Inclusive Hadron Production in
Electron-Positron Collisions with
Center-of-Mass Energies from 50 to 61.4 GeV
by
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Committee Chairman: Alexander Abashian

Physics

(ABSTRACT)

The $K^0$, $K^*(892)$, $\rho^0(770)$ and $\phi(1020)$ mesons along with the $\Lambda^0$ baryon have been observed in the TRISTAN energy region of 50 to 61.4 GeV using a data sample of 245.4 pb$^{-1}$. Their multiplicities and total cross sections are found and compared with the results from experiments at other center-of-mass energies. The multiplicities are compared with various theoretical and phenomenological models. The differential cross sections for the $K^0$ and $\Lambda^0$ are calculated and compared with other experiments. Measurements of the ratio of production of vector mesons to vector plus pseudoscalar mesons and the ratio of the production of excited $s\bar{s}$ quark pairs to the production of excited $u\bar{u}$ plus $d\bar{d}$ quark pairs are compared with other experiments along with the phenomenological predictions. The HERWIG Monte Carlo is tuned with regard to the inclusive production of hadrons.
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I'm grateful to my family for keeping the heckling that I've well-earned to a minimal level.

Sister:  "So, Mark, when are you graduating?"
Mark:  "Uhhhhhhh, in about a year, I guess."

6 months later.

Sister:  "So, Mark, when are you graduating?"
Mark:  "Uhhhhhhh, in about a year, I guess."

Seriously, I want to thank all of them for their words of encouragement. On more than one
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Chapter 1

Introduction

The data used in this dissertation were taken at the TRISTAN (an abbreviation of the unwieldy name "Transposable Ring Intersection STorage Accelerator in Nippon") electron-positron collider. Located at the National Laboratory for High Energy Physics (abbreviated as "KEK" in Japanese) in Tsukuba Science City, TRISTAN first became operational in late 1986. At this point in time it was the state of the art in electron-positron colliders as it exceeded the collision energy of the PETRA collider at DESY. Not to be outdone, CERN got into the game with the $Z^0$ factory called LEP (Large Electron-Positron collider), which went on line in July, 1989. Nevertheless, in spite of the higher energy of LEP, TRISTAN is unique in the energy range that it is exploring; thus, it is still very capable of doing original physics.

At TRISTAN there are four areas where collisions are allowed to take place. Located at three of those sites are the general purpose detectors known as AMY, TOPAZ and VENUS. The fourth site was reserved for the now-defunct SHIP detector which specialized in searching for highly ionizing particles. The AMY detector, from which the data used in this thesis were taken, was designed with the idea of making it compact through the use of a magnetic field that is up to 6 times stronger than the magnetic fields in other similar experiments.
The AMY detector was also designed with the intent of easily identifying leptons. The analysis in this thesis was performed on data with a total luminosity of 240 pb$^{-1}$ taken over an energy range of 50 to 61.4 GeV, with over 195 pb$^{-1}$ of the data taken at the single center of mass energy of 58 GeV. A more detailed description of the AMY detector is provided in chapter 2.

As for the rest of this thesis, it will proceed as follows:

- The rest of the first chapter will provide some background on the Standard Model and the motivation for this thesis;

- Chapter 2 is devoted to a description of both TRISTAN and AMY as well as providing the statistics of the data sample used in the analysis;

- In Chapter 3, the software routines that provide the backbone for this dissertation are described;

- Chapter 4 details the methods used to find both $K^0_S$ and $\Lambda^0$ and their results;

- Chapter 5 contains the analysis of searches for $K^*(892)$, $\rho(770)$ and $\phi(1020)$ particles;

- Chapter 6 deals with tuning the HERWIG Monte Carlo hadronic event generator, a set of computer routines that will be dealt with in detail in Chapter 3;

- The concluding chapter summarizes the results of the previous chapters.

1.1 The Standard Model

Currently, experimental high energy physics relies on the theory known as the “Standard Model.” This theory, a combination of the Glashow-Weinberg-Salam model [1] unifying the familiar electromagnetic force with the weak force and Quantum Chromodynamics
(QCD) [2], the model of the strong force, has withstood every battery of tests thrown at it. In fact, its success has been quite remarkable. The basic premise of the Standard Model is that everything in existence boils down to interactions between spin 1/2 particles mediated by spin 1 particles; included with these interactions is the Higgs mechanism, which introduces the Higgs boson and the concept of symmetry breaking. The spin 1/2 particles are subdivided into the two classifications of “quarks” and “leptons”, each of which has its own anti-particle. From the standpoint of the electroweak portion of the Standard Model, it is an easy task to further subdivide the quarks and leptons as shown below:

\[
\begin{pmatrix}
  u \\
  d \\
  \nu_e \\
  e^-
\end{pmatrix}_{L} \quad \begin{pmatrix}
  c \\
  s \\
  \nu_\mu \\
  \mu^-
\end{pmatrix}_{L} \quad \begin{pmatrix}
  t \\
  b \\
  \nu_\tau \\
  \tau^-
\end{pmatrix}_{L}
\]

(1.1)

where the subscript \( L \) means that these particles have a left-handed chirality and couple with the \( W^\pm \) gauge boson. There are also the right-handed singlets which couple with the \( Z^0 \) boson:

\[
e^R, \mu^R, \tau^R, u_R, c_R, t_R, d_R, s_R, b_R.
\]

(1.2)

The top group of particles in Equation 1.1 (and in the right part of Equation 1.2) are the quarks. In each pair, the upper quark has an electric charge of +2/3 while the lower quark has a charge of −1/3. The bottom group of particles are the leptons. The upper lepton in each pair is a massless particle known as a “neutrino” and carries no charge (it is also purely left-handed). The bottom lepton in each pair is massive and carries a charge of −1. Each quark pair is associated with the lepton pair below it and the quartet is called a “generation”. Currently, there are only three known generations, as depicted above. Additional generations have not been ruled out, but it has been found at LEP [3] that there exist only three generations that have a neutrino with a mass less than 45 GeV/c^2. While this summarizes the electroweak aspect of the Standard Model, the QCD part requires that each of the quarks come in three colors: “red”, “green” and “blue”. Thus, there are really three quarks for each lepton. In addition, each quark and lepton has an anti-
matter counterpart; for example, the anti-matter counterpart of the electron is the positron while for the up quark it is the up-bar quark. Mediating all of the interactions among the quarks and leptons are spin 1 particles known as “gauge bosons”. For the electromagnetic interaction the gauge boson is the photon, \( \gamma \), while for the weak interaction there are three mediating particles known as the \( Z^0 \) and \( W^\pm \) bosons. The electroweak portion also requires the existence of yet another particle called the Higgs boson (\( H^0 \)) which has lately gained the absurd label of “The God Particle” [4]. This particle is a manifestation of the mechanism responsible for the splitting of the electroweak force via symmetry breaking into its two component forces at low energies and also accounts for the masses of the electroweak particles. Finally, the strong interaction is mediated by eight massless, electrically neutral but color charge-carrying “gluons”. QCD will be discussed in more detail in Section 1.2.

Despite the successes of the Standard Model, it has generally gotten a “thumbs down” from the physics community. Aside from the lack of gravitational interactions, the Standard Model possesses quite a few deficiencies:

- The values for the masses of the quarks and leptons remain unexplained;

- No reason for why the electron and proton charges are exactly opposite is given;

- There is no reason given for the observed asymmetry between matter and anti-matter in the universe.

The list goes on, but an enumeration of all the shortcomings of the Standard Model is not the province of this work. Suffice it to say that the major efforts in particle physics are devoted to finding deviations from the Standard Model or evidence of physics beyond it. To do this, the full implications of the theory must be understood, a situation that has not yet arisen. This is because at the heart of the Standard Model is QCD, which is where this thesis comes in to play.
1.2 QCD and Monte Carlo Methods

The difficult with QCD lies in the current lack of understanding of its non-perturbative regime, which accounts for the spectra of hadronic particles and their interactions at an energy scale up to about 1 GeV. What that means is that within a very small region (less than the radius of a proton, for instance) quarks do not really pay attention to each other, at least as far as the strong force is concerned. But as the quarks separate, the strength of their attraction to each other due to the strong force increases. This is known as quark confinement. So now the question is, “How does quark confinement affect the data taken at TRISTAN?” To understand this, a typical QCD event must be examined. In such an event, the electron and positron annihilate each other to produce a virtual gauge boson (either a virtual photon or a virtual $Z^0$); this boson can subsequently produce a quark and an anti-quark. The large amount of energy pushes the two apart. In order to maintain color confinement, a quark–anti-quark pair will arise from the sea of energy in a process called “quark fragmentation.” Another way for the system to rid itself of the stress is for the quarks to radiate gluons in a manner similar to the electron bremsstrahlung of photons; unlike photons, though, gluons can couple to themselves (since they carry a color charge) meaning that one gluon can branch into two gluons. These processes are represented by the diagrams in Figures 1-1 and 1-2. This portion of the event is well understood through the use of the perturbative aspect of QCD; unfortunately, things soon get complicated. The whole system will continue to stretch out and create more and more quark–anti-quark pairs and gluons until the amount of excess energy is not enough to overcome the desire of adjacent quarks to team up and form independently existing particles known as “hadrons”; this is called “hadronization” and these events are called “hadronic events.” There are two types of hadrons. One type, called mesons, are composed of a quark and an anti-quark. The quarks are such that their total charge adds up to an integer and their colors are exactly opposite so that they cancel, i.e., if the quark’s color is blue then the anti-quark’s color is anti-blue. The second type of hadron is a baryon. A baryon is made up of three quarks
whose total charge adds up to an integer. One quark will be red, another will be blue and the third will be green in order to satisfy the requirements of QCD; naturally, an anti-baryon is made up of three anti-quarks whose colors are anti-red, anti-blue and anti-green. In a hadronic event, the mesons and baryons have, in general, been created along the paths of the original quarks’ momenta. The resulting event looks like two jets of particles in opposite directions, as seen in Figure 1-3. It is also possible for a radiated gluon to have enough energy of its own so as to create a third such jet as seen in Figure 1-4. Similar processes can lead to events with even more jets.

So, where does the non-perturbability feature come into play? The answer to that lies in what is known as the strong coupling constant, \(\alpha_s\). The probability of a quark or gluon radiating more quarks and gluons is equal to \(\alpha_s\). The expression for \(\alpha_s\) to second order is [5]

\[
\alpha_s(s) = \frac{12\pi}{(33 - 2n_f)\ln(s/\Lambda_{\overline{MS}}^2) + 6^{\frac{133 - 19n_f}{33 - 2n_f}}\ln(\ln(s/\Lambda_{\overline{MS}}^2))}
\]

(1.3)

where \(\sqrt{s}\) is equal to the energy of the system, \(n_f\) is the number of available quark flavors at that energy and \(\Lambda_{\overline{MS}}\) is the QCD scale parameter. Clearly, as the energy of the system decreases, \(\alpha_s\) increases, implying that it is a “running” coupling constant. This behavior is shown in Figure 1-5. While the expression above is not exact, it appears that in a hadronic event there comes a point when the available energy is so low that \(\alpha_s\) is very nearly 1, meaning that the perturbative techniques used in fragmentation do not apply. It is technically difficult to calculate what is going on in this situation, which is where experimental analyses such as this come in.

To make up for any ignorance of the goings-on in a hadronic event, Monte Carlo event generators are employed which try to simulate phenomenologically the actual processes underlying quark fragmentation and hadronization. The idea is that if enough hadronic events are simulated on a computer then they can be compared to the actual data. Monte Carlo

\footnote{It is also possible that a diquark-anti-diquark pair will arise; this construction of four quarks forms the basis of baryon formation in the Lund model, which will be discussed in Section 3.1.1.}
Figure 1-1: (a) Feynman diagram for $e^+e^-\rightarrow q\bar{q}$, (b) Feynman diagram for $e^+e^-\rightarrow q\bar{q}g$
Figure 1.2: Feynman diagrams for $e^+e^- \rightarrow q\bar{q}g\bar{g}$
Figure 1-3: (a) \( z \)-\( y \) View of 2-Jet Hadronic Event, (b) \( y \)-\( z \) View of 2-Jet Hadronic Event.
Figure 1-4: (a) z-y View of 3-Jet Hadronic Event, (b) y-z View of 3-Jet Hadronic Event.
$\alpha_s$ versus the Energy of the System

$\Lambda_{\overline{MS}} = 0.2$ GeV

$n_f = 5$

Figure 1-5: $\alpha_s$ as a Function of Available Energy
models which closely approximate the data are further revised to improve the comparisons while those models which do not fare as well are abandoned. The primary features of the Monte Carlos are the scheme used for the parton cascade in the perturbative portion, the scheme for the hadronization of the quarks and gluons, and the means of determining at which the transition from perturbative to non-perturbative QCD is made. For this analysis two of the most widely used generators, the University of Lund's version 7.2 model and the HERWIG (Hadron Emission Reactions With Interfering Gluons) model version 5.5 by B. R. Webber and G. Marchesini, are used. These models will be more fully discussed in Chapter 3.

1.3 Mesons and Baryons

Of particular interest to this study are the individual species of mesons and baryons, namely the lighter, strange quark-bearing hadrons, the $K_S^0$ meson and the $\Lambda^0$ baryon, as well as the vector mesons $K^{*}(892)$, $\rho^{0}(770)$ and $\phi(1020)$.

The $K_S^0$ meson and $\Lambda^0$ baryon bear many similarities to each other in the way their decays are reconstructed. Because of this, they will be treated in conjunction with each other as much as possible. So, at this time it would be prudent to present some information about the $K_S^0$ and $\Lambda^0$ vital to this thesis (all information regarding particle properties such as decay modes and lifetimes are taken from [10]). The $K_S^0$ is a special breed of meson. It is, in fact, a hybrid made up of equal parts $K^0$ and $\bar{K}^0$ where a $K^0$ is composed of a down quark and an anti-strange quark. This hybridity is due to the fact that the strong interaction conserves the property of strangeness (the $K_S^0$ has a strangeness of -1 since it has an anti-strange quark) and also because the $K^0$ is the lightest strange meson. This results in the inability of the $K^0$ to decay via the strong force. What then happens is that the $K^0$ and $\bar{K}^0$ mix with each other through weak transitions, for instance, $K^0 \leftrightarrow 2\pi^0 \leftrightarrow \bar{K}^0$. The upshot of this mixing is that instead of a $K^0$ and $\bar{K}^0$, there are the $K_S^0$ and the $K_L^0$. The
$K_S^0$ may be expressed as [11]

$$|K_S^{0}\rangle = \frac{1}{\sqrt{2(1 + |\epsilon|^2)}}[(1 + \epsilon) |K^0\rangle - (1 - \epsilon) |\bar{K}^0\rangle].$$

(1.4)

Similarly, the $K_L^0$ can be represented as

$$|K_L^{0}\rangle = \frac{1}{\sqrt{2(1 + |\epsilon|^2)}}[(1 + \epsilon) |K^0\rangle + (1 - \epsilon) |\bar{K}^0\rangle].$$

(1.5)

$\epsilon$ is a measure of the rate of CP violation in the $K^0$-$\bar{K}^0$ system. If CP is assumed to be conserved (and for purposes of this thesis, since $\epsilon$ is so small this assumption is good enough) then $\epsilon = 0$. Since $C|K^0, \bar{K}^0\rangle = + |K^0, \bar{K}^0\rangle$ and $P|K^0, \bar{K}^0\rangle = - |K^0, \bar{K}^0\rangle$, CP $|K_S^0\rangle = + |K_S^0\rangle$ and CP $|K_L^0\rangle = - |K_L^0\rangle$. CP conservation then means that

$$K_S^0 \rightarrow 2\pi \text{ while}$$

$$K_L^0 \rightarrow 3\pi.$$  (1.6) (1.7)

The phase space available for the decay of the $K_L^0$ is much smaller than that for the decay of the $K_S^0$; therefore, the mean lifetime of the $K_L^0$ is much longer than for the $K_S^0$. In fact, their respective mean lifetimes are $(5.17 \pm 0.04) \times 10^{-8}$ and $(8.922 \pm 0.0020) \times 10^{-11}$ seconds. The $K_L^0$ lives too long for it to be detected and is of little further relevance to this thesis.

The $\Lambda^0$ baryon has properties similar to the $K^0$ but does not experience the mixing; the three quarks in question are the up quark, the down quark and the strange quark. A $\Lambda^0$ has a mass of 1115.63 $\pm$ 0.05 MeV/c$^2$ and a $K_S^0$ has a mass of 497.671 $\pm$ 0.031 MeV/c$^2$. The mean life of a $\Lambda^0$ is $(2.632 \pm 0.020) \times 10^{-10}$ seconds; as mentioned above, the $K_S^0$ mean life is $(8.922 \pm 0.020) \times 10^{-11}$ seconds. Thus, should a $\Lambda^0$ happen to be cruising along at 0.9$c$ (corresponding to a momentum of 2.3 GeV/c), then the distance it will travel is on the order of 16.3 cm before decaying; a $K_S^0$ with a similar velocity (with a momentum of just over 1 GeV/c) would travel an average of 5.5 cm before decaying. The two primary decay modes of the $\Lambda^0$ are

$$\Lambda^0 \rightarrow p + \pi^-$$

(1.8)

---

2No, there won’t be a discussion of CP violation as there’s too much depth to the subject. The interested reader is referred to [11].
\[ \Lambda^0 \rightarrow n + \pi^0 \] (1.9)

while the two primary decay modes of the \( K^0_S \) are

\[ K^0_S \rightarrow \pi^+ + \pi^- \] (1.10)

\[ K^0_S \rightarrow \pi^0 + \pi^0. \] (1.11)

The first decay mode of the \( \Lambda^0 \) occurs \((64.1 \pm 0.5)\)% of the time while the second decay mode takes place \((35.7 \pm 0.5)\)% of the time. Of the \( K^0_S \) decay modes, the first happens \((68.61 \pm 0.28)\)% of the time and the second \((31.39 \pm 0.28)\)% of the time. Any remaining decay modes for each particle occur too infrequently to be taken into consideration in this analysis. The second decay mode of each particle is also not taken into consideration because the two decay products have no electric charge. As will be discussed in Chapters 2 and 3, it is necessary for the two decay products to have a charge in order for reliable reconstruction to take place. In addition to the \( \Lambda^0 \) there is also the \( \Lambda^0 \), the anti-matter counterpart. This particle has the same mass and mean life as the \( \Lambda^0 \) but it has two notable differences. First, it consists of three anti-quarks, \( \bar{u}, \bar{d} \) and \( \bar{s} \). Second, the primary decay mode is

\[ \Lambda^0 \rightarrow \bar{p}^- + \pi^+. \] (1.12)

But despite the difference, from here on, unless specifically mentioned otherwise, analysis of the \( \Lambda^0 \) will be assumed to apply equally in the case of the \( \Lambda^0 \).

Another particle within the scope of this thesis is the \( K^*(892) \) meson. This meson is known as a vector meson because it has a spin of 1. This is to be compared with pseudoscalar mesons such as the \( K^0 \), which have a spin of 0. The charged \( K^*(892) \) meson is composed of a \( u \) and an \( s \) quark for the positively charged meson and a \( \bar{u} \) and an \( s \) quark for the negatively charged meson. The particular interest in regard to this thesis is its primary decay, which is

\[ K^{*+} \rightarrow K^0_S + \pi^+. \] (1.13)

This decay of the \( K^{*+} \) takes place 25% of the time. This shows that if a \( K^0_S \) can be successfully reconstructed, then it is worthwhile to delve further into its origins to examine
its parentage. Another important fact is that the $K^{*\pm}(892)$ decays via the strong force, so its decay happens instantaneously. The $K^{*\pm}$ has been found to have a mass of $891.59 \pm 0.24$ MeV/c$^2$.

Similar in nature to the $K^{*\pm}(892)$ is the neutral $K^{*0}(892)$, which is made up of an $s$ and a $\bar{d}$ quark. This should be compared with the $K^0$ meson, which is also made of an $s$ and a $\bar{d}$ quark. This makes the $K^{*0}(892)$ the vector counterpart to the pseudoscalar $K^0$. The $K^{*0}(892)$ decays via the strong force. The signature decay by which it is recognized in AMY is

$$K^{*0} \rightarrow K^{\pm} \pi^{\mp},$$

(1.14)

decays that occur 50% of the time. Unlike its charged counterpart, the $K^{*0}$ does not need to first have the kaon identified. The assumption, which will be borne out in Chapter 5, is that the particle in the pair with the higher momentum is the charged kaon.

Similar in topology to the $K^{*0}$ are the $\rho(770)$ and $\phi(1020)$ mesons. The $\rho^0$ has the following representation:

$$| \rho^0(770) \rangle = \frac{1}{\sqrt{2}} (| u\bar{u} \rangle - | d\bar{d} \rangle).$$

(1.15)

The $\phi(1020)$ is composed of $s$ and $\bar{s}$ quarks. The decays of interest for these particles are

$$\rho^0 \rightarrow \pi^+ \pi^- \text{ and}$$

$$\phi \rightarrow K^+ K^-.$$

(1.16)

(1.17)

These decays occur 50% and (49.1 $\pm$ 0.8)% of the time, respectively. The mass of the $\rho(770)$ has been measured to be $(768.1 \pm 0.5)$ MeV/c$^2$ and the mass of the $\phi(1020)$ to be $(1019.413 \pm 0.008)$ MeV/c$^2$. The $\rho(770)$ particle is the vector meson counterpart of the pseudoscalar meson $\pi$ while the $\phi(1020)$ is the vector counterpart to the $\eta'$ meson.
1.4 Tests of the Data and the Monte Carlos

There are many features in simulated and real data that can be compared. Two of the most common comparisons are the multiplicity and cross section of production of specific particles, i.e., on average how many times does particle $X$ appear in a simulated hadronic event vs. a real hadronic event and how well does this represent the total fraction of all particles produced? The reason for these studies is the insight they can provide regarding the details of QCD. Deviations between the data and the Monte Carlo would potentially indicate either improper production of the various quarks in the quark-gluon cascade of the perturbative process or an imbalance in the non-perturbative hadronization. The multiplicities and cross sections can also be compared to studies at other center-of-mass energies to examine the scaling properties of the particles; these can be compared with the predictions of the Monte Carlos as well. From the standpoint of particle multiplicity, scaling would take the form of increasing multiplicity with increasing center-of-mass energy. This increase should be of a form proportional to that for the increase in the multiplicity of all charged particles [6]. However, a quantitative calculation for this relationship using the Standard Model is impossible at the current level of understanding. Instead, there are three equations used that independently describe this relationship in a phenomenological manner. The simplest, proposed by Enrico Fermi in 1950 [7] has the multiplicity, $\langle n \rangle$, related to the square of the center-of-mass energy, $s$, by a function of the form

$$\langle n \rangle = a \cdot s^b$$  \hspace{1cm} (1.18)

where Fermi, based on purely statistical considerations, predicted a value of $\frac{1}{4}$ for $b$. The other two relationships between $\langle n \rangle$ and $s$ have been suggested by perturbative QCD calculations [8] and studies of proton-proton collisions [9] respectively:

$$\langle n \rangle = a + b \cdot \exp[1.769 \cdot \sqrt{\ln(s/Q_0^2)}]$$ and  \hspace{1cm} (1.19)

$$\langle n \rangle = a + b \cdot \ln s + c \cdot \ln^2 s.$$  \hspace{1cm} (1.20)
Using the data from [6], which examined the total charged multiplicity in hadronic events, fitting to Equation 1.18 gave values of $2.20 \pm 0.03$ for $a$ and $0.252 \pm 0.002$ for $b$. The QCD-inspired equation gave fitted values of $a = 2.46 \pm 0.02$, $b = 0.091 \pm 0.001$ and $Q_0^2 = 0.85 \pm 0.02$ GeV$^2$. The fit based on $pp$ collisions came up with $a = 3.57 \pm 0.09$, $b = -0.43 \pm 0.06$ and $c = 0.262 \pm 0.007$.

In addition to the tests of multiplicity and cross section it is also possible to examine the differential cross section of some particles; the differential cross section can be scaled so that a direct comparison may be made with the differential cross sections obtained at other center-of-mass energies in other experiments. The $K_S^0$ and $\Lambda^0$ will be the only particles with sufficient purity in the signal region such that the differential cross sections can be calculated.

The extraction of $K^*(892)$'s from the data provides an opportunity to explore the relationship between the production of the $K^*$ and $K_S^0$ mesons. If $P$ represents the rate of production of pseudoscalar mesons and $V$ represents the rate of production of vector mesons, then the ratio $V/(P + V)$ should be equal to $3/4$ based on simple spin counting ($2J + 1$ spin states for vector mesons vs. only 1 spin state for the pseudoscalar mesons). However, experimental evidence has indicated that the actual ratio is more about $1/2$; hence, the various Monte Carlo models have permitted this value to be a variable parameter in event generation. The default value in Lund for the production of strange quarks is 0.6; this number is 0.5 for up and down quarks and 0.75 for charm and bottom quarks.

Calculation of the the production rates of the $K^*$, $\rho$ and $\phi$ vector mesons can lead to a more accurate determination of yet another parameter in the Lund model, that being the ratio of the probability of producing an excited $s\bar{s}$ pair from the vacuum to the probability of producing an excited $u\bar{u}$ or $d\bar{d}$ pair. This number, set to 0.3 in Lund, can be calculated in two ways:

$$\gamma_s/\gamma_u = \langle N_{K^*} \rangle / 2 \langle N_{\rho} \rangle \quad \text{and}$$

$$\gamma_s/\gamma_u = 2 \langle N_{\phi} \rangle / \langle N_{K^*} \rangle.$$  

(1.21)  

(1.22)
Chapter 2

TRISTAN and AMY

2.1 TRISTAN

The TRISTAN $e^+e^-$ Collider, shown in Figure 2-1, consists of three major parts. Electrons are produced with an initial energy of 30 MeV in a Van de Graaf accelerator while positrons are created by a 200 MeV electron beam striking a tantalum target. Next is the 390 meter long linear accelerator, known as a “linac”, which takes positrons and then electrons and accelerates each group of particles up to an energy of 2.5 GeV. These particles are then deposited in the Accumulator Ring (AR). When the total current of electron and positron beams reaches $\sim 10\mu$A, the 377 meter circumference AR accelerates them to an energy ranging from 6 to 8 GeV. Having reached this stage, the two beams are injected into the Main Ring (MR), a 3 km circumference storage ring that further accelerates the counter-rotating electrons and positrons to the desired center-of-mass energy. Upon attaining this energy, the accelerator goes into collision mode, the beams are focused to collide at each of the four detector locations and data-taking by the detectors can start. The beams themselves each consist of two bunches from 1 to 2 cm in length and $\sim 1$ mm in width and height. The total beam current has been as high as 14 mA and the instantaneous luminosity
has reached $\sim 10^{31}\text{cm}^{-2}\text{s}^{-1}$. When the accelerator is running, actual data-taking goes on for about 10 hours per day, providing researchers with as much as 1 pb$^{-1}$ of data per day. Further information on the TRISTAN Accelerator can be found in [13].

2.2 The AMY Detector

Known as a general purpose detector, the AMY detector is distinguished from other detectors by its unusually high magnetic field of 3 Tesla (other detectors have a magnetic field typically in the range of 0.5 to 1T). Because of this high magnetic field, AMY, shown in Figure 2-2, is more compact than other detectors. As originally conceived, AMY was to have good resolution in the determination of charged tracks and also provide excellent electron and muon recognition. The compactness of the overall detector also resulted in less expenditure of money, which was deemed by many to be a good thing.

An understanding of all the parts of AMY can only be had in conjunction with a brief history of AMY. The AMY collaboration was started up substantially later than the VENUS and TOPAZ collaborations. Because of this the full detector as originally envisioned could not be installed. In the original implementation of AMY, called AMY 1.0, the whole detector consisted of a 1.5 mm thick aluminum beam pipe with an outer radius of 11.65 cm, the Inner Tracking Chamber (ITC), the Central Drift Chamber (CDC), the Shower Counter (SHC), the solenoid coil, the cryostat, the iron yoke and the Muon Chambers (MUO) in the barrel region and the Ring Veto Counter (RVC), Pole Tip Counter (PTC) and Luminosity Monitor (LUM) in the forward and backward directions of the electron beam. This configuration lasted from 1986 to 1989.

Between the Spring and Summer of 1989, the X-Ray Detector (XRD) was inserted and the gas in the CDC, previously HRS, was changed to a combination of neon and ethane. The new CDC gas was transparent to the x-rays that the XRD was designed to find.
Figure 2-1: Overview of TRISTAN at KEK
After TRISTAN shut down in the summer of 1989, AMY underwent a transformation. The beampipe was replaced with one of beryllium that was 1 mm thick and was intended to cut down on multiple scattering. The new beampipe was slimmer than the original, having an outer radius of 4.85 cm, to facilitate the installation of the Vertex Chamber (VTX) inside of the ITC. A new set of focusing magnets was inserted that was designed to increase the luminosity of TRISTAN. The RVC and PTC were both removed and replaced with the Endcap Shower Counter (ESC). In addition, the LUM was replaced in favor of the Small Angle Counter (SAC). Unfortunately, during a brief data-taking period at the end of 1989, it was discovered that there was much more background than anticipated. The culprit was identified as the new magnets. So, for the data taken in 1990, the new magnets, beampipe and VTX were removed and replaced with the old beampipe and magnets. This configuration of detectors has come to be unofficially known as AMY 1.25.

After the 1990 data-taking period, AMY was further modified. The XRD was never able to work effectively and was turned off. In came the new magnets, slimmer beryllium beampipe and VTX along with a new set of lead shielding to prevent the increase in background. Also new was the Forward Tracking Chamber (FTC). In the CDC, the Neon-Ethane gas had proven to have a complicated drift function for which it was difficult to compensate (see Section 2.2.3); therefore, the CDC gas was switched back to HRS. This configuration is known as AMY 1.5 and represents the basic set-up of AMY for the 1991 through 1993 data-taking periods.

Since 1991, only one new detector has been installed, that being the Beam Pipe Counter (BPC) in early 1993. However, there has been quite a bit of tinkering with the lead shielding and various masks in the beam line. The most important to this thesis was the addition of a 100 μm thick lining of titanium on the inside of the beam pipe. This was designed to cut down on the high number of soft x-rays originating from the lead shielding. Prior to the 1993 data-taking period, the titanium was changed to a 10 μm thick lining of copper because the copper more readily dissipated the large amount of heat that was building up near the VTX and causing part of it to melt. This build-up of heat was due in part to
the titanium liner pulling away from the beampipe in certain areas. This led to discharges along its length. A fuller account of the beampipe problems and alterations can be found in [14].

2.2.1 The Vertex Chamber

The innermost of all of AMY's detectors, the VTX [15] was designed to identify charged particles with high resolution with emphasis on charged particles arising from the decay of heavy-flavor hadrons. It consists of four layers of wires covering 5.2 to 7.0 cm in the radial direction and 60 cm in the longitudinal direction giving it full coverage in the transverse plane and \(-0.88 \leq \cos \theta \leq 0.88\) in the longitudinal direction. Based on beam tests, the VTX provides an \(r-\phi\) resolution of 50 \(\mu m\) and a \(z\) resolution of 3 to 8 mm. The thickness of the VTX is approximately 0.6%/\(\sin \theta\) of a radiation length. As of this writing, though, the VTX has not yet been incorporated into the standard analysis of charged tracks and is thus not used in this thesis. However, the addition of the VTX to the analysis routines would not seriously change the results presented here as the ITC and CDC provide sufficient tracking information for these purposes.

2.2.2 The Inner Tracking Chamber

The ITC [16] is one of the two charged particle tracking chambers used in this thesis (the other being the CDC). The ITC extends over a physical region of 12.2 to 14.2 cm in the \(r-\phi\) plane and 55 cm along \(z\). This allows it to cover \(-0.75 \leq \cos \theta \leq 0.75\) along the longitudinal direction. However, the ITC provides no information on a track's longitudinal behavior. Based on analysis of Bhabha events (\(e^+e^- \rightarrow e^+e^-\), meaning that the event consists only of two charged particles, in contrast to a hadronic event as shown in Figures 1-3 and 1-4), the ITC has an \(r-\phi\) spatial resolution of 80 \(\mu m\).
Figure 2.2. The AMY Detector
The ITC is constructed of 576 tubes arranged in four layers of 144 tubes each and arranged in a staggered manner as shown in Figure 2-3. The tubes average 0.56025 cm in diameter while the sense wires themselves are 16.3 μm in diameter for the inner two layers and 15 μm in diameter for the outer two layers; they are made of tungsten plated with gold. In between the layers is a mixture of epoxy and microscopic glass spheres. The detector is filled with a mixture of argon and ethane in equal proportions at a pressure of 1.56 atm. To a particle passing through the chamber, the ITC averages about 0.5% of a radiation length.

The philosophy of finding a track in the ITC is very similar to that for the CDC. This will be discussed in the ensuing section and in Section 3.2.

2.2.3 The Central Drift Chamber

The detector most important to this thesis is the Central Drift Chamber [5]. It is designed to track charged particles in a high magnetic field and accurately reconstruct them. It does this through a circular array of 9048 “drift cells” as shown in Figure 2-4. A drift cell consists of one sense wire (composed of tungsten with a diameter of 20 μm and plated with gold) surrounded by six field shaping wires (each composed of aluminum with a diameter of 160 μm and also plated with gold); in the CDC there are a total of 9048 sense wires and 22994 field shaping wires. The drift cells are arranged in 40 layers broken up into 11 bands. The first band consists of five layers of wires oriented so as to be parallel with the electron beam. Wires with this orientation are known as “axial” wires and provide primary information on the behavior of charged particles in the transverse plane of the detector. After the first band of axial wires comes a band of three layers of wires oriented roughly four degrees from being parallel with the electron beam. These wires are known as “stereo” wires and, coupled with information gained from the axial wires, provide information on the longitudinal behavior of the charged tracks. After this band the CDC alternates between bands of 4 axial layers and 3 stereo layers for a total of 25 layers of axial wires and 15 layers of stereo wires; the band structure of the CDC is shown in Figure 2-5. The innermost layer is situated at a
Figure 2-3: The Inner Tracking Chamber (ITC) of AMY
designed radius of 15.5020 cm while the outermost is at a designed radius of 63.8899 cm. In addition, there are an increasing number of drift cells per layer as the radius increases. This helps keep the physical distance between adjacent cells roughly constant throughout the entire CDC. Longitudinally, wires in the first band are 92.4 cm long. Wires in succeeding pairs of adjacent axial and stereo bands share common lengths which increase as the radius increases; wires in the two outermost bands have a length of 179.2 cm. This gives the CDC an angular coverage of $-0.8 \leq \cos \theta \leq 0.8$. Table 2-1 provides the specifications for each of the layers. The resulting geometry gives the CDC the appearance of a cylinder that has had cones ripped out from each end.

The drift cells detect the presence of a charged particle when the particle ionizes the gas in the CDC; a charged particle will typically strip off about 30 electrons/cm along its path. The sense wires are maintained at a voltage of about 1.9 kV while the field shaping wires are grounded. Thus, if an electron is inside a drift cell it will be attracted to the sense wire at the center. As the electron moves towards the sense wire it in turn ionizes more electrons from the gas in an effect known as an “avalanche.” The increase in the total number of ionized electrons is on the order of $10^4$ to $10^5$. Because of the 3T magnetic field, the trajectory of the avalanching electrons towards the sense wire is quite complicated. In Figure 2-6 the drift trajectories and equipotential lines about a sense wire and its field wires are shown for both the case where there is no magnetic field and for a 3T field (the 3T case is based on a computer model). Near the center of the cell there is very little deviation from the 0T case but towards the outer edge of the cell there is a substantial difference that must be accounted for. For instance, in the case of no magnetic field the maximum drift time for an electron is typically 150 ns (corresponding to a cell size of about 5.5 mm); for the case where there is a 3T magnetic field the maximum drift time jumps to 750 ns.

To take care of this, a “drift function” must be employed. The drift function converts a measured time from a sense wire into the closest distance from the sense wire the charged particle actually came. This allows the CDC to have a resolution finer than the distance between sense wires of adjacent cells. In fact, the CDC has a claimed spatial resolution of
Figure 2-4: The Central Drift Chamber (CDC) of AMY
Figure 2.5: The band structure of the CDC
<table>
<thead>
<tr>
<th>Layer #</th>
<th>Type</th>
<th># Wires</th>
<th>Radius (cm)</th>
<th>Length (cm)</th>
<th>Disk #</th>
<th>Angular Deviation from Parallel (°)</th>
</tr>
</thead>
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<td>179.2</td>
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0.170 mm and resultant transverse momentum resolution of $\Delta p_t/p_t = 0.7\%p_t(\text{GeV}/c)$; when coupled with the ITC the claimed resolution drops down to $\Delta p_t/p_t = 0.6\%p_t(\text{GeV}/c)$ [17]. These values were arrived at based on a study of Bhabha events, meaning that they were primary, isolated, high-momentum particles. Further discussion of momentum resolution will be deferred to Section 3.2.4. The body of the CDC itself is composed of a 1 mm thick KEVLAR tube which holds the innermost endplates apart and 6 equally-spaced aluminum posts which hold the outermost endplates apart. In addition to the outer aluminum posts are panels made of MYLAR, ROHACELL and aluminized MYLAR which are molded to conform to the shape of the CDC and attached to the aluminum posts. A 150 $\mu$m thick foil of MYLAR surrounds the entire outer part of the CDC to act as a gas seal. The end plates are made of aluminum disks and aluminum hoops held together by aluminum screws and epoxy, which also acts as a gas seal. Including the beampipe and ITC, a particle will travel through only 3.0% of a radiation length before encountering the first layer of wires.

2.2.4 The X-Ray Detector

Designed to be in between the CDC and Barrel Shower Counter was the X-Ray Detector [18]. It was supposed to help improve electron identification by detecting the synchrotron X-rays emitted by electrons as they looped around inside the 3T magnetic field. Unfortunately, it was never gotten to work in any satisfactory manner. Its only effect on this thesis was the change in gas in the CDC in 1990. Since HRS gas absorbs X-rays, it was decided to change to a different gas that was transparent to that radiation. A mixture of neon and ethane was chosen. But the determination of the drift function in neon gas was very challenging—the work wasn’t completed until a full two years had elapsed. But the neon data is now fully competitive with the early HRS gas in the quality of the data and no further distinguishing is made between the two running periods.
Figure 2-6: (a) Drift trajectories and equipotential lines about sense wire, (b) Drift trajectories and equipotential lines in 3T magnetic field.
2.2.5 The Barrel Shower Counter

While the VTX, ITC and CDC all detect charged particles, the detection of photons and identification of electrons produced in the angular region $-0.73 \leq \cos \theta \leq 0.73$ is up to the Barrel Shower Counter [19] (SHC for short). While a detector designed to find neutral particles seems to be beyond the province of a hadron search, the ability of the SHC to distinguish electrons from other charged particles is exploited.

A typical electromagnetic calorimeter such as the SHC incorporates dense materials into itself (in the case of the SHC that material is lead). This is done so as to provide a medium in which incoming particles will interact and lose most (if not all) of their original energy. When a photon or an electron enters the SHC it interacts with the material in there to form secondary particles through either bremsstrahlung ($e^- \rightarrow e^- + \gamma$) or pair creation ($\gamma \rightarrow e^+e^-$). These secondary particles will in turn create tertiary particles through similar processes and so on. If there is sufficient material in which the particles interact then eventually the particles will have insufficient energy to create new particles. Thus, the shower development is complete. To study the shower, it is necessary to employ within the interacting medium a means in which the energy of the shower at a certain point can be read without corrupting the shower itself. This design philosophy for the SHC provides a nice segue into its actual construction.

The SHC has 20 layers to it. In each layer is a cylinder of tubes which are used to detect incoming particles. Each tube has a gold-plated 50 μm thick tungsten wire running down the middle of it and is filled with gas (typically, a mixture of argon, ethane and alcohol in proportions of 49.3% : 49.3% : 1.4%, respectively). A tube is made of a resistive plastic and has dimensions of 7 mm by 10 mm by 220 cm; the walls of the tube itself are 0.8 mm thick. The wire at the center is normally maintained at a voltage of 2.15 kV (though that value is not carved in stone); from these wires come the “anode” signals while from the conducting tubes come the “cathode” signals. Surrounding the tube layers are sheets of etched copper-clad boards of G-10 which read in the induced charges on the cathode tubes.
The anode signals in each layer are ganged together in groups of about 10 and are also read in. Sandwiching the G-10 are sheets of lead (except for the interior of the first layer). These sheets are 3.5 mm thick for the first 16 layers and 7.0 mm thick for the outer 4. In addition, there are thin layers of epoxy interspersed among the layers. This is shown in Figure 2-7 along with the 1 cm thick stainless steel top plate and 2.4 mm thick stainless steel bottom plate which help provide the needed mechanical support. The SHC is 30 cm thick radially and 220 cm in length. A particle travelling through it encounters a total of $14.4 / \sin \theta$ radiation lengths. Furthermore, the SHC is subdivided into six equal “sextants” to facilitate ease of handling. The dividing walls are each composed of a 2.4 mm thick sheet of stainless steel.

As mentioned above, SHC cathode signals are read in via the G-10 boards. These boards have been etched in copper so as to be able to read in both the $\theta$ and $\phi$ information provided by the cathode tubes. There are a total of 5400 $\theta$ channels and an equal number of $\phi$ channels. Areas where the $\phi$ and $\theta$ pads intersect is called a “block.” Each sextant has 8 blocks and each block is made up of 2 $\phi$ pads by 4 $\theta$ pads; each type of pad intersects with pads of the other type only within a single block. This gives the SHC good angular resolution: it boasts a resolution of 0.3° in $\theta$ and 0.1° in $\phi$. Signal lines etched in copper on the face of the G-10 opposite to the tubes are used to transmit the cathode information to the end of the detector. Both $\theta$ and $\phi$ cathode signals are ganged up into layers of 4. This is in contrast to the anode signals, where each layer is individually represented. This provides good information on the development of a shower through the SHC. However, the anodes are only ganged in the $\phi$ direction (in 48 groups of 8 known as “towers”) and they have a spatial resolution of 131 mrad. The energy resolution of the SHC has not fared quite as well. In Table 2-2 the SHC energy resolution for different energies is shown.

Aside from its ability to measure the energy of photons, the SHC’s ability to distinguish electrons from other charged particles plays a role in this thesis. The intensity of the emitted radiation in bremsstrahlung is proportional to the inverse mass squared [20]. Since the mass of an electron is only about 1/200 the mass of the next lightest charged particle (the muon),
Figure 2-7: Structure of the Barrel Shower Counter (SHC) of AMY
Table 2-2: SHC energy resolution. Values are given for the center-of-mass energy shown and make use of the formula $E = aE^{-\frac{1}{2}} + b$

<table>
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<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>a</th>
<th>b (GeV)</th>
<th>$\sigma$ (%)</th>
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<tr>
<td>50</td>
<td>0.230</td>
<td>0.060</td>
<td>11.4 ± 0.9</td>
</tr>
<tr>
<td>52</td>
<td>0.1811 ± 0.0193</td>
<td>0.0791 ± 0.0046</td>
<td>11.4 ± 0.2</td>
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<tr>
<td>55</td>
<td>0.358 ± 0.040</td>
<td>0.040 ± 0.008</td>
<td>10.9 ± 0.2</td>
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<tr>
<td>56</td>
<td>0.2116 ± 0.0164</td>
<td>0.0804 ± 0.0038</td>
<td>11.6 ± 0.2</td>
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<tr>
<td>58</td>
<td>0.266 ± 0.016</td>
<td>0.082 ± 0.003</td>
<td>13.1 ± 0.9</td>
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<tr>
<td>60</td>
<td>0.2346 ± 0.0453</td>
<td>0.1403 ± 0.0106</td>
<td>18.5 ± 0.5</td>
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</tbody>
</table>

only electrons suffer enough from bremsstrahlung for it to have a noticeable effect on the SHC. Other charged particles are considered to be "minimum ionizing", meaning they typically won't deposit more than a few hundred MeV in the SHC. Once all the showers in the SHC have been reconstructed by the software analysis (described in 3.3.1) and charged tracks in the CDC found (described in 3.2) then it is possible to see if tracks in the CDC can be matched up with showers in the SHC. If a track and shower match then the ratio of the track's momentum to the shower's energy is calculated. For an electron, $\frac{p_{track}}{E_{shower}}$ is approximately 1 while for other charged particles that value can run the gamut from 1 on up.

2.2.6 The Superconducting Magnet

Information on the superconducting magnet of AMY can be found in [21]. It is situated outside of the SHC. Its 3 Tesla field allows AMY to be as compact as it is. It is cooled with liquid helium at 4.4 K. The current in the coil reaches 5 kA.
2.2.7 The Muon Detector

Surrounding the magnet is a large mass of iron shaped in the form of a hexagon. This 650 metric ton mass serves the dual purpose of flux return for the magnet and hadron filter for the muon detector [22], which is also hexagonal in shape. The muon detector (MUO for short) detects charged particles that have traversed the distance through the iron. This only leaves muons since other particles will interact in the iron (e.g., pions, protons and other long-lived hadrons), undergo bremsstrahlung and lose their energy (in the case of electrons) or decay too quickly to reach the MUO (in the case of the \( \tau \) lepton).

The MUO is actually composed of two detectors. One detector, known as the muon chamber, provides information on where the muon struck the detector. The other, called the muon counter, gives timing information and is used in the rejection of cosmic ray events. The MUO has an angular coverage of \(-0.74 \leq \cos \theta \leq 0.74\). Azimuthally, the top and bottom chambers reach 410 cm in length; the two upper sides are 360 cm azimuthally. The design of the MUO insures that there are no areas in the transverse plane where a muon can pass through undetected. The six parts of the muon chamber are each made up of four layers of 5 \( \times \) 10 cm aluminum drift cells. Layers 1 and 2 are perpendicular to the last two, thus providing information along the \( z \) direction. The aluminum tube acts as the cathode while a 100 \( \mu \)m gold-plated tungsten wire acts as the anode; the wire is operated at a voltage of about 3.1 kV.

The angular coverage of the muon counter is the same as for the chambers. When a \( \mu \) passes through the muon counter it creates a signal in a plastic scintillator panel that is then read in through a photomultiplier tube. The anode signals from the drift tubes and the photomultiplier tube outputs are processed by LeCroy 27358 preamp and discriminator boards and digitized by a FASTBUS TDC system. By themselves, the scintillators can provide a resolution of only 15 ns but when that information is coupled with information from the muon chamber and corrected for the propagation of light in the scintillators then the resolution was expected to be as low as 2.5 \( \sim \) 3.5 ns; however, a resolution of about
10 ns is observed. Since a \( \mu \) arising from an \( e^+e^- \) collision will take only 12 or so ns to reach the muon detector and a cosmic muon must take 25 ns to traverse the whole detector, this information is vital to weeding out cosmic ray events from real \( e^+e^- \rightarrow \mu^+\mu^- \) and \( e^+e^- \rightarrow \tau^+\tau^- \) events.

2.2.8 The Forward Region

In the forward region of AMY (i.e., when \( 0.85 \leq |\cos \theta| \leq 1.0 \)) there either have been or are several detectors of little or no importance to this thesis. Among them are the Luminosity Monitor (LUM), the Small Angle Counter (SAC) and the Ring Veto Counter (RVC). These detectors are basically calorimeters and, like the SHC, detect only photons and electrons. A recent addition is the Forward Tracking Chamber (FTC). This detector is designed to track charged particles in the region \( 0.82 \leq |\cos \theta| \leq 0.97 \). Like the VTX, though, it has not been incorporated into the standard charged track analysis routines and is thus not of importance to this thesis.

In this region, the only detectors of any importance to this thesis are the Pole Tip Calorimeter (PTC) [23] and its replacement, the Endcap Shower Counter (ESC) [24]. These chambers measure the energy only of photons and electrons (treating other particles to be minimum ionizing particles, much like the SHC) but because they lie in a region where many Bhabha and \( e^+e^- \rightarrow \gamma \gamma \) events take place they are the primary instruments in the calculation of total luminosity. Bhabha events are a very well understood phenomenon and since it is known how many Bhabhas should be seen in a given region of space at a given center-of-mass energy and since those events will cluster along the axis of the beam, the high statistics of the PTC and ESC can be used to good effect.

To facilitate installation in the AMY 1.0 scheme, the PTC, which lies in \( 0.89 \leq |\cos \theta| \leq 0.97 \), has two sections, with one in the forward and one in the rear. The forward section, known as the pole piece, has three layers of scintillator in between sheets of lead. This
gives it a total of five radiation lengths. The rear section has eight layers of scintillator and lead intermixed and has 14.1 radiation lengths. Both the forward and rear sections have a single layer of proportional tube array to provide spatial information. The calibration of the detector is based on simulation studies and Bhabha analysis. It has an energy resolution of 11% and a spatial resolution of 13.96 mrad in $r$-$\phi$ and 3.49 mrad in $z$.

The ESC, which replaced both the PTC and RVC, fully covers the angular range $0.82 \leq \cos \theta \leq 0.98$; it also provides some information for angles where $\cos \theta \leq 0.99$ and $0.80 \leq \cos \theta$. The ESC is composed of two sections of lead and scintillators with a total thickness of 15 radiation lengths. In between the two sections are resistive plastic tubes divided into $\theta$ and $\phi$ pads to retrieve spatial location. The energy resolution of the ESC is $\frac{\delta E}{E} = \frac{14.2\%}{\sqrt{E}} + 6.2\%$ and the spatial resolution is 2.4 mrad in $z$ and 8.0 mrad in $r$-$\phi$.

### 2.2.9 Triggering and Data Acquisition

When there is a set of pulses and signals in AMY it must be decided immediately whether it is due to a genuine electron-positron collision or is merely a randomly produced sequence of uninteresting “noise.” This is where the triggering system comes into play. If the set of signals within AMY fulfills one of the trigger criteria then it is read in as being potentially noteworthy. The criteria to set off a trigger are somewhat loose so that none of the wheat is tossed out with the chaff. Further weeding out of uninteresting events is done offline. However, since the chaff typically overwhelms the wheat, the triggering system is unequivocally necessary. What results is an event rate of about 2 or 3 Hz, well within the ability of the data acquisition system to read in. In Table 2.3 are the triggers used for the AMY 1.5 configuration. The triggers of interest to those studying hadronic events are trigger bits 8, 17 and 18. Trigger bit 8 requires that the SHC register at least 3 GeV of energy. Trigger bit 17 asks for $\geq 5$ track segments (segments will be described in Section 3.2) in at least one of disks 2 through 6 of the CDC and $\geq 4$ segments in at least four of those disks as well as requiring that all of those disks have at least 3 segments. Trigger bit 18 loosens
the requirement on the number of track segments but it also asks for a minimum ionizing shower in the SHC. After applying the hadronic event cuts, described in Section 4.1, it was found that the efficiency of the triggering system was better than 99.7% [5], meaning that the effect of the triggering system is negligible.

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<th>Description</th>
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<tr>
<td>3</td>
<td>Prescaled beam-crossing</td>
</tr>
<tr>
<td>4</td>
<td>≥ 2 CDC and ≥ 1 CDC/minimum ionizing HSC radial track and ITC signal</td>
</tr>
<tr>
<td>5</td>
<td>ESC Bhabha</td>
</tr>
<tr>
<td>6</td>
<td>2 CDC/minimum ionizing HSC back-to-back radial tracks</td>
</tr>
<tr>
<td>8</td>
<td>Total energy in HSC</td>
</tr>
<tr>
<td>9</td>
<td>HSC cluster energy</td>
</tr>
<tr>
<td>11</td>
<td>ESC 2γ and ≥ 4 CDC tracks</td>
</tr>
<tr>
<td>13</td>
<td>2 ITC tracks and ≥ 5 CDC segments and Sh Min I</td>
</tr>
<tr>
<td>14</td>
<td>2 back-to-back ITC tracks and ≥ 4 CDC segments</td>
</tr>
<tr>
<td>15</td>
<td>2 ITC tracks and ≥ 4 CDC segments and Sh Lo Maj 1</td>
</tr>
<tr>
<td>16</td>
<td>≥ 7 ITC tracks</td>
</tr>
<tr>
<td>17</td>
<td>CDC multitrack</td>
</tr>
<tr>
<td>18</td>
<td>Looser CDC multitrack and Sh Min I</td>
</tr>
<tr>
<td>19</td>
<td>(Sh Hi Maj 1 and sh Lo Maj 2) OR (Sh Lo Maj 3)</td>
</tr>
<tr>
<td>20</td>
<td>≥ 1 segment in 4 CDC disks and (Sh Lo Maj 2 OR Sh Hi Maj 1) and NOT Trigger Bit 19</td>
</tr>
<tr>
<td>21</td>
<td>varying # of segments in CDC and ITC signal and Sh Min I</td>
</tr>
<tr>
<td>22</td>
<td>varying # of segments in CDC and Sh Min I Maj 1</td>
</tr>
<tr>
<td>23</td>
<td>≥ 2 ITC tracks and 2 hits in MUO scintillators</td>
</tr>
<tr>
<td>24</td>
<td>≥ 2 ITC tracks and ≥ 5 segments in CDC and Sh Min I</td>
</tr>
<tr>
<td>25</td>
<td>ESC and CDC dimuon</td>
</tr>
<tr>
<td>26</td>
<td>ESC and FTC dimuon</td>
</tr>
<tr>
<td>27</td>
<td>SAC and CDC</td>
</tr>
<tr>
<td>29</td>
<td>2 γ’s in ESC</td>
</tr>
<tr>
<td>30</td>
<td>ITC signal and 2 perfect CDC tracks</td>
</tr>
<tr>
<td>31</td>
<td>ITC signal and (1 perfect CDC track OR bachelor V)</td>
</tr>
</tbody>
</table>

After an event has successfully passed the triggers, it is read in through a FASTBUS Processor Interface that digitizes analog and timing signals from the various detectors. These data are read into a VAX-11/780 computer for temporary storage. While there, the data
are checked to ensure that the entire detector is operating correctly. When this is done, the online system allows the data to be transmitted to a FACOM M-780 OS IV MSP computer by way of an optical link. During the transmission, the data are reformatted to permit offline analysis.

2.3 Data Sample Specifics

Tables 2-4 and 2-5 show the various energies and accumulated luminosities for those energies used in this thesis. Also shown are the number of events that survived the hadronic event cuts which will be described in Section 4.1. It is from those events that the data presented in this thesis are taken.
Table 2-4: AMY 1.0 integrated luminosity

<table>
<thead>
<tr>
<th>Run Period</th>
<th>Date</th>
<th>√s</th>
<th>PTC ( \int \mathcal{L} , dt )</th>
<th># Hadronic Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2733 - 2987</td>
<td>Spring 1987</td>
<td>50.00</td>
<td>0.636 ± 0.016</td>
<td>88</td>
</tr>
<tr>
<td>3048 - 3568</td>
<td>Summer 1987</td>
<td>52.00</td>
<td>3.976 ± 0.080</td>
<td>482</td>
</tr>
<tr>
<td>3712 - 4416</td>
<td>Fall 1987</td>
<td>55.00</td>
<td>3.266 ± 0.039</td>
<td>368</td>
</tr>
<tr>
<td>4511 - 5170</td>
<td>Spring 1988</td>
<td>56.00</td>
<td>5.993 ± 0.053</td>
<td>727</td>
</tr>
<tr>
<td>5173 - 5361</td>
<td>Summer 1988</td>
<td>56.50</td>
<td>0.994 ± 0.022</td>
<td>123</td>
</tr>
<tr>
<td>5369 - 5692</td>
<td>Summer 1988</td>
<td>57.00</td>
<td>4.398 ± 0.046</td>
<td>492</td>
</tr>
<tr>
<td>5816 - 6121</td>
<td>Fall 1988</td>
<td>60.00</td>
<td>2.465 ± 0.037</td>
<td>290</td>
</tr>
<tr>
<td>6134 - 6223</td>
<td>Spring 1989</td>
<td>58.50</td>
<td>0.801 ± 0.016</td>
<td>89</td>
</tr>
<tr>
<td>6226 - 6230</td>
<td>Spring 1989</td>
<td>57.25</td>
<td>0.0582 ± 0.0043</td>
<td>10</td>
</tr>
<tr>
<td>6231 - 6237</td>
<td>Spring 1989</td>
<td>57.50</td>
<td>0.0803 ± 0.0050</td>
<td>6</td>
</tr>
<tr>
<td>6238 - 6243</td>
<td>Spring 1989</td>
<td>57.75</td>
<td>0.0781 ± 0.0050</td>
<td>9</td>
</tr>
<tr>
<td>6244 - 6250</td>
<td>Spring 1989</td>
<td>58.00</td>
<td>0.0772 ± 0.0050</td>
<td>7</td>
</tr>
<tr>
<td>6251 - 6256</td>
<td>Spring 1989</td>
<td>58.75</td>
<td>0.0865 ± 0.0054</td>
<td>12</td>
</tr>
<tr>
<td>6257 - 6265</td>
<td>Spring 1989</td>
<td>59.00</td>
<td>0.0939 ± 0.0056</td>
<td>16</td>
</tr>
<tr>
<td>6266 - 6272</td>
<td>Spring 1989</td>
<td>59.25</td>
<td>0.0984 ± 0.0058</td>
<td>16</td>
</tr>
<tr>
<td>6274 - 6279</td>
<td>Spring 1989</td>
<td>59.50</td>
<td>0.0724 ± 0.0056</td>
<td>7</td>
</tr>
<tr>
<td>6280 - 6286</td>
<td>Spring 1989</td>
<td>59.125</td>
<td>0.0755 ± 0.0050</td>
<td>13</td>
</tr>
<tr>
<td>6290 - 6332</td>
<td>Spring 1989</td>
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<td>0.505 ± 0.013</td>
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</tr>
<tr>
<td>6334 - 6410</td>
<td>Spring 1989</td>
<td>60.00</td>
<td>0.757 ± 0.020</td>
<td>79</td>
</tr>
<tr>
<td>6423 - 6674</td>
<td>Spring 1989</td>
<td>60.80</td>
<td>1.376 ± 0.059</td>
<td>52</td>
</tr>
<tr>
<td>6676 - 6697</td>
<td>Spring 1989</td>
<td>59.80</td>
<td>0.178 ± 0.010</td>
<td>19</td>
</tr>
<tr>
<td>6698 - 6703</td>
<td>Spring 1989</td>
<td>60.80</td>
<td>0.0575 ± 0.006</td>
<td>4</td>
</tr>
<tr>
<td>6705 - 6740</td>
<td>Spring 1989</td>
<td>59.00</td>
<td>0.371 ± 0.014</td>
<td>44</td>
</tr>
<tr>
<td>6744 - 6822</td>
<td>Spring 1989</td>
<td>60.80</td>
<td>0.708 ± 0.020</td>
<td>87</td>
</tr>
<tr>
<td>6906 - 6997</td>
<td>Spring 1989</td>
<td>60.00</td>
<td>0.347 ± 0.013</td>
<td>34</td>
</tr>
<tr>
<td>7006 - 7176</td>
<td>Spring 1989</td>
<td>60.80</td>
<td>1.181 ± 0.028</td>
<td>124</td>
</tr>
<tr>
<td>7192 - 7629</td>
<td>Summer 1989</td>
<td>61.40</td>
<td>4.287 ± 0.060</td>
<td>431</td>
</tr>
<tr>
<td>7682 - 7795</td>
<td>Summer 1989</td>
<td>54.00</td>
<td>0.531 ± 0.017</td>
<td>61</td>
</tr>
</tbody>
</table>
Table 2.5: AMY "1.25" and 1.5 integrated luminosity.

<table>
<thead>
<tr>
<th>Run Period</th>
<th>Date</th>
<th>$\sqrt{s}$</th>
<th>$\text{ESC } \int \mathcal{L} , dt \ (\text{pb}^{-1})$</th>
<th># Hadronic Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>8378 - 10896</td>
<td>Spring 1990</td>
<td>58.00</td>
<td>27.16 ± 0.10</td>
<td>2759</td>
</tr>
<tr>
<td>10983 - 11865</td>
<td>Spring 1991</td>
<td>58.00</td>
<td>8.16 ± 0.07</td>
<td>673</td>
</tr>
<tr>
<td>11821 - 12639</td>
<td>Fall 1991</td>
<td>58.00</td>
<td>26.57 ± 0.10</td>
<td>2631</td>
</tr>
<tr>
<td>12650 - 14579</td>
<td>Spring 1992</td>
<td>58.00</td>
<td>64.46 ± 0.54</td>
<td>5236</td>
</tr>
<tr>
<td>14594 - 15259</td>
<td>Fall 1992</td>
<td>58.00</td>
<td>19.705 ± 0.083</td>
<td>1917</td>
</tr>
<tr>
<td>15260 - 15292</td>
<td>Fall 1992</td>
<td>59.70</td>
<td>0.982 ± 0.019</td>
<td>100</td>
</tr>
<tr>
<td>15293 - 15330</td>
<td>Fall 1992</td>
<td>58.20</td>
<td>1.401 ± 0.022</td>
<td>135</td>
</tr>
<tr>
<td>15331 - 15373</td>
<td>Fall 1992</td>
<td>59.20</td>
<td>1.375 ± 0.022</td>
<td>141</td>
</tr>
<tr>
<td>15374 - 15412</td>
<td>Fall 1992</td>
<td>58.45</td>
<td>1.337 ± 0.022</td>
<td>142</td>
</tr>
<tr>
<td>15413 - 15458</td>
<td>Fall 1992</td>
<td>58.70</td>
<td>1.342 ± 0.022</td>
<td>126</td>
</tr>
<tr>
<td>15459 - 15519</td>
<td>Fall 1992</td>
<td>58.95</td>
<td>1.741 ± 0.025</td>
<td>180</td>
</tr>
<tr>
<td>15520 - 15562</td>
<td>Fall 1992</td>
<td>59.45</td>
<td>1.221 ± 0.021</td>
<td>135</td>
</tr>
<tr>
<td>15563 - 15630</td>
<td>Fall 1992</td>
<td>57.60</td>
<td>2.064 ± 0.027</td>
<td>206</td>
</tr>
<tr>
<td>15657 - 17681</td>
<td>Spring 1993</td>
<td>58.00</td>
<td>54.32 ± 0.32</td>
<td>5559</td>
</tr>
</tbody>
</table>
Chapter 3

Monte Carlo Generators, Detector Simulation and Detector Analysis

3.1 Event Generation and Simulation

As mentioned in Section 1.2, it is important to have models that accurately represent (though not necessarily predict) the physics taking place when $e^+e^- \rightarrow q\bar{q}, \, q\bar{q}g, \, q\bar{q}gg, \, etc.$ Since these models have a strong probabilistic nature they are called, for entirely unobscure reasons, "Monte Carlo" models. After a Monte Carlo event generator outputs an event, the final state particles of that event must be run through a sequence of programs that will move it through a computer simulation of the entire detector. The final state simulation retains all information in the event including the particles in the quark cascade, the intermediate particles which decay either in the generator or the simulator, the number and type of particles into which they decay, the number and type of particles produced in an interaction and the final state particles which don't promptly decay: photons, electrons, muons, neutrinos, pions, kaons and protons. For this thesis, a total sample of $\sim 1.3 \, fb^{-1}$ worth of simulated data was used; this translates into over 210,000 hadronic events.
3.1.1 Generation

The two event generators used for this thesis are the Lund 7.2 model and the HERWIG (Hadron Emission Reactions With Interfering Gluons) 5.5 model. These two models are among the most common of the e⁺e⁻-event generators. The Lund model is used as the primary Monte Carlo for this thesis as its parameters have already been adjusted to reflect the inclusive production of individual species of hadrons. The HERWIG Monte Carlo has not been adjusted in this manner; this will be dealt with in Chapter 6. For the record, in this analysis, a total of 960 pb⁻¹ of Lund 7.2 and 340 pb⁻¹ of HERWIG 5.5 was used.

The Lund model [25] was developed at the University of Lund in Sweden back in 1978 and has undergone many updates and revisions. Version 7.2, used here, starts with an e⁺e⁻-collision and allows the virtual γ or Z⁰ to decay into a q̅q̅ pair, the flavor being decided by using perturbative techniques on the Standard Model prediction. For instance, at the TRISTAN center-of-mass energy there are five possible quark flavors that could result. If quark mass effects are neglected then the probabilities go as the square of the quark charge, i.e., there would be a $\frac{4}{11}$ chance of $e^+e^-\rightarrow u\bar{u}$, a $\frac{1}{11}$ chance for $d\bar{d}$, a $\frac{1}{11}$ chance for $s\bar{s}$, a $\frac{4}{11}$ chance for $c\bar{c}$ and a $\frac{1}{11}$ chance for $b\bar{b}$. Of course, quark mass effects are taken into account but at the TRISTAN beam energy their corrections are small. After the initial quarks are generated, the Lund program has the responsibility of cascading them into the final state quarks. At high energies, perturbation theory is sufficient to describe the creation of gluons through a process similar to electron bremsstrahlung of photons. However, it can not describe the creation of additional q̅q̅ pairs nor is it sufficient as the available energy for a reaction decreases. In these instances, the Lund model has implemented a scheme whereby a leading-logarithm approximation calculates the probability of a quark or gluon showering into a subsequent pair of particles ($q \rightarrow qg$, $g \rightarrow gg$ or $g \rightarrow q\bar{q}$); this is known as the Parton Shower model. The probability of a shower exists so long as the virtual mass of the partons exceeds $1 \frac{\text{GeV}}{\text{c}^2}$, a parameter tuned to data taken in $e^-e^-$ collisions at 30 GeV.

After producing the final state quarks, gluons and photons the Lund Monte Carlo col-
lects them into the initial state hadrons. Lund 7.2 has a variety of ways to perform this hadronization. The one used for this thesis is known as “string fragmentation.” A string is basically a conglomeration of final state partons. In a 2-jet event, a string will stretch across the entire range of partons; in a 3-jet event, there will be one string stretching from one quark to a high-momentum gluon and another string from the gluon towards the other end of the line of partons. While it is a fictitious particle, the string provides the mechanism by which the initial state hadrons are formed. As the available energy forces the string to stretch it is eventually forced to break by creating a new $q\bar{q}$ pair (or, similarly, a diquark—anti-diquark pair, which enhance the production of baryons). Two strings then exist where one did before and the process continues. When there is no longer enough energy to break up any more strings, the quarks that are at the end of adjacent breaks form the initial state hadrons. Because of the emission of soft gluons, the momentum spectrum of the initial hadrons is softer than what it should be. To compensate for this, a fragmentation function is used. $f(z)$ represents the distribution calculating the probability that a hadron will end up with 100% $x_z$ of the momentum of the parent quark of the jet of which the hadron is a part. For Lund, the function is

$$f(z) \propto \frac{1}{z} (1-z)^a e^{-\frac{b m_T^2}{z^2}}$$

(3.1)

where $a$ and $b$ are experimentally determined values (set to default values of 0.5 and 0.8 (GeV/c$^2$)$^{-2}$, respectively, in Lund) and $m_T$ is the so-called transverse mass: $m_T^2 = m_{\text{hadrons}}^2 + p_T^2 + p_T^2$. After the momentum correction, the short-lived hadrons are allowed to decay. What is left winds up as Lund’s output. An example of Lund output is shown in Table 3-1. The first column contains the serial number of the particle in the event record. The second column is the name of the particle itself. In column three is information on which partons make up the string(s). The fourth column displays the parentage of the particle by naming the serial number of the particle that gave rise to it. The fifth through ninth columns are for kinematic information about the particle. As can be seen in this example, this was originally a $c\bar{c}$ event. The shower of partons is shown in lines 4 through 22. Particles 16 through 22 are the final state partons and they make up the string in line 23. Lines 24 through 32 are
the initial state hadrons that formed from the string. The remaining lines are concerned with the decay of those initial state hadrons. A particle not shown in parentheses is a final state particle and gets input into the detector simulator.

The HERWIG 5.5 routines attempt to model lepton-lepton, lepton-hadron and hadron-hadron collisions within one programming package. Its purpose is to accurately simulate parton shower development. It incorporates the interference and polarization effects from gluons within the parton shower and considers the effect from interactions among partons within different jets. After the final state partons have been generated, HERWIG uses a cluster fragmentation approach to form the initial state hadrons. Like the string “particle” shown in Table 3-1, the cluster is also listed as a separate particle. However, the cluster scheme differs from the string fragmentation scheme in that at the end of the parton shower, when the non-perturbative effects are no longer negligible, all remaining gluons are forced to decay into a $q\bar{q}$ pair. The resulting set of quarks and anti-quarks can be combined into several separate color-singlet clusters. These clusters will then decay through a variety of mechanisms into the initial state hadrons. As with the Lund model, the short-lived hadrons decay, leaving the final state hadrons. The HERWIG model has fewer adjustable parameters than Lund, making it somewhat more inflexible in some areas than the former, but it has the advantage over Lund in having a more solid foundation in the current theories of hadronization and shower development. Unfortunately, it hasn’t been as extensively tuned to the data as the Lund model. This shortcoming will be addressed to an extent in Chapter 6.

Varying the primary parameters used in the Monte Carlo models gives a good indication of the size of the systematic measurement errors invoked when using those models. For Lund, it has been found that the particle multiplicity is insensitive to perturbative-to-non-perturbative cutoff value within its uncertainty [25, 26]. The other primary parameters, $a$, $b$, $\Lambda_{\text{LDA}}$ (used in the leading logarithm approximation) and $\sigma_q$, which is the width of a Gaussian distribution used to assign transverse momentum to the initial hadrons, have a more substantial effect. The default parameters in Lund are $a = 0.5$, $b = 0.9$ cm$^4$/GeV$^2$. 
<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Particle Name</th>
<th>String Information</th>
<th>Parent's Serial #</th>
<th>(P_x) (GeV/c)</th>
<th>(P_y) (GeV/c)</th>
<th>(P_z) (GeV/c)</th>
<th>Energy (GeV)</th>
<th>Mass (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(c)</td>
<td></td>
<td>0</td>
<td>-11.954</td>
<td>-3.765</td>
<td>-26.117</td>
<td>29.000</td>
<td>1.350</td>
</tr>
<tr>
<td>2</td>
<td>(E)</td>
<td></td>
<td>0</td>
<td>11.954</td>
<td>3.765</td>
<td>26.117</td>
<td>29.000</td>
<td>1.350</td>
</tr>
<tr>
<td>3</td>
<td>(CMshower)</td>
<td></td>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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</tr>
<tr>
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<td>(c)</td>
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<td>3</td>
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<td>-3.470</td>
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<td>31.010</td>
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</tr>
<tr>
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<td></td>
<td>3</td>
<td>11.018</td>
<td>3.470</td>
<td>24.071</td>
<td>26.990</td>
<td>3.955</td>
</tr>
<tr>
<td>6</td>
<td>(c)</td>
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<td>4</td>
<td>-12.957</td>
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<td>-24.977</td>
<td>28.806</td>
<td>5.421</td>
</tr>
<tr>
<td>7</td>
<td>(g)</td>
<td></td>
<td>4</td>
<td>1.939</td>
<td>-0.526</td>
<td>0.906</td>
<td>2.204</td>
<td>0.000</td>
</tr>
<tr>
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<td>(E)</td>
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<td>5</td>
<td>10.755</td>
<td>3.167</td>
<td>23.982</td>
<td>26.580</td>
<td>2.378</td>
</tr>
<tr>
<td>9</td>
<td>(g)</td>
<td></td>
<td>5</td>
<td>0.263</td>
<td>0.302</td>
<td>0.089</td>
<td>0.410</td>
<td>0.000</td>
</tr>
<tr>
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<td>(c)</td>
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<td>6</td>
<td>-11.158</td>
<td>-3.456</td>
<td>-23.689</td>
<td>26.535</td>
<td>2.548</td>
</tr>
<tr>
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<td>(g)</td>
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<td>-1.799</td>
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<td>-1.288</td>
<td>2.271</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>(E)</td>
<td></td>
<td>8</td>
<td>9.200</td>
<td>2.865</td>
<td>21.896</td>
<td>23.960</td>
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</tr>
<tr>
<td>13</td>
<td>(g)</td>
<td></td>
<td>8</td>
<td>1.555</td>
<td>0.303</td>
<td>2.086</td>
<td>2.620</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>(c)</td>
<td></td>
<td>10</td>
<td>-10.066</td>
<td>-3.088</td>
<td>-22.504</td>
<td>24.882</td>
<td>1.350</td>
</tr>
<tr>
<td>15</td>
<td>(g)</td>
<td></td>
<td>10</td>
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<td>-0.367</td>
<td>-1.185</td>
<td>1.653</td>
<td>0.000</td>
</tr>
<tr>
<td>16</td>
<td>(E)</td>
<td></td>
<td>12</td>
<td>9.200</td>
<td>2.865</td>
<td>21.896</td>
<td>23.960</td>
<td>1.350</td>
</tr>
<tr>
<td>17</td>
<td>(g)</td>
<td></td>
<td>13</td>
<td>1.555</td>
<td>0.303</td>
<td>2.086</td>
<td>2.620</td>
<td>0.000</td>
</tr>
<tr>
<td>18</td>
<td>(g)</td>
<td></td>
<td>9</td>
<td>0.263</td>
<td>0.302</td>
<td>0.089</td>
<td>0.410</td>
<td>0.000</td>
</tr>
<tr>
<td>19</td>
<td>(g)</td>
<td></td>
<td>7</td>
<td>1.939</td>
<td>-0.526</td>
<td>0.906</td>
<td>2.204</td>
<td>0.000</td>
</tr>
<tr>
<td>20</td>
<td>(g)</td>
<td></td>
<td>11</td>
<td>-1.799</td>
<td>0.512</td>
<td>-1.288</td>
<td>2.271</td>
<td>0.000</td>
</tr>
<tr>
<td>21</td>
<td>(g)</td>
<td></td>
<td>15</td>
<td>-1.093</td>
<td>-0.367</td>
<td>-1.185</td>
<td>1.653</td>
<td>0.000</td>
</tr>
<tr>
<td>22</td>
<td>(c)</td>
<td></td>
<td>14</td>
<td>-10.066</td>
<td>-3.088</td>
<td>-22.504</td>
<td>24.882</td>
<td>1.350</td>
</tr>
<tr>
<td>23</td>
<td>(string)</td>
<td></td>
<td>16</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>58.000</td>
<td>58.000</td>
</tr>
<tr>
<td>24</td>
<td>(D^0)</td>
<td></td>
<td>23</td>
<td>6.379</td>
<td>2.407</td>
<td>14.271</td>
<td>15.943</td>
<td>2.007</td>
</tr>
<tr>
<td>25</td>
<td>(\rho^-)</td>
<td></td>
<td>23</td>
<td>2.231</td>
<td>0.454</td>
<td>5.754</td>
<td>6.243</td>
<td>0.824</td>
</tr>
<tr>
<td>26</td>
<td>(\rho^+)</td>
<td></td>
<td>23</td>
<td>2.527</td>
<td>0.166</td>
<td>3.632</td>
<td>4.472</td>
<td>0.626</td>
</tr>
<tr>
<td>27</td>
<td>(s^0)</td>
<td></td>
<td>23</td>
<td>0.507</td>
<td>0.035</td>
<td>1.033</td>
<td>1.159</td>
<td>0.135</td>
</tr>
<tr>
<td>28</td>
<td>(K'^-)</td>
<td></td>
<td>23</td>
<td>0.374</td>
<td>-0.034</td>
<td>-0.947</td>
<td>1.321</td>
<td>0.841</td>
</tr>
<tr>
<td>29</td>
<td>(K'^+)</td>
<td></td>
<td>23</td>
<td>-1.056</td>
<td>0.002</td>
<td>0.441</td>
<td>1.463</td>
<td>0.912</td>
</tr>
<tr>
<td>30</td>
<td>(s^0)</td>
<td></td>
<td>23</td>
<td>0.392</td>
<td>0.074</td>
<td>-0.913</td>
<td>1.006</td>
<td>0.135</td>
</tr>
<tr>
<td>31</td>
<td>(\omega)</td>
<td></td>
<td>23</td>
<td>-1.296</td>
<td>-0.495</td>
<td>-1.393</td>
<td>2.090</td>
<td>0.709</td>
</tr>
<tr>
<td>32</td>
<td>(D^*)</td>
<td></td>
<td>23</td>
<td>-10.059</td>
<td>-2.609</td>
<td>-21.878</td>
<td>24.304</td>
<td>2.007</td>
</tr>
<tr>
<td>33</td>
<td>(D^0)</td>
<td></td>
<td>24</td>
<td>6.037</td>
<td>2.418</td>
<td>13.561</td>
<td>15.154</td>
<td>1.865</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>71</td>
<td>K^0</td>
<td></td>
<td>65</td>
<td>3.699</td>
<td>2.155</td>
<td>9.715</td>
<td>10.628</td>
<td>0.498</td>
</tr>
<tr>
<td>72</td>
<td>\gamma</td>
<td></td>
<td>68</td>
<td>-0.085</td>
<td>-0.080</td>
<td>-0.386</td>
<td>0.403</td>
<td>0.000</td>
</tr>
<tr>
<td>73</td>
<td>\gamma</td>
<td></td>
<td>68</td>
<td>-0.439</td>
<td>-0.193</td>
<td>-0.969</td>
<td>1.081</td>
<td>0.000</td>
</tr>
<tr>
<td>74</td>
<td>\gamma</td>
<td></td>
<td>70</td>
<td>-2.236</td>
<td>-0.526</td>
<td>-4.201</td>
<td>4.788</td>
<td>0.000</td>
</tr>
<tr>
<td>75</td>
<td>\gamma</td>
<td></td>
<td>70</td>
<td>-0.047</td>
<td>0.008</td>
<td>-0.084</td>
<td>0.097</td>
<td>0.000</td>
</tr>
</tbody>
</table>
\[ \Lambda_{\text{LLA}} = 0.4 \text{ GeV} \text{ and } \sigma_q = 0.35 \text{ GeV/c}. \text{ } a \text{ and } b \text{ are strongly correlated and were allowed to vary synchronously by } \pm 5\%. \text{ } \Lambda_{\text{LLA}} \text{ was allowed to vary by } 4\% \text{ and } \sigma_q \text{ was allowed to vary by } \pm 0.01 \text{ GeV/c}. \text{ Another important effect comes from initial state radiation. The default for Lund is to disallow initial state radiation while the bulk of events in this study were generated with initial state radiation; this was examined by the generation of events with no initial state radiation. The variable examined under these variations was the multiplicity of } K^0\text{s. As will be shown in Section 4.4, the peak efficiency for finding } K^0\text{s is in the region } 0.05 < x_E < 0.35 \text{ where } x_E = \frac{\text{particle energy}}{\text{beam energy}}; \text{ the effect of the variations within only that energy region was examined. Table 3.1.1 shows the results of the variations normalized to the multiplicity found using the default values.}

**Table 3.2: Effect of the variation of the Lund parameters on the multiplicities of } K^0\text{s. The multiplicities have been normalized to the values found from the default parameters.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>( K^0 \text{ Multiplicity} )</th>
<th>Est. Sys. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td></td>
<td>1.00</td>
<td>—</td>
</tr>
<tr>
<td>( a &amp; b )</td>
<td>0.525 &amp; 0.943 ( (\text{GeV/c})^{-2} )</td>
<td>0.988</td>
<td>—</td>
</tr>
<tr>
<td>( a &amp; b )</td>
<td>0.475 &amp; 0.855 ( (\text{GeV/c})^{-2} )</td>
<td>0.997</td>
<td>0.8%</td>
</tr>
<tr>
<td>( \Lambda_{\text{L}} )</td>
<td>0.416 GeV</td>
<td>0.991</td>
<td>—</td>
</tr>
<tr>
<td>( \Lambda_{\text{L}} )</td>
<td>0.384 GeV</td>
<td>0.986</td>
<td>1.1%</td>
</tr>
<tr>
<td>( \sigma_q )</td>
<td>0.36 GeV/c</td>
<td>0.974</td>
<td>—</td>
</tr>
<tr>
<td>( \sigma_q )</td>
<td>0.34 GeV/c</td>
<td>0.977</td>
<td>2.5%</td>
</tr>
<tr>
<td>No Initial State Radiation</td>
<td></td>
<td>1.032</td>
<td>3.3%</td>
</tr>
<tr>
<td>Total Systematic Error from Lund</td>
<td></td>
<td></td>
<td>4.4%</td>
</tr>
</tbody>
</table>

3.1.2 Event Simulation

As a particle passes through a material it can undergo one of several different reactions. Each of these reactions is well-understood and can be assigned a probability of occurrence with great accuracy. This forms the reasoning behind the simulation techniques used in high energy physics. But while the concept is simple enough, the actual implementation is truly laborious. Each type of particle reacts differently; this must be accounted for. As described in Section 2.2, there are many different detectors and each detector makes use
of many different materials in its composition; this must also be accounted for. When a particle undergoes a reaction it often produces secondary particles; these must be accounted for as well. In point of fact, the amount of code devoted solely to simulation is roughly an order of magnitude larger than this thesis.

While the volume of programming is sufficient for a dull week of reading, a sketch of the underlying details is not nearly so gruesome. Each particle is allowed to incrementally creep through the detector in a process unofficially known as "swimming." For leptons and photons the size of the increment is proportional to the radiation length of the medium while for hadrons it depends on the interaction length. After each step the chance of a particle decaying or undergoing some interaction with the medium is calculated. A random number generator is used to determine its fate. A charged particle can experience Coulomb scattering that will change its direction or it may also lose energy by ionizing atoms in the material through which it is travelling. Electrons and positrons can emit bremsstrahlung photons. Photons themselves can convert into an electron-positron pair. More complicated processes take place in a dense medium like the lead of the SHC. In those instances, special programs are used. For electrons and photons a package of subroutines called Electron-Gamma Simulation, otherwise known as EGS4 [27], is used. While this package is CPU-intensive, it is extremely effective in simulating the shower development described in Section 2.2.5. Hadron-induced showers in the SHC and iron yoke are simulated with a package known as GHEISHA [28]. This set of routines takes into account the possibility of a hadron undergoing a strong interaction with one of the nuclei making up the medium.

Because of their importance to this thesis, close attention must be paid to the simulation of the ITC and CDC; hadrons bear special emphasis. The ITC and CDC simulations do not attempt to duplicate the actual drift functions. When a charged particle passes within a drift cell, the drift time read in is proportional to the distance of closest approach between the particle and the sense wire. The constant of proportionality is equal to \(50 \, \text{ns} \, \mu\text{m}^{-1}\). If more than one charged particle passes through an individual drift cell, the drift time winds up
Table 3-3: CDC drift time smearing parameters

<table>
<thead>
<tr>
<th>Momentum Range (GeV/c)</th>
<th>$\sigma$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 to 0.4</td>
<td>6.48</td>
</tr>
<tr>
<td>0.4 to 1.0</td>
<td>5.34</td>
</tr>
<tr>
<td>1.0 to 3.0</td>
<td>5.06</td>
</tr>
<tr>
<td>3.0 to 8.0</td>
<td>3.90</td>
</tr>
<tr>
<td>8.0 and up</td>
<td>3.58</td>
</tr>
</tbody>
</table>

being the value calculated for the particle that comes nearest to the sense wire. Technically, this is all there is to the measurement of drift times in the simulated data. The AMY code, however, goes a few extra steps\(^1\). The drift times are smeared so as to appear more like the real data. The smearing method used for the simulated data in this thesis involves Gaussian distributions with widths that depend on the momentum of the charged particle as shown in Table 3-3.

The new, smeared values are allowed to vary along 8 standard deviations. Next, since it is often the case that individual wires habitually tend to "misfire", providing bad measurements in the real data, a probability is assigned to those wires in the simulated data to also misfire; in the simulations, a misfiring wire is assigned a drift time of 10,000 ns, which equates to a drift distance of 50 cm. The end product is treated as if it were real data. This estimation of the systematic error for this smearing is performed by allowing the smearing parameters to change by a known factor. A previous study [29] showed that when the parameters had increased by a factor of 1.5 significant deviations in the CDC time residuals between the real data and the simulated data started to appear. With a factor of 1.5 multiplied into the smearing parameters, the efficiency of finding $K^0_S$, to be discussed in detail in the next chapter, was found to change by 5.3%. This number is used as the systematic error due to the detector simulation.

\(^1\) For some reason that was never adequately explained, these corrections to the simulated data are done in the analysis portion of the code.
The failure of the simulator to fully mimic the actual performance of the CDC must be accounted for. As can be seen in Figure 3-1, there tend to be more hits in the real data than in the simulated data. This results in more tracks (track-finding will be discussed in the next section). The average number of tracks in a real hadronic event is 16.21 (track-finding will be discussed in detail in the next section). The average number of tracks in a simulated event is 15.07 for a shift of 7.03%. A plot of the ratio of the number of tracks in the analysis to the number of tracks in the simulator as a function of momentum is shown in Figure 3-2. The picture shows that in the low-momentum region, where the particle multiplicity is highest, the simulator tends to underestimate the number of particles. The reverse is true at higher momenta, though the lower particle multiplicity in those regions significantly damps this effect. Because of the egregious failure of the simulator for particles at high momenta, an artificial cut had to be introduced in the selection of candidate track pairs. This will be discussed in detail in Chapters 4 and 5.

3.2 Track-Finding in AMY

Finding the trajectory of particles from the jumble of tracking chamber wires that have signalled a hit is the task of ACE and DUET. ACE (Amy Cdc Event finder) is a fast track-finder that has the dual purpose of triggering and analysis. Its speed (approximately 20 ms per hadronic event) makes it useful for an online determination of whether or not an event passes a CDC multi-track trigger. Speed is also a priority in the offline handling of events. DUET, originally developed for use in the CLEO detector [30], is an exhaustive attempt to find all tracks in an event. This is a time-consuming process. To alleviate this situation, ACE is used to input tracks into DUET. This speeds track-finding from about a full minute per event to roughly 15 seconds per event. The output of DUET is then modified to correct for the fact that AMY has an inhomogeneous magnetic field. It is from the end result of that set of subroutines that the analysis presented in this thesis begins.
CDC Hits/Event in Simulator and Data

Average = 791.6 ± 1.9

σ = 268.4 ± 1.9

Average = 864.1 ± 1.6

σ = 298.4 ± 1.6

Figure 3-1: Comparison of number of CDC hits/event in real data and Monte Carlo data.
Figure 3-2: Ratio of number of tracks in a real event vs. number of tracks in a Monte Carlo event as a function of momentum.
3.2.1 ACE

As mentioned above, ACE is fast. This speed is achieved by making one key assumption: every charged particle can be easily extrapolated back very near to the center of the coordinate system of AMY. Since the center of AMY's coordinate system is where the beams collide (ideally, anyway) then a feature of this assumption is that every particle produced is an initial state particle. This falls down flat in the case of particles produced from a \( \Lambda^0 \) or \( K_S^0 \) decay, but since the vast majority of charged particles are actually produced near the origin, the concept flies well enough for it to be fairly successful.

ACE starts by looking at only the axial hits. Taking advantage of the hexagonal, staggered structure between two adjacent layers in a single band, ACE takes a hit in the innermost band and starts looking for hit wires in the succeeding layers of the band. In the second layer it looks only at the two cells that are adjacent to the starting cell of the first layer. In the third layer, it looks at the three cells adjacent to the two cells in the second layer and in the fourth layer it looks at the four cells adjacent to the three cells in the third layer (the region through which ACE scans looks rather like a set of bowling pins). ACE also starts with hits in the second layer, looking similarly at adjacent hits in the third and fourth layers. If ACE finds at least three hits from three different layers in that region, it has found a "vector."\(^2\)

Vectors are fit to a straight line. Only those that pass a \( \chi^2_{d.o.f.} \) cut at the 99% confidence level are accepted for future use. The form of the equation used for the straight line fit is

\[
\psi_i - \phi = \xi (r_i - r_1)
\]  

(3.2)

where \( i \) goes from 1 to the total number of hits in the vector (this approximation is valid so long as \( \psi_i - \phi \) is small); \( \psi_i \) is the azimuthal angle of each hit and \( r_i \) is the radius of the layer of the hit. The values for \( \phi \) and \( \xi \) are obtained from this fit. \( \phi \) is the azimuthal angle of the vector and \( \xi \) is the slope of the line scaled by \( r_1 \). From \( \phi \) and \( \xi \), a circle passing through

\(^{2}\)This is also known as a "segment" as mentioned in the discussion of triggering in Section 2.2.9.
both the vector and the origin can be calculated. The circle's curvature and azimuthal production angle are given by

\[ qC = \frac{2 \sin \beta}{r_1} \quad \text{and} \quad \phi_0 = \phi - \beta \] (3.3)

respectively, where \( \beta = \tan^{-1}(r_1 \xi) \) and represents the direction of the vector in a coordinate system that has been rotated by \( \phi \) (see Figure 3-3). Consequently, all vectors belonging to the same track will have similar values for \( \phi_0 \) and \( C \). Furthermore, for tracks that have \( p_t > 400 \text{MeV}/c \), \( q \frac{dC}{d\phi_0} \sim 2/r_1 \). Thus, if a search window in which similar values are placed together is defined in one variable, it is automatically defined for the other. In this case, \( \pm 3\sigma \) is used for \( \phi_0 \); this value is approximately 0.0033 \( r_1 \) radians for axial hits. So, starting from the outermost bands (where tracks are the most separated) and moving in, vectors which satisfy the requirement of falling within the search window are placed on the same “cluster.”

A cluster is not blindly considered to be composed of vectors from one track. Indeed, some vectors may be entirely ersatz, made up by considering the wrong left-right ambiguities of the hits, as shown in Figure 3-4. To distinguish between more than one track within a single cluster and to remove so-called “ghost vectors,” vectors in adjacent bands may be linked together if they pass a tighter cut of being no more than about 0.8/\( r_1 \) radians from \( \phi_0 \). The resulting connection of links is called a “tree” and the longest continuous set of links is used for the track candidate (this method, not surprisingly, is known as the “Link-and-Tree” method [30] and will be discussed later in the description of DUET). The hits, corrected for drift distance, that are within the selected vectors are then fit to a circle. If the circle comes within 5 cm of (0, 0) and if it has a \( \chi^2_{d.o.f.} \) less than 6, then it is considered to be an acceptable track.

Assigning stereo hits to the axial tracks found previously involves a similar, though abbreviated, process. It starts by taking the track candidates with the greatest number of assigned axial hits (if two tracks have the same number of hits then the track with the lower \( \chi^2 \)
Figure 3-3: ACE's coordinate system
Figure 3-4: How ACE finds a ghost vector. The crosses represent the two possible ambiguities available to each CDC hit. The solid lines are the actual tracks and the dashed line represents the ghost vector.
is done first) and finding all possible stereo hits that could physically belong to the track candidate. From this subset, vectors are found as above, though because there are only three layers per band, a vector is accepted as such if it contains only two hits. However, if a vector is extrapolated such that it comes no closer than 50 cm to the center of AMY or if its angle relative to the beam axis is smaller than 30° then it is rejected from further consideration.

The accepted vectors undergo a Link-and-Tree clustering similar to what took place with the axial vectors. However, whereas the axial vectors were clustered based on their closeness of \( \phi \), the stereo vectors are associated based on their \( s-z \) gradients (where \( s \) is the arc length of the circle from the distance of its closest approach to \((0,0)\) to the \((x,y)\) coordinate of the stereo hit). A link of three vectors is considered a tree if the difference in \( \cot \theta \) of vectors 1 and 2 is less than 0.2 from the difference in \( \cot \theta \) of vectors 2 and 3, with \( \theta \) being the angle subtended from the beam line in the \( s-z \) plane. All found trees are fit to a straight line. The final candidate is the one with the best \( \chi^2 \), provided the \( \chi^2 \) is less than 15 and the extrapolated distance from \( z = 0 \) when \( s = 0 \) is less than 50 cm.

Once all the axial and stereo hits have been assigned to the track, it undergoes a refit. Corrections are made in the real data to account for the left-right and \( z \) dependence of the drift function, the time-of-flight of the particles and the delay due to the propagation of the signals along the sense wire. It is this output that is fed into DUET.

### 3.2.2 DUET

A track found by ACE is used as a seed track for DUET. While actual hits are not passed to DUET, track parameters are. To define a track in the \( r-\phi \) plane, the parameters are the curvature, the impact parameter and the azimuthal angle at that point. The track in the \( s-z \) plane is a straight line and the parameters used for that are the cotangent of the angle subtended from the beam line and the distance in \( z \) from \( z = 0 \) when \( s = 0 \).
These parameters are shown in Figure 3-5. In AMY-speak these parameters are known, respectively, as CRVTRK, DSTORG, $\phi_0$, $\cot \theta$ and ZTRL0 (the value of DSTORG shown in Figure 3-5 is $> 0$ since $(0,0)$ lies outside the circle that describes the particle's trajectory; if $(0,0)$ lay within the circle then DSTORG would be negative).

Using seed tracks enables DUET to partially avoid the laborious task of using the Link-and-Tree algorithm to find tracks. The employment of this algorithm in DUET differs somewhat from what is used in ACE but the philosophy remains the same. DUET finds tracks by building up first from hits to make "links", then from links to "trees", from trees to "chains" and from chains to tracks. This cuts down on the number of permutations that would otherwise have to be performed. If DUET were to work by considering all possible permutations and ambiguities and then choosing the pattern with the lowest $\chi^2$ then even one track with 40 hits would require DUET to look at over 1 trillion combinations—if one permutation required 1 $\mu$s of CPU time then that one track would take almost 13 days to find. Thus enters the concept of grouping together hits with a high probability of belonging to one track in ever-expanding subsets.

In the case where there is no initial seed track, DUET attempts to find one by only considering a subset of the axial layers. These are layers 1, 3, 5 and the innermost and outermost layers of the subsequent bands. Links are then formed. A link consists of three hits in adjacent, used layers. A circle fit is done to the three hits and if the circle passes a cut on the distance of closest approach to $(0,0)$ (known as $d_0$) the link is accepted for further use; this cut is very loose, being on the order of 10 cm for the case of some of the inner layers and 40 to 50 cm for the outer layers. The next step is to construct elementary trees from the accepted links. A tree is comprised of two links which have two hits common to each and have values for the radii of their calculated circles that are within approximately 50 cm of each other. This is also a rather loose cut: because of AMY's relatively large magnetic field, a 50 cm difference in the radius of a circle means a difference of 430 MeV/c^2 in the transverse momentum of the particle. From the elementary trees, DUET then makes chains. If two trees share one link, then those two trees make up part of a chain; it is important to
Figure 3-5: The geometry of charged tracks in AMY. The arcs represent the actual trajectory of the track in the $x-y$ and $y-z$ planes while the "X" in the lefthand plot represents the center of the circle in the $x-y$ plane. The origins in both plots are situated at the center of AMY.
note that the two links that are not shared by the two trees have no requirement relative to each other. From the resulting “Gordian Snarl” of hits, links and trees are extracted all of the longest strands. The one with the best $\chi^2$ is used as a seed track.

Getting the stereo information for a seed track closely follows the process used for the axial hits. All tracks found from the axial wire fits described above are examined. The subset of layers used are the inner- and outermost layers of each of the 5 stereo bands. In addition, only stereo hits that are physically capable of having been signalled by the axial track in question are considered. A link is composed of two hits. These are fitted to a straight line and must pass a cut such that the point of closest approach to $z = 0$ is less than a certain value ranging from about 10 cm for the inner layers to 70 cm for the outer layers. Trees are made from links with one common hit and must have slopes that are within 1.285 to 1.565 of each other, again depending on the layers being examined. Straight lines fits are made to all complete chains and the one with the best $\chi^2$ is considered the counterpart to the seed track found from the axial layers previously.

At this stage, DUET has found its own seed track or one has been provided for it (e.g., by ACE). All layers of the CDC are now used; ITC hits are included at this stage as well. At the radius of each layer, the position along the trajectory of the seed track is calculated. In axial layers, hits in the cell and adjacent to the cell through which the putative track passes are kept; in stereo layers, hits which come within 5 to 8 cells of the track are kept. Also, unlike when DUET was finding seed tracks, both ambiguities are considered. Links, trees and chains are formed from those hits in the manner described above. The hits are all corrected for chamber effects and the resulting candidates are placed on a track stack. It then becomes necessary to choose from among the candidates the one that is most likely to be the actual track. Each one is fit to a helix. In general, the one with the most hits and lowest $\chi^2$ is retained. DUET then proceeds on to the next seed track. It is important to note that once a track has been found, its hits are sequestered—they will not be placed onto any subsequently found track.
This description of DUET does not account for the ways in which the program compensates for the effect of missing layers, "bad" hits (e.g., noise from faulty signal lines), curlers (low momentum tracks that pass through one layer several times) and other possible sources of contamination. The interested reader is directed towards [30] for further details.

3.2.3 Correction for the inhomogeneous magnetic field

An important assumption made in ACE and DUET is that AMY's magnetic field is homogeneous, meaning that the trajectory of particles in the transverse plane is purely circular; furthermore, the magnetic field in the transverse plane is assumed to be 0. Regrettably, this is not so. To account for the inhomogeneity, a member of the AMY collaboration, Koji Ueno, has come up with a method that has proven to be more effective in accurately determining the positions and momenta of charged particles [31]. This method starts by parametrizing the radial and longitudinal components of the magnetic field into the forms

\[ B_x(r, z) = B_0[1 + \alpha(r^2 - 2z^2) + \beta(r^4 - 8r^2z^2 + \frac{8}{3}z^4)] \text{ and} \]

\[ B_r(r, z) = B_0[2\alpha rz + \beta(4r^3z - \frac{16}{3}rz^3)] \]  

where \( B_0 \) is the magnitude of the magnetic field at \((0, 0, 0)\) and \( \alpha \) and \( \beta \) are parameters determined by measuring the actual magnetic field at various points in the volume of the detector and then fitting to the above equations. For AMY 1.0, \( B_0 = 3.03 \) Tesla, \( \alpha = 1.643 \times 10^{-5} \) cm\(^{-2} \) and \( \beta = 6.245 \times 10^{-10} \) cm\(^{-4} \); for AMY 1.25 and 1.5 these values are \( 2.8878 \) Tesla, \( 2.266 \times 10^{-5} \) cm\(^{-2} \) and \( 3.983 \times 10^{-10} \) cm\(^{-4} \), respectively. From these numbers, it can be shown that AMY's magnetic field varies from \( 1.05 \times B_0 \) to \( 0.82 \times B_0 \) over the volume of the CDC.

Note that since the magnetic field of AMY is axially symmetric (i.e., \( B_\phi = 0 \)), the only component of \( \vec{A} \) that is non-zero is \( A_\phi(r, z) \). Thus,

\[ \vec{A}(r, z) = A_\phi(r, z)\hat{\phi} = \frac{1}{r} \int_0^r B_x(r, 0) r dr - \int_0^z B_r(r, z) dz. \]
The next part of this technique employs the law of conservation of angular momentum which, for these purposes, takes the form

\[ \mathbf{r} \times (p_{\text{linear}} + q \mathbf{A}) = \text{constant}. \]  

(3.8)

In addition to the conservation equation there are also the conditions

\[ \frac{d}{dr} \sin \theta = \frac{q}{p} \tan \phi \frac{\partial A}{\partial z}, \]  

(3.9)

\[ \frac{d \psi}{dr} = \frac{\tan \psi}{r} \text{ and } \]  

(3.10)

\[ \frac{dz}{dr} = \frac{\tan \theta}{\cos \psi} \]  

(3.11)

where \( \psi \) is the 2-dimensional angle between the direction of the particle at \((r, \phi)\) and \( \phi \).

Armed with Equations 3.5 through 3.11, it is possible to calculate the exact particle trajectory as a function of \( r \) and the 5 parameters necessary to describe a helix, \( d_0, \phi_0, C, z_0 \) and \( \theta_0 \). Here, \( z_0 \) is the longitudinal distance of the particle from \( z = 0 \) when \( s = 0 \) and \( \theta_0 \) is the initial angle in the \( s - z \) plane in which the particle is moving. Ignoring terms with a factor of \( \beta \), the equation becomes

\[ \phi = \phi_0 - \frac{r}{2} \text{sign}(d_0) - \arcsin \left( \frac{r^2 - 2d_0 \rho + d_0^2}{2r(r - d_0)} \right) \left( \sum_{i=1}^{\infty} G_i(2i + 1)D_{2i+1}(r) + \sum_{i=1}^{\infty} i G_i(2i + 1)D_{2i-1}(r) + \cdots \right) \]  

(3.12)

where

\[ \rho = \frac{p_{\text{c}}}{qB_0} \propto \frac{1}{C}, \]  

(3.13)

\[ G_i = \frac{1 \times 3 \times \cdots \times 2i - 1}{i! \times 2 \times \cdots \times 2i}, \quad G_0 = 1 \]  

(3.14)

\[ D_{ij} = \int_{|d_0|}^{r} \left( \frac{r - d_0}{2 \rho} - \frac{d_0B_0A_{\phi}(d_0, 0)}{\rho} \right)^i \left( \frac{ar^3}{4 \rho} \right)^j \frac{dr}{r}. \]  

(3.15)

Similar equations exist for the evaluation of \( z(r) \) but these are not currently implemented in the analysis. Evaluating the integrals is somewhat tedious but is nevertheless straightforward. Using the assumption that \( z_0 \) and \( d_0(1 - \frac{A_0(d_0, 0)}{p_{\text{c}}}) \) are small relative to \( \rho \) and \( r \), only the first two terms in each summation are kept. A least-squares fit to the data is performed to calculate the five track parameters and the resulting output is retained.
3.2.4 Momentum resolution

The results spit out by these programs have a strong dependence upon the multiplicity of charged particles within an event. For cases such as Bhabha events, the momentum resolution has been measured to be as low as $\Delta p_t/p_t = 0.6\%p_t$. But in that situation, there are only two well-separated tracks which are produced at the origin. When the tracks are arranged in narrow jets like in hadronic events, misassignment of hits occurs and the momentum resolution degrades. This is shown in Table 3-4. The results of fitting to a function of the form $\Delta p = a + b p^2$ are based only on particles with low momentum, i.e., those whose total momenta did not exceed 3 GeV/c, and are shown at the bottom of the Table.

Table 3-4: Momentum resolution in the CDC. All values of momenta are in MeV/c.

<table>
<thead>
<tr>
<th></th>
<th>AMY 1.0</th>
<th>AMY 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_t$</td>
<td>$\Delta p_t$</td>
<td>$p_x$</td>
</tr>
<tr>
<td>315 ± 11</td>
<td>6.45 ± 0.02</td>
<td>119.0 ± 1.5</td>
</tr>
<tr>
<td>622 ± 21</td>
<td>9.96 ± 0.03</td>
<td>290.9 ± 3.4</td>
</tr>
<tr>
<td>1043 ± 49</td>
<td>17.2 ± 0.2</td>
<td>493.8 ± 7.5</td>
</tr>
<tr>
<td>1486 ± 80</td>
<td>30.8 ± 0.5</td>
<td>678 ± 13</td>
</tr>
<tr>
<td>2040 ± 110</td>
<td>61.0 ± 1.4</td>
<td>909 ± 18</td>
</tr>
<tr>
<td>4850 ± 190</td>
<td>179 ± 2</td>
<td>2340 ± 33</td>
</tr>
<tr>
<td>$\Delta p_t = 0.049 + 1.26% p_t^2$</td>
<td>$\Delta p_x = 0.148 + 5.1% p_t^2$</td>
<td>$\Delta p_t = 0.085 + 1.75% p_t^2$</td>
</tr>
</tbody>
</table>

3.2.5 Advantages and disadvantages

Without too much needless editorializing, it is sufficient to say that the premise of ACE that all particles originate at the origin is simpleminded at best and, from the standpoint of analyzing the decay products of long-lived particles, actively hostile at worst. DUET buffers this effect to a lesser extent, but the die has been cast. A symbolic portrayal of ACE passing the track parameters on to DUET is shown in Figure 3-6. Note the look of placid idiocy in the eyes of ACE and the frenzy apparent in DUET. DUET, by accepting
these parameters, is biased towards tracks that can be traced back to the origin. This bias takes shape when DUET assigns hits to tracks and then refuses to consider the hits for later track candidates. It is not uncommon to find hits stolen from one track and placed onto a track considered earlier. In point of fact, it often turns out that the hit that should have been placed on the earlier track is placed on a later track. This situation is shown in Figure 3-7, which is a histogram showing the fraction of incorrectly assigned hits versus the layer number in which it occurred. It can be seen that misassignment takes place more often in the inner layers; this is due to the higher density of tracks in the inner region, which can be seen in the event shown in Figure 1-3. The significant advantage in using ACE and DUET is in time. For many analyses, these results are quite satisfactory and are found in a reasonably short period of time. Notably different methods for finding tracks, such as neural networks, can take unreasonable periods of time.

As for the correction for the inhomogeneous field, there is an improvement in the determination of the momentum of charged particles. Prior to this correction, for AMY 1.0 \( \frac{\Delta p_t}{p_t} = 3.29\%p_t \) and \( \frac{\Delta p_z}{p_z} = 6.6\%p_z \) while for AMY 1.5 the values are 4.16\%p_t and 7.7\%p_z, respectively. Compared with the values shown in Table 3-4, the improvement is obvious. But it, too, is biased towards original particles. The five parameters it spits out, while correcting for the fact that the tracks are not perfect helices, are still used to describe perfect helices. Nothing is done to correctly determine the location of the particle at any place in the detector aside from its distance of closest approach to \((0,0,0)\). In addition, in its description it is said that the correction assumes that \(d_0\) and \(z_0\) are small, which is not necessarily the case for the decay products of the \(\Lambda^0\) and \(K^0\). There is also, as yet, no correction performed on the longitudinal component of the particles' momenta.

### 3.2.6 Matching Analyzed Tracks with Simulated Tracks

All hits assigned to a track by ACE and DUET do not necessarily belong to that track. And all hits that were created by a track in the AMY event simulator are not necessarily
Figure 3-6: ACE (left) passes tracks to DUET (right).
% Incorrectly Assigned CDC Hits

Figure 3-7: Misassignment of hits in the CDC.
assigned to the track. This leads to a problem in the study of simulated events in that one frequently wishes to know to which simulated track the analyzed track corresponds. This is done by way of the hits. In a simulated event, it is known precisely to which track each hit belongs. So, all hits assigned to a single track by ACE and DUET are examined to see to which simulated track they truly belong. If at least 50% of hits that were assigned to a track belong to a single simulated track, then it is assumed that the analyzed track corresponds to that simulated track. If the hits have been drawn from so many different simulated tracks that there doesn’t exist a single one who contributed at least 50% of the hits, then no simulated track is assigned to the analyzed track. This turn of events occurs roughly 1.4% of the time.

This is not the whole story, however. For tracks that curl around inside the CDC at least once (requiring a transverse momentum less than about 400 MeV/c and a longitudinal momentum low enough for the track to circumscribe a circle within the volume of the CDC) it is possible for more than one track to be assigned to it. This happens when ACE and DUET use the hits that are curling back in towards (0, 0) to form a separate track. Thus, it is easily possible for an analyzed track to be assigned to a simulator track yet have virtually no similarity to it. This problem will have special bearing on the decay of the $\Lambda^0$ as the pion resulting from the decay typically has low momentum.

### 3.3 Analyses of Other Detectors

Of the other detectors in AMY, the one of most importance to this study is the SHC. It figures into the hadronic event selection and also plays a small role in the selection of $\Lambda^0$s. The other detectors, having little or nothing to do with either hadronic event selection or extraction of $K_S^0$s and $\Lambda^0$s, will be mentioned only briefly at best.
3.3.1 Analysis of the SHC

Analysis of SHC data [32] starts by correcting the raw ADC counts that are read in from the cathode lines. Among the corrections are those for high voltage problems, dead cathode channels, dead anode channels, noise, crosstalk, abnormal pedestals and monitor tube gain. After the corrections to the raw ADC counts, cluster-finding begins in earnest. At first, only single θ-φ blocks are considered. Peaks (measured in ADC counts) for each layer are found for both the φ and θ views separately; any number from 0 to 3 peaks per layer may be found. The peaks are then matched with one from the opposing view. Clusters that overlap block boundaries are matched. Final corrections are made to the clusters. AMY’s strong magnetic field has a noticeable effect on the shower of charged electrons and positrons and is accounted for by an empirically calculated function. Because the SHC is only 14.4/\sin θ radiation lengths thick, a high energy shower may not deposit all of its energy in the detector. This “leakage” has been corrected based on studies of the EGS4 Monte Carlo [27]. Lastly, it is possible for a high energy shower to ionize the SHC gas to the point where it is saturated. A correction, based on a study of Bhabha and acollinear electron events takes care of this. The final output for a cluster used in this analysis provides the position of the centroid of the cluster as well as in each ganged cathode layer; the energy of the entire cluster along with the layer-by-layer energy depositions are also given.

3.3.2 Analyses of other detectors

For an explanation of the ways in which the data used in the detectors listed below are analyzed, the following references should be consulted:

XRD [34].

MUO [33].
PTC and RVC [35].

ESC [24].

FTC [36].
Chapter 4

A How-To Manual for Finding $\Lambda^0$'s and $K_S^0$'s

4.1 Hadronic Event Selection

Since this analysis is a study of QCD and the process of hadronization, events that are most likely to be $e^+e^- \rightarrow q\bar{q}$ must be extracted. To do this, all of the data passed by the triggers are analyzed with ACE and the SHC cluster reconstruction scheme (called “SHW” in AMY-speak). With the data all nice and analyzed, it then becomes necessary to pigeonhole the events into nice, neat categories. The primary categories are called “prehadronic”, “QED”, “LOW”, “basic” and “junk.” The lattermost group consists of events such as collisions with the gas remaining within the beam pipe and other uninteresting phenomena that are discarded. The prehadronic sample is made up of events that have at least 3 GeV of energy deposited in clusters in the SHC and have at least three charged tracks which each come within 5 cm of the origin in the $r$-$\phi$ plane and 10 cm in $z$.

Events making it into the prehadronic sample are then fully analyzed using better calibration
constants by ACE, DUET, SHW and the various routines used by the other detectors. For an event to be accepted into the hadronic sample, it must pass the following cuts:

- For a charged track to be considered "high quality", it must:
  - Have at least 8 axial hits.
  - Have at least 5 stereo hits.
  - Have a $\chi^2_{d.o.f.} < 8$ for the $r$-$\phi$ circle fit.
  - Have a $\chi^2_{d.o.f.} < 6$ for the $s$-$z$ line fit.
  - Come within 5 cm of the origin in $r$-$\phi$.
  - Come within 15 cm of the origin along $z$.
  - Must subtend an angle $\theta$ relative to the beam line at the distance of closest approach such that $|\cot \theta| < 0.85$.

A higher momentum track, where $p > 0.5$ GeV/c, must satisfy more stringent requirements:

- It must have at least 12 axial hits.
- It must have at least 10 stereo hits.
- It must come within 2 cm of the origin in the $r$-$\phi$ plane.

A very high momentum track, where $p > \frac{1}{4} \times$ Beam Energy, must come within 1 cm of the origin in the $r$-$\phi$ plane.

- There must be at least 5 high quality tracks. This removes much of the background due to radiative Bhabha and $e^+ e^- \rightarrow \tau^+ \tau^-$ events.

- High quality neutral shower clusters must be identified:
  - They must each have at least 200 MeV of energy.
  - They can not have more than 95% of their energy in one cathode layer.
They must have $\theta$ lying between $43^\circ$ and $137^\circ$.

They must not be identified with any charged track.

- The sum of all the energy, from both charged and neutral particles considered to be high quality, deposited in SHC clusters must be at least 5 GeV (3 GeV if the beam energy is less than 27.5 GeV).

- The sum of the energies of all high quality charged and neutral particles, known as the "visible energy", must be at least the beam energy. This serves to largely remove spurious events due to interaction with the beam wall or beam gas as well as further cut down on $\tau^+\tau^-$ events and remove two-photon events.

- The sum of all of the longitudinal momenta of all particles, $p_{\text{tot}} = \sum_i^{\text{charged}} p_{\text{ix}} + \sum_i^{\text{neutral}} p_{\text{ix}}$, divided by the visible energy must be no more than 0.4. This is designed to cut down on the background due to two-photon events.

According to the Monte Carlo simulations, 60.2% of the hadronic events survive these cuts. The hadronic data is estimated to be 98.4% pure, with the background coming from $\tau^-\tau^+$ and $\gamma\gamma$ events.

Cutting out certain events based on these cuts introduces another systematic error. The magnitude of this effect is determined by varying the cuts of the event selection and examining the change in the $K^0\pi^0$ reconstruction efficiency. The variations of the cuts suggested in [5] were used in this analysis. It was found that the cut on the visible energy, $E_{\text{vis}}$, easily had the greatest effect on the data. Changing the cut on the number of good tracks in the CDC from 5 to 6 gave rise to a loss of 0.096% of the events. Raising the cut on the energy in the SHC from 5 GeV to 8 GeV resulted in a loss of 1.83%. The cut on momentum imbalance when changed from 0.4 to 0.36 gave a loss of 0.771% of the total number events. But the cut on $E_{\text{vis}}$, when raised from being greater than $E_{\text{beam}}$ to $1.28E_{\text{beam}}$, caused the loss of 13.1% of the events. The Monte Carlo data was re-examined with the new $E_{\text{vis}}$ cut using the cuts described in Section 4.3 to obtain a new efficiency in the reconstruction of $K^0\pi^0$s.
Applying this efficiency to the real data resulted in a shift of 5.9% in the determination of the multiplicity of $K^0$'s. This number is used as the systematic error for the hadronic event selection.

### 4.2 The Event Vertex

Since the TRISTAN electron and positron beams have a finite, measurable width, they don’t meet exactly at (0, 0, 0) in the AMY coordinate system. However, the exact location of this interaction, known as the “event vertex” or the “primary vertex” or the “primary production point” or a bevy of other names, has a bearing on many arenas in particle physics, including this analysis (see Section 4.3). This section details how the event vertex varied during the operation of the beams.

#### 4.2.1 Variation of the event vertex

The variation in the TRISTAN beam lines can be determined using Bhabha events. In these events, the only final state particles are, effectively, an electron and a positron. Due to their extreme collinearity, an event-by-event record of the event vertex is quite difficult to obtain. However, using Bhabhas from events within the same run, a run-by-run fluctuation is rather simple to determine. By superimposing one Bhabha event over the immediately succeeding Bhabha event in the sample and confining these superpositions to within one run, the event vertex, averaged over each run, can be found. In this study [37], using data from 1986 to 1989, it was found that the distributions in $x$, $y$ and $z$ were all Gaussian. The central values of the Gaussians were at -0.21, 0.78 and 0.16 mm in $x$, $y$ and $z$ respectively. The standard deviations of the distributions were 1.60 mm, 0.96 mm and 10.0 mm, respectively. A later study of the position along $z$ using three photon events [32] in data taken from 1986 through Spring, 1992 confirmed this result. Because the average values were less than 1 mm and because the variation was only 1 mm in $x$ and $y$ and because the determination of
Table 4-1: Estimated systematic error.

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Est. Sys. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lund Generator</td>
<td>4.4%</td>
</tr>
<tr>
<td>AMY Simulator</td>
<td>5.4%</td>
</tr>
<tr>
<td>Event Selection</td>
<td>5.9%</td>
</tr>
<tr>
<td>Primary Vertex</td>
<td>7.7%</td>
</tr>
<tr>
<td>Total Error</td>
<td>11.9%</td>
</tr>
</tbody>
</table>

the primary vertex in z is not necessary to this analysis, no refinement to the data based on a non-(0, 0, 0) primary vertex was performed. To determine the systematic error from this assumption, samples of data were generated with vertices at (0.1, 0, 0) and (0, 0, 1.0) cm. After simulation and analysis, the change in the $K^0$ multiplicity was 3.6% for the non-0 $x$ vertex and 6.8% for the non-0 $z$ vertex. These values result in a systematic error of 7.7% for the event vertex fluctuations. This result is shown with the systematic errors from generation, simulation and event selection in Table 4.2.1 along with the total estimated systematic error.

4.3 Selection of $K^0_S$ and $\Lambda^0$'s

Because of the very similar topologies of $\Lambda^0$ and $K^0_S$ decays, the cuts used to extract them from the data are very similar. First, it should be noted that only pairs of oppositely charged tracks are considered in these searches. While both tracks are assumed to be $\pi$’s when considering the pair as a possible $K^0_S$, when the $\Lambda^0$ hypothesis is tested the track with the higher momentum is considered to be the proton while the lower-momentum track is taken to be the pion. For hadronic events at $\sqrt{s} = 58$ GeV, Monte Carlo studies have shown this assumption holds true in 98% of the cases; in those instances where it does not apply, the momenta of the pion and proton are so close as to fail cut #9 in Table 4-2.

Cuts 1 and 2 enhance the likelihood of the particles being produced away from the pro-
<table>
<thead>
<tr>
<th>Cut #</th>
<th>Description of Cut</th>
<th>Value in $K_S^0$ Selection</th>
<th>Value in $\Lambda^0$ Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[DSTORG]hi\text{g} nom. track</td>
<td>&gt; 3 mm</td>
<td>&gt; 0.5 mm</td>
</tr>
<tr>
<td>2</td>
<td>[DSTORG]lo\text{w} nom. track</td>
<td>&gt; 3 mm</td>
<td>&gt; 3 mm</td>
</tr>
<tr>
<td>3</td>
<td># of axial hits on each track</td>
<td>&gt; 8</td>
<td>&gt; 8</td>
</tr>
<tr>
<td>4</td>
<td># of stereo hits on each track</td>
<td>&gt; 4</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>5</td>
<td>$\chi^2$/d. o. f. of r-\phi Fit of each track</td>
<td>&lt; 4.0</td>
<td>&lt; 4.0</td>
</tr>
<tr>
<td>6</td>
<td>$\chi^2$/d. o. f. of s-z Fit of each track</td>
<td>&lt; 2.0</td>
<td>&lt; 2.0</td>
</tr>
<tr>
<td>7</td>
<td>$</td>
<td>\phi_{\text{hi\text{g} nom. track}} - \phi_{\text{lo\text{w} nom. track}}</td>
<td>$</td>
</tr>
<tr>
<td>8</td>
<td>Separation of Track Circles in r-\phi Plane</td>
<td>&lt; 1.5 mm</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>$\frac{p_{\text{lo\text{w} nom. track}}}{p_{\text{hi\text{g} nom. track}}}$</td>
<td>--</td>
<td>&lt; 0.34</td>
</tr>
<tr>
<td>10</td>
<td>Distance of nearer intersection from (0,0) in r-\phi plane</td>
<td>3.0 cm</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>11</td>
<td>Angular difference between reconstructed decay particle momentum and vector from (0,0) to intersection point in r-\phi plane</td>
<td>3.4°</td>
<td>3.4°</td>
</tr>
<tr>
<td>12</td>
<td>Invariant Mass When Reconstructed as $e^+e^-$</td>
<td>&gt; 130 MeV/$c^2$</td>
<td>&gt; 130 MeV/$c^2$</td>
</tr>
<tr>
<td>13</td>
<td>$E_p$ of High-Mom. Track Reaching SHC</td>
<td>--</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>14</td>
<td>Invariant Mass When Reconstructed as $K_S^0$</td>
<td>--</td>
<td>&lt; 477.67 MeV/$c^2$ and 517.67 MeV/$c^2$</td>
</tr>
<tr>
<td>15</td>
<td>Invariant Mass When Reconstructed as $\Lambda^0$</td>
<td>&lt; 1104 MeV/$c^2$ and &gt; 1128 MeV/$c^2$</td>
<td>--</td>
</tr>
<tr>
<td>16</td>
<td>Energy Cut</td>
<td>$E_{\text{particle}} &lt; 0.2E_{\text{beam}}$</td>
<td>$E_{\text{particle}} &lt; 0.2E_{\text{beam}}$</td>
</tr>
</tbody>
</table>
duction point. Cuts 3, 4, 5 and 6 are cuts on the quality of the tracks—it does nobody any good to work with tracks that are poorly measured, so these are discarded. After the cuts on track quality and \(|DSTORC|\) three more cuts, numbers 7, 8 and 9, are made. Cut 7 gets rid of the embarrassing situation where a high momentum particle is combined with a low momentum particle headed in the opposite direction; no other cut is capable of getting rid of this physically nonsensical occurrence. Next, the intersection points of the tracks in the \(r-\phi\) plane, if any, are found (cut 8 is then applied followed by cut \#9). This analysis is organized such that there is no need to choose between either intersection point since the total momenta of each of the two tracks do not change and the opening angle between the two tracks is equal no matter which intersection is being considered. If there is no intersection, then the secondary vertex is considered to be the average of the two points of closest approach on each track to each other. After the intersection(s) has been found, cuts 10 and 11 are applied. Cuts 12 through 15 are invoked to remove processes that mimic \(K^{0}_{S}\) and \(\Lambda^{0}\) decay. These processes are, specifically, photon conversion (12 and 13), \(K^{0}_{S}\)'s mimicking \(\Lambda^{0}\)'s (cut 14) and \(\Lambda^{0}\)'s mimicking \(K^{0}_{S}\) (cut 15). Cut 16 is a software-inspired cut as opposed to a physics-inspired cut. After the previous cuts and the ensuing mass cut, it was found that the simulated data was thoroughly inadequate in describing the data. The simulated production of high-momentum particles was typically as much as 10 times higher than the actual production. As of this writing, the problem is believed to lie in the AMY simulator; further study is currently underway to solve this difficulty. However, time constraints require that this physically unjustifiable cut remain within this thesis. Finally, there is the mass cut. These cuts, showing a comparison in the simulated data between the genuine \(K^{0}_{S}\) or \(\Lambda^{0}\) decay products and pair mimicking them, are displayed in Figures 4-1 through 4-27. In each case, the pairs that arose from an actual \(K^{0}_{S}\) or \(\Lambda^{0}\) decay are shown on top while the pairs arising from fake \(K^{0}_{S}\)'s and \(\Lambda^{0}\)'s are shown on the bottom.

Prior to cut \#17, the \(K^{0}_{S}\)'s have a Gaussian distribution centered at \(493.1 \pm 4.9\) MeV/c² and a standard deviation of \(21.1 \pm 2.1\) MeV/c². Similarly, the Gaussian describing the \(\Lambda^{0}\)'s has an average of \(1116.3 \pm 1.4\) MeV/c² and a standard deviation of \(6.3 \pm 0.6\) MeV/c². The
Figure 4-1: Plot of $|\text{DSTORG}|$ along with location of cut for $K_S^0$ candidates.
Figure 4-2: Plot of number of axial hits along with location of cut for $K^0_S$ candidates.
Figure 4-3: Plot of number of stereo hits along with location of cut for $K^0_S$ candidates.
Figure 4-4: Plot of $\chi^2_{r-\phi}/\text{d.o.f.}$ along with location of cut for $K^0_S$ candidates.
$\chi^2_{s-w}$/d.o.f. for $\pi^+$/s from $K^0_S$

$\chi^2_{s-w}$/d.o.f. for $\pi^\pm$/s from Fake $K^0$

Figure 4-5: Plot of $\chi^2_{s-w}$/d.o.f. and location of cut for $K^0_S$ candidates.
Figure 4-6: Plot of opening angle of decay products at intersection and location of cut for \( K_S^0 \) candidates.
Closest Approach of $K^0_S$ Decay Products

Closest Approach of Fake $K^0_S$ Decay Products

Figure 4-7: Plot of closest approach of decay products in $r$-$\phi$ plane and location of cut for $K^0_S$ candidates.
Figure 4-8: Plot of distance of nearer intersection from (0, 0) in $r$-$\phi$ plane and location of cut for $K^0_s$ candidates.
Figure 4-9: Plot of invariant mass if decay products are $e^+e^-$ and location of cut for $K^0_s$ candidates.
Figure 4-10: Plot of invariant mass if higher-momentum particle is a proton and lower-momentum particle is a pion and location of cut for $K_S^0$ candidates.
mass cut, #17, is optimized to provide the best signal-to-noise ratio while preserving as many candidates as possible; for both the $K_S^0$ and $\Lambda^0$, a cut of ~2 standard deviations was found to work best. From the Monte Carlo, the signal-to-noise ratio for $K_S^0$s in the mass range $497 \pm 40$ MeV/c$^2$ is 1.5:1; for $\Lambda^0$s in the range $1116 \pm 12$ MeV/c$^2$ the ratio is 1:3.2. The percentage of $K^0$s and $\Lambda^0$s surviving all the cuts are 0.553% and 0.57% respectively. These low values are mostly due to the efficiency of reconstruction of the decay particles. Only 57.9% of the pions from $K^0_S$ decay are found by ACE and DUET and only 75% of the protons from $\Lambda^0$ decay are found. The pions from $\Lambda^0$ decay are especially difficult to reconstruct. Nominally, it would appear that 41% of pions are found. But as described in Section 3.2.6, the percent accurately reconstructed is actually even lower than that. The true value is only 23.5%. Multiplied by that effect is that only $(68.61 \pm 0.28)\%$ of $K_S^0$s and $(64.1 \pm 0.5)\%$ of $\Lambda^0$s decay into two charged particles. Multiplying these numbers together shows that only 23.1% of the $K_S^0$s and 11.3% of the $\Lambda^0$s along the entire mass range have any hope of being detected in the first place. The further degradations of the cuts on the number of remaining $K_S^0$s and $\Lambda^0$s are synthesized in Table 4-3. The percentages shown for the surviving background candidates represents only those pairs that were reconstructed to have a mass within the region specified for cut #17.

After the application of these cuts, the Monte Carlo background has a correction applied to it. This is due to the inability of the simulator to duplicate the total number of tracks per event in the real data. The correction would naively be $(\frac{16.21}{15.09})^2 = 1.157 \Rightarrow +15.7\%$ to the Monte Carlo background. However, the effect of the cuts on the multiplicity as a function of momentum has not been fully explored. The correction that is applied is found by calculating a multiplicative factor that, when multiplied to the background distribution as a whole (in order that the shape remain the same), gives it the best fit to the real data. For this purpose, the respective signal regions are excluded from the fit. The factors that are used are $(1.05 \pm 0.04) \times$ Luminosity normalization for the $K_S^0$ background distribution and $(1.21 \pm 0.04) \times$ Luminosity normalization for the $\Lambda^0$ background distribution.

The invariant mass distributions after the application of these cuts on the hadronic data
are shown in Figures 4-28 and 4-29. Peaks are clearly evident at the predicted values. The solid lines in the figures represent the distribution of the background fitted to a threshold function of the form

\[ N_{\text{background}} = A_1 \left| m - m_{\text{min}} \right|^{A_2} \exp(-A_3 m - A_4 m^2) \]  

(4.1)

fitted to the predicted background as found from the Monte Carlo. The \( A_n \)'s are free fit parameters and \( m_{\text{min}} \) is the sum of the masses of the two decay products. The Monte Carlo sample is normalized to the data based on the total luminosity and the multiplicative correction factor prior to the fit.

4.3.1 Sources of background

The primary background in both \( K_0^0 \) and \( \Lambda^0 \) decay is due to combinatorials. A typical pair in the combinatorial background will have at least one particle that arose from a late decay or some off-vertex interaction such as a photon conversion. It is also very likely that at least one of the particles, if not both, is a pion. The overall background is usually well-represented by a threshold function as described above.

A less random background source can arise from a particle that decays off the beamline and produces at least one pair of oppositely charged particles. Examples of this include \( K^\pm \rightarrow \pi^+\pi^-\pi^\pm \) and \( K_L^0 \rightarrow \pi^\pm e^\mp \nu_e \). These are three-body decays, so reconstruction of any pair of charged particles resulting from the decay does not show a peak in the invariant mass distribution. In addition, they are, statistically speaking, dominated by the combinatorial background. These contributions are simply absorbed into the threshold function used for the overall background.

There is a non-random background source that, unlike the reactions discussed above, involves a neutral particle decaying into two charged particles in statistically significant num-
Figure 4-11: Plot of $|\text{DSTORG}|$ for high-momentum particle and location of cut for $K_S^0$ candidates.
Figure 4-12: Plot of $|\text{DSTORG}|$ for low-momentum particle and location of cut for $K_S^0$ candidates.
Figure 4-13: Plot of # of axial hits for low-momentum particle and location of cut for $\Lambda^0$ candidates.
Figure 4-14: Plot of # of stereo hits for low-momentum particle and location of cut for $\Lambda^0$ candidates.
Figure 4-15: Plot of # of axial hits for high-momentum particle and location of cut for $\Lambda^0$ candidates.
Figure 4-16: Plot of # of stereo hits for high-momentum particle and location of cut for Λ⁰ candidates.
Figure 4-17: Plot of $\chi^2$ / d.o.f. for high-momentum particle and location of cut for $\Lambda^0$ candidates.
Figure 4-18: Plot of $\chi^2_{r-\phi}/\text{d.o.f.}$ for low-momentum particle and location of cut for $\Lambda^0$ candidates.
Figure 4-19: Plot of $\chi^2_{d.o.f.}$ for high-momentum particle and location of cut for $\Lambda^0$ candidates.
Figure 4-20: Plot of $\chi^2_{\pi-2}/d.o.f.$ for low-momentum particle and location of cut for $\Lambda^0$ candidates.
Figure 4-21: Plot of angular difference at $|\text{DSTORG}|$ for $\Lambda^0$ candidates.
Figure 4.22: Plot of distance of nearer intersection from (0, 0) and location of cut for $\Lambda^0$ candidates.
Figure 4-23: Plot of $\frac{P_{\text{low}}}{P_{\text{high}}}$ and location of cut for $\Lambda^0$ candidates.
Figure 4-24: Plot of angular difference between momentum of reconstructed $\Lambda^0$ and radial vector to nearer intersection and location of cut for $\Lambda^0$ candidates.
Figure 4-25: Plot of invariant mass when reconstructed as $e^+e^-$ and location of cut for $\Lambda^0$ candidates.
Figure 4-26: Plot of $p/E$ of high-momentum particle reaching SHC and location of cut for $\Lambda^0$ candidates.
Figure 4-27: Plot of invariant mass when reconstructed as $K^0_S$ and location of cut for $\Lambda^0$ candidates.
Table 4-3: Effect of cuts used to find $K_0^0$ and $\Lambda^0$.

<table>
<thead>
<tr>
<th>Cut #</th>
<th>$\epsilon_{\text{cut}} (K_0^0)$</th>
<th>$\epsilon_{\text{cut}} (K_0^0 \text{ Background})$</th>
<th>$\epsilon_{\text{cut}} (\Lambda^0)$</th>
<th>$\epsilon_{\text{cut}} (\Lambda^0 \text{ Background})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.04</td>
<td>38.91</td>
<td>60.05</td>
<td>43.86</td>
</tr>
<tr>
<td>2</td>
<td>39.34</td>
<td>17.84</td>
<td>44.11</td>
<td>18.56</td>
</tr>
<tr>
<td>3</td>
<td>37.39</td>
<td>17.09</td>
<td>43.14</td>
<td>17.82</td>
</tr>
<tr>
<td>4</td>
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</tr>
<tr>
<td>5</td>
<td>30.85</td>
<td>6.36</td>
<td>35.96</td>
<td>10.41</td>
</tr>
<tr>
<td>6</td>
<td>21.92</td>
<td>2.40</td>
<td>30.91</td>
<td>6.02</td>
</tr>
<tr>
<td>7</td>
<td>21.92</td>
<td>2.30</td>
<td>30.91</td>
<td>5.97</td>
</tr>
<tr>
<td>8</td>
<td>19.19</td>
<td>2.14</td>
<td>30.91</td>
<td>5.97</td>
</tr>
<tr>
<td>9</td>
<td>19.19</td>
<td>2.14</td>
<td>23.83</td>
<td>4.11</td>
</tr>
<tr>
<td>10</td>
<td>14.95</td>
<td>0.83</td>
<td>15.94</td>
<td>1.46</td>
</tr>
<tr>
<td>11</td>
<td>12.22</td>
<td>0.53</td>
<td>15.50</td>
<td>1.42</td>
</tr>
<tr>
<td>12</td>
<td>12.18</td>
<td>0.44</td>
<td>14.70</td>
<td>1.26</td>
</tr>
<tr>
<td>13</td>
<td>12.18</td>
<td>0.44</td>
<td>13.82</td>
<td>0.91</td>
</tr>
<tr>
<td>14</td>
<td>12.18</td>
<td>0.44</td>
<td>11.96</td>
<td>0.72</td>
</tr>
<tr>
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<td>11.96</td>
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<td>16</td>
<td>11.22</td>
<td>0.37</td>
<td>11.85</td>
<td>0.72</td>
</tr>
<tr>
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<td>7.97</td>
<td>0.37</td>
<td>7.35</td>
<td>0.72</td>
</tr>
</tbody>
</table>
bers. For $K^0_S$, the $\Lambda^0S$ are a source of background and vice versa. However, very few $\Lambda^0S$ survive cut #15; any residual $\Lambda^0S$ are absorbed into the threshold function. But the cut to reject $K^0_S$ from the $\Lambda^0$ mass distribution was not as tight, being $\sim \pm 1\sigma$ as opposed to the $\sim \pm 2\sigma$ cut used to reject $\Lambda^0S$ from the $K^0_S$ distribution. This easing in the cut arose since too many $\Lambda^0S$ were lost with a more restrictive cut. As a result, a $K^0_S$ tagged as a $\Lambda^0$ maintaining a Gaussian distribution, has a central value and standard deviation of $1151.2 \pm 8.2$ and $30.2 \pm 10.1$ MeV/c$^2$. This Gaussian was normalized by the luminosity and added to the threshold function.

Another source of background separate from the combinatorials arises from a photon converting to an $e^+e^-$ pair at the beampipe (or within either the CDC or the ITC). This background is effectively removed in the case of the $\Lambda^0S$ by the cuts on the invariant mass of the pair when reconstructed as $e^+e^-$ and on the value of $P_T$ of the higher-momentum particle assuming there is a shower counter cluster associated with it. But since the latter cut is not used in the selection of $K^0_S$, the background from photon conversion must be carefully examined. As it turned out, though, the photon conversions clustered away from the mass region used in the final $K^0_S$ cut, and were not a factor in the analysis.

### 4.4 Multiplicity and Cross Section of $K^0$'s and $\Lambda^0$'s

To calculate the number of a certain type of particle produced per hadronic event, i.e., the multiplicity, it is necessary to be able to measure the background over which the signal rises and the efficiency with which the particle is reconstructed. The Monte Carlo data, with the signal subtracted out, is used for the shape of background distribution. When the resulting curve is normalized so that the luminosity of the Monte Carlo data and the real data is equal and then the correction for the low multiplicity of the simulated data is applied, the curve can, in effect, be placed over the real data. From that point on, finding the multiplicity and cross section is a simple calculation.
Figure 4-28: Invariant mass distribution for $K_S^0$. 
Figure 4-29: Invariant mass distribution for $\Lambda^0$s.
4.4.1 Multiplicity

For $K^0\bar{s}$s in the mass region between 457 and 537 MeV/c², there is an excess of $354 \pm 24$ entries above the expected background. The excess number of entries in the $\Lambda^0$ invariant mass distribution between 1104 and 1128 MeV/c² is $84 \pm 21$. To calculate the multiplicity of a particle, the following formula is used:

$$\langle N_{\text{particle}} \rangle = \frac{N_{\text{found}} \epsilon_{\text{had. event}}}{\epsilon N_{\text{hadron}}}.$$  \hspace{1cm} (4.2)

In this formula, $\epsilon$ represents the expected fraction of particles originally produced that survives all cuts, $N_{\text{hadron}} = 24488$ is the total number of hadronic events in the sample, $N_{\text{found}}$ is the excess of entries and $\epsilon_{\text{had. event}} = 0.602$ is the efficiency of the hadronic event selection. For $K^0\bar{s}$s, $\epsilon$ is 0.00553 and $N_{\text{found}}$ is 354; these numbers are 0.0057 and 84 for the case of $\Lambda^0$s. Plugging these numbers into Equation 4.2 gives the values

$$\langle N_{K^0, \bar{K}^0} \rangle = 1.57 \pm 0.13 \pm 0.19$$ \hspace{1cm} (4.3)

$$\langle N_{\Lambda^0, \bar{\Lambda}^0} \rangle = 0.36 \pm 0.11 \pm 0.04.$$ \hspace{1cm} (4.4)

where the first error is statistical and the second is systematic. The values for the multiplicities are plotted with values from other experiments in Figures 4-30 and 4-31 as a function of center-of-mass energy. The other data points come from [38, 39, 40, 41, 42, 43, 44] for the $K^0$s and [44, 45, 46, 47, 48, 49, 50] for the $\Lambda^0$s.

When the multiplicity values at different center-of-mass energies are fitted to the curves described in Equations 1.18 through 1.5 the fits as displayed in Table 4-4 are found. For the Fermi formulation, there is good agreement between the fit based on the $\Lambda^0$ multiplicities and the predicted value of $\frac{1}{4}$ for the value of $b$ while the value for $a$ is consistent with the value of $a$ for the total charged particle multiplicity when taking the relative multiplicities of all charged particles vs. only $\Lambda^0$s into account. The $K^0$s don't show this agreement. The value for $b$ deviates substantially from the predicted value while the value for $a$ is approximately a factor of 2 too large to be consistent with the multiplicities of the charged
particles and the $\Lambda^0$s. Thus, as a result of the fit, the decrease in the value of $b$ may be due to the increase of the value of $a$. In the QCD-inspired parametrization, the value of $Q_0^2$ is consistent with the value obtained from the charge particle multiplicity distribution. The $\Lambda^0$s show a deviation from this value. The values for $b$ in all three cases are consistent with the values for the multiplicity, so this may arise from the unusually low value of the additive constant, $a$, for the $\Lambda^0$s. In the third situation, using the empirical formulation from $pp$ collisions, there does not appear to be any consistency between the various multiplicities and the fitted values. In fact, the fitted values for the $\Lambda^0$ are entirely contrary in their signs to the values obtained for the charged particles and $K^0$s.

### 4.4.2 Cross Section

The total cross section for a particle is given by

$$\sigma = \frac{N_{\text{bound}}}{\epsilon \int \mathcal{L} dt}$$

(4.5)

where $\int \mathcal{L} dt$ represents the total integrated luminosity of the sample. Using the values in Section 2.3, the total cross sections for the production of $K^0$s and $\Lambda^0$s are, respectively, $262 \pm 22 \pm 30$ and $60 \pm 17 \pm 6$ pb. The cross sections for the two particles are shown in

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Total Charged Multiplicity</th>
<th>$K^0$ Multiplicity</th>
<th>$\Lambda^0$ Multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>$2.20 \pm 0.03$</td>
<td>$0.43 \pm 0.02$</td>
<td>$0.039 \pm 0.004$</td>
</tr>
<tr>
<td>$b$</td>
<td>$0.252 \pm 0.002$</td>
<td>$0.171 \pm 0.005$</td>
<td>$0.24 \pm 0.04$</td>
</tr>
<tr>
<td>QCD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>$2.46 \pm 0.02$</td>
<td>$0.662 \pm 0.002$</td>
<td>$0.047 \pm 0.002$</td>
</tr>
<tr>
<td>$b$</td>
<td>$0.091 \pm 0.001$</td>
<td>$0.00670 \pm 0.00002$</td>
<td>$0.00136 \pm 0.00004$</td>
</tr>
<tr>
<td>$Q_0^2$</td>
<td>$0.85 \pm 0.02$</td>
<td>$0.826 \pm 0.003$</td>
<td>$0.68 \pm 0.02$</td>
</tr>
<tr>
<td>$pp$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>$3.37 \pm 0.09$</td>
<td>$0.61 \pm 0.03$</td>
<td>$-0.67 \pm 0.05$</td>
</tr>
<tr>
<td>$b$</td>
<td>$-0.43 \pm 0.06$</td>
<td>$-0.171 \pm 0.009$</td>
<td>$0.173 \pm 0.012$</td>
</tr>
<tr>
<td>$c$</td>
<td>$0.262 \pm 0.007$</td>
<td>$0.012 \pm 0.003$</td>
<td>$-0.0066 \pm 0.0006$</td>
</tr>
</tbody>
</table>

Table 4-4: Results of fit to multiplicity relations for $K^0$s and $\Lambda^0$s.
Figure 4-30: Multiplicity of $K^0$'s in AMY and other experiments.
Figure 4-31: Multiplicity of $\Lambda^0$s in AMY and other experiments.
comparison with data from other experiments along with the prediction of the Lund Monte Carlo in Figures 4-32 and 4-33.

4.4.3 Differential cross section

The differential cross section, \(d\sigma/dx_E\) is a measure of how the total cross section depends upon the scaled energy, \(x_E = E_{\text{particle}}/E_{\text{beam}}\). For comparisons with data from other experiments, \(d\sigma/dx_E\) is normalized by the total hadronic cross section and the average velocity of all particles at a given \(x_E\). The sample of particles in question is divided into bins of finite width in \(x_E\) and the plot of the scale invariant differential cross section follows the form

\[
\left( \frac{d\sigma}{dx_E} \right)_{\text{scaled}} = \frac{p_i N_{\text{found}}}{\bar{\beta}_i \sigma_{\text{hadronic}} \epsilon_i W_i \int L dt}
\] (4.6)

where \(N_{\text{found}}\) is the number of entries in the \(i^{th}\) bin, \(p_i\) is the purity of the sample in the \(i^{th}\) bin (based on the Monte Carlo prediction), \(\bar{\beta}_i\) is the average velocity of all particles in the \(i^{th}\) bin, \(\epsilon_i\) is the efficiency of reconstruction of particles in the \(i^{th}\) bin and \(W_i\) is the width of the \(i^{th}\) bin. The distributions of \(\bar{\beta}_i\) and \(\epsilon_i\) for both \(K^0\) and \(\Lambda^0\) candidates found in the data are shown in Figures 4-34, 4-35 and 4-36. When these values are folded in together with the \(x_E\) distributions found from the surviving \(K^0\)'s and \(\Lambda^0\)'s the scale invariant differential cross sections in Figures 4-37 and 4-38 are found. Along with those values are the values obtained in other experiments at different center-of-mass energies along with the prediction from Lund. For the low \(x_E\) region, the agreement between the AMY data and previous experiments is good. The high region has been cut out; the disagreement between the AMY data and the previously published results is an anomalous order of magnitude different.
Figure 4-32: Cross Section of $K^0$s in AMY and other experiments.
Figure 4-33: Cross Section of $\Lambda^0\bar{\Lambda}$ in AMY and other experiments.
Figure 4-34: Average $\beta$ for $K^0$s and $\Lambda^0$s as a function of $x_B$. 
Figure 4-35: Efficiency for $K^0$ reconstruction as a function of $x_E$. 

$x_E = \frac{E_{K^0}}{E_{beam}}$
Figure 4-36: Efficiency for $\Lambda^0$ reconstruction as a function of $x_E$. 

$\mathbf{E}^\mathbf{E} = \mathbf{E}_{\Lambda^0}/\mathbf{E}_{\text{beam}}$
Figure 4-37: Differential cross section of $K^0$'s in AMY and other experiments.
Figure 4-38: Differential cross section of $\Lambda^0$s in AMY and other experiments.
Chapter 5

$K^*(892)'s$, $\rho^0(770)'s$ and $\phi(1020)'s$

5.1 Production of $K^*(892)$

The measurement of the production of the vector meson $K^*(892)$ provides an important comparison between the data and the Lund Monte Carlo. One of the variable parameters in the Lund model is the ratio of production of vector mesons, such as the $K^*(892)$, to the production of the corresponding pseudoscalar meson, such as the $K^0$. Based on spin statistics, the ratio of production of spin-1 type mesons versus spin-1 plus spin-0 mesons is 0.75. The default value for the Lund Monte Carlo varies depending upon the flavor of the meson under consideration. In the case of strange mesons, the value used is 0.6; for up and down mesons the value is 0.5 and for charm and bottom mesons the ratio is 0.75.

5.1.1 Selection of $K^{*\pm}'s$

The $K^0_S$s found in the previous chapter can be used to reconstruct the $K^{*\pm}$ via its decay into the pair $K^0_S \pi^{\pm}$. For the sake of a clean signal, the $K^0_S$s are required to be within 1 standard deviation of the PDG value for the $K^0_S$ mass, 497.671 MeV/c$^2$. The sample
is further enriched by requiring that the \( \pi^\pm \) candidate come within 0.2 cm of (0, 0) and that the opening angle between the \( K_S^0 \) and \( \pi^\pm \) be such that \( \cos \theta_{\text{open}} > 0.90 \). Cutting on the \( \chi^2_{\pi-\phi} / \text{d.o.f.} \) and \( \chi^2_{\pi-z} / \text{d.o.f.} \) was not performed as the statistics were already extremely limited. Additionally, no cut was made on the maximum value for \( x_E \) as the contribution from the high-momentum particles was statistically small (less than 5%) and because since these decay products are produced promptly, their reconstruction is more reliable. The cuts are displayed in Figures 5-1, 5-2 and 5-3; the format is the same as was used in Figures 4-1 through 4-27. Based on Monte Carlo studies, these cuts result in a Breit-Wigner \( K^{*-\pm} \) distribution with a centroid of 893.4 GeV/c\(^2\) and a FWHM of 59.2 MeV/c\(^2\). The resulting sample of AMY data appears in Figure 5-4. The background as predicted by the Monte Carlo was normalized according to the luminosity and then, similar to the necessary multiplicative factor described in Section 4.3, was multiplied by a factor of 1.16. The sample after the normalized Monte Carlo background has been subtracted off is shown in Figure 5-5. Cutting on the mass between 840 and 940 GeV/c\(^2\) gives an excess of 27 ± 10 entries. The Lund prediction for the efficiency in this region is 0.052 ± 0.010% which translates into a multiplicity and total cross section of 1.66 ± 0.61 ± 0.20 \( K^{*-\pm} \)'s/hadronic event and 272 ± 101 ± 32 pb.

### 5.1.2 Selection of \( K^{*0} \)s

The decay of the \( K^{*0} \) is recognized through the charged decay products \( K^\pm \pi^\mp \). As this decay is prompt, the two candidate tracks are required to come within 0.2 cm of (0, 0). Furthermore, the cut on the opening angle is such that \( \cos \theta_{\text{open}} > 0.90 \). The total energy of the reconstructed particle is such that \( x_E > 0.15 \). The two decay products are also constrained to have \( \chi^2_{\pi-\phi} / \text{d.o.f.} < 4 \) and \( \chi^2_{\pi-z} / \text{d.o.f.} < 2 \). These cuts are plotted in Figures 5-6 through 5-13. The charged kaon mass of 493.646 MeV/c\(^2\) is assigned to the track with the higher momentum; this assumption is correct 75% of the time. Based on the Lund Monte Carlo, the resulting distribution of \( K^{*0} \)'s, when fitted to a Breit-Wigner
Figure 5-1: Difference between candidate $K_S^0$ and actual $K_S^0$ mass and location of cut for $K^{*\pm}$ candidates.
\[ |\text{DSTORG}| \text{ of } \pi^\pm \text{ from } K^{*\pm}(892) \text{ Decay} \]

\[ |\text{DSTORG}| \text{ of } \pi^\pm \text{ from Fake } K^{*\pm}(892) \text{ Decay} \]

Figure 5-2: \[ |\text{DSTORG}| \text{ of } \pi \text{ and location of cut for } K^{*\pm} \text{ candidates.} \]
Figure 5-3: $\cos \theta_{\text{open}}$ of decay products and location of cut for $K^{*\pm}$ candidates.
Figure 5-4: Invariant mass distribution for $K^{*\pm}$'s.
Figure 5-5: Invariant mass distribution for $K^{*\pm}$'s after the subtraction of the normalized Monte Carlo background distribution. The curve shown is the result of a Breit-Wigner fit to the data. The statistical errors are approximately 5 at 0.7 GeV/c$^2$; at 1 GeV/c$^2$ they are down to 3 and drop down to 1 at 1.5 GeV/c$^2$. 
function, has a centroid of $895 \pm 5$ MeV/c$^2$ and a full width at half maximum (FWHM) of $87 \pm 21$ MeV/c$^2$. The efficiency of reconstruction is 3.13% over a mass range of 0.8 to 1.0 GeV/c$^2$. When the cuts are applied to AMY data, the distribution shown in Figure 5-14 is obtained. The background found from the Lund Monte Carlo simulations is fitted to a Chebyshev function (which fit the background prediction better than the threshold function of Equation 4.1), normalized by way of the luminosity and plotted with the data; an additional normalization factor, similar to what was described in Section 4.3, of 1.15 was needed. The Monte Carlo background was subtracted from the data; the result is shown in Figure 5-15. The peak in the low end of the subtracted mass distribution is due to the steepness of the slope in the invariant mass distribution and a slight shift in the fitted curve relative to the histogram. Fitting with a Breit-Wigner function gives a mass of $887^{+13}_{-7}$ MeV/c$^2$ for the $K^{*0}$ mass with a width of 57 MeV/c$^2$. Over the mass range of 0.8 to 1.0 GeV/c$^2$, there is an excess $745 \pm 178$ entries, giving a calculated multiplicity of $0.59 \pm 0.14 \pm 0.07$ $K^{*0}$s per event. The total cross section is $94 \pm 22 \pm 11$ pb. The multiplicity is plotted in Figure 5-16 with the results from other experiments at different center-of-mass energies.

5.1.3 Production of vector versus pseudoscalar mesons

With the multiplicities of $K^0$'s and $K^*(892)$'s found above, the ratio of vector meson production to total meson production, $\frac{V}{F+V}$, can be evaluated (because of the large uncertainty in the determination of the multiplicity of the $K^{*\pm}$ meson and since there is no calculation of the multiplicity of the $K^{\pm}$ meson as the AMY detector lacks any sort of charged particle identification ability, only the neutral strange mesons will be considered). To do this, the production of mesons from other sources must be calculated and subtracted out. These sources are, primarily, from the decay of charm and bottom quarks and, to a lesser extent, from the decay of the $\phi(1020)$ meson as well as other heavier mesons consisting exclusively of up and down quarks. The Lund Monte Carlo, which best models the production of
Figure 5-6: Plot of the $|\text{DSTOR}_G|$ of the high-momentum particles and the location of the cut for $K^{*0}$ candidates.
Figure 5-7: Plot of the |DSTORG| of the low-momentum particles and the location of the cut for $K^{*0}$ candidates.
Figure 5-8: $\cos \theta_{\text{open}}$ of decay products and location of cut for $K^{*0}$ candidates.
$x_E$ of $K^{*0}(892)$ Candidates

$x_E$ of Fake $K^{*0}(892)$ Candidates

Figure 5-9: $x_E$ of decay products and location of cut for $K^{*0}$ candidates.
Figure 5-10: Plot of the $\chi^2_{r-q}/\text{d.o.f.}$ of the high-momentum particles and the location of the cut for $K^{*0}$ candidates.
Figure 5-11: Plot of the $\chi^2_{r-\phi}/\text{d.o.f.}$ of the low-momentum particles and the location of the cut for $K^{*0}$ candidates.
Figure 5-12: Plot of the $\chi^2_{z-z}$/d.o.f. of the high-momentum particles and the location of the cut for $K^{*0}$ candidates.
Figure 5.13: Plot of the $\chi^2_{s-z}/\text{d.o.f.}$ of the low-momentum particles and the location of the cut for $K^{*0}$ candidates.
Figure 5-14: Invariant mass distribution for $K^*\pi$'s.
Figure 5-15: Invariant mass distribution of $K^{*-0}$'s after subtraction of normalized Monte Carlo background distribution. Statistical errors for each bin (not shown) in the low mass regions are on the order of 45. Out in the 1 GeV/$c^2$ region, the statistical errors are approximately 40; this drops to 17 at 1.5 GeV/$c^2$ and 7 at 2 GeV/$c^2$. 
Figure 5-16: Multiplicity of $K^{*0}$ at different center-of-mass energies; the solid curve represents the Lund prediction.
charged particles [6] in AMY, is used to calculate the contributions from these sources. For $K^0$s, the multiplicity resulting from the decay of $\phi(1020)$ is 0.017. The contribution from bottom and charm meson decays is 0.252 $K^0$s per hadronic event. The only significant contribution to $K^{*0}$'s is from charm and bottom decays; this number is 0.04 $K^{*0}$'s per hadronic event. After subtracting off these values, the multiplicities of $K^0$s and $K^{*}(892)$'s arising from either direct production in a strange quark event or from the background sea during hadronization are $1.32 \pm 0.14 \pm 0.19$ and $0.53 \pm 0.14 \pm 0.07$. The multiplicity of $K^0$s includes those from the decay of the $K^*(892)$'s; therefore, $\frac{V}{V_{+P}} = \frac{N_{K^{*0}(892)}}{N_{K^0}} = 0.40 \pm 0.11 \pm 0.08$. This result is shown along with the results of other collaborations as well as the prediction of Lund in Table 5-1. The value is consistent with the results from lower energies, but is greater than $1\sigma$ away from the default Lund value and the value obtained at DELPHI.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Center-of-mass energy (GeV/c)</th>
<th>$\frac{V}{V_{+P}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC [39]</td>
<td>29</td>
<td>$0.47 \pm 0.11 \pm 0.09$</td>
</tr>
<tr>
<td>JADE [51]</td>
<td>35</td>
<td>$0.30 \pm 0.15 \pm 0.11$</td>
</tr>
<tr>
<td>AMY</td>
<td>57.9</td>
<td>$0.40 \pm 0.11 \pm 0.08$</td>
</tr>
<tr>
<td>DELPHI [44]</td>
<td>$M_{Z^0}$</td>
<td>$0.70 \pm 0.18$</td>
</tr>
<tr>
<td>Lund</td>
<td>58</td>
<td>0.6</td>
</tr>
</tbody>
</table>

5.2 Production of $\rho^0(770)$ Mesons

To extract the $\rho^0(770)$ meson, several cuts are applied to all combinations of oppositely charged pairs of particles. Each particle must come within 0.2 cm of (0,0), the opening angle, $\theta$, must satisfy the condition $\cos \theta > 0.75$ and the tracks must pass track quality cuts such that $\chi^2_{d.o.f.}$ of the r-$\phi$ fit must be less than 4 and $\chi^2_{d.o.f.}$ of the s-$z$ fit must be less than 2.
The total energy of the reconstructed particle is such that \( x_E > 0.1 \). The cuts are shown in Figures 5-17 through 5-21. The efficiency of reconstruction is 2.06% based on \( \rho^0 \)'s from 620 to 920 MeV/c\(^2\). The distribution of all candidates is shown in Figure 5-22. The subtraction of the normalized Monte Carlo (with the multiplicative factor of 1.08) prediction is shown in Figure 5-23. In the Monte Carlo subtracted mass distribution, there is an excess of particles around 0.5 GeV/c\(^2\). This arises from the subtraction of the fit to the background distribution as opposed to the background distribution itself. The Chebyshev smears out the peak due to the decay of the \( K_S^0 \) seen at 0.5 GeV/c\(^2\) and there is a residual number of candidates left over after the subtraction. But this is also well away from the \( \rho^0 \) mass of 768.1 MeV/c\(^2\). The resulting Breit-Wigner fit gives masses of 759 ± 12 and a \( \Gamma \) of 132 ±25. There is an excess of 1139 ± 205 entries. The multiplicity and cross section of the \( \rho^0 \) meson from the Monte Carlo-subtracted case are found to be 1.37 ± 0.25 ± 0.16 \( \rho^0 \)'s per event and 225 ± 43 ± 27 pb. The multiplicity and total cross section of \( \rho^0 \)'s in AMY are compared with data from other experiments in Figures 5-24 and 5-25. Other points are taken from [51] and [52].

5.3 Production of \( \phi(1020) \) Mesons

The methodology of searching for \( \phi(1020) \rightarrow K^+K^- \) is very similar to the \( \rho^0 \) and \( K^{*0} \) searches in that cuts are placed on all pairs of oppositely charged particles to extract a signal. The major difference is that both particles are assumed to have the charged kaon mass of 493.646 MeV/c\(^2\). The two tracks are required to pass the quality cuts of \( \chi^2_{d.o.f.} \) in the \( r-\phi \) plane of less than 4 and \( \chi^2_{d.o.f.} \) in the \( s-z \) plane of less than 2. Additionally, both tracks must have a DSTORG less than 2 mm and their opening angle at (0, 0, 0) must satisfy the condition that \( \cos \theta_{open} > 0.97 \). The low-momentum particle in the pair of decay products must have a momentum greater than 1.5 GeV/c. The cuts are displayed in Figures 5-26 through 5-30. When these cuts are applied to the data, the invariant mass distribution shown in Figure 5-31 is obtained. Subtracting the normalized Monte Carlo distribution
Figure 5-17: Plot of $x_E$ and location of cut for $\rho^0(770)$ candidates.
Figure 5-18: Plot of $\cos \theta_{\text{open}}$ between the decay products and location of cut for $\rho^0(770)$ candidates.
Figure 5-19: Plot of $|DSTORG|$ and location of cut for $\rho^0(770)$ candidates.
Figure 5-20: Plot of $\chi^2_{r-\phi}$/d.o.f. and location of cut for $\rho^0(770)$ candidates.
Figure 5-21: Plot of $\chi^2 / \text{d.o.f.}$ and location of cut for $\rho^0(770)$ candidates.
Figure 5-22: Invariant mass distribution for $\rho^0$'s.
Figure 5-23: Invariant mass distribution of $\rho^0$'s after subtraction of normalized Monte Carlo background distribution. Statistical errors for each bin (not shown) range from about 45 at 0.5 GeV/c$^2$ to 38 at 1.0 GeV/c$^2$ to 20 at 1.5 GeV/c$^2$. 
Figure 5-24: Multiplicity of the $\rho^0$ meson at different center-of-mass energies. The solid curve represents the Lund prediction.
Figure 5-25: Cross section of the $\rho^0$ meson at different center-of-mass energies. The solid curve represents the Lund prediction.
(with a factor of 1.23) gave the result in Figures 5-32. Based on the study of the Monte
Carlo, a Breit-Wigner fit to the $\phi$ distribution should have resulted in a FWHM of 5 MeV/c$^2$
centered at 1020 MeV/c$^2$. But because of contamination from other meson decays such as
\[
\omega(783) \rightarrow \pi^+\pi^-\pi^0, \quad (5.1)
\]
\[
\eta \rightarrow \pi^+\pi^-\pi^0, \quad \text{and} \quad (5.2)
\]
\[
\eta' \rightarrow \pi^+\pi^-\eta, \quad (5.3)
\]
and because of the smearing resulting from the fit, the resulting peak in the subtracted
distribution is meaningless. Clearly, there is no indication of a bona-fide $\phi$ peak in that
region. Nevertheless, if the entries between 1.005 and 1.035 GeV/c$^2$ are assumed to be $\phi$'s
and only $\phi$'s, then the multiplicity, assuming an efficiency of $(4.15 \pm 0.29)$% for that mass
range, is found to be $0.193 \pm 0.060 \pm 0.023$ with a cross-section of $31.8 \pm 9.9 \pm 3.8$ pb.

5.4 Production of Excited $s\bar{s}$ Pairs

As mentioned in Section 1.4, a free parameter in the Lund Monte Carlo is the ratio of
production of excited $s\bar{s}$ quark pairs from the vacuum to that for $u\bar{u}$ pairs. This factor,
$\gamma_s/\gamma_u$, has a default value of 0.3 in the Lund model. Before evaluating Equations 1.21, the
production rates of the vector mesons need to be corrected for heavy flavor particle decays.
However, those particles also must be corrected by removing contributions from the primary
quarks in the event. The total multiplicity of the $K^{*0}$ meson is $0.57 \pm 0.14 \pm 0.07$ per hadronic
event. Based on the Lund model, the contribution from heavy flavor particle decays is 0.04
per event and the contribution from primary strange quarks is 0.08. The total multiplicity
of the $\rho^0$ meson is $1.37 \pm 0.28 \pm 0.16$ per hadronic event. The contribution from heavy flavor
particle decays plus the contributions from primary up and down quarks is 0.31. Based
on these numbers, the calculated value of $\gamma_s/\gamma_u$ is found to be $0.21 \pm 0.09 \pm 0.05$. This is
compared with values from other experiments in Table 5-2. The AMY value is consistent
with the other experiments as well as with the default Lund value of 0.3.
Table 5-2: Evaluation of $\gamma_s/\gamma_u$ at different center-of-mass energies.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Energy (GeV)</th>
<th>$\gamma_s/\gamma_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC$^1$</td>
<td>29.0</td>
<td>0.37 ± 0.15 ± 0.08</td>
</tr>
<tr>
<td>TPC &amp; TASSO</td>
<td>29.0</td>
<td>0.32 ± 0.09 ± 0.05</td>
</tr>
<tr>
<td>AMY</td>
<td>57.9</td>
<td>0.21 ± 0.39 ± 0.05</td>
</tr>
<tr>
<td>DELPHI</td>
<td>91.1</td>
<td>0.30 ± 0.02</td>
</tr>
<tr>
<td>Lund</td>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>

$^1$The first TPC number uses $\phi(1020)'s$ and $K^-\pi^+$'s. The second TPC value uses the TPC $K^0$ multiplicity and the TASSO $\rho^0(770)$ multiplicity. The DELPHI number is based on tuning the $\gamma_s/\gamma_u$ parameter in Lund to get a spectrum that agreed with the $K^0$ differential cross section.
We interrupt this dissertation for a little something to clear the palate.

There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact. *Mark Twain*

We now return you to this dissertation, already in progress.
Figure 5-26: Plot of the momentum of the soft particle and location of cut for $\phi(1020)$ candidates.
Figure 5-27: Plot of the $\cos \theta_{\text{open}}$ of the decay products and location of cut for $\phi(1020)$ candidates.
Figure 5-28: Plot of the |DSTORG| of the decay products and location of cut for $\phi(1020)$ candidates.
Figure 5-29: Plot of $\chi^2_{r-\phi}/\text{d.o.f.}$ and location of cut for $\phi(1020)$ candidates.
Figure 5-30: Plot of $\chi^2_{s-z}/\text{d.o.f.}$ and location of cut for $\phi(1020)$ candidates.
Figure 5-31: Invariant mass distribution for $\phi(1020)$'s.
Figure 5-32: Invariant mass distribution of $\phi(1020)$'s after subtraction of normalized Monte Carlo background distribution. Statistical errors in the low mass region are around 35, tapering off to 15 at 1.5 GeV/$c^2$ and down to 5 at 2.0 GeV/$c^2$. 
Chapter 6

Tuning the HERWIG Monte Carlo Model

This chapter is concerned with the adjustment of the available parameters in the HERWIG Monte Carlo generator in a process known as "tuning." HERWIG has been tuned by many groups to reflect the global hadronic event properties such as thrust, sphericity and total multiplicity of all charged particles; however, HERWIG has not been tuned for inclusive hadron production [53]. This analysis has tuned various HERWIG parameters to reflect the relatively well-measured multiplicities of the $K^0$, $\Lambda^0$, $K^{*0}(892)$ and $\rho^0(770)$ particles in the AMY experiment.

6.1 HERWIG Parameters

HERWIG does not have the menagerie of adjustable parameters that can be found in the Lund Monte Carlo hadronic event generator. There are even fewer parameters in HERWIG that have an influence on the production of individual species of hadrons. Those parameters that have been found to have an effect are itemized below:
CLPOW A cluster with mass $m_{cl}$ made up of quarks with masses $m_1$ and $m_2$ will be split into lighter clusters before decaying if the condition $m_{cl}^{\text{CLPOW}} > \text{CLMAX}^{\text{CLPOW}} + (m_1 + m_2)^{\text{CLPOW}}$ is fulfilled where $\text{CLMAX} = 3.35 \text{ GeV/c}^2$. Thus, the smaller the value of CLPOW, the greater the production of heavier clusters, particularly those that result in baryons. This also has a greater effect on the heavier quarks than on the lighter ones. The default value of CLPOW is 2.

PSPLT This parameter is used for determining the mass distribution when a cluster described above is split before decaying. The mass of a cluster fragment is chosen by first subtracting from the total energy of the parent cluster the masses of the two constituent quarks (this value is called PXY). A random number between 0 and 1 is found and raised to the power PSPLT. This value is multiplied by PXY and added to the mass of one of the quarks to calculate the energy of one of the new clusters. This process is repeated for the second quark in the parent cluster. The condition that the energies of the two new clusters be less than the energy of the parent cluster is imposed; if this condition is not satisfied, the process is repeated until it is. The resultant loss of overall energy is taken care of by rescaling the energies of the daughter clusters so that they add up to the original energy of the parent cluster. The tendency is that a low value for PSPLT will produce baby clusters with slightly higher energies than would otherwise take place with a high value for PSPLT. The default value of PSPLT is 1.

PWT(3) This is the weight assigned to the production of s quarks. So, the higher PWT(3) is, the more likely the production of strange hadrons. This has a default value equal to 1, which is the same as that for the production of other quarks.

RMASS(3) This is the effective mass used for the s quarks. A heavier strange quark mass provides more energy to strange quark-bearing clusters, which increases the production of heavier strange hadrons relative to the lighter ones. The default value is 0.5 GeV/c$^2$. 
VECWT  This is the weight given to vector meson production relative to the production of
tensor mesons and decuplet baryons. Thus, increasing it has the tendency to increase
the production of vector mesons at the expense of the production of baryons. The
default value is 1.

No other parameters were found to have a statistically significant influence on the inclusive
production of these hadrons.

6.2  Methodology of Tuning

The specific tuning method involved slowly varying each parameter of the HERWIG Monte
Carlo independently of the others, i.e., all parameters were left at their default values with
the exception of the parameter under consideration. The assumption of no correlations
between these parameters has no a priori justification. However, the smallest uncertainty,
coming with the \( K^0 \) meson, is 15\% of the measured value. At the extremes of the ranges
for the parameters being explored, there was sometimes deviations of greater than 15\%.
However, the values ultimately chosen were well within the uncertainties ascribed to the
multiplicities of the particles used in this analysis, meaning that any correlations were typ-
ically swamped out by the large uncertainties. For each different value of each parameter,
10,000 hadronic events were generated. The multiplicities of the four particles were then
compared with the experimentally obtained values. After a sufficient number of different
values of the parameter had been examined, curves were fit to the different values of mul-
tiplicity for each of the particles. A \( \chi^2 \) plot was then calculated from these fitted functions
with the optimum value being at the minimum of this plot.

To illustrate this procedure in more detail, CLPOW is examined step-by-step. CLPOW has
a default value of 2. During the tuning process, it was allowed to vary incrementally in steps
of size 0.25 (with the exception that CLPOW = 0 was not used; instead, CLPOW = 0.19
was used). After the generation of 10,800 events at each point, the multiplicities for each of the four particles was calculated and divided by the multiplicity found from the AMY data. These data are shown in Figure 6-1. Also shown are the curves that were fitted to those points for each of the four particles; the forms of the functions used in the curve fits was based entirely on empirical considerations. Those four functions are shown along with the functions obtained for the other parameters in Table 6.2. Since the data were scaled to the AMY data, the optimum point for CLPOW is where all four of the curves come closest to 1. Thus, the $\chi^2$ distribution was found by using Equation 6.1,

$$
\chi^2 = \frac{(f_{K^0}(\text{CLPOW}) - 1)^2}{\sigma_{K^0}^2} + \frac{(f_{\Lambda}(\text{CLPOW}) - 1)^2}{\sigma_{\Lambda}^2} + \frac{(f_{K^{*0}(892)}(\text{CLPOW}) - 1)^2}{\sigma_{K^{*0}(892)}^2} + \frac{(f_{\rho}(770)(\text{CLPOW}) - 1)^2}{\sigma_{\rho}^2(770)}.
$$

(6.1)

This is shown in Figure 6-2 (the scaled multiplicity and $\chi^2$ curves for the other parameters are shown in Figures 6-3 through 6-6). From it, it can be seen that the minimum is at $1.4^{+2.0}_{-1.4}$. The values found for this and the other parameters are shown in Table 6.2. None of the values was found to statistically deviate from the default values that are currently used. With the new, tuned values, the multiplicity for inclusive hadron production from the HERWIG generator is shown in Table 6.2 with the AMY and Lund values. The tuned HERWIG values are competitive with the Lund values in their closeness to the AMY data.

\[\text{\footnote{Statistically speaking, the lower bound for RMASS(3) was less than 0, but as this result makes no sense physically, the lower bound is considered to be 0.}}\]
Figure 6-1: Scaled multiplicity distributions for $K^0$, $\Lambda^0$, $K^{*0}(892)$ and $\rho^0(770)$ as a function of CLPOW.
Figure 6-2: $\chi^2$ distribution of scaled multiplicity distribution as a function of CLPOW.
Figure 6-3: Scaled multiplicity distribution and resultant $\chi^2$ distribution for PSPLT.
Figure 6-4: Scaled multiplicity distribution and resultant $\chi^2$ distribution for PWT(3).
Figure 6-5: Scaled multiplicity distribution and resultant $\chi^2$ distribution for RMASS(3).
Figure 6-6: Scaled multiplicity distribution and resultant $\chi^2$ distribution for VECWT.
Table 6-1: Empirically fitted functions based on relative multiplicities of hadrons in HERWIG and AMY data.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Empirical Function for $\left(\frac{N_{hadrons}}{N_{AMY}}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0$</td>
<td>$0.98 + (CLPOW - 0.15)^{0.24}$</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$0.36 + (CLPOW - 0.83)^{2.1} e^{-2.1(CLPOW-0.83)}$</td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td>$0.01 + (CLPOW - 0.19)^{0.13}$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$-0.21 + (CLPOW + 0.01)^{0.69}$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$0.23 + (PSPLT + 0.21)^{0.25}$</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$-0.64 + (PSPLT + 0.84)^{0.29}$</td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td>$-0.32 + (PSPLT + 0.63)^{0.29}$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$-0.36 + (PSPLT + 0.78)^{0.15}$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$0.221 + (PWT(3) - 0.039)^{0.5}$</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$-0.398 + (PWT(3) - 0.093)^{0.331}$</td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td>$-0.266 + (PWT(3) - 0.104)^{0.378}$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$0.345 + (PWT(3) + 1.789)^{-0.931}$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$1.25 - 0.18$RMASH(3)</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$0.39 + 0.30$RMASH(3)</td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td>$0.99 - 0.11$RMASH(3)</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$0.76 + 0.05$RMASH(3)</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$-0.25 + (VECWT + 5.2)^{0.24}$</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$0.23 + (VECWT + 1.2)^{-1.4}$</td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td>$0.90 + (VECWT + 0.1)^{0.44}$</td>
</tr>
<tr>
<td>$\rho^0$</td>
<td>$-0.33 + (VECWT + 0.6)^{0.37}$</td>
</tr>
</tbody>
</table>
Table 6-2: Tuned values of the HERWIG Monte Carlo hadronic event generator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default Value</th>
<th>Tuned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLPOW</td>
<td>2.0</td>
<td>$1.44^{+1.20}_{-0.78}$</td>
</tr>
<tr>
<td>PSPLT</td>
<td>1.0</td>
<td>$0.60^{+0.85}_{-0.51}$</td>
</tr>
<tr>
<td>RMASS(3)$^1$</td>
<td>$0.5 \text{GeV}$</td>
<td>$1.5^{+2.5}_{-1.5} \text{GeV}$</td>
</tr>
<tr>
<td>PWT(3)</td>
<td>1.0</td>
<td>$1.21^{+0.74}_{-0.51}$</td>
</tr>
<tr>
<td>VECWT</td>
<td>1.0</td>
<td>$0.78^{+0.34}_{-0.39}$</td>
</tr>
</tbody>
</table>

Table 6-3: Results of tuning on the multiplicity of hadrons.

<table>
<thead>
<tr>
<th>Particle</th>
<th>AMY Multiplicity</th>
<th>HERWIG Multiplicity</th>
<th>Lund Multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0$</td>
<td>$1.57 \pm 0.14 \pm 0.19$</td>
<td>1.36</td>
<td>1.58</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$0.36 \pm 0.11 \pm 0.04$</td>
<td>0.43</td>
<td>0.23</td>
</tr>
<tr>
<td>$K^{*0}(892)$</td>
<td>$0.59 \pm 0.14 \pm 0.07$</td>
<td>0.43</td>
<td>0.78</td>
</tr>
<tr>
<td>$\rho^0(770)$</td>
<td>$1.37 \pm 0.25 \pm 0.16$</td>
<td>1.05</td>
<td>1.21</td>
</tr>
</tbody>
</table>
Chapter 7

Conclusion

The data from the AMY detector at TRISTAN have been analyzed for the production of strange hadrons; the $\rho(770)$ and $\phi(1020)$ mesons have also been examined. The results of this analysis are shown in Table 6-1 along with the same result using both the Lund 7.2 and HERWIG 5.5 Monte Carlo generators. For the first time, the HERWIG Monte Carlo event generator has been tuned to reflect the inclusive production of these hadrons. Within the statistics, there is little difference in the values of the multiplicities between the data and the tuned Monte Carlo models. The scaled differential cross sections for the $K^0$ and $\Lambda^0$ are shown in Figures 4-37 and 4-38. The $\Lambda^0$s are in good agreement with previous data, but the $K^0$ distribution tends to underestimate the production of $K^0$s as a function of energy; the speculation is that this is a problem with the simulations as opposed to any new physics. The ratio of production of vector mesons to vector plus pseudoscalar mesons has been analyzed. The value, $0.40 \pm 0.11 \pm 0.08$, does not differ from the data at lower energies but does differ somewhat from the Lund prediction of 0.6. The $s\bar{s}$ suppression factor, $\gamma_s/\gamma_u$, was found to be $0.21 \pm 0.09 \pm 0.05$; this value does not represent a statistically significant departure from previous results nor from the default Lund value of 0.3. The results of fitting to the multiplicity relations described in Chapter 1 for the $K^0$ and $\Lambda^0$ particles are shown in Table 4-4. The values obtained from the $\Lambda^0$ multiplicities
agree rather well with the results from all charged particles in the Fermi model. There is also agreement in the value of $Q_0^2$ between the $K^0$'s and the charged particles. There is no agreement in the third, empirical model.
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    Phys. C.


[36] This has yet to be written up.


[53] B. Webber, private communication.
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