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SEARCH FOR AN INVISIBLE VECTOR BOSON FROM π^0 DECAYS AT NA62

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Abstract

The high-intensity setup, trigger system flexibility and detector performance make the NA62 experiment at CERN particularly suitable to perform direct searches for long-lived hidden-sector particles, such as dark photons, dark scalars, axion-like particles, and heavy neutral leptons, using kaon and pion decays as well as operating the experiment in dump mode. Results from NA62 will be presented on a search for π^0 decays to one photon and an invisible massive dark photon. From about 400 M π^0 decays, no signal is observed beyond the expected fluctuation of the background and limits are set in the plane of the dark photon coupling to ordinary photon versus the dark photon mass. The analysis has been also interpreted in terms of the branching ratio for the electroweak decay $\pi^0 \to \gamma\nu\bar{\nu}$.

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1 Introduction

The discovery of the Higgs boson at LHC completed the Standard Model of particle physics (SM) with the last missing piece. However, there are evidence that yet unknown particles or interactions are still needed in order to explain some observed phenomena, like the matter-antimatter asymmetry of the universe, the existence of the dark matter, neutrino masses and oscillations. So far, direct searches for new-physics at the energy frontier have not yet turned up any convincing evidence. In these searches, models with TeV energy scale have received most of the attention. However if physics beyond the SM is only very weakly coupled to the SM particles, some or all of the gaps might be filled in by the existence of light dark matter particles with the mediators of their interactions very weakly coupled to SM particles. One possible extension of the SM aimed to explain the dark matter abundance introduces a new $U(1)$ gauge-symmetry mediated by a vector field A', the dark photon. In a simple realization of this scenario [1, 2], the interaction between the A' field and the SM photon occurs through a kinetic-mixing Lagrangian with a coupling parameter $\epsilon << 1$,

$$\epsilon A'_{\mu\nu} F^{\mu\nu} \tag{1}$$

A consequence of this interaction [3] is the transition $\pi^0 \to \gamma A'$ with a branching ratio

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

Additional interactions might accompany the above Lagrangian, with the dark photon coupled both with SM matter fields and with a hidden sector of possible dark matter candidate fields. If these are lighter than the A', the dark photon would decay mostly invisibly and a missing-energy signature might reveal its presence. Exploiting the extreme photon-veto capability and high resolution tracking of the NA62 experiment, the search for an invisible A' is performed with a missing-mass technique by fully reconstructing the decay chain

$$K^+ \to \pi^+\pi^0, \pi^0 \to \gamma A' \tag{3}$$

The results from a subsample of 2016 data are reported, corresponding to 1% of the statistics collected by NA62 in 2016–2018.

2 NA62 experiment

The NA62 experiment is the latest in a series of fixed-target experiments located at the CERN SPS using the decay-in-flight technique to explore kaon decays. The main goal of the experiment is to precisely measure the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$ ($\mathrm{BR_{SM}} = (8.4 \pm 1.0) \times 10^{-11}$ [4]) with 10% accuracy. [5] The experiment uses the SPS proton beam (400 GeV/c), which hitting on a beryllium target produces a secondary hadron beam, with kaons contributing to only 6% of all particles. The beam has a momentum of (75 ± 1) GeV/c and a nominal intensity of 750 MHz. The beryllium target is followed by two 1.6 m long, water-cooled copper collimators (TAX) consisting on a series of graduated holes in which the beam passes trough, while the non interacting primary proton and unwanted secondary particles are absorbed. The detector apparatus (fig. 1) extends over 270 m from the target to the beam dump located at the end of the experiment. The kaon tagging and a precise timing measurement of the beam particles are provided by a Cherenkov detector (KTAG), followed by three silicon pixel stations which form the beam spectrometer (Gigatracker or GTK). A magnetic spectrometer of four STRAW chambers placed in vacuum provides the momenta and directions of the charged particles produced in the kaon decays. The particle identification is performed by a Ring Imaging Cherenkov (RICH) detector, an electromagnetic (LKr) calorimeter and a muon veto system (MUV). Large Angle (LAV) and Small Angle (IRC and SAC) Veto form together with the LKr calorimeter the high-efficiency photon veto system, covering angles from 0 to 50 mrad. A pair of charged hodoscopes (CHODs) complete the experimental apparatus. Detailed information on the detector layout and performances can be found in [6].

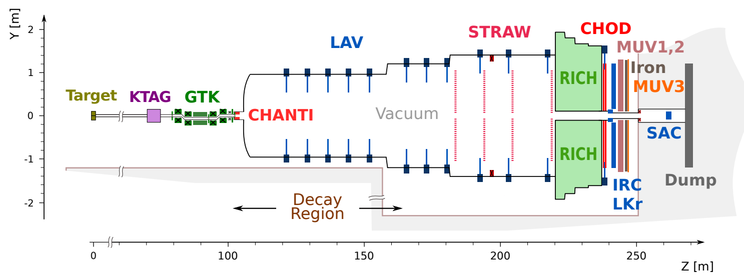

Figure 1: *NA62 experimental apparatus.* [6]

3 Dark photon analysis principle

The experimental signature for the events described in eq. 3, assuming a dominant invisible decay of the A' or a long-lived A' escaping the experimental apparatus, is given by a kaon decaying into a charged pion and a photon hitting the electromagnetic calorimeter (LKr) accompanied by missing energy and momentum. Given the kaon (P_{K^+}) and pion (P_{π^+}) 4-momenta measured by the GTK and STRAW respectively, the photon 4-momentum is obtained, assuming emission from the decay vertex, by measuring the photon position and energy in the LKr, the squared missing mass

$$M^2_{\text{miss}} = (P_{K^+} - P_{\pi^+} - P_\gamma)^2 \tag{4}$$

is expected to peak around the squared A' mass ($M^2_{A'}$) for the signal and around zero for the most relevant background $\pi^0 \to \gamma\gamma$ with one photon undetected (fig. 2).

A pure sample of $K^+ \to \pi^+\pi^0$ decays is selected by reconstructing only the K^+ and π^+ particles and requiring their missing mass $(P_{K^+} - P_{\pi^+})^2$ to be compatible with the squared π^0 mass. The number of $K^+ \to \pi^+\pi^0$ decays selected in control-sample data defines the statistics of tagged π^0 meson, which is about 4×10^8. For the $\pi^0 \to \gamma A'$ signal events, additional conditions are required in order to enforce the sole presence of a π^+ and one photon reconstructed in the final state:

- No additional signal from photons, except for the one reconstructed in the LKr, must be detected in the photon-veto system.
- No in-time activity must be detected in the hodoscope (NA48-CHOD) placed upstream the LKr, except for that associated to the π^+. This condition is particularly useful to reject events with one photon lost because of pair production upstream of the hodoscope.

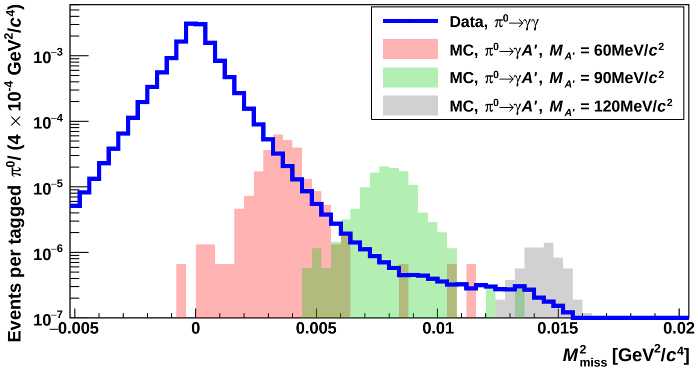

Figure 2: *Distribution of the squared missing mass evaluated from K^+ decays with on photon and one π^+ reconstructed. The blue line represents data from $\pi^0 \to \gamma\gamma$ decays with one photon (randomly chosen) assumed to be undetected. The expected spectra from Monte Carlo (MC) simulation of $\pi^0 \to \gamma A'$ are also shown. In the MC the coupling strength is set to $\epsilon^2 = 2.5 \times 10^{-4}$ and different A' mass are simulated: $M_{A'}$ =60 (red), 90 (green) and 120 MeV/c^2 (grey).*

- The missing momentum given in eq. 4 must point to the LKr calorimeter.
- The $K^+ \to \pi^+\nu\bar{\nu}$ trigger stream [5], which requires one-track and small forward energy in the final state, is used for the signal sample.

About 9×10^3 events pass the signal selection, and a peak scan is performed on the positive tail of $M^2_{\rm miss}$ distribution by comparing the number of events in a sliding $M^2_{\rm miss}$ window to the background expectation. The estimated number of signal events (n_{sig}) in a given $M^2_{\rm miss}$ window is normalized to the number of tagged π^0 meson (n_{π^0}) to give the branching ratio for $\pi^0 \to \gamma A'$ decays:

$$\mathrm{BR}(\pi^0 \to \gamma A') = \mathrm{BR}(\pi^0 \to \gamma\gamma) \times \frac{n_{sig}}{n_{\pi^0}} \frac{1}{\epsilon_{sel}\epsilon_{trg}\epsilon_{mass}} \tag{5}$$

where ϵ_{sel} accounts for the selection efficiency due to the additional requirements in the signal selection, ϵ_{trg} for the signal-trigger efficiency and ϵ_{mass} for the mass-window acceptance of the peak search in $M^2_{\rm miss}$. The three correction factors depend on $M_{A'}$ and are evaluated with a combination of Monte Carlo (MC) simulations and data control-sample. The geometrical acceptance and the π^0-tagging efficiency cancel in the ratio between signal and normalization.

4 Background evaluation

As shown by MC simulations, the most relevant background comes from $K^+ \to \pi^+\pi^0(\gamma)$ events with one photon from $\pi^0 \to \gamma\gamma$ undetected due to photon conversion. The expected background is evaluated with a data-driven approach: the same selection of the signal sample is applied with the exception of the NA48-CHOD extra activity condition, which is partially inverted. Events with in-time activity in the hodoscope not geometrically associated either with the π^+ or with the detected photon are selected. This requirement allows selecting a data control sample of $\pi^0 \to \gamma\gamma$ events with one photon detected in the LKr and the second lost because of conversion upstream the NA48-CHOD, without making any assumption on the shape of the $M^2_{\rm miss}$ tail and with no analytical extrapolation of the background. Since the presence of the second photon lost by conversion ensures no overlap with the signal sample and the signal pollution is verified to be below 1% with MC simulations, the enriched background sample is used to evaluate the expected $M^2_{\rm miss}$ background distribution. The background sample is scaled to the signal sample in a side-band region adjacent to but not overlapping with the A' signal region as shown in fig. 3 left.

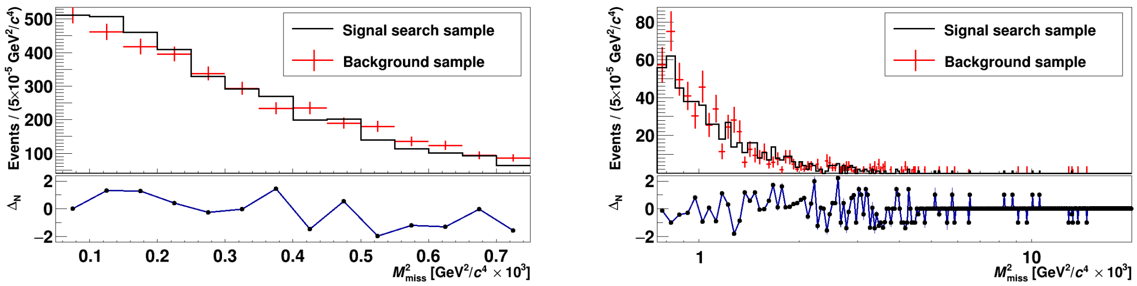

Figure 3: $M^2_{\rm miss}$ *distribution of the* A' *signal search sample (black) and background sample (red). The left panel shows the region used to evaluate the scaling factors, while the search region is shown in the right panel. In the bottom panels, the difference* Δ_N *between the two* $M^2_{\rm miss}$ *spectra is plotted in units of its standard deviation.*

5 Results

A peak search is performed on the $M^2_{\rm miss}$ distribution in the region $0.00075 < M^2_{\rm miss} < 0.01765$ GeV/c^4, corresponding to test the A' mass in the range 30–130 MeV/c^2. The observed data and the expected background events are evaluated for each of the $M_{A'}$ hypothesis by integrating the corresponding $M^2_{\rm miss}$ spectrum as shown in fig. 3 right. The width of the sliding window is set to $\pm 1\sigma_{M^2_{\rm miss}}$ around the tested mass hypothesis. In each mass hypothesis, the frequentist 90% confidence intervals are computed for the number of signal events using the CLs algorithm. [7] Given eq. 5, 90% confidence level (CL) upper limits are obtained on the coupling parameter ϵ^2 as a function of the A' mass as shown in fig. 4. The observed upper limits are compatible with fluctuations expected in the absence of signal and no statistically significant excess is detected. The result obtained improves the previous limits over the mass range 60–110 MeV/c^2 as shown in fig. 5. It must be underlined that the experimental technique used by NA62 is totally different than the one of the other recent results. Therefore, in general dark-photon models, the channel searched for by NA62 can be sensitive to possible new-physics effects notwithstanding the null result from other experiments (e.g. BaBar and NA64).

Slight modifications to the A' analysis allow performing a search for the decay $\pi^0 \to \gamma\nu\bar{\nu}$. The branching ratio of this process is expected to be of $\mathcal{O}(10^{-18})$ in the SM, while the present experimental limit [11] is $\mathrm{BR}(\pi^0 \to \gamma\nu\bar{\nu}) < 6 \times 10^{-4}$ at 90% CL. The strategy used for the A' search, based on the comparison of observed data and expected background events in a given $M^2_{\rm miss}$ interval, has been adopted. A peak search on the $M^2_{\rm miss}$ distribution is performed in the region 0.0054 GeV/$c^4 < M^2_{\rm miss} < M^2_{\pi^0}$, allowing to set an upper limit on the branching ratio of $\mathrm{BR}(\pi^0 \to \gamma\nu\bar{\nu}) < 1.9 \times 10^{-7}$ at 90% CL.

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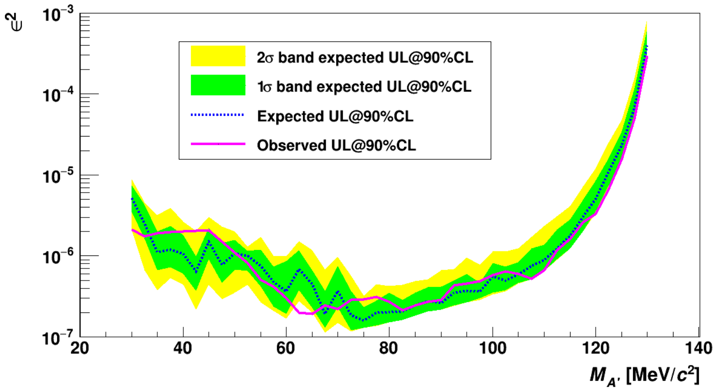

Figure 4: *Upper limit at 90% CL on the A' coupling strength as a function on the dark photon mass. The limit obtained from data (solid line) is compared to that expected in the absence of signal. The expected median of the upper limit is shown together with the bands at 68% and 95% coverage.*

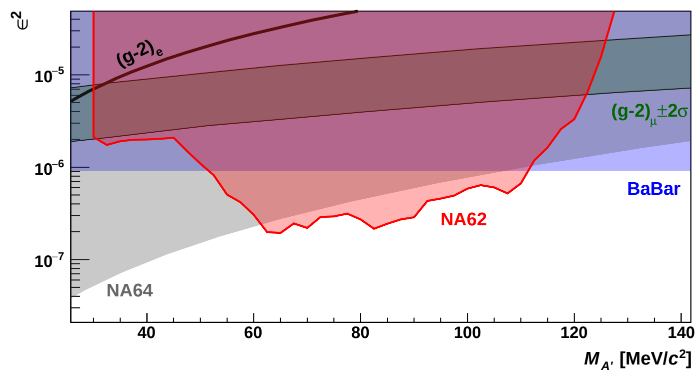

Figure 5: *Upper limit at 90% CL from NA62 (red region) in the ϵ^2 vs $M_{A'}$ plane, assuming a dark photon decaying into invisible final state. The limits from BaBar [8] (blue) and NA64 [9] (light grey) experiments are also shown. A new experimental technique is used by NA62 with respect to the previous experiments.*

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