KLOE Results on Rare K^0 Decays

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Abstract

This paper describes the neutral Kaon dataset and physics measurements of KLOE at DAΦNE. A brief discussion on the prospects for detector upgrades and analysis of other K_S rare decays is also included.

K^0 DATASET

The KLOE detector is described in detail elsewhere [1]. The experiment has integrated a luminosity of 25/170/280 pb^{-1} in the years 2000/1/2, corresponding to 27/180/296 $\cdot 10^6$ produced $K_L K_S$ events. The highest instantaneous luminosity has been $8 \cdot 10^{31}$ cm^{-2} sec-1, while the highest daily luminosity has been 4.5 pb^{-1}.

BENCHMARK K^0 MEASUREMENTS

KLOE has started its K^0 physics program with benchmark measurements which have firmly established its capability in this field. Most analysis share these features:

- Request a K_L or K_S tag. The tagging efficiency is measured from data control samples (an ultimate 0.1% accuracy is expected for the full 0.5 fb^{-1} luminosity).
- Trigger efficiency is measured mainly from the data.
- $\sqrt{s}$, and e^+e^- interaction point (IP) are measured online run-by-run with Bhabha scattering events. Typical accuracies for 0.1 pb^{-1} runs are: $\sigma(\sqrt{s}) \sim 40$ keV, $\sigma(P_\Phi) \sim 30$ keV, $\sigma(X_{IP}) \sim \sigma(Y_{IP}) \sim 30$ μm.
- ϕ production time, T_ϕ, are reconstructed offline with accuracy $\sigma(T_\phi) \sim 50$ psec.
- Monte Carlo simulation (MC) are used mainly for acceptance and geometry corrections. The MC photon and track reconstruction efficiencies are properly scaled to data control samples.

An important measurement performed by KLOE is the ratio of the branching ratios (BR) of $K_S \to \pi\pi$ decays.

$K_S \to \pi\pi$ *Decays*

K_S decays are tagged via the reconstruction of K_L interactions in the EM calorimeter. The measurement of $\Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0)$ is a benchmark for the measurement of ϵ'/ ϵ via the double ratio method and it can shed light on the $\Delta I = 1/2$ suppression rule. It also gives information on the values of the strong phase shifts ($\delta_0 - \delta_2$) and the electromagnetic isospin breaking ($\gamma_0 - \gamma_2$). The KLOE result is fully inclusive of $\pi^+\pi^-\gamma$ final states, it has an unprecedented statistical accuracy of ~0.1% and is limited at present by the systematic uncertainty which is estimated primarily from the data. $\Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0) = 2.236 \pm 0.003$(stat) $\pm$ 0.015(syst) [2] (see Figure 1). The present 0.7% systematic error is expected to scale down to below 0.2% for 0.5 fb^{-1}. From this measurement we extract $\chi_0 - \chi_2$ = (48 $\pm$ 3)° ($\chi_I = \delta_I + \gamma_I$), which is to be compared to the estimate from the PDG widths of $\chi_0 - \chi_2$ = (56 $\pm$ 8)° [3]. Other estimates are: $\delta_0 - \delta_2$ = (45 $\pm$ 6)° [4] from chiral perturbation theory (χPT) and $\delta_0 - \delta_2$ = (47.7 $\pm$ 1.5)° [5] from $\pi\pi$ scattering.

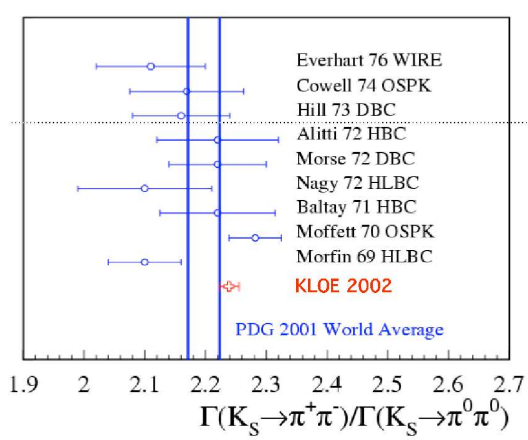

Figure 1: KLOE measurement performed with 17 pb^{-1} ($1.1 \cdot 10^6/0.8 \cdot 10^6$ tagged $K_S \to \pi^+\pi^-/K_S \to \pi^0\pi^0$) compared to previous results and to the PDG average.

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Invariant Mass and Lifetimes

KLOE has also performed preliminary measurements of the K_S invariant mass ($K_S \to \pi^+\pi^-$ channel) and of the K_L lifetime, reaching accuracies which are better or comparable to previous measurements (see figures 2 and 3).

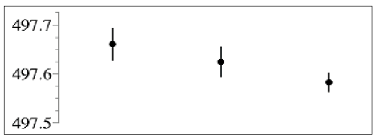

Figure 2: The K_S mass as measured by CMD-2 (left data point), NA48 (center) and KLOE (right, see [6]).

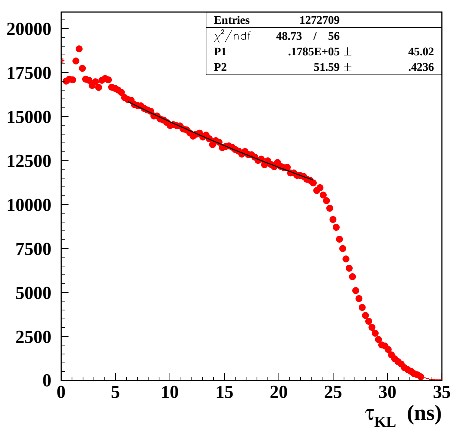

Figure 3: The KLOE $K_L \to 3\pi^0$ lifetime (statistical error only): (51.6 $\pm$ 0.4) nsec. PDG: (51.7 $\pm$ 0.4) nsec [7].

The $K_S \to \pi^+\pi^-$ lifetime has also been studied and found to be consistent with the PDG average (see fig. 4). The vertex resolution is ~1/3 of the decay length (~6 mm).

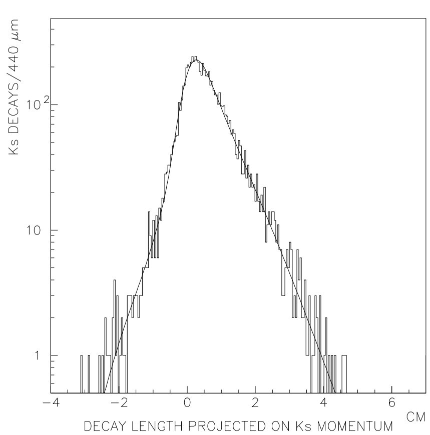

Figure 4: The $K_S \to \pi^+\pi^-$ decay length distribution [8].

BR($K_L \to \gamma\gamma$)

This BR has a large long-distance contribution via the pseudoscalar mesons (π^0, η, η'). It can be calculated in χPT and is sensitive to the pseudoscalar meson mixing angle, θ_P. Its value enters and dominates the long-distance contribution in $K_L \to \mu^+\mu^-$. The measurement reported here is based on 362 pb^{-1} and 1.6×10^8 K_L decays tagged by observing $K_S \to \pi^+\pi^-$ [9]. The large $K_L \to 3\pi^0$ background is suppressed by exploiting the 2-body kinematics, yielding 27375 estimated signal events (see figure 5). We measure the ratio $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$ = (2.79 $\pm$ 0.02 $\pm$ 0.02)$\times 10^{-3}$. The NA48 measurement is (2.81 $\pm$ 0.01 $\pm$ 0.02)$\times 10^{-3}$ [10]. Using the PDG value of BR($K_L \to 3\pi^0$), KLOE gets BR($K_L \to \gamma\gamma$) = (5.89 $\pm$ 0.07$_{stat \oplus syst}$ $\pm$ 0.08$_{BR(K_L \to 3\pi^0)}$)$\times 10^{-4}$. This value of the BR is in agreement with χPT, if θ_P is close to the KLOE measurement θ_P = (-12.9$^{+1.9}_{-1.6}$)$^\circ$ [11].

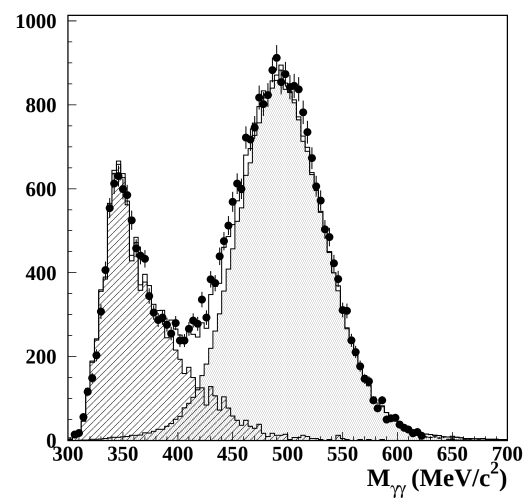

Figure 5: $\gamma\gamma$ invariant mass spectra: data (points) and Monte Carlo (histogram) used to measure BR($K_L \to \gamma\gamma$); signal is at the right peak.

BR($K_S \to \pi e \nu$)

K_S decays are tagged via reconstruction of K_L interactions in the EM calorimeter. The $K_S \to \pi^+\pi^-$ background, which is 10^3 times larger, is suppressed by exploiting the 3-body kinematics and the e/π discrimination based on time-of-flight measurement with the calorimeter. The remaining background (~5%) is given by $K_S \to \pi^+\pi^-$ with $\pi \to \mu\nu$ inside the drift chamber. The data is fit to the sum of signal and background MC shapes and normalized to the KLOE-measured BR($K_S \to \pi^+\pi^-$) to get the signal branching ratio. Using 170 pb^{-1} of 2001 data we report the preliminary measurement (which supersede our first published result obtained with 17 pb^{-1} [12]):

- BR($K_S \to \pi^\mp e^\pm \nu(\bar{\nu})$) = (6.81 $\pm$ 0.12 $\pm$ 0.10) $\cdot$ 10^{-4}

- BR($K_S \to \pi^- e^+ \nu$) = (3.46 ± 0.09 ± 0.06) · 10^{-4}
- BR($K_S \to \pi^+ e^- \bar{\nu}$) = (3.33 ± 0.08 ± 0.05) · 10^{-4}.

These results agree with the Standard Model expectations and improves significantly the previous CMD-2 measurement: (7.2 ± 1.4) · 10^{-4} [13]. Work is in progress to take into account the contribution of radiative K_S semileptonic decays, to employ an improved version of the MC. Figures 6 and 7 show preliminary estimates of the number of signal events in 0.5 fb^{-1}.

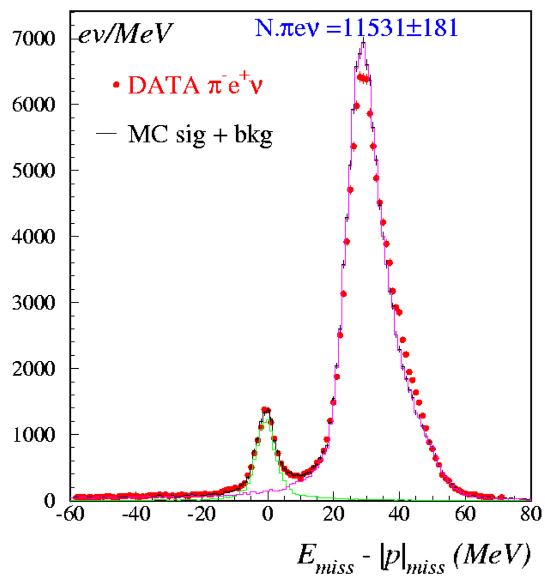

Figure 6: $K_S \to \pi^+ e^- \bar{\nu}$ signal (peak at 0) and background (mostly π decays in flight) in $\sim$ 0.5 fb^{-1}.

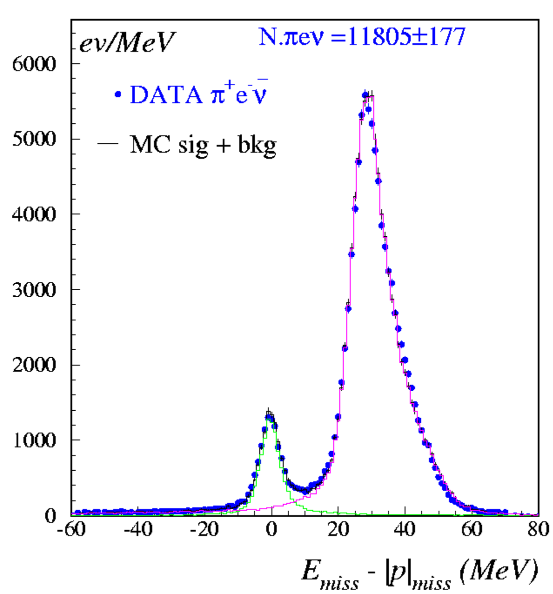

Figure 7: $K_S \to \pi^- e^+ \nu$ signal (peak at 0) and background (mostly π decays in flight) in $\sim$ 0.5 fb^{-1}.

K_S Charge Asymmetry and Test of CPT

The charge asymmetry of the K_S semileptonic decay, A_S, has been measured for the first time by KLOE. The preliminary result for 170 pb^{-1} is:

$$A_S = (19 \pm 17 \pm 6) \cdot 10^{-3}. \quad (1)$$

A non-zero difference between A_S and the K_L semileptonic asymmetry, A_L, would imply the violation of the CPT conservation law:

$$A_S - A_L = 4\ Re(\delta_K - D), \quad (2)$$

where: δ_K is the CPT violation in the K^0 mixing and D is a term containing the K^0 semileptonic decay amplitudes of the weak Hamiltonian, which violates both CPT and the $\Delta S = \Delta Q$ rule. The world-average value of A_L is (3.322 ± 0.055)·10^{-3}. For comparison: the CPLEAR measurement of CPT violation is [14] $Re(\delta_K)$ = (2.9 ± 2.7)·10^{-4} if $\Delta S = \Delta Q$ is assumed and $Re(\delta_K)$ = (3.0 ± 3.4)·10^{-4} if $\Delta S = \Delta Q$ is not assumed.

Test of $\Delta S = \Delta Q$ Rule

In the Standard Model the are no $\Delta S \neq \Delta Q$ transitions at the lowest order. Such transitions are described by the phenomenological parameters x ($\Delta S \neq \Delta Q$ in the $\bar{K}^0$ decay to e^+) and $\bar{x}$ ($\Delta S \neq \Delta Q$ in the K^0 decay to e^-), which contain the K^0 semileptonic amplitudes. The combination $x_+ = (x + \bar{x})/2$ describes the amount of $\Delta S \neq \Delta Q$ when CPT is conserved. x_+ can be expressed as:

$$\frac{BR(K_S \to \pi e \nu)/\tau_S}{BR(K_L \to \pi e \nu)/\tau_L} = \frac{\Gamma_S^{semil}}{\Gamma_L^{semil}} = 1 + 4\ Re(x_+). \quad (3)$$

The value measured by KLOE with 170 pb^{-1} of 2001 data is: $Re(x_+)$ = (3.3 ± 5.2 ± 3.5) · 10^{-3}, which is to be compared with $Re(x_+)$ = (−1.8±4.1±4.5)·10^{-3} (and $Im(x_+)$ = (1.2 ± 1.9 ± 0.9) · 10^{-3}) by CPLEAR [14]. An update of this meaasurement with 0.5 fb^{-1} will follow soon.

MEASUREMENT OF V_{US}

KLOE is giving a significant contribution to the measurement of the V_{us} CKM matrix element, which constrains the internal consistency of the Standard Model. The experimental inputs to extract V_{us} from the Kaon semileptonic decays are BRs and lifetimes. The theoretical inputs are the linear slopes of the $K_{\ell 3}$ form factors, $\lambda_\pm$, and the values of these form factors at zero 4-momentum transfer to the leptons, $f_\pm(0)$. The uncertainty on V_{us} for K_{e3} (for which f_- is negligible) depends on these inputs as:

$$\frac{\delta V_{us}}{V_{us}} = \frac{1}{2}\frac{\delta BR}{BR} \oplus \frac{1}{2}\frac{\delta \tau}{\tau} \oplus \frac{1}{20}\frac{\delta \lambda_+}{\lambda_+} \oplus \frac{\delta f_+(0)}{f_+(0)}. \quad (4)$$

In addition to the above mentioned K_S semileptonic BR, KLOE has also preliminary measurements of the K_L BRs in both the electron and muon channel, based on a statistics

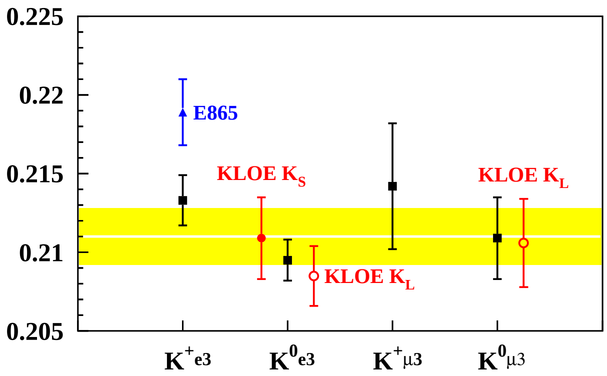

Figure 8: $V_{us} \cdot f_+(0)$ vs semileptonic Kaon decay mode from old (black points) and the recent E865 measurement. The KLOE preliminary results are also indicated.

of 78 pb^{-1}. Our measurements of $V_{us} \cdot f_+(0)$ are consistent with old K^0_{e3} and $K^0_{\mu 3}$ measurements and are lower than the recent E865 result [15], as shown in figure 8.

KLOE will have BR(K^+_{e3}) soon and plans on measuring BRs with $\ll$1% accuracy. KLOE can also improve the measurements of λ_+, λ_0, τ_L and τ_S.

CONCLUSIONS AND PROSPECTS

Current K^0 physics program is driven significantly by statistics (0.5 fb^{-1}) and, to a lesser extent, by the DAΦNE background level (which, however, has been constantly decreasing through the years). The MC has been vastly improved: (i) background events from data are injected into simulated events on a run-by-run basis; (ii) the detector/trigger response, materials and geometry have been refined, (iii) generators for radiative K^0 decays have been added. The new MC allows us to tackle the next K_S rare decays. For example, with 0.5 fb^{-1} we set the preliminary limit BR($K_S \to 3\pi^0$) $< 2.2 \cdot 10^{-7}$, 90% CL (5 events on a background of 3.1 $\pm$ 1.9), the best limit to date.

The results on BR($K_S \to \pi e \nu$), BR($K_L \to \gamma\gamma$) and BR($K_S \to 3\pi^0$) show that KLOE can measure rare decays. A factor 10 luminosity increase is needed to measure the next more rare K_S decays and ϵ'/ϵ.

In the prospect of a long term running of KLOE (and more than 5 fb^{-1} statistics) some detector upgrades are strongly advisable and beficial to the analysis.

- New and smaller KLOE-DAΦNE interaction region (IR). As a consequence, new and smaller EM calorimeters around the IR quadrupoles (QCAL) are necessary in order not to introduce large dead regions into the detector volume).

- With the new IR+QCAL there will be room for a new compact inner vertex detector inside the drift chamber (10 $<$ radius $<$ 25 cm), capable of measuring $also$ the longitudinal coordinate. This detectod will have the following features:
  - help the track pattern recognition at small radii where beam background is more severe;
  - improve vertexing at IP and interferometry for all-charged events, like $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$, $K_S K_L \to \pi^+\pi^-\pi e\nu$ and $K_S K_L \to \pi e\nu\pi e\nu$;
  - help the identification of Kaon interactions in the drift chamber inner wall (esp. Q-exchange);
  - the beam pipe at IP will be made of pure Beryllium, to ease complexity in offline event reconstruction; the current spherical geometry can be abandoned in favor of an easier machinable shape.

- The readout granularity of existing calorimeter will be increased by removing light guides and phototubes, to be replaced by smaller light-collections elements. This would improve the energy clustering algorithm and enhance particle ID (PID)

The specific choices for the new inner vertex detector and calorimeter readout devices are to be studied. It should be noted that in 2002 KLOE has completed its first successful detector upgrade: the drift chamber has been instrumented with ADCs to help PID by means of dE/dx, which is effective especially for charged Kaon physics.

KLOE expects to collect $\sim$ 2 fb^{-1} in the physics run starting in spring 2004, which should benefit from the upgrades performed by DAΦNE in 2003, which included a new IR with simplified optics.

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