

$|V_{us}|$ AND K_S DECAYS FROM KLOE

THE KLOE COLLABORATION^a
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Abstract

Recent results obtained by the KLOE experiment operating at DAΦNE, the Frascati ϕ -factory, are presented. They mainly concern neutral kaon decays including the K_L dominant branching ratios, the K_L lifetime and the extraction of the CKM parameter V_{us} from the K_L semileptonic decays and lifetime. The best world upper limit on $K_S \rightarrow \pi^0 \pi^0 \pi^0$ channel is also presented.

1 Introduction

The determination of $|V_{us}|$ and $|V_{ud}|$ provide the most precise test of CKM unitarity. In fact the first row unitarity requires $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ which, since $|V_{ub}|^2 \sim 10^{-5}$, is equivalent to $|V_{ud}|^2 + |V_{us}|^2 = 1$. The 2004 edition of Particle Data Group¹ gives $|V_{ud}| = 0.9738 \pm 0.0005$ and $|V_{us}| = 0.2200 \pm 0.0026$ from which the sum of the squares gives 0.9966 ± 0.0015 which deviates from unitarity by $\sim 2\sigma$. Semileptonic kaon decays are the cleanest

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way to obtain an accurate value of $|V_{us}|$. In fact, since $K \rightarrow \pi$ is a $0^- \rightarrow 0^-$ transition, only the vector part of the weak current has a non vanishing contribution and such processes are protected by the Ademollo-Gatto theorem against SU(3) breaking corrections to the lowest order in $m_s - m_d$.

In order to extract $|V_{us}|$ from semileptonic kaon decays we need to measure the branching fraction and the K_L lifetime. The most accurate determination of $|V_{us}|$ from K_L semileptonic decays comes from KTeV collaboration². The K_{e3} branching fraction is found to be 0.4067 ± 0.0011 , strikingly different from PDG fit value, 0.3881 ± 0.0027 . The KTeV result has been partially confirmed by the NA48 Collaboration³, 0.4010 ± 0.0045 , even if with an error ~ 4 times bigger.

The K_L lifetime value in the PDG relies on a single direct measurement $\tau_L = (51.54 \pm 0.44)$ ns that was performed more than 30 years ago⁴. K_L lifetime is, at present, the major experimental source of error in the determination of $|V_{us}|$.

KLOE has the unique possibility to measure simultaneously K_L absolute branching fractions and lifetime. The measurement of the K_L absolute branching is possible at the ϕ -factory since the production of $K_S K_L$ pairs in ϕ decays provides a tagged, monochromatic K_L beam of known flux. Moreover K_L have low momentum ($|\vec{p}_{K_L}| \sim 110$ MeV/c) and, therefore, a big fraction ($\sim 50\%$) of them decays inside the detector.

This is important since the statistical error on the lifetime depends on the number of events, $\propto 1/\sqrt{N}$ and, very strongly, on the time interval covered:

$$\frac{\delta\tau}{\tau}(\text{stat}) = \frac{\delta\Gamma}{\Gamma} = \frac{1}{\sqrt{N}} \times \left[\frac{-1 + e^{3T} + (e^T - e^{2T})(3 + T^2)}{(-1 + e^T)^3} \right]^{-0.5} \quad (1)$$

where $T = \delta t/\tau$ is the interval covered by the fit in lifetime units and N is the number of events in that interval. With $T \sim 0.4$ and $N \sim 9 \cdot 10^6$ (which is the KLOE case) a statistical error of $\sim 0.3\%$ can, in principle, be reached.

2 Experimental Setup

DAΦNE, the Frascati ϕ factory, is an e^+e^- collider working at $W \sim m_\phi \sim 1.02$ GeV with a design luminosity of $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. The ϕ mesons are produced, almost at rest, with a visible cross section of $\sim 3.2 \text{ } \mu\text{b}$ and decay into K^+K^- ($K_S K_L$) pairs with BR of $\sim 49\%$ ($\sim 34\%$). These pairs are produced in a pure $J^{PC} = 1^{--}$ quantum state, so that observation of a K_S (K^+) in an event signals (tags) the presence of a K_L (K^-) and vice-versa; highly pure and nearly monochromatic K_S, K_L, K^+ and K^- beams can thus be obtained. Neutral kaons get a momentum of ~ 110 MeV/c which translates in a slow speed, $\beta_K \sim 0.22$. K_S and K_L can therefore be distinguished by their mean decay lengths: $\lambda_S \sim 0.6$ cm and $\lambda_L \sim 340$ cm.

The KLOE detector consists of a drift chamber, DCH, surrounded by an electromagnetic calorimeter, EMC. The DCH⁵ is a cylinder of 4 m diameter and 3.3 m in length which constitutes a large fiducial volume for K_L decays ($1/2 \lambda_L$). The momentum resolution for tracks at large polar angle is $\sigma_p/p \leq 0.4\%$. The EMC is a lead-scintillating fiber calorimeter⁶ consisting of a barrel and two endcaps which cover 98% of the solid angle. The energy resolution is $\sigma_E/E \sim 5.7\%/\sqrt{E(\text{GeV})}$. The intrinsic time resolution is $\sigma_T = 54 \text{ ps}/\sqrt{E(\text{GeV})} \oplus 50 \text{ ps}$. A super-conducting coil surrounding the barrel provides a 0.52 T magnetic field.

During 2002 data taking, the maximum luminosity reached by DAΦNE was $7.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. Although this is lower than the design value, the performance of the machine was improving during the years and, at the end of 2002, we collected $\sim 4.5 \text{ pb}^{-1}/\text{day}$. The whole data sample in the years 2001-2002 amounts to 450 pb^{-1} , equivalent to 1.4 billion ϕ decays. The analyses presented here are based on $\sim 400 \text{ pb}^{-1}$ of integrated luminosity of the 2001 and 2002 runs.

Recently, the machine has been upgraded and KLOE has resumed its data taking in April 2004. Up to now (15th May, 2005) $\sim 1 \text{ fb}^{-1}$ have already been collected with a peak luminosity of $1.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. We foresee to reach $\sim 2 \text{ fb}^{-1}$ by the end of the year.

3 Measurement of the dominant K_L branching ratios

The K_L absolute branching fractions are determined on a tagged K_L events sample by counting the number of K_L decays in each channel, N_i , in the used fiducial volume and correcting for acceptance, reconstruction efficiency and tagging efficiency:

$$BR(K_L \rightarrow i) = \frac{N_i}{N_{tag}} \times \frac{1}{\epsilon_{rec}(i) \times \epsilon_{FV}(\tau_L) \times \epsilon_{tag}(i)/\epsilon_{tag}(all)} \quad (2)$$

where $i = \pi^0\pi^0\pi^0, \pi^\pm e^\mp\nu, \pi^\pm\mu^\mp\nu, \pi^+\pi^-\pi^0$, N_{tag} is the number of tagging events, ϵ_{rec} is the reconstruction efficiency ($\sim 45\%$ for $\pi^+\pi^-\pi^0$ events, $\sim 60\%$ for $\pi^\pm e^\mp\nu, \pi^\pm\mu^\mp\nu$ events and $\sim 100\%$ for $\pi^0\pi^0\pi^0$ events), $\epsilon_{FV}(\tau_L)$ is the fiducial volume geometrical acceptance which depends on the K_L lifetime and $\epsilon_{tag}(i)/\epsilon_{tag}(all)$ is the fractional variation of the tagging efficiency when the K_L decays in a given channel with respect to the average. We define this ratio *tag bias*.

3.1 The tag

The tag is provided by $K_S \rightarrow \pi^+\pi^-$ events selected requiring the presence of a vertex with two opposite curvature tracks within a cylinder of radius $r < 10$ cm and height $h < 20$ cm around the interaction point (IP). The two-tracks invariant mass, in the pions hypothesis, must be within 5 MeV around m_{K_S} . The magnitude of the total momentum of the two tracks must be within 10 MeV of the value expected from the value of \vec{p}_ϕ . The K_L momentum is obtained from the decay kinematics of $\phi \rightarrow K_SK_L$ using the K_S direction reconstructed from the measured momenta of $\pi^+\pi^-$ tracks and the known value of \vec{p}_ϕ .

The main source of tag bias is due to the dependence of the trigger efficiency on the K_L behaviour. The hardware calorimeter trigger which requires two local energy deposits above some thresholds (50 MeV on the barrel and 150 MeV on the end caps) is used for the present analysis. The trigger efficiency is essentially 100% for $\pi^0\pi^0\pi^0$, between 95 – 85% for charged decays. To reduce the tag bias due to trigger efficiency we require that the trigger conditions are satisfied by the pions from K_S . We further reinforce these conditions by requiring that the two pions impinge on the calorimeter barrel and produce two clusters with an energy $E \geq 80$ MeV each.

The *FV* used for the analysis is defined inside the drift chamber by $35 \text{ cm} < \sqrt{x^2 + y^2} < 150 \text{ cm}$ and $|z| < 120 \text{ cm}$, where (x, y, z) are the K_L decay vertex position coordinates. Since the K_L mean decay path length in KLOE is ~ 340 cm, the *FV* contains $\sim 26.1\%$ of the K_L decays. This choice minimize the difference in tag bias among the decay modes. The average tag bias is 0.985, 0.99 and 1.02 for $\pi^\pm e^\mp\nu$ or $\pi^\pm\mu^\mp\nu, \pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ decays respectively.

3.2 Charged K_L decays

The K_L in charged decay modes are selected by requiring the presence of two good tracks forming a vertex in the *FV* and not belonging to the K_S decay tree. A track is associated to the K_L if the point of closest approach to the K_L line of flight has a distance with respect to the K_L line of flight $d_c < a\sqrt{x^2 + y^2} + b$, with $a = 0.03$ and $b = 5$ cm.

The tracking efficiency has been determined by counting the number of events with at least one found K_L track and the number of events in which there are two opposite sign decay tracks. The tracking efficiency is also evaluated from Monte Carlo simulation and it is 60.5% for K_{e3} , 58.5% for $K_{\mu 3}$ and 43.0% for $\pi^+\pi^-\pi^0$. A correction to the tracking efficiency has been applied by comparing the results for data and Monte Carlo simulation. The correction is evaluated as a function of the track momentum using $K_L \rightarrow \pi^+\pi^-\pi^0$ and $K_L \rightarrow \pi^\pm e^\mp\nu$ events and ranges between 1.03 and 0.99 depending on the channel.

The variable to discriminate among the different charged decay modes is the lesser of the two values of $\Delta_{\pi\mu} = |\vec{p}_{miss}| - E_{miss}$, where \vec{p}_{miss} is the missing momentum and E_{miss} is the missing energy evaluated in the two mass assignments π^+, μ^- or π^-, μ^+ . An example of this distribution is shown in Fig. 1 where the different components are shown.

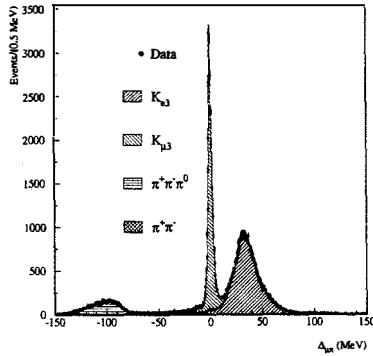


Figure 1: $\Delta_{\pi\mu}$ distribution for an event subsample. Dots are data, solid histograms are Monte Carlo.

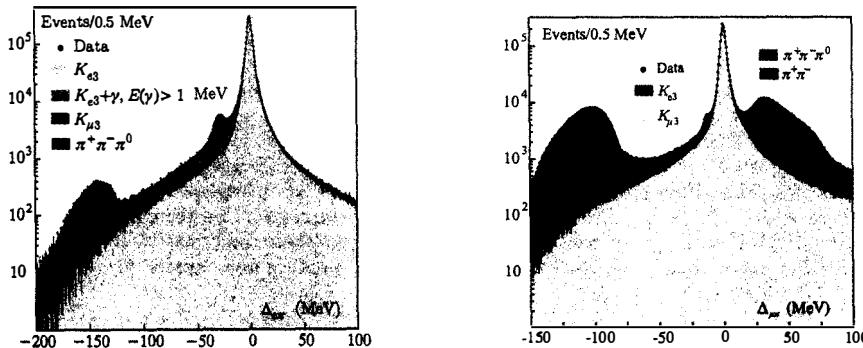


Figure 2: $\Delta_{\pi e}$ (left) and $\Delta_{\pi\mu}$ (right) distributions for data (dots) and Monte Carlo (solid histograms).

The $\Delta_{\pi\mu}$ distribution obtained with data is fitted with a linear combination of three Monte Carlo distributions (for $\pi^\pm e^\mp \nu$, $\pi^\pm \mu^\mp \nu$ and $\pi^+ \pi^- \pi^0$ events) by leaving free the relative weights. The contribution from the CP violating decay $K_L \rightarrow \pi^+ \pi^-$ and the $K_L \rightarrow \pi^0 \pi^0 \pi^0$ with Dalitz conversion is kept fixed in the fit and amounts to 0.3 %. In Fig. 2 we show enriched samples of K_{e3} (left) and $K_{\mu 3}$ (right) events obtained by selecting the e or μ by time of arrival and energy deposition in the calorimeter. The radiative corrections which affect mainly the K_{e3} decays have been properly taken into account in the Monte Carlo simulation⁷.

3.3 Neutral K_L decays

$K_L \rightarrow \pi^0 \pi^0 \pi^0$ decays are selected using time of flight techniques. In fact, the position of the K_L vertex for $K_L \rightarrow \pi^0 \pi^0 \pi^0$ decays is measured using the photon arrival times on the EMC. Each photon defines a time of flight triangle shown in Fig.3. The three sides are the K_L decay length, L_K ; the distance from the decay vertex to the calorimeter cluster centroid, L_γ ; and the distance from the cluster to the ϕ vertex, L . The equations to determine the unknowns L_K and L_γ are:

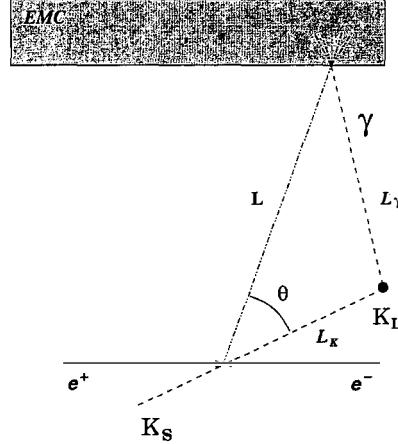


Figure 3: Left: the time of flight triangle.

$$\begin{aligned}
 L^2 + L_K^2 - 2LL_K \cos\theta &= L_\gamma^2 \\
 L_K/\beta_K + L_\gamma &= ct_\gamma
 \end{aligned} \tag{3}$$

where t_γ is the photon arrival time on the EMC, $\beta_K c$ is the K_L velocity and θ is the angle between \vec{L} and \vec{L}_K . Only one of the two solutions is kinematically correct. The K_L vertex position is obtained by the energy weighted average of each L_K measurement.

The accuracy of this method is checked with $K_L \rightarrow \pi^+\pi^-\pi^0$ decays, comparing the position of the K_L decay vertex from tracking using the $\pi^+\pi^-$ pair with the one from timing with the two photons from π^0 . The vertex reconstructed by the calorimeter has on average an offset of 2 mm almost uniform in the fiducial volume.

To select the $K_L \rightarrow \pi^0\pi^0\pi^0$ events we require at least three photons with energy greater than 20 MeV originating from the same vertex.

The main sources of inefficiencies are: 1) geometrical acceptance; 2) cluster energy threshold; 3) merging of clusters; 4) accidental association to a charged track; 5) Dalitz decay of one or more π^0 's. The effect of these inefficiencies is to modify the relative population for events with 3, 4, 5, 6, 7 and ≥ 8 , clusters with a loss of efficiency of $\sim 0.8\%$.

Background contamination affects only events with three and four clusters. The main source of background comes from $K_L \rightarrow \pi^+\pi^-\pi^0$ decays where one or two charged pions produce a cluster not associated to a track and neither track is associated to the K_L vertex. This background is rejected by requiring at least one cluster with at least 50 MeV energy and a polar angle satisfying $|\cos\theta| < 0.88$. Other sources of background are $K_L \rightarrow \pi^0\pi^0$ decays, possibly in coincidence with machine background particles (e^\pm or γ) that shower in the QCAL and generate soft neutral particles and $K_S \rightarrow \pi^0\pi^0$ following the $K_L \rightarrow K_S$ regeneration in the drift chamber material.

3.4 Results

A total of ~ 13 millions of tagged K_L are used to compute the branching fractions, almost ~ 40 millions to evaluate systematic uncertainties. Using the published result of the K_L lifetime ($\tau_L = 51.54 \pm 0.44$ ns)⁴ we obtain the following results:

| | $\pi^\pm e^\mp \nu$ | $\pi^\pm \mu^\mp \nu$ | $\pi^+ \pi^- \pi^0$ | $\pi^0 \pi^0 \pi^0$ |
|--------------|---------------------|-----------------------|---------------------|---------------------|
| Selection | 0.0011 | 0.0007 | 0.0004 | 0.0020 |
| Signal Shape | 0.0006 | 0.0009 | 0.0010 | - |
| Tag Bias | 0.0013 | 0.0008 | 0.0007 | 0.0005 |
| lifetime | 0.0023 | 0.0017 | 0.0007 | 0.0012 |

Table 1: Summary of systematic uncertainties on the absolute branching fractions measurements.

$$BR(K_L \rightarrow \pi^\pm e^\mp \nu) = 0.4049 \pm 0.0010_{\text{stat}} \pm 0.0031_{\text{syst}} \quad (4)$$

$$BR(K_L \rightarrow \pi^\pm \mu^\mp \nu) = 0.2726 \pm 0.0008_{\text{stat}} \pm 0.0022_{\text{syst}}$$

$$BR(K_L \rightarrow \pi^0 \pi^0 \pi^0) = 0.2018 \pm 0.0004_{\text{stat}} \pm 0.0026_{\text{syst}}$$

$$BR(K_L \rightarrow \pi^+ \pi^- \pi^0) = 0.1276 \pm 0.0006_{\text{stat}} \pm 0.0016_{\text{syst}} \quad (5)$$

where the sources of systematic uncertainties are shown in Table 1. The sum of all measured branching fraction above, plus the PDG value for rare decays, 0.0036, is $\sum BR_i = 1.0104 \pm 0.0018_{\text{correlated}} \pm 0.0074_{\text{uncorrelated}}$ where the correlated error includes all contributions to the uncertainties on the branching ratios that are 100% correlated between channels, such as the uncertainty in the value of the K_L lifetime. This result depends on the value of the K_L lifetime through the acceptance (Eq. 2). Turning the argument around, by normalizing the sum to 1 we obtain an indirect estimate of the K_L lifetime:

$$\tau(K_L) = (50.72 \pm 0.14_{\text{stat}} \pm 0.36_{\text{syst}}) \text{ns}$$

and a new set of values for the branching fractions:

$$BR(K_L \rightarrow \pi^\pm e^\mp \nu) = 0.4007 \pm 0.0006_{\text{stat}} \pm 0.0014_{\text{syst}} \quad (6)$$

$$BR(K_L \rightarrow \pi^\pm \mu^\mp \nu) = 0.2698 \pm 0.0006_{\text{stat}} \pm 0.0014_{\text{syst}}$$

$$BR(K_L \rightarrow \pi^0 \pi^0 \pi^0) = 0.1997 \pm 0.0005_{\text{stat}} \pm 0.0019_{\text{syst}}$$

$$BR(K_L \rightarrow \pi^+ \pi^- \pi^0) = 0.1263 \pm 0.0005_{\text{stat}} \pm 0.0011_{\text{syst}} \quad (7)$$

4 Direct measurement of the K_L lifetime

We have measured the K_L lifetime using $\sim 15 \times 10^6$ events of the fully neutral decay $K_L \rightarrow \pi^0 \pi^0 \pi^0$ tagged by $K_S \rightarrow \pi^+ \pi^-$ events. This choice is motivated by the fact that we want to maximize the number of tagged events to reduce the statistical error and, simultaneously, we want to avoid any coupling among tagging and tagged events in order to minimize the systematic uncertainty.

The $K_L \rightarrow \pi^0 \pi^0 \pi^0$ sample selected for the BR measurement has been used also for the K_L lifetime measurement plus some additional cuts.

For lifetime measurement we must keep under control the variation of the selection efficiency with L_K . Monte Carlo simulation shows that the selection efficiency has a linear dependence with L_K , $\epsilon(L_K) = (0.9921 \pm 0.002) - (1.9 \pm 0.2) \cdot 10^{-5} \cdot L_K(\text{cm})$ mainly due to the vertex reconstruction efficiency. The vertex reconstruction efficiency as a function of L_K has been checked also using $K_L \rightarrow \pi^+ \pi^- \pi^0$ events both in data and in Monte Carlo simulation. We find the same linear dependence as in the $K_L \rightarrow \pi^0 \pi^0 \pi^0$ case with slopes compatibles within their statistical uncertainties.

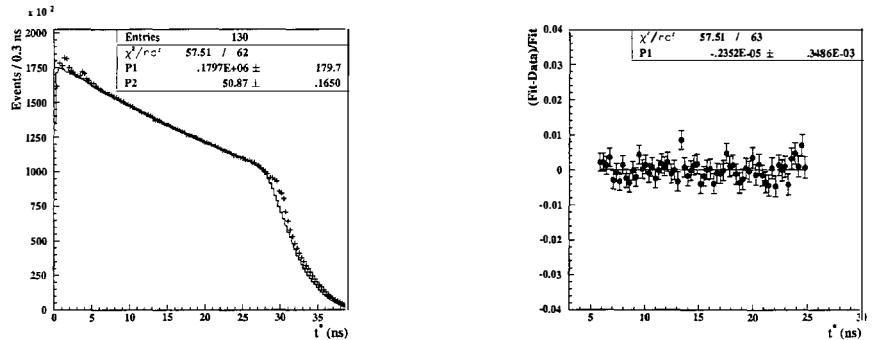


Table 2: Left: fit of the proper time distribution. Right: residuals of the fit.

The K_L lifetime is measured using events with a vertex reconstructed in the region $40 \text{ cm} < L_K < 165 \text{ cm}$ and with a flight direction defined by a polar angle θ with respect to the beam axis between $40^\circ < \theta < 140^\circ$. These two conditions define the fiducial volume.

The K_L proper time, t^* , is obtained event by event dividing the decay length L_K by $\beta\gamma$ of the K_L in the laboratory, $t^* = L_K/(\beta\gamma c)$. The residual background is subtracted bin by bin using Monte Carlo predictions.

The variations of the vertex reconstruction efficiency as a function of the decay length are taken into account by correcting bin by bin the decay vertex distribution with the efficiency values obtained with the $K_L \rightarrow \pi^0\pi^0\pi^0$ Monte Carlo sample multiplied by the data - Monte Carlo ratio of the efficiencies evaluated with $\pi^+\pi^-\pi^0$ sample.

The statistical uncertainty of the efficiency values ($\sim 0.1\%$) has been taken into account by adding it in quadrature to the statistical fluctuation of the entries in each bin of the t^* distribution after the background subtraction.

The distribution is fitted with an exponential function inside the fiducial volume, which, in terms of proper time ranges from 6 ns to 24.8 ns. This corresponds to a time interval $T \sim 0.37$ expressed in lifetime units. With $\sim 8.5 \cdot 10^6$ events inside the fit region we obtain $\tau = (50.87 \pm 0.17_{\text{stat}})$ ns with a $\chi^2 = 58$ for 62 degrees of freedom. The major sources of systematic uncertainties come from the background evaluation, tagging and selection efficiency and from the estimate of the K_L nuclear interactions in the drift chamber material. The total systematic error is $\sim 0.5\%$. Our result is:

$$\tau(K_L) = (50.87 \pm 0.17_{\text{stat}} \pm 0.25_{\text{syst}}) \text{ ns}$$

It is compatible at 1.3σ level with the other measurement⁴ and only at 1.7σ level with the PDG 2004 fit¹.

5 Determination of $|V_{us}|$

$|V_{us}|$ is proportional to the square root of the semileptonic BR of K mesons. For $K_L^{\pm 3}$ decays we can write⁸:

$$|V_{us}| \times f_+^{K^0\pi}(0) = \left[\frac{128\pi^3 BR(K_L \rightarrow \pi e \nu)}{\tau_L G_\mu^2 M^5 S_{ew} I_K^e(\lambda_+, \lambda'_+)} \right]^{1/2} \times \frac{1}{1 + \delta_{\text{em}}^{K^0}} \quad (8)$$

where $f_+^{K^0}(0)$ is the vector form factor at zero momentum transfer and $I_i(\lambda_+, \lambda'_+)$ is the integral of the phase space density, factoring out $f_+^{K^0\pi}$ and without radiative corrections. Radiative corrections at large scale of form factor and phase space density are contained in

the term $\delta_{em}^{K\pi} = (0.55 \pm 0.10)\%$ ^{9,10}. The short-distance electroweak corrections are included in the parameter S_{ew} . λ_+ and λ'_+ are the slope and curvature of the vector form factor $f_+^{K^0\pi}(0)$. From eq. 8 we see that the lifetime value enters directly in the determination of the product $|V_{us}| \times f_+^{K^0\pi}(0)$. The three most recent results are:

$$\begin{aligned} BR(K_L \rightarrow \pi^\pm e^\mp \nu) &= (40.67 \pm 0.11)\% \text{ KTeV} \\ BR(K_L \rightarrow \pi^\pm e^\mp \nu) &= (40.10 \pm 0.45)\% \text{ NA48} \\ BR(K_L \rightarrow \pi^\pm e^\mp \nu) &= (40.07 \pm 0.15)\% \text{ KLOE} \end{aligned}$$

where the error is the sum in quadrature of the statistical and systematic uncertainties. Fig. 4 (left) shows the product $|V_{us}| \times f_+^{K^0\pi}(0)$ extracted from the three recent measurements of $BR(K_L \rightarrow \pi^\pm e^\mp \nu)$ using the PDG 2004 average $\tau = (51.50 \pm 0.40)$ ns.

In the extraction of V_{us} we use the values of λ_+ and λ'_+ obtained by KTeV experiment from a quadratic fit¹¹. In the same plot we show also the value of $|V_{us}| \times f_+^{K^0\pi}(0)$ obtained from the KLOE preliminary measurement¹² of $BR(K_S \rightarrow \pi^\pm e^\mp \nu) = (7.09 \pm 0.07_{stat} \pm 0.08_{syst}) \cdot 10^{-4}$ and the $\pm 1\sigma$ band from the $|V_{ud}|$ and unitarity where we use $f_+^{K^0\pi}(0) = 0.961 \pm 0.008$ following Ref. ¹³. Fig. 4 (right) shows the same product extracted using the KLOE K_L lifetime value, $\tau_L = (50.87 \pm 0.17 \pm 0.25)$ ns. The K_L data are now in better agreement with K_S ones and unitarity.

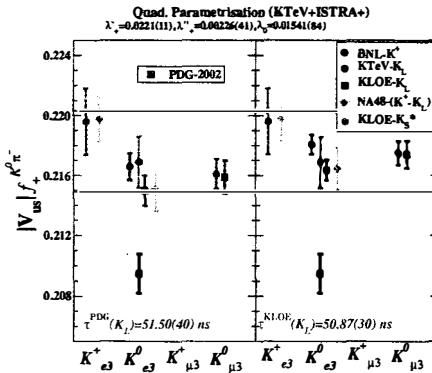


Figure 4: $|V_{us}| \times f_+^{K^0\pi}(0)$ for various K semileptonic decays.

6 Direct search of $K_S \rightarrow \pi^0 \pi^0 \pi^0$ decay

The decay $K_S \rightarrow 3\pi^0$ is a pure CP violating process. The related CP violation parameter η_{000} is defined as the ratio of K_S to K_L decay amplitudes: $\eta_{000} = A(K_S \rightarrow 3\pi^0)/A(K_L \rightarrow 3\pi^0) = \varepsilon + \varepsilon'_{000}$ 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} ($|\eta_{00}| \sim 2 \times 10^{-3}$). The expected branching ratio of this decay is therefore $\sim 2 \times 10^{-9}$, making its direct observation really challenging. The best upper limit on the BR (i.e. on $|\eta_{000}|^2$) has been set to 1.4×10^{-5} by SND¹⁴ where, similarly 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 $\eta_{000} \Re \eta_{000} \cos(\Delta mt) - \Im \eta_{000} \sin(\Delta mt)$. The best published result using this method comes from the NA48 Collaboration¹⁵. Fitting the $K_S - K_L \rightarrow \pi^0 \pi^0 \pi^0$ interference pattern at small decay times, they find $\Re \eta_{000} = -0.002 \pm 0.011_{stat} \pm 0.015_{syst}$ and $\Im \eta_{000} = -0.003 \pm 0.013_{stat} \pm 0.017_{syst}$ corresponding to $BR(K_S \rightarrow 3\pi^0 \pi^0 \pi^0) \leq 7.4 \times 10^{-7}$ at 90% C.L.

The signal selection requires a K_L interacting with the calorimeter and six neutral clusters coming from the interaction point (IP). A first rejection of the huge background coming from the decay $K_S \rightarrow \pi^0 \pi^0 + 2 \text{ fake } \gamma$ is obtained by applying a kinematic fit imposing as

constraints the K_S mass, the K_L 4-momentum and $\beta = 1$ for each photon. Two pseudo- χ^2 variables are then built: $\chi^2_{3\pi^0}$ which is based on the best 6γ combination into $\pi^0\pi^0\pi^0$ and $\chi^2_{2\pi^0}$ which selects four out of six photons providing the best kinematic agreement with the $K_S \rightarrow \pi^0\pi^0$ decay. A signal box is defined in the $\chi^2_{2\pi^0}$ vs $\chi^2_{3\pi^0}$ plane by optimising the upper limit in the Monte Carlo sample. Residual background comes from $K_S \rightarrow \pi^+\pi^-$, $K_L \rightarrow 3\pi^0$ events in which one of the two pions interacting with the quadrupoles produces a late cluster simulating a K_L -crash. This background is rejected by vetoing events with two charged tracks from IP.

At the analysis end we find 2 events in the signal box with an estimated background of $B = 3.13 \pm 0.82_{\text{stat}} \pm 0.37_{\text{syst}}$. To derive the upper limit on the number of signal counts, we build the background probability distribution function, taking into account our finite MC statistics and the uncertainties on the MC calibration factors. This function is folded with a Gaussian of width equivalent to the entire systematic uncertainty on the background. Using the Neyman construction¹⁶ we limit the number of $K_S \rightarrow \pi^0\pi^0\pi^0$ decays observed to 3.45 at 90% C. L. with a total reconstruction efficiency of $(24.36 \pm 0.11_{\text{stat}} \pm 0.57_{\text{syst}})\%$. In the same tagged sample, we count $3.78 \times 10^7 K_S \rightarrow \pi^0\pi^0$ events. We use them as normalization. Finally, using the value $BR(K_S \rightarrow \pi^0\pi^0) = 0.3105 \pm 0.0014$ ¹ we obtain $BR(K_S \rightarrow \pi^0\pi^0\pi^0) \leq 1.2 \times 10^{-7}$ at 90 % C.L. which represents an improvement by a factor ~ 6 with respect to the best previous limit⁷.

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