Probing new physics at the LUXE experiment

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The proposed LUXE experiment (LASER Und XFEL Experiment) at DESY, Hamburg, using the electron beam from the European XFEL, aims to probe QED in the non-perturbative regime created in collisions between high-intensity laser pulses and high-energy electron or photon beams. This setup also provides a unique opportunity to probe physics beyond the standard model. In this talk we show that by leveraging the large photon flux generated at LUXE, one can probe axion-like-particles (ALPs) up to a mass of 350 MeV and with photon coupling of $3 \times 10^{-6}\,\text{GeV}^{-1}$. This reach is comparable to the background-free projection from NA62. In addition, we will discuss other probes of new physics such as ALPs-electron coupling.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

1. Introduction

LUXE [1] (Laser Und XFEL Experiment) is a future experiment that will be located at DESY and the European XFEL (EuXFEL) near Hamburg, Germany. Its design aims at using the EuXFEL's 16.5 GeV electron beam - or *bremsstrahlung* photons obtained using a converter target - and make them interact with a high-intensity laser. The data-taking will be split into two phases: in the first period, a 40 TW laser will be used and then replaced by a 350 TW one in the second stage. The physics goal of the LUXE experiment is twofold:

- Compare the predictions of the non-perturbative QED in the Schwinger limit with the experimental results. The Schwinger limit is a scale above which non-linear processes in QED become relevant. For a static electrical field, the Schwinger limit is:

$$\mathcal{E} = \frac{m_e^2 c^3}{e\hbar} = 1.32 \cdot 10^{18} \text{ V/m}. \tag{1}$$

  LUXE will be able to enter the non-perturbative QED regime in the probe particle rest frame thanks to its high-intensity laser and the large Lorentz boost of the high-energy electron beam.

- The inverse Compton scattering interaction between the electrons from the EuXFEL and the laser will produce a beam of photons with energies up to 15 GeV. These photons travel until a *physical* dump located at the end of the experimental apparatus, where they can produce axion-like particles (ALPs) interacting with the material of the dump, in the so-called secondary production mode. ALPs can also be produced directly in the electron-laser interaction. However, this primary production allows to reach masses of around 100 keV, significantly smaller than the $O(1)$ GeV obtained in the secondary production [2]. The ALPs then decay into pairs of photons. If they do so in the decay volume after the dump, the photons are detected by an electromagnetic calorimeter.

Figure 1a shows the LUXE setup in the e-laser interaction mode, while in Figure 1b, the signal and backgrounds production in the *new physics searches with an optical dump* (NPOD) layout are sketched.

2. Signal Production and Acceptance

The ALPs production in the physical dump happens via the Primakoff mechanism, i.e., the photon interaction with the magnetic field of the dump material nuclei. More generally, the expected number of ALPs detected at the calorimeter is approximately:

$$N_a \approx \mathcal{L}_{eff} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a(E_\gamma) \left(\exp^{-\frac{L_D}{L_a}} - \exp^{-\frac{L_V + L_D}{L_a}} \right) \mathcal{A}, \tag{2}$$

where $\mathcal{L}_{eff} = N_e N_p \frac{9\rho_N X_0}{7 A_N m_0}$ is the *effective luminosity*, and depends on:

- the number of electrons per bunch, $N_e = 1.5 \cdot 10^9$;

- the number of bunches per year, $N_p \sim 10^7$;

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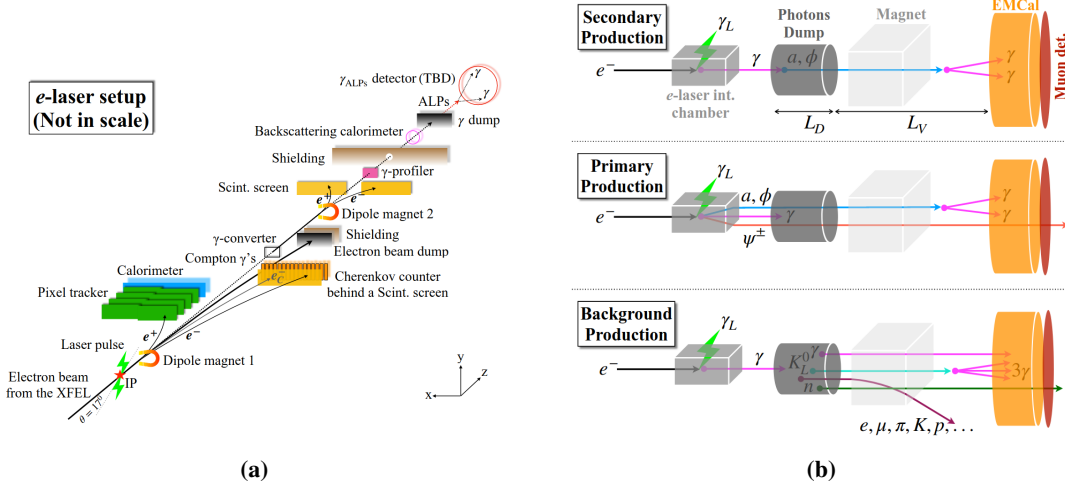
Figure 1: e-laser experimental setup (a) and signal and backgrounds productions in LUXE-NPOD (b). The secondary signal production happens with the interaction of the photons in the physical dump material, with ALPs masses up to $\mathcal{O}(1)$ GeV. In the primary production, the ALPs are produced at the electron-laser interaction, with masses limited to $\mathcal{O}(100)$ keV [2].

- the properties of the material of the dump: the density ρ_N, the mass number A_N, and the radiation length X_0;

- the nucleon mass, $m_0 = 1.66 \cdot 10^{-24}$ g (~ 930 MeV).

L_V is the decay volume length, L_D is the dump length, and $\mathcal{A}$ is the detector geometric acceptance. The acceptance is estimated as a function of the decay volume length, detector transverse size, and ability to resolve close-by photons. For that, dedicated signal simulations have been produced for a large set of ALP parameters (mass m and coupling to photons $1/\Lambda$). Figure 2 shows the energy range, distance at detector surface, and maximum distance from the detector center for photons coming from ALPs with a mass of 0.35 GeV and coupling with photons of 5.25 GeV^{-1}. In each plot, distributions assuming different decay volume lengths are compared. Despite one single point in the probed phase space is shown, a few general conclusions can be derived: the ALPs will produce photons with energies of the order of few GeV; a longer decay volume will require a detector with larger surface; on the other hand, a shorter decay volume implies that photons may be very close when hitting the detector, meaning that an excellent ability to resolve close-by showers will be needed.

3. Expected Results

More quantitative information is obtained looking at the expected results. They are interpreted in terms of exclusion limits, assuming zero background reaching the detector. In Figure 3a, the expected results are presented as a function of the decay volume, showing how a longer decay volume enhance the sensitivity to low coupling values, without affecting the sensitivity to higher masses. Figure 3b, however, shows that these low coupling values are already excluded by previous beam dump experiments or naturalness. This means that a layout with a short decay volume and a

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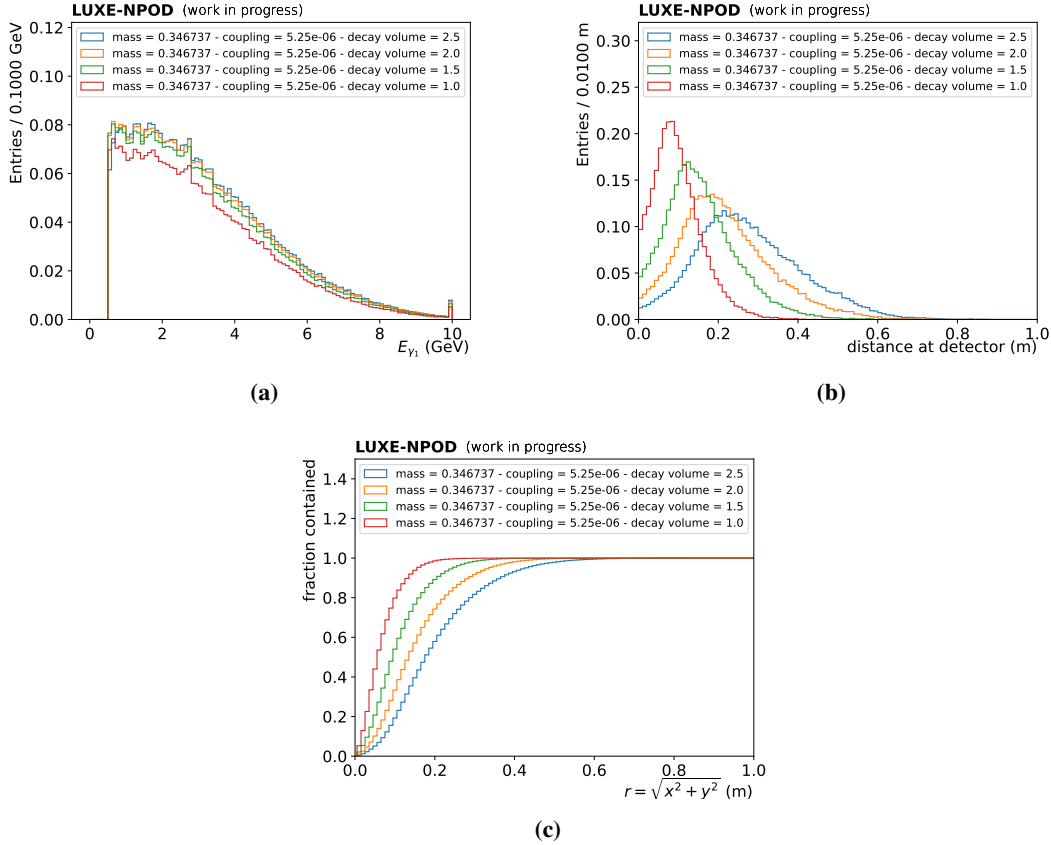
Figure 2: A few kinematical properties of photons produced by the ALP decay. Here, the ALP mass is set to 0.35 GeV and the coupling to photons to 5.25 GeV^{-1}. The different lines refer to different decay volume length, between 1 m and 2.5m. The quantities shown are the energy of the leading photon (a), the distance between the two photons at the detector surface (b), and the maximum photon distance from the detector center (c).

small detector surface could be a viable option, if the detector has a good enough shower resolution capability. Further studies are needed to evaluate this last requirement.

## 4. Background Contamination and Dump Studies

Interactions of the photons beam with the dump and secondary particles produced along the LUXE beamline can cause significant background levels to the LUXE-NPOD ALPs search. It is therefore important to study how to suppress backgrounds or how to estimate irreducible backgrounds. Several dump layouts (material, length, radius) have been compared, in order to enhance the ALP production and acceptance, and suppress non-ALP particles reaching the detector. Figure 4 shows the expected photon and neutron energy spectra considering different dump radius and materials. In general, the best material is tungsten, given it provides the highest ALP production and background reduction. Given the high price that a full tungsten dump may have, a design with a tungsten core and a lead wrap is considered, with comparable results. Previous studies showed

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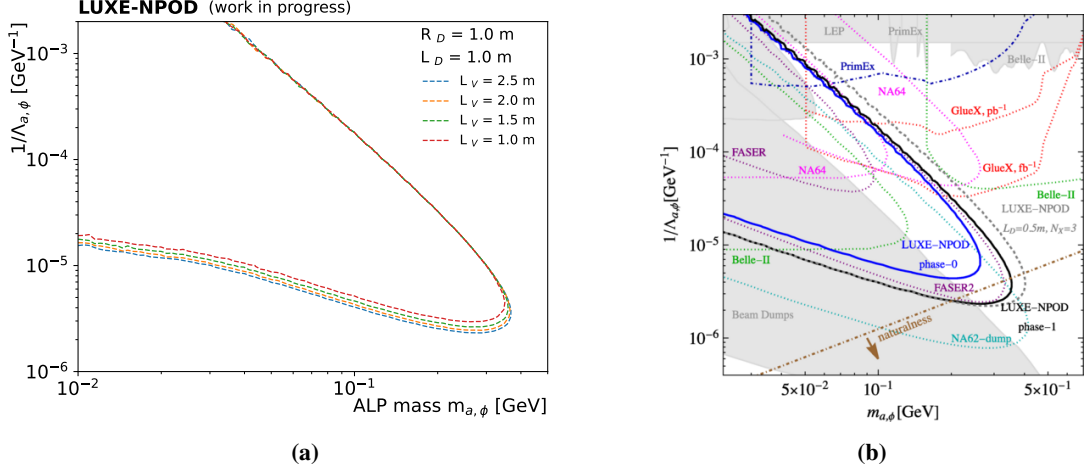
Figure 3: LUXE-NPOD expected exclusion limits as a function of the decay volume length (a) and comparison of the LUXE-NPOD exclusion limit with constraints from past and future experiments [2]. In particular, the LUXE-NPOD phase-1 exclusion contour (solid black line) improves the NA62 background-free projection (cyan dotted line). The LUXE-NPOD projection considering a shorter dump of 0.5 m (grey dashed line) shows a larger excluded phase space, but is currently incompatible with the zero-background assumption.

that shorter dumps will allow to gain sensitivity to high ALP masses. However, they would imply larger backgrounds reaching the detectors, making them not suitable for LUXE-NPOD.
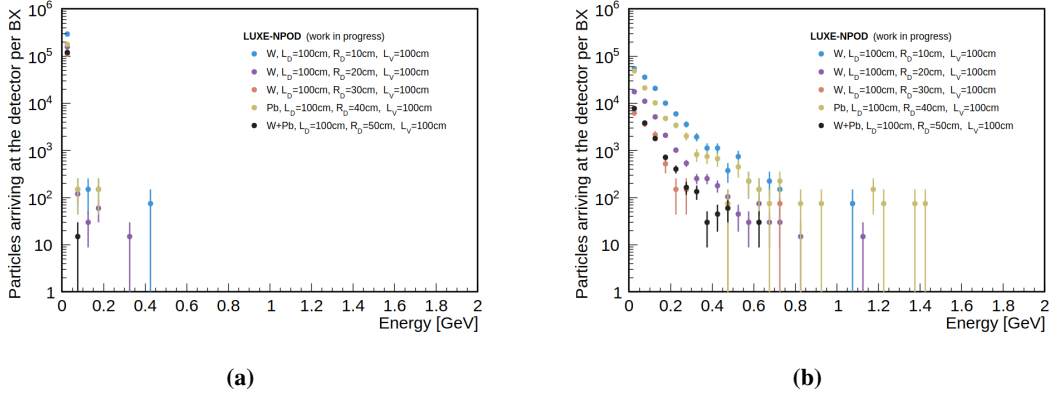
Figure 4: Expected energy spectra of photons (a) and neutrons (b) reaching the detector assuming different dump layouts.

5. Detector Requirements and Proposals

The LUXE-NPOD detector has to fulfill two main tasks: detect signal photons with high efficiency and suppress the residual background that may leave the dump. For the former, one fundamental property is the ability to separate close-by photons shower. In addition, good resolution of the photons direction and energy would also allow to reconstruct the ALP invariant mass and reject fake signals from non-resonant photons. To reject backgrounds, shower-shape determination

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would help in distinguishing photons from neutrons. Similarly, a time resolution of about 1 ns would allow to identify and suppress slower neutrons. All these requirements are fulfilled by tracking calorimeters, such as the Alice forward calorimeter [3] or the CALICE SiPM-on-tile calorimeter [4, 5]. In addition, the spaghetti calorimeter from the H1 experiment [6] is also considered for preliminary tests.

6. Conclusions

The LUXE-NPOD project has the potential to inspect an uncharted ALPs phase space, in particular, light ALPs ($m_a \sim O(100)$ MeV) with large couplings ($1/\Lambda \sim 10^{-3} - 10^{-4}$ GeV^{-1}). The results presented assume zero background. Detailed studies using signal simulations allowed to optimize parameters of the experimental apparatus: a short decay volume will allow to use a relatively small detector, if its photons shower reconstruction properties allow to distinguish close-by photons (1 or 2 cm separation at the detector surface). The dump design is selected in order to enhance the signal production and background rejection, with tungsten as the preferred material. A detector with good photons direction and energy resolution, time resolution of the order of 1 ns, and shower shape separation resolution of 1-2 cm would fit the experimental requirements.

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