Limit on the Branching Ratio of $K_L \rightarrow \pi^0\mu^+\mu^-$

D. A. Harris, R. A. Briere, E. Cheu, G. Makoff,* K. S. McFarland, A. Roodman, B. Schwingenheuer, S. V. Somalwar,† Y. W. Wah, B. Winstein, and R. Winston
The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

K. Arisaka, D. Roberts, W. Slater, and M. Weaver
University of California at Los Angeles, Los Angeles, California 90024

A. R. Barker
University of Colorado, Boulder, Colorado 80309

E. C. Swallow
Elmhurst College, Elmhurst, Illinois 60126
and The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

G. J. Bock, R. Coleman, M. Crisler, J. Enagonio, R. Ford, Y. B. Hsiung, D. A. Jensen, E. Ramberg, and R. Tschirhart
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

E. M. Collins and G. D. Gollin
University of Illinois, Urbana, Illinois 61801

T. Nakaya and T. Yamanaka
Department of Physics, Osaka University, Toyonaka, Osaka, 560 Japan

P. Gu, P. Haas, W. P. Hogan, S. K. Kim,‡ J. N. Matthews, S. S. Myung,‡ S. Schnetzer, G. B. Thomson, and Y. Zou
Rutgers University, Piscataway, New Jersey 08855
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We report the results of a search for the decay $K_L \rightarrow \pi^0\mu^+\mu^-$ conducted by E799 at Fermilab. This decay mode is expected to have significant CP-violating contributions and a direct measurement could either confirm the standard model mechanisms for CP violation or point to physics beyond the standard model. No such events were seen. The 90% confidence level upper limit is determined to be $B(K_L \rightarrow \pi^0\mu^+\mu^-) < 5.1 \times 10^{-9}$.

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The decays $K_L \rightarrow \pi^0 l\bar{l}$ are useful for understanding the mechanisms of CP violation and are a potential window for observing non-standard-model effects. The possible contributions to these modes result from CP-conserving, indirectly CP-violating, and directly CP-violating processes. The CP-conserving contribution proceeds through the $K_L \rightarrow \pi^0\gamma^*\gamma^*$ intermediate state. The dominant indirect CP-violating contributions are due to the decay $K_1 \rightarrow \pi^0\gamma^*$, while the direct CP-violating amplitude has contributions from electroweak penguin diagrams and a W box diagram [1–3]. Predictions in non-standard-model theories can be significantly higher due to exotic massive particles contributing to the penguin diagrams [4].

The relative contributions from each process vary for different final state leptons. For example, in the decay $K_L \rightarrow \pi^0\nu\bar{\nu}$ the direct CP-violating process is the only significant contribution to the branching ratio and would therefore be theoretically the cleanest signal of direct CP violation [5]. However, measuring a final state with two neutrinos and a neutral pion is experimentally challenging, and the experimental limit is still 7 orders of magnitude above theoretical predictions [6]. For the decay $K_L \rightarrow \pi^0e^+e^-$ the CP-conserving contribution has been predicted to be at least an order of magnitude smaller than the CP-violating contributions [2,3], although there are also models which predict comparable CP-violating and CP-conserving rates [7]. Better measurements of the decay $K_L \rightarrow \pi^0\gamma\gamma$ are needed to discriminate among theoretical predictions. In the following article we present the results from the E799 search for this decay [8]. Finally, in the decay $K_L \rightarrow \pi^0\mu^+\mu^-$ all three processes are predicted to be of comparable size [2,7]. Before this measurement was made, the experimental upper limit for the electron mode was significantly lower than the limit involving muons, but both are still well above standard model predictions [9]. Although these decays are fully reconstructible, there is a significant background which

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becomes important at the level of standard model predictions, namely, the decay $K_L \rightarrow l^+l^-\gamma\gamma$ [10]. However, the background from $K_L \rightarrow \mu^+\mu^-\gamma\gamma$ relative to the CP-violating signal is expected to be more than a factor of 2 smaller [11] than the background from $K_L \rightarrow e^+e^-\gamma\gamma$ relative to $K_L \rightarrow \pi^0 e^+e^-$. Branching ratio predictions for $K_L \rightarrow \pi^0\mu^+\mu^-$ in the standard model are in the range $(3\text{–}6)\times10^{-12}$. The best experimental limit is 1.2×10^{-6} at the 90% confidence level [12]. Here we report the results from a much more sensitive search.

In experiment E799, two K_L beams were produced by interactions of 800 GeV protons from the Fermilab Tevatron in a beryllium target. The detector begins 120 m downstream of the target and was optimized for track reconstruction and electromagnetic calorimetry. As detailed descriptions of the detector can be found elsewhere [13,14], we describe here only the apparatus most pertinent to this analysis. Charged particle reconstruction was performed using four drift chambers, two on each side of an analysis magnet which gave a 200 MeV/c transverse momentum kick. The single hit resolution of the drift chambers was 100 μm, and the resulting momentum resolution was $(\sigma_p/p)^2 = (5\times10^{-3})^2 + (1.4\times10^{-4}(p[\text{GeV}/c]))^2$, where the first contribution was due to multiple scattering in material inside the spectrometer, and the second was from the chamber resolution. The average muon momentum in this analysis was about 20 GeV/c. Two trigger scintillator banks followed the drift chambers; one bank was segmented horizontally and one vertically. An electromagnetic calorimeter consisting of 804 lead-glass blocks which were $(5.8\text{ cm})^2 \times 18.7$ radiation lengths deep was used to measure photon energies. The π^0 mass resolution measured in $K_L \rightarrow \pi^+\pi^-\pi^0$ decays was about 6.0 MeV/c^2. Downstream of the calorimeter was a lead wall 1.0 interaction length deep, a steel muon filter 20 interaction lengths deep, and a muon trigger plane, consisting of 16 vertically oriented nonoverlapping counters, each measuring 8.75 cm$\times$108 cm. The efficiency of the muon trigger plane was about 99%, due to spaces between the counters.

The trigger for the decay $K_L \rightarrow \pi^0\mu^+\mu^-$ required at least two hits in each of the two scintillator banks located directly upstream of the calorimeter, two hits in nonadjacent counters in the muon trigger plane, and at least 6 GeV deposited in the calorimeter. The trigger also used a track processor which required that there be hits in the drift chambers consistent with two tracks. There were vetoes to reject events with charged particles escaping the detector fiducial region as well as a veto on events with photons or electrons of more than 3.5 GeV pointing down the beam holes of the lead-glass. Counters located immediately behind the lead wall rejected events with hadron showers originating in the calorimeter or the lead wall. A "minimum bias" trigger was also used in this analysis to select $K_L \rightarrow \pi^+\pi^-\pi^0$ decays which were used for normalization. This trigger required two hits in each of the scintillator banks upstream of the calorimeter, used the identical track processor requirement as the $\pi^0\mu^+\mu^-$ trigger, and vetoed events with charged particles escaping the detector fiducial region.

Events were first selected by looking for two tracks in the drift chambers which originated from a common vertex. Once the tracks were selected, the remaining clusters of energy in the lead-glass which did not have tracks pointing to them were considered photon candidates. Two of these candidates were then required to have been selected by an on-line hardware cluster finder which had a minimum cluster energy requirement of 2.5 GeV per cluster and a 20 ns gate rather than the 100 ns gate used for the calorimeter analog-to-digital converters. This requirement reduces background due to accidental photon candidates, because they tend to be lower in energy than real photons from $K_L \rightarrow \pi^0\mu^+\mu^-$ decays, and do not always arrive in time with the parent K_L decay. Once the final state particles were identified, various kinematic quantities could be calculated. If the only source of detector activity were due to K_L decays, this analysis would have been complete after making cuts on kinematic quantities such as the π^0 mass and the total invariant mass of the event. This, however, was not the case.

To conduct searches for decays at the 10^{-9} level the experiment ran with high intensity neutral beams. So, while there was a high flux of K_L's in the beam there were also neutrons and Λ's present. When considering backgrounds to the decay $K_L \rightarrow \pi^0\mu^+\mu^-$ in this experiment one must consider backgrounds from all three particles entering the detector. For example, when neutrons hit the lead-glass they sometimes produced hadronic showers which would pass the photon candidate requirements in the analysis. The products of Λ decay, namely, protons and pions, could sometimes pass the muon trigger requirements by showering in the muon filter. The most significant backgrounds due to K_L decays are $K_L \rightarrow \pi^\pm\mu^\mp\nu_\mu(\overline{\nu_\mu})$ ($K_{\mu3}$) in coincidence with two accidental photon candidates (possibly from neutrons), and $K_L \rightarrow \pi^+\pi^-\pi^0$. In these events a charged pion is misidentified as a muon, or a charged pion decays to a muon before it reaches the lead-glass. The average probability of a pion from a $K_L \rightarrow \pi^+\pi^-\pi^0$ event decaying in the detector before reaching the muon trigger bank is about 3% per pion. Although kinematic cuts greatly reduced the background from all of these processes, cuts on signals of accidental activity in the detector were also made.

To properly simulate backgrounds associated with accidental activity and to better understand detector acceptance, this activity was included in the Monte Carlo simulation. During the course of the run accidental triggers were taken using a muon telescope pointed at the target but outside the acceptance of the rest of the detector. The events accepted by this trigger were correlated with proton beam intensity but uncorrelated with K_L decays in the fiducial region. These accidental events were then embedded in both the signal and normalization Monte Carlo events before they were analyzed.

To discriminate between muons and pions or protons a cut was made on the energy in the lead-glass blocks closest to the projected position of the muon at the calorimeter. The sum of the energies in the nine closest blocks (in a 3×3 array) constituted the muon cluster energy. Since a minimum ionizing particle should leave about 0.7 GeV in the lead-glass, the muon cluster energy was required to be less than 3.0 GeV. In the case where a muon hit one of the lead-glass blocks surrounding the two beam holes, a "pipe block," where there was the most accidental activity, this cut was loosened to 5.0 GeV. Overall this cut induced 10% losses due to accidental energy in the glass, but greatly reduced contamination from charged pions. Events with tracks that did not extrapolate to the muon trigger bank were rejected, as were events without muons energetic enough to traverse both the lead wall and the muon filter.

Aside from muon identification cuts there were also fiducial cuts and cuts on the self-consistency of the event. Events with photons or tracks within 6 mm of the beam holes in the lead-glass were rejected. To discriminate against events in which a charged pion decays in the chamber system, tight track-quality cuts were made. For example, a cut was made requiring the two segments of a given track (upstream and downstream of the analysis magnet) to extrapolate to the same position at the plane of the magnet, to within 3σ. Events where both tracks extrapolated to the pipe blocks were rejected since the muon identification cuts there are less effective at discriminating against pions. Events with bremsstrahlung photons were eliminated by cutting on the minimum angle in the lab between a track upstream of the analysis magnet and a photon candidate. Finally, there was a maximum track momentum cut at 70 GeV to reduce background from protons from Λ decays which typically have higher momenta. Kinematic cuts were the most effective for eliminating background from real decays, since the good π^0 mass resolution and track momentum resolution allowed tight π^0 and total invariant mass cuts. The two tracks in the event were treated as the products of a $\Lambda \to p\pi$ decay, and the event was rejected if the reconstructed $p\pi$ invariant mass was within 10 MeV/c^2 of the Λ mass. To reject events not containing real π^0's, a χ^2 was formed for the hypothesis that the two photons in the event were from a π^0 decaying at the track vertex. A χ^2 cut was used rather than a π^0 mass cut to account for varying energy resolutions in the lead glass. A χ^2 of less than 8.0 for 2 degrees of freedom was required. The $\pi^0\mu^+\mu^-$ invariant mass and the component of momentum transverse to the initial K_L direction (P_t) were then computed using a kinematic fit which constrained the invariant $\gamma\gamma$ mass to the nominal π^0 mass.

Figure 1 shows the P_t^2 versus total invariant mass for all the remaining $K_L \to \pi^0\mu^+\mu^-$ candidates. Signal events were required to have a P_t^2 of less than

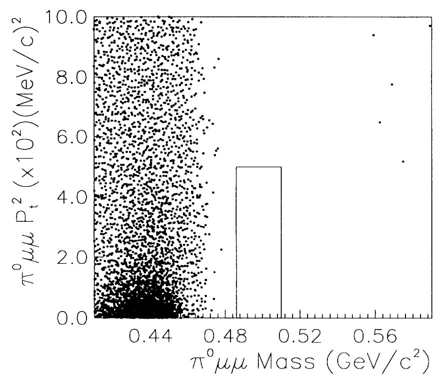

FIG. 1. The total P_t^2 versus the total invariant mass of $K_L \to \pi^0\mu^+\mu^-$ candidates. The box shows the 3σ cuts used in the analysis.

500 (MeV/c)^2 (a 3σ cut), and a reconstructed $\pi^0\mu^+\mu^-$ invariant mass within 15 MeV/c^2 of the K_L mass (also a 3σ cut). The events at low mass are consistent with being from $K_L \to \pi^+\pi^-\pi^0$ events. Those few events at high mass contain significant accidental activity and are consistent with $K_{\mu 3}$ decays with two accidental photons. Figure 2 shows the mass distribution for all events after the P_t^2 cut, for both data and $K_L \to \pi^0\mu^+\mu^-$ Monte Carlo simulation. There are no candidate events in the signal region. To compute the single-event sensitivity for this decay mode, the acceptance for the decay $K_L \to \pi^0\mu^+\mu^-$ was compared with the acceptance for the decay $K_L \to \pi^+\pi^-\pi^0$ and the number of $K_L \to \pi^+\pi^-\pi^0$ decays observed in the minimum bias trigger. Since the normalization decay is kinematically similar to the signal, the analysis cuts were almost identical; only the cuts on the muon cluster energy and the muon trigger requirements were not made on the normalization sample. These differences in acceptance were studied in the Monte Carlo

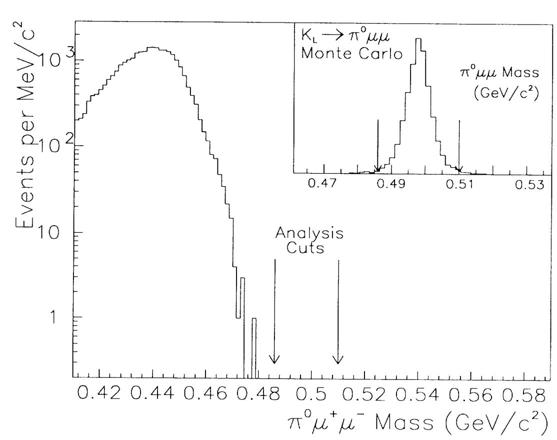

FIG. 2. The invariant mass of all $K_L \to \pi^0\mu^+\mu^-$ candidates. The arrows indicate the mass cut chosen in the analysis. The inset is the mass plot after all cuts for the $K_L \to \pi^0\mu^+\mu^-$ Monte Carlo simulation.

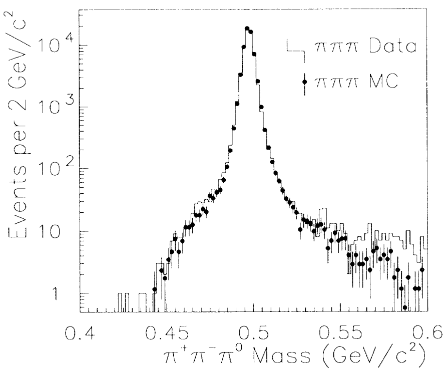

FIG. 3. The invariant mass of all $K_L \to \pi^+\pi^-\pi^0$ candidates for both data and Monte Carlo simulation.

simulation, and their uncertainties are included in the systematic error on the single-event sensitivity. Figure 3 shows the reconstructed K_L mass distribution for all $K_L \to \pi^+\pi^-\pi^0$ candidates after all cuts except the invariant mass cut were made, for both the data and the Monte Carlo simulation.

The dominant systematic errors were due to the different trigger requirements in the signal and normalization mode. In particular, the hadron shower veto and muon trigger plane requirement were both present in the $K_L \to \pi^0\mu^+\mu^-$ trigger but not in the minimum bias trigger. Well-identified muons from the proton beam dump were used to measure the efficiencies of both the muon trigger plane and the hadron shower veto. The efficiency of the muon trigger bank was measured as a function of extrapolated track position at the bank and muon momentum. The uncertainty in muon trigger efficiencies contributes a 2.5% uncertainty to the $K_L \to \pi^0\mu^+\mu^-$ acceptance. The hadron shower veto threshold and counter response as a function of the extrapolated muon position were also measured and included in the Monte Carlo simulation. Although the hadron shower veto efficiency was well understood for single muons the efficiency for muon pairs is the important quantity in this analysis. The largest systematic error in the analysis is due to the small number of available events with muon pairs which were used to check the hadron shower veto efficiency. This efficiency was $(55 \pm 5)\%$ and therefore contributed a 9.1% systematic error to the $K_L \to \pi^0\mu^+\mu^-$ acceptance.

Other systematics considered were the effects of uncertainties in the understanding of the calorimeter, such as the effect of varying the energy scales, lead-glass gains and pedestals, and the effects of momentum scale and resolution uncertainties in the charged spectrometer; the total systematic error from these sources is 0.6%. All sources of error were added in quadrature to obtain a total systematic error of 9.4%.

After all cuts were made on both the $K_L \to \pi^+\pi^-\pi^0$ sample and the $K_L \to \pi^0\mu^+\mu^-$ sample, there were 50 352 candidate $K_L \to \pi^+\pi^-\pi^0$ events in the minimum bias sample. Using the Monte Carlo simulation we determine the acceptance for the decay $K_L \to \pi^+\pi^-\pi^0$ to be 4.26%, and for $K_L \to \pi^0\mu^+\mu^-$ to be $(1.4 \pm 0.1)\%$, where the $K_L \to \pi^0\mu^+\mu^-$ decay was generated with a phase-space distribution. For both decay modes the acceptances quoted are for K_L's with a momentum between 20 GeV/c and 220 GeV/c and which decayed between 90 m and 160 m downstream of the target. Given that the minimum bias trigger was taken with a prescale of 3600, and taking the branching ratio of $K_L \to \pi^+\pi^-\pi^0$ to be 0.1238 ± 0.0021 [15], the single-event sensitivity for the decay $K_L \to \pi^0\mu^+\mu^-$ is therefore $[2.2 \pm 0.01(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-9}$. The 90% confidence level limit on the branching ratio, taking into account both statistical and systematic errors, is 5.1×10^{-9}. This measurement represents an improvement in $K_L \to \pi^0\mu^+\mu^-$ sensitivity of over a factor of 200. Since this measurement is not dominated by background, similar experiments (for example, E799, Phase II) should be able to achieve still higher sensitivities in the future.

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* Present address: Solomon Brothers, New York City, New York 10048.

† Present address: Rutgers University, Piscataway, New Jersey 08855.

‡ Present address: Seoul National University, Seoul 151-742, Korea.

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