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Status and First Results of BNL Experiment 777: A Search for $K^+ \rightarrow \pi^+\mu^+e^-$ and a Study of $K^+ \rightarrow \pi^+e^+e^-$

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DISCLAIMER

1 Introduction

The goal of Experiment 777 at the Brookhaven National Laboratory is to search for the decay $K^+ \to \pi^+\mu^+e^-$ to the 10^{-11} level and to study the decay $K^+ \to \pi^+e^+e^-$. The observation of the decay $K^+ \to \pi^+\mu^+e^-$ would be evidence for a lepton number violating, flavor changing neutral current. Lepton number violation, of course, is not allowed within the framework of the Standard Model of the strong, weak, and electromagnetic interactions. Observation of $K^+ \to \pi^+\mu^+e^-$ would therefore be evidence for new physics. Our motivation to search this decay, whose present branching ratio limit[1] is 5×10^{-9}, comes from the large number of questions that the Standard Model does not address, despite its often spectacular agreement with experiment to date. Among these are the origins of the large (of order 20) number of free parameters in the model describing, for example, the quark and lepton masses, the mixing angles between the strong and weak interaction eigenstates, and the various coupling constants. The model does not specify the mass of the Higgs boson, and in the Gauge Hierarchy problem, if the model is studied to higher order, constants must be fined tuned to incredible accuracy to prevent infinities. Furthermore, the model offers no insight into the number of quark and lepton generations, and allows for the possiblity of CP violation in the strong force which is much larger than present experimental limits.

A large number of extensions to the Standard Model have been proposed in order to remedy these problems. Such extensions include: technicolor,[2] supersymmetry,[3] models with additional Higgs scalars,[4] new horizontal gauge bosons,[5] leptoquarks,[6] composite models[7] and models that allow for intermixing (e.g. heavy neutrinos) within the generations of the Standrd Model. Many of these extensions allow for lepton number violation, including decays such as $K^+ \to \pi^+\mu^+e^-$, $K^0 \to \mu^\pm e^\mp$, $\mu^- \to e^-\gamma$, and others.

In order to give an estimate of the mass scale to which our search for $K^+ \to \pi^+\mu^+e^-$ will be sensitive, we compare the decay $K^+ \to \pi^+\mu^+e^-$ mediated by a heavy neutral gauge boson, E^0, with the decay $K^+ \to \pi^0\mu^+\nu$ mediated by the W boson. (See Fig. 1 for Feynmann diagrams for the two decays.) Following the model of Ref. 5, we find that the branching ratio

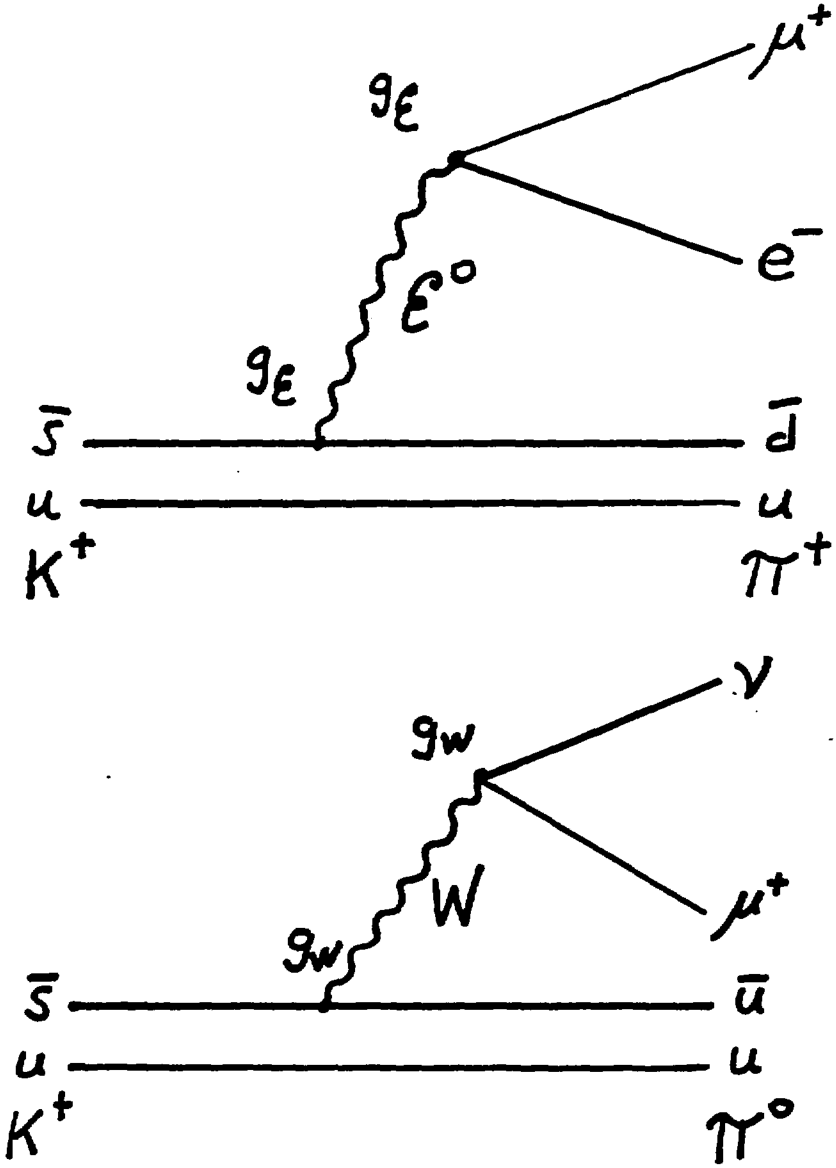

Figure 1: Feynmann Diagrams for $K^+ \to \pi^+\mu^+e^-$ and $K^+ \to \pi^0\mu^+\nu$

(BR) for $K^+ \to \pi^+\mu^+e^-$ is given by

$$BR(K^+ \to \pi^+\mu^+e^-) = 8 \times 10^{-11} \times \left(\frac{50TeV}{M_{E^0}}\right)^4 \times \left(\frac{g_{E^0}}{g_W}\right)^4.$$

Here M_{E^0} is the mass of the heavy neutral gauge boson. g_W is the Standard model coupling constant of the W boson, and g_{E^0} is the (unknown) coupling constant of the heavy gauge boson. If g_{E^0} is of the same order as g_W, then a measurement of $K^+ \to \pi^+\mu^+e^-$ to the 8×10^{-11} level should be sensitive to new physics in the 50 TeV region, an energy even higher than that of the proposed new Super Conducting Super Collider.

In addition to searching for $K^+ \to \pi^+\mu^+e^-$, our experiment will also study the decay $K^+ \to \pi^+e^+e^-$ which occurs through a flavor changing neutral current. The measured branching ratio of this decay is $(2.5 \pm 0.5) \times 10^{-7}$ based on 41 events from a single experiment.[8] In this experiment the e^+e^- pair mass was required to be above the π^0 mass in order to avoid background from the decay $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$ (Dalitz decay). We will examine the mechanism for this decay and search for possible e^+e^- states with masses greater than the π^0 mass. Our experiment is also sensitive to the decay $K^+ \to \pi^+e^+e^-$ when the e^+e^- inveriant mass (M_{ee}) is less than the π^0 mass. Interest in low mass particles decaying into e^+e^- has been sparked by the observation of correlated electron positron energy peaks in heavy ion collisions at GSI in Darmstadt.[9] If these peaks are due to the production of a particle, its mass would be 1.8 MeV/c^2, and it would have to have a short ($\leq 10^{-10}$ second) lifetime in order to have been detected.[10] Results of our search for such short lived neutral particles emitted in K^+ decay are given later in this paper.

We will also seek to make an accurate measurement of the branching ratio for $\pi^0 \to e^+e^-$ by looking for the decay chain $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$. The world average branching ratio[11] for this decay is $(1.8 \pm 0.7) \times 10^{-7}$ based on about 30 events from two experiments.[12,13] Theory[14] predicts that this branching ratio should be of order 6×10^{-8}. If the branching ratio remains at the 2×10^{-7} level when measured with smaller errors, this could be an indication of new physics.

2 Apparatus

The apparatus was designed to search for the decay $K^+ \rightarrow \pi^+\mu^+e^-$. The most significant K^+ decay that can give an e^-, and a μ^+ and a π^+ in the final state is from the decay sequence $K^+ \rightarrow \pi^+\pi^+\pi^-$ followed by $\pi^+ \rightarrow \mu^+\nu$ and $\pi^- \rightarrow e^-\nu$. Since each pion has a 10% probability for decay, the combined branching ratio for this process is 5×10[illegible]. All backgrounds from other decays require that at least one particle be misidentified. Accordingly, the apparatus was designed emphasizing excellent particle identification. Since it is easier to separate pions from electrons at a few GeV/c than at a few hundred GeV, it was decided to perform the experiment at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) rather than at Fermilab. The desired K^+ are produced by 28 GeV/c protons from the AGS in a one interaction length platinum target. A series of magnets and collimators forms a 5.8 GeV/c unseparated positively charged beam and transports the kaons seven meters from the target to the experiment. There are 1×10^7 K^+ in the beam for 1×10^{12} protons on target; the fraction of kaons in the beam is 5% .

A plan view of the apparatus is shown in Fig. 2. The decay vaccuum box is 6 meters long and extends from the exit of the last quadrupole in the beam line to the exit of the first spectrometer magnet, M1. This magnet directs positive particles to the right side of the apparatus and negative particles to the left. Our acceptance for decays inside M1 is small, and, therefore, the effective decay volume for the K^+ is five meters. The second spectrometer magnet, M2, along with the four (P1–P4) multiwire proportional chambers (MWPC), provides momentum measurement for charged particles. The MPWC are deadened in the beam region. Each MPWC has three planes of wires. One oriented vertically (X wires), and one each at $\pm 18^\circ$ to the vertical (U and V wires). Each plane has two mm wire spacing. The Cerenkov counters C1 and C2 provide electron identification. C1 and C2 are divided in half by a vertical opaque baffle along the beam direction. The left sides of both Cerenkov counters (C1L and C2L) are filled with hydrogen to minimize the number of pions faking electrons. The right sides of each counter (C1R and C2R) are filled with CO_2 to increase the light yield and minimize the number of electrons faking pions or muons. C1 is segmented into 24 cells and C2 into 12 cells. An opaque baffle in each Cerenkov counter isolates the beam from the decay particles. Additional particle identification is provided

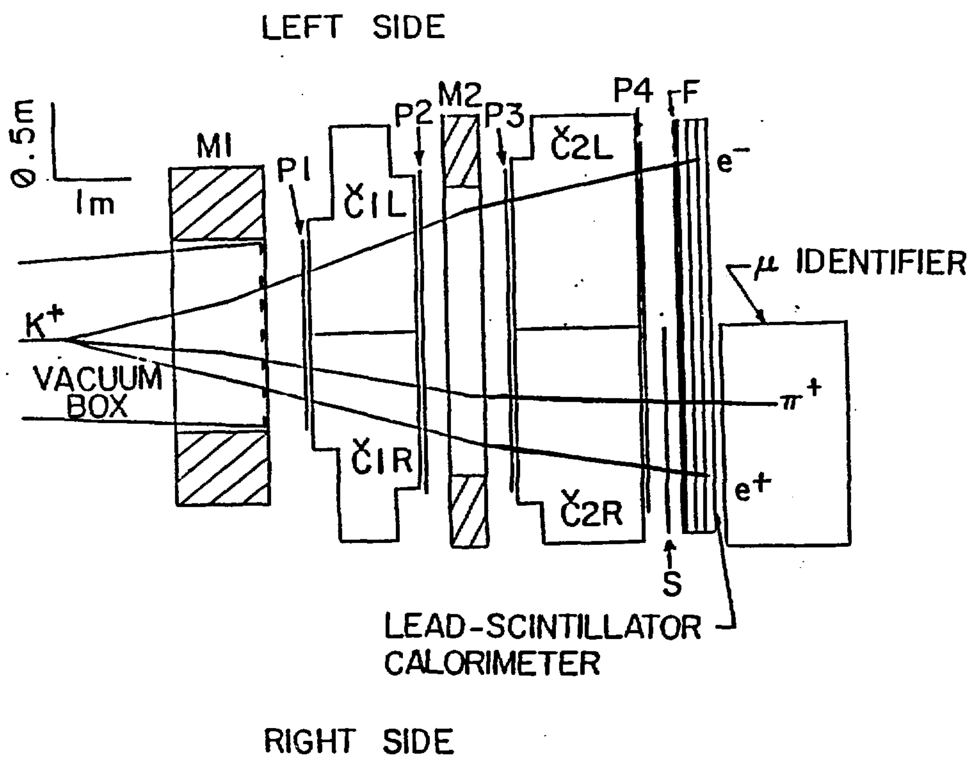

Figure 2: Plan View of E777 Apparatus showing a $K^+ \to \pi^+ e^+ e^-$ event

by an 11 radiation length lead scintillator calorimeter. The calorimeter has 144 cells (24 horizontal $\times$ 2 vertical $\times$ 3 longitudinal). Combining the information from C1, C2, and the calorimeter, we have found, using $K^+ \to \pi^+\pi^+\pi^-$ decays, that the probability of a pion being identified as an electron is less than 1×10^{-6} on the left side of the apparatus, and is less than 1×10^{-4} on the right side of the apparatus. Muon identification is provided by eight layers of alternating proportional tube chambers and nine cm steel plates. Each muon chamber has one layer of horizontal and one layer of vertical wires. The effective wire spacing in all planes is 1.3 cm. With better than 95% muon efficiency, the probability of a pion being misidentified as a muon is less than 5% . There are three layers of trigger scintillators. The F layer is located just upstream of the calorimeter and has 48 elements (24 horizontal $\times$ 2 vertical). The S layer with 24 elements (12 horizontal $\times$ 2 vertical) is located between the F counters and P4 on the right side of the apparatus. The Q layer (not shown in Fig. 2) also has 24 elements and is located just downstream of the fourth layer of the muon detector.

3 Triggers

The apparatus is typically triggered in four modes simultaneously. The first trigger requires at least one F counter on the left side of the detector in coincidence with at least two F and S counter coincidences on the right side. In addition, all four triggers typically require at least three hits in at least one plane of P1, and at least two spatially correlated pairs of hits on the right side of P3U and P4U or P3V and P4V. This trigger is sensitive to any K+ decay into three or more charged tracks. Because of its high rate, it is typically prescaled by a factor of 8192. The second trigger requires light on both sides of both Cerenkov counters, C1L $\cdot$ C2L $\cdot$ C1R $\cdot$ C2R. It also requires two F and S counter coincidences on the right side. This trigger is sensitive to all K^+ decays with an e^+e^- pair and at least one other charged track. This trigger is sensitive to all e^+e^- pair masses (e.g. converted photons) and is usually prescaled by a factor of eight.

The third trigger is similar to the second trigger, but requires the electron and the positron to be in different vertical halves of the apparatus, $(C1L_{bottom} \cdot C2L_{bottom} \cdot C1R_{top} \cdot C2R_{top}) + (C1L_{top} \cdot C2L_{top} \cdot C1R_{bottom} \cdot C2R_{bottom})$. This preferentially selects events with larger e^+e^- invariant mass ($M_{ee} \geq$ 100 MeV/c^2). The fourth trigger is the $\pi\mu e$ trigger. It requires C1L $\cdot$ C2L $\cdot$ muon, where a muon is defined as a Q counter aligned with typically four out of the first five muon chambers.

4 Running History

We first took data with the complete apparatus in the spring of 1986. During this run , we were able to study the K^+ beam and to tune up the detector, the trigger, and the event reconstruction software. In December 1986 and January 1987, we took $\pi\mu e$ data and πee data, concentrating on low mass e^+e^- events. In late January, February, and May 1987, we took more $\pi\mu e$ data and πee data, concentrating on high mass e^+e^- events. The break between the last two data sets was caused by a fire in one of the coils of the M2 magnet in January 1987. After the fire, with the damaged coil still in place, the transverse momentum (P_T) kick of M2 was reduced from 135 MeV/c to 99 MeV/c. During the shutdown in March and April, the magnet was completely repaired, including both the coil damaged in the January 1987 fire and another coil damaged in a fire in May 1986, and we were able to run in May 1987 with an M2 P_T kick of 155 MeV/c. The higher P_T kick improved our mass resolution slightly, and decreased the rate of background triggers.

5 Data Reduction

The data from the experiment is processed through a chain of programs for track reconstruction, vertex fitting, and particle identification. In all cases, we are searching for K^+ decays into three charged particles plus, possibly, missing neutrals. Accepted events are therefore first required to have three charged tracks extrapolating to a vertex with the negative track on the left side of the apparatus and and both positive tracks on the right.

A plot of the vertex miss distance, S, is given in Fig. 3 for a sample of $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$ events. S is defined to be the square root of the sum of the squares of the distances of closest approach of each track to the vertex. The vertex position is found by minimizing S in each event. The calculated vertex position and the kaon momentum, for decays without missing neutrals, are required to be consistent with the properties of our K^+ beam as determined from $K^+ \to \pi^+\pi^+\pi^-$ events. A plot of the $\pi^+\pi^+\pi^-$ invariant mass distribution for events taken with the prescaled three charged particle trigger and with $S \leq 1.4$ cm is shown in Fig. 4. We note that these events are clearly dominated by $K^+ \to \pi^+\pi^+\pi^-$ decays. The background is less than 2% even before correct particle identification has been required. This occurs because the branching ratio for $K^+ \to \pi^+\pi^+\pi^-$ is larger than all other decays of the K^+ into three charged particles (5% vs. 0.1%). Also, our acceptance for $K^+ \to \pi^+\pi^+\pi^-$ decays is greater than that for other K^+ decays (16% vs. 4% or less). Events are next required to have the correct particle identification in both Cerenkov counters, the calorimeter, and the muon chambers. Decays without neutral particles (neutral particles are not measured) are further required to have their reconstructed K^+ extrapolate back to the production target.

6 Search for $K^+ \to \pi^+ A^0$, $A^0 \to e^+e^-$

We have searched for light, short lived, neutral particles that decay into e^+e^- and are produced in K^+ decay. This search was motivated by the observation of e^+e^- energy peaks in heavy ion collisions.[9] Attempts have been made to explain these peaks as due to the production of a 1.8 MeV/c^2 particle that decays into e^+e^-. This particle could possibly be a light Higgs particle or a variant of the axion, the particle used by a number of authors to avoid the problem of CP violation by the strong force.[15] This search is discussed in detail in Ref. 16, and we will present only the results here. The search was performed using the January 1987 and December 1986 data that was obtained before the magnet coil fire. The main background to the search comes from Dalitz decay, $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$, which has a combined branching ratio of 2.5×10^{-3}. These decays were used to normalize our search for $K^+ \to \pi^+ A^0$, $A^0 \to e^+e^-$, since both decays have the same charged particles in the final state. All the decays with the e^+e^- invariant

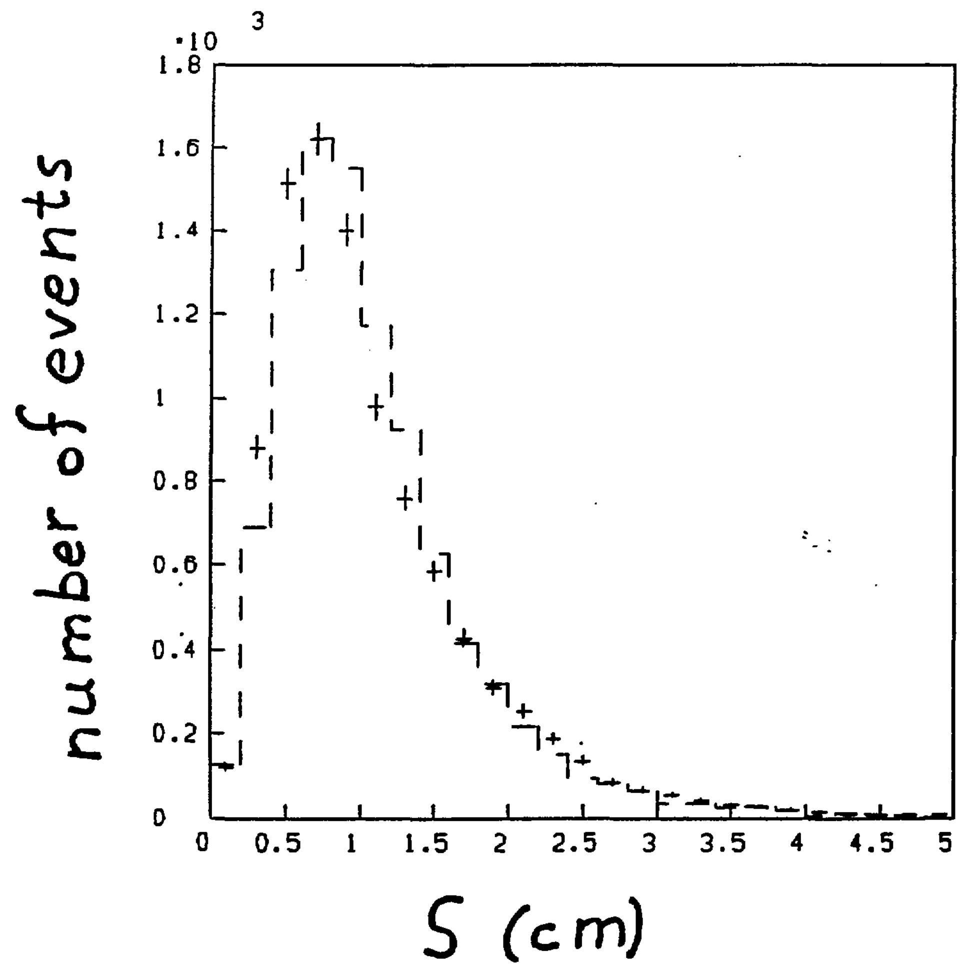

Figure 3: Vertex Miss Distance, S, for $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$ Events. The points are our data; the dashed line is from our Dalitz decay Monte Carlo .

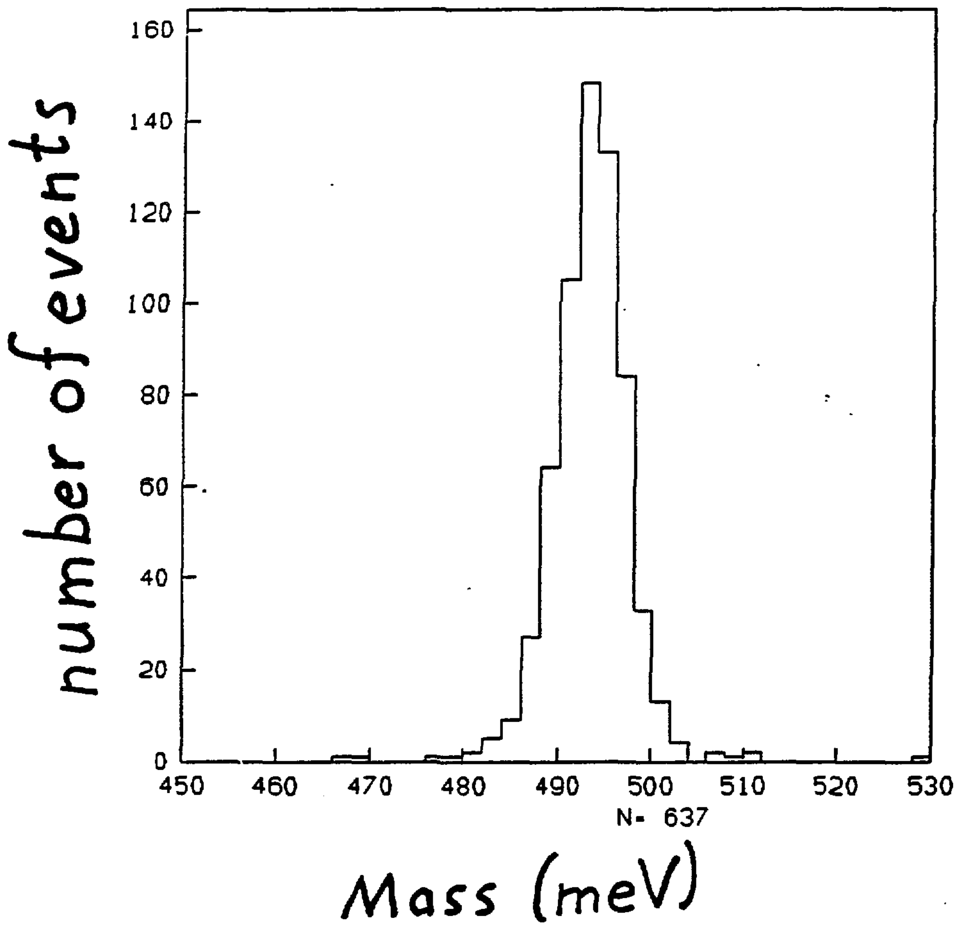

Figure 4: $\pi^+\pi^+\pi^-$ Invariant Mass Distribution

mass , M_{ee}, less than the π^0 mass were consistent with our Dalitz decay Monte Carlo. Figure 5, for example, shows a plot of M_{ee} for events with πee invariant masses between 400 MeV/c^2 and 470 MeV/c^2. The distribution shows the peaking at small M_{ee} as expected for the Dalitz decay matrix element smeared by our experimental resolution. We have also observed $K^+ \rightarrow \pi^+ e^+ e^-$ direct decays where M_{ee} is greater than 150 MeV/c^2. See Fig. 6. We note that the apparatus acceptance is greater for large M_{ee} than for small M_{ee}. The "Top Bottom" tigger requirement, of course, makes this acceptance difference larger. A plot showing the 90% confidence level limit on the branching ratio for $K^+ \rightarrow \pi^+ A^0$; $A^0 \rightarrow e^+ e^-$, is shown in Fig. 7. The limits are plotted as a function of A^0 lifetime for two A^0 masses. The 90% confidence level limit on the branching ratio is 4.5×10^{-7} for a 1.8 MeV/c^2 A^0 with a lifetime shorter than 10^{-13} seconds. When combined with the results of π^+ decay searches for the A^0 particle,[20] it can be used to rule out models of an axion variant that have been used to explain the e^+e^- peaks seen in havy ion collisions.[21] Particles decaying into e^+e^- consistent with the heavy ion results have not been seen in beam dump experiments as well.[22] These beam dump results when combined with the limits on the A^0 e^+e^- coupling from analysis of (g-2) experiments also appear to rule out the particle interpretation of the heavy ion e^+e^- energy peaks.[22] Our limit on A^0 production in K^+ decay is lower than the 10^{-4} branching ratio calculated for the standard model Higgs in Ref. 23, but it is larger than the branching ratio of 10^{-8} calculated by the authors of Ref. 24.

7 Future Plans

We are continuing to analyze our data for the decay $K^+ \rightarrow \pi^+ \mu^+ e^-$. We have sufficient statistics from our 1987 running to improve the present limit (5×10^{-9}) by an order of magnitude. We have accumulated about five times the present world sample of $K^+ \rightarrow \pi^+ e^+ e^-$ decays where M_{ee} is greater than M_{π^0}. We will also search our πee data for the decay $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow e^+ e^-$.

Our next run is scheduled for January 1988. By that time, we will have made changes to our beam line to reduce the flux of background tracks which, at present, limits the rate at which we can take data. We will add a high speed MPWC at the entrance to the decay volume. This will improve

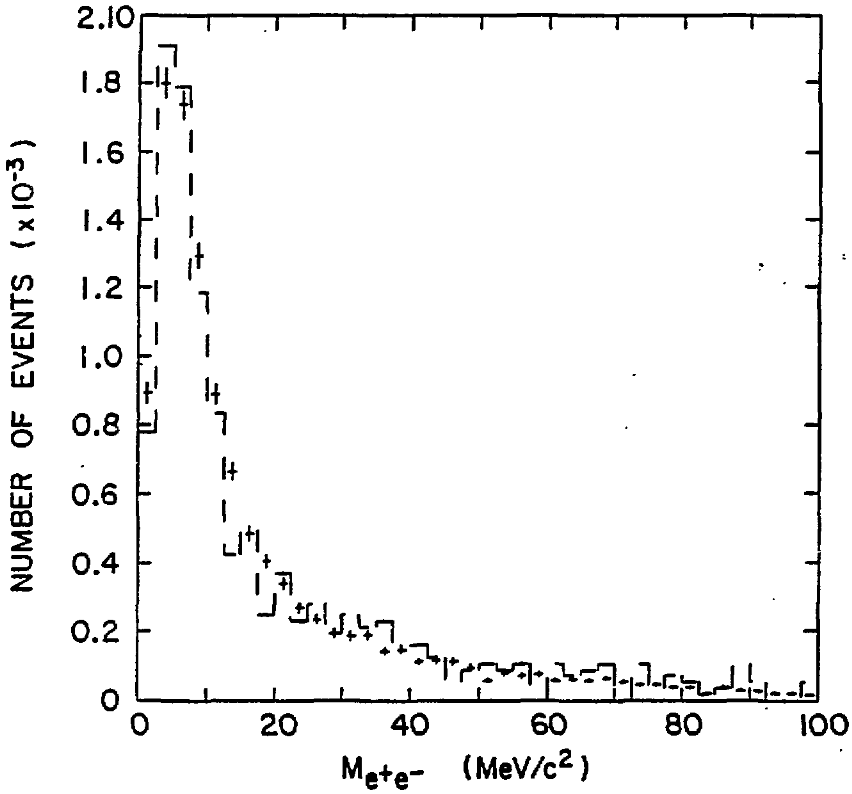

Figure 5: M_{ee} for $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$ Events. The points are our data; the dashed line is from our Dalitz decay Monte Carlo

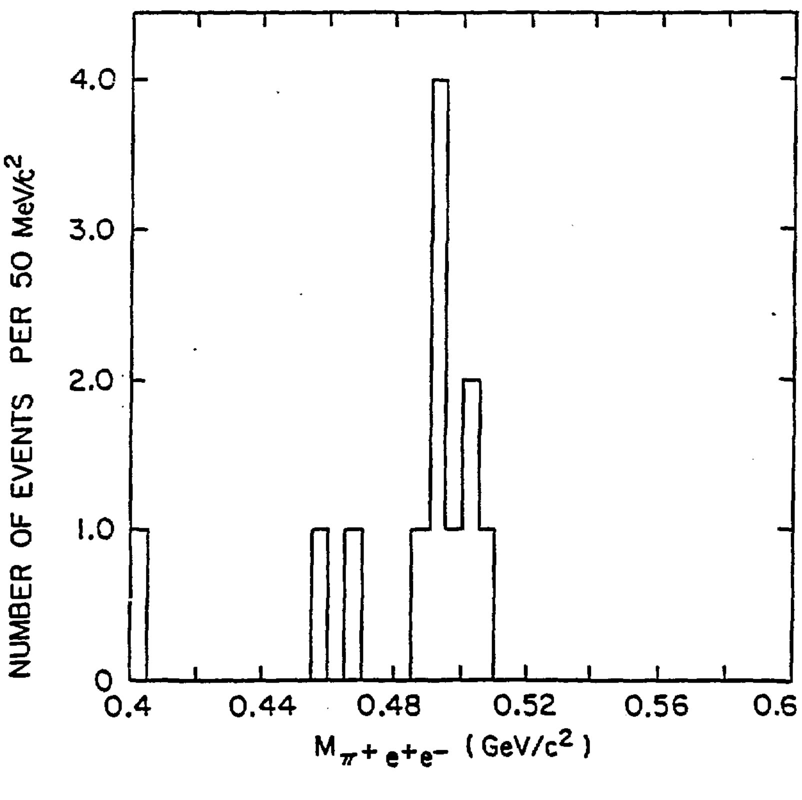

Figure 6: πee Invariant Mass. Events with $M_{ee} \geq 150$ MeV/c^2

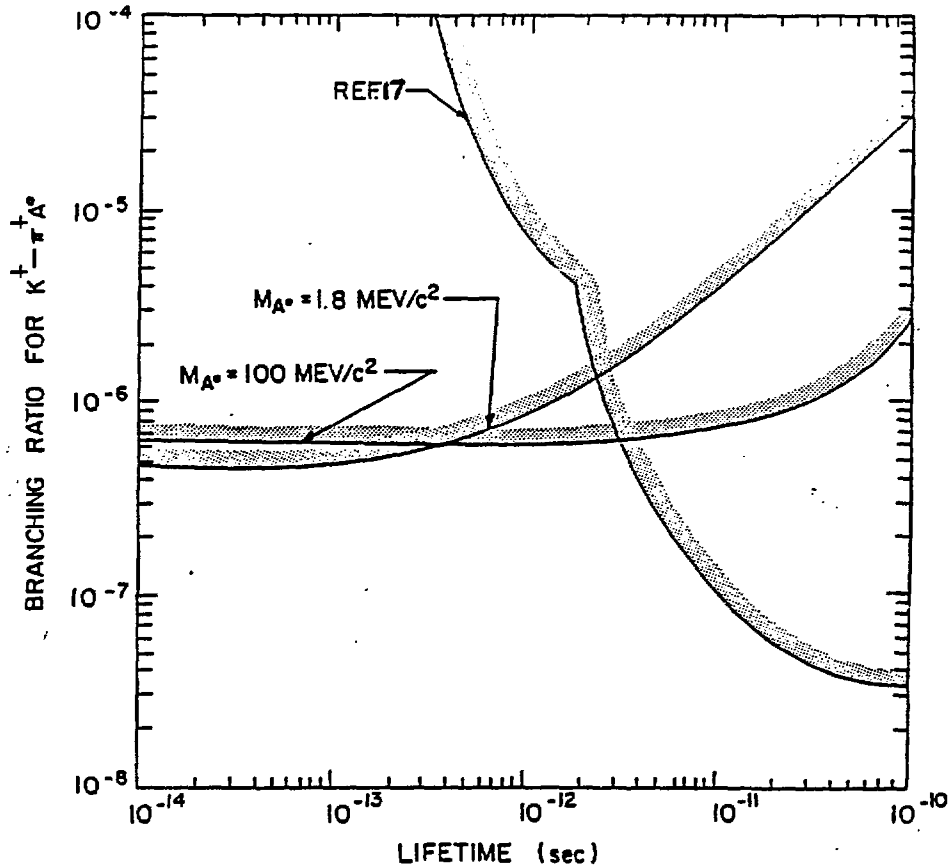

Fig 7: BR(A^0) for A^0 mass equal to 1.8 MeV/c^2 and 100 MeV/c^2 (this experiment), and for A^0 mass equal to 1.8 MeV/c^2 from Ref. 17 for data from Refs. 18 and 19. Areas above the respective lines are excluded with greater than a 90% confidence level.

our knowledge of the incident K^+ and, therefore, our mass resolution. It will also improve our ability to study K^+ decays with missing neutrals. We are also improving our data acquistion system by using Fermilab designed Smart Crate Controllers (SCC) to readout our CAMAC system. This will enable us to increase our data acquistion rate by a factor of three. More importantly, we will then be able to use the Fermilab Advanced Computer System (ACP) for online data processing. We will have 16 nodes of ACPs giving us the equivalent computing power online of three VAX 8600s. With these improvements, we expect to increase our sensitivity to $K^+ \to \pi^+\mu^+e^-$ to 8×10^{-11} at the 90% confidence level. At the same time, we will be able to examine about 2000 $K^+ \to \pi^+e^+e^-$ events, enough to perform a Dalitz plot analysis and to study the mechanism for this decay. We should also see 100 $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$ decays if the branching ratio is as now measured, and be able to improve the measurement of this branching ratio to the 10% level.

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