Search for the decay $K_S \to e^+e^-$

F. Archilli for KLOE collaboration[a]
Dipartimento di Fisica dell'Università di Roma Tor Vergata & sezione INFN Roma Tor Vergata, Rome, Italy

We present results of a direct search for the decay $K_S \to e^+e^-$ with the KLOE detector, obtained with a sample of $e^+e^- \to \phi \to K_S K_L$ events produced at DAΦNE, the Frascati ϕ–factory, for an integrated luminosity of 1.9 fb^{-1}. The Standard Model prediction for this decay is BR($K_S \to e^+e^-$) = 2×10^{-14}. The search has been performed by tagging the K_S decays with simultaneous detection of a K_L interaction in the calorimeter. Background rejection has been optimized by using both kinematic cuts and particle identification. At the end of the analysis chain we find BR($K_S \to e^+e^-$) $< 9.3 \times 10^{-9}$ at 90% CL, which improves by a factor of ~ 15 on the previous best result, obtained by CPLEAR experiment.

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]. For both K_S andK_L, the e^+e^- channel is much more suppressed than the $\mu^+\mu^-$ one (by a factor of ~ 250) because of the $e-\mu$ mass difference. The diagram corresponding to the process $K_S \to \gamma^*\gamma^* \to \ell^+\ell^-$ is shown in Fig. 1. Using Chiral Perturbation Theory (χpT)

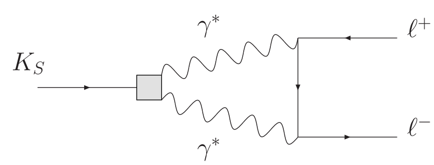

Figure 1: Long distance contribution to $K_S \to \ell^+\ell^-$ process, mediated by two-photon rescattering.

to order $\mathcal{O}(p^4)$, the Standard Model prediction BR($K_S \to e^+e^-$) is evaluated to be $\sim 2 \times 10^{-14}$. A value significantly higher than expected would point to new physics. The best experimental limit for $BR(K_S \to e^+e^-)$ has been measured by CPLEAR [2], and it is equal to 1.4×10^{-7}, at 90% CL. Here we present a new measurement of this channel, which improves on the previous result by a factor of ~ 15.

[a]F. Ambrosino, A. Antonelli, M. Antonelli, F. Archilli, P. Beltrame, G. Bencivenni, S. Bertolucci, C. Bini, C. Bloise, S. Bocchetta, F. Bossi, P. Branchini, P. Campana, G. Capon, T. Capussela, F. Ceradini, F. Cesario, P. Ciambrone, F. Crucianelli, E. De Lucia, A. De Santis, P. De Simone, G. De Zorzi, A. Denig, A. Di Domenico, C. Di Donato, B. Di Micco, M. Dreucci, G. Felici, M. L. Ferrer, S. Fiore, P. Franzini, C. Gatti, P. Gauzzi, S. Giovannella, E. Graziani, W. Kluge, V. Kulikov, G. Lanfranchi, J. Lee-Franzini, D. Leone, M. Martini, P. Massarotti, S. Meola, S. Miscetti, M. Moulson, S. Müller, F. Murtas, M. Napolitano, F. Nguyen, M. Palutan, E. Pasqualucci, A. Passeri, V. Patera, F. Perfetto, P. Santangelo, B. Sciascia, A. Sciubba, A. Sibidanov, T. Spadaro, M. Testa, L. Tortora, P. Valente, G. Venanzoni, R.Versaci

2 Experimental setup

The data were collected with KLOE detector at DAΦNE, the Frascati ϕ–factory. DAΦNE is an e^+e^- collider that operates at a center-of-mass energy of $\sim 1020\,\text{MeV}$, the mass of the ϕ meson. ϕ mesons decay $\sim 34\%$ of the time into nearly collinear $K^0\bar{K}^0$ pairs. Because $J^{PC}(\phi) = 1^{--}$, the kaon pair is in an antisymmetric state, so that the final state is always K_SK_L. Therefore, the detection of a K_L signals the presence of a K_S of known momentum and direction, independently of its decay mode. This technique is called K_S *tagging*. A total of ~ 4 billion ϕ were produced, yielding ~ 1.4 billion of K_SK_L pairs.

The KLOE detector consists of a large cylindrical drift chamber (DC), surrounded by a lead/scintillating-fiber sampling calorimeter (EMC). A superconductig coil surrounding the calorimeter provides a 0.52 T magnetic field. The drift chamber [3], 4 m in diameter and 3.3 m long, is made of carbon-fibers/epoxy and filled with a light gas mixture, 90% He-10%iC_4H_{10}. The DC position resolutions are $\sigma_{xy} \approx 150\mu\text{m}$ and $\sigma_z \approx 2\,\text{mm}$. DC momentum resolution is $\sigma(p_\perp)/p_\perp \approx 0.4\%$. Vertices are reconstructed with a spatial resolution of $\sim 3\,\text{mm}$.

The calorimeter [4] is divided into a barrel and two endcaps and covers 98% of the solid angle. The energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$ and $\sigma_t = 57\,\text{ps}/\sqrt{E(\text{GeV})} \oplus 100\,\text{ps}$, respectively.

To study the background rejection, a MC sample of ϕ decays to all possible final states has been used, for an integrated luminosity of $\sim 1.9\,\text{fb}^{-1}$. A MC sample of ~ 45000 signal events has been also produced, to measure the analysis efficiency.

3 Data analysis

The identification of K_L-interaction in the EMC is used to tag the presence of K_S mesons. The mean decay lenghts of K_S and K_L are $\lambda_S \sim 0.6\,\text{cm}$ and $\lambda_L \sim 350\,\text{cm}$, respectively. About 50% of K_L's therefore reach the calorimeter before decaying. The K_L interaction in the calorimeter barrel (K_{crash}) is identified by requiring a cluster of energy greater than 125 MeV not associated with any track, and whose time corresponds to a velocity $\beta = r_{cl}/ct_{cl}$ compatible with the kaon velocity in the ϕ center of mass, $\beta^* \sim 0.216$, after the residual ϕ motion is considered. Cutting at $0.17 \leq \beta^* \leq 0.28$ we selected ~ 650 million K_S-tagged events (K_{crash} events in the following), which are used as a starting sample for the $K_S \to e^+e^-$ search.

$K_S \to e^+e^-$ events are selected by requiring the presence of two tracks of opposite charge with their point of closest approach to the origin inside a cylinder 4 cm in radius and 10 cm in length along the beam line. The track momenta and polar angles must satisfy the fiducial cuts $120 \leq p \leq 350\,\text{MeV}$ and $30° \leq \theta \leq 150°$. The tracks must also reach the EMC without spiralling, and have an associated cluster. In Fig. 2, the two-track invariant mass evaluated in electron hypothesis (M_{ee}) is shown for both MC signal and background samples. A preselection cut requiring $M_{ee} > 420\,\text{MeV}$ has been applied, which rejects most of $K_S \to \pi^+\pi^-$ events, for which $M_{ee} \sim 409\,\text{MeV}$. The residual background has two main components: $K_S \to \pi^+\pi^-$ events, populating the low M_{ee} region, and $\phi \to \pi^+\pi^-\pi^0$ events, spreading over the whole spectrum. The $K_S \to \pi^+\pi^-$ events have such a wrong reconstructed M_{ee} because of track resolution or one pion decaying into a muon. The $\phi \to \pi^+\pi^-\pi^0$ events enter the preselection because of a machine background cluster, accidentally satisfying the K_{crash} algorithm. After preselection we are left with $\sim 5 \times 10^5$ events. To have a better separation between signal and background, a χ^2-like variable is defined, collecting informations from the clusters associated to the candidate electron tracks. Using the MC signal events we built likelihood functions based on: the sum and the difference of δt for the two tracks, where $\delta t = t_{cl} - L/\beta c$ is evaluated in electron hypothesis; the ratio E/p between the cluster energy and the track momentum, for both charges; the cluster depth, evaluated respect to the track, for both charges. In Fig. 2, the scatter plot of χ^2 versus M_{ee} is shown, for MC signal and background sources. The χ^2 spectrum for background is concentrated at higher values respect to signal, since both $K_S \to \pi^+\pi^-$ and $\phi \to \pi^+\pi^-\pi^0$ events have pions in the final state.

A signal box to select the $K_S \to e^+e^-$ events can be conveniently defined in the $M_{ee} - \chi^2$ plane (see Fig. 2); nevertheless we investigated some more independent requirements in order to reduce the background contamination as much as possible before applying the $M_{ee}-\chi^2$ selection.

Charged pions from $K_S \to \pi^+\pi^-$ decay have a momentum in the K_S rest frame $p^*_\pi \sim 206\,\mathrm{MeV}$. The distribution of track momenta in the K_S rest frame, evaluated in the pion mass hypothesis, is shown in Fig. 2, for MC background and MC signal. For most of $K_S \to \pi^+\pi^-$ decays, at least one pion has well reconstructed momentum, so that the requirements

$$\min(p^*_\pi(1), p^*_\pi(2)) \geq 220\,\mathrm{MeV} \quad , \quad p^*_\pi(1) + p^*_\pi(2) \geq 478\,\mathrm{MeV} \tag{1}$$

rejects $\sim 99.9\%$ of these events, while retaining $\sim 92\%$ of the signal.

To reject $\phi \to \pi^+\pi^-\pi^0$ events we have applied a cut on the missing momentum, defined as:

$$P_{\mathrm{miss}} = \left|\vec{P}_\phi - \vec{P}_L - \vec{P}_S\right| \tag{2}$$

where $\vec{P}_{L,S}$ are the neutral kaon momenta, and $\vec{P}_\phi$ is the ϕ momentum. The distribution of P_{miss} is shown in Fig. 2, for MC background and for MC signal events. We require

$$P_{\mathrm{miss}} \leq 40\,\mathrm{MeV}\,, \tag{3}$$

which rejects almost completely the 3π background source which is distributed at high missing momentum.

A signal box is defined in the $M_{ee} - \chi^2$ plane as shown Fig. 2. The χ^2 cut for the signal box definition has been chosen to remove all MC background events: $\chi^2 < 70$. The cut on M_{ee} is practically set by the p^*_π cut, which rules out all signal events with a radiated photon with energy greter than 20 MeV, correspondig to an invariant mass window: $477 < M_{ee} \leq 510\,\mathrm{MeV}$. The signal box selection on data gives $N_{obs} = 0$. The upper limit at 90% CL on the expected number of signal events is $UL(\mu_S) = 2.3$.

4 Results

The total selection efficiency on $K_S \to e^+e^-$ events is evaluated by MC, using the following parametrization:

$$\epsilon_{sig} = \epsilon(K_{crash}) \times \epsilon(sele|K_{crash})\,, \tag{4}$$

where $\epsilon(K_{crash})$ is the tagging efficiency, and $\epsilon(sele|K_{crash})$ is the signal selection efficiency on the sample of tagged events. The efficiency evaluation includes contribution from radiative corrections. The number of $K_S \to \pi^+\pi^-$ events $N_{\pi^+\pi^-}$ counted on the same sample of K_S tagged events is used as normalization, with a similar expression for the efficiency. The upper limit on $\mathrm{BR}(K_S \to e^+e^-)$ is evaluated as follows:

$$UL(BR(K_S \to e^+e^-)) = UL(\mu_s) \times \mathcal{R}_{tag} \times \frac{\epsilon_{\pi^+\pi^-}(sele|K_{crash})}{\epsilon_{sig}(sele|K_{crash})} \times \frac{BR(K_S \to \pi^+\pi^-)}{N_{\pi^+\pi^-}}, \tag{5}$$

where $\mathcal{R}_{tag}$ [5] is the tagging efficiency ratio, corresponding to a small correction due to the K_{crash} algorithm dependence on K_S decay mode, and it is equal to 0.9634(1).Using $\epsilon_{sig}(sele|K_{crash}) = 0.465(4)$, $\epsilon_{\pi^+\pi^-}(sele|K_{crash}) = 0.6102(5)$ and $N_{\pi^+\pi^-} = 217,422,768$, we obtain

$$UL(BR(K_S \to e^+e^-(\gamma))) = 9.3 \times 10^{-9}, \text{ at } 90\%\,\mathrm{CL}\,. \tag{6}$$

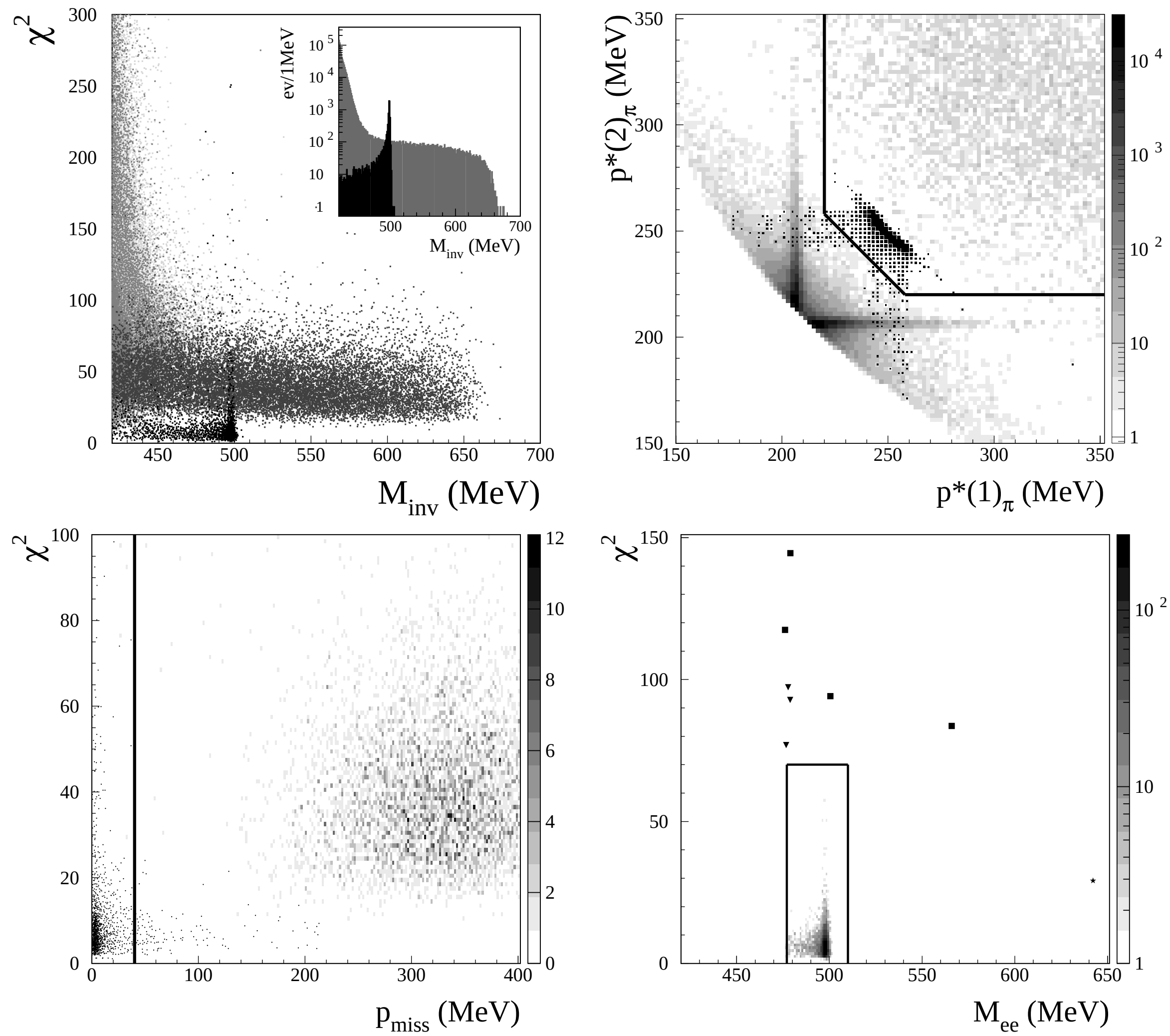

Figure 2: Top left: χ^2 vs M_{ee} distributions for MC signal (black), MC backgrounds $K_S \to \pi^+\pi^-$ and $\phi \to \pi^+\pi^-\pi^0$ (light and dark grey respectively), M_{ee} distributions for MC signal (black) and MC backgrounds (grey) is shown in the inset; top right: p^*_π distributions for MC signal (black) and MC background (grey scale); bottom left: χ^2 vs $P_{\rm miss}$ distributions for MC signal (black) and MC background (grey scale); bottom right: χ^2 vs M_{ee} distributions for MC signal (grey scale), data (■), $K_S \to \pi^+\pi^-$ (▼) and $\phi \to \pi^+\pi^-\pi^0$ (★) after background rejection cuts.

Our measurement improves by a factor of $\sim$ 15 on the CPLEAR result [2], for the first time including radiative corrections in the evaluation of the upper limit.

References

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