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KTeV E799II search for the lepton-flavor-number violating decay $K_L \rightarrow \pi^0 \mu^\pm e^\mp$

by

Angela M. Bellavance

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF ARTS

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ABSTRACT

KTeV E799II search for the lepton-flavor-number violating decay $K_L \rightarrow \pi^0\mu^\pm e^\mp$

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Experiments E799 Phase-II (E799II) and ES32 of the Kaons at the TeVatron (KTeV) project at the Fermi National Accelerator Laboratory (Fermilab), are in the process of studying rare and CP-violating kaon decays. The experiment ran during 1996 and 1997, and the resulting data are being analyzed. This study focuses on the E799II search for the decay mode $K_L \rightarrow \pi^0\mu^\pm e^\mp$, and its accompanying background decays, in approximately 60% of the 1996-7 KTeV data.
Acknowledgments

An experiment with the size and scope of KTeV requires the dedication of many people. Figure 0.1 lists the KTeV collaborators without whom this research would have been impossible. I wish to say thank you to my officemates John Belz, Amit Lath, and Rick Tesarek for all their time and help even though I am not their student. A special thank you goes to Eva Halkiadakis for her support and empathy as a fellow graduate student and good friend. Thank you to my parents for their love and "reminders" to get this paper done. Most of all, I owe a great deal of gratitude to my advisor Dr. Marjorie Corcoran. Without her guidance, efforts, patience, and encouragement this thesis would not have happened.
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Figure 0.1 List of collaborators in KTeV for 1996-1997.
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Chapter 1
Introduction: High Energy Physics and the Standard Model

The field of high energy physics (HEP) deals with the study of atomic and subatomic particles. HEP is a relatively young science. It began in 1897 with J.J. Thompson’s discovery of the electron, took a major step forward with Rutherford’s nuclear model in 1911, and moved into the modern era with the construction of the first particle accelerator in 1932. The use of particle accelerators allows experimentalists to briefly turn time back to the high-energy particle soup which followed the Big Bang.

Our current state of knowledge is summarized by the Standard Model for particle physics. The Standard Model indicates that all matter is formed of quarks and leptons. Leptons, which include electrons, can be found free in nature. Quarks exist only in pairs or triples. Quark triplets are particles called baryons, and include the familiar proton and neutron. Quark pairs are called mesons and are always matter-antimatter pairs.

The Standard Model also contains a set of rules by which particles act and interact. Some of these rules are based on symmetry or invariance principles while other rules have no such basis but have been shown experimentally to be true.
1.1 Symmetries and Conserved Quantities

Uniformity of space is the simple classical idea that events will occur in the same way no matter what location in space they occupy or in what direction they might be traveling. Many common conservation laws come from the symmetries relating to the uniformity of space. Invariance under translations in space leads to the conservation of linear momentum. Invariance under spatial rotations leads to the conservation of angular momentum. Energy conservation is a consequence of invariance under time translations.

Another symmetry operation is that of coordinate inversion, or parity. For three dimensions, it is conventional to use a right-handed coordinate system, where \( \hat{x} \times \hat{y} \) is in the positive \( \hat{z} \) direction. Conceivably one could just as easily use a left-handed coordinate system, where \( \hat{x}' \times \hat{y}' \) is in the negative \( \hat{z}' \) direction. The two systems are related to each other by a mirror-like reflection in one plane followed by a 180° rotation [1]. No amount of transposition and rotation can make a right-handed system left-handed, or vice-versa, without the mirror reflection. The transformation is achieved via the parity operator (\( P \)), which reflects the spatial coordinates along their axes, resulting in the transformation (\( P(x, y, z) \rightarrow (x' = -x, y' = -y, z' = -z) \)). If a wavefunction is an eigenstate of an operator, then the operator has the effect of just multiplying the entire wavefunction by a real number, which is called the eigenvalue. The eigenvalues of (\( P \)) are +1 and -1. If the parity eigenvalue is +1 (-1), then the
wavefunction is said to have *even* (*odd*) parity. The total parity of a system is a multiplicative quantum number. or in other words, it is the product of the parities of the components of the system. Since so many other dimensionally-based conservation laws hold, it is natural to think that parity would also be conserved. We know in some cases it is not.

Unlike the parity operator, which affects only the spatial coordinates of a particle, the *charge conjugation operator* \((C)\) reverses the sign of electric charge and the magnetic moment of a particle, and exchanges a particle for its antiparticle, but leaves the coordinates unchanged. Like parity, the value of charge conjugation is multiplicative rather than additive, with eigenvalues of +1 or -1. It has been known since 1956, when suggested by T.D. Lee and C.N. Yang and confirmed by others through experiment[1], that \((P)\) and \((C)\) are not conserved individually in weak interactions. However, the relationship between these two operators leads one to ask if the combined operation \((CP)\) might be conserved (see Section 1.2).

Quantities which are conserved experimentally but for which there seem to be no underlying symmetry principles include *baryon number* \((B)\), *lepton number* \((L)\), and *lepton flavor* \((L_f)\). All three are additive, as opposed to multiplicative, properties. The values for \(B\) are +1 for baryons (or +1/3 for each quark), -1 for anti-baryons (or -1/3 for each anti-quark), and 0 for all other particles. The values for \(L\) are +1 for leptons and neutrinos, -1 for antileptons and antineutrinos, and 0 for all other particles.
Lepton flavor is related to lepton number, but makes a distinction between the three generations (or flavors) or leptons. Each flavor has its own number designated by the subscript of the lepton type ($L_e$, $L_{\mu}$, or $L_{\tau}$). Like $L$, $L_f$ has a value of +1 for each kind of lepton $l^-$ or neutrino $\nu_l$, -1 for each kind of antilepton $l^+$ or antineutrino $\bar{\nu}_l$, and 0 for all other particles including leptons and neutrinos of other generations. For example, the dominant muon decay mode is

$$\mu^- \rightarrow e^- \nu_e \nu_{\mu}$$  \hspace{1cm} (1.1)$$

which has lepton number $L=1$, and lepton flavor numbers of $L_{\mu}=1$ and $L_e=0$ in both the initial and final states. On the other hand, the decay

$$\mu^- \rightarrow e^- \gamma$$  \hspace{1cm} (1.2)$$
is lepton number conserving (again with $L=1$) but lepton flavor violating (with a $L_{\mu}=1$, $L_e=0$ state going into a $L_{\mu}=0$, $L_e=1$ state). The decay mode in equation (1.2) has never been observed and has a branching ratio limit of $4.9 \times 10^{-11}$.

One can compare baryon number, lepton number, and lepton flavor to the basic charge of the electromagnetic (EM) field. Electric charge is conserved because of the invariance of the EM field under gauge transformations. When a particle with a given amount of charge is created, other particles with an equal but opposite amount of charge must also be created. In this way, the quantity of charge is analogous to the quantity of flavor or number. On the other hand, the same invariance that leads
to charge conservation also predicts the action of EM fields at a distance and the existence of the photon. If a similar underlying symmetry existed for baryons, for example, we would expect a coupling field associated with baryons and a photon-like baryonic particle. However, no such field has ever been observed and there is no particle analogous to the photon of the EM field for B. L. or Ll [2].

The conservation of baryon number and lepton number implies that matter is only created in conjunction with antimatter. However, our physical universe is composed mostly of matter. The absence of the corresponding antimatter is a major outstanding question in cosmology. CP violation has been known since 1968 to be a necessary condition for generation of the matter/antimatter asymmetry in the early universe [3]. Experiment E832 investigates the amount of direct CP violation in the kaon system through the measurement of $\epsilon'/\epsilon$. Experiment E799II studies a wide range of rare kaon decays, including CP violating, lepton number violating, and lepton flavor violating decays.

1.2 CP Violation

All particles have an intrinsic parity (P) eigenvalue, but only particles which are their own antiparticles are also eigenstates of charge conjugation (C). The $K^0$ and $\bar{K}^0$ particles each have a negative intrinsic parity but individually they are not eigenstates of C. Fortunately eigenstates of C can be formed by taking linear combinations of the two particles. However parity is not conserved in the weak interaction and since
kaons only decay through the weak interaction, the final parity value is undetermined.

Yet the combined operator CP may be conserved so that the final CP state can be determined. C can be defined so that

\[
    C | K^0 \rangle = - | \bar{K}^0 \rangle \quad (1.3)
\]

\[
    C | \bar{K}^0 \rangle = - | K^0 \rangle \quad (1.4)
\]

and then

\[
    CP | K^0 \rangle = + | \bar{K}^0 \rangle \quad (1.5)
\]

\[
    CP | \bar{K}^0 \rangle = + | K^0 \rangle \quad (1.6)
\]

Then the CP eigenstates of \( K^0 \) and \( \bar{K}^0 \) are expressed as \( K_1 \) and \( K_2 \):

\[
    | K_1 \rangle = \frac{1}{\sqrt{2}} [ | K^0 \rangle + | \bar{K}^0 \rangle ]; \quad CP | K_1 \rangle = + | K_1 \rangle \quad (1.7)
\]

\[
    | K_2 \rangle = \frac{1}{\sqrt{2}} [ | K^0 \rangle - | \bar{K}^0 \rangle ]; \quad CP | K_2 \rangle = - | K_2 \rangle \quad (1.8)
\]

However, kaons are generated through the strong interaction as either \( K^0 \) or \( \bar{K}^0 \), so we need to invert equations (1.7) and (1.8):

\[
    | K^0 \rangle = \frac{1}{\sqrt{2}} [ | K_1 \rangle + | K_2 \rangle ] \quad (1.9)
\]

\[
    | \bar{K}^0 \rangle = \frac{1}{\sqrt{2}} [ | K_1 \rangle - | K_2 \rangle ] \quad (1.10)
\]

If CP were conserved, then only the following decays into pions would be seen:

\[
    K_1 \rightarrow 2\pi: \quad CP = +1 \quad (1.11)
\]
with the $K_1$ state having a much shorter lifetime than the $K_2$ state, because of the amount of phase space available to $2\pi$ but not available to $3\pi$. By forcing a kaon beam to travel a relatively long distance, the $K_1$ particles will decay out and leave behind only the $K_2$ state. When this resulting beam is observed, CP conservation would allow only the $3\pi$ decay mode to occur. However, experiments have shown that the $2\pi$ decay mode occurs about 0.2% of the time[4], in violation of CP conservation. Since CP is not conserved, the CP eigenstates are not the same as the mass eigenstates of the kaon system.

A more general formalism using an admixture of the two CP eigenstates must be used to find the mass eigenstates. By diagonalizing the matrix $H = M - i\Gamma / 2$, where $M$ and $\Gamma$ are $2 \times 2$ Hermitian matrices, the mass eigenstates are found to be[5]:

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}[|K_1\rangle + \epsilon|K_2\rangle]$$

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}[|K_2\rangle + \epsilon|K_1\rangle]$$

where $\epsilon$ is given by

$$\epsilon = \frac{\langle K^0 | H | K^0 \rangle - \langle K^0 | H | K^0 \rangle}{i(\Gamma_S - \Gamma_L)/2 - (m_S - m_L)}$$

with $m_{S,L}$ and $\Gamma_{S,L}$ being the eigenvalues of $M$ and $\Gamma$ respectively. In these eigenstates, the parameter $\epsilon$ measures the amount of mixing in the wave functions of the
CP eigenstates \( K_1 \) and \( K_2 \), and is referred to as *indirect* CP violation. \( K_S \) represents a "short-lived kaon" and is the part of the beam which decays quickly. Likewise, \( K_L \) represents a "long-lived kaon" and is the part of the beam investigated in E799II. If \( \varepsilon \) represented the only source of CP violation then the decay-rate ratios

\[
\frac{\Gamma(K_L \rightarrow \pi^0\pi^0)}{\Gamma(K_S \rightarrow \pi^0\pi^0)} = |\eta_{00}|^2
\]

(1.16)

and

\[
\frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^+\pi^-)} = |\eta_{+-}|^2
\]

(1.17)

should be equal. However, the Standard Model permits another source of CP violation in which \( K_L \) decays directly to \( 2\pi^0 \). This source is called *direct* CP violation and is parameterized by \( \varepsilon' \). The parameter \( \varepsilon' \) is related to \( \eta_{00} \) and \( \eta_{+-} \) by[6]:

\[
\eta_{00} \approx \varepsilon - 2\varepsilon'
\]

(1.18)

\[
\eta_{+-} \approx \varepsilon + \varepsilon'
\]

(1.19)

It relates to physically measurable quantities in the following way:

\[
\frac{\Gamma(K_L \rightarrow \pi^0\pi^0)/\Gamma(K_S \rightarrow \pi^0\pi^0)}{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)} = \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 \approx 1 - 6R \varepsilon (\varepsilon'/\varepsilon)
\]

(1.20)

If \( \varepsilon' \) is zero then CP violation only occurs indirectly. If \( \varepsilon' \) is not zero then the ratio of charged decays differs from the ratio of neutral decays by some amount. The value of \( \varepsilon' \) can be calculated from the measured values on the left side of equation (1.20).
Currently the Standard Model predicts a positive value for $\epsilon'/\epsilon$, but the exact value is difficult to calculate.

Experiments at Fermilab (namely experiments E731, E773, and E799 Phase-I (E799I) at the MCenter facility) have studied neutral kaons in fixed target experiments for many years, but the experimental data were not precise enough to obtain satisfactory measurements of the CP violating parameters. Experiment E731 released a value of $7.4 \pm 5.2 \pm 2.9 \times 10^{-4}$ for $Re(\epsilon'/\epsilon)$[7], while competing experiment NA31 (at the CERN laboratory in Switzerland) released a value of $23 \pm 3.4 \pm 6.5 \times 10^{-4}$[8]. Since the results did not agree, it was decided to redo both experiments. The design report for KTeV was proposed and approved in January of 1992, and the KTeV experiment ran from August of 1996 to September of 1997. Results on the $Re(\epsilon'/\epsilon)$ measurement for E832 were released on February 24, 1999. Using 20% of the data, we quoted a value of $28.0 \pm 4.1 \times 10^{-4}$[9]. A paper on the result has recently been published[10]. The remounted effort at CERN was named NA48 and has released a preliminary value of $18.5 \pm 4.5 \pm 5.8 \times 10^{-4}$ [11].

1.3 Rare Kaon Decays

While experiment E832 studied CP violation, experiment E799II studied rare decay modes of $K_L$. Rare decays are modes with a branching ratio of less than 0.1%. The branching ratio of a decay mode is the probability that the particle will undergo that decay, and not any of the other possible ones. The decay modes examined in
the E799II experiment have branching ratios of $10^{-7}$ or less. The focus of this report is a search for the rare decay mode:

$$K_L \rightarrow \pi^0 \mu^\pm \epsilon^{\mp} \quad (\text{called } K_{\pi 0\mu\epsilon}) \quad (1.21)$$

which displays lepton flavor violation. The pion ($\pi^0$), having a very short lifetime (relative to the distance traversed in the detector) will decay almost immediately into a photon pair. Therefore in looking for this event, one would look for a muon ($\mu$), an electron ($\epsilon$), and two photons ($\gamma$) to appear in the detector. If recent evidence for neutrino oscillation is confirmed [12], the Standard Model will need to (and can easily) be modified to allow for the possibility of lepton flavor violation through oscillation (see Figure 1.1). The muon-type neutrino could become an electron-type neutrino and annihilate with the electron-type anti-neutrino also in the system. The annihilation energy would be given as momentum to the remaining particles in the system, allowing the kaon's mass to be fully reconstructed. Evidence for neutrino oscillation has been seen by the Super-Kamiokande experiment in Japan. Those results predict a branching ratio for the $K_{\pi 0\mu\epsilon}$ decay mode on the order of $10^{-21}$ [13]. If this theoretical estimate is correct we have no chance of observing any events as we expect a sensitivity in the range of $10^{-10}$. If we see any signal events in this analysis, they would be clear evidence of new physics beyond the Standard Model. No limit on the $K_{\pi 0\mu\epsilon}$ decay mode is currently listed in the Particle Data Book.
Figure 1.1  The decay $K_L \rightarrow \pi^0 \mu e$, with a possible avenue for Lepton Flavor violation.
and the first limit ever was published in 1997 as $3.1 \times 10^{-9}$ [14]. It is hoped that this study will improve upon that previous result, or that it will be a source of new physics should events be seen.

Since this decay mode occurs so infrequently (if at all), decay modes that might leave a similar signature in the detector must be investigated as well. These modes (called backgrounds) are listed in Table 1.1 and will be discussed in detail in Section 3.4. Briefly, backgrounds can appear to be signal events through a combination of daughter particle decays, neutrinos going through the detector unseen, and/or particle misidentification.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Common name</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L^+ \to \pi^+\pi^0\pi^-\pi^-$</td>
<td>K3pi</td>
<td>12.56 ± 0.20 %</td>
</tr>
<tr>
<td>$K_L^+ \to \pi^+\mu^+\nu_\mu$</td>
<td>Kmu3</td>
<td>27.17 ± 0.25 %</td>
</tr>
<tr>
<td>$K_L^+ \to \pi^+\epsilon^+\nu_\epsilon$</td>
<td>Ke3</td>
<td>26.78 ± 0.27 %</td>
</tr>
<tr>
<td>$K_L^+ \to \pi^0\pi^+\pi^-\pi^0\nu_\epsilon$</td>
<td>Ke4</td>
<td>(5.18 ± 0.29) $\times$ 10^{-5}</td>
</tr>
</tbody>
</table>

**Table 1.1** Background decay modes for $K_L^+ \to \pi^0\mu^+\epsilon^-$ (Branching ratios according to the 1996 PDB).
Chapter 2
Experimental Equipment and Setup

2.1 Beam Acceleration and Structure

Fermi National Accelerator Laboratory (FNAL or Fermilab) is a synchrotron proton accelerator with facilities for both colliding-beam experiments and fixed-target experiments. The beam begins as protons in a bottle of hydrogen gas. The particles are injected into the beam line in a stream and are sent through a Cockroft-Walton accelerator, a linear accelerator, a small booster ring, a main ring, and finally the TeVatron ring (see Figure 2.1). The main ring and TeVatron ring have a radius of one kilometer.

![Diagram of Fermilab Accelerator]

**Figure 2.1** Simplified overhead view of the Fermilab Accelerator.
Acceleration of particles in the main ring and TeVatron is achieved using radio-frequency (RF) accelerating cavities. The RF cavities divide the stream of particles into bunches or "buckets". Like someone pushing a playground merry-go-round, the RF cavities give each bunch a shove as it goes by. Simultaneously the current (and thereby the field strength) of the dipole magnets around the ring is increased to keep the accelerating particles in a curved path. Alternating pairs of quadrupole magnets with the accelerator magnets keeps the protons focused into a beam. Dipole bending magnets allow the beam to be directed in a circle.

One cycle for fixed-target operation mode consists of (a) particle injection and acceleration, (b) a brief storage plateau, (c) a period of beam spillage into the fixed-target experiments’ pipe, and (d) a ramping down of the main ring’s magnet current (see Figure 2.2). A spill (period (c)) is the diversion of a portion of the beam into the switchyard and out to all fixed target experiments (of which KTeV is one) until the beam is exhausted. In experiments E832 and E799II, a spill occurred for 20 seconds per cycle, with one cycle lasting one minute.

The main ring accelerates particles to an energy of $150 GeV$ and the Tevatron takes them to $800 GeV$. Nominal beam intensity for E799II was $5 \times 10^{12}$ particles on target per spill, and we wrote about 15,000 events to tape per spill.
Figure 2.2 Qualitative plot of magnet current and proton beam population in the accelerator over the time period of one cycle. The stages include (a) injection and acceleration: (b) storage; (c) beam delivery to targets; and (d) ramping down of the magnets.

2.2 Detector

KTeV is set up as a "fixed target" experiment, which means elements of the experiment are laid out in a linear fashion with the beam first going through a target and then travelling through a decay region, a spectrometer, and finally a calorimeter. Figure 2.3 shows a plan view of the KTeV detector as set up for E799II running.

2.2.1 Target and Decay Region

The KTeV production target is made of a 30cm length (1.4 interaction lengths) of beryllium-oxide (BeO), where nuclear interactions produce a variety of particles. This target is used as the origin of KTeV's coordinate system. X is measured in the horizontal (east-west) direction, Y is measured in the vertical (up-down) direction, and the beam travels in the positive Z direction. The beam is filtered using a lead filter and sweeping magnets until only neutrons, kaons and neutral hyperons are left. The beam is then collimated into two beams and sent down an evacuated pipe a
Figure 2.3  A plan view of the KTeV detector for E799II running. The target is not shown, but it rests at 0m on the Z-axis.
distance of 99 meters which allows nearly all the $K_S$ particles to decay out of the beam. The beams then travel through a 60 meter evacuated decay region kept at a pressure of $10^{-6}$ Torr. Finally the beams enter the detector hall through a thin window of Kevlar and aluminized Mylar. The highest nominal flux of kaons in each beam for E799II was $2 \times 10^8$ per spill.

### 2.2.2 Regenerator

One of the two beams can be sent through a "regenerator" which produces $K_S$ particles from the $K_L$ particles. The regenerator is an active detector consisting of 1.7 meters of scintillator with a beryllium mask upstream. Through strong interactions of the kaons with the regenerator's nuclear matter, the quantum states of the $K_L$ particles are rotated through the $K_1$ and $K_2$ phase space to regenerate some component of $K_S$ particles. Hence with the regenerator in the beam line, the detector ends up looking at one beam of $K_L$ and one beam of a coherent superposition of $K_S$ and $K_L$. Non-coherent $K_S$ (generated from inelastic events) also occur, but are vetoed by the active regenerator. For experiment ES32, the regenerator can be moved into either of the beams so that location-specific detector errors can be averaged out. For experiment E799II, the regenerator is completely removed from the beam line, as $K_L$ particles are the focus of the rare decay studies.
2.2.3 Spectrometer

Upon entering the experimental hall through the Kevlar/Mylar window, the beams pass through a spectrometer which consists of two pairs of drift chambers separated by a magnet. The spectrometer's purpose is to measure the momentum of all charged particles in the beams. After exiting the decay region through the vacuum window, the beams enter the first pair of drift chambers which measure each charged particle's X-Y location and hence the direction of travel. The particles then travel through the spectrometer magnet in which they pick up a controlled amount of transverse momentum. After the magnet, the beams go through another pair of drift chambers to detect their new position. Since the amount of transverse momentum picked up in the magnet is known, each particle's momentum can be calculated. The spectrometer has a momentum-dependent resolution of $\sigma(P)/P = 0.38\% \div 0.016\% P(\text{GeV}/c)$ [15].

Multi-wire Drift Chambers

The multi-wire drift chambers for the spectrometer were Rice University's major contribution to KTeV. These chambers, also known simply as "drift chambers", are an extension of the simple, single wire proportional counter. A single wire proportional counter is a metallic tube with a wire running down its central axis. The tube is filled with a mixture of gases which readily ionize and it is kept at ground potential while the inner wire is raised to a high positive voltage (usually 2000 to 3000 volts). When
a charged particle passes through the counter, it ionizes the gas mixture. The freed electrons are then attracted to the wire. As they near the wire (where the electric field gradient is the largest), the free electrons are rapidly accelerated and knock additional electrons out of the gas. The result is a large number of free electrons, called an avalanche, being drawn away through the wire and producing a signal (see Figure 2.4).

![Diagram of a single wire proportional counter](image)

**Figure 2.4** Single wire proportional counter (side view).

Multi-wired proportional chambers (MWPCs) work on the same principle, with the single, positive voltage detector wire being replaced by planes of grounded sense wires interspersed with planes of negative voltage cathode wires. The sense and cathode wires are spaced so as to create a uniformly shaped, mappable electric field within the chamber. A signal on a particular wire gives a volume around that wire, called a cell, within which the particle passed. By layering planes of such MWPCs at right angles to each other, the path of a particle can be determined within a range limited by the cell size (see Figure 2.5). Electrostatic limitations do not permit
MWPCs with a sense wire spacing closer than about 1 mm.

Figure 2.5 An end-on view of a multiwire proportional counter (MWPC). The black circles are cathode wires and the white circles are sense wires.

To produce an even more precise positioning of the particle track, one must move on to drift chambers. Drift chambers and MWPCs are physically constructed very similarly. However, the sense wire planes of a drift chamber are usually offset from each other by one half of a cell width, creating a much smaller and better defined cell volume around each sense wire than in the MWPC. This also removes the ambiguity as to which side of the wire the particle passed by. The other major difference is the gas used to fill the chamber. In regular MWPCs, one wants to receive a signal of the particle's passage as quickly as possible. It is therefore advantageous to accelerate the electrons all the way to the sense wire. The terminal velocity of the electron should be high enough that it is never reached, and response time is not lost.
the gas. In drift chambers, the mix of gasses is selected so that the gas limits the velocity of the electrons. The strong electrical field ensures that the electron will reach terminal velocity quickly, but the gas ensures it will travel at that constant velocity the majority of the distance to the sense wire. Drift gases are characterized by their electron terminal velocity, and so given an initial time (provided by other parts of the detector), the point of origin of the electron shower can be calculated very accurately.

The drift chambers in use in the KTeV E832 and E799II experiments range in size from \((1.251m \times 1.251m)\) to \((1.759m \times 1.759m)\). There are four chambers (DC1-4) numbered in order of increasing \(Z\). Each contains two layers (or "views") of sense wires in the \(X\)-plane (\(X\) and \(X'\)), and two layers in the \(Y\)-plane (\(Y\) and \(Y'\)) with layers offset in a hexagonal cell geometry of radius \(0.635cm\). Figure 2.6 shows an end-view of the wire layout for one plane, and Figure 2.7 shows the electric field generated by one plane. The cathode wires are gold-plated aluminum with a diameter of 100 microns, and the sense wires are gold-plated tungsten with a diameter of 25 microns. The wires are placed in a "pac-man" system (see Figure 2.8) to ensure the accuracy of the wire's position in the center of the input location. The gas in the chambers is 50% argon with 50% ethane as the quenching gas. This mixture is bubbled through isopropyl at \(0^\circ C\) on its way into the chamber to prevent polymerization of the gas on the cathode wires. Each chamber can measure the location of a particle to within 100 microns.
Figure 2.6  End-on view of wire layout for one plane of the drift chambers. The black circles are cathode wires and the white circles are sense wires.

Figure 2.7  Contour diagram of the electric field generated by one view of the KTeV drift chamber wires.
The analog signals from the chambers are recorded by time to digital converters (TDCs) with a resolution of 0.5 nanoseconds. The data-taking time window is set at the maximum drift time of 150 nanoseconds and an exemplary drift-time distribution is shown in Figure 2.9. The sense wire is represented by the sharp drop-off around 650 counts with each X-axis count equalling the TDC resolution of 0.5\textit{nsec}. The background band comes from out-of-time hits.

**Spectrometer Magnet**

The magnet gives charged particles a momentum "kick" (nominally \(400 \frac{MeV}{c}\) for E832 and \(200 \frac{MeV}{c}\) for E799II) perpendicular to their direction of travel. This bending of a charged particle's path allows measurement of the momentum and charge of a particle. The magnet consists of an iron yoke with "race-track" copper coils wrapped around the rectangular poles [16]. The operational aperture of the magnet is \((2m \times 2m)\) and the field integral uniformity is \(\pm 5\%\) over the aperture.
Figure 2.9  Exemplary drift-time distribution (histogram) for one of the drift chambers in KTeV (run #9225). Each count on the X-axis is 0.5nsec. Signals occurring right on top of the sense wire form the sharp drop-off near 650 counts. The background is from out-of-time signals.
Photon Vetos

If not all of the particles from an event are contained within the active part of the spectrometer, then information about the decay will be lost. To prevent partial information from wasting detector readout time or tape space, ring veto counters are placed along the decay region and around the spectrometer apertures. There are 5 ring counters (RC6-RC10) around the evacuated decay region whose outer circular edges vary from 0.75m to 1.2m in radius. The inner boundaries are rectangular and sized so that the veto counters will not interfere with the active regions of the spectrometer. Three more veto counters, called spectrometer anti's (SA2-SA4), surround each of the second, third, and fourth drift chambers. A fourth spectrometer anti, known also as the Cesium Iodide Anti (CIA) surrounds the operational aperture just in front of the calorimeter. Both the inner and outer boundaries of these counters are rectangular with the inner aperture being the same dimensions as the active region of the corresponding drift chamber or calorimeter.

The veto counters are all constructed of a lead and scintillator sandwich structure with a single photon veto inefficiency better than $10^{-4}$ including both counter performance and gaps in the physical geometry. While this veto system does not completely cover all possible escape paths of decay particles, it does either hermetically cover kaon decays with an angular region of less than 80 milliradians, or it forces the decay into a kinematically unfavored state that can be cut by software logic. All
numbers cited about system inefficiency and coverage were determined by computer
simulation[16].

2.2.4 Trigger Counters V and V'

For triggering purposes, KTeV uses two planes of hodoscopes (V and V') consisting
of 32 counters each. Each counter is (13cm wide × 1.10m tall × 5mm thick) and they
are arranged to cover a cross-section of (2m × 2m). The counters are arranged in two
rows (one above the other) of 16 counters each, with a seam running horizontally at
the midplane of the detector and allowing for gaps around the neutral beams in the
center. To ensure complete geometric coverage, one hodoscope is offset 5cm vertically
and 6.5cm horizontally from the other. These hodoscopes serve as the primary triggers
and timing reference for the entire detector. V and V' are located after the fourth
drift chamber and 1.5m upstream of the calorimeter.

2.2.5 CsI Calorimeter

After the spectrometer, the particles pass into a cesium iodide (CsI) electromagnetic
calorimeter so that the energies of the photons and electrons can be measured.
Calorimeters serve the purpose of "energy collectors". A calorimeter is made up of
blocks of dense, light conducting material which both produces a photon cascade and
channels it to the photo tube collectors. Blocks of CsI crystal were chosen instead of
the previously-used lead glass because of their excellent energy resolution and radia-
tion resistance. Lead glass provides an energy resolution of \((\Delta E)/E = (3\%)/\sqrt{E}\) while the KTeV experiments require a resolution of better than \((1\%)/\sqrt{E}\). Tests with CsI have shown it is a good selection since experimental energy resolution for electrons has reached \((0.5\%)/\sqrt{E}\) for blocks 50\(cm\) long, like those used in the KTeV detector. Even given the resistance of CsI to radiation damage, allowance was made in the center of the calorimeter for the majority of the beam debris (a barrage of neutrons and undecayed kaons) to miss the calorimeter and instead be absorbed by the steel wall behind it (see Figure 2.10). The holes are each \((15cm \times 15cm)\) and are separated by 15\(cm\) [16]. The blocks in the middle of the calorimeter number 2.232 and measure \((2.5cm \times 2.5cm \times 50cm)\), while the 868 blocks around the outside measure \((5cm \times 5cm \times 50cm)\). Total number of blocks is 3.100. The lateral dimensions of the blocks were chosen to balance the spatial resolution of the calorimeter with its construction cost. Data readout for the calorimeter is done in 34 slices of 20 nanoseconds each, although only 4 or 6 slices (including one pre-slice) are saved to tape per event. A pre-slice is the information taken just before the event should have reached the CsI according to the trigger hodoscope timing and chamber hits.

Most of the energy deposited in the calorimeter comes from photons and electrons. The two dominant processes for energy loss by electrons and photons are bremsstrahlung radiation and pair production, respectively. Bremsstrahlung radiation involves momentum loss via photon production as the electron travels through
Figure 2.10  Sketch of the CsI electromagnetic calorimeter showing approximate size [16]. The actual calorimeter has one fewer row of crystals around the outside. The two holes in the center allow undecayed beam to pass through the calorimeter without damaging the crystals.
dense material. In pair production a photon decays into a pair of electrons. The combined result of these processes is a cone of energy distribution (see Figure 2.11) with a Molier radius of 3.8 cm for CsI. The Molier radius is the lateral radius around the center of the energy distribution which contains 90% of the energy deposited. The distance that an electron travels before its energy drops to $\frac{1}{e}$ of its original value.

Figure 2.11  Energy deposition of an electron in lead glass. Note that the KTeV calorimeter is cesium iodide, not lead glass, but the energy deposition profile is essentially the same. The horizontal axes are in cm and the vertical axis is in MeV. Direction of propagation is left to right. [17].
is called a radiation length, and is characteristic of the material through which the electron travels. The same length multiplied by 1.3 gives the distance in the material over which the number of photons surviving the journey is $1/e$ of the original number. In short, an electron or photon will lose all of its energy upon traversing just a few radiation lengths. A 50 cm long piece of CsI contains 27 radiation lengths. This ensures that all of the electrons and photons in an event will deposit all of their energy in the calorimeter. Total energy combined with the energy distribution pattern gives a unique and identifiable electron/photon signature. The lower two clusters of energy in Figure 2.12 show a typical electron/photon signature as detected by KTeV's CsI calorimeter.

In contrast, all other particles in an event, namely pions and muons, often deposit only a minimal amount of energy in the calorimeter. These particles do not radiate like electrons, but do ionize the atoms of the material. Pions (which are hadrons) can also interact strongly with nuclei in the material. Thus the counterpart to the radiation length for leptons is an interaction length for hadrons, which is defined as the average distance a particle travels before interacting with a nucleus. The probability of collision with a nucleus is so small that interaction lengths are generally much longer than radiation lengths. In this case, the interaction lengths for all particles are greater than the 50 cm length of the crystals. A hadron can interact strongly to produce an energy shower, but it will typically not deposit all of its energy in less than
Figure 2.12  Energy deposition in the KTeV CsI calorimeter. The deposition signatures shown here could come from four kinds of particles. On the upper left is a cluster characteristic of a muon or minimum ionizing pion. The upper right cluster is characteristic of a strongly-interacting pion. The two lower signatures are characteristic of an electron or a photon (photon in this case). This is a real $K_L \rightarrow \pi^+\pi^-\pi^0$ (K3pi) data event.
an interaction length. Figure 2.13 shows the profile of energy deposition of a pion in lead glass. Note the distance traveled by the pion, during which it leaves a trail of minimum ionization, before interaction occurs (especially as compared to the scale of Figure 2.11). After the first interaction, note the linear tracks of debris knocked

![Figure 2.13](image-url)  

**Figure 2.13** Energy deposition of a pion in lead glass. Note that the KTeV calorimeter is cesium iodide, not lead glass, but the energy deposition profile is essentially the same. Compare the scales of both energy deposited and distance traveled to those of the electron of Figure 2.11. The pion only minimum ionizes for the first 20 cm. After that, note the uneven peaks and rays of deposition from nuclear interaction debris that are perpendicular to the original direction of travel. As in Figure 2.11, units are (MeV/cm^2) and propagation is left to right [17].
perpendicularly out of the nuclei. When this deposition profile is translated to CsI, a range of patterns can be seen. Figure 2.12 shows an example of energy deposition of charged pions in CsI. In the upper left cluster, the pion has left only a trail of minimum ionization in one crystal. In the upper right cluster, a pion's strong interaction with a nucleus is visible as ray-like protrusions of debris coming off of the center cluster of energy. Finally, the pion can sometimes deposit energy in a fairly even pattern, mimicking the signature of an electron or photon (the lower two clusters). Muons interact only electromagnetically and because of their relatively large mass they do not bremsstrahlung. Hence their only mechanism of energy deposition in the CsI crystal is minimum ionization, as seen in the upper left cluster of Figure 2.12. Very rarely the energy deposition from a muon can be wide enough that it looks like a photon or electron cluster.

In order to distinguish between real electrons and a faking pion or muon, the parameter E/p (energy deposited in the CsI divided by the momentum of the charged track) is used. This parameter is described more thoroughly in Section 3.3.

2.2.6 Collar-Anti and Back-Anti

The Collar-Anti (CA) and Back-Anti (BA) are additional veto detectors placed directly in front of and behind the calorimeter, respectively. The CA is similar to the RCs and SAs in that it is ring-shaped and lies along a boundary between the active and inactive parts of the detector. It covers the inside edge of the beam holes and
is used to veto events with particles that would just scrape the calorimeter crystals around the beam holes. The BA fills the beam holes behind the calorimeter and completely contains the undecayed neutral beams laterally. It has a cross section of \(24\text{cm} \times 60\text{cm}\) and is divided into two longitudinal sections: an upstream electromagnetic (EM) section and a downstream hadronic section. The EM section is a stack of lead and scintillator 30 radiation lengths deep in 30 layers. Each scintillator layer is 0.5\text{cm} thick. The hadronic section is 8 layers of lead and 1\text{cm} thick scintillator combining for 5 interaction lengths. The total depth is about 1.2\text{m} [16].

The CA is applied as a veto in most trigger settings. While the BA is used as a veto in some triggers, it was not applied in the trigger configuration used in this analysis. However, BA information was considered during off-line analysis.

2.2.7 Muon Counters

Downstream of the Back-Anti is a muon filter consisting of approximately 10\text{cm} of lead and 5\text{m} of steel. This filter serves as a beam dump for the neutral beam, and will also stop most charged particles. Only muons should be able to make it past the lead and steel into the following muon counter banks. The muon counter banks are three scintillator detectors labeled Mu2, Mu3X, and Mu3Y. Each detector has 15\text{cm} wide paddles that are 1.5\text{m} in length. Mu2 has 56 scintillators segmented along the X-axis so that the paddles stand vertically in two rows of 28 each. Mu3X has 40 scintillators also segmented along the X-axis in two rows of 20. Mu3Y has 40
scintillators segmented along the Y-axis in two stacks of 20.

2.3 Triggers

The most common type of decays are often not wanted and need to be kept out of the stored data set. Also, events in the detector occur so quickly and frequently that unwanted or "faking" (that look like the desired $K_L$ or $K_S$ decays but are not) events happen very often. The multitude of data sent by the detector components pass through at least four levels of triggers before being saved to tape.

2.3.1 Hardware Triggers

The first three trigger levels (levels 0 through 2) are implemented entirely by hardware logic modules, some of which are located below ground in the experimental hall and the rest of which are located in a ground-floor counting room.

Level 0

Trigger level 0's digital and analog electronics are all physically housed in the downstairs KTeV experimental hall. Multiple copies of the analog signals from each detector are made with at least one copy being sent to the upstairs counting room for recording purposes. The general purpose of level 0 trigger logic is to take the analog signals, discriminate them, and provide at least one level 1 source signal per piece of detector equipment.

The simplest logic is performed on the HA and the MU banks. Analog signals are
simply summed by section and discriminated to generate level 1 source signals. For
the photon veto detectors (MA, RC, SA, CIA) the analog signals from modules which
might share energy are linearly summed, the results discriminated, and a logical OR
taken on a detector-by-detector basis (e.g. there are 5 level 1 source signals for the
RC's, one for each of RC6 though RC10).

Only drift chambers 1 and 2 are used in the level 0 trigger. At this stage each
chamber is represented as a collection of "paddles" that are eight sense wires wide
(10.16 cm) and contain 16 wires each, eight from the unprimed view and the corre-
spending eight from the primed view of the same dimension (see Section 2.2.3 for
the definition of the chamber views). If one of these "paddles" is hit, a 90 nsec NIM
output pulse is produced. The outputs of a plane are then discriminated to search for
a combination of "in-time" hits, with "in-time" being defined as having a TDC value
between 400 and 650 nsecs as in Figure 2.9. This custom discriminator gives outputs
for number of hits greater than 0, 1, 2, and 3, for a total of four level 1 source signals
per chamber.

The most complicated level 0 logic involves the calorimeter and the trigger ho-
doscopes. Four different threshold signals for the calorimeter's total energy sum
are sent as level 1 source signals. In addition, two threshold signals are generated
per calorimeter quadrant's energy total. Signals from individual trigger hodoscope
paddles are sent to a "look-up table" module which distinguishes between hit com-
binations that indicate a valid decay in the detector and hit combinations which are unphysical.

**Level 1**

The level 1 trigger is designed to be fast, but where possible it requires coincidence with the beam’s RF spill signal which leads to a 50% duty factor. Using the RF signal, coincidence is made between the trigger hodoscopes and the calorimeter at this level. The drift chambers are not synchronized with the RF signal because of their long drift time. The level 1 source signals are divided into 24 groups of 8 and each group sent to a look-up table. Each look-up table produces an 8-bit output word. These outputs are compared in two groups of 12 to produce two 8-bit words. The 8-bit words are combined into one 16-bit word that is called the “Level 1 Trigger Mask”. Fifteen of those bits tell which of the fifteen different kinds of triggers were satisfied during a particular bucket. The sixteenth bit tells if the other fifteen are “beam triggers” or “calibration triggers” and determines how they are handled by the level 2 system. “Calibration triggers” are used to test various detector components or to test trigger hardware and are always accepted. “Beam triggers” contain the physics information during normal operating conditions and go through the entire gambit of acceptance decisions. The trigger mask bits are ORed with each other and with a “busy with previous bucket” from level 2 to generate the level 1 trigger signal (level 2 source signal).
Level 2

The level 2 trigger consists of trigger processing, trigger control, and readout control. The trigger processing section receives a trigger mask from level 1 and receives data from the level 2 processors. It then either generates a level 2 trigger mask or aborts the event. The trigger control section vetos the level 1 signal if there is a BUSY signal coming from the level 2 processors or from level 3. The readout control section creates the necessary control signals for reading data from an accepted event into level 3.

Dead time first enters at the level 2 trigger, as the acceptance decision rate drops from hundreds of kiloHertz to ten kiloHertz. The main processors at this level are in five groups. Processors in the first group are nicknamed “bananas” and “kumquats” and count the number of hits in the drift chamber signals. Second is the hardware cluster counter or HCC. The third group does y-track finding in the drift chambers, while the fourth and fifth groups generate information for the stiff-track and TRD triggers. Since the trigger for this analysis (Trigger 7) just uses information from the HCC and bananas and kumquats, only they are described in detail here.

Calorimeter energy clusters are classified as either “hardware” (hard) clusters or “software” (soft) clusters. To qualify as a hard cluster, the energy pattern must be identifiable by the Hardware Cluster Counter (HCC) logic here at trigger level 2, or in other words it must be identifiable by KTeV’s hardware. A soft cluster is an
energy pattern that is missed by the HCC, but which, with software calculations and corrections, could be resolved. The HCC deals with 3.100 bits of information, one signal for each calorimeter crystal being above (on) or below (off) a preset threshold (nominally 1GeV). The HCC also has strict timing requirements that the bit signals be accepted only during the event's in-time trigger window. A Column Alignment Buffer (CAB) recreates the crystals' stacking pattern and a Cluster Counter Unit (CCU) outputs the number of clusters it found as either 0, 1, 2, 3, 4, 5, 6, 7, or 8 or more. This output is the number of hardware clusters.

Also done at level 2 is the analysis of the hits in each view of the drift chambers by processors known as "bananas" and "kumquats". The banana processors are so named because of the shape of the time distribution plot they produce. It has since become a tradition to name all parts of the same processing system after fruit. The total number of hits is given a value of 0, 1, 2, 3, 4, 5, 6, or 7 or more per view. The logic for a "hit" is such that signals on isolated wires count as one "hit" and signals on N adjacent wires count as N-1 "hits." This way a pair of adjacent wires that give a signal only count as one "hit."

Due to the multiple processors running in parallel, there is a level 2 controller to assure the processes integrate smoothly. The level 2 controller receives as input the level 2 trigger mask (beam or calibration), signals from each level 2 processor, a BUSY signal from some of the electronics, a RESET signal from the data acquisition
system (level 3), and Almost Full signals from level 3 processors. If the trigger mask from level 1 is a “calibration trigger”, then the resulting level 2 mask is identical. If the mask is a “beam trigger”, then the level 2 output mask is the logical AND of the level 1 beam trigger and the triggers which pass the level 2 processors. In addition to the trigger mask, the readout control section of level 2 generates a sparsification mask that tells level 3 what data is to be read out and to which level 3 processors each type of information is to be sent.

2.3.2 Software Triggers

Level 3 is where the trigger logic moves from hardware to software. The final decision of whether the event gets written to tape or not is made at this level. The data is sent through software which attempts to trace charged particle tracks in the drift chambers, identify corresponding energy deposition clusters in the calorimeter, and assign a particle type to each coherent trace. Please see Section 2.4.2 for a more complete description of the level 3 trigger.

2.4 Software

As KTeV was going through the planning stages, collaborators wrote and adapted code (mostly from E731, a previous direct CP violation search at Fermilab) for detector simulation, on-line triggers, and off-line event analysis. A Monte Carlo program was needed that would simulate a particle traveling through various parts of the de-
tector and how those components would react and/or effect the particle. An analyzing program was also needed to look at both the results of the Monte Carlo program and the results from the run itself. The end product was the programs KTeVMC and KTeVAna.

2.4.1 Monte Carlo simulation program (KTeVMC)

The Monte Carlo (MC) code was written in FORTRAN and makes use of a histogram booking package called HBook. It contains detailed information about the structure of the experimental setup and requires an input file containing information on what type of decay to simulate. The program then steps each particle through the length of the detector, decides what happens to each particle at each point, and records the detectors' reactions at each point.

Since events can happen as frequently as 20 nanoseconds apart, an event other than the desired event may deposit information in the detector. Hence one of the settings in the Monte Carlo program can overlay this extraneous information, called "accidentals", on the clean event data. The accidental events themselves are collected from data using an accidental trigger (Trigger #14). Output from the program includes both a data output file which resembles raw data, and a text output to the screen of the steps and their results as they are completed. The text output can be re-routed into a log file and used as a quick reference for that simulation. The data in the output file is in the same format as data taken during the actual run, so both
can be used as input for the analysis program KTeVA.

2.4.2 Online software triggers (Level 3 trigger)

Early versions of the analysis program were the proto-type for level 3 triggers in the real experiment. All user interface with the trigger is done at this level. Code for many of the basic routines were written by various collaborators or adopted from older experiments and put into a shared library.

The level 3 software is in charge of attempting a preliminary event reconstruction. It searches for charged tracks in the spectrometer and combines this with calorimeter information from the level 2 Hardware Cluster Counter (HCC). Matches are made between a charged track and the nearest calorimeter cluster that it points to. As stated before, the HCC timing considerations assure that a hard cluster is in the same bucket as the triggering event, while a soft cluster has no such requirement. Hence all of our signal particles that would leave more than 1GeV in the calorimeter, namely photons and electrons, should each have a matching hard cluster in the corresponding trigger to ensure they are part of a single kaon decay event. Electrons should also have a matching charged track. For event muons, since they deposit little energy in the calorimeter, the only requirement is that the charged track match to any kind of cluster, hard or soft, as determined offline. Charged pions look like electrons to the level 3 trigger since they deposit hard clusters most of the time and have an associated track. The level 3 software also decides which triggers are enabled for the current
running configuration, and sends control signals to the level 2 hardware about when and where data is to be written to tape.

There can be up to sixteen different trigger logics online as supplied by level 2. Table 2.1 contains the trigger numbers and a brief description of each beam trigger used in E799II data taking. The trigger logic for the signal mode $K_L \rightarrow \pi^0 \mu e$ (Kpiome) is called “Trigger 7” or the “EMU trigger”. Trigger 2 events were used as a source of normalization.

Since this analysis uses Trigger 2 and Trigger 7, their requirements are described in more detail here. The more complicated of the two triggers is Trigger 7 and its acceptance is determined by the logical OR of the following requirements:

- simple begin readout signal [GATE]
- 2 hits (allowing for one lost hit) in VV' [2V]
- ETOT value from the calorimeter passes the next to lowest threshold (= 18GeV) [ET.DTHR]
- at least 1 hit in (X or Y of) both DC1 and DC2 [DC12]
- no HA veto (threshold = 7 MIPs) [HA.DC]
- 1 or more hits in both X and Y views of MU3 [MU3]
- no photon vetos (in RCs or SAs, including SA3) [PHVBAR1]
- no CA veto ![CA]
- “loose” 2 hits for all DC Y-views (allows 1 lost hit in DC1 or DC2) [2HCV_LOOSE]
- 3 or more clusters in the calorimeter (hardware) [HCC.GE3]

In sum, as stated in Table 2.1, the trigger for our signal event has 2 charged tracks, 3 or more hardware clusters, and 1 or more hits in the muon detector banks. Trigger 2 is much looser, requiring only the logical OR of the GATE, 2V, DC12, and
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<td>4 tracks</td>
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<td>5+ clusters: no HA, CA or photon vetos</td>
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**Table 2.1** The various beam triggers used in experiment 799II for data taking, and a short description of each. A number with a plus sign (+) after it indicates a value greater than or equal to that number. "Tracks" refers to charged tracks in the spectrometer and a "hole track" is a track that projects to one of the beam holes in the calorimeter. "Clusters" refers to hardware clusters in the calorimeter. Unless stated otherwise, each trigger also has an in-time gate requirement.
2HCY_LOOSE. plus at least 2 hits in any chamber’s X-view and any kind of activity in the calorimeter.

2.4.3 Analysis Program (KTeVAna)

The data output files from KTeVMC and real data are used as input for the KTeVAna analysis program. KTeVAna produces a file of histograms written in the HBook format as well as a “mini” data file or ntuple. These two types of files are readable by a program called the Physics Analysis Workstation (PAW) which allows additional cutting and displaying of the event data. KTeVAna can also produce a file of events which passed the analysis that is written in the same format as the input data file, and also a text output to the screen of the steps taken and their results. Again, the text output can be re-directed into a file and used as a quick reference to an analysis. Please see Section 3.3 for a detailed description of the steps taken in the KTeVAna program to examine the $K_L \rightarrow \pi^0 \mu e$ (Kpi0me) decay.

Event display program “kdisp”

A program called “kdisp” can read in a raw data file and display specific events in the format shown in Figure 2.14. This event happens to be a Kpi0me MC event. Kdisp does enough analysis to identify tracks in the drift chambers, match them to clusters of energy deposition in the calorimeter, and find a preliminary decay vertex. The tracks and clusters are listed numerically (under “Track and Cluster Info” in the
figure), both are projected onto the two-dimensional image of the calorimeter, and the tracks are overlaid on a side and top view of the entire detector. Only two of the four tracks in the lower two plots of Figure 2.14 (solid lines) were actually detected in the drift chambers. The straight tracks (dashed lines) are drawn from clusters not having corresponding tracks to the projected charged vertex of the event and are assumed to be photons.
Figure 2.14  Example event (Kpi0me MC) display using “kdisp”.
Chapter 3
Analysis

After data was collected using the “Trigger 7” online requirements (see Section 2.4.2), three levels of analysis were done. The parameter cuts for the first two levels were relatively loose. Their purpose was to shrink the number of events down to a manageable size. The first level of cuts was to crunch down the amount of data from 18 DLT tapes to three DLT tapes, and hence will be called the crunch cuts. The second level of cuts will be called ntuple cuts because they were made in going from the raw data to filling a PAW ntuple. The third level of cuts were made upon events that reached the ntuple level and consisted of applying a selection file within PAW. Hence this level of cuts will be called selection cuts. Details of each level are given below.

It is important to emphasize that we have performed a “blind analysis” (see Section 3.2) on the data using Monte Carlo (MC) simulations of both the signal decay and four kinds of background decays. It was hoped to reproduce the characteristics of the data with a proportional combination of the background decays so that any discrepancies would clearly show the presence of a signal.

Over time since the end of the 1996-1997 run, there have been periodic updates of the calibration constants used to attune the MC detector simulation to the real
detector, and the MC software itself has been updated as real-time quirks of the detector are discovered. The plots presented and numbers quoted here were generated using the standard program version of KTeVMC and KTeVAna (Version 4.11) and the database as of October 1, 1998, unless otherwise noted.

3.1 Analysis Strategy

Since the objective for this study is the search for $K_L \rightarrow \pi^0 \mu^+ \mu^-$ (Kpi0me), cuts were optimised to find a well-reconstructed Kpi0me decay. Requirements were made on the quality of the data so that all the information needed for a full reconstruction was present. A Kpi0me decay would leave two charged tracks in the spectrometer (the muon and the electron) and a pattern of four or more clusters in the calorimeter (see Figure 2.14). The two tracks are each required to match to a cluster in the calorimeter and have a momentum greater than $7 GeV$ so that the track is stiff enough to have the opportunity to reach the muon banks without excessive multiple scattering. Three of the clusters must be "hardware" clusters (see Section 2.4.2) indicating they were from in-time electrons or photons. Since the electron should deposit most of its energy in the calorimeter, one of the hardware clusters must match to a charged track. The cluster for the muon will be a "software" cluster since it is expected to minimum ionize and deposit less than $1 GeV$ of energy ($1 GeV$ is the hardware cluster threshold). Particle identification is done by selecting the cluster/track combination with the greater cluster energy as being the electron and the other combination as
being the muon. Additional kinematic variables are then used to double check that the tagged electron really behaves like an electron, and that the tagged muon really behaves like a muon. The two charged tracks are used to calculate the decay vertex of the event, which must lie inside the evacuated decay region. Additional quality cuts are made on the charged tracks and the vertex.

Two clusters in the calorimeter not corresponding to charged tracks are assumed to be photons from the immediate decay of the neutral pion. Using the vertex found from the charged tracks, the two photons are reconstructed as having come from one particle decaying at that vertex and that particle’s mass is checked against the mass of a neutral pion. If there are more than two clusters not matching to charged tracks, then the combination that results in a mass closest to the neutral pion mass is selected. Eventually the energies and momenta of all four particles are combined to find an originating particle rest mass that hopefully agrees with the mass of the neutral kaon (see Figures 3.1-3.3). The acceptance for simulated signal events is 4.77±0.03%.

3.2 Blind Analysis

The availability of KTeVMC code allowed the majority of the analysis to be done using Monte Carlo (MC) generated signal and background events. Doing so meant that a “blind analysis” could be done with a high level of confidence because detailed comparisons could be made between the MC events and the data events. A blind
Figure 3.1  Signal Monte Carlo (MC) events that pass all cuts except those on the kaon mass \((m_K)\), on the x-axis in \(\text{GeV}\) and the transverse momentum squared \((p_T^2)\), on the y-axis in \((\text{GeV}^2)\). Events that also pass the \(m_K\) and \(p_T^2\) (i.e. are inside the red "box") number 4,771 and give a signal acceptance of 4.77\(\pm\)0.03\%. 
Figure 3.2  A histogram of the mass of the kaon \((m_K)\) for signal MC events which passed all cuts for the "one day". This is a projection onto the X-axis of Figure 3.1. The nominal kaon mass is 0.49767\(GeV\). To be within the signal region, events must have \(m_K\) greater than 0.48767\(GeV\) and less than 0.50767\(GeV\), a deviation of 10\(MeV\).
Figure 3.3  A histogram of the square of the transverse momentum ($p_T^2$) for signal MC events which passed all cuts for the "one day". This is a projection onto the Y-axis of Figure 3.1. Ideally this value should be near zero. To be within the signal region, events must have $p_T^2$ less than $0.00025 \frac{GeV^{2}}{c^{4}}$. 
analysis is one in which the majority of the study is done using a data set from which possible signal events have been removed. The advantage of such an analysis is that the experimenter is prevented from artificially biasing the results since one does not see potential signal events until after the cuts are determined. A signal region is defined by putting tight limits on a few parameters so that any events falling within those limits is believed to be a valid signal event. Since a signal region is most often defined by exactly two parameters, it is commonly referred to as the signal box or simply the box. Typical parameters for defining the signal box include the originating particle’s mass, the originating particle’s transverse momentum, the mass of a daughter (or intermediate decay) particle, and the originating particle’s lifetime. The signal box for this analysis is defined by cuts on the originating particle’s mass and its transverse momentum squared (see the red outline in Figure 3.1). Any events in the experimental data that fall within the box are masked out of the data set while the analysis evolves. In plots of the data the signal box is blackened in, or closed. For MC event sets it is already known what kind of events are present and so keeping the box closed is unnecessary. Once the analysis process and all cut values are finalized using MC to data comparisons, the experimental data set is analyzed one last time with no event masking, the box is opened, and the results interpreted.
3.3 Analysis Parameters

Even before the data was collected, a list of possible parameters for the signal was created. Preliminary cutoff values for each parameter were decided upon based on past knowledge and theoretical predictions. The effectiveness of each parameter cut was examined individually and most of the remaining analysis was done concentrating on using those cuts which favored the signal and disfavored the backgrounds.

3.3.1 Crunch cuts

The intention of the crunch level of cuts was to eliminate badly-recorded events and events that had no chance of reconstructing to a decent Kpi0me. Most of these cuts have to do with analysis routines returning to the main program in an error state, plus a few very basic characteristic or kinematic requirements.

An event was rejected at this level if any of the following were true:

- KTSPILL was bad
- GET_VETO returned in error
- KTCLUS returned in error
- T3MATCH returned in error
- KTTDC returned in error
- T3MASS returned in error
- T3FPI0 returned in error
- num. of clusters, hard or soft. < 4
- num. hard clusters < 3 or > 6
- num. prelim tracks < 2
- no vertex candidate
- Z vertex not between target (0m) and vacuum window (165m)
- \( m_{\pi^0} < 110 \text{MeV} \) or > 160 MeV
- \( \frac{E_{Z}}{p_{Z}} < 0.25 \) or > 1.75
\[ p_T^2 > 0.05 \text{GeV}^2 \]

The variables that are in all capital letters represent subroutines within the KTeVAna program and will be discussed in separate subsections below. The other variables listed above are discussed here.

Clusters are defined as described in Section 2.4.2 with hard(ware) clusters being energy deposits found online with more than 1 GeV of energy and being in-time with the event trigger. Soft(ware) clusters are found offline with looser energy requirements and no timing requirement. The two photons and one electron from the signal decay should create hard clusters with the looser cuts allowing extra clusters from accidentals to be present for a total of up to six clusters at this level. With the signal muon creating a soft cluster, a minimum total (hard or soft) cluster number of four is required.

A rough track-finding routine looks for preliminary tracks with loose requirements. If the event has any chance of being reconstructed well as a signal event, at least two charged tracks should be found in the spectrometer at this level. Later in the analysis program a more exhaustive, CPU intensive track search is done. The preliminary track finding routine is intended to save this processing time by cutting events that obviously have fewer than two tracks.

The segments of the two tracks which are upstream of the analysis magnet are projected back towards the target. If they come reasonably close to meeting at a
point, then that point is chosen as the vertex for the decay of the parent particle. Otherwise the event is cut. Using this charged track vertex, calorimeter hardware clusters unmatched to tracks are combined in pairs and are reconstructed as having come from the vertex. Assuming these clusters are from the decay of the neutral pion, the pair which best reconstructs to the mass of the neutral pion \((m_{\pi^0})\) are tagged. There is then an additional wide quality cut on the pion mass from \(110 Me\)\(V\) and \(160 Me\)\(V\) \((m_{\pi^0} \approx 135 Me\)\(V\)).

As discussed in Section 3.1, one of the charged tracks must match to a cluster containing less than \(1 Ge\)\(V\) of energy. Such a track/cluster combination is assumed (and tagged) to be a muon since it is the particle most likely to minimum ionize in the CsI and we want a muon present in our decay. The other charged track/cluster combination is tagged to be an electron. For each of the track/cluster combinations, the ratio is taken of the energy deposited in the calorimeter over the momentum of the associated track \((\frac{E}{p})\). If the \(\frac{E}{p}\) of the tagged electron \((\frac{E_e}{p_e})\) is less than 0.25 or greater than 1.75, then it probably is not an electron and the event is cut. Using the vertex found, the decay particles are combined into a parent particle and the parent particle's mass, forward momentum, and transverse momentum are calculated. If the parent particle is a kaon from within the beam then nearly all of its momentum should be in the forward direction. Hence if the squared transverse momentum \((p_T^2)\) of the parent particle is calculated to be above a loose requirement of 0.05 \((\frac{GeV}{c})^2\) at
this level, then its reconstruction as a Kπ0me is unreasonable and the event is cut.

**KTSPILL error**

Ideally, once an experiment is running it should be able to continually take good quality data. Real life is never ideal. Occasionally various data-taking systems would write out garbage or simply fail. A routine called **KTSPILL** was written to look for information about how well each system was working. We cut events which did not have good information taken in the following systems:

**Triggers** - If the trigger hodoscopes were not working correctly, all the timing information about an event becomes suspect. Timing information is critical in determining if the particles detected were from the same event.

**Pipeline** - This system was responsible for holding information from the calorimeter while the software analysis package decided to keep the event or throw it away. Problems here indicate lost or misplaced calorimeter information.

**Global CsI** - Since the calorimeter is an essential part of measuring the energy of particles, events where there was a problem with the calorimeter's hardware systems should be cut.

**ETOT** - This is a subsystem of the calorimeter readout which does a quick summation of total energy deposited and determines whether to trigger on the event. If this parameter is flagged, there was a problem reading out the amount of energy in the calorimeter.
**Drift chambers** - If a chamber's high voltage tripped off. or a feedback loop created oscillations on the chamber readout, the chamber's power would have to be cycled back on. This process could take several spills, and information gathered while a chamber is turning back on is always suspect.

**Muon banks** - Since one of the major aspects of the trigger for our signal decay was the presence of a muon, reliable data from the muon banks is a necessity.

**HCC** - HCC stands for Hardware Cluster Counter and is another subsystem of the calorimeter that is also used in the trigger. Energy in the calorimeter needs to be resolvable into clusters to tell were the center of each particle's hit was located. The timing in this system is sharp and it requires that a significant amount of energy be deposited to identify a hit as a cluster. Since three of the four particles in the decay must deposit hardware clusters (see Section 2.4.2). HCC information must be complete and correct. If there is trouble with cluster resolution, this bit is flagged.

Obviously, the MC generated events will have no such detector-based errors since doing so would be counter-productive.

**KTeVAna subroutine errors**

The analysis program is broken down into subroutines that are each responsible for reconstructing some part of the event. If the subroutine has a problem getting the information it needs, or is unsuccessful at performing the task requested, it returns an error. An event is cut if any of the following subroutines returned an error:
GET·VETO - Information from the veto system was lost or garbled, so it is unknown if all the particles from an event were contained.

KTCLUS - Similar to the “HCC” tag in KTSPILL: there was a problem resolving information about clusters of energy in the calorimeter.

T3MATCH - The program was unable to satisfactorily match the tracks found with the calorimeter clusters that were found.

T3FVTX - The program was unable to resolve a reasonable vertex for the event.

T3FTRK - A more detailed search for particle tracks in the drift chambers discovers information problems.

KTTCDC - There was a problem with information conversion in the reading out of the time to digital converters (TDCs). This includes all TDCs except for the ones associated with the drift chambers.

T3MASS - There was a problem reconstructing the mass of the charged system from the information known about the charged decay products.

T3FPI0 - The program was unable to reconstruct a $\pi^0$ (within 250 MeV of the $\pi^0$ mass) from any combination of calorimeter clusters and the charged vertex that was found.

3.3.2 Ntuple cuts

The intention of the ntuple level of cuts was to get rid of events that had little chance of reconstructing to a decent Kpi0me. Since the Monte Carlo (MC) events
were not put through the "crunch" process. The crunch cut requirements were included again with the ntuple cut requirements and are marked with an dagger (\(^\dagger\)). Please see the previous section for a description of these cuts. The main difference between this level of cuts and the crunch cuts is that slightly stricter kinematic and characteristic requirements are made.

An event was cut before reaching the ntuple if any of the following was true:

\(^\dagger\) T3FPI0 returned in error
\(^\dagger\) number of clusters, hard or soft, < 4
\(^\dagger\) number hard clusters < 3 or > 5
\(^\dagger\) number preliminary tracks < 2
\(^\dagger\) no vertex candidate
number of final tracks is not equal to 2
both clusters matching to tracks have energy > 1 GeV
\(^\dagger\) Z vertex not between 0 and vacuum window
\(^\dagger\) \(m_{\phi} < 110 \text{ MeV} \) or > 160 MeV
\(E_{T} < 0.8 \) or > 1.2
\(^\dagger\) \(p_T^{2} > 0.05 \text{ GeV}^{2}/c^{2}\)

If an event passed the ntuple cut level, information about it was saved in a PAW-readable ntuple file consisting of fifty parameters. The more important of the ntuple parameters are listed and described here:

\(K_{mass}\) - the total reconstructed mass of the event assuming it was the decay of a single particle. This includes the contribution of both charged and neutral decay products. If the event was a Kpi0me decay, then this value should equal the mass of a neutral kaon.
$K_{\text{energy}}$ - the amount of laboratory-frame energy (momentum) the reconstructed kaon had.

$pt^2$ - the transverse momentum squared of the event after reconstruction, as measured with respect to the flight direction of the kaon so that beam dispersion is accounted for. If all the particles in an event are decay products, and all the decay products are observed, then this parameter is the transverse momentum of the original particle. Since the original particles are coming from a reasonably straight beam line, nearly all of their momentum will be along the $Z$ direction and their transverse momentums will be very small.

$pill_{\text{mass}}$ - the mass of the particle reconstructed from two calorimeter clusters not associated with tracks, and using the charged vertex. If the event was a Kp$\pi$me decay, then this value should equal the mass of a neutral pion.

$eop_{\text{elec}}$ and $eop_{\text{mu}}$ - "eop" stands for "energy ($E$) over (or divided by) momentum ($p$)" and is calculated for the two charged particles in the event. This calculation is an important check on what kind of particle made the associated track and cluster. The energy in this case is the amount of energy that was deposited in the calorimeter by the particle. The momentum is that calculated from the amount of bending the track underwent through the analysis magnet in the spectrometer. For a muon, which should only minimum ionize through the calorimeter, this ratio will be very close to zero because only a small portion of the particle’s momentum will be lost in the CsI.
For an electron, the ratio should be very close to one, because we expect an electron to lose all of its energy and completely stop within the calorimeter crystal. Pions, with their wide range of energy deposition (see Figure 2.12), will have a range of values for $E_p/E_p$ between zero and one. If we have correctly tagged the muon and electron tracks, then the values of cop.mu and eop.elec should be close to zero and close to one, respectively. Figure 3.4 shows the $E_p/E_p$ distributions for all three types of particles. One can clearly see a peak at 1 from electrons, a peak approaching 0 from muons, and a rounded distribution centered around 0.4 from pions.

$vtxz$ - the Z-position of the reconstructed vertex.

$vtx.chi$ - this parameter is the chi squared divided by the degrees of freedom ($\chi^2$/d.f.) from the fit of a decay vertex to the crossing in three dimensional space of the two charged tracks. The closer the tracks are to meeting, the better the fit for the decay vertex, and the closer this parameter's value is to 1.

$ncslides$ - the total number of clusters found in the CsI calorimeter, including both hard and soft clusters.

$nhCsiecls$ - the number of hardware clusters in the calorimeter.

$Etotal$ - the total energy deposited in the calorimeter within a time coincidence window.

$eShShape$ - a rating given to the shape of the reconstructed cluster tagged as being the electron cluster. The lower the number, the more similar the shape of the shower
Figure 3.4  Histogram of the energy to momentum ratio ($\frac{E}{p}$ or “eop”) for electrons, pions and muons. The electrons are peaked around 1, the muons are peaked around 0, and the pions have a broad distribution peaked near 0.4.
is to that expected from a single electron or photon based on GEANT simulations.

A true electron or photon should have a shower shape value of less than 5.

\texttt{n\_tracks} - the total number of tracks found in the event.

\texttt{npairs} - the number of hit pairs in the drift chambers.

\texttt{pel} - the momentum of the reconstructed electron track.

\texttt{pmu} - the momentum of the reconstructed muon track.

\texttt{eoffx} - in the X-direction, the offset between the reconstructed electron track upstream of the analysis magnet and the same track downstream of the magnet. Ideally the track segments should intersect and this value should be zero.

\texttt{eoffy} - in the Y-direction, the offset between the reconstructed electron track upstream of the analysis magnet and the same track downstream of the magnet. Ideally the track segments should intersect and this value should be zero.

\texttt{muoffx} - in the X-direction, the offset between the reconstructed muon track upstream of the analysis magnet and the same track downstream of the magnet. Ideally the track segments should intersect and this value should be zero.

\texttt{muoffy} - in the Y-direction, the offset between the reconstructed muon track upstream of the analysis magnet and the same track downstream of the magnet. Ideally the track segments should intersect and this value should be zero.

\texttt{xbrdist} - the distance in X between the projected upstream segment of the electron track and the nearest cluster identified as coming from a photon. The trajectory of
the electron track before passing through the analysis magnet (or “upstream” of the magnet) is extended mathematically to a point on the face of the calorimeter. If the detected photon was a result of bremsstrahlung radiation, it is most likely to have occurred during the passage of the electron through the vacuum window. Such a photon will follow closely the trajectory of its parent electron, and being unaffected by the analysis magnet, will land close to the projected point. Hence, the smaller this number, the more likely the photon was a result of bremsstrahlung radiation off the electron and not from the decay of a neutral pion.

\textit{ybrdist} - the distance in Y between the projected upstream segment of the electron track and the nearest cluster identified as coming from a photon. See “xbrdist” for a more detailed explanation. The smaller this number, the more likely the photon was a result of bremsstrahlung radiation off the electron and not from the decay of a neutral pion.

\textit{numumats} - number of muon banks with a successful “muon” track match. The maximum possible value is 3 (if Mu2, Mu3X, and Mu3Y all match).

\textit{mu2dist} - the difference in distance between the projected muon track and the nearest actual hit in detector Mu2.

\textit{mu3xdist} - the difference in distance between the projected muon track and the nearest actual hit in detector Mu3x.

\textit{mu3ydist} - the difference in distance between the projected muon track and the
nearest actual hit in detector Mu3y.

\textit{rc\_flag} - a logical flag; true if there was an above-threshold hit in any ring counter (RC). The threshold value was 0.5GeV.

\textit{RCmaxene} - the maximum amount of energy deposited in any single RC detector.

\textit{sa\_flag} - a logical flag; true if there was an above-threshold hit in any spectrometer anti (SA). The threshold value was 0.5GeV.

\textit{SAmaxene} - the maximum amount of energy deposited in any single SA detector.

\textit{ca\_flag} - a logical flag; true of the collar anti (CA) detector had a hit.

\textit{ha\_flag} - a logical flag; true if the amount of energy deposited in the hadron anti (HA) was above threshold. The threshold value was 7MIPs.

\textit{ha\_energy} - the total amount of energy deposited in the hadron anti (HA).

\textit{mu\_flag} - a logical flag; true of the muon banks detected an in-time hit.

\textit{tripiflg} - a logical flag; true if the event could be satisfactorily reconstructed as a \( K_L \rightarrow \pi^+\pi^-\pi^0 \) (K3pi) event using requirements similar to the signal selection cuts.

\textit{pp0\_kine} - a kinematic variable involved in reconstructing a \( K_L \rightarrow \pi^+\pi^-\pi^0 \) (K3pi) event. For this variable, the event is assumed to be a K3pi decay. The two track-cluster combinations are each associated with a charged pion mass and the parent particle is assumed to be a kaon. Using such assumptions, the square of the longitudinal momentum \( p \) for the remaining neutral pion \( (p0) \) can be calculated kinematically (kine). The value for \textit{pp0\_kine} must be positive for a true K3pi event. A negative
value indicates an incorrect assumption about the charged particle masses or the parent particle mass was made.

\( e_{clusel} \) - the amount of energy deposited in the cluster associated with the electron track.

### 3.3.3 Selection cuts

Selection cuts are the final level of cuts made. The number of events which pass these cuts is used in the calculation of signal acceptance and background contamination within the “box”. Events are accepted if all of the following requirements are true (see previous section for variable definitions):

\[
0.13 \text{GeV} \leq \text{pi0_mass} \leq 0.14 \text{GeV} \\
0.975 \leq \text{eop_elec} \leq 1.025 \\
| \text{muoffx} | \leq 0.001 m \\
| \text{muoffy} | \leq 0.001 m \\
| \text{coffx} | \leq 0.001 m \\
| \text{coffy} | \leq 0.001 m \\
\text{numumats} = 3 \\
\text{vtx.chi} \leq 20 \\
100 m \leq \text{vtx.z} \leq 155 m \\
\text{eShShape} \leq 5 \\
\text{RCmaxene} \leq 0.1 \text{GeV} \\
\text{SAmaxene} \leq 0.1 \text{GeV} \\
| \text{pmu} | \geq 7 \text{GeV} \\
| \text{pel} | \geq 7 \text{GeV} \\
\text{pt2} \leq 0.0005 \frac{\text{GeV}^2}{c^2}
\]

The cut on the momentum of the “electron” track is done to make it symmetric to the cut on the “muon” track. The “muon” track has such a cut to ensure that the
particle has the chance to make it all the way to the muon banks without excessive multiple scattering.

The full set of cuts was run on the "one day" of data and a set of background Monte Carlo (MC), resulting in the distributions seen in Figures 3.5–3.8. It is encouraging to see no events near the kaon mass. Please see Section 3.5 for a detailed discussion of comparisons between these MC and data events.

3.4 Background Decays

A crucial part of any analysis is to reduce background as much as possible. To do this one needs to understand how other processes can look like a $K_L \rightarrow \pi^0 \mu e$ (Kpi0mc) decay and how they can be excluded from the final data sample. There are four backgrounds to the Kpi0me decay, as listed in Table 1.1 at the end of Chapter 1. For the $K_L \rightarrow \pi^+ \pi^- \pi^0$ (K3pi) decay mode, the $\pi^0$ will go to two photons as in the signal mode. A charged pion ($\pi^\pm$) can decay into a muon plus a neutrino ($\mu^\pm \nu_\mu$). Alternatively, a charged pion could interact very early in its passage through the calorimeter and shower to look like, or fake, an electron. If one of the charged pions muon-decays, and the other fakes an electron, the result looks like the particle combination ($\pi^0 \mu^\pm e^\pm \nu_\mu$). Since the neutrino will travel through the detector without being seen, the final state looks like a Kpi0me decay mode of a $K_L$. Such an event will pass triggers and must be filtered out offline. The K3pi decay mode can also imitate a signal decay mode in another way. One of the charged pions can undergo
Figure 3.5 Distribution of events for the composite MC (nominally 10% of the "one day" data set) after selection cuts are applied. Transverse momentum squared (pt2) is on the Y-axis in $GeV^{2}$ and kaon mass (k_mass) is on the X-axis in GeV. Total number of events is 35, with those events not appearing on the plot having lower values for k_mass.
Figure 3.6  Distribution of events for "one day" of data after selection cuts are applied. Transverse momentum squared (pt2) is on the Y-axis in $GeV^2$ and kaon mass (k_mass) is on the X-axis in $GeV$. Total number of events is 883, with those events not appearing on the plot having lower values for k_mass. There are more events in this plot than expected according to the MC. Please see Section 3.5.2 for a discussion of this discrepancy.
Figure 3.7  A histogram of the mass of the kaon (k-mass, in GeV) for data and MC background events which passed all cuts for the "one day". This is a projection onto the X-axis of Figures 3.5 and 3.6. Any possible signal events are still masked out at this point.
Figure 3.8  A histogram of the square of the transverse momentum (pt^2, in (GeV/c)^2) for data and MC background events which passed all cuts for the “one day”. This is a projection onto the Y-axis of Figures 3.5 and 3.6. Any possible signal events are still masked out at this point.
muon decay as before, and the other charged pion can decay into a real electron and electron-like neutrino. Missing both neutrinos again gives a Kpi0me-type signature. The electron-mode decay of a pion is suppressed \( \left( \text{BR}(\pi^\pm \to e^\pm \nu_e) / \text{BR}(\pi^\pm \to \mu^\pm \nu_\mu) \approx 10^{-3} \right) \), so this type of background is less likely, yet still a concern. Taking either of these faking avenues, the K3pi decay is the primary background.

Several avenues are open for removing K3pi decays from the data set. If one of the charged pions decays into a muon or electron, the track for that particle will have a direction change in it from the kinematics of emitting a neutrino. While the spectrometer information is not fine-grained enough to pinpoint the location of a daughter particle's inflight decay vertex, the track reconstruction is accurate enough that an inflight decay would result in a mis-match of segments within one track, or a mis-match at the vertex of the two charged tracks. If the in-flight decay happened before passing through the analysis magnet, the reconstruction of the original decay vertex will be bad. Parameters to cut on in that case would be the vertex's chi-squared (vtxchi) and the vertex's Z-position (vtxz). If the in-flight decay happened after passing through the analysis magnet, the matching of the upstream (pre-magnet) and downstream (post-magnet) segments of the track will be bad, and/or the X-Y position of the original decay vertex will be off. Important parameters in this case would correspond to a non-zero value for muoffx, muoffy, eoffx, and/or eoffy for a magnet mismatch. In addition to a track mismatch, the production of a neutrino
means that part of the energy of the decay is lost. When the masses and momentums of the detected particles are added up, the total energy will be less than the mass of the originating kaon. Even if the muon takes most of the energy from the decay of the pion, assigning it a muon mass rather than the pion mass will again cause the reconstructed k-mass to be low. Hence the cut requirement on k-mass helps to remove these events. Since this decay process also involves one type of particle "faking" another, analysis includes looking at parameters having to do with particle identification: eop_el, eShShape, eop_mu, and mmumat.

The $K_L \rightarrow \pi^{\pm} \mu^{\mp} \nu_{\mu}$ (Knu3) and $K_L \rightarrow \pi^{\pm} e^{\mp} \nu_e$ (Ke3) decay modes have larger branching ratios than K3pi, but are less likely to satisfy the trigger requirements. In the Knu3 mode, the charged pion would have to fake an electron (or decay into an electron and neutrino), and the neutral pion would have to come from other overlapping events (commonly called accidentals) or from a real electron undergoing bremsstrahlung radiation. The Ke3's charged pion would have to decay into a muon and neutrino, and again the neutral pion would have to come from accidentals or from bremsstrahlung radiation.

As in trying to remove K3pi events, particle identification parameters and track matching parameters are important for removing faking events and decays in flight. To identify the two photons as coming from an event outside the kaon decay, one has on-line cuts requiring the photons to be detected within a certain time-window around
the detection of the two charged tracks. One can also look at the reconstructed mass of the neutral pion. The neutral pion is reconstructed from the two photons using the decay vertex found from the charged tracks. If the photons did not come from the decay of a neutral pion within the kaon decay, the reconstructed pion mass for the event (pi0_mass) will be different from the true \( \pi^0 \) mass. Photons coming from bremsstrahlung radiation are emitted with very little transverse momentum and so will travel a path close to that of its parent electron. If the bremsstrahlung radiation occurs in the vacuum window (as is most likely) then the photon will continue to follow the electron's original trajectory even though the electron itself is later bent by the analysis magnet. Therefore the electron track segment upstream of the magnet is projected to an X-Y point on the calorimeter and a minimum distance requirement made between this point and the nearest photon cluster (xbrdist and ybrdist). It was discovered that cuts on xbrdist and ybrdist were not very effective and so they were left out of the final analysis.

Finally, a \( K_L \rightarrow \pi^0\pi^\pm \bar{\epsilon}\nu_e \) (Ke4) decay can fake a Kpi0me decay if its charged pion decays into a muon and muon neutrino. This again gives the particle combination \( (\pi^0\mu^\pm \bar{\epsilon}\nu_\mu\nu_e) \) where the neutrinos will be missed. Ke4 gives a final state most like the search target Kpi0me, and so it is one of the greatest concerns for a background. Fortunately it has a very small branching ratio \( \text{BR}(\text{Ke4}) = (5.18 \pm 0.29) \times 10^{-5} \), see Table 1.1) which keeps it from being a dominant background.
To remove this background, one would again use track reconstruction parameters \((vtx.chi, coffx, effy, nuoffx, and nuoffy)\) to remove decays-in-flight of the charged pion. In addition, for a background event of this type the mass of the originating particle \((k, mass)\) should reconstruct to a value lower than the actual kaon mass because of the missing neutrino energy.
3.5 Comparing Data and Monte Carlo

After the crunch and ntuple cuts, but before the selection cuts, the data distributions were compared to the Monte Carlo (MC) distributions on a parameter-by-parameter and decay-by-decay basis. The data events used in this comparison are from a subset called the “one day” of data and consist of runs $384, 387,$ and $397.$

3.5.1 Generation of Monte Carlo Events

For the background decays $K_{3pi}, K_{3nu},$ and $K_{3e},$ ten percent (10%) of the expected number of events in the one day of data were generated. Since the branching ratio of $K_{3e}$ events is much smaller, a full 100% of the events expected in the one day data set was generated to get reasonable statistics for individual background comparison. Table 3.1 shows the exact numbers of MC events generated. Figure 3.9 shows the distributions of the MC events for each of the four types of background after the ntuple cuts but before the selection cuts. Figure 3.10 shows individual background distributions after the final selection cuts are applied.

3.5.2 Comparision Studies

Values for the final selection cuts were adjusted based on the quality of the data/MC agreement at the ntuple level. For these studies, the MC distribution was made up of a combination of all four backgrounds to produce 10% of the expected flux for the one day. As can be seen from the plots in Appendix A, the data and MC
Figure 3.9  Distributions of the four types of background decays (Monte Carlo) after ntuple cuts are applied but before selection cuts are applied. For the K3pi, Ke3, and Kmu3 decays, the events shown represent 10% of the "one day" of data. 100% of the "one day" of Ke4 events are shown here to give a statistically reasonable distribution. X-axis units are in GeV and Y-axis units are in $\frac{GeV^2}{c^2}$.  

Figure 3.10  Distributions of the four types of background decays (Monte Carlo) after selection cuts are applied. For the K3pi, Ke3, and Knu3 decays, the events shown represent 10% of the “one day” of data. 100% of the “one day” of Ke4 events are shown here to give a statistically reasonable distribution. X-axis units are in GeV and Y-axis units are in GeV/c^2.


<table>
<thead>
<tr>
<th>Event type</th>
<th>Flux generated</th>
<th>fraction of “one day”</th>
</tr>
</thead>
<tbody>
<tr>
<td>K3P1 MC</td>
<td>$1.65 \times 10^8$</td>
<td>10%</td>
</tr>
<tr>
<td>KMU3 MC</td>
<td>$1.5 \times 10^8$</td>
<td>10%</td>
</tr>
<tr>
<td>KE3 MC</td>
<td>$2 \times 10^8$</td>
<td>10%</td>
</tr>
<tr>
<td>KE4 MC</td>
<td>$2.6 \times 10^5$</td>
<td>100%</td>
</tr>
<tr>
<td>KPI0ME MC</td>
<td>$1 \times 10^5$</td>
<td>unknown</td>
</tr>
<tr>
<td>data</td>
<td>$5 \times 10^9$</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Table 3.1** Number of Monte Carlo (MC) events generated as compared to the flux of data during the “one day” (runs 8384, 8387, and 8397). More Ke4 was generated to get reasonable statistics when comparing just the Ke4 events to the data. However, only 10% of the Ke4 MC events were included in the composite MC set seen in Figures A.12 – A.17 (and 3.11 – 3.13).

profiles agree for most variables. The major exceptions are the variables HA_energ, eop_elec, and eShShape in the plots reproduced in Figures 3.11–3.13. The discrepancy in the plot of HA energy is a known problem with poor modelling in the MC program of the HA itself. Attempts have been made to correct this behavior but have so far been unsuccessful. This is not of major concern because no cuts are made on this variable.

The discrepancy for eop_elec and eShShape appears as too few events getting through the selection cuts of the background MC (Figure 3.5) compared to data (Figure 3.6). Since the number of MC events generated was 10% of the one day of data, one would expect (35×10) or about 350 events in the data plot of Figure 3.6. The 883 events present is a factor of 2.52 more than expected. It was worried that there were more real electrons in the data than were being generated by the MC.
Figure 3.11 A histogram of the amount of energy deposited in the hadron-anti (HA) by each event. The discrepancy in the distribution results from incorrect HA behavior modelling in the Monte Carlo (MC). Corrections to the MC have been attempted but have been unsuccessful so far. No selection cut is made on this variable.
Figure 3.12  A histogram of the energy of the "electron" as measured in the calorimeter divided by the momentum of the "electron" as measured in the spectrometer. The ideal ratio value is 1 if the particle is really an electron. To pass the selection cuts, events have to be between 0.975 and 1.025.
Figure 3.13  A histogram of the quantification of the shape of the energy distribution left in the CsI by the "electron". If the particle was really an electron, this value should be less than 5. To pass the selection cuts, events have to have an eShShape value of less than 5.
To investigate this discrepancy, the same plots were done for properly reconstructed $K_L \rightarrow \pi^+\pi^-\pi^0$ (K3pi's) events (using Trigger 2) since such events would contain only pions and no electrons. Figure 3.14 shows the comparison between data K3pi's and MC K3pi's for the variable eop_elec. There is a discrepancy present exactly like the one in Figure 3.12 for the Trigger 7 data and MC. Likewise there is a discrepancy in the distribution of the variable eShShape (Figure 3.15 versus Figure 3.13). For the plots shown in Figures 3.14 and 3.15, there are 68.895 data events and 30.942 MC events present. Adding only the nominal cuts for the eop_elec and eShShape variables results in 133 data events passing and only 24 MC events passing. Taking a ratio (data to MC) of ratios (post-cut to pre-cut), one gets a factor of 2.49 more data than MC accounted for by just these two variables compared to the factor of 2.52 in Trigger 7. Since these two factors agree so well, it is believed that the problem is in the MC modelling of the pion behavior for these two variables and not an incorrect assumption of the kind of decays taking place. This also means that were we are confident that we understand our data and MC at this level.

It was decided to see how much the cuts on eop_elec and eShShape would have to be widened for the MC distribution so that the number of events passing agreed with data. Increasing the cuts on eop_elec from 0.975 & 1.025 to 0.964 & 1.036, and the cuts on eShShape from 5 to 6.9 resulted in 88 MC background events passing as shown in Figure 3.16. There are still no events close to the signal box.
Figure 3.14 A histogram of the variable eop.elec for reconstructed K3pi events from Trigger 2. The fact that there is a discrepancy here just as in Figure 3.12 indicates a problem in the MC program for this variable, and not an unknown source of real electrons in the data.
Figure 3.15  A histogram of the variable eShShape for reconstructed K3pi events from Trigger 2. The fact that there is a discrepancy here just as in Figure 3.13 indicates a problem in the MC program for this variable, and not an unknown source of real electrons in the data.
Figure 3.16  Distribution of events for the composite MC (nominally 10% of the one day data set) after modified selection cuts are applied. Cut values for eop_elec and eShShape were widened since there is not good agreement between data and MC for these variables. Transverse momentum squared (pt2) is on the Y-axis in GeV$^2$ and kaon mass (k_mass) is on the X-axis in GeV. Cuts were widened until the total number of events equalled 88 (was 35), with those events not appearing on the plot having lower values for k_mass.
Chapter 4
Results

KTeV E799II was able to collect 25,277,686 Trigger 7 events to tape during the winter of 1996-7. which is the basis for this analysis and which is approximately 60% of the full KTeV data set. Of these, 7,206,653 events or 28.5% passed the crunch cuts. Table 4.1 gives a summary of how many events failed each cut. Because of the structure of the analysis program, the cuts are taken sequentially as listed in the tables. For example, an event which is cut at the crunch level because it had a T3FP10 error had already successfully passed the other subroutine cuts but never reached the kinematic cuts. A few events (27 to be exact) that passed the crunch cuts were not written out to the next level because of an I/O problem. These events will be analyzed at a later date.

Next, events were put through the ntuple cuts. A summary of events passing the ntuple level cuts is given in Table 4.2. Of the events that made it past the crunch cuts, 44.4% also passed the ntuple cuts for a total acceptance thus far of 12.7%. Again, cuts are taken sequentially as listed.

Finally the selection cuts were applied as listed in Table 4.3. It was hoped that all of these cuts would remove any events near the signal box. Unfortunately this is not the case as can be seen by the full data set distribution in Figure 4.1. Additional
<table>
<thead>
<tr>
<th>Cut (evt. fails if true)</th>
<th>Number data events lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTSPILL was bad</td>
<td>2.329.400</td>
</tr>
<tr>
<td>GET_VETO returned in error</td>
<td>143.321</td>
</tr>
<tr>
<td>KTCLUS returned in error</td>
<td>0</td>
</tr>
<tr>
<td>T3MATCH returned in error</td>
<td>313.147</td>
</tr>
<tr>
<td>KTTDC returned in error</td>
<td>0</td>
</tr>
<tr>
<td>T3MASS returned in error</td>
<td>0</td>
</tr>
<tr>
<td>T3FPI0 returned in error</td>
<td>4.050.766</td>
</tr>
<tr>
<td>num. of clusters. hard or soft. $&lt; 4$</td>
<td>79.489</td>
</tr>
<tr>
<td>num. hard clusters $&lt; 3$ or $&gt; 6$</td>
<td>1.489.331</td>
</tr>
<tr>
<td>num. prelim tracks $&lt; 2$</td>
<td>61.522</td>
</tr>
<tr>
<td>no vertex candidate</td>
<td>2.243.608</td>
</tr>
<tr>
<td>$Z$ vtx. not btw. target (0m) and vac. window (165m)</td>
<td>114.590</td>
</tr>
<tr>
<td>$m_{\pi^0} &lt; 110.0,\text{MeV}$ or $&gt; 160.0,\text{MeV}$</td>
<td>4.428.859</td>
</tr>
<tr>
<td>$E_{\pi^0} &lt; 0.25$ or $&gt; 1.75$</td>
<td>1.646.956</td>
</tr>
<tr>
<td>$p_{\pi^0} &gt; 0.05 \frac{E_{\pi^0}}{c^2}$</td>
<td>1.168.044</td>
</tr>
<tr>
<td>Number of events cut</td>
<td>18.071.033</td>
</tr>
<tr>
<td>Number of events processed</td>
<td>25.277.686</td>
</tr>
<tr>
<td>Number of events passing</td>
<td>7.206.653 ($=28.5%$)</td>
</tr>
</tbody>
</table>

**Table 4.1** Summary of data events cut by the “crunch” level of analysis. Note that cuts are applied sequentially so that an event failing a cut later in the list has passed all the cuts preceding that one.
<table>
<thead>
<tr>
<th>Cut (evt. fails of true)</th>
<th>Number data events lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of clusters, hard or soft. &lt; 4</td>
<td>9.414</td>
</tr>
<tr>
<td>number hard clusters &lt;&gt; 3</td>
<td>1.236.254</td>
</tr>
<tr>
<td>T3MATCH returned in error</td>
<td>88.699</td>
</tr>
<tr>
<td>T3FPI0 returned in error</td>
<td>401</td>
</tr>
<tr>
<td>no vertex candidate</td>
<td>1.382</td>
</tr>
<tr>
<td>number of final tracks is not equal to 2</td>
<td>225.253</td>
</tr>
<tr>
<td>both track clusters have energy &gt; 1GeV</td>
<td>537.207</td>
</tr>
<tr>
<td>Z vtx. not btw. target (0m) and vac. window (165m)</td>
<td>1.143</td>
</tr>
<tr>
<td>$\frac{E_z}{p_t} &lt; 0.8$ or $&gt; 1.2$</td>
<td>1.880.243</td>
</tr>
<tr>
<td>$p_t^2 &gt; 0.05 E_z^2$</td>
<td>73</td>
</tr>
<tr>
<td>other (including but not limited to signal masking)</td>
<td>777.844</td>
</tr>
<tr>
<td>Number of events cut</td>
<td>3.980.069</td>
</tr>
<tr>
<td>Number of events processed</td>
<td>7.206.626</td>
</tr>
<tr>
<td>Number of events passing</td>
<td>3.202.225 ($=12.7%$)</td>
</tr>
</tbody>
</table>

**Table 4.2**  Summary of data events cut by the “ntuple” level of analysis. Note that cuts are applied sequentially so that an event failing a cut later in the list has passed all the cuts preceeding that one.
work on modifying cuts and studying Monte Carlo is needed before the signal box is ready to be opened. Of most concern are the events which reconstruct to a kaon mass greater than 0.500GeV since similar events did not appear in the “one day” of data.

<table>
<thead>
<tr>
<th>Cut (evt. passes if true)</th>
<th>Number data events lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13GeV ≤ pi0.masse &lt; 0.14GeV</td>
<td>964.225</td>
</tr>
<tr>
<td>0.975 ≤ eop.elec ≤ 1.025</td>
<td>1992.383</td>
</tr>
<tr>
<td></td>
<td>nuoffx</td>
</tr>
<tr>
<td></td>
<td>nuoffy</td>
</tr>
<tr>
<td></td>
<td>coffx</td>
</tr>
<tr>
<td></td>
<td>coffy</td>
</tr>
<tr>
<td>numumats = 3</td>
<td>47.788</td>
</tr>
<tr>
<td>vtx.chi ≤ 20</td>
<td>20.638</td>
</tr>
<tr>
<td>100m ≤ vtx.z ≤ 155m</td>
<td>11.320</td>
</tr>
<tr>
<td>eshshape ≤ 5</td>
<td>223.177</td>
</tr>
<tr>
<td>RCmaxene ≤ 0.1GeV</td>
<td>4.087</td>
</tr>
<tr>
<td>SAmxene ≤ 0.1GeV</td>
<td>896</td>
</tr>
<tr>
<td></td>
<td>pnu</td>
</tr>
<tr>
<td></td>
<td>pel</td>
</tr>
<tr>
<td>pt2 ≤ 0.0005 GeV</td>
<td>19.218</td>
</tr>
</tbody>
</table>

| Number of events cut | 3.175.265 |
| of events processed | 3.202.225 |
| Number of events passing | 26.960 (=0.11%) |

Table 4.3 Summary of data events cut by the “selection” level of analysis. Note that cuts are applied sequentially so that an event failing a cut later in the list has passed all the cuts proceeding that one.

Several sources could be responsible for these high-mass events. Looking back at the Monte Carlo (MC) in Figure 3.9 before the selection cuts, there are high-mass events for the Kmu3 and Ke3 decay modes. These events failed the selection cuts, but
Figure 4.1 Transverse momentum squared versus kaon mass for all the data in this analysis (60% of the KTeV data set). There are a total of 26,960 events (0.11% of the starting set) that passed the final selection cuts, most of which fall within this plot. Too many events lie too close to the signal region for the box to be opened yet.
perhaps there were not enough statistics (not enough events were generated) to give an accurate representation of the larger data set. Larger MC samples will be generated and examined. Another possibility is that the sampling of accidental events was not statistically large enough. In generating the MC used here, only accidental events collected during the "one day" of data were superimposed on the background decays. Accidentals for other time periods (run numbers) may be significantly different from the one day, especially since we do know the beam structure varied over the runs. New MC events will need to be generated which draw on accidentals throughout the runs. Earlier in the analysis studies were done of double decays, in which two kaon decays occur at almost the same time and their data overlap within the detector. It was decided at the time that such background events would not be statistically significant. However, $K\Sigma$ decays overlapped with any other decay did reconstruct to high-mass events. Such events deserve a second look. A final possibility is that these events could be hyperon decays like $\Xi^0 \rightarrow \pi^0 \Lambda$ with the lambda decaying as $\Lambda \rightarrow p\pi^-$. MC of this decay will be investigated and possibly added to the background MC mix. Whatever these events turn out to be, the first order of business will be to use the viewing program kdisp to actually look at the events to see if we can gain any more information about what they are.

It was hoped that this analysis would be able to give a new upper limit on the branching ratio of $K_L \rightarrow \pi^0 \mu^\pm e^\mp$ by the time of its defense. Although it is not
possible (or at least not prudent) to open the signal box at this point in time. It is hoped that a final result will not be much longer in coming. As the analysis stands now, we have a single event sensitivity level for the signal region of $3.88 \times 10^{-9}$ for the one day of data and $1.44 \times 10^{-10}$ for the 60% data set. If the signal region is empty, this will hopefully give a branching ratio limit of $3.3 \times 10^{-10}$ or better when analysis is complete.
Appendix A
Plots of data verses Monte Carlo studies

The histograms in this appendix show comparisons between data and MC events for important variables in this analysis. The distributions for most variables agree. The ones that do not are discussed in Section 3.5.2. For each plot shown here, the MC distribution was made up of a combination of all four backgrounds to produce 10% of the expected flux for the one day. Again, the "signal" data events have been masked off at this point, so the comparison is nominally background data to background MC at the ntuple level. The MC distributions are renormalized so that the units on the Y axes are the number of data events. Black lines with arrows on some of the plots indicate where selection cuts are to be applied.
Figure A.1  Mass of the reconstructed “kaon” (k_mass). If the reconstruction was done correctly, the “kaon” should have a mass near 0.5 GeV. One can see that the events immediately around the kaon mass have been removed from this sample.
Figure A.2  Amount of energy (momentum) the reconstructed "kaon" had (K_energy). No selection cut is made on this variable.
Figure A.3  Squared transverse momentum (pt2) of the event if reconstructed as a $K_L \rightarrow \pi^0 \mu^+ \nu$. For a signal event, the value should be near zero. Events with a pt2 value of less than $0.00025 \frac{GeV^2}{c^2}$ have been masked out of this plot.
Figure A.4  Mass of the reconstructed $\pi^0$ (pi0_mass). If the reconstruction was done correctly, the pion should have a mass near 0.135$\text{GeV}$. To pass the selection cuts, events have to have a pi0_mass value between 0.13$\text{GeV}$ and 0.14$\text{GeV}$. 
Figure A.5  Distribution of energy of the "electron" as measured in the calorimeter divided by the momentum of the "electron" as measured in the spectrometer (eop_elec). The ideal ratio value is 1 if the particle is really an electron. To pass the selection cuts, events must have a eop_elec value between 0.975 and 1.025. Please see Section 3.5.2 for a discussion of the discrepancy.
Figure A.6  Distribution of energy of the "muon" divided by the momentum of the "muon" (eop\_mu). Ideal ratio values are small if the particle is really a muon. No selection cut is made on this variable.
Figure A.7  Z-distribution of the reconstructed vertex. To pass selection cuts, events must have a vtxZ value between 100m and 155m.
Figure A.8  Distribution of the $\chi^2/d.f.$ of the reconstructed vertex (vtx.chi). Ideally this value should be near 1. To pass the selection cuts, events must have a vtx.chi value of less than 20.
Figure A.9  A quantification of the shape of the energy distribution left in the CsI by the "electron" (eShShape). If the particle was really an electron, this value should be less than 5. To pass the selection cuts, events must have a eShShape value of less than 5. Please see Section 3.5.2 for a discussion of the discrepancy.
Figure A.10  Momentum distribution of the "electron" track as measured in the spectrometer (pEl). To pass the selection cuts, events had to have an absolute pEl value of greater than 7 GeV. This cut is to ensure that the particle had enough momentum to make it to the muon banks without excessive multiple scattering. While the "electron" is not expected to reach the muon banks, this cut is made to be symmetric with the cut on the momentum of the "muon" track.
Figure A.11 Momentum distribution of the "muon" track as measured in the spectrometer (pMu). To pass the selection cuts, events had to have an absolute pMu value of greater than 7GeV. This cut is to ensure that the particle had enough momentum to make it to the muon banks without excessive multiple scattering.
Figure A.12  Distribution of the difference in X between the segment of the "electron" track upstream of the magnet and the corresponding track segment downstream of the magnet (coffx). The ideal value is 0$m$. To pass the selection cuts, events have to be between -0.001$m$ and 0.001$m$. 
Figure A.13  Distribution of the difference in Y between the segment of the "electron" track upstream of the magnet and the corresponding track segment downstream of the magnet (eoffy). The ideal value is 0 m. To pass the selection cuts, events have to be between -0.001 m and 0.001 m.
Figure A.14  Distribution of the difference in X between the segment of the “muon” track upstream of the magnet and the corresponding track segment downstream of the magnet (muoffx). The ideal value is 0 m. To pass the selection cuts, events have to be between -0.001 m and 0.001 m.
Figure A.15  Distribution of the difference in Y between the segment of the "muon" track upstream of the magnet and the corresponding track segment downstream of the magnet (muoffy). The ideal value is 0 m. To pass the selection cuts, events have to be between -0.001 m and 0.001 m.
Figure A.16  Distance in X between the projection on to the CsI of the upstream electron track segment and the nearest photon CsI cluster (xbrdist). The closer this value is to 0, the more likely the photon is from bremsstrahlung radiation of the electron. No selection cut is made on this variable.
Figure A.17  Distance in Y between the projection on to the CsI of the upstream electron track segment and the nearest photon CsI cluster (ybrdist). The closer this value is to 0, the more likely the photon is from bremsstrahlung radiation of the electron. No selection cut is made on this variable.
Figure A.18  Spatial distribution of energy deposited in the second muon bank (Mu2Dist). No selection cut is made on this variable.
Figure A.19  Spatial distribution of energy deposited in the third muon bank’s X-view (Mu3XDist). No selection cut is made on this variable.
Figure A.20  Spatial distribution of energy deposited in the third muon bank's Y-view (Mu3YDist). No selection cut is made on this variable.
Figure A.21  Energy deposited in the ring counters (rcmaxene). To pass the selection cuts, events must have a rcmaxene value of less than 0.1.
Figure A.22  Energy deposited in the spectrometer anti-antis (samaxene). To pass the selection cuts, events must have a samaxene value of less than 0.1.
Figure A.23  Amount of energy deposited in the hadron-anti (HA.energ). The discrepancy in the distribution results from incorrect HA behavior modelling in the Monte Carlo (MC). Corrections to the MC have been attempted but have been unsuccessful so far. No selection cut is made on this variable.
Figure A.24  The square of the longitudinal momentum for a neutral pion (pp0_kine) if the event is reconstructed as a $K_L^+ \rightarrow \pi^+\pi^-\pi^0$ (K3pi) using a charged track vertex. If this value is positive the event may be a K3pi. If this value is negative (i.e. the square root is imaginary), the K3pi solution is not reasonable. True Kpi0me signal events should have a negative value for this parameter. No selection cut is made on this variable.
References


13. J. Ellis. personal communication.

