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Implications on the Unitarity Triangle from kaons: KLOE results

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Summary. — We present the KLOE measurements on K_S, K_L, $K^{\pm}$ semileptonic decays from which we find $|V_{\rm us}| = 0.2237(13)$. From the KLOE measurement of $\mathrm{BR}(K^+ \to \mu^+\nu)$ we obtain $|V_{\rm us}/V_{\rm ud}| = 0.2323(15)$. An overall fit gives $|V_{\rm us}| = 0.2249(10)$ and $|V_{\rm ud}| = 0.97417(26)$, compatible with unitarity: $1-(V_{ud}^2+V_{us}^2+V_{ub}^2) = (4\pm 7)\times 10^{-4}$.

PACS `12.15.Hh` – Determination of Kobayashi-Maskawa matrix elements.

1. – Introduction

KLOE has measured all the relevant parameters to compute V_{us} from $K_{\ell 3}$ decay rates of both charged and neutral kaons: BRs, lifetimes, form factor slopes and the K^0 mass [1]. We have tested the unitarity of the first row of the CKM mixing matrix $|V_{\rm ud}|^2+|V_{\rm us}|^2 = 1$ using $|V_{\rm ud}|$ measured from $0^+ \to 0^+$ nuclear β decays, $|V_{\rm ub}|^2$ being negligible, $\mathcal{O}(10^{-5})$.

The V_{us} matrix element appears in the kaon semileptonic decay rate:

$$\Gamma(K_{\ell 3}) = \frac{C_K^2 G_{\rm F}^2 M_K^5}{192\pi^3}|V_{\rm us}|^2|f_+(0)|^2 I_{K\ell} S_{\rm EW}\left(1+\delta_K^{SU(2)}+\delta_{K\ell}^{\rm EM}\right)^2, \tag{1}$$

where $K = K^0$, $K^{\pm}$, $\ell = e$, μ and $C_K^2 = 1/2$, 1 for $K^{\pm}$ and K^0, respectively. We can evaluate the decay width $\Gamma(K_{\ell 3})$ by measuring the kaon lifetimes and the semileptonic BR totally inclusive of radiation. $f_+(0)$ is the transition form factor, FF, for $K^0 \to \pi^+$ at

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TABLE I. – *KLOE results for* $|V_{us}|\, f_+(0)$.

Mode	K_{Le3}	$K_{L\mu3}$	K_{Se3}	$K^{\pm}_{e3}$	$K^{\pm}_{\mu3}$
$\|V_{us}\|\, f_+(0)$	0.2155(7)	0.2167(9)	0.2153(14)	0.2152(13)	0.2132(15)

zero momentum transfer. The dependence of the form factor on the momentum transfer $t = (p_K - p_\pi)^2 \propto E_\pi$ is measured from the pion spectra and allows evaluation of the phase space integral $I_{K\ell}$. Theory also provides the universal short-distance electroweak correction $S_{\mathrm{EW}} = 1.0232$, the $SU(2)$-breaking $\delta_K^{SU(2)}$ and long-distance electromagnetic corrections $\delta_{K\ell}^{\mathrm{EM}}$, which depend on the kaon charge and on the lepton flavor.

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

We used a sample of $1.3 \times 10^7 \phi \to K_S K_L$ events tagged by $K_S \to \pi^+\pi^-$ decay to measure the absolute BRs for the four main K_L decay channels [2]. The results are: $\mathrm{BR}(K_L \to \pi e \nu(\gamma)) = 0.4008(15)$, $\mathrm{BR}(K_L \to \pi \mu \nu(\gamma)) = 0.2699(14)$, $\mathrm{BR}(K_L \to 3\pi^0) = 0.1996(20)$ and $\mathrm{BR}(K_L \to \pi^+\pi^-\pi^0) = 0.1261(11)$ after imposing the constraint $\sum \mathrm{BR}(K_L) = 1$. This corresponds to also measuring the lifetime by counting the number of decays in a time interval for a beam of known intensity: $\tau_L = 50.72(37)\,\mathrm{ns}$ [2]. A direct, independent measurement of the K_L lifetime is obtained from a fit to the proper decay time distribution for $K_L \to 3\pi^0$ events, since they have high and uniform recostruction efficiency over a fiducial volume of $\sim 0.4\lambda_L$: the result is $\tau_L = 50.92(30)\,\mathrm{ns}$ [3].

Assuming a quadratic form for the f_+ FF and a linear f_0 FF we measured slope and curvature λ'_+, λ''_+ from K_{e3} decays [4]. We obtain the slope λ_0 for the scalar FF from the neutrino energy spectrum [5]. Because of correlation between the parameters we use a dispersive parametrization to get more accurate results for the $I_{K\ell}$ [6].

3. – K_S branching ratio

A ϕ-factory provides the unique opportunity of having a pure K_S-beam. We use a sample of 1.2×10^8 $\phi \to K_S K_L$ events with the K_L identified by its interaction on the calorimeter, measuring $\Gamma(K_{Se3})/\Gamma(\pi^+\pi^-) = 10.19(13) \times 10^{-4}$ [7] and $\Gamma(\pi^+\pi^-)/\Gamma(2\pi^0) = 2.2549(54)$ [8]. These two ratios completely determine the value of K_S main BRs and allow us to measure $\mathrm{BR}(K_{Se3}) = 7.046(91) \times 10^{-4}$. Using the K_S lifetime from PDG fit [9] we obtain $|V_{us}|\, f_+(0)$, see table I.

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

The absolute measurement of $\mathrm{BR}(K^{\pm}_{\ell 3})$ uses $\phi \to K^+K^-$ events with one of the two kaons decaying to $\mu^{\pm}\nu$ or $\pi^{\pm}\pi^0$, providing the normalization of the sample for BR estimation and the tag for the signal selection.

We determine separately $\mathrm{BR}(K^{\pm}_{e3})$ and $\mathrm{BR}(K^{\pm}_{\mu3})$ for K^+ and K^-, each from four independent measurements, therefore the systematic effect arising from the tagging procedure is well under control. We extract the signal count from a constrained likelihood fit to the distribution of the squared lepton mass estimated by time of flight. Using $\tau_{\pm} = 12.385(25)\,\mathrm{ns}$ [9] to take into account for the acceptance dependence on kaon lifetime ($\tau_{\pm}$), we obtain $\mathrm{BR}(K^{\pm}_{e3}) = 0.04965(53)$, and $\mathrm{BR}(K^{\pm}_{\mu3}) = 0.03233(39)$ [10].

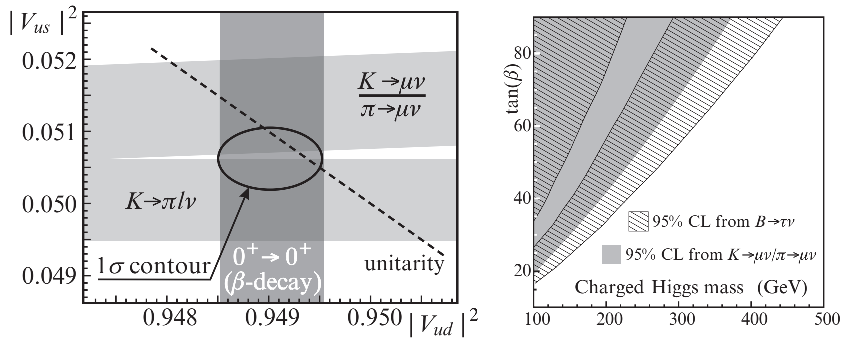

Fig. 1. – Results of fits to $|V_{\text{ud}}|$, $|V_{\text{us}}|$, and $|V_{\text{us}}|/|V_{\text{ud}}|$(left). Excluded region in the m_{H^+}-$\tan\beta$ plane by the measurement $R_{\ell 23}$; the region excluded by $B\to\tau\nu$ is also indicated (right).

The world average accuracy on $K^\pm$ lifetime is 0.2% [9] while the measurements spread is 0.8%, originated from a poor consistency between measurements performed with the two different methods: decay at rest and in flight. KLOE has measured $\tau_\pm$ with $K^\pm\to\mu^\pm\nu$ tagged kaons and fitting the distribution of the kaon proper decay time t^* evaluated with two independent methods: the kaon decay length and the kaon decay time from the time of flight of the photons from the π^0 in the final state. The first method gives $\tau_\pm = 12.364(31)(31)\,\text{ns}$, the second $\tau_\pm = 12.337(30)(20)\,\text{ns}$ and the average is $\tau_\pm = 12.347(30)\,\text{ns}$ [11].

5. – $|V_{us}|\,f_+(0)$ and $|V_{\text{us}}|$

We need the theoretical inputs of eq. (1) to extract $|V_{us}|\,f_+(0)$: the $SU(2)$-breaking correction [12] and the long-distance EM corrections to the full inclusive decay rate [12, 13], of both neutral and charged kaons [14]. The measurements of $|V_{us}|\,f_+(0)$ for K_Le3, $K_L\mu3$, K_Se3, $K^\pm e3$ and $K^\pm\mu3$ decay modes are shown in table I. The five decay modes agree well within the quoted errors and average to $|V_{us}|\,f_+(0) = 0.2157(6)$, with $\chi^2/\text{ndf} = 7.0/4$ (Prob. = 13%), to be compared with the world average $|V_{us}|\,f_+(0) = 0.2166(5)$ [6].

Using the measurement of $|V_{us}|\,f_+(0)$ from $K_{\ell 3}$ decays and the result $f_+(0) = 0.964(5)$ from the UKQCD/RBC Collaboration [15], we obtain $|V_{\text{us}}| = 0.2237(13)$. Furthermore we can obtain a measurement of V_{us}/V_{ud} from a comparison of the radiative inclusive decay rates of $K^\pm\to\mu^\pm\nu(\gamma)$ and $\pi^\pm\to\mu^\pm\nu(\gamma)$ combined with a lattice calculation of f_K/f_π [16]. Making use of $\text{BR} = 0.6366(17)$ from KLOE [17] and the preliminary lattice result $f_K/f_\pi = 1.189(7)$ from the HP/UKQCD '07 [15], we get $V_{us}/V_{ud} = 0.2323(15)$. We can use this value to perform a fit together with the measurements of V_{us} from $K_{\ell 3}$ and $V_{ud} = 0.97418(26)$, as shown in fig. 1. The fit result is $V_{ud} = 0.97417(26)$ and $V_{us} = 0.2249(10)$, with $\chi^2/\text{ndf} = 2.34/1$ (CL = 13%), from which we get $1-(V_{ud}^2+V_{us}^2+V_{ub}^2) = 4(7)\times 10^{-4}$ compatible with unitarity at 0.6σ level. We can use these results to evaluate $G_{\text{CKM}} = G_{\text{F}}(V_{ud}^2+V_{us}^2+V_{ub}^2)^{1/2} = 1.16614(40)\times 10^{-5}\,\text{GeV}^{-2}$ which is in agreement with the measurement from the muon lifetime $G_{\text{F}} = 1.166371(6)\times 10^{-5}\,\text{GeV}^{-2}$ and is competitive with the present accuracy of the measurements from tau-lepton decays and electroweak precision tests.

6. – Bounds on new physics

The ratio of the V_{us} values obtained from helicity-suppressed and helicity-allowed kaon modes is a particularly interesting observable, equal to 1 in the SM. The presence of a scalar current due to a charged Higgs H^+ exchange is expected to lower the value of $R_{\ell 23}$ [18]:

$$R_{\ell 23} = \left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\mu 2})} \right| = \left| 1 - \frac{m^2_{K^+}}{m^2_{H^+}} \left(1 - \frac{m^2_{\pi^+}}{m^2_{K^+}} \right) \frac{\tan^2 \beta}{1 + 0.01 \tan \beta} \right| \tag{2}$$

with $\tan \beta$ the ratio of the two Higgs vacuum expectation values in the MSSM. To estimate $R_{\ell 23}$ we perform a fit of our experimental data on $K_{\mu 2}$ and $K_{\ell 3}$ decays, using as external inputs the lattice calculations of $f_+(0)$ [19] and f_K/f_π [15], the value of V_{ud} from [20], and $|V_{ud}|^2 + |V_{us}(K_{\ell 3})|^2 = 1$ as a constraint. The result is $R_{\ell 23} = 1.008(8)$ [6]. The region excluded at 95% CL in the charged Higgs mass m_{H^+} and $\tan \beta$ plane together with the bounds from $\mathrm{BR}(B \to \tau\nu)$ [21] is shown in fig. 1: Kaon physics and B physics provide complementary information.

7. – CP violation in kaon physics

The SM prediction of ϵ_K wih the new input $B_K = 0.720(39)$ evaluated from RBC-UKQCD [22] and previously neglected contributions lead to $|\epsilon_K|^{\mathrm{SM}} = 1.78(25) \times 10^{-3}$, to be compared with the experimental value obtained using the existing measurements of KLOE, KTeV and NA48 $|\epsilon_K|^{\mathrm{exp}} = 2.229(12) \times 10^{-3}$ [23].

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