KLOE results on kaon decays and summary status of $V_{us}$

T. Spadaro

Laboratori Nazionali di Frascati dell’INFN
Via E. Fermi, 40 00044 Frascati (Roma) Italia

Recent KLOE measurements allowing the extraction of the $V_{us}$ element of the CKM matrix are here briefly described. The status of the resulting value of $V_{us}$ is summarized. The perspectives for the completion of ongoing analyses are discussed, with particular emphasis on the measurements of scalar form factor slopes from study of $K_{L,\mu3}$ and of $V_{us}$ from the decay width of $K_{L}^{0}$.

I. $V_{us}$ EXTRACTION FROM SEMILEPTONIC KAON DECAYS

The most precise test of the unitarity of the CKM matrix can be performed from its first row. Letting $\Delta = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$, an accuracy of few parts in $10^{-4}$ on $\Delta$ can be reached. The contribution of $|V_{ub}|^2$ is negligible [1]; the determination of $V_{ud}$ from super-allowed beta decays gives an uncertainty of $5 \times 10^{-4}$ on $\Delta$ (see Hardy’s contribution in this volume), and a similar accuracy can be reached by extracting $|V_{us}|$ from the rates $\Gamma$ for semileptonic kaon decays:

$$\Gamma_i(K_{\ell3(\gamma),\mu3(\gamma)}) = |V_{us}|^2 \frac{G^2 F^2 M^5}{128\pi^3} S_{\text{EW}} |f^0_{K_i}(0)|^2,$$

where $i$ indexes $K_0^0 \rightarrow \pi^-$ and $K^+ \rightarrow \pi^0$ transitions for which $C_i^2 = 1$ and 1/2, respectively, $G$ is the Fermi constant, $M$ is the appropriate kaon mass, and $S_{\text{EW}}$ is a universal short-distance electroweak correction [2]. The $\delta^i$ term accounts for long-distance radiative corrections depending on the meson charges and lepton masses and, for $K^\pm$, for isospin-breaking effects. These corrections are presently known at the few-per-mil level [3]. The $f^0_{K_i}(0)$ form factor parametrizes the vector-current transition $K^0 \rightarrow \pi^-$ at zero momentum transfer $t$, while the dependence of vector and scalar form factors on $t$ enters into the determination of the integrals $I_{\ell3,\mu3}$ of the Dalitz-plot density over the physical region. Since $f_+, f_0$ are dominated by the vector $K \pi$ resonances, the closest being the $K^+(892)$, the natural form for its dependence on $t$ is:

$$f_+(t) \propto \frac{M^2}{M_\nu^2 - t^2},$$

but it is also customary to expand the form factor in powers of $t$ up to first or second orders, as

$$f_+(t) \propto 1 + \lambda_\pi \frac{t}{m_\pi^2} \text{ or } 1 + \lambda_\pi' \frac{t}{m_\pi^2} + \lambda_\pi'' \frac{t^2}{2 m_\pi^2}.$$

For the scalar form factor a linear parametrization is typically used:

$$f_0(t) \propto 1 + \lambda_0 \frac{t}{m_{\pi^+}^2}.$$  (3)

The difference of $f_+(0)$ from unity reflects $SU(3)$- and $SU(2)$-breaking corrections and is evaluated from purely theoretical calculations. The reader can refer to Sachrajda’s and Portolés’s contributions in this volume for recent updates, while we will use the old Leutwyler and Roos evaluation,

$$f_+(0) = 0.961(8),$$

in the following. The experimental inputs in the above formulae are the semileptonic decay widths, evaluated from the $\gamma$-inclusive BR’s and from the lifetimes, and the parameters describing the $t$-dependence of the vector and scalar form factors. Results from KLOE measurements of all these inputs are reported in the following.

II. EXPERIMENTAL SETUP

DAΦNE, the Frascati $\phi$ factory, is an $e^+e^-$ collider working at $\sqrt{s} \sim m_\phi \sim 1.02$ GeV, $\phi$ mesons are produced, essentially at rest, with a visible cross section of $\sim 3.1 \mu b$ and decay into $K_S K_L$ ($K^+ K^-$) pairs with a BR of $\sim 34\%$ ($\sim 49\%$). Kaons get a momentum of $\sim 100$ MeV/c which translates into a low speed, $\beta_K \sim 0.2$. $K_S$ and $K_L$ can therefore be distinguished by their mean decay lengths: $\lambda_S \sim 0.6$ cm and $\lambda_L \sim 340$ cm. $K^+$ and $K^-$ decay with a mean length of $\lambda_\pm \sim 90$ cm and can be distinguished from their decays in flight to one of the two-body final states $\mu\nu$ or $\pi\pi^0$.

The kaon pairs from $\phi$ decay are produced in a pure $J^{PC} = 1^{--}$ quantum state, so that observation of a $K_S$ ($K^+$) in an event signals, or tags, the presence of a $K_L$ ($K^-$) and vice versa; highly pure and nearly monochromatic $K_S$, $K_L$, and $K^\pm$ beams can thus be obtained and exploited to achieve high precision in the measurement of absolute BR’s.

The analysis of kaon decays is performed with the KLOE detector, consisting essentially of a drift chamber, DCH, surrounded by an electromagnetic calorimeter, EMC. A superconducting coil provides a 0.52 T mag-

*Electronic address: tommaso.spadaro@lnf.infn.it
netic field. The DCH is a cylinder of 4 m in diameter and 3.3 m in length, which constitutes a fiducial volume for $K_L$ and $K^\pm$ decays extending for $\sim 0.4 \Delta L$ and $\sim 1 \Delta L$, respectively. The momentum resolution for tracks at large polar angle is $\sigma_p/\rho \leq 0.4\%$. The invariant mass reconstructed from the momenta of the two pion tracks of a $K_S \to \pi^+\pi^-$ decay peaks around $m_K$ with a resolution of $\sim 800$ keV, thus allowing clean $K_L$ tagging. The c.m. momenta reconstructed from identification of 1-prong $K^\pm \to \mu\nu$, $\pi^0\pi^0$ decay vertices in the DC peak around the expected values with a resolution of 1–1.5 MeV, thus allowing clean and efficient $K^\mp$ tagging.

The EMC is a lead/scintillating-fiber sampling calorimeter consisting of a barrel and two endcaps, with good energy resolution, $\sigma_E/E \sim 5.7\% \sqrt{E(\text{GeV})}$, and excellent time resolution, $\sigma_T = 54 \text{ps} \sqrt{E(\text{GeV})} \pm 50 \text{ps}$. About 50% of the $K_L$'s produced reach the EMC, where most interact. A signature of these interactions is the presence of an high-energy cluster not connected to any charged track, with a time corresponding to a low velocity: the resolution on $\beta_0$ corresponds to a resolution of $\sim 1$ MeV on the $K_L$ momentum. This allows clean $K_S$ tagging. The timing capabilities of the EMC are also exploited to precisely reconstruct the position of decay vertices of $K_L$ and $K^\pm$ to $\pi^0$'s from the cluster times of the emitted photons, thus allowing precise measurements of the $K_L$ and $K^\pm$ lifetimes.

In early 2006, the KLOE experiment completed data taking, having collected $\sim 2.5 \text{ fb}^{-1}$ of integrated luminosity at the $\phi$ peak, corresponding to $\sim 2.5$ (3.6) billion $K_SK_L$ ($K^+K^-$) pairs. The results presented here are based on the first 400 pb$^{-1}$ collected and are based on analyses published in 2006.

III. $V_{us}$ FROM SEMILEPTONIC $K_L$ DECAYS

A. Measurements of $K_{Le3}$ and $K_{Lu3}$ BR's

The analysis of $K_L$ decays starts with the identification of $K_S \to \pi^+\pi^-$ decays, which gives a pure $K_L$ "beam" of known momentum and direction. In a fiducial volume extending for $\sim 0.4 \Delta L$, two-track decay vertices are selected around the $K_L$ line of flight and the number of events for each of the decay modes $K_L \to \pi\nu\nu$, $\pi\mu\nu$, and $\pi^+\pi^-\pi^0$ are obtained from the distribution of the difference $E_{\text{miss}} - P_{\text{miss}}$ of missing momentum and missing energy in the hypotheses of pion and muon daughter particles. Photon vertices from $K_L \to 3\pi^0$ decays are reconstructed on the $K_L$ line of flight from the times of at least 3 photon clusters. Since the geometrical acceptance of these selections depends on the value of the $K_L$ lifetime, the output values of the BR's are expressed as a function of $\tau_L$:

$$\begin{align*}
\text{BR}(K_L \to \pi\nu\nu) &= \frac{40.49 (10)_{\text{stat}} (18)_{\text{sys}} \%}{1 + k \Delta \tau} \quad (5) \\
\text{BR}(K_L \to \pi\mu\nu) &= \frac{27.26 (9)_{\text{stat}} (14)_{\text{sys}} \%}{1 + k \Delta \tau} \quad (6) \\
\text{BR}(K_L \to \pi^0\pi^0\pi^0) &= \frac{20.18 (5)_{\text{stat}} (23)_{\text{sys}} \%}{1 + k \Delta \tau} \quad (7) \\
\text{BR}(K_L \to \pi^+\pi^-\pi^0) &= \frac{12.76 (6)_{\text{stat}} (14)_{\text{sys}} \%}{1 + k \Delta \tau} \quad (8)
\end{align*}$$

where $\Delta \tau = 51.7 \text{ ns} - \tau_L$, $k = 0.0128 \text{ ns}^{-1}$, and the uncertainties on the above results are correlated with the following coefficients:

$$\begin{pmatrix}
1 & 0.09 & 0.07 & 0.49 \\
1 & -0.03 & 0.27 \\
1 & 0.07 \\
1 &
\end{pmatrix}$$

The above inputs are to be used for the evaluation of world-average $K_L$ BR's. Imposing the unitarity of the above ratios, $\sum_i \text{BR}_i = 1 - \text{BR}(K_L \to \pi\pi) - \text{BR}(K_L \to \gamma\gamma) = 1 - 0.36\%$, we can extract both the four main BR's and $\tau_L$. This calculation is handled by performing a fit to the above measurements, together with the direct KLOE measurement of $\tau_L$ from the $K_L \to \pi^0\pi^0\pi^0$ decay distribution, $\tau_L = 50.92 [17]_{\text{stat}} (25)_{\text{sys}} \text{ ns}$. The results are

$$\begin{align*}
\text{BR}(K_L \to \pi\nu\nu) &= 40.08 (6)_{\text{stat}} (14)_{\text{sys}} \% \quad (10) \\
\text{BR}(K_L \to \pi\mu\nu) &= 26.99 (6)_{\text{stat}} (13)_{\text{sys}} \% \quad (11) \\
\text{BR}(K_L \to \pi^0\pi^0\pi^0) &= 19.96 (5)_{\text{stat}} (19)_{\text{sys}} \% \quad (12) \\
\text{BR}(K_L \to \pi^+\pi^-\pi^0) &= 12.61 (5)_{\text{stat}} (10)_{\text{sys}} \% \quad (13) \\
\tau_L &= 50.84 [14]_{\text{stat}} (18)_{\text{sys}} \text{ ns}, \quad (14)
\end{align*}$$

with correlation matrix

$$\begin{pmatrix}
1 & -0.31 & -0.55 & -0.01 & 0.16 \\
1 & -0.41 & -0.14 & 0.22 \\
1 & -0.47 & -0.14 \\
1 & -0.26 \\
1 &
\end{pmatrix}$$

B. $K_L$ form factor slopes

From the sample of charged $K_L$ decays, additional loose cuts on kinematics and improved particle identification from the time of flight (TOF) of daughter particles (evaluated from connected EMC clusters) allow the selection of a high-purity $2 \times 10^6$ event sample of $K_L \to \pi^\pm e^\mp \nu(\bar{\nu})$ decays. Within this sample, the probability of misidentifying an electron as a pion is negligible, so that the momentum transfer $t$ can be safely evaluated from the $K_L$ momentum and from the momenta of the daughter tracks. The vector form factor slopes are extracted through binned log-likelihood fits of $t$ distributions to the parametrizations of Eqs. [1] and [2]. The results
Part of a document containing scientific text discussing K_{L\pi} decays and the application of a PID technique. The text is too long to summarize accurately here, but it pertains to experimental data and analysis techniques in particle physics.
the \( t \)-distribution yields the first measurement ever made of the vector form factor slope \( \lambda_+ \) for \( K_{S3} \):
\[
\lambda_+ = (33.9 \pm 4.1) \times 10^{-3}.
\] (27)

Using the much more precise determination of the slopes from \( K_{L3} \) decays and the precise average value of \( \tau_S \) from the PDG \[1\], our value for BR\((K_S \to \pi e\nu)\) gives \( f_+ \times |V_{us}| = 0.2154(14) \), i.e., with an accuracy of 0.67%. This determination is unique to KLOE.

The event sensitivity at KLOE to \( K_{\mu3} \) decays is lower than that for \( K_{S3} \). The reasons are similar to those presented for the analysis of the \( K_{L3} \) form factor slopes. In addition, in this case the background is dominated by events having the same particles as the signal: in \( K_S \to \pi^{+}\pi^{-} \) decays, a \( \pi \) may decay to \( \mu \nu \beta \) before entering the DCH. The BR for \( K_{S\mu3} \) decay has never been measured before. The analysis is in progress and a total accuracy of 3% on the BR should be obtained after the entire data set is analyzed.

V. \( V_{us} \) FROM SEMILEPTONIC \( K^+ \) DECAYS

A. Measurements of \( K_{\mu3,\mu3}^\pm \) BR’s

The analysis of \( K^\pm \) decays starts with the identification of \( K^\pm \) decays to \( \mu^\pm \nu (\bar{\nu}) \) or \( \pi^\pm \pi^0 \) final states, which gives a pure sample of \( K^\pm \)-tagged events. One-prong decay vertices of \( K^\pm \) are then selected in the DCH and the photons coming from \( \pi^0 \) decay are identified from TOF using the associated clusters in the EMC. In order to reject the background for \( K_{\mu3,\mu3}^\pm \) identification, which is dominated by \( \pi^+\pi^- \) and \( \pi^0 \) decays, the lepton TOF is evaluated exploiting the time of the cluster connected to the \( K^+ \) daughter track. The number of events for each of the \( K^+ \to \pi^+ \nu (\bar{\nu}) \) and \( \pi^+ \nu (\bar{\nu}) \) decay modes are obtained from the distribution of the squared lepton mass evaluated from TOF. By normalizing to the number of tagged events and correcting for the selection efficiency, we obtain the following preliminary results \[16\]:
\[
\text{BR}(K^+ \to e^+ \pi^0 \nu (\bar{\nu})) = 5.047(39)_{\text{stat}}(81)_{\text{syst}} \% \quad (28)
\]
\[
\text{BR}(K^+ \to \mu^+ \pi^0 \nu (\bar{\nu})) = 3.310(45)_{\text{stat}}(65)_{\text{syst}} \% \quad (29)
\]
\[
\rho(\text{BR}(K_{\mu3}^+), \text{BR}(K_{\mu3}^-)) = 0.42. \quad (30)
\]

B. Measurements of \( K^\pm \) lifetime

The experimental status of \( \tau_+ \) is unclear: the PDG quotes an average of \( \tau_+ = 12.385(25) \) ns \[1\] with a relative accuracy of 0.2% and a confidence level of 0.2%. At KLOE there are two methods to perform a direct measurement of \( \tau_+ \) from the distribution of the proper decay times \( t^* \). One can obtain \( t^* \) from the \( K^\pm \) track length in 1-prong kaon decays, properly accounting for kaon energy loss in each track segment \( L_t \); \( t^* = \sum_i L_t / (\beta_i \gamma_i c) \). An independent determination of \( t^* \) can be obtained from \( K^\pm \) decays to final states containing \( \pi^0 \)'s, by using the photon TOF’s. While this second method is still under development, a preliminary result from the first approach has been obtained using a sample of \( \sim 175 \text{ pb}^{-1} \):
\[
\tau_+ = 12.367 \pm 0.044_{\text{stat}} \pm 0.065_{\text{syst}} \text{ ns}, \quad (31)
\]
where the systematic uncertainty has been conservatively evaluated. After the analysis of the entire data set, KLOE results are expected to clarify the experimental situation concerning \( \tau_+ \). In the following, we will use the PDG value of \( \tau_+ \).

VI. KLOE SUMMARY OF \( f_0 \times |V_{us}| \)

Using the form factor slopes (FF) from Eq. \[18\] for \( K_{e3} \) and the averages of Eq. \[19\] for \( K_{\mu3} \) modes, the values of \( f_+ \times |V_{us}| \) from KLOE measurements are:

| Mode     | \( f_+ \times |V_{us}| \) | Error, % | KLOE | External |
|----------|--------------------------|---------|------|---------|
| \( K_{\mu3}^+ \) | 0.21561(69) | 0.32    | FF, BR, \( \tau_L \) | |
| \( K_{\mu3}^- \) | 0.21633(78) | 0.36    | FF, BR, \( \tau_L \) | FF |
| \( K_{S3} \) | 0.2154(14) | 0.67    | FF, BR | \( \tau_S \) |
| \( K_{\mu3}^+ \) | 0.2170(21) | 0.96    | FF, BR | \( \tau_+ \) |
| \( K_{\mu3}^- \) | 0.2150(28) | 1.3     | FF, BR, \( \tau_L \) | FF, \( \tau_+ \) |

The best accuracy is obtained from \( K_L \) modes, with errors dominated by \( \tau_L \); intermediate accuracy is obtained from \( K_{S3} \), with error dominated by the BR measurement. If the average FF’s are used for each mode, the following results are obtained:

| Mode     | \( f_+ \times |V_{us}| \) | Error, % | KLOE | External |
|----------|--------------------------|---------|------|---------|
| \( K_{L3}^+ \) | 0.21572(64) | 0.30    | FF, BR, \( \tau_L \) | FF |
| \( K_{L3}^- \) | 0.21633(78) | 0.36    | FF, BR, \( \tau_L \) | FF |
| \( K_{e3} \) | 0.2155(14) | 0.66    | FF, BR | \( \tau_S \) |
| \( K_{e3}^+ \) | 0.2171(21) | 0.96    | FF, BR | \( \tau_+ \) |
| \( K_{e3}^- \) | 0.2150(28) | 1.3     | FF, BR, \( \tau_L \) | FF, \( \tau_+ \) |

The average in the last line is evaluated taking correlations into account and has a 86% \( \chi^2 \) probability. Using the Leutwyler-Roos value for \( f_+(0) \) gives
\[
|V_{us}| = 0.2247(19). \quad (34)
\]

Using the world-average value of \( V_{ud} = 0.97377(27) \) as obtained from 0\(^+\) to 0\(^+\) nuclear beta decays \[17\], we get \( \Delta = (-13 \pm 10) \times 10^{-4} \). At the time of the 2004 PDG compilation \[18\], the world-average value was \( \Delta = (-35 \pm 15) \times 10^{-4} \), i.e., \( \sim 2.3\sigma \) away from zero.

The universality of \( e \) and \( \mu \) couplings to the \( W \) demands that the values of \( V_{us} \) obtained from \( K_{e3} \) and \( K_{\mu3} \) decays be the same. The KLOE data satisfy the \( e/\mu \) universality test: unlike at the time of 2004 PDG \[18\], the
ratios of effective Fermi constants are now compatible with unity:

\[
\begin{array}{|c|c|c|}
\hline
\text{Source} & G^2(\mu^3)/G^2(e^3) \\
K_L & 1.0059(83) & 1.047(14) \\
K^\pm & 0.981(25) & 1.004(16) \\
\text{KLOE 06} & \text{PDG 04} \\
\hline
\end{array}
\]

(VII. KLOE CONTRIBUTION TO \(|V_{us}/V_{ud}|\))

By comparing radiation-inclusive kaon and pion widths for \(\mu \nu\) decays, one can extract the ratio \(|V_{us}/V_{ud}|\) from the following relation \(19\):

\[
\frac{\Gamma(K \to \mu \nu)}{\Gamma(\pi \to \mu \nu)} = \frac{m_K}{m_\pi} \left(1 - \frac{m_\mu^2/m_K^2}{m^2} \right)^2 |V_{us}|^2 \frac{f_\pi^2}{f_K^2} C
\]

(36)

The theoretical inputs are the form-factor ratio \(f_K/f_\pi\) and the radiative corrections are described by the factor \(C\). We use \(f_K/f_\pi = 1.208(2)_{\text{lat}}^{\text{lat}}\) from lattice calculations by the MILC collaboration \(20\), and \(C = 0.9930(35)\) from \(19\).

From the precise KLOE measurement \(21\) \(\text{BR}(K^+ \to \pi^+ \nu) = 63.66(9)_{\text{stat}}(15)_{\text{syst}}\)% and using the PDG values \(1\) for the other experimental inputs, we get \(|V_{us}/V_{ud}| = 0.2286(5^{+25}_{-15})\). This result can be fit together with the world-average value \(V_{ud} = 0.97377(27)\) and the \(|V_{us}|\) evaluation from KLOE results, Eq. \(24\). The fit is shown in fig. \(2\) It yields \(V_{us} = 0.2240(16)\) and \(\Delta = 1.60(89) \times 10^{-3}\) with a \(\chi^2\) probability of 53%, demonstrating the consistency of the KLOE measurements, and giving no indication of any violation of CKM unitarity.

FIG. 2: The result of a fit combining the world-average value of \(V_{ud}\) with the KLOE measurements of \(V_{us}\) and \(V_{us}/V_{ud}\) is shown in the \(V_{us}-V_{ud}\) plane by the solid ellipse, which corresponds to a 1-\(\sigma\) contour. The unitarity constraint is also shown by the solid line. The segment highlighted on it represents the result of a fit assuming unitarity as a constraint.

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