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Study of the Decay $K_L \to \pi^\pm \pi^0 e^\mp \bar{\nu}(\nu)$

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ABSTRACT

We have observed 729 ± 15 $K_L \to \pi^{\pm}\pi^0 e^{\mp}\bar{\nu}(\nu)$ decays in the data set collected in the 1987-88 run of Fermilab experiment E731. We found the K_{e4} branching ratio to be $(5.16 \pm 0.20_{stat} \pm 0.22_{sys}) \times 10^{-5}$. We also performed the first measurement of the form factors parameterizing the decay. Our branching ratio result agrees with a prediction using a vector meson exchange model. An interpretation of the data in terms of chiral perturbation theory implies a value $L_3 = (3.4 \pm 0.4) \times 10^{-3}$ in the $O(p^4)$ chiral lagrangian.

The kaon decay, $K \rightarrow \pi\pi e\nu$, commonly known as the K_{e4} decay, provides an excellent system for studying the long-distance contributions to $K\pi\pi$ and $\pi\pi$ interactions. The charged K_{e4} decay, $K^+ \rightarrow \pi^+\pi^- e^+\nu$, was studied in a 1975 experiment which collected 30,000 events, yielding measurements of the dominant form factors in the decay [1]. These data have recently been re-analyzed in the context of chiral perturbation theory to provide measurements of three of the ten parameters in the $O(p^4)$ chiral lagrangian [2]. The observation of neutral K_{e4} decays, $K_L \rightarrow \pi^\pm\pi^0 e^\mp\bar{\nu}(\nu)$, was most recently reported in a 1980 study based on a sample of 16 events [3]. The neutral kaon version of the decay is unique within the K_{e4} family because isospin symmetry and the $\Delta I=1/2$ rule dictate that the final state $\pi\pi$ system is predominantly in a P-wave. A measurement of the branching ratio of this decay allows a clean determination of the parameter L_3 in the $O(p^4)$ chiral lagrangian. This parameter plays a role in the chiral perturbation theory interpretation of $\pi\pi$ scattering, $K\pi$ scattering, and the decay $\eta \rightarrow 3\pi$. The neutral K_{e4} branching ratio measurement has also been predicted in a parameter-free way in a vector meson exchange model [4].

To study the decay distributions in the K_{e4} decay we first write the matrix element factored into hadronic and leptonic parts

$$M = \frac{G_F}{\sqrt{2}} \sin\theta_C \bar{\nu}\gamma_\mu(1-\gamma_5)e\langle\pi\pi|V_\mu + A_\mu|K\rangle,$$

where G_F is the Fermi coupling constant and θ_c is the Cabbibo angle. The hadronic part of the matrix element may be parameterized by the four form factors F, G, H, and R [5] as

$$\langle\pi\pi|A_\mu|K\rangle = \frac{1}{M_K}[F(p_1+p_2)_\mu + G(p_1-p_2)_\mu + R(k-p_1-p_2)_\mu],$$

$$\langle\pi\pi|V_\mu|K\rangle = \frac{1}{M_K^3}[H\epsilon_\mu^{\nu\alpha\beta}k_\nu(p_1+p_2)_\alpha(p_1-p_2)_\beta],$$

where p_1, p_2, and k are the momenta of the $\pi^\pm$, π^0 and the kaon respectively. The decay is described in terms of five kinematic variables: two masses $M_{\pi\pi}$, $M_{e\nu}$, and three angles θ_π, θ_e, and ϕ. $\theta_\pi(\theta_e)$ is the angle between the $\pi^\pm(e^\mp)$ and the kaon in the $\pi\pi(e\nu)$ center of mass frame; ϕ is the angle between the decay planes formed by the $\pi\pi$ and the $e\nu$.

Since the four form factors are in general complex numbers we write $F = f_s e^{i\delta_s} + f_p cos(\theta_\pi) e^{i\delta_p}$, $G = ge^{i\delta_p}$, and $H = he^{i\delta_p}$ where δ_s and δ_p are the S- and P-wave final state phase shifts [6]. The R term enters the decay distributions multiplied by m_e^2 and can therefore be neglected. The f_s contribution to the decay is suppressed by isospin symmetry and the h contribution is multiplied by a small kinematic factor. As a result, 99% of the decay rate of this decay is expected to come from the g term alone. This decay therefore allows a clean measurement of g as well as its possible $M_{\pi\pi}$ dependence which can be parameterized by λ_G where $g(M_{\pi\pi}) = g(0)(1+\lambda_G q^2)$ and $q^2 = \frac{M_{\pi\pi}^2 - 4M_\pi^2}{4M_\pi^2}$.

The data discussed here were collected during the E731 experiment at Fermilab, the primary goal of which was to measure the CP-violation parameter ϵ'/ϵ. The characteristics of the detector have been described elsewhere [7], so we summarize here only the features essential to this analysis. Charged particles were measured and momentum-analyzed with four drift-chambers each with two horizontal and two vertical planes. The chambers have a $100\mu m$ hit resolution per plane. The energies and positions of photons and electrons were measured using an array of 804 lead glass blocks. The energy resolution of this calorimeter for electrons is approximately $1.5\% + 5.0\%/\sqrt{E}$; for photons the constant term is 2.5%. A bank of scintillators located behind 3 meters of steel was used to identify muons with an efficiency of 99.9% for momenta greater than 7 GeV/c. The trigger used to collect these data required events to contain two charged tracks and vetoed events with muons. The mean momentum of kaons in our beam was 60 GeV/c.

We identified K_{e4} decays by looking for events with a $\pi^{\pm}$ and an $e^{\mp}$ candidate track originating at a common vertex matched to energy clusters in the lead glass, together with two additional clusters in the glass not matched to tracks, corresponding to the two photons from a π^0 decay. The $\pi^{\pm}$ candidate was required to have $E/p < 0.8$, where E is the energy deposited in the lead glass by the particle, and p is the track momentum measured in the drift chamber system. The $e^{\mp}$ candidate had to have $0.88 < E/p < 1.12$. The two extra clusters in the event were combined to form the π^0 candidate with the requirement $125 < M_{\gamma\gamma} < 145$ MeV/c^2. We also required that the invariant mass of all the observed particles be less than M_K and that the vector sum of their measured momenta have a magnitude, p_t, which does not exceed the maximum value possible in a K_{e4} decay by more than 15 MeV/c.

Data satisfying only the cuts described above contain substantial background. The largest background was from $K_L \to \pi^+\pi^-\pi^0$ decays in which one of the charged pions showered in the lead glass and faked an electron in the E/p identification. Additional background came from the decays $K_{e3} + 2\gamma_{Extra}$ in which the two extra photon clusters combined to fake a π^0.

In order to reject background from $K_L \to \pi^+\pi^-\pi^0$ we reconstructed the invariant mass of the observed system, assuming a $\pi^+\pi^-\pi^0$ decay. We then rejected events with $p_t < 77$MeV/c and $475 < M_{3\pi} < 530$ MeV/c^2. A number of $\pi^+\pi^-\pi^0$ events survived these cuts due to poor π^0 reconstruction. These were suppressed by requiring that the momentum of the two charged tracks transverse to the kaon line of flight be less than the kinematic maximum for a $\pi^+\pi^-\pi^0$ decay in the region $M_{3\pi} < 525$ MeV/c^2 where the residual background is large. 37% of otherwise good K_{e4} candidates are lost in removing the $\pi^+\pi^-\pi^0$ background.

Background due to $K_{e3} + 2\gamma_{Extra}$ (K_{e3} events with two extra clusters due to internal or external bremsstrahlung) were rejected by cutting all events with small $p_e \cdot p_\gamma$, where p_e is the electron four-momentum, and p_γ is the four-momentum of either photon detected in the calorimeter. We also required that photons from the π^0 candidate deposit at least 2 GeV/c^2 in the lead glass since accidental clusters typically are of low energy.

In this study we selected events with kaon momentum between 22 and 160 GeV/c and with a decay vertex between 110 and 137 meters from our target.

With all of these cuts applied 810 events remained in the data sample. Figure 1 shows the reconstructed E/p and $M_{\gamma\gamma}$ distributions, showing $\pi^{\pm}$, $e^{\mp}$, and π^0 signals with low background. The small residual background in the $M_{\gamma\gamma}$ and E/p figures was subtracted in two steps. First we subtracted 38 ± 10 $\pi^+\pi^-\pi^0$ background events from under the electron peak using an extrapolation of the E/p lineshape from kinematically selected $\pi^+\pi^-\pi^0$ events. Next we turned to the $M_{\gamma\gamma}$ spectrum, which is plotted after the E/p subtraction has been applied in each bin. The small residual background here is due to $K_{e3} + 2\gamma_{Extra}$ and is expected to fall smoothly. We estimated its level to be 43 ± 11 by linear interpolation. The errors on the two background subtractions were determined by varying both the range of the fits and the shape of the backgrounds used in the fits.

The acceptance for the K_{e4} decay in our detector depends on the *a priori* unknown form factors, so we based our branching ratio result on the form factors determined by a maximum likelihood fit. Our fit was performed using a kinematic expansion of the matrix element following Rosselet [1]. The fit was made in the 3 kinematic parameters $M_{\pi\pi}$, $\cos\theta_\pi$, and $\cos\theta_e$ with the following binning: 5 equal bins in $\cos\theta_\pi$ and $\cos\theta_e$ from -1 to 1 and 5 equal bins in $M_{\pi\pi}$ from 280 to 430 MeV/c^2. The angles $\cos\theta_\pi$ and $\cos\theta_e$ were reconstructed from the data using the smaller of the two possible solutions for the kaon lab momentum which can be calculated by combining the observed $\pi\pi e$ momentum and p_t with the assumption these particles result from a K_{e4} decay. Using this procedure the wrong solution for the kaon lab momentum is used in the reconstruction 45% of the time. $M_{e\nu}$ and ϕ were integrated over in the fit because they were poorly reconstructed due to this ambiguity in determining the kaon momentum, and because this simplified the analysis. The results of the fit projected in these two dimensions are consistent with the observed spectra. In the fit the values of δ_s, δ_p, and λ_F were fixed according to previously measured values [8]. Our results are not very sensitive to these experimental inputs. Background was included in the fit using events from the sidebands in $M_{\gamma\gamma}$ and E/p.

The results of the simultaneous fit to 5 parameters are $g(0)\sin\theta_C = 1.71 \pm 0.15 \pm 0.04$; $f_s/g = 0.010 \pm 0.016 \pm 0.017$; $f_p/g = -0.079 \pm 0.049 \pm 0.022$; $h/g = -0.07 \pm 0.31 \pm 0.31$; and $\lambda_G = 0.014 \pm 0.087 \pm 0.070$ with the first of these errors statistical and the second systematic. As expected from isospin symmetry we have found that the g parameter is the most significant parameter for describing the K_{e4} decay. The magnitude of h/g is somewhat smaller than (but has the same sign as) the expected value -0.56 based upon a calculation using the chiral anomaly [9], and verified in charged K_{e4} decays [1]. The value of f_p/g is expected to be small [2], and our result is close to zero. We find f_s/g within errors of both zero and the value 0.013 expected based upon a recent current algebra calculation [10]. The fit result for λ_G is consistent with 0.08, the value expected in chiral perturbation theory [2]. Figure 2 shows comparisons of the data projected in the five kinematic variables with the Monte Carlo simulation based on the fit results.

The systematic errors quoted for the form factor fit indicate the range of our fit results as we varied the cuts applied to select the fit data sample and the amount and treatment of the background in the fit. Since our detector efficiency is very well understood by detailed studies employing high statistics samples of K_{e3} and $K_{2\pi}$ decays we expect a very small contribution to the error in our form factor results due to any possible misunderstanding of our efficiency for accepting K_{e4} events [11].

The K_{e4} branching ratio was normalized to the known K_{e3} decay rate. The K_{e3} acceptance was 11.300±0.060% and that for K_{e4} was 1.470±0.056% based upon our Monte Carlo simulation of our detector, with the K_{e4} calculation assuming the form factors measured in the fit described above. The uncertainty of 3.8% on the K_{e4} acceptance results from a 3.6% uncertainty in the K_{e4} acceptance due to uncertainties in the form factors used in the calculation, and from a 1.3% uncertainty in corrections applied to the acceptance to account for the effect of accidental activity in the detector and for the loss of events due to inner-Bremstrahlung in the K_{e4} decay. The ratio of decay rates K_{e4}/K_{e3} is $(1.334 \pm 0.052_{stat} \pm 0.058_{sys}) \times 10^{-4}$. Using the known K_{e3} decay rate [13], we find that the branching ratio for K_{e4} is then $(5.16 \pm 0.20_{stat} \pm 0.22_{sys}) \times 10^{-5}$. The systematic errors quoted for these results include our uncertainty in the background subtractions.

Our branching ratio result agrees within errors with the 1980 result of Carroll et al of $(6.2 \pm 2.0) \times 10^{-5}$ [3]. In chiral perturbation theory the g form factor, and thus the K_{e4} decay rate, depends strongly on the parameter L_3 [2]. Our measured decay rate implies that $L_3 = (3.4 \pm 0.4) \times 10^{-3}$. This result is consistent with the original estimate of this parameter $(4.4 \pm 2.2) \times 10^{-3}$ using $\pi\pi$ D-wave scattering data [12], and with the value $(2.8 \pm 0.5) \times 10^{-3}$ based upon an analysis of the charged K_{e4} data [2]. A recent calculation based on 'vector meson symmetry' [4], predicts that the K_{e4} branching ratio should be 5.2×10^{-5}, in agreement with our measurement.

In summary, we have reported a neutral K_{e4} branching ratio with substantially improved precision and a first measurement of the form factors describing the decay. Our results are consistent with the expectation that the decay distrubutions are dominated by the g form factor term. Future high-statistics experiments may allow a measurement of a small S-wave dipion amplitude in the decay if it occurs at the predicted 1.3% level. In addition, a search can be made for a T-violating observable in the K_{e4} decay distributions [14].

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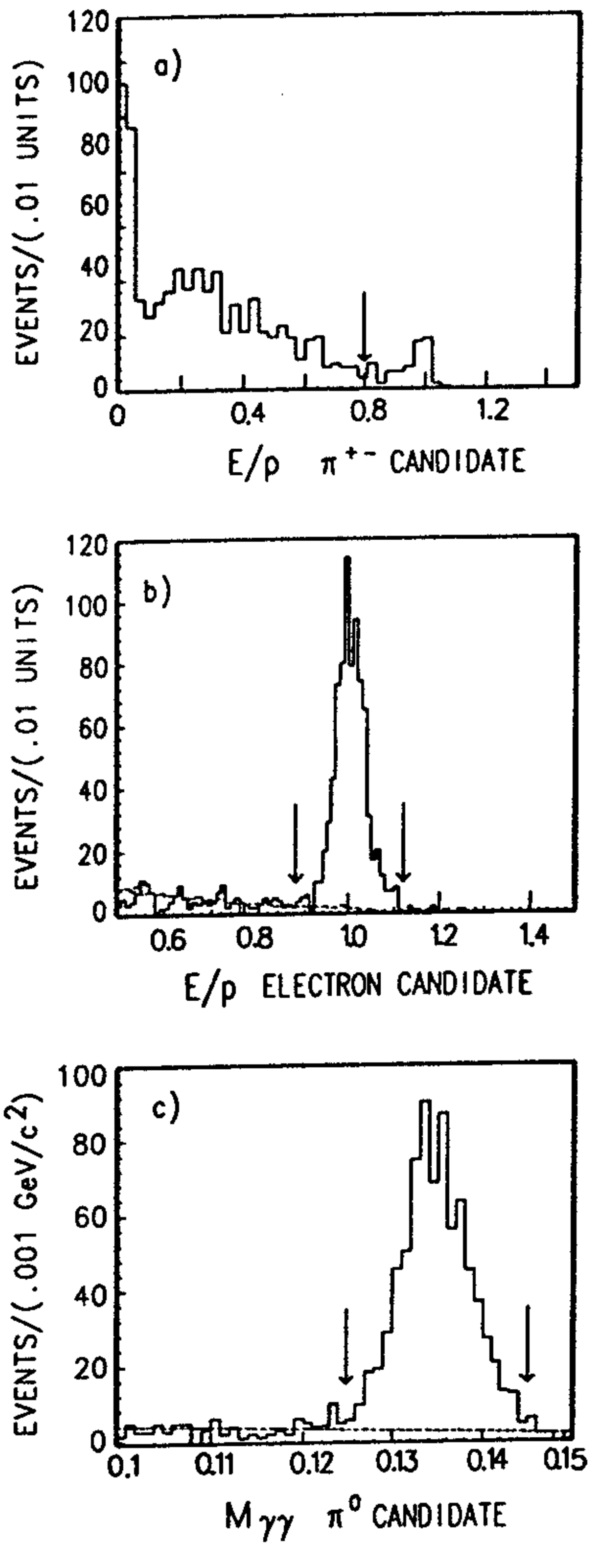
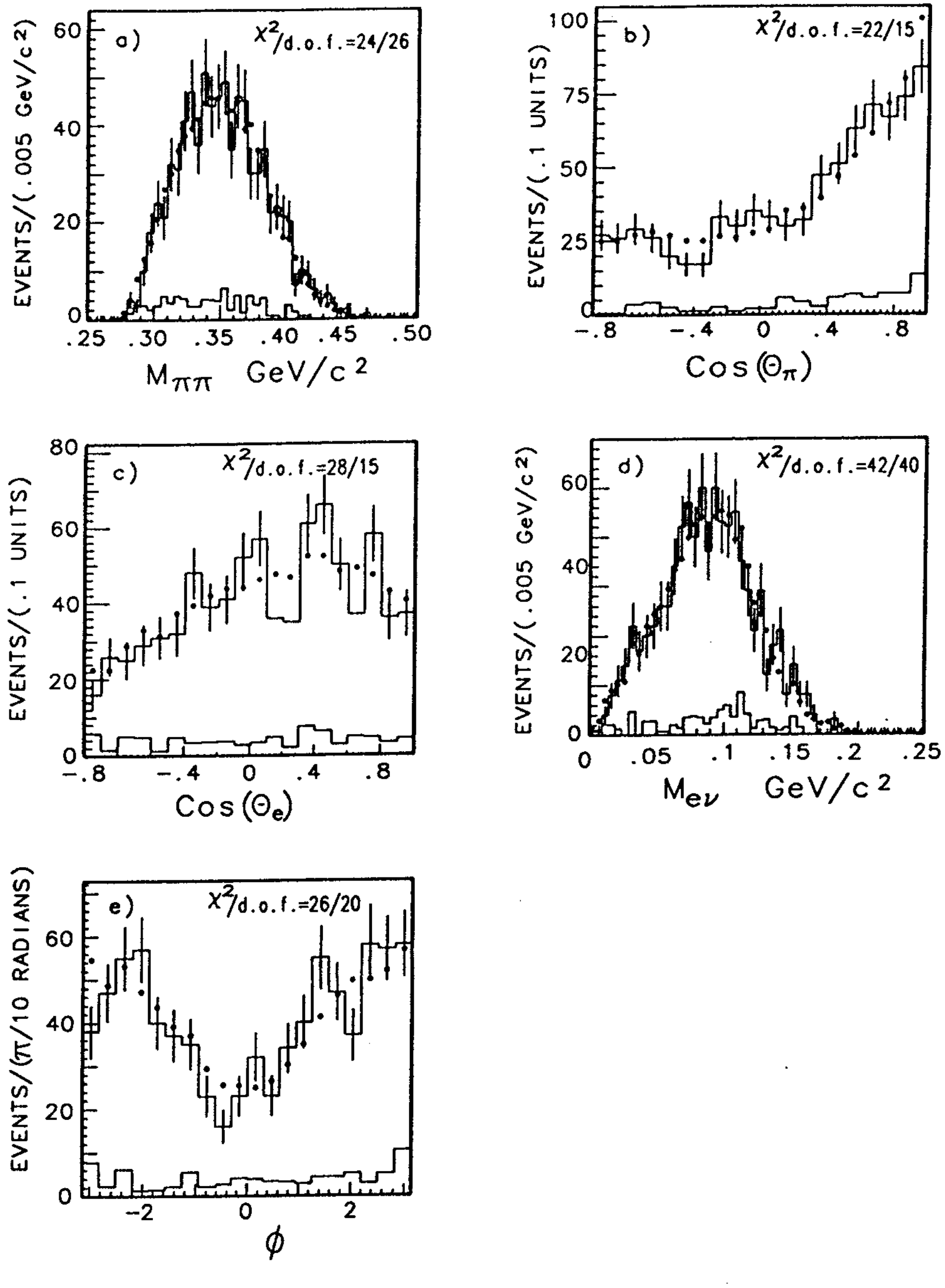
Figure 1: a) Charged pion candidate E/p, where E is the energy measured for the particle in the calorimeter and p is the momentum measured by the drift-chamber spectrometer. b) Electron candidate E/p. The solid histogram is the data. The dashed histogram shows the E/p spectrum of pions from kinematically selected $\pi^+\pi^-\pi^0$ events scaled to mock up the residual $\pi^+\pi^-\pi^0$ background in the data. c) $M_{\gamma\gamma}$ spectrum for the π^0 candidates formed from the two clusters in the electromagnetic calorimeter not matched to tracks. The solid histogram is the data. The dashed histogram shows the estimated background. Arrows indicate the location of cuts applied in selecting K_{e4} events.



a)
EVENTS/(.01 UNITS)
E/p π+- CANDIDATE
b)
EVENTS/(.01 UNITS)
E/p ELECTRON CANDIDATE
c)
EVENTS/(.001 GeV/c²)
Mγγ π0 CANDIDATE

Figure 2: The five kinematic variables describing the K_{e4} decay. Plots a-c show the three variables included in a maximum likelihood fit to the data a) $M_{\pi\pi}$, b) $\mathrm{Cos}(\theta_\pi)$, and c) $\mathrm{Cos}(\theta_e)$. Figures d-e show the two variables not included in the fit d) $M_{e\nu}$ and e) ϕ. The solid histograms with error bars show the data and the points show the Monte Carlo simulation of the decay using the results of the fit. Background levels are determined from the data in the regions $E/p < 0.85$ and $100 < M_{\gamma\gamma} < 125\mathrm{GeV/c^2}$; and are shown as solid histograms at the bottom of the plots. The χ^2 statistics for these comparisons are displayed.



a)
χ^2/d.o.f.=24/26
EVENTS/(.005 GeV/c²)
0
20
40
60
.25
.30
.35
.40
.45
.50
$M_{\pi\pi}$ GeV/c²
b)
χ^2/d.o.f.=22/15
EVENTS/(.1 UNITS)
0
25
50
75
100
−.8
−.4
0
.4
.8
Cos(Θ_π)
c)
χ^2/d.o.f.=28/15
EVENTS/(.1 UNITS)
0
20
40
60
80
−.8
−.4
0
.4
.8
Cos(Θ_e)
d)
χ^2/d.o.f.=42/40
EVENTS/(.005 GeV/c²)
0
20
40
60
0
.05
.1
.15
.2
.25
$M_{e\nu}$ GeV/c²
e)
χ^2/d.o.f.=26/20
EVENTS/(π/10 RADIANS)
0
20
40
60
−2
0
2
ϕ