{N_{h\Lambda}}{N_h}$	$R_{e\Lambda} =$ $\frac{N_{eh}}{N_e}$
0	229	79	0.34 ± 0.05	17	5.8 ± 1.6	$1.25 \pm .14 \times 10^{-3}$	$1.13 \pm .31 \times 10^{-3}$
100	112	74	$0.66 \pm .10$	11	7.3 ± 2.5	$1.17 \pm .14 \times 10^{-3}$	$1.42 \pm .49 \times 10^{-3}$
200	73	58	$0.79 \pm .14$	5	4.0 ± 1.9	$0.91 \pm .12 \times 10^{-3}$	$0.77 \pm .37 \times 10^{-3}$
300	61	51	$0.84 \pm .16$	4	3.4 ± 1.8	$0.80 \pm .11 \times 10^{-3}$	$0.66 \pm .35 \times 10^{-3}$
400	48	43	$0.90 \pm .19$	4	3.6 ± 2.0	$0.68 \pm .10 \times 10^{-3}$	$0.66 \pm .35 \times 10^{-3}$

expected to stand out as clearly as the Λ^0 signal (Figure IV-14).

To isolate K_S^0 's the same procedure as in the Λ^0 case is followed except that π masses are assigned to both tracks. The resulting $\pi^+\pi^-$ mass spectra for minimum separation distances of 0, 50, 125, and 175 mm are given in Figure IV-15. To decrease the background those events with a $p\pi$ pass in the Λ^0 peak ($1.095-1.135 \text{ GeV}/c^2$) are not plotted. A peak at the K_S^0 mass with a width of about $80 \text{ MeV}/c^2$ is seen to develop. However, this peak is not well defined for the lower separation distance plots and not statistically significant for the higher distance plots. These plots are for all hadron events. For thin bicone hadrons the statistics are reduced by a factor of two. For thin bicone electron events, the statistical reduction factor relative to Figure IV-15 is twenty. Thus, it is not possible to do a statistically significant correlation study with identified K_S^0 's.

J. Electron-V Coincidence

The basic problem with using this setup to search for $e-K^0$ or $e-\Lambda^0$ coincidences is the small acceptance of both the electron and forward spectrometers. The solid angle they subtend at the crossing point of the ISR beam is only $0.0012 \times 4\pi$ steradian and $0.0016 \times 4\pi$ steradian respectively. However, it is possible to increase the solid

NO DISTANCE CUT

DISTANCE CUT OF 50 MM

DISTANCE CUT OF 125 MM

DISTANCE CUT OF 175 MM

MASS OF $\pi^+\pi^-$ FOR HADRON COINCIDENCE

Figure IV-15

angle of the forward spectrometer by 50% by requiring that the Λ^0 and K^0 charged decay products transverse only the supermodules before the magnet. The momentum determination and thus the effective mass determination are sacrificed.

As described earlier the minimum separation distance between a V and the interaction vertex that can be resolved by the spectrometer is about 200 mm. Table IV-3 gives the fraction of Λ^0 's, K_S^0 's, and K_L^0 's decaying between 200 mm and 2500 mm, the position of the front supermodules as a function of $\beta\gamma$.

Furthermore, the actual increase in acceptance for these particles is greater than the 1.5 solid angle factor especially for low momentum particles. The probability of detection depends upon the detection of the two charged particles of the V which are correlated in space by the vertex and opening angle. Table IV-4 gives the Monte Carlo calculated increase of acceptances for Λ^0 and K_S^0 between the front chambers and the chambers in the magnet. Isotropic production and phase space decay are assumed.

J.1 Event Reconstruction

To detect such V's from strange particle decays the following steps are followed:

- (1) Pairs of lines are formed in the front supermodules and are required to meet in a vertex ($CDA < 20$ mm).

TABLE IV-3

Fraction of Λ^0 , K_S^0 , and K_L^0 Decaying Between 200 and 2500 mm as a Function of $\beta\gamma$

$\beta\gamma$	Λ^0		K_S^0		K_L^0	
	p (GeV)	Fraction	p (GeV)	Fraction	p (GeV)	Fraction
2	2.23	27%	1.00	2%	1.00	7%
5	5.58	59%	2.49	22%	2.49	3%
8	8.92	71%	3.98	39%	3.98	2%
11	12.27	74%	5.48	51%	5.48	1%
14	15.61	73%	6.97	59%	6.97	1%
17	18.96	71%	8.47	64%	8.47	1%
20	22.30	-	9.96	68%	9.96	1%
25	27.88	-	12.45	72%	14.56	1%
30	33.45	-	14.94	74%	14.94	0.5%

TABLE IV-4

Relative Gain in Acceptance for Λ and K_S^0 Between Reconstruction Through the Supermodules in Front of the Magnet and Reconstruction Through the Supermodules in the Magnet as a Function of the Momentum.

p	Λ Gain	K_S^0 Gain
1-3	3.5	19.3
3-5	2.8	3.6
5-7	2.5	2.7
7-9	2.3	2.6
9-11	2.1	2.4
11-13	2.0	2.1
13-15	1.8	2.0
15-17	1.8	1.9
17-19	1.8	1.9

- (2) To eliminate those events where the V comes from the primary interaction vertex, the two lines and the track from the electron must not meet. This condition is ensured by requiring SSQ to be greater than 20 mm.

Figure IV-16 shows the vertex position of the pair of lines from the forward arm for all events. Figure IV-17 shows the vertex position for events with SSQ greater than 20 mm. The elimination of the ISR diamond in the second figure can clearly be seen indicating that the two tracks satisfy the criteria of a V. However, before we conclude that these tracks are from the decay of long lived particles, we must consider the possible backgrounds.

J.2 Backgrounds

The possible sources of background to Λ^0 , K_S^0 , and K_L^0 in these events are:

- (1) falsely reconstructed V's,
- (2) beam-gas interactions,
- (3) events where the two tracks of the V and the electron arm track come from the same vertex, and
- (4) e^+e^- pairs from γ -conversion.

These backgrounds are discussed below.

When considering all possible combinations of points in the front supermodules, false solutions may arise which just happen to meet all the criteria. This background is

V VERTEX FOR ALL V'S X-Z

V VERTEX FOR ALL V'S Y-Z

HADRON COINCIDENCE-NO SSQ CUT

Figure IV-16

V VERTEX FOR ALL V'S X-Z

V VERTEX FOR ALL V'S Y-Z

HADRON COINCIDENCE-BAD SSQ

Figure IV-17

estimated to be about 10% by continuing the flat distribution at large CDA (Figure IV-6) into the peak at small CDA.

The V could be from a beam-gas interaction and have no connection with the electron arm track. However, experimental timing gates minimize this background which is already small due to the good ISR vacuum. The V vertex plots (Figure IV-17) indicate that most of the V's have vertexes outside the beam position. In fact, many are outside the beam pipe.

Another source of background is events with three tracks which actually originate from the same vertex but somehow simulate the V topology (Figure IV-1). This may occur through experimental measurement error or multiple scattering in the vacuum chamber walls. However, the plane root mean square angle of deflection for multiple scattering of a 1 GeV proton is about 1 milliradian through the thick section of the vacuum chamber and 0.4 milliradian through the thin section and the forward window. The angular resolution of both spectrometers is also about 1 milliradian. Since the angle of the electron arm track relative to the two forward arm tracks is large ($\sim 30^\circ$) compared to these errors, the probability for three track vertex events having an SSQ greater than 20 mm is extremely small as shown below.

To be more quantitative, a Monte Carlo calculation similar to the one for mass resolution finds that all three track vertex events have a SSQ of less than 10 mm (Figure IV-18a). When Λ^0 , K_S^0 , and K_L^0 decays are simulated, the SSQ

3 TRACK VERTEX

LAMBDA

KZERO SHORT

KZERO LONG

MONTE CARLO SSQ

Figure IV-18a,b,c,d

distribution widens considerably (Figure IV-18b,c,d). Thus, by requiring the SSQ to be greater than 20 mm the single vertex events are eliminated.

Electron-positron pairs from γ -conversion could give a V topology. However, as seen in Chapter III, hadrons dominate over electrons by at least two orders of magnitude. Thus, it is very unlikely that many of these events are e^+e^- pairs. Furthermore, if γ -conversion were a substantial source, then the outline of the vacuum chamber would be seen in the V vertex plots. Figure IV-17 shows that this is not the case.

A particle with $\beta\gamma = 2$ takes a proper time of 3.3×10^{-10} second to travel 200 mm in the lab. Since 200 mm is the minimum resolvable decay distance, a particle must have a lifetime of around 10^{-10} second or greater to be detected in this analysis. Furthermore, since the distance to the front supermodules from the intersection is 2.5 meter, the maximum lifetime cannot be greater than about 10^{-8} second.

Thus, except for a 10% background due to falsely reconstructed events, the V's can be identified with particles with lifetimes between about 10^{-8} and 10^{-10} second. The only particles with lifetimes in this range that decay appreciably into two or more charged particles are Λ^0 , K_S^0 , and K_L^0 . Therefore, most of the V's can be ascribed to the decay of these particles.

J.3 Efficiency of Detection

The Monte Carlo calculated SSQ distributions for Λ^0 , K_S^0 , and K_L^0 (Figure IV-18 b,c,d) show that many of these particles are lost when the SSQ is required to be greater than 20 mm. These distributions are obtained by assuming isotropic production ($0 < \theta < 150$ mrad) and phase space decay into all modes giving two or more charged particles and by simulating the measurement error mechanisms. Tables IV-5, IV-6, and IV-7 give the acceptance as a function of momentum for events with and without the SSQ cut. The ratio between the acceptances with and without the SSQ cut is also given to show the resultant loss. For comparison with the results yet to be described, these acceptances are also listed for V's where the two tracks go through the same supermodules or through different supermodules.

J.4 Results

When considering the forward arm detector from the standpoints of track reconstruction and acceptance, the problem of detecting V's from long lived particles can be separated into two distinct parts. There are V events where (i) two tracks pass through the same two supermodules and (ii) where one track is above the beam pipe while the other is below ("different supermodule" events).

Those that transverse different supermodules obviously have larger opening angles on the average. The error in the vertex position is thus less. The minimum decay distance

Figure IV-19

TABLE IV-5

Calculated geometric acceptance of the front supermodules of the forward arm spectrometer for $K_S^0 \rightarrow \pi^+ \pi^-$. Results are given for (a) all events and (b) events where the K_S^0 decay vertex is clearly separated from the production vertex ($SSQ > 20$ mm). The acceptance is separately listed for events where the pions transverse the same set and different sets of supermodules. R is the fraction of events surviving the SSQ cut.

$p_{K_S^0}$ GeV/c	All Events			Events with $SSQ > 20$ mm			$R = \frac{A_{SSQ}^{Total}}{A_{Total}}$
	A_{same} $\times 10^4$	$A_{Different}$ $\times 10^4$	A_{Total} $\times 10^4$	A_{SSQ}^{same} $\times 10^4$	$A_{SSQ}^{Different}$ $\times 10^4$	A_{SSQ}^{Total} $\times 10^4$	
0-1	<.5	<.5	<.5	<.5	<.5	<.5	-
1-2	1.03	3.6	4.6	<.5	.5	.5	.11
2-3	14.4	21.0	35.4	.5	7.7	8.2	.23
3-4	28.4	172	200	4.7	81.1	85.8	.43
4-5	77.1	535	612	25.7	205	231	.38
5-6	274	665	939	129	224	353	.38
6-7	601	594	1194	288	161	449	.38
7-8	984	466	1450	450	131	581	.40
8-9	1380	407	1787	600	96.3	696	.39
9-10	1715	283	1997	718	55.5	773	.39
10-11	2000	240	2240	827	44.8	872	.39
11-12	2212	197	2409	859	24.9	884	.37
12-13	2415	148	2563	956	22.9	979	.38
13-14	2538	108	2646	964	4.5	968	.37
14-15	2630	70.7	2701	943	3.3	947	.35

TABLE IV-6

Calculated geometric acceptance of the front supermodules of the forward arm spectrometer for $K_L^0 \rightarrow \pi^+ \pi^- \pi^0$, $\pi^\pm e^\mp \nu$, $\pi^\pm \mu^\mp \nu$. Results are given for (a) all events and (b) events where $SSQ > 20\text{mm}$. The acceptance is separately listed for events where the two charged particles transverse the same set and different sets of supermodules. R is the fraction of events surviving the SSQ cut.

pK_L^0 (GeV)	All Events			Events with $SSQ > 20\text{ mm}$			$R' = \frac{A_{SSQ}^{total}}{A_{total}}$
	A_{same} ($\times 10^4$)	$A_{diff.}$ ($\times 10^4$)	A_{total} ($\times 10^4$)	A_{same}^{SSQ} $\times 10^4$	$A_{diff.}^{SSQ}$ $\times 10^4$	A_{total}^{SSQ} $\times 10^4$	
0-1	1.35	.95	2.30	1.28	.95	2.23	.97
1-2	7.13	3.10	10.23	6.97	2.91	9.88	.97
2-3	13.43	6.43	19.86	12.22	5.85	18.07	.91
3-4	18.74	5.64	24.38	17.10	4.91	22.01	.90
4-5	20.02	4.59	24.61	17.53	3.95	21.48	.87
5-6	22.66	3.82	26.48	19.40	2.80	22.20	.84
6-7	23.70	2.81	26.51	19.68	1.93	21.61	.82
7-8	22.79	2.07	24.86	17.82	1.38	19.20	.77
8-9	22.67	1.20	23.87	17.04	.77	17.81	.75
9-10	21.24	1.02	22.26	15.22	.69	15.91	.71
10-11	20.62	.69	21.31	14.86	.36	15.22	.71
11-12	19.68	.66	20.33	12.94	.37	13.33	.66
12-13	19.13	.53	19.67	12.41	.29	12.70	.65
13-14	18.33	.33	18.66	10.72	.18	10.90	.58
14-15	17.53	.29	17.82	10.52	.16	10.68	.60

TABLE IV-7

Calculated geometric acceptance of the front supermodules of the forward arm spectrometer for $\Lambda^0 \rightarrow p\pi^-$. Results are given (a) all events and (b) events where $SSQ > 20$ mm. The acceptance is separately listed for events where the particles transverse the same set and different sets of supermodules. R is the fraction of events surviving the SSQ cut.

p_{Λ^0} GeV/c	All Events			Events with $SSQ > 20$ mm			$R = \frac{A_{SSQ \text{ total}}}{A_{\text{total}}}$
	A_{same} $\times 10^4$	$A_{\text{diff.}}$ $\times 10^4$	A_{total} $\times 10^4$	A_{same}^{SSQ} $\times 10^4$	$A_{\text{diff.}}^{SSQ}$ $\times 10^4$	A_{total}^{SSQ} $\times 10^4$	
0-1	9.5	8.3	17.8	<.6	.6	.6	.03
1-2	55.7	70.0	126	1.1	3.3	4.4	.03
2-3	163	166	329	10.6	34.0	44.6	.14
3-4	374	344	718	52.1	140	192	.27
4-5	593	497	1090	137	181	318	.30
5-6	992	490	1482	272	179	451	.30
6-7	1353	413	1766	466	125	591	.33
7-8	1795	298	2093	650	82.2	732	.36
8-9	2077	254	2331	757	69.9	826	.35
9-10	2358	178	2536	837	40.5	877	.35
10-11	2570	135	2705	881	23.8	905	.33
11-12	2686	92.5	2779	910	21.2	931	.34
12-13	2807	64.0	2871	916	10.6	926	.32
13-14	2891	62.0	2953	912	5.3	918	.31
14-15	2945	45.3	2990	924	4.0	928	.31

enforced by the SSQ cut is also less. Furthermore, since the two tracks are separated, the problem of track recognition is much easier and cleaner. Thus, those V's transversing different supermodules are in general better defined than those passing through the same supermodules.

The numbers of V's associated with an electron for same and different supermodule events are given in Table IV-8. As in the case of the Λ^0 -e coincidence, the electrons are restricted to those transversing the thin section of the bicone. The ratio ($R_e = N_{eV}/N_e$) representing the number of V's per electron is also given in the table.

The data is listed for various cuts on the z coordinate of the vertex of the V. The first cut ($z > -500$ mm) restricts the vertex to be from or downstream of the ISR diamond. The V's whose vertex is behind the diamond are either background events or small opening V's for which the error in reconstruction gives a false vertex position. The second cut ($z > 410$ mm) restricts the V's to have a vertex downstream of the diamond. The third cut ($z > 1005$ mm) requires a large decay distance. The next three cuts give the slices in between the first three cuts.

The corresponding data for V's associated with a hadron is given in Table IV-9. Again, to equalize acceptance with electrons the hadrons are restricted to come from the thin section of the vacuum chamber.

TABLE IV-8

Number of V's associated with an electron for various ranges of the Z coordinate of the vertex of the V. The number of electrons E is 5147. R is the ratio of $e^{\pm}$ -V coincidences to the total number of $e^{\pm}$ events. The subscripts S and D refer to events where the V decay tracks transverse the same set and different sets of supermodules respectively. The subscript T refers to the sum of S and D.

	Z>-500 units	Z>410	Z>1005	-500<Z<410	410<Z<1005	410<Z<1005
N_S^e	69	55	37	14	32	18
N_D^e	113	55	37	59	75	16
N_T^e	182	109	75	73	107	34
$R_S^e = N_S^e/E$	$134 \pm .16$ $\times 10^{-2}$	$1.07 \pm .14$ $\times 10^{-2}$	$.72 \pm .12$ $\times 10^{-2}$	$.27 \pm .07$ $\times 10^{-2}$	$.62 \pm .11$ $\times 10^{-2}$	$.35 \pm .08$ $\times 10^{-2}$
$R_D^e = N_D^e/E$	$2.20 \pm .21$ $\times 10^{-2}$	$1.05 \pm .14$ $\times 10^{-2}$	$.74 \pm .12$ $\times 10^{-2}$	$1.15 \pm .15$ $\times 10^{-2}$	$1.46 \pm .17$ $\times 10^{-2}$	$.31 \pm .08$ $\times 10^{-2}$
$R_T^e = N_T^e/E$	$3.54 \pm .26$ $\times 10^{-2}$	$2.12 \pm .20$ $\times 10^{-2}$	$1.46 \pm .17$ $\times 10^{-2}$	$1.42 \pm .17$ $\times 10^{-2}$	$2.08 \pm .20$ $\times 10^{-2}$	$.66 \pm .11$ $\times 10^{-2}$

TABLE IV-9

Number of V's associated with a hadron in the electron arm for various ranges of the Z coordinate of the vertex of the V. The number of hadrons H is 19029. R is the ratio of hadron-V coincidences to the total number of hadron events. The subscripts S and D refer to events where the V decay tracks transverse the same set and different sets of supermodules respectively. The subscript T refers to the sum of S and D.

	$Z > -500$	$Z > 410$	$Z > 1005$	$-500 < Z < 410$	$410 < Z < 1005$	$410 < Z < 1005$
N_S^h	282	235	170	47	112	65
N_D^h	510	287	182	223	328	105
N_T^h	792	522	352	270	440	170
$R_S^H = N_S^h / H$	$1.47 \pm .09$ $\times 10^{-2}$	$1.23 \pm .08$ $\times 10^{-2}$	$0.89 \pm .07$ $\times 10^{-2}$	$.25 \pm .04$ $\times 10^{-2}$	$.59 \pm .06$ $\times 10^{-2}$	$.34 \pm .04$ $\times 10^{-2}$
$R_D^H = N_D^h / H$	$2.68 \pm .12$ $\times 10^{-2}$	$1.51 \pm .09$ $\times 10^{-2}$	$.96 \pm .07$ $\times 10^{-2}$	$1.17 \pm .08$ $\times 10^{-2}$	$1.72 \pm .10$ $\times 10^{-2}$	$.55 \pm .05$ $\times 10^{-2}$
$R_T^h = N_T^h / H$	$4.16 \pm .15$ $\times 10^{-2}$	$2.74 \pm .12$ $\times 10^{-2}$	$1.85 \pm .10$ $\times 10^{-2}$	$1.42 \pm .09$ $\times 10^{-2}$	$2.31 \pm .11$ $\times 10^{-2}$	$.89 \pm .07$ $\times 10^{-2}$

A comparison of the ratios of electron and hadron associated V's for the various cases is given in Table IV-10. There is no statistically significant difference between electron associated V's and hadron associated V's. However, there is some suggestion in different supermodule events (type ii) that there are more V's associated with hadrons than electrons. This is opposite of what we had hoped to find to indicate possible charmed particle production.

J.5 Discussion

The overall result from this experiment is that no statistically significant electron-strange particle correlation is seen. But what does this mean in terms of charmed particle production?

Bourquin and Gaillard have recently proposed a rather convincing model for charmed $D\bar{D}$ production.¹⁷ They have parameterized the invariant cross section for π production in such a manner that ρ , ω , and J/ψ production is also correctly described with only a change in overall normalization. For particles with nonzero hypercharge or charm a variable mass "particle" R which decays into the particle-antiparticle pair is assumed to be produced according to this parameterization. The production of $\bar{p}$ and K^- is found to be parameterized in this manner.

A Monte Carlo calculation using this model has been done to determine the number of V's from K^0 decay expected per accepted electron from $D, \bar{D} \rightarrow K^* (890) eV$ and $DD \rightarrow K^0 eV$.

TABLE IV-10

Comparison of R^e and R^h for various ranges of the z coordinate of the vertex of the V . $R^{e(h)}$ is the ratio of the number of $e(h)$ - V coincidences to the total number of electrons (hadron) events. The data is separately listed for events where the particles of the V transverse the same set and different sets of supermodules respectively.

		Same	Different	Total
		$\times 10^2$	$\times 10^2$	$\times 10^2$
$z > -500$	R^e	$1.34 \pm .16$	$2.20 \pm .21$	$3.54 \pm .26$
	R^h	$1.47 \pm .09$	$2.68 \pm .12$	$4.16 \pm .15$
	$R^e - R^h$	$-0.13 \pm .18$	$-0.48 \pm .24$	$-0.62 \pm .30$
$z > 410$	R^e	$1.07 \pm .14$	$1.05 \pm .14$	$2.12 \pm .20$
	R^h	$1.23 \pm .08$	$1.51 \pm .09$	$2.74 \pm .12$
	$R^e - R^h$	$-0.16 \pm .16$	$-0.46 \pm .17$	$-0.62 \pm .23$
$z > 1005$	R^e	$.72 \pm .12$	$0.74 \pm .12$	$1.46 \pm .17$
	R^h	$0.89 \pm .07$	$0.96 \pm .07$	$1.85 \pm .10$
	$R^e - R^h$	$-0.17 \pm .14$	$-0.22 \pm .14$	$-0.39 \pm .20$
$-500 < z < 410$	R^e	$.27 \pm .07$	$1.15 \pm .15$	$1.42 \pm .17$
	R^h	$.25 \pm .04$	$1.17 \pm .08$	$1.42 \pm .09$
	$R^e - R^h$	$+.02 \pm .08$	$-.02 \pm .17$	$0.00 \pm .19$
$-500 < z < 1005$	R^e	$.62 \pm .11$	$1.46 \pm .17$	$2.08 \pm .20$
	R^h	$.59 \pm .06$	$1.72 \pm .10$	$2.31 \pm .11$
	$R^e - R^h$	$+.03 \pm .13$	$-.26 \pm .20$	$-.23 \pm .23$
$410 < z < 1005$	R^e	$.35 \pm .08$	$.31 \pm .08$	$.66 \pm .11$
	R^h	$.34 \pm .04$	$.55 \pm .05$	$.89 \pm .07$
	$R^e - R^h$	$+.01 \pm .09$	$-.24 \pm .09$	$-.23 \pm .13$

This number is independent of the cross section of production of $D\bar{D}$. Table IV-11 gives the results. All of the various decay modes give on the order of 1 V per 10000 accepted electrons. Since there are only 5147 electrons of which only about 60% are direct, this model predicts that there should not be any detectable correlation in the data due to $D\bar{D}$.

TABLE IV-11

Predicted R^e for the $D\bar{D}$ decay sequences listed in column 1. The DD system was generated according to the parameterization by Bourquin and Gallard (Reference 17).

Decay Mode	R_S^e	R_D^e	R_T^e
$D\bar{D}$ $\rightarrow K^*(890)ev$ $\rightarrow K_S^0\pi$ $\rightarrow \pi\pi$	0.46 $\times 10^{-4}$	1.00 $\times 10^{-4}$	1.46 $\times 10^{-4}$
$D\bar{D}$ $\rightarrow K^*(890)ev$ $\rightarrow K_L^0\pi$ $\rightarrow \pi\pi\pi$ πev $\pi\mu\nu$	0.57 $\times 10^{-4}$	0.30 $\times 10^{-4}$	0.89 $\times 10^{-4}$
$D\bar{D}$ $\rightarrow K_L^0 ev$ $\rightarrow \pi\pi\pi$ πev $\pi\mu\nu$	0.48 $\times 10^{-4}$	0.17 $\times 10^{-4}$	0.65 $\times 10^{-4}$
$D\bar{D}$ $\rightarrow K_S^0 ev$ $\rightarrow \pi\pi$	0.83 $\times 10^{-4}$	2.05 $\times 10^{-4}$	2.87 $\times 10^{-4}$

APPENDIX I

DATA ACQUISITION SYSTEM

The data acquisition system consisted of a CAMAC read-out system,²⁸ an HP-2100 computer, a videotape recorder, and an IBM 360/44. The system is diagrammed in Figure AI-1. Analog and NIM data from the experiment was converted into digital data by CAMAC modules. The data was then read by the HP-2100 through the CAMAC system and recorded on the video tape. When the HP-2100 had time available, it sent, upon request, events to the IBM 360/44 for on-line monitoring.

Upon the occurrence of a trigger, the experimental electronics was gated "off" so that no more triggers could occur to destroy the experimental data before it could be recorded. When the readout was finished, the computer sent a signal via a CAMAC output register to the experiment. The experimental electronics was then gated "on" so that a new trigger could be accepted.

The CAMAC modules included one octal and seven 12-channel ADC's (Analog to Digital Converters) for the recording of counter pulseheights, three quad TDC's (Time to Digital Converters) for measuring time of flight, several scalars for recording live and real time, seven 16-channel pattern units to record counter hit patterns, forty-two special proportional chamber read out modules²⁹, four special TDC's,

DATA ACQUISITION SYSTEM

Figure AI-1

a control unit, and two octal ADC's for drift chamber read out, an output register, and several LAM-graders.

Upon receiving a trigger, the HP-2100 issued a series of read-out instructions to the CAMAC. The data was stored in a buffer for eventual transfer to the videotape.

Events could be transferred in a sampling mode to the IBM 360/44 for on-line monitoring of the equipment. Chamber fillings, pulseheight spectra, and event displays were made to check the condition of the equipment.

When the data buffer was full (~ 10 events), it was written onto the videotape, a special I/O device based upon TV video-recording techniques.³⁰ The videotape records at about 40 times the data packing density and 4 times the recording rate than normal magnetic tape. One 6000 foot roll of videotape records the same data as 200 conventional 2400 foot 1600 bpi magnetic tapes.

This is achieved through use of a rotating head assembly over which the tape moves at low speed. The tape is guided nearly along the circumference of the rotating head deviating from parallelism by an angle of about 5 degrees (Figure AI-2). The data is thus written at about 1100 bpi on a track, called a scan line, which crosses the width of the tape at an angle of five degrees. Since only one track is written at a time, intertrack distance is no longer determined by the number of heads which can be packed into a head

Figure AI-2

assembly. A transverse track density of 100 per inch is achieved.

In addition to the high density scan lines, four other tracks are recorded longitudinally at low density (Figure AI-2). These tracks contain synchronization, address, write status, and read status information for each individual scan line. Each scan line has an address associated with it so that it can be read or written at will. The read and write status information is used to tell whether the scan line has been written or read.

The tape moves continuously at 6.91 ips. When a buffer of events is full, it is written onto the next blank scan line. The scan line's write status is then updated from the unwritten 0 to the run number of the data being taken.

The tape has been divided up by software into files typically 10,000 scan lines long. When the end of the file is reached, the tape is rewound to the beginning of the file. The file is then scanned again so that unused scan lines may be written. This continues until the fraction of scan lines written is above a certain number, typically about 80%. Then one last pass through the file is made. If there is no full buffer ready to be written when an unwritten scan line comes up, then a junk pattern is written on that scan line. Not every scan line is filled with data because as more and more scan lines are written on the file

the average waiting time to find an empty scan line grows eventually affecting the data taking rate. The junk pattern is written because for some reason every scan line must be written on the file to be read without many read errors.

A similar procedure is followed when reading back the data. The data is read back and passed to the IBM 360/44 where it is analyzed and summarized onto conventional magnetic tapes. When the IBM 360 is ready for a buffer, it is read from the video tape with the read status being updated to a number chosen by the user. On the following passes this scan line will not be read again as long as the user chosen read status stays the same. When a certain fraction, typically about 90%, of a particular run on a particular file is used, then one last pass is made and the run is considered fully read.

APPENDIX II

ELECTRON ARM TRACK RECONSTRUCTION

The purpose of the track reconstruction procedure in the electron arm is to find events with a single particle transversing the spectrometer and to determine the particle's momentum. A brief description of this procedure is given below. A more detailed description is given elsewhere.³¹

The electron arm spectrometer consisted of sixteen drift chamber planes and a magnet of $\int B dl$ of 0.6 T m as described in Chapter II Section A. For each drift chamber the coordinate corresponding to each hit is determined. Then within each module coordinate pairs are found. Track reconstruction then proceeds separately for the xz and yz planes. Both a track in the xz plane, the main bending plane, and a track in the yz plane are required for a good event.

A track in the xz plane in front of the magnet is formed if all three x-modules in front of the magnet have one and only one pair of points each and these pairs form a good fit to a straight line. If two of the modules have one and only one pair each and the third module has only a hit in one of its chambers within 15 mm of the extrapolated point formed from the line between the two pairs, then a track in the xz plane in front of the magnet is also formed.

A track in the yz plane in front of the magnet is formed if the two y-modules in front of the magnet have one and only

one pair each. If one of the modules has one and only one pair while the other modules has only a hit in one of its chambers within 20 mm of the extrapolated point formed from the line between the pair in the other module and the center of the ISR diamond, then a track in the yz plane in front of the magnet is also formed.

The tracks in the xz plane in front of the magnet are then projected through the magnet to the modules behind the magnet by the single point bending approximation (Figure AII-1). The xz track (i.e. neglecting x, z components), in front of the magnet is straight-line extrapolated to the center of the magnet. A track in the xz plane is formed if the two x-modules behind the magnet have one and only one pair each and the pair of the module nearest the magnet is within 15 mm of the line between the other pair and the extrapolated point at the center of the magnet. If one of the modules behind the magnet has one and only one pair while the other has only a hit within 15 mm of the extrapolated point at the center of the magnet and the good pair, then a track in the xz plane also is formed. If one of the modules has no hits but the other has one and only one pair, then a track is formed too.

The momentum of the track is first estimated using the single point bending approximation and the $\int B dl$ of the magnet. An iterative tracking procedure using the field map of the magnet is then used to obtain the final value of the momentum.

Finally, using the tracking procedure the expected y coordinate in the y-module behind the magnet is calculated. A track in the yz plane is formed if a hit in at least one of the two chambers of the module is within 15 mm of this point.

APPENDIX III

FORWARD ARM TRACK RECONSTRUCTION

The track finding method consists of three major steps: (1) points are found in each supermodule, (2) lines are formed between the two supermodules in front of the magnet, and (3) tracks are formed by matching this line with a point in the magnet chamber.

The raw data consists of the wire numbers in each of the four chambers in the six supermodules. These wire numbers are converted into hit positions in actual space. Then within each supermodule points are found by searching for combinations of hit positions which have at least three of the four planes satisfying

$$X = (U-V)/\sqrt{2} + \epsilon$$

$$Y = (U+V)/\sqrt{2} + \epsilon$$

$$U = (X+Y)/\sqrt{2} + \epsilon$$

$$V = (X-Y)/\sqrt{2} + \epsilon$$

where ϵ is a tolerance which varies between 5 and 10 mm depending on the module. Furthermore, in order to reduce the possibility of multiple solutions for one real point, no two solutions are allowed to have any one wire in common. This is accomplished by taking the solution which has the smallest error.

Lines are formed in the front supermodules by taking various combinations of points and performing a least squares fit of the hits in the eight planes of the two supermodules. Combinations of these lines are then taken to see if they meet in a vertex. A combination is rejected if the two lines have one or more chamber hits in common.

Two lines meet if their closest distance of approach (CDA) is less than 20 mm. (Chapter IV, Section E). The vertex is taken to be the midpoint of the line connecting the two at the closest distance of approach. A plot of the CDA distribution is given in Figure IV-6. Plots of the vertex distribution are given in Figure IV-8 showing that most of the events come from the ISR diamond.

Each line of the resulting pair is then projected to the magnet chamber in the plane in which there is no bending (yz). A track is formed if there is a point within 6 mm of this projection. The momentum is then calculated from geometrical construction. The U and V positions of the track at the magnet chamber can then be predicted from this momentum and the parameters of the line in front. If there is more than one track corresponding to the same line in front then the one with the best fit in U and V is taken ($\Delta U^2 + \Delta V^2 \rightarrow \text{minimum}$).

APPENDIX IV

MOMENTUM AND MASS RESOLUTION OF THE FORWARD SPECTROMETER

A. Momentum Resolution--Analytic

First, for simplicity the following assumptions are made:

- (1) A particle enters a magnetic field in the y direction at a point $x=z=0$ with a slope $\frac{\Delta x}{\Delta z} = 0$ (Figure AIV-1).

- (2) ℓ = effective length of magnetic field.

$AP = r$ = radius of curvature.

f = deviation from straight line projection at the end of magnetic field.

P = momentum.

$A = 33356/B$.

B = magnetic field strength = 4.7 KG

- (3) $\ell \gg f$.

$r \gg \ell$.

Then

$$f = AP - \sqrt{A^2 P^2 - \ell^2}$$

$$\rho = \frac{f^2 + \ell^2}{2Af}$$

Thus since $f \ll \ell$

$$\rho \approx \frac{\ell^2}{2Af}$$

Figure AIV-1

Figure AIV-2

Now if the error in f is Gaussian

$$\sigma_p^2 = \left(\frac{\partial p}{\partial f}\right)^2 \sigma_f^2 = \frac{4A^2 p^4}{\ell^4} \sigma_f^2$$

Consider the case of the spectrometer (Figure AIV-2).

The slope a of the incoming particle is less than 0.012 so that the angle between f' and ℓ' is approximately a right angle. Then the formula just derived holds if we make the substitution

$$f \rightarrow f' = |a\ell - (x_{\text{out}} - x_{\text{in}})|$$

$$\ell^2 \rightarrow \ell^2 + a^2 \ell^2$$

Thus,

$$\rho = \frac{\ell^2 + a^2 \ell^2}{2A(a\ell - (x_{\text{out}} - x_{\text{in}}))}$$

But $a^2 \ell^2 \ll \ell^2$ so that

$$\rho \approx \frac{\ell^2}{2A|a\ell - (x_{\text{out}} - x_{\text{in}})|}$$

Thus,

$$\sigma_p^2 = \frac{4A^2 p^2}{\ell^4} [\sigma_{\text{out}}^2 + \sigma_{\text{in}}^2 + \ell^2 \sigma_a^2]$$

or

$$\sigma_p = \frac{2Ap^2}{\ell^2} \sqrt{\sigma_{\text{out}}^2 + \sigma_{\text{in}}^2 + \ell^2 \sigma_a^2}$$

Now if (x_1, z_1) and (x_2, z_2) are the particle's coordinates at the two chambers in front, then

$$a = \frac{x_2 - x_1}{z_2 - z_1}$$

Thus,

$$\sigma_a^2 - \frac{2\sigma_{ch}^2}{(z_2 - z_1)^2} = 2.9 \times 10^{-6} \sigma_{ch}^2$$

where σ_{ch} is σ for the coordinate determination of the supermodule. Also,

$$x_{in} = \frac{(x_2 - x_1)}{(z_2 - z_1)} (z_F - z_1) + x_1,$$

so that

$$\sigma_{x_{in}}^2 = \left(\frac{z_F - z_1}{z_2 - z_1}\right)^2 (2\sigma_{ch}^2) + \sigma_{ch}^2 = 11.9 \sigma_{ch}^2$$

Furthermore $\sigma_{out}^2 = \sigma_{in}^2$, so that

$$\sigma_F^2 = 18.2 \sigma_{ch}^2$$

But the distribution for σ_{ch} is flat with a standard deviation of 0.6. Thus, taking $\sigma_{ch} = 0.6$

$$\sigma_p = \frac{2Ap^2}{\ell^2} \sqrt{18.2} (0.6) = 0.02 p^2$$

R. Momentum Resolution--Monte Carlo

The momentum resolution can also be calculated by use of a computer model of the spectrometer. Events are generated with momentum $\vec{p}$ distributed evenly in ϕ and $\cos\theta$. The actual coordinates at the positions of the chambers and then the corresponding chamber hit coordinates are calculated. The "measured" momentum of the particle is then calculated by the same method used in the track reconstruction program. The difference in momentum

$\Delta P = |P_{\text{measured}}| - |P_{\text{generated}}|$ is then calculated.

Figures AIV-3 and AIV-4 are plots of ΔP for various values of $P_{\text{generated}}$. The quantization of P due to the quantization of the coordinates of the proportional wire chambers can clearly be seen in Figure AIV-3.

Furthermore, as P increases the ΔP distribution becomes more and more non-Gaussian. A tail toward over estimated momentum develops. To see the reason for this consider the formula derived in the last section

$$\rho \approx \frac{\ell^2}{2Af}$$

Expanding

$$\rho \approx \frac{\ell^2}{2Af_0} \left[1 - \frac{\Delta f}{f_0} + \frac{(\Delta f)^2}{f_0^2} + \dots \right]$$

where f_0 is the true value.

As P increases f gets smaller. Thus when f becomes on the order of Δf the nonlinear terms become important and the distribution of ΔP becomes non-Gaussian.

The resolution (FWHM) for momenta between 1 and 10 GeV/c as determined by the Monte Carlo are listed along with the corresponding analytical value in Table AIV-1. Considering the non-Gaussian nature of the distributions, the two methods are in agreement.

$P = 1$ GEV

MOMENTUM RESOLUTION

Figure AIV-3

$P = 2$ GEV $P = 4$ GEV $P = 7$ GEV $P = 10$ GEV

MOMENTUM RESOLUTION

Figure AIV-4

TABLE AIV-1

Comparison of Analytic and Monte Carlo Calculated Momentum Resolution as a Function of Momentum.

P (GeV/c)	Analytic Resolution (FWHM) (GeV/c)	Monte Carlo Resolution* FWHM GeV/c
1	0.048	0.051±.001
2	0.19	1.24 ±.06
3	1.43	0.48 ±.06
4	0.77	0.84 ±.12
5	1.20	1.3 ±.2
6	1.73	1.8 ±.3
7	2.4	2.2 ±.4
8	3.1	3.3 ±.5
9	3.9	3.5 ±.7
10	4.8	4.1 ±.9

*Error is twice the bin width of the ΔP plots.

C. Mass Resolution

The Monte Carlo method can also be used to determine the mass resolution of the spectrometer for Λ^0 and K_S^0 . As before, events are generated with momentum P_{Λ^0, K_S^0} evenly in ϕ and $\cos\theta$. Furthermore, an event vertex is generated according to the ISR intersection diamond distribution. A decay path distance is generated according to the exponential decay rate law. The vertex of the decay is then calculated. The final state particles' momenta are then calculated assuming a phase space decay. The "measured" momenta of these particles are then calculated as before. The "measured" effective mass M_{measured} can then be calculated.

Figures AIV-5 and AIV-6 are plots of $\Delta M = M_{\text{measured}} - M_{\text{true}}$ for Λ^0 and K_S^0 respectively. At higher values of P_{Λ^0, K_S^0} , a tail toward overestimated mass appears. This is a direct result of the tail in the momentum resolution plots. Table AIV-2 lists the mass resolution (FWHM) as a function of P_{Λ^0, K_S^0} .

LAMBDA MASS RESOLUTION

Figure AIV-5

$P = 4$ GEV $P = 6$ GEV $P = 10$ GEV $P = 14$ GEV

KZERO MASS RESOLUTION

Figure AIV-6

TABLE AIV-2
 Monte Carlo Mass Resolution of Λ^0 , K_S^0 as a Function of
 Momentum

P_{Λ^0, K_S^0} (GeV/c)	M_{Λ^0} (FWHM) MeV	$M_{K_S^0}$ (FWHM) MeV
1	-	-
2	6 ± 2	-
3	9 ± 2	-
4	7 ± 2	30 ± 5
5	8 ± 2	40 ± 5
6	10 ± 2	50 ± 10
7	10 ± 2	55 ± 10
8	11 ± 2	55 ± 10
9	11 ± 2	65 ± 10
10	13 ± 2	70 ± 10
11	13 ± 2	85 ± 10
12	14 ± 2	80 ± 10
13	15 ± 2	90 ± 10
14	17 ± 2	90 ± 10
15	18 ± 3	105 ± 10
16	18 ± 3	105 ± 10
17	20 ± 3	110 ± 10
18	21 ± 3	120 ± 10
19	23 ± 3	125 ± 10
20	24 ± 3	135 ± 10

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