Proceedings of the VIIIth International Workshop on Heavy Quarks and Leptons

HQL06

October 2006

Deutsches Museum, Munich

Editors

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Organized by the Physics Department of the Technical University of Munich
and the Max-Planck Institute for Physics, Munich

Recent results on V_{us} from KLOE, KTeV and NA48

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1 Introduction

The flavour structure in the quark sector of the Standard Model is described by the CKM matrix [1], [2]. Its unitarity leads to a number of relations for its elements and in particular for the first raw:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \tag{1}$$

Since $V_{ub} \cong 4 \times 10^{-3}$ the contribution of the last term could be neglected at the current level of uncertainty in V_{ud} and V_{us}. This approximation gives $V_{us} = \sin\theta_c$ as originally suggested by Cabibbo.

The most precise value of V_{ud} comes from the super-allowed $0^+ \rightarrow 0^+$ beta transitions between nuclei and V_{us} is usually calculated from the branchings of the kaon semileptonic decays. Going back to PDG 2004 [3] $V_{us} = 0.2195 \pm 0.0025$ and $V_{ud} = 0.9738 \pm 0.0005$ giving a deviation from unitarity at the level of 2.3σ where the contribution from the uncertainties of V_{ud} and V_{us} in the final error are almost equal.

In the last few years a significant progress in the kaon physics has been made by three experiments - KLOE, KTeV and NA48. The reflection of their results to the extraction of V_{us} is subject of this review.

KTeV at the Main Injector (Fermilab) [5] and NA48 at SPS (CERN) [6] are fixed target experiments and exploit similar techniques of kaon decays in flight. Both consist of a spectrometer system measuring the charged particles momentum and a calorimetry system used for measurement of the energy of photons and electrons. The calorimetry system also provides a way to distinguish between the different type of charged particles through their interactions with matter. A muon veto system is placed at the end of each detector complex. The primary purpose of both experiments

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was to measure the direct CP violation parameter ϵ'/ϵ in the neutral kaon system [4]. In 2003 NA48 modified its setup in order to study charged kaon decays.

KLOE experiment [7] is situated at $DA\Phi NE$, the Frascati ϕ factory, where e^+e^- beams collide with a center of mass energy at the ϕ meson mass (1020 MeV). With a probability of $\approx$ 83% ϕ decays into neutral or charged kaons, anticolinear in the ϕ center of mass (almost true also in the laboratory system). The presence of $K_{L/S}$ ($K^{\pm}$) tags $K_{S/L}$ ($K^{\mp}$). KLOE detector has 2π symmetry, the momentum of the decay products is measured by a magnetic spectrometer which is followed by an elecromagnetic calorimeter.

2 Kaon semileptonic decays

Within the Standard Model $K \rightarrow \pi l \nu$ (so called $Kl3$) decay appear as a tree level process of $s \rightarrow u$ transition. The inclusive branching ratios of all four modes (K^0e3, $K^0\mu3$, $K^{\pm}e3$ and $K^{\pm}\mu3$) could be written conveniently in the form

$$Br(K_{l3(\gamma)}) = \frac{G_F^2 M_K^5 S_{EW}}{128\pi^3/\tau_K} I_K C^2 (1+\delta^I_{EM}) \times |V_{us} f_+^{K\pi}(0)|^2 \tag{2}$$

where G_F is the Fermi constant, M_K and τ_K are the corresponding kaon mass and lifetime, S_{EW} is the the short distance electroweak enhancement factor, $S_{EW} \cong 1 + \frac{2\alpha}{\pi}(1-\frac{\alpha_s}{4\pi}) \times log\frac{M_Z}{M_\rho} = 1.023$ [8], C is the Klebsh-Gordon coefficient , $C = 1$ for K^0 and $C = \sqrt{\frac{1}{2}}$ for $K^{\pm}$, δ^I_{EM} represents the long-distance electromagnetic correction [9,10], $f_+^{K\pi}(0)$ is the value of the vector form-factor at zero transferred momentum and I_K is the phase space integral dependent on the mode and the shape of the form-factor.

The values of S_{EW}, δ^I_{EM} and $f_+^{K\pi}(0)$ are calculated theoretically while the rest could be obtained from experimental measurements.

2.1 Form factors

The kaon form factors are defined as [11]

$$\langle \pi(q)|\, s\gamma_\mu u\, |K(p)\rangle = f_+^{K\pi}(t) \times (p+q) + f_-^{K\pi}(t) \times (p-q) \tag{3}$$

where $t = (p-q)^2$ is the transferred momentum. Instead of the couple f_+, f_- usually another set of form-factors is used $f_+(t)$ and $f_0(t) = f_+(t) + \frac{t}{M_K^2 - M_\pi^2} f_-(t)$ inspired by the VMD model. The dependence of the transferred momentum could be written as

$$f_{+,0}^{K\pi}(t) = f_+^{K\pi}(0)(1 + \delta f_{+,0}(t)) \tag{4}$$

It is convenient to express the charged kaon form factor by the neutral one $|f_+^{K^+\pi^0}(0)|^2 = (1+\delta_{SU2}) \times |f_+^{K^0\pi^-}(0)|^2$. The SU2 breaking parameter is obtained within the Chiral

Perturbation Theory, $\delta_{SU2} = 0.046 \pm 0.004$ [9,12]. $f_+(0)$ was calculated for the first time in the 80s [12]

$$f_+(0) = 0.961 \pm 0.008. \tag{5}$$

However more recent analysis give higher values $f_+(0) = (0.981 \pm 0.012)$ [10]. Another result $f_+(0) = (0.960 \pm 0.009)$ comes from lattice QCD [13] which is consistent with (5). Since $f_+(0)$ enters directly in the calculation of V_{us} a clarification of this problem is highly desirable. In this review (5) is used.

The term $\delta f_{+,0}(t)$ enters in the phase space integral calculation and is subject to different parametrization. The Taylor expansion gives

$$\delta f_{+,0}(t) = \lambda'_{+,0} \frac{t}{M_\pi^2} + \frac{1}{2} \lambda_{+,0}\text{''} \frac{t^2}{M_\pi^4}. \tag{6}$$

while within the VMD model $f_{+,0}$ correspond to vector or scalar meson exchange and are parametrized by the mass of the pole:

$$\delta f_{+,0}(t) = \frac{M_{V,S}^2}{M_{V,S}^2 - t} - 1 \tag{7}$$

In both cases the unknown parameters are determined experimentally. If in equation (6) the quadratic term is neglected then the shape of the form factor is given only by its slope λ_+. The three collaborations have studied the form factors in the case of $K_L \to \pi^0 e \nu$ decays and the results can be summarized in the following table:

	λ'_+	λ_+"	λ_+	Pole mass
NA48 [14]	0.0280 ± 0.0024	0.0004 ± 0.0009	0.0288 ± 0.0012	859 ± 18
KTeV [15]	0.0217 ± 0.0020	0.0029 ± 0.0008	0.0283 ± 0.0006	881 ± 7.1
KLOE [16]	0.0255 ± 0.0018	0.0014 ± 0.0008	0.0286 ± 0.0006	870 ± 9.2

The values agree in the case of linear and pole parametrization but there is a discrepancy for the necessity of a quadratic term in (6). Recently the KTeV collaboration has performed a new calculation of the phase space integral with a reduced model uncertainty, $I_{K0e3} = 0.10262 \pm 0.00032$ [17]. For the rest of the phase-space integrals we use $I_{K0\mu3} = 0.06777 \pm 0.00053$ with the KTeV quadratic form factor parametrization, $I_{K^\pm e3} = 0.1060 \pm 0.0008$ and $I_{K^\pm\mu3} = 0.0702 \pm 0.0005$ with the ISTRA+ measurement of the form factors [18]. A 0.7% error is added to account for the difference between the quadratic and the pole parametrization of the form-factors.

2.2 Kaon lifetime

During the last year two new measurements of the K_L lifetime have been published by KLOE. One of them is obtained from the the proper time distribution of $K_L \to 3\pi^0$

decays [19], giving $\tau_{KL} = (50.92 \pm 0.30) ns$. The second method produces a result for the lifetime as a byproduct of the measurement of the major K_L branching fraction imposing the condition that their sum should be unity [20]. The result is $\tau_{KL} = (50.72 \pm 0.37) ns$, independent of the previous measurement. The combined value including also the only previous measurement in the 70s is $\tau_{KL} = (51.01 \pm 0.20) ns$. For the K_S lifetime the PDG [22] average is used.

Concerning the charged kaons a new preliminary result for the $K^\pm$ lifetime has been presented by KLOE $\tau_{K^\pm} = (1.2367 \pm 0.0078) \times 10^{-8} s$ [21]. For the moment the PDG average $\tau_{K^\pm} = (1.2385 \pm 0.0025) \times 10^{-8} s$ is used and we are waiting for the final result.

2.3 Branching ratios

For a long time the branching ratios of the kaon semileptonic decays were fixed in the PDG due to the lack of new measurements. The BNL result for $Br(K^+e3) = (5.13 \pm 0.10)\%$ [23] published in 2003 was in disagreement with the PDG 2002 value ($Br(K^+e3) = (4.87 \pm 0.06)\%$) [24] and initiated a lot of experimental activity.

All six major K_L branching fractions have been measured by KTeV determining their ratios of decay rates [25]. The results for $Br(K_Le3)$ and $Br(K_L\mu3)$ are

$$Br(K_L \to \pi^\pm e^\mp \nu) = (40.67 \pm 0.11)\% \tag{8}$$

$$Br(K_L \to \pi^\pm \mu^\mp \nu) = (27.01 \pm 0.09)\% \tag{9}$$

KLOE has also measured the dominant K_L branchings [20] as mentioned above obtaining for the semileptonic decays

$$Br(K_L \to \pi^\pm e^\mp \nu) = (40.07 \pm 0.15)\% \tag{10}$$

$$Br(K_L \to \pi^\pm \mu^\mp \nu) = (26.98 \pm 0.15)\% \tag{11}$$

Apart from the K_L KLOE has studied K_Se3 decays [26]. Using $K_S \to \pi^+\pi^-$ for normalization channel the result is four times more precise than the previous value:

$$Br(K_S \to \pi^\pm e^\mp \nu) = (7.046 \pm 0.091)\% \tag{12}$$

The NA48 experiment has measured the ratio of the branching ratios of K_Le3 and all two track events [27]. In this way $Br(K_Le3) = R_e(1.0048 - Br(K_l3\pi^0)$, where $Br(K_L3\pi^0)$ is the external input. Using the measured $R_e = 0.4978 \pm 0.0035$ and the current PDG value for $Br(K_L3\pi^0) = (19.69 \pm 0.26)\%$ the result for the K_Le3 branching is

$$Br(K_L \to \pi^\pm e^\mp \nu) = (40.22 \pm 0.31)\% \tag{13}$$

Preliminary results for the charged semileptonic decays have also been presented by NA48 [28], [29] and KLOE [21]

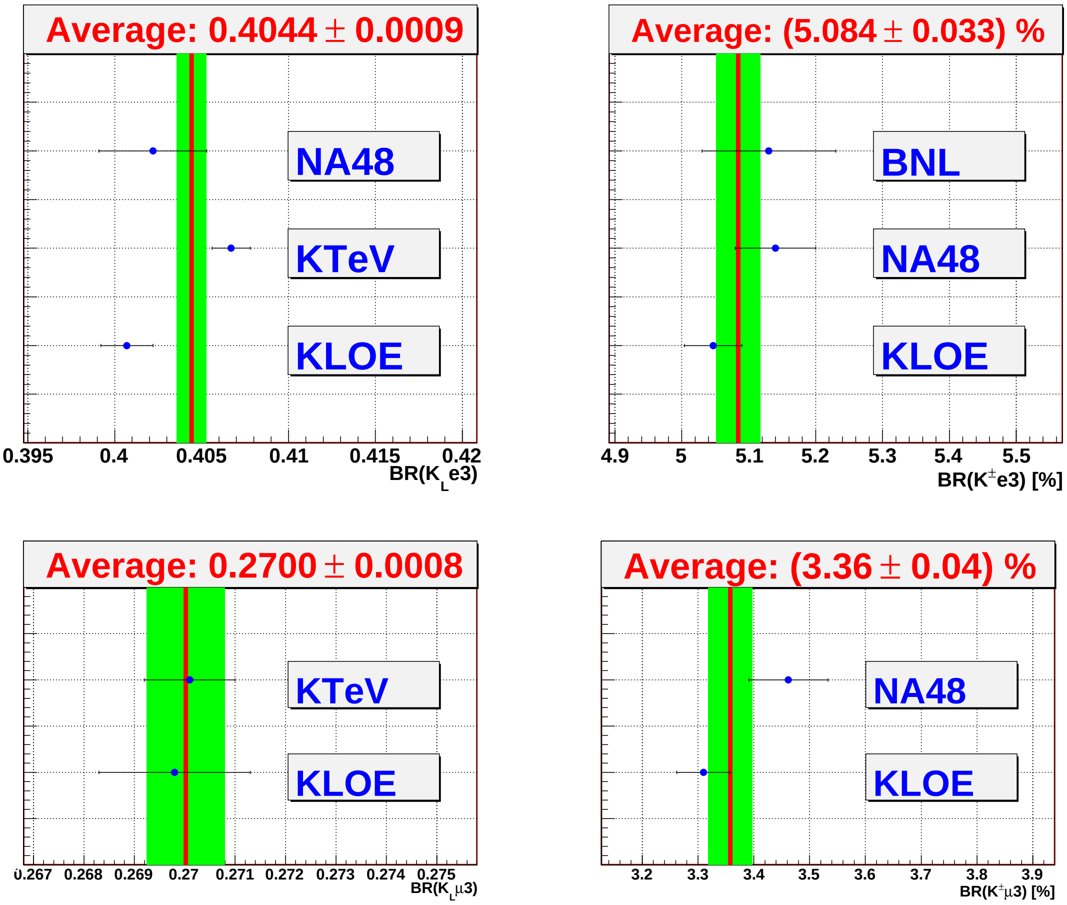

Figure 1: Recent measurements of the kaon semileptonic branching ratios. $Br(K_S \to \pi^{\pm} e^{\mp} \nu) = (7.046 \pm 0.091)\%$

NA48

$$Br(K^{\pm} \to \pi^0 e^{\pm} \nu) = (5.14 \pm 0.06)\% \qquad (14)$$

$$Br(K^{\pm} \to \pi^0 \mu^{\pm} \nu) = (3.46 \pm 0.07)\% \qquad (15)$$

KLOE

$$Br(K^{\pm} \to \pi^0 e^{\pm} \nu) = (5.047 \pm 0.043)\% \qquad (16)$$

$$Br(K^{\pm} \to \pi^0 \mu^{\pm} \nu) = (3.310 \pm 0.048)\% \qquad (17)$$

which confirm the discrepancy with the PDG observed by BNL.

This ten new measurements of the kaon semileptonic branching ratios together with the BNL result for $Br(K^{\pm}e3)$ are averaged depending on the decay mode and are shown on Figure 1 (apart from $Br(K_Se3)$, measured only by KLOE). As can be seen they show very good consistency.

2.4 V_{us} from kaon semileptonic decays

Combining all the inputs mentioned above the values for $V_{us} \times f_+(0)$ from the different modes together with the average are shown of Figure 2.

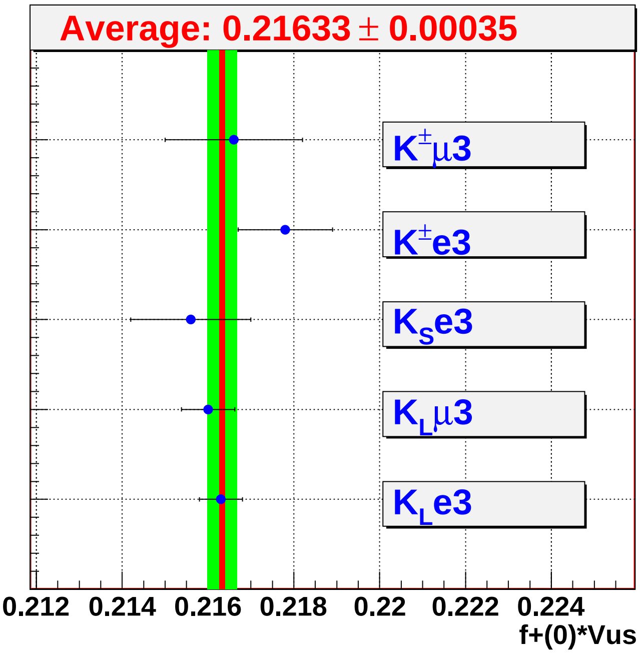

Figure 2: The experimentally measured quantity $V_{us} \times f_+(0)$ from kaon semileptonic decays

The precision on the combined measurement of $V_{us} \times f_+(0)$ is approximately 0.16%. Using for $f_+(0)$ the value obtained by Leutwyler and Roos the result for V_{us} is

$$V_{us} = 0.2251 \pm 0.0019 \tag{18}$$

where the dominant contribution to the error comes from the uncertainty of $f_+(0)$.

3 V_{us} from $Kl2$ decays

A complementary way to extract V_{us} is to use the ratio of the branching ratios of the pion and the kaon leptonic decays [30]. It can be written as

$$\frac{Br(K^{\pm} \to \mu^{\pm}\nu(\gamma))}{Br(\pi^{\pm} \to \mu^{\pm}\nu(\gamma))} = \frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2} \times \frac{\tau_K}{\tau_\pi}\frac{M_K(1-\frac{M_\mu^2}{M_K^2})^2}{M_\pi(1-\frac{M_\mu^2}{M_\pi^2})^2} \times \frac{1+\frac{\alpha}{\pi}C_K}{1+\frac{\alpha}{\pi}C_\pi} \tag{19}$$

where $\tau_{K,\pi}$ and $f_{K,\pi}$ are the meson lifetimes and decay constants correspondingly and $C_{K,\pi}$ parametrize the electroweak correction. Using the new measurement of $Br(K^{\pm} \to \mu^{\pm}\nu(\gamma)) = (63.66 \pm 0.17)\%$ from KLOE [31] and the lattice QCD calculation of f_K/f_π [32] we get $|V_{us}|/|V_{ud}| = 0.2286^{+0.0026}_{-0.0014}$ which together with the measurement of V_{ud} [33] gives

$$V_{us} = 0.2223^{+0.0026}_{-0.0014} \tag{20}$$

The accuracy of the result is comparable to (18). The dominant error comes from the uncertainty on the ratio f_K/f_π.

4 Conclusions

The values of V_{us} extracted from kaon semileptonic decays and from $K\mu2$ decay agree. The average is

$$V_{us} = 0.2241 \pm 0.0015. \tag{21}$$

Using $V_{ud} = 0.97377(27)$ we have

$$|V_{ud}|^2 + |V_{us}|^2 = 0.9985 \pm 0.0009. \tag{22}$$

This result is compatible with the Standard Model and the unitarity of the CKM matrix.

Acknowledgements

I would like to thank prof. dr. Leandar Litov for the valuable help during the preparation of this review and the Joint Institute for Nuclear Research - Dubna for the sponsorship.

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