Search for invisible dark photon at NA62

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Abstract. Very weakly coupled new-physics particles in the MeV-GeV range appear as mediators in various "portals" to a hidden sector. Their interaction with Standard Model particles is feeble and these states are usually long-lived, so that the experimental search fully profits of a high-intensity setup, such as that of fixed-target experiments. Within the vector portal hidden-sector model a dark photon might exist which predominantly decays to dark matter particles. A search for such an invisible particle has been performed, exploiting the efficient photon-veto capability and high resolution tracking of the NA62 detector at CERN. The signal stems from the chain $K^+ \to \pi^+ \pi^0$ followed by the π^0 decay to a photon-dark-photon pair. No significant statistical excess has been identified. Upper limits on the dark photon coupling to the ordinary photon as a function of the dark photon mass have been set.

1. Introduction
Firm cosmological indications exist of a gravitationally-active abundant dark matter (DM). No Standard Model (SM) field satisfies the proporties of DM, as deduced from observational cosmology. If DM has been generated as a thermal relic from the hot early universe, one can hunt for it in particle physics. In particular, the dominance of DM on ordinary matter in the

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universe might suggest the existence of an entirely new dark sector with specific forces and particles fleebly coupled to the SM.

As an example, in a rather general set of hidden sector models with an extra U(1) gauge symmetry [1], the interaction of a dark photons (denoted A') with the visible sector proceeds through kinetic mixing with the SM hypercharge. Such scenarios with MeV- or GeV-scale dark matter provide possible explanations to the observed rise in the cosmic-ray positron fraction with energy and the muon gyromagnetic ratio $(g-2)$ measurement [2].

In general, the dark photon dynamics will include the interaction with the SM fermions f and a number of dark-matter fields, indicated as χ in the following:

$$\mathcal{L} \subset g_X \sum_f x_f \overline{f} \gamma^\mu f A'_\mu + \sum_\chi \mathcal{L}_{A'\chi\overline{\chi}}, \tag{1}$$

where the couplings $g_X x_f$ are model dependent. In a minimal scenario where the A' is coupled to the SM photon through a kinetic-mixing lagrangian, the couplings are proportional to the electromagnetic charge, $g_X = \epsilon e$ where ϵ is a parameter at or below the per-mil level, and $x_l = 1$ for any charged lepton, $x_\nu = 0$ for any neutrino, $x_u = 2/3$ for any up-type quark, and $x_d = -1/3$ for any down-type quark. Other models often considered in the literature involve dark-photon interactions with the current conserving the difference of baryon (B) and lepton (L) numbers (so-called $B - L$ interaction), with the baryon-number-conserving current $(B$ interaction), or with a purely leptonic current (the so-called proto-phobic scenario) [3].

If, for some dark-matter field χ, the dark photon mass were to exceed twice the χ mass, the $A' \to \chi\overline{\chi}$ transition would dominate the A' width. The interaction of the χ fields with ordinary SM fields would be loop-suppressed so that they would escape detection. The signature of such a process is the production of an "invisible" dark photon. The search for such a new-physics phenomenology can profit of a high-intensity experimental setup with excellent particle identification capabilities, as that of the NA62 experiment.

2. The NA62 experiment

The main goal of NA62 [4], a fixed target experiment at CERN, is the measurement of the branchin fraction (BR) of the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$ with 10% precision. The SM predicts $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ [5], therefore about 10^{13} K^+ decays for a 10% signal acceptance need to be collected. Keeping the background to signal ratio at the 10% level requires the use of redundant experimental techniques to suppress unwanted final states. Fig. 1 shows a schematic view of the NA62 experimental apparatus [4]. NA62 has been designed and built requiring high intensity, full particle identification, hermetic coverage and low material budget, high rate tracking.

Primary SPS protons hit a beryllium target from which a secondary charged hadron beam of 75 GeV/c is selected and transported to the decay region, more than 100 m downstream the target. Incoming kaons are positively identified by a differential Cerenkov counter (KTAG). This particle-ID information can be time-matched with the measurements of momentum and direction of each charged particle in the beam, which are provided by an achromat system hosting three stations of Si-pixel detectors (GTK). Kaon decays taking place in a $\sim$ 60 m long sensitive volume, kept in a 10^{-6} mbar vacuum, can be reconstructed: the momentum of daughter particles is measured by a spectrometer made of a 270 MeV-P_T-kick bending magnet and 4 straw-based chambers; photons are detected by a hermetic system made of two small angle calorimeters in the very-forward region (IRC and SAC), an electromagnetic calorimeter based on liquid krypton (LKr) in the forward region, and lead-glass annular calorimeters (LAV) at large angle. The total rejection capability for a π^0 of energy above 40 GeV is at the 10^8
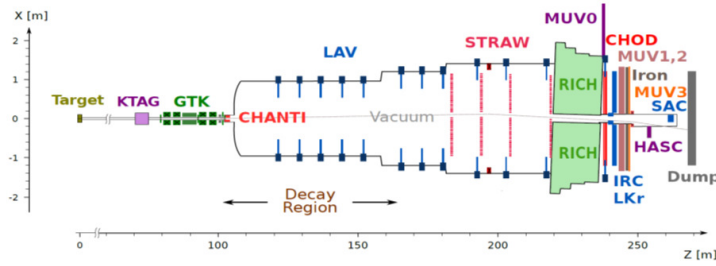
Figure 1. NA62 experimental apparatus

level. A RICH identifies secondary charged pions; plastic scintillators (CHOD, NA48-CHOD) are used for triggering and timing. Hadron calorimeters (MUV1,2) and a plastic scintillator detector (MUV3) placed downstream an iron absorber are used to detect hadrons and muons. The overall μ-vs-π rejection in the chosen signal momentum range, between 15 and 35 GeV/c, is of the order of 10^7. Information from CHOD, RICH, MUV3 and LKr are hardware processed to issue level zero trigger conditions up to 1 MHz bandwidth [6]. Software-based algorithms from KTAG, CHOD, LAV and STRAW information provide tighter higher level trigger requirements, reducing the rate by a factor of 100. Low-intensity data have been taken in 2015 to study detector performances and to perform physics analysis. Since 2016, NA62 is collecting data for the measurement of the BR($K^+ \to \pi^+ \nu \bar{\nu}$) and other physics goals.

3. Search for exotic particles from Kaon decays

A search for invisible decays of a dark photon in the decay chain $K^+ \to \pi^+ \pi^0, \pi^0 \to \gamma A'$ has been performed using NA62 data corresponding to about 1% of the dataset collected. In the kinetic-mixing model [7]:

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

Events with a single downstream track reconstructed in the STRAW spectrometer are selected within the same trigger stream used for the $K^+ \to \pi \nu \bar{\nu}$ 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 and the GTK track is identified as a K^+ by the KTAG detector. The RICH and the calorimeter system allow the identification of the downstream track as a pion. The missing mass obtained from the momentum of the downstream and GTK tracks is required to be close to the π^0 mass peak. These conditions select a sample of $K^+ \to \pi^+ \pi^0$ decays with relative contamination well below 10^{-3}. The number n_{π^0} of selected $K^+ \to \pi^+ \pi^0$ decays defines the statistics of tagged π^0 mesons: $n_{\pi^0} \simeq 412 \times 10^6$ for the sample used.

Events with a single photon cluster in the LKr calorimeter are selected. In order to enforce the sole presence of a π^+ and one photon in the final state, further conditions are imposed, the most relevant being:

- No in-time signals from the photon veto system must be present, except for the ones related to the single photon and to the π^+ detected by the LKr.
- No in-time hits in the hodoscope upstream of the LKr calorimeter (NA48-CHOD) must be found except for those geometrically associated with the π^+. This condition is referred to as the *NA48-CHOD Extra-activity cut* and it is useful to reject events in which one photon is lost because it converted upstream of the hodoscope.

Given the kaon, pion, and photon momenta, the squared missing mass

$$M^2_{\mathrm{miss}} = (P_K - P_\pi - P_\gamma)^2 \tag{3}$$

is expected to peak around the squared A' mass for the $\pi^0 \to \gamma A'$ decay and around zero for the background process $\pi^0 \to \gamma\gamma$ with one photon undetected. Fig. 2 shows the distributions of M^2_{miss} from a Monte Carlo (MC) simulation of the NA62 apparatus when injecting A' signals with masses of 60, 90, and 120 MeV/c^2 and a coupling strength $\epsilon^2 = 2.5 \times 10^{-4}$ (see Eq. 2). These are superimposed to the expected contribution from a data sample with fully reconstructed $\pi^0 \to \gamma\gamma$ in which one of the two photons hitting the LKr calorimeter, randomly chosen, is artificially excluded.
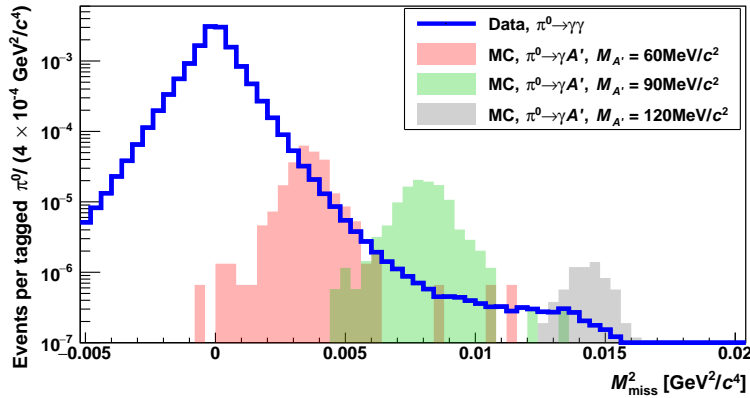

Figure 2. Distributions of the squared missing mass evaluated from K^+ decays with one photon and one π^+ reconstructed (Eq. 3). Data from $\pi^0 \to \gamma\gamma$ with one photon, randomly chosen, assumed to be undetected are shown by the blue line. The expected spectra from MC simulations of $\pi^0 \to A'\gamma$ with a coupling strength $\epsilon^2 = 2.5 \times 10^{-4}$ and A' masses of 60 (red), 90 (green) and 120 MeV/c^2 (grey) are also shown. The data distribution is scaled to n_{π^0}. Each MC distribution is scaled to the equivalent number of tagged π^0 mesons corresponding to the generated statistics.

The background is dominated by $\pi^0 \to \gamma\gamma$ decays with one photon undetected: this most often occurs when one of the photons undergoes pair production in the passive material upstream the sensitive volumes of the detectors downstream the RICH (NA48-CHOD, CHOD, LKr, etc.), A data-driven background estimate, based on the inversion of the *NA48-CHOD Extra-activity cut*, is used. For each A' mass, the signal region is defined as a 1.5-standard deviation range around the expected invariant mass peak. Frequentist 90% confidence level intervals have been determined, taking into account the statistical and systematic uncertainties on signal efficiency from MC determination and the statistical uncertainties of data counts and background expectations. Various parameters used in the statistical procedure have been varied to evaluate the systematic uncertainty on the calculated upper limits and no significant deviation beyond the statistical uncertainty has been observed. No statistically significant excess has been detected and upper limits have been computed on the number of signal events.

4. Results

The 90% confidence level exclusion limit on the kinetic mixing parameter ϵe versus the mass of the dark photon is shown in Fig. 3. The NA62 result, fully described in [11], has been lately

surpassed by the exclusion from NA64 [8] based on a missing-energy search for beam-dumped electrons. The limit from BaBar [9] and the expected sensitivity from Belle-II [10] derive from single-photon triggered e^+e^- annihilation at the center of mass of the Υ resonances.
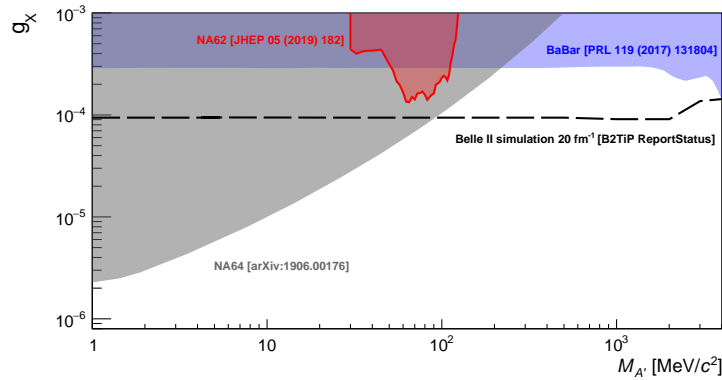
Figure 3. Kinetic-mixing dark photon model: exclusion limit at 90% CL in the g_X coupling versus $M_{A'}$ plane from the NA62 search for $\pi^0 \to \gamma A'$ with A' decaying into invisible final states (red-bounded area). In this model, $g_X = \epsilon e$. The limits from BaBar [9], NA64 [8] together with the expectation from the analysis of 20 fb^{-1} of integrated luminosity at Belle-II [10] are also shown.
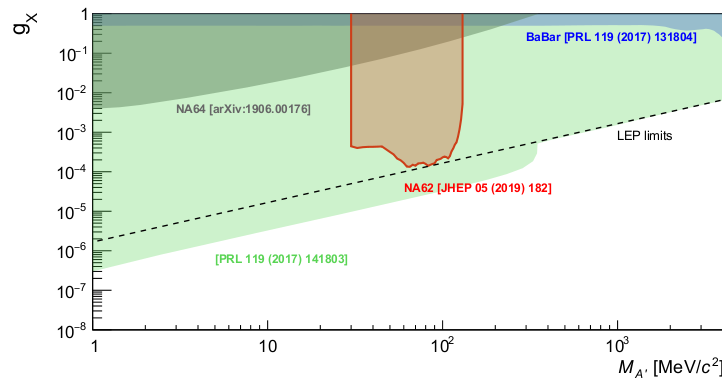
Figure 4. Lepto-phobic dark photon model: exclusion limit at 90% CL in the g_X versus $M_{A'}$ plane from the NA62 search for $\pi^0 \to \gamma A'$ with A' decaying into invisible final states (red-bounded area). In this model, the dark photon couples to the baryonic current. The limits from BaBar [9], NA64 [8] are shown. The sensitivity is dominated by the search for $K \to \pi + \text{invisible}$ decays at E949 [12] and KTeV [13] (green area) and by the search for $Z \to \gamma + \text{invisible}$ at the LEP experiments L3 [14] and DELPHI [15] (area above the dashed line).

An exclusion plot identical to that shown in Fig. 3 is obtained for a $B - L$ dark-photon model, if the appropriate coupling constant g_{B-L} is substituted to $g_X = \epsilon e$. A different phenomenology is predicted for dark photons coupled to the baryonic current: the NA64, Belle-II, and Babar results would be suppressed by $\alpha^2/4\pi$ relative to NA62, while the implication of $K \to \pi + \text{invisible}$ searches at E949 [12] and KTeV [13] and the limits put on $Z \to \gamma + \text{invisible}$ from the L3 [14]

and DELPHI [15] experiments at LEP would dominate, as shown in Fig. 4.

5. Conclusions and outlook

A first search for an invisible dark photon in the decay $\pi^0 \to A'\gamma$ has been discussed. Results from the analysis of 1% of the NA62 data set imply competitive limits on the kinetic-mixing and $B - L$ dark photon models. Models with unsuppressed flavour-changing neutral currents, such as that involving a baryon-number-current dark-photon coupling, tend to be dominated by the implication of $K \to \pi\nu\bar{\nu}$ results. A direct by-product of the analysis is the search for the decay $\pi^0 \to \gamma\nu\bar{\nu}$, with an expected branching ratio BR $\simeq 10^{-18}$ in the SM. No signal is detected and an upper limit at 90% CL is set, BR $< 1.9 \times 10^{-7}$, improving by a factor of 1000 over previous results.

An analysis update using the full data set is in progress, with perspectives of significant sentitivity improvements.

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