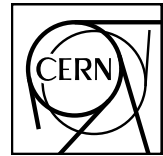


Search for a new $X(16.7)$ boson and dark photons in the NA64 experiment at CERN

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We report the first results on a direct search for a new 16.7 MeV boson (X) which could explain the anomalous excess of e^+e^- pairs observed in the excited ${}^8\text{Be}^*$ nucleus decays. Due to its coupling to electrons, the X could be produced in the bremsstrahlung reaction $e^-Z \rightarrow e^-ZX$ by a 100 GeV e^- beam incident on an active target in the NA64 experiment at the CERN SPS and observed through the subsequent decay into a e^+e^- pair. With 5.4×10^{10} electrons on target no evidence for such decays was found, allowing to set first limits on the $X-e^-$ coupling in the range $1.3 \times 10^{-4} \lesssim \epsilon_e \lesssim 4.2 \times 10^{-4}$ excluding part of the allowed parameter space. We also set new bounds on the mixing strength of photons with dark photons (A') from non-observation of the decay $A' \rightarrow e^+e^-$ of the bremsstrahlung A' with a mass $\lesssim 23$ MeV.

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The ATOMKI experiment of Krasznahorkay et al. [1] has reported the observation of a 6.8σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the nuclear transitions of excited ${}^8\text{Be}^*$ to its ground state via internal pair creation. It has been shown that the anomaly can be interpreted as the emission of a new protophobic gauge X boson with a mass of 16.7 MeV followed by its $X \rightarrow e^+e^-$ decay [2, 3]. This explanation of the anomaly was found to be consistent with all existing constraints assuming that the X has non-universal coupling to quarks, coupling to electrons in the range $2 \times 10^{-4} \lesssim \epsilon_e \lesssim 1.4 \times 10^{-3}$ and the lifetime $10^{-14} \lesssim \tau_X \lesssim 10^{-12}$ s. Interestingly, such relatively large charged lepton couplings can also resolve the so-called $(g_\mu - 2)$ anomaly, a discrepancy between measured and predicted values of the muon anomalous magnetic

moment. This has motivated worldwide efforts towards the planned experimental searches, see, e.g. [4, 5], and various phenomenological aspects of light vector bosons weakly coupled to quarks and lepton, see e.g. [6–11]

Another strong motivation to the search for a new light boson decaying into e^+e^- pair is provided by the Dark Matter puzzle. An intriguing 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 [12, 13]. Such A' could have a mass $m_{A'} \lesssim 1$ GeV, associated with a spontaneously broken gauged $U(1)_D$ symmetry, and would couple to the Standard Model (SM) through kinetic mixing with the ordinary photon, $-\frac{1}{2}\epsilon F_{\mu\nu}A'^{\mu\nu}$, parametrized by the mixing strength $\epsilon \ll 1$ [14–16], for a review see, e.g. [4, 17, 18]. A number of previous experiments, such as beam dump [19–33], fixed target [34–36], collider [37–39] and rare particle decay [40–51] experiments have already put stringent constraints on the mass $m_{A'}$ and ϵ of such dark photons excluding, in particular, the parame-

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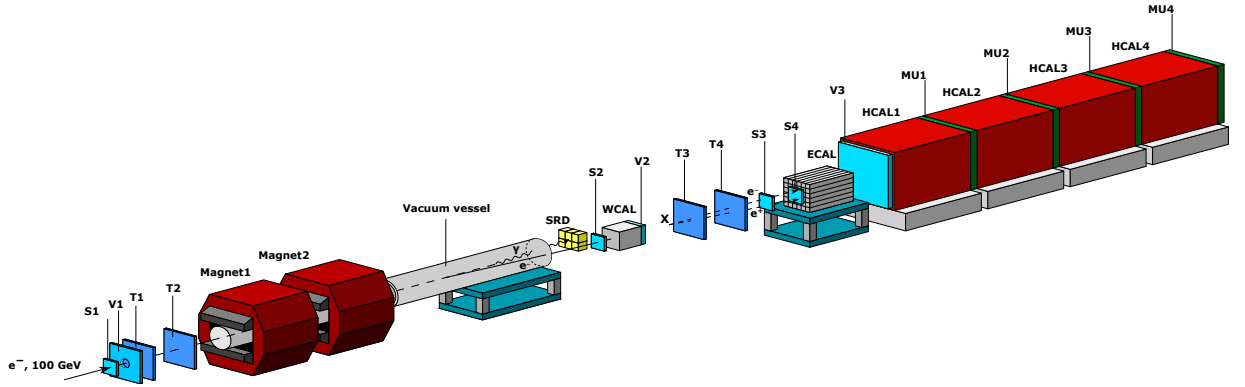


FIG. 1: Schematic illustration of the setup to search for $A', X \rightarrow e^+e^-$ decays of the bremsstrahlung A', X produced in the reaction $eZ \rightarrow eZA'(X)$ of 100 GeV e^- incident on the active WCAL target.

ter space region favored by the $g_\mu - 2$ anomaly. However, a large range of mixing strengths $10^{-4} \lesssim \epsilon \lesssim 10^{-3}$ corresponding to a short-lived A' still remains unexplored. These values of ϵ could naturally be obtained from the loop effects of particles charged under both the dark and SM $U(1)$ interactions with a typical 1-loop value $\epsilon = eg_D/16\pi^2$ [16], where g_D is the coupling constant of the $U(1)_D$ gauge interactions. In this Letter we report the first results from the NA64 experiment specifically designed for a direct search of the e^+e^- decays of new short-lived particles at the CERN SPS in the sub-GeV mass range [52–55].

The experiment employs the optimized 100 GeV electron beam from the H4 beam line in the North Area (NA) of the CERN SPS. The beam delivers $\simeq 5 \times 10^6$ e^- per SPS spill of 4.8 s produced by the primary 400 GeV proton beam with an intensity of a few 10^{12} protons on target. The NA64 setup designed for the searches of X bosons and A' is schematically shown in Fig. 1. Two scintillation counters, S1 and S2 were used for the beam definition, while the other two, S3 and S4, were used to detect the e^+e^- pairs. The detector is equipped with a magnetic spectrometer consisting of two MPBL magnets and a low material budget tracker. The tracker was a set of four upstream Micromegas (MM) chambers (T1, T2) for the incoming e^- angle selection and two sets of downstream MM, GEM stations and scintillator hodoscopes (T3, T4) allowing the measurement of the outgoing tracks [56, 57]. To enhance the electron identification the synchrotron radiation (SR) emitted by electrons was used for their efficient tagging and for additional suppression of the initial hadron contamination in the beam $\pi/e^- \simeq 10^{-2}$ down to the level $\simeq 10^{-6}$ [55, 58]. The use of SR detectors (SRD) is a key point for the hadron background suppression and improvement of the sensitivity compared to the previous electron beam dump searches [23, 24]. The dump is a compact electromagnetic (e-m) calorimeter WCAL made as short as possible to maximize the sensitivity to short lifetimes while keeping the leakage of particles at a small level. It is followed by another e-m calorimeter (ECAL), which is a matrix of 6×6 shashlik-

type modules [55]. The WCAL(ECAL) was assembled from the tungsten(lead) and plastic scintillator plates with wave lengths shifting fiber read-out. The ECAL has $\simeq 40$ radiation lengths (X_0) and is located at a distance $\simeq 3.5$ m from the WCAL. Downstream the ECAL the detector was equipped with a high-efficiency veto counter, V3, and a massive, hermetic hadron calorimeter (HCAL) [55] used as a hadron veto and muon identifier.

The method of the search for $A' \rightarrow e^+e^-$ decays is described in [52, 53]. The application of all further considerations to the case of the $X \rightarrow e^+e^-$ decay is straightforward. If the A' exists, it could be produced via the coupling to electrons wherein high-energy electrons scatter off a nuclei of the active WCAL dump target, followed by the decay into e^+e^- pairs:

$$e^- + Z \rightarrow e^- + Z + A'(X); A'(X) \rightarrow e^+e^- \quad (1)$$

The reaction (1) typically occurs within the first few radiation lengths (X_0) of the WCAL. The downstream part of the WCAL served as a dump to absorb completely the e-m shower tail. The bremsstrahlung A' would penetrate the rest of the dump and the veto counter V2 without interactions and decay in flight into an e^+e^- pair in the decay volume downstream the WCAL. A fraction (f) of the primary beam energy $E_1 = fE_0$ is deposited in the WCAL by the recoil electron from the reaction (1). The remaining part of the primary electron energy $E_2 = (1 - f)E_0$ is transmitted through the dump by the A' , and deposited in the second downstream calorimeter ECAL via the $A'(X) \rightarrow e^+e^-$ decay in flight, as shown in Fig. 1. For the mass range $1 \leq m_{A'} \leq 25$ MeV and energy $E_{A'} \gtrsim 20$ GeV, the opening angle $\Theta_{e^+e^-} \simeq 2m_{A'}/E_{A'} \lesssim 2$ mrad of the decay e^+e^- pair is too small to be resolved in the tracker T3-T4, and the pairs are mostly detected as a single-track e-m shower in the ECAL. The occurrence of $A' \rightarrow e^+e^-$ decays produced in e^-Z interactions would appear as an excess of events with two e-m-like showers in the detector: one shower in the WCAL, and another one in the ECAL with the total energy $E_{tot} = E_{WCAL} + E_{ECAL}$ equal to

the beam energy (E_0), above those expected from the background sources. The results reported here are obtained from data samples in which 2.4×10^{10} of electrons on target (EOT) and 3×10^{10} EOT were collected with the WCAL of 40 X_0 (with a length of 290 mm) and of 30 X_0 (220 mm), respectively. The events were collected with a hardware trigger requiring in-time energy deposition in the WCAL and $E_{WCAL} \lesssim 70$ GeV. Data of these two runs (hereafter called the 40 X_0 and 30 X_0 run) were analyzed with similar selection criteria and finally summed up, taking into account the corresponding normalization factors. A detailed Geant4 based Monte Carlo (MC) simulation was used to study the detector performance and acceptance, to simulate backgrounds and to select cuts and estimate the reconstruction efficiency.

The candidate events were selected with the following criteria chosen to maximize the acceptance of signal events and to minimize the number of background events, using both MC simulation and data: (i) There should be only one track entering the dump. No cuts on reconstructed outgoing tracks were used; (ii) No energy deposition in the V2 counter exceeding about half of the energy deposited by the minimum ionizing particle (MIP); (iii) The signal in the decay counter S4 is consistent with two MIPs; (iv) The sum of energies deposited in the WCAL+ECAL is equal to the beam energy within the energy resolution of these detectors. At least 30% of the total energy should be deposited in the ECAL. The latter cut was based on the simulation of the A' spectra [59, 60]; (v) The showers in the WCAL and ECAL should start to develop within a few first X_0 ; (vi) The lateral and longitudinal shape of the shower in the ECAL are consistent with a single e-m one. This requirement does not decrease the efficiency to signal events because the distance between e^- and e^+ in the ECAL is very small. However, for the A' decays with energy $\lesssim 5$ GeV the ECAL shower is not well described by the single shower shape, therefore, the additional ECAL energy cut $E_{ECAL} > 5$ GeV was applied. The rejection of events with hadrons in the final state was based on the veto V3 and/or the energy deposited in the HCAL. As in the previous analyses [54, 55], in order to check various efficiencies and the reliability of the MC simulations, we selected a clean sample of $\simeq 10^5$ $\mu^+\mu^-$ events with $E_{WCAL} < 60$ GeV originated from the QED dimuon production in the dump. This rare process is dominated by the reaction $e^-Z \rightarrow e^-Z\gamma; \gamma \rightarrow \mu^+\mu^-$ of a hard bremsstrahlung photon conversion into the dimuon pair on a dump nucleus. We performed various comparisons between these events and the corresponding MC simulated sample, and applied the estimated efficiency corrections to the MC events. These corrections do not exceed 20%.

In order to avoid biases in the determination of selection criteria for signal events, a blind analysis was performed. The signal box was defined as $90 < E_{tot} < 110$ GeV. Events from the signal box were excluded from the analysis of the data until the validity of the background

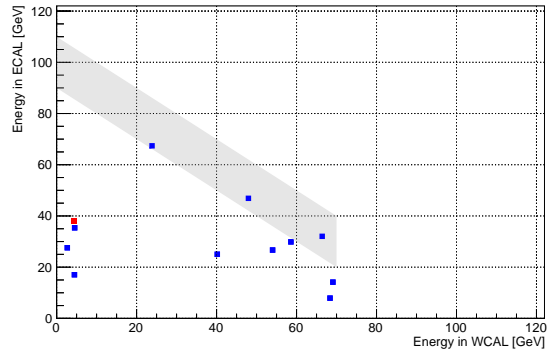


FIG. 2: Distribution of selected e-m neutral and signal-like events in the $(E_{WCAL}; E_{ECAL})$ plane from the combined 30 X_0 and 40 X_0 runs. Neutral events are shown as blue squares. The only signal-like event is shown as a red square. The dashed band represents the signal box region, which is open.

estimate in this region was established. For the selection criteria optimization 20% of the data from each run were used, while the full data sample was used for the background estimate.

The search for the $A' \rightarrow e^+e^-$ decays requires particular attention to backgrounds. Every process with a track in the tracker and an e-m cluster in the ECAL was considered as a potential source of background. There are several processes that can fake the $A' \rightarrow e^+e^-$ signal. Among them the two most important were expected from the K_S^0 decays in flight. The first one included the e^+e^- pair production either from decay chain $K_S^0 \rightarrow \pi^0\pi^0; \pi^0 \rightarrow \gamma e^+e^-$ of K_S^0 produced in the WCAL dump or from the $\gamma \rightarrow e^+e^-$ conversion of photons from $\pi^0 \rightarrow \gamma\gamma$ decays either in the T3 plane or earlier in the upstream part of the beamline. Another background could come from the $K_S^0 \rightarrow \pi^+\pi^-$ hadronic decays that could be misidentified as an e-m event in the ECAL at the level $\lesssim 2.5 \times 10^{-5}$ evaluated from the measurements with the pion beam. The leading K^0 can be produced in the dump either by misidentified beam π^-, K^- or directly by beam electrons. Since the simulation predictions for these hadronic processes cannot be sufficiently reliable, especially at the level lower than $\lesssim 10^{-6}$, we used MC simulations combined with the the data themselves for the estimation of such backgrounds in the signal region. The main background from the K_S^0 decay chain was evaluated using the direct estimation of the K_S^0 flux from the dump with the following method. It is well known that the K^0 produced in hadronic reactions is a linear combination of the short- and long-lived components $|K^0 \rangle = (|K_S^0 \rangle + |K_L^0 \rangle)/\sqrt{2}$. The flux of K^0 was evaluated from the measured ECAL+HCAL energy spectrum of long-lived neutral hadrons selected with the requirement of no signal in V2 and S4, taking into account corrections due to the K_S^0 decays in-flight. The main fraction of $\simeq 10^3$ events observed in the HCAL calorimeter were neutrons produced in the same processes as

K^0 in the WCAL. According to simulations, $\lesssim 10\%$ of them were predicted to be other neutral hadrons, i.e. Λ and K^0 , that were also included in the data sample. The conservative assumption that $\simeq 100 K^0$ were produced allows us to calculate the number of K_S^0 from the dump and simulate the corresponding background from the $K_S^0 \rightarrow \pi^+\pi^-$ and $K_S^0 \rightarrow \pi^0\pi^0$; $\pi^0 \rightarrow \gamma e^+e^-$ decay chain, which was found to be $\lesssim 0.04$ events per 5.4×10^{10} EOT. To cross-check this result another estimate of this background was used. The true neutral e-m events were selected with requirements of no signals in V2 and S4 counters plus a single e-m like shower in the ECAL. Three such events were found in the signal box as shown in Fig. 2. Using simulations we calculated that there were $\simeq 150$ leading K_S^0 produced in the dump. This number is in a reasonable agreement with the previous estimate. We used the most pessimistic estimate from these two for the K_S^0 background: 0.06 events.

TABLE I: Expected numbers of background events in the signal box that passed the selection criteria (i)-(vi) estimated for 5.4×10^{10} EOT.

Source of background	Events
e^+e^- pair production by punchthrough γ	< 0.001
$K_S^0 \rightarrow 2\pi^0$; $\pi^0 \rightarrow \gamma e^+e^-$ or $\gamma \rightarrow e^+e^-$; $K_S^0 \rightarrow \pi^+\pi^-$	0.06 ± 0.034
$\pi N \rightarrow (\geq 1)\pi^0 + n + \dots$; $\pi^0 \rightarrow \gamma e^+e^-$ or $\gamma \rightarrow e^+e^-$	0.01 ± 0.004
π^- hard bremsstrahlung in the WCAL, $\gamma \rightarrow e^+e^-$	< 0.0001
$\pi, K \rightarrow e\nu$, K_{e4} decays	< 0.001
$eZ \rightarrow eZ\mu^+\mu^-$; $\mu^\pm \rightarrow e^\pm\nu\nu$	< 0.001
punchthrough π	< 0.003
Total	0.07 ± 0.035

The mistakenly tagged μ , π and K could also interact in the dump though the $\mu Z \rightarrow \mu Z\gamma$ or π, K charge-exchange reactions, accompanied by the poorly detected scattered μ , or secondary hadrons. This misidentification is caused by knocking electrons off the downstream window of the vacuum vessel when a particle passes through it [58]. These electrons then hit the SRD creating a fake tag of a 100 GeV e^- . The misidentified pion could mimic the signal either directly (small fraction of showers that look like an e-m one) or by emitting a hard bremsstrahlung photon in the last layer of the dump, which then produces an e-m- shower in the ECAL, accompanied by the scattered pion track. Another background can appear from the beam $\pi \rightarrow e\nu$ decays downstream the WCAL. The latter two backgrounds can only pass the selection due to the V2 inefficiency ($\simeq 10^{-4}$), which makes them negligible.

The charge-exchange reaction $\pi^- p \rightarrow (\geq 1)\pi^0 + n + \dots$ which can occur in the last layers of the WCAL with decay photons escaping the dump without interactions and accompanied by poorly detected secondaries is another source of fake signal. To evaluate this background we used the extrapolation of the charge-exchange cross sections, $\sigma \sim Z^{2/3}$, measured on different nuclei

[61]. Taking into account the beam pion flux suppression by the SRD tagging, the estimation is 0.015 events. The contribution from the beam kaon decays in-flight $K^- \rightarrow e^- \nu \pi^+ \pi^-$ (K_{e4}) and dimuon production in the dump $e^- Z \rightarrow e^- Z \mu^+ \mu^-$ with either $\pi^+\pi^-$ or $\mu^+\mu^-$ pairs misidentified as e-m event in the ECAL was found to be negligible.

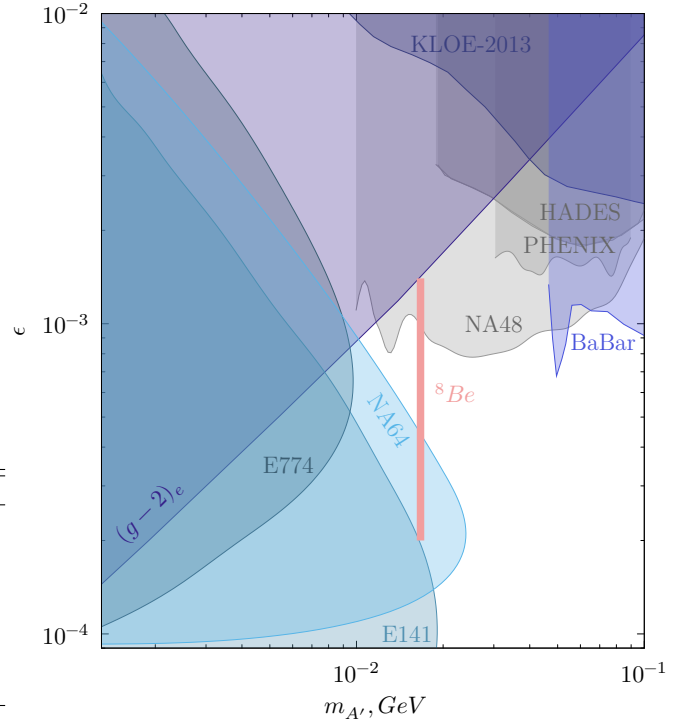


FIG. 3: The 90% C.L. exclusion areas in the $(m_X; \epsilon)$ plane from the NA64 experiment (blue area). For the mass of 16.7 MeV, the $X - e^-$ coupling region excluded by NA64 is $1.3 \times 10^{-4} < \epsilon_e < 4.2 \times 10^{-4}$. The full allowed range of ϵ_e explaining the ${}^8\text{Be}^*$ anomaly, $2.0 \times 10^{-4} \lesssim \epsilon_e \lesssim 1.4 \times 10^{-3}$ [2, 3], is also shown (red area). The constraints on the mixing ϵ from the experiments E774 [24], E141 [21], BaBar [39], KLOE [44], HADES [46], PHENIX [47], NA48 [49], and bounds from the electron anomalous magnetic moment $(g-2)_e$ [67] are also shown.

Table I summarizes the conservatively estimated background inside the signal box, which is expected to be 0.07 ± 0.034 events per 5.4×10^{10} EOT. The dominant contribution to background is 0.06 events from the K_S^0 decays. The main uncertainty of this number is from the statistical error of the 3 observed e-m neutral events. The systematic error includes also the uncertainty in the cross sections of the π, K charge-exchange reactions on lead (30%).

After determining and optimizing the selection criteria and estimating the background levels, we examined the entire signal box and found no candidates. In Fig. 2 the final distribution of neutral and signal candidate events from the reaction $e^- Z \rightarrow \text{anything}$ in the

($E_{ECAL}; E_{WCAL}$) plane that passed the selection criteria (i)-(iii), (v), (vi) is shown. The conclusion that the background is small is confirmed by the data.

The combined 90% confidence level (C.L.) upper limits for the mixing strength ϵ were determined from the 90% C.L. upper limit for the expected number of signal events, $N_{A'}^{90\%}$ by using the modified frequentist approach for confidence levels (C.L.), taking the profile likelihood as a test statistic in the asymptotic approximation [62–64]. The total number of expected signal events in the signal box was the sum of expected events from the 30 X_0 and 40 X_0 runs:

$$N_{A'} = \sum_{i=1}^2 N_{A'}^i = \sum_{i=1}^2 n_{EOT}^i \epsilon_{tot}^i n_{A'}^i(\epsilon, m_{A'}) \quad (2)$$

where ϵ_{tot}^i is the signal efficiency in the run i , and $n_{A'}^i(\epsilon, m_{A'})$ is the number of the $A' \rightarrow e^+e^-$ decays in the decay volume with energy $E_{A'} > 30$ GeV per EOT, calculated under assumption that this decay mode is predominant, see e.g. Eq.(3.7) in Ref. [53]. Each i -th entry in this sum was calculated by simulating signal events for the corresponding beam running conditions and processing them through the reconstruction program with the same selection criteria and efficiency corrections as for the data sample from the run- i . In the overall signal efficiency for each run the acceptance loss due to pileup ($\simeq 7\%$ for 40 X_0 and $\simeq 10\%$ for 30 X_0 runs) was taken into account and cross-checked using dimuon events. The total effective number of collected $n_{EOT} = 5.4 \times 10^{10}$ EOT takes into account the trigger suppression factor and dead time. The trigger (SRD tagging) efficiency were obtained using unbiased samples of events that bypass selection criteria

and were found to be 0.95 (0.97) with a small uncertainty 2%. The A' yield from the dump was calculated as described in Ref.[60]. These calculations were cross-checked with the calculations of Ref.[65, 66]. The $\lesssim 10\%$ difference between the two calculations, presumably due to the difference in computation program used, was accounted for as a systematic uncertainty in $n_{A'}(\epsilon, m_{A'})$. The efficiency corrections obtained from the cross check with the dimuon sample do not exceed 20% with uncertainty of 10% and 15%, for the 40 X_0 and 30 X_0 runs, respectively. The total systematic uncertainty on $N_{A'}$ calculated by adding all errors in quadrature did not exceed $\simeq 25\%$ for both runs. The combined 90% C.L. exclusion limits on the mixing ϵ as a function of the A' mass is shown in Fig. 3 together with the current constraints from other experiments. Our results exclude X-boson as an explanation for the ${}^8\text{Be}^*$ anomaly for the $X - e^-$ coupling $\epsilon_e \lesssim 4.2 \times 10^{-4}$ and mass value of 16.7 MeV, leaving the still unexplored region $4.2 \times 10^{-4} \lesssim \epsilon_e \lesssim 1.4 \times 10^{-3}$ as quite an exciting prospect for further searches.

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