Probing ALPs at the LUXE experiment

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Abstract

The proposed LUXE experiment (LASER Und XFEL Experiment) at DESY, Hamburg, aims to probe QED in its non-perturbative regime. In order to do this, LUXE will study the interactions between 16.5 GeV electrons from the European XFEL and high-intensity laser pulses. This experiment also provides a unique opportunity to probe physics beyond the Standard Model: exploiting the large photon flux generated at LUXE, it is possible to design a dedicated detector to probe axion-like-particles up to a mass of 350 MeV and with photon coupling of $3 \cdot 10^{-6}$ GeV^{-1}. This reach is comparable to the projected sensitivity of experiments like FASER2 at the HL-LHC and NA62 operating in dump mode.

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1 Introduction

The LUXE experiment [1] proposed at DESY and the European XFEL (Eu.XFEL) is intended to study strong-field QED processes in the interactions of a high-intensity optical laser and the 16.5 GeV electron beam of the Eu.XFEL, as well as with high-energy secondary photons. A strong background field is provided by a Terawatt-scale laser-pulse and enhanced by the Lorentz boost of the electrons, allowing LUXE to explore a previously uncharted intensity regime.

In this regime, one of the main goals of the LUXE experiment is to measure the positron rate as a function of the laser intensity parameter ξ and the quantum parameter χ and to compare it to theoretical predictions from strong-field QED. When considering electron-laser collisions, the most important process is the *non-linear Compton scattering*. In non-linear Compton scattering, the incident electron absorbs multiple laser photons, emitting a Compton photon, which can then interact again with the laser field to produce e^+e^- (ee) pairs. For long laser pulses ($\mathcal{O}(100)$ fs), multiple outgoing photons can be produced for each incoming electron.

Together with its main non-perturbative regime QED programme, the LUXE experiment provides a unique opportunity to look for Beyond-the-Standard Model (BSM) particles that may be produced in the primary electron-laser or photon-laser interactions, or in secondary interactions of the outgoing Compton photons with matter. In this scenario, the high energy photons could scatter on a target nucleus, N, to produce BSM scalars or pseudoscalars via Primakoff production. If the BSM states have a non-negligible lifetime, they can be detected via their decays beyond the target. The LUXE extension dedicated to such scenario is referred to as LUXE-NPOD: New Physics at Optical Dump [2].

New spin-0 particles (pseudo-scalar states a or scalar states ϕ) are motivated by many extensions of the SM. The pseudo-scalar states, often referred to as axion-like-particles, can naturally address the strong CP problem [3,4], address the Hierarchy problem [5,6], or can be a valid dark matter candidate [7–9]. If only a/ϕ-photon interactions are allowed to minimise the model dependence, the phenomenology of the processes expected at LUXE can be mapped as a function of two key quantities: the a/ϕ-photon effective coupling and the a/ϕ mass. For a given mass, if the coupling strength is small enough, the BSM states can become long-lived and their decays can be detected in a dedicated forward detector.

2 An optical dump

The intense laser used in the LUXE experiment can be seen as an effective "optical dump" for electrons, where electrons emit a large flux of hard photons. In order to emit free streaming hard photons from the incoming electron beam, the time scales of the relevant processes should have the following relation:

$$\omega_{\mathrm{L}} \ll \tau_{\gamma} \lesssim t_{\mathrm{L}} \ll \tau_{ee}\,, \tag{1}$$

with ω_{L} being the laser angular frequency, τ_{γ} the typical timescale of the Compton scattering, t_{L} the laser pulse length and τ_{ee} the typical pair production time scale.

LUXE can successfully meet all these conditions. A 800 nm laser [1], corresponding to $\omega_{\mathrm{L}} \sim 0.4$ fs, will be used in the setup. The typical timescale of non-linear Compton scattering is $\mathcal{O}(10)$ fs, to be compared with a laser pulse length of $\mathcal{O}(10-200)$ fs and a pair production timescale $\mathcal{O}(10^4 - 10^6)$ fs. This establishes the LUXE experiment as a source of free hard photons from the incoming electrons, acting like a dump made of laser light, from which the term "optical dump" is born. Figure 1 shows the expected photon spectra compared to a traditional tungsten-based photon converter.

3 Experimental setup

The free photons produced in the optical dump will travel towards a final target. In the target, the photons will interact with the nuclei and might produce new a or ϕ states via the Primakoff process. New BSM states could also be produced in the primary electron-laser interactions. However, their production rates become vanishingly small for masses above few tens of keV and will not be discussed further.

The proposed LUXE-NPOD setup, shown in Figure 2, starts with a target dump of length L_D positioned about 13 m away from the electron-laser interaction point in LUXE. An empty decay volume of length L_V is reserved along the beam-line after the physical dump where the long-lived a/ϕ particles could decay to photon pairs. A calorimeter system will be installed beyond the reserved decay volume to measure the energy and direction of the two photons.

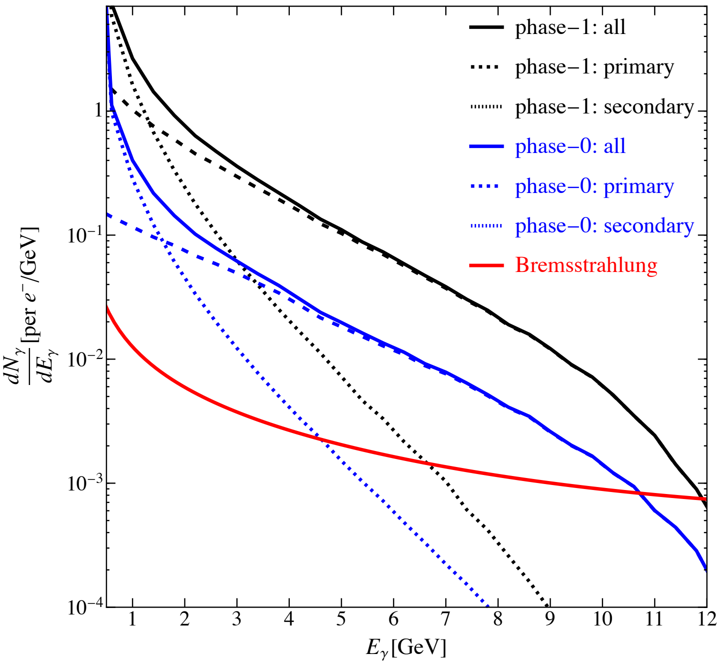

Figure 1: Emitted photon spectrum for two laser powers: 40 TW (phase-0 in blue) and 350 TW (phase-1 in black). The Bremsstrahlung spectrum for 16.5 GeV electrons and a target depth of 0.01 radiation lengths is shown in red. The primary photons are those which come from the electron-laser interaction point, and the secondary photons come from showers in the final target. Taken from Ref. [2].

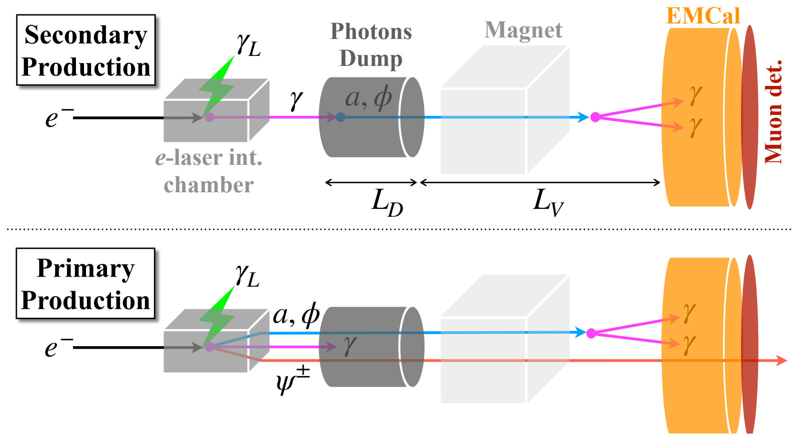

Figure 2: Schematic diagram of the LUXE-NPOD setup. The photon pairs from the decays of a/ϕ particles in the decay volume L_V are detected by a calorimeter. A muon detector is used to detect muons produced in the dump. A dipole magnet enclosing L_V is installed to deflect the background charged particles. Adapted from Ref. [2].

The total expected signal yields can be described by the following relation:

$$N \approx \mathcal{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_{a/\phi}(E_\gamma) \left(e^{-\frac{L_D}{L_{a/\phi}}} - e^{-\frac{L_V + L_D}{L_{a/\phi}}} \right) \mathcal{A}, \tag{2}$$

where $\sigma_{a/\phi}$ is the Primakoff cross-section, $\mathcal{L}_{\text{eff}}$ is the effective luminosity, E_γ is the incoming photon energy, $\mathcal{A}$ is the product of the geometric acceptance and efficiency of the detector. The symbol $L_{a/\phi}$ denotes the decay length of the a/ϕ particle.

4 Results

A conceptual design and feasibility study of the proposed LUXE-NPOD setup was performed in Ref. [2]. The rates of the main expected background processes were estimated in a simulation using the GEANT4 software and assuming a minimum photon energy detection threshold of 0.5 GeV. The main backgrounds consist of (i) charged leptons or hadrons, (ii) neutrons that are misidentified as photons and (iii) real photons produced in shower interactions close to the end of the dump.

The background component comprising charged particles can be made negligible with the addition of a magnetic field of approximately 1 T over a length of 1 m after the end of the target dump. A muon detector can be used to identify any remaining muons that could still reach the NPOD detector. The background component arising from misidentified neutrons could be reduced by exploiting time-of-flight measurements. Further background rejection can be obtained from the use of a calorimeter with pointing capabilities to suppress the contribution from pairs of photons incompatible with an origin located on the primary photon beam axis. It is expected that a detector with a time resolution of $\mathcal{O}(10-100)$ ps and a position and angular resolutions of $\mathcal{O}(100)$ μm and $\mathcal{O}(100)$ mrad, respectively, will have a negligible background contribution.

The sensitivity of LUXE-NPOD is then estimated assuming a background-free scenario, as a function of the main model parameters. Figure 3 shows the expected 95% CL limits as a function of the effective coupling and the mass of the new scalar or pseudoscalar particle, assuming 10^7 s of data-taking time. When considering operation with a 350 TW laser, the LUXE experiment will be able to search for unprobed axion-like particles or new scalars with masses from 40 MeV to 350 MeV for an effective coupling $1/\Lambda_{a/\phi} > 2\cdot 10^{-6}$ GeV^{-1}. The reach of the LUXE-NPOD is comparable to the projection of other future experiments such as NA62 (in dump mode) [10] and FASER2 in the HL-LHC run [11].

5 Conclusion

The LUXE-NPOD extension represents a new approach to search for feebly interacting spin-0 scalar or pseudoscalar particles, with the potential to probe a challenging region of parameter space. The interactions between high energy electrons and an intense laser pulse are exploited to produce free streaming GeV-scale photons. These photons can be directed towards a target dump to produce new BSM states via the Primakoff process. New particles with a lifetime long enough to traverse the target dump could decay to pairs of photons, which in turn can be detected by a calorimeter system in an effectively background free experiment. This experiment will allow to exclude new scalar or pseudoscalar states with masses between 40 MeV and 350 MeV for an effective coupling $1/\Lambda_{a/\phi} > 2\cdot 10^{-6}$ GeV^{-1}.

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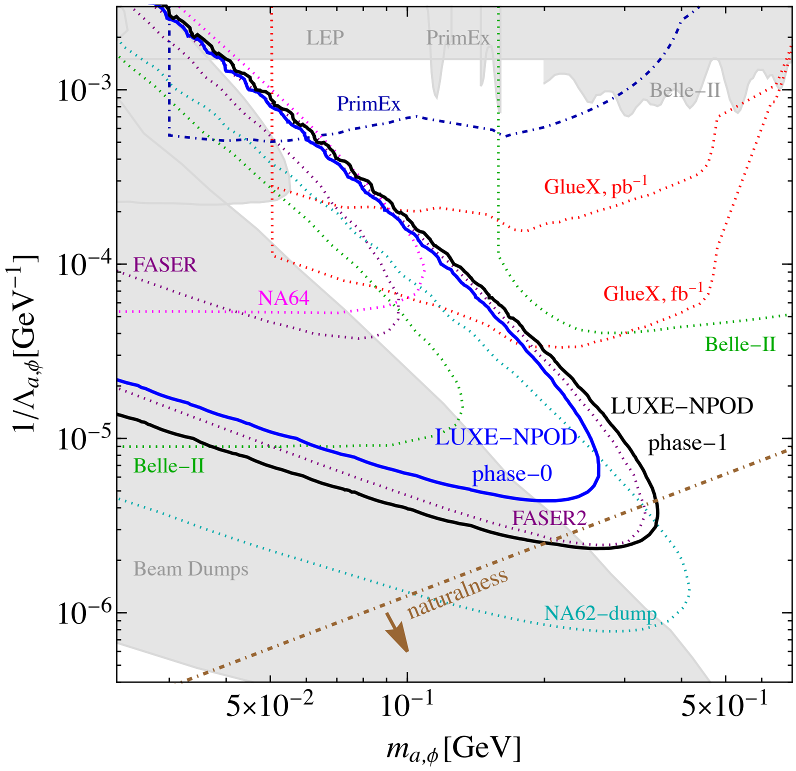

Figure 3: Projected reach of the LUXE-NPOD extension as a function of the effective coupling $1/\Lambda_{a/\phi}$ and the mass $m_{a/\phi}$. The blue (black) lines show the expected 95% CL limits for 10^7 s of data-taking time assuming a 40 TW (350 TW) laser. The current bounds are reported as shaded grey areas. Taken from Ref. [2].

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