Search for invisible decays of sub-GeV dark photons in missing-energy events at the CERN SPS

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We report on a direct search for sub-GeV dark photons ($A'$) which might be produced in the reaction $e^-Z \rightarrow e^-'ZA'$ via kinetic mixing with photons by 100 GeV electrons incident on an active target in the NA64 experiment at the CERN SPS. The $A'$ would decay invisibly into dark matter particles resulting in events with large missing energy. No evidence for such decays was found with 2.75 · 10^9 electrons on target. We set new limits on the $\gamma - A'$ mixing strength and exclude the invisible $A'$ with a mass $\lesssim$ 100 MeV as an explanation of the muon $g_\mu - 2$ anomaly.

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Despite the intensive searches at the LHC and in non-accelerator experiments Dark Matter (DM) still is a great puzzle. Though stringent constraints obtained on DM coupling to Standard Model (SM) particles ruled out many DM models, little is known about the origin and dynamics of the dark sector itself. One difficulty so far is that DM can be probed only through its gravitational interaction. An exciting possibility is that in addition to the dark sector itself. One difficulty so far is that DM can be probed only through its gravitational interaction. An exciting possibility is that in addition to gravity, a new force between the dark sector and visible matter transmitted by a new vector boson $A'$ (dark photon) might exist. Such $A'$ could have a mass $m_{A'} \lesssim 1$ GeV - associated with a spontaneously broken gauged $U(1)_D$ symmetry- and couple to the SM through kinetic mixing with the ordinary photon, $\frac{-i}{2} \epsilon F_{\mu\nu} A'^{\mu\nu}$, parameterized by the mixing strength $\epsilon \ll 1$. This has motivated a worldwide theoretical and experimental effort towards dark forces and other portals between the visible and dark sectors, see [1] [3] for a review. An additional motivation has been provided by hints on astrophysical signals of dark matter [5], as well as the 3.6 $\sigma$ deviation from the SM prediction of the muon anomalous magnetic moment $g_\mu - 2$ [7], which can be explained by a sub-GeV $A'$ with the coupling $\epsilon \approx 10^{-3}$ [8-10]. Such small values of $\epsilon$ could naturally be obtained from loop effects of particles charged under both the dark and SM $U(1)$ interactions with a typical 1-loop value $\epsilon = e g_D / 16\pi^2$ [12]. However, in the presence of light dark states, in particular dark matter, with the masses $< m_{A'}$, the $A'$ would predominantly decay invisibly into those particles provided that $g_D > \epsilon$. Models introducing such invisible interactions have been proposed [11, 12].
The occurrence of significant missing energy deposition. While the remaining part is carried away by \( \chi \)'s which penetrate the detector without decaying visibly in order to give a missing energy signature. No any other assumptions on the nature of the \( A' \rightarrow invisible \) decay are made.

The NA64 detector is schematically shown in Fig. 1. The experiment employed the upgraded 100 GeV electron beam from the H4 beamline. The beam has a maximal intensity \( \approx (3 - 4) \times 10^6 \) per SPS spill of 4.8 s produced by the primary 450 GeV/c proton beam with an intensity of few \( 10^{12} \) protons on target. The detector utilized the beam defining scintillator (Sc) counters S1-S3, and magnetic spectrometer consisting of two successive dipole magnets with the integral magnetic field of \( \approx 7 \) T-m and a low-material-budget tracker. The tracker was a set of two upstream Micromegas chambers (T1, T2) and two downstream GEM stations (T3, T4) allowing the measurements of \( e^- \) momenta with the precision \( \delta p/p \approx 1\% \). The magnets also served as an effective filter rejecting low energy component of the beam. To enhance the electron identification the synchrotron radiation (SR) emitted by electrons was used for their efficient tagging. A 15 m long vacuum vessel between the magnets and the ECAL was installed to minimize absorption of the SR photons detected immediately at the downstream end of the vessel with a SR detector (SRD), which was either an array of BGO crystals or a PbSc sandwich calorimeter of a very fine segmentation. By using the SRD the initial level of the hadron contamination in the beam \( \pi/e \lesssim 10^{-2} \) was further suppressed by a factor \( \approx 10^3 \). The detector was also equipped with an active target, which is an electromagnetic (e-m) calorimeter (ECAL) for measurement of the electron energy with the accuracy \( \delta E/E \approx 10\% / \sqrt{E} \). The ECAL is a matrix of 6x6 Shashlik-type modules assembled from Pb and Sc plates with wave-shifting fiber read-out. Each module is \( \approx 40 \) radiation lengths. Downstream the ECAL the detector is equipped with a high-efficiency veto counter V2, and a massive, hermetic hadronic calorimeter (HCAL) of \( \approx 30 \) nuclear interaction lengths. The HCAL served as a dump to completely absorb and measure the energy of hadronic secondaries produced in the \( e^- A \rightarrow anything \) interactions in the target. Four muon plane counters, MU1-MU4, located between the HCAL modules were used for the muon identification in the final state. The events were collected with the hardware trigger requiring an in-time cluster in the ECAL with the energy \( E_{\text{ECAL}} \lesssim 80 \) GeV. The results reported here came mostly from a set of data in which \( n_{\text{eot}} = 1.88 \times 10^9 \) of electrons on target (eot) were collected with the beam intensity \( \approx 1.4 \times 10^6 \) e\(^-\) per spill with the PbSc calorimeter. While a smaller sample of \( n_{\text{eot}} = 0.87 \times 10^9 \) and an intensity \( I_e = 0.3 \times 10^6 \) e\(^-\) was also recorded with the BGO detector. Data of these two runs (hereafter called the BGO and PbSc run) were analyzed with similar selection criteria and finally summed up, taking into account the corresponding normalization.
FIG. 2: The left panel shows the measured distribution of events in the \((E_{ECAL};E_{HCAL})\) plane from the combined BGO and PbSc run data at the earlier phase of the analysis. Another plot shows the same distribution after applying all selection criteria. The dashed area is the signal box region which is open. The side bands A and C are the one used for the background estimate inside the signal box. For illustration purposes the size of the signal box along \(E_{HCAL}\)-axis is increased by a factor five.

In order to avoid biases in the determination of selection criteria for candidate events, a blind analysis was performed. Candidate events are expected to have the missing energy in the range \(50 < E_{miss} < 100\) GeV, which was defined by taking into account the energy spectrum of \(A'\)s emitted in the primary reaction \(\bar{B}\) by \(e^\pm\) from the e-m shower generated by the beam \(e^-\)'s in the ECAL target [54]. Events from a signal box \((E_{ECAL} < 50\) GeV; \(E_{HCAL} < 1\) GeV) were excluded from the analysis of the data until the validity of the background estimate in this region was established. For the selection criteria optimization, 10% of the data was used, while the full sample was used for the background estimate. The number of signal candidate events were counted after unblinding. A detailed Geant4 based Monte Carlo (MC) simulation was used to study the detector performance and acceptance, to simulate background sources, and to select cuts and estimate the reconstruction efficiency. The candidate events were selected with the criteria chosen to maximize the acceptance for MC signal events and to minimize the numbers of background events, respectively. The following selection criteria were applied: i) The incoming particle track should have a small angle w.r.t. the beam axis to reject large angle tracks from the upstream \(e^-\) interactions. ii) The energy deposited in the SRD detector should be within the SR range emitted by \(e^-\)'s and in-time with the trigger; iii) The lateral and longitudinal shape of the shower in the ECAL should be consistent with the one expected for the signal shower [54]; iv) No activity in V2. Only \(\approx 300\) events passed these criteria from combined BGO and PbSc runs.

The search for the \(A' \rightarrow invisible\) decays requires particular attention to backgrounds. Every process with a track and a single e-m cluster in the
TABLE I: Expected numbers of events in the signal box from different background sources estimated for 2.75 \cdot 10^6 eot.

| Source of background | Events | 
|----------------------|--------|
| loss of e^− energy due to punch-through $\gamma$s | $< 0.001$ |
| loss of hadrons from $e^− Z \rightarrow e^− + hadrons$ | $< 0.01$ |
| loss or $\mu \rightarrow e\nu$ decays | | 
| of muons from $e^− Z \rightarrow e^− Z\gamma\gamma \rightarrow \mu^+\mu^−$ | $< 0.01$ |
| $e^−$ interactions in the beamline materials | 0.03 |
| $\mu \rightarrow e\nu\nu$, $\pi$, $K \rightarrow e\nu$, $K_{e3}$ decays | 0.03 |
| pile-up of low energy $e^−$ and $\mu$, $\pi$, $K$ followed by their decays | 0.05 |
| $\mu$, $\pi$, $K$ interactions in the target | 0.02 |
| Total | 0.15 |

ECAL was considered as a potential source of background. There are several sources which may fake the $A' \rightarrow invisible$ signal, e.g. upstream $e^−$ interactions, $\mu \rightarrow e\nu\nu$, $\pi$, $K \rightarrow e\nu$, $K_{e3}$ decays in-flight, energy leakage from particle punch-through in the HCAL, processes due to pile-up of two or more particles, and instrumental effects due to energy loss through cracks in the upstream detector coverage. The selection cuts to eliminate these backgrounds have been chosen such that they do not affect the shape of the true $E_{miss}$ spectrum.

Two independent methods were used for the background estimation in the signal region. The first method is based on the MC. Due to the small coupling strength of the $A'$ reaction, it occurs typically with a rate $\lesssim 10^{-9}$ per incoming electron. To study the SM distribution and background at this level is very time-consuming. Consequently, we have evaluated with MC all known backgrounds to the extent that it is possible. Events from particle interactions or decays in the beam line, pile-up activity created from them, hadron punch-through from the target and the HCAL were included in the simulation of all background events. Small event-number backgrounds such as the decays of the beam $\mu$, $\pi$, $K$ or $\mu$ from the reaction of dimuon production were simulated with the full statistics of the data. Large event-number processes, e.g. upstream beam interactions, punch-through of secondary hadrons were also studied extensively, although simulated samples with statistics similar to the data were not feasible. To eliminate possible instrumental effects not present in the MC, the uniformity scan of the central part of the ECAL target was performed with $e^−$ by using T3 and T4. We also examined the number of events observed in several regions around the signal box, which were statistically consistent with the estimates.

Two largest sources of background are expected from the beam $\mu$, $\pi$, $K$ decays in-flight. In one case, when, e.g. a pion passes through the vacuum vessel it could knock electrons off the downstream window, which hit the SRD creating a fake tag for a 100 GeV $e^−$. Then the pion could decay into $e\nu$ in the upstream ECAL region thus producing the fake signal. Similar background is caused by the pile-up of an electron from the low-energy beam tail ($\lesssim 60−80$ GeV) and a beam $\mu$, $\pi$, or $K$. The electron could emit the amount of SR energy above the threshold which is detected in the SRD as a tag of 100 GeV $e^−$ and then is deflected by the magnets out of the detector’s acceptance angle. While the accompanied muon or hadron could then decay in flight. For both sources the dominant background came from the $K_{e3}$ decays. The mistakenly tagged $\mu$, and $\pi$ and $K$ could also interact in the target producing an $e^{-}$-like cluster below 50 GeV though the $\mu Z \rightarrow e\nu\nu\gamma$ or $\pi$, $K$ charge-exchange reactions in the target, accompanied by the poorly detected scattered $\mu$, or secondary hadrons, respectively. Another background is due to $e^−$ interactions with the beamline materials resulting in $e^−$ energy loss. Table I summarizes the conservatively estimated number of background events inside the signal box. The expected number of background events is $0.15 \pm 0.03(stat) \pm 0.06(syst)$. The systematic error includes the uncertainties in the amount of passive material for upstream $e^−$ interactions, and in the cross sections of the of $\pi$, $K$ charge-exchange reactions on lead (30%).

The second method used the background estimate extracted from the data themselves. MC signal events and the background extrapolated from sidebands A and C shown in the right panel of Fig. 2 were used. Events in the region A are pure neutral hadronic secondaries produced by electrons in the ECAL target, while events from the region C are likely from the $e^−$ interactions in the downstream part of the beamline accompanied by bremsstrahlung photons absorbed in the HCAL. The yield of the background events was estimated by extrapolating the observed events to the signal region assessing the systematic uncertainties by varying the background fit models. Using this we obtained a second background estimate of $0.4 \pm 0.3$ events. The background estimates with the two methods are in agreement with each other within errors. After determining all the selection criteria and estimating background levels, we examined the events in the signal box and found no candidates, as shown in Fig. 2. The conclusion that the background is small is confirmed by the data.

The $m_{A'}$ dependent upper limit on the mixing $\epsilon$ is calculated as follows. For a given number $n_{e\nu}$ and the mass $m_{A'}$, the number of signal events $N_{A'}$ expected from the reaction $[1]$ in the signal box is given by:

$$N_{A'} = n_{e\nu} \cdot n_{A'}(\epsilon, m_{A'}, \Delta E_{A'}) \cdot \epsilon_{A'}(m_{A'}, \Delta E_{A'})$$

where $n_{A'}(\epsilon, m_{A'}, \Delta E_{A'})$ is the yield of A’s with the coupling $\epsilon$, mass $m_{A'}$, and energy in the range $\Delta E_{A'}$, $0.5 E_0 < E_{A'} < E_0$, per $e\nu$ shower generated by a single 100 GeV electron in the ECAL [24]. These events corresponds to the missing energy $0.5 E_0 < E_{miss} < E_0$. The overall signal efficiency, $\epsilon_{A'}$ is weakly $m_{A'}, E_{A'}$ dependent and is given by the product of efficiencies accounting for the NA64 geometrical acceptance (0.97), the analysis efficiency (0.8) which is slightly $m_{A'}$ dependent, veto V2 (0.96) and HCAL signal efficiency (0.94) and the accep-
the corresponding zero-energy thresholds. The shape of the energy distributions in these detectors from the leak of signal shower energy from the ECAL was simulated for different $A'$ masses \cite{54} and cross-checked with measurements at the $e^-$ beam. The uncertainty in the V2 and HCAL efficiency for the signal events, dominated mostly by the pile-up effect from penetrating hadrons in the high intensity PbSc run, was estimated to be $\simeq 3\%$. The trigger (SRD) efficiency is measured in unbiased random samples of events that bypass the trigger (SRD) selection and the uncertainty is $2\% (3\%)$. Other effects, e.g. $e^-$ loss due to conversion into $e^-\gamma$ pair in the upstream detector material were measured to be $\lesssim 3\% (2\%$ uncertainty). Finally, the dominant source of systematic errors on the expected number of signal events comes from the uncertainty in the estimate of the yield $n_{A'}(\epsilon, m_{A'}, \Delta E_{A'})$ (19\%). The overall signal efficiency $\epsilon_{A'}$ varied from 0.69\pm 0.09 to 0.55\pm 0.07 decreasing for the higher $A'$ masses.

In accordance with the $CL_s$ method \cite{57}, for zero observed events the 90\% C.L. upper limit for the number of signal events is $N_{A'}^{90\%}(m_{A'}) = 2.3$. Taking this and Eq.\,(2) into account and using the relation $N_{A'}(m_{A'}) < N_{A'}^{90\%}(m_{A'})$ results in the 90\% C.L. exclusion area in the $(m_{A'}; \epsilon)$ plane shown in Fig.\,3. The limits are determined mostly by the number of accumulated eot. These results exclude the invisible $A'$ as an explanation of the $g_\mu - 2$ muon anomaly for the masses $m_{A'} < 100$ MeV. Moreover, the results also allow to restrict other models with light particles interacting with electron and decaying predominantly to invisible modes. For instance for light scalar particle $s$ with the interaction $L_{cs} = s\bar{e}(h_s + h_{as}\gamma_5)e$ the bound on $\epsilon_s$ ($\epsilon_s^2 \equiv \frac{h_s^2 + h_{as}^2}{4\pi}$) is approximately 1.5 times weaker than the one obtained on $\epsilon$ for the model with light vector bosons \cite{58}. Here $h_s$ and $h_{as}$ are scalar and pseudoscalar Yukawa coupling constants of the light scalar field $s$ with electron field $e$, respectively.

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