

# Prospects for exotics and LFV at NA62

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**Abstract.** The NA62 experiment at the CERN SPS is designed to measure the branching ratio of the ultra-rare decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  with 10% precision. For this purpose the experiment aims to collect of the order of 100  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events which would require at least  $10^{13} K^+$  decays in the fiducial volume of the detector. The large sample of  $K^+$  decays that will be available at NA62 allows the experiment to carry out a rich program for rare and forbidden  $K^+$  and  $\pi^0$  decays, including lepton flavour and/or number violating modes, sterile neutrinos, exotic particles (e.g. Dark Photons). NA62's potential for such searches in  $K^+$  and  $\pi^0$  decays is discussed, with initial sensitivity estimates. In addition, plans for continuing the experiment after 2021 (Long Shutdown 2) are presented, including in particular the possibility to operate in a beam-dump mode for exploring various Dark Matter scenarios.

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## 1. Introduction

NA62 [1] is a fixed target experiment located in the North Area of the CERN SPS which makes use of an unseparated 75 GeV/c positive secondary beam produced by 400 GeV/c protons from the SPS impinging on a beryllium target. The secondary beam has a 6% component of  $K^+$  which are allowed to decay in-flight inside a 65 m long fiducial decay volume (see Figure 1). The goal of the NA62 experiment is to measure the branching ratio of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay, a theoretically very clean process that is considered to be a sensitive probe for physics beyond the Standard Model (SM). While the SM prediction  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$  [2] is quite precise it is not matched by the current experimental state-of-art  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$  [3], based on only 7 candidate events. The high uncertainty of the experimental result motivates the new measurement by the NA62 which plans to collect of the order of 100  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events. Considering the SM decay rate and assuming a 10% signal acceptance, the kaon flux should correspond to at least  $10^{13}$   $K^+$  decays in the fiducial volume. Furthermore, since  $BR(K^+ \rightarrow \pi^+ \pi^0) = 20.69\%$ , NA62 will be exposed to  $\sim 10^{12}$  tagged  $\pi^0$  decays.

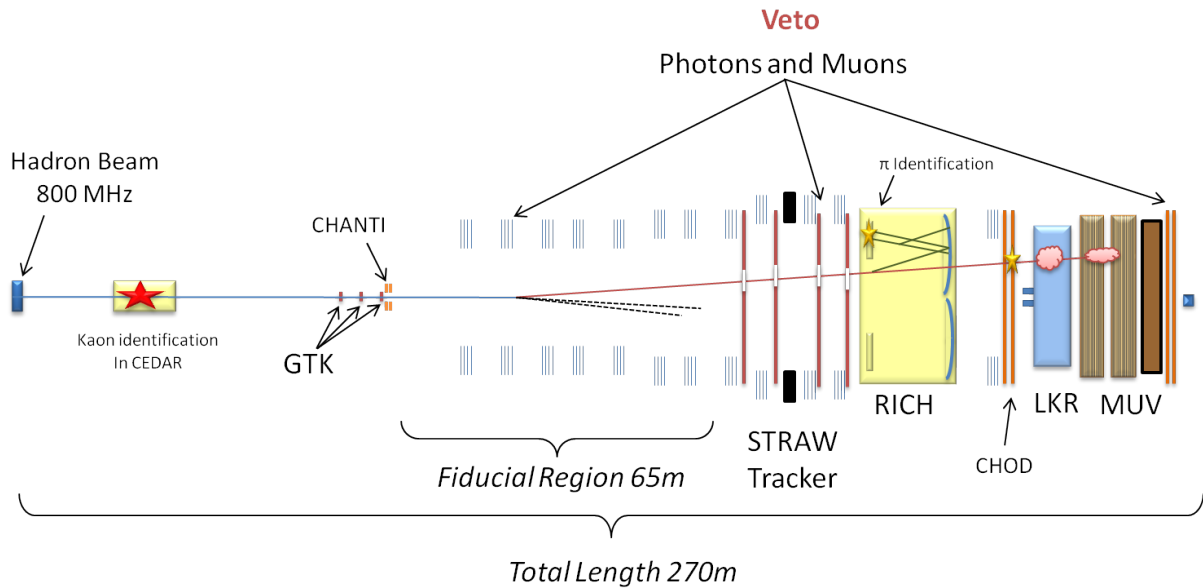
These large samples of kaon and pion decays provide an opportunity to perform searches for a range of novel phenomena and forbidden decay modes with an unprecedented precision. In particular, NA62 is well positioned to improve the current limits in the searches for  $K^+$  decays with explicit violation of the conservation of lepton flavour (LFV) or number (LNV). These include the LNV modes:  $K^+ \rightarrow \pi^- \mu^+ \mu^+$ ,  $K^+ \rightarrow \pi^- e^+ e^+$  and  $K^+ \rightarrow \pi^- \mu^+ e^+$ ; and the LFV:  $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$ . NA62 can also search for heavy neutrinos produced in  $K^+ \rightarrow l^+ \nu_N (l = e, \mu)$ , where  $\nu_N$  does not decay inside the fiducial volume of the detector.

The exploitation of rare and forbidden decay physics beyond the flagship mode will rely critically on the implementation of dedicated trigger chains. The NA62 trigger is divided into three logical levels: hardware L0 trigger that reduces the  $\sim 10$  MHz input rate at nominal beam to  $\sim 1$  MHz using trigger algorithms based on multiplicity signals from the ring-imaging Cerenkov (RICH), the charged-particle hodoscope (CHOD) and the muon-veto (MUV3) detectors, and the energy deposited in the LKr calorimeter; software L1 and L2 triggers that reduce the input rate further by using the  $K^+$  beam tagging detector (CEDAR), the large-angle photon vetoes (LAV), reconstructed tracks and decay topologies using the STRAW spectrometer, as well as refined information from all other detectors, including those used at L0. Depending on the beam intensity, the trigger bandwidth at L0 for final states other than "single positive track + missing energy" ( $\pi \nu \bar{\nu}$ ) is limited to a few 100 KHz.

The NA62 detector and the adjoining beamline have been commissioned up to the designed beam intensity in pilot runs in 2014 and 2015, and at present the experiment is taking data for physics. The physics program of NA62 is approved until 2018 when the Long Shutdown 2 (LS2) period starts and the SPS will not provide beam to the North Area. The SPS will resume in 2021 and the NA62 collaboration is considering various proposals for rare and exotic searches that could be done with minimal modifications of the existing apparatus. A particularly interesting possibility, also discussed here, is to operate the detector and the beam-line in a "beam-dump" mode, similar to the SHiP proposal [4], to search for MeV-GeV mass hidden-sector candidates, such as Dark Photons ( $A'$ ), heavy neutral leptons (HNL), axion-like particles (ALP), etc.

## 2. LNV and LFV in $K \rightarrow \pi ll$ decays

The apparent lepton flavour and/or number conservation observed so far in particle physics is conveniently accommodated in the SM if the neutrino masses are zero. The discovery of neutrino oscillations has led to a conclusion that the lepton flavour symmetry is approximate rather than exact. It also implies that the neutrinos have non-zero masses which, in addition to constituting a non-SM phenomenon by itself, opens the questions about the possible Majorana nature of the neutrino as well as the origin of the small observed neutrino mass scale. Simply



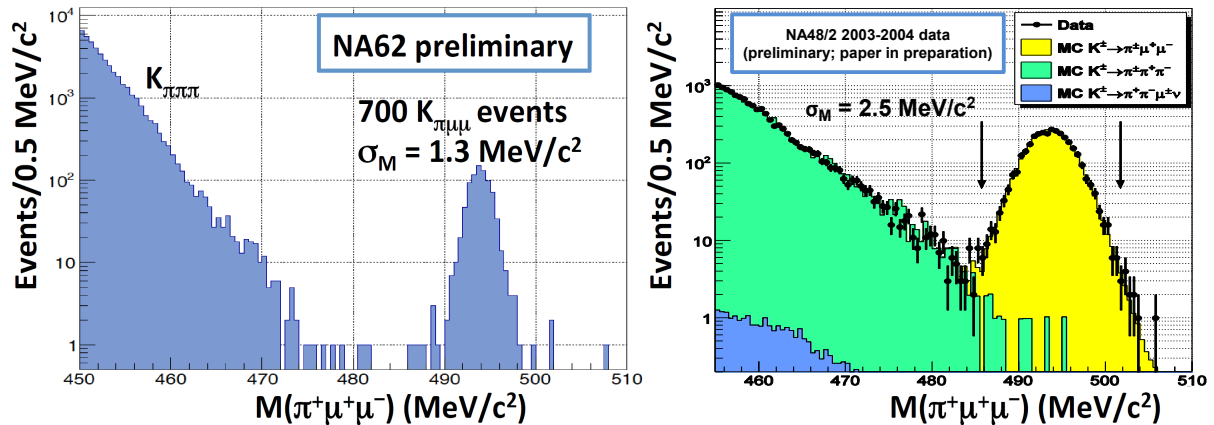
**Figure 1.** Schematic view of the NA62 experiment, excluding the beam line.

**Table 1.** Status of searches for LFV and LNV  $K^+$  decays for which limits can potentially be improved by NA62.

Decay mode	SM violation	Limits on BR	Experiment
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	LNV	$8.6 \times 10^{-11}$	CERN NA48/2 [5]
$K^+ \rightarrow \pi^- e^+ e^+$	LNV	$6.4 \times 10^{-10}$	BNL E865/CERN NA48/2 [6]
$K^+ \rightarrow \pi^- \mu^+ e^+$	LNV	$5.0 \times 10^{-10}$	BNL E865/CERN NA48/2 [6]
$K^+ \rightarrow \pi^+ \mu^- e^+$	LFV	$5.2 \times 10^{-10}$	BNL E865/CERN NA48/2 [6]
$K^+ \rightarrow \pi^+ \mu^+ e^-$	LFV	$1.3 \times 10^{-11}$	BNL E777/E865 [7]

incorporating massive neutrinos into the SM results in a prediction of LFV and LNV decays with an unobservably low branching ratios. Therefore, an observation of any of the  $K^+ \rightarrow \pi^\pm ll$  processes in Table 1 would serve as a clear indication of physics beyond the SM, such as supersymmetry, Little Higgs models, extra dimensions,  $Z'$  vector bosons, etc.

The LNV decays  $K^+ \rightarrow \pi^- l^+ l'^+$  could be mediated by heavy Majorana neutrino exchange in the same way that could lead to the neutrinoless nuclear double  $\beta$  decay. One extension of the SM that could provide simultaneously explanation for neutrino oscillations, Dark Matter and the baryon asymmetry of the Universe, the so called  $\nu$ MSM [8], introduces three heavy right-handed sterile neutrinos with Majorana mass terms. The first, with low mass, could be a dark matter candidate. The others, with masses ranging from 100 MeV/ $c^2$  to few GeV/ $c^2$ , could be responsible for the standard neutrino masses through the Seesaw mechanism and introduce extra CP violating phases, which can account for the observed baryon asymmetry. The heavy neutrinos can be produced in charged kaon decays as long as their masses are within the kinematically accessible range of a few  $\sim 100$  MeV. Provided that the heavy neutrinos are short lived in order to decay within the detector, NA62 is in excellent position to look for  $K^+ \rightarrow \pi^- l^+ l'^+$  decays mediated by them.



**Figure 2.**  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  invariant mass distribution as measured by the NA62 (left), using 2016 data collected with a dedicated  $\pi\mu\mu$  trigger chain, and by NA48/2 (right) [5].

Recent anomalies in the semileptonic decays  $B \rightarrow K^* \mu^+ \mu^-$  ( $P'_5$  observable) and  $B_s^0 \rightarrow \phi \mu^+ \mu^-$  (LHCb [9, 10]), in  $H \rightarrow \mu\tau$  (ATLAS/CMS [11]), and the tensions in the ratio  $\varepsilon'/\varepsilon$  [12] have hinted at New Physics, consistent with MFV [13], that could produce LFV in  $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$  decays. Furthermore, the parameter space relevant for the explanation of the B-meson anomalies lies within the sensitivities of the NA62 experiment. Of course pushing down the limits on the  $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$  modes depends critically on the availability of trigger bandwidth so that the corresponding triggers are used without any downscaling.

The trigger chains that are used at the moment are based on multiple tracks final states with additional conditions to identify the lepton pairs (multiplicity in MUV3 and energy deposits in the LKr) in order to reject the high-rate  $K_{3\pi}$  contribution. Figure 2 shows a comparison between the invariant mass distribution of the  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  candidates (a lepton number conserving decay with  $BR = (9.4 \pm 0.6) \times 10^{-8}$ ) from a recent NA48/2 measurement (right) and using NA62 data collected during the 2016 run with a dedicated trigger for  $\pi\mu\mu$  final states (left). The mass resolution at NA62 is better by a factor  $\sim 2$  as compared to NA48/2 thanks to the new spectrometer and the higher B-field of the dipole magnet (0.36T). The tail towards higher values of invariant mass from  $K_{3\pi}$  seen in the NA48/2 measurement is eliminated. Thus in the period until the LS2 it may be possible for NA62 to push the limits on the branching ratios of the LNV and LFV  $K^+ \rightarrow \pi l l$  decays down to  $\sim 10^{-12}$ . Furthermore, it is possible that the searches for LNV and LFV would be continued in the period after the LS2, when the  $K \rightarrow \pi \nu \bar{\nu}$  measurement will be finished and more trigger and acquisition bandwidth will be available.

### 3. Heavy neutrinos in $K_{l2}$ decays

In 2015 NA62 collected a large sample of  $\sim 700$ M minimum-bias triggered events which allows to carry out a search for HNL production in  $K^+ \rightarrow l^+ \nu$  decays. The search is model independent and it is based on scanning for a peak in the missing mass distributions of  $K_{\mu 2}$  and  $K_{e 2}$  type decays. The preliminary analysis shows that the background can be kept low and with the current data sample NA62 can improve the upper limits on the two mixing matrix elements  $|U_{\mu N}|^2$  and  $|U_{e N}|^2$  in the mass ranges  $250 < m_N < 375$  GeV/ $c^2$  and  $180 < m_N < 450$  GeV/ $c^2$ .

#### 4. Hidden sector candidates in "beam dump" mode

Despite the discovery of the Higgs boson, it is clear that the SM is not a complete theory as it fails to explain a number of observed phenomena, including neutrino masses and oscillations, the baryon asymmetry of the Universe, Dark Matter, etc. Various models of Hidden sectors that attempt to solve these puzzles predict some yet unobserved particles which mediate interactions with the SM sector, i.e HNL [8, 14], Dark Photon  $A'$  (vector) [15]), ALPs (pseudoscalar coupled to two photons) [16], etc. Searches for such heavy exotic particles can be carried out at the LHC. However, it is possible that we have not observed any of these potential DM candidates due to their extremely feeble interactions with the SM sector rather than due to their heavy masses. Fixed target (or "beam-dump") experiments are particularly useful to search for new weakly coupled, long-lived particles in the MeV to GeV range. The high intensity at the SPS and the large production of charm mesons with the 400 GeV proton beam allow accessing a wide variety of light long-lived exotic particles. While an experiment dedicated to such exotic searches is proposed at the SPS, the SHIP experiment [4], in the shorter term, after the LS2 in 2021, there is a possibility to operate NA62 in "beam dump" mode [17, 18]. The Beryllium target used by NA62 is followed by two 1.6 m long, water-cooled, beam-defining copper collimators (TAX) which can act as a dump ( $\sim 10.7\lambda_I$ ).

ALPs can be produced directly in the beam dump in the fusion of two photons coming from the proton-nucleus interaction (Primakoff production [19]). Although the transverse momenta of the produced ALPs are small the detector is placed far away from the target ( $> 100$  m) and therefore covers only a small angle from the production point. Taking the detector acceptance into account and assuming that all background can be suppressed, even with a rather modest beam-time of a few weeks, NA62 would have a sizeable discovery potential for ALPs in the mass range of  $\sim 30 - 200$  MeV (Figure3, left).

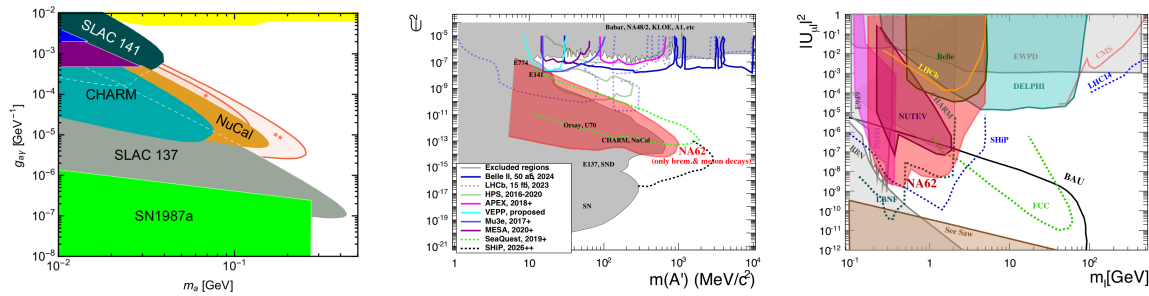
Dark Photons can be produced in decays of mesons created in the beam dump, assuming  $A'$  is coupled to quarks, or in hard Bremsstrahlung from the beam protons ( $\gamma^* N \rightarrow N' A'$ ). NA62 can look for visible decays of  $A'$  to  $e^+e^-$  pairs, dominant decay channel for  $2m_e < M_{A'} < 210$  MeV, and  $\mu^+\mu^-$ , which is as frequent as  $e^+e^-$  for heavier  $A'$ . Figure 3 (middle) shows the expected sensitivities assuming  $2 \times 10^{18}$  protons on target (equivalent of 2 years of running) and zero background, and taking into account the trigger efficiency and detector acceptance. NA62 could be sensitive to even larger phase space as only production in the Beryllium target is considered in this estimate, and not in the TAX.

Concerning the HNL, they can be produced in decays of mesons created in the dump and NA62 can search for them in the 60 m long decay volume of the detector. Unlike the heavy neutrino search done in  $K^+ \rightarrow l^+ \nu$  decays the searches for visible decays of the HNL are model dependent. Possible final states to look for are  $e^\pm \pi^\mp$  (for the mass range of  $140 < M_{A'} < 250$  MeV/ $c^2$ ),  $\mu^\pm \pi^\mp$  ( $M_{A'} > 250$  MeV/ $c^2$ ) and  $e^+e^- \nu$  ( $2m_e < M_{A'} < 140$  MeV/ $c^2$ ). The expected sensitivity is shown in Figure 3 (right).

During the 2015 and 2016 runs NA62 collected several hours of data at different intensities with a closed TAX. In addition, during the 2016 run, in normal data-taking conditions, the trigger configuration included chains for exotic searches which were ran in parallel with the main trigger: RICH & 2 $\times$ CHOD quad. & 2 $\times$ MUV3 hits ( $\mu\mu$  trigger) and RICH & 2 $\times$ CHOD quad. & MUV3 hit &  $E_{LK\tau} > 10$  GeV ( $\pi\mu$  trigger). The collected data is used for feasibility studies and tests of the zero background hypothesis. The preliminary analysis indicates that zero background is achievable [18].

#### 5. Summary

NA62 is designed to make a precise measurement of the  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ . The high-intensity kaon beam provides an opportunity to extend the physics program beyond the flagship mode



**Figure 3.** (left) Projected sensitivity of NA62 in the  $(m_{ALP}, ALP-\gamma \text{ coupling})$  parameter space for a number of protons on target equivalent to one day, or  $1.3 \times 10^{16}$  protons on target (marked with \*), and equivalent to one month (marked with \*\*) [17]; (middle) NA62 sensitivity (90% CL) to  $A'$  in the  $(m_{A'}, A' \text{ coupling to } \gamma)$  parameter space considering 2 years of data-taking ( $2 \times 10^{18}$  protons on the Beryllium target); (right) NA62 sensitivity (90% CL) to HNL in the  $(m_l, \text{HNL coupling to } \mu)$  parameter space considering 2 years of data-taking [18]; Regions covered by previously performed experiments and astrophysical constraints are overlayed in the plots.

and search for a number of rare and forbidden decays, including the LNV and LFV  $K^+ \rightarrow \pi^\pm l l$  decays and heavy neutrinos in  $K^+ \rightarrow l^\pm \nu$ . The detector and the beamline were commissioned during runs in 2014 and 2015, and in 2016 the experiment is taking data for physics with a number of dedicated triggers for exotic decays which are ran in parallel with the main trigger. NA62 is currently approved to take data until the end of 2018 when the LS2 of the SPS/LHC starts. Without major modifications of the existing apparatus NA62 can operate in beam-dump mode using one of the beam-defining collimators as a dump. The experiment has a potential to search for weakly-interacting sub-GeV Dark Matter candidates. Such a run is currently being considered for the period after the LS2 in 2021.

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