Determination of $V_{us}$ at the KLOE experiment: present results and future perspectives

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Precise measurements of semileptonic kaon decay rates at KLOE provide the measurement of the CKM mixing matrix element $V_{us}$ and information about lepton universality. Leptonic kaon decays provide an independent measurement of $|V_{us}|^2 / |V_{ud}|^2$, through the ratio $\Gamma(K \rightarrow \mu\nu)/\Gamma(\pi \rightarrow \mu\nu)$. These measurements, together with the result of $|V_{ud}|$ from nuclear $\beta$ transitions, provide the most precise test of CKM unitarity, allowing the universality of lepton and quark weak couplings to be tested. After the completion of the KLOE data taking, the proposal of a new run with an upgraded KLOE detector, KLOE-2, at an upgraded DAΦNE machine has been accepted by INFN and it is now starting. Present results from KLOE and future perspectives from KLOE-2 are reported.

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1 Introduction

The KLOE experiment \[1\] collected an integrated luminosity $\int L \, dt \sim 2.5 \text{fb}^{-1}$ at the Frascati $\phi-$factory DAFNE, an $e^+e^-$ collider operated at the energy of 1020 MeV, the $\phi$-meson mass. With its general purpose detector, consisting of a large cylindrical drift chamber surrounded by a lead-scintillating fiber electromagnetic calorimeter entirely immersed in an axial magnetic field, KLOE produced the most comprehensive set of results on kaon physics from a single experiment using the unique availability of pure $K_S, K_L$ and $K^\pm$ beams at a $\phi-$factory. After the completion of the KLOE data taking, the proposal of a new run with an upgraded KLOE detector, KLOE-2 \[2\], at an upgraded DAFNE machine has been accepted and it is now starting.

An overview of KLOE results for $K_L$, $K_S$ and $K^\pm$ used to extract $V_{us}$ is presented (sec. 2) together with the future perspectives within the KLOE-2 project (sec. 3).

2 $V_{us}$ from kaon decays: unitarity and universality

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 $|V_{ud}|$ measured from superallowed $0^+ \rightarrow 0^+$ nuclear $\beta$ transitions, $|V_{us}|$ from semileptonic kaon decays and $|V_{ub}|^2$ being negligible. The kaon semileptonic decay rate is given by:

$$\Gamma(K_{l3}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW}|V_{us}|^2 |f_+(0)|^2 I_{K,l}(\lambda)(1 + 2\Delta_{SU}^{SU(2)} + 2\Delta_{EM}^{EM})$$

(1)

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, inclusive of radiation. The theoretical inputs are: the universal short-distance electroweak correction $S_{EW} = 1.0232$, the $SU(2)$-breaking $\Delta_{SU}^{SU(2)}$ and the long-distance electromagnetic corrections $\Delta_{EM}^{EM}$, and the form factor $f_+(0) \equiv f_+^{0\pi\pi}(0)$ evaluated at zero momentum transfer. The form factor dependence on the momentum transfer can be described by one or more slope parameters $\lambda$, measured from the decay spectra, and enters in the phase space integral $I_{K,l}(\lambda)$.

All the relevant inputs to extract $V_{us}$ from $K_{l3}$ decay rates have been measured at KLOE \[1\]: branching ratios (BRs), lifetimes and form factors (Table 1). Complementary to $K_{l3}$ decays, the measurement of BR($K^\pm \rightarrow \mu^\pm \nu$) allowed us to extract $V_{us}/V_{ud}$ and the result of BR($K^+ \rightarrow \pi^+\pi^0(\gamma)$) improved the accuracy. Recently KLOE has also measured the $K_S$ lifetime from the fit to the proper time distribution obtained with a sample of $\sim 20$ million $K_S \rightarrow \pi^+\pi^-$ decays. The final result, presently the most precise, is $\tau_S = 89.562 \pm 9.029_{\text{stat}} \pm 0.043_{\text{syst}} \text{ps}$ \[3\]. To extract $V_{us}f_+(0)$ we use eq. 1 together with the $SU(2)$-breaking and long distance $EM$ corrections to the full
The measured values of $V_{us}f_+(0)$ are \([5]\): 0.2155(7) for $K_L\rho$$3$, 0.2167(9) for $K_L\mu$$3$, 0.2153(14) for $K_S\rho$$3$, 0.2152(13) for $K^\pm\rho$$3$, and 0.2132(15) for $K^\pm\nu$$3$ decays. Their average is $V_{us}f_+(0) = 0.2157(6)$ ($\chi^2/ndf = 7.0/4$, Prob=13\%), with 0.28\% accuracy to be compared with the 0.23\% of the world average $V_{us}f_+(0) = 0.2165(5)$ \([6]\). Defining $r_{\mu e} = |f_+(0) V_{us}|^2 / |f_+(0) V_{us}|^2 = g_\mu^2/g_e^2$, with $g_\mu$ the coupling strength at the $W \to \ell\nu$ vertex, lepton universality can be tested comparing the measured value with its Standard Model (SM) prediction $r_{\mu e}^{SM} = 1$. We obtain $r_{\mu e} = 1.000(8)$, averaging between charged and neutral modes, to be compared with $(r_{\mu e})_\pi = 1.0042(33)$ from leptonic pion decays, and $(r_{\mu e})_\tau = 1.0005(41)$ from leptonic $\tau$ decays \([7]\). Using $V_{us}f_+(0)$ from $K_{3\tau}$ decays and $f_+(0) = 0.964(5)$ \([8]\), we get $V_{us} = 0.2237(13)$. Furthermore $V_{us}/V_{ud}$ can be measured using 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 $f_K/f_\pi$. Using $BR(K^\pm \to \mu^\pm\nu) = 0.6366(17)$ from KLOE \([9]\) and $f_K/f_\pi = 1.189(7)$ \([10]\), we get $V_{us}/V_{ud} = 0.2323(15)$. Combining this result with $V_{us}$ from $K_{3\tau}$ decays and $V_{ud} = 0.97418(26)$ \([11]\), CKM unitarity has been verified to the level of $1 - V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 4(7) \times 10^{-4}$. We then obtained $G_{\text{CKM}} = G_F(V_{ud}^2 + V_{us}^2 + V_{ub}^2)^{1/2} = 1.16614(40) \times 10^{-5}$ GeV$^{-2}$, is in perfect agreement with the measurement from the muon lifetime $G_F = 1.166371(6) \times 10^{-5}$ GeV$^{-2}$. This result significantly improves the accuracy obtained with evaluations from tau-lepton decays and electroweak precision tests.

### Table 1: Summary of KLOE results useful for $V_{us}$ measurement

| Branching ratios | Lifetimes and Form factors (dispersive approach) |
|------------------|-----------------------------------------------|
| $K_L \to \pi e\nu$ | $V_{us}$ = 0.4008 ± 0.0015 |
| $K_L \to \pi \mu\nu$ | 0.2699 ± 0.0014 |
| $K_S \to \pi^+\pi^-$ | 0.60196 ± 0.00051 |
| $K_S \to \pi^0\pi^0$ | 0.30687 ± 0.00051 |
| $K^+ \to \mu^+\nu(\gamma)$ | 0.6366 ± 0.0017 |
| $K^+ \to \pi^+\pi^0(\gamma)$ | 0.2067 ± 0.0012 |
| $K^+ \to \pi^0e^+\nu(\gamma)$ | 0.04972 ± 0.00053 |
| $K^+ \to \pi^0\mu^+\nu(\gamma)$ | 0.03237 ± 0.00039 |

The KLOE-2 project aims at improving the successful and fruitful results achieved by the KLOE Collaboration in Kaon and Hadron Physics and extending the physics program \([12]\) to: $\gamma\gamma$-physics from $e^+e^- \to e^+e^- \gamma^\ast \gamma^\ast \to e^+e^- + X$ and search for particles

### 3 The KLOE-2 project

The KLOE-2 project aims at improving the successful and fruitful results achieved by the KLOE Collaboration in Kaon and Hadron Physics and extending the physics program \([12]\) to: $\gamma\gamma$-physics from $e^+e^- \to e^+e^- \gamma^\ast \gamma^\ast \to e^+e^- + X$ and search for particles
from hidden sectors that might explain dark matter. The project will exploit the new interaction scheme implemented and tested on the Frascati DAΦNE collider with the SIDDHARTA experiment in 2009 [13] with larger beam crossing angle and crab-waist sextupoles. This allowed a luminosity increase of factor of ∼3 to be reached with a peak luminosity $L = 4.5 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ and an integrated luminosity $\int L dt \sim 1 \text{pb}^{-1}/\text{h}$. With this new configuration $\int L dt \sim 5 \text{fb}^{-1}/\text{y}$ can be delivered.

After a first phase with the installation of the low-energy $e^+e^-$ (LET) [14, 15] and high-energy $e^+e^-$ (HET) [14, 16] tagging systems for the identification and study of $\gamma\gamma$ events, the detector will be upgraded with the insertion of an Inner Tracker (IT) [17, 18], between the beam pipe and the Drift Chamber (DC) inner wall, and with crystal calorimeters (CCALT) [19], covering the low $\theta$ region, and two new tile calorimeters (QCALT) [20] instrumenting the DAΦNE focusing system.

Using KLOE present data set together with the 5 fb$^{-1}$ KLOE-2/step0 foreseen statistics, we can improve the accuracy with respect to present world average [6] on the measurement of $K_L$, $K^\pm$ lifetimes and $K_{S\pi3}$ branching ratio, presently the main contributors to $f_\pi(0)V_{us}$ uncertainties. Statistical uncertainties on BRs and lifetimes have been obtained scaling present statistics to 7.5 fb$^{-1}$ total integrated luminosity and a conservative estimate of systematic errors has been obtained based on KLOE published analyses, without improvements from detector upgrades. Systematic errors in KLOE are partially statistical in nature, efficiencies are measured with data control samples, then also these contributions to the total uncertainty decrease with statistics.

The accuracy on the measurement of $\tau_L$ from the fit to the proper time distribution of $K_L \to 3\pi^0$ decays is expected to be reduced to 0.27% and furthermore below 0.2% with the QCALT insertion, improving photon reconstruction and control of systematic effects. With 7.5 fb$^{-1}$ total integrated luminosity a 0.1% accuracy on the $\tau_\pi$ measurement is expected to be reached and a factor of ∼2 improvement with the IT detection of $K^\pm$ tracks closer to the interaction point, improving the accuracy of the decay length technique.

The branching ratio of $K_{S\pi3}$ decays is expected to be measured with 0.6% accuracy and further improved to 0.3% with the IT. As a matter of fact the measurement of $K_{i3}$ decay rates will strongly benefit from the insertion of the IT detector: this upgrade will increase the acceptance for decays close to the interaction point with low momentum tracks and improve the resolution on their track and vertex parameters.

In conclusion, a significant reduction of the present experimental uncertainty on $V_{us}f_\pi(0)$ is expected: the present 0.23% fractional uncertainty on $V_{us}f_\pi(0)$ can be reduced to 0.14%, using KLOE present data set together with the KLOE-2/step0 statistics. Detector upgrades have not been considered in this evaluation. This, together with more precise measurements of $f_\pi(0)$ and $V_{ud}$ would allow us to reach the level of precision of a few $10^{-4}$ in the test on the unitarity relation thus improving the potential to investigate new physics within SM extensions with gauge universality breaking.
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