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Measurement of the Branching Fraction of the Decay $K_L \to \pi^+\pi^-e^+e^-$

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Abstract

We report the first branching fraction measurement of the decay $K_L \to \pi^+\pi^-e^+e^-$. With a sample of 46 candidates, and an expected background level of 9.4 events, the branching fraction is determined to be $B(K_L \to \pi^+\pi^-e^+e^-) = (3.2 \pm 0.6(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-7}$. This measurement was carried out as part of the Fermilab KTeV (E799-II) experiment and is in good agreement with the expectations from the mechanisms of Direct Emission and Inner Bremsstrahlung.

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The decay $K_L \to \pi^+\pi^-e^+e^-$ is expected to proceed via a virtual photon intermediate state $K_L \to \pi^+\pi^-\gamma^* \to \pi^+\pi^-e^+e^-$ [1, 2]. The amplitude for $K_L \to \pi^+\pi^-\gamma^*$ has two distinct components that have been observed in $K_{S,L} \to \pi^+\pi^-\gamma$[3]: one from the primarily CP-conserving Direct Emission process (DE), the second from a CP-violating $K_L \to \pi^+\pi^-$ decay with Inner Bremsstrahlung (IB). The interference of the CP-even and CP-odd amplitudes gives the virtual photon a CP-violating circular polarization, which gives rise to an asymmetry in ϕ, where ϕ is the angle between the $\pi^+\pi^-$ and e^+e^- planes in the kaon center of mass frame. The ϕ asymmetry, which explicitly violates CP and T separately, is predicted to be about 14%[1], mostly due to indirect CP violation. This decay consequently provides another window for the study of CP violation.

The branching fraction for the decay $K_L \to \pi^+\pi^-e^+e^-$ is predicted to be approximately 3×10^{-7}[1]. A recent measurement of the 90% confidence level upper limit on the branching fraction is 4.6×10^{-7} [4]. In this Letter, we present a branching fraction measurement for this decay based upon 2% of the data collected in the Fermilab experiment KTeV(E799-II).

Figure 1 shows the KTeV (E799-II) detector. Only those detector elements relevant to the analysis in this Letter are described below. Kaons were produced by an 800 GeV proton beam focused on a 30 cm long beryllium-oxide target. Collimators downstream of the target defined two side-by-side neutral beams with a solid angle of 0.25 μstr each. Charged particles in the beam were removed by a series of sweeping magnets. The two beams entered a 70 meter long decay volume starting 90 meters downstream of the target. The vacuum in the decay volume was 10^{-6} Torr.

The charged particle spectrometer consisted of four planar drift chambers, two upstream and two downstream of a dipole analyzing magnet with a momentum kick of 205 MeV/c in the horizontal plane. Each chamber measured positions in two orthogonal views (x and y). A view consisted of two planes of wires, spaced 6.35 mm apart, in which single hit position resolutions between 90 and 110 microns were obtained. Helium was used to fill the spaces between the drift chambers in order to reduce multiple scattering.

A pure CsI calorimeter of 3100 crystals was used for photon detection and for charged particle identification. To distinguish electrons from pions, the energy (E) measured by the calorimeter was compared to the momentum (p) measured by the charged spectrometer. Electrons were identified by $0.9 < \mathrm{E/p} < 1.1$, and pions were identified by $\mathrm{E/p} < 0.9$. The calorimeter was calibrated using electrons from 4×10^5 $K_L \to \pi e \nu$ decays. The resulting E/p resolution for this analysis was 1.1% averaged over the electron energy range 2 to 60 GeV. Two beam holes, each 15 x 15 cm^2, were symmetrically located on both sides of the center of the CsI array to let the two neutral beams pass through. Just upstream of the calorimeter were two scintillator trigger-hodoscope planes used for charged particle triggering. A photon veto system, consisting of eleven stations of lead/scintillator sandwich detectors, was used to detect particles that escaped the fiducial volume of the detector. Finally, a scintillator hodoscope behind 4 meters of iron filter was used to veto muons. To select high-multiplicity tracks consistent with $K_L \to \pi^+\pi^-e^+e^-$, the hardware trigger required at least three hits in each of the two trigger-hodoscopes, and a minimum of three hits in five of the eight drift chamber views. In addition to selecting charged tracks, the hardware trigger enhanced the electron content in these events by requiring at least 11 GeV of energy deposited in the calorimeter and at least two separated clusters of energy greater than 1 GeV. An online software filter required that the drift chamber hits were consistent with at least three tracks from a common vertex.

The offline analysis required candidate $K_L \to \pi^+\pi^-e^+e^-$ events to have four charged tracks from particles which hit the CsI for particle identification. Both the electron and pion pairs were required to have opposite-sign tracks. The reconstructed decay vertex position along the beam was required to be within a fiducial decay volume between 95 meters and 158 meters from the target. In order to help remove events with a missing particle, we demanded that the P_T^2, defined as the square of the total momentum of the observed decay products transverse to the parent kaon's line of flight, be less than 0.0002 GeV^2/c^2.

After all the above cuts, the major background to $K_L \to \pi^+\pi^-e^+e^-$ came from $K_L \to \pi^+\pi^-\pi^0_D$ decays where π^0_D denotes the π^0 Dalitz decay $\pi^0 \to e^+e^-\gamma$, and where the extra photon was not detected. To reduce this background, we use a kinematic variable which is calculated assuming the $\pi^+\pi^-$ pair came from a $K_L \to \pi^+\pi^-\pi^0$ decay. This quantity is equal to the square of the longitudinal momentum of the π^0 in the frame in which the sum of the charged pion momenta is orthogonal to the kaon momentum[5] and is given by

$$P^2_{\pi^0} = \frac{[(M^2_K - M^2_{\pi^0} - M^2_{\pi\pi})^2 - 4M^2_{\pi^0}M^2_{\pi\pi} - 4M^2_K(P^2_T)_{\pi\pi}]}{4[(P^2_T)_{\pi\pi} + M^2_{\pi\pi}]}$$

where $M_{\pi\pi}$ is the invariant mass of the $\pi^+\pi^-$ system, M_{π^0} is the mass of the π^0, M_K is the mass of the K_L, and $(P^2_T)_{\pi\pi}$ is the square of the transverse momentum of the $\pi^+\pi^-$ system with respect to the kaon momentum. For $K_L \to \pi^+\pi^-\pi^0_D$ events, $P^2_{\pi^0}$ is positive-definite, except for some smearing into the negative region due to resolution effects. Figure 2 shows the distribution of $P^2_{\pi^0}$ for $K_L \to \pi^+\pi^-e^+e^-$ candidates with a charged invariant mass between 0.48 GeV/c^2 $< M_{\pi\pi ee} <$ 0.52 GeV/c^2.

The component with $P^2_{\pi^0} > 0$ agrees well with a Monte Carlo simulation of $K_L \to \pi^+\pi^-\pi^0_D$ decays, normalized to the absolute flux of kaons decaying in the detector. We also note a collection of events with $P^2_{\pi^0} < -0.0025$ GeV^2/c^2; their distribution agrees with expectations from a $K_L \to \pi^+\pi^-e^+e^-$ Monte Carlo and they constitute our candidate events for this decay. Cutting at $P^2_{\pi^0} < -0.0025$ GeV^2/c^2 removes 94% of the residual $K_L \to \pi^+\pi^-\pi^0_D$ background in this invariant mass range, but only 10% of the $K_L \to \pi^+\pi^-e^+e^-$ signal.

Figure 3(a) shows the $M_{\pi\pi ee}$ vs. P^2_T distribution after all the above cuts except the P^2_T cut. There is clear evidence for a $K_L \to \pi^+\pi^-e^+e^-$ signal, with 46 events within the signal region defined by $P^2_T < 0.0002$ GeV^2/c^2 and 0.485 GeV/c^2 $< M_{\pi\pi ee} <$ 0.511 GeV/c^2. Events at lower invariant mass are predominantly from $K_L \to \pi^+\pi^-\pi^0_D$ decays. Fig. 3(b) shows the $M_{\pi\pi ee}$ distribution for events passing all the above cuts including the P^2_T cut. The number of $K_L \to \pi^+\pi^-\pi^0_D$ events remaining in the signal region was estimated to be 7.6 ± 2.0(Monte Carlo stat.) $\pm$ 2.0(syst.) by simulating the decay and normalizing to the number of events with 0.40 GeV/c^2 $< M_{\pi\pi ee} <$ 0.48 GeV/c^2. The background was also estimated by normalizing to the overall flux and the difference in the number of estimated background events was assigned as the systematic error.

Another background to the $K_L \to \pi^+\pi^-e^+e^-$ decay is from events with two simultaneous $K_L \to \pi e \nu$ decays. By studying events with the wrong sign pairing, $\pi^\pm\pi^\pm e^\mp e^\mp$, we determined this background to be 0.6 ± 0.6 events.

The last source of background considered is from photon conversions in the 0.4% radiation length vacuum window from either $K_L \to \pi^+\pi^-\pi^0$ or $K_L \to \pi^+\pi^-\gamma$ decays. Monte Carlo studies predicted the number of background events from $K_L \to \pi^+\pi^-\pi^0$ decays to be 1.2 ± 1.2. The corresponding background from $K_L \to \pi^+\pi^-\gamma$ decays is estimated to be less than 0.1 event. The total number of $K_L \to \pi^+\pi^-e^+e^-$ event candidates after background subtraction was 36.6 $\pm$ 6.8 where the uncertainty is statistical only.

To calculate a branching fraction, the decay mode $K_L \to \pi^+\pi^-\pi^0_D$ was used for normalization. Because the trigger was the same for the signal and normalization modes and because both the signal and the normalization modes consist of four-track events, uncertainties due to track reconstruction tended to cancel in the ratio of their acceptances. Cuts similar to those used in the signal mode analysis were applied. In addition, one extra cluster of energy ≥ 2 GeV and separated by at least 20 cm at the CsI from either pion track was required. After all cuts, 54,031 $K_L \to \pi^+\pi^-\pi^0_D$ event candidates remained with negligible background.

By using the acceptance of this mode from Monte Carlo studies, and the measured branching fractions for $K_L \to \pi^+\pi^-\pi^0$ and $\pi^0 \to e^+e^-\gamma$[6], the total number of decaying K_L mesons within the fiducial region was calculated to be $(4.92 \pm 0.02(\text{stat.}) \pm 0.34(\text{syst.})) \times 10^9$. The systematic uncertainty in the kaon flux was based on variations of flux measurements from other K_L decay modes, such as $K_L \to \pi^+\pi^-\pi^0$, $K_L \to \pi^0\pi^0_D\pi^0_D$, $K_L \to \pi^0\pi^0_D$ and $K_L \to e^+e^-\gamma$.

The calculated acceptance of the $K_L \to \pi^+\pi^-e^+e^-$ decay mode depends on the theoretical model used for its decay matrix element. The branching fraction presented here assumes a matrix element of the form given in Ref.[1]. In this model, the size of the relative contributions from DE and IB come from measurements of the $K_L \to \pi^+\pi^-\gamma$ photon energy spectrum[3]. A $\pm 6.4\%$ error was assigned to the calculated acceptance and was determined by varying the experimentally measured parameters in the matrix element by $\pm 3\sigma$ in a way that maximized the change in the acceptance. An additional uncertainty of 1.8% in the acceptance is due to the effects of accidental activity in the detector.

Figure 4(a) shows the generated $\pi^+\pi^-$ invariant mass for $K_L \to \pi^+\pi^- e^+e^-$ decays using a constant matrix element and using the matrix element calculated in Ref. [1]. In Fig. 4(b) both of these curves are shown after acceptance. The $\pi^+\pi^-$ invariant mass distributions after acceptance are very similar, however the acceptance is much smaller for the model in Ref. [1] because of the enhancement at large $\pi^+\pi^-$ invariant mass. Note that in this model about 26% of the spectrum involves $\pi^+\pi^-$ masses larger than 0.46 GeV/c^2 where our acceptance is below 0.1%. The $\pi^+\pi^-$ invariant mass distribution for the data is overlaid in Fig 4(b) after subtracting the background estimate generated from Monte Carlo. With such small statistics we cannot clearly distinguish between the two matrix elements.

Using the matrix element from Ref.[1] to calculate the overall acceptance, we obtained a branching fraction of $(3.2 \pm 0.6(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-7}$. The sources of uncertainty in the measurement are listed in Table 1. If we were to use a constant matrix element instead of Ref.[1], the branching fraction would decrease by a factor of about 2.

Table 1: Sources of uncertainty in the branching fraction measurement of $K_L \to \pi^+\pi^- e^+e^-$

Effect	% Uncertainty
Statistical	18.5 %
Background Subtraction	8.6 %
$K_L \to \pi^+\pi^- e^+e^-$ acceptance	6.6 %
K_L Flux Measurement	6.9 %
Total Uncertainty	22.5 %

In summary, we have observed the decay $K_L \to \pi^+\pi^- e^+e^-$ and made the first measurement of its branching fraction. The KTeV(E799-II) experiment has accumulated about 50 times more data than the sample discussed here and will be able to explore details of the dynamics of this decay as well as search for the predicted CP violating ϕ asymmetry.

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References

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[1] L. M. Sehgal and M. Wanninger, Phys. Rev. **D46**, 1035 (1992),
L. M. Sehgal and M. Wanninger, *ibid.,* **D46**, 5209(E)(1992),
P. Heilger and L. M. Sehgal, *ibid.,* **D48**, 4146 (1993).

[2] J. K. Elwood *et al.* Phys. Rev. **D52**, 5095 (1995),
J. K. Elwood *et al.*,*ibid.,* **D53**, 2855(E) (1996),
J. K. Elwood *et al.*,*ibid.,* **D53**, 4078 (1996).

[3] E. J. Ramberg *et al.*, Phys. Rev. Lett. **70**, 2525 (1993),
E. J. Ramberg *et al.*, *ibid.,* **70**, 2529 (1993).

[4] T. Nomura *et al.*, Phys. Lett. **B408**, 445 (1997).

[5] D. Leurs *et al.*, Phys. Rev. **133**, B1276 (1964),
A. Carrol *et al.*, Phys. Rev. Lett. **44**, 525 (1980).

[6] R. M. Barnett *et al.*, Phys. Rev. **D54**, 1 (1996).

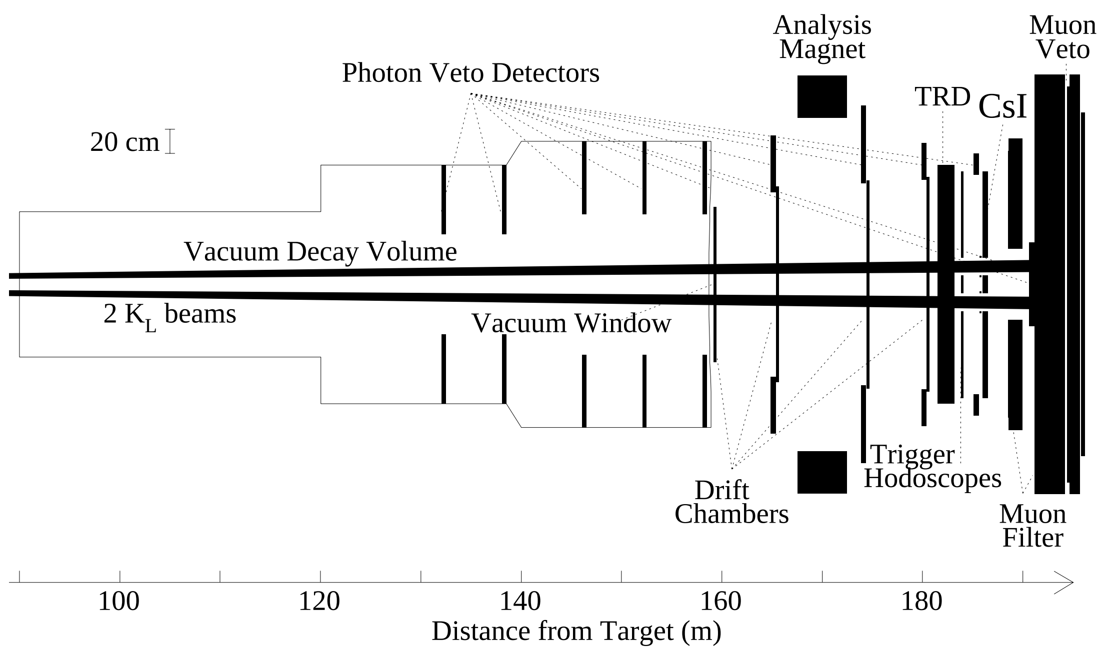

Figure 1: The KTeV (E799-II) Detector.

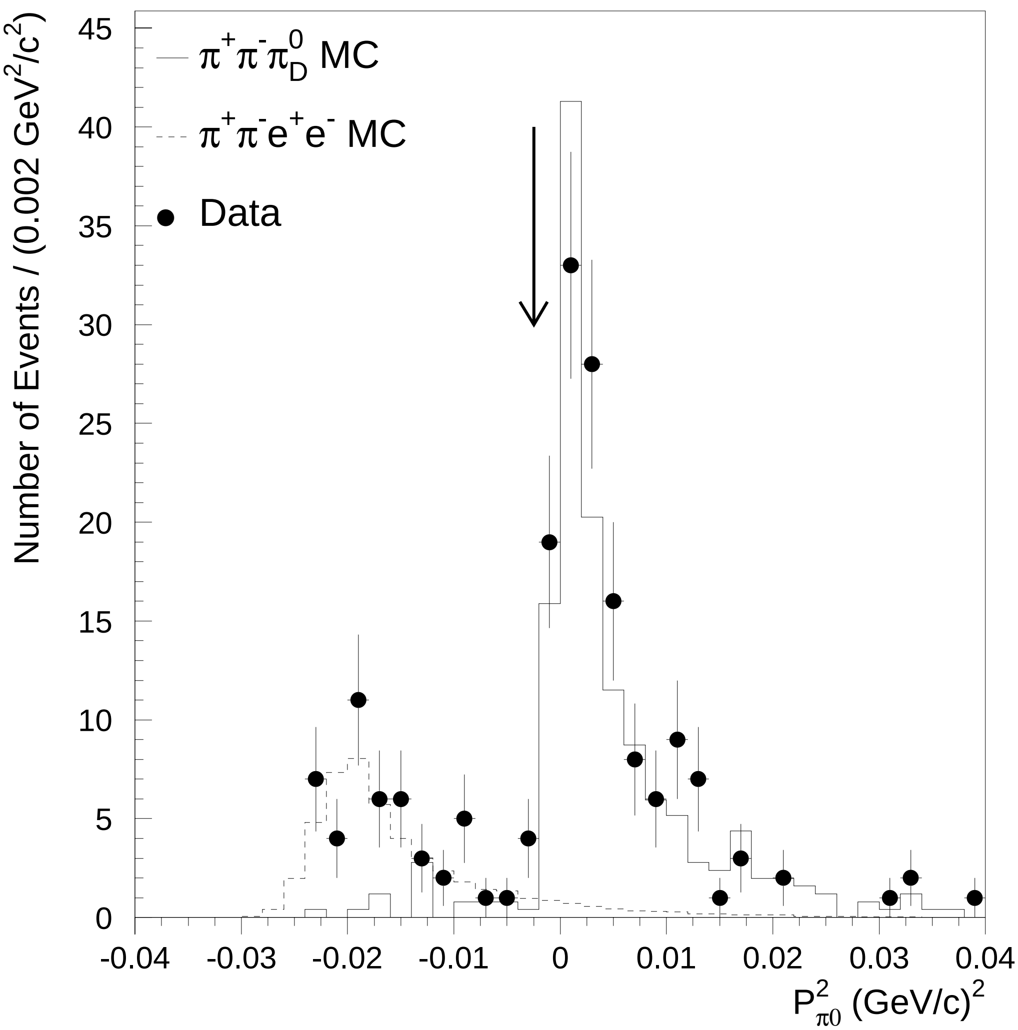

Figure 2: $P^2_{\pi^0}$ for $K_L \rightarrow \pi^+\pi^-e^+e^-$ event candidates from the data (solid dots). The solid line is the predicted distribution from a Monte Carlo simulation of $K_L \rightarrow \pi^+\pi^-\pi^0_D$ events and the dotted line is the predicted distribution from a Monte Carlo simulation of $K_L \rightarrow \pi^+\pi^-e^+e^-$ using the model of [1]. The $K_L \rightarrow \pi^+\pi^-\pi^0_D$ Monte Carlo is normalized to the flux of decaying K_L from the data sample (see text). The $K_L \rightarrow \pi^+\pi^-e^+e^-$ Monte Carlo is arbitrarily normalized. The arrow shows the cut value of -0.0025 GeV^2/c^2.

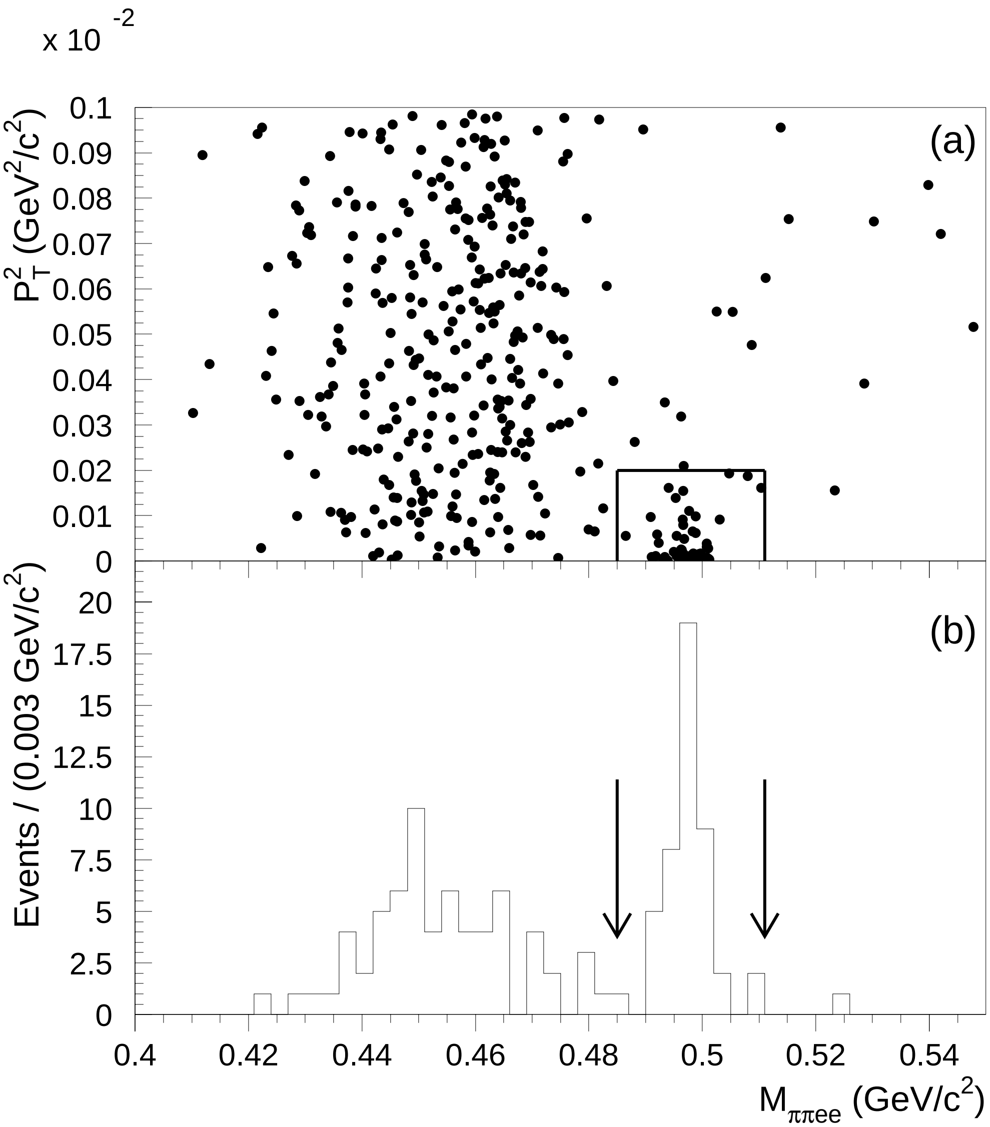

Figure 3: (a) The P_T^2 vs. the $M_{\pi\pi ee}$ distribution for data. (b) The $M_{\pi\pi ee}$ distribution for events with $P_T^2 \leq 0.0002$ GeV^2/c^2.

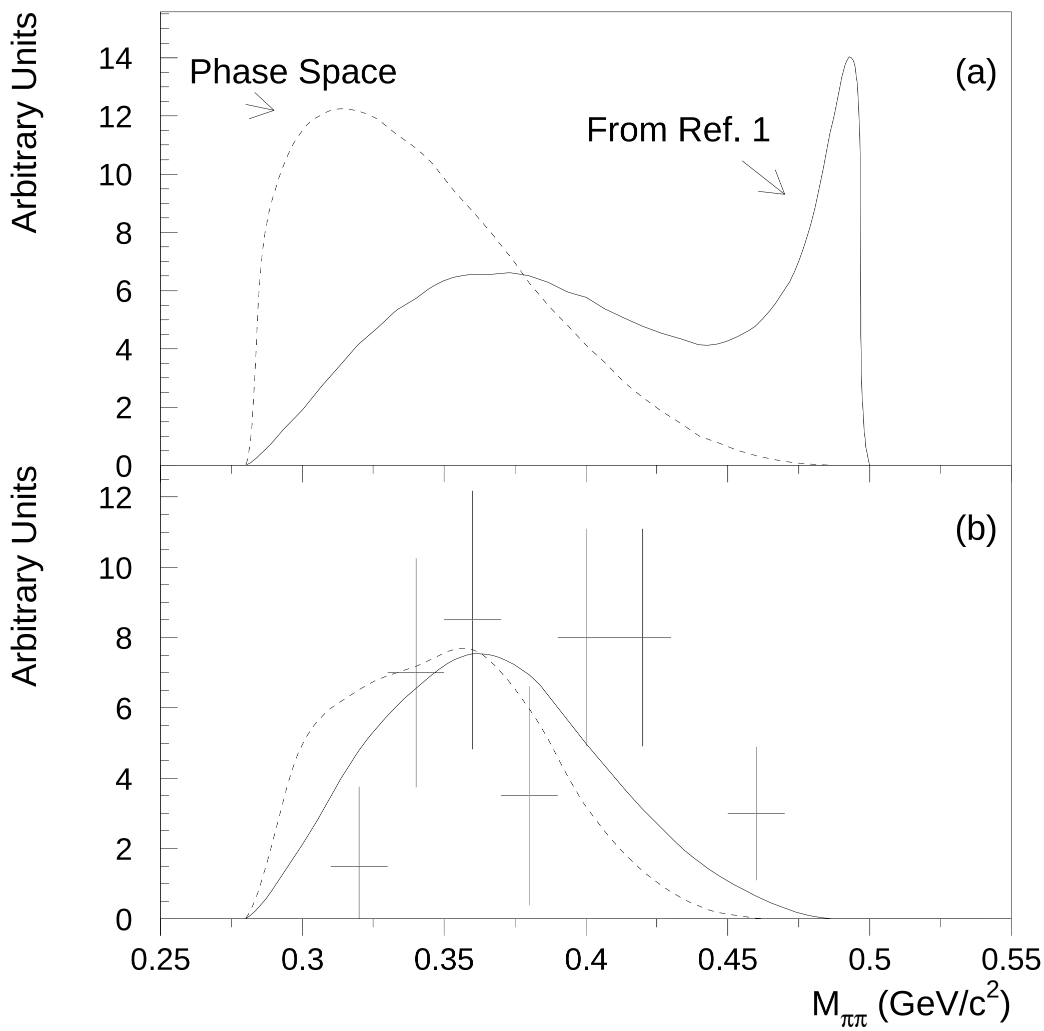

Figure 4: (a) The $\pi^+\pi^-$ invariant mass distributions for $K_L \to \pi^+\pi^-e^+e^-$ using the model cited in Ref.[1] (solid curve) and phase space (constant matrix element) (dashed curve). (b) The $\pi^+\pi^-$ invariant mass distributions for $K_L \to \pi^+\pi^-e^+e^-$ after acceptance using the model cited in Ref.[1] (solid curve) and phase space (dashed curve). The final event candidates are overlaid after background subtraction.