The CERN-NA48 Experiment: Lepton Universality Tests and New Prospects

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Abstract

NA48 experiment at CERN is testing physics beyond the Standard Model (SM) checking lepton universality in various charged kaons decays.

Recent measurements of the ratio $R_K = \Gamma(Ke2)/\Gamma(K\mu2)$ based on two short data taking are presented. The obtained result for R_K is two times more precise than the world average but is still insufficient to probe the existence of physics beyond the SM. A new dedicated run taking place this year and aiming to obtain a sub-percent precision measurement of R_K, is described.

Measured ratios of decay rates for $\mathcal{R}_{Ke3/K2\pi}$ and $\mathcal{R}_{K\mu3/K2\pi}$ based on a dedicated short run in 2003 are presented. Using the Particle Data Group (PDG) average for the $K^\pm \to \pi^\pm\pi^0$ normalization mode, we obtain a measure of $|V_{us}|$ CKM element, larger than previously accepted and this result is in good agreement with unitarity of the CKM matrix. Comparing $|V_{us}|$ obtained using the $Ke3$ decay to $K\mu3$ no indication of lepton universality violation is observed.

The NA48/3-P326 proposal for an experiment to measure the branching ratio of the rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$ at the CERN-SPS is described. This should allow a 10% measurement of the CKM parameter $|Vtd|$. The proposed experiment aims to collect about 80 $K^+ \to \pi^+\nu\bar{\nu}$ events with a 10% of background in two years of data taking. The status of the project, the R&D and future perspectives for the experiment are discussed.

1 Testing $\mu - e$ universality with $K^\pm \to l^\pm\nu$ decays

1.1 Introduction

The measurement of the ratio $R_K = \Gamma(Ke2)/\Gamma(K\mu2)$ provides a sensible test of lepton universality and of the weak interactions structure.

This ratio of decay rates benefits from cancellation of hadronic uncertainties to a large extent and therefore can be computed, within the SM, with high precision. It can be written as: $R_K = m_e^2/m\mu^2[(m_K^2 - m_e^2)/(m_K^2 - m_\mu^2)](1 - \delta R_K)$, where the term $\delta R_K = -(3.78 \pm 0.04)\%$ represents the radiative corrections [1]. The theoretical prediction, including radiative corrections, is $R_K = (2.472 \pm 0.001) \times 10^{-5}$[1] , the uncertainty is only 0.04% of the total.

[1]All experimental measurements are inclusive, so a proper treatment of radiative corrections is important.

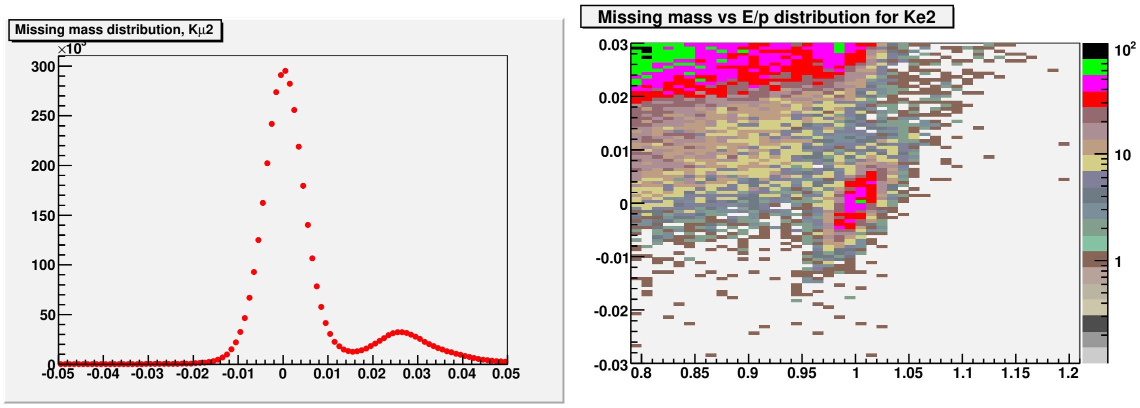

Figure 1: Left-side: Missing mass distribution for $K\mu 2$ candidates. Right-side: E/p vs. Missing mass distribution for $Ke2$ candidates before cuts. Logarithmic scale for event density is used to show background contribution.

Since Ke2 decay is helicity-suppressed by the V-A structure of the charged weak current, R_K can be affected by physics beyond the SM. Considering different extensions of the SM, contributions to R_K as high as $\pm 3\%$ could be achieved [2].

The value of R_K has been measured by three experiments [3] in the 70s but the precision of the combined result, $R_K = (2.45 \pm 0.11) \times 10^{-5}$, is two orders of magnitude larger than the theoretical uncertainty not allowing to perform a significant test of the lepton universality.

1.2 NA48/2 results and NA62 new measurement

NA48 experiment has collected data in two special runs using diminished beam intensity and special trigger set-up to study mainly semileptonic decays. The huge statistics allows also to study rare kaon decays. For the measurement of the ratio R_K we have analyzed two independent data samples with similar statistics (one month of data taking using a downscaled trigger in 2003 and 56 hours of data taking in a special dedicated run in 2004).

In the analysis we kept at maximum the same cuts for both modes to exploit systematic cancellations. We cut on the missing mass distribution compatible with the hypothesis of a Kl2 decay, computed with the right lepton mass assignment.

For particle identification, at low energy, we can rely on the kinematic separation between Ke2 and $K\mu 2$ in the missing mass parameter, but, above 35 Gev/c momentum, the particle identification is obtained using the ratio of the energy deposited in the liquid Krypton electromagnetic calorimeter versus the momentum measured in the spectrometer E_{LKr}/p_{spectr}. [2]. For electron identification $E_{LKr}/p_{spectr} > 0.95$, while for muon $E_{LKr}/p_{spectr} < 0.2$.

In Fig.1, left side, you can see the missing mass distribution for $K\mu 2$ candidates. Only a 0.6% background from $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ leaks through the cut at squared missing mass smaller than $0.015 Gev^2$.

In Fig. 1, right side, the missing mass versus E_{LKr}/p_{spectr} distribution is shown for Ke2 candidates before cuts. Logarithmic scale for event density is used to see background contribution. The major contribution to the background in the Ke2 sample is identified to come from $K\mu 2$ events with muons losing almost all their energy in the liquid Krypton e.m. calorimeter (catastrophic energy loss, probability $\sim 5 \times 10^{-6}$).

[2] for a description of the NA48 apparatus [4] see also S.Bifani and M.Valdata papers in this proceedings

The dominant contribution to the uncertainty is the background subtraction error, it is obtained from data and scales with the statistics.

From the two independent data samples we obtain about 4,000 Ke2 events each and the final results are $R_K = (2.416 \pm 0.043 \pm 0.024) \times 10^{-5}$ from 2003 data, and $R_K = (2.455 \pm 0.045 \pm 0.041) \times 10^{-5}$ from 2004 data.

Our result for R_K is two times more precise than the world average and compares well with the recent preliminary result from KLOE experiment at Frascati ($R_K = (2.55 \pm 0.05 \pm 0.05) \times 10^{-5}$) [5] but is still insufficient to probe the existence of physics beyond the SM.

NA48 experiment at CERN, has been approved, with the name NA62, to continue testing lepton universality in $K^{\pm} \to l^{\pm}\nu$ decays in a long dedicated data taking this year. We have collected $\sim 120,000$ Ke2 events aiming to reach a sub-percent precision measurement of R_K.

To improve the kinematic separation of Ke2 events we have optimized the beam parameters. The beam momentum is now 75 Gev/c (was 60 GeV/c in 2004), with a slightly better momentum bite (2.5 GeV/c wrt 3 GeV/c) and a larger momentum kick in the spectrometer magnet (263 MeV/c wrt 120 MeV/c). To improve on the systematic error we are measuring the catastrophic muons background directly by putting, for part of the data taking, a $9X_0$ lead bar in a limited area in front of the LKr calorimeter. We lose 18% of acceptance but in this region only muon can reach the calorimeter and we can estimate the probability of catastrophic interactions.

2 Testing $\mu - e$ universality with $Ke3$ and $K\mu3$ decays

2.1 Recent results

New measurements of the charged kaon semileptonic decays $K^{\pm} \to \pi^0 e^{\pm}\nu$ (Ke3) and $K^{\pm} \to \pi^0 \mu^{\pm}\nu$ (Kμ3) are presented. The measured ratios of decay rates are $\mathcal{R}_{Ke3/K2\pi} = \Gamma(K^{\pm} \to \pi^0 e^{\pm}\nu)/\Gamma(K^{\pm} \to \pi^{\pm}\pi^0)$ and $\mathcal{R}_{K\mu3/K2\pi} = \Gamma(K^{\pm} \to \pi^0 \mu^{\pm}\nu)/\Gamma(K^{\pm} \to \pi^{\pm}\pi^0)$.

These measurements are based on $K^{\pm}$ decays collected in a dedicated run in 2003 by the NA48/2 experiment at CERN. In both the numerator and denominator, the decays contain a charged track and at least two γ 's that are consistent with a π^0, thus leading to a partial cancellation in the acceptance and reconstruction uncertainties. Contributions from internal bremsstrahlung are included. The reconstruction methods are the same in all cases, the main selection differences are due to particle identification. The correction to Ke3 due to particle identification efficiency amount to a few percent, while for Kμ3 is below the percent level. The data samples are 87×10^3 Ke3 candidates with 0.02% background and 77×10^3 Kμ3 candidates with 0.2% background.

The semileptonic kaon decays, being pure vector transitions, provide the most accurate and theoretically cleanest way to measure the $|V_{us}|$ parameter in the CKM matrix.

The results obtained are $\mathcal{R}_{Ke3/K2\pi} = 0.2470 \pm 0.0009(stat) \pm 0.0004(syst)$ and $\mathcal{R}_{K\mu3/K2\pi} = 0.1637 \pm 0.0006(stat) \pm 0.0003(syst)$ [6]. Both the results are several standard deviations higher than the current world average and the uncertainties are significantly smaller ($\mathcal{R}_{Ke3/K2\pi}(PDG) = 0.234 \pm 0.004$ and $\mathcal{R}_{K\mu3/K2\pi}(PDG) = 0.157 \pm 0.003$).

Using $K^{\pm} \to \pi^{\pm}\pi^0 = 0.2103 \pm 0.0013$, the PDG average for the normalization mode, we obtain $BR(Ke3) = 0.05168 \pm 0.00019(stat) \pm 0.00008(syst) \pm 0.00030(norm)$ and $BR(K\mu3) = 0.03425 \pm 0.00013(stat) \pm 0.00006(syst) \pm 0.00020(norm)$. Both values are found to be larger than the current world averages and lead to a larger magnitude of the $|V_{us}|$ CKM element than previously accepted.

The values of $|V_{us}|f_+(0)$ are computed for Ke3 (0.2193±0.0012) and Kμ3 (0.2177±0.0013) decays. Here the dominating contribution to the uncertainty comes from the long-distance corrections. Combining these results, assuming lepton universality and using the form fatcor at zero momentum transfer $f_+(0) = 0.961(8)$[7], we obtain $|V_{us}| = 0.2277 \pm 0.0023$.

When combined with the latest PDG value of $|V_{ud}|$, the result is in good agreement with unitarity of the CKM matrix.

Comparing $|V_{us}|$ measured using the $Ke3$ to the one from $K\mu3$ decay we obtain $r_{\mu e} = (R_{\mu e})_{obs}/(R_{\mu e})_{SM} = 1.0059(87)$, no indication of lepton universality violation is observed.

3 The $K^+ \to \pi^+\nu\bar{\nu}$ Experiment at CERN

3.1 Introduction

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a flavor changing neutral current process which proceed through box and purely electroweak penguin diagrams. It is very clean theoretically, short distance dynamics dominates, c-quark contributions have been evaluated to NNLO order at 5%, the hadronic matrix elements can be parameterized in terms of the $K^+ \to \pi^0 e^+\bar{\nu}$ branching ratio, well known experimentally [8]. For these reasons $K^+ \to \pi^+\nu\bar{\nu}$, together with the other golden decay $K_L \to \pi^0\nu\bar{\nu}$, is extremely sensitive to new physics contributions. Moreover it allows a precise measurement of the CKM parameter $|V_{td}|$, independent from B oscillation measurements.

The computed branching ratio is $(8.0 \pm 1.1) \times 10^{-11}$ [9]. The existing measurement, based on 3 $K^+ \to \pi^+\nu\bar{\nu}$ events from E787/949 experiments at BNL, is $(1.47 + 1.30 - 0.89) \times 10^{-10}$ [10]. It is compatible with SM within errors but a 10% accuracy measurement is required to provide a significative test of new physics scenarios. This is the goal of the proposed P326 experiment [11] at CERN-SPS, that aims to collect about 80 events in two years keeping the background contamination at 10%.

3.2 The P-326 proposal

The experiment will be based on the NA48 apparatus and will use the same CERN-SPS beam line which produced the kaon beam for NA48 experiments. An R&D program has started in 2006 and we hope to be approved and ready for data taking in 2011. The goal of the experiment can be achieved by exploiting a decay-in-flight technique which allows to reach a 10% signal acceptance. The beam line should be able to provide of the order of 10^{13} kaon decays.

3.2.1 The beam line

An intense 400 Gev/c proton beam from the SPS accelerator (3.3×10^{12} proton/pulse, duty cycle 4.8/16.8 s), produces a secondary charged beam by impinging on a berillium target. A 100 m long beam line selects the positive charged beam with a central momentum of 75 Gev/c and 1.1% RMS momentum bite. The main components are an achromat system made of four dipole magnets, a momentum selection slit and a second achromat where the kaon tracker system (Gigatracker) is installed. The average rate in the Gigatracker is about 800 MHz, while the rate seen by the downstream detector is about 11 MHz due to kaon decays and accidentals coming from the beam line. The beam is positrons free and is composed by 6.6% of K^+. Since the beam is unseparated a particle ID detector is necessary to tag the

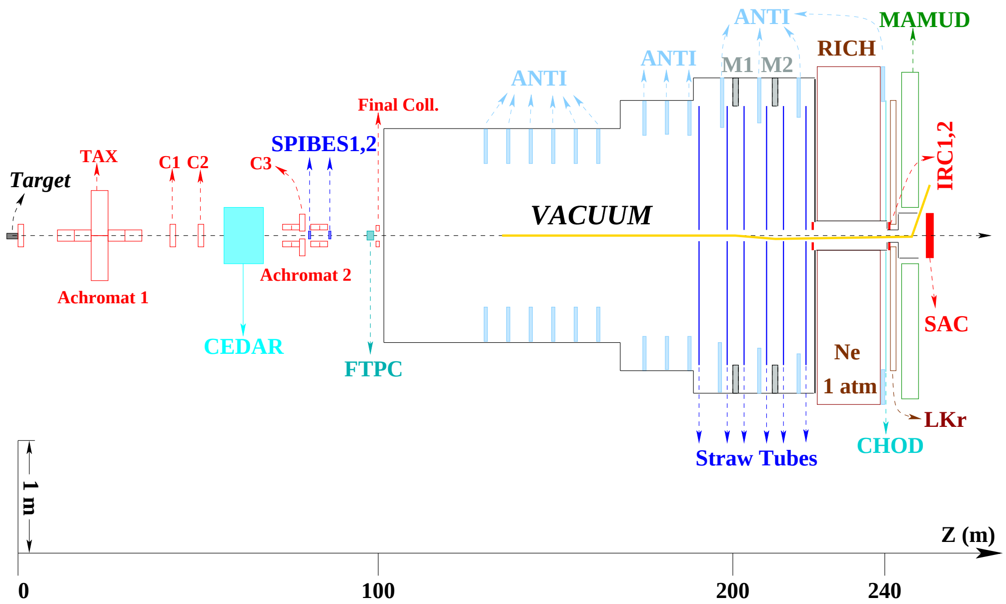

Figure 2: Schematic layout of CERN-P326 experiment: beam line, decay volume and detector (not to scale).

kaons. Assuming a 100 days data taking at 60% efficiency and a 60 m long decay region, $5 \times 10^{12} K^+$ decays/year are expected, which is a realistic estimate based on the decennial experience of NA48 at the SPS.

3.2.2 The detector

The layout of the experiment is shown in Fig.2. The detector consists of:

- **The tracking system** composed by the beam spectrometer (Gigatracker) and the pion spectrometer.

  The Gigatracker must be highly performing in terms of time and spatial resolution and able to sustain a particle rate of about $60 MHz\ cm^-2$. The detector should be located across the second achromat and consists of three Si pixels stations made up by $300 \times 300 \mu m^2$ pixels each of them composed by a $200 \mu m$ thick Si sensor and a chip $100 \mu m$ thick, bump-bonded on the sensor. At least 200 ps time resolution per station is required to provide a suitable tag of the kaon track.

  The downstream pion spectrometer is made of four chambers with four double layers of straw tubes each ($0.1\% X_0$ per view) and one magnet ($270 MeV/c\ p_t$ kick). It will also act as veto for charged particles. Since multiple scattering is the main limitation to kinematical reconstruction accuracy we minimize the material budget and we place the straw chambers in vacuum. A reduced-size prototype has been integrated in the na48/NA62 set-up and is under test during this year data taking at CERN.

- **The particle ID system** is composed of a CEDAR detector [12] to identify the kaon in the beam and a RICH to identify the pions in the decay. The CEDAR is a differential Cerenkov counter available at the beam lines at CERN, tested and upgraded for the new beam conditions. The RICH is located after the spectrometer. It is 18 m long and filled with Ne at atmospheric pressure and contains a 11 cm radius beam pipe.

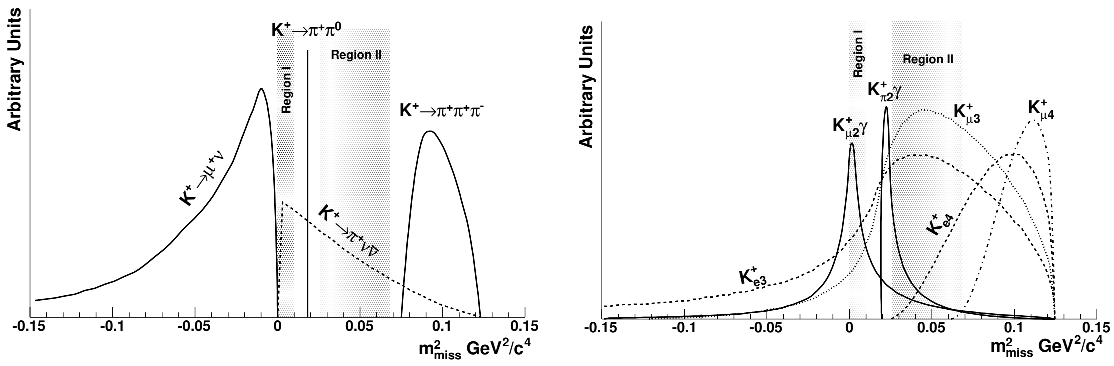

Figure 3: Squared missing mass for kaon decays. The signal regions are compared to the kinematically (left) and not kinematically (right) constrained backgrounds.

Two tilted mirrors, at the downstream end, reflects the Cerenkov light toward an array of about 200 PMTs placed in the focal plane. The RICH should provide timing information for downstream tracks with a required time resolution of about 100 ps. A prototype counter is actually under test on the beam line.

- **The veto system** identifies photons from kaon decays and is made of a combination of calorimeters hermetically covering up to 50 mrad. At large angle (10-50 mrad) ring shaped calorimeters should guarantee photon detection down to 50 MeV with 10^{-4} inefficiency at most and should be placed in vacuum. Two solutions are under test consisting of lead-scintillator crystals or lead-scintillator fibers. At medium angle (1-10 mrad) the existing NA48 liquid Krypton electromagnetic calorimeter with upgraded electronics will be used. An inefficiency lower than 10^{-5} for high energy photons ($E_\gamma >$ 10 GeV) has been measured using $K^+ \to \pi^+\pi^0$ decays collected by NA48/2 in 2004, and this result matches our requests. The inefficiency for intermediate energies ($2 < E_\gamma < 10$ GeV) is under studies using 2006 data from bremsstrahlung photons produced by electrons interacting with the NA48 apparatus. A small angle calorimeter built with Shashlyk technology covers the region below 1 mrad. In this region only photons with energy larger than 10 GeV illuminate the detector, making a 10^{-5} inefficiency achievable. A prototype has been tested with electrons on the NA48 beam line in 2006. An hadronic sampling calorimeter should provide a 10^5 rejection of muons. A magnet should deflect the charged beam out of the acceptance of the small angle calorimeter.

3.2.3 Background rejection and sensitivity

The experimental signature of a $K^+ \to \pi^+\nu\bar{\nu}$ decay consists of a single positive track in the downstream detector in coincidence with a kaon in the beam line. A 10^{-13} background rejection is needed. The beam and pion tracking system should provide a precise reconstruction of the kinematics, measuring the squared missing mass defined as $m^2_{miss} = (P_K - P_\pi)^2$ under the hypothesis that the final charged particle is a pion. A kinematical separation between signal and more than 90% of the total background should be achievable.

In Fig.3, left side, the two backgrounds with largest branching ratio, $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu_\mu$ define two signal regions where background enters only because of non-gaussian tails in the squared missing mass resolution.

The remaining 8% background, shown in Fig.2, right side, is not kinematically constraint and its rejection must rely on the veto system. The detectors give redundancy both in kinematic reconstruction and particle identification allowing background estimation directly from the data. A preliminary analysis using Geant3, Geant4 and Fluka simulation of the apparatus obtains an acceptance of 17% , showing that our goal of 10% acceptance should be safely within reach. The 35 GeV upper momentum cut coming from RICH constraints is an important loss of signal but assures also that events like $K^+ \to \pi^+\pi^0$ deposit at least 40 GeV of electromagnetic energy, making rejection easier.

The main sources of background have been considered and a simple counting of signal and background events in the signal regions indicates that the 10% background level is nearly achievable.

3.2.4 P326 prospects

The $K \to \pi\nu\bar{\nu}$ decay is a unique environment to search for new physics. The experiment CERN-P326 has been proposed to collect O(100) events of the $K^+ \to \pi^+\nu\bar{\nu}$ very rare decay. The detector requires a sophisticated technology for which an intense $R\&D$ program is started. We are designing an experiment able to reach a 10^{-12} sensitivity per event using existing infrastructures and detectors. The beam will provide a K^+ flux about 100 times higher than NA48/2 addressing many other physics opportunities.

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