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A measurement of the branching ratio of the decay $K_L \to \pi^0\gamma\gamma$

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ABSTRACT

Using the complete Fermilab E731 data set, we find

$$\frac{\Gamma(K_L \rightarrow \pi^0\gamma\gamma, m_{\gamma\gamma} \geq 0.280 GeV)}{\Gamma(K_L \rightarrow all)} = (1.86 \pm 0.60 \pm 0.60) \times 10^{-6}$$

in good agreement with a recent report of the first observation of this decay. For the low $\gamma\gamma$ mass region we find $\frac{\Gamma(K_L \rightarrow \pi^0\gamma\gamma, m_{\gamma\gamma} < 0.264 GeV)}{\Gamma(K_L \rightarrow all)} < 5.1 \times 10^{-6}$ (90% confidence).

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The decay $K_L \to \pi^0\gamma\gamma$ is of current interest[1-6] within the context of both Chiral Perturbation Theory and the Vector Meson Dominance model, and also for its contribution to the decay $K_L \to \pi^0 e^+ e^-$ as a CP conserving intermediate state. Predictions for its branching ratio vary from 6.3 x 10^{-7} to 6.2 x 10^{-6}, and predicted $\gamma\gamma$ mass distributions differ markedly. At the one-loop level in chiral perturbation theory[1], the branching ratio is estimated to be 6.8 x 10^{-7} with a characteristic $\gamma\gamma$ invariant mass distribution ($m_{\gamma\gamma}$) peaking at about 325 MeV.

Earlier we reported[7] an upper limit for the branching ratio of this decay of 2.7 x 10^{-6} (90% confidence) assuming the $\gamma\gamma$ invariant mass distribution expected by Chiral Perturbation Theory. That result was based on a subset of our data; here we report results from the entire data sample which therefore supersede the earlier results. In the meantime, CERN experiment NA31 has recently reported[8] an observation of the decay: they have found a signal primarily at high $\gamma\gamma$ invariant mass and a branching ratio significantly greater than that predicted by Chiral Perurbation Theory. They find

$$\frac{\Gamma\,(K_L \to \pi^0\gamma\gamma, m_{\gamma\gamma} \geq 280 MeV)}{\Gamma\,(K_L \to all)} = (2.1 \pm 0.6) \times 10^{-6}.$$

The primary goal of experiment E731 is the determination of the CP violation parameter ε'/ε[9]. The characteristics of the detector and the event reconstruction have been described in detail elsewhere[7,10]; here we summarize the essential features of the analysis and its differences from that used in our previous publication. Energies and positions of photons were measured with an 804 block lead glass calorimeter. Candidates for the $K_L \to \pi^0\gamma\gamma$ decay were required to have exactly four electromagnetic showers (clusters) in the lead glass, each with an energy of at least 1 GeV, and total energy between 40 and 150 GeV. The decay vertex was determined from the measured cluster energies and positions by assuming that the invariant mass of the four photons was that of the neutral kaon. The two photons, labeled (12), with invariant mass closest to the nominal neutral pion mass (m_{π^0}) were taken to be the decay products of the candidate π^0. The π^0 mass resolution was about 3 MeV and it was required that $|m_{12}-m_{\pi^0}| \leq 5$MeV.

Background rejection is critical since the signal is poorly constrained. The rejection of the $K_L \rightarrow 2\pi^0$ background was done in two steps. First, it was required that the mass of the non-π^0 pair ($m_{\gamma\gamma}$ or m_{34}) differ from m_{π^0} by at least 14 MeV. Second, the candidate event was reconstructed as a $K_L \rightarrow 2\pi^0$ decay by constraining the invariant masses of each pair of photons to the nominal π^0 mass, and if it satisfied the criteria described in references 7 and 10, it was rejected as a mispaired $2\pi^0$ decay. $K_L \rightarrow 3\pi^0$ decays, which are the dominant remaining background, can masquerade as four-cluster events either when photons escape the detector or when multiple photons fuse in the lead glass to form a single cluster. This background was considerably reduced (1) by using the many photon veto counters for the detection of escaping photons; (2) by requiring that the transverse center of energy of the four photons be in the K_L beam region; and (3), by considering only decays in the upstream part of the decay region, starting at 110 meters and ending at 128 meters from the target. The selection of the downstream edge of this decay region was made on the basis of a Monte Carlo study to maximize the sensitivity to a signal in the presence of known amounts of $3\pi^0$ and $2\pi^0$ backgrounds; the data themselves were not used. Background with overlapping clusters was substantially reduced by rejecting events with cluster shapes inconsistent with that of a single photon. Additional suppression of the $3\pi^0$ background came from kinematically rejecting events with two superimposed π^0s (double fusion events) where each photon from one π^0 overlaps with a photon from the other π^0 so that $m_{\gamma\gamma} > 2m_{\pi^0}$. By assuming that clusters 3 and 4 are fused clusters (true about 70% of the time) the fraction of the cluster energies belonging to each of the fused photons was determined. The rejection was based on the fact that energetic photons are more likely to fuse (see Reference 10). The drift chamber spectrometer and four scintillation hodoscopes were used to reject K_L decays with charged particles in the final state (eg. $K_L \rightarrow \pi^+\pi^-\pi^0$) or events with photon conversions. The contribution from accidental clusters in our data sample is found to be negligible. Finally we rejected events with photons projecting outside the holes of the lead mask photon veto which is located at about 122 m from the target and is one of our defining apertures.

Figure 1 shows the comparison of data and background Monte Carlo for the $\gamma\gamma$ effective mass. A characteristic feature in this distribution is the prominent double fusion peak appearing at about $m_{\gamma\gamma}$=270 MeV. The background coming from the $3\pi^0$ and $2\pi^0$ modes is absolutely normalized to the data by means of a sample of fully reconstructed $K_L \rightarrow 2\pi^0$ decays observed simultaneously and selected with criteria similar to those used for the $\pi^0\gamma\gamma$ candidates. Although for low $\gamma\gamma$ mass the data-Monte Carlo agreement is good within statistics, at high masses there is a significant excess of data. The background in the high mass region consists predominantly of events where both gammas are fused clusters. The Monte Carlo correctly reproduces the prominent double fusion peak, which is important in establishing that the excess at higher values is indeed a signal. Figure 2 shows the comparison of data and background Monte Carlo for the reconstructed z decay vertex distributions with $m_{\gamma\gamma} \geq$ 280 MeV, including the region downstream of the fiducial cut. The data excess is uniformly distributed over the decay region as is expected for a signal.

In Figure 3 we show data-Monte Carlo comparison for the m_{12} distribution for $m_{\gamma\gamma} \geq$ 280 MeV. The excess over the background Monte Carlo is peaked at the nominal π^0 mass with a width consistent with the prediction of a $\pi^0\gamma\gamma$ Monte Carlo. (It should be noted that the background also peaks near, but not at, the nominal neutral pion mass. This happens because the background often has a true π^0 but, because of the overlaps of the other two clusters, its mass is somewhat shifted and broadened due to the non-linearity in the lead-glass response.) The $\pi^0\gamma\gamma$ signal is normalized at a branching ratio 1.86 x 10^{-6} (see below). The agreement is good and gives additional confidence that the excess of data at high $m_{\gamma\gamma}$ is $\pi^0\gamma\gamma$ signal.

For the high mass sample ($m_{\gamma\gamma} \geq 280$ MeV) we have 232 candidate events from which 104 come from a data set with a 0.09 radiation length lead sheet inserted in the beams 137.8 m from the target. The effect of the lead sheet is that it will sometimes convert one (or more) of the photons causing both signal and background events to be lost. The Monte Carlo simulation properly accounts for this and the total predicted background is 171.9 events (150.7 from $3\pi^0$'s and 21.2 from $2\pi^0$'s). Based on background studies and many comparisons of data with Monte Carlo distributions, we assign a 11% systematic error to the estimate of the background in the high mass region. There are three sources to this systematic uncertainty which are added in quadrature. The first is due to imperfect knowledge of the efficiencies of the photon vetoes and this is estimated to result in a 5% uncertainty. The second arises from possible errors in the understanding of the photon energy resolution and this is estimated to result in a 3% uncertainty. The third, which is the largest, is associated with the discarding of a few remaining events with photons projecting outside the aperture of the lead mask. These events are not well simulated and this is estimated to result in a 9% uncertainty. The $\pi^0\gamma\gamma$ acceptance is 3.4% (4.4%) for data with (without) the lead sheet inserted and the normalization is provided by 45000 $K_L \to 2\pi^0$ decays taken simultaneously. Using the world average value[11] for the $K_L \to 2\pi^0$ branching ratio we conclude that:

$$\frac{\Gamma(K_L \to \pi^0\gamma\gamma, m_{\gamma\gamma} \geq 0.280 GeV)}{\Gamma(K_L \to all)} = (1.86 \pm 0.60 \pm 0.60) \times 10^{-6}$$

where the first error is statistical and the second is systematic.
If we assume the $m_{\gamma\gamma}$ distribution predicted by Chiral Perturbation Theory we then have:

$$\frac{\Gamma(K_L \to \pi^0\gamma\gamma)}{\Gamma(K_L \to all)} = (2.2 \pm 0.7 \pm 0.7) \times 10^{-6}.$$

We have also looked for a signal at lower $\gamma\gamma$ masses. Our acceptance for masses below the double fusion peak is smooth and averages[7,10] about 5%, except for the narrow region excluded around the nominal π^0 mass. For the region $m_{\gamma\gamma} < 264$ MeV we have (367±19.2) data events and (377.5±18.4) expected background events. This gives

$$\frac{\Gamma(K_L \to \pi^0\gamma\gamma, m_{\gamma\gamma} < 0.264 GeV)}{\Gamma(K_L \to all)} < 5.1 \times 10^{-6} \text{ (90\% confidence)}$$

where we have used a phase space distribution for $m_{\gamma\gamma}$ and have included a 15% systematic error on the background prediction.

We thus confirm both the substantial branching ratio and the peaking at high mass first reported by the NA31 group. Our analysis uses less stringent kinematic cuts so that our acceptance is smooth and substantial over the entire mass region, leading to a limit at lower mass values. The central value for the branching ratio is a factor of three higher than the Chiral Perturbation Theory prediction. More statistics and better background rejection will be necessary for additional studies of this decay mode.

FIGURE CAPTIONS

Figure 1. Data-Monte Carlo comparison of the $\gamma\gamma$ mass distribution for $\pi^0\gamma\gamma$ candidates and background events based on the full data set. The normalization is absolute. The error bars correspond to the data, the shaded histogram to the $2\pi^0$ background Monte Carlo, and the dashed histogram to the sum of the $3\pi^0$ and $2\pi^0$ background Monte Carlos.

Figure 2. Data-Monte Carlo comparison for the z decay vertex distribution for $\pi^0\gamma\gamma$ candidates and background events with $m_{\gamma\gamma} \geq 0.280$ GeV. The normalization is absolute. The error bars correspond to the data, the shaded histogram to the $2\pi^0$ background Monte Carlo, and the dashed histogram to the sum of the $3\pi^0$ and $2\pi^0$ background Monte Carlos.

Figure 3. Data-Monte Carlo comparison for the m_{12} (π^0 candidate) distribution for $\pi^0\gamma\gamma$ candidates and background events including $\pi^0\gamma\gamma$ signal Monte Carlo, for $m_{\gamma\gamma} \geq 0.280$ GeV. The error bars correspond to the data; the diagonally shaded histogram to the sum of the $3\pi^0$ and $2\pi^0$ background Monte Carlos; the horizontally shaded histogram to the $\pi^0\gamma\gamma$ signal normalized with the branching ratio of 1.86×10^{-6}, and the dashed histogram to the sum of the background and signal. The normalization is absolute.

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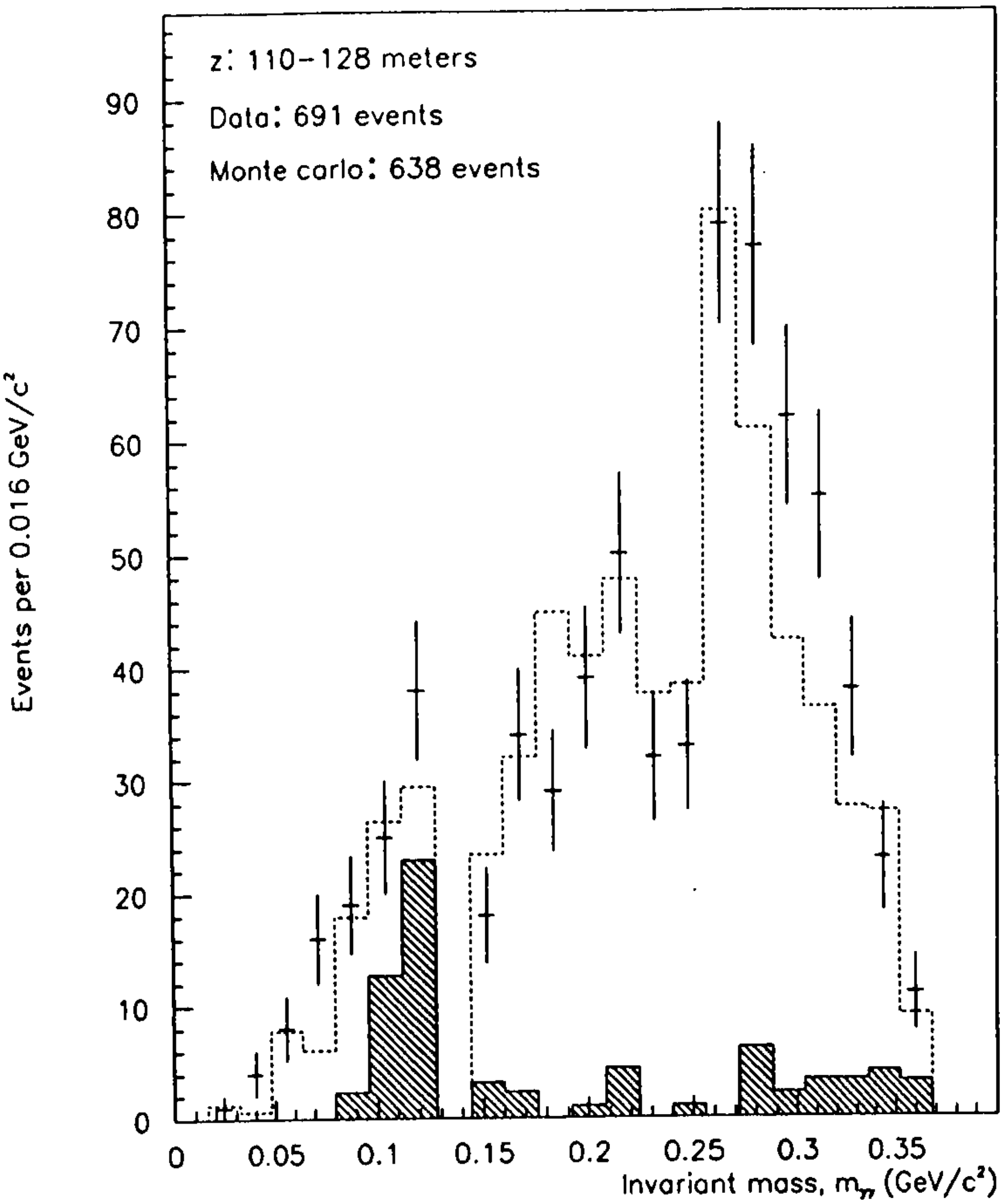
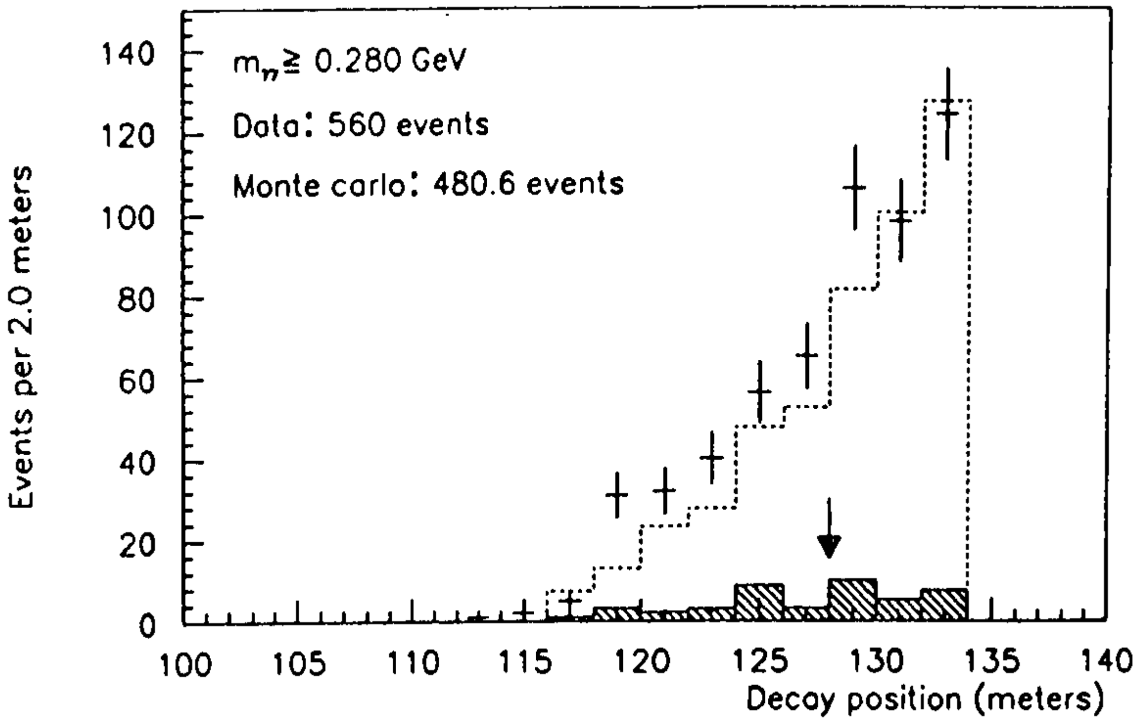


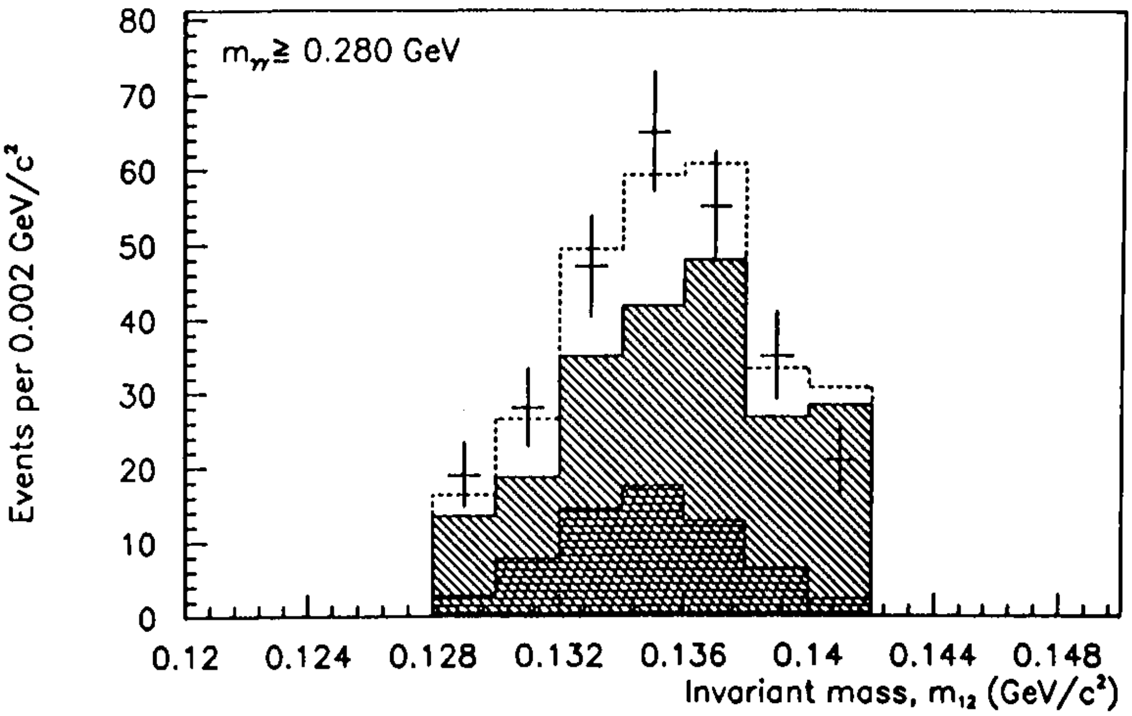
z: 110-128 meters
Data: 691 events
Monte carlo: 638 events
Events per 0.016 GeV/c²
Invariant mass, mγγ (GeV/c²)
0
10
20
30
40
50
60
70
80
90
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

Figure 1



$m_{\eta} \geq 0.280$ GeV
Data: 560 events
Monte carlo: 480.6 events
Events per 2.0 meters
Decay position (meters)
0
20
40
60
80
100
120
140
100
105
110
115
120
125
130
135
140

Figure 2



$m_{\gamma\gamma} \geq 0.280$ GeV
Events per 0.002 GeV/c²
Invariant mass, m_{12} (GeV/c²)
0.12
0.124
0.128
0.132
0.136
0.14
0.144
0.148
0
10
20
30
40
50
60
70
80

Figure 3