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Search for exotics at NA62

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Abstract. Fixed target experiments are a particularly useful tool in the search of very weakly coupled particles in the MeV-GeV range, which are of interest as potential dark matter mediators. Owing to the high beam energy and a hermetic detector coverage, NA62 also has the opportunity to directly search for a variety of long-lived beyond the Standard Model particles, such as axion-like particles and dark photons. Furthermore, the large sample of K^+ decays available at NA62 allows a rich program for rare and forbidden decay studies. In this paper the status of these searches is reviewed, giving prospects for future data taking at NA62.

1. Introduction

Although the Standard Model (SM) currently describes elementary particles and their interactions with extreme precision, it still fails to explain a number of observed phenomena, such as neutrino masses and oscillations, dark matter (DM) and baryon asymmetry of the universe. Search for the existence of new particles at high masses and sizeable couplings to SM particles has been widely performed. However, new particles might also be found at much lower energy scales, interacting very feebly with SM particles and thus escaping strong constraints from searches at colliders.

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The NA62 experiment has been designed to measure precisely the branching ratio (BR) of the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. Besides the main measurement, NA62 has a program to search for lepton number (LNV) and lepton flavor (LFV) violating decays. Furthermore, the intensity and energy of the SPS proton beam used to produce the K^+ , as well the full particle identification, hermetic coverage and high rate tracking, make the set-up suitable for a number of exotic searches.

2. The NA62 experimental set-up

NA62 is a fixed-target experiment at CERN SPS: primary SPS protons hit a berillium target from which a secondary charged hadron beam of 75 GeV/c, with 6% charged kaons, is selected and transported to the decay region, more than 100 m downstream of the target. The incoming kaon is positively identified by a differential Cerenkov counter (KTAG) and its momentum and direction are measured by three stations of Si pixel detectors (GTK). A decay tank, holding a 10^{-6} mbar vacuum, is surrounded by lead-glass annular calorimeters (LAV) designed to efficiently detect photons up to 50 mrad. Four stations of straw chambers (STRAW) in vacuum trace downstream charged particles. A RICH identifies secondary charged pions; plastic scintillators (CHOD) are used for triggering and timing. Photon rejection in the forward region is provided by an electromagnetic liquid krypton calorimeter (LKr) and two small angle calorimeters (IRC and SAC). Hadron calorimeters (MUV1,2) and a plastic scintillator detector (MUV3) placed downstream of an iron-based absorber are used to detect hadrons and muons. Information from CHOD, RICH, MUV3 and LKr are hardware processed to issue level zero trigger conditions. Software-based algorithms from KTAG, CHOD, LAV and STRAW information provide higher level trigger requirements. Low-intensity data have been taken in 2015 to study detector performance and to perform physics analysis. Since 2016, NA62 is collecting data for the measurement of the $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and other physics cases.

3. Lepton number/ flavor violation in $K \rightarrow \pi ll$ decays

Lepton number and/or flavor conservation is conveniently accommodated in the SM if neutrinos are massless, due to the absence of right-handed neutrino states. However, since the discovery of neutrino oscillations has unambiguously demonstrated the massive nature of neutrinos, right-handed neutrino states must be included. Extensions of the SM involving the inclusion of sterile neutrinos which mix with ordinary neutrinos could explain simultaneously neutrino oscillations, dark matter and baryon asymmetry of the Universe [1]. Further extensions add a scalar field to incorporate inflation and provide a common source for electroweak symmetry breaking and right-handed neutrino masses [2]. New particles predicted by these models, such as heavy neutrinos and inflatons, could be produced in LNV and LNC $K^\pm \rightarrow \pi \mu \mu$ decays.

The large statistics of the samples of charged kaon decays into final states with multiple charged particles collected in 2003-2004 by the NA48/2 experiment at CERN allowed to search for the forbidden LNV $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ decay, as well for two-body resonances in $K^\pm \rightarrow \pi \mu \mu$ decays [3]. The selection of final states containing two same-sign muons and one odd sign pion was optimized with a blind analysis based on Montecarlo (MC) samples. The total number of reconstructed $K^\pm \rightarrow 3\pi$ decays was used for normalization, leading to first order cancellation of systematic effects given the similar topologies of signal and normalization channels. One data event was observed after the selection, while the expected number of background events was 1.160 ± 0.865 , leading to the upper limit (UL) on the number of $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ signal events of $N^{LNV} < 2.92 @ 90\% \text{ CL}$ and on the branching ratio $BR(K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11} @ 90\% \text{ CL}$, improving by a factor 13 previous results.

The large samples of kaon and pion decays in NA62 provide an opportunity to perform searches for a range of novel phenomena and forbidden K^+ decay modes with an unprecedented precision, improving the current limits in the searches for LNV ($K^+ \rightarrow \pi^- \mu^+ \mu^+$, $K^+ \rightarrow \pi^- e^+ e^+$,

$K^+ \rightarrow \pi^- \mu^+ e^+$) and LFV ($K^+ \rightarrow \pi^+ \mu^- e^+$, $K^+ \rightarrow \pi^+ \mu^+ e^-$) decays: these searches are not limited by backgrounds and sensitivity down to 10^{-11} can be reached.

4. Exotic searches in Kaon decays

A large variety of searches for hidden sector particles can be performed at NA62 exploiting the high-intensity kaon beam. As an example, axion-like particles (a) and dark scalars (S) are produced in $K^+ \rightarrow \pi^+ a$ and $K^+ \rightarrow \pi^+ S$ decays, while a dark photon (A') originates from the decay chain $K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \gamma A'$. These exotic particles could decay into invisible states or escape detection being long-lived and faintly interacting with the SM fields. A search for invisible decays of a dark photon has been performed using $1.5 \times 10^{10} K^+$ decays, corresponding to about 5% of the dataset collected in 2016. Events with a single downstream track reconstructed in the STRAW are selected using the same trigger stream as for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay. The downstream track is required to match in time and space a GTK track, forming a vertex in the fiducial volume of the experimental apparatus. The GTK track is identified as a K^+ by the KTAG, while the RICH and the calorimeters system identify the downstream track as a pion. The missing mass obtained from the momentum of the downstream and GTK tracks is required to be around the π^0 mass peak. Events with a single photon cluster in the LKr calorimeter are selected and no activity in time with the selected events in LAV, IRC and SAC detectors is required. The squared missing mass $M_{miss}^2 = (P_K - P_\pi - P_\gamma)^2$ obtained from the kaon, pion and photon momenta, is expected to peak around the A' mass for the $\pi^0 \rightarrow \gamma A'$ decay and around zero for the background process $\pi^0 \rightarrow \gamma\gamma$ with one photon undetected. A data-driven background estimate, based on the tail with negative missing mass values, is used. For each A' mass, the signal region is defined as a 1.5 standard deviation range around the expected invariant mass peak. Frequentistic 90% CL intervals have been determined, taking into account the uncertainties of signal efficiency from MC and the statistical uncertainties of data counts and background expectations. No statistically significant excess has been detected and UL have been computed on the number of signal events. The 90% CL exclusion limit on the kinetic mixing parameter versus the mass of the dark photon is shown in Figure 1 together with the limits from BaBar [4], NA64 [5] and E949 [6] experiments.

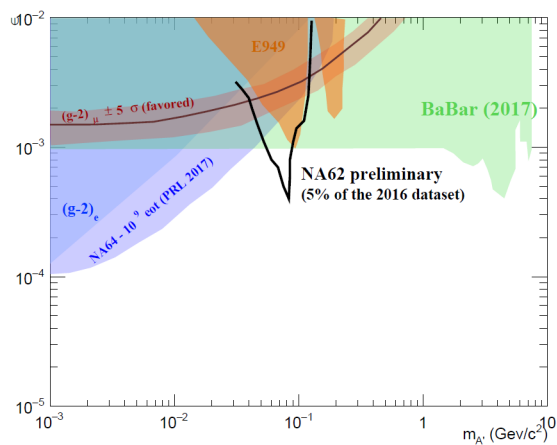


Figure 1. NA62 90% CL exclusion limit for $\pi^0 \rightarrow \gamma A'$ events with A' decaying into invisible final states. Limits from BaBar, NA64 and E949 are also shown together with the region of the parameters that could explain $(g-2)_\mu$ anomaly (faint band) and the region excluded by the agreement of $(g-2)_e$ with expectations (dark shaded area).

5. Exotic searches in NA62 beam-dump mode

Feebly-interacting exotic particles can be originated also by the decay of beauty and charm hadrons, mesons and virtual photons produced in the interaction of protons with a dump. Their couplings to SM particles are very suppressed leading to expected production rates of 10^{-10} or

less. Since in our energy range the charm and beauty cross-sections steeply increase with the energy, a high-intensity, high-energy proton beam as the 400 GeV/c primary proton beam line serving the NA62 experiment can produce high intensity fluxes (10^{18} proton on target (POT) per nominal year) of beauty and charm hadrons. The beryllium target used by NA62 is followed by two 1.6 m long, water-cooled, beam defining copper collimators (TAX) which can act also as a dump ($\sim 10.7\lambda_I$). In the standard NA62 operation roughly 50 % of the beam protons punch through the beryllium target and are absorbed by the TAX. The experimental signature of hidden sector decays into SM particles is two or more tracks or two photons originating from the same point of the decay volume and nothing else.

As an example a dark photon can be produced in mesons decays from beam dump, assuming that the A' couples to quarks, or in hard bremsstrahlung from the beam protons. NA62 can search for the visible decays $A' \rightarrow e^+e^-$ and $A' \rightarrow \mu^+\mu^-$. Figure 2 shows the expected sensitivity for dark photon, in the coupling versus mass plane, assuming 10^{18} POT and zero background for the search of dilepton vertices, taking into account trigger efficiency and detector acceptance. NA62 could be sensitive to a even larger phase space than shown, since in the estimate of Figure 2 only production in the beryllium target is considered and not in the TAX. Other physics cases similarly under study concern the search for visible decays of dark scalars (Figure 3) and heavy neutral leptons.

During the 2016 run, NA62 collected several hours of data at different intensities with the beryllium target lifted from the beam and closed TAX to perform feasibility studies: the preliminary analysis indicates that a zero-background condition might be achievable.

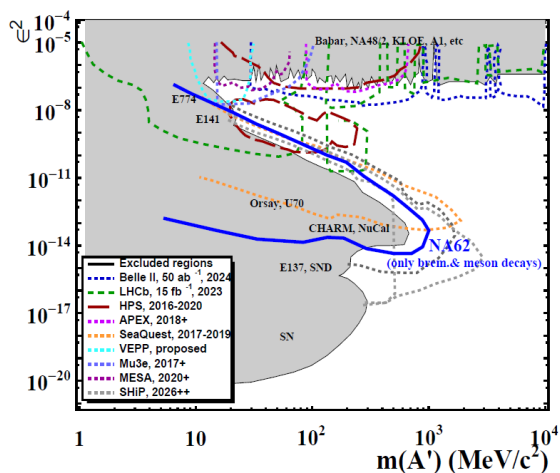


Figure 2. NA62 expected sensitivity for 10^{18} POT (90% CL exclusion limit, solid line) for a dark photon originated by the dump.

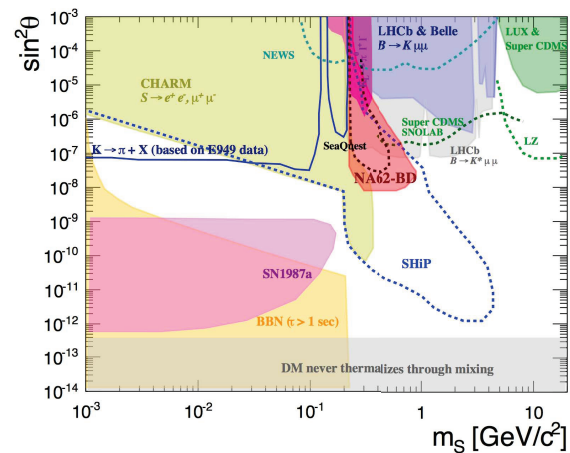


Figure 3. NA62 expected sensitivity for 10^{18} POT (shaded region labelled as NA62-BD corresponding to a 90% CL exclusion limit) for a dark scalar originated by the dump.

The search for axion-like particles decaying to two photons can only be pursued with a beam-dump setup. The Primakoff production mechanism from interaction onto the TAX is considered [7] and the analysis of 5×10^{15} POT collected by NA62 in 2017 is in progress. The expected sensitivity in the zero-background hypothesis after collection of 10^{18} POT is shown in Figure 4, in the coupling versus mass plane, for an axion-like particle new physics scenario with photon coupling dominance [7]. Figure 4 also shows previous results from electron and proton beam-dump experiments, while the bottom region has been excluded after the observation of the supernova SN1987A [8].

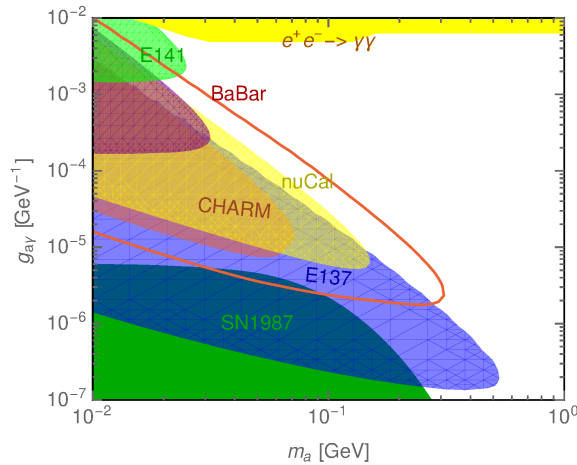


Figure 4. NA62 expected sensitivity for 10^{18} POT (90% CL exclusion limit indicated by the line) for an axion-like particle. The regions excluded by other beam-dump experiments and by the observation of SN1987A are also shown.

6. Conclusions

The NA62 experiment is successfully running in the North Area of the CERN SPS with the main goal of measuring the $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with 10% accuracy. Owing to the high beam energy and high beam intensity, the long decay volume and the hermetic detector coverage, NA62 also has the opportunity to directly search for a plethora of hidden-sector particles, both in visible or invisible final states. A large variety of searches for hidden sector particles can be already performed before the LS2 using kaon decays. The NA62 collaboration is currently discussing the possibility to use a fraction of the beam time during Run 3 (2021-2023) to operate NA62 in beam-dump mode, opening a window of opportunity to search for hidden particles. The current NA62 run can be exploited to evaluate background rejection capability up to $10^{17} - 10^{18}$ protons on target.

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