A direct search for $K_S \rightarrow 3\pi^0$ decay with the KLOE detector at DAΦNE

The KLOE Collaboration

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Abstract

A search for $K_S \to 3\pi^0$ decay has been carried out using 450 pb^{-1} of e^+e^- collisions at a center of mass energy $W \sim M_\phi$ collected by the KLOE experiment at DAΦNE. We based our search on the requirements of a K_S tag, provided by the K_L interaction in the calorimeter, and on the counting of six prompt photons. The development of discriminant variables between $K_S \to 3\pi^0$ and $K_S \to 2\pi^0$ with two fake photons, allows us to set an upper limit on the branching ratio to 2.1×10^{-7} at 90% C.L. This result is a factor ~ 70 better than the previous measurement and improves of a factor > 2 the accuracy on the CPT violation parameter in the mixing $\Im(\delta)$.

Key words: e^+e^- collisions, DAΦNE, KLOE, rare K_S decays, CP, CPT

1 Introduction

The decay $K_S \to 3\pi^0$ is a pure CP violating process. The related CP violation parameter η_{000} [1] is defined as the ratio of K_S to K_L decay amplitudes: $\eta_{000} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0) = \varepsilon + \varepsilon'_{000}$ where ε describes the CP violation in the mixing matrix and ε'_{000} is a direct CP violating term. In the Standard

Model we expect η_{000} to be similar to η_{00}. The expected branching ratio, BR, of this decay, $\mathrm{BR}(K_S \to 3\pi^0) = \frac{\Gamma_L^{000}}{\Gamma_S} \cdot |\eta_{000}|^2 \sim \mathrm{BR}(K_L \to 3\pi^0) \cdot \frac{\tau_S}{\tau_L} \cdot |\eta_{00}|^2$, is therefore $\sim 2 \cdot 10^{-9}$, making its direct observation really challenging. The best upper limit on the BR (i.e. on $|\eta_{000}|^2$) has been set to $1.5 \cdot 10^{-5}$ by SND [2] where, similar to KLOE, it is possible to tag a K_S beam. The other existing technique is to detect the interference term between $K_S K_L$ in the same final state which is proportional to η_{000}. The weighted average of the best published values [3,4] gives: $\eta_{000} = (0.08 \pm 0.11) + i \cdot (0.07 \pm 0.16)$. The study of this decay is also important because of the uncertainty on η_{000} limits the precision on CPT test via the unitarity relation [5]. A neutral kaon state [6] can be expressed as: $K_{S,L} = K_{1,2} + (\varepsilon \pm \delta) K_{2,1}$ where K_1 and K_2 are the two CP eigenstates and δ is a CPT violation parameter in mixing. A possible form of the unitarity relation is:

$$(1 + i\tan(\phi_{sw}))(\Re(\varepsilon) - i\Im(\delta)) = \sum (A^*(K_S \to f) A(K_L \to f)/\Gamma_S) \qquad (1)$$

where the sum runs over all the possible decay channels f, and $\tan(\phi_{sw}) = 2\Delta m_{S,L}/(\Gamma_S - \Gamma_L)$. According to ref. [7], the value of $\Im(\delta) = (2.4 \pm 5.0) \cdot 10^{-5}$ is limited by the measurement on η_{000}. Neglecting this term, the same analysis yields $\Im(\delta) = (-0.5 \pm 2.0) \cdot 10^{-5}$; that is an improvement of around a factor 2.5 on the accuracy.

2 The direct search of $K_S \to 3\pi^0$

The data were collected with the KLOE [8] - [11] detector at DAΦNE [12], the Frascati ϕ-factory. DAΦNE is an e^+e^- collider which operates at a center of mass energy W of $\sim$ 1020 MeV, the mass of the ϕ-meson. Equal-energy positron and electron beams collide at an angle of 25 mrad, producing ϕ-mesons nearly at rest. ϕ-mesons decay 34% of the time into nearly collinear $K^0\overline{K}^0$ pairs. Because $J^{PC}(\phi) = 1^{--}$, these pairs are in an antisymmetric state, so that the final state is always $K_S K_L$. All of the above implies that the detection of a K_L guarantees the presence of a K_S of given momentum and direction. This fact can be exploited to identify K_S-mesons independently of their decay mode. We refer to this technique as K_S *tagging*.

In this analysis we have used the whole sample of 450 pb^{-1} collected during 2001+2002 data taking, corresponding to $\sim$ 0.45 billion of $\phi \to K_S K_L$ decay. We expect 0.9 “standard model” $K_S \to 3\pi^0$ events produced.

K_S's are tagged with high efficiency ($\sim$ 30%) by identifying a K_L interaction, K_L-crash, in the calorimeter, which has a very distinctive signature given by a late ($\beta_K = 0.2$) high-energy cluster not associated to any track. The average

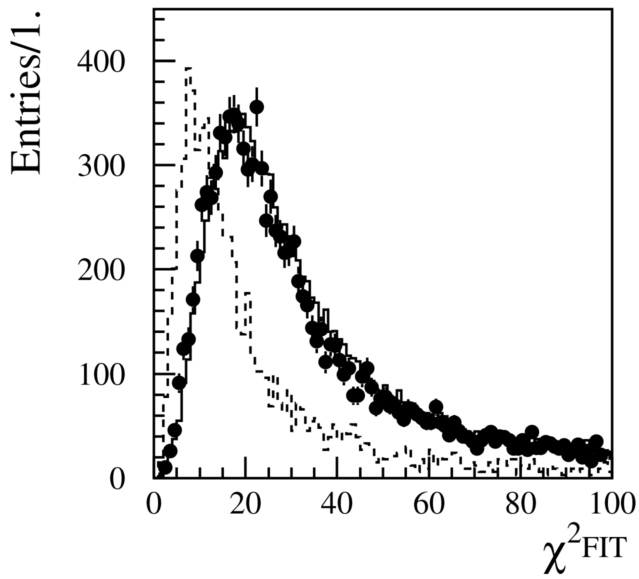

Fig. 1. Distribution of χ^2_{fit} for data (dark points), MC background (solid line) and 10000 events of MC signal (dashed line) after K_L-crash and preselection.

value of the center of mass energy, W, is obtained with a precision of 3 keV, for each 100 nb^{-1} running period, by reconstructing large angle Bhabha's. This value and the K_L-crash cluster position allows us to establish, in each event, the trajectory of the K_S with an angular resolution of 1° and a momentum resolution of $\sim$ 2 MeV.

Our selection starts by requiring a K_L-crash tag and six neutral clusters coming from the interaction point, IP. A tight constraint on β and moderate requirements on energy and angular acceptance are applied in order to have a large control sample for the background, while retaining a large selection efficiency for the signal. Applying this selection we have an initial sample of $\sim$39000 events. To get the branching ratio we then normalize the final event counting to the rate of $K_S \to 2\pi^0$ by requiring four photons after tagging.

Since $K_S \to 3\pi^0$ decay has 6 photons in the final state, the major expected background in this search is $K_S \to 2\pi^0$ +2 fake photons coming from shower fragments, machine background clusters in overlap with the events or both the possibilities. For the Monte Carlo, MC, background we use the production of $\phi \to K_S K_L$ decays corresponding to an equivalent statistics of $\sim$ 540 pb^{-1} and $\sim$ 90 nb^{-1} of $\phi \to$ all decays. The photon properties on the simulation (resolutions and detection-efficiency) have been tuned with data using a large sample of γ tagged in $\phi \to \pi^+\pi^-\pi^0$ events [13] selected by drift chamber only information. The presence of additional clusters in the events due to accidental overlap with machine background, *dafbkg*, clusters has been taken into account by inserting these events at hit level in the simulation. The *dafbkg* insertion follows its rate dependence along the running period [13]. Similarly, all other basic running conditions, such as beam parameters ($W, \vec{P}_\phi, \vec{X}_\phi$) follow the run

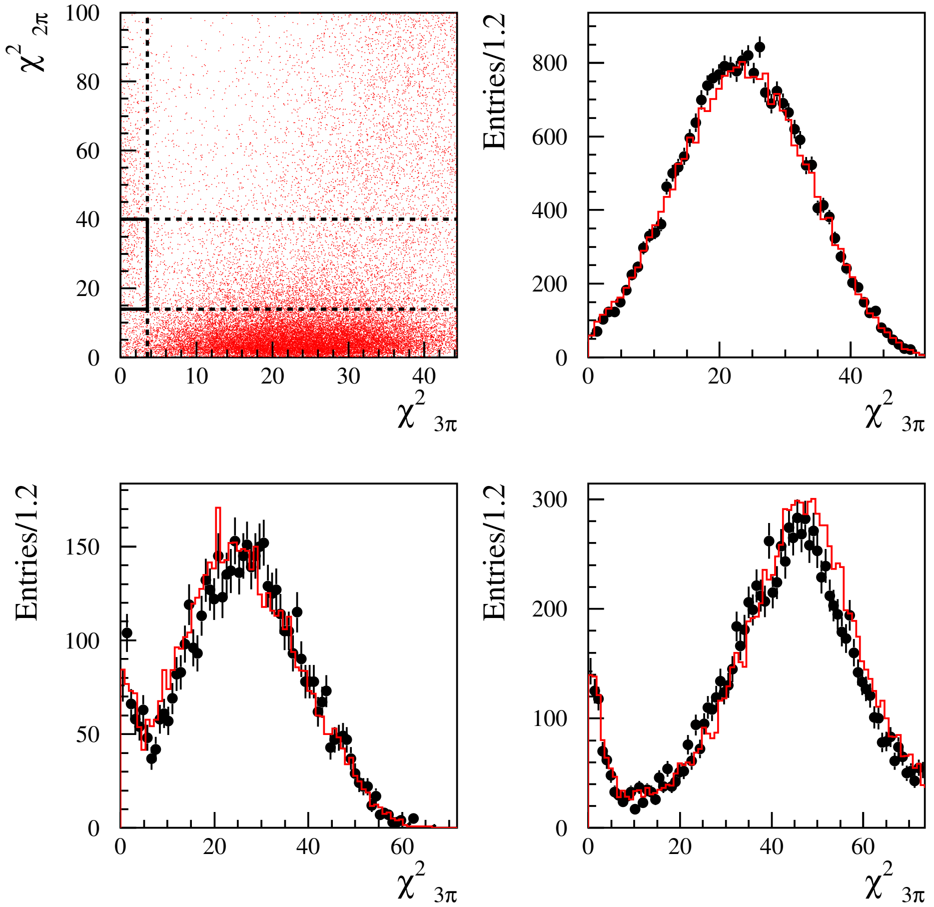

Fig. 2. Signal sample (K_L-crash tag and six photons). $\chi^2_{3\pi}$ vs $\chi^2_{2\pi}$ scatter-plot for data (a) with the control boxes defined for our analysis: *upper left* (u_L), *upper right* (u_R), *central left* (c_L), *central right* (c_R), *lower left* (l_L), *lower right* (l_R); $\chi^2_{3\pi}$ projections when: (b) $\chi^2_{2\pi}$ <14 (lower band), (c) 14< $\chi^2_{2\pi}$ <40 (central band), (d) $\chi^2_{2\pi}$ >40 (upper band). For all cases, data are black points and MC are solid line.

variation. In this MC production, the $K_S \to 3\pi^0$ signal is simulated with a BR equal to the SND limit. We have also generated 10000 signal events with average running conditions to have a better statistical determination of the efficiency (for the considered process).

The first step to reduce the background is the application of a kinematic fit procedure which imposes K_S mass, K_L 4-momentum conservation and $\beta = 1$ for each γ. In Fig. 1 the distribution of this variable for data and MC background is shown. The good agreement between the two distributions proves that the shapes and relative proportions of the backgrounds are well reproduced by Monte Carlo. In the same plot we also show the expected signal shape. By cutting at reasonable χ^2_{fit} value (ndf=11, $\chi^2_{\rm fit}/{\rm ndf} < 3$) we retain 70% of the signal and reduce of a factor ~ 3 the background.

To further improve the rejection and disentangle 3 π^0 from 2 π^0 final states, we define 2 pseudo-χ^2, $\chi^2_{3\pi}$ and $\chi^2_{2\pi}$. The $\chi^2_{3\pi}$ is based only on the 3 best reconstructed pion masses, while the $\chi^2_{2\pi}$ selects 4 out of the 6 photons providing the best kinematic agreement with the $K_S \to 2\pi^0$decay. By studying the correlation between $\chi^2_{3\pi}$ and $\chi^2_{2\pi}$ we define a signal box and five surrounding control boxes as shown in Fig. 2. To determine how well the data-MC normalization holds in different scatter-plot regions we have projected $\chi^2_{3\pi}$ in bands of $\chi^2_{2\pi}$ (Figs. 2.b,c,d). All bands show a reasonable data-MC agreement. The large peak at low $\chi^2_{3\pi}$ values in the central and upper bands is due to fake K_L-crash tags given mostly by $K_S \to \pi^+\pi^-$, $K_L \to 3\pi^0$ events. For this background, the K_S charged pions interact on the quadrupoles creating late clusters which simulate the K_L-crash, while part of the K_L's decay close to the IP thus mimicking our signal. Our Monte Carlo simulates well the shapes of the fake K_L-crash background and we have calibrated its amount fitting data with a linear combination of MC with and without K_L-crash fakes.

Although by cutting on χ^2_{fit} we have a good handle on the fake K_L-crash background we reduce it to a negligible amount by vetoing events with tracks coming from the IP. Moreover, in order to enforce the $\chi^2_{2\pi}$ selection of photons we add a cut on the variable $\Delta E = M_\phi/2 - \sum E_i$, where the sum runs over the four γ's chosen by the $\chi^2_{2\pi}$ algorithm. For a $K_S \to 2\pi^0 + 2\gamma$ fake events $\Delta E \sim 0$ MeV, while for a signal event the missing π^0 mass reflects in a larger ΔE value (~ 135 MeV).

Before opening the signal-box we have optimized the limit [15] by varying the cuts on χ^2_{fit}, $\chi^2_{2\pi}$, $\chi^2_{3\pi}$ and ΔE on the MC samples. As a result of this procedure the final cuts have been set to: $\chi^2_{fit} < 31$, $\Delta E > 37$ MeV and we have defined the following signal box region ($14 < \chi^2_{2\pi} < 60$ and $\chi^2_{3\pi} <3.7$). In Fig. 3 the events surviving this selection for data and MC are reported.

With an efficiency, after tagging, of $\varepsilon_{3\pi} = (22.6 \pm 0.8)\%$, we count 4 events for an expected background $N_b = 3.2 \pm 1.4_{MCstat} \pm 0.5_{syst}$. The systematic error on the background is evaluated by comparing data and MC expectations in the five control boxes while varying the analysis cuts. Folding a gaussian behavior to the background uncertainty, we quote the number of $K_S \to 3\pi^0$ decay to be below 5.8 at 90% C.L. In the same tagged sample, we count $3.8 \cdot 10^7$ $K_S \to 2\pi^0$ events to normalize the counting to the BR($K_S \to 2\pi^0$). By this normalization we finally derive BR($K_S \to 3\pi^0$) $\leq 2.1 \cdot 10^{-7}$ at 90% C.L. which improves of a factor ~ 70 the previous measurement.

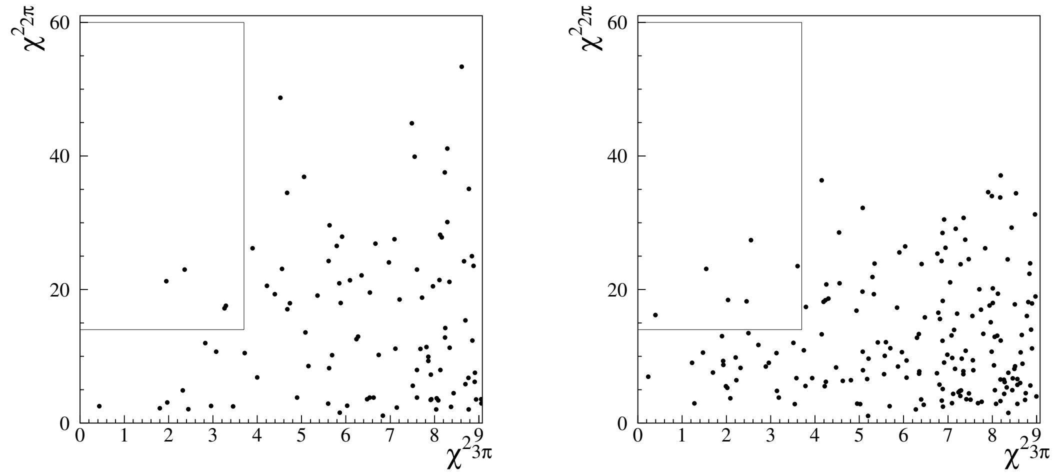

Fig. 3. $\chi^2_{2\pi}$ versus $\chi^2_{3\pi}$ for our sample at the end of the analysis chain: data (left) and Monte Carlo (right). The rectangular regions represent the signal box.

3 Related physical results

Our result on the upper limit can be used to calculate other parameters directly related to CPT test. From relation:

$$|\eta_{000}| = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)} = \sqrt{\frac{\tau_S}{\tau_L}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}} \tag{2}$$

we obtain $|\eta_{000}| \leq 0.024$ at 90% C.L. which reduces by a factor ~ 5 the uncertainty on this parameter [3,4].

We can also set a conservative limit on the contribution of the $K_S \to 3\pi^0$decay to $\Im(\delta)$ ($\Im(\delta_{000})$). From eq. 1 we obtain:

$$\Im(\delta_{000}) = -\Im\left[\frac{1}{1 + i\tan(\phi_{SW})}\alpha_{000}\right] \tag{3}$$

where $\alpha_{000} = \tau_S/\tau_L BR(K_L \to 3\pi^0)\eta_{000}$ [5]. We finally derive:

$$\Im(\delta_{000}) = BR(K_L \to 3\pi^0)\frac{\tau_S}{\tau_L}|\eta_{000}|cos(\phi_{SW})sin(\phi_{SW} - \phi_{000}) \tag{4}$$

where ϕ_{000} is the η_{000} complex-phase. For any possible value of ϕ_{000} our limit on $|\eta_{000}|$ bounds $|\Im(\delta_{000})| < 6.34 \cdot 10^{-6}$ at 90% C.L.

Our measurement makes η_{000} comparable to the existing measurement of $\eta_{+-0} = [(-2 \pm 8) + i(-2 \pm 9)] \times 10^{-3}$. Hence, following the analysis of CPLEAR [7] we conclude that the accuracy on $\Im(\delta)$ is now reduced to $2.5 \cdot 10^{-5}$ without any further assumption.

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