

Searches for New Physics at the NA62 experiment

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Abstract. The experiment NA62 at CERN collected a large sample of K^\pm leptonic decays in order to perform precise test of lepton universality, by measuring the helicity suppressed ratio $R_K = \Gamma(K^\pm \rightarrow e^\pm \nu)/\Gamma(K^\pm \rightarrow \mu^\pm \nu)$. The final result of the analysis based on 59,963 $K^+ \rightarrow e^+ \nu$ candidates ($\sim 40\%$ of the total data set) is $R_K = (2.486 \pm 0.013) \times 10^{-5}$ and consistent with the predictions of the Standard Model. The aim for the future program of the experiment is to measure the branching ratio of the ultra-rare decay $K^+ \rightarrow \pi^+ \nu \nu$ with 10% precision.

1. The present of NA62: Search for lepton flavour violation

1.1. Introduction

The ratio of kaon leptonic decay rates $R_K = \Gamma(K_{e2}^\pm)/\Gamma(K_{\mu 2}^\pm)$ is known in the Standard Model (SM) with excellent precision due to cancellation of the hadronic effects: $R_K^{SM} = (m_e/m_\mu)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 (1 + \delta R_{QED}) = (2.477 \pm 0.001) \times 10^{-5}$ [1], where $\delta R_{QED} = (-3.78 \pm 0.04)\%$ is a correction due to the inner bremsstrahlung (IB) $K_{l2\gamma}$ process which is included by definition into R_K ¹. Being helicity suppressed due to $V - A$ structure of the charged weak current, R_K is sensitive to non-SM effects. In particular MSSM allows non-vanishing $e - \tau$ mixing, mediated by H^+ , which can lead to few percent enhancement of R_K [2].

The present world average of $R_K = (2.493 \pm 0.031) \times 10^{-5}$ [3] is dominated by the recent KLOE final result [4]. The NA62 experiment collected data during 2007 and 2008 aiming to reach accuracy of $\sim 0.4\%$. The final result on partial data set is presented here.

1.2. Experimental setup

The NA62 experiment used the NA48/2 beam line [5] and detector setup [6] with optimisations for K_{e2} data collection. The beam line of NA48/2 experiment is designed to deliver simultaneously K^+ and K^- , produced on a beryllium target from SPS primary protons. The beams of (74 ± 2) GeV/ c momentum are selected by a system of magnetic elements. After cleaning, shaping and focusing, the beams enter 114 m long vacuum decay volume. The momenta of the charged decay products are measured by magnetic spectrometer consisting of four drift chambers (DCHs) and a dipole magnet. The resolution of the spectrometer is $\sigma(p)/p = 0.5\% \oplus 0.009\%p$ (p in GeV/ c). A scintillator hodoscope (HOD), located after the spectrometer, sends fast trigger signals from charged particles and measures their time with a resolution of 150 ps. The electromagnetic energy of particles is measured by a liquid krypton

¹ Unlike the structure dependent (SD) $K_{l2\gamma}$.

calorimeter (LKr), a quasi-homogeneous ionization chamber with an active volume of 10 m^3 , $27 X_0$ deep and segmented transversely into 13,248 cells ($2 \times 2 \text{ cm}^2$ each). The energy resolution is $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ and the spatial resolution in the transverse coordinates x and y for a single electromagnetic shower is $\sigma_x = \sigma_y = 0.42/\sqrt{E} \oplus 0.06 \text{ cm}$ (E in GeV). A beam pipe traversing the centers of the detectors allows undecayed beam particles and muons from decays of beam pions to continue their path in vacuum.

The K_{e2} decays are selected by trigger requiring coincidence of hits in the HOD planes (Q_1 signal) together with sufficient energy deposit ($> 10 \text{ GeV}$) in LKr. The $K_{\mu2}$ events are selected by Q_1 signal, downscaled by a factor 150. Both triggers also use loose requirement on DCH multiplicity.

1.3. Analysis strategy

Due to the topological similarity of K_{e2} and $K_{\mu2}$ decays a large part of the selection conditions are common for both decays. We require the presence of single reconstructed charged track with momentum $13 \text{ GeV}/c < p < 65 \text{ GeV}/c$ (the lower limit is due to the 10 GeV LKr energy deposit requirement in K_{e2} trigger). The track extrapolated to DCH, LKr and HOD should be within their geometrical acceptances. The CDA between the charged track and the nominal kaon beam axis should be less than 1.5 cm . The event is rejected if a cluster in the LKr with energy larger than 2 GeV and not associated with track is present, in order to suppress the background from other kaon decays.

A kinematical separation between K_{e2} and $K_{\mu2}$ for low track momenta is possible, based on the reconstructed missing mass, assuming the track to be an electron or a muon: $M_{\text{miss}}^2(l) = (P_K - P_l)^2$, where P_l ($l = e, \mu$) is the four-momentum of the lepton. Since the kaon four-momentum P_K is not measured directly in every event, its average is monitored in each SPS spill with fully reconstructed $K^\pm \rightarrow 3\pi^\pm$ decays. A cut $M_1^2 < M_{\text{miss}}^2(e) < M_2^2$ is applied to select K_{e2} candidates, and $M_1^2 < M_{\text{miss}}^2(\mu) < M_2^2$ for $K_{\mu2}$ ones, where M_1^2 and M_2^2 vary from 0.010 to $0.016 (\text{GeV}/c^2)^2$ for different track momenta, 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 $0.95 < E/p < 1.1$ for $p > 25 \text{ GeV}/c$ and $0.90 < E/p < 1.1$ otherwise², are identified as electrons, while particles with $E/p < 0.85$ – as muons.

The analysis is based on counting the number of reconstructed K_{e2} and $K_{\mu2}$ candidates with the selection described above. Since the decays are collected simultaneously, the result does not depend 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

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

where $N(K_{l2})$ are the numbers of selected K_{l2} candidates ($l = e, \mu$), $N_B(K_{l2})$ are numbers of background events, f_l are efficiencies of electron and muon identification criteria, $A(K_{l2})$ are geometrical acceptances, $\epsilon(K_{l2})$ 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. In order to compute $A(K_{l2})$, a detailed Geant3-based Monte-Carlo simulation is employed.

1.4. Backgrounds

$N_B(K_{e2})$ in (1) is dominated by $K_{\mu2}$ events with track misidentified as electron, mainly in case of high energetic bremsstrahlung after the magnetic spectrometer, when the photon takes more

² The background to K_{e2} is concentrated in the region $p > 25 \text{ GeV}/c$, hence the need of tighter electron ID.

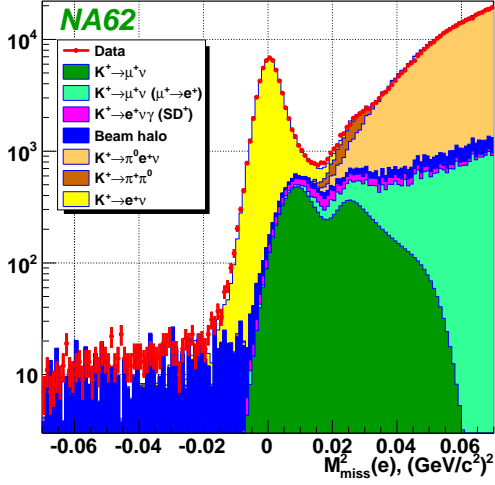


Figure 1. $M_{\text{miss}}^2(e)$ distributions for K_{e2} candidates and for various backgrounds.

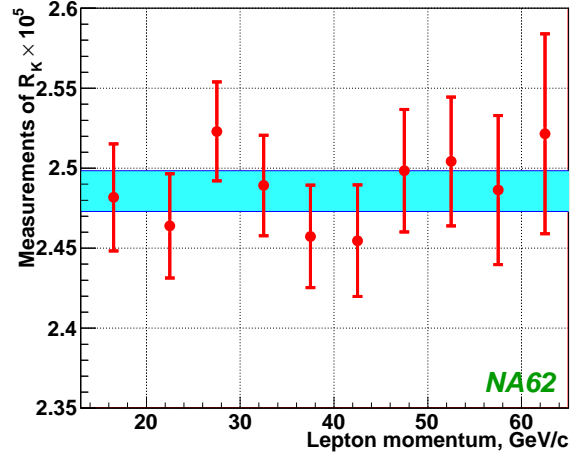


Figure 2. R_K in track momentum bins.

than 95% of muon's energy. The probability for such process is measured directly by clean sample of muons passing $\sim 10X_0$ of lead (Pb) before hitting the LKr. A Geant4 simulation is used to evaluate the Pb correction to the probability for muon misidentification which occurs via two principal mechanisms: 1) muon energy loss in Pb by ionization, dominating at low momenta; 2) bremsstrahlung in the last radiation lengths of Pb increasing the probability for high track momenta. The background is evaluated to be $(6.10 \pm 0.22)\%$.

Since the incoming kaon is not tracked and the signature of K_{l2} decays is a single reconstructed track, the background from beam halo should be considered. The performance of muon sweeping system results in lower background in K_{e2}^+ sample ($\sim 1\%$) than in K_{e2}^- sample ($\sim 20\%$), therefore $\sim 90\%$ of data were collected with the K^+ beam only, and small fractions were recorded with simultaneous beams and K^- beam only. The halo background in K_{e2}^+ was measured to be $(1.14 \pm 0.06)\%$ directly by using data, collected when no K^+ beam is present.

The other backgrounds considered are: $(0.27 \pm 0.04)\%$ from $K_{\mu 2}$ with subsequent $\mu \rightarrow e$ decay³; $(1.15 \pm 0.17)\%$ from $K_{e2\gamma}(\text{SD})^4$; 0.06% for both K_{e3} and $K_{2\pi}$ decays.

The number of K_{e2} candidates is 59,963 before background subtraction. The $M_{\text{miss}}^2(e)$ distribution of data events and backgrounds are presented in Fig. 1.

1.5. Systematic uncertainties and results

The electron identification efficiency is measured directly as a function of track momentum and its impact point at LKr using electrons from K_{e3} decays. The average f_e is $(99.27 \pm 0.05)\%$ (f_μ is negligible). The geometric acceptance correction $A(K_{\mu 2})/A(K_{e2})$ is known with permille precision and depends on the radiative $K_{e2\gamma}(\text{IB})$ decays, simulated following [7] with higher order corrections according to [8]. The trigger efficiency correction $\epsilon(K_{e2})/\epsilon(K_{\mu 2}) \approx 99.6\%$ is significant only in the first analysis bin $13 < p < 20$ GeV/c and accounts for the difference in the trigger conditions, namely the requirement of $E > 10$ GeV energy deposited in LKr for K_{e2} only. Additional small systematic uncertainty arises due to the global LKr readout efficiency, measured to be $(99.80 \pm 0.01)\%$.

³ This background is suppressed according to Michel distribution, as muons from $K_{\mu 2}$ decays are fully polarized.

⁴ The recent KLOE measurement [4] is used for this estimation. The uncertainty on the background is dominated by R_K stability with respect to the level of suppression of events with extra activity in LKr.

The independent measurements of R_K in track momentum bins are presented in Fig. 2. The final NA62 result, based on 40% of the accumulated statistics is $R_K = (2.486 \pm 0.011_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5} = (2.486 \pm 0.013) \times 10^{-5}$, consistent with SM expectation. The analysis of the whole data set will allow to reach uncertainty of 0.4%. The combined new world average is $(2.487 \pm 0.012) \times 10^{-5}$.

2. The future of NA62: Measurement of $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

2.1. Introduction

The future program of the experiment NA62 at CERN SPS is currently in an advanced stage of development. The main goal of the experiment is to measure the branching ratio of the very rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay, by detecting approximately 100 events with 10% background.

The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decays are exceptionally clean modes, dominated by short distance dynamics due to power-like GIM mechanism, and therefore are excellent probes in flavour physics. At the quark level the process $d \rightarrow s \nu \bar{\nu}$ is realised by combination of Z^0 penguin and double W exchange. The leading SM contribution to the matrix element is generated by top quark loops and can be computed with negligible theoretical uncertainty. In case of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay there is a small contribution from charm quark, while the contribution from up quark is negligible in both decay modes. The hadronic matrix element can be extracted from the well measured $K \rightarrow \pi e \nu$ decays rates with negligible theoretical uncertainty. The current estimations of the branching ratios for the the $K \rightarrow \pi \nu \bar{\nu}$ decays within the SM are $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.22 \pm 0.84) \cdot 10^{-11}$ and $BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (2.76 \pm 0.40) \cdot 10^{-11}$ [9].

Measurement of the branching ratios of both $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay modes leads to the determination of the V_{td} element in the CKM matrix, i.e. of the Wolfenstein parameters (ρ, η) that define the unitarity triangle, independently of the results from B -physics.

The strong suppression of $K \rightarrow \pi \nu \bar{\nu}$ decays within the SM follows from the absence of tree-level contributions and the hard GIM mechanism. However, this also leads to high sensitivity to possible new-physics effects. Since the cleanness of these decays modes remains valid in all realistic extensions of SM, a precise measurement of their branching ratios provide sensitive test of the flavour structure of any model beyond SM. Evidence of new physics can be seen in $K \rightarrow \pi \nu \bar{\nu}$ decays even without significant signals in B -decays or without particles within LHC reach [10].

Only three $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events were discovered by BNL E949 Collaboration. The measured value of the branching ratio is compatible with the SM prediction: $(1.47^{+0.30}_{-0.89}) \cdot 10^{-10}$ [11].

The NA62 experiment [12] will use kaon decays in-flight technique, based on the NA48 apparatus and infrastructure, and the same CERN-SPS beam line which produced the kaon beam for all NA48 experiments.

2.2. Backgrounds

The experimental signature of the studied $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays is a single reconstructed track in the detector downstream the decay volume in time coincidence with a kaon measured by the upstream beam tracker. The kinematics of a one-track event can be fully described by the variable $m_{\text{miss}}^2 = (P_K - P_\pi)^2$, where P_K and P_π are the four-momenta of the kaon and pion, respectively. Two categories of backgrounds can be considered:

- **Kinematically constrained background.** The decays in this category correspond to $\sim 95\%$ of the total K^+ branching fraction. The $K^+ \rightarrow \pi^+ \pi^0$ decay splits the kinematical region of the signal in two parts, called region I and region II. $K^+ \rightarrow \mu^+ \nu$ and $K^+ \rightarrow \pi \pi \pi$ decays sit on the opposite sides of these regions where cuts must be applied as well. A rejection factor larger than 10^{12} can be achieved only if efficient photon rejection and particle identification complements the kinematical rejection.

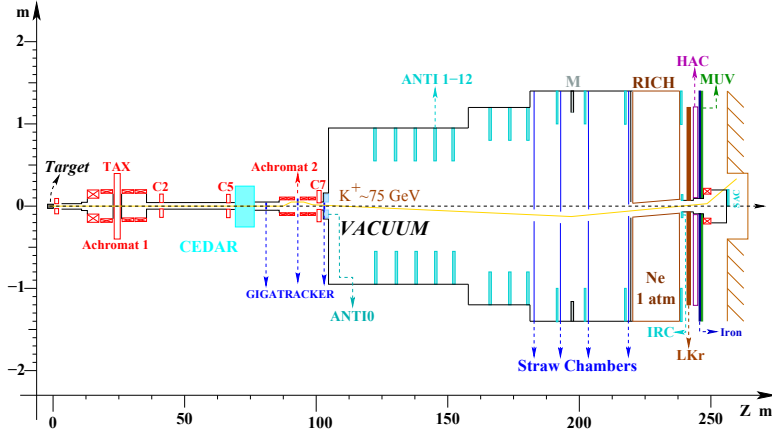


Figure 3. Layout of NA62 experimental apparatus.

- **Kinematically not constrained background.** The rejection of such background profits from relatively small branching fractions. However, photon veto system and particle identification are the only experimental tools available to reduce such a background.

The expected level of background is $\sim 13.7\%$. The signal acceptance is found to be 14.4% . With a flux of about $4.8 \cdot 10^{12}$ kaon per year of data taking, the expected number of signal events is 55 events/year.

2.3. The Experimental set-up

The layout of the experimental apparatus is presented in Fig. 3.

The K^+ beam will be produced from SPS protons hitting a beryllium target with momentum $400 \text{ GeV}/c$ and intensity $1.1 \cdot 10^{12}$ protons/s. The nominal momentum of the K^+ beam will be $P_K = 75 \text{ GeV}/c$ with $\Delta P_K/P_K = 1\%$. The expected fraction of K^+ in the beam is 6%. After the first achromat a differential Cerenkov counter (CEDAR) existing at CERN, will be used after its upgrade for new experimental conditions for kaon tagging, in order to keep the beam background under control.

The beam spectrometer (Gigatracker) will be placed in the second achromat station. It consists of thin silicon micro-pixel detectors ($< 0.5\% X_0$ per station) for redundant momentum measurement of the incoming beam with 200 ps time resolution, necessary to provide a tight coincidence between incoming kaon and outgoing pion. The integrated beam rate at the Gigatracker will be 750 MHz. A set of ring anti-counters (CHANTI) will be placed after the last Gigatracker station and a large one around the beginning of the decay volume, in order to veto secondary charged particles produced in the collimator.

After the 80 m long decay volume, a magnetic spectrometer, operating in vacuum, will be used to measure the momentum of the out-going pion. The spectrometer is designed with four straw chambers with four coordinate views each. Chambers should introduce a small material contribution ($0.5\% X_0$ per chamber) and have a good spatial resolution ($130 \mu\text{m}$ per view). Full-size prototypes were built and tested in beam during 2007 run of NA62 experiment and in 2010.

After the magnetic spectrometer a gas Ring Imaging Cerenkov counter (RICH) will be placed, providing muon/pion separation in the momentum interval (15–35) GeV/c . The detector will be used also for precise measurement of the pion crossing time with resolution ~ 100 ps, sending signals to the trigger system. In addition the RICH will provide a redundant measurement of velocity of the charged particles. The detector consists of a 18 m long tube with a diameter

of 2.8 m, filled with Neon at atmospheric pressure. The Cerenkov radiation will be collected by two mirrors with 17 m focal length. A full-length, 60 cm in diameter prototype has been integrated in the NA62 set-up and tested during the 2007 run.

A full hermeticity for photons up to 50 mrad will be provided by four subdetector systems. The decay volume and the region after the straw spectrometer will be surrounded by 12 sets of ring-shaped lead glass anti-counters (Large Angle Veto - LAV). The construction phase is advanced, with two of the stations built and tested. The Liquid Krypton Calorimeter, built for the NA48 experiment, will be used as part of the photon veto system in the forward region. During test run in 2006 it was shown that inefficiency below 10^{-5} can be reached. A program of consolidation and update of the readout electronics of the LKr is under way. The photon veto system is completed by the Intermediate Ring Calorimeter (IRC), placed at the entrance of LKr, and Small Angle Calorimeter (SAC) at the very end of the detector system, after the muon deflecting magnet, both covering the angular regions around and in the beam. A SAC prototype was tested during 2006 and an upper limit on its inefficiency was found to be $6.4 \cdot 10^{-5}$.

The muon veto system of the experiment will consist of three parts - the first two modules (MUV1 and MUV2) follow directly the LKr and work as hadronic calorimeters for measurement of deposited energies and shower shapes of incident particles. The third station will be used in the on-line selection.

The trigger system of NA62 experiment will be at two levels. The first one (L0) is a hardware trigger, which will decrease the events rate from ~ 10 MHz to ~ 1 MHz, employing signals from the RICH, the photon veto system and the muon detector. The second level (L1/2) is software and its aim is to decrease the event rate to kHz level.

The R&D program of the NA62 experiment is near completion with some of the detectors already in construction phase. The data taking is foreseen for 2013 and 2014. Other physics opportunities, such as searches for lepton flavour violation and new low mass particles are being considered as part of the program of the experiment.

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