Search for scalar and axionlike particles with the NA64 experiment


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This publication is dedicated to the memory of our colleague Danila Tlisov.

We carried out a model-independent search for light scalar (s) and pseudoscalar axionlike (a) particles that couple to two photons by using the high-energy CERN SPS H4 electron beam. The new particles, if they exist, could be produced through the Primakoff effect in interactions of hard bremsstrahlung photons generated by 100 GeV electrons in the NA64 active dump with virtual photons provided by the nuclei of the dump. The a(s) would penetrate the downstream HCAL module, serving as shielding, and would be observed either through their a(s) → γγ decay in the rest of the HCAL detector or as events with large missing energy if the a(s) decays downstream of the HCAL. This method allows a substantial increase in the sensitivity to the a(s) parameter space unexplored by previous experiments. No evidence of such processes has been found from the analysis of the data corresponding to 2.84 × 10^{11} electrons on target allowing to set new limits on the a(s)γγ-coupling strength for a(s) masses below 55 MeV.

Neutral spin-zero scalar (s) or pseudoscalar (a) massive particles are predicted in many extensions of the standard model (SM). The most popular light pseudoscalar, the axion, postulated in Refs. [1] to provide a solution of the "strong CP" problem, emerges as a consequence of the breaking of the Peccei-Quinn (PQ) symmetry [2]. It is now believed that the axion has a mass much smaller than \( O(100) \) keV that was originally expected [3, 4].

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The axionlike particles (ALPs), which are pseudo-Nambu-Goldstone bosons, arise in models containing spontaneously broken PQ symmetry, see, e.g., [3, 4], with arbitrary masses and small couplings, making them natural candidates for the mediator of interactions between dark and visible sectors or as candidates for the dark matter (DM) themselves. ALPs could also provide a solution to both the electron [7] and muon [8] $g − 2$ anomalies [9]. This has motivated a worldwide theoretical and experimental efforts towards dark forces and other portals between the visible and dark sectors, see, e.g., [10–20] for a review.

The $a − \gamma\gamma$ interaction is given by the Lagrangian

$$L_{\text{int}} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a,$$

(1)

where $g_{a\gamma\gamma}$ is the coupling constant, $F_{\mu\nu}$ is the photon field strength and $a$ is the axionlike particle field. For the scalar case, an example of a $s$-particle weakly coupled to two photons is the dilaton, which arises in superstring theories and interacts with matter through the trace of the energy-momentum tensor [21], and its two-photon interaction is given by Eq. (1) with the replacement $\tilde{F}^{\mu\nu} \to F^{\mu\nu}$. Usually, it is assumed that $g_{a\gamma\gamma} = O(M_{Pl}^{-1})$ and that the dilaton mass $m_a = O(M_{Pl})$, where $M_{Pl}$ is the Planck mass. However, in some models, see, e.g., [22], the dilaton could be rather light. Since there are no firm predictions for the coupling $g_{a\gamma\gamma}$ the searches for such particles become interesting.

Experimental bounds on $g_{a\gamma\gamma}$ for light a’s in the eV-MeV mass range can be obtained from laser experiments [23, 24], from experiments studying $J/\psi$ and $Y$ particles [25], from the NOMAD experiment by using a photon-regeneration method at the CERN SPS neutrino beam [26], and from orthopositronium decays [27]. Limits on ALPs in the sub-GeV mass range have been typically placed by the beam-dump experiments or from searches at $e^+e^-$ colliders [6], leaving the large area $10^{-2} \lesssim g_{a\gamma\gamma} \lesssim 10^{-5}$ GeV$^{-1}$ of the $(g_{a\gamma\gamma}; m_a)$-parameter space still unprobed. Additionally, since the theory predictions for the coupling, mass scale, and decay modes of ALPs are still quite uncertain it is crucial to perform independent laboratory tests on the existence of such particles in the mass and coupling strength range discussed above. One possible way to answer these questions is to search for ALPs in a beam dump experiment. However, for the coupling lying in the range $10^{-2} \lesssim g_{a\gamma\gamma} \lesssim 10^{-4}$ GeV$^{-1}$ this method is not very promising, because for the masses in sub-GeV region the $a$ is expected to be a relatively short-lived particle.

In this Letter, we propose and describe a direct search for ALPs with the coupling to two photons from the $(g_{a\gamma\gamma}; m_a)$-parameter space uncovered by previous searches, which might be produced in the NA64 experiment at the CERN SPS. The application of the obtained results to the $s \to \gamma\gamma$ decay case is straightforward.

The NA64 detector located at the CERN SPS H4 electron beam [28] is schematically shown in Fig. 1. It consists of a set of beam defining scintillator counters $S_{1−4}$ and veto $V_{1,2}$, a magnetic spectrometer consisting of two dipole magnets (MBPL1,2) and a low-material-budget tracker, composed of two upstream Micromegas chambers MM1,2, and four downstream MM3–6 stations, two straw-tube ST1,2 and GEM1,2 chambers [29]. A synchrotron radiation detector (SRD) is used for the identification of incoming $e^−$'s [30, 31] and suppression of the hadron contamination in the beam down to the level $\pi^0e^− \lesssim 10^{-5}$. An active dump, consisting of a preshower detector (PRS) and an electromagnetic (e-m) calorimeter (ECAL), made of a matrix of 6 × 6 Shashlik-type modules, is assembled from Pb and Sc plates of $\sim 40$ radiation lengths ($X_0$). A large high-efficiency veto counter VETO, and a massive, hermetic hadronic calorimeter (HCAL) composed of three modules HCAL1-3 completes the setup. Each module is a $3 \times 3$ cell matrix with a thickness of $\lesssim 7.5$ nuclear interaction lengths. The events from $e^−$ interactions in the PRS and ECAL were collected with the trigger provided by the $S_{1−4}$ requiring also an in-time cluster in the ECAL with the energy $E_{ECAL} \lesssim 80$ GeV. The detector is described in more detail in Ref. [32].

If ALPs exist, one would expect a flux of such high energy particles from the dump. Both scalars and pseudoscalars could be produced in the forward direction through the Primakoff effect in interactions of high energy bremsstrahlung photons, generated by 100 GeV...
electrons in the target, with virtual photons from the electrostatic field of the target nuclei:

$$e^- Z \rightarrow e^- Z \gamma; \gamma Z \rightarrow aZ; a \rightarrow \gamma \gamma$$

(2)
as illustrated in Fig.2. If the ALP is a relatively long-lived particle, it would penetrate the first downstream HCAL1 module serving as shielding and would be observed in the NA64 detector with two distinctive signatures, either 1) via its decay into 2$\gamma$ inside the HCAL2 or HCAL3 modules (denoted further as HCAL2,3), or 2) as an event with large missing energy if it decays downstream of the HCAL2,3.

The selection criteria for signal and background samples have been obtained using a GEANT4 based Monte Carlo (MC) simulation of the NA64 detector. The code for the simulation of signal events is implemented in the same program according to the general scheme described in [36, 37], with the $a \rightarrow \gamma \gamma$ decay width given by $\Gamma_a = g_{a\gamma\gamma} m_a^2/64\pi$.

FIG. 2: Diagrammatic illustration the $a$ production in the reaction of Eq. (2).

FIG. 3: Distributions of the variable $R$ for the 80 GeV $e^-$, $\pi^-$, $K^0_L$, and $n$ events obtained from data and simulations.

The event from the incoming electron interacting in the dump was required to have the incoming track momentum in the range of $100 \pm 3$ GeV, the SRD signal within the range of SR emitted by $e^-$'s, a single PRS cluster matched to an isolated ECAL cluster with the energy to be greater than 0.5 GeV and an ECAL cluster with the shape expected from a single e-m shower [32, 36]. As the $2\gamma$ opening angle for the $a \rightarrow \gamma \gamma$ decay is very small, it was not possible to distinguish this decay from a single e-m shower in the HCAL. Therefore, the candidate events with the signature 1 were selected as a single shower in the neutral final state, i.e. no activity in the VETO and the HCAL1, with e-m-like lateral shape, the shower maximum in the HCAL2,3 central cell and the energy deposition $E_{HCAL} \gtrsim 15$ GeV. This allowed to reduce background to a small level, while maximising the $a$-yield by using the cut on the ECAL energy $E_{ECAL} \lesssim 85$ GeV. For events with the signature 2, we required the ECAL energy to be $E_{ECAL} \lesssim 50$ GeV and no activity in the VETO and the HCAL. The above event selection criteria, as well as the efficiency corrections, backgrounds and their systematic errors were similar to those used in our searches for the invisible decays of dark photons [32, 35].

An additional background suppression for the case 1 was achieved by using the lateral shower shape in the HCAL module. It was characterised by a variable $R$, defined as $R = E_{HCAL}/E_{ECAL}$, where $E_{HCAL}$, $E_{ECAL}$ are the total HCAL energy and the energy deposited in the central cell, respectively. An example of $R$ distributions obtained from data and MC is shown in Fig. 3. As expected, the distribution for $e^- s$ is narrower than for hadrons, and can be employed for effective particle identification. Using the cut $R < 0.06$ rejects $\gtrsim 98\%$ of hadrons, while keeping the signal efficiency $\gtrsim 95\%$.

The search described in this paper uses a data sample of $n_{EOT} = 2.84 \times 10^{11}$ electrons on target (EOT) collected during the 2016-2018 run period with the beam intensity in the range $\simeq (2-9) \times 10^6$ e$^-$/spill. In Fig. 4, the distribution of $\simeq 3 \times 10^4$ events from the reaction $e^- Z \rightarrow \gamma \gamma$ in the $(E_{ECAL}; E_{HCAL})$ plane obtained by requiring the presence of a beam $e^- \gamma$ identified with the SR tag is shown. Events from the horizontal band with $E_{HCAL} \approx 10$ GeV originate from the QED dimuon pair production in the ECAL and were used to cross-check the reliability of the MC simulation and background estimate [32]. The further requirement of no activity in the VETO identified a sample of $\simeq 7 \times 10^3$ events shown in Fig. 4d. This sample corresponds to the neutral hadronic secondaries from electroproduction in the dump with full energy deposition in the HCAL1 module. The events located mostly along the diagonal satisfy the condition of energy conservation $E_{ECAL} + E_{HCAL} \approx 100$ GeV.

The signal events with the signature 1 are expected to exhibit themselves as an excess of e-m like events in the $(E_{ECAL}; E_{HCAL})$ plane in the signal box around the diagonal $E_{ECAL} + E_{HCAL} = 100 \pm 10$ GeV satisfying the energy conservation within the energy resolution of the detectors and the cut $R < 0.06$, as shown in Fig. 4. By inverting this cut we obtain the control region, where the signal events are almost absent. The signal box $2, 0 \lesssim E_{ECAL} \lesssim 55$ GeV, $E_{HCAL} \lesssim 1$ GeV for signal events having a large missing energy is also shown [36, 37].

The following processes that may fake the $a \rightarrow \gamma \gamma$ decay in the HCAL2,3 were considered: (i) The production of leading neutrons ($n$) or $K^0_s$ mesons in the ECAL by $e^- s$ in the reaction $e^- A \rightarrow n(K^0_s) + m\pi^0 + X$, that punchthrough the HCAL1 and deposited all their energy...
by using measured absorption cross sections from Refs. The values $P_{\text{em}}(K^0) \approx 5 \times 10^{-3}$ were evaluated from MC distributions of Fig. 3. The systematic errors of 10% and 30% have been assigned to $P_{\text{em}}(K^0)$ and $P_{\text{em}}(K^0)$ values, respectively, by taking into account the data-MC difference in punchthrough and transverse shapes of showers (see Fig. 3) generated by $\pi^0$'s. In the second method we used the number of $n_e = 12 \pm 4$ neutral events in the control region, shown in Fig. 4. This number was found to be in a good agreement with 9 ± 4 events expected from the sample of neutral events shown in Fig. 4. The background then was estimated by taking into account the relative composition of these events which was found to be $\approx 25\%$ of neutrons and 75% of $K^0$'s.

All background estimates were then summed up, taking into account the corresponding normalisation factors. These factors were calculated from beam composition, cross-sections for the processes listed above, and punchthrough probabilities evaluated directly from the data and MC. The total number of expected candidate events after applying the selection criteria are given in Table I for each background component. The total background of 0.17±0.026 events, where statistical and systematic errors were added in quadrature, estimated with the first method was found to agree with the second estimate resulting in 0.18±0.04 events. For the signature 2, the total background in the data sample was estimated to be 0.53±0.17 events, as described in detail in Ref. 33.

After determining all the selection criteria and background levels, we unblinded the signal box. No event in the signal boxes shown in Fig. 4 was found, allowing us to obtain the $m_n$-dependent upper limits on the coupling strength $g_{\alpha\gamma}$.

The exclusion limits were calculated by employing the multi-bin limit setting technique in the RooStats package 41 with the modified frequentist approach, using
the profile likelihood as a test statistic. The combined 90% confidence level (C.L.) limits on the coupling strength \(g_{a\gamma\gamma}\) were obtained from the corresponding limit for the expected number of signal events, \(n_a\), which is given by the sum:

\[
n_a = \sum_{i=1}^{2} \varepsilon_a^i n_a^i (g_{a\gamma\gamma}, m_a) \tag{3}
\]

where \(\varepsilon_a^i\) is the signal efficiency and \(n_a^i (g_{a\gamma\gamma}, m_a)\) is the number of the \(a\) decays for the signature \(i\). The \(a\) yield from the reaction chain was obtained with the calculations described in Ref. assigning \(\lesssim 10\%\) systematic uncertainty due to different form-factor parametrizations. An additional uncertainty of \(\approx 10\%\) was accounted for the data-MC difference for the dimuon yield. The signal detection efficiency for each signature was evaluated by using signal MC and were found slightly \(m_a\) dependent. For instance, for the signature 1 and \(m_a \approx 10\) MeV, the \(\varepsilon_a^i\) and its systematic error was determined from the product of efficiencies accounting for the geometrical acceptance (0.97 \(\pm\) 0.02), the primary track (\(\approx 0.83 \pm 0.04\)), SRD (\(\gtrsim 0.95 \pm 0.03\)), ECAL (0.95 \(\pm\) 0.03), VETO (0.94 \(\pm\) 0.04), HCAL1 (0.94 \(\pm\) 0.04), and HCAL2.3 (0.97 \(\pm\) 0.02) signal event detection. The signal efficiency loss \(\lesssim 7\%\) due to pileup was taken into account using reconstructed dimuon events. The VETO and HCAL1 efficiencies were defined as a fraction of events below the corresponding energy thresholds with the main uncertainty estimated to be \(\lesssim 4\%\) for the signal events, which is caused by the pileup effect from penetrating hadrons. The trigger efficiency was found to be 0.95 with a small uncertainty of 2\%. The total signal efficiency \(\varepsilon_a\) varied from 0.51 \(\pm\) 0.09 to 0.48 \(\pm\) 0.08 for the \(a\) mass range of 10-50 MeV. The total systematic uncertainty on \(n_a\) calculated by adding all errors in quadrature did not exceed 20\% for both signatures. The attenuation of the \(a\) flux due to interactions in the HCA\(L\) was found to be negligible. The combined signal region excluded in the \((m_a; g_{a\gamma\gamma})\) plane at 90 % C.L. is shown in Fig. together with the results of other experiments. Our limits are valid for both scalar and pseudoscalar cases and exclude the region in the coupling range \(2 \times 10^{-4} \lesssim g_{a\gamma\gamma} \lesssim 5 \times 10^{-2}\) GeV\(^{-1}\) for masses \(m_a \lesssim 55\) MeV.

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