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Search for lepton number violation and other exotic processes at NA62

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Summary. — NA62 is a fixed target experiment at CERN, with the main goal of measuring the branching ratio of the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$. However, the wide physics program covered by the experiment allows the search for other possible indications of new physics beyond the Standard Model. In this document, the searches for lepton number violation and invisible vector bosons ("dark photon") are reported.

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1. – The NA62 experiment at CERN

The NA62 experiment is located in the CERN North Area; its main goal is the measurement of the branching ratio of the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$ at 10% precision level. The decay is a flavour-changing neutral-current (FCNC) process, suppressed in the SM by the GIM mechanism. The isospin symmetry allows to retrieve the hadronic matrix element from the one of the semileptonic kaon decays, experimentally very well known. This leads to a very accurate theoretical prediction: $BR(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ [1]. The challenging requirements for this measurement make the experiment suitable for other searches for new physics beyond the Standard Model: two of these searches are described in the following sections.

The experimental layout of NA62 is reported in fig. 1. Kaons are produced in a non-separated hadron beam by the interaction of a 400 GeV/c proton beam coming from CERN SPS with a beryllium target; the secondary beam has a momentum of 75 GeV/c and it is mainly made by pions (70%) and protons (23%), with only 6% of K^+. The nominal intensity of the secondary beam is 800 MHz. Kaons are identified by a differential Cherenkov detector (KTAG) and their momentum is measured by a three-station silicon tracker (GTK). A veto detector (CHANTI) rejects events with inelastic interactions between the beam and GTK. After the 60 m long decay region, a straw chamber spectrometer measures the momenta of the particles in the final state. Particle identification is performed by a RICH detector, which also provides fast timing information together with a charged hodoscope (CHOD). A hermetic photon veto system (LKr, LAV, IRC, SAC) ensures π^0 detection up to 50 mrad while muons are rejected by a three-station system (MUV).

Detailed description of the NA62 apparatus and its data acquisition system can be found, respectively, in [2] and [3]. The experiment took data from 2016 to 2018. Results from analyses of the 2016–2017 datasets are reported.

2. – Searches for lepton number violation

Lepton number conservation is an emergent property, not related to any symmetry in the SM; therefore, a violation of this quantity could give a strong indication of new

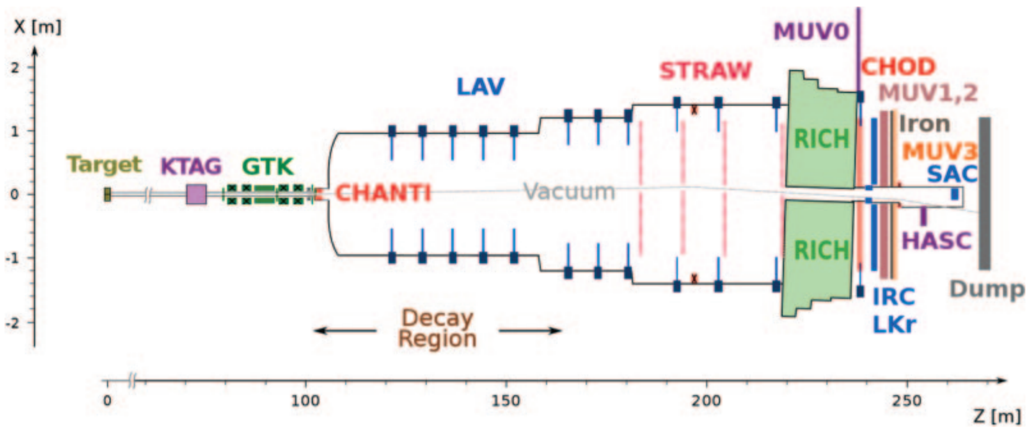

Fig. 1. – Schematic layout of the NA62 experiment.

physics. NA62 performed searches for $K^+ \to \pi^- l^+ l^+$ decays with $l = (e, \mu)$, which represent the analogous in the kaon sector of $0\nu\beta\beta$ decays [4]. The most recent results come from the E949 [5] and NA48 [6] experiments. Data used for this search belong to a subsample of 2017 data, collected with dedicated trigger streams in order to select charged leptons in the final state. In both cases, the SM allowed decays $K^+ \to \pi^+ l^+ l^-$ are used as normalization, minimizing most of the systematic uncertainties since the selection for normalization and signal is almost the same, except for the charges of the particles in the final state. The selection for both channels proceeds through the following steps: reconstruction of a three-track vertex in the decay region, with a total electric charge $q = 1$ and a separation between the tracks to suppress fake candidates; kinematic cut on the track momentum and on the total momentum of the vertex with respect to the nominal beam momentum; timing coincidence between the tracks using the information of CHOD and RICH; pion identification based on the ratio E/p between the energy deposit in LKr and the track momentum; lepton identification. Signal regions, defined around m_K in the distribution of the missing mass $m_{\pi ll}$, are kept blind until the background evaluation is finalized.

2·1. *Search for* $K^+ \to \pi^- e^+ e^+$. – In addition to the criteria listed above, an additional cut is in the πee channel: for the SM decay, the mass of the dilepton couple m_{ee} has to be greater than 140 MeV/c^2 to suppress contribution from $\pi^0_D \to e^+ e^- \gamma$ and $\pi^0_{DD} \to e^+ e^- e^+ e^-$ following a $K^+ \to \pi^+ \pi^0$ decay. Positron identification is based not only on E/p measurement but also on the RICH response using a maximum likelihood algorithm to discriminate between the different mass hypotheses.

The main background for the analysis come from particle misidentification (pion as electrons and vice versa): background evaluation is based on Monte Carlo simulation fed with the measured PID efficiencies, as well as particle misidentification probabilities. The left plot of fig. 2 shows the missing mass distribution for the SM decay $K^+ \to \pi^+ e^+ e^-$: the main background contributions come from $K^+ \to \pi^+ \pi^+ \pi^-$ with π^+ and π^- misidentifications and from $K^+ \to \pi^+ \pi^- e^+ \nu$ with π^- misidentification. However, positron identification with the RICH significantly reduces these background contribution in both SM and LNV cases.

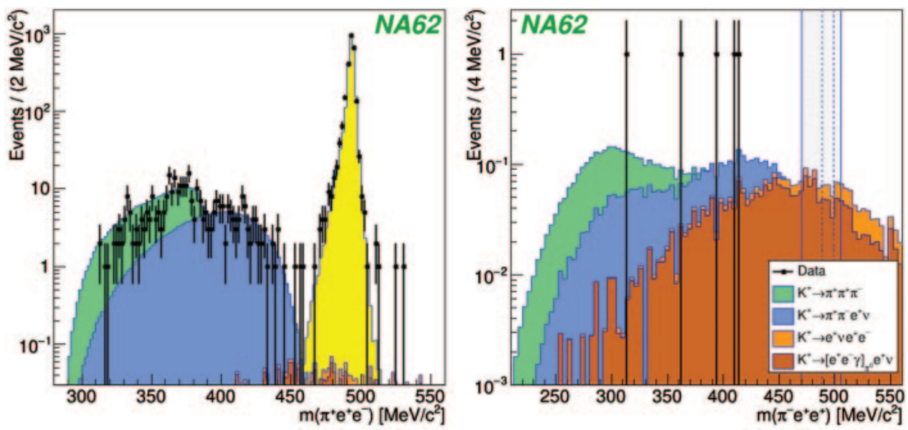

Fig. 2. – Missing mass distributions for $K^+ \to \pi^+ e^- e^+$ (left) and $K^+ \to \pi^- e^+ e^+$ (right) decays. Unblinded signal and control regions are represented by dashed and solid lines, respectively.

The total number of kaon decays selected is $(2.14 \pm 0.07) \times 10^{11}$, with a signal acceptance of 4.98% and an expected background of 0.16 ± 0.03. No events are found in the signal region at the end of the analysis; this leads to an upper limit at 90% CL three times better than previous results:

$$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}. \quad (1)$$

2$\cdot$2. *Search for* $K^+ \to \pi^- \mu^+ \mu^+$. – For this search, particle identification is based on E/p and MUV3 rather than on the RICH response. In this case, the main background contribution comes from $K^+ \to \pi^+\pi^+\pi^-$ decays, with either $\pi \to \mu\nu$ decays or pion-muon misidentification. In addition, pileup activity in MUV3 has to be taken into account as a possible background source. Both pileup activity and misidentification probability have been measured on data and used for Monte Carlo simulation. The background coming from $K_{3\pi}$ events with no or single pion decay have been evaluated using a data driven method and the misID probability. For $K_{3\pi}$ events with at least two pion decays, which not necessarily imply pion mis-identification, a specific Monte Carlo simulation has been used.

The number of kaon decays selected is $(7.94 \pm 0.23) \times 10^{11}$, with a signal acceptance of 9.81% and a total expected background of 0.91 ± 0.41. One event was found in the signal region, which corresponds to the following upper limit at 90% CL:

$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-10}. \quad (2)$$

This result improves the previous limit by a factor 2.

The missing mass distributions for $K^+ \to \pi^- l^+ l^-$ modes with unblinded signal regions are shown in fig. 3.

3. – Search for invisible vector bosons

Possible extensions of SM that could explain the abundance of dark matter in the universe contain a new $U(1)$ symmetry [7], mediated by a vector field A' ("dark photon")

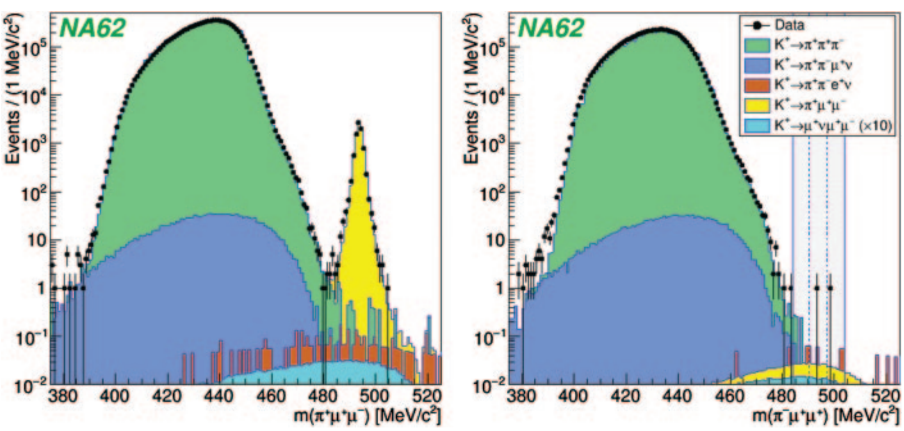

Fig. 3. – Missing mass distributions for $K^+ \to \pi^+\mu^+\mu^-$ (left) and $K^+ \to \pi^-\mu^+\mu^+$ (right) decays. Unblinded signal and control regions are represented by dashed and solid lines, respectively.

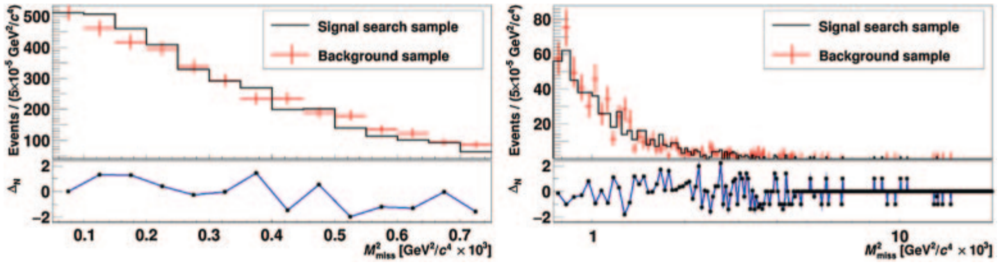

Fig. 4. – M^2_{miss} distributions for signal (black) and background (red) samples. The two distributions are scaled using the sideband shown in the left plot, while the dark photon search is performed in the range shown in the right plot.

that is coupled to the SM photon via a kinetic mixing term in the Lagrangian. This interaction could lead to an exotic decay of neutral pion, whose branching ratio can be written as

$$BR(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{M^2_{A'}}{M^2_{\pi^0}}\right) \times BR(\pi^0 \to \gamma\gamma), \tag{3}$$

where ϵ is the coupling and $M_{A'}$ is the dark photon mass. NA62 performed a search for A' in the range $m_{A'} \in [60 - 130]\,\text{MeV}/c^2$ using a subsample of the 2016 dataset [8].

The analysis is based on the selection of events from the decay chain $K^+ \to \pi^+\pi^0$ and $\pi^0 \to A'\gamma$; the signal can be seen as a peak in the distribution of the missing mass,

$$m^2_{miss} = (P_K - P_\pi - P_\gamma)^2, \tag{4}$$

around $M^2_{A'}$ while the dominant background contribution, coming from $\pi^0 \to \gamma\gamma$ decays with one undetected photon, has a peak at zero (fig. 5, left). Kaon and pion momenta are measured by GTK and STRAW respectively, while photon momentum is computed given the energy deposit in LKr and the vertex position.

A pure sample of $K^+ \to \pi^+\pi^0$ is selected reconstructing the charged tracks and requiring a momentum $(P_K - P_\pi)$ consistent with the squared mass of π^0. Additional

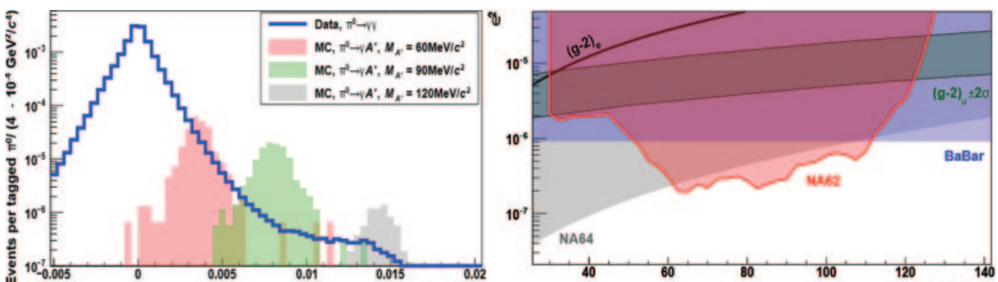

Fig. 5. – Left: distribution of m^2_{miss} for data from $\pi^0 \to \gamma\gamma$ with one photon randomly discarded, and Monte Carlo, in three different dark photon mass hypotheses and with a signal strength $\epsilon^2 = 2.5 \times 10^{-4}$. Right: 90% CL upper limit obtained by NA62 in the (ϵ, A') plane; results from other experiments are also shown.

conditions are used to ensure the presence of a single photon and the π^+ in the final state: no activity in the photon veto system, except for clusters in LKr due to γ and π^+, and no activity in time in CHOD, except for the one due to the charged pion. Studies performed with Monte Carlo simulations suggested that background is almost entirely due to $K^+ \to \pi^+\pi^0\gamma$ events in which one photon from the neutral pion decays is lost because of photo-nuclear interactions or conversion downstream the CHOD. Background events have been evaluated using a data-driven method: the signal selection is used but the requirements on the extra activity in the CHOD is inverted, asking for events with activity in the hodoscope far from the pion and the expected impact point for the photon. This selection allows to collect events with one photon lost to interaction upstream the CHOD; requiring the presence of a second photon is possible to have a distribution for M^2_{miss} for background events, with no overlap with the signal sample. The two samples are normalized using a sideband of the signal region, as shown in fig. 4.

Since no statistically relevant excess is found in the signal region, a 90% CL limit has been put in the (ϵ, A') plane (fig. 5, right).

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