Rare decays of the K_L and π^0: New results from E799-II and E832[1]

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Abstract. Recent rare decay results from Fermilab experiments E799-II and E832 (the KTeV experiments) are shown. Results of searches for the direct CP-violating decay $K_L \to \pi^0 \nu\bar{\nu}$ are given, as well as measurements of the decays $K_L \to \pi^0\gamma\gamma$ and $K_L \to \pi^0 e^+e^-\gamma$, which provide information on CP-conserving contributions to $K_L \to \pi^0 e^+e^-$. A new measurement of the rare decay $\pi^0 \to e^+e^-$ is also presented; this result is the first significant measurement of the excess rate above the unitarity limit for this mode.

INTRODUCTION

We present rare decay results from Fermilab experiments E799-II and E832 (the KTeV experiments). A measurement of the rare decay $\pi^0 \to e^+e^-$ is presented. Direct CP-violation in rare kaon decays is discussed, including measurement of the CP-conserving decay $K_L \to \pi^0\gamma\gamma$ and searches for $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\nu\bar{\nu}$.

E799-II and E832, two neutral kaon experiments, took data in the 1996-97 Tevatron fixed target run. The two experiments used the same beamline and spectrometer in different configurations. E799-II was a high-rate experiment designed to search for rare K_L decays, primarily those with two leptons and one or more photons in the final state. The primary goal of the experiment was to search for $K_L \to \pi^0 e^+e^-$ with about 50 times the sensitivity of its predecessor experiment, E799-I. The primary goal of E832 was to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ to a precision of $\sim 10^{-4}$. The current status of this measurement is described in a separate paper from this conference [1]. Certain rare decay measurements were performed in E832 as well.

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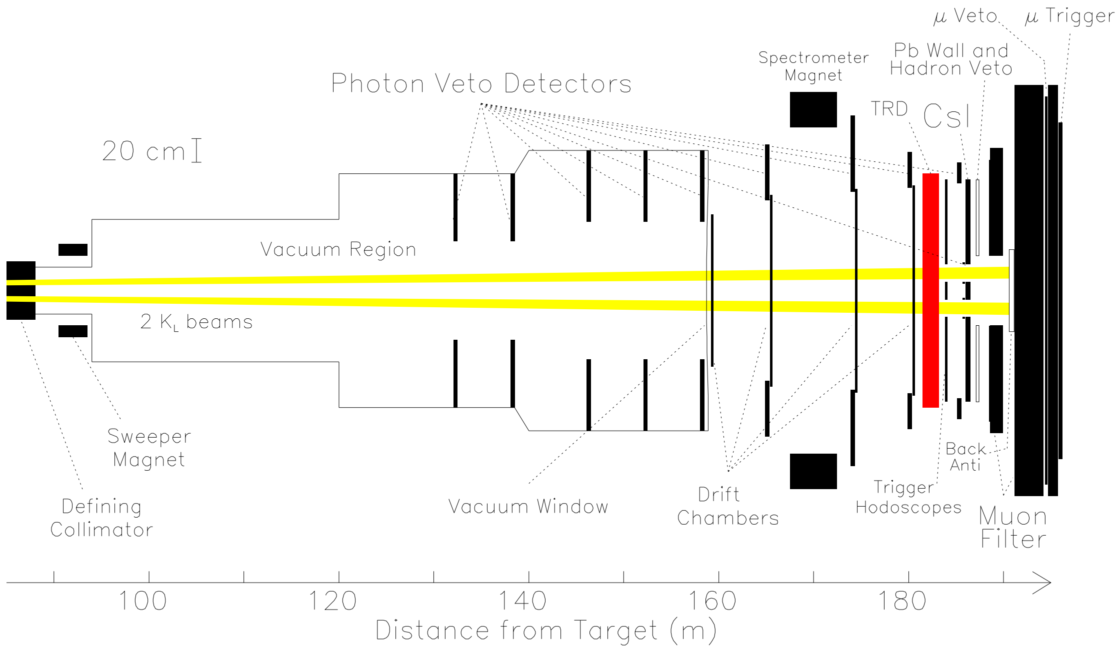

FIGURE 1. Plan view of the decay region and the spectrometer configured for E799-II. The horizontal scale is compressed.

THE E799-II/E832 SPECTROMETER

The experiments used two nearly-parallel neutral kaon beams produced by 800 GeV protons which struck a BeO target. The neutral beams were defined by a series of collimators; photons were converted by a lead absorber, and charged particles were removed by a series of sweeping magnet. The beams traveled through a 65 meter vacuum decay region, where approximately 5% of the K_L decayed. The beams in the decay region were composed mostly of neutrons and K_L, with small numbers of K_S, Λ^0, $\bar{\Lambda}^0$, Ξ^0, $\bar{\Xi}^0$. These short-lived particles tended to decay upstream. The K_L momentum ranged from ~ 20 to ~ 200 GeV/c.

The decay region and the detector are shown in Fig. 1, in the E799-II configuration. The charged-particle spectrometer consisted of four drift chambers, each with two orthogonal views, and a spectrometer magnet between the second and third chamber which bent charged particles in the horizontal direction. A pure cesium iodide calorimeter (CsI) provided electron identification and photon energy measurement. Photon veto detectors lined the vacuum region and the perimeter of each drift chamber; these detectors defined the fiducial region. The primary difference between E799-II and E832 was a regenerator in the decay region which reintroduced a K_S component to one beam in E832 only. In addition, an extra photon veto detector called the "mask anti" (MA) was placed immediately upstream of the regenerator in E832 to reject upstream decays. The E832 configuration is shown in Ref. [1]. In E799-II, a set of transition radiation detectors (TRD) provided

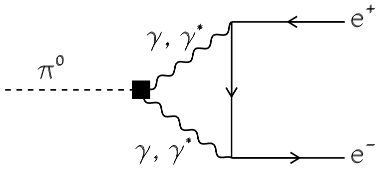

FIGURE 2. Feynman diagram of the Standard Model electromagnetic contribution to $\pi^0 \to e^+e^-$.

additional electron identification.

THE DECAY $\pi^0 \to e^+e^-$

E799-II has performed rare π^0 decay studies using the copious $K_L \to 3\pi^0$ decay. Here we present a new result on the decay $\pi^0 \to e^+e^-$. This decay has received theoretical and experimental attention for nearly four decades, since Drell first calculated its branching ratio in 1959 [2]. The decay is helicity suppressed, and is expected to proceed predominantly through a two-photon intermediate state (Fig. 2). The decay rate can be expressed in terms of the $\pi^0\gamma^*\gamma^*$ form factor, and contains a contribution from off-shell internal photons as well as from on-shell photons. The contribution from on-shell photons is exactly calculable in QED, and yields the *unitarity bound* [3], a lower limit on the decay rate:

$$\frac{\mathrm{BR}(\pi^0 \to e^+e^-)}{\mathrm{BR}(\pi^0 \to \gamma\gamma)} \geq 4.75 \times 10^{-8}$$

ignoring final-state radiative corrections. The off-shell photon contribution should manifest itself as an excess above unitarity, providing a constraint on the $\pi^0\gamma^*\gamma^*$ form factor. Corrections from electron bremsstrahlung can produce a $e^+e^-\gamma$ final state with $m_{e^+e^-} < m_{\pi^0}$, indistinguishable from the Dalitz decay (tree-level $\pi^0 \to e^+e^-\gamma$). We therefore impose a cutoff $(m_{e^+e^-}/m_{\pi^0})^2 > 0.95$, selecting the region where the Dalitz decay rate is very small. The branching ratio for $\pi^0 \to e^+e^-$with this cutoff is 13.5% lower than it would be in the absence of all radiative corrections [4].

The E799-II analysis identified events with two electron candidates (charged tracks with $E/p \approx 1$) and four photon clusters (CsI clusters with no tracks pointing to them), and no more than 0.4 GeV in any photon veto counter. The four photons were paired as two $\pi^0 \to \gamma\gamma$ decays: of the three possible pairing combinations, we selected the one with the best χ^2 for the hypothesis that the two π^0 decays occured at the same distance from the calorimeter, using the π^0 mass as a constraint. This χ^2 was required to be less than 4.5 (with one degree of freedom). Events were required to reconstruct with total transverse momentum $|p_T| < 30$ MeV/c, and total mass $|m_{\pi^0\pi^0e^+e^-} - m_{K^0}| < 10$ MeV/c^2. Four-electron events (multiple

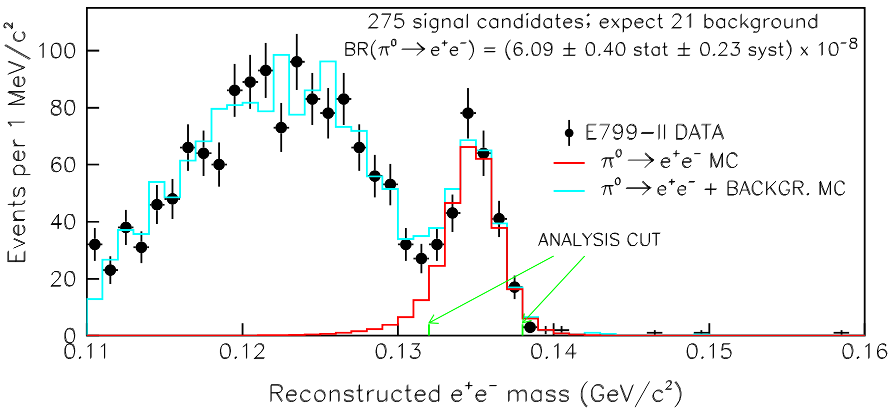

FIGURE 3. $m_{e^+e^-}$ spectrum for $\pi^0 \to e^+e^-$ candidate events. Background MC is normalized to data in the region $0.110 < m_{e^+e^-} < 0.125$ GeV/c^2. There are 275 candidates in the signal region.

Dalitz decays, or photon conversions in the vacuum window), where two electrons were removed by the spectrometer magnet, were a major background; these were removed by cutting events which had extra in-time activity in the second drift chamber. Finally, $\pi^0 \to e^+e^-$ candidates were required to have electron pair mass $|m_{e^+e^-} - m_{\pi^0}| < 6$ MeV/c^2.

After all cuts, there were 275 $\pi^0 \to e^+e^-$ candidates in the data.; the Monte Carlo (MC) estimated a residual background of 21.4 ± 6.2 events. About 85% of the background was from high-$m_{e^+e^-}$ Dalitz decays, with four-electron modes accounting for the rest. The $\pi^0 \to e^+e^-$ sample was normalized to the $\pi^0 \to e^+e^-\gamma$ sample, canceling out any uncertainty in the $K_L \to 3\pi^0$ branching ratio. The branching ratio for $\pi^0 \to e^+e^-$ was found to be:

$$\mathrm{BR}(\pi^0 \to e^+e^-, (m_{e^+e^-}/m_{\pi^0})^2 > 0.95) = (6.09 \pm 0.40_{(\mathrm{stat})} \pm 0.24_{(\mathrm{syst})}) \times 10^{-8}$$

Note that this is a preliminary result.

The largest component of the systematic error was the 2.7% uncertainty in the branching ratio of the normalization mode, followed by a 2.4% systematic error resulting from the uncertainty in the background. This measurement represents a factor of four improvement over the current PDG average. Fig. 4 summarizes the existing measurements.

The number stated above is the physical branching ratio for the decay. In order to compare this result to the unitarity bound and to models which ignore radiative corrections, we invert the radiative corrections and extrapolate this measurement to the "lowest-order" rate (what the branching ratio would be if there were no

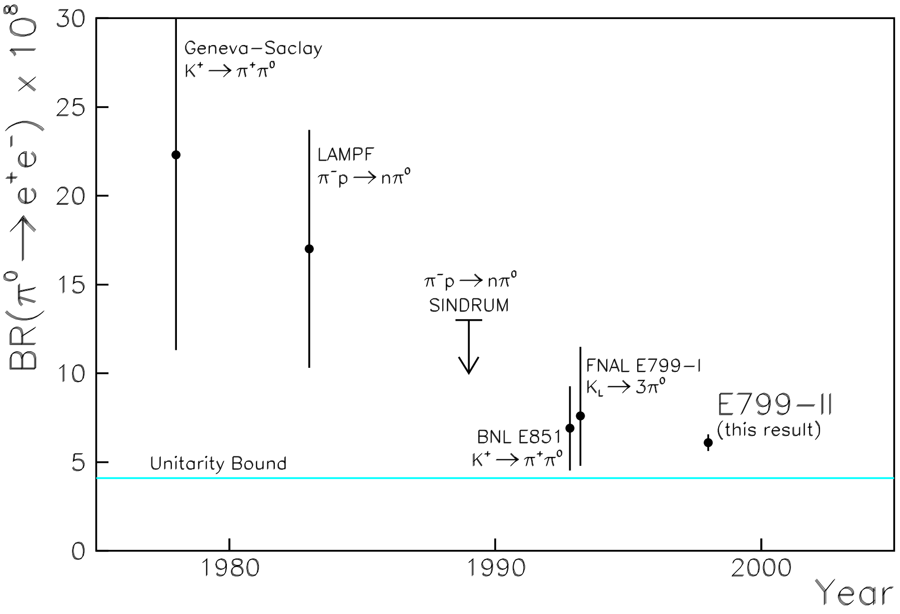

FIGURE 4. Measurements of the branching ratio of $\pi^0 \rightarrow e^+e^-$, including this preliminary result.

final-state radiation). This yields

$$\frac{\Gamma^{\text{lowest order}}_{e^+e^-}}{\Gamma_{\text{all}}} = (7.04 \pm 0.46_{(\text{stat})} \pm 0.28_{(\text{syst})}) \times 10^{-8}$$

which is over four standard deviations above the unitarity bound. This result is in reasonably good agreement with recent Chiral Perturbation Theory (χPT) [5] [6] and Vector Meson Dominance (VMD) [7] models.

CP-VIOLATION SEARCHES IN FCNC K_L DECAYS

The flavor-changing neutral current decays $K_L \rightarrow \pi^0\ell\bar{\ell}$ have been considered promising avenues to search for direct CP-violation. Although these decays are very rare, direct CP-violating weak penguin and W box diagrams are expected to make significant contributions to them. In addition, it has recently been suggested [8] that supersymmetric extensions to the Standard Model could produce large enhancements to these decay rates.

E799-II is searching for all three of these decays ($K_L \rightarrow \pi^0\mu^+\mu^-$, $K_L \rightarrow \pi^0e^+e^-$, $K_L \rightarrow \pi^0\nu\bar{\nu}$). The status of the latter two is described here, as well as a preliminary measurement from E832 of $K_L \rightarrow \pi^0\gamma\gamma$, a CP-conserving decay which is used to calculate long-distance contributions to $K_L \rightarrow \pi^0e^+e^-$.

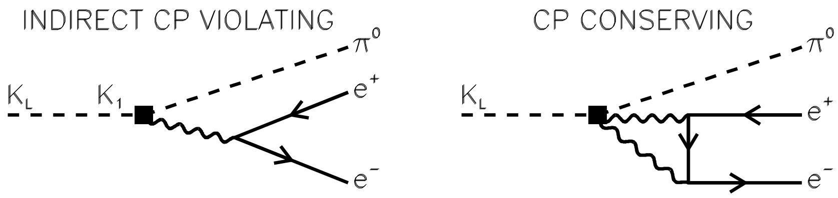

FIGURE 5. Long-distance contributions to $K_L \to \pi^0 e^+ e^-$.

The decay $K_L \to \pi^0 e^+ e^-$

Direct CP-violating diagrams are expected to contribute to the decay $K_L \to \pi^0 e^+ e^-$ at the level of $\sim 4 \times 10^{-12}$ [9]. Here we present the status of the search for direct CP-violation in this mode.

Experimental situation on $K_L \to \pi^0 e^+ e^-$

The current experimental limit on $K_L \to \pi^0 e^+ e^-$ is [10] $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) < 4.3 \times 10^{-9}$; this result is from E799-I. E799-II expects to achieve a single-event sensitivity of $\mathcal{O}(10^{-10})$ from the data collected in 1997. The analysis is currently in progress. The major background to this mode [11] is expected to be the radiative Dalitz decay $K_L \to e^+ e^- \gamma\gamma$ ($K_L \to e^+ e^- \gamma$ with a hard bremsstrahlung photon). This mode has a much higher branching ratio than $K_L \to \pi^0 e^+ e^-$, and can be indistinguishable from the signal if the two photons have invariant mass $m_{\gamma\gamma} \approx m_{\pi^0}$.

Other contributions to $K_L \to \pi^0 e^+ e^-$

Unfortunately, direct CP-violation is not the only Standard Model contribution to $K_L \to \pi^0 e^+ e^-$. Long-distance processes (Fig. 5) can contribute to the decay at comparable rates.

An indirect CP-violating component can arise from an intermediate $\pi^0 \gamma^*$ state, which proceeds through the CP-even (K_1) component of the K_L. Theoretical expectations for this process are currently imprecise and model-dependent [12]. This contribution to $K_L \to \pi^0 e^+ e^-$ could, however, be limited or measured by searching for the decay $K_S \to \pi^0 e^+ e^-$ with a sensitivity of $\mathcal{O}(10^{-9})$. The current limit on this decay is $\mathrm{BR}(K_S \to \pi^0 e^+ e^-) < 1.1 \times 10^{-6}$ [13]. It is hoped that E832, KLOE, and NA48 can make substantial improvements to this limit.

The $K_L \to \pi^0 \gamma\gamma$ intermediate state produces a CP-conserving component to $K_L \to \pi^0 e^+ e^-$. The two photons can be in either a relative S-wave or a D-wave. When the photons are in an S-wave, the $\gamma\gamma \to e^+ e^-$ process is helicity suppressed (as in $\pi^0 \to e^+e^-$), making this contribution to $K_L \to \pi^0 e^+e^-$ very small. However, when the photons are in a D-wave, the process is helicity-allowed and may contribute significantly ($\gtrsim 10^{-12}$) to $K_L \to \pi^0 e^+e^-$.

$K_L \to \pi^0\gamma\gamma$

The decay $K_L \to \pi^0\gamma\gamma$ has been calculated in χPT to $\mathcal{O}(p^6)$ [14]. The D-wave component of the $\gamma\gamma$ spectrum in this decay is dominated by vector-meson exchange, which is parameterized by the quantity a_V. In E832, we have measured the branching ratio of the $K_L \to \pi^0\gamma\gamma$ decay, and analyzed its decay spectrum to estimate a_V and the CP-conserving contribution to $\pi^0 \to e^+e^-$.

The analysis required events with exactly four CsI clusters and no tracks. The four photons were constrained to form the kaon mass, giving the decay distance from the calorimeter. Assuming this decay position, the $\gamma\gamma$ invariant mass of each pair of photons was calculated. The pair which came closest to the π^0 mass was selected. If the other pair also formed a π^0 mass, the event was considered $K_L \to 2\pi^0$ and rejected from the $K_L \to \pi^0\gamma\gamma$ sample.

The major background came from $K_L \to 3\pi^0$ decays with either missing decay products or "fused" photons (photons which struck the CsI very close together, and merged to form a single cluster). These were rejected by requiring very little energy deposited in the photon vetoes, and by requiring that the transverse shape of each photon cluster was consistent with a single electromagnetic shower. Another background was multiple π^0 and η production in detector material. Events were rejected if they were consistent with $\pi^0\pi^0$ or $\pi^0\eta$ production at the vacuum window or farther downstream.

The $m_{\gamma\gamma}$ distribution of the remaining 907 events is shown in Fig. 6. The estimated background was 111 ± 14 events. Normalizing to $K_L \to 2\pi^0$, we found the branching ratio:

$$\mathrm{BR}(K_L \to \pi^0\gamma\gamma) = (1.76 \pm 0.06_{(\mathrm{stat})} \pm 0.09_{(\mathrm{syst})}) \times 10^{-6}.$$

This preliminary result is in agreement with the previous measurement of $(1.7 \pm 0.3) \times 10^{-6}$ from the NA31 experiment [15].

Our result provides the first firm evidence for the low-$m_{\gamma\gamma}$ tail ($m_{\gamma\gamma} < 0.240$ GeV/c^2) which is dominated by vector meson exchange. A fit to the distribution of the kinematic parameters of the decay gives $a_V = -0.77 \pm 0.06$. Given the model of Ref. [14], this translates into a CP-conserving component to $K_L \to \pi^0 e^+e^-$ of $(1-2) \times 10^{-12}$, somewhat smaller than the expected direct CP-violating component.

The decay $K_L \to \pi^0\nu\bar{\nu}$

The decay $K_L \to \pi^0\nu\bar{\nu}$ is expected to proceed via direct CP-violating weak penguin and W box diagrams, analagous to $K_L \to \pi^0 e^+e^-$ [16]. However, CP-

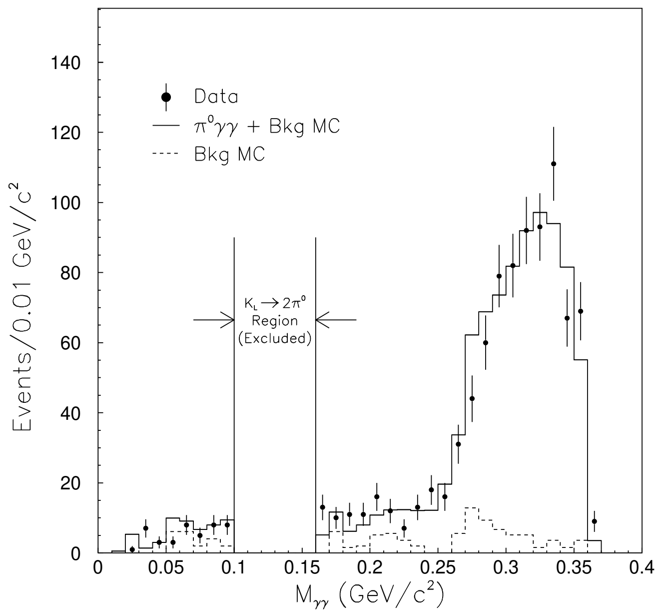

FIGURE 6. $m_{\gamma\gamma}$ distribution for candidate $K_L \rightarrow \pi^0\gamma\gamma$ events in E832 data and MC.

conserving and indirect CP-violating long-distance physics cannot contribute significantly to this decay because the neutrinos cannot couple directly to photons. This makes the decay theoretically straightforward. In the Wolfenstein parameterization of the CKM matrix, the branching ratio of $K_L \rightarrow \pi^0\nu\bar{\nu}$ is directly proportional to the phase η^2. The decay is expected to occur at the level of $(1-5)\times 10^{-11}$. The uncertainty is in the measured parameters; the theoretical uncertainty is only about 1% [17], making this decay one of the best potential measurements of η.

Of course, although $K_L \rightarrow \pi^0\nu\bar{\nu}$ is theoretically very clean, it presents a formidable experimental challenge. The signature of the decay is an isolated π^0 with high p_T (up to 231 MeV/c); there are, of course, many potential backgrounds.

$K_L \rightarrow \pi^0\nu\bar{\nu}$ searches using $\pi^0 \rightarrow e^+e^-\gamma$

The most sensitive searches to date for $K_L \rightarrow \pi^0\nu\bar{\nu}$ have used the $\pi^0 \rightarrow e^+e^-\gamma$ decay. This method is expensive, as the $\pi^0 \rightarrow e^+e^-\gamma$ branching ratio is only 1.2%, and the experimental acceptance is low due to the small opening angle between the tracks in a Dalitz decay. However, being able to reconstruct a charged vertex, and hence both the π^0 mass *and* the decay position, allows much improved background rejection.

In E799-II, we identified events with an isolated $\pi^0 \rightarrow e^+e^-\gamma$ decay inside the vacuum decay region. The major backgrounds to this search included the K_{e3}

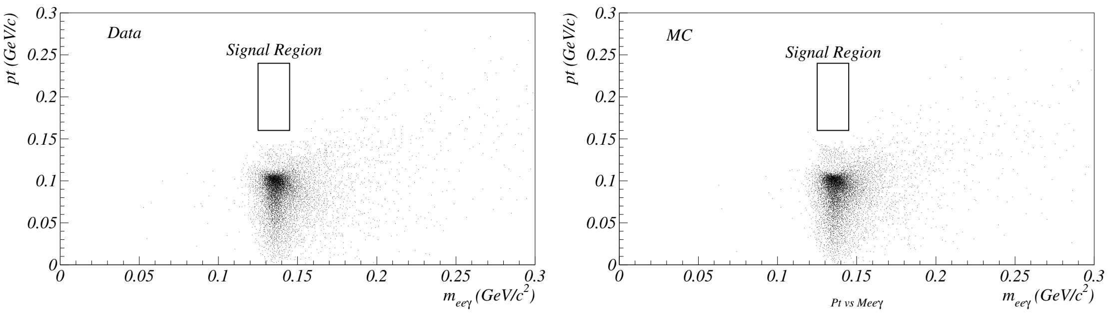

FIGURE 7. $e^+e^-\gamma$ mass vs. $|p_T|$ for $K_L \to \pi^0\nu\bar{\nu}$, $\pi^0 \to e^+e^-\gamma$ data (left) and background MC (right).

($K_L \to \pi^\pm e^\mp \nu$) decay with an extra photon and the pion misidentified as an electron. This background was reduced by making tight particle identification requirements using the CsI and TRD, as well as kinematic cuts which rejected high-$m_{e^+e^-}$ events. Other backgrounds came from $K_L \to 3\pi^0$ and $K_L \to 2\pi^0$, with one π^0 Dalitz decay and multiple lost particles. These were removed by tight cuts requiring no energy in the photon veto detectors. Hadronic interactions in the detector could produce multiple π^0's with high p_T; these were rejected by requiring the reconstructed decay vertex to be at least 8 meters upstream of the vacuum window. Finally, hyperon decays ($\Lambda^0 \to n\pi^0$ and $\Xi^0 \to \Lambda^0\pi^0$) with secondary or tertiary $\pi^0 \to e^+e^-\gamma$ decays presented backgrounds, as the detector did not have efficient neutron detection. These were removed by requiring $|p_T| > 160$ MeV/c, above the kinematic cutoff for hyperon decays. This cut cost nearly half of the signal acceptance.

After all cuts, our single event sensitivity (SES) for $K_L \to \pi^0\nu\bar{\nu}$, $\pi^0 \to e^+e^-\gamma$ was 3.1×10^{-9}. Dividing by the Dalitz decay branching ratio, the SES for all $K_L \to \pi^0\nu\bar{\nu}$ decays was 2.6×10^{-7}. The expected background was 0.12 events. The data and background MC are shown in Fig. 7. No events were observed in the data; this yields the preliminary E799-II limit:

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) < 5.9 \times 10^{-7} \quad (90\%\ \mathrm{C.\ L.})$$

which is a factor of 100 improvement over the current PDG value.

$K_L \to \pi^0\nu\bar{\nu}$ search using $\pi^0 \to \gamma\gamma$

For the same number of kaon decays in our experiment, our single-event sensitivity for $K_L \to \pi^0\nu\bar{\nu}$ would have been over three orders of magnitude better using the $\pi^0 \to \gamma\gamma$ decay mode than using $\pi^0 \to e^+e^-\gamma$. However, the backgrounds (and the trigger rate) would have been prohibitive. To search for $K_L \to \pi^0\nu\bar{\nu}$ using the $\pi^0 \to \gamma\gamma$ mode, a one-day special run was taken with one beam closed off, and the remaining beam reduced in solid angle by a factor of 6.

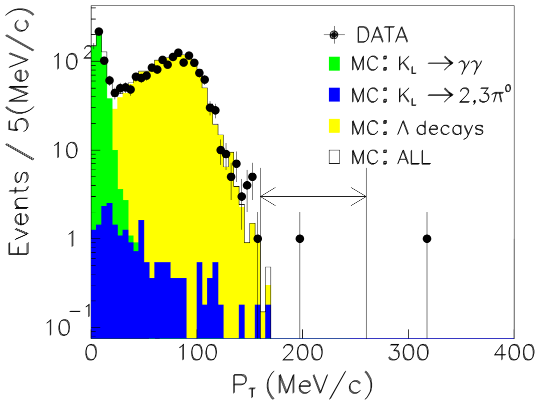

FIGURE 8. $|p_T|$ distribution of $K_L \to \pi^0\nu\bar{\nu}$, $\pi^0 \to \gamma\gamma$ sample.

The analysis required events with two isolated CsI clusters (photons) and no in-time activity in any other detector element. The two photons were constrained to form a π^0 mass, and the decay position of the π^0 had to fall within the vacuum decay region. The π^0 had to have $160 < p_T < 260$ MeV/c to reject background from hyperons and $K_L \to \gamma\gamma$ decays. Very tight cuts were applied to remove events with energy in the photon vetoes. Figure 8 shows the distribution of p_T for events which pass all other cuts.

The single event sensitivity for $K_L \to \pi^0\nu\bar{\nu}$ was 4.0×10^{-7}. One event was observed, which was consistent with the expectation from neutron interactions producing multiple π^0's or η's in the detector material. However, in calculating the limit, we made the conservative assumption that the event is signal, obtaining

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) < 1.6 \times 10^{-6} \quad (90\% \text{ C. L.}).$$

This result is described in detail in Ref. [18].

CONCLUSIONS

The KTeV experiments have a broad program of rare kaon and pion decay studies. Many interesting decay modes, which have not been described here, are being studied or searched for. A partial list includes $K_L \to \pi^0\mu^+\mu^-$, $K_L \to \pi^0 e^+e^-\gamma$, $K_L \to \pi^0 e^\pm\mu^\mp$, and the Dalitz and double Dalitz decays of the K_L and π^0.

Although the observation of Standard Model direct CP-violation in rare K_L decays is not yet within reach, the situation for current and future experiments is far from grim. The current limits on $K_L \to \pi^0\nu\bar{\nu}$ are four to five orders of magnitude above Standard Model expectations, and the $\pi^0 \to \gamma\gamma$ mode is background-limited in our current experiment. However, our detector was optimized to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$, not $K_L \to \pi^0\nu\bar{\nu}$. The most serious backgrounds affecting our searches can be removed easily in any new experiments: keeping the neutral beam in vacuum up to the face of the calorimeter will remove nearly all beam interaction backgrounds, and lowering the primary beam energy (for example, using 120 GeV Main Injector beam) will remove hyperon contamination from the beams. Obtaining the necessary kaon flux should not be a problem; experiments at BNL have already produced $\mathcal{O}(10^{13})$ kaon decays. The major challenge for future experiments will be the design of hermetic photon veto systems to reject $K_L \to 3\pi^0$ and $K_L \to 2\pi^0$ backgrounds.

A Tevatron fixed-target run is scheduled for 1999, in which we expect to accumulate 2 to 4 times more statistics on all the modes described here. This new data set will allow us to search for exotic enhancements to these decays, as well as provide a valuable next step toward the search for these decays at Standard Model sensitivities.

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