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Measurements of the Decay $K_L \to e^+e^-\mu^+\mu^-$

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The KTeV experiment at Fermilab has isolated a total of 132 events from the rare decay $K_L \to e^+e^-\mu^+\mu^-$, with an estimated background of 0.8 events. The branching ratio of this mode is determined to be $[2.69 \pm 0.24(\text{stat}) \pm 0.12(\text{syst})] \times 10^{-9}$, with a radiative cutoff of $M^2_{ee\mu\mu}/M^2_K > 0.95$. The first measurement using this mode of the parameter α from the D'Ambrosio-Isidori-Portolès (DIP) model of the $K_L\gamma^*\gamma^*$ vertex yields a result of -1.59 ± 0.37, consistent with values obtained from other decay modes. Because of the limited statistics, no sensitivity is found to the DIP parameter β. We use this decay mode to set limits on CP and lepton violation.

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The rare decay $K_L \to e^+e^-\mu^+\mu^-$ offers the most direct means for studying the dynamics of the $K_L\gamma^*\gamma^*$ vertex. This information is useful for models that relate the $K_L \to \mu^+\mu^-$ branching ratio to ρ, the real part of the Cabibbo-Kobayashi-Maskawa matrix element V_{td} [1–3]. This decay mode can also be used to determine the presence of any CP-violating contributions to the $K_L\gamma^*\gamma^*$ interaction [4]. Additionally, a search for the lepton flavor-violating counterpart $K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$ provides a constraint on physics beyond the standard model.

In the model of D'Ambrosio, Isidori, and Portolès (DIP) [5], the $K_L\gamma^*\gamma^*$ form factor is written in the most general form compatible with chiral perturbation theory:

$$f(q_1^2, q_2^2) = 1 + \alpha\left(\frac{q_1^2}{q_1^2 - M_\rho^2} + \frac{q_2^2}{q_2^2 - M_\rho^2}\right) + \beta\frac{q_1^2 q_2^2}{(q_1^2 - M_\rho^2)(q_2^2 - M_\rho^2)}. \quad (1)$$

Here, q_1 and q_2 are the momenta of the two-virtual photons, and M_ρ is the mass of the ρ vector meson. In this model, α and β are two arbitrary real parameters and are expected to be of order one. The determination of both α and β is possible through the decay $K_L \to e^+e^-\mu^+\mu^-$ by examining the dilepton invariant masses and the integrated decay rate. Knowledge of the $K_L\gamma^*\gamma^*$ form factor is important for understanding the long distance contributions to $K_L \to \mu^+\mu^-$ and extracting the value of ρ [5].

Two measurements have been made of the linear DIP parameter α to date, both by the KTeV Collaboration. From the mode $K_L \to \mu^+\mu^-\gamma$, the shape of the dimuon invariant mass distribution ($M_{\mu\mu}$) and the measured branching ratio have been used to determine $\alpha = -1.54 \pm 0.10$ [6]. A fit to the dielectron mass distribution (M_{ee}) from $K_L \to e^+e^-e^+e^-$ determines $\alpha = -1.1 \pm 0.6$ [7], where the larger error results from the smaller q^2 of the dielectron distribution. No measurements have yet been made of the quadratic DIP parameter β. Because the effects of the β parameter are most significant in the region where both q_1^2 and q_2^2 are large, the decay $K_L \to e^+e^-\mu^+\mu^-$ currently represents the best means for determining β. The decay $K_L \to \mu^+\mu^-\mu^+\mu^-$ also could be used to measure β, but the predicted branching ratio for this decay is approximately 10^{-13} [8].

KTeV, a fixed target experiment located at Fermilab, collected rare decay data during run periods in 1997 and 1999. Forty-three $K_L \to e^+e^-\mu^+\mu^-$ events were observed in the 1997 data, leading to a published branching ratio of $[2.62 \pm 0.40(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-9}$ [9]. However, no attempt has been made to extract form factor information from this limited data set. The results presented in this Letter are based on a reanalysis of the 1997 KTeV data set, combined with the analysis of new data collected during the 1999 run. Further details of this analysis can be found in [10].

The two parallel K_L beams used by KTeV are created by focusing 800 GeV/c protons from the Fermilab Tevatron onto a BeO target. A 65 m long vacuum region, starting 94 m downstream from the target, defines the fiducial region for kaon decays. Charged particles are detected with a spectrometer system consisting of four drift chambers and an analysis magnet. The hit position resolution in the chambers is approximately 100 μm, while the overall momentum resolution is just over 1% in the range of interest. The transverse momentum kick from the magnet was lowered by 25% for the 1999 run for the purpose of increasing acceptance for four-track decay modes.

Downstream of the spectrometer system are two trigger hodoscope planes, followed by an electromagnetic (EM) calorimeter. This $1.9 \times 1.9\ \text{m}^2$ array of 3100 pure CsI crystals has a resolution of under 1% in the energy range of interest. Photon vetos are located along the decay region to reject particles that would miss the CsI calorimeter.

Behind the calorimeter are a 10 cm thick lead wall and 4 m of steel, the last 3 m of which serve as the neutral beam dump. A muon hodoscope (MU2) consisting of 56 overlapping scintillator paddles is located behind the dump. Following MU2 is another 1 m thick steel filter, behind which are two scintillator planes, one oriented horizontally and the other vertically. Known as MU3Y and MU3X, these planes are used for muon identification and have 15 cm segmentation. The momentum threshold for muons to reach the MU3 bank has been measured to be 7 GeV/c. The lead and steel filters add up to a total of 31 hadronic interaction lengths. A more detailed description of the KTeV detector can be found elsewhere [11,12].

The trigger requires hits in the upstream drift chambers and the trigger hodoscope planes consistent with at least two charged tracks. During the 1997 run, at least two hits were required in both MU3X and MU3Y. This condition was loosened during the 1999 run to allow for one missing hit. This change accepts events in which the muons are well separated in one view but happen to strike the same paddle in the other view. To counter the increased trigger rate from this change, the minimum number of calorimeter clusters with at least 1 GeV of energy was raised from one in 1997 to two in 1999 [13]. If at least 0.5 GeV of energy is found in any of the photon vetos, the event is discarded. Events in which at least three tracks form a loosely defined vertex are tagged as candidate signal events.

During the analysis stage, the ratio E/P is used for particle identification, where E is the energy deposited by the track in the EM calorimeter, and P is the track momentum as measured by the spectrometer. Tracks with $0.95 < E/P < 1.05$ are identified as electrons. Tracks are identified as muons if they have $E/P < 0.8$, deposit less than 1.5 GeV in the calorimeter, have momentum greater than 7 GeV/c, and hit at least two out of the three muon identification planes (MU2, MU3X, and MU3Y). The E/P requirement rejects about 99.6% of pions while retaining 98% of electrons. Events are accepted if they contain exactly four tracks, with oppositely charged electron and muon pairs.

Additional requirements imposed on the data set include cuts on the reconstructed kaon momentum ($20\ \text{GeV}/c < P_K < 220\ \text{GeV}/c$) and the z position of the reconstructed vertex ($90\ \text{m} < z_{vtx} < 158\ \text{m}$). Because the detector acceptance for K_L decays falls off quickly outside of these ranges, any events observed outside of the boundaries are most likely misreconstructed K_L, K_S, or hyperon decays. To further reduce the number of misreconstructed and background events, a cut is made at $P_t^2 < 250\ \text{MeV}^2/c^2$, where P_t is the transverse component of the reconstructed kaon momentum relative to the kaon line of flight. The signal mass region is defined to be $482\ \text{MeV}/c^2 < M_{ee\mu\mu} < 512\ \text{MeV}/c^2$.

Three sources of background are considered. The decay $K_L \to \pi^+\pi^-\pi_D^0$ (where π_D^0 signifies the Dalitz decay $\pi^0 \to e^+e^-\gamma$) could appear as signal if the charged pions decay to muons, or punch through the muon filter and fire MU3. The P_t^2 requirement strongly suppresses these events. In addition, we require exactly two EM clusters in the calorimeter, to veto on the photon from the Dalitz decay of the π^0. This requirement reduces the background by a factor of 4 while removing only 4% of the signal. Two simultaneous $K_L \to \pi^\pm\mu^\mp\nu$ ($K_{\mu3}$) decays could also simulate signal if both pions hadronically interact and shower in the calorimeter, mimicking electrons. As two separate two-track decays are unlikely to form a good four-track vertex, a cut on four-track vertex quality is successful in removing this background. Other simultaneous backgrounds involving $K_L \to \pi^\pm e^\mp \nu$ decays are negligible. The vertex cut reduces the background by a factor of about 30 while cutting signal events only by about 2%.

The most significant source of background comes from $K_L \to \mu^+\mu^-\gamma$ events in which the photon converts to an e^+e^- pair in the material upstream of the first drift chamber. Monte Carlo simulations predict almost 50 of these events in the signal mass region at this stage of cuts. Requiring that the e^+e^- hit separation transverse to the beam at the first drift chamber be greater than 2 mm or that $M_{ee} > 2.75$ MeV/c^2 eliminates 99% of these conversion events, while retaining approximately 85% of the signal (Fig. 1). The remaining 1% of the background is uniformly distributed throughout the region shown.

After all cuts, 132 signal events remain (Fig. 2) with an estimated background of 0.8 events, dominated by $K_L \to \mu^+\mu^-\gamma$ conversions. The background estimate is determined from Monte Carlo simulations.

We extract the branching ratio by normalizing to $K_L \to \pi^+\pi^-\pi^0_D$ events, which are collected in a similar trigger. In addition to the cuts described, for the normalization mode the charged pions are required to strike the calorimeter away from the edges of the array (7 cm from the outer perimeter, 5 cm from either beam hole), the energy deposited in the calorimeter by the Dalitz photon is required to be greater than 2 GeV, and the mass of the reconstructed π^0 is required to be between 125 and 145 MeV/c^2. The π^0 mass cut removes only about 0.7% of the normalization sample. Using these normalization events, and an acceptance of approximately 1.7% determined from Monte Carlo, the total yield of kaon decays within the detector from the 1997 and 1999 runs is calculated to be $(6.39 \pm 0.04) \times 10^{11}$, the error being purely statistical.

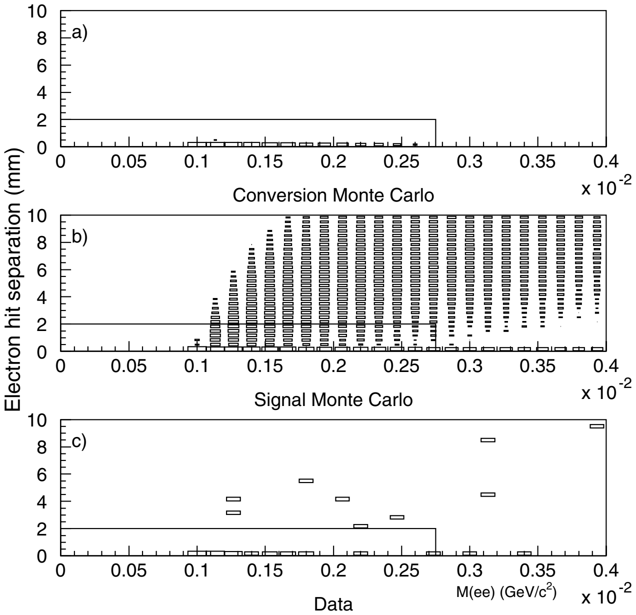

FIG. 1. Transverse electron hit separation at the first drift chamber versus M_{ee} for (a) $K_L \to \mu^+\mu^-\gamma$ conversion Monte Carlo, (b) signal Monte Carlo, and (c) data. Plots are logarithmic in z. The box indicates the cut region.

Because muons are present in the signal mode but not in the normalization mode, an accurate simulation of the efficiency and threshold of the muon system and a good understanding of multiple scattering through the muon filters are crucial. These effects are studied using a combination of GEANT simulations and calibration muons collected with special magnet and absorber configurations. The single muon detection efficiency is measured to be over 99%, determined to within 0.5% of itself [14].

Systematic errors in the determination of the number of kaon decays and the signal acceptance are dominated by uncertainties in the $K_L \to \pi^+\pi^-\pi^0_D$ (1.6%) and $\pi^0 \to e^+e^-\gamma$ (2.7%) branching ratios. Estimates of systematic errors were determined mainly through detailed comparisons of Monte Carlo and data, and by varying the analysis cuts. Other significant effects include a disagreement between data and Monte Carlo in the decay position distribution of normalization events from the 1999 run (1.9%), the rate of accidental activity in the detector (1.7%), and limited Monte Carlo statistics (1.1%). Other

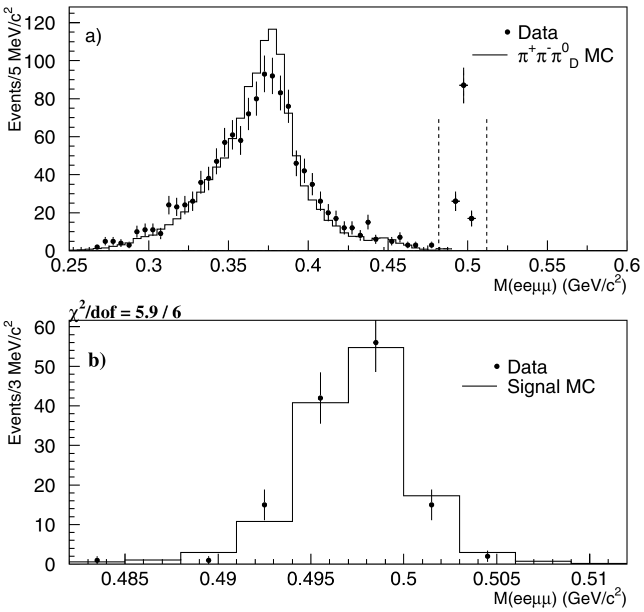

FIG. 2. (a) $M_{ee\mu\mu}$ for all data (dots) and $K_L \to \pi^+\pi^-\pi^0_D$ decay/punchthrough Monte Carlo (histogram) after all cuts. In the signal mass region 132 events remain. The vertical lines indicate the expected signal region. (b) Close-up of the signal mass region. The Monte Carlo is normalized to the integrated number of events in the data. The mismatch in (a) between data and Monte Carlo is due to a slight imperfection in simulating the pion punchthrough and pion decay processes.

effects include sensitivity to the vertex quality (1.1%), the trigger (1.0%), and the fitting procedure (0.8%). The remaining effects result from uncertainties in the background and the calibration (0.7%). The total systematic error on the branching ratio is 4.6%.

Because the branching ratio and α are linked through the form factor, the following method is used to determine both of these parameters. The measured branching ratio is determined as a function of α, where the α dependence results from the Monte Carlo acceptance correction. Theoretical predictions for the branching ratio are also calculated as a function of α. Full single-loop QED radiative corrections are included [15] with a cutoff at $M^2_{ee\mu\mu}/M^2_K > 0.95$, and the quadratic DIP parameter β is assumed to be zero. The intersection of these two curves, shown in Fig. 3, determines $\mathcal{B}(K_L \rightarrow e^+e^-\mu^+\mu^-) = [2.69 \pm 0.24(\text{stat}) \pm 0.12(\text{syst})] \times 10^{-9}$ and $\alpha = -1.51 \pm 0.34(\text{stat}) \pm 0.17(\text{syst})$. Varying the value of β between -20 and 20 has a negligible effect on the results.

Because α and β are connected to q_1^2 and q_2^2 [Eq. (1)], independent measurements of the form factor parameters can be made by studying the shape of the $M_{\mu\mu}$ and M_{ee} distributions of the 132 signal events. With β fixed at 0, the signal Monte Carlo is reweighted over a range of values for α. Comparison to the data for each value of α leads to a log-likelihood distribution that is maximized when $\alpha = -4.53^{+1.81}_{-2.70}$. A comparison between data and Monte Carlo at this value of α is shown in Fig. 4. Because of the limited statistics, we find that this analysis is insensitive to the value of the quadratic form factor parameter β.

A weighted average of the two $K_L \rightarrow e^+e^-\mu^+\mu^-$ measurements of α leads to the final result $\alpha = -1.59 \pm 0.37$, consistent with the two previously published values.

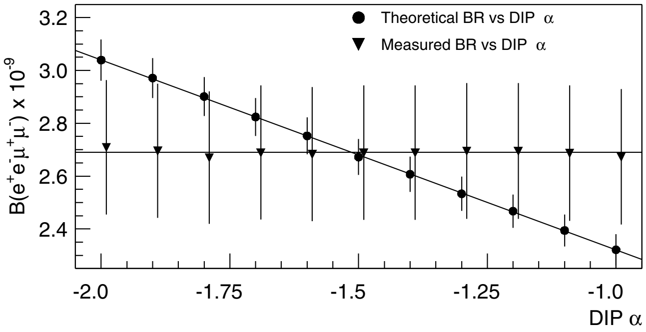

FIG. 3. Simultaneous determination of the $\mathcal{B}(K_L \rightarrow e^+e^-\mu^+\mu^-)$ and the DIP α parameter. The triangles show values for the branching ratio, based on 132 signal events with 0.8 background events. The error bars include statistical and systematic errors. The dots show the theoretical dependence of the branching ratio on α, where the errors result from the uncertainty in $\mathcal{B}(K_L \rightarrow \gamma\gamma)$. The branching ratio and α are determined from the intersection of the two lines.

Combining the results from $K_L \rightarrow \mu^+\mu^-\gamma$, $K_L \rightarrow e^+e^-e^+e^-$, and $K_L \rightarrow e^+e^-\mu^+\mu^-$ gives a world average of $\alpha = -1.53 \pm 0.10$, a result that is dominated by the measurement from $K_L \rightarrow \mu^+\mu^-\gamma$.

The Bergström-Massó-Singer (BMS) model for the $K_L\gamma^*\gamma$ vertex can be generalized to the two-virtual photon case [16]. The BMS form factor contains only one unknown parameter, α_{K^*}, which can be algebraically related to the DIP parameter α [5]. Using this relation, along with the measured value of α, we find that $\alpha_{K^*} = -0.19 \pm 0.11$ from $K_L \rightarrow e^+e^-\mu^+\mu^-$. This is consistent with other KTeV measurements [6,7], as well as those from the NA48 experiment at CERN [17].

Some models of the $K_L\gamma^*\gamma^*$ vertex allow for CP-violating contributions to the interaction, the presence of which would lead to an asymmetry in the angular distribution of the decay products [4]. The distribution of events in $\sin\phi\cos\phi$ is shown in Fig. 5. ϕ is the angle between the normals to the electron and muon decay planes in the kaon rest frame. The asymmetry $\mathcal{A}$ is defined by the ratio $(N_+ - N_-)/(N_+ + N_-)$, where N_+ (N_-) is the acceptance corrected number of signal events in the positive (negative) region of Fig. 5. It is found that $\mathcal{A} = -5.3\% \pm 12.3\%$, which translates to a 90% confidence limit of $|\mathcal{A}| < 25.5\%$. We conclude that no evidence currently exists for a CP-violating component of the $K_L\gamma^*\gamma^*$ interaction.

By changing the charge requirement on the lepton pairs, a search can be performed for the lepton flavor-violating decay $K_L \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp$. After imposing a set of analysis cuts otherwise identical to those described earlier, no events remain in the signal region. Four-body phase space Monte Carlo was generated to calculate an overall acceptance for this mode of approximately 9%. This leads to a 90% C.L. limit of $\mathcal{B}(K_L \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp) < 4.12 \times 10^{-11}$, a factor of 3 improvement over the previously published limit [9].

In conclusion, 132 $K_L \rightarrow e^+e^-\mu^+\mu^-$ events have been observed from the 1997 and 1999 runs of the KTeV experiment, with an estimated background of 0.8 events.

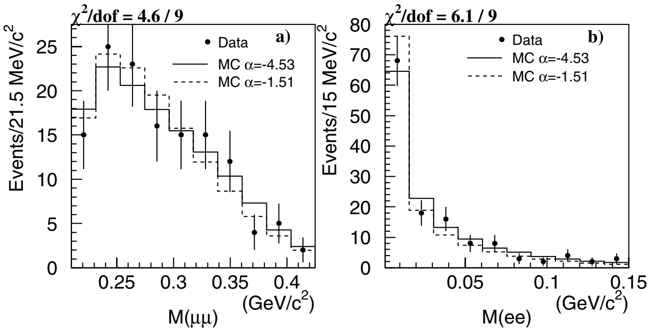

FIG. 4. (a) $M_{\mu\mu}$ and (b) M_{ee} distributions for the 132 signal events, compared to Monte Carlo generated with $\alpha = -1.51, -4.53$. β is zero for both overlays.

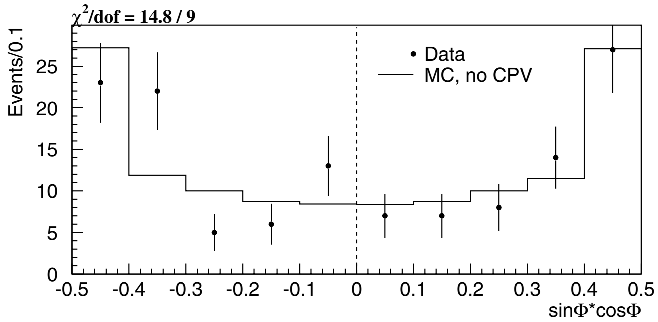

FIG. 5. Angular distribution of the decay products for $K_L \to e^+e^-\mu^+\mu^-$ events (dots) and Monte Carlo with no CP-violation (histogram).

This signal leads to a measured branching ratio of $[2.69 \pm 0.24(\mathrm{stat}) \pm 0.12(\mathrm{syst})] \times 10^{-9}$, consistent with previously published results. In the first measurement of the parameter α using this decay mode, we find that $\alpha = -1.59 \pm 0.37$, in agreement with measurements from other modes. Additional measurements of α using $K_L \to e^+e^-\gamma$ are expected soon. Because of the limited statistics, no sensitivity is found to the quadratic form factor parameter β. In order to reduce the error on β to be on the order of 1, we estimate that approximately 1000 times more data would be required. Furthermore, no evidence is found for CP-violating contributions to the $K_L\gamma^*\gamma^*$ interaction. Finally, we constrain the branching ratio of the lepton flavor-violating mode $K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$ to $<4.12 \times 10^{-11}$, at 90% confidence.

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