Measurement of $BR(K_{e2})/BR(K_{\mu2})$ in the NA62 experiment at CERN

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Abstract. The Measurement of the helicity suppressed ratio of charged kaon leptonic decay rates $R_K = \Gamma(K^\pm \rightarrow e^\pm \nu_e) / \Gamma(K^\pm \rightarrow \mu^\pm \nu_\mu)$ has long been considered as an excellent test of lepton universality and the Standard Model (SM) description of weak interactions. It was realized recently that the suppression of the SM contribution might enhance the sensitivity to SUSY-induced effects to an experimentally accessible level. The NA62 experiment at the CERN SPS has collected over $10^5 K \rightarrow e \nu$ decays during a dedicated run in 2007, aiming at achieving 0.5 % precision. Experimental strategy, details of the analysis and the final result on a partial set of data will be described. The result $R_K = (2.487 \pm 0.013) \times 10^{-5}$ is in agreement with the Standard Model expectation.

1. Introduction
In the Standard Model (SM) the decays of pseudoscalar mesons to light leptons are helicity suppressed. Although the SM predictions for such decay rates are limited by hadronic uncertainties, their specific ratios do not depend on decay constants (QCD related) and can be computed very precisely. In particular, the SM prediction for the ratio $R_K = \Gamma(K \rightarrow e\nu) / \Gamma(K \rightarrow \mu\nu)$ of kaon leptonic decay widths inclusive of internal bremsstrahlung (IB) radiation is [1]:

$$R_K^{SM} = \left( \frac{M_e}{M_\mu} \right)^2 \left( \frac{M_K^2 - M_e^2}{M_K^2 - M_\mu^2} \right)^2 (1 + \delta R_{QED}) = (2.477 \pm 0.001) \times 10^{-5}$$

where $M_e$ is the electron mass, $M_\mu$ is the muon mass and $M_K$ is the kaon mass and $R_{QED} = (-3.79 \pm 0.04)\%$ is an electromagnetic correction due to the IB and structure-dependent effects.

Within the two Higgs doublet models (2HDM), including the minimal supersymmetric model, $R_K$ is sensitive to lepton flavour violating (LFV) effects appearing at the one-loop level via the charged Higgs boson ($H^\pm$) exchange [2, 3], representing a unique probe into mixing in the right-handed slepton sector [4]. The dominant contribution due to the LFV coupling of the $H^\pm$ is

$$R_{LFV}^{SM} = R_K^{SM} \left[ 1 + \left( \frac{M_K}{M_H} \right)^4 \left( \frac{M_\tau}{M_e} \right)^4 |\Delta_R^{31}|^2 \tan^6 \beta \right]$$

where $\tan\beta$ is the ratio of the two Higgs vacuum expectation values, and $|\Delta_R^{31}|$ is the mixing parameter between the superpartners of the right-handed leptons, which can reach $\sim 10^{-3}$. 

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This can enhance $R_K$ by $\mathcal{O}(1\%)$ without contradicting any experimental constraints known at present.

The current PDG world average \cite{5} is based on a recent result $R_K = (2.493 \pm 0.031) \times 10^{-5}$ \cite{6}. A new measurement of $R_K$ based on a part of the data sample collected by the NA62 experiment at CERN in 2007 is reported here. The analyzed $K^+ \rightarrow e^+\nu_e$ (from now on $K_{e2}$) sample is $\sim 4$ times larger than the total world sample, allowing a measurement of $R_K$ with a sub-percent precision.

2. Beam, detector and data taking

The beam line and setup of the NA48/2 \cite{7} experiment have been used for the NA62 data taking in 2007. Experimental conditions have been optimized for the $K_{e2}/K_{\mu2}$ measurement ($K_{\mu2}$ identifies the $K^+ \rightarrow \mu^+\nu_\mu$ decay).

The beam line was originally designed to deliver simultaneous unseparated $K^+$ and $K$ beams derived from the primary 400 GeV/c protons extracted from the CERN SPS. In 2007, the muon sweeping system was optimized for the positive beam, and the sample used for the present analysis was collected with the $K^+$ beam only with a central momentum of 74.0 GeV/c and a spread of 1.4 GeV/c (rms). The fractions of $K^+$, $\pi^+$, $p$, $e^+$ and $\mu^+$ in the secondary beam are 0.05, 0.63, 0.21, 0.10 and 0.01, respectively. The fraction of kaons decaying in the vacuum tank at nominal momentum is 18\%. The beam transverse size at the entrance to the decay volume is $\delta x = \delta y = 4$ mm (rms), and its horizontal and vertical angular divergences are about 20 $\mu$rad (rms).

Concerning the detector, charged particle properties are measured in a magnetic spectrometer, housed in a tank filled with helium at nearly atmospheric pressure, placed after the decay volume and separated from the vacuum by a thin (\sim 0.4\% radiation lengths) Kevlar window. The spectrometer comprises four drift chambers (DCHs), two upstream and two downstream of a dipole magnet which gives a horizontal transverse momentum kick of 265 MeV/c to singly-charged particles. Each DCH is composed of eight planes of sense wires, and provides a spatial resolution of 90 $\mu$m in each projection. The measured momentum resolution is $\delta p / p = 0.48\% \pm 0.009\%$ p, where p is expressed in GeV/c.

A plastic scintillator hodoscope (HOD) producing fast trigger signals and providing precise time measurements of charged particles is placed after the spectrometer. It consists of a plane of vertical strips, followed by a similar plane of horizontal strips (128 counters in total). Both planes have regular octagonal shapes and a central hole for the passage of the beam.

The HOD is followed by a quasi-homogeneous liquid krypton electromagnetic calorimeter (LKr) used for lepton identification and as a photon veto in the present analysis. The LKr is 127 cm (or 27 radiation lengths) thick along the beam, with projective readout consisting of copper/beryllium ribbons extending from the front to the back of the detector. The 13248 readout cells have a transverse size of approximately $2 \times 2$ cm$^2$ each and have no longitudinal segmentation. The energy resolution is $\delta E / E = 0.032 / \sqrt{E} \pm 0.09 / E \pm 0.0042$ (E in GeV). The spatial resolution for the transverse coordinates $x$ and $y$ of an isolated electromagnetic shower is $\delta x = \delta y = 0.42 / \sqrt{E} \pm 0.06$ cm (E in GeV).

An aluminium beam pipe of 158 mm outer diameter and 1.1 mm thickness traversing the centres of all detector elements allows the undecayed beam particles to continue their path in vacuum. The outer transverse sizes of the subdetectors are about 2.4 m.

During the data taking a minimum bias trigger configuration has been employed to ensure high efficiency. The $K_{e2}$ trigger condition consists of coincidences of signals in the two HOD planes (the $Q_1$ signal), loose lower and upper limits on DCH hit multiplicity (the $1-\text{track}$ signal), and LKr energy deposit ($E_{LKr}$) of at least 10 GeV. The $K_{\mu2}$ trigger condition requires a coincidence of the $Q_1$ and $1-\text{track}$ signals downscaled by a factor $D = 150$. The non-downscaled $K_{\mu2}$ trigger rate is 0.5 MHz, and is dominated by beam halo muons; the $K_{e2}$ trigger rate is about
10 kHz. Downscaled control samples based on trigger signals from the DCHs, HOD and LKr have been collected to monitor the performance of the main trigger signals. The data taking took place during four months starting in June 2007. About 40% of the 350k recorded good SPS spills are used for the present analysis.

3. Data analysis

The analysis strategy is based on counting the numbers of reconstructed $K_{e2}$ and $K_{\mu2}$ candidates collected concurrently. Therefore the analysis does not rely on an absolute beam flux measurement, and several systematic effects (due to beam simulation, accidental activity, charged track reconstruction, $Q1$ trigger efficiency, and time-dependent effects) cancel at first order. Due to the significant dependence of acceptance and background on lepton momentum, the $R_K$ measurement is performed independently in 10 momentum bins covering a range from 13 to 65 GeV/$c$. The lowest momentum bin spans 7 GeV/$c$, while the others are 5 GeV/$c$ wide. The selection criteria have been optimized separately in each momentum bin. The data samples in the momentum bins are statistically independent, however the systematic errors are partially correlated. The ratio $R_K$ in each bin is computed as

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

where $N(K_{l2})$ are the numbers of selected $K_{l2}$ candidates ($l = e, \mu$), $N_B(K_{l2})$ are the numbers of background events, $A(K_{l2})$ and $A(K_{e2})$ are the geometric acceptances, $f_l$ are the lepton identification efficiencies, $\epsilon(K_{l2})$ are the trigger efficiencies, $f_{LKr}$ is the global efficiency of the LKr readout (which affects only the $K_{e2}$ selection), and $D = 150$ is the $K_{\mu2}$ trigger downscaling factor. To evaluate the geometric acceptance and the geometric parts of the acceptances for background processes entering the computation of $N_B(K_{l2})$, a detailed Monte Carlo (MC) simulation based on Geant3 [8] is used. It includes a description, with time variations, of the beam line optics, the full detector geometry, materials, magnetic fields, local inefficiencies of DCH wires and inactive LKR cells (0.8% of channels). Particle identification, trigger and readout efficiencies are measured directly from data.

Charged particle trajectories are reconstructed from hits and drift times in the spectrometer. Track momenta are evaluated using a detailed magnetic field map. Fine calibrations of spectrometer field integral and DCH alignment are performed by monitoring the mean reconstructed $K^+ \rightarrow \pi^+\pi^-\pi^+$ invariant mass, and the missing mass in $K_{\mu2}$ decays. Clusters of energy deposition in the LKr are found by locating the maxima in the digitized pulses from individual cells in both space and time and accumulating the energy within a radius of approximately 11 cm. Shower energies are corrected for energy outside the cluster boundary, energy lost in inactive cells and cluster energy sharing. The energy response has been calibrated with samples of positrons from $K^+ \rightarrow \pi^0e^+\nu_e$ decays. Due to the topological similarity of $K_{e2}$ and $K_{\mu2}$ decays, a large part of the selection is common for the two decay modes, which leads to significant cancellations of the related systematic uncertainties. The main selection criteria are listed below:

- Exactly one reconstructed charged particle track (lepton candidate) geometrically consistent with originating from a kaon decay is required.
- The extrapolated track impact points in the DCHs, HOD and LKr must be within their geometrical acceptances. The LKr acceptance condition includes appropriate separations from the detector edges and inactive cells.
- The reconstructed track momentum must be in the range 13 to 65 GeV/$c$. The lower limit ensures high efficiency of the $E_{LKr} > 10$ GeV trigger condition. Above the upper limit, the analysis is affected by large uncertainties due to background subtraction.
• The decay vertex is reconstructed as the point of closest approach of the lepton candidate track extrapolated upstream, and the kaon beam axis. The measured stray magnetic field in the vacuum tank is taken into account. The position of the kaon beam axis is monitored with a sample of fully reconstructed $K^+ \to \pi^+\pi^-\pi^+$ decays.

• The distance from the kaon decay vertex to the beginning of the vacuum tank is required to exceed a minimum value ranging from 8 m at low lepton momentum to 43 m at high momentum.

The following two main criteria are used to distinguish $K_e^2$ from $K_\mu^2$ decays. The kinematic identification of $K_e^2$ ($K_\mu^2$) decays is based on constraining the reconstructed squared missing mass in the positron (muon) hypothesis:

$$-M_1^2 < M_{\text{miss}}^2(l) = (P_K - P_l)^2 < M_2^2,$$

where $P_K$ is the average kaon four-momentum (monitored with $K^+ \to \pi^+\pi^-\pi^+$ decays), and $P_l$ is the reconstructed lepton four-momentum (under the positron or muon mass hypothesis). The limits $M_1^2$ and $M_2^2$ have been optimized for each lepton momentum bin, taking into account the $M_{\text{miss}}^2(l)$ resolution, the radiative mass tails, and the background conditions. $M_1^2$ varies between 0.013 and 0.016 (GeV/$c^2$) and $M_2^2$ between 0.010 and 0.013 (GeV/$c^2$). The kinematic separation of $K_e^2$ and $K_\mu^2$ decays is illustrated in Fig. 1. The lepton identification is based on the ratio $E/p$ of energy deposition in the LKr to momentum measured by the spectrometer. Charged particles with $(E/p)_{\text{min}} < E/p < 1.1$, where $(E/p)_{\text{min}} = 0.95$ for $p > 25$ GeV/$c$ and $(E/p)_{\text{min}} = 0.9$ otherwise, are identified as positrons. The relaxed condition at low lepton momentum, significantly improving the identification efficiency, is applied due to the absence of backgrounds induced by particle mis-identification in that momentum range. Charged particles with $E/p < 0.85$ are classified as muons. The data $E/p$ spectra of positrons and muons are shown in Fig 2.

![Figure 1. Squared missing mass assuming the positron mass hypothesis $M_{\text{miss}}^2(e)$ as a function of lepton momentum for reconstructed $K_e^2$ and $K_\mu^2$ decays (data).](image1)

![Figure 2. $E/p$ spectra of positrons and muons (data); the positron identification limits for $p > 25$ GeV/$c$ are indicated by arrows.](image2)
3.1. The $K_{e2}$ sample and related background

After all the selection criteria have been applied, the number of $K_{e2}$ candidates in the signal region is $N(K_{e2}) = 59813$. The sources of background in the $K_{e2}$ sample is now discussed.

The main background to $K_{e2}$ comes from $K_{\mu2}$ decays. In fact kinematic separation of $K_{e2}$ from $K_{\mu2}$ decays is achievable at low lepton momentum only ($p \leq 35$ GeV/c), as shown in Fig. 1. At high lepton momentum, the $K_{\mu2}$ decay with a mis-identified muon having $E/p > 0.95$ is the largest background source. The dominant process leading to mis-identification of the muon as a positron is “catastrophic” bremsstrahlung inside or in front of the LKr, leading to significant energy deposit in the LKr. The muon mis-identification probability $P_{\mu e}$ has been measured as a function of momentum. To collect a muon sample free from positron contamination due to $\mu$ to $e$ decays, a 9.2 radiation lengths thick lead (Pb) wall, covering $\sim 20\%$ of the geometric acceptance, was installed approximately 1.2 m in front of the LKr calorimeter (between the two HOD planes) during a dedicated period of data taking with $K^+$ and $K^-$ beams. The Pb wall reduce to a negligible level the number of electrons reaching the LKr and giving an $E/p > 0.95$, however muon passage through the Pb wall affects the measured $P_{\mu e}$ via two principal effects: ionization energy loss in Pb decreases $P_{\mu e}$ and dominates at low momentum; bremsstrahlung in Pb increases $P_{\mu e}$ and dominates at high momentum. Then to correctly evaluate $P_{\mu e}$, a dedicated MC simulation based on Geant4 (version 9.2) [9] has been developed to describe the propagation of muons downstream from the last DCH, involving all electromagnetic processes including muon bremsstrahlung. The $K_{\mu2}$ background contamination integrated over lepton momentum has been computed to be $(6.11 \pm 0.22)\%$ using the corrected $P_{\mu e}$ measurement. A stability check of $R_K$ with respect to variation of $(E/p)_{\text{min}}$ in the range from 0.90 to 0.97 has been performed. The observed relative stability of $R_K$ within $\pm 0.2\%$, although the $K_{\mu2}$ background varies from 17% to 3%, is consistent with the uncertainty assigned to the $K_{e2}$ background. The $K_{\mu2}$ decay also contributes to background via $\mu^+ \rightarrow e^+ \nu \bar{\nu}_{\mu}$ decays in flight. Energetic forward secondary positrons compatible with $K_{e2}$ kinematics and topology are suppressed by muon polarization effects. This background contamination has been estimated to be $(0.27 \pm 0.04)\%$, where the dominant uncertainty is due to the simulated statistics.

$R_K$ is defined to be fully inclusive of internal bremsstrahlung (IB) radiation. The structure-dependent (SD) $K^+ \rightarrow e^+ \nu \gamma$ process not suppressed by helicity represents a significant background source. The interference between the IB and SD processes is negligible. A recent measurement of the $K^+ \rightarrow e^+ \nu \gamma$ (SD) differential decay rate [6] has been used to evaluate the background contamination to be $(1.07 \pm 0.05)\%$, where the uncertainty is due to the limited precision on the $K^+ \rightarrow e^+ \nu \gamma$ (SD) decay rate, and is therefore correlated with lepton momentum bins.

Two other decays are source of background for the $K_{e2}$ sample, $K^+ \rightarrow \pi^0 e^+ \nu$ and $K^+ \rightarrow \pi^+ \pi^0$. The $K^+ \rightarrow \pi^0 e^+ \nu$ decay produces a $K_{e2}$ signature if the only reconstructed particle is an $e^+$ from $K^+$ or $\pi^0 \rightarrow e^+ e^- \gamma$ Dalitz ($\pi^0_d$) decays. The $K^+ \rightarrow \pi^+ \pi^0$ decay leads to a $K_{e2}$ signature if the only reconstructed particle is a $\pi^+$ mis-identified as $e^+$, or an $e^+$ from $\pi^0_d$ Dalitz decay. The pion mis-identification probability $(0.95 < E/p < 1.1)$ has been measured to be $(0.41 \pm 0.02)\%$ in the relevant momentum range from samples of $K^+ \rightarrow \pi^+ \pi^0$ and $K^0_d \rightarrow \pi^+ e^+ \nu$ decays (the latter collected during a special run). The systematic uncertainties due to subtraction of these backgrounds have been estimated as 50% of the contributions themselves, due to the limited precision of the simulation of the kaon momentum-distribution tails. The backgrounds are both at the level of $(0.05 \pm 0.03)\%$.

As no tracking is available in the beam region to tag an incoming kaon, beam halo muons can become a source of background to $K_{e2}$ decays in case of $\mu^+ \rightarrow e^+ \nu e^- \nu_{\mu}$ decay or muon mis-identification as a positron. The choice of the signal region in terms of the longitudinal position of the kaon decay vertex has been dictated by the kinematic distribution of this background (which peaks in the upstream part of the vacuum volume). The halo background has been
measured directly by reconstructing the $K_e^2$ candidates from one control data sample collected with the $K^-$ beam transmitted by the beam line and with the $K^+$ beam (but not its halo) blocked. Another control data sample was collected with both $K^+$ and $K^-$ beams blocked. The background contamination has been estimated to be $(1.16 \pm 0.06)\%$, where the error comes from the limited size of the control samples (uncorrelated between lepton momentum bins) and the normalization uncertainty due to decays of beam kaons and pions upstream of the decay volume (correlated between momentum bins).

The $M_{\text{miss}}^2(e)$ of $K_{e^2}$ candidates and backgrounds are shown in Fig. 3. The total background contamination is $(8.71 \pm 0.24)\%$.

3.2. The $K_{\mu^2}$ sample

The reconstructed $M_{\text{miss}}^2(\mu)$ spectrum is presented in Fig. 4. The number of $K_{\mu^2}$ candidates collected with a trigger chain involving downscaling by a factor of 150 is $N(K_{\mu^2}) = 1.803 \times 10^7$. The only significant background source in the $K_{\mu^2}$ sample is the beam halo. Its contribution is mainly at low lepton momentum, and has been measured to be $(0.38 \pm 0.01)\%$ using the same technique described for the $K_{e^2}$ sample.

3.3. Corrections to $R_K$ and systematic checks

The ratio of geometric acceptances $A(K_{\mu^2})/A(K_{e^2})$ in each lepton momentum bin has been evaluated with MC simulation. The radiative $K^+ \rightarrow e^+\nu\gamma$ (IB) process, which is responsible for the loss of about 5% of the $K_{e^2}$ acceptance by increasing the reconstructed $M_{\text{miss}}^2(e)$, is taken into account following [10], including higher order corrections. The acceptance correction is
strongly influenced by bremsstrahlung suffered by the positron in the material upstream of the spectrometer magnet (Kevlar window, helium, DCHs). This results in an almost momentum-independent loss of $K_{e2}$ acceptance of about 6%, mainly by increasing the reconstructed $M_{miss}^2(e)$. The relevant material thickness has been measured by studying the spectra and rates of bremsstrahlung photons produced by low intensity 25 GeV/c and 40 GeV/c electron and positron beams steered into the DCH acceptance, using special data samples collected with the same setup by the NA48/2 experiment in 2004 and 2006. Using these measurements, the material thickness during the 2007 run has been estimated to be (1.56±0.03)% radiation lengths. The acceptance correction $A(K_{\mu2})/A(K_{e2})$ is enhanced at low lepton momentum because the radial distributions of positrons from $K_{e2}$ decays in the DCH planes are wider than those of muons from $K_{\mu2}$ decays, and low momentum leptons are not fully contained within the geometric acceptance due to the limited transverse sizes of the DCHs.

The track reconstruction inefficiency due to interactions in spectrometer material is included into the acceptance correction. Simulation of the positron track reconstruction inefficiency (which is $\sim 10^{-3}$ in the analysis track momentum range) has been validated with a sample of $K^+ \rightarrow \pi^+\pi^0_D$ decays. The muon track reconstruction inefficiency evaluated with MC simulation is $\sim 2 \times 10^{-4}$. The main sources of systematic uncertainty of the acceptance correction are the helium purity, the limited knowledge of beam profile and divergence and the simulation of soft radiative photons. A separate uncertainty has been assigned to account for the finite precision of the DCH alignment.

Concerning the lepton identification efficiencies, the $E/p$ ratio provides powerful particle identification criteria. The momentum-dependent positron identification window $(E/p)_{min} < E/p < 1.1$ includes more than 99% of the $K_{e2}$ events, while suppressing muons by a factor of $1/P_{mu} \sim 10^6$. The requirement $E/p < 0.85$ leads to a negligible inefficiency of the muon identification.

A pure sample of $4 \times 10^7$ positrons, selected kinematically from $K^+ \rightarrow \pi^0 e^+\nu$ (charged $K_{e3}$) decays collected with the $K_{e2}$ trigger concurrently with the main $K_{\mu2}$ data set, is used to calibrate the energy response of each LKr cell and to study $f_e$ with respect to local position and time stability. However, the momentum range of the positrons from charged $K_{e3}$ decays is kinematically limited, preventing a precise measurement of $f_e$ only above 50 GeV/c. Therefore a dedicated data sample was recorded in a special 15 hour long run with a broad momentum band $K_L^0$ beam. Electrons and positrons from the $4 \times 10^6$ collected $K_L^0 \rightarrow \pi^\pm e^\mp\nu$ (neutral $K_{e3}$) decays allow the determination of $f_e$ in the whole analysis momentum range. The measurements of $f_e$ have been performed in bins of lepton momentum. The inefficiency averaged over the $K_{e2}$ sample is $(1 - f_e) = (0.73 \pm 0.05)\%$, where the uncertainty takes into account the statistical precision and the small differences between charged and neutral kaon results.

The efficiency of the Q1 trigger condition has been measured using $K_{\mu2}$ events triggered with a control LKr signal. The inefficiency integrated over the $K_{\mu2}$ sample is $(1.4 \pm 0.1)\%$. As a consequence of its geometric uniformity and the similarity of the $K_{e2}$ and $K_{\mu2}$ distributions over the HOD plane, it nearly cancels between the $K_{e2}$ and $K_{\mu2}$ samples, then the residual systematic bias is negligible. The inefficiency of the 1-track condition also largely cancels in the ratio $R_K$, but is anyway negligible. Thus the trigger efficiency correction $\epsilon(K_{\mu2})/\epsilon(K_{e2})$ is determined by the efficiency $\epsilon(E_{LKr})$ of the LKr energy deposit trigger signal $E_{LKr} > 10$ GeV entering the $K_{e2}$ trigger chain only. The efficiency $1-\epsilon(E_{LKr})$ is only significant in the lowest lepton momentum bin of (13, 20) GeV/c, which is close to the trigger energy threshold and is thus affected by the online energy resolution. A sample of events triggered with a control Q1 signal passing all $K_{e2}$ selection criteria except the $M_{miss}^2(e)$ constraint, therefore dominated by charged $K_{e3}$ events with two lost photons, has been used to measure $1-\epsilon(E_{LKr})$ in the lowest momentum bin to be $(0.61 \pm 0.2)\%$, once difference of positron distributions in the LKr plane between the $K_{e2}$ sample and the control sample is taken into account. The resulting uncertainty on $R_K$
is negligible. Trigger efficiencies has been measured also for the main backgrounds to the $K_{e2}$ sample in order to correctly evaluate their contributions. The global LKr readout inefficiency, affecting the $K_{e2}$ reconstruction only, has been measured using an independent readout system to be $1 - f_{LKr} = (0.20 \pm 0.03)\%$, stable in time.

4. Result and conclusions

A $\chi^2$ fit to the measurements of $R_K$ in the 10 lepton momentum bins has been performed, taking into account the bin-to-bin correlations between the systematic errors. To validate the assigned systematic uncertainties, extensive stability checks have been performed in bins of kinematic variables by varying selection criteria and analysis procedures. The fit result is

$$R_K = (2.487 \pm 0.011_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5} = (2.487 \pm 0.013) \times 10^{-5},$$ \quad (5)

with $\chi^2/ndf = 3.6/9$. The uncertainties of the combined result are summarized in Table 1. This is the most precise $R_K$ measurement to date. It is consistent with the KLOE measurement and with the SM expectation $R_K = (2.477 \pm 0.001) \times 10^{-5}$ and it can be used to set constraints in the phase space of relevant parameters of multi-Higgs new physics scenarios.

| Source                                      | $\delta R_K \times 10^{-5}$ |
|---------------------------------------------|-----------------------------|
| Statistical                                 | 0.011                       |
| Backgrounds to $K_{e2}$ sample              | 0.005                       |
| Helium purity                               | 0.003                       |
| Acceptance correction                       | 0.002                       |
| Spectrometer alignment                      | 0.001                       |
| Positron identification efficiency          | 0.001                       |
| 1 track trigger efficiency                  | 0.002                       |
| LKr readout efficiency                      | 0.001                       |
| Total systematic                            | 0.007                       |
| Total                                        | 0.013                       |

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