Precision Tests of the Standard Model with Kaon Decays at CERN

Tommaso Spadaro[1] for the NA62 collaboration

[1]Laboratori Nazionali di Frascati dell'INFN, Via E. Fermi 40, 00044 Frascati, Italy

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/14

Selected precision Standard Model tests performed in the recent past or possible in the near future using kaon decays are discussed, with a focus on unambiguous signatures, such as those for Lepton-Flavor violation (LFV) and Lepton-Number violation (LNV) transitions, and on the physics reach at the high-intensity beams produced at the CERN SPS for the NA48/2 and NA62 experiments. Recent results on the search for the LNV process $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ and for LFV-induced deviations from the SM expectation for the ratio of decays widths for $K^{+} \to e^{+}\nu$ and $K^{+} \to \mu^{+}\nu$ are briefly discussed. Sensitivity improvements with the new phase of NA62 on a variety of observables are outlined.

1 The Kaon physics framework

The Standard Model appears remarkably simple at a c.m. energy around the kaon mass, with few unknown parameters in the QCD dynamics, namely light and strange quark masses and e.m.- or QCD-induced isospin-breaking effects. This leaved room for a thouough study of the symmetry of the electro-weak lagrangian performed in the last decades. Searches with kaons have been competitive with those with B-mesons for lepton-flavor (LF) or CP violation transitions (most notably, the precise measurements of CPV in the mixing ϵ [1] and of the direct CPV in the decay [2]) and reached the highest sensitivity in the search for CPT and quantum mechanics violation effects. The most precise gauge-universality test comes for the unitarity of the first row of the CKM matrix, thanks to the results from kaon decays giving V_{us}, and from super-allowed nuclear transitions giving V_{ud} [3]. This translated into a severe constraint for every new-physics extension of the SM [4].

2 Search for lepton number violation from kaon decays

The lepton-number violation transition $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ is forbidden in the SM. It might be possible in new-physics models, if mediated by a Majorana neutrino. For neutrino masses ranging from 100 to 300 MeV, the cited channel would be that with the highest sensitivity [5].

The search for this decay has been performed at the NA48/2 experiment. The main goal of NA48/2 was the search for direct CPV from precise measurement of the charge asymmetry in the Dalitz-plot density slopes between the decays $K^{+} \to \pi^{+}\pi^{0\pm}\pi^{0,\mp}$ and their charge conjugates [6]. NA48/2 operated with high-intensity, unseparated, simultaneous, highly-collimated, 60-GeV momentum $K^{\pm}$ beams, with a 3.8% momentum bite. The beams entered a decay region in vacuum instrumented with a magnetic spectrometer to measure the momentum of charged decay products, a fast scintillator hodoscope establishing the event time and initiating the trigger, and a liquid Krypton calorimeter downstream the hodoscope with high transversal segmentation and an excellent energy and spatial resolution. The LKr calorimeter was followed by a hadron calorimeter and a muon-veto system (MUV) used both for muon identification and for muon triggering. For details on the apparatus, see [7].

Samples were acquired in 2003-2004 by requiring the presence of three tracks at the trigger level using both the hodoscope and the spectrometer information. A single vertex was reconstructed from the three tracks, and for two of them associated hits in the MUV were required. The sample left for normalization had the same angular acceptance and vertex requests for the three tracks as the two-muon sample, while no request was made on the MUV system, and was equivalent to about 1.4×10^{11} kaon decays in a given fiducial volume.

Two-muon samples were divided into correct-sign (wrong-sign), candidates for the LN conserving (violating) decay $K^\pm \to \pi^\pm \mu^\pm \mu^\mp$ ($K^\pm \to \pi^\mp \mu^\pm \mu^\pm$). The three-track invariant mass distribution for the correct (wrong) sign sample, is shown in the left (right) panel of Fig. 1. A clear peak around the kaon mass is present for the correct sign events, while no peak is observed for the wrong sign sample. The number of events counted in the signal region agrees with the pure-background expectation. The corresponding upper limit, $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9}$ at 90% CL [8], improves on previous results by a factor of 3.

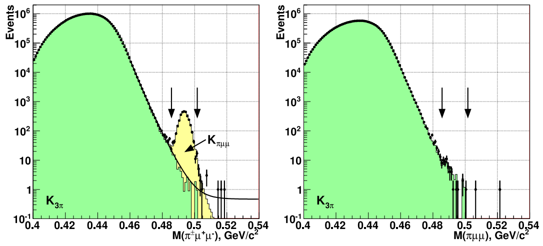

Figure 1: Three-track invariant mass from correct-sign (left-panel) and wrong-sign (right panel) $K \to \pi\mu\mu$ samples. The vertical arrows define the signal region.

3 Search for lepton flavor violation from kaon decays

Thanks to the cancellation of hadronic uncertainties, the ratio R_K of decay widths for kaon decays to $e\nu$ and $\mu\nu$ final states can be predicted with extremely high accuracy in the SM: $R_K = 2.477 \pm 0.001 \times 10^{-5}$ [9]. In large-tan β super-symmetric models R_K might deviate from the SM estimate by up to the percent [10, 11] and this NP effect should be dominated by a LFV contribution from $e\nu_\tau$ final states. After the Higgs discovery made the large-tan β scenario less probable and after the constraints from the $B \to \tau\nu$ and $B_{(s)} -> \mu^+\mu^-$ are taken into account, NP effects on R_K above the per-mil level are disfavoured [12]. Nevertheless, NP effects at the percent level might still be envisaged in scenarios with SM extensions including sterile fermions and inverse see-saw [13].

A data taking at the NA62 experiment was performed in 2007-2008, dedicated to the measurement of R_K. At that time, the most precise measurement of R_K had a total uncertainty of 1.3% [14]. The design of NA62 was optimized for the R_K measurement with respect to that used for NA48/2, by increasing the beam momentum to 74 GeV, decreasing the momentum bite to 2.5%, and by increasing the momentum kick provided by the spectrometer magnet.The resolution on the missing mass from kaon decays from a single track was therefore significantly improved, thus increasing the kinematic separation of $K \to e\nu$ (a.k.a. K_{e2}) decays with respect to $K \to \mu\nu$ decays ($K_{\mu 2}$). Beam particles with a single charge were used and the majority of the data taking was devoted to a positively charged beam.

The main trigger for $K_{\mu 2}$ events required a single track observed at the hodoscope together with activity in the drift chambers corresponding to a single track. To trigger K_{e2} events, the request of having an energy deposition of at least 10 GeV in the LKr calorimeter was added. In the offline analysis, K_{e2} decays were identified by requiring a cluster of energy in the LKr calorimeter, geometrically associated to the kaon daughter track, and by selecting events with a ratio of energy measured by the calorimeter to momentum measured by the spectrometer around unity. Events with a squared missing mass at the K decay point around zero are considered K_{e2} candidates, see the left panel of Fig 2. The misidentification probability of high-energy muons mimicking the electron energy release in the calorimeter has been precisely evaluated comparing a muon-enriched control sample acquired by interspersing a lead bar between the two hodoscope planes. The probability was measured to be at the level of 4×10^{-6} and depends on the muon energy.

NA62 selected the largest K_{e2} data set ever, with almost 150000 events. The total background amounts to almost 11%, dominated by $K_{\mu 2}$ decays with muons mimicking the electron energy release in the calorimeter (5.64±0.20%). Radiative structure-dependent $K_{e2\gamma}$ decays contribute for 2.60±0.11%, while the beam halo due to muons from upstream in flight decay of beam pions constitute the third background source, 2.11±0.09%. The analysis for R_K was performed in 10 bins of lepton momentum and separating runs according to the beam charge and to the setup (with and without the lead bar). The results are found to be mutually compatible and average to

$$R_K = (2.488 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5}. \quad (1)$$

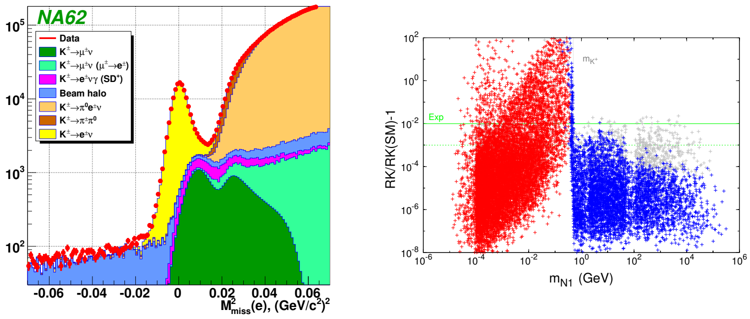

Figure 2: Left: Squared missing mass at the K decay vertex, evaluated assuming the daughter track has the electron mass, for K_{e2} candidate events. Right: fractional deviation of R_K with respect to its SM expectation as a function of the lightest sterile neutrino mass for NP models with sterile neutrinos with inverse see-saw (from Ref. [13]). Models above the solid green line representing the upper bound from the NA62 result of Eq. 1 are excluded.

	K Mode	UL at 90% CL	Experiment
LFV	$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	E777/E865 [17]
LFV	$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	E865 [18]
LNV	$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	E865 [18]
LNV	$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	E865 [18]
LNV	$K^+ \to \pi^- \mu^+ \mu^+$	1.1×10^{-9}	NA48/2 [8]
LNV	$K^+ \to \mu^- \nu e^+ e^+$	2.0×10^{-8}	Geneva-Saclay [19]
LNV	$K^+ \to e^- \nu \mu^+ \mu^+$	no data	

	π^0 Mode	Status	Experiment
LFV, ν_R	$\pi^0 \to$ inv.	$< 3 \times 10^{-7}$	E949 [20]
LFV	$\pi^0 \to e\mu$	$< 4 \times 10^{-10}$	KTeV [21]
NP scalars	$\pi^0 \to 4\gamma$	$< 2 \times 10^{-8}$ at 90% CL	Crystal box [22]
NP scalars	$\pi^0 \to e^+e^-e^+e^-$	$3.34(16)10^{-5}$	KTeV [21]
NP vectors	$\pi^0 \to U\gamma$, $U \to e^+e^-$	Various exclusions	see [23]
C violation	$\pi^0 \to 3\gamma$	$< 3.1 \times 10^{-8}$ at 90% CL	Crystal box [22]

Table 1: Upper (lower) panel: LFV/LNV K-decay modes (π^0 decay modes) possibly studied at the imminent run of NA62: the single-event sensitivity is expected to reach 10^{-12} (10^{-10}).

The residual systematic uncertainty is due to a number of different contributions [15]. Notwithstanding an uncertainty improvement on the previous data by a factor of 4, the result is in agreement with the SM expectation. Exclusion plots for NP contributions can be obtained: the right panel of Fig. 2 refers to models with sterile neutrino and inverse see-saw.

4 Near-future sensitivity from NA62 on NP searches

The NA62 collaboration developed a new detector setup, including the trigger and data acquisition systems, optimized to measure the branching fraction for the rare flavor-changing neutral current decay $K^+ \to \pi^+ \nu\bar{\nu}$ with a 10% total uncertainty. For a detailed description of the new setup and of the measurement itself, see [16]. The data taking will begin in 2014 and will last for at least two years. Higher proton intensity and much larger beam accepted solid angle compared to the NA48/2 setup will allow 1.2×10^{13} K decays in a 60-meter long fiducial region to be studied, an improvement by a factor of 50. This, together with the possibility to apply flexible and dedicated trigger strategies using PID information and multi-track requests, will allow a single-event sensitivity at the level of 10^{-12} for the lepton-flavor violation channels listed in the upper panel of Table 1. The background rejection for the identification of the cited LNV decay $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ will be increased hugely, thanks to the redundant PID capability of the new setup and to the lowering of the invariant mass resolution by more than a factor of 2. The expected sentitivity will increase by a factor from 100 to 1000. Major impact on other topics are foreseen. One year of data taking at the new NA62 corresponds to more than 10^{11} π^0's produced from $K^+ \to \pi^+\pi^0$. This intense and possibly tagged π^0 *beam* will allow other interesting studies, as listed in the lower panel of Table 1. Among these, we cite the search for NP vectors, also called *dark photons* [24]. In one year of data taking $\sim 10^{15}$ $D^\pm$ will be produced, thus allowing interesting searches for long-lived exotic particles reaching the NA62 apparatus, such as the heavy neutral leptons of the NP model by Shaposhnikov and others [25].

References

[1] A. J. Buras, D. Guadagnoli and G. Isidori, Phys. Lett. B **688** (2010) 309 and references therein.

[2] V. Fanti *et al.* [NA48 Collaboration], Phys. Lett. B **465** (1999) 335 [hep-ex/9909022]. J. R. Batley *et al.* [NA48 Collaboration], Phys. Lett. B **544** (2002) 97 [hep-ex/0208009]. A. Alavi-Harati *et al.* [KTeV Collaboration], Phys. Rev. Lett. **83** (1999) 22 [hep-ex/9905060].

[3] M. Antonelli *et al.*, Phys. Rept. **494** (2010) 197 [arXiv:0907.5386 [hep-ph]].

[4] A. Czarnecki, W. J. Marciano and A. Sirlin, Phys. Rev. D **70** (2004) 093006 [hep-ph/0406324].

[5] A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP **0905** (2009) 030 [arXiv:0901.3589 [hep-ph]].

[6] J. R. Batley *et al.* [NA48/2 Collaboration], EPJ C52 (2007) 875.

[7] V. Fanti *et al.* [NA48 Collaboration], Nucl. Instrum. Meth. A **574** (2007) 433.

[8] J. R. Batley *et al.* [NA48/2 Collaboration], Phys. Lett. B **697** (2011) 107.

[9] V. Cirigliano, I. Rosell, Phys. Rev. Lett. **99** (2007) 231801.

[10] A. Masiero, P. Paradisi, R. Petronzio, Phys. Rev. D **74** (2006) 011701 and JHEP 0811 (2008) 042.

[11] J. Girrbach, U. Nierste, arXiv:1202.4906.

[12] R. M. Fonseca, J. C. Romao and A. M. Teixeira Eur. Phys. J. C **72** (2012) 2228.

[13] A. Abada, *et al.* JHEP **1402** (2014) 091 [arXiv:1311.2830v2 [hep-ph]]

[14] F. Ambrosino, *et al.* [KLOE Collaboration], Eur. Phys. J. C **64** (2009) 627.

[15] C. Lazzeroni, *et al.* [NA62 Collaboration], Phys. Lett. B **719** (2013) 326.

[16] G. Ruggiero [NA62 Collaboration], proceedings of PANIC 2014 conference.

[17] A. Sher, *et al.*, Phys. Rev. D **72** (2005) 012005 [hep-ex/0502020].

[18] R. Appel, *et al.*, Phys. Rev. Lett. **85** (2000) 2877 [hep-ex/0006003].

[19] A. M. Diamant-Berger, *et al.*, Phys. Lett. B **62** (1976) 485.

[20] A.V. Artamonov, *et al.* [E949 Collaboration], [arXiv:hep-ex/0506028v2] (2005).

[21] E. Abouzaid, *et al.* [KTeV Collaboration], Phys. Rev. Lett. **100** (2008) 182001 [arXiv:0802.2064 [hep-ex]].

[22] J. McDonough, *et al.*, Phys. Rev. D 38 (1988) 2121.

[23] see Fig. 6 in arXiv:1311.0029v1 [hep-ph] and references therein.

[24] B. Holdom, Phys. Lett. B 166 (1986) 196; P. Galison and A. Manohar, Phys. Lett. B 136 (1984) 279.

[25] L. Canetti *et al.* [arXiv:1208.4607v2 [hep-ph]].