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An upper limit for the branching ratio of the decay $K_S \rightarrow e^+e^-$

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Abstract

A search for the decay $K_S \to e^+e^-$ was performed within the framework of the CPLEAR experiment. Full event reconstruction together with e/π separation allowed powerful background rejection and high signal acceptance. The analysis of the complete set of data yields the result: $BR(K_S \to e^+e^-) < 1.4 \times 10^{-7}$ (90% CL), an improvement on the current experimental limit by a factor of 20.

1. Introduction

The decay $K_S \to e^+e^-$, like the decay $K_L \to e^+e^-$ or $K_L \to \mu^+\mu^-$, is a flavour-changing neutral-current process, suppressed in the Standard Model and dominated by the two-photon intermediate state [1–3]. For both K_S and K_L the e^+e^- channel is much more suppressed than the $\mu^+\mu^-$ channel (by a factor of $\approx 2 \times 10^3$) because of the e-μ mass difference [1,2]. In terms of branching ratios there is a further suppression from K_L to K_S (by a factor of ≈ 600) resulting from the mean-life ratio τ_S/τ_L. The branching ratio $BR(K_S \to e^+e^-)$ is expected to be $\approx 7 \times 10^{-15}$ [1–3]. A value significantly higher than expected would point to new physics.

The current experimental limit on $BR(K_S \to e^+e^-)$ is $< 2.8 \times 10^{-6}$ (90% CL) [4]. Here we report on a new measurement of this branching ratio using the CPLEAR detector at LEAR.

2. The experiment

The CPLEAR experiment was designed to study CP violation in the neutral-kaon system using strangeness-tagged $K^0$and $\overline{K}^0$. The experiment covering the decay time interval from 0 to 20 τ_S is well suited for the search for rare K_S-decays, since all K_S decay inside the detector while $\approx 96\%$ of the long-lived component decay outside.

Neutral kaons are produced in $p\bar{p}$ annihilations,

$$p\bar{p} \to K^-\pi^+K^0 \quad \text{or} \quad K^+\pi^-\overline{K}^0 \qquad (1)$$

with a branching ratio of 0.2% per channel. Antiprotons with a momentum of 200 MeV/c are supplied by LEAR at a rate of 1 MHz. They annihilate at rest with protons, in a pressurized hydrogen gas target, in the centre of the detector. The detector is placed in a solenoid providing a uniform magnetic field of 0.44 T. Annihilation products are detected with ten tracking-chamber layers consisting of multiwire proportional chambers, drift chambers and streamer tubes. Particle identification, in particular charged-kaon identification, is performed by a 32-sector scintillator-Cherenkov-scintillator detector (PID - Particle Identification Detector) allowing pulse-height and time-of-flight measurements. Electron and photon showers are sampled by an 18-layer electromagnetic (e.m.) calorimeter consisting of high-gain tubes of 4×4.5 mm^2 cross-section in active layers interleaved with lead plates ($\approx 1/3$ radiation length per layer). A fast, dedicated, hardwired trigger system is tuned to an efficient selection of the annihilation channels (Eq. (1)) at the highest possible rate. A detailed description of the detector can be found in Ref. [5].

3. Data selection

We searched for $K_S \to e^+e^-$ events starting from the raw data sample used also for the study of the $\pi^+\pi^-$ decay channel [6,7], containing the e.m. calorimeter information. To maximize track reconstruction quality and in order to keep the background from the K_L decays low, the search was restricted to decays before the proportional chambers, resulting in an effective lifetime cut of 6 τ_S. Most of the raw data in this region consist of $K_S \to \pi^+\pi^-$ decays.

The background is obtained from a Monte Carlo (MC) simulation. Simulation data include all the main K^0 decay channels with two charged tracks in the final state ($\pi^+\pi^-$, $\pi e\nu$, $\pi\mu\nu$, $\pi^+\pi^-\pi^0$) and are normalized to the number of $\pi^+\pi^-$ decays measured in the time interval from 1 to 2 τ_S using similar criteria to Refs. [6,7]. This number is $N(\pi^+\pi^-) = 5.4 \times 10^7$.

The first step of the analysis consists in the selection of a clean sample of events given by Eq. (1) above, including correct assignment of the K^0 decay particles.

Events with four tracks, zero total charge and at least one charged kaon are selected. The probability of the kinematical 1C-fit requiring a missing mass equal to the K^0 mass at the annihilation vertex must be > 10%.

Events from other annihilation channels – without a K^0 in the final state – are further reduced by requiring that no more than two tracks can be attached to a single vertex.

The MC simulation shows that in a fraction of the events the primary (annihilation) pion is misidentified as the secondary (decay) pion having a charge opposite to that of the kaon. Such events can be recognized because the distribution of the invariant mass $m(\pi_p,\pi_s)$ of the primary pion (π_p) and the opposite-charge secondary pion (π_s) clusters at the K^0 mass. These events are rejected by requiring that the probability of the invariant mass $m(\pi_p,\pi_s)$ being equal to the K^0 mass is < 5%.

In a second step, we proceed to the selection of

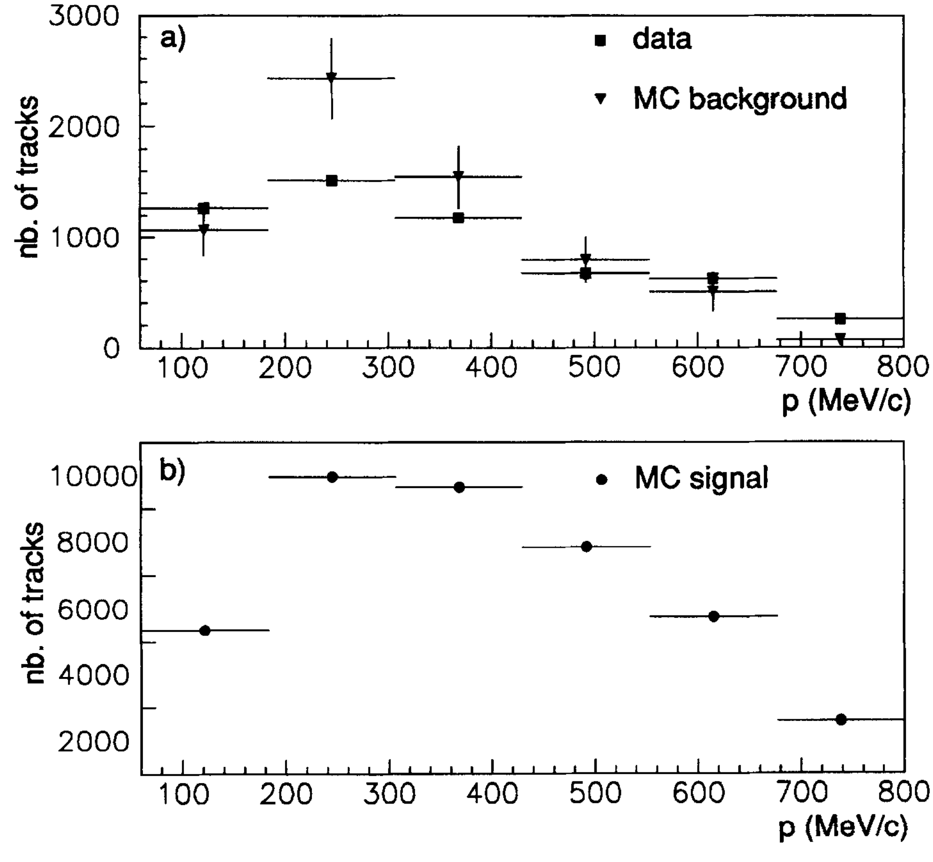

Fig. 1. Momentum distribution of secondary tracks: (a) data and MC-simulated background, (b) MC-simulated signal (arbitrary scale).

the $K_S \to e^+e^-$ decay channel by using kinematical methods and electron identification.

3.1. Kinematical selection

The opening angle of the secondary tracks has to be larger than 11° in order to remove e^+e^- pairs from γ conversions or π^0 Dalitz decays.

The optimal separation between signal and background is obtained by performing a kinematical and geometrical fit to the $\bar{p}p \to K^\pm\pi^\mp K^0(K^0 \to e^+e^-)$ hypothesis with nine constraints. The constraints require conservation of energy and momentum, the missing mass at the annihilation vertex to be equal to the K^0 mass, the intersection of two track-helices at the annihilation vertex and two at the decay vertex, and the K^0 momentum to be collinear with the line joining the two vertices. After requiring a 9C-fit probability > 20% and all the above-mentioned selection criteria, we are left with 2745 events (data set). As a reference, the number of events selected at a similar level of the analysis as $\pi^+\pi^-$ decays is $\approx 8 \times 10^7$ in the same time interval.

The MC simulation indicates that the bulk of the data at this stage is still background, hardly separable from a potential signal (see Figs. 1 and 2). This background consists of 86% $\pi^+\pi^-$ decays and 14% $\pi e \nu$ decays. The contribution of the other two channels is < 0.5%. The signal acceptance relative to the background from $\pi^+\pi^-$ decays is 1.5×10^4. The 9C-fit probability distribution for the data-set events is shown in Fig. 2 overlayed with the distribution of the MC background. Fig. 2b displays this distribution for simulated $K_S \to e^+e^-$ events.

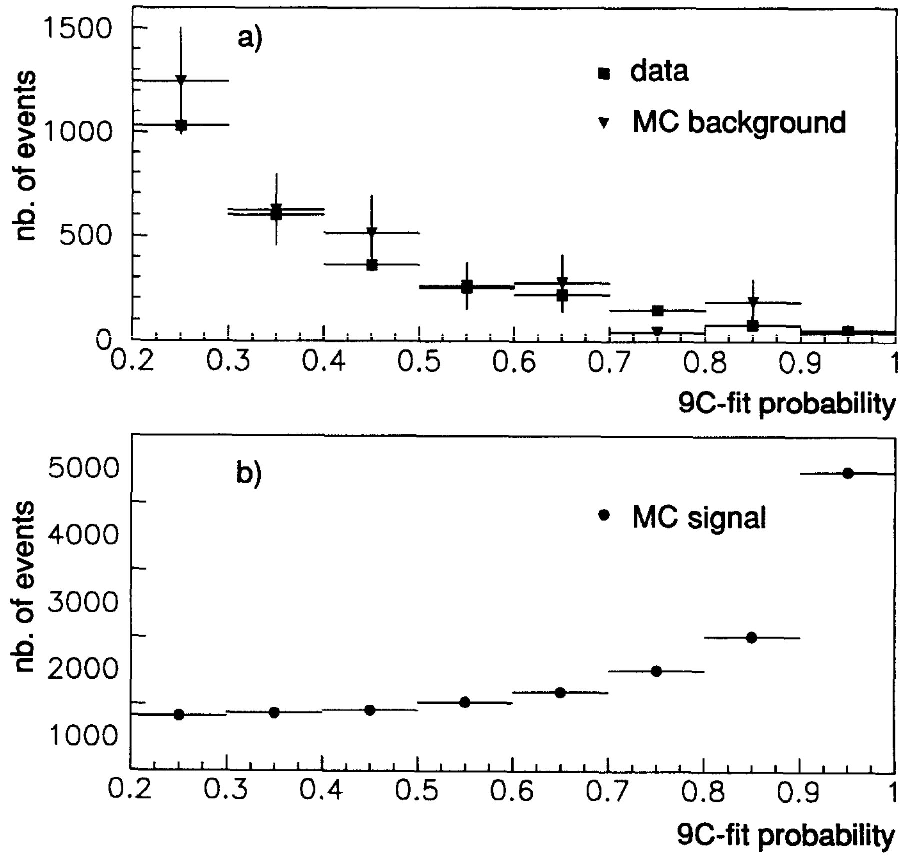

Fig. 2. 9C-fit probability distribution for (a) data and MC-simulated background, (b) MC-simulated signal (arbitrary scale).

3.2. Electron identification

The electron identification is the main tool that provides further reduction of the background. At high momenta (above 200 MeV/c) the identification is provided exclusively by the e.m. calorimeter [8] where, because of the high granularity, e/π separation can be performed by exploiting shower topologies. Below 200 MeV/c, the electrons are further identified using energy loss in the scintillators, number of photoelectrons per unit path length in the Cherenkov counter and time-of-flight information [9]. The bulk of the data-set and MC-signal events corresponds to a high e^+/e^- momentum (see Fig. 1).

The full power of electron identification is obtained by requiring both secondary tracks to be recognized as electrons, that is both tracks must have a low pion-probability $\mathscr{P}(\pi)$ in the calorimeter (and be identified as electrons by the PID for momenta < 200 MeV/c). For a pion-probability cut of 4 % the dependence of the electron identification efficiency on the momentum is shown in Fig. 3.

Fig. 4a gives, for the data and the expected background, the number of events that survive the kinematical selection and the electron identification, as a function of the pion-probability cut used for e/π separation. In Fig. 4b the efficiency of the electron identification is shown for MC signal events. As a result, electron identification provides an additional background rejection factor of $\approx 10^2$ with an 18% probability cut and of $\approx 10^3$ with a 2% probability cut, accompanied by a signal loss of 57% and 85%, respectively. For these cuts the remaining

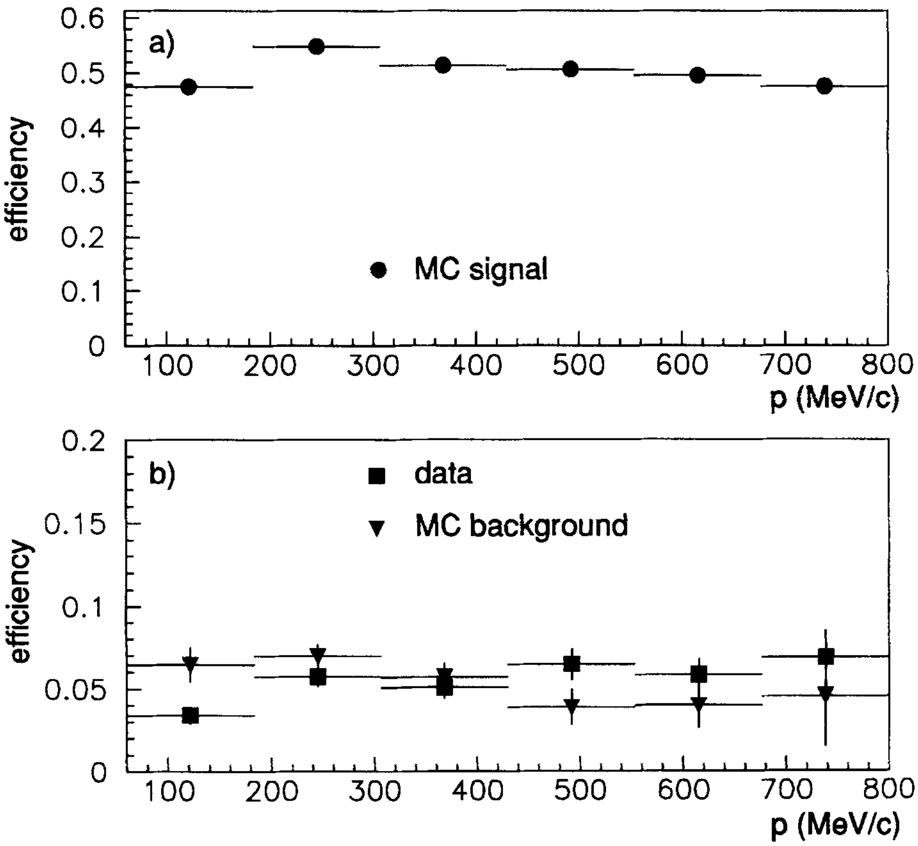

Fig. 3. Efficiency of electron identification with a pion probability $\mathscr{P}(\pi) = 4\%$ for (a) MC-simulated signal, (b) data and MC-simulated background (see text).

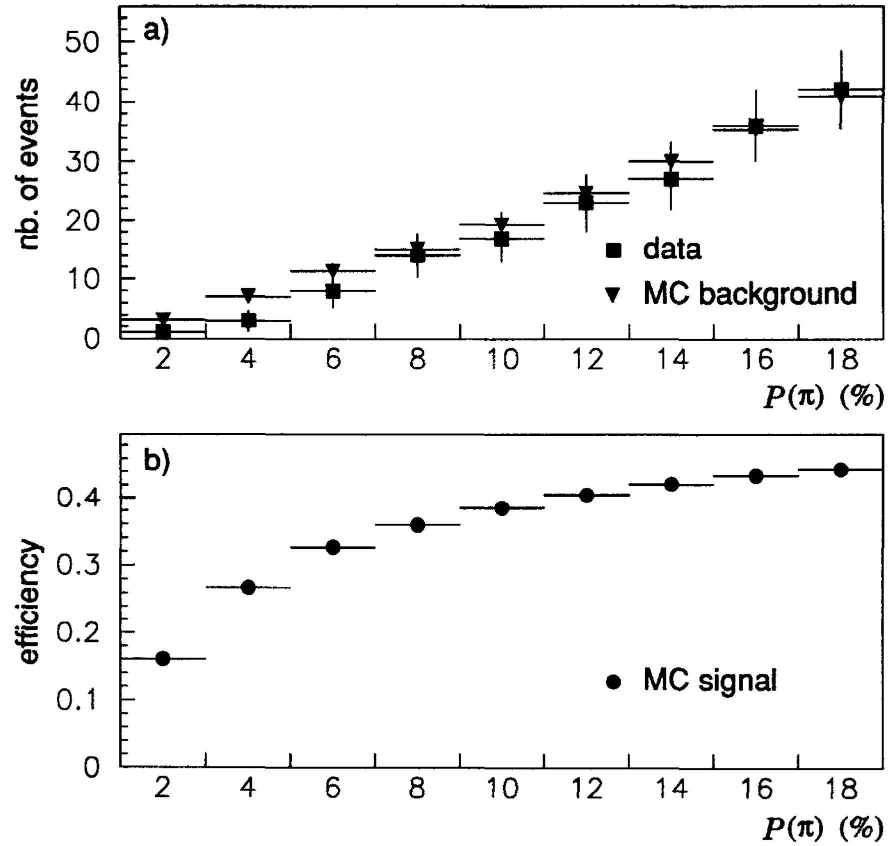

Fig. 4. Number of data and MC-simulated background events (a) and efficiency for MC-simulated signal events (b) as a function of the pion probability $\mathscr{P}(\pi)$ (see text).

background consists of $K^0 \to \pi e \nu$ events to a level of 80% and 95%, respectively.

4. Results

We have compared the number of data events surviving the 9C-fit and electron identification cuts with the number of MC background events, over a wide range of confidence levels. In addition, having an exponential signal and a flat background, the upper limit of the lifetime interval was varied to search for the optimum value. Different combinations of cuts were tested by varying the 9C-fit probability cut from 20% to 90% in steps of 10%, the pion-probability cut from 2% to 18% in steps of 2% and the lifetime cut from 2 to 6 τ_S in 1 τ_S steps. In all cases, regardless of the cut combination, the number of data events found was consistent with the number of background events expected from the MC simulation, μ_b. The number of data events surviving the cuts ranged from 0 (at 90% 9C-fit, 2% pion probability and 2 τ_S lifetime cuts) to 42 (at 20% 9C-fit, 18% pion-probability and 6 τ_S lifetime cuts). The corresponding values for μ_b are < 0.003 and 41 ± 4.

The final cuts are 70% for the 9C-fit probability, 4% for the pion-probability and 3 τ_S for the lifetime. They correspond to the maximum significance of the potential signal, defined as $\eta(e^+e^-)/\sqrt{\mu_b}$, where $\eta(e^+e^-)$ is the signal acceptance. After applying these cuts on data, no events are left, while $\mu_b = 0.22 \pm 0.10$.

The upper limit for the number of signal events from a Poisson-distributed process including a background is obtained using the following equation [10] for the confidence level $1-\epsilon$:

$$1-\epsilon = 1 - \frac{e^{-(\mu_b+\mu_s)} \sum_{0}^{n_0} (\mu_b+\mu_s)^n/n!}{e^{-\mu_b} \sum_{0}^{n_0} \mu_b^n/n!}, \qquad (2)$$

where μ_s and n_0 are the number of signal events and the number of observed events, respectively. At 90% CL with no observed events and 0.2 expected (MC) background events, the upper limit for the number of signal events is $\mu_s = 2.3$.

Systematic uncertainties that could influence our result were tested as follows:

- By shifting the number of expected background events by one sigma in each direction and repeating the optimization of cuts we obtained upper limits on μ_s equal to the value given above.
- Normalization and estimation of acceptances were checked by using similar electron identification and selection criteria, and the same normalization method on a sample of $K^0 \to \pi e \nu$ events (data and MC-simulated sets). We found good agreement between data and MC simulation, proving that acceptances and normalization are well understood.

We conclude that there is no significant systematic error on μ_s. The number of signal events (μ_s) is related to the branching ratios $BR(e^+e^-)$ and $BR(\pi^+\pi^-)$ by

$$\mu_s = \frac{\eta(e^+e^-)}{\eta(\pi^+\pi^-)} \times \frac{N(\pi^+\pi^-)}{BR(\pi^+\pi^-)} \times BR(e^+e^-), \qquad (3)$$

where the relative acceptance $\eta(e^+e^-)/\eta(\pi^+\pi^-)$ is 21% and $\eta(\pi^+\pi^-)$ is the acceptance for the $K_S \to \pi^+\pi^-$ events giving the normalization $N(\pi^+\pi^-) = 5.4 \times 10^7$.

With the values reported above, Eq. (3) translates to an upper limit for the branching ratio of the decay $K_S \to e^+e^-$:

$$BR(K_S \to e^+e^-) < 1.4 \times 10^{-7} \quad (90\%\ \mathrm{CL}), \qquad (4)$$

representing an order of magnitude improvement compared with the previous measurement [4].

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