FERMILAB-Conf-99/266-E
KTeV/E832-E799

New Rare Decay Results from KTeV

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October 1999

Published Proceedings of the *Chicago Conference on Kaon Physics-Kaon 99*,
Chicago, Illinois, June 21-26, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

New Rare Decay Results from KTeV

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October 15, 1999

Abstract

Recent rare decay results from the KTeV fixed target experiment at Fermilab are shown. Results of searches for the CP violating decay modes $K_L^0 \to \pi^0 e^+ e^-$, $K_L^0 \to \pi^0 \mu^+ \mu^-$, and $K_L^0 \to \pi^0 \nu\overline{\nu}$ are presented. In addition, new branching ratio measurements of $K_L^0 \to \pi^0 \gamma\gamma$, $K_L^0 \to e^+ e^- \gamma\gamma$, and the first observation of the decay $K_L^0 \to \mu^+ \mu^- \gamma\gamma$ are discussed.

1 Introduction

KTeV (Kaons at the TeVatron) is a fixed target experiment at Fermilab designed to study the properties of the neutral kaon system. The experimental program has two main experimental goals: to make a precision measurement of the direct CP violation parameter ϵ'/ϵ via decays of neutral kaons into two pions [1] and to search for the direct CP violating rare decay $K_L^0 \to \pi^0 e^+ e^-$ with a factor of 50 improvement in sensitivity over the previous measurement. In this article, we present results on the family of CP violating rare decays $K_L^0 \to \pi^0 \ell\overline{\ell}$. We also discuss a new branching ratio measurement of $K_L^0 \to e^+ e^- \gamma\gamma$ and a first observation of the decay $K_L^0 \to \mu^+ \mu^- \gamma\gamma$.

The rare decays presented in this article contain leptons and photons in the final state; the salient features for detecting these particles in KTeV will be described below. The plan view of the KTeV detector in the E799-II configuration is shown in Fig. 1. Neutral beams are produced by striking a BeO target with an 800 GeV proton beam. The neutral beam passes through a series of collimators, a Pb absorber which converts photons, and a series of sweeping magnets which bend the charged particles out of the beamline. Two nearly parallel neutral kaon beams, composed mainly of kaon and neutrons (~1:1) with a small contamination of hyperons, then enter the 65m

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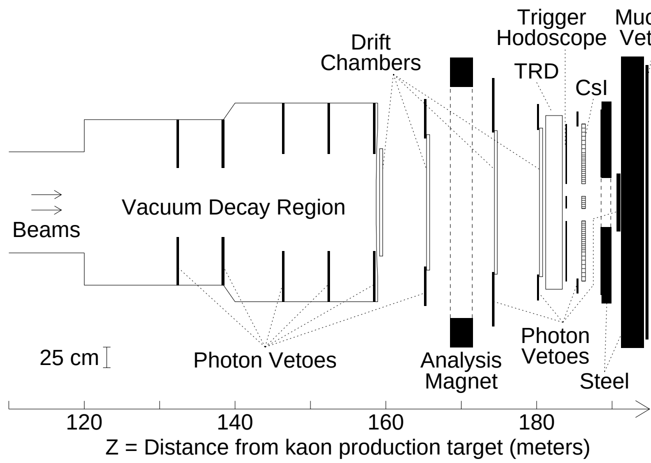

Figure 1: The plan view of the KTeV detector in the E799-II configuration.

vacuum decay region where approximately 5% of the kaons decay. The range of K_L^0 momenta is 20-200 GeV/c. The charged spectometer consists of 4 planar drift chambers, two located upstream and two downstream, of an analysis magnet which imparts a 205 GeV/c transverse momentum kick to the charged particles. A pure CsI calorimeter provides electron identification and photon energy measurements. Additional electron identification information comes from a set of 8 transition radiation detectors (TRD). Muons are identified with two banks of orthogonal scintillation counters located downstream of 3m of filter steel. Photon veto detectors line the vacuum decay region and the perimeters of the drift chambers and CsI and form the defining aperture of the fiducial region. All analyses described below with the exception of the decays $K_L^0 \to \pi^0 \nu\overline{\nu}$ ($\pi^0 \to 2\gamma$) and $K_L^0 \to \pi^0\gamma\gamma$ are based on the 1997 E799-II data set which contained 2.7E11 kaon decays. The $K_L^0 \to \pi^0 \nu\overline{\nu}$ ($\pi^0 \to 2\gamma$) analysis used a special 1 day run which corresponded to 6.8E7 K_L decays. The data for the $K_L^0 \to \pi^0\gamma\gamma$ measurement were collected during the 1996-97 E832 running period and include 5.9E10 kaon decays.

Theoretical predictions [2, 3] for the direct and indirect CP violating components as well as the CP conserving part of the $K_L^0 \to \pi^0 \ell\overline{\ell}$ branching ratios are listed in Table 1.

Mode	Direct CPV	Indirect CPV	CP Conserving
$B(K_L^0 \to \pi^0 \nu\overline{\nu})$	3×10^{-11}	$\sim 10^{-15}$	$\sim 2 \times 10^{-15}$
$B(K_L^0 \to \pi^0 e^+e^-)$	5×10^{-12}	$1 - 5 \times 10^{-12}$	$1 - 2 \times 10^{-12}$
$B(K_L^0 \to \pi^0 \mu^+\mu^-)$	1×10^{-12}		$0.5 - 10 \times 10^{-12}$

2 $K_L^0 \to \pi^0 \nu\overline{\nu}$

The theoretical calculation of the branching ratio for $K_L^0 \to \pi^0 \nu\overline{\nu}$ is dominated by short distance diagrams, allowing theoretical determination with few uncertainties. The direct CP violating component to the branching ratio is predicted to be

$$B(K_L^0 \to \pi^0 \nu\overline{\nu})_{DIR} = (\tfrac{m_t}{m_W})^{2.2} A^4 \eta^2 \sim 3 \times 10^{-11} \text{ [4]},$$

where m_t is the top mass, m_W is the W mass, A and η are variables from the Wolfenstein parametrization of the CKM matrix, in which η governs CP violation and represents the height of the unitarity triangle.

While the $K_L^0 \to \pi^0 \nu\overline{\nu}$ mode is compelling because it is predominantly direct CP violating, it is experimentally challenging. The more prevalent decay mode with $\pi^0 \to 2\gamma$ has significant backgrounds because the kinematics make it difficult to reconstruct the event. If the Dalitz decay of the π^0 is used to tag the event, the decay vertex helps constrain the event but there is a factor of ~ 100 reduction in acceptance due to the branching ratio and the detector geometry. KTeV has set branching ratio limits using both π^0 decay modes. The measurement using $\pi^0 \to 2\gamma$ is based on a dedicated special run in which a single kaon beam was used and events with high transverse momentum were selected. After all cuts, the single event sensitivity (SES) is 4.0×10^{-7}. One event is found in the signal region, which is consistent with the expectation from neutron interactions in material in the detector. Assuming the event is signal, we set an upper limit of

$$B(K_L^0 \to \pi^0 \nu\overline{\nu}, \pi^0 \to 2\gamma) < 1.6 \times 10^{-6} \text{ (90\% C.L.) [5]}.$$

This represents a first time measurement using this decay chain. Using the full KTeV data set with the Dalitz decay tag, the SES for $K_L^0 \to \pi^0 \nu\overline{\nu}$ is 2.6×10^{-7} after all cuts and after correcting for the Dalitz decay branching ratio. A plot of the transverse momentum of the data along with overlays from signal Monte Carlo and Monte Carlo from the most prevalent backgrounds ($\Lambda \to n\pi^0$ and $\Xi \to \Lambda\pi^0$) is shown in Fig. 2; there are no events in the signal region. The preliminary upper limit set using the Dalitz decay of the π^0 is

$$B(K_L^0 \to \pi^0 \nu\overline{\nu}, \pi^0 \to e^+e^-\gamma) < 5.9 \times 10^{-7} \text{ (90\% C.L.) [6]},$$

a factor of 100 improvement over the previous measurement [7]. Assuming experimental inputs for the top and W masses and the Wolfenstein parameter A, the branching ratio limit implies $\eta < 52$.

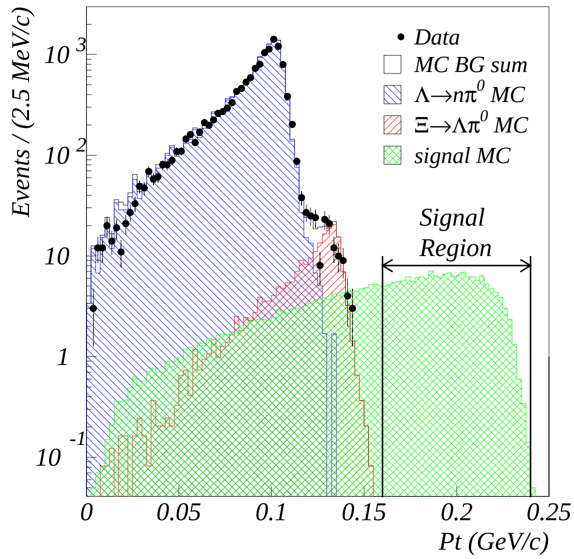

Figure 2: P_T distribution for $K_L^0 \to \pi^0 \nu \overline{\nu}$ ($\pi^0 \to e^+e^-\gamma$) with all cuts except the P_T cut. Signal and background Monte Carlo are overlayed on data. There are no events in the signal region.

3 $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to e^+e^-\gamma\gamma$

Although the decay $K_L^0 \to \pi^0 e^+ e^-$ is a fundamentally easier mode to select because the final state can be fully reconstructed, it is not a pure direct CP violating decay and it has a serious background from $K_L^0 \to e^+e^-\gamma\gamma$. The indirect CP violating and CP conserving amplitudes (see Table 1) are comparable in size to the direct CP violating contribution and must be understood before the direct CP violation component can be determined.

The CP conserving amplitude can be estimated from theory and from a measurement of the effective vector coupling, a_v, from $K_L^0 \to \pi^0\gamma\gamma$ [8]. KTeV accumulated a sample of $K_L^0 \to \pi^0\gamma\gamma$ events during E832 running. After all analysis cuts are applied, a significant excess in the low mass region of the 2γ invariant mass distribution from $K_L^0 \to \pi^0\gamma\gamma$ decays is apparent and indicates contributions in the Chiral Perturbation Model from vector meson exchange calculations [9]. The normalization mode for this measurement is $K_L^0 \to \pi^0\pi^0$. The branching ratio for $K_L^0 \to \pi^0\gamma\gamma$ is

$$B(K_L^0 \to \pi^0\gamma\gamma) = (1.68 \pm 0.07(stat.) \pm 0.08(syst.)) \times 10^{-6},$$

representing a factor of 3 improvement over previous results [7]. From the shape of the 2γ invariant mass distribution, the effective vector coupling is determined to be $-0.72 \pm 0.05 \pm 0.06$ and inidicates a contribution from the CP conserved amplitude of the $B(K_L^0 \to \pi^0 e^+ e^-)$ of $1 - 2 \times 10^{-12}$.

The background limiting mode to the decay $K_L^0 \to \pi^0 e^+ e^-$ comes from the radiative Dalitz decay, $K_L^0 \to e^+ e^- \gamma\gamma$, which KTeV also has measured. The previous measurement of the branching ratio for $K_L^0 \to e^+ e^- \gamma\gamma$ was based on 58 events and yielded $(6.5 \pm 1.3) \times 10^{-6}$ [7]. The major backgrounds to $K_L^0 \to e^+ e^- \gamma\gamma$ come from $2\pi^0$ decays in which one π^0 Dalitz decays and $K_L^0 \to e^+ e^- \gamma$ with an accidental photon. The new measurement has 1988 events in the signal region with a background estimate of 76.6 ± 3.3 events. With a photon energy cutoff of 5 GeV, the preliminary measurement of the branching ratio [10] is

$$B(K_L^0 \to e^+ e^- \gamma\gamma, E_\gamma \leq 5 GeV) = (6.31 \pm 0.14(stat.) \pm 0.42(syst.)) \times 10^{-7},$$

roughly an order of magnitude improvement over the previous measurement.

In addition to $K_L^0 \to e^+ e^- \gamma\gamma$, there are backgrounds from radiative $K_L^0 \to \pi^\pm e^\mp \overline{\nu}$ decay with an accidental photon, $K_L^0 \to \pi^\pm e^\mp \overline{\nu}$ decay with an accidental π^0, $3\pi^0$ ($2\pi^0$) decay in which two(one) pion(s) Dalitz decays, and $K_L^0 \to \pi^+ \pi^- \pi^0$ decay with $\pi^\pm$ misidentified as $e^\pm$. The modes which contain a Dalitz decay are easily rejected by cutting on the invariant mass of the $e^+ e^-$ pair. Modes in which charged pions mimic electrons are reduced through the excellent π/e separation in the calorimeter and TRDs. Event selection criteria includes requiring that the $e^+ e^-$ came from a good vertex and that the photons form a π^0. The event also is required to have small transverse momentum squared (P_t^2) with respect to the kaon direction.

The remaining background after all cuts have been applied comes from $K_L^0 \to e^+ e^- \gamma\gamma$, which is reduced with cuts on kinematic variables (see Fig. 3). One such variable is $Cos(\Theta_\pi)$, the direction of the photon with respect to the direction of the π^0 (defined by a momentum vector opposite the $e^+ e^-$ pair) in the pion rest frame. This variable is flat for $K_L^0 \to \pi^0 e^+ e^-$ decays since the π^0 is a spinless particle and the photons emerge back to back, while it is peaked near 0 for $K_L^0 \to e^+ e^- \gamma\gamma$ since the non-Bremsstrahlung photon tends to go off in the direction opposite the electron-positron pair. A second variable that is used to distinguish signal from background is Θ_{MIN}, the angle between the photon and the nearest e^+ or e^-. This variable is flat for the signal mode and peaked near 0 for the Bremsstrahlung photon in $K_L^0 \to e^+ e^- \gamma\gamma$. A lego plot of $|Cos(\Theta_\pi)|$ versus Θ_{MIN} from signal and background Monte Carlo is also shown in Fig. 3. The plot on the left in Fig. 4 shows the 2γ invariant mass versus the $e^+ e^- \gamma\gamma$ invariant mass with all cuts applied except those specific to suppressing $K_L^0 \to e^+ e^- \gamma\gamma$. The long box is populated by $K_L^0 \to \pi^0 \pi^0 \pi^0$ event fragments in which one $\pi^0 \to 2\gamma$ while the other two π^0s Dalitz decayed. Events in the low M($e^+ e^- \gamma\gamma$) and low M(2γ) region are from $K_L^0 \to \pi^\pm e^\mp \overline{\nu}$ decays with accidental γs in which the π is misidentified. The band near the signal region is $K_L^0 \to e^+ e^- \gamma\gamma$.

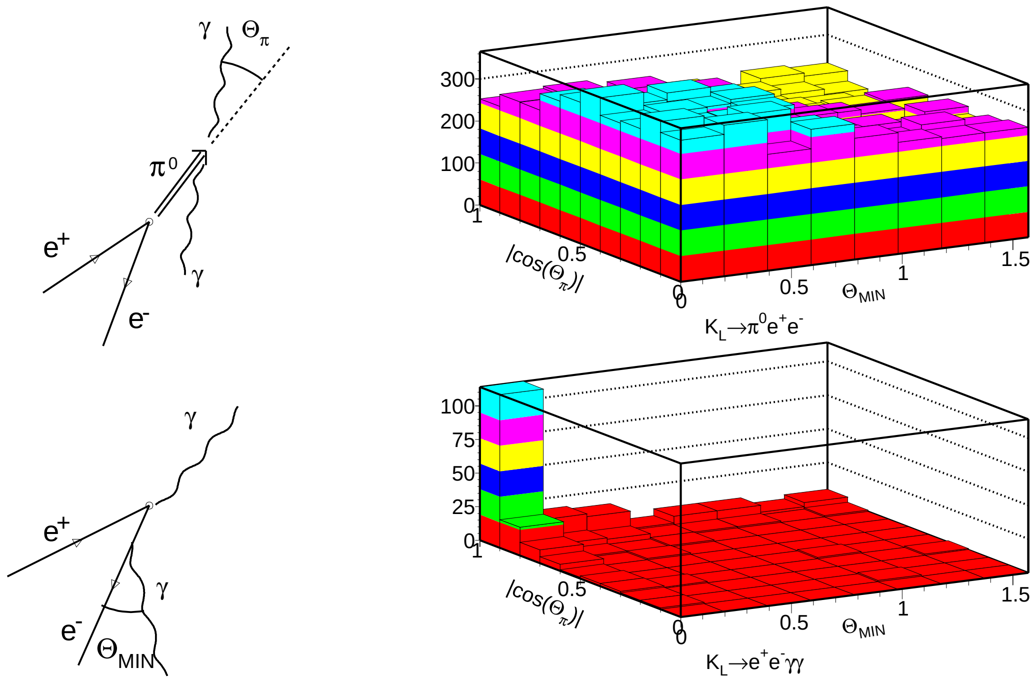

Figure 3: Diagrams defining the kinematic variables $|COS(\Theta_{\pi})|$ vs. Θ_{MIN} and Monte Carlo lego plots of these variables for $K_L^0 \to \pi^0 e^+ e^-$ (upper) and $K_L^0 \to e^+ e^- \gamma\gamma$ (lower).

The small box hides the signal region. A Monte Carlo background estimate predicts 1.51 ± 0.44 events in the signal region from $K_L^0 \to e^+ e^- \gamma\gamma$. After all cuts, the SES is measured to be 1.26×10^{-10}. The right side of Fig. 4 reveals the signal box after all cuts have been applied. There are 2 events observed in the signal region which are consistent with background. We quote a preliminary measurement of the upper limit [11] of

$$B(K_L^0 \to \pi^0 e^+ e^-) < 5.64 \times 10^{-10} \text{ (90\% C.L) [10]},$$

roughly an order of magnitude improvement over the previous limit. If we assume that the only contribution to the branching ratio comes from direct CP violation and we take the experimental inputs of m_t, m_W, and the Wolfenstein paramter A, we find $\eta < 5$.

4 $K_L^0 \to \pi^0 \mu^+ \mu^-$ and $K_L^0 \to \mu^+ \mu^- \gamma\gamma$

Like the electron mode, the decay $K_L^0 \to \pi^0 \mu^+ \mu^-$ is a probe of direct CP violation, although the direct CP violating component is small relative to the CP conserving component. In addition to the challenges of measuring a very small branching ratio, there is potential background from $K_L^0 \to \mu^+ \mu^- \gamma\gamma$, which has a branching ratio calculated to be $(9.1 \pm 0.8) \times 10^{-9}$.

The event selection requires that 2 photons form a π^0 and that a good

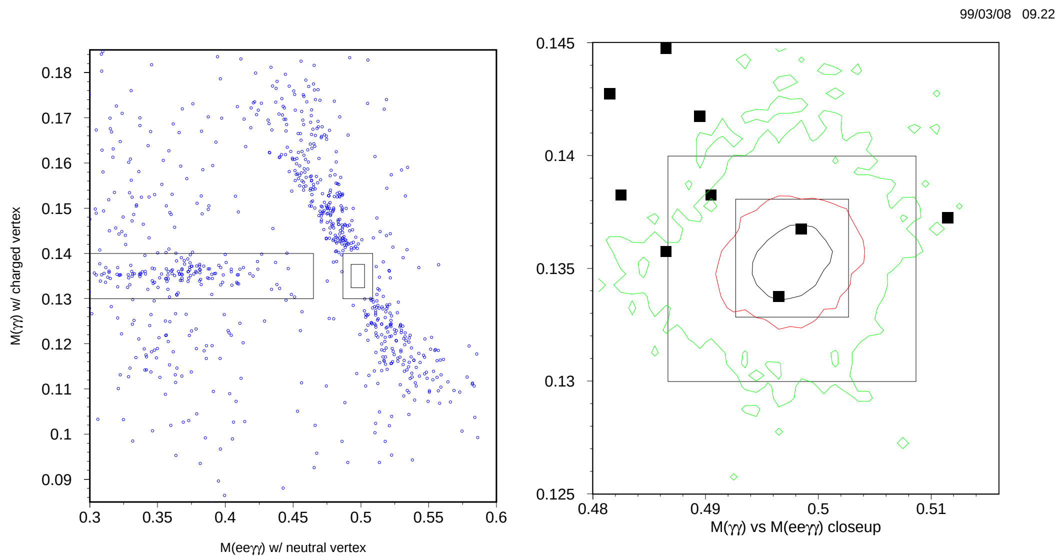

Figure 4: The left plot is the reconstructed $M(2\gamma)$ versus $M(e^+e^-\gamma\gamma)$ invariant masses with all cuts applied except kinematic cuts suppressing $e^+e^-\gamma\gamma$. The small box hides the signal region. The plot on the right shows the signal region box after all cuts have been applied. The curves are 68.27%, 94.45% and 99.73% contours of the signal Monte Carlo. There are 2 events in the signal region.

vertex is reconstructed from two oppositely charged tracks which leave minimum ionizing deposits (MIP) in the calorimeter and fire the muon counters. Backgrounds come from pion punch-through from $K_L^0 \to \pi^+\pi^-\pi^0$, pion decay-in-flight from $K_L^0 \to \pi^+\pi^-\pi^0$, and $K_L^0 \to \pi^\pm\mu^\mp\overline{\nu}$ decay with 2 accidental photons. The most significant single background comes from $K_L^0 \to \mu^+\mu^-\gamma\gamma$ and is estimated to be 0.343 ± 0.048 events in the signal region. The angular cuts which were used to reduce the background from $K_L^0 \to e^+e^-\gamma\gamma$ decays in the $K_L^0 \to \pi^0 e^+e^-$ analysis are less effective for the muon mode, since the photon and muon directions are less correlated and thus are not used in this analysis. The SES for this mode corresponds to a branching ratio of 7×10^{-10}. The total background contribution is expected to be 1.02 ± 0.18 events. The normalization mode for this measurement is $K_L^0 \to \pi^+\pi^-\pi^0$. Fig. 5 shows the invariant mass spectrum. There are 2 events in the signal region which are consistent with background. We set a preliminary upper limit on the branching ratio of

$$B(K_L^0 \to \pi^0\mu^+\mu^-) < 3.4 \times 10^{-10} \text{ (90\% C.L.) [12]},$$

which is an order of magnitude improvement over the previous measurement.

The decay $K_L^0 \to \mu^+\mu^-\gamma\gamma$ is of interest because it is expected to be a dangerous background to $K_L^0 \to \pi^0\mu^+\mu^-$ and it has never before been

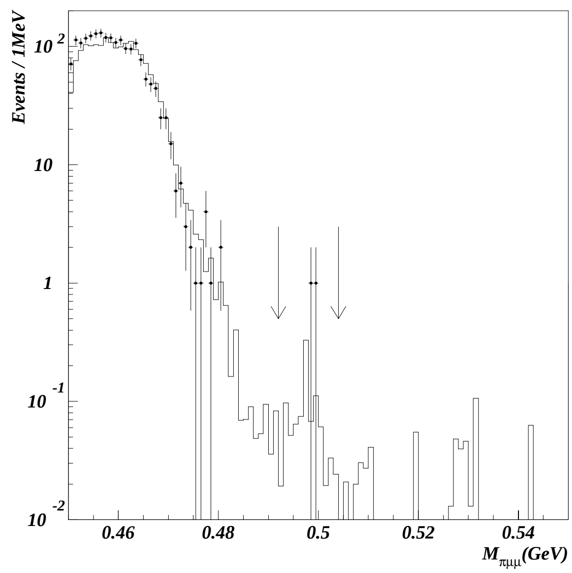

Figure 5: The M($\pi^0\mu^+\mu^-$) invariant mass distribution. Signal and background Monte Carlo (histogram) are overlayed on data (dots). The signal region is indicated by arrows.

observed. The QED prediction for the branching ratio is $(9.1 \pm 0.78) \times 10^{-9}$. Candidate events are required to have two photons which do not reconstruct as a π^0, and a good vertex formed from two tracks which MIP in the calorimeter and fire the muon counters. Backgrounds come from $K_L^0 \to \pi^\pm\mu^\mp\overline{\nu}$ decay with two accidental photons and $K_L^0 \to \mu^+\mu^-\gamma$ decay with one accidental photon. Since accidental photons tend to be of low energy, these backgrounds can be reduced by a cut on the minimum photon energy. The total contribution from backgrounds is estimated to be 0.155 ± 0.081 events. The normalization mode is $K_L^0 \to \pi^+\pi^-\pi^0$. A plot of the invariant mass is shown in Fig. 6. Four events are within the signal region, significantly above predicted background levels. The branching ratio is presented in two ways. In order to compare this with the QED prediction, the branching ratio is calculated with a 1 MeV/c^2 cutoff in the 2γ invariant mass during Monte Carlo generation and is found to equal

$$B(K_L^0 \to \mu^+\mu^-\gamma\gamma, M_{\gamma\gamma} > 1\ MeV/c^2) = (10.4^{+7.5}_{-5.9}(stat.) \pm 1.0(syst.)) \times 10^{-9},$$

and is consistent with theoretical prediction. Finally, the preliminary measurement of the branching ratio [13] using a 10 MeV infrared cutoff for photon energies in the kaon rest frame is

$$B(K_L^0 \to \mu^+\mu^-\gamma\gamma, E_\gamma^* > 10\ MeV) = 1.42^{+1.02}_{-0.81}(stat.) \pm 0.14(syst.)) \times 10^{-9}.$$

This constitutes a first observation of this decay mode.

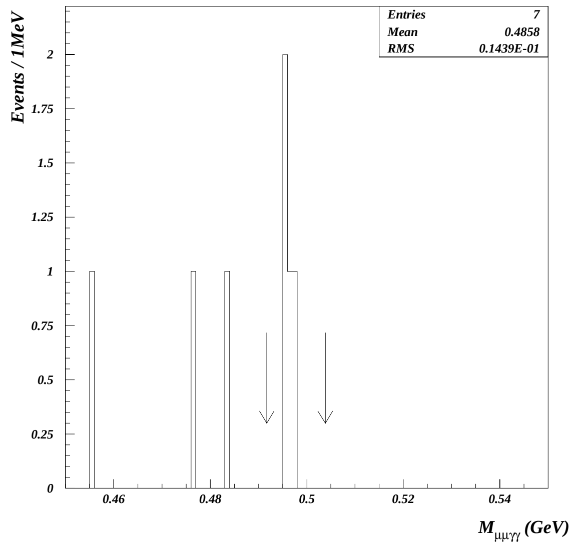

Figure 6: The M($\mu^+\mu^-\gamma\gamma$) invariant mass distribution in data. The signal region is indicated by arrows.

5 Summary and Future Outlook

KTeV has improved its branching ratio measurements of $K_L^0 \to e^+e^-\gamma\gamma$ and set new upper limits for the branching ratios of the direct CP violating decays $K_L^0 \to \pi^0\nu\overline{\nu}$, $K_L^0 \to \pi^0 e^+e^-$, and $K_L^0 \to \pi^0\mu^+\mu^-$. All of these results represent approximately an order of magnitude improvement over previous measurements. KTeV also has made the first measurement of the branching ratio $K_L^0 \to \mu^+\mu^-\gamma\gamma$.

KTeV's rare decay program has been approved for an additional 10 week run starting in October 1999, with the goal of collecting three times the statistics of the 1997 run. With the gain in statistics from the 1999 run and a single event sensitivity on the order of 2×10^{-11} for the charged lepton modes, KTeV will start to probe the branching ratio regions predicted when including possible enhancements from SUSY contributions. [14] In addition to near term improvements on the $K_L^0 \to \pi^0\ell\overline{\ell}$ modes, there is a rare decay program which has been proposed at Fermilab which will use a neutral kaon beam from the Main Injector. The main goal of the experiment, KAMI, is to collect roughly a hundred $K_L^0 \to \pi^0\nu\overline{\nu}$ events. [15]

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