Measurement of the absolute branching ratio for the $K^+ \to \mu^+ \nu(\gamma)$ decay with the KLOE detector

KLOE Collaboration

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Abstract

We have measured the fully inclusive $K^+ \to \mu^+ \nu(\gamma)$ absolute branching ratio with the KLOE experiment at DAΦNE, the Frascati ϕ-factory. From some 865 283 $K^+ \to \mu^+ \nu(\gamma)$ decays obtained from a sample of $\sim 5.2 \times 10^8$, ϕ-meson decays, we find BR($K^+ \to \mu^+ \nu_\mu(\gamma)) =

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$0.6366 \pm 0.0009_{\text{stat.}} \pm 0.0015_{\text{syst.}}$, corresponding to an overall fractional error of 0.27%. Using recent lattice results on the decay constants of pseudoscalar mesons one can obtain an estimate for the CKM mixing matrix element $|V_{us}| = 0.2223 \pm 0.0026$.

1. Introduction

The most recent measurement of the $K \to \mu\nu$ branching ratio, Ref. [1], based on 62 000 events, dates back to 1972, more than 30 years ago, and relies on a sample of $\sim 10^5$ kaon decays. The authors of Ref. [1] quote an error of $\sim 0.7\%$, the statistical error due to the event count being 0.4%. This error is reduced in the PDG fit [2] to 0.27% and the value changed by 0.3%. While the procedure is correct in principle, it can lead to incorrect results because of incorrect data included in the fit. This has been the case sometimes, leading among other things to the suggestion, also in Ref. [2], of a value for $|V_{us}|$ apparently inconsistent with unitarity of the CKM mixing matrix [3]. Another problem with measurements performed more than 30 years ago is due to the fact that the effect of radiative corrections was not fully appreciated. It is therefore impossible to understand what fraction of the radiative decay is included in the quoted results. Inclusion of all radiation is however necessary to compare to models or to extract fundamental parameters such as a coupling constant. With all the above in mind as well as recent developments in numerical or lattice QCD calculation, we have begun a program of new precise, fully inclusive, kaon branching ratio measurement.

We report in the following a measurement of BR($K^+ \to \mu^+\nu(\gamma)$) performed with the KLOE detector at DAΦNE, the Frascati ϕ-factory. The measurement is based on an integrated luminosity of ~ 175 pb^{-1}, collected in 2001–2002. DAΦNE is an e^+e^- collider operated at a total energy of $W = 1020$ MeV, the mass of the $\phi(1020)$-meson. Equal energy positron and electron beams collide at an angle of $(\pi-)25$ mrad and produce ϕ-mesons with a small transverse momentum of ~ 12.5 MeV/c. The collision frame moves therefore in the laboratory with a velocity $\beta \sim 0.0125$. In the center of mass, the ϕ-meson decays into anti-collinear $K^\pm$ pairs of ~ 125 MeV/c momentum. In the laboratory this remains approximately true: detection of a $K^\pm$ tags the presence of a $K^\mp$ of given momentum and direction. The decay products of the $K^\pm$ pair define two spatially well separated regions called in the following the tag and the signal hemispheres. Identified $K^\mp$ decays tag a $K^\pm$ beam and provide an absolute count. This procedure is a unique feature of a ϕ-factory and provides the means for measurements of absolute branching ratios, i.e., ratios $\Gamma_i/\Gamma_{\text{tot}}$ rather than ratios of BR's Γ_i/Γ_j.

2. The KLOE detector

The KLOE detector consists of a large volume drift chamber and a sampling calorimeter. The drift chamber (DC) [4], of 3.3 m length and 2 m radius, has a full stereo geometry and operates with a 90% helium-10% isobutane gas mixture. Tracking in the DC provides measurements of the vector momentum of charged particles with $\sigma(p_\perp)/p_\perp \leqslant 0.4\%$ and two track vertices to 3 mm. In the following we use a coordinate system with the z-axis defined as the bisectrix of the e^+e^- beams, the y-axis vertical and the x-axis toward the center of the collider rings.

The calorimeter (EMC) [5] consists of a cylindrical barrel and two endcaps covering a solid angle of 98% of 4π. Photons showering in the lead-scintillator-fiber EMC structure are detected as local energy deposits by clustering signals from read-out elements. The calorimeter information consists of energy, position of entry point and time of arrival with accuracies of $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$, $\sigma_z = 1.2$ cm$/\sqrt{E(\text{GeV})}$, $\sigma_\phi = 1.2$ cm and $\sigma_t = 54$ ps$/\sqrt{E(\text{GeV})} \oplus 50$ ps. Calorimeter clusters not associated with a DC track indicate arrival of neutral particles and the computed time of flight identifies photons with excellent precision. Time of flight also allows good separation of electrons from muons, pions and kaons.

A superconducting coil surrounds the entire detector and produces a solenoidal field $B = 0.52$ T. The trigger [6] is based on the detection of isolated energy deposits in the calorimeter and on hit multiplicity in the drift chamber. Only events triggered by the calorimeter have been used in the present analysis. This choice ensures a far more reliable estimate of all necessary efficiencies. The trigger system also includes a veto for cosmic-ray muons (cosmic ray veto or CRV) based on energy deposits in the outermost layers of the calorimeter and followed by a third-level software trigger able to identify most of the ϕ events. A software filter (filfo or FLF), based on the topology and multiplicity of calorimeter clusters and drift chamber hits, is applied to filter out machine background.

Both CRV and FLF are sources of event rejection. Their effect on the BR measurement has been studied on control samples which do not undergo, respectively, the CRV, and the FLF filter.

3. The measurement

The entire data sample of 175 pb^{-1} is divided into two subsamples.

Some 60 pb^{-1} of data have been used for the BR measurement. The remaining 115 pb^{-1} have been used to evaluate efficiencies and the background. The control sample is uniformly distributed in the time throughout the exposure. The branching ratio measurement [7] is based on the use of $K^- \to \mu^-\nu$ decays for event tagging and to search for the $K^+ \to \mu^+\nu(\gamma)$ signal among K^+ decays. The tagging selection is based on the presence of a two-tracks vertex in the DC which signals the K^- decay [7].

Nuclear interactions, NI, of kaons affects the branching ratio measurement but not the tagging procedure. Since $\sigma_{\text{NI}}(K^+) \sim \sigma_{\text{NI}}(K^-)/10^2$, the choice above minimizes the corrections to be calculated to account for the effect. The corrections are in
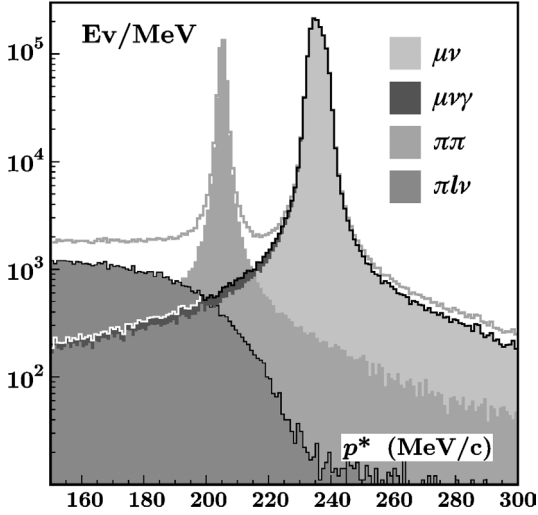
Fig. 1. Monte Carlo spectra of the charged decay particle momentum transformed to the kaon rest frame, assuming the pion mass. The two peaks corresponds to pions from $K^+ \to \pi^+\pi^0$ at 205 MeV/c and $K^+ \to \mu^+\nu$ at 236 MeV. The black/white line represents the signal while the grey line the signal plus background. Contributions from $K^+ \to \mu^+\nu\gamma$ are also shown.

fact negligible. The large number of K^+ decays is sufficient for achieving a statistic accuracy at the 0.1% level, comparable with the systematic error.

To avoid any bias due to differences in the trigger efficiency among the K^+ decay modes on the signal "hemisphere", the particles on the tagging side are required to deposit enough energy in the calorimeter to trigger the data acquisition. Nevertheless, the tagging criteria exhibit a residual, small dependence on the decay mode of the K^+ on the signal hemisphere, introducing a tag bias or TB, that has been studied using Monte Carlo simulation (MC) samples [8] and checked on data.

The search for positive kaon moving outwards in the DC, with momentum $70 < p_K < 130$ MeV/c, is performed on the sample of tagged events. The point of closest approach to the beam line with coordinates $\{x, y, z\}$ is evaluated extrapolating the kaon track backwards to the beam line, taking into account the kaon energy loss. Kaon tracks with $|z| < 20$ cm and $\sqrt{x^2 + y^2} < 10$ cm, and kaon decay vertices in the fiducial volume, $40 < \sqrt{x_V^2 + y_V^2} < 150$ cm, are selected.

The number of $K^+ \to \mu^+\nu(\gamma)$ decays is obtained counting the events with $225 \leqslant p^* \leqslant 400$ MeV/c; p^* is the charged decay particle momentum computed in the kaon rest frame assuming the pion mass. The p^* distribution is shown in Fig. 1.

The spectrum in Fig. 1, obtained from MC simulation, shows a 2% contamination from various background sources, namely $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^0 l^+\nu$. Since the maximum momentum of the pions from three-pion decays is 125 MeV/c, these channels do not contribute to the background. All the background sources in this analysis have one neutral pion in the final state. The neutral pions are identified by detecting the photons from $\pi^0 \to \gamma\gamma$ decay. The photons are identified as isolated energy deposits in EMC not associated with tracks and satisfying the constraints on π^0 mass reconstruction and time correlation with the kaon decay vertex [7]. This selection allows us to obtain di-

rectly from data the p^* distribution of the background. The p^* distribution for the signal events has been obtained from a data control sample described in the following efficiency evaluation. This distribution has been used together with the shape of the background sources to fit the overall p^* spectrum, Fig. 2 left, and to perform background subtraction. The result, after background subtraction, is shown in Fig. 2 right.

The branching ratio is obtained from

$$\mathrm{BR}\big(K^+ \to \mu^+\nu(\gamma)\big) = \frac{N_{K^+ \to \mu^+\nu(\gamma)}}{N_{\mathrm{Tag}}} \frac{1}{\epsilon C_{\mathrm{CRV}} C_{\mathrm{FF}} C_{\mathrm{TB}}}, \qquad (1)$$

where $N_{K^+ \to \mu^+\nu(\gamma)}$ are the events selected as signal (hereafter signal count), N_{Tag} is the number of tagged events and ϵ is the efficiency. C_{CRV} and C_{FF} are the corrections for the effects due to the cosmic-ray veto and the filfo procedure, and C_{TB} accounts for the tag bias effect.

The efficiency of the analysis cuts has been determined directly on data using a control sample of $K \to \mu\nu(\gamma)$ events selected exploiting their typical signature in the EMC. The control sample consists of events with $K^- \to \mu^-\nu(\gamma)$, providing the tag, and signal events $K^+ \to \mu^+\nu(\gamma)$ selected using only EMC information. This criterion is mostly independent from the selection procedure based on DC information that has been used for obtaining the signal count. The EMC selection requires only one cluster with $E > 80$ MeV (high energy cut), plus any number of clusters with energy below 20 MeV (low energy cut) which can be due to photons from $K^+ \to \mu^+\nu\gamma$. Further cuts on the energy (E_{cl}) and on the distance in the transverse plane from the z-axis (R_{xy}) of the cluster are applied to get rid of machine background and spurious clusters. Namely we require the cluster either to be on the barrel $R_{xy} > 197$ cm or to satisfy the relation $E_{\mathrm{cl}}/(1\ \mathrm{GeV}) + R_{xy}/5(\mathrm{cm}) \geqslant 110$. We have checked that the distributions of various quantities are quite similar, small differences have been included in the systematic uncertainties. A correction of about 0.1%, due to a tiny difference between the efficiency evaluated on the control sample and the selection efficiency on the signal sample, has been estimated from MC. The efficiency is $\epsilon = 0.3153 \pm 0.0002$.

The corrections to the event rejection described above, $C_{\mathrm{CRV}} = 1.0005$ and $C_{\mathrm{FF}} - 1 = \mathcal{O}(10^{-5})$, have been directly measured on control samples which do not undergo, respectively, the cosmic-ray veto, and the filfo filter. The correction for the tag bias, $C_{\mathrm{TB}} = 1.0164 \pm 0.0002$, has been evaluated on Monte Carlo samples and the distribution of the variables used for the tag selection have been checked on data. The following sources of systematic uncertainties have been studied varying the selection cuts, larger than reasonably required [7]:

- the requirements on the tagging hemisphere;
- the trigger requirements;
- the definition of the fiducial volume;
- the background evaluation procedure;
- the choice of the $[p^*_{\min}, p^*_{\max}]$ range;
- the energy cuts for the efficiency sample;
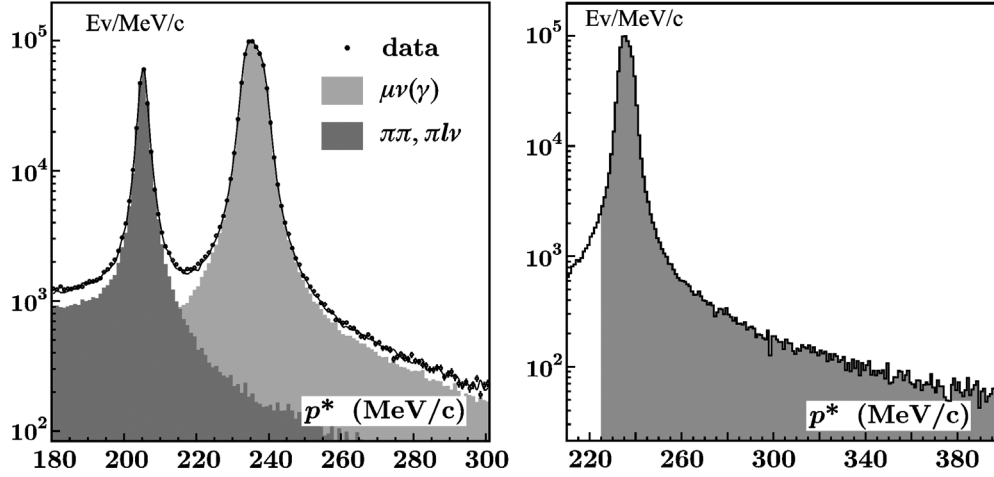- the effect of high-energy radiative photons ($E_\gamma > 20$ MeV).

Fig. 2. Left: spectrum of the charged-secondary momentum in the kaon rest frame for data. The solid line indicates the fit done with a linear combination of signal and background distributions obtained from data. Right: the same spectrum after background subtraction. The range used for counting $K^+ \to \mu^+ \nu(\gamma)$ events is indicated.

Table 1
Summary table of systematic uncertainties

Source	Value
Low energy cut	5×10^{-4}
$E_\gamma > 20$ MeV	7×10^{-4}
High energy cut	2×10^{-4}
Fiducial volume	5×10^{-4}
Background	3×10^{-4}
p^* range	3×10^{-4}
Tag definition	1×10^{-4}
MC lifetime	$< 10^{-6}$
Nuclear interactions	$< 4 \times 10^{-4}$
Filfo	$< 3 \times 10^{-4}$
Cosmic ray veto	$\mathcal{O}(10^{-6})$
Trigger	9×10^{-4}
Total syst.	15×10^{-4}

The maximum variation of the BR with respect to the variable has been used as measure of the systematic uncertainty. Furthermore, the dependence of the measurement on the charged kaon lifetime, which affects the estimate of the geometrical acceptance, has been studied varying the lifetime value used in the MC simulation. The effects due to K^+ nuclear interactions have been evaluated from MC simulation and measurements available in literature. The stability of the measurement with respect to different data taking conditions has been checked. The corresponding systematic errors are listed in Table 1.

The statistical error due to the event count is 6×10^{-4} and becomes 9×10^{-4} including the statistics of MC simulation and data used for the efficiency evaluation.

4. Conclusions

4.1. BR measurement

On a sample of tagged events $N_{\text{Tags}} = 4\,237\,329$, we found a number of signal events, with $225 \leqslant p^* \leqslant 400$ MeV/c, of $N_{K^+ \to \mu^+ \nu(\gamma)} = 865\,283$.

Using Eq. (1), the absolute branching ratio is

$$\text{BR}\big(K^+ \to \mu^+ \nu(\gamma)\big) = 0.6366 \pm 0.0009_{\text{stat.}} \pm 0.0015_{\text{syst.}}. \quad (2)$$

The KLOE measurement of the BR($K^+ \to \mu^+ \nu(\gamma)$), fully inclusive of final-state radiation, has a 0.27% accuracy and it is based on an unprecedented statistics and carefully controlled systematics.

4.2. V_{us} extraction

The recent publication [9] of the results of lattice QCD calculations has renewed the interest in improving the accuracy of the BR($K^+ \to \mu^+ \nu(\gamma)$), which represents an experimental alternative to the semileptonic kaon decays in measuring $|V_{us}|$ as pointed out by Marciano in Ref. [10].

The extraction of this CKM matrix element is based on the ratio of the decay rates for the inclusive decays $K^+ \to \mu^+ \nu(\gamma)$ and $\pi^+ \to \mu^+ \nu(\gamma)$:

$$\frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = \frac{m_K(1 - \frac{m_\mu^2}{m_K^2})^2}{m_\pi(1 - \frac{m_\mu^2}{m_\pi^2})^2} \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{1 + \frac{\alpha}{\pi} C_K}{1 + \frac{\alpha}{\pi} C_\pi}, \quad (3)$$

where f_K and f_π are, respectively, the kaon and the pion decay constants; C_π and C_K parametrize the radiative-inclusive electroweak corrections, taking into account bremsstrahlung emission of real photons and of virtual-photon loop contributions as well. Using the branching ratios of $K^+ \to \mu^+ \nu(\gamma)$ and $\pi^+ \to \mu^+ \nu(\gamma)$ decays, the $|V_{ud}|$ value from super-allowed nuclear beta decays, C_π and C_K from Ref. [10] and references therein, and the new lattice calculation of f_K/f_π [9], it is possible to extract $|V_{us}|$ with an uncertainty at the percent level, whose error is mainly dominated by the accuracy of lattice calculations. From the BR measurement, using the determination of $f_K/f_\pi = 1.210(4)(13)$, we have obtained the ratio

$$\left|\frac{V_{us}}{V_{ud}}\right|^2 = 0.05211 \pm 0.00016 \pm 0.00019 \pm 0.00117, \quad (4)$$

where the errors correspond, respectively, to the experimental, the structure-dependent radiative corrections, and the lattice uncertainties. Taking V_{ud} from super-allowed nuclear β decays, $V_{ud} = 0.9740 \pm 0.0005$ [11], one determines $|V_{us}|$

$$|V_{us}|_{K^+ \to \mu^+ \nu(\gamma)} = 0.2223 \pm 0.0026. \tag{5}$$

The accuracy is dominated by the knowledge of f_K/f_π from lattice calculation. Alternatively, the unitarity relationship $|V_{ud}|^2 = 1 - |V_{us}|^2$ can be assumed in Eq. (4) giving:

$$|V_{us}|_{\text{unitarity}} = 0.2225 \pm 0.0025 \tag{6}$$

independent of the V_{ud} measurement. The result quoted in Eq. (5) is in agreement with the unitarity of the CKM matrix (Eq. (6)) and with the determinations of V_{us} from semileptonic decays, whose precision is dominated by the $f_+(0)$ calculations [12].

Acknowledgements

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