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Search for the Decay $K_L \rightarrow 3\gamma$

G.D. Barr, P. Buchholz[1], D. Cundy, N. Doble, L. Gatignon, P. Grafström,
R. Hagelberg, H. Wahl
CERN, CH-1211 Geneva 23, Switzerland
K.J. Peach
Physics Department, University of Edinburgh, Edinburgh EH9 3JZ, UK
T. Beier, H. Blümer, D. Coward[2], R. Heinz, K. Kleinknecht, F. Leber, B. Renk, H. Rohrer, H.G. Sander,
F. Scheerer, J. Scheidt, J. Staeck, A. Wagner[3]
Institut für Physik, Universität Mainz, D-55099 Mainz[4], Germany
E. Augé, D. Fournier, L. Iconomidou-Fayard, O. Perdereau, A.C. Schaffer, L. Serin
Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Université de Paris-Sud, F-91406 Orsay[5], France
L. Bertanza, P. Calafiura[6], M. Calvetti[7], R. Carosi, R. Casali, C. Cerri, I. Mannelli[6], V.M. Marzulli[6],
A. Nappi[8], G.M. Pierazzini
Dipartimento di Fisica e Sezione INFN di Pisa, I-56100 Pisa, Italy
M. Holder, A. Kreutz, M. Rost, R. Werthenbach
Fachbereich Physik, Universität Siegen, D-57068 Siegen[9], Germany

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Johannes Gutenberg (Kupferstich von Thevet)

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M. Holder, A. Kreutz, M. Rost, R. Werthenbach
Fachbereich Physik, Universität Siegen, D-57068 Siegen[9], Germany

Abstract Data from the NA31 experiment at the CERN SPS have been used for the first search for the decay mode $K_L \to 3\gamma$. Seven events have been found with an estimated background of 6.7 ± 1.5 events. The corresponding upper limit for the branching ratio is $\Gamma(K_L \to 3\gamma)/\Gamma(K_L \to all) = 2.4 \times 10^{-7}$ at the 90% confidence level, assuming a phase-space decay distribution.

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[1] Present address: Institut für Physik, Universität Mainz, D-55099 Mainz, Germany

[2] Present address: SLAC, Stanford, CA 94309, USA

[3] Present address: CERN, CH-1211 Geneva 23, Switzerland

[4] Funded by the German Federal Minister for Research and Technology (BMFT) under contract 054MZ18

[5] Funded by Institut National de Physique des Particules et de Physique Nucléaire (IN2P3), France

[6] Present address: Scuola Normale Superiore, I-56100 Pisa, Italy

[7] Present address: Dipartimento di Fisica e Sezione INFN, I-06100 Perugia, Italy

[8] Present address: Dipartimento di Scienze Fisiche e Sezione INFN, I-09100 Cagliari, Italy

[9] Funded by the German Federal Minister for Research and Technology (BMFT) under contract 054SI7

1 Introduction

Rare decays of neutral kaons are a useful tool for testing various models based on, e.g., chiral perturbation theory or vector-meson couplings. Since the decay mode $K_L \to 3\gamma$ is CP allowed, a naive estimate would predict a branching ratio of $\mathrm{BR}(K_L \to 3\gamma) \approx \alpha_{\mathrm{em}} \times \mathrm{BR}(K_L \to 2\gamma) \approx 10^{-6}$; therefore, this decay mode should be detectable in the data sample of more than $10^9 K_L$ decays recorded in the NA31 experiment. A recent calculation by Heiliger, McKellar and Sehgal [1], however, predicts a branching ratio of $\mathrm{BR}(K_L \to 3\gamma) \approx 3 \times 10^{-19}$. Gauge invariance and Bose statistics give rise to suppression factors which reduce the naive estimate by thirteen orders of magnitude. As there is no experimental limit on this decay, the $K_L \to 3\gamma$ decay offers a large range in which new effects can be sought.

We present here the first experimental search [2] for the decay $K_L \to 3\gamma$ using data collected with the NA31 detector. The limit on the $K_L \to 3\gamma$ branching ratio is obtained from the observed number of $K_L \to 3\gamma$ candidates normalized to the number of $K_L \to 2\pi^0$ events with acceptance corrections determined by Monte Carlo simulation.

2 Experimental Set-up and Data Taking

The NA31 experiment was set up at the CERN SPS primarily to measure the parameter ϵ'/ϵ of direct CP violation in the neutral kaon system [3]. The beam and the detector for the experiment have been described in detail elsewhere [4]. Long-lived kaons with an average momentum of 100 GeV/c are produced by 450 GeV/c protons striking a beryllium target located 244 m upstream of the electromagnetic calorimeter. Charged particles are removed by sweeping magnets, and a neutral beam is defined by collimation to ±0.2 mrad. The final collimator, with diameter 6 cm, is located 124 m upstream of the electromagnetic calorimeter and is followed by a 95 m long evacuated region. The neutral beam continues in an evacuated tube of diameter 20 cm through a central hole in the detectors. Decays occurring in the upstream part of the evacuated region are measured. The outer diameter of each of the detectors is typically 2.5 m. We summarize the detectors relevant for the present analysis:

- a liquid-argon/lead-sandwich calorimeter with 1.25 cm wide strips read out in x- and y-projections transverse to the beam and separated into quadrants. For photons, the energy resolution is $7.5\%/\sqrt{E/GeV}$ and the position resolution is 0.5 mm in each projection. Groups of eight neighbouring strips are connected to a TDC system to allow a time measurement of electromagnetic activity with respect to the trigger time.

- a scintillator hodoscope inside the liquid-argon calorimeter used to trigger on electromagnetic energy and to define the event time;
- four ring-shaped anti-counters surrounding the decay region, and placed between 60 and 120 m from the final collimator, to veto events with photons missing the calorimeter;
- two wire chambers 23 m apart to veto events with charged particles;
- an iron/scintillator-sandwich hadron calorimeter to veto events with hadronic energy.

The 3γ and the $2\pi^0$ final states are accepted by the same trigger, which requires at least 40 GeV in the electromagnetic calorimeter and less than 8 GeV of energy deposited in the hadron calorimeter. Loose requirements are made on the decay position of purely electromagnetic final states under the assumption that the decaying particle has the kaon mass.

3 Event Selection and Analysis

Data from the run period in 1989 which contain TDC information on the timing of each electromagnetic shower in the liquid-argon calorimeter are used to select 3γ candidates and normalization events. The position and energy of electromagnetic showers in the liquid-argon calorimeter are reconstructed by the same program as used in the $K_L \rightarrow 2\pi^0 \rightarrow 4\gamma$ analysis of ϵ'/ϵ [3]. $K_L \rightarrow 3\gamma$ or $K_L \rightarrow 2\pi^0$ candidates are selected by requiring three or four photons. Events with charged tracks are removed by admitting at most one reconstructed spacepoint in the second and none in the first wire chamber. The data set then consists of 1×10^5 $K_L \rightarrow 3\gamma$ and 3.6×10^5 $K_L \rightarrow 2\pi^0$ candidates.

To select $K_L \rightarrow 3\gamma$ candidates, two sets of cuts are applied in order to select events without ambiguities and to suppress potential background.

3.1 Selection of $K_L \rightarrow 3\gamma$ Candidates

$K_L \rightarrow 3\gamma$ candidates must meet the following requirements:

- They have exactly three reconstructed electromagnetic showers, with each of these showers having an energy between 5 and 100 GeV, a distance from the beam axis larger than 16 cm but lying within an octagon whose inscribed circle is centered on the beam axis with a radius of 116 cm, and a distance larger than 2.5 cm from the borderlines separating the electromagnetic calorimeter into quadrants.

- The total energy in the liquid-argon calorimeter is between 50 and 190 GeV, and the energy deposited in the hadronic calorimeter is less than 3 GeV. The energy barycentre in the electromagnetic calorimeter is within 5 cm from the beam axis. This cut rejects events with large missing transverse energy. The distance between two photon shower centres is more than 3.0 cm.
- The longitudinal position of the decay vertex z_K, as measured from the downstream face of the final beam collimator, is calculated under the assumption that the invariant mass of the three showers is the nominal kaon mass:

$$z_K = z_{LAC} - \frac{1}{m_K}\sqrt{\sum_{i,j;i<j} E_i E_j (\vec{r}_i - \vec{r}_j)^2}, \tag{1}$$

  where $E_{i,j}$ are the photon energies, $\vec{r}_i, \vec{r}_j$ are the position vectors of the impact points of the photons i and j at the front face of the liquid-argon calorimeter, and $z_{LAC} = 123.7$ m is the distance from the downstream end of the final K_L collimator to the front face of the electromagnetic calorimeter. The quantity z_K determines the decay region; it is restricted to $-10 \text{ m} \leq z_K \leq +40$ m.
- If two photons in one quadrant have no overlaps in either projection and are assigned to the energies E_1 and E_2, the asymmetry $|E_1 - E_2|/(E_1 + E_2)$ must be larger than 0.1 to ensure that the energy projections can be assigned to photons without ambiguity. Another form of shower overlap in one quadrant can arise when one photon shower overlaps a second photon shower in the x-projection, and simultaneously overlaps a third photon shower in the y-projection. Then the energies of the x- and y-clusters, E_x and E_y, are, in general, unequal. For each photon, we require that the energy asymmetry A_{xy}, defined as:

$$A_{xy} = \left[100 \times \frac{|E_x - E_y|}{(E_x + E_y)} - 1\right] \times \sqrt{E_x + E_y} \tag{2}$$

  be less than $25\sqrt{GeV}$.

These requirements reduce the event sample by a factor of five to 1.9×10^4 events.

For the decay $K_L \to 3\gamma$ three background sources are relevant: (i) $K_L \to 2\pi^0$ events in which only three photons are detected and the fourth one is lost or overlaps with one of the detected photons; (ii) $K_L \to 3\pi^0$ events in which only three photons are detected and the other three are lost and/or overlap with the detected photons; (iii) Events with two photons in time from K_L decays, where in addition an accidental photon not correlated with the decay occurs; the reconstruction of these three photons may appear as a 3γ event.

The following cuts are applied to reduce the background in the 3γ candidate sample:

- In order to help distinguish $K_L \to 3\gamma$ from $K_L \to 2\pi^0$ background events, the longitudinal position of the vertex of a neutral pion of mass m_{π^0} decaying into two photons i, j is calculated from the observed photon energies and impact points:

$$z_{ij}(\pi^0) = z_{LAC} - \frac{1}{m_{\pi^0}}\sqrt{E_i E_j (\vec{r}_i - \vec{r}_j)^2}. \tag{3}$$

  For a $2\pi^0$ final state with only three photons detected, only one out of the three possible z_{ij} corresponds to the true kaon vertex. With the help of Monte Carlo studies, a sorting algorithm was developed to determine the z_{ij} which corresponds to the true vertex. The assignment is done such that the smallest, positive z_{ij} is called $z1(\pi^0)$ and the z_{ij} with the largest absolute value is called $z3(\pi^0)$. If all z_{ij} are negative, the z_{ij} with the smallest absolute value becomes $z1(\pi^0)$. With this definition $z1(\pi^0)$ has the highest probability (90%) to match the true vertex, $z2(\pi^0)$ the second highest and $z3(\pi^0)$ the lowest. There is a strong correlation between the vertex calculated from the kaon hypothesis z_K (eq.(1)) and the vertex from pion decay hypothesis $z1(\pi^0)$ for $2\pi^0$ Monte Carlo background events (eq.(3)), and no correlation at all for 3γ Monte Carlo events (Fig. 1). The requirement for accepted 3γ candidates is that $z1$ is outside the region bounded by $[z1(\pi^0) > z_K]$ and by $[z1(\pi^0) < (0.1 \times z_K) - 20 \text{ m}]$.
- By applying a cut in the $z1(\pi^0)$-$z2(\pi^0)$ plane, in which an accumulation of $2\pi^0$ background Monte Carlo events is found in contrast to the distribution of the 3γ Monte Carlo events, a further reduction of $2\pi^0$ background by a factor of 137 is achieved, whereas the acceptance for $K_L \to 3\gamma$ events is just reduced by a factor of 1.1. The $K_L \to 3\gamma$ candidates must fulfil the conditions $\left[z2(\pi^0) > 0 \text{ m}\right]$ or $\left[z1(\pi^0) < -30 \text{ m}\right]$ or $\left[(z1(\pi^0) > 0 \text{ m}) \text{ and } (z2(\pi^0) < -30 \text{ m})\right]$, where the kinematical regions are selected in order to suppress the $2\pi^0$ background as it appears in the Monte Carlo simulation.
- In the case of two overlapping photons in a $K_L \to 2\pi^0$ event, the three observed photon energies are denoted E_1, E_2 and E_3. If energy E_2 is assumed to be the sum of the two overlapping photons, then two invariant pion masses can be calculated:

$$m_{\pi^0} = \frac{1}{z_{LAC} - z_K} \times \sqrt{E_1 k_1 E_2 (\vec{r}_1 - \vec{r}_2)^2}, \tag{4}$$

$$m_{\pi^0} = \frac{1}{z_{LAC} - z_K} \times \sqrt{E_2 (1 - k_2) E_3 (\vec{r}_2 - \vec{r}_3)^2}, \tag{5}$$

  where k_1 and $(1 - k_2)$ are the fractions of the energy of photon 2 allotted to the two neutral pions. This procedure is iterated through all three possible combinations of invariant two-photon masses, and the minimum of $|k_1 - k_2|$

is formed. Events are kept only if $min|k_1 - k_2| > 0.05$. A Monte Carlo study shows that this cut removes more than 88% of the remaining $K_L \to 2\pi^0$ background events whereas the acceptance of $K_L \to 3\gamma$ is reduced by only 1.1%.

- For $K_L \to 3\pi^0$ background events, three of the six photons are undetected and the reconstructed vertex shifts towards the electromagnetic calorimeter (see eq.(1)). The region $0 \text{ m} \leq z_K \leq +15$ m offers the best balance between acceptance for 3γ and suppression of background.
- The event time relative to the trigger as measured with the TDCs of the liquid-argon calorimeter is required to be in a time window of 144ns length. Fig. 2a shows the time distribution of the photons of the 3γ candidates. There are three entries per event; 23 entries lie outside the time window between 848 ns and 992 ns. Since these events have one photon outside and two photons inside the time window, 46 entries must be subtracted from 67 in-time entries. Therefore, we observe $21/3 = 7$ events in time.

3.2 Estimation of the Background to $K_L \to 3\gamma$ events

The three main sources of background to the decay channel $K_L \to 3\gamma$ have been studied:

(i) Accidental photons: The accidental background consists of events where, in addition to two in-time photons from a kaon decay, an accidental photon occured. The rate of accidental photons in the "in-time" window is measured using random triggers. Such triggers are obtained from a downscaled monitor signal in the neutral beam, proportional to the beam intensity and delayed by 69 μs (three times the SPS period) to avoid correlations with good events in the detector. The time of photons above 5 GeV energy in the liquid-argon calorimeter relative to the random trigger time is given in fig. 2b. The observed asymmetry of events with timing before and after the "in-time" window comes from the fact that an energy deposit before the random trigger has itself a probability for triggering, and a random trigger is only possible if the system is not blocked by a real trigger. By taking the ratio of photons inside the time window (986) and outside (4171) and by normalizing to the 23 accidental 3γ candidates containing one photon outside we obtain the accidental background inside the time window of $5.4 \pm 1.1(stat.) \pm 0.9(syst.)$ events. (ii) $K_L \to 3\pi^0$: From 2.9×10^8 generated $K_L \to 3\pi^0$ Monte Carlo events, 22 events pass all the 3γ cuts. There are $1.2 \pm 0.3(stat.) \pm 0.4(syst.)$ $K_L \to 3\pi^0$ events expected in the 3γ signal region ($0 \leq z_K \leq 15$ m) after normalization to the vertex region between 25 and 30 m. (iii) $K_L \to 2\pi^0$: From 1.7×10^7 generated $K_L \to 2\pi^0$ Monte Carlo events, 9 events pass all the 3γ cuts. From the total number of K_L decays, $0.12 \pm 0.04(stat.) \pm 0.04(syst.)$ events are expected in the 3γ signal region.

The combined expected background from these three sources is 6.7±1.5 events. The error is a combination of statistical errors and the estimated systematic uncertainty.

3.3 Normalization

The normalization of the $K_L \to 3\gamma$ events is obtained by the topologically similar events $K_L \to 2\pi^0$. Because both event classes were taken with the same trigger, trigger efficiencies cancel in the determination of the branching ratio. The events pass the same cuts as applied to the $K_L \to 3\gamma$ candidates on the geometry, energies, barycentre, minimum photon distance, decay vertex and time.

The four photons can be paired into three different combinations of two photons, and two invariant π^0 masses m_{ij} and m_{kl} can be determined for each combination. The best χ^2 fit pairings are chosen as the solution for $K_L \to 2\pi^0$.

The background from $K_L \to 3\pi^0$ events with two missing photons contained in the signal region is 17 events to be subtracted from the $K_L \to 2\pi^0$ signal. Another small background arises from accidental photons. This background is determined from the time distribution of photons to be 21 events. The total number of $K_L \to 2\pi^0$ signal events in this analysis is 19395.

3.4 Acceptance Determination

For $K_L \to 3\gamma$ decays, an acceptance of 12.1% was determined from 4.7×10^5 Monte Carlo events generated with phase-space decay distribution. The acceptance for $K_L \to 2\pi^0$ decays is 8.8% as determined from 3.7×10^5 generated Monte Carlo events. Using the number of $K_L \to 2\pi^0$ normalization events, the $K_L \to 2\pi^0$ branching ratio of 9.14×10^{-4} as given in Ref. [5], and the acceptance as determined above, the number of K_L decays in this sample is 2.4×10^8.

The systematic errors on the acceptances of 3γ and $2\pi^0$ final states and the normalization have been estimated by varying the most important cuts: the minimum photon energy, the minimum distance of photons from the beam tube, the cut of the energy barycentre, and the area of the χ^2 ellipse considered for the normalization sample. The variation of these cuts produced changes in the normalization and the acceptance ranging from −3.7% to +4.1%. The combined systematic error on the kaon flux is ±5.6%. Combining this error with the error on the 3γ acceptance yields a total systematic error of ±6.3%.

4 Results

Fig. 3 shows the vertex distribution of candidate 3γ events and expected background after all but the vertex cut. From the observed signal of 7 events in the vertex region between 0 and 15 m ("signal region") and the background of 6.7 ± 1.5 events as obtained in sect. 3.2, we obtain an upper limit of 6.5 events at the 90% confidence level [6]. This limit includes the statistical and systematic error on the background determination. Taking the +6.3% systematic error on the kaon flux and the acceptances into account, this translates into an upper limit of the branching ratio:

$$\Gamma(K_L \rightarrow 3\gamma)/\Gamma(K_L \rightarrow all) < 2.4 \times 10^{-7} \text{ (90\% C.L.)}$$

This is the first reported upper limit of the $K_L \rightarrow 3\gamma$ branching ratio, and excludes the naive estimate of 10^{-6}.

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5 Figure Captions

Figure 1. Correlation between $z1(\pi^0)$ and z_K for $2\pi^0$ background (upper plot) and 3γ Monte Carlo events (lower plot). The region between the dotted lines is excluded by the cut.

Figure 2. (a) Time distribution of photons of the 3γ candidates in the signal region $0\ \mathrm{m} \leq z_K \leq 15\ \mathrm{m}$. The peak corresponds to photons which are detected in the liquid-argon calorimeter in the expected time region of $(848 - 992)$ ns after the trigger. If one photon is outside the time window, the two photons inside belonging to the same 3γ candidate are discarded as well. (b) Time distribution of photons with energy above 5 GeV in the liquid-argon calorimeter after a random trigger.

Figure 3. Vertex distribution of 3γ candidates before the vertex cut but after all other cuts, and vertex distributions of different expected backgrounds for z_K between 0 and 35 m.

6 Figures

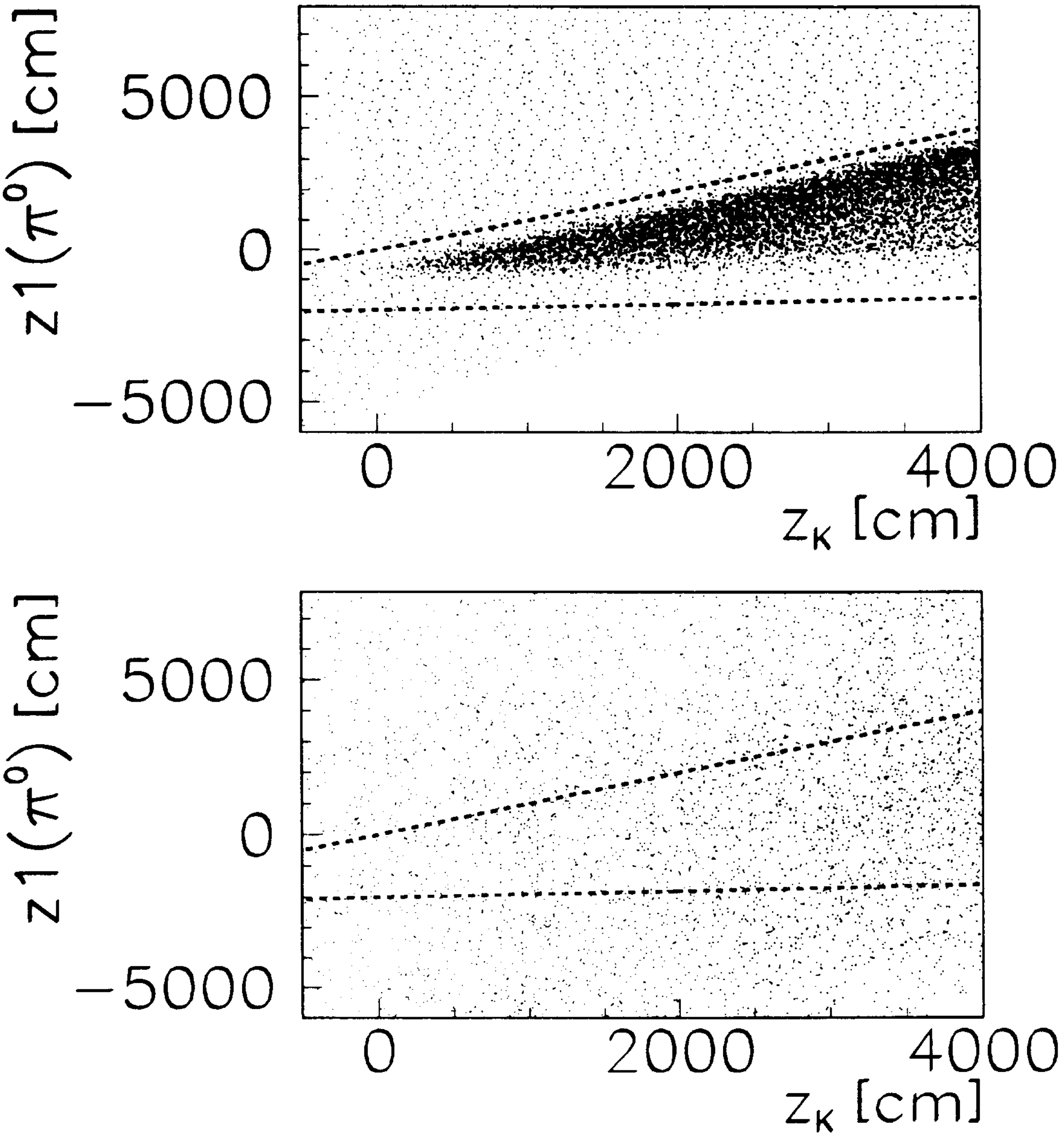
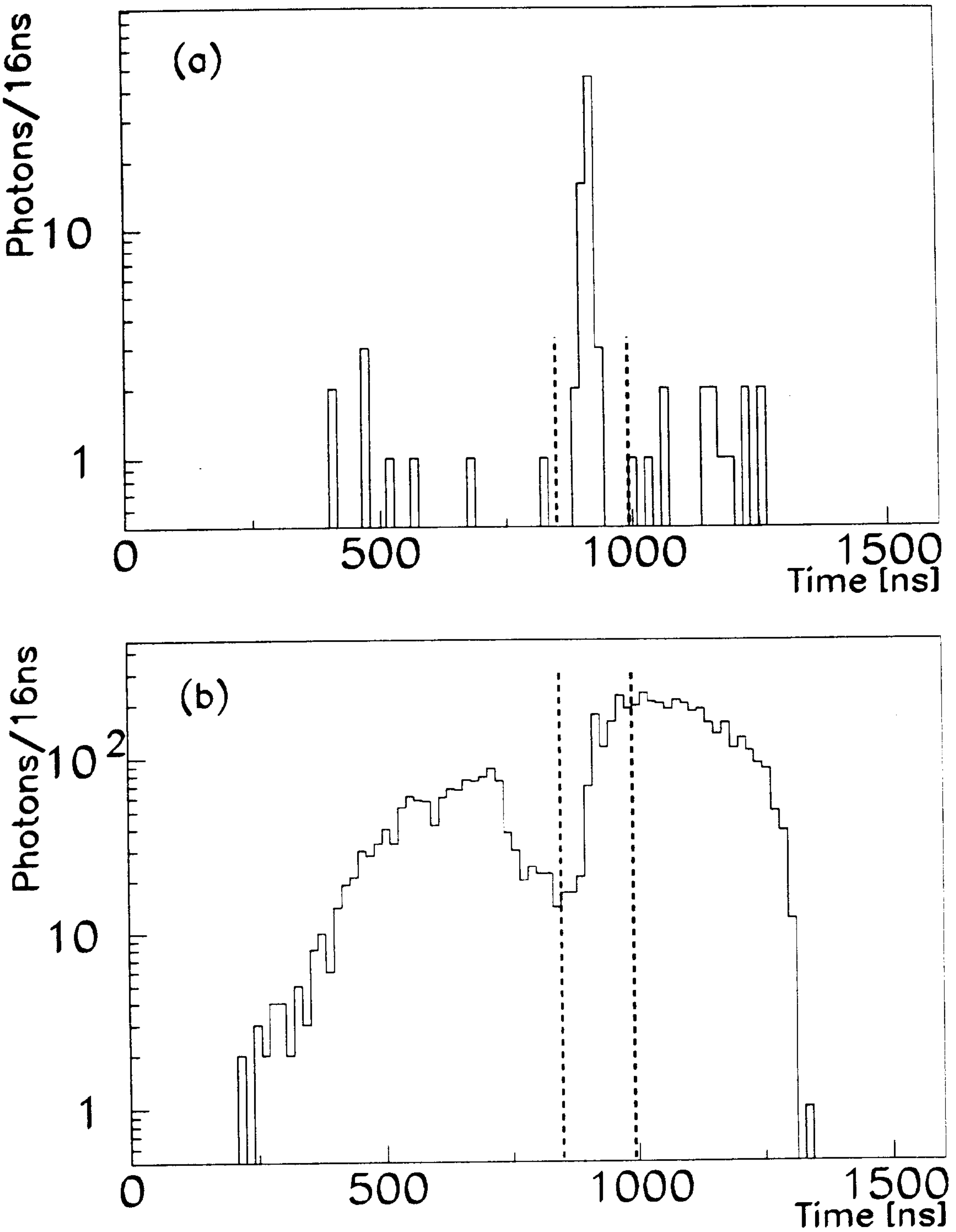


Fig.1



Photons/16ns
(a)
10
1
0
500
1000
1500
Time [ns]
Photons/16ns
(b)
10^2
10
1
0
500
1000
1500
Time [ns]

Fig.2

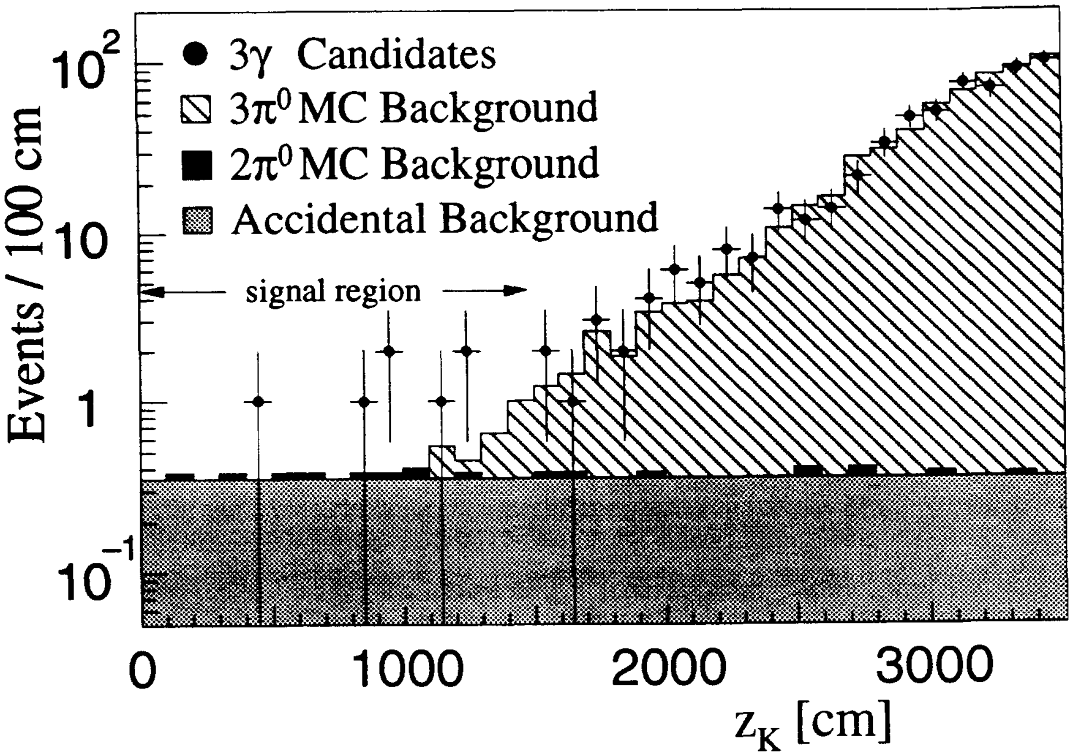

● 3γ Candidates
▧ 3π⁰ MC Background
■ 2π⁰ MC Background
▩ Accidental Background
signal region
Events / 100 cm
10²
10
1
10⁻¹
0
1000
2000
3000
z_K [cm]

Fig.3