KLOE results on lepton flavor universality tests

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Abstract. Recent KLOE measurements allowing precision tests of lepton flavor universality are here briefly described, with particular emphasis on the analysis for the ratio of branching fractions for the $K^\pm \to e^\pm \nu_e$ and $K^\pm \to \mu^\pm \nu_\mu$ decays. The sensitivity of these tests, all obtained from the study of kaon decays, is compared to that from other sources.

1. Introduction
In the standard model (SM), electrons and muons differ only by mass and coupling to the Higgs boson. However, new-physics extensions of the SM with violation of the lepton flavor are not ruled out by the experiment. Therefore, one can either search for processes forbidden or ultra-rare in the SM, like $K^\pm \to e^\pm \nu_e$; or can measure with high precision the ratio of coupling constants for electrons and muons, seeking deviations from unity in processes which are well known in the SM. At KLOE, we followed the second approach by measuring the ratios of decay widths: $R_{e\mu} = \Gamma(K_{e3})/\Gamma(K_{\mu3})$, $R_K = \Gamma(K^\pm \to e^\pm \nu_e)/\Gamma(K^\pm \to \mu^\pm \nu_\mu)$, $R_{K\pi} = \Gamma(K^\pm \to \mu^\pm \nu_\mu)/\Gamma(\pi^\pm \to \mu^\pm \nu_\mu)$, discussed in Secs. 3, 4, and 5, respectively.

2. 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 $K^+K^-$ pairs with a BR of $\sim 49\%$. Kaons get a momentum of $\sim 100$ MeV/c which translates into a low speed, $\beta_K \sim 0.2$. The analysis of kaon decays is performed with the KLOE detector, consisting essentially of a drift chamber, DC [1], surrounded by an electromagnetic calorimeter, EMC [2]. A superconducting coil provides a 0.52 T magnetic field. In early 2006, the KLOE experiment completed data taking, having collected $\sim 2.5$ fb$^{-1}$ of integrated luminosity at the $\phi$ peak, corresponding to $\sim 3.6$ billion $K^+K^-$ pairs. A Monte Carlo (MC) data set was produced on a run-by-run basis, with luminosity scale factors equal to 1 for the main $K^\pm$ decay channels and to 100 for decay channels with BR’s less than $10^{-4}$.

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### 3. Lepton universality test from semileptonic kaon decays

At present, the measurement of decay width for semileptonic kaon decays allows the most accurate extraction of the CKM matrix element $V_{us}$. The master formula involves as theoretical inputs the $K^0 \rightarrow \pi^0$ form factor (FF) at zero momentum transfer $t$ ($f_+(0)$), corrected with a precision of few per mll [3] to account for long-distance radiative corrections and (for $K^+$ decays) isospin-breaking effects ($\delta_{i3,µ3} = 2\Delta'(em) + 2\Delta'(SU(2))$, and a short-distance electroweak correction [4] ($S_{EW} = 1.0232$):

$$
\Gamma_i(K_{e3(\gamma),µ3(\gamma)}) = |V_{us}|^2 \frac{C_2^2 G_F^2 M^5}{128\pi^3} S_{EW} |f_+^{K^0}(0)|^2 \cdot \frac{1}{\epsilon_{e3,µ3}} (1 + \delta_{i3,µ3}),
$$

where $i$ indexes $K^0 \rightarrow \pi^-$ and $K^+ \rightarrow \pi^0$ transitions for which $C_2^2 = 1$ and 1/2, respectively, $G_F$ is the Fermi constant, and $M$ is the appropriate kaon mass. The experimental inputs are the decay widths $\Gamma_i(K_{e3(\gamma),µ3(\gamma)})$, obtained from the measurement of the radiation-inclusive semileptonic branching ratio and of the kaon lifetime, and the phase-space integrals $I_{e3,µ3}$, calculated from the measured dependence of the vector and scalar form factors on $t$. At present, the uncertainty induced on $|f_+(0)|V_{us}|$ by the $\delta^p$ corrections is less than 0.2% [5].

All of the relevant experimental inputs to Eq. 1 have been measured at KLOE [6], yielding five measurements of $|f_+(0)|V_{us}|$ with accuracies from the various decay modes ranging from $\sim 0.7\%$ to $\sim 0.3\%$:

| Mode      | $f_+(0) \times |V_{us}|$ | Error, % | Input          | KLOE                  | External                  |
|-----------|-----------------|---------|----------------|---------------------|--------------------------|
| $K_{e3}$  | 0.21547(72)     | 0.34    | FF, BR, $\tau_L$ | $\tau_L$            |
| $K_{µ3}$  | 0.21661(93)     | 0.43    | FF, BR, $\tau_L$ | $\tau_S$            |
| $K_{e\ell}$ | 0.21522(145)   | 0.68    | FF, BR, $\tau_L$ | $\tau_L$            |
| $K_{µ\ell}$ | 0.21465(137)   | 0.64    | FF, BR, $\tau_L$ | $\tau_L$            |
| $K_{e\bar{\ell}}$ | 0.21302(155) | 0.73    | FF, BR, $\tau_L$ | $\tau_L$            |
| Average   | 0.21556(59)     | 0.27    | $P(\chi^2/n_{df}= 6.1/4) = 19\%$ |                      |

From the above results, the ratio $R_{µe} = |V_{us}(µ3)/V_{us}(e3)|^2$ of muon and electron effective couplings are: 1.0054(44) and 0.9924(54), for $K_L$ and $K^+$ respectively. While the $K_L$ BR’s in the 2004 PDG compilation [7] signalled a $> 3\sigma$ violation of lepton flavor universality, $R_{µe} = 1.0232(68)$, present KLOE results indicate equality of electron and muon couplings to better than 0.4%. The accuracy of this result is comparable to that obtained from $\tau \rightarrow l\nu\bar{\nu}$ and $\pi \rightarrow l\nu$ decays, $R_{µe} = 1.0005(41)$ [8] and $R_{µe} = 1.0034(30)$ [9].

### 4. New-physics potential of $R_K$

The SM prediction of $R_K$ benefits from cancellation of hadronic uncertainties to a large extent and therefore can be calculated with high precision. Including radiative corrections $^2$, the total uncertainty is less than 0.05% [10]. Deviations from the SM of up to few percent on $R_K$ are quite possible in minimal supersymmetric extensions of the SM, in particular due to lepton-flavour violating contributions with tauonic neutrinos emitted [11]. Using 1.7 fb$^{-1}$ of KLOE data, we obtained an accuracy of about 3% in the preliminary measurement of $R_K$, improving by a factor of two on the present error.

Given the $K^\pm$ decay length of $\sim 90$ cm, the selection of one-prong $K^\pm$ decays in the DC required to tag the presence of $K^\pm$ has an efficiency smaller than 50%. In order to keep the statistical uncertainty on the number of $K^\pm \rightarrow e^\pm \bar{\nu}_e$ counts below 1%, we decided to perform

$^2$ This prediction is made including all photons emitted by the process of internal bremsstralung (IB) while ignoring any contribution from structure-dependent direct emission (DE).
a "direct search" for $K^\pm \to e^\pm \nu_e$ and $K^\pm \to \mu^\pm \nu_\mu$ decays, without tagging. Selection starts requiring the presence of a one-prong decay vertex in a fiducial volume in the DC, reconstructed from a track which can be extrapolated backward to a region near the interaction point and a secondary track of relatively high momentum. Quality cuts are applied using $\chi^2$-like variables for the tracking of kaon and secondary particle and for the vertex fit. A powerful kinematic variable used to distinguish $K^+ \to e^+ \nu_e$ and $K^\pm \to \mu^\pm \nu_\mu$ decays from the background is calculated from the momenta of the kaon and the secondary particle measured in DC: assuming zero neutrino mass one can obtain the squared mass of the secondary particle, or lepton mass ($M^2_{lep}$).

The one-prong selection allows clean identification of a $K^\pm \to \mu^\pm \nu_\mu$ sample: we counted $499\,251\,584 \pm 35403$ $K^\pm \to \mu^\pm \nu_\mu$ events, fitting the $M^2_{lep}$ distribution and subtracting a fraction of less than 0.1% of background events under the peak at $m^2_{\mu\mu}$. Further rejection is needed in order to identify $K^\pm \to e^\pm \nu_e$ events, the background due to badly reconstructed $K^\pm \to \mu^\pm \nu_\mu$ events being ~10 times more frequent than the signal in the region around the peak at $m^2_{\mu\mu}$.

Information from the EMC is used to improve the background rejection. The secondary track is extrapolated to the EMC surface and associated to the nearest calorimeter cluster. For electrons, the energy $E_{cl}$ of the associated cluster is a measurement of the particle momentum $p_{ext}$ and is concentrated mainly in the first plane of EMC, so that the position $d_1$ along the track is only a few cm. On the contrary, muons behave like minimum ionizing particles in the first plane while they deposit a sizeable fraction of their kinetic energy from the third plane onward when they are slowed down to rest (Bragg peak). Cuts are therefore applied in the plane $E_{cl}/p_{ext} - d_1$ and on the asymmetry $A_1$ of energy deposits between the second and the first planes hit, the position $r_{\max}$ of the plane with the maximum energy, and the asymmetry $A_1$ of energy deposits between the last and the next-to-last planes. Using this PID technique, $K^\pm \to e^\pm \nu_e$ events are selected with an efficiency $\varepsilon_{Ke^2} \sim 64.7(6)\%$ and a rejection power for background of about 300 is reached. These numbers have been evaluated from MC.

The distributions of the spread $E_{RMS}$ of energy deposits on each cluster plane and of the missing mass $M^2_{lep}$ are finally used to extract the number of signal events. A two-dimensional likelihood fit was performed, using input distribution shapes for signal and background taken from MC and letting the normalizations for the two components as only fit parameters. The number of signal events obtained from the fit is $N_{Ke^2} = 8090 \pm 156$. Projections of the fit results onto the two axes are compared to real data in Fig. 1.

The following formula has been used to evaluate the ratio $R_K$:

$$R_K = \frac{N_{Ke^2}}{N_{K\mu^2}} \left[ \frac{\varepsilon^{TRK}_{Ke^2}}{\varepsilon^{TRK}_{K\mu^2}} \right] \left[ \frac{C^{TRK}_{Ke^2}}{C^{TRK}_{K\mu^2}} \right] \left[ \frac{1}{C^{PID}_{Ke^2}C^{PID}_{K\mu^2}} \right] \frac{1}{\varepsilon^{IB}}; \quad (3)$$

where $\varepsilon^{TRK}_{Ke^2}$ and $\varepsilon^{TRK}_{K\mu^2}$ are the efficiencies for the one-prong selection for $K^\pm \to e^\pm \nu_e$ and $K^\pm \to \mu^\pm \nu_\mu$ decays, evaluated from MC; the correction $C^{TRK} = 0.994(9)$ to their ratio accounts for possible differences between the data and the MC prediction and has been evaluated from small (10 pb$^{-1}$) data and MC samples of $K^\pm \to \mu^\pm \nu_\mu$ events. The quoted statistical error will be reduced to a negligible level after processing of the entire statistics. The PID efficiency for $K^\pm \to e^\pm \nu_e$ events $\varepsilon^{PID}_{Ke^2}$ has been evaluated from MC, while a correction $C^{PID}$ has been evaluated to account for possible discrepancies between data and MC in the description of PID variables. From a 600-pb$^{-1}$ data sample of $K_{Le3}$ events, we evaluated $C^{PID} = 1.009(9)(15)$, where the

The primary generators for $K^\pm \to e^\pm \nu_e$ and $K^\pm \to \mu^\pm \nu_\mu$ decay include radiative corrections and allow for the emission of a single photon in the final state [12]. $K^\pm \to e^\pm \nu_e + \gamma$ with photon energy in the kaon rest frame $E_\gamma < 20$ MeV were considered as signal: the DE contribution is indeed negligible in this range. While evaluating the shape for $K \to e\nu(\gamma)$, the present PDG value has been used for the ratio of IB and DE contributions. The fit has been repeated with different values of this ratio, varied within its range of uncertainty. This procedure gave a $\sim 0.3\%$ error on the number of signal counts.
Figure 1. Lepton mass squared $M_{lep}^2$ of the secondary track (left panel) and spread $E_{RMS}$ of the energy deposits among the planes of its connected EMC cluster (right panel). Filled dots are data, open dots are the result from a maximum-likelihood fit using signal and background (solid line) distributions as input from MC.

first error is due to the sample statistics and the second is due to its incomplete coverage of the $K^\pm \to e^\pm \tau_e$ kinematics. Trigger efficiencies $\varepsilon^{TRG}$ were instead evaluated directly from data, by comparing two almost independent trigger algorithms based on DC and EMC information. We evaluated $\varepsilon^{TRG}_{K,\mu^2}/\varepsilon^{TRG}_{K,\ell^2} = 0.998(9)(6)$, where again the first and second errors are statistical and systematic, respectively. Finally, $\varepsilon^{IB}$ is the fraction of the IB component accepted in the selection of $K^\pm \to e^\pm \tau_e$ events and has been evaluated from MC to be $\varepsilon^{IB} = 0.9528(5)$.

The preliminary result is $R_K = 2.55(5)(5) \times 10^{-5}$, which is compatible within the error with the SM prediction $R_K = 2.477(1) \times 10^{-5}$ and with the result from two preliminary measurements from NA48 experiment $R_K = 2.43(4) \times 10^{-5}$ [13].

5. New-physics sensitivity from $K^\pm \to \mu^\pm \nu_\mu$ decays

The helicity suppression due to the $V-A$ structure of the charged weak current makes the leptonic decays $K, \pi \to \ell \nu$ capable of receiving contributions from NP, e.g., from multi-Higgs effects inducing an effective pseudoscalar hadronic weak current. In minimal supersymmetric extensions of the SM, the charged Higgs contribution to the leptonic widths at tree level is [14]:

$$\Gamma(M \to \ell \nu)_{NP} = \Gamma(M \to \ell \nu)_{SM} \left(1 - \tan^2 \beta \frac{m_{d,s}}{m_{d,s} + m_u} \frac{m_M^2}{m_H^2}\right)^2,$$

where $m_{u,d,s}$ are the quark masses, $M = \pi, K$, and $\tan \beta$ is the ratio of vacuum expectations values of the up and down Higgs fields. For $M_H = 500$ GeV and $\tan \beta = 50$, a deviation of $\sim 0.4\%$ is expected on the ratio $\Gamma(K \to \mu \nu)/\Gamma(\pi \to \mu \nu)$ with respect to the SM prediction,

$$\frac{\Gamma(K \to \mu \nu)}{\Gamma(\pi \to \mu \nu)}_{SM} = \frac{|V_{ua}|^2}{V_{ud}|^2} \times \frac{f_K^2}{f_\pi^2} \times \frac{m_K}{m_\pi} \left(1 - \frac{m_\mu^2}{m_K^2}\right) \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2 \times (1 + \delta),$$

where the $\delta$ correction including radiative effects for $K$ and $\pi$ decays [15] and the ratio $f_K/f_\pi$ of form factors [16] are presently known better than 1%. Using the precise KLOE measurement $BR(K \to \mu \nu) = 63.66(17)\%$, the KLOE-PDG average for the kaon lifetime, and the PDG
values for the masses and for $\Gamma(\pi \to \mu \nu)$, we obtain: $V_{us}/V_{ud} = 0.2323(15)$. From Eq. 4, we observe that NP effects mainly affect the $K \to \mu \nu$ widths, so we allowed for a possible difference between the value $V_{us}(\mu2)$ entering in Eq. 5 and that, $V_{us}(l3)$, obtained from semileptonic kaon decays. To check this assumption, we performed a fit leaving as free parameters $V_{us}(\mu2)$ and $V_{us}(l3)$, with the following inputs: the above measurement $V_{us}(\mu2)/V_{ud} = 0.2323(15)$; the KLOE measurement $V_{us}(l3) = 0.22635(86)$, obtained using recent lattice result $f_+(0) = 0.9609(51)$ [17]; the world-average value from super-allowed nuclear $\beta$-decays, $V_{ud} = 0.97372(27)$ [18]. The fit assumes CKM unitarity for the semileptonic decays, $V_{us}(l3)^2 + V_{ud}^2 = 1$. The results are: $V_{us}(\mu2) = 0.22626(186)$ and $V_{us}(l3) = 0.22635(86)$, with a $\sim 3\%$ correlation. The result can be translated into an 95%-CL exclusion plot in the plane $\tan\beta$ vs $M_H$ (see Fig. 2), showing that this analysis is complementary to and competitive with that [19] using the average $\text{BR}(B \to \tau \nu) = 1.42(44) \times 10^{-4}$ of Babar and Belle measurements [20].

![Figure 2](image_url)

**Figure 2.** Excluded regions at 95% CL from analysis of decays $K \to \mu \nu$ (filled area) and $B \to \tau \nu$ (hatched area).

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