RECENT RESULTS FROM THE KLOE EXPERIMENT AT DAPHNE

THE KLOE COLLABORATION*
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Abstract

Recent results from the KLOE experiment at the DAΦNE e^+e^- collider are presented. KLOE has collected $\sim 450pb^{-1}$ of data in the years 2001 and 2002. Preliminary results are obtained using the full statistics and include: the search for the decay $K_S \to \pi^0\pi^0\pi^0$, the BR of the K_{e3} decay of the K_S (with the related $|V_{us}|$ determination)

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and the first measurement of its charge asymmetry, the measurement of the total e^+e^- hadronic cross section, exploiting the radiative return process to scan energies down to 600 MeV, the search for the C violating decay $\eta \to \gamma\gamma\gamma$.

1 Introduction

DAΦNE [1] is an e^+e^- collider working at the ϕ resonance peak, and located in the Frascati INFN laboratories. The ϕ meson is produced essentially at rest and decays abundantly ($\sim 34\%$) to $K_S K_L$, which is a pure $J^{PC} = 1^{--}$ quantum state. Thus DAΦNE provides two highly pure, almost monochromatic, back-to-back K_S and K_L beams.

The KLOE experiment [2] is designed to exploit the unique features of a ϕ-factory environment for the measurement of CP and CPT violation in the $K^0 - \bar{K}^0$ system, and more generally for the study of kaons' decays. In particular, KLOE has the unique capability of tagging the presence of a K_S (K_L) by detecting a K_L (K_S) flying in the opposite direction. K_S and K_L are easily distinguishable on the basis of their lifetimes: K_S's have a mean decay path $\lambda_S \sim 6\,mm$ and they all decay near the interaction point, while $\lambda_L \sim 340\,cm$. Other abundant ϕ decay modes are K^+K^- ($\sim 49\%$), for which a tagging technique can be applied similar to the neutral kaon case, $\rho\pi$ ($\sim 15\%$) and $\eta\gamma$ ($\sim 1.3\%$).

The DAΦNE collider has been commissioned in 1999, when it delivered its first 2 pb^{-1} of data, and it has been operated with continously improving luminosity up to 2002, when it reached a maximum peak luminosity of $7.8 \cdot 10^{31} cm^{-2} s^{-1}$. During the 2003 shutdown the machine has been upgraded, and in april 2004 has restarted delivering luminosity to KLOE.

The 25 pb^{-1} year 2000 data sample has been fully analized and results have been published [6, 7, 8, 9, 10, 12]. The total integrated luminosity collected by KLOE in the years 2001-2002 amounts to 450 pb^{-1} : few results have been published up to now[11], but many analyses are in progress. Some preliminary results are presented here.

2 The KLOE detector

The KLOE detector consists mainly in a large volume drift chamber surrounded by an electromagnetic calorimeter. A superconducting coil provides a 0.52 T solenoidal magnetic field.

The calorimeter[3] is a fine sampling lead-scintillating fiber one, composed by 24 barrel modules and 2x32 endcap modules, with photomultiplier readout at both sides. Module thickness is 23 cm ($\sim 15X_0$) and the total solid angle coverage is 98% . The energy resolution, as measured using $e^+e^- \to e^+e^-\gamma$ events, is $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$. The intrinsic time resolution, as measured using $e^+e^- \to e^+e^-\gamma$ and $e^+e^- \to 2\gamma$ events, is $\sigma_t = 54\,ps/\sqrt{E(GeV)} \oplus 50\,ps$. Two smaller calorimeters, QCAL[4], made with lead and scintillating tiles are wrapped around the low beta quadrupoles to complete the hermeticity.

The drift chamber[5] is a cylinder, 3.3 m long and having 4 m diameter, strung with $\sim$ 52000 wires (of which $\sim$ 12000 are sense wires) in an all stereo configuration. In order to minimize multiple scattering and K_L regeneration and to maximize detection efficiency of low energy photons, the chamber works with a 90% helium - 10% isobutane gas mixture, while its walls are made of light materials (mostly carbon fiber composites). The momentum resolution for tracks at large polar angle is $\sigma_p/p \leq 0.4\%$, the spatial resolutions are $\sigma_{r,\phi} \approx 150\mu m$ and $\sigma_z \approx 2mm$.

3 Neutral kaon decays

The presence of a K_S is tagged by identifying the interactions of the K_L in the calorimeter. Approximately 30% of the K_L's produced in $\phi \to K_S K_L$ events reaches the calorimeter before decaying and interacts therein. Such an interaction, referred to as K_L *crash*, has a very clear signature consisting of a high energy ($E > 100\,MeV$) cluster in the calorimeter, which is also neutral (i.e. not associable to any track in the event) and delayed ($\sim 30\,ns$ after all other clusters in the event, due to K_L small velocity, $\beta \sim 0.218$). The cluster position, exploiting the ϕ decay kinematics, provides the direction and momentum of the K_S. Moreover about 40% of the K_L crashes independently satisfy the trigger conditions, thus facilitating trigger efficiency studies.

The presence of a K_L is tagged by identifying the decay $K_S \to \pi^+\pi^-$. Such events are easily selected by requiring two oppositely charged tracks which form a vertex laying in a cylindrical fiducial volume centered in the interaction region, having radius of $4\,cm$ and length of $16\,cm$. No other tracks must be connected to the vertex, and loose cuts are applied to its total momentum and invariant mass. The measured K_S momentum provides a very good estimate of the K_L one, with an angular resolution of $\sim 1^\circ$ and a momentum resolution of $\sim 2\,MeV$. The overall tag efficiency is about 85%. K_L decays analyses are quite advanced, but preliminary results have not yet beeen released, and they will not be discussed here.

3.1 Search for the decay $K_S \to \pi^0\pi^0\pi^0$

Observation of this decay signals CP violation in kaon mixing and/or in decay. In the Standard Model (SM) the transition width for $K_L \to \pi^0\pi^0\pi^0$ is related to that of $K_S \to \pi^0\pi^0\pi^0$, whose branching ratio is predicted to be 1.9×10^{-9}, well below the present upper limit by SND[13], $BR(K_S \to \pi^0\pi^0\pi^0) < 1.4\times10^{-5}$ with 90% of confidence level (CL). The present uncertainty on the amplitude for $K_S \to \pi^0\pi^0\pi^0$ limits the precision of a CPT invariance test via the unitarity relation (Bell-Steinberger) for the kaon system: a limit on $K_S \to \pi^0\pi^0\pi^0$ at the level of 10^{-7} (in the reach of KLOE) translates into an improvement on the accuracy of the difference between K^0 and $\overline{K}^0$ masses from 10^{-18} GeV to 4×10^{-19} GeV.

A K_L-crash tag is first required in an event with no charged tracks coming from the interaction point. Clusters originated by photon interactions in the calorimeter are required to be not connectable with any charged track and to have velocity $\beta_{\rm cl} \sim 1$. Moderate requirements on the minimum cluster energy and polar angle are applied to reject machine background clusters. Events with 6 candidate photon clusters are retained.

To reduce the background from non-K_SK_L events, a kinematic fit which imposes K_S mass, K_L 4-momentum conservation and $\beta = 1$ for each γ cluster is applied. Only the events with $\chi^2_{\rm fit}/{\rm ndf} < 3$ are retained for further analysis.

The surviving background events are dominated by $K_S \to \pi^0\pi^0$ decays plus two fake γ clusters. To better discriminate $2\pi^0$ vs $3\pi^0$ final state, two pseudo-χ^2 variables have been defined: $\chi^2_{3\pi}$, which is based on the 3 best π^0 mass estimates among all the possible γ-γ pairs and $\chi^2_{2\pi}$, which selects 4 out of the 6 photons providing the best kinematic agreement with a $K_S \to \pi^0\pi^0$ decay. The scatter plot $\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$ is shown for data (blue points) and a Monte Carlo simulation of the signal (red dots) in the left part of fig 1. The distribution of $\chi^2_{3\pi}$ projected in the band $14 < \chi^2_{2\pi} < 40$ is shown in the right picture, where data (black dots) is compared with the simulations of the background (solid blue line) and of the signal (solid red line).

A signal box region in the $\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$ plane has been defined by optimizing the upper limit in the MC sample. With an efficiency $\varepsilon_{3\pi} = (22.6 \pm 0.8)\%$,

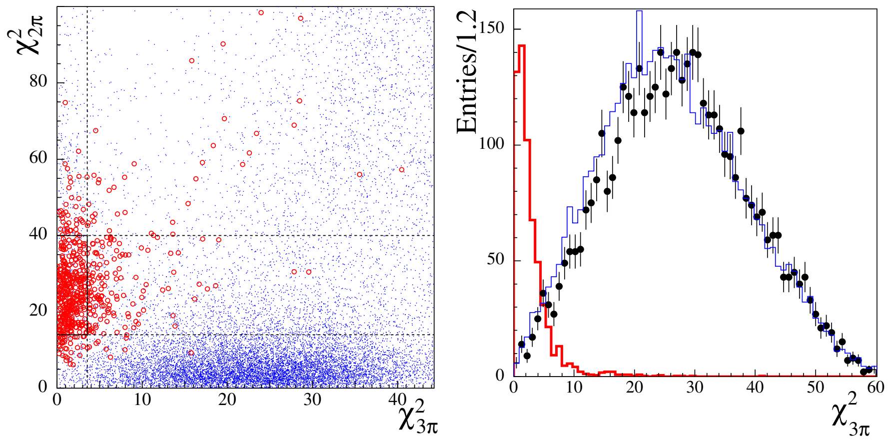

Figure 1: *Left: scatter plot $\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$ for selected candidate events; (blue) points and (red) open dots represent data and the simulated signal respectively. Right: distribution of $\chi^2_{3\pi}$ for events lying in the band $14 < \chi^2_{2\pi} < 40$; black dots, (blue) solid thinner line, and (red) solid thicker line represent data, MC background, and the MC signal respectively.*

we count 4 events for an expected background $N_b = 3 \pm 1.4 \pm 0.2$. Then, the number of observed $K_S \to \pi^0\pi^0\pi^0$ decays is below 5.8 at 90% CL. In the same tagged sample, we count 38.4×10^6 $K_S \to \pi^0\pi^0$ events used for normalization. We finally derive $BR(K_S \to \pi^0\pi^0\pi^0) \leq 2.1 \times 10^{-7}$ at 90 % CL, which improves by a factor of ~ 100 the present upper limit.[1]

3.2 BR($K_S \to \pi^{\pm} e^{\mp} \bar{\nu}(\nu)$)

Assuming CPT conservation and the $\Delta S = \Delta Q$ rule, the K_S and K_L partial widths for the K_{e3} decay must be equal[15], and the corresponding K_S branching ratio can be easily obtained from that of the K_L. The charge asymmetries of such K_S and K_L decays are related to CP and CPT violation parameters.

$K_S \to \pi e \nu$ events are selected, in the K_L-crash tagged sample, by requiring the presence of two oppositely charged tracks which form a vertex in the interaction region. Loose momentum and angular cuts are applied, and the vertex invariant mass, in the hypothesis that both tracks belong to pions, is

[1] after this conference was published the NA48 limit hep-ex/0408053

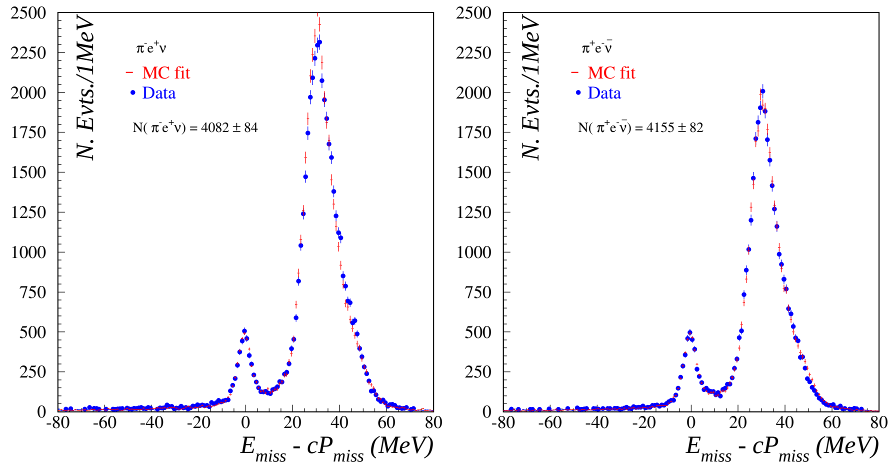

Figure 2: *$E_{miss} - cP_{miss}$ spectrum for $\pi^- e^+ \nu$ (left) and for $\pi^+ e^- \bar{\nu}$ (right) candidate events. Solid dots represent data from year-2001 data set; the crosses are the result of a fit varying the normalization of MC distributions for signal and background.*

required to be $< 490MeV$, thus rejecting 95% of the $K_S \to \pi^+\pi^-$ decays. Vertex reconstruction and preselection efficiencies are evaluated by MC.

The $K_S \to \pi e \nu$ decays are identified and the π/e assignement is made by means of the time of flight of the two tracks, which are both required to be associated to a calorimeter cluster. For each track the difference $\delta_t(m) = t_{cl} - L/\beta(m)$ is computed, where t_{cl} is the time of the associated cluster, L is the measured track length and $\beta(m)$ is the particle velocity obtained from the measured momentum with a mass hypotesis $m = m_e$ or $m = m_\pi$. In order to avoid any systematics related to the T_0 determination, the selection is made on the difference $\delta_{t,ab} = \delta_t(m_a)_1 - \delta_t(m_b)_2$, where mass hypothesis a (b) is used for track 1 (2). For the correct mass assignement we expect $\delta_{t,ab} \sim 0$, therefore we require $\delta t, \pi\pi > 1.7$ ns and $\delta t, \pi e(e\pi) < 1.4$ ns with $\delta t, e\pi(\pi e) > 3.2$ ns. The π/e identification efficiency is measured in a sample of $K_L \to \pi e \nu$ in which the K_L decays near the interaction region.

The track-to-cluster association efficiency is also measured in the same K_L decays sample, in a $K_S \to \pi^+\pi^-$ sample and in a $\phi \to \pi^+\pi^-\pi^0$ sample. In all such topologies the events are reconstructed independently on the presence of a calorimeter clusters associated to tracks.

In fig.2 it is shown the distribution of the selected events in $E_{miss} - P_{miss}$

(the neutrino energy and momentum, if the mass assignement is correct) for the two possible charge states (solid markers). Signal events are included in the peak around zero, while the residual $K_S \to \pi^+\pi^-$ background shows up in the positive region. The number of signal events in the distribution is obtained from a fit (shown with crosses) using the MC distributions for signal and background having as a free parameter their independent normalizations. The signal simulation includes an infrared-finite treatment of the radiative corrections.Three independent fits and efficiency evaluations are performed for the two charge states and the inclusive case. The branching rations are obtained by normalizing the fitted number of events to the number of $K_S \to \pi^+\pi^-$ events in the same data sets, thus cancelling the uncertainties coming from the integrated luminosity, the ϕ production cross section and the tagging efficiency. The preliminary KLOE results are then:

$$\begin{aligned} BR(K_S \to \pi^+ e^- \bar{\nu}) &= (3.54 \pm 0.05 \pm 0.04) \cdot 10^{-4} \\ BR(K_S \to \pi^- e^+ \nu) &= (3.54 \pm 0.05 \pm 0.05) \cdot 10^{-4} \\ BR(K_S \to \pi^\pm e^\mp \nu(\bar{\nu})) &= (7.09 \pm 0.07 \pm 0.08) \cdot 10^{-4} \end{aligned} \tag{1}$$

On the basis of such results it is possible to build the K_S semileptonic charge asimmetry $A_S = (\Gamma_S^+ - \Gamma_S^-)/(\Gamma_S^+ + \Gamma_S^-)$, where $\Gamma_S^{+(-)}$ are the partial decay widths of the K_S into $\pi^{+(-)}e^{-(+)}\nu$. If CPT invariance holds, A_S must be equal to the corresponding K_L asimmetry A_L[15]. KLOE has performed the first measurement of A_S ever done, obtaining the following result

$$A_S = (-2 \pm 9_{stat} \pm 6_{syst}) \cdot 10^{-3} \tag{2}$$

which is compatible with the present (more precise) A_L measurement [16].

3.2.1 V_{us} extraction

The most accurate test of the CKM matrix unitarity comes from its first row, for which we can define $1-\Delta = |V_{ud}|^2 + |V_{us}|^2$, where we expect $\Delta = 0$ at the level of 10^{-5}. V_{ud} is precisely determined from superallowed nuclear decays and the neutron lifetime[17], while the experimental accuracy on $|V_{us}|$ is the crucial issue to test Δ. K_S semileptonic decays are related to $|V_{us}|$ via

$$|V_{us}| \ \times f_+^{K^0\pi^-}(0) = \left[\frac{128\pi^3 BR(K_S \to \pi e \nu)}{\tau_S G_\mu^2 M_K^5 S_{\mathrm{ew}} I_K^e(\lambda_+, \lambda'_+)}\right]^{1/2} \frac{1}{1+\delta_{\mathrm{em}}^{Ke}}, \tag{3}$$

where $f_+^{K^0\pi^-}(0)$ is the vector form factor at zero momentum transfer and $I_K^e(\lambda_+, \lambda'_+)$ is the result of the phase space integration after factorizing out

$f_+^{K^0\pi^-}(0)$. λ_+ and λ'_+ are the slope and curvature of the vector form factor. The long-distance radiative corrections for both the form factor $f_+^{K^0\pi^-}$ and the phase space integral are included in the parameter[18] $\delta_{\rm em}^{Ke} = 0.55\pm0.10\%$. The short-distance electroweak corrections are included in the parameter[19] $S_{\rm ew} = 1.0232$. Using the recent KTeV measurement of the f_+ dependence on the momentum transfer [20] to evaluate the phase-space integral, and assuming the PDG value of τ_S we obtain:

$$|V_{us}| \times f_+^{K^0\pi^-}(0) = 0.2171 \pm 0.0017$$

in excellent agreement with the unitarity band $|V_{us}| \times f_+^{K^0\pi^-}(0) = 0.2171 \pm 0.0017$ which is obtained using[17] $|V_{ud}| = 0.9740\pm0.0005$ and [21] $f_+^{K^0\pi^-}(0) = 0.961 \pm 0.0028$.

4 Hadronic cross section

The recent measurements of a_μ by the E821 collaboration[22] has stimulated new interest in the measurement of the cross section of $e^+e^- \to hadrons$ at low energy. In fact, the hadronic contribution to a_μ at low energy cannot be computed, but is related to $\sigma(e^+e^- \to hadrons)$ via a dispersion integral. The process $e^+e^- \to \pi^+\pi^-$, with $M_{\pi\pi} < 1\,GeV$ accounts for about 70% of δa_μ^{had} and for 12% of the hadronic corrections to $\alpha(M_Z)$. The most recent measurement of such process has been perfomed by the CMD-2 experiment[23] via an energy scan with a total relative uncertainty of 0.9% . Using this measurement the SM prediction of a_μ is 2.7σ away from the E821 measurement. Moreover there is a significant disagreement with the a_μ value obtained using τ data after isospin rotation[24].

KLOE can measure $d\sigma(e^+e^- \to \pi^+\pi^-/ds_\pi$ (where s_π is the squared $\pi\pi$ invariant mass) by studying $e^+e^- \to \pi^+\pi^-\gamma$ events in which the photon is radiated in the initial state. This has the advantage that sistematic errors due to luminosity and beam energy enter into the measurement only once, and not for each point as in an energy scan, but on the other hand it requires theoretic understanding of ISR to better than 1% which is provided by the PHOKARA generator[25]. Events are selected requiring two oppositely charged tracks, with polar angle $40 < \theta < 140^\circ$ and forming a vertex near the interaction region. To enhance ISR, with respect to FSR and $\phi \to \pi^+\pi^-\pi^0$ background, only small angle photons are accepted. In

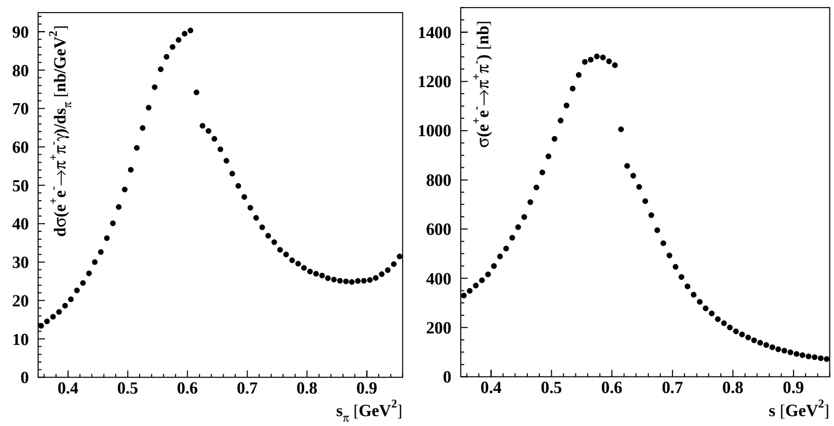

Figure 3: *Left: cross section for the process* $e^+e^- \to \pi^+\pi^-\gamma$*, inclusive in pion emission angles and with* $\sin\theta_\gamma < \sin 15^o$*, where* θ_γ *is the photon emission angle with respect to the beam axis. Right: bare cross section for* $e^+e^- \to \pi^+\pi^-$*.*

this region photons are not detected, but the $\pi^+\pi^-$ missing momentum is required to have polar angle $< 15°$ or $> 165°$. Moreover at least one of the two tracks has to be identified as a pion, on the basis of time of flight and shower shape in the calorimeter. Selection efficiency is $> 96\%$. KLOE data are shown in fig.3. They can be used to evaluate the $\pi\pi$ contribution to the hadronic correction to a_μ, which turns out to be:

$$a_\mu^{had-\pi\pi}(0.35 < s_\pi < 0.95\ \mathrm{GeV}^2) = (388.7 \pm 0.8_{\mathrm{stat}} \pm 3.5_{\mathrm{syst}} \pm 3.5_{\mathrm{th}}) \times 10^{-10}.$$

Integrating in the same region used by CMD-2, we get

$$a_\mu^{had-\pi\pi}(0.37 < s_\pi < 0.93\ \mathrm{GeV}^2) = (375.6 \pm 0.8_{\mathrm{stat}} \pm 4.8_{\mathrm{syst+th}}) \times 10^{-10}.$$

which is in good agreement with $(378.6 \pm 2.7_{\mathrm{stat}} \pm 2.3_{\mathrm{syst+th}}) \times 10^{-10}$ obtained by CMD-2 and confirms the discrepancy with what is obtained from the analysis of τ data.

5 Search for $\eta \to \gamma\gamma\gamma$

The ϕ meson radiative decays are studied in details at KLOE[8, 10, 9] and many analyses are being completed with the full statistics. Here we present only the search for the C violating decay $\eta \rightarrow \gamma\gamma\gamma$. The η is produced together with a monocromatic photon ($E_{rad} = 363MeV$) by a ϕ radiative decay, and then the final state we are searching for is formed by 4 photons. Its main background is due to the $e^+e^- \rightarrow \omega\gamma$ process in which $\omega \rightarrow \pi^0\gamma$, and also to 3 and 5-photons events in which misreconstructions or machine background mimic a 4-photon final state. Four photons with $E > 50MeV$ and $|cos\theta| < 0.91$ are required, and the minimum angle between two of them must be above $15°$ to reduce the 3γ background. A kinematic fit imposing energy and momentum conservation is then applied to each candidate to improve the energy resolution. Finally a veto on events in which any γ pair has the π^0 mass is applied. The signal selection efficiency evaluated by Monte Carlo is 20.3%. Signal is searched for as a peak in the maximum photon energy, which should appear around $363MeV$. The backgound level is evaluated from the data itself. No signal is observed. The ratio $BR(\eta \rightarrow 3\gamma)/BR(\eta \rightarrow 3\pi^0)$ is evaluated, thus cancelling systematic errors arising from the MC efficiency evaluation. Then, using the PDG value for $BR(\eta \rightarrow 3\pi^0)$ we get

$$BR(\eta \rightarrow \gamma\gamma\gamma) \; < \; 2.2 \, \times \, 10^{-5} \;\; 95\% \, C.L.$$

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