# Improved Upper Limit on the Branching Ratio $B(K_L^0 \to \mu^\pm e^\mp)$

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A search for the decay $K_L^0 \to \mu^\pm e^\mp$ with significantly increased experimental sensitivity has yielded no events. The 90% confidence level limit on the branching ratio is $B(K_L^0 \to \mu^\pm e^\mp) < 3.9 \times 10^{-11}$. When this data set is combined with earlier data the upper limit is $3.3 \times 10^{-11}$.

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The decay $K_L^0 \to \mu^\pm e^\mp$ is forbidden by conservation of the separate additive quantum numbers for electron- and muon-type leptons. Unlike the conservation law for electric charge, these laws are not a consequence of a gauge theory of particle interactions. The standard model contains no mechanism violating these laws; hence an observation of this decay would be evidence of new interactions. For example, the decay could occur through the production and decay of a virtual particle $X^0$ which couples to the $s$ and $d$ quarks at one vertex and to muons and electrons at the other. An observation of this decay with a branching ratio of $10^{-10}$ would imply a mass for $X^0$ of $\sim 100$ TeV/$c^2$, if the coupling strength is the standard electroweak coupling $g$. Typically, extensions to the standard model allow for muon and electron number violation [1].

In this Letter we describe a search for $K_L^0 \to \mu^\pm e^\mp$ at a sensitivity greater than previously achieved [2–6]. The experiment (E791) was performed at the B-5 beam line of the Alternating Gradient Synchrotron (AGS) at BNL. Data were collected during two running periods in 1989 and 1990 of approximately 15 and 12 weeks duration, respectively. Minor differences in the detector and data analysis used for the two data sets are described below. This Letter reports the final results of E791.

An average of $4.5 \times 10^{12}$ protons per spill at 24 GeV/$c$ were incident on a 1.3-interaction-length Cu target. A neutral beam subtending a solid angle of 4.1 (hor.) ×15.0 (vert.) mrad$^2$ (FWHM) was produced at a mean angle of 2.75° to the proton beam. Following the beam-defining elements, an 8.5-m-long vessel evacuated to 0.020 Torr served as a fiducial decay region. A three-piece decay region end window assembly used during 1989 was replaced by a single-round Kevlar/Mylar window for the 1990 run. Figure 1 shows a plan view of the E791 spectrometer and neutral beam line [5, 7, 8].

The spectrometer consisted of five pairs of drift chambers (DC1–5) and two analyzing magnets with transverse momentum impulses of 300 MeV/$c$ and 318 MeV/$c$ of opposite sign. The chambers contained two $x$- and two $y$-measuring planes, each with 120-$\mu$m single-wire resolution. For the 1990 run the two most upstream chambers were replaced with larger modules placed closer to the neutral beam, resulting in a 30% increase in acceptance. Downstream of the drift chambers were two pairs of trigger scintillation hodoscopes (TSC's) and particle identification detectors (PID's). Electrons were identified with a threshold gas Cherenkov counter (CER) and a lead-glass array (PBG), both with time and pulse height information. The PBG array was composed of two layers, a converter array (3.3 r.l.) and an absorber array (10.5 r.l.). Muons were identified with a scintillator hodoscope (MHO) and a range finder (MRG) [9] located downstream of 0.91 m of iron. The latter contained drift tube detectors inserted in marble and aluminum absorber at intervals corresponding to 10% increments of range.

A level 0 (L0) hardware trigger was defined by an overlap coincidence of the four TSC's. A "minimum bias" sig-

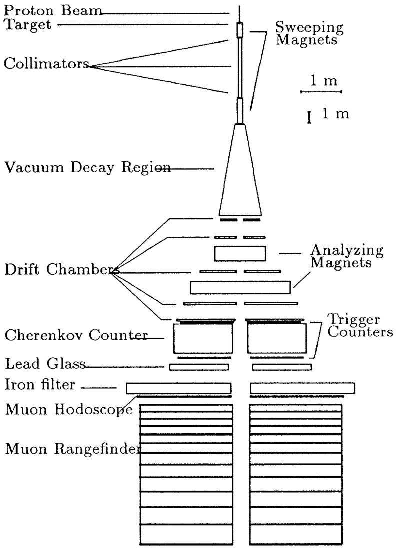

FIG. 1. The E791 beam line and detector.

nal was formed from a coincidence of the L0 trigger with the three most upstream drift chambers on each side of the spectrometer. The level 1 (L1) trigger selected minimum bias events prescaled by 2000 and dilepton events defined by a coincidence of the minimum bias signal and a MHO or CER signal on each side of the apparatus. A level 2 trigger, which selected high mass events through the use of memory lookup hardware, was constructed but never used in either data-taking period. Events satisfying the L1 trigger were processed in one of eight 3081/E computers [10].

The level 3 (L3) trigger algorithm used hit information from DC1–3 and a lookup table of field integrals for the first magnet to calculate a two-body mass ($M_{12}$) and collinearity angle ($\theta_K$) defined as the difference between the kaon direction calculated from the target and vertex positions and the reconstructed two-body momentum direction. Values of $M_{12}$ for each combination of lepton masses consistent with the L1 trigger were calculated. Dilepton triggers were required to have $\theta_K^2 < 100$ mrad$^2$, $M_{12} > 460$ MeV/$c^2$ and, during 1989 only, $M_{12} < 550$ MeV/$c^2$. There were no L3 requirements on the minimum bias triggers. Events passing the L3 selection criteria were written to magnetic tape. The efficiency of this algorithm was measured using minimum bias events, subject to the event quality and kinematic cuts described below, to be 66% (1989) and 91% (1990). The improved efficiency in 1990 was achieved with modifications of the algorithm to find events with missing hits and events contaminated with extra hits in the chambers more effectively.

Off line, events were reconstructed with a pattern recognition algorithm which used the hit information from all drift chambers to find tracks that originated from a common vertex and traversed the full spectrometer. For each view ($x$ and $y$) of each track, at least eight of ten expected drift chamber signals were required. The invariant mass and collinearity were recalculated and the transverse momentum ($P_T$), defined to be the product of the two-body momentum with the collinearity angle, was calculated. Events with $M_{12} > 470$ MeV/$c^2$ and either $\theta_K^2 < 10$ mrad$^2$ or $P_T^2 < 800$ (MeV/$c$)$^2$ were selected. For the 1989 run it was also required that $M_{12} < 530$ MeV/$c^2$. Events satisfying these criteria were then fit using a full magnetic field map to determine more accurately their kinematics.

Fitted tracks were projected to the PID detectors and measured responses compared to those expected. Tracks were identified as electrons if they had an associated CER hit within 4 ns of the event time, if the ratio of energy in the PBG to the particle momentum was greater than 0.65, and if they deposited sufficient energy in the converter blocks [11]. The efficiencies of the cuts on the CER and PBG were measured to be 0.908 ± 0.001 and 0.958 ± 0.001 using electrons from $K_L^0 \to \pi e \nu$ ($K_{e3}$) decays obtained from the minimum bias data sample.

Muons were identified by requiring that the positions of struck MHO counters and their times agree with expected values, that a minimum fraction of expected MRG hits were found by a tracking algorithm, and that the measured range in the MRG exceeded 90% of that expected from the particle's momentum [7, 8, 11, 12]. The efficiencies of the cuts on the MHO and MRG were measured to be 0.969 ± 0.001 and 0.975 ± 0.001 using muons from $K_L^0 \to \pi \mu \nu$ ($K_{\mu 3}$) decays obtained from the minimum bias data sample.

The primary source of background in the search for $K_L^0 \to \mu^\pm e^\mp$ is $K_{e3}$ decays. One class of background consists of the pion being misidentified as or decaying to a muon. In the absence of measurement errors, this class of events has a $\mu e$ mass distribution with a kinematic end point 8.4 MeV/$c^2$ below the kaon mass. Excellent kinematic resolution is required to reject such events. A particularly serious source of background was found to come from such events, with a decayed pion, where in addition a mistake was made in the kinematic reconstruction of the event. In this case the reconstructed mass can be equal to or larger than $M_K$. A second class of background arises from the misidentification of the pion as an electron and the misidentification of the electron as a muon. These events can also have a reconstructed $\mu e$ mass greater than $M_K$. Rejection of these events requires excellent particle identification.

The data from each period have been separately analyzed prior to the analysis described here and preliminary results reported elsewhere [11]. After minor changes to the pattern recognition and event fitting software, both data samples have been reanalyzed. The analysis proceeded by studying background events with $M_{\mu e}$ within 5 MeV/$c^2$ of $M_K$ and with $144 < P_T^2 \leq 800$ (MeV/$c$)$^2$ and choosing cuts to reduce this background. The mass interval was chosen to be approximately ±3 times the expected resolution in $M_{\mu e}$ (1.74 MeV/$c^2$), based on the measured resolution in $M_{\pi\pi}$ (1.40 MeV/$c^2$) and a Monte Carlo calculation of the ratio of the resolution for $M_{\mu e}$ (1.57 MeV/$c^2$) to that for $M_{\pi\pi}$ (1.26 MeV/$c^2$). The $P_T^2$ cut at 144 (MeV/$c$)$^2$ was chosen in a similar fashion. These events were studied to understand the classes of events that were the most troublesome and to devise selection criteria to eliminate them. Events inside the signal region $P_T^2 \leq 144$ (MeV/$c$)$^2$ were examined only after the final event selection criteria had been chosen.

Events were required to have a vertex at least 9.75 m from the target and within a region defined by the beam divergence. Events with charged particle trajectories which projected to large amounts of material (e.g., vacuum flange, magnet coils) or which missed the PID detectors were eliminated. The momenta of charged particles were required to be above 1.5 GeV/$c$ and below 12.0 GeV/$c$.

The ratio of the lepton momenta was required to be less than 5 to reduce the number of $K_{e3}$ events with a decaying pion that are reconstructed with a $\mu e$ mass near the kinematic end point. Most events with pion decays within the tracking spectrometer were eliminated by requirements on the track and vertex quality, and on the consistency of the momenta as measured by the front and back halves of the spectrometer.

Mistakes in the kinematic reconstruction were reduced by removing events with missing hits where the fitting routine chose an ambiguity resolution that had a low probability of being correct, for example, if the side of the wire opposite to a "dead" wire was chosen. Further cuts in the 1990 sample included removing events with two or more misses in the $x$ view of any track, and removing events which had both a high momentum track ($P > 7$ GeV/$c$) and an $x$-view miss. Events with large $P_T$ in the putative kaon decay plane were found more often to have high values of $M_{\mu e}$; hence the accepted region in $P_T^2$ was further reduced by requiring $P_T$ in the decay plane to be less than 7 MeV/$c$.

After final determination of the selection criteria, events in the signal region were analyzed and the cuts applied. No events were found. Figure 2 is a plot of $P_T^2$ vs $M_{\mu e}$ for our final sample of $K_L^0 \to \mu^\pm e^\mp$ candidates from both data sets.

The total $K_L^0$ flux is obtained by counting the $K_L^0 \to \pi^+\pi^-$ decays in the prescaled minimum bias data sample. The distribution of the two-body invariant mass, assuming pion masses for the charged particles ($M_{\pi\pi}$), is shown for this sample in Fig. 3. Superimposed is a Monte Carlo simulation of the $M_{\pi\pi}$ distribution for semileptonic decays of $K_L^0$. This distribution is normalized to the data outside the $K_L^0$ mass peak and then subtracted to obtain a $\pi\pi$ count. Both distributions have been corrected to account for the $K_S^0$ contamination of the $\pi\pi$ sample. The value of this correction has been calculated to be $\xi_{K_S} = 0.987 \pm 0.001$ (1989) and $0.992 \pm 0.001$ (1990). The resulting number of $K_L^0 \to \pi^+\pi^-$ events is $N_{\pi\pi} = 15\,033 \pm 151$ (1989) and $29\,430 \pm 217$ (1990).

Since no events consistent with the decay $K_L^0 \to \mu^\pm e^\mp$ were observed we compute a 90% confidence level limit on the branching ratio from

$$B(K_L^0 \to \mu^\pm e^\mp) < 2.3 \times \alpha \times \frac{B(K_L^0 \to \pi^+\pi^-)}{R \times N_{\pi\pi}} \times \frac{A_{\pi\pi}}{A_{\mu e}} \times \frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}}.$$

The factor $\alpha = 1 + 1.15\sigma_r^2$ incorporates the effects of the fractional systematic uncertainty $\sigma_r$ [13]. Including all the uncertainties listed below and the uncertainty on the $\pi\pi$ counting, we estimate $\sigma_r$ to be less than 5%, resulting in a negligible effect on the upper limit quoted. The branching ratio $B(K_L^0 \to \pi^+\pi^-) = (2.03 \pm 0.04) \times 10^{-3}$ [14]. The acceptance ratio determined from a Monte Carlo simulation of the detector is $A_{\pi\pi}/A_{\mu e} = 1.47 \pm 0.01$ (1989) and $1.42 \pm 0.01$ (1990). These values include a small correction to account for the difference in measured and calculated mass resolution. The total $\pi\pi$ prescale factor $R$, including both the L1 prescale and an off-line prescale, is 6000 (1989) and 4000 (1990). We have broken $(\epsilon_{\pi\pi}/\epsilon_{\mu e})$ down into four

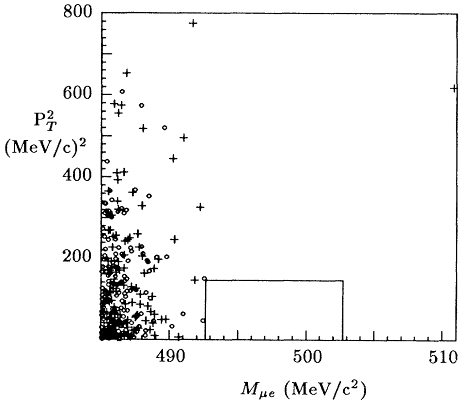

FIG. 2. Plot of $P_T^2$ vs $M_{\mu e}$. Plus signs are 1989 data and circles are 1990 data.

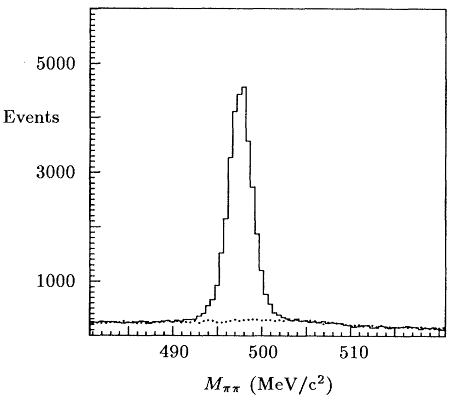

FIG. 3. Distribution in $M_{\pi\pi}$ for minimum bias data (histogram) and Monte Carlo semileptonic background (circles).

components:

$$\frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}} = \left(\frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}}\right)^{\rm L3} \times \epsilon_{\pi\pi}^{\rm int} \times \frac{1}{\epsilon_{\mu e}^{\rm PID}} \times \frac{1}{\epsilon_{\mu e}^{\rm L1}}.$$

The first factor, the L3 correction, has been measured using the minimum bias sample to be $(\epsilon_{\pi\pi}/\epsilon_{\mu e})^{\rm L3} = 1.001 \pm 0.003$ (1989) and $1.002 \pm 0.001$ (1990). The correction for pion loss due to interactions in the spectrometer has been estimated, from data with the downstream trigger scintillators removed from the trigger, to be $\epsilon_{\pi\pi}^{\rm int} = 0.954 \pm 0.004$. The efficiency for identifying the $\mu e$ pair from $K_L^0 \to \mu^\pm e^\mp$ has been measured from $K_{e3}$ and $K_{\mu 3}$ decays in our minimum bias sample to be $\epsilon_{\mu e}^{\rm PID} = 0.790 \pm 0.006$ (1989) and $0.814 \pm 0.005$ (1990). These numbers are integrations of the lepton detection efficiencies over kinematic distributions expected for $K_L^0 \to \mu^\pm e^\mp$. Finally the L1 lepton trigger efficiency has been measured to be $\epsilon_{\mu e}^{\rm L1} = 0.988 \pm 0.003$ (1989) and $0.990 \pm 0.002$ (1990). This factor is the efficiency of the L1 trigger being satisfied, given that the off-line PID criteria have been satisfied.

The resulting 90% confidence limit on the branching ratio is $B(K_L^0 \to \mu^\pm e^\mp) < 9.3 \times 10^{-11}$ (1989) and $< 6.7 \times 10^{-11}$ (1990). The combined result from both data sets is $B(K_L^0 \to \mu^\pm e^\mp) < 3.9 \times 10^{-11}$ at 90% C.L. Combined with our earlier result using a similar apparatus [5], the limit is $B(K_L^0 \to \mu^\pm e^\mp) < 3.3 \times 10^{-11}$. We have found no evidence that the additive quantum numbers associated with muon- and electron-type leptons are not conserved and have further restricted the effective coupling strengths of new interactions which allow for violation of these conservation laws.

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