A STRINGENT TEST OF $\mu - e$ UNIVERSALITY IN $K \to l\nu$ DECAYS BY NA62 AT CERN

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New interest has arisen in measuring the ratio $R_K = K_{e2}/K_{\mu 2}$, as recent high-intensity kaon experiments are able to largely improve the precision. With ~150000 collected K_{e2} decays, the NA62 experiment has increased the world K_{e2} sample by an order of magnitude, allowing a stringent test of $\mu - e$ lepton universality. Here, we describe the experiment and summarize the status of the analysis based on ~40 % of the total data sample taken in 2007.

1 Introduction

In the Standard Model (SM), ratios of purely leptonic decay rates of K and π mesons ($R_l = \Gamma(l^\pm \to e^\pm \nu)/\Gamma(l^\pm \to \mu^\pm \nu), l = K, \pi$) are predicted with excellent sub-permille accuracy due to the cancellation of hadronic uncertainties. The ratio R_K, denoted as $K_{e2}/K_{\mu 2}$, is given as [1]

$$R_K^{SM} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \delta R_{QED}) = (2.477 \pm 0.001) \times 10^{-5} \, , \tag{1}$$

where $\delta R_{QED} = (3.78 \pm 0.04)\,\%$ is a correction due to the IB part of the radiative $K_{l2\gamma}$ process. By definition, the IB part is included in R_K, while the DE structure-dependent (SD) part is not. The factor $(m_e/m_\mu)^2$ accounts for the strong helicity suppression of the electron channel, which makes the K_{e2} amplitude sensitive to contributions from physics beyond the SM. Recently, it has been pointed out that in minimal supersymmetric extensions lepton flavour violating (LFV) processes mediated by the charged Higgs could occur, in particular in the kaon decay to an electron and a tau neutrino [2]

$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right] . \tag{2}$$

In a large (not extreme) $\tan\beta$ regime with relatively massive charged Higgs, an enhancement of R_K by a few percent is possible, while analogous SUSY effects in the pion decay are suppressed by a factor $(\mathrm{m_\pi/M_K})^4 \approx 6 \times 10^{-3}$.

Due to the helicity suppression, the thus rare K_{e2} decay limited the experimental precision of R_K measurements in the past; the current world average $R_K^{PDG} = (2.45 \pm 0.11) \times 10^{-5}$ is based on three experiments from the 1970's [3]. A series of preliminary results by the high-intensity kaon experiments NA48/2 and KLOE has improved the situation, yielding a 1.3 % precision in combination. Recently, the KLOE collaboration announced the final result on R_K based on $\sim$14000 K_{e2} candidates with 1.3 % accuracy [4]. For a stringent test of $\mu - e$ universality, however, the uncertainty must be reduced even further. In order to reach this goal, the NA62 experiment collected $\sim$150000 K_{e2} decays in a dedicated run in 2007, aiming at measuring R_K with a precision better than 0.5 %. [5]

The following results presented here are based on a partial data sample ($\sim$ 40 %) with pure K^+ beam.

2 Data Taking, Beams and Detector

For the 2007 data taking, beam setup and detector of the NA48/2 experiment, located at the North Area of the CERN SPS, were used. Based on the experience of previous NA48/2 studies, the running conditions were optimized for the K_{e2} measurement. The main sample was collected during four months of data taking in 2007 with a minimum bias trigger condition to ensure high trigger efficiencies. About 400k SPS spills were recorded with a data volume of $\sim$90 TB on tape. Offline data reprocessing and preparation have been finished. Two more weeks of data taking were allocated in 2008. A number of special data sets were recorded, which will provide a better understanding of systematic effects whose precision is limited by statistics of the control samples they are measured with.

Generally, the beam line delivered simultaneous K^+ and K^- beams with narrow momentum band (75 ± 2 GeV/c) by 400 GeV/c primary SPS protons interacting with a beryllium target. However, the performance of the muon sweeping system was such that the beam halo background was much higher for K^-_{e2} ($\sim$ 20%) than for K^+_{e2} ($\sim$ 1%). As a result, most of the data ($\sim$ 90%) were taken with K^+ beam only and about 10% with K^- beam only. In both cases, the second beam had been dumped upstream the decay volume. As a benefit of this method, samples of reconstructed K_{l2} candidates with the charge of the blocked kaon beam provide a direct measurement of background from the corresponding beam halo, as it passed the beam dump unaffectedly.

After passing a set of collimators, the kaon beam entered a fiducial decay volume in a 114 m long cylindrical vacuum tank, which is followed by the main detector. The subdetectors relevant for the K_{e2} measurement are:

- A magnetic spectrometer consisting of four drift chambers (DCHs) with a central dipole magnet and four views per chamber, used to measure the momenta of charged particles. The resolution of the track momentum is $\sigma(p)/p = (0.47 \oplus 0.02 \cdot p)$ %, with p in GeV/c.
- A plastic scintillator hodoscope with good time resolution to provide fast trigger signals.
- The liquid krypton electromagnetic calorimeter (LKr) used for γ detection and particle identification. It's a quasi homogeneous ionization chamber with 7 m^3 of krypton as active medium and transversally segmented into 13248 projective cells (2×2 cm^2 each). The calorimeter is 27 radiation lengths deep and fully contains electromagnetic showers with energies up to 100 GeV. The energy resolution obtained is $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)$ %, with E in GeV.

A detailed description of the apparatus can be found elsewhere [6].

3 Data Analysis

3.1 Measurement method

In this experiment, K_{e2} and $K_{\mu 2}$ decays were collected simultaneously, making the measurement independent of the kaon flux and leading to cancellation (at first order) of several systematic effects, e.g. parts of the trigger and detection efficiencies. Detailed Monte Carlo (MC) simulations have been performed to describe the data, however, they are used only to a limited extent to rely on the simulation as little as possible. The MC is needed to 1) evaluate the geometric acceptance corrections; 2) simulate the very special high energetic bremsstrahlung process of muons, which will be discussed in detail below. Trigger and particle identification efficiencies were measured directly from the data.

As a matter of principle, this is a counting experiment of reconstructed K_{e2} and $K_{\mu 2}$ candidates. As the backgrounds and acceptances strongly depend on the momentum of the charged track (ptrack), the analysis is performed in bins of this variable. In each bin, the ratio R_K is computed as follows:

$$R_K = \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2}) \times f_\mu \times \epsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \epsilon(K_{e2})} \cdot \frac{1}{f_{LKr}} \cdot \frac{1}{D}\,, \tag{3}$$

where $N(K_{l2})$ are the numbers of selected K_{l2} candidates ($l = e, \mu$), $N_B(K_{l2})$ are the numbers of background candidates, f_l represent the particle (e/μ) ID efficiencies, $A(K_{l2})$ are the geometrical acceptances determined with MC simulations, $\epsilon(K_{l2})$ are the trigger efficiencies, f_{LKr} is the global readout efficiency of the LKr, and D is the downscaling factor of the $K_{\mu 2}$ trigger.

3.2 Event selection

Due to the topological similarity of K_{e2} and $K_{\mu 2}$ decays, a large part of the event selection is common for both channels, leading to cancellations of systematic uncertainties in the ratio R_K.

Main common requirements:

- Exactly one charged track reconstructed by the spectrometer.
- The impact points of the extrapolated track must be within the geometrical acceptances of the relevant subdetectors.
- The decay vertex is defined as the point of closest approach between the charged track and the nominal beam axis. The minimum vertex position must be 18 m downstream the final collimator to suppress the beam halo background.
- The track momentum must be between 15 and 65 GeV/c. The lower limit is due to the requirement of at least 10 GeV energy deposit in the LKr calorimeter in the K_{e2} trigger condition, the upper restriction is close to the kinematical limit.

$K_{e2}/K_{\mu 2}$ separation:

- Kinematical K_{l2} identification by reconstruction of the squared missing mass (= neutrino mass) assuming the track to be an electron or a muon:

  $$M^2_{miss}(l) = (P_K - P_l)^2\,, \tag{4}$$

  where P_K, P_l ($l = e, \mu$) are the kaon and lepton four-momenta. The kaon momentum was measured with reconstructed $K^\pm \to 3\pi$ decays which had been recorded in parallel during the data taking. The selection requires $M^2_{miss}(l) < 0.01\,(GeV/c^2)^2$. A clear kinematical separation is possible only up to track momenta of 25 GeV/c (see Fig. 1, left plot), corresponding to ~15 % of the data.
- Particle identification by the ratio E/p (= LKr energy deposit over track momentum), requiring E/p < 0.85 for muons and 0.95 < E/p < 1.10 for electrons. Fig. 1, right plot, shows the E/p spectra for electrons and muons in log scale. It's obvious that the particle IDs have very low inefficiencies (~1 % for electrons, a few 10^{-5} for muons).

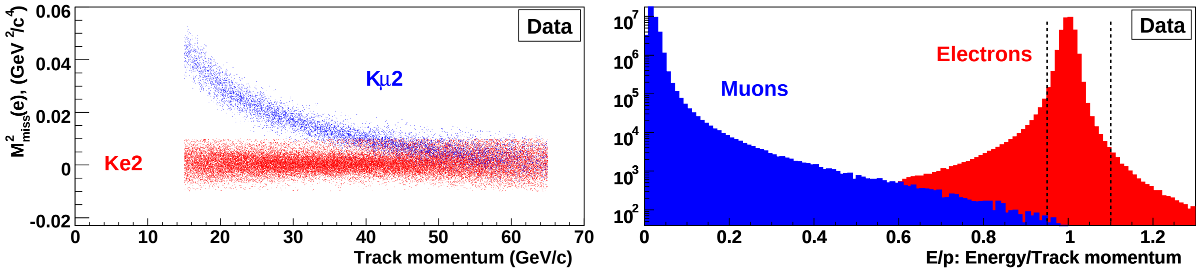


Figure 1: Variables for $K_{e2}/K_{\mu 2}$ separation. Left: Missing mass (with electron mass hypothesis) vs. track momentum for K_{e2} (red) and $K_{\mu 2}$ candidates (blue). Right: Ratio E/p for electrons and muons.

3.3 Muonic background in the K_{e2} sample

In very rare cases, a muon can deposit over 95 % of its energy in the LKr by high energetic ('catastrophic') bremsstrahlung, thus faking an electron. The probability $P(\mu \to e)$ for such a process is only a few 10^{-6}, however, due to the helicity suppression of the electron channel by approx. five orders of magnitude, the background in the K_{e2} sample originating from $K_{\mu 2}$ decays naturally amounts to several percent and represents one of the major issues of this analysis.

A direct measurement of $P(\mu \to e)$ with a few percent accuracy is a necessary requirement for validation of the theoretical computation of the bremsstrahlung cross-section [7] in the highly energetic γ region used to evaluate the $K_{\mu 2}$ background. For this purpose, a $\sim 9X_0$ thick lead wall covering $\sim$20 % of the geometric acceptance had been installed between the hodoscope planes during approx. 50 % of the data taking (see sketch in Fig. 2). Tracks traversing the wall and depositing over 95 % of their energy in the calorimeter represent a sufficiently pure sample of muons with catastrophic bremsstrahlung; the electron contamination is $< 10^{-7}$ due to the high energy loss in the lead wall.

The following pure muon samples with high E/p were collected: 1) from the $K_{\mu 2}$ decays during the nominal data taking; 2) from special muon runs with the hadron beam absorbed. In the present analysis, only a sample from a 20h long special muon run in 2007 has been used. In 2008, an additional sample has been collected, containing about twice as many muons.

The momentum-dependence of $P(\mu \to e)$ measured with the lead wall technique is shown in Fig. 2, right plot, and is in excellent agreement with the results obtained with a dedicated Geant4-

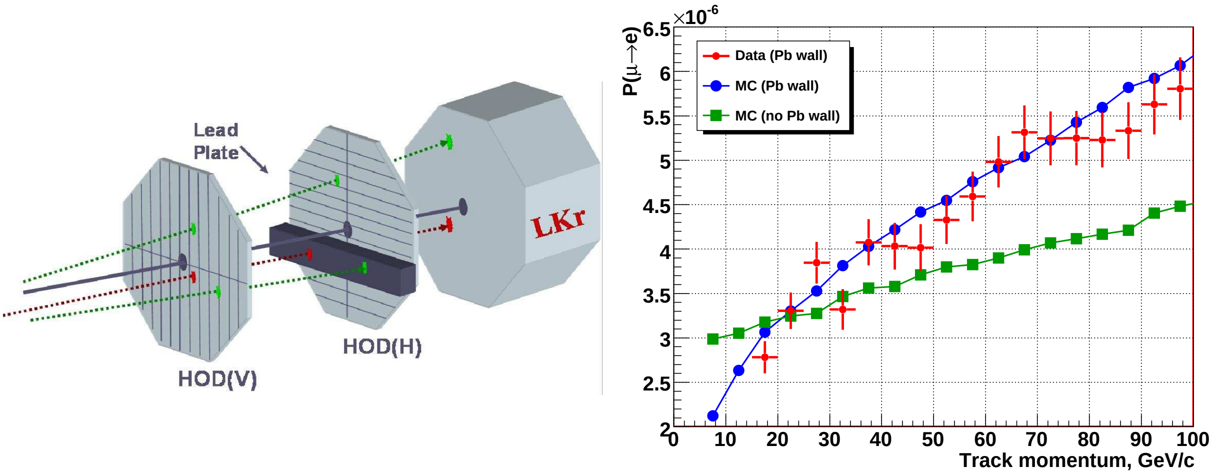


Figure 2: Left: Illustration of the lead wall installed between the two planes of the hodoscope. Tracks passing the wall form a sample of pure muons. Right: Measured and simulated probability $P(\mu \to e)$ for muons identified as electrons due to catastrophic bremsstrahlung. Including modifications due to the lead wall (ionization losses, bremsstrahlung), the simulation describes the data very well.

based MC simulation. To obtain this level of agreement, the pure $P(\mu \to e)$ from the MC had to be modified due to muon ionization losses (affects the low ptrack region) and bremsstrahlung in the lead (high ptrack region).

The preliminary background to signal ratio is $B/S = (7.4 \pm 0.2)\,\%$; the uncertainty is mainly due to the limited size of the data sample used to validate the simulation. Including the larger 2008 sample and studying muons from $K_{\mu2}$ decays in the clear $K_{e2}/K_{\mu2}$ separation region ($\mathrm{p} < 25\,\mathrm{GeV}/c$) will clearly help to reduce the error in the future.

3.4 Other background sources in the K_{e2} sample

Beam halo: Electrons produced by beam halo muons via $\mu \to e$ decay are kinematically and geometrically compatible with a genuine K_{e2} decay. As described above, the halo background can be measured directly with the K^- only sample, yielding a background to signal ratio $B/S = (1.3 \pm 0.1)\,\%$. The reasonably small uncertainty is due to the limited size of the control sample, and will be further reduced by including the additional 2008 K^- sample.

The beam halo background in the $K_{\mu2}$ sample is measured with the same technique as for K_{e2} decays. With only $\sim$0.2 % it represents the only relevant background, i.e. the $K_{\mu2}$ sample is quasi background-free.

$Ke2\gamma$ (SD$^+$): The structure-dependent (SD) $Ke2\gamma$ decay is considered a background by the definition of R_K, and its rate is similar to that of K_{e2}. The existing theoretical predictions are form factor model-dependent and have large uncertainties ($\sim$15 %). The experimental precision is of similar precision: $\mathrm{BR} = (1.52 \pm 0.23) \times 10^{-5}$.[3]

Only energetic electrons ($E_e^* > 230\,\mathrm{MeV}$) are compatible with the K_{e2} kinematic identification. The background contamination is estimated by a MC simulation to be $B/S = (1.6 \pm 0.3)\,\%$, where the uncertainty is due to the poor knowledge of the process. A measurement based on the NA62 2007 data sample has started, and a strong improvement of the uncertainty is expected.

$K_{\mu2}$ with $\mu \to e$ decay in flight: The muon decay has been included in the MC, and naïvely seems to be a major background. Fortunately, only energetic forward electrons, which are strongly suppressed due to the muon polarization, can be selected as K_{e2} candidates. The background to signal ratio is estimated to be $B/S = (1.3 \pm 0.1)\,\%$.

Minor background sources: Two other background sources in the K_{e2} sample have been identified by MC simulations: $K^+ \to \pi^0 e^+ \nu$ (called K_{e3}) and $K^+ \to \pi^+\pi^0$ (called $K_{2\pi}$). Both contributions to the signal are less than one percent.

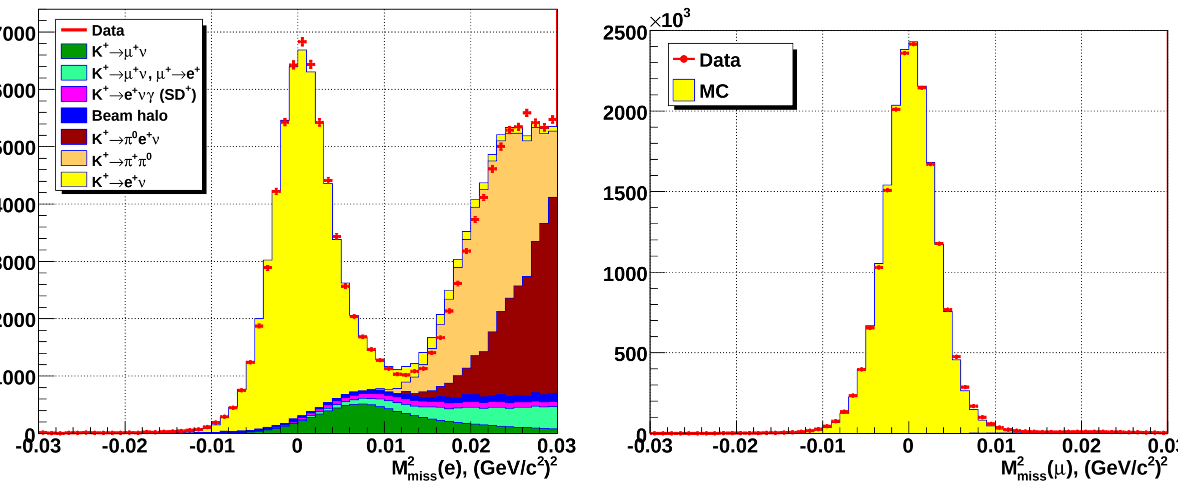
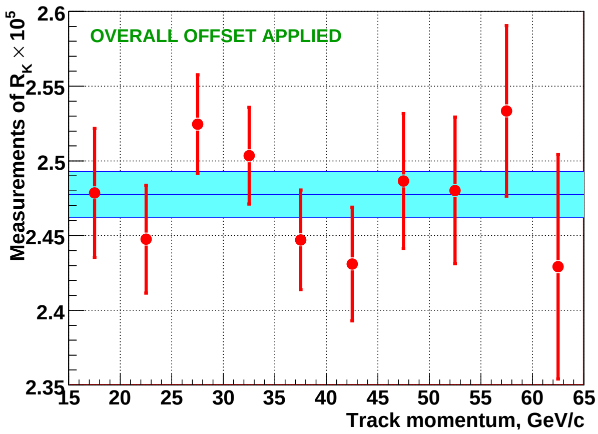


Figure 3: Reconstructed squared missing mass distributions for K_{e2} (left) and $K_{\mu2}$ (right) candidates. Data (crosses) and expectations for backgrounds and signal (filled areas). The $K_{\mu2}$ sample is quasi background-free.



Main uncertainties (40 % data sample)	
Statistical	0.4 %
$K_{\mu 2}$	0.2 %
$Ke2\gamma\,(\mathrm{SD}^+)$	0.3 %
Beam halo	0.1 %
IB simulation	0.3 %
Expected total error	0.6 – 0.7 %

Figure 4: Left: 10 independent measurements of R_K in track momentum bins for the 40 % data sample. An overall offset is applied to hide the result, setting it to the SM expectation. The error band represents the total error, including the correlated uncertainties. Right: Summary of the main uncertainties.

4 Summary and prospects

After applying all selection criteria, about 60000 K_{e2} candidates and 17.5 M $K_{\mu 2}$ candidates remain from the partial 40 % data sample. The total background to signal ratio in the K_{e2} sample is estimated to be $B/S(K_{e2}) = 12.3\,\%$. The largest background fraction is at high track momenta, and the systematic effect due to background is $\delta R_K/R_K = 0.4\,\%$. Fig. 3 shows the squared missing mass distributions for K_{e2} and $K_{\mu 2}$ candidates. For the K_{e2} sample, the sum of estimated background and K_{e2} signal contributions describe the data well. The $K_{\mu 2}$ sample is almost background-free. Improvements for each background source are foreseen as described in the text above.

The ten independent measurements of R_K in track momentum bins are presented in Fig. 4, with an artificial offset being applied to hide the result. The stability of R_K demonstrates that the strongly momentum-dependent systematic effects (acceptances, backgrounds etc.) are under control. The table in Fig. 4 summarizes the main systematic uncertainties. The estimated total uncertainty for this data sample is $0.6 - 0.7\,\%$, breaking the 1 % level for the first time.

The whole NA62 data sample of > 150000 K_{e2} decay candidates is an order of magnitude larger than the world sample and allows to push the statistical uncertainty below 0.3 %. The analysis of the partial data sample is well advanced, significant improvements of various uncertainties are realistic. To conclude, an overall uncertainty of 0.4 %, as declared in the proposal, is within reach.

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