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Search for $K^+ \to \pi^+ \nu\bar{\nu}$ and Future Searches for Exotic Processes at NA62

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NA62 is a fixed target experiment at CERN with the main goal of measuring the Branching Ratio of the decay $K^+ \to \pi^+ \nu\bar{\nu}$ at 10% precision level. It also searches for exotic

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particles such as invisible vector bosons or axion-like particles. First preliminary results of a subset of 2016 data sample are shown.

Keywords: NA62; FCNC; dark photons; axion-like particles.

1. Introduction

1.1. *Theoretical motivations for* $K^+ \to \pi^+\nu\bar{\nu}$

The rare decay $K^+ \to \pi^+\nu\bar{\nu}$ is a golden channel for high-precision tests of the Standard Model (SM). It is a Flavour Changing Neutral Current (FCNC) process, forbidden at the tree-level in the SM. The decay can be described by a short-distance effective hamiltonian in which the main contribution comes from top quark loops with a subleading contribution from charm. The hadronic matrix element can be related via isospin simmetry to the one of K^+_{e3} decay, measured with good accuracy. For this reason, the prediction is essentially not affected by hadronic uncertaninties. The SM prediction for the Branching Ratio (BR) of $K^+ \to \pi^+\nu\bar{\nu}$ is [1]:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11} \tag{1}$$

The main source of theoretical uncertainties comes from the experimental values of SM parameters, in particular CKM matrix elements. Due to its suppression, deviations of the measured BR from the prediction might reveal new physics beyond the SM. Measuring the BR with a 10% precision level allows to look for new physics up to 100 TeV scale. Experiments E787 and E949 at Brookhaven National Laboratory performed a measurement of this BR using stopped kaons; the result was [2]:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \tag{2}$$

1.2. *The NA62 experiment at CERN*

NA62 aims to detect O(100) $K^+ \to \pi^+\nu\bar{\nu}$ decays. Assuming an acceptance of 10%, 10^{13} decays must be collected to reach this goal. After a calibration run in 2015, the first period of data taking started in 2016 and it is going to continue until the end of 2018.

The experiment is located in the North Area of CERN; here, a primary beam of protons with a momentum of 400 GeV/c hits a beryllium target to create a non-separated beam of hadrons of 75 GeV/c momentum. This secondary beam, made of pions (70%), protons (23%) and kaons (6%) reaches the 260 m long apparatus of NA62, shown in Fig. 1. The experimental tecnique used by NA62 is the in-flight detection of kaon decays in a 80 m long fiducial volume. Kaons are identified by a Cherenkov differential counter (KTAG) which also provides timestamps for them. Kaon momentum is measured by the GigaTracKer (GTK), a three-station silicon spectrometer. To reject background coming from inelastic interactions between the kaons and the GTK, a veto detector (CHANTI) is located downstream the last station of the tracker. The momenta of the downstream particles are measured by a straw tubes spectrometer; a Ring Imaging CHerenkov detector (RICH) provides

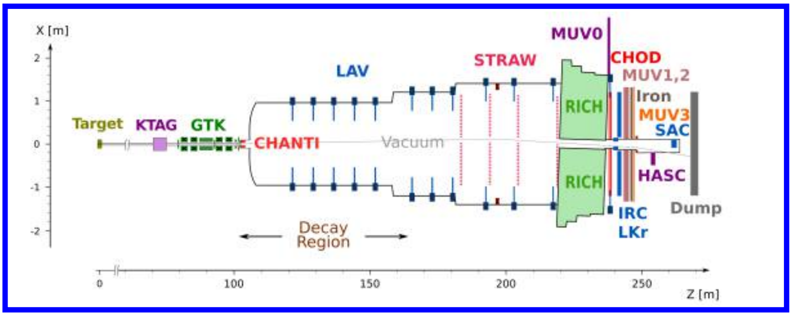

Fig. 1. A schematic illustration of NA62 apparatus in x-z plane.

pion identification and reject positrons and muons. Fast timing informations come from the RICH and a scintillation hodoscope (CHOD), placed downstream to it. A background rejection factor at the order of 10^{12} is required to separate the signal from the other kaon decays, whose braching ratios are several order of magnitudes higher than the signal, like $K^+ \to \mu^+\nu$ ($K_{\mu 2}$, $BR = 63\%$) and $K^+ \to \pi^+\pi^0$ ($K_{2\pi}$, $BR = 21\%$). To reject those backgrounds, Photon and Muon Vetoes are included in NA62 apparatus. Photon Veto system is made of different detectors, according to the angular coverage: the Large Angle Veto (LAV), a liquid krypton calorimeter (LKr), the Intermediate Ring Counter (IRC) and the Small Angle Calorimeter (SAC). All these detectors reject electromagnetic activity up to 50 mrad. Muon Veto (MUV) system is made by three stations in which MUV1 and MUV2 can also be used as an hadronic calorimeter. A more detailed description of NA62 apparatus can be found in Ref. 3 .

1.3. *Exotic searches at NA62*

Several features make NA62 particularly suitable for searching for new physics processes:

- high-intensity;
- trigger system flexibility;
- detector performance (high-frequency tracking of beam particles, redundant PID, high-efficiency photon veto).

In the following, two searches belonging to this sector are presented.

1.3.1. *Search for invisible vector bosons*

One possible extension of the SM that could explain the presence of the dark matter in our universe is based on a new U(1) gauge symmetry mediated by a bosonic field A', called "dark photon". This new field could couple to the SM photon, described by the usual tensor $F_{\mu\nu}$, through a kinetic mixing term in the lagrangian [4]:

$$\epsilon A'^{\mu\nu} F_{\mu\nu} \tag{3}$$

In this extended lagrangian, other fields associated to new particles belonging to the "dark sector" may be present; if this particles are lighter than the dark photon, it decay essentially "invisibly", with only missing energy as experimental signature.

The search for dark photons at NA62 is focused on the following decay chain:

$$K^+ \to \pi^+\pi^0 \quad , \quad \pi^0 \to A'\gamma \tag{4}$$

The Branching Ratio of the latter decay is related to the one of $\pi^0 \to \gamma\gamma$ via:

$$BR(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_A^2}{m_{\pi^0}^2}\right) \times BR(\pi^0 \to \gamma\gamma) \tag{5}$$

1.3.2. *Search for axion-like particles (ALPs)*

Besides the standard data-taking mode, with the secondary beam of hadron of 75 GeV/c, NA62 can also run in a dump-mode data taking, with all the 400 GeV/c protons stopped in copper collimators. Proton interactions with the collimator could be the source of ALPs, so far undiscovered. ALPs can be produced in several processes but in beam dump experiments the main production mechanism is the coherent scattering between protons and nuclei (Primakoff effect). This is due essentially to two reasons:

- the amplitude is proportional to Z^2 while the other contributions to ALP production are proportional to the mass number of the target nucleus: hence, there is an enhancement of the Primakoff effect rate in heavy or even medium weight materials;
- momenta transfers are small and, consequently, the cross sections are peaked in the forward direction. This allows even small detector far away from the target to have large geometrical acceptance.

After propagating along a distance D = 81 m, the ALPs reach the fiducial volume (L = 135 m) in which the decay $a \to \gamma\gamma$ can be detected. In particular, this search is focused on the detection of both photons in the LKr.

2. Preliminary results

2.1. $K^+ \to \pi\nu\bar{\nu}$

The analysis is based on the measurement of the kinematic variable:

$$m^2_{miss} = (P_K - P_\pi)^\mu (P_K - P_\pi)_\mu \tag{6}$$

The distribution of m^2_{miss} for the signal and for the main background channels is plotted in Fig. 2: it is possible to define two signal regions, at both sides of $K_{2\pi}$ peak. The standard computation of m^2_{miss} is done measuring the momenta of the kaon and the pion with GTK and STRAW, respectively; however, it is useful to measure it in other two ways: $m^2_{miss}(RICH)$, with the momentum of the pion measured by the RICH, and $m^2_{miss}(NOGTK)$, assuming the nominal beam momentum as

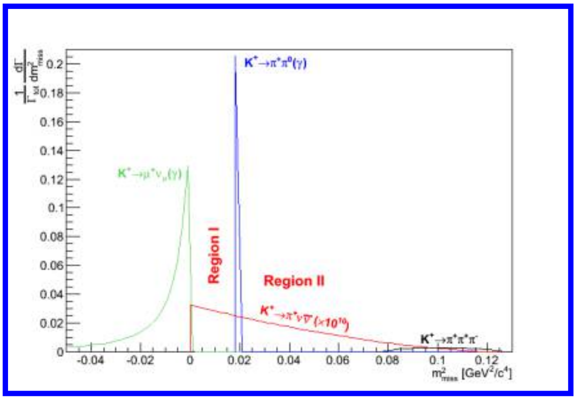

Fig. 2. Theoretical distributions of m^2_{miss} for the signal and for the main backgrounds.

the kaon momentum. The signal regions, thus, are three-dimensional regions in the space of this three variables.

5% of 2016 data set has been analyzed, corresponding to $\sim 2.3 \times 10^{10}$ kaon decays. Events with only one track in the STRAW spectrometer are selected; pion momentum range accepted is 15-35 GeV in order to have at least 40 GeV as missing energy in the photon veto systems. The upstream kaon, identified by the KTAG and kinematically reconstructed by the GTK, is associated to the downstream track. Time resolution for both tracks are O(100 ps) and the association efficiency is 75% with 1.7% of mis-tagging probability. PID techinques using RICH and calorimeters are then applied together with π^0 suppression to reject background. Muon and π^0 suppression factors are O(10^{-7}). Fig. 3 shows the distribution of m^2_{miss} versus pion momentum, with selected momentum range and signal regions drawn as red boxes. In the right side of the figure, two-dimensional projection of the signal regions can be seen. The expected number of signal events is 0.064 with 0.024, 0.011 and 0.017

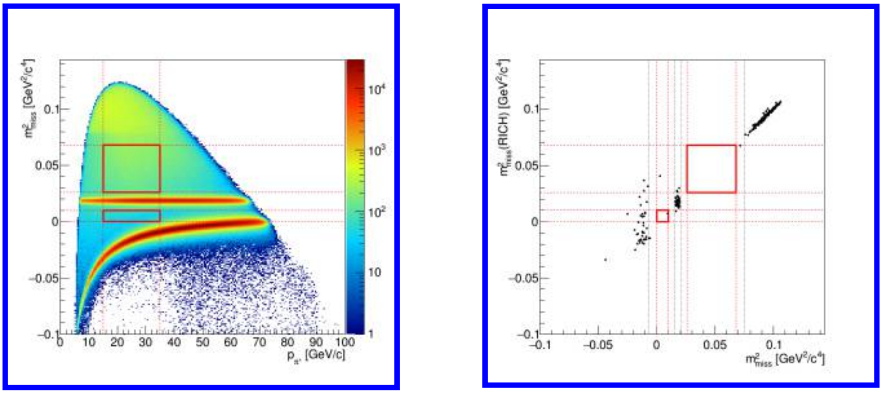

Fig. 3. Left: distribution of m^2_{miss} vs pion momentum. Signal regions and selected momentum range are artificially drawn in red. Right: 2-d projection of signal regions after the full selection.

expected events from $K_{2\pi}$, $K_{\mu 2}$ and $K_{3\pi}$ respectively. No events in signal regions have been observed.

2.2. *Search for dark photons*

The distribution of the invariant mass

$$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2 \tag{7}$$

is expected to peak around the A' mass for the signal and around zero for the background coming from the usual decay $\pi^0 \to \gamma\gamma$ with one undetected photon. Monte-Carlo simulations for different values of A' mass were performed (40-120 MeV), as shown in Fig. 4 . Background is evaluated through a data-driven method: the width of the peak is due to resolution effects, which are left-right symmetric. It is possible, then, to evaluate the background looking at the negative tail of the distribution, that have no physical meaning. Using this procedure and having observed no signal events, new upper limits in the $(\epsilon, m_{A'})$ plane at 90% CL have been obtained (Fig. 4).

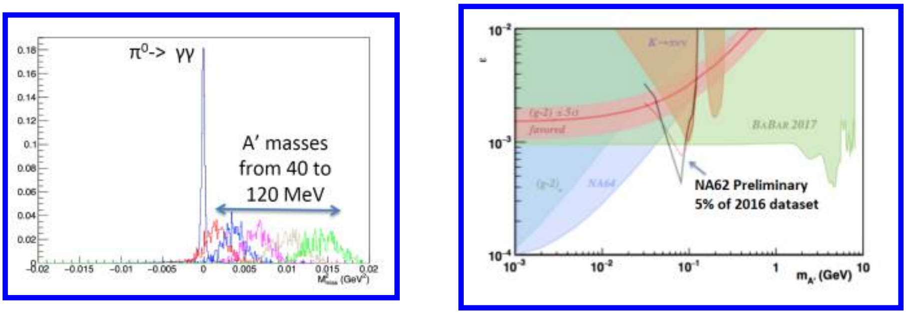

Fig. 4. Left: invariant mass distributions obtained for different A' mass hypoteses. Right: new 90% CL limits obtained by NA62 in $(m_{A'}, \epsilon)$ plane.

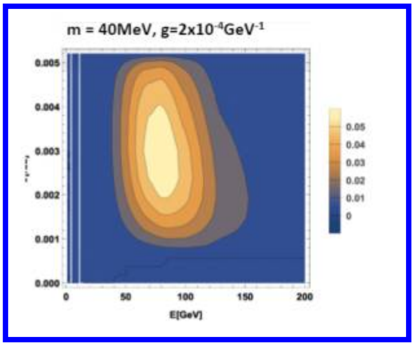

Fig. 5. Product of the differential ALP production cross section and detection probability at NA62 as a function of the angle and ALP energy.

2.3. *Search for ALPs*

The analysis of 2016 dump-mode runs, corresponding to 17 hours of data taking, is still ongoing. Here, the analysis strategy is reported. Two clusters in the LKr are required. There is no upstream tracking information for this search, then mass of the ALP or decay vertex must be imposed to discriminate between signal and backgrounds. The barycenter of the cluster can be computed to get the flight direction of the ALP. Due to the presence of the beam pipe at the center of the calorimeters, only non-zero angles can be scanned. A toy MonteCarlo simulation is used to obtain the product of production cross section and detection probability. Calorimeter geometrical acceptance, from 1 to 8.5 mrad, allows only to search for small decay-lenght ALPs. Background can be evaluated using sideband to deduce the expected number of events in the signal region.

3. Summary and outlook

The NA62 experiment and its physics program were presented. Preliminary results based on 5% of 2016 data sample were shown. NA62 has been collecting data in 2017 and it will run until LS2 at the end of 2018. With the full data sample of this first period of data taking (2016-2018), tens of $K^+ \to \pi^+\nu\bar{\nu}$ events will be collected. Concerning exotic searches, new upper limits for dark photons existence have been obtained. The search for ALPs is ongoing and results from this analysis will be presented soon.

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