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LUXE: A new experiment to study non-perturbative QED in e^-–laser and γ–laser collisions

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The LUXE experiment (LASER Und XFEL Experiment) is a new experiment in planning at DESY Hamburg that will use the electron beam of the European XFEL. LUXE is intended to study collisions between a high-intensity optical laser and 16.5 GeV electrons from the XFEL electron beam, as well as collisions between the optical laser and high-energy secondary photons. The physics objectives of LUXE are processes of Quantum Electrodynamics (QED) at the strong-field frontier, where the electromagnetic field of the laser is above the Schwinger limit. In this regime, QED is non-perturbative. This manifests itself in the creation of physical electron-positron pairs from the QED vacuum. LUXE intends to measure the positron production rate in an unprecedented laser intensity regime. This document presents an overview of the LUXE physics potential, the experimental setup and the expected sensitivity.

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1. Introduction

Quantum Electrodynamics (QED) is the most precisely known, and tested, theory in physics. However, in the presence of a strong background field, the perturbative calculations of QED break down. If the field energy (i.e. the work by the field over one Compton wavelength) is larger than the rest mass of a virtual particle, the vacuum becomes polarised. In strong-field QED this polarisation is expected to manifest itself in the creation of physical electron-positron pairs from virtual electron-positron vacuum fluctuations [1]. The "Schwinger limit" [2] defines the critical field strength $\mathcal{E}_{\text{crit}}$ required for this process. For an electric field, this corresponds to $\mathcal{E}_{\text{crit}} = m_e^2 c^3/e\hbar \approx 1.32 \times 10^{18}$ V/m. This regime is relevant for several of recently observed astrophysical phenomena such as the gravitational collapse of black holes [3], the propagation of cosmic rays [4], and the surface of strongly magnetised neutron stars [5–7].

The LUXE experiment [8] proposed at DESY and the European XFEL (Eu.XFEL) is intended to study strong-field QED processes in collisions of a high-intensity optical laser and the 16.5 GeV electron beam of the Eu.XFEL, as well as collisions of the high-intensity optical laser and high-energy secondary photons. The strong background field is provided by a Terawatt laser-pulse and enhanced by the Lorentz boost of the electrons, allowing LUXE to explore a previously uncharted intensity regime.

Two parameters are typically used when describing processes of non-linear QED: the *classical non-linearity parameter* ξ of the laser field and the *quantum parameter* χ_e for electron-laser collisions or χ_γ for photon-laser collisions. The ξ parameter is purely classical and describes the energy transfer from a classical field to a probe charge, while χ can be interpreted as the energy transferred from the laser pulse to a probe electron over a reduced electron Compton wavelength, in units of the electron rest energy. The region of parameter space that is accessible by the LUXE experiment is shown in Fig. 1 together with several other past and future strong-field QED experiments. The χ and ξ values accessible with LUXE depend on the power of the laser system as well as on the laser spot size. A staged approach in two phases is foreseen, in which for the latter (*phase-1*) a 350 TW laser with a spot size of 3 μm will be used. In this operation mode, LUXE is expected to probe the non-perturbative regime of $\chi > 1$ and $\xi > 1$. Compared to the previous E144 experiment [9, 10], the LUXE *phase-1* setup will achieve a factor of 20 higher χ and a factor of 60 higher ξ. LUXE will also pioneer the study of collisions between real GeV-scale photons and the laser.

2. Physics goals

The main goal of the LUXE experiment is to measure the positron rate from vacuum polarisation 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.

In electron-laser collisions, the relevant processes are *non-linear Compton scattering* and subsequent *non-linear Breit-Wheeler pair production*. In non-linear Compton scattering, the incident photon absorbs multiple laser photons, emitting a Compton photon that subsequently undergoes non-linear Breit-Wheeler pair creation by absorbing multiple laser photons and creating an electron-

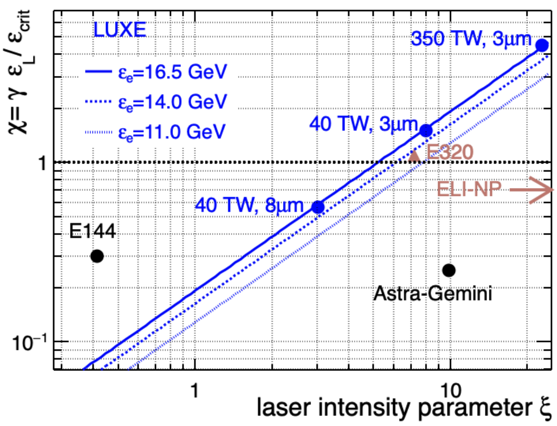

Figure 1: LUXE and other strong-field QED experiments in the strong-field QED parameter space [8].

positron pair. In photon-laser collisions, the incident high-energy Bremsstrahlung photons undergo non-linear Breit-Wheeler pair production directly [11].

Figure 2a shows the expected probability of Breit-Wheeler pair production as a function of the laser intensity parameter ξ and the quantum parameter χ. The probability to create an electron-positron pair via Breit-Wheeler pair production P is expected to have a tunneling-like dependence $P \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$, for $\xi \gg 1$. At low $\xi \ll 1$, the rate can be approximated by a power law $P \propto \xi^{2n}$. However, the perturbative expansion breaks down for values of $\xi > 1$: the rate predicted by strong-field QED departs from the power-law expectation from perturbative calculation in the parameter regime that will be reached by LUXE.

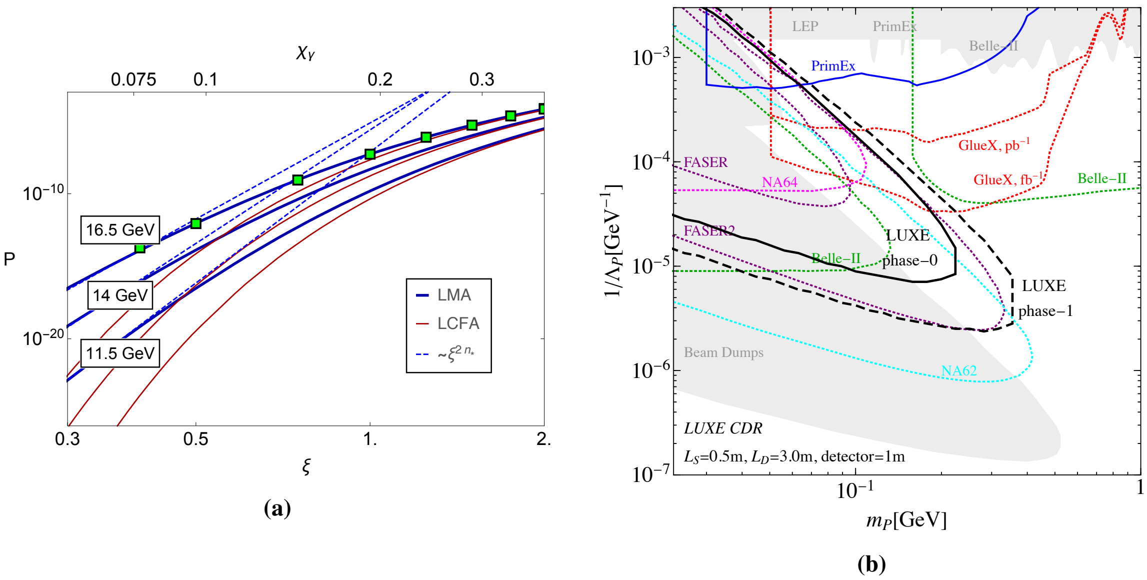

Figure 2: (a) Predicted probability of Breit-Wheeler pair production as a function of ξ and χ. (b) Expected 95% CL sensitivity to axion-like particles (ALPs) in the plane of the ALP mass (m_P) versus the coupling parameter $1/\Lambda_P$ [8].

A secondary target for the LUXE experiment is 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 in the electron-laser mode with matter. In this scenario, the high energy photons scatter on a nucleus target, 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 nucleus target. The expected sensitivity of LUXE to pseudoscalar particles in the lifetime-mass plane is comparable with that of other ongoing and future experiments [12], as shown in Fig. 2b.

3. LUXE experimental setup

The LUXE experiment will be located at the end of the Eu.XFEL electron accelerator. A dedicated beam-line has been designed to extract one electron bunch to be guided to the LUXE experimental area at a repetition rate of 10 Hz [13]. The laser will operate at a 1 Hz repetition rate, enabling in-situ background and calibration data-taking.

The laser intended for the LUXE experiment is a femtosecond-pulsed Titanium-Sapphire optical laser ($\lambda_L = 800$ nm) using the chirped-pulse-amplification technique [14]. During the first phase of LUXE, *phase-0*, the existing and well-characterised Jenaer Titan:Saphir 40 TW Laser System (JETI40) will be used. The JETI40 will then be replaced by an upgraded 350 TW laser system for *phase-1*. Among the most important characteristics of the laser system is its precise shot-to-shot stability. Several redundant diagnostics measurements are foreseen to ensure the laser stability, as well as to precisely determine the particle spectra after the interaction point.

Two dedicated setups will be used to study the electron-laser and the photon-laser interactions. Both setups employ a magnetic dipole spectrometer to measure the energy spectrum of electrons and positrons after the interaction point. Redundant detector technologies are foreseen across the experiment to enable cross-calibration and reduction of systematic uncertainties. One of the main challenges of the LUXE experiment is the large variation in particle rates in different detection areas of the setup: the positron rates vary between $10^{-3} - 10^4$/shot, while electrons and photons rates can go up to 10^9/shot. Pixel silicon trackers and high-granularity calorimeters are foreseen in the low $e^{\pm}$-rate regions, while Cherenkov detectors and scintillator screens will be used in the high $e^{\pm}$-rate regions. The photon energy and flux are characterised with a spectrometer (exploiting conversions on a target), a beam profiler and a backscattering crystal calorimeter.

A photon beam dump is foreseen at the end of the LUXE setups to investigate possible BSM scenarios. A calorimeter system with pointing capabilities will be placed behind the photon beam dump to reveal possible decay products from the BSM particles [12].

4. Conclusion

The LUXE experiment aims to investigate electron-laser and photon-laser interactions, with the potential of being the first to enter the non-perturbative Schwinger regime of Quantum electrodynamics. A rich programme of precision measurements of strong-field QED and parasitical BSM searches has been planned while the experimental setup is being prepared.

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