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

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We present results of a direct search for the decay $K_S \rightarrow e^+e^-$ with the KLOE detector, obtained with a sample of $e^+e^- \rightarrow \phi \rightarrow K_SK_L$ events produced at DAΦNE, the Frascati $\phi$-factory, for an integrated luminosity of 1.9 fb$^{-1}$. The Standard Model prediction for this decay is $\text{BR}(K_S \rightarrow e^+e^-) = 2 \times 10^{-14}$. 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 $\text{BR}(K_S \rightarrow e^+e^-) < 9.3 \times 10^{-9}$ at 90% CL, which improves by a factor of $\sim 15$ on the previous best result, obtained by CPLEAR experiment.

1 Introduction

The decay $K_S \rightarrow e^+e^-$, like the decay $K_L \rightarrow e^+e^-$ or $K_L \rightarrow \mu^+\mu^-$, is a flavour-changing neutral-current process, suppressed in the Standard Model and dominated by the two-photon intermediate state. For both $K_S$ and $K_L$, the $e^+e^-$ channel is much more suppressed than the $\mu^+\mu^-$ one (by a factor of $\sim 250$) because of the $e^{-}\mu$ mass difference. The diagram corresponding to the process $K_S \rightarrow \gamma^*\gamma^* \rightarrow \ell^+\ell^-$ is shown in Fig. 1. Using Chiral Perturbation Theory ($\chi$PT) to order $O(p^4)$, the Standard Model prediction $\text{BR}(K_S \rightarrow e^+e^-)$ 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 $\text{BR}(K_S \rightarrow e^+e^-)$ has been measured by CPLEAR and it is equal to $1.4 \times 10^{-7}$ at 90% CL. Here we present a new measurement of this channel, which improves on the previous result by a factor of $\sim 15$.

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

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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 $\sim 1020$ MeV, the mass of the $\phi$ meson. $\phi$ 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 $\sim 4$ billion $\phi$ were produced, yielding $\sim 1.4$ 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 superconducting coil surrounding the DC position resolutions are $\sigma_{xy} \approx 150\mu m$ and $\sigma_z \approx 2\, mm$. DC momentum resolution is $\sigma(p_\perp)/p_\perp \approx 0.4\%$. Vertices are reconstructed with a spatial resolution of $\sim 3\, mm$.

The calorimeter 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 $\sigma_t = 57 \, \text{ps}/\sqrt{E/(\text{GeV})} \pm 100 \, \text{ps}$, respectively.

To study the background rejection, a MC sample of $\phi$ decays to all possible final states has been used, for an integrated luminosity of $\sim 1.9\, \text{fb}^{-1}$. A MC sample of $\sim 45000$ 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 lengths 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 ($K_{\text{crash}}$) is identified by requiring a cluster of energy greater than $125\, \text{MeV}$ not associated with any track, and whose time corresponds to a velocity $\beta = r_{cl}/ct_{cl}$ compatible with the kaon velocity in the $\phi$ center of mass, $\beta^* \sim 0.216$, after the residual $\phi$ motion is considered. Cutting at $0.17 \leq \beta^* \leq 0.28$ we selected $\sim 650\, \text{million} K_S$-tagged events ($K_{\text{crash}}$ 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 $4\, \text{cm}$ in radius and $10\, \text{cm}$ 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 $30^\circ \leq \theta \leq 150^\circ$. 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 $K_{\text{crash}}$ algorithm. After preselection we are left with $\sim 5 \times 10^5$ events. To have a better separation between signal and background, a $\chi^2$-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 $\delta t$ 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 $\chi^2$ versus $M_{ee}$ is shown, for MC signal and background sources. The $\chi^2$ spectrum for background is concentrated at higher values respect to signal, since both $K_S \rightarrow \pi^+\pi^-$ and $\phi \rightarrow \pi^+\pi^-\pi^0$ events have pions in the final state.

A signal box to select the $K_S \rightarrow e^+e^-$ 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 $K_S \rightarrow \pi^+\pi^-$ decay have a momentum in the $K_S$ rest frame $p_\pi^* \sim 206\text{ MeV}$. 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 $K_S \rightarrow \pi^+\pi^-$ decays, at least one pion has well reconstructed momentum, so that the requirements

$$\min(p_\pi^*(1), p_\pi^*(2)) \geq 220\text{ MeV}, \quad p_\pi^*(1) + p_\pi^*(2) \geq 478\text{ MeV}$$

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

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

$$P_{\text{miss}} = |\vec{P}_\phi - \vec{P}_L - \vec{P}_S|$$

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

$$P_{\text{miss}} \leq 40\text{ MeV},$$

which rejects almost completely the $3\pi$ 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 $\chi^2$ 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 $p_\pi^*$ cut, which rules out all signal events with a radiated photon with energy greater than 20 MeV, correspondig to an invariant mass window: $477 < M_{ee} \leq 510\text{ MeV}$. The signal box selection on data gives $N_{\text{obs}} = 0$. 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 $K_S \rightarrow e^+e^-$ events is evaluated by MC, using the following parametrization:

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

where $\epsilon(K_{\text{crash}})$ is the tagging efficiency, and $\epsilon(\text{sele}|K_{\text{crash}})$ is the signal selection efficiency on the sample of tagged events. The efficiency evaluation includes contribution from radiative corrections. The number of $K_S \rightarrow \pi^+\pi^-$ 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 $BR(K_S \rightarrow e^+e^-)$ is evaluated as follows:

$$UL(BR(K_S \rightarrow e^+e^-)) = UL(\mu_S) \times R_{\text{tag}} \times \frac{\epsilon_{\pi^+\pi^-}(\text{sele}|K_{\text{crash}})}{\epsilon_{\text{sig}}(\text{sele}|K_{\text{crash}})} \times \frac{BR(K_S \rightarrow \pi^+\pi^-)}{N_{\pi^+\pi^-}},$$

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

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

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