**V_{us} determination from KLOE**

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**Abstract.** KLOE recent experimental results on \(K_L\), \(K_S\) and \(K^\pm\) decays relevant for the extraction of the CKM matrix element \(V_{us}\) are reported, including the preliminary measurement of BR(\(K^{+}_{\pi^-}\)) presented at this conference. From a global fit using only KLOE results a value of \(|V_{us}|f_+(0) = 0.21556 \pm 0.00059\) is obtained, where \(f_+(0)\) is the form factor parametrizing the hadronic matrix element evaluated at zero momentum transfer. From the ratio of the radiative inclusive decay rates of \(K^\pm \to \mu^\pm \nu(\gamma)\) and \(\pi^\pm \to \mu^\pm \nu(\gamma)\), combined with the KLOE measurement of BR(\(K^0 \to \mu^0 \nu(\gamma)\)) and the lattice calculation of the ratio of decay constants \(f_K/f_\pi = 1.189(7)\), the value \(V_{us}/V_{ud} = 0.2323(15)\) has been obtained. These results, together with \(V_{ud} = 0.97372(26)\), are compatible at 1.5σ level with CKM matrix unitarity.

1. Introduction

The most precise test of CKM unitarity is given by the constraint on its first row \(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1\) with \(|V_{ud}|^2\) measured from superallowed 0\(^+\) \(\to 0^+\) nuclear \(\beta\) transitions, \(|V_{us}|\) from semileptonic kaon decays and \(|V_{ub}|^2\) negligible. The \(V_{us}\) matrix element is related to the kaon semileptonic decay rate through the following equation:

\[
\Gamma(K_{l3}) = \frac{C^2_{l3}G_F^2M_K^5}{192\pi^3}S_{EW}|V_{us}|^2|f_+(0)|^2I_{Kl}(\lambda)(1 + 2\Delta_{SU}^{(2)} + 2\Delta_{EM}^{(2)})
\]

where \(K = K^0, K^\pm, l = e, \mu\) and \(C_K\) is a Clebsch-Gordan coefficient, equal to 1/2 and 1 for \(K^\pm\) and \(K^0\), respectively. The decay width \(\Gamma(K_{l3})\) is experimentally determined by measuring the kaon lifetime and the semileptonic BRs totally inclusive of radiation. The theoretical input \(f_+(0) \equiv f_{K^0\pi^-}(0)\) is the form factor parametrizing the hadronic matrix element of the \(K \to \pi\) transition, evaluated at zero momentum transfer and for neutral kaons. The form factor dependence on the momentum can be described by one or more slope parameters \(\lambda\), measured from the decay spectra, and enters in the phase space integral \(I_{Kl}(\lambda)\). Further inputs from theory are: the universal short-distance electroweak correction \(S_{EW} = 1.0232, \Delta_{SU}^{(2)}\) and \(\Delta_{EM}^{(2)}\).

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which are the $SU(2)$-breaking and long-distance electromagnetic corrections respectively and depend on the kaon charge and on the lepton flavor.

The KLOE experiment at the Frascati $\phi$-factory DAΦNE can measure all the relevant inputs to extract $V_{us}$ from $K_{l3}$ decay rates of both charged and neutral kaons: BRs, lifetimes and form factors. In sections from 2 to 4 most recent measurements for $K_L$, $K_S$ and $K^{\pm}$ will be presented, followed by the extraction of $V_{us}$ in section 5.

2. $K_L$ branching ratios, lifetime and form factor slopes.

The absolute BRs for the four main $K_L$ decay channels have been measured from a sample of $1.3 \times 10^7 \phi \to K_S K_L$ events tagged by $K_S \to \pi^+\pi^-$ decay. The results depend on the $K_L$ lifetime through the geometrical acceptance of the apparatus. Using as reference value $\tau_L = 51.54$ ns we get $BR(K_{L\phi}) = 0.4049(21)$, $BR(K_{L\mu3}) = 0.2726(16)$, $BR(3\pi^0) = 0.2018(24)$, and $BR(\pi^+\pi^-\pi^0) = 0.1276(15)$ [1]. An independent measurement of $\tau_L$ is obtained from the fit of the proper decay time distribution for $K_L \to 3\pi^0$ events, exploiting their high and uniform reconstruction efficiency over a fiducial volume of $\sim 0.4\lambda_L$. The result is $\tau_L = 50.92(30)$ ns [2].

The form factor slopes for $K_{e3}$ decays have been measured using again $K_S \to \pi^+\pi^-$ tagged events. Background rejection and particle identification use time-of-flight technique (TOF). The fit of the $t/m^2_{\ell\nu}$ distribution, with $t$ the squared momentum transfer, is sensitive to both linear and quadratic terms of the power expansion of the form factor and agreement has been found between the results obtained with quadratic and pole parametrization. With the quadratic parametrization we get: $\lambda^e_+ = 25.5(1.8) \times 10^{-3}$ and $\lambda^e_- = 1.4(0.8) \times 10^{-3}$ [3].

The form factor slopes for $K_{\mu3}$ decays are measured on the same sample of $K_S \to \pi^+\pi^-$ tagged events. After pre-selection cuts and background rejection based on kinematics, a further reduction of the $K_{e3}$ background is obtained exploiting TOF and using a Neural-Network technique based on $E/p$ and cluster shape. However $\pi/\mu$ identification is very difficult at low energies therefore the slope $\lambda_0$ is obtained fitting the distribution of the neutrino energy $E_{\nu}$ while $\lambda^e_+$ and $\lambda^e_-$ are measured from the combined fit with $K_{e3}$ decays. The preliminary results are: $\lambda^e_+ = 25.6(1.8) \times 10^{-3}$, $\lambda^e_- = 1.5(0.8) \times 10^{-3}$ and $\lambda_0 = 15.4(2.1) \times 10^{-3}$ [4].

3. $K_S$ branching ratios

A $\phi$-factory provides the unique opportunity of having a pure $K_S$-beam. Therefore, using a sample of $1.2 \times 10^8 \phi \to K_S K_L$ events in which the $K_L$ is identified by its interaction in the calorimeter, we have measured $\Gamma(K_{S\phi}$/$/\Gamma(\pi^+\pi^-) = 10.19(13) \times 10^{-4}$ [5] and $\Gamma(\pi^+\pi^-)/\Gamma(2\pi^0) = 2.2549(54)$ [6]. These two ratios completely determine the value of $K_S$ main BRs and allow us to measure $BR(K_{S\phi}) = 7.046(91) \times 10^{-4}$ to be used in the $V_{us}$ extraction. The value of $K_S$ lifetime used in the present determination of $|V_{us}|f_+(0)$ is $\tau_S = 0.08958(5)$ ns, from PDG fit to $CP$ parameters [7].

4. $K^{\pm}$ branching ratios and lifetime

The absolute measurement of $BR(K_{3\phi})$ uses $\phi \to K^+K^-$ events in which one of the two kaons decays to $\mu^+\nu$ or $\pi^+\pi^0$ final state, providing the normalization sample for BR evaluation and the tag for the signal search. $BR(K_{3\phi}^\pm)$ and $BR(K_{3\phi}^\mp)$ are determined separately for $K^+$ and $K^-$, each from four independent measurements, hence the systematic effect arising from the tagging procedure is well under control. The background rejection uses kinematics and the signal count is extracted from a constrained likelihood fit to the distribution of the squared lepton mass evaluated by TOF. Using $\tau_{\pm} = 12.385(25)$ ns [7] in order to account for acceptance dependence on kaon lifetime ($\tau_L$), we obtain $BR(K_{3\phi}^\pm) = 0.04965(53)$, and $BR(K_{3\phi}^\mp) = 0.03233(39)$.

The world average accuracy on $K^{\pm}$ lifetime is 0.2% [7] while from the measurements’ spread we have 0.8%, originated from a poor consistency between measurements performed with the
two different techniques: at rest and in flight. Hence some confirmation is needed. The KLOE experiment has preliminary results on \( \tau_{\pm} \) obtained with two independent methods, both using \( K^\pm \rightarrow \mu^\pm \nu \) tagged decay vertices and fitting the distribution of the kaon proper decay time \( t^* \). The first measurement, \( \tau_{\pm} = 12.367(44)(65) \) ns, is obtained from the \( t^* \) distribution evaluated from the kaon decay length and has a 1.1\( \tau_{\pm} \) coverage. The second measurement is \( \tau_{\pm} = 12.391(49)(25) \) ns, to evaluate the \( t^* \) distribution uses the photons’ time of flight in \( K^\pm \) decay with a \( \pi^0 \) in the final state and its coverage is 2.3\( \tau_{\pm} \). The combined result is \( \tau_{\pm} = 12.384(48) \) ns, in perfect agreement with PDG average.

The preliminary result of \( \text{BR}(K^+\pi^2) = 0.20658(65)(90) \), inclusive of final state radiation, has been presented at this conference. The normalization sample is given by \( K^-\rightarrow \mu^-\nu \) tagged events. The number of \( K^+\pi^2 \) decays is obtained from the fit of the distribution of the momentum of the charged decay particle in the kaon rest frame (\( p^* \)) evaluated assuming the pion mass, see figure 1. The efficiency has been evaluated on a data control sample selected using calorimetric information only. This new absolute BR measurement has a twofold importance: firstly the only measurement previously available was done in ’72 [8] without a proper treatment of radiative corrections, and secondly this BR enters in the normalization of all present \( \text{BR}(K^l_3) \) measurements but the KLOE one. With this new measurement the 3\( \sigma \) inconsistency between KLOE and NA48 results [9] on \( K^\pm_3 \) decays is partially solved: for \( K^\pm_3 \) decays we have a 2\( \sigma \) difference while for \( K^\pm\mu_3 \) decays the disagreement is reduced but still present. The agreement with the ISTRA+ measurement [10] of the \( K^\pm_3 \) branching ratio improves.

Figure 1. The \( p^* \) distribution used for \( K^+_{\pi^2} \) signal counting. Black dots are data and solid black line is the fit output obtained using the contributions from: \( K^+_{\mu^2} \) peak (red), \( K^+_{\pi^2} \) peak (green) and \( K^+ \) three-body decays (light blue).

Figure 2. Results of fits to \( |V_{us}| \), \( |V_{us}| \), and \( |V_{us}|/|V_{ud}| \).

5. Extraction of \( |V_{us}|f_+(0) \) and \( |V_{us}| \)
To extract \( |V_{us}|f_+(0) \) and \( |V_{us}| \) we need the theoretical inputs of eq. 1: the \( SU(2)-\)breaking [11] and the long distance \( EM \) corrections to the full inclusive decay rate [11, 12], evaluated for the first time for \( K_{\mu3} \) channels of both neutral and charged kaons [13]. The values of \( |V_{us}|f_+(0) \) measured for \( K_L\epsilon_3, K_L\mu_3, K_S\epsilon_3, K^\pm\epsilon_3, \) and \( K^\pm\mu_3 \) decay modes are shown in table 1. The five decay modes agree well within the quoted errors and average to \( |V_{us}|f_+(0) = 0.21556(59) \), with \( \chi^2/ndf = 6.1/4 \) (Prob= 19%).
averages of $|SU_f|$ result from the UKQCD/RBC Collaboration average to neutral and charged kaons respectively. Both results are in agreement with 1 within errors and in good agreement with the value estimated from theory [11].

Using the determination of $r_{\mu e}(L,S)$ from KLOE BRs results, we obtain $r_{\mu e}(K_L,S) = 1.0109(89)$ and $r_{\mu e}(K^\pm) = 0.9848(108)$ for neutral and charged kaons respectively. Both results are in agreement with 1 within errors and average to $r_{\mu e} = 1.0011(76)$ with Prob($\chi^2$) = 3.43%. Many other KLOE results on lepton flavor universality tests have been presented at this conference [14].

Using the determination of $|V_{us}|f_+(0)$ from $K_{l3}$ decays and assuming for $f_+(0)$ the preliminary result from the UKQCD/RBC Collaboration $f_+(0) = 0.9609(51)$ [15], in agreement with Leutwyler-Roos evaluation [16] but more precise, we get $|V_{us}| = 0.2254(19)$. Furthermore a value of $V_{us}/V_{ud}$ can be obtained from a comparison of the radiative inclusive decay rates of $K^\pm \rightarrow \mu^\pm \nu(\gamma)$ and $\pi^\pm \rightarrow \mu^\pm \nu(\gamma)$ combined with a lattice calculation of $f_K/f_{\pi}$ [18]. Using $\text{BR}(K^\pm \rightarrow \mu^\pm \nu) = 0.6366(17)$ from KLOE [19] and the preliminary lattice result $f_K/f_{\pi} = 1.189(7)$ from the HP/UKQCD '07 [20], we get $V_{us}/V_{ud} = 0.2323(15)$.

The $V_{us}/V_{ud}$ ratio can be used in a fit together with the measurements of $V_{us}$ from $K_{l3}$ decays and $V_{ud} = 0.97372(26)$ [17], as shown in figure 2. The results of this fit are $V_{ud} = 0.97371(26)$ and $V_{us} = 0.2252(10)$, with $\chi^2/ndf = 0.85/1$ (Prob= 36%), which is compatible with unitarity at 1.5$\sigma$ level. If we add the constraint of unitarity we get $V_{ud} = 0.97405(17)$ and $V_{us} = 0.2263(7)$, with $\chi^2/ndf = 3.8/2$ (Prob= 14.6%).

Table 1. Values of $|V_{us}|f_+(0)$ extracted from $K_{l3}$ decay rates with their fractional accuracies.

| Mode     | $K_L e3$ | $K_L \mu3$ | $K_S e3$ | $K^+ e3$ | $K^+ \mu3$ |
|----------|----------|------------|----------|----------|------------|
| $|V_{us}|f_+(0)$ | 0.21547(72) | 0.21661(93) | 0.21522(145) | 0.21465(137) | 0.21302(155) |
| % err | 0.34 | 0.43 | 0.68 | 0.64 | 0.73 |

To evaluate the reliability of the $SU(2)$—breaking correction we compared the separate averages of $|V_{us}|f_+(0)$ for neutral and charged channels and they agree within 1.3$\sigma$. Alternatively, an experimental estimate of $\Delta_K^{SU(2)}$ can be obtained by comparing the neutral result with the charged one evaluated without correcting for $SU(2)$—breaking. We get $\Delta^{SU(2)}_{\exp} = 1.52(63)$% in good agreement with the value estimated from theory [11].

Lepton universality can be tested comparing the value of $R_{\mu e} = \Gamma(K_{c3})/\Gamma(K_{\mu3})$ from $K_{l3}$ measurements and its Standard Model prediction $R^{SM}_{\mu e}$. Defining $r_{\mu e} = R_{\mu e}/R^{SM}_{\mu e}$ and using KLOE BRs results, we obtain $r_{\mu e}(K_L,S) = 1.0109(89)$ and $r_{\mu e}(K^\pm) = 0.9848(108)$ for neutral and charged kaons respectively. Both results are in agreement with 1 within errors and average to $r_{\mu e} = 1.0011(76)$ with Prob($\chi^2$) = 3.43%. Many other KLOE results on lepton flavor universality tests have been presented at this conference [14].

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