LUXE: a high precision experiment to study non-perturbative QED in electron-laser and photon-laser collisions

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On behalf of the LUXE Collaboration,

EPS-HEP, July 7th-11th 2025, Marseille

Quantum electrodynamics

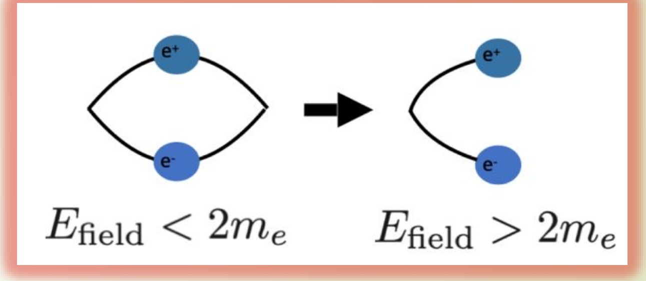
- In quantum electrodynamcs, we use a perturbation theory:
  - Start with a situation we can solve exactly (free particles not interacting)
  - Add interactions (electron emitting a photon) as a small correction
  - Expand the full solution in powers of the interaction strength (α ~1/137)
- Reach a very precise measured and calculated (includes terms in α^5) theory, with a precision better than 10^{-9}

QED in presence of strong fields

- QED expected that vacuum becomes unstable in presence of strong fields: spontaneous creation of e+e- pairs
- Few important dates:
  - 1930s: first discussion of EM in strong fields and introduction of critical fields
  - 1951: first non-perturbative calculation by Julian Schwinger

$$\epsilon_{crit} = \frac{mc^2}{e\lambda_c} = \frac{m^2c^3}{eh} = 1.3 \times 10^{16}\ V/cm$$

  - 1990s: E144 experiment at SLAC, first to approach ϵ_{crit}
- Relevant in different fields:
  - Astrophysics: surface of neutron stars (magnetars)
  - Condensed matter and atomic physics (nuclei with $Z > 137$)
  - Accelerator physics: high energy e^+e^- colliders



$$E_{field} = \frac{\varepsilon}{m_e}$$

Why explore strong field QED ?

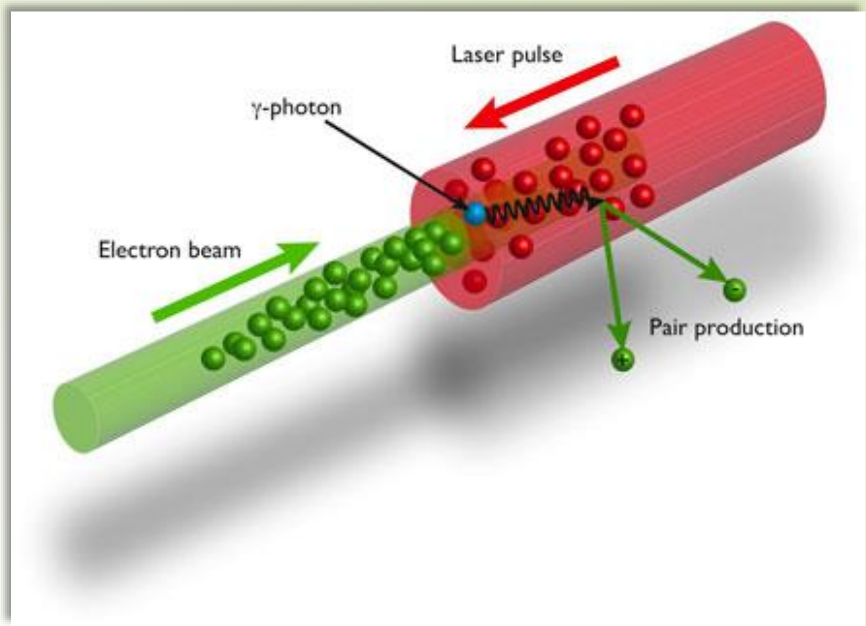
- Testing theoretical predictions in novel regime
- Measure transition from perturbative to non-perturbative regime

LUXE

LASER Und XFEL Experiment

LUXE

- Propose to provide this field using the TeraWatt laser-pulse and the European XFEL electron beam in the only long term dedicated experiment : **LUXE .**
- two important parameters:



$$\xi = \frac{e\,\epsilon_L}{m_e\,\omega_L\,c}$$

$$\chi = \frac{E_{\mathrm{beam}}(1-\cos\alpha)}{m_e\,c^2}\frac{\epsilon_L}{\epsilon_{\mathrm{crit}}} \sim \gamma_e\frac{\epsilon_L}{\epsilon_{\mathrm{crit}}}$$

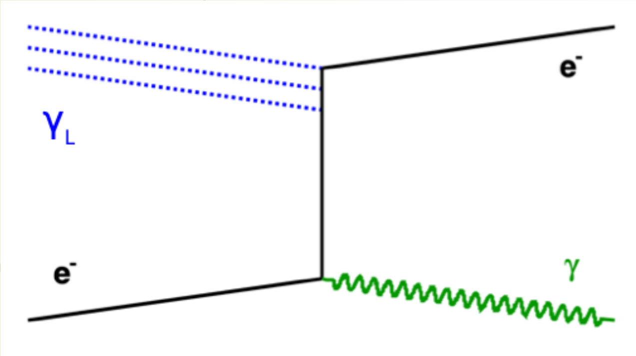
- ξ (laser intensity) is the classical non-linear field. If ξ <<1, QED is perturbative and above 1, the perturbative expansion breaks down and QED becomes non-perturbative
- χ is the quantum parameter (ratio of the effective field strength in the electron rest frame and the critical field)

LOI: 2019
CDR: 2021, published Eur. Phys. J. Spec. Top. 230, 2445–2560
TDR: 2023, published Eur. Phys. J. Spec. Top. 233, 1709-1974

Main processes

Nonlinear Compton scattering

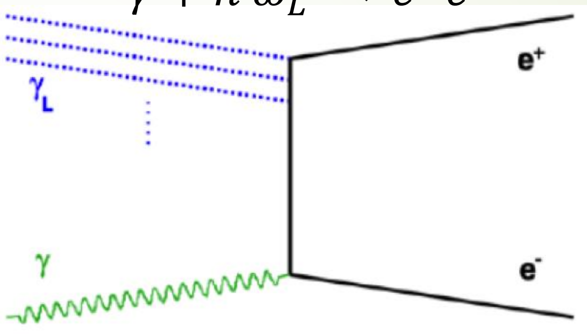
$$e^- + n\omega_L \longrightarrow e^- + \gamma$$



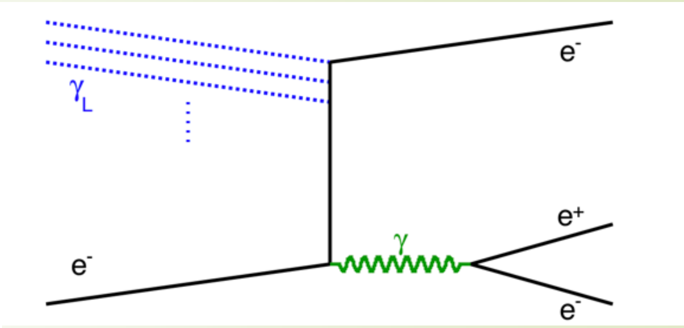
Pair production

Nonlinear Breit-Wheeler

$$\gamma + n\,\omega_L \longrightarrow e^+e^-$$

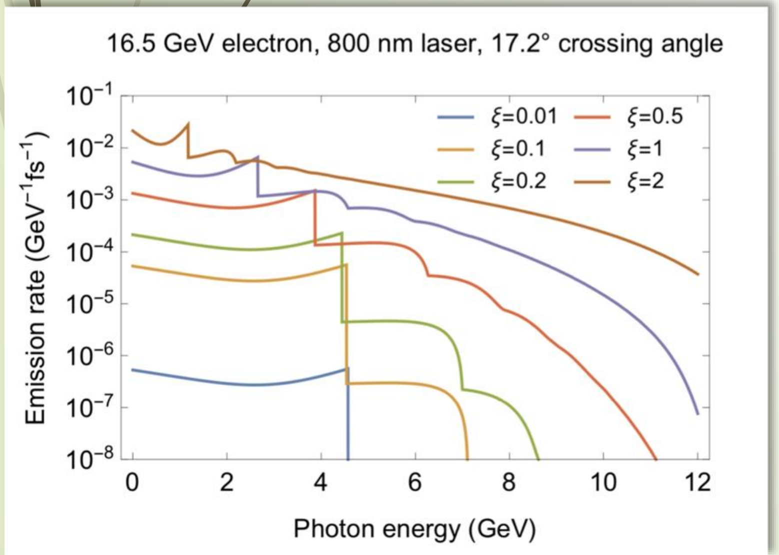


trident



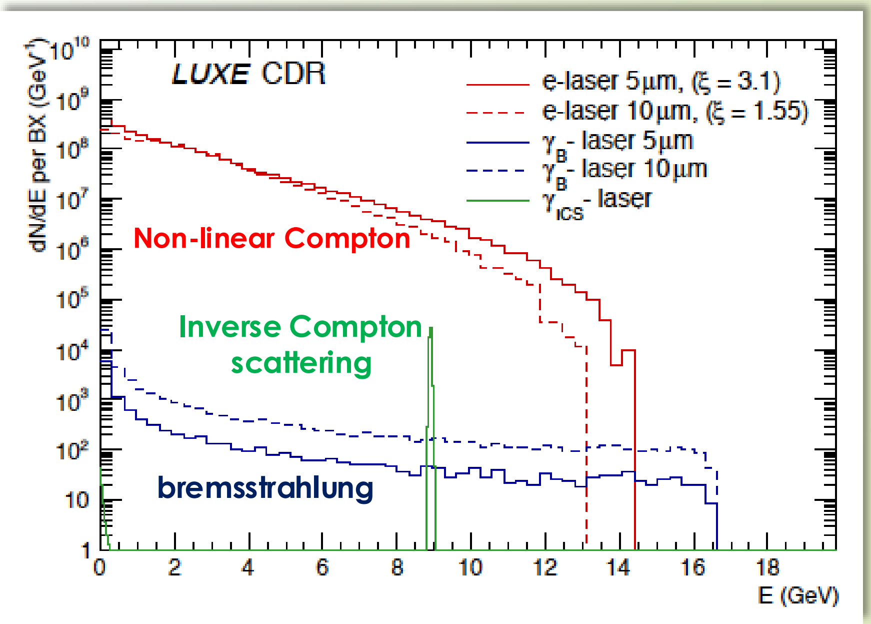
Observables :

- Compton edges
- Intensity of nγ scattering

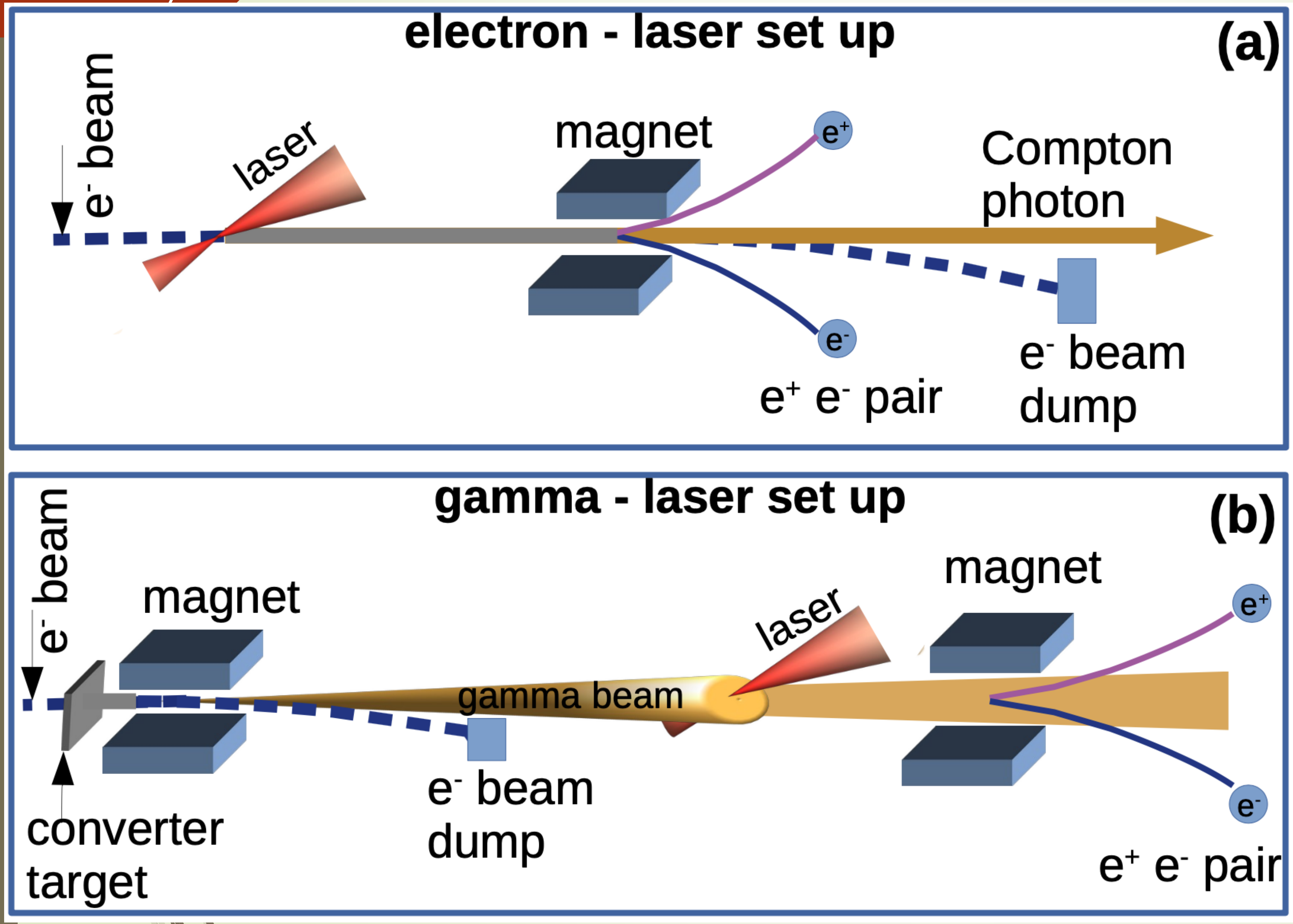


Three methods to generate incident photon:

1. **Compton photons** inside same laser pulse => largest rate
2. **Bremsstrahlung photons** produced upstream => highest E
3. **Inverse Compton scattering** upstream (E=9 GeV)



LUXE production : two set ups and two phases

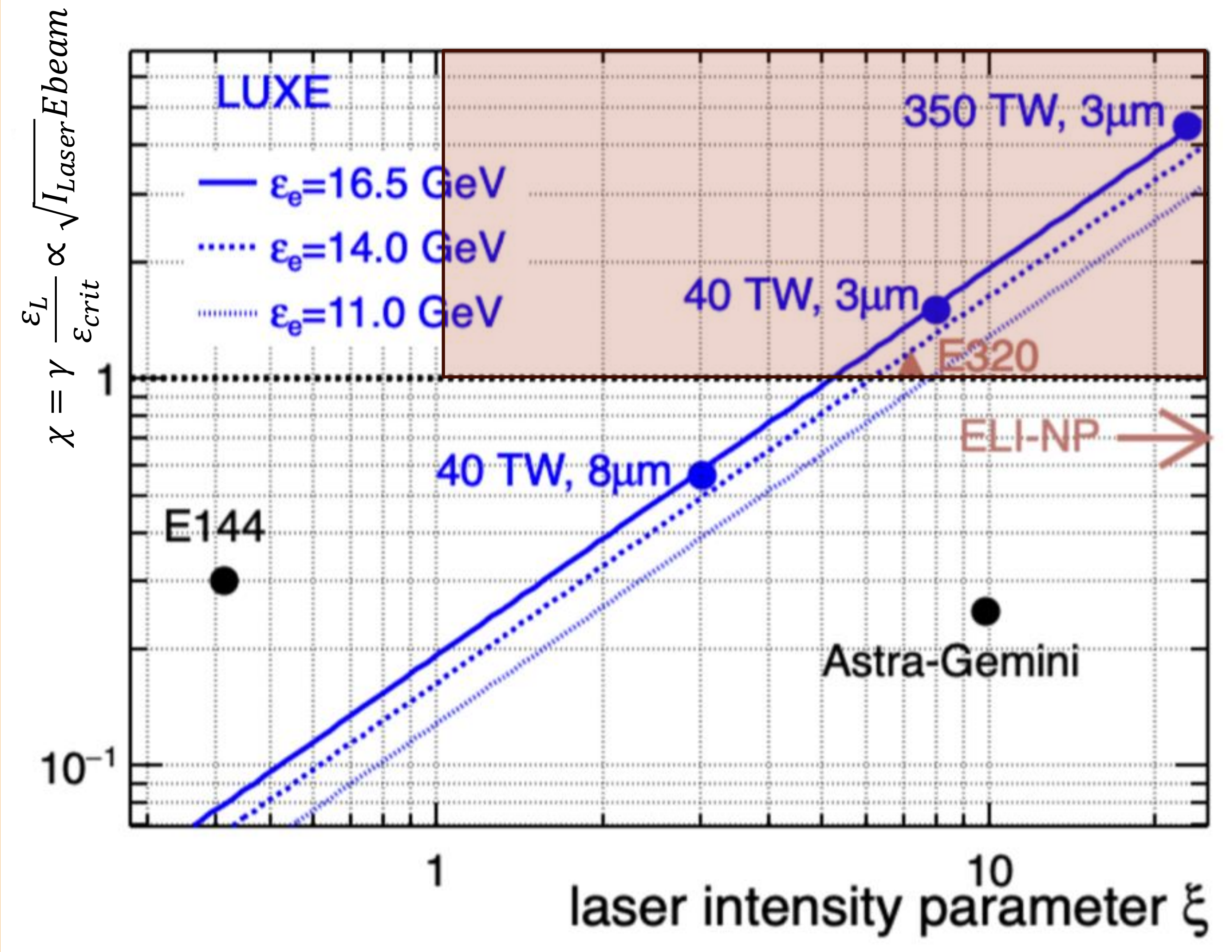


Electron beam:
- 16.5 GeV (possibility 10 and 14 GeV)
- 10 Hz
- LUXE uses one out of 7200 bunches per train
- 10^9 e-/bunch

Laser:
- Wavelength is 800nm
- Rate: 1 Hz
- Focal spot size : 3 or 8 μm

Two phases :
- Phase 0: laser power 40 TW (ξ=7.9)
- Phase 1: laser power 350TW (ξ=23.6)

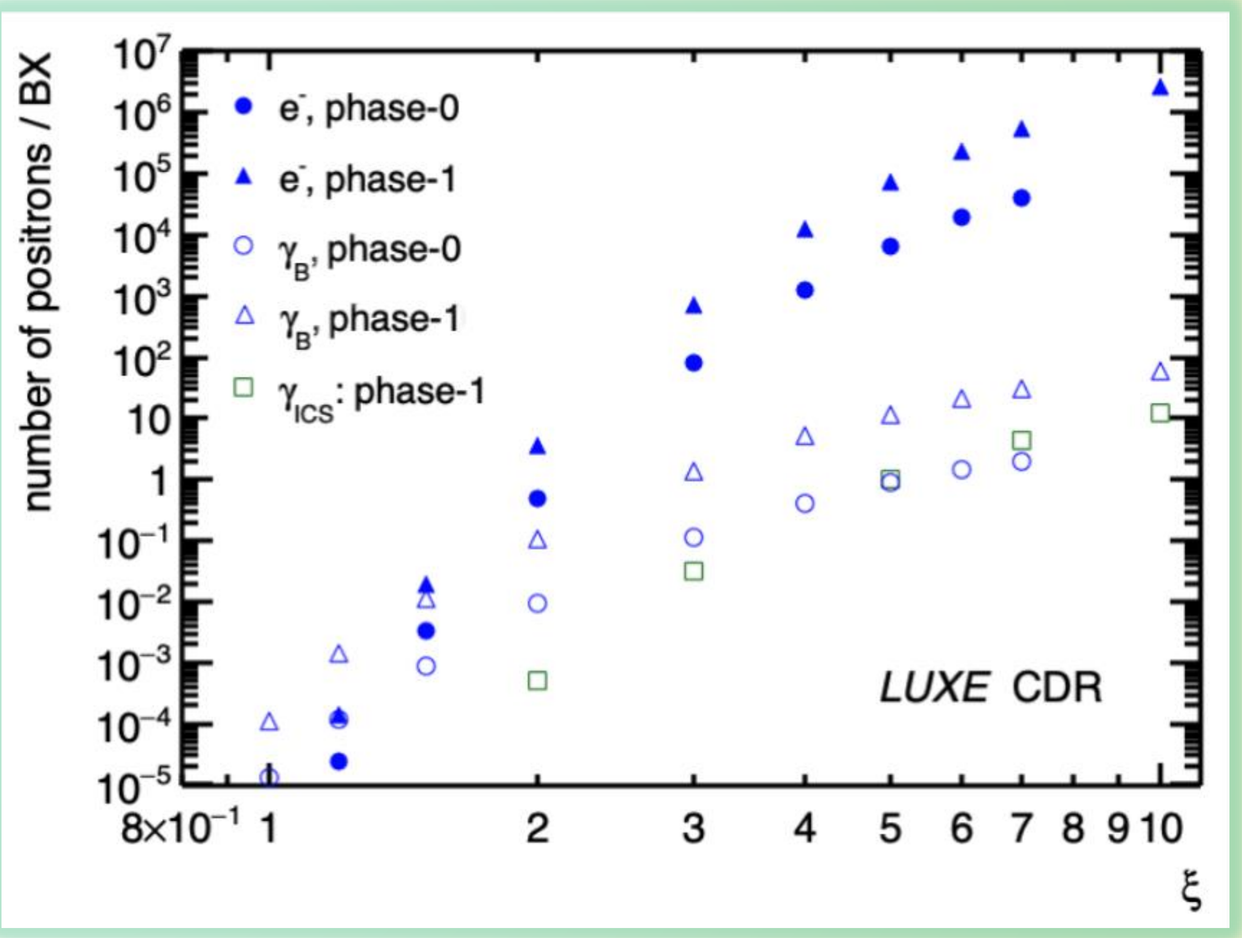
Parameter space



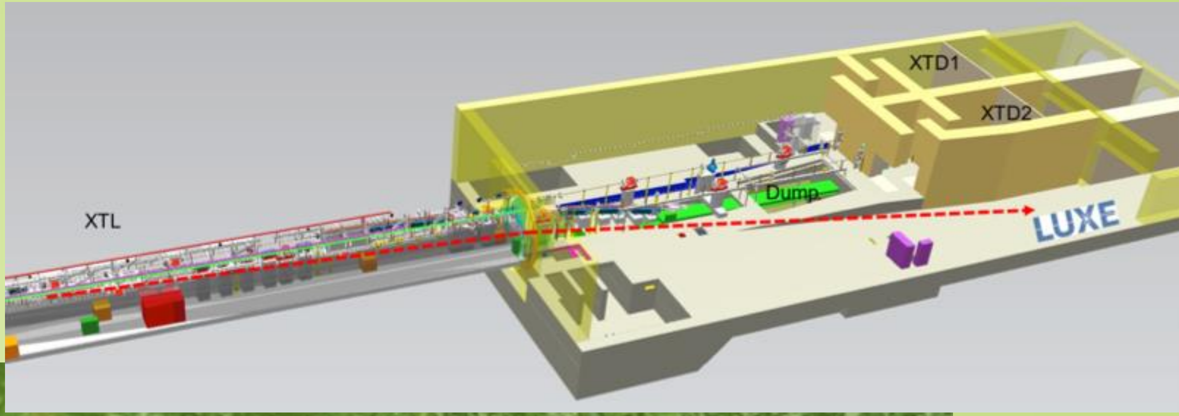
$$\xi = \frac{e\,\varepsilon_L}{m_e \omega_L c} \propto I_{Laser}$$

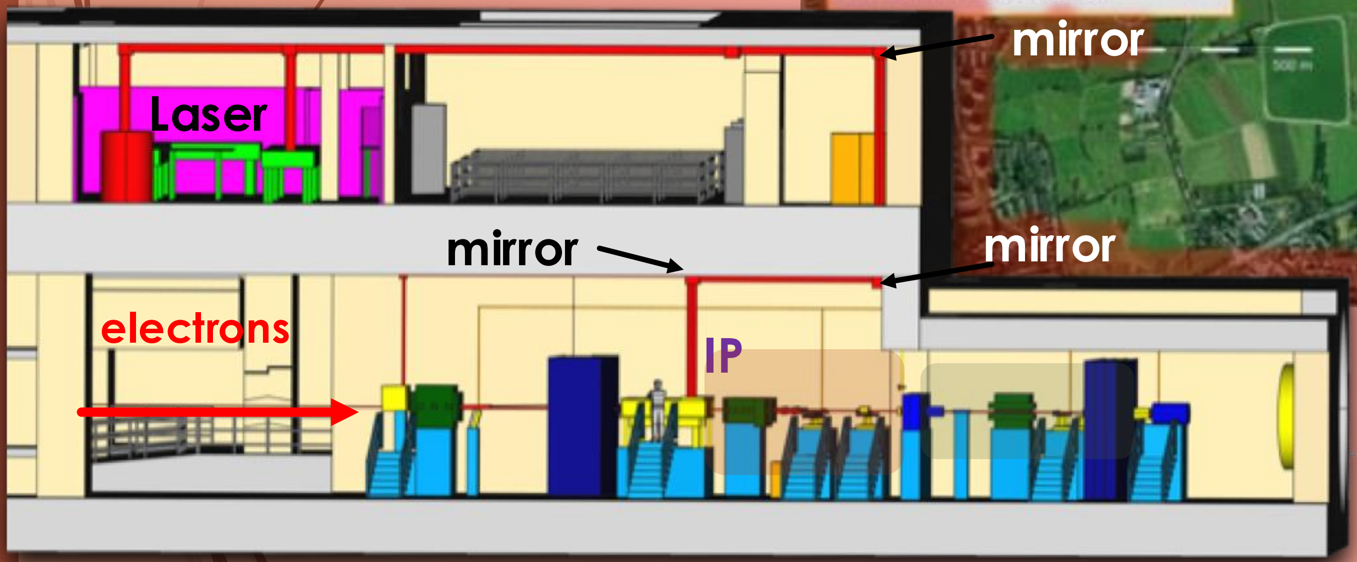
Rates per bunch crossing

- Electron-laser
  - Signal pairs created: **10^{-4} to 10^{6}**
  - Background particles flux:
    - e^- side : up to **10^9** particles
    - e^+ side: up to **10^3** particles
- Gamma-laser:
  - Signal pairs created: **10^{-5} to 10**
  - Background particles flux:
    - e^- side: up to **10** particles
    - e^+ side: up to **10** particles
    - Bremsstrahlung target: **10^6** particles
- In both setup, **10^9** photons to detect

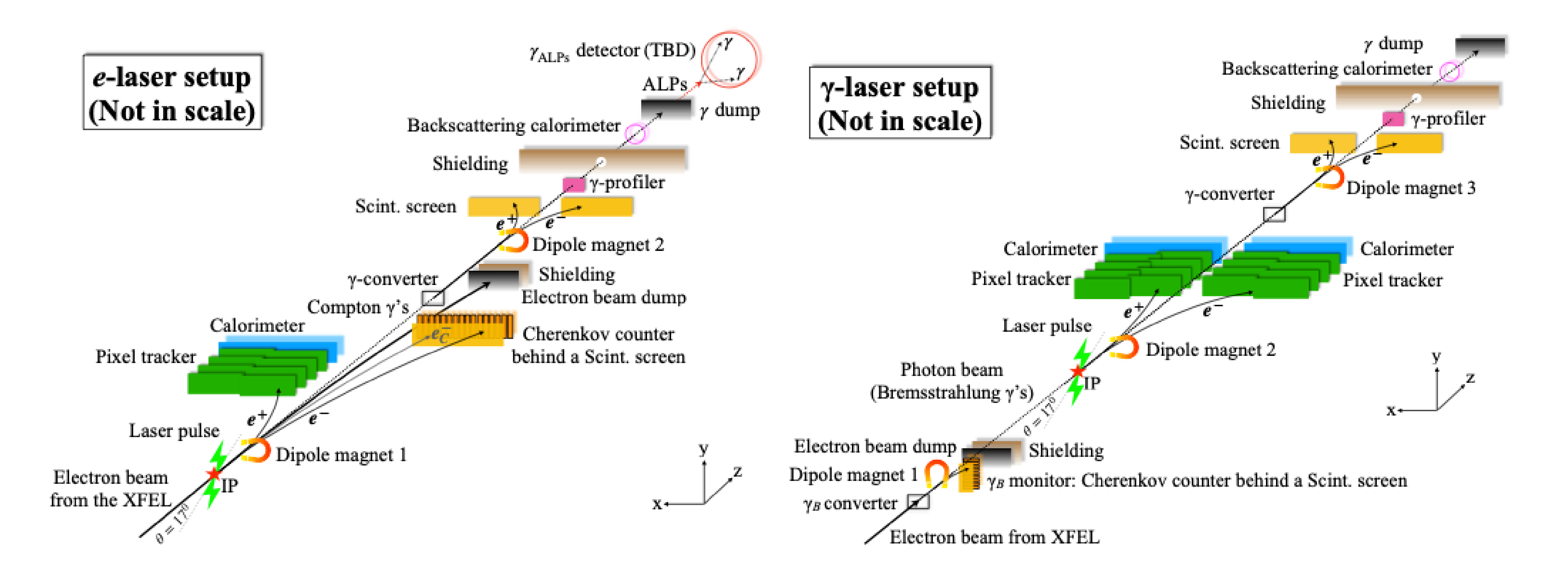


LUXE at the Eu.XFEL





LUXE detection system

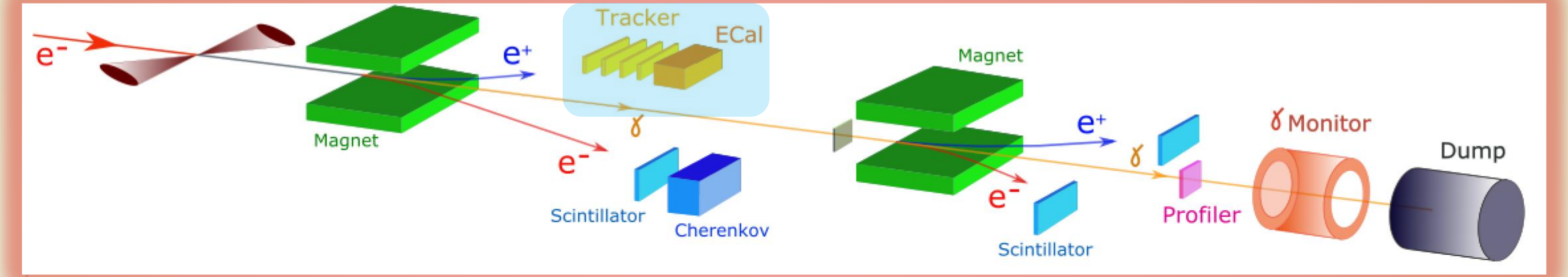


Detectors used for background rejection

e- side: Cherenkov and scintillating screen
e+ side: calorimeter and tracker

e- side: calorimeter and tracker
e+ side: Cherenkov and scintillating screen

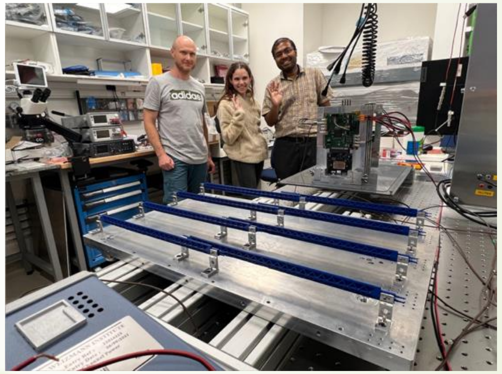
Positron detection

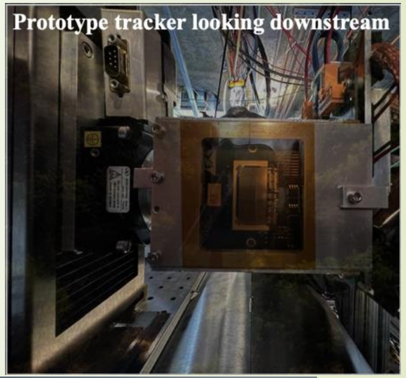


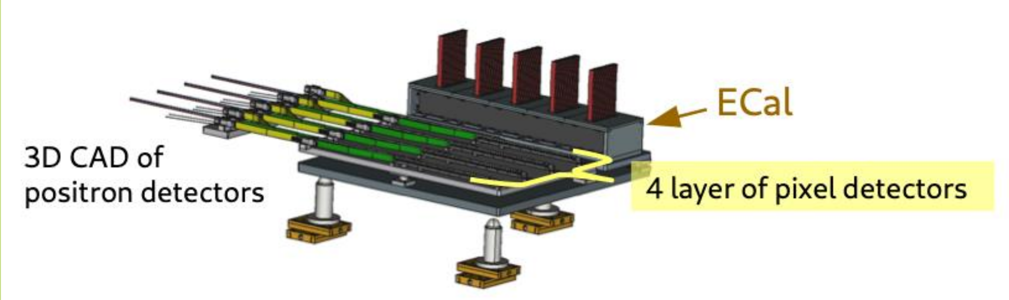
Expected event rates per laser shot
- electron-laser mode: 10^{-2}-10^{4} e^+e^- pairs
- gamma-laser mode: 10^{-2}-1 e^+e^- pairs

Spectrometer:
- Magnet: 1T-1.5 T
- **4 layers if silicon pixel detectors**
- **Compact electromagnetic calorimeter**

- ALPIDE silicon pixel sensors (ALICE ITS)
- Spatial resolution ~5 μm
- Good performance under radiation

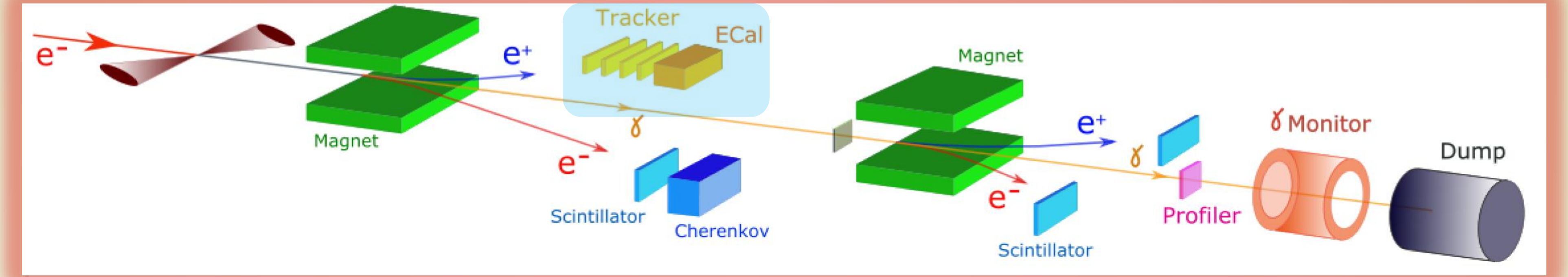






E320 Tracker by WIS @FACET-II
- Based on ALPIDE technology
- Physics, plans, & system: arXiv:2506.04992
- Installed: Aug 2024
- Preliminary runs: Nov 2024 & Feb 2025
- *e*+laser collisions data: May 2025 and on…
- Tracking at ~1.7 hits/mm² shown to work well

Positron detection



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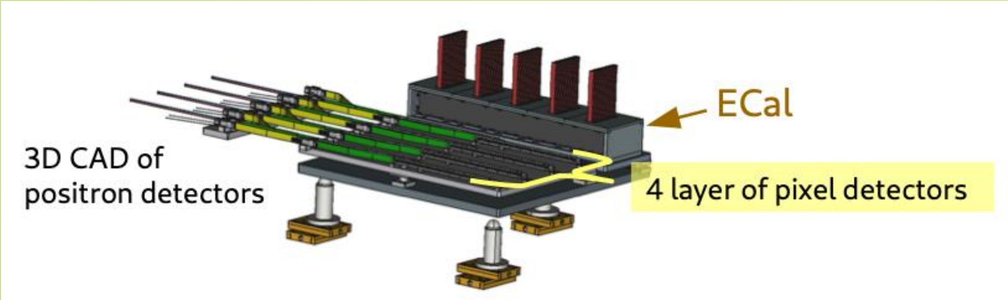
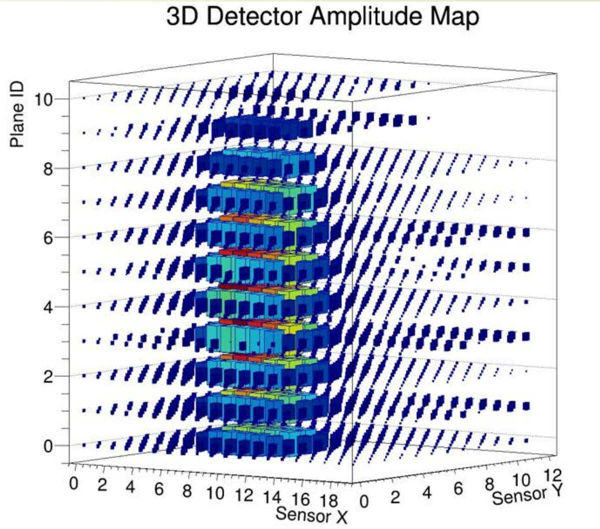
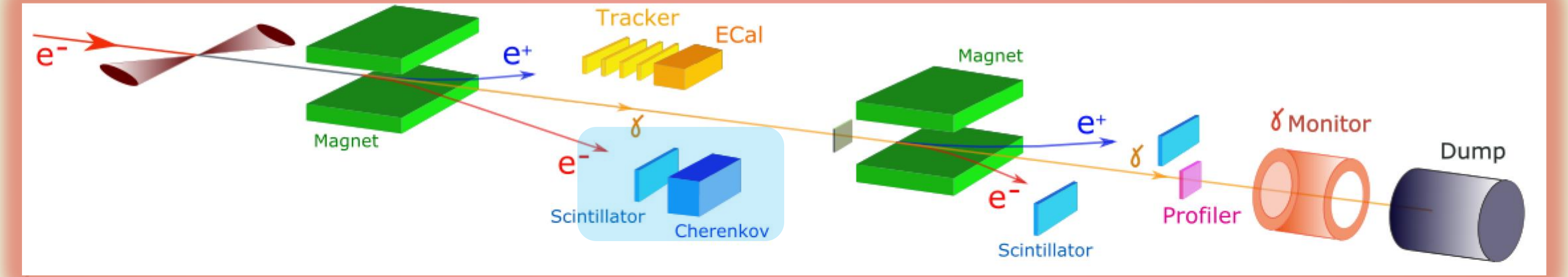


- Ultra compact ecal (550x55x90 mm^3)
- Sampling calorimeter: 20 layers of 3.5 mm thick tungsten absorber plates ($20X_0$)
- Silicon sensors (5x5 mm^2 pads)
- Dedicated readout FLAXE ASIC



Electron detection

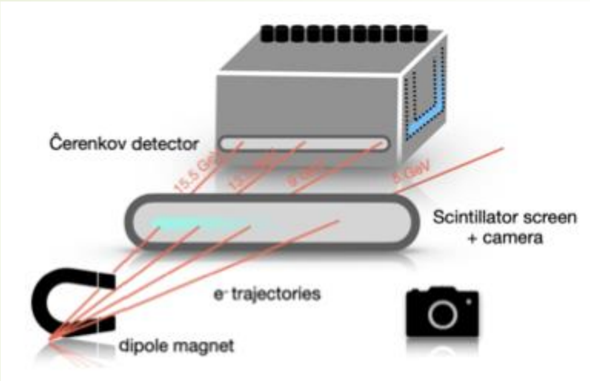


Expected event rates up to 10^9 electrons

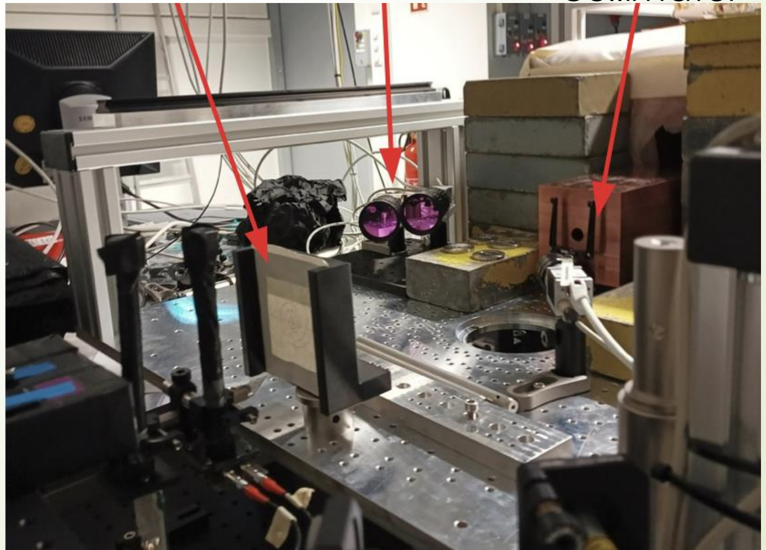
systems:

- **Scintillator screen**
- **Cherenkov detector**

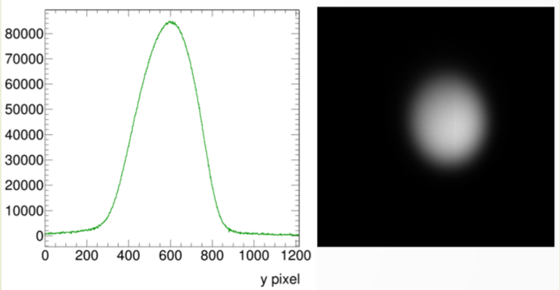
- Technology used by AWAKE experiment at CERN
- High resolution CMOS camera take pictures of scintillating screen
- Signal/background ~100
- Position resolution <0.5 mm



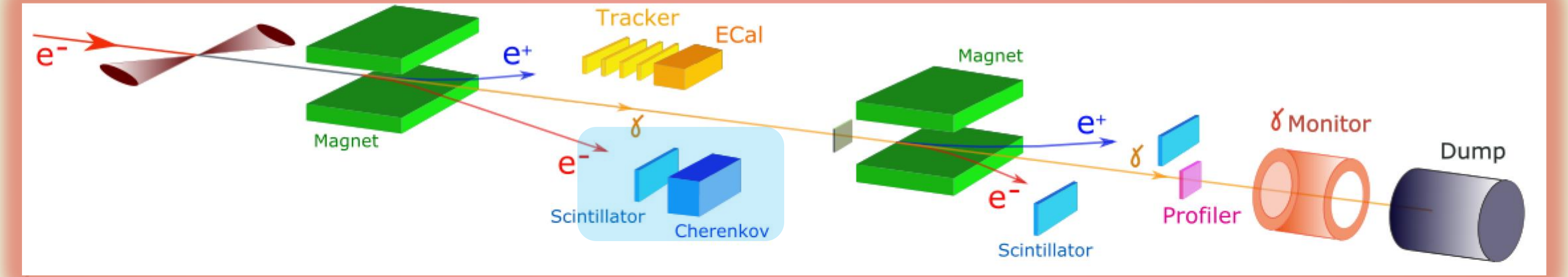
screen cameras 1cm diameter collimator



High flux laser-plasma test beam at DESY



Electron detection

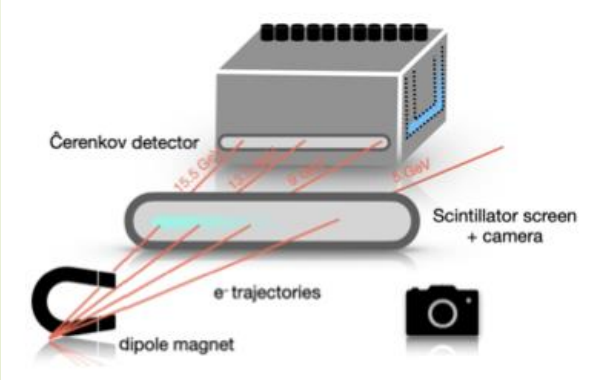


Expected event rates up to 10^9 electrons

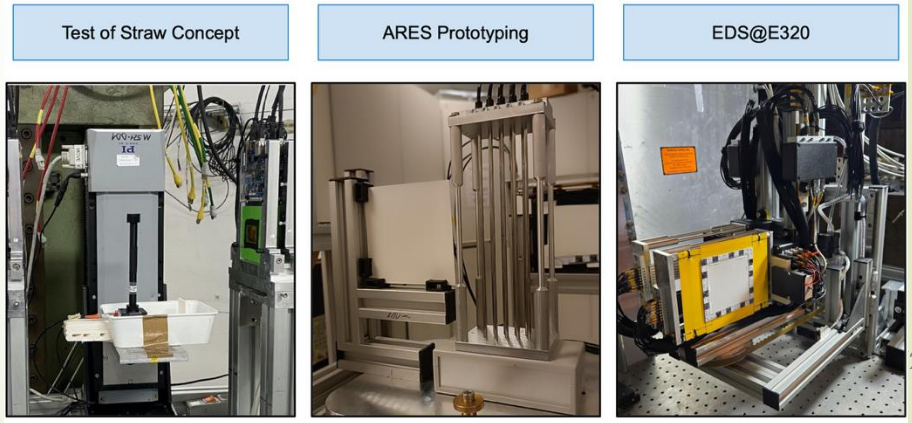
systems:

- Scintillator screen
- **Cherenkov detector**

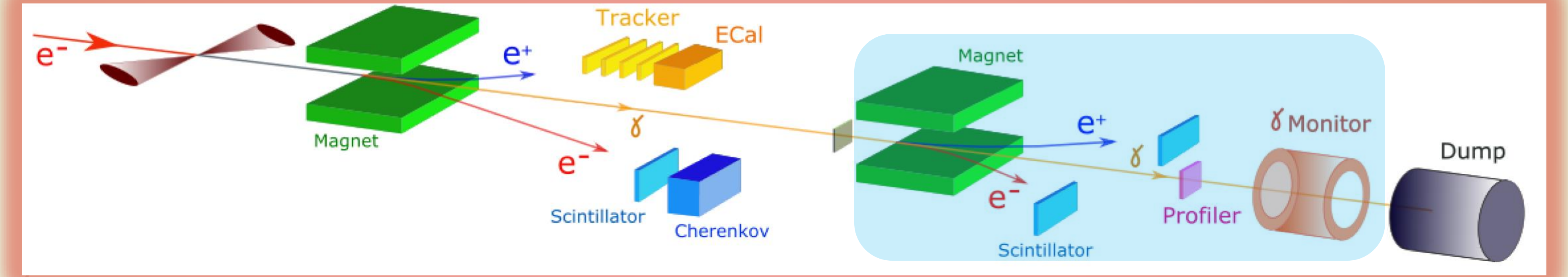
- Segmented straws
- Gaseous detector. Readout with SiPM
- Developed for ILC polarimeter
- Signal/background > 1000



Prototypes tested



photon detection system



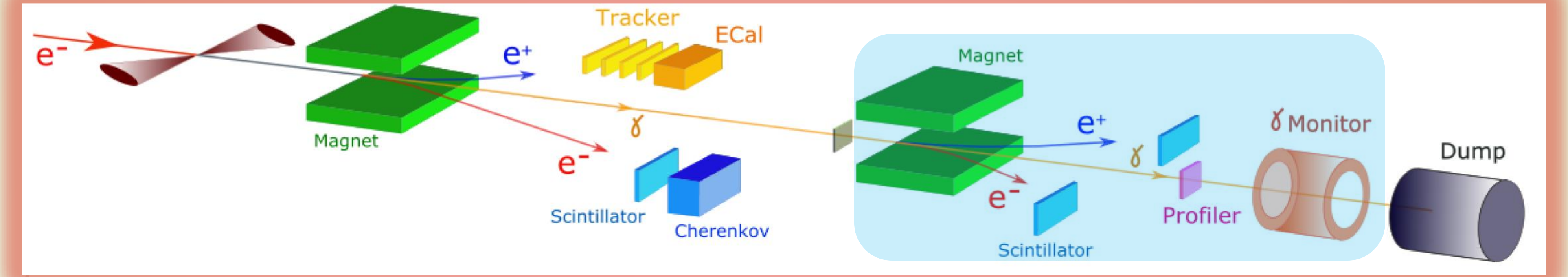
Expected event rates up to 10^9 photons
Tungsten convertor target (10 μm) generates 10^4 - 10^5 electron/positron pairs;

systems:

- **Spectrometer**
- **Gamma profiler (ξ measurement)**
- **Gamma monitor**: Measure energy flow of particles back-scattered from the photon beam dump

LANEX scintillator screens coupled with photo cameras (similar to electron spectrometer)

photon detection system



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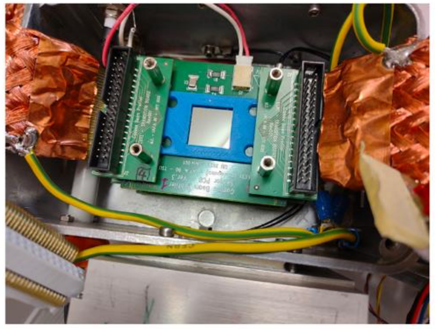
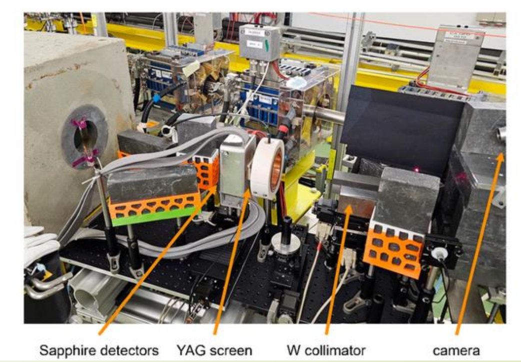
systems:

- Spectrometer
- **Gamma profiler** (ξ measurement)
- **Gamma monitor**: Measure energy flow of particles back-scattered from the photon beam dump

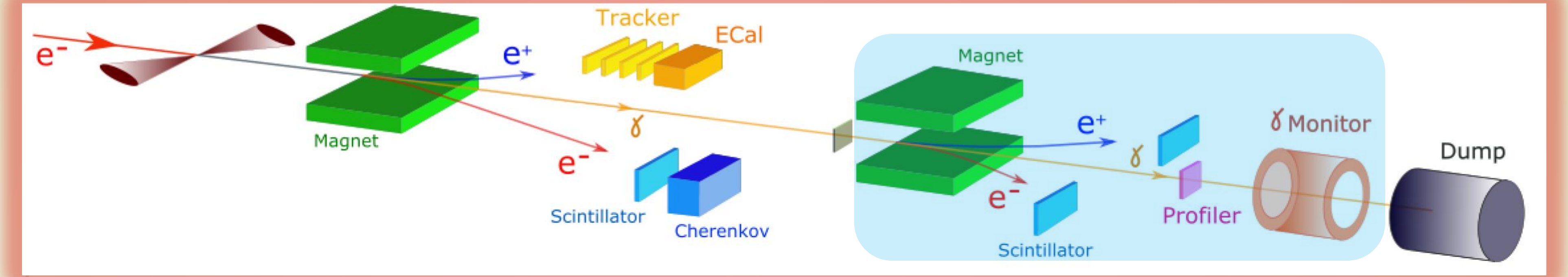
- Two sapphire strip detectors placed on a table movable with micron precision in both directions perpendicular to beam.
- 2 sensors 2 × 2 cm^2 (100 μm thickness) with 100 μm strip pitch
- very radiation hard material (up to 10 MGy)
- 5% precision in laser intensity reconstruction.





Tested in 2022

photon detection system



- 8 lead glass blocks, 3.8 × 3.8 × 45 cm^3
- Placed on cylinder surface with R = 120 mm.
- Almost linear dependence of the deposited energy and the number of incident photons.
- Estimated uncertainty is 3-10%

Expected event rates up to 10^9 photons
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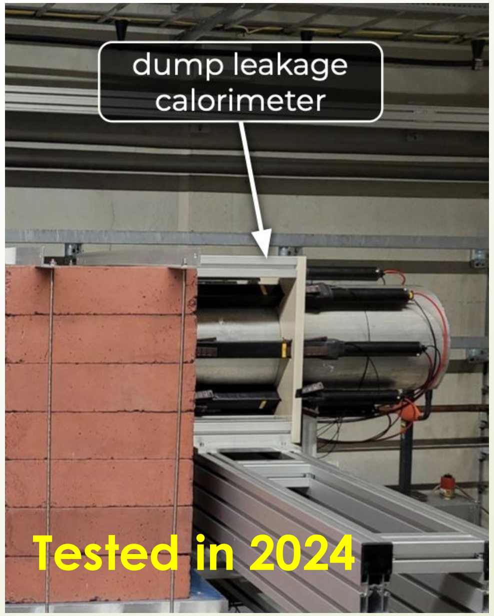
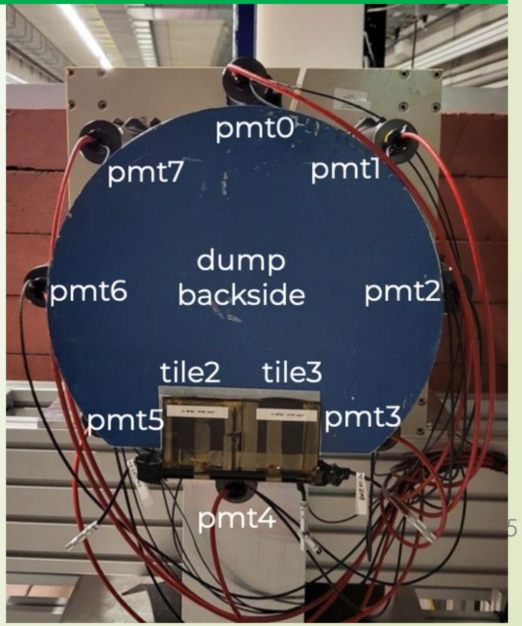
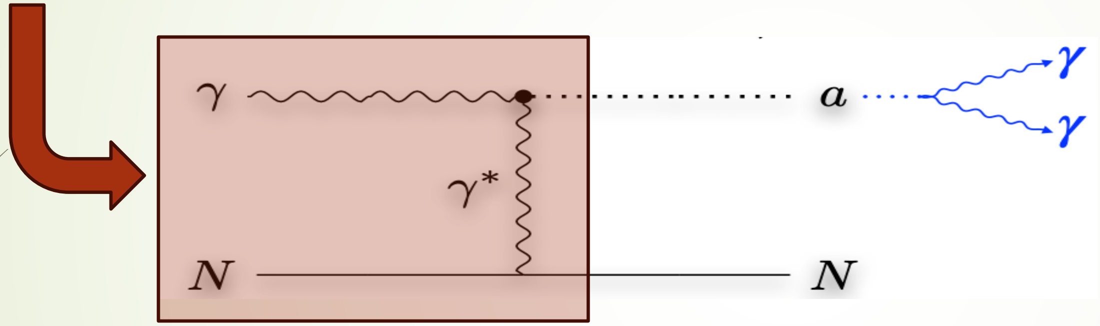


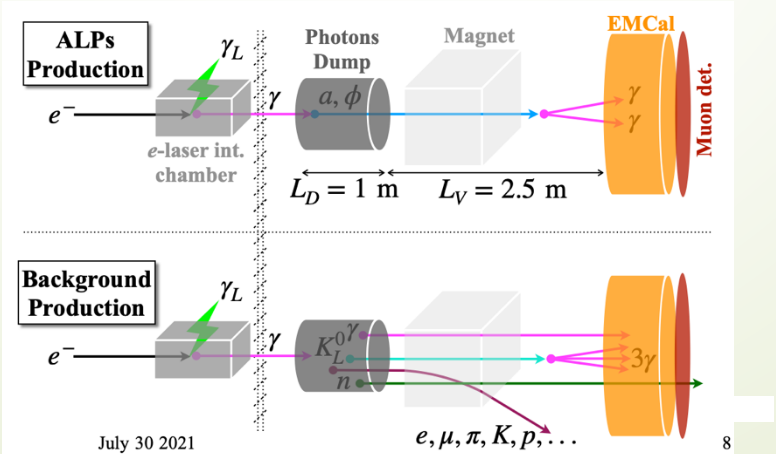


BSM physics at LUXE: New Physics at Optical Dump (NPOD)

- High photons flux offers opportunities to search for new phenomena beyond the standard model.
- Axion-like particles (ALP) could be produced in the optical dump (Primakoff effect). ALP will decays to two hard photons



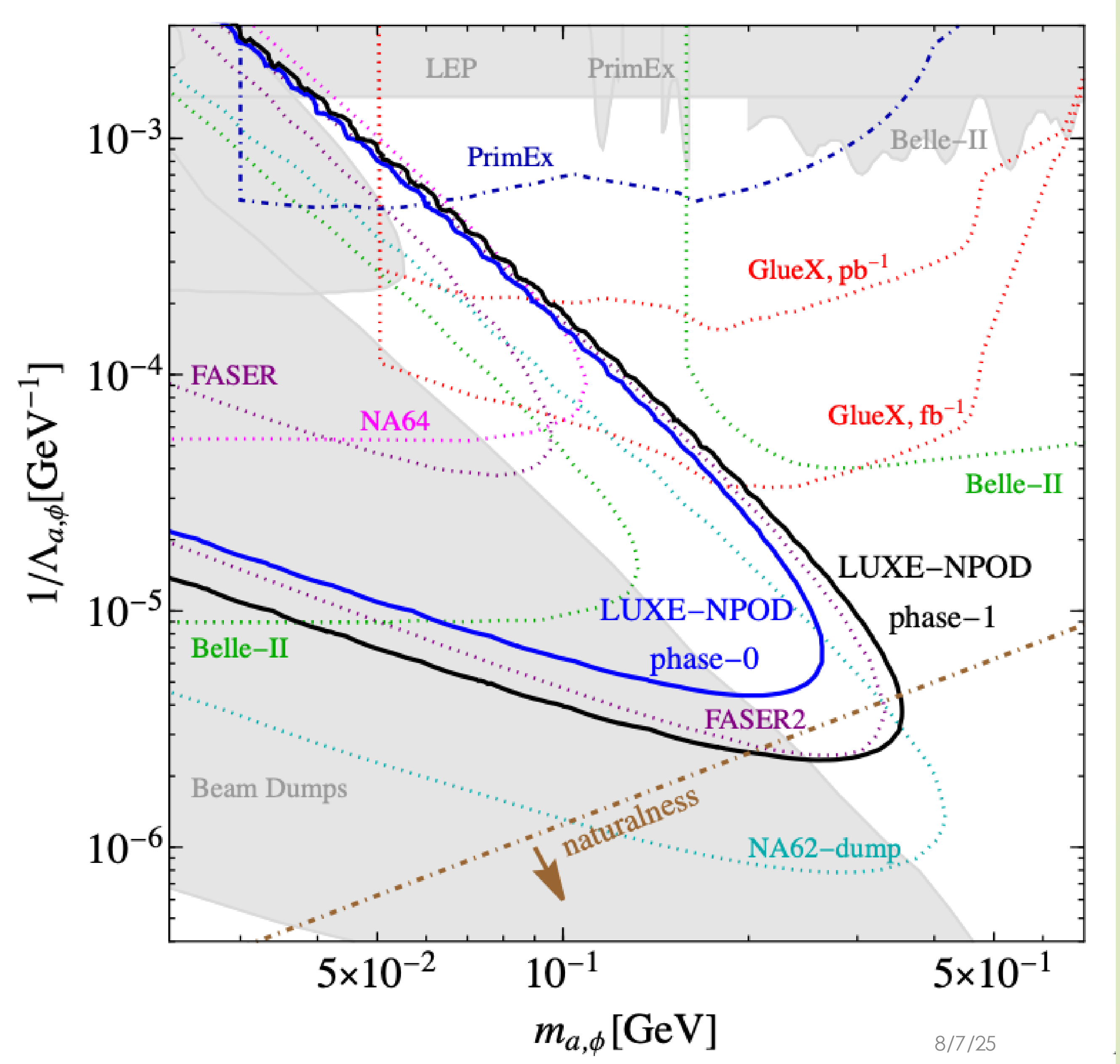
- Electromangetic calorimeter will be installed after the dump. Good pointing resolution to constrain decay point



LUXE-NPOD

Sensitivity to masses m(a) ~ 100 MeV

Results within one year



Timeline …


2025
2026
2027
2028
2029
2030
2031+
Extraction beamline (ELBEX)
Design
Procurement
Installation*
(*pending EuXFEL council approval)
LUXE Laser
JeTi 40 operated at DESY
Procurement + Installation LUXE @10TW
LUXE @ 40TW**
(** later upgrade to 350TW)
LUXE Detectors
Design, Procurement
Construction, Testing
Installation Minimal Detectors
Installation Full Detectors

outlook

- LUXE is a new exciting experiment with a novel baseline plan to test strong-field QED predictions in a region never explored before in clean environments
- Designed detector systems will allow LUXE to achieve physics goals in experimental measurements. All the detectors have been designed and tuned to cope with rate measurements, from 10^{-2} to 10^{9} per bunch crossing
- LUXE can also search for new physics exploiting the optical dump concept
- Extraction beam line is partially funded, and the detector installation should start in 2029

Thanks for your attention !