Particle Physics at its Best
KTEV Analysis of $K_L \rightarrow \pi^+\pi^-e^+e^-$

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Abstract

The main purpose of KTEV (Kaons at the Tevatron) is to understand how CP-violation occurs in neutral kaons as they decay by using a high-energy precision detector, and we have found the decay mode of $K_L \rightarrow \pi^+\pi^-e^+e^-$ to have a BR (branching ratio or branching fraction) of $3.2 \pm 0.6(stat) \pm 0.4(syst) \times 10^{-7}$.

1 Introduction

KTEV is made up of two experiments E832 and E799. E799 deals with rare decays of which we are able to detect making various cuts to our real data and Monte Carlo, which is a computer generated simulation of what we are looking for. One of the rare decays being studied in E799 is $K_L \rightarrow \pi^+\pi^-e^+e^-$. Cuts were made to the data analyzed to better understand what is happening. E832 deals with K_s (k short) and K_L (k long) decays.

When $K_s \rightarrow \pi\pi$, CP is conserved, and when $K_L \rightarrow \pi\pi$, CP is violated. In order to explain what CP-violation is we must introduce new terminology. There are two types of operations we must understand,

and they are parity or space inversion, P, and charge conjugation, C. Space inversion, P, changes the sign of any true(polar) vector. Charge conjugation, C, changes a particle into its anti-particle and vise versa. CP is conserved when charge conjugation and parity are invariant. Invariant meaning, the operations are not changing. For instance, mass is not changing when it is invariant. Since K_L decays abnormally into two pions which makes CP variant or violated, the decay of neutral kaons have led to the fall of CP invariance.

2 Experimental Setup

Our experiment begins in the Tevatron, which is the biggest particle accelerator in the world. Photons are accelerated from the Tevatron at 800 GeV into the high energy precision detecter 90 meters in front of a beryllium-oxide target (see Figure 1: on page 3). Two beams made up of neutral kaons enter the vaccum decay region, which had pressure 10^{-6} Torr. The drift chambers (see Figure 2: on page 4) which are located two in front and two in back of the magnet are used for tracking to see where hits occur on each DC (drift chamber). The magnet (see Figure 3: on page 5) bends the charged particles according to their momentum, and we use what we call a PTKick, which was set at 205 MeV/c, to measure the angle from the horizontal plane of the magnet. Behind the last DC are two 2m x 2m in area trigger hodoscopes designed to be particle counters. A track is a trail of hits on each drift chamber, and for $K_L \rightarrow \pi^+\pi^-e^+e^-$ we are scanning to find four charged tracks. Four hits are required in the x view and y view of the trigger hodoscopes. The Cesium Iodide calorimeter (see Figure 4: on page 6) is in a 2m x 2m array, and is the most important part of our spectrometer. The CsI calorimeter is made up of 3100 crystals which detects electrons and photons. Data from our detector was read out into online computers, running software "filters" which decide if an event is interesting. If it is the computer writes the event to tape to be analized later.

3 Theory of $K_L \rightarrow \pi^+\pi^-e^+e^-$

$K_L \rightarrow \pi^+\pi^-e^+e^-$ has two different components called Direct Emmission (or DE) and Inner Bremstrahlung (or IB). The DE part of the

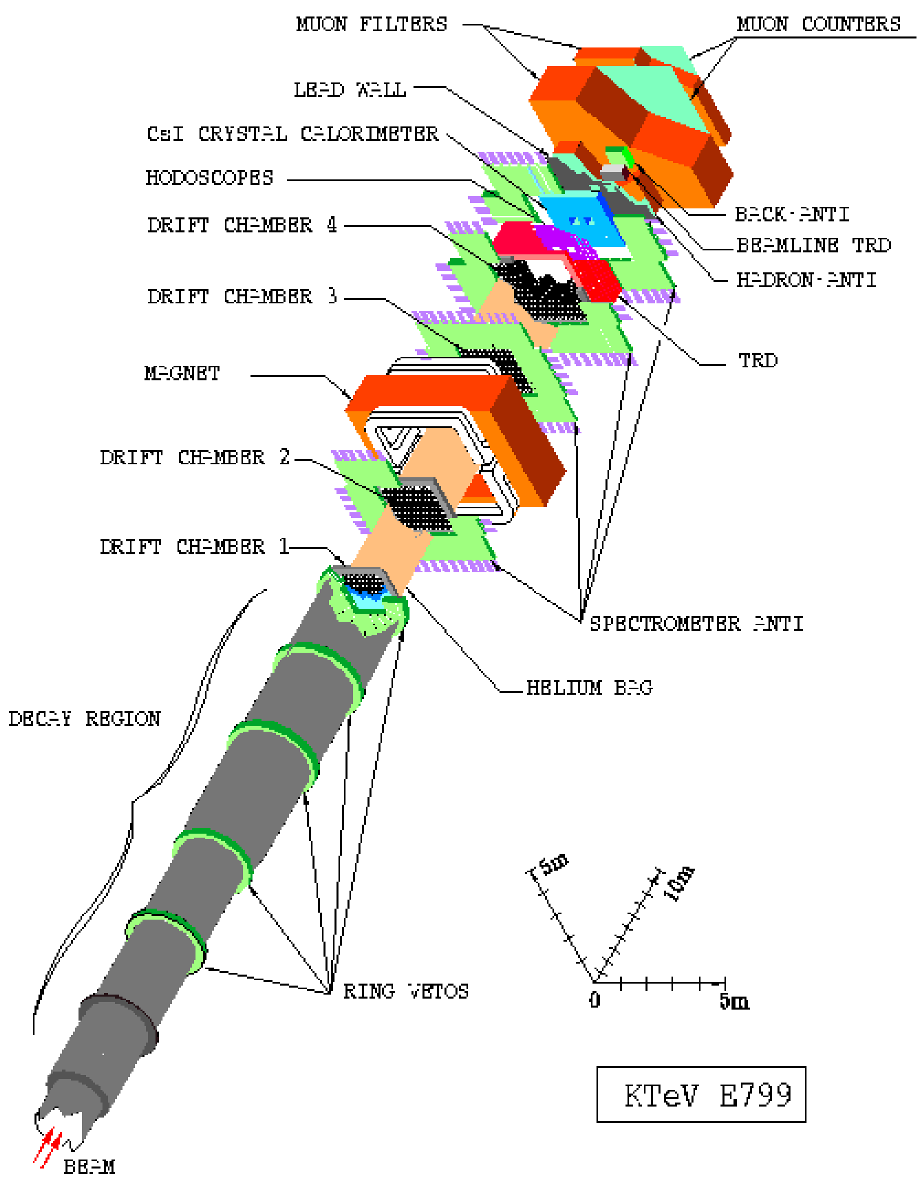

Figure 1: Three dimensional view of high energy precision detector 90 meters in front of a beryllium-oxide target.

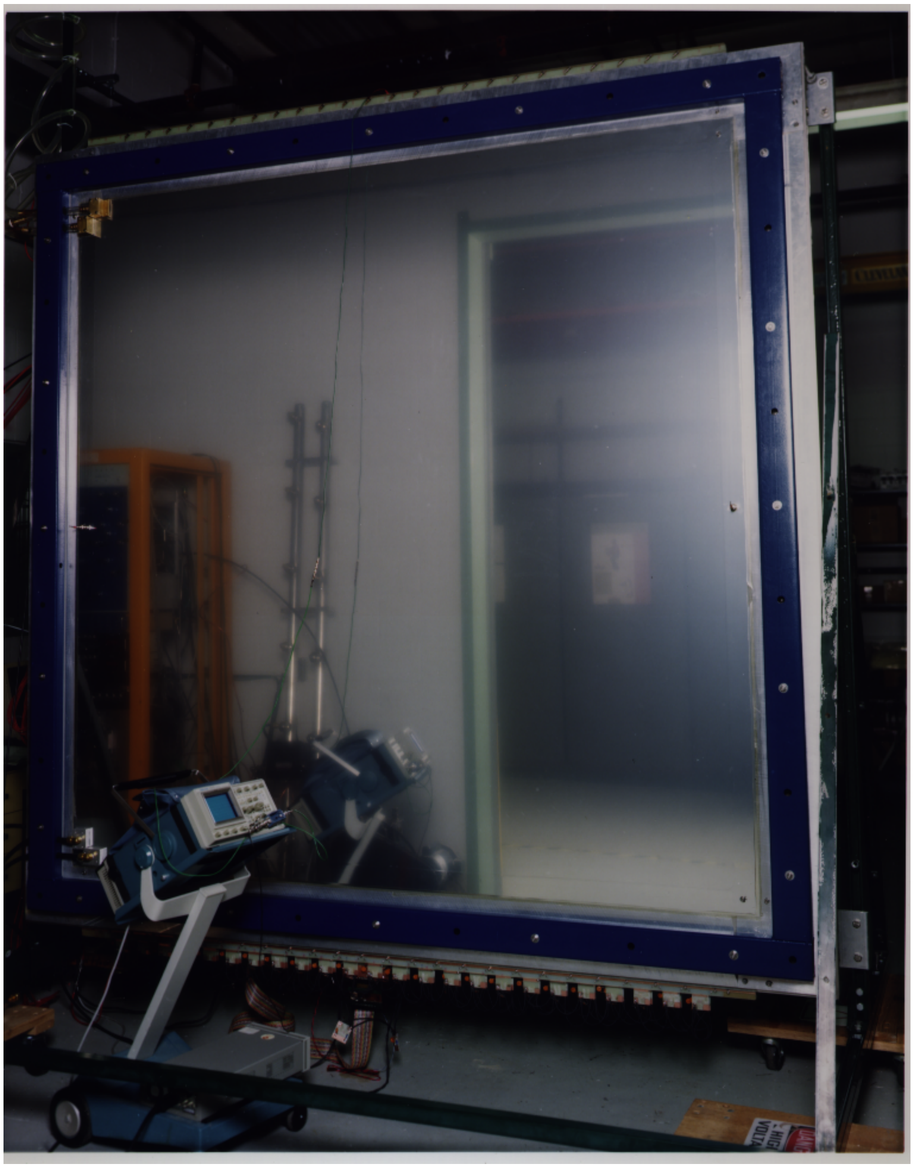

Figure 2: Hits are required in the x view and y view of the four drift chambers to verfy a track.

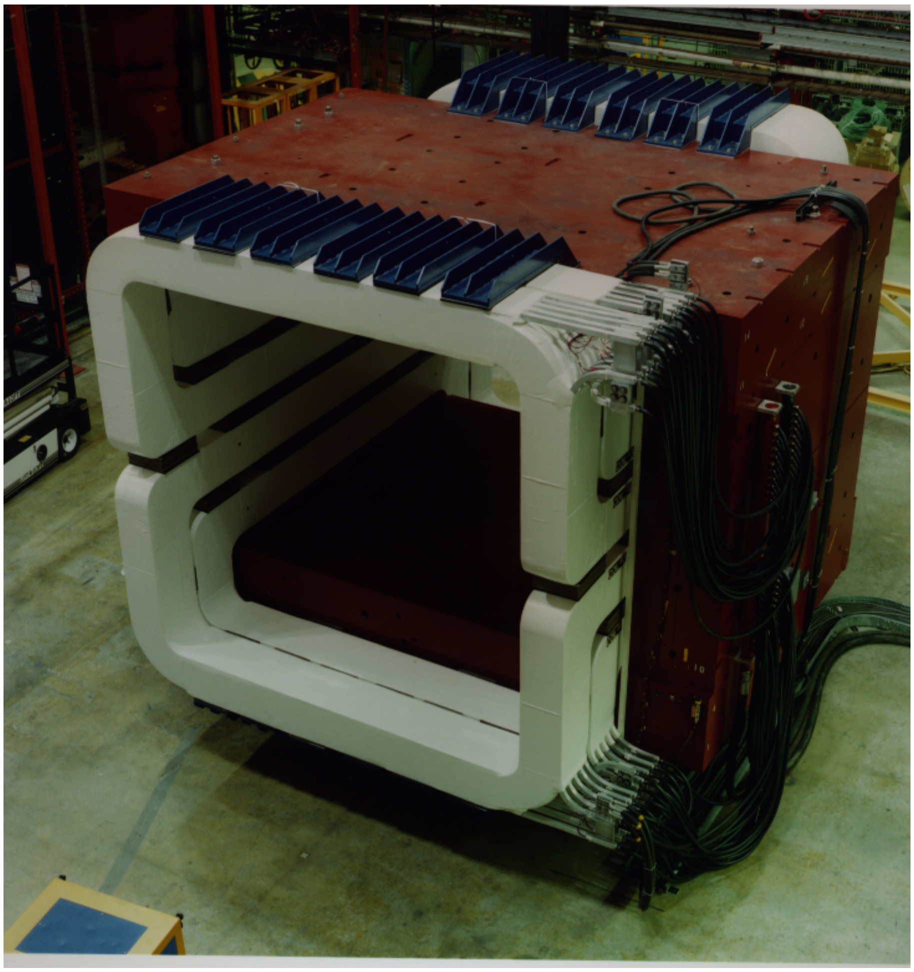

Figure 3: The magnet bends the charged particles according to their momentum. The amount of bend is determined by the PTKick, which was set at 205 MeV/c during normal running.

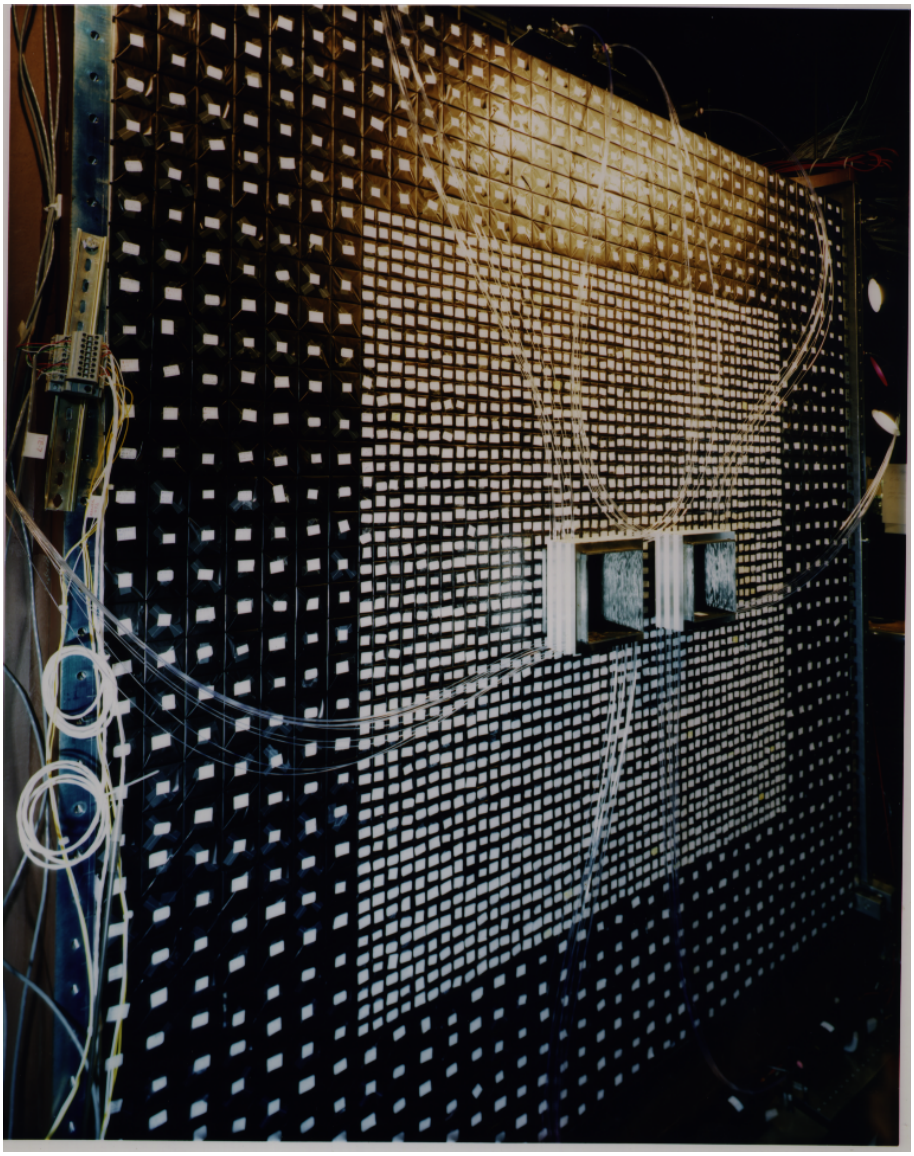

Figure 4: CsI calorimeter made up of 3100 crystals which detects electrons and photons.

decay is CP conserving and the IB part is CP violating. Our acceptance (or ability to reconstruct decays) for the IB part is very small because it is dominated by low energy electrons. For this reason, E799 ran for about a week with a special configuration where the magnet PTKick was set at a value of 20 MeV/c. This increases our ability to see low energy electron pairs.

The analysis presented in the paper is a look at the Monte Carlo predictions for the background to accentuate the signal for this special running condition.

4 Method

What we are trying to measure is the branching ratio (BR) of $K_L \to \pi^+\pi^-e^+e^-$. If we can determine the number of $K_L \to \pi^+\pi^-\pi^0_D$ (Dalitz decay mode) and $K_L \to \pi^+\pi^-e^+e^-$ events we see, and we know the branching ratio of $K_L \to \pi^+\pi^-e^+e^-\gamma$ (Dalitz decay mode), which is 0.150%,

$$\frac{\#\ K_L \to \pi^+\pi^-e^+e^- \text{ events}}{\#\ K_L \to \pi^+\pi^-e^+e^-\gamma \text{ events}} = \frac{\text{BR of } K_L \to \pi^+\pi^-e^+e^-}{\text{BR of } K_L \to \pi^+\pi^-e^+e^-\gamma} \tag{1}$$

we can use equation (1) to find the BR of $K_L \to \pi^+\pi^-e^+e^-$.

5 Analysis

We can understand what particles are passing through the CsI calorimeter by the event display. From Figure 5. (on page 8) we can see clusters (where energy is stored), tracks (the path in which particles travel), and the amount of energy in GeV. For the decay $K_L \to \pi^+\pi^-e^+e^-$ we are looking for 2 electrons and 2 pions. We identify a track as being an electron if it leaves most of its energy in the calorimeter. If the track does not leave much energy in the calorimeter, then it is probably a pion.

5.1 Definition of Important Quantities

Invariant mass is the total mass or the sum of the rest masses of the system of particles. To calculate the invariant mass of a system of

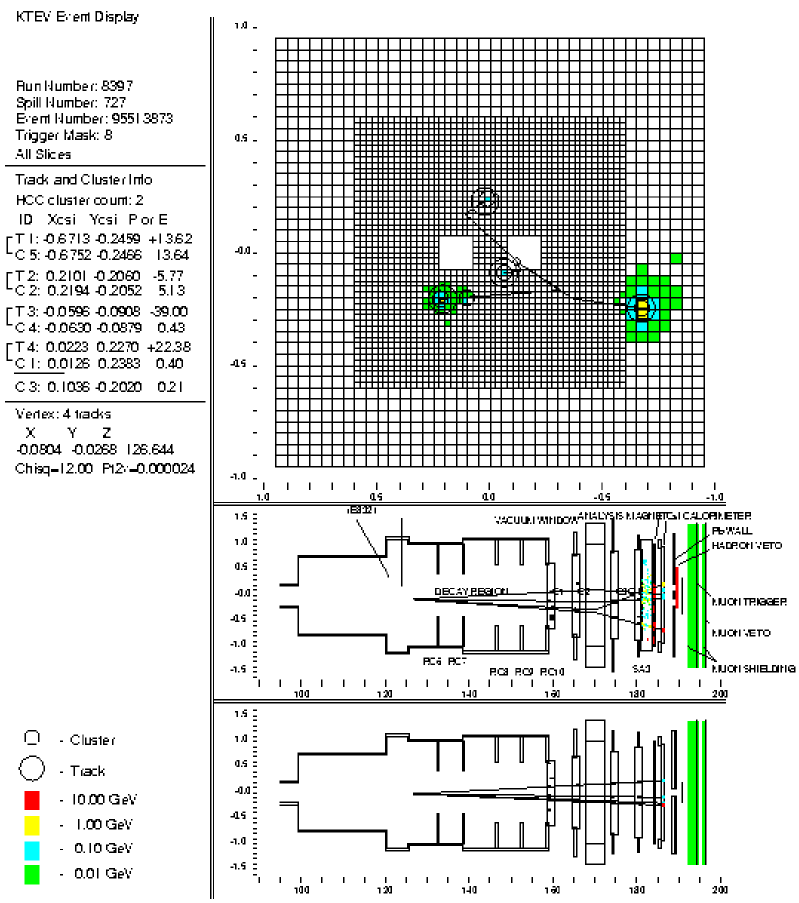

Figure 5: Event display for a $K_L \to \pi^+\pi^-e^+e^-$ Candidate. Using the tracks in the drift chambers and clusters in the CsI calorimeter allows us to identify the event.

particles, the following equations are needed:

$$E^2 = p^2c^2 + m^2c^4 \tag{2}$$

$$p = m\gamma v \tag{3}$$

$$\gamma = \frac{1}{(1-(v/c)^2)^{1/2}} \tag{4}$$

with total energy, E, total momentum, p, velocity, v, speed of light, c. However, γ becomes a factor when the invariant mass becomes relativistic. Invariant mass is relativistic when the object, which is usually a particle, is traveling near the speed of light, c, which means its mass is increasing.

P_T^2 is defined as the square of the total momentum of the observed decay products transverse to the parent kaon's line of flight. We use P_T^2 to remove unwanted events which have a missing particle.

$P_{\pi^0}^2$ is defined by the following equation:

$$P_{\pi^0}^2 = \frac{[(M_K^2 - M_{\pi^0}^2 - M_{\pi\pi}^2)^2 - 4M_{\pi^0}^2 M_{\pi\pi}^2 - 4M_K^2(P_T^2)_{\pi\pi}]}{4[(P_T^2)_{\pi\pi} + M_{\pi\pi}^2]} \tag{5}$$

where $M_{\pi\pi}$ is the invariant mass of the $\pi^+\pi^-$ system, M_{π^0} is the mass of the π^0, M_K is the mass of the K_L, and $(P_T^2)_{\pi\pi}$ is the square of the transverse momentum of the $\pi^+\pi^-$ system with respect to the kaon momentum. $P_{\pi^0}^2$ is used to cut out the Dalitz decays in which the extra photon was not detected.

5.2 Description of Cuts to Monte Carlo for the Signal Mode

1. Data Quality Cuts. Cuts were made to make sure the data were of good quality.
   - $90.0 <$ Zvertex < 155
   - χ^2vertex < 40.0 ensures a reasonable 4 track vertex and cuts out some double decay background.
   - The four tracks must extrapolate to at least 3 different counters in the V1 bank. This is to ensure that accidental tracks or hits in the V0/V1 bank did not fire the L1 trigger.
   - No extra cluster not associated with a track. This cuts out $K_L \to \pi^+\pi^-\pi^0_D$ decays.

2. The four tracks are consistant with two electrons ($0.8 < E/p < 1.2$) and two pions (E/p < 0.8) (see Figure 6: on page 10). Electrons leave a large amount of energy in the calorimeter and pions leave only a little amount of energy in the calorimeter. We expect E/p for an electron to be close to 1.0 because energy, E, should have the same value as momentum, p. Since are resolution is not perfect, we cut between 0.8 and 1.2. Most of the pions have an E/p of zero.

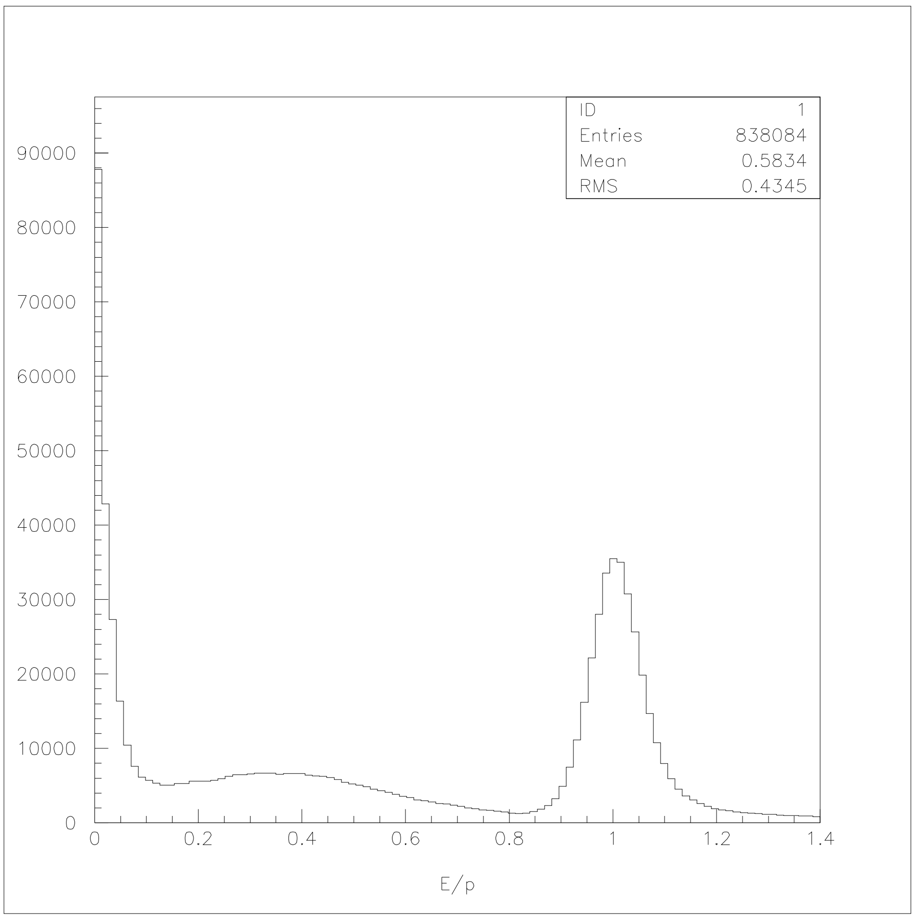

Figure 6: E/p distribution for all four tracks from MC.

3. $P_T^2 < 0.001$ and $P_{\pi^0}^2$ is cut at $-0.05 MeV^2/c^2$ in order to distinguish between $K_L \to \pi^+\pi^-\pi^0_D$ and $K_L \to \pi^+\pi^-e^+e^-$ decays

(see Figure 7: on page 11).

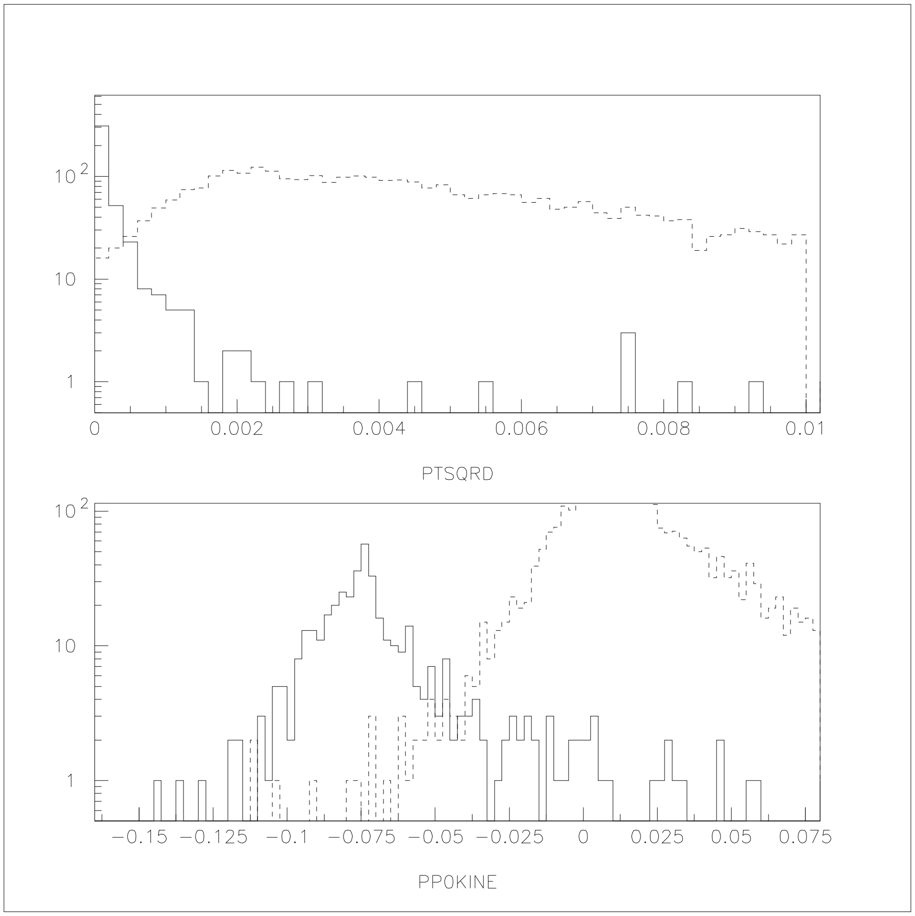

Figure 7: P_T^2 and $P_{\pi^0}^2$ distributions for signal(solid) and background(dashed).

4. Invariant Mass of the four tracks is between $0.475 GeV/c^2$ and $0.525 GeV/c^2$ (see Figure 8: on page 12). We expect invariant mass to be $0.5 GeV/c^2$.

5.3 Description of Cuts to Normalization Mode

1. Data Quality Cuts. Cuts were made to make sure the data were of good quality.

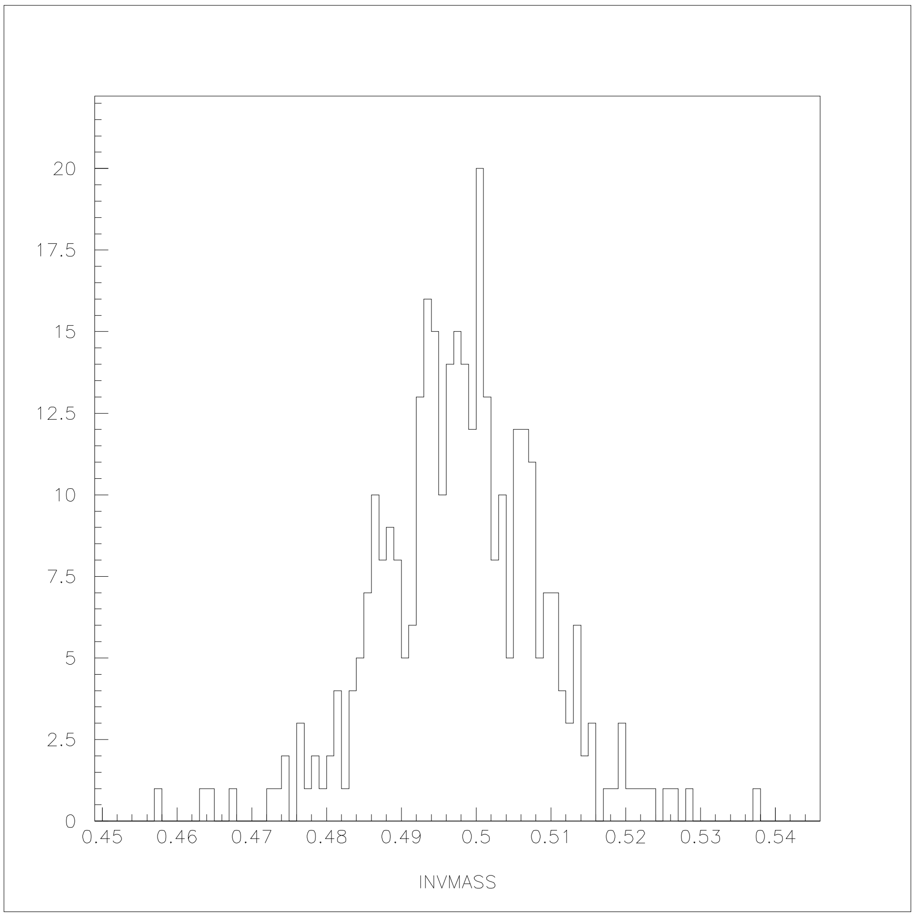

Figure 8: Predicted Invariant mass of signal mode for all 4 tracks.

- $90.0 < \text{Zvertex} < 155$
- χ^2vertex < 40.0 ensures a reasonable 4 track vertex and cuts out some double decay background.
- The four tracks must extrapolate to at least 3 different counters in the V1 bank. This is to ensure that accidental tracks or hits in the V0/V1 bank did not fire the L1 trigger.
- No extra cluster not associated with a track. This cuts out $K_L \to \pi^+\pi^-\pi^0_D$ decays.

2. The four tracks are consistant with two electrons ($0.8 < E/p < 1.2$) and two pions (E/p < 0.8) (see Figure 6: on page 10). Electrons leave a large amount of energy in the calorimeter and pions leave only a little amount of energy in the calorimeter. We expect E/p for an electron to be close to 1.0 because energy, E, should have the same value as momentum, p. Since are resolution is not perfect, we cut between 0.8 and 1.2. Most of the pions have an E/p of zero.
3. There is an extra cluster in the calorimeter not associated with any tracks. An extra cluster could be a photon, γ, from the Dalitz decay mode.
4. The invariant mass of the four tracks and the photon cluster is between 0.475 GeV/c^2 and 0.525 GeV/c^2 (see Figure 9: on page 14). We expect invariant mass to be at or about $0.5 GeV/c^2$.

6 Results

By examining the Monte Carlo for the signal and background modes, we were able to determine cuts that should allow us to reduce the background enough to see the signal. The next step is to analyze the data using these cuts.

7 Acknowledgments

I would like to acknowledge my savior Jesus, my supervisor Dr. Vivian O'Dell, and my friends. In working with KTEV, I learned hyper text markup language, vi editing, and latex (Computer programing system used to write reports, proposals, and memos) which are good tools to

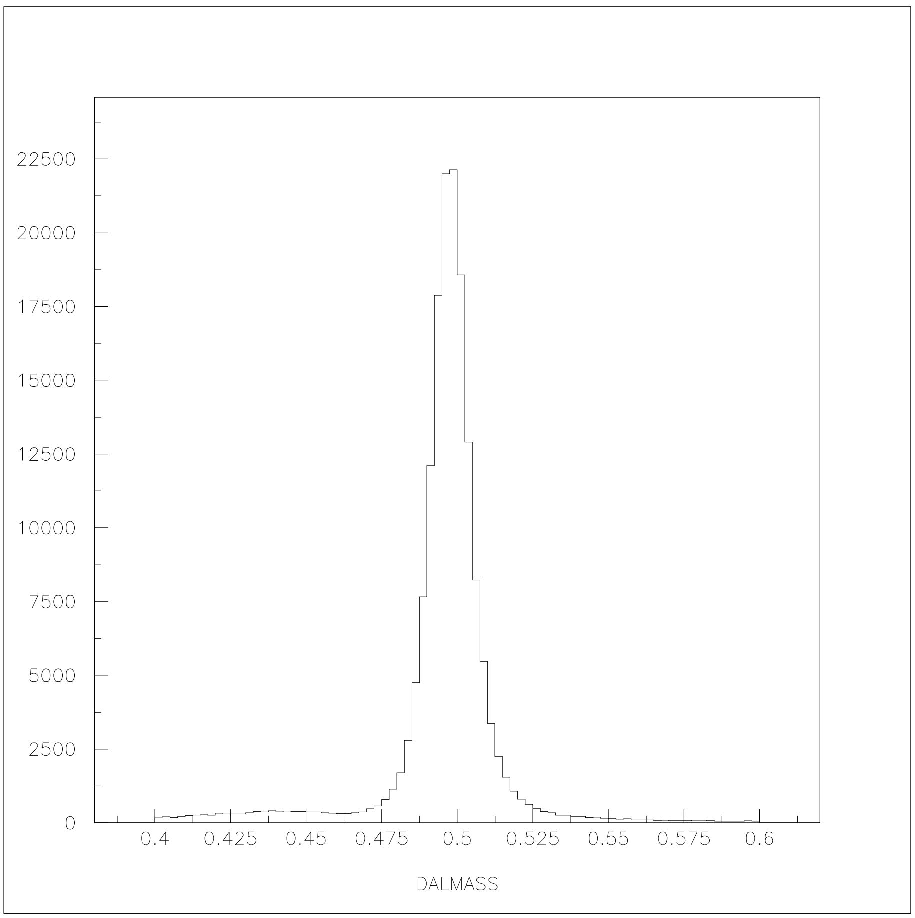

Figure 9: Predicted invariant mass of normalization mode.

understand and use for future purposes. The pictures in this report were scaned in by myself to inhance the KTEV home page. In addition to enhancing my professional skills, I have made a few friends, and my attitude towards life and friendship have changed. A certain type of strength and knowledge has hit me from various people, and my stay here at Fermilab has been one of the greatest experiences in my life.

References

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[4] Hans Frauenfelder and Ernest M. Henley, Sub-atomic Physics. Prentice-Hall, Inc., Englewood Cliffs, N.J.: 1974, 196-225.

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