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Searches for exotic particles at NA62

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Fixed target experiments are a useful tool in the search for very weakly coupled particles in the MeV–GeV range, which are of interest, e.g. as potential dark-matter mediators. The NA62 experiment at the CERN SPS is currently taking data for rare kaon decay measurements. Due to the high beam energy and hermetic detector coverage, NA62 also has the opportunity to directly search for a multitude of long-lived beyond-Standard-Model particles, such as dark photons, dark scalars, axion-like particles, and heavy neutral leptons. We review the status of these searches and give prospects for future data taking at NA62.

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Direct searches for new physics at the energy frontier have so far not turned up any convincing new evidence. Data from the LHC experiments place strong constraints on the existence of supersymmetric particles [1] and other manifestations of new physics, from new gauge groups to extra dimensions [2]. In these searches, models with TeV-scale degrees of freedom with order-one couplings to Standard Model (SM) particles have received most of the attention. However, if the new physics is only very weakly coupled to the SM, its degrees of freedom do not necessarily have to be so massive. Some of the gaps in the SM might be filled in by the existence of light dark-matter particles and the mediators of their interactions, which would be very weakly coupled to SM particles. Candidates for these exotic particles include dark photons, dark scalars, axion-like particles, and heavy neutrinos [3].

The primary goal of the NA62 experiment at the CERN SPS is to measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with a precision of about 10%. This flavor-changing neutral-current decay has an SM BR of $(8.4 \pm 1.0) \times 10^{-11}$ [4]. The experimental signature is a K^+ decaying to a π^+, with no other particles present. Abundant decays such as $K^+ \to \mu^+ \nu$ (BR = 63%) and $K^+ \to \pi^+ \pi^0$ (BR = 21%) are backgrounds and must be rejected to the level of 10^{-12}. These backgrounds can be suppressed by a factor of 10^{-4} by precisely reconstructing the missing mass of the primary and secondary tracks. The remainder of the required background rejection in NA62 comes from the redundant particle identification systems and hermetic, highly-efficient photon veto detectors. These characteristics of the detector, together with the high-intensity beam and flexible trigger system, make NA62 particularly suitable for searching for the decays of exotic, long-lived particles produced in the target and dump collimator or in the decays of kaons in the beam. The NA62 detector and measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$) are further described in [5] and [6], respectively.

At NA62, long-lived exotic particles or exotic particles without decays to SM particles may be observed in the spectrum of missing mass from K decays such as $K^+ \to \pi^+ X$. Long-lived exotic particles with decays to SM particles may also be produced in the target and their decays reconstructed in the fiducial volume of the detector. Dedicated triggers for signatures such as $\mu\mu$, ee, $\pi\mu$ and πe can be used, with scaledowns chosen to use a small fraction of the $K^+ \to \pi^+ \nu\bar{\nu}$ bandwidth. NA62 can pursue both of these approaches in parallel to the $K^+ \to \pi^+ \nu\bar{\nu}$ program.

Alternatively, in dedicated running, the target may be lifted and the dump collimator 25 m downstream of the target (22 $\lambda_{\rm int}$ of copper and iron) closed, so that the whole beam interacts in a higher Z material closer to the detector, increasing the sensitivity. This operation is reversible in 15 minutes, and samples of O(10^{15}) protons on target (pot) have been collected in dump mode for sensitivity studies. Longer periods of dedicated data taking in dump mode to collect samples of O(10^{18}) pot, perhaps with additional beam line modifications, have been proposed for future running [7].

One simple hidden-sector model introduces a new U(1) gauge symmetry with one extra gauge boson, the dark photon A', which may mediate the interactions between light vector dark-matter particles and SM fermions [8]. The interaction of the A' with the visible sector occurs through kinetic mixing with the SM weak hypercharge. The dark photon then has QED-like interactions with the SM fermions, described by the coupling ε and the mass of the A'.

NA62 can search for dark photons with no decays to SM particles, for example, in $K^+ \to \pi^+ A'$ or $K^+ \to \pi^+ \pi^0$ with $\pi^0 \to \gamma A'$. Fig. 1, left, shows preliminary 90%CL exclusion limits in the $(m_{A'}, \varepsilon)$ plane for invisible dark photons, in which the missing-mass distribution for candidate

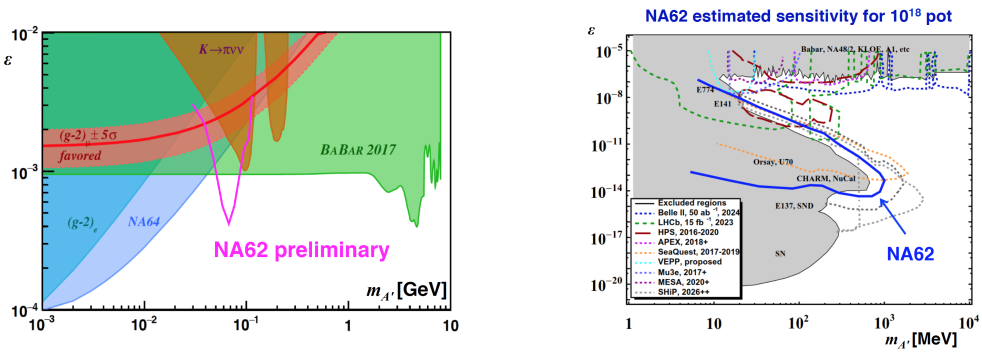

Figure 1: Left: Preliminary 90%CL exclusion limits in the ($m_{A'}$,ε) plane for dark photons A' with no decays to SM particles, from a 5% subset of NA62 2016 data. Right: Estimated NA62 90%CL exclusion limits in ($m_{A'}$,ε) assuming 10^{18} pot and zero background for dark photons A' decaying to e^+e^- or $\mu^+\mu^-$.

events with one track, one photon, and missing energy is examined for evidence of the peak from the A'. The main background is from $K_{\pi 2}$ decays with $\pi^0 \to \gamma\gamma$ in which one photon is not detected. These events have $M_{\rm miss} = 0$; the tail towards negative values of $M^2_{\rm miss}$ is used to obtain the resolution for background studies. This result was obtained with a sample of 1.5×10^{10} K^+ decays, corresponding to 5% of the 2016 data sample. Analysis of the full data set is in progress.

NA62 can also search for dark photons produced in the target that decay to ee or $\mu\mu$ inside of the fiducial volume. Production mechanisms for dark photons in the target include decays of mesons produced in the primary beam interaction (e.g., $pN \to X\pi^0$, $\pi^0 \to \gamma A'$), or in bremsstrahlung processes from the primary beam ($pN \to XA'$). The sensitivity estimate shown in Fig 1, right, assumes both mechanisms contribute. This sensitivity is obtained for 10^{18} pot, with both the $A' \to ee$ and $A' \to \mu\mu$ channels. Zero background is assumed. This assumption has been proven to be valid up to exposures of 10^{15} protons with data collected in running with parasitic ee and $\mu\mu$ triggers. This sensitivity estimate does not take into account dark-photon production from QCD processes or dark photons produced in the beam dump as opposed to the target (about 40% of the primary beam protons pass through the target and interact in the beam dump instead). In 2016–2017, effective exposures of 3×10^{17} pot and 5×10^{16} pot were collected with the $\mu\mu$ and ee triggers, respectively. Analysis of this data is underway.

A simple extension of the SM scalar sector is to add a real singlet scalar S [9], leading to mixing of the physical h with the S, with angle θ. The dark sector could then be coupled to the Higgs via S. We consider a scenario in which the S couples to dark matter candidates $\chi\bar{\chi}$ but does not decay into them because $m_S < 2m_\chi$ [10]. Then, S would decay to SM particle-antiparticle states. In NA62, the S is expected to be produced most efficiently from the decays of B mesons produced in the beam dump, even if the proton beam is first incident on the beryllium target during normal data taking. Fig. 2, left, shows an estimate of the 90%CL exclusion that NA62 could obtain with 10^{18} pot, based on the reconstruction of two-track final states ee, $\mu\mu$, $\pi\pi$, and KK, with vertices pointing back to the dump collimator. Zero background is assumed. As in the case of the dark photon, the analysis of the 2016–2017 data (3×10^{17} pot and 5×10^{16} pot with $\mu\mu$ and ee triggers, respectively) is underway.

If all of the quarks have mass, CP-violating terms appear in the QCD Lagrangian. The apparent conservation of CP in QCD requires fine tuning of the vacuum parameter θ. The existence

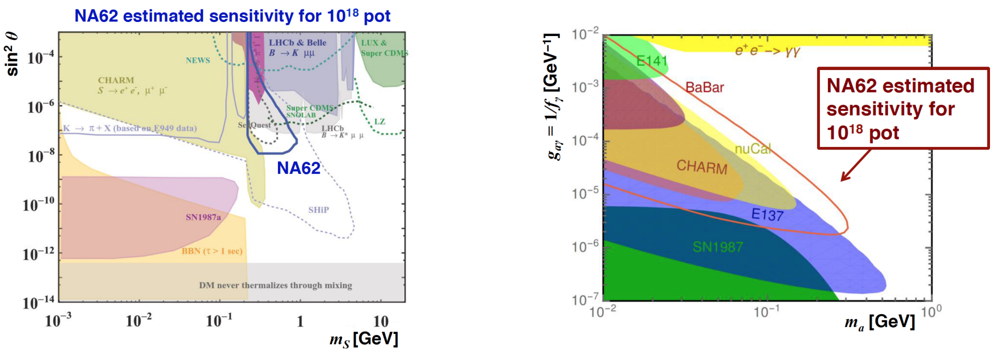

Figure 2: Left: NA62 estimated 90%CL exclusion limits in the (m_S, $\sin^2\theta$) plane, assuming 10^{18} pot and zero background, for dark scalars S decaying to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, or K^+K^-. Right: NA62 estimated 90%CL exclusion limits in the (m_a, $g_{a\gamma}$) plane, assuming 10^{18} pot and zero background, for axion-like particles a decaying to $\gamma\gamma$.

of an axion, the pseudo-Goldstone boson of the spontaneously broken Peccei-Quinn symmetry, may resolve the strong CP problem while providing a dark matter candidate [11]. As a generalization, axion-like particles (ALPs) may arise from the breaking of other global symmetries. A light pseudoscalar ALP may act as a mediator between SM and dark matter particles [12]. NA62 can search for ALPs with masses in the MeV–GeV range. We focus on pseudoscalar ALPs a whose dominant interaction is with photons [13], and consider ALPs produced by the Primakoff process ($\gamma\gamma$ fusion) in interactions in the dump, followed by $a \to \gamma\gamma$ decay [14]. The ALPs are produced at low $p_\perp$, leading to a large acceptance even with the detector far from the production point. Fig. 2, right, shows an estimate of the 90%CL exclusion that NA62 could obtain with 10^{18} pot and zero background. NA62 can improve on current results for ALPs with shorter lifetimes. In the short term, NA62 can obtain interesting results with as little as one day of data taking (1.3×10^{16} pot). In 2017, 5×10^{15} pot were collected in dump mode; analysis of this data is in progress.

The dark-sector Lagrangian may include mass terms, which may be of either the Dirac or Majorana type, for one or more heavy neutral leptons N. Mixing of the Ns with the neutrino mass eigenstates $\nu_{1,2,3}$ gives the physical neutrinos $\nu_{e,\mu\tau}$, plus right-handed "sterile" neutrinos. NA62 can search for Ns produced in kaon decays in the $M_{\rm miss}$ spectrum for $K^+ \to \ell^+ N$, as discussed in detail in [15]. In addition, NA62 can search for Ns produced in the dump that decay to two charged particles. Two-track final states are reconstructed with no requirement that the vertex point back to the dump (channels with open kinematics are included). Fig. 3 shows NA62's estimated 90%CL exclusion for 10^{18} pot in the plane of $|U_\alpha|$ vs. m_N, where U_α is the element of the neutrino-mixing matrix relating N to SM neutrino $\alpha \in \{e, \mu, \tau\}$. The sensitivity is shown for each of the coupling scenarios discussed in [16], corresponding to maximal Yukawa couplings between the N and SM neutrinos of each flavor. In 2017, NA62 took 10^{17} pot with a $\pi\mu$ trigger and a few 10^{16} pot with a πe trigger in parallel with the $K^+ \to \pi^+\nu\bar{\nu}$ program; analysis of this data is ongoing.

The NA62 hidden-sector physics program up to the LHC shutdown at the end of 2018 is based on the collection of samples with dedicated triggers for searches for dark photons, dark scalars, and heavy neutral leptons, collected in parallel with the main $K^+ \to \pi^+\nu\bar{\nu}$ program, as well as short, dedicated beam-dump runs to search for ALP decays to $\gamma\gamma$. Running after LS2 would allow collection of 10^{18} pot in beam-dump mode, providing greater sensitivity to hidden-sector

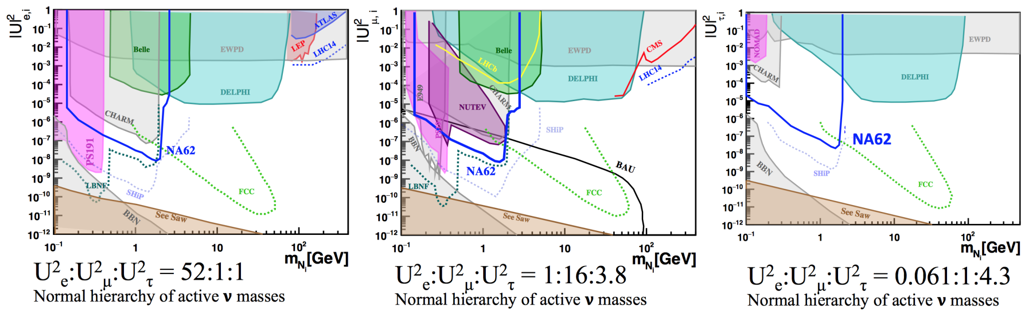

Figure 3: NA62 estimated 90%CL exclusion limits in the $(m_N, |U|^2_\alpha)$ plane, in the scenario in which each of the couplings to SM neutrinos $\alpha = e, \mu, \tau$ is dominant.

physics than that of other initiatives with the same timescale. Meanwhile, data from the current NA62 run will be used to refine strategies for background rejection in samples of 10^{18} pot and to define optimizations for future beam-dump running, including, if needed, minor modifications to the existing apparatus.

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