

Lepton universality test with $K^+ \rightarrow l^+ \nu$ decays at the NA62 experiment at CERN

Evgueni Goudzovski*

University of Birmingham

E-mail: eg@hep.ph.bham.ac.uk

The NA62 experiment at CERN collected a large sample of $K^+ \rightarrow e^+ \nu$ decays during a dedicated run in 2007, which allows a precise test of lepton universality by measurement of the helicity suppressed ratio $R_K = \Gamma(K^+ \rightarrow e^+ \nu) / \Gamma(K^+ \rightarrow \mu^+ \nu)$. The preliminary result of the analysis of a partial data sample of 51089 $K^+ \rightarrow e^+ \nu$ candidates is $R_K = (2.500 \pm 0.016) \times 10^{-5}$, consistent with the Standard Model expectation.

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*Speaker.

Introduction

The ratio of kaon leptonic decay rates $R_K = \Gamma(K_{e2}^\pm)/\Gamma(K_{\mu 2}^\pm)$ has been calculated with an excellent accuracy within the Standard Model (SM) [1]: $R_K^{\text{SM}} = (m_e/m_\mu)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 (1 + \delta R_{\text{QED}}) = (2.477 \pm 0.001) \times 10^{-5}$, where $\delta R_{\text{QED}} = (-3.78 \pm 0.04)\%$ is a correction due to the inner bremsstrahlung (IB) $K_{\ell 2\gamma}$ process which is, unlike the structure dependent (SD) $K_{\ell 2\gamma}$ process, by definition included into R_K . The factor $(m_e/m_\mu)^2$ accounts for the helicity suppression of the K_{e2} decay due to the $V - A$ structure of the charged weak current, and enhances sensitivity to non-SM effects. In particular, enhancement of R_K by a few percent (relative) is possible in the MSSM with non-vanishing $e - \tau$ lepton mixing [2], compatible to the presently known experimental constraints.

The current world average composed of three 1970s measurements [3] and a recent KLOE result [4] is $R_K^{\text{WA}} = (2.467 \pm 0.024) \times 10^{-5}$. It has 1% relative precision and is compatible to the SM. The NA62 experiment at CERN collected data in 2007–08 aiming at an R_K measurement with 0.4% precision. The preliminary result obtained with a partial data sample is presented here.

1. Beams, detector and data taking

The NA48/2 beam line and setup were used; running conditions were optimized for the K_{e2} measurement in 2007 using the experience of earlier studies based on NA48/2 data sets [5].

The beam line is capable of delivering simultaneous narrow momentum band K^+ and K^- beams; a central momentum 74 GeV/c was used in 2007. Momentum of the incoming kaon is not measured directly in every event; the beam average monitored with $K^\pm \rightarrow 3\pi^\pm$ decays is used to reconstruct K_{l2} kinematics by missing mass M_{miss} . A narrow momentum spectrum ($\Delta p_K^{\text{RMS}}/p_K \approx 2\%$) is used to minimize the corresponding contribution to the M_{miss} resolution.

The K_{l2} decay signature consists of a single reconstructed track. Since the incoming K^+ is not tracked, backgrounds induced by the beam halo have to be considered. The performance of the muon sweeping system results in lower background in K_{e2}^+ sample ($\sim 1\%$) than in K_{e2}^- sample ($\sim 20\%$), therefore $\sim 90\%$ of the data were taken with the K^+ beam only, and small fractions were recorded with simultaneous beams and K^- beam only. The halo background is directly measurable using the samples of reconstructed K_{l2} candidates of the sign not present in the beam.

Among the subdetectors located downstream a vacuum decay volume, a magnetic spectrometer, a plastic scintillator hodoscope (HOD) and a liquid krypton electromagnetic calorimeter (LKr) are principal for the measurement. The spectrometer, used to detect charged products of kaon decays, is composed of four drift chambers (DCHs) and a dipole magnet. The HOD, used to produce fast trigger signals, consists of two planes of strip-shaped counters. The LKr, used for γ detection and particle identification, is an almost homogeneous ionization chamber, $27X_0$ deep, segmented transversally into 13,248 cells (2×2 cm² each), and with no longitudinal segmentation. A beam pipe traversing the centres of the detectors allows undecayed beam particles and muons from decays of beam pions to continue their path in vacuum.

A minimum bias trigger configuration is employed, resulting in high efficiency with relatively low purity. The K_{e2} trigger condition consists of coincidence of hits in the HOD planes (the so called Q_1 signal) with 10 GeV LKr energy deposition. The $K_{\mu 2}$ trigger condition consists of the Q_1 signal alone downscaled by a factor of 150. Loose upper limits on DCH activity are also applied.

Most data taking took place during four months in 2007. Two weeks of data taking allocated in 2008 were used to collect special data samples for studies of systematic effects. The present analysis is based on $\sim 40\%$ of the 2007 data sample collected with the K^+ beam only.

2. Analysis strategy and event selection

Monte Carlo (MC) simulations are used to a limited extent only: 1) to evaluate a correction for the difference of K_{e2} and $K_{\mu2}$ geometric acceptances; 2) to simulate energetic bremsstrahlung by a muon, which is not directly accessible experimentally as discussed below.

In order to compute geometrical acceptances, a detailed Geant3-based MC simulation is employed. It includes full detector geometry and material description, stray magnetic fields, local inefficiencies, misalignment, detailed simulation of the beam line, and time variations of the above throughout the running period. The $K_{\ell2(\gamma)}$ processes are simulated in one-photon approximation [1]. Unlike the KLOE analysis [4], the resummation of leading logarithms [6] is not included into the simulation for the preliminary result.

The analysis strategy is based on counting the numbers of reconstructed K_{e2} and $K_{\mu2}$ candidates collected simultaneously, consequently the result does not rely on kaon flux measurement, and the systematic effects due to the detector efficiency cancel to first order. To take into account the momentum dependence of signal acceptance and background level, the measurement is performed independently in bins of reconstructed lepton momentum. The ratio R_K in each bin is computed as

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{f_\mu \times A(K_{\mu2}) \times \varepsilon(K_{\mu2})}{f_e \times A(K_{e2}) \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{\text{LKr}}}, \quad (2.1)$$

where $N(K_{\ell2})$ are the numbers of selected $K_{\ell2}$ candidates ($\ell = e, \mu$), $N_B(K_{\ell2})$ are numbers of background events, f_ℓ are efficiencies of e/μ identification criteria, $A(K_{\ell2})$ are geometrical acceptances computed with MC, $\varepsilon(K_{\ell2})$ are trigger efficiencies, f_{LKr} is the global efficiency of the LKr readout, and $D = 150$ is the downscaling factor of the $K_{\mu2}$ trigger.

Due to topological similarity of K_{e2} and $K_{\mu2}$ decays, a large part of the selection conditions is common for both decays: (1) exactly one reconstructed charged particle track; (2) its momentum $15 \text{ GeV}/c < p < 65 \text{ GeV}/c$ (the lower limit is due to the 10 GeV LKr energy deposit trigger requirement in K_{e2} trigger); (3) extrapolated track impact points in DCH, LKr and HOD are within their geometrical acceptances; (4) no LKr energy deposition clusters with energy $E > 2 \text{ GeV}$ and not associated to the track to suppress background from other kaon decays; (5) distance between the charged track and the nominal kaon beam axis $\text{CDA} < 1.5 \text{ cm}$, decay vertex longitudinal position within the nominal decay volume (the latter condition is optimized in each momentum bin).

The following two principal selection criteria are different for the K_{e2} and $K_{\mu2}$ decays. $K_{\ell2}$ kinematic identification is based on the reconstructed squared missing mass assuming the track to be an electron or a muon: $M_{\text{miss}}^2(\ell) = (P_K - P_\ell)^2$, where P_K, P_ℓ ($\ell = e, \mu$) are the four-momenta of the kaon (average beam momentum assumed) and the lepton (electron or muon mass assumed). A cut $|M_{\text{miss}}^2(e)| < M_0^2$ is applied to select K_{e2} candidates, and $|M_{\text{miss}}^2(\mu)| < M_0^2$ for $K_{\mu2}$ ones, where M_0^2 varies from 0.009 to 0.013 $(\text{GeV}/c^2)^2$ among track momentum bins depending on M_{miss} resolution. Particle identification is based on the ratio E/p of track energy deposit in the LKr to its momentum measured by the spectrometer. Particles with $0.95 < E/p < 1.1$ ($E/p < 0.85$) are identified as electrons (muons).

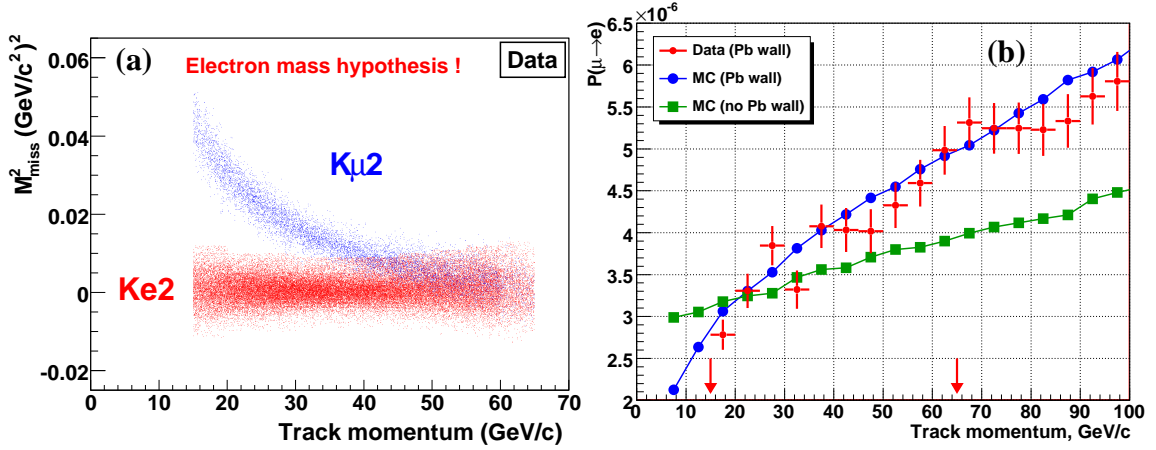


Figure 1: (a) Missing mass squared in electron hypothesis $M_{\text{miss}}^2(e)$ vs track momentum for reconstructed K_{e2} and $K_{\mu2}$ decays: kinematic separation of K_{e2} and $K_{\mu2}$ decays is possible at low track momentum only. (b) Measured and simulated probability of muon identification as electron $P(\mu \rightarrow e)$ vs track momentum: data with the Pb wall, MC simulations with and without the Pb wall (signal region marked with arrows).

3. Backgrounds

$K_{\mu2}$ **decay** is the main background source in the K_{e2} sample. Kinematic separation of K_{e2} and $K_{\mu2}$ decays is not achievable at high lepton momentum ($p > 40$ GeV/c), as shown in Fig. 1a. The probability of muon identification as electron ($E/p > 0.95$ due to ‘catastrophic’ bremsstrahlung) is $P(\mu \rightarrow e) \sim 3 \times 10^{-6}$ in the NA62 experimental conditions, non-negligible compared to $R_K^{\text{SM}} = 2.477 \times 10^{-5}$. Direct measurement of $P(\mu \rightarrow e)$ to $\sim 10^{-2}$ precision is necessary for validation of a theoretical calculation of the bremsstrahlung cross-section [7] in the high γ energy range, which is used to evaluate the $K_{\mu2}$ background. Typical μ samples are affected by relatively large ($\sim 10^{-4}$) electron contamination due to $\mu \rightarrow e$ decays in flight. To collect pure μ samples, a $\sim 10X_0$ thick lead (Pb) wall covering $\sim 20\%$ of the geometric acceptance was installed between the HOD planes during a part of the data taking. In the samples of tracks traversing the Pb and having $E/p > 0.95$, the electron component is suppressed to a level much below $P(\mu \rightarrow e)$ due to energy loss in Pb.

The momentum dependence of $P(\mu \rightarrow e)$ for muons traversing Pb was measured with a data sample collected during a special 20h muon run, and compared to the results of a dedicated Geant4-based MC simulation involving standard muon energy loss processes and bremsstrahlung according to [7]. The data/MC comparison (Fig. 1b) shows excellent agreement in a wide momentum range within statistical errors, which validates the cross-section calculation at the corresponding precision level. The simulation shows that the Pb wall modifies $P(\mu \rightarrow e)$ via two principal mechanisms: 1) muon energy loss in the Pb by ionization decreasing $P(\mu \rightarrow e)$ and dominating at low momentum; 2) bremsstrahlung in Pb increasing $P(\mu \rightarrow e)$ and dominating at high momentum.

To estimate the $K_{\mu2}$ background contamination, the kinematic suppression factor is computed with the standard setup simulation, while the validated simulation of muon interaction in the LKr is employed to account for $P(\mu \rightarrow e)$. The uncertainty of the background estimate comes from the limited size of the data sample used to validate the simulation with the Pb wall.

$K_{\mu2}$ **decay followed by $\mu \rightarrow e$ decay:** energetic forward electrons contributing to background are suppressed according to the Michel distribution as muons from $K_{\mu2}$ decays are fully polarised.

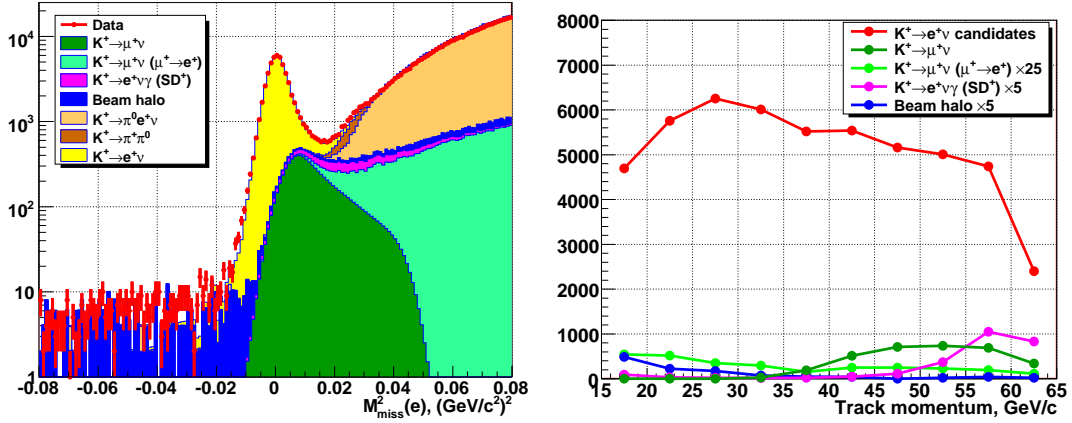


Figure 2: (a) Reconstructed squared missing mass distribution $M_{\text{miss}}^2(e)$ for the K_{e2} candidates: data (dots) presented as sum of signal and backgrounds (filled areas). (b) Numbers of K_{e2} candidates and background events in track momentum bin.

Source	N_B/N_{tot}	Source	N_B/N_{tot}	Source	N_B/N_{tot}
$K_{\mu 2}$	$(6.28 \pm 0.17)\%$	$K_{e2\gamma}$ (SD)	$(1.02 \pm 0.15)\%$	K_{e3}	0.03%
$K_{\mu 2} (\mu \rightarrow e)$	$(0.23 \pm 0.01)\%$	Beam halo	$(1.45 \pm 0.04)\%$	$K_{2\pi}$	0.03%
Total background: $(8.03 \pm 0.23)\%$					

Table 1: Summary of the background sources in the K_{e2} sample.

$K_{e2\gamma}$ (SD) decay, a background by R_K definition, has a rate similar to that of K_{e2} : experimentally $\text{BR} = (1.52 \pm 0.23) \times 10^{-5}$ [3]. Theoretical BR calculations have similar precision, depending on the form factor kinematic dependence model. Energetic electrons ($E_e^* \gtrsim 230$ MeV in K frame) with γ escaping detector acceptance contribute to the background. MC background estimation has a 15% uncertainty due to limited knowledge [3] of the process. A recent precise measurement by KLOE [4], published after announcement of the NA62 preliminary result, is not taken into account.

Beam halo background in the K_{e2} sample induced by halo muons undergoing $\mu \rightarrow e$ decays in flight is measured directly using the K^- data samples. Background rate and kinematical distribution are qualitatively reproduced by a muon halo simulation. The uncertainty is due to the limited size of the K^- sample. Beam halo is the only significant background source in the $K_{\mu 2}$ sample, measured to be 0.25% (with a negligible uncertainty) with the same technique as for K_{e2} decays.

The number of $K_{\ell 2}$ candidates is $N(K_{e2}) = 51,089$ (about four times the statistics reported by KLOE [4]) and $N(K_{\mu 2}) = 15.56 \times 10^6$. The $M_{\text{miss}}^2(e)$ distributions of data events and backgrounds are presented in Fig. 2a. Backgrounds integrated over track momentum are summarized in Table 1; their distributions over track momentum are presented in Fig. 2b.

4. Systematic uncertainties and results

Electron identification efficiency is measured directly as a function of track momentum and LKr impact point using pure samples of electrons obtained by kinematic selection of $K^+ \rightarrow \pi^0 e^+ \nu$ decays collected concurrently with the K_{e2} sample, and $K_L^0 \rightarrow \pi^\pm e^\mp \nu$ decays from a special 15h K_L^0 run. The K^+ and K_L^0 measurements are in good agreement. The measured f_e averaged over the K_{e2} sample is 99.2%, with a precision better than 0.05%. Muon identification inefficiency is negligible.

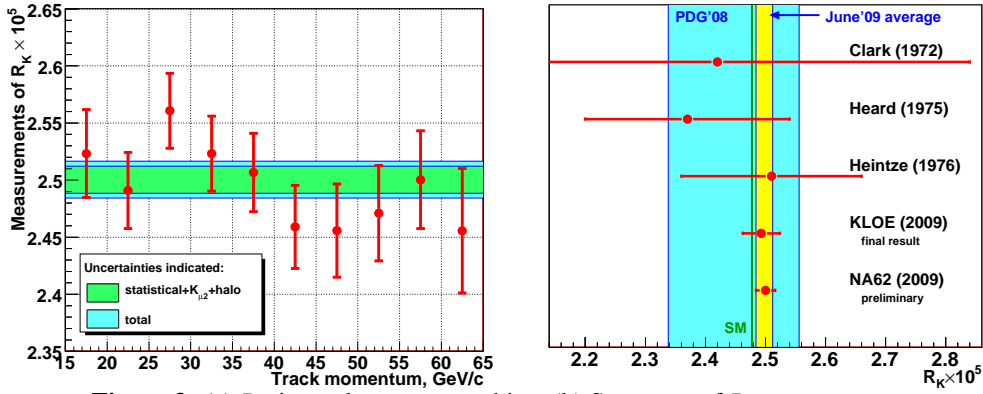


Figure 3: (a) R_K in track momentum bins. (b) Summary of R_K measurements.

Source	$\delta R_K \times 10^5$	Source	$\delta R_K \times 10^5$	Source	$\delta R_K \times 10^5$
Statistical	0.012	Beam halo	0.001	Geom. acceptance	0.002
$K_{\mu 2}$	0.004	Electron ID	0.001	Trigger dead time	0.007
$K_{e 2 \gamma}$ (SD)	0.004	IB simulation	0.007		

Table 2: Summary of uncertainties of R_K : statistical and systematic contributions.

The geometric acceptance correction $A(K_{\mu 2})/A(K_{e 2})$ depends on the radiative $K_{e 2 \gamma}$ (IB) decays. A conservative systematic uncertainty is attributed to approximations used in the $K_{e 2 \gamma}$ IB simulation, which follows [1]. The resummation of leading logarithms [6] is not taken into account, however no systematic error is ascribed due to that. An additional systematic uncertainty reflects the precision of beam line and apparatus description in the MC simulation.

Trigger efficiency correction $\varepsilon(K_{e 2})/\varepsilon(K_{\mu 2}) \approx 99.9\%$ accounts for the fact that $K_{e 2}$ and $K_{\mu 2}$ decay modes are collected with different trigger conditions: the $E > 10$ GeV LKr energy deposition signal enters the $K_{e 2}$ trigger only. A conservative systematic uncertainty of 0.3% is ascribed due to effects of trigger dead time which affect the two modes differently. **LKr global readout efficiency** f_{LKr} is measured directly to be $(99.80 \pm 0.01)\%$ using an independent LKr readout.

The independent measurements of R_K in track momentum bins with are presented in Fig. 3a. The uncertainties are summarised in Table 2. The preliminary NA62 result is $R_K = (2.500 \pm 0.012_{\text{stat.}} \pm 0.011_{\text{syst.}}) \times 10^{-5} = (2.500 \pm 0.016) \times 10^{-5}$, consistent with the SM expectation. The whole 2007–08 data sample will allow pushing the uncertainty of R_K down to 0.4%. A summary of R_K measurements is presented in Fig. 3b: the new world average is $(2.498 \pm 0.014) \times 10^{-5}$.

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