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Search for pseudoscalar bosons decayi

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We report the results of a search for a light pseudoscalar particle a that couples to electrons and decays to e^+e^- performed using the high-energy CERN SPS H4 electron beam. If such pseudoscalar with a mass $\simeq 17$ MeV exists, it could explain the ATOMKI anomaly. We used the NA64 data samples collected in the "visible mode" configuration with total statistics corresponding to 8.4×10^{10} electrons on target (EOT) in 2017 and 2018. In order to increase sensitivity to small coupling parameter ϵ we used also the data collected in 2016 - 2018 in the "invisible mode" configuration of NA64 with a total statistics corresponding to 2.84×10^{11} EOT. A thorough analysis of both these data samples in the sense of background and efficiency estimations was already performed and reported in our previous papers devoted to the search for light vector particles and axion-like particles (ALP). In this work we recalculate the signal yields, which are different due to different cross section and life time of a pseudoscalar particle a, and perform a new statistical analysis. As a result, the region of the two dimensional parameter space $m_a - \epsilon$ in the mass range from 1 to 17.1 MeV is excluded. At the mass of the ATOMKI anomaly the values of ϵ in the range $2.1 \times 10^{-4} < \epsilon < 3.2 \times 10^{-4}$ are excluded.

I. INTRODUCTION

Gauge-singlet pseudoscalar particles have been attracting attention for many years in view of understanding the phenomenology of the strong CP problem (lack of CP violation in QCD) [1–3]. Such particles appear in models with a spontaneously broken global symmetry and are considered as a candidate to dark matter or a mediator to dark sector, see, e.g., Refs. [4–9].

Previously, a neutral pseudoscalar particle a decaying to e^+e^- [10, 11] was proposed to explain the ATOMKI anomaly - an excess of e^+e^- pairs in the nuclear transitions of ^{8}Be and ^{4}He nuclei [12, 13]. Such particles could also cause a deviation from the expected value of the electron anomalous magnetic moment [14, 15].

The NA64 experiment determined previously the limits on the light vector particles decaying to e^+e^- [16]. The production cross section and decay width of a pseudoscalar particle differ from the corresponding values predicted for a vector particle with the same mass. In this paper we use the available data of the NA64 experiment and some results of the previous analyses of these data to derive limits on the particle a.

II. THE SEARCH METHOD

The NA64 experiment in the "visible mode" configuration, i.e. configured for searches for dark matter particles, such as dark photons A' or a particles, decaying visibly, into e^+e^- pairs, is described in Refs. [16–18] and shown in Fig. 1.

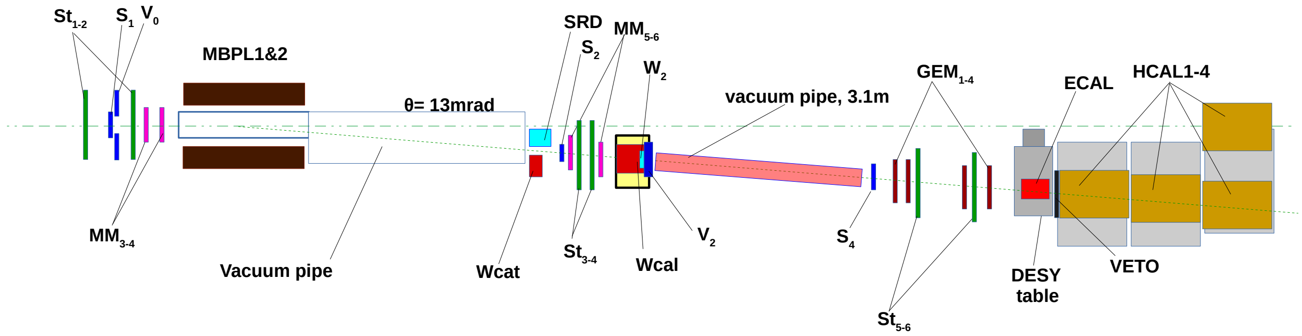

FIG. 1: The NA64 setup to search for $A'(a) \to e^+e^-$ decays of the bremsstrahlung $A'(a)$ produced in the reaction $eZ \to eZA'(a)$ of the 150 GeV electrons incident on the active WCAL target.

The experiment uses the high purity H4 electron beam at the CERN SPS (beam energy 100 GeV in 2017 and 150 GeV in 2018). The backgrounds coming from the beam are further significantly suppressed by using the synchrotron radiation detector (SRD) to identify electrons [19]. This suppression factor for the hadron contamination of the beam is $\sim 10^{-4}$. The most important subdetectors in this setup are the two electromagnetic (EM) calorimeters: the compact target-calorimeter WCAL assembled from the tungsten and plastic scintillator plates with wavelength shifting fiber read-out and ECAL, a matrix of 6×6 shashlik-type lead - plastic scintillator sandwich modules [19]. We also use a veto counter W_2 placed immediately after the WCAL and a decay counter S_4 installed downstream the vacuum decay tube. Measuring the energy deposition in W_2 ensures that no charged particle exits from the WCAL, while a signal compatible with two Minimum Ionizing Particle (MIP) in S_4 indicates that a decay to e^+e^- happened in the decay volume. The hadron calorimeter HCAL is installed downstream the ECAL. It consists of four modules, three of them are placed at the axis of the beam deflected by the MBPL magnets. They are usually used as a veto against electroproduction of hadrons in the WCAL. The fourth module serves as a veto against upstream interactions of electrons before reaching the target.

If the particle a exists, it would be produced via scattering of high-energy electrons off nuclei of an active target-dump WCAL due to its coupling to electrons ϵe, where e is the electron charge and ϵ is a coupling parameter [10]. Its production is followed by the decay into e^+e^- pairs:

$$e^- + Z \to e^- + Z + a;\ a \to e^+e^- \,. \tag{1}$$

The a can be detected if it decays in flight beyond the rest of the dump and the counter W_2 in the decay volume. The occurrence of the process (1) would manifest itself as an excess of events with two EM-like showers in the setup, one in the WCAL and another one in the ECAL, with the total energy $E_{tot} = E_{WCAL} + E_{ECAL}$ compatible with the beam energy (E_0), above those expected from background sources.

The candidate events are selected by applying the following main criteria:

1. The upper cut on the energy deposition in W_2 is $\sim$0.7 MIP (most probable energy deposition of a minimum ionizing particle);

2. The lower cut on the signal in S_4 is 1.5 MIPs;

3. The total energy deposited in the WCAL+ECAL should be compatible with the beam energy and $E_{ECAL} >$ 25 GeV;

4. The shower in the WCAL should be compatible with electron as a primary particle, the WCAL pre-shower energy lower cut of 0.5 GeV serving to check this;

5. The cell with maximal energy deposition in the ECAL should be the one on the deflected beam axis;

6. The longitudinal and lateral profiles of the shower in the ECAL are consistent with a single EM shower. The longitudinal shape is checked by requiring an energy deposition of at least 3 GeV in the ECAL pre-shower. The lateral profile of the shower was compared to the profile measured in the calibration beam using the χ^2 method. This does not decrease the efficiency for signal events because the distance between e^- and e^+ in the ECAL is significantly smaller than the ECAL cell size;

7. The rejection of events with hadrons in the final state is based on the energy deposition in the VETO counter (less than 0.9 MIP required) and the hadron calorimeter HCAL (less than 1 GeV for each module required).

The cuts used for the event selection are explained in more details in the previous paper [16].

In order to increase the sensitivity to a at small values of ϵ (below $\sim 2\times10^{-4}$), we also used the NA64 data collected in 2016 - 2018 in the "invisible mode" configuration (Fig. 2), with an analysis scheme exactly as in our ALP search [20]. In this method the HCAL is used not only as a veto, but also as a detector of possible $a \to e^+e^-$ decays.

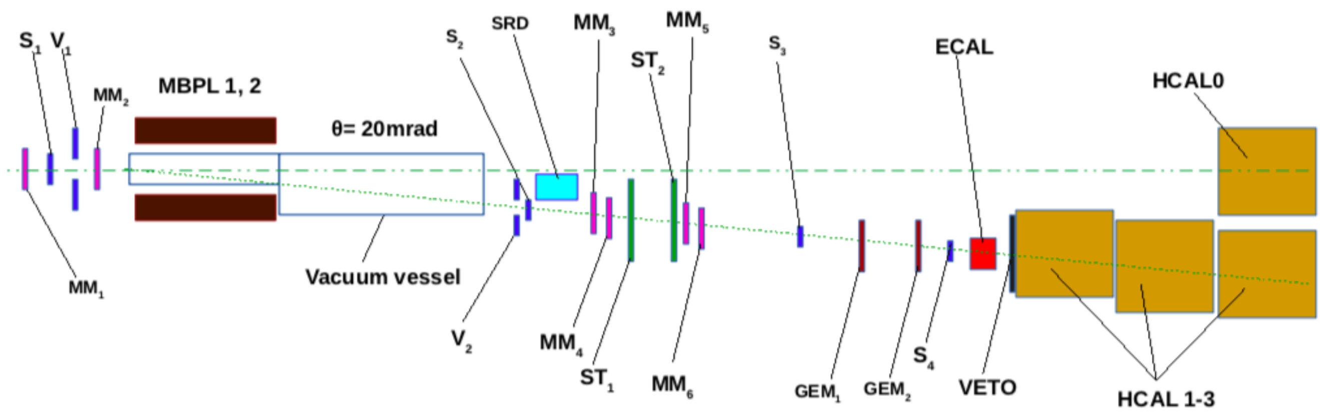

FIG. 2: The NA64 "invisible mode" setup [21].

For small values of ϵ the particle a is a relatively long-lived particle. There is a significant probability that after its creation in the ECAL and passing the first HCAL1 module serving as a shield/veto it would be observed in the NA64 detector in one of the two signatures: (S1) as an event with $a \to e^+e^-$ decay inside the HCAL2 or HCAL3 modules (HCAL2,3 in the following), or (S2) as an event with a significant missing energy if it decays beyond HCAL2,3, see Fig. 2. In both cases the main requirements were that the shower profile in ECAL is compatible with electron, the VETO counter signal is smaller than 0.9 MIP and that the energy deposition in HCAL1 is smaller than 1 GeV. The main requirements for the signature (S1) event were that the total energy deposition in HCAL $E_{HCAL} \gtrsim 15$ GeV, and that the energy deposited in HCAL2,3 is concentrated in the central cell [20]. For the signature (S2) the total energy deposition in ECAL was required to be smaller than 50 GeV and the energy in all HCAL modules should be smaller than 1 GeV. There was also a number of other criteria explained in more details for the signature (S1) in [20] and for the signature (S2) in [19, 21].

As the event selection was exactly the same as in the previous analyses, we reused the results of the background estimation from them. The main background in the NA64 "visible mode" configuration comes from the electroproduction of K^0_S and their decays $K^0_S \to \pi^0\pi^0$ in flight, followed by conversion of one of the decay photons. After optimization of the setup in 2018 this background, determined from data, amounted to less than 0.005 events per 10^{10} EOT [16]. The main background in the "invisible mode" configuration comes from neutral hadron production by electrons in the target. These neutral hadrons either pass without interaction the first HCAL module and deposit energy in the downstream modules HCAL2,3, or completely escape detection because of insufficient aperture of the HCAL. These backgrounds, of the order of 0.1 events, were also determined from data [20, 21].

III. SIGNAL YIELD AND RESULTS

In the calculations of the signal yield we used the fully Geant4 [22] compatible package DMG4 [23]. This package can simulate the production of four types of DM mediator particles in the electron bremsstrahlung processes, including the vector and pseudoscalar cases. It contains a collection of corresponding cross sections, total and differential, including the ones for a pseudoscalar particle a from the model of Ref. [10]. The total cross sections are calculated at the exact tree level (ETL). We assumed that the a decay branching ratio to e^+e^- is 100%.

The package DMG4 was compiled together with the program based on Geant4 for the full simulation of the NA64 experimental setup. The produced signal samples were processed by the same reconstruction program as the real data and passed the same selection criteria.

For the statistical analysis, the data were divided into three main bins: 1) data collected in the "visible mode" configuration of the experimental setup; 2) data from the "invisible mode" configuration selected according to the signature (S1) criteria above; 3) data from the "invisible mode" configuration selected using the signature (S2) criteria. The bins 1 and 3 were further subdivided into bins corresponding to different years. The backgrounds and various uncertainties in these bins were estimated in the previously published analyses [16, 19–21] and reused. This concerns also most of the signal yield uncertainties. The uncertainties depending on the a energy and path to decay distributions were recalculated for the new signal samples, but turned out to be compatible with the values determined previously and remained unchanged. All uncertainties, summed up in quadrature, don't exceed 20%. The exclusion limits were calculated by employing the multi-bin limit setting technique in a program based on RooStats package [24] with the modified frequentist approach, using the profile likelihood as a test statistic [25–27]. The 90% C.L. excluded region in the two-dimensional plot $m_a - \epsilon$ is shown in Fig. 3.

IV. CONCLUSION

We performed a model-independent search for light pseudoscalar particles that couple to electrons and decay predominantly to e^+e^- pairs in the NA64 experiment at the CERN SPS North Area. The active target-calorimeter of this experiment was exposed to the electron beams with the energy from 100 to 150 GeV. No signal of such particles was found, allowing us to exclude the region of the (m_a, ϵ) parameter space in the mass range from 1 to 17.1 MeV. More statistics is needed to increase the sensitivity region, in particular at the mass of the ATOMKI anomaly of 16.7 MeV [32].

V. AKNOWLEDGEMENTS

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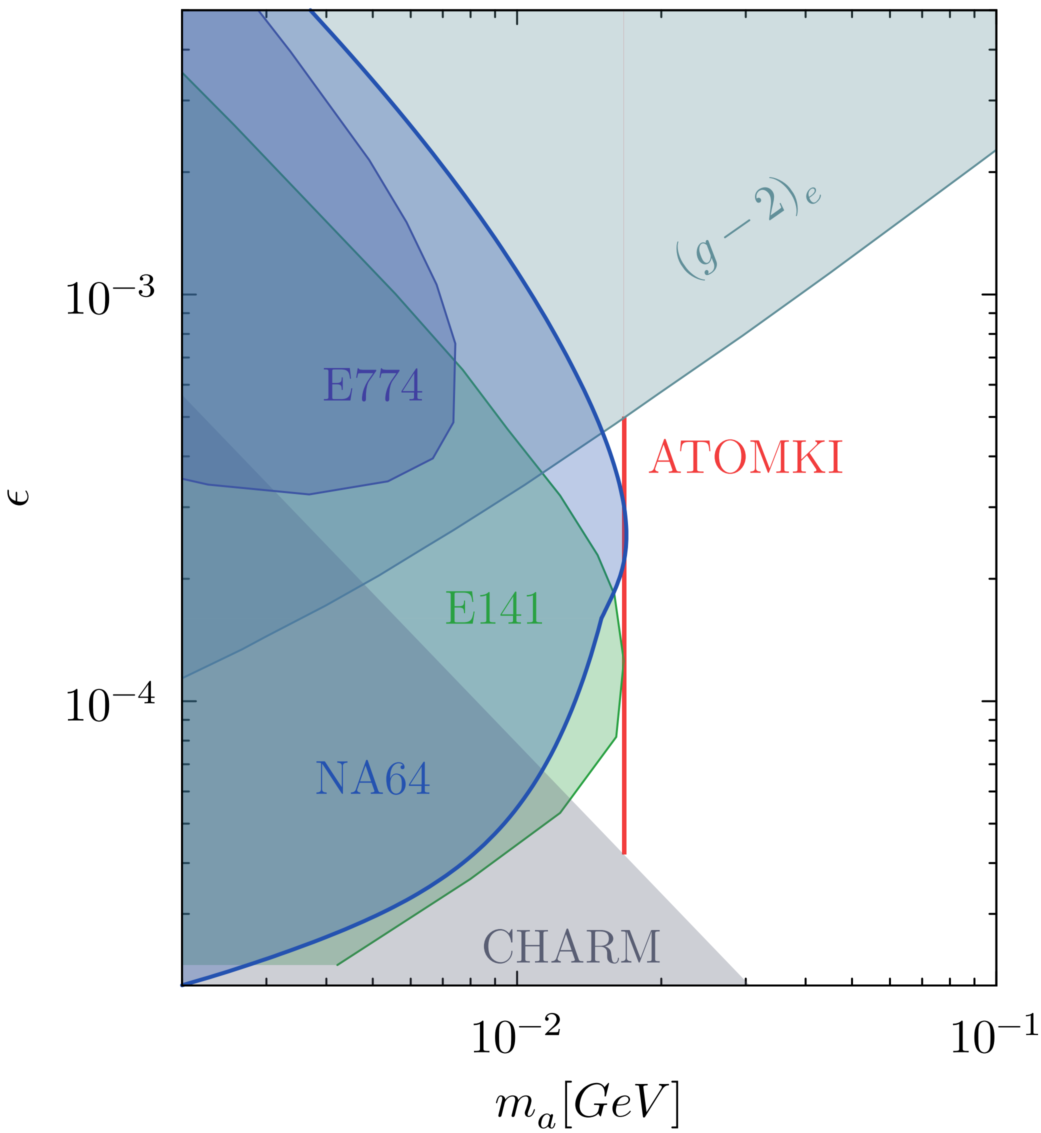

FIG. 3: The 90% C.L. limits on the pseudoscalar particles decaying to e^+e^- pairs. The red vertical line corresponds to the ATOMKI anomaly at $m_a = 16.7$ MeV. The ϵ range excluded at this mass is $2.1 \times 10^{-4} < \epsilon < 3.2 \times 10^{-4}$. The discontinuity in the lower boundary curve at $m_a \sim 15$ MeV is due to the appearence of non-negligible sensitivity from the invisible mode geometry data. The region excluded by the $(g-2)_e$ measurement is shown [14, 15]. The limits from the electron beam-dump experiments E141 [28], E774 [29] and proton beam-dump experiment CHARM [30] are taken from Ref. [31].

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