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**KTeV**

**Search for the Decay  $K_L \rightarrow \pi^0 \mu^+ \mu^-$**

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# Search for the Decay $K_L \rightarrow \pi^0 \mu^+ \mu^-$

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## Abstract

We report on a search for the decay  $K_L \rightarrow \pi^0 \mu^+ \mu^-$  carried out as a part of the KTeV experiment at Fermilab. This decay is expected to have a significant  $CP$  violating contribution and a direct measurement will either support the CKM mechanism for  $CP$  violation or point to new physics. Two events were observed in the 1997 data with an expected background of  $0.87 \pm 0.15$  events, and we set an upper limit  $\mathcal{B}(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$  at the 90% confidence level.

13.20.Eb, 11.30.Er, 14.40.A

The decays  $K_L \rightarrow \pi^0 l \bar{l}$  are interesting decays for the study of  $CP$  violation and can be used to search for new physics. There are three expected contributions to the amplitude: a  $CP$  conserving contribution which proceeds through the  $\pi^0 \gamma^* \gamma^*$  intermediate state, an indirectly  $CP$  violating contribution from  $K_1 \rightarrow \pi^0 l \bar{l}$ , and a directly  $CP$  violating contribution from electroweak penguin and  $W$  box diagrams [1–3]. Branching ratio predictions in theories containing exotic (*e.g.*, SUSY) particles that contribute to the penguin amplitudes are significantly higher [4].

The sizes of the three contributions depend on the flavor of the final state lepton. The greatest theoretical interest is in the  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  case, where the direct  $CP$  violating amplitude dominates and a theoretically clean measurement [5] of the Wolfenstein [6] parameter  $\eta$  should be possible. However, measuring a final state with two neutrinos and a single pion is experimentally challenging, and the current experimental limit [7] remains four orders of magnitude above the Standard Model expectation of  $\sim 3 \times 10^{-11}$ .

In contrast,  $K_L \rightarrow \pi^0 e^+ e^-$  and  $K_L \rightarrow \pi^0 \mu^+ \mu^-$  are comparatively straightforward to detect, although all three amplitudes are present in these modes. This letter presents a new limit on  $\mathcal{B}(K_L \rightarrow \pi^0 \mu^+ \mu^-)$ ; the existing limit [8] is  $5.1 \times 10^{-9}$  at the 90% C.L. For the data taken by KTeV in 1997 and discussed here, a single event observed in the muon mode would correspond to a branching ratio of  $7 \times 10^{-11}$ , which approaches the Standard Model expectation [9,10] of  $\mathcal{B}(K_L \rightarrow \pi^0 \mu^+ \mu^-) \sim (0.44 - 1.00) \times 10^{-11}$ .

Figure 1 shows a plan view of the KTeV detector, which has been described elsewhere [7,11]. An 800 GeV proton beam, with typically  $3.5 \times 10^{12}$  protons per 19 s Fermilab Tevatron spill every minute, was targeted at a vertical angle of 4.8 mrad on a 1.1 interaction length (30 cm) BeO target. Photons were converted by 76 mm of lead immediately downstream of the target. Charged particles were then removed with magnetic sweeping. Collimators defined two  $0.25 \mu\text{sr}$  beams that entered the KTeV apparatus 94 m downstream of the target. The 65 m vacuum ( $\sim 10^{-6}$  Torr) decay region extended to the first drift chamber. The spectrometer consisted of a dipole magnet surrounded by four ( $1.28 \times 1.28 \text{ m}^2$  to  $1.77 \times 1.77 \text{ m}^2$ ) drift chambers with  $\sim 100 \mu\text{m}$  position resolution in both horizontal and

vertical directions. Helium filled bags occupied the spaces between the drift chambers; the magnetic field imparted a  $\pm 205$  MeV/c horizontal momentum kick. The spectrometer had a momentum resolution of  $\sigma(P)/P = 0.38\% \oplus 0.016\%P$ , where  $P$  is in GeV/c. The electromagnetic calorimeter consisted of 3100 pure CsI crystals. Each crystal was 50 cm (27 radiation lengths, 1.4 interaction lengths) long. Crystals in the central  $1.2 \times 1.2$  m<sup>2</sup> section of the calorimeter had a cross-sectional area of  $2.5 \times 2.5$  cm<sup>2</sup>, and those in the outer region (out to  $1.9 \times 1.9$  m<sup>2</sup>) had a  $5 \times 5$  cm<sup>2</sup> area. The calorimeter's energy resolution for photons was  $\sigma(E)/E = 0.45\% \oplus 2\%/\sqrt{E}$ , where  $E$  is in GeV, and its position resolution was  $\sim 1$  mm. Nine photon veto assemblies (lead scintillator sandwiches) detected particles leaving the fiducial volume. Two scintillator hodoscopes in front of the calorimeter were used to trigger on charged particles. The hodoscopes and the calorimeter had two holes ( $15 \times 15$  cm at the calorimeter) to let the neutral beams pass through without interaction. The muon filter, located behind the calorimeter, was constructed of a 10 cm thick lead wall followed by three steel walls totaling 511 cm thickness. Scintillator planes with 15 cm segmentation in both horizontal and vertical directions (MU3) were located after the third steel wall. The segmentation was comparable to the multiple scattering angle of 10 GeV muons at MU3. Pion punch-through probabilities, including decays downstream of the calorimeter, were taken as a function of momentum from  $K_L \rightarrow \pi^\pm e^\mp \nu$  data and are on the order of  $2 \times 10^{-3}$ . The data acquisition system reconstructed events online, and the results were used to filter the data.

The signature we searched for is two tracks from oppositely charged particles with a common vertex that deposit little energy in the calorimeter and created two hits at MU3 from these muons. The  $\pi^0$  creates two electromagnetic showers in the calorimeter with  $m_{\gamma\gamma} = m_{\pi^0}$  and which are unassociated to tracks.

There are three important backgrounds. The first is  $K_L \rightarrow \pi^+ \pi^- \pi^0$  where both  $\pi^\pm$  either decay upstream of the calorimeter (decay in flight) or punch through to MU3. The second is  $K_L \rightarrow \pi^\pm \mu^\mp \nu$  with one decay in flight or punch-through and accidentally coincident calorimeter activity that appears as a  $\pi^0$ . The third and largest background is the radiative

muonic Dalitz decay  $K_L \rightarrow \mu^+ \mu^- \gamma \gamma$  when  $m_{\gamma\gamma} = m_{\pi^0}$ . Because of the low expected [12] branching ratio,  $K_L \rightarrow \pi^0 \pi^\pm \mu^\mp \nu$  is not a large background.

Two triggers were used for this analysis. To determine the number of  $K_L$  decays in the data, we identified  $K_L \rightarrow \pi^+ \pi^- \pi^0$  decays in a minimum bias trigger. This trigger required hits in the trigger hodoscopes and the drift chambers which were consistent with two coincident charged particles passing through the detector. Events with a reconstructed vertex from oppositely charged tracks were recorded with a prescale factor of 500:1. For the signal trigger further requirements were made. Two or more hits in MU3 were required, and activity in the photon veto counters rejected events. The trigger system counted the number of calorimeter clusters over  $\sim 1$  GeV in a narrow (20nsec) time gate; for the signal mode, at least one such cluster was required. We also required that the calorimeter energy reconstructed online and associated with each track be less than 5 GeV. The signal trigger was not prescaled.

Muons passing through the calorimeter typically deposit  $\sim 400$  MeV, and so in searching offline for the signal we required that the clusters associated to the tracks had less than 1 GeV of energy. Track momenta were required to be greater than 10 GeV/c to ensure that they penetrated to MU3 and less than 100 GeV/c to ensure that the momentum was well measured. The two-muon system was required to have a mass less than 350 MeV/c<sup>2</sup> to reduce backgrounds from  $K_L \rightarrow \pi^\pm \mu^\mp \nu$ . We required two non-adjacent hits in both views of MU3. We did not compare the MU3 hit positions to the extrapolation of the tracks to MU3, because the major backgrounds passed this requirement as well as the signal did.

To suppress  $\pi^\pm$  decays in flight, we required that the reconstructed vertex occurred in the beam volume of the decay region and had a  $\chi^2$  of 10 for 1 d.o.f. or less, and that the track segments upstream and downstream of the spectrometer magnet passed within 1 mm (94% signal acceptance) of each other at the bend plane of the magnet. The mass of the two unassociated clusters under the hypothesis that they were produced by photons from the decay vertex was required to be between  $135 \pm 6$  MeV/c<sup>2</sup> ( $\pm 2.5\sigma$ ). These clusters both had to have been found by the trigger cluster counter.

A number of kinematic criteria were studied to suppress background from  $K_L \rightarrow \mu^+ \mu^- \gamma \gamma$  decays. The kinematics of this decay are very different from the analogous  $K_L \rightarrow e^+ e^- \gamma \gamma$  background to  $K_L \rightarrow \pi^0 e^+ e^-$ , and the branching ratio is lower. Consequently the methods [13,14] which are effective in the  $e^\pm$  case are less effective in the  $\mu^\pm$  case and were not applied.

It is possible to suppress backgrounds from  $K_L \rightarrow \pi^+ \pi^- \pi^0$ , and  $K_L \rightarrow \pi^\pm \mu^\mp \nu$  by using

$$R_{\parallel}^{\mu\mu} \equiv \frac{(m_K^2 - m_{\mu\mu}^2 - m_{\pi^0}^2)^2 - 4m_{\mu\mu}^2 m_{\pi^0}^2 - 4m_K^2 p_{\perp\mu\mu}^2}{p_{\perp\mu\mu}^2 + m_{\mu\mu}^2} \quad (1)$$

where  $m_K$  is the kaon mass,  $m_{\mu\mu}$  the mass of the two-muon system,  $m_{\pi^0}$  the  $\pi^0$  mass, and  $p_{\perp\mu\mu}$  is the two-muon systems's momentum perpendicular to the kaon momentum. This quantity is proportional to the  $\pi^0$  momentum squared in the  $K_L$  flight direction in the frame colinear with the  $K_L$  but where the  $\mu^+ \mu^-$  pair has no longitudinal momentum. We required  $R_{\parallel}^{\mu\mu}$  to lie between -0.01 and 0.10  $GeV^2/c^4$ . This cut keeps 89.2% of the signal and rejects 73% of  $K_L \rightarrow \pi^\pm \mu^\mp \nu$  decays with coincident photons and 95% of the  $K_L \rightarrow \pi^+ \pi^- \pi^0$  decays.

To ensure that we observed all the products of a  $K_L$  decay, we required that the total squared momentum transverse to the  $K_L$  flight direction ( $P_{\perp}^2$ ) be less than 100  $MeV^2/c^2$ , and that the reconstructed mass ( $m$ ) of the  $K_L$  be between 492 and 504  $MeV/c^2$ . With these requirements, which were selected by examining Monte Carlo simulation results and data outside the signal region before examining the data for  $K_L \rightarrow \pi^0 \mu^+ \mu^-$  candidates, the overall acceptance for the signal was 5.0%. The simulation distributed the products of the decay uniformly in phase space.

Figure 2 shows the  $P_{\perp}^2$  vs.  $m$  distributions for the data, and Fig. 3 shows the mass distribution after the  $P_{\perp}^2$  requirement for the data and the backgrounds as estimated from the simulation. The correspondence between the data and the simulation is good, and is also good in the distributions of  $m_{\mu\mu}$ ,  $P_{\perp}^2$ , track momentum, vertex position and (for  $K_L \rightarrow \pi^+ \pi^- \pi^0$ ) of  $m_{\gamma\gamma}$ . The background levels in the signal region are given in Table I; they are calculated from the simulations, published [16] branching ratios, and the number of  $K_L$  decays in the data sample. Although we have observed  $K_L \rightarrow \mu^+ \mu^- \gamma \gamma$  [15] in this data, this

background was more precisely estimated from QED and the measured  $\mathcal{B}(K_L \rightarrow \mu^+ \mu^- \gamma)$ ; a value of  $\mathcal{B}(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) = (9.1 \pm 0.8) \times 10^{-9}$  with an  $m_{\gamma\gamma} > 1 \text{ MeV}/c^2$  cutoff was used. All Monte Carlo samples were over 10 times the data sample. The background from  $K_L \rightarrow \pi^+ \pi^- + 2\gamma$  (Acc) and  $K_L \rightarrow \pi^+ \pi^- \gamma + \gamma$  (Acc) was negligible.

To normalize any possible signal's branching ratio, we identified  $K_L \rightarrow \pi^+ \pi^- \pi^0$  decays in as similar a manner to the  $K_L \rightarrow \pi^0 \mu^+ \mu^-$  identification as possible. Apart from the trigger differences, the calorimeter energy requirement for clusters associated to tracks was changed to less than 0.9 times the momentum measured with the spectrometer; the MU3 and  $R_{\parallel}^{\mu\mu}$  requirements were removed, and  $m_{\pi^\pm}$  rather than  $m_{\mu^\pm}$  was used in calculating kinematic quantities. The acceptance for the normalization mode was 8.1%. There were  $(268 \pm 0.4_{\text{STAT}} \pm 0.4_{\text{MC}} \pm 4.3_{\text{BR}}) \times 10^9$   $K_L$  decays between 90 and 160 m from the target with  $K_L$  momentum between 20 and 220 GeV/c.

In calculating the number of  $K_L$  decays in the data and the acceptance for  $K_L \rightarrow \pi^0 \mu^+ \mu^-$  relative to the acceptance for  $K_L \rightarrow \pi^+ \pi^- \pi^0$ , we allowed for the uncertainties summarized in Table II. We calculated the  $K_L$  flux using  $K_L \rightarrow \pi^\pm \mu^\mp \nu$  rather than  $K_L \rightarrow \pi^+ \pi^- \pi^0$  decays and attributed the difference of 4.20% to the quality of our simulation of muons in the detector. We varied the scale and resolution of the calorimeter and spectrometer in the simulation to conservatively cover the range of variations seen in the data. Apart from uncertainties in published branching ratios, other sources of uncertainty were small.

From Figs. 2 and 3, two events exist in the signal region for the data. Sidebands in both  $m$  and  $P_\perp^2$  show correspondence between data and background predictions as given in Table III. With the above acceptance and  $K_L$  flux, and allowing for a background level of  $0.87 \pm 0.15$  events, we set [17] an upper limit  $\mathcal{B}(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$  at the 90% confidence level.

This limit is approximately one order of magnitude more stringent than the previous limit. If we assume that the only contribution to the branching ratio is from direct  $CP$  violation, we may conclude that  $|\eta| < 7$  at the 90% confidence level. In comparison to the search for  $K_L \rightarrow \pi^0 e^+ e^-$ ,  $K_L \rightarrow \pi^0 \mu^+ \mu^-$  searches will have better single event sensitivity for

any given sample of  $K_L$  decays because the level of irreducible  $K_L \rightarrow l^+l^-\gamma\gamma$  background is less. While not yet as sensitive as B decays, where a recent indirect global analysis [18] finds  $\eta$  to be below 1, it is valuable to test if the same parameterization is valid for both B and K decays.

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## FIGURES

FIG. 1. The KTeV detector configuration for rare decay studies. The TRD, Hadron Veto, and the Photon Veto in the beamline were not used in this analysis.

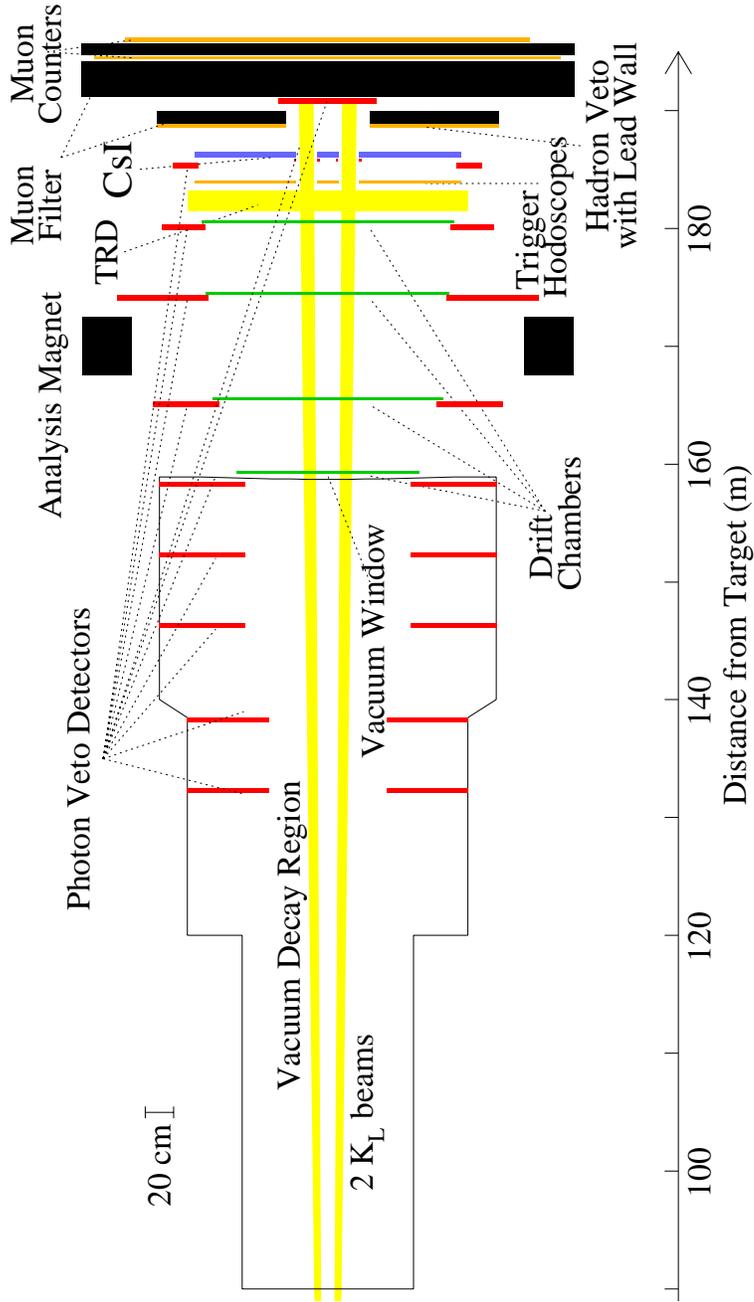


FIG. 2. Reconstructed  $P_{\perp}^2$  vs.  $m$  after all other selection criteria, for the data. The box indicates the signal region; events in the lower left are predominantly  $K_L \rightarrow \pi^+ \pi^- \pi^0$  with  $\pi^{\pm}$  decays in flight.

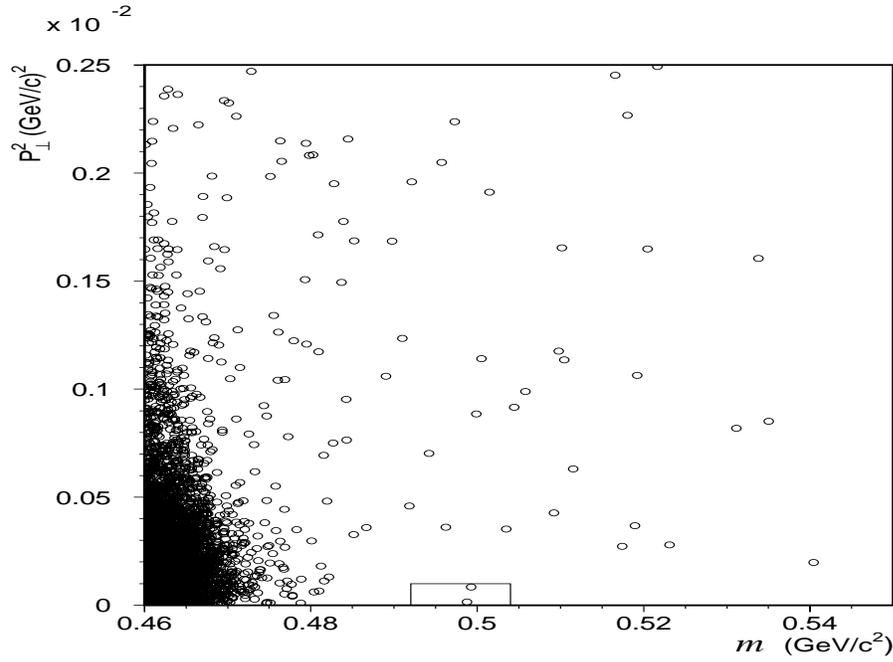
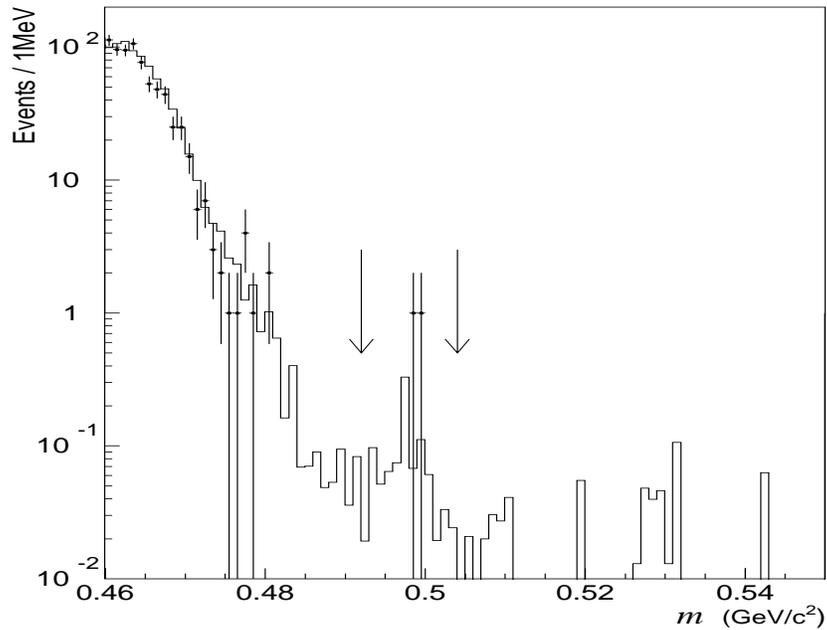


FIG. 3. Reconstructed  $m$  after all other selection criteria, for the data (dots), and the total background estimate (line). The arrows indicate the range of values of  $m$  accepted. The small bump in the background at the  $K_L$  mass is from  $K_L \rightarrow \mu^+ \mu^- \gamma \gamma$ .



## TABLES

TABLE I. Summary of expected backgrounds in the signal region. “Acc.” refers to particles from other sources which were accidentally time-coincident with the interesting decay; “D” and “P” refer respectively to decay in flight or punch-through. Limits are 90% C.L.; uncertainties are due to uncertainties in published branching ratios, simulation statistics, and the statistics of the normalization mode.

Decay mode	Expected number of events
$K_L \rightarrow \mu^+ \mu^- \gamma \gamma$	$0.373 \pm 0.032$
$K_L \rightarrow \mu^+ \mu^- \gamma + \gamma(\text{Acc})$	$< 0.029$
$K_L \rightarrow \pi^+ \pi^- \pi^0$ (DD)	$0.252 \pm 0.095$
$K_L \rightarrow \pi^+ \pi^- \pi^0$ (DP)	$0.007 \pm 0.007$
$K_L \rightarrow \pi^+ \pi^- \pi^0$ (PP)	$0.007 \pm 0.007$
$K_L \rightarrow \pi^\pm \mu^\mp \nu + 2\gamma(\text{Acc})$ (D)	$0.161 \pm 0.093$
$K_L \rightarrow \pi^\pm \mu^\mp \nu + 2\gamma(\text{Acc})$ (P)	$0.063 \pm 0.037$
$K_L \rightarrow \pi^0 \pi^\pm \mu^\mp \nu$ (D)	$0.009 \pm 0.009$
$K_L \rightarrow \pi^0 \pi^\pm \mu^\mp \nu$ (P)	$< 0.009$
Total	$0.87 \pm 0.15$

TABLE II. Systematic and statistical sources of uncertainty. Sources marked with (\*) contribute to uncertainty in both the  $K_L$  flux and the acceptance for  $K_L \rightarrow \pi^0 \mu^+ \mu^-$  relative to the acceptance for  $K_L \rightarrow \pi^+ \pi^- \pi^0$ ; other sources contribute only to the acceptance ratio.

Source	Relative Uncertainty
$\mathcal{B}(K_L \rightarrow \pi^+ \pi^- \pi^0)$	1.59% (*)
Data statistics for $K_L \rightarrow \pi^+ \pi^- \pi^0$	0.16% (*)
Simulation statistics for $K_L \rightarrow \pi^+ \pi^- \pi^0$	0.14% (*)
Simulation statistics for $K_L \rightarrow \pi^0 \mu^+ \mu^-$	0.16%
Calorimeter scale and resolution	3.33%
Spectrometer scale and resolution	1.12%
Muon identification	4.20%
Signal trigger requirements	0.80%
Vertex quality requirement	0.22%
Spectrometer wire inefficiency	0.15%
Total	5.77%

TABLE III. Number of observed and predicted events in regions near the signal region.

Region	Prediction	Observed
$480 \text{ MeV}/c^2 < m < 492 \text{ MeV}/c^2; P_{\perp}^2 < 0.0001 (\text{ GeV}/c)^2$	$2.75 \pm 0.73$	2
$504 \text{ MeV}/c^2 < m < 515 \text{ MeV}/c^2; P_{\perp}^2 < 0.0001 (\text{ GeV}/c)^2$	$0.14 \pm 0.08$	0
$492 \text{ MeV}/c^2 < m < 504 \text{ MeV}/c^2; 0.0001 (\text{ GeV}/c)^2 < P_{\perp}^2 < 0.0005 (\text{ GeV}/c)^2$	$2.65 \pm 1.53$	2
$492 \text{ MeV}/c^2 < m < 504 \text{ MeV}/c^2; 0.0005 (\text{ GeV}/c)^2 < P_{\perp}^2 < 0.0010 (\text{ GeV}/c)^2$	$2.80 \pm 2.59$	2