The Strong-Field QED Experiment LUXE at the European XFEL



Probing New Physics at the LUXE Experiment

Thomas Schörner (DESY) for the LUXE Collaboration Lepton-Photon Conference 2023, Melbourne, 19 July 2023





Strong-Field QED in a Nutshell

Aim of LUXE: extend QED knowledge into "strong-field" regime beyond "Schwinger limit" (increasing α_{EM} , begin of non-pert. effects)

Important regime – role in astrophysical phenomena, magnetars, atomic & laser physics, high-energy colliders ...

Schwinger limit characterized by "critical field" \rightarrow e⁺e⁻ pairs torn apart (real and observable)

Intensity parameter:

$$\xi = rac{m_e E_L}{\omega_L E_{ ext{crit}}}$$

 E_L : Laser field

- $E_{\rm crit}$: Schwinger critical field
- ω_L : Laser frequency

- · Relates laser field to critical field
- Measure of coupling between probe and laser field (also square root of laser intensity).
- $\xi \ge 1$: non-perturbative regime
- Only chance (and LUXE concept) to reach E_{crit}: high-intensity lasers → 10¹⁴ V/m
 Additional 10⁴ V/m through collision with high-energy electrons or photons (Lorentz factor)





Strong-Field QED in a Nutshell

Aim of LUXE: extend QED knowledge into "strong-field" regime beyond "Schwinger limit" (increasing α_{EM} , begin of non-pert. effects)

Important regime – role in astrophysical phenomena, magnetars, atomic & laser physics, high-energy colliders ...

Schwinger limit characterized by "critical field" \rightarrow e⁺e⁻ pairs torn apart (real and observable)

Non-linear Compton scattering (measure Compton e⁻ / γ spectrum)





DESY. LUXE BSM Searches - LP23 Melbourne | 19 July 2023 | TS

The LUXE Experiment at the European XFEL



The LUXE Experiment at the European XFEL



Two different modes: electron-laser and photon-laser



Here relevant: Electron-laser mode



Electron-laser mode: GeV Compton photons from e⁻-laser IP impinging on photon dump



Electron-laser mode: Focus on axion-like particle (pseudo-scalar "a" or scalar "Φ") search



ALPs appear in any theory with a spontaneously broken global symmetry; they solve the strong CP problem and can explain anomalous magnetic moment of the muon, and they serve as portal to the dark sector

ALPS Scenario

Is it useful? Axion landscape – excluded regions (LSW, cosmology – SN1987a, colliders, beam dump ...)



Backgrounds

GEANT4 simulation - currently being updated with higher statistics!



Determination computationally challenging: so far simulated 10¹⁰ photons, corresponding to only 2 BX.

- Photon background too soft to bother, neutron statistics beyond 500 MeV extremely low (and timing cuts)
- Charged particles bent away by 1 T magnet; muon veto detectors
- Some low-energy particles (backscattering, escaping through dump sides)
- Di-photons from ALPS selected using topology cuts etc. (shower shape against neutrons, vertex reconstruction, ...)

DESY. LUXE BSM Searches - LP23 Melbourne | 19 July 2023 | TS

Conclusion: < 1 background event / year!
Much more for e⁻ directly on target (*500)!

Detector design and optimisation ongoing!

LUXE BSM Detector

Final layout to be defined

Detector requirements: Good energy & vertex resolution

- ALPs invariant mass reconstruction
- Background suppression (photon / neutron discrimination using shower shapes and time of arrival)
- Timing resolution < 0.1 ns

Phase-0 (40 TW laser): reuse existing calorimeter, e.g. spaghetti calorimeter (SpaCal) from H1:

- Lead / fiber (2.3:1) with 4x4x25 cm³ cells
- Energy resolution 7.5%/ \sqrt{E} +2%
- Time resolution < 1ns

Phase-1 (350 TW laser): Design new system (ongoing)

- Preshower and vetoes
- Tracking calorimeter, e.g. high granularity calorimeter (CALICE Si-W ECAL etc.)



Physics Reach

Two NPOD optimisation strategies studied using Geant4



If no signal observed ...

Exclusion limits ...

... 95% CL for background-free search after one year of data taking – projections for phase-0 and phase-1 compared to existing limits and other projections



Exclusion bounds for pseudo-scalar & scalar ALPS:

- Masses between 40 and 350 MeV
- 1/Λ between 10⁻⁶ and 10⁻³ GeV⁻¹

LUXE phase-1 can reach the naturalness bound for scalars! Also shown: optimised LUXE phase-1.

Potential results comparable to NA62 and FASER2 (>2029) reach

ALPs Production Photon Spectra

Also "primary" axion production directly in electron-laser interaction – but much lower rates!



Outlook – NPOD Experiments Elsewhere ...

... e.g. at the International Linear Collider ILC?



Summary

LUXE – exciting new experiment to study QED in uncharted territory

LUXE: started in 2017

- ~100 participants from ~20 institutes;
- Hosted at DESY using EU-XFEL beam

Searches for BSM signatures possible

thanks to large photon fluxes: LUXE NPOD acts as optical dump allowing the production of light ALPs with large couplings. Concept applicable to other experiments

LUXE phase-1 competitive with FASER2
 or NA62-dump

A number of challenges for the detectors

- Final BSM detector system to be defined
- TDR out soon!
- Start of data taking in 2026? (relies on XFEL shutdown period)

Open to new ideas and collaborators!



Thank you

Thanks to G. Grzelak, F. Meloni, R. Quishpel. Schulthess, M. Wing

CDR: H. Abramowicz et al., *Eur. Phys. J. ST* **230** (2021) 2445, arXiv:2102.02032.

https://luxe.desy.de

Contact

DESY. DeutschesThomas SchörnerElektronen-SynchrotronDESY FHE-Mail:thomas.schoerner@desy.dewww.desy.dePhone: +49 40 8998 3429

Backup

The LUXE Experiment

Two data-taking modes: electron-laser collisions (\rightarrow high-rate Compton) AND photon-laser collisions via Bremsstrahlung (low-rate Breit-Wheeler pair production, unique to LUXE)



Need varied detector technologies to cater for varying fluxes of signal and background e⁺, e⁻, γ
 Master large range of rates between ~10⁻⁴ (e⁺) and 10⁹ (e⁻ and photons) per bunch crossing

Data Handling and Systematic Uncertainties

Off-the-shelf DAQ, existing / extendable software; systematics studied \rightarrow can be handled

Data handling – straight forward:

- Low data-taking frequency < 10 Hz, 1 Hz collision data, up to 9 Hz background
- Maximum rate per sub-detector O(10 MB/s) → 1 PC per sub-detector

All data are kept – no physics trigger

Should be able to use **known / off-theshelf solutions** for control, synchronisation; use / adapt existing software for DAQ

Systematic uncertainties – particle detection:

- At low multiplicities (pair production):
 - Efficiencies for individual particles < 2-3% (crosschecks and in-situ calibration)
 - Linearity of response <2% (current tests)
 - Background: statistical uncertainty based on 9 Hz data, significant at low ξ
- High multiplicities (Compton):
 - Linearity of response <2% for Cherenkov and scintillator (test beam & experience)
 - Calibration <2% (test beam)
 - Background (for scintillators): constrain in situ
- Energy scales (all):
 - Calibration / knowledge of magnetic field ~1%
 - Alignment of <50 µm results in <0.5% uncertainty