Breaking into the Strong-Field QED Regime at LUXE

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Strong-Field Quantum Electro-Dynamics

- QED relies on **perturbative series expansions** of infinite terms
- As the energy scale of QED interactions increases, **the effective coupling constant runs**
- Higher order QED expansion terms include the coupling at higher and higher powers, so after it runs to ≥ 1 **the sum is divergent and the theory fails**
- Corresponds to Schwinger Critical Field

$$E_{Schwinger} \equiv m_e^2 c^3/e\hbar = 1.32 \times 10^{18}\ Vm^{-1}$$

Quantum Electrodynamics can be described as the most quantitatively accurate physical theory in history – yet we plan to push it to breaking point.

- Applicable to LASER beams, the unitless intensity parameter ξ :

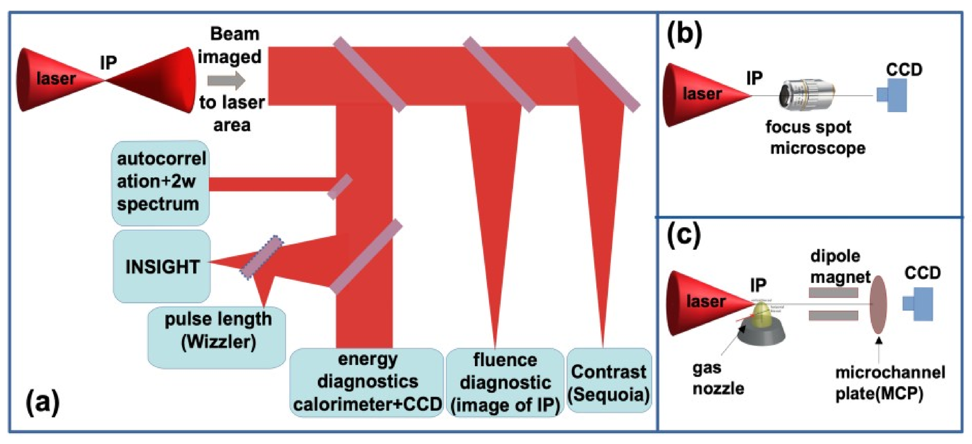
$$\xi = \frac{eE_L}{m_e \omega_L c} = \frac{m_e E_L c^2}{\omega_L E_{Schw.}\hbar}$$

- E-field experienced by relativistic particles is **Lorentz-Contracted**
- Quantum non-linearity parameter χ where **χ = 1 denotes transition into a tunneling regime**

$$\chi = \frac{E_p}{E_{Schw.}} = \frac{p}{m_e}\frac{E_L}{E_{Schw.}}(1 + \beta cos(\theta)) = 2\gamma_p \frac{E_L}{E_{Schw.}}$$

LASER

- LUXE is envisioned with **two phases of running**: a phase-0 with a 40 TW 'JETI40' LASER, and a phase-1 up to 350 TW
- The 800 nm LASER light is **focussed with optical mirrors** to a focus within the beamline
- Diagnostic tools are used in-situ to **measure independently the intensity** achieved shot-to-shot by the LASER(s)
- LASER pulses are expected to be produced at **1Hz**, but electron bunches will be directed to the apparatus at 10Hz for background measurement

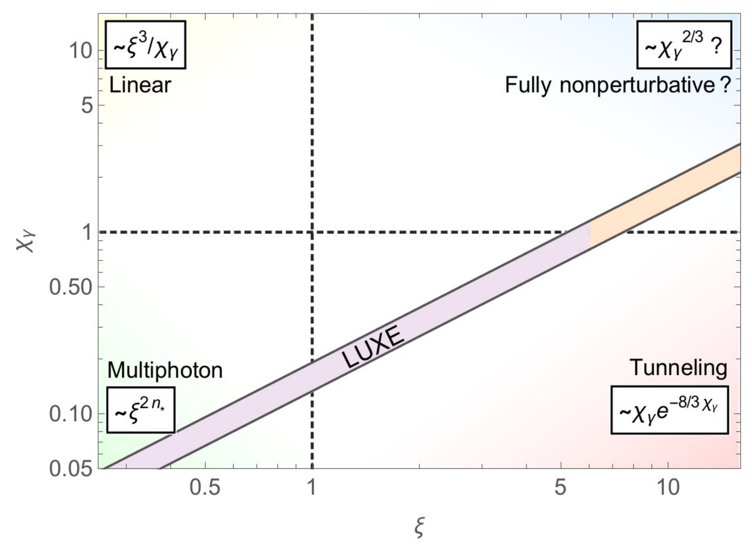


LUXE / XFEL Technical Aspects

- At DESY in Hamburg, we have access to a **high-quality, high-energy electron beam** in the EuXFEL – up to 17.5 GeV, with bunch population of around 10^9
- Strongest E-fields in the lab come from extremely **powerful & short 'chirped' LASER pulses**
- LUXE will **collide LASER pulses in two modes with both high-energy electron bunches (e-laser) and photons (γ-laser)** produced via the electrons radiating via bremsstrahlung or Inverse Compton Scattering

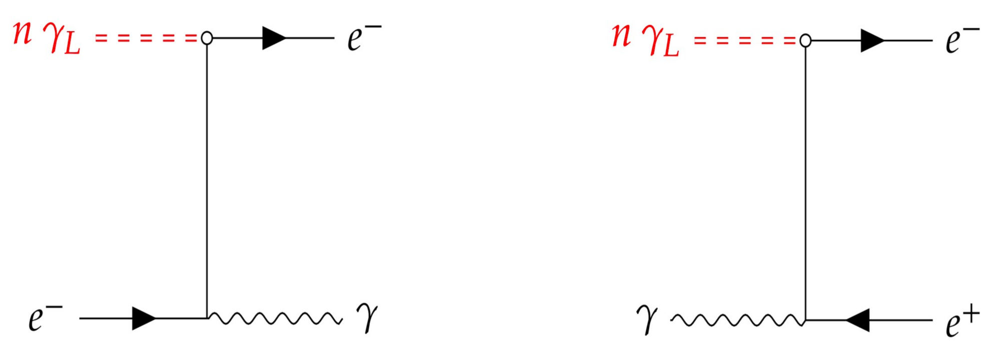
With the combination of the focussed high-power LASER pulse and high-energy particles, LUXE is expected to reach and exceed the Critical Field and so achieve χ > 1 in a clean environment for the first time.

- Photon beam is produced by intercepting e^- bunches with thin Tungsten target, expected to produce order 10^8 **photons with falling energy distribution** typical of bremsstrahlung interaction
- Inverse Compton Scattering provides a relatively **monoenergetic source photons of specific polarisation**, requiring splitting of the main LASER beam
- The experiment remains under planning / development, and we anticipate to install and start running in **summer 2024** while the XFEL has a shutdown



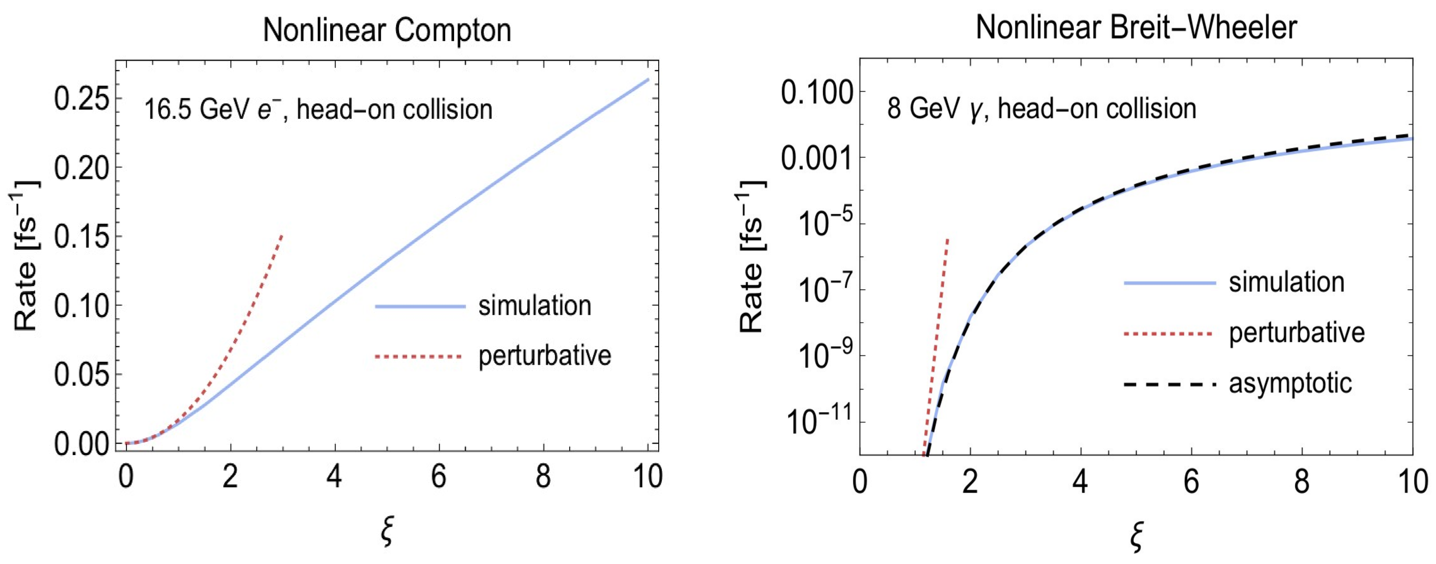
Nominal Laser Energy Focus Size	40 TW 8 μm	40 TW 3 μm	350 TW 3 μm
LASER pulse energy	1.2 J	1.2 J	10 J
LASER pulse duration	30 fs	30 fs	30 fs
Peak Intensity (Power / Area)	0.19 10^{20} Wcm^{-2}	1.33 10^{20} Wcm^{-2}	12.0 10^{20} Wcm^{-2}
Peak Intensity (ξ)	3.0	7.9	23.6
Quantum Parameter (χ) (E = 16.5 GeV)	0.56	1.50	4.45

Interactions

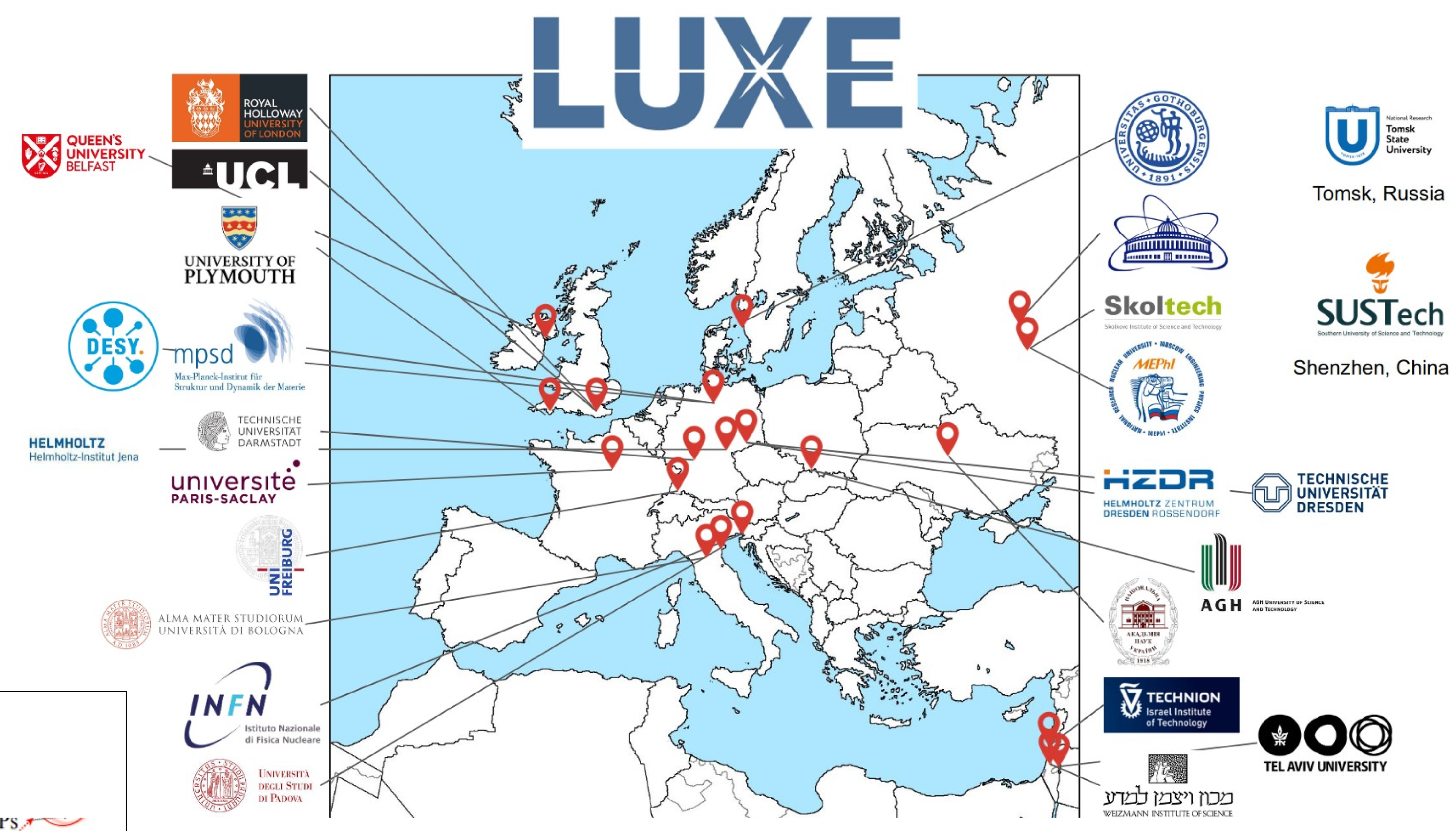


Electrons in a Strong EM Field can undergo **Non-Linear Compton Scattering** (left) and photons can produce an e− e+ pair in a spontaneous boiling of the vacuum (right) or **Non-Linear Breit-Wheeler Process**

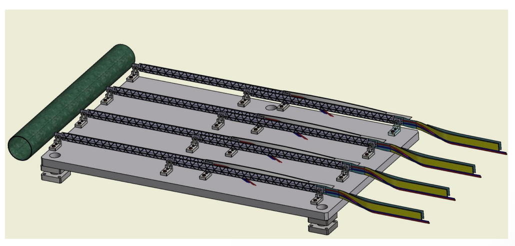
- After the interaction, each of the three outgoing particle types are separated by magnetic fields
- In the e-laser mode, beam electrons undergo Non-Linear Compton-scattering, a frequent interaction. With expected bunch population of 1.5 × 10⁹, detecting these electrons and the radiated photons means dealing with prohibitively high fluxes for many successive collisions at 1 Hz
- Conversely, positrons (Breit-Wheeler process) in both modes of running are much more rare and difficult to resolve above background

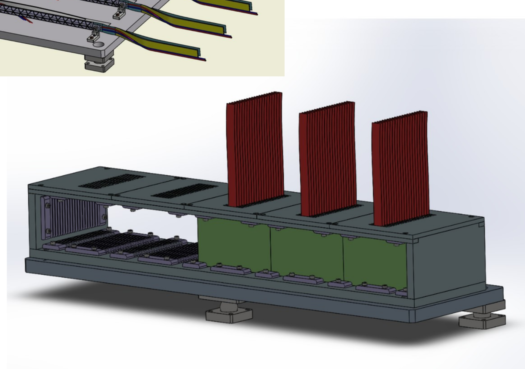


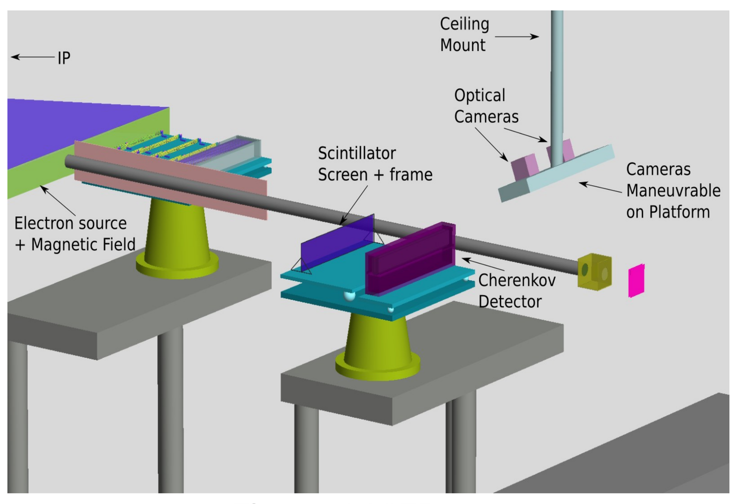
Simple Perturbative, asymptotic and simulation-based analysis of the **Nonlinear Compton Scattering rate (left)** changing **Non-Linear Breit-Wheeler interaction rate (right)** for sample 8 GeV photon in a LASER field of intensity parameter ξ. The steep gradient at lower ξ highlights the challenge in measuring the transition between the perturbative and non-perturbative regime.



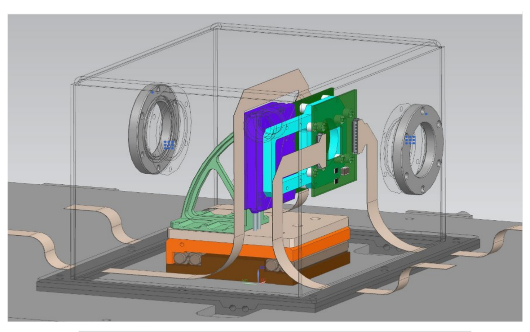
Detection

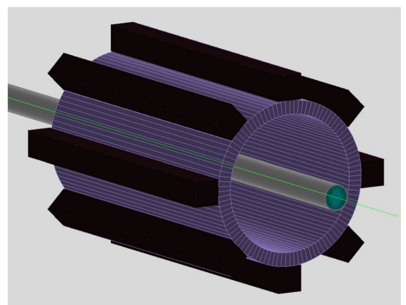






Electron-LASER setup.





- The Dipoles used to separate outgoing particles direct them to their respective detectors, and for the charged particles act as **spectrometers**

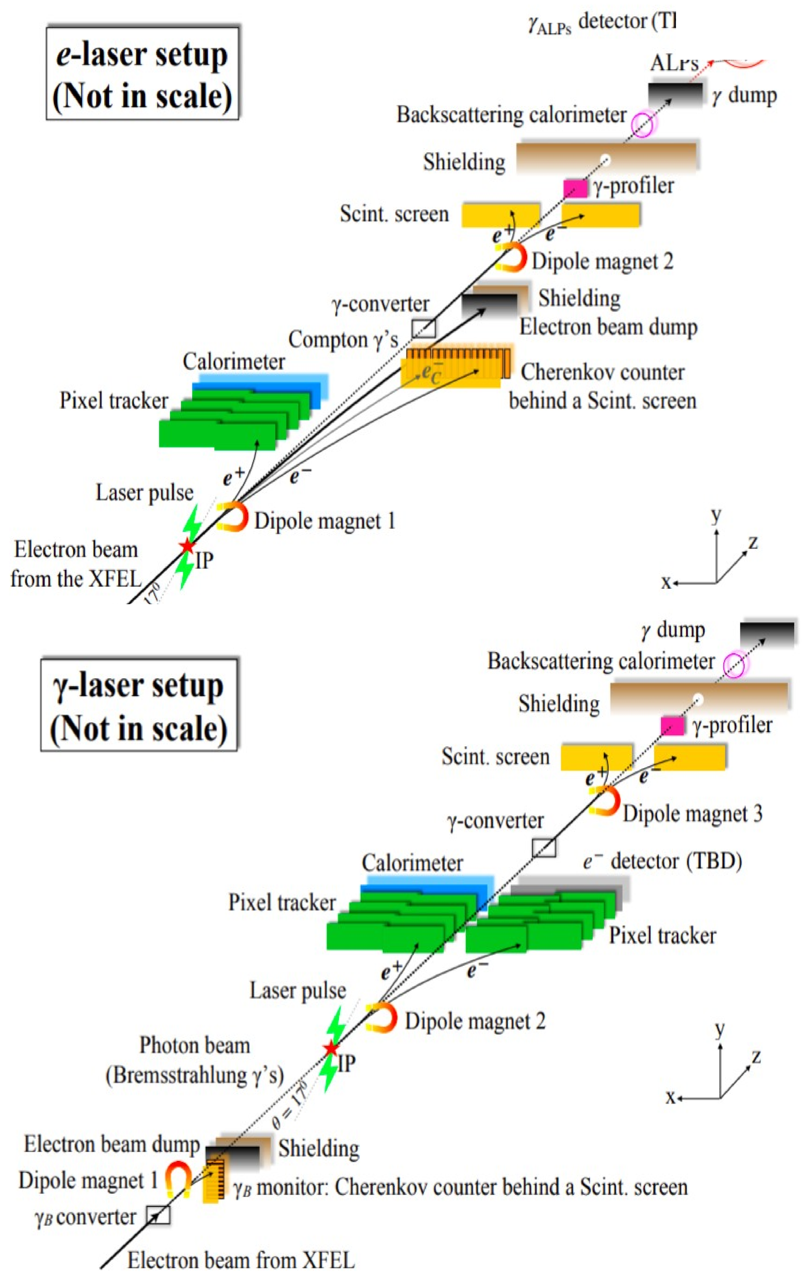
Positrons

- The low rates expected for the Breit-Wheeler process motivates the use of silicon pixel trackers and calorimeter(s) to **resolve individual positrons above considerable background**
- **Cutting-edge tracking, calorimetry reconstruction and neural networks** are used to retain high sensitivity to signal

The three particles to be detected, with hugely varying fluxes, motivate the use of a variety of detector technologies.

Electrons

- Non-linear Compton-scattered electrons are produced in high numbers and are **counted and reconstructed with respect to energy**, rather than analysed indivdually
- A **screen of scintillating material** is used in this region in conjunction with a **segmented Cherenkov detector**
- The high flux means high light levels within the scintillator, allowing **remote optical cameras** to detect signal
- The flux also means a **Cherenkov medium with low refractive index** can be used, which otherwise provides few signal photons but excludes low energy (background) charged particles E < 20 MeV
- The Scintillator / Cherenkov setup is replicated to detect electrons which radiate photons to be used in the gamma-laser mode

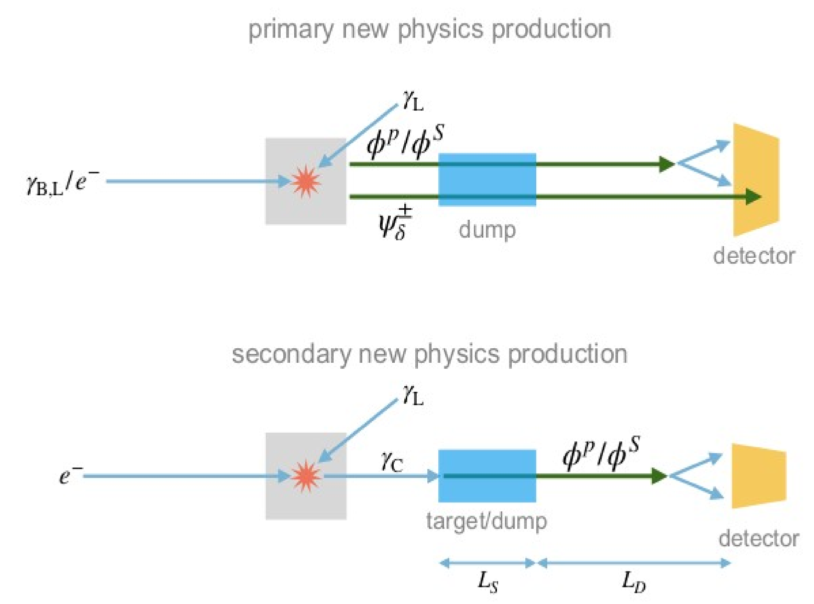


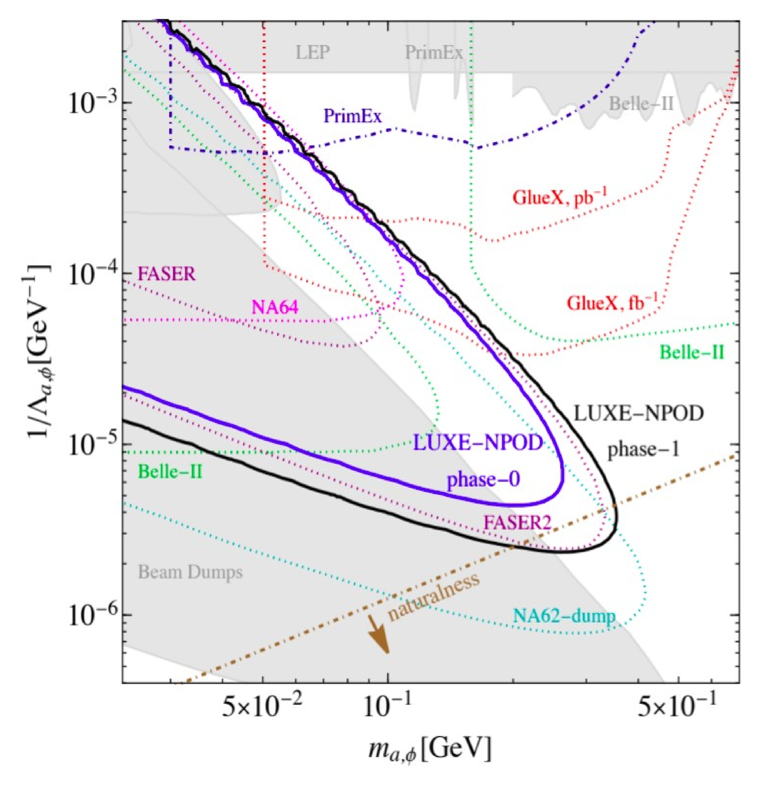
Photons

- Photons propagate to the 3-part gamma monitor to reconstruct the high-energy photon spectrum
- The first detector is a **Sapphire Beam profiler**, which directly measures the photon beam spread in both setups
- Downstream is the **Gamma Spectrometer,** which incorporates a thin metal target to convert via pair production, the photon to an electron positron pair. The pair is separated and deflected once more onto scintillating screens and imaged remotely
- Reconstructing the photon spectrum with this detector involves **deconvolution** using the energy-dependent cross-section for pair-production
- In front of a final photon beam dump is the **Backscattering Calorimeter**, comprised of 8 Lead-Glass blocks, which can be used to recover total photon flux using the energy deposited by photon backscatters

Opportunities Beyond the Standard Model

By virtue of the fact LUXE dumps high-flux, high-energy photons in every running mode, searches can be made for particles outside the Standard Model such as ALPs.





Further Reading: Conceptual Design Report for the LUXE Experiment, H. Abramowicz et al., *Eur. Phys. J. Spec. Top.* (2021) https://arxiv.org/abs/2102.02032v2;
LUXE-NPOD: new physics searches with an optical dump at LUXE, Z. Bai, https://arxiv.org/abs/2107.13554;