Detector Challenges of the strong-field QED experiment LUXE at the European XFEL

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on behalf of LUXE collaboration

LUXE

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WEIZMANN INSTITUTE OF SCIENCE

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Outline

- new experiment proposed at DESY and Eu.XFEL
- collisions of XFEL electron beam and high-power LASER

More on LUXE physics:

Talk: Yee Chinn Yap
Talk: Shan Huang

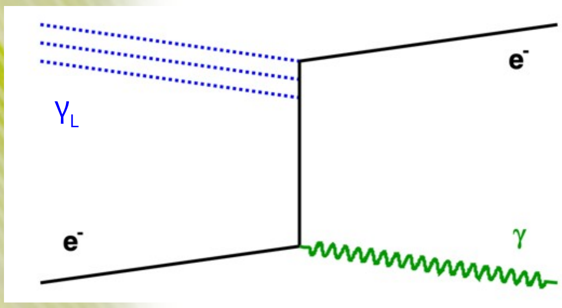
- LUXE CDR: Eur. Phys. J. Spec. Top. (2021) 230:2445–2560
- LUXE website: https://luxe.desy.de

- LUXE physics observables
- Design of experimental setup at European XFEL
- Summary

LUXE: Physics processes

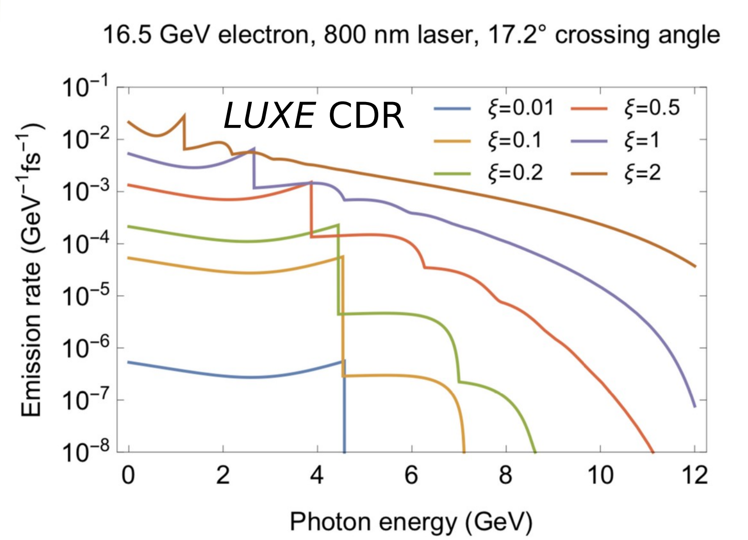
Non-linear Compton Scattering:

$$e^- + n\,\gamma_L \rightarrow e^- + \gamma$$



Observables:

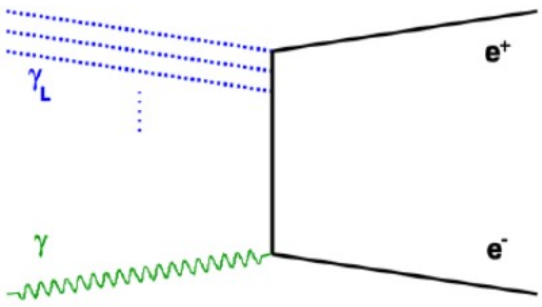
- Shift of first kinematic edge because of increase of electron effective mass: $m^* = m\sqrt{1+\xi}$;
- Position of other kinematic edges;
- Intensity of nγ scattering.



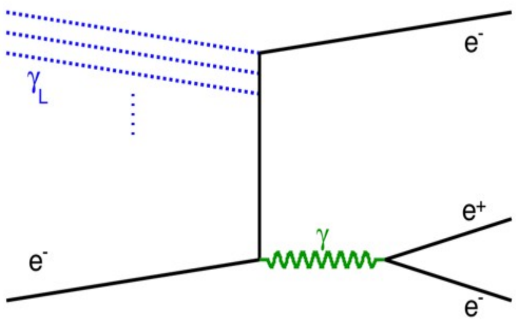
Pair production:

non-linear Breit-Wheeler and trident

$$\gamma + n\,\gamma_L \rightarrow e^+ + e^-$$



$$e^- + n\,\gamma_L \rightarrow e^- + e^+ + e^-$$



- Three methods for generating incident photon:
  - Compton photons inside same laser pulse => largest rate
  - Bremsstrahlung photons produced upstream => highest E
  - Inverse Compton scattering upstream (E=9 GeV)

LUXE setup

European XFEL electron beam:

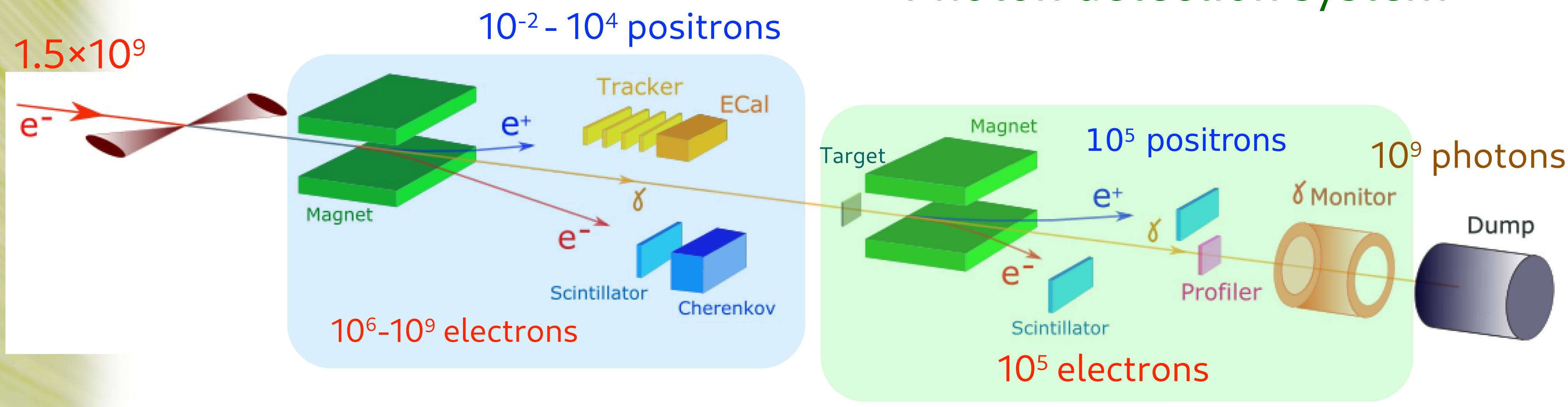
- Energy 16.5 GeV (possible 10 GeV, 14 GeV);
- LUXE uses one out of 2700 bunches per train;
- Repetition rate 10 Hz;
- Focusing down to $\sigma_{x,y}$: 5 - 10 μm;

Laser:

- Laser wavelength = 800.00 nm (1.55 eV);
- Repetition rate ~1 Hz;
- Pulse duration 25-30 fs;
- Power:
  - Phase 0: 40 TW, (1.3×10^{20} W/cm², $\xi = 7.9$);
  - Phase 1: 350 TW, (1.2×10^{21} W/cm², $\xi = 23.6$);

LUXE setup conceptually contains two detector subsystems:

- Electron positron spectrometer
- Photon detection system

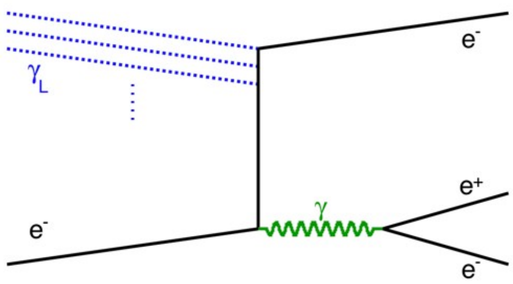


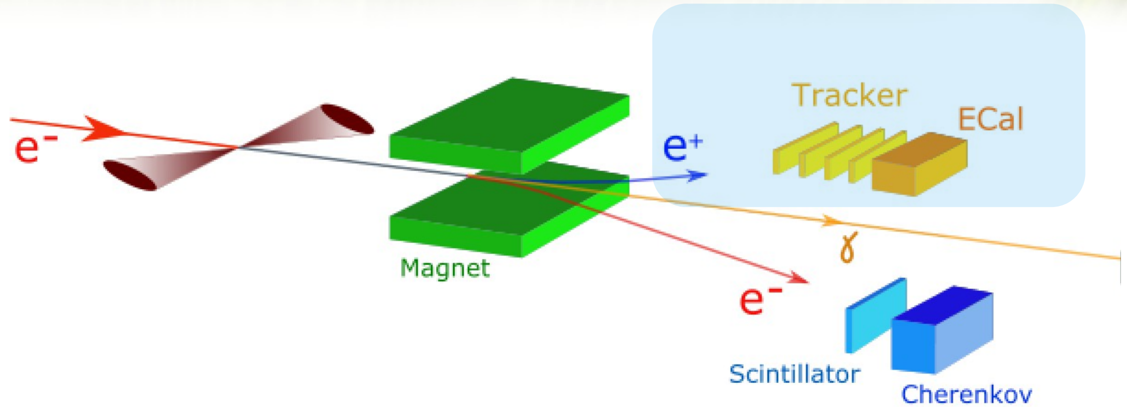
- Detector performance in LUXE setup was studied in GEANT4 and FLUKA simulations.
- Collision processes were simulated using strong field QED MC code PTARMIGAN*.

* T. Blackburn & B. King, EPJC 82, 44.

Positron Detection

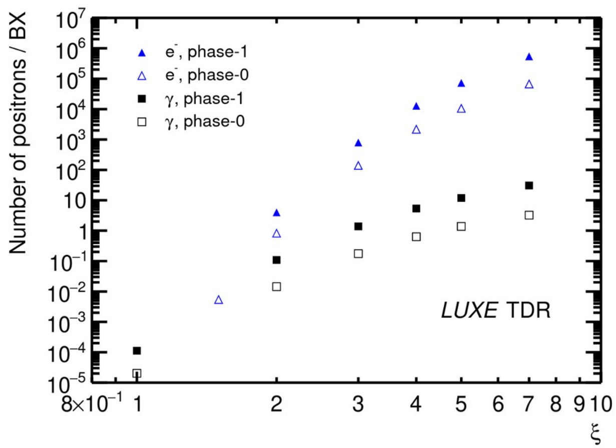
Study e+e- pair production





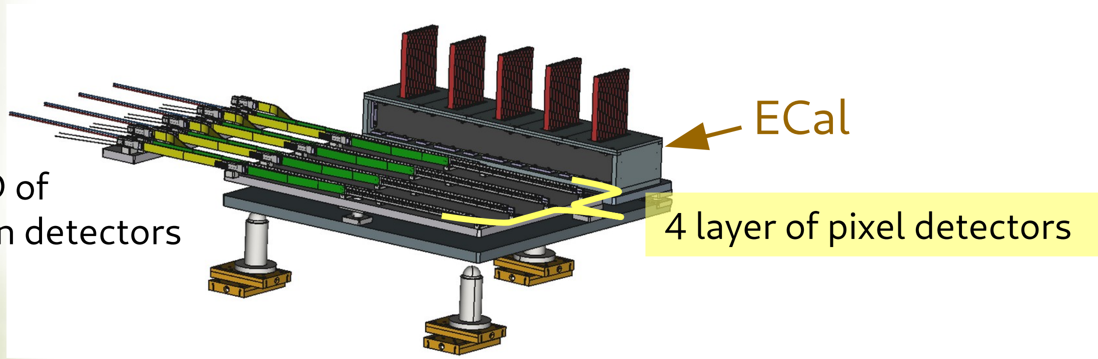
Expected event rates per laser shot

- electron-laser mode: 10^{-2}-10^{4} e^+e^- pairs
- gamma-laser mode: 10^{-2}-10 e^+e^- pairs

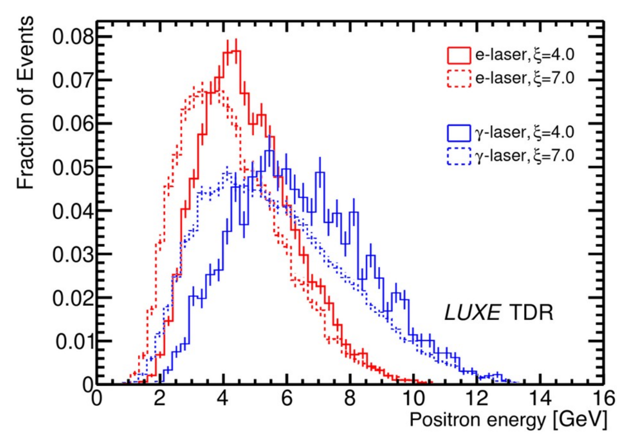


Spectrometer:

- Magnet: 1 T – 1.5 T of ~1 m;
- 4 layers of silicon pixel detectors;
- Compact electromagnetic calorimeter.



3D CAD of positron detectors



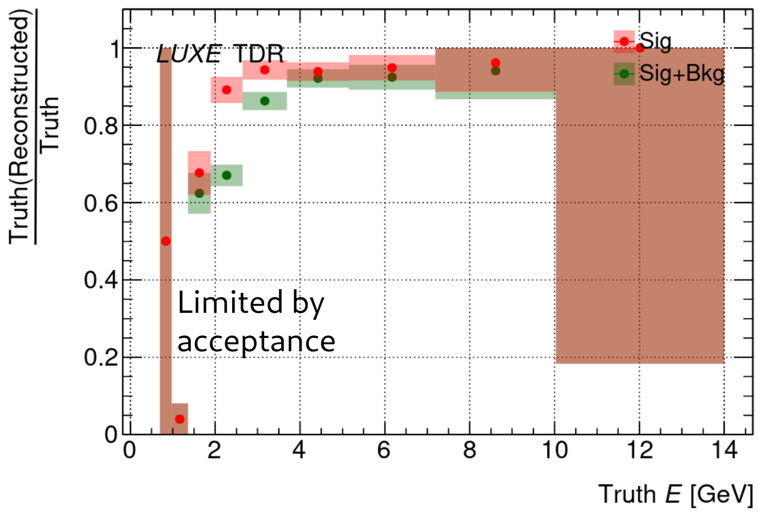
Tracker

- ALPIDE silicon pixel sensors: 15 x 30 mm^2;
- Sensors developed for upgrade of ALICE Inner Tracking System (currently is installed);
- Pixel size: 27 x 29 μm^2, spatial resolution ~5 μm;
- Good performance under irradiation - able to tolerate an ionization dose of up to 2.7 Mrad.

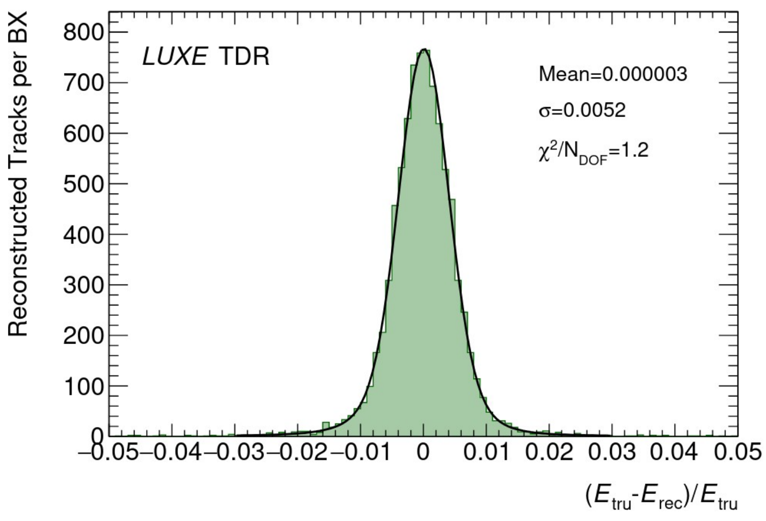
Performance in MC simulation

- Four layers of two staves;
- Track reconstruction efficiency is above 95%;
- Energy resolution < 1%, independent of energy.

Reconstruction efficiency for events with ~1000 positrons

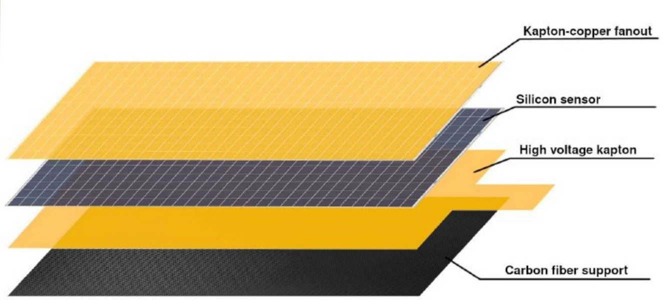


Energy resolution



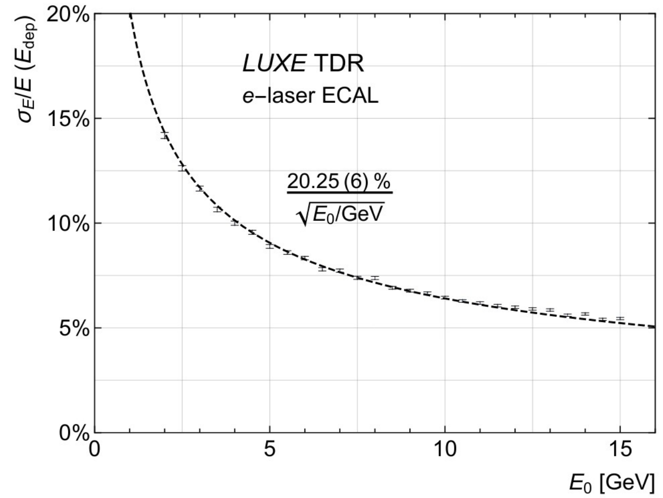
Electromagnetic Calorimeter

- Ultra compact ECal ~ 550 x 55 x 90 mm^3
- Developed by FCAL collaboration;
- Sampling calorimeter: 20 layers of 3.5 mm thick tungsten absorber plates (20 X0)
- Silicon or GaAs sensors (5x5 mm^2 pads, 320 (500) µm thick), installed in 1mm gap between absorbers;
- Small Molière radius, high spatial resolution of local energy deposits
- Readout via dedicated FLAME ASIC (developed in FCAL).



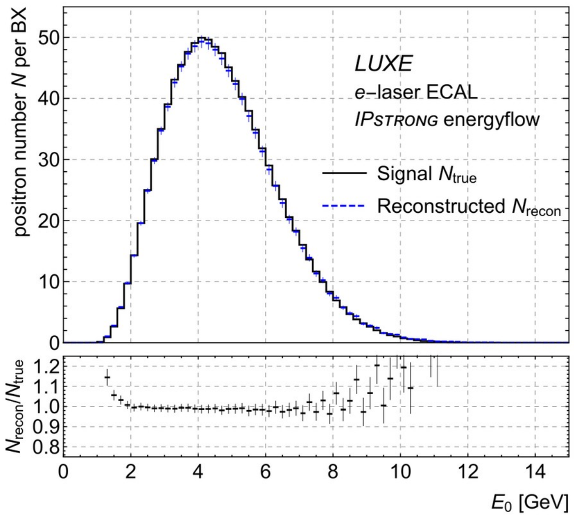
Performance in MC simulation

- Energy resolution ~20%;
- Single particle position resolution ~0.8 mm at 10GeV;
- Complementary measurement of positron energy spectra;
- Low energy distributed background rejection.



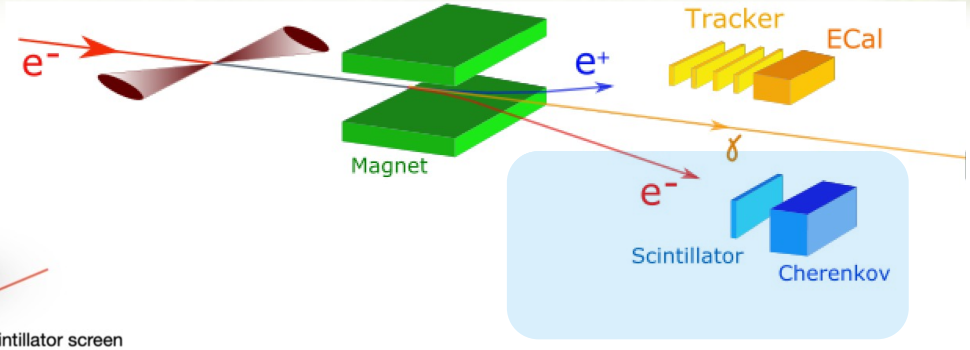
Special algorithm for high multiplicity events

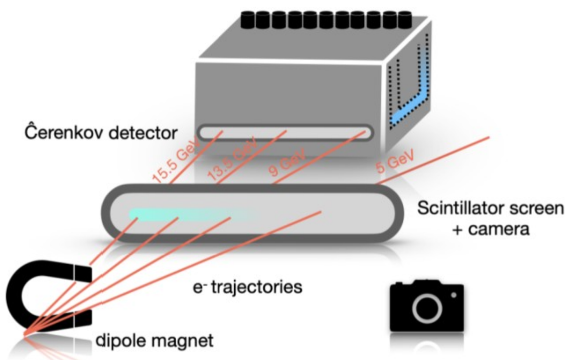
capable of reconstructing spectra and number of particles based on distribution of deposited energy



Electron Detection

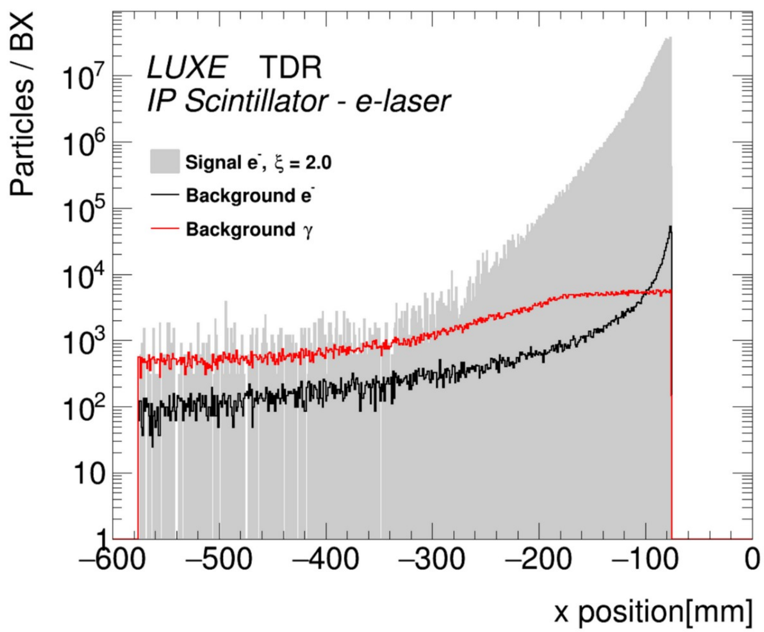
- Expected event rate: up to 10^9 electrons;
- Chosen technologies:
  - Scintillator screen,
  - Cherenkov gas detector.





Scintillator Screen

- Technology is widely used for laser monitoring
- High resolution CMOS camera takes pictures of scintillation screen as it emits the light;
- Scintillator: Tb-Doped Gadolinium Oxysulfide (GadOx) screen;
- Radiation hard (up to 10 MGy).

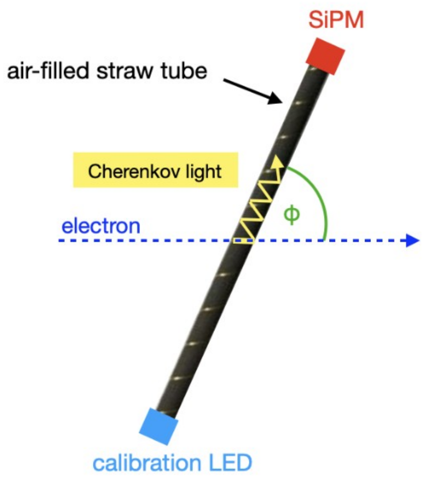


Performance

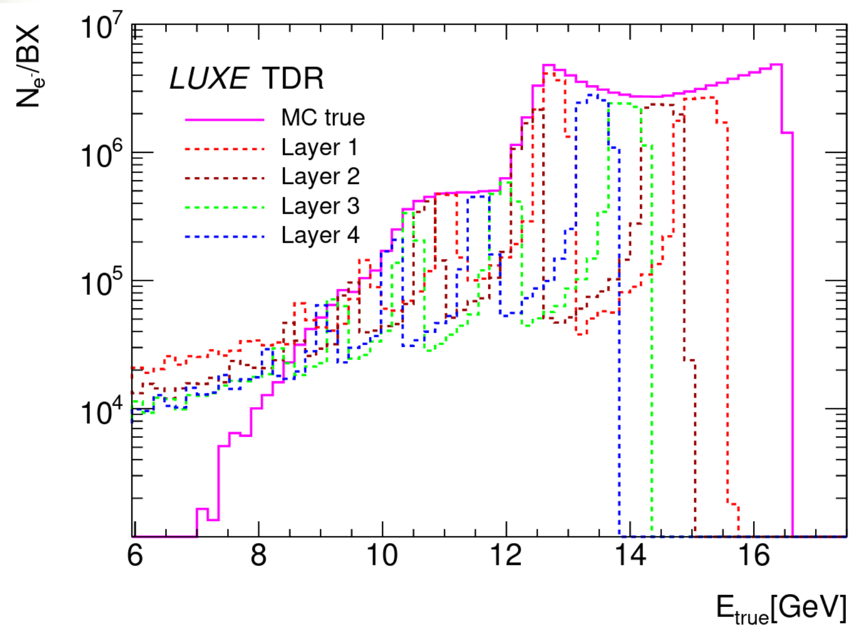
- Signal/background ~100;
- Position resolution <0.5 mm (~50 MeV);
- Sufficiently high dynamic range (40dB);
- Successfully tested with electron beam.

Cherenkov Detector

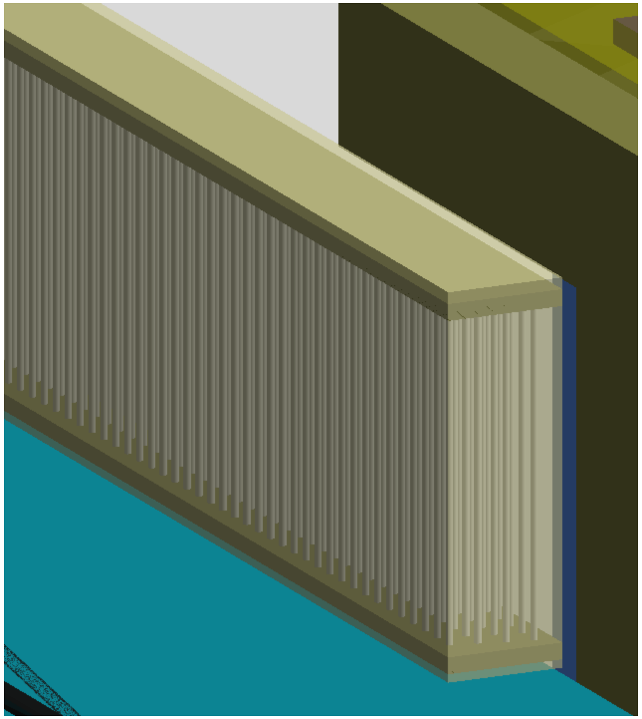
- Gaseous Cherenkov detector;
- Low refractive index gas (air, n=1.0028), possibly optical filter to reduce light yield;
- Fine segmentation to resolve kinematic edges in Compton spectra
- Not sensitive to electrons <20 MeV and photon background;
- Signal/background >1000;
- The concept was successfully tested with the electron beam.



Electrons spectrum reconstructed from the layers of straws with Cherenkov light measurement



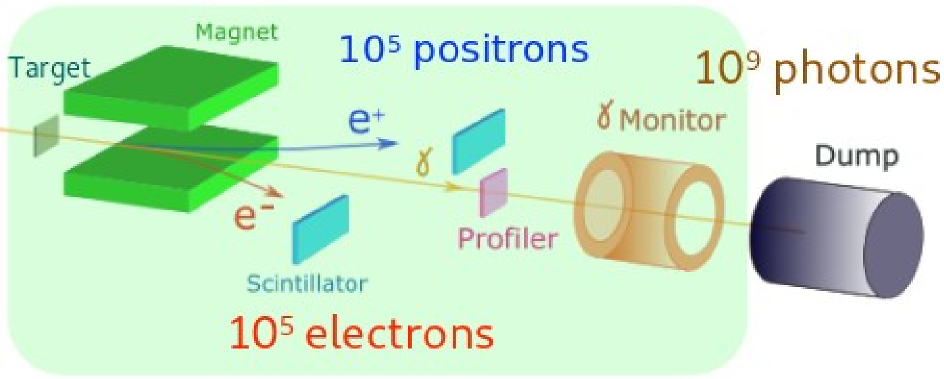
Cherenkov detector in Geant4 model: 240 straws of R = 2 mm in 4 layers



Photon Detection System

High number of photon:

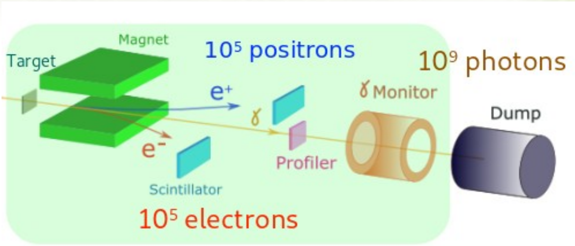
- up to 10^9 photons;
- summing up to TeV energies.



Three subsystems:

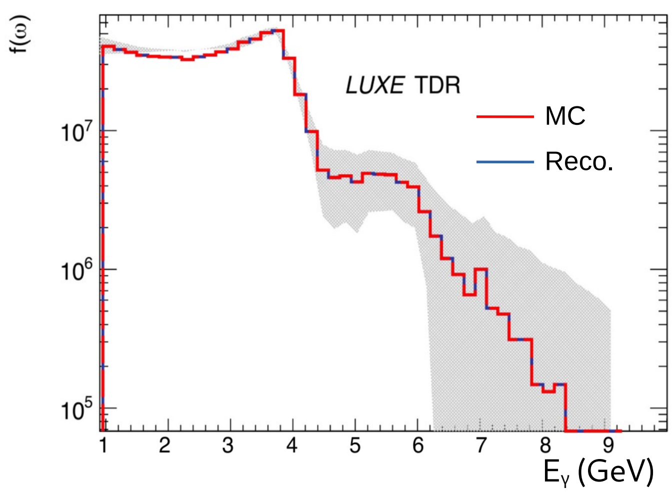
- Photon spectrometer
  - Measure photon energy spectrum and flux.
- Gamma profiler made of sapphire strip sensors:
  - Measure transverse profile of the beam.
- Backscattering calorimeter:
  - Measure flux.

Photon Spectrometer

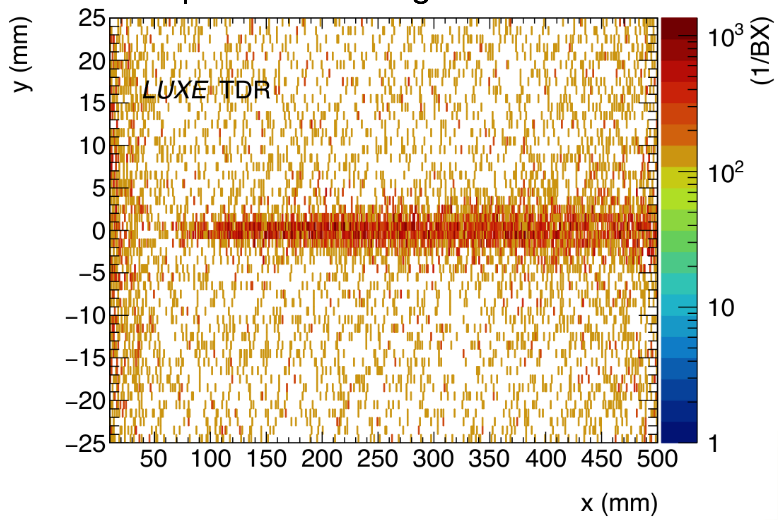


- Tungsten convertor target (10 μm) generates 10^4 - 10^5 electron/positron pairs;
- Dipole magnet: 1.4T, 120cm;
- Electrons and positrons are detcted by GadOx (Gd_2S_2O:Tb) scintillator screens coupled with photo cameras (implementation is similar to electron spectrometer);
- Energy resolution is better than 1%;
- Recorded electron and positron spectra are deconvoluted to extract the spectrum of the photons;

Reconstructed photon spectrum

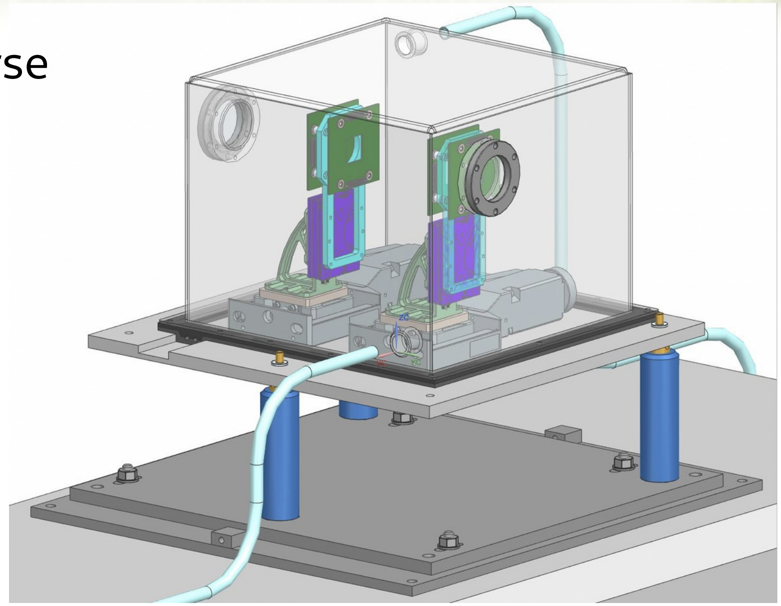


Signal and background particles hitting the screen



Gamma Profiler

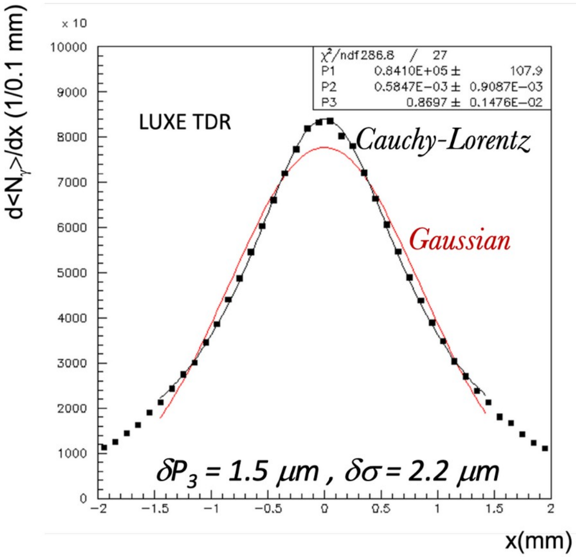
For linearly polarized laser the asymmetry in transverse profile of photon beam depends on laser intensity (ξ).



<u>Design:</u>

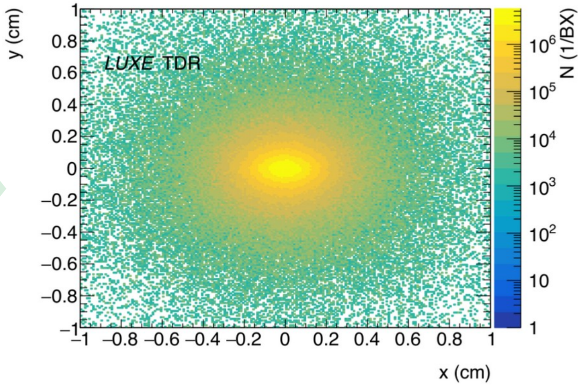
- Two sapphire strip detectors placed on a table movable with micron precision in both directions perpendicular to beam.
- 2 sensors 2 × 2 cm^2 (100 μm thickness) with 100 μm strip pitch.
- 5% precision in laser intensity reconstruction.

- Sapphire is a novel, not widely used, detector material;
- High band gap (9.9 eV);
- very radiation hard (up to 10 Mgy);
- Charge collection efficiency is relatively low;
- Suites for high beam intensities.



Reconstructed beam profile with different fit functions

Spatial distribution of the Compton photons hitting sapphire sensor



Photon Flux Monitor

- Measure energy flow of particles back-scattered from the photon beam dump.
- Optimization of the design:
  - Reduce radiation load to provide reasonable lifetime
  - Measure sufficient fraction of the energy of the back scattering particles to be sensitive to the direct photon flux variation

Design:

- 8 lead glass blocks, 3.8 × 3.8 × 45 cm^3
- Placed on cylinder surface with R = 120 mm.

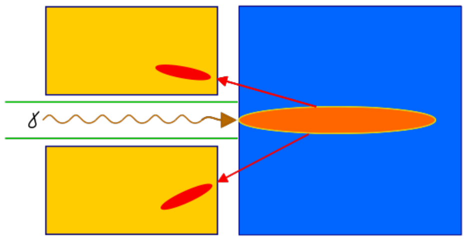
Performance in simulation:

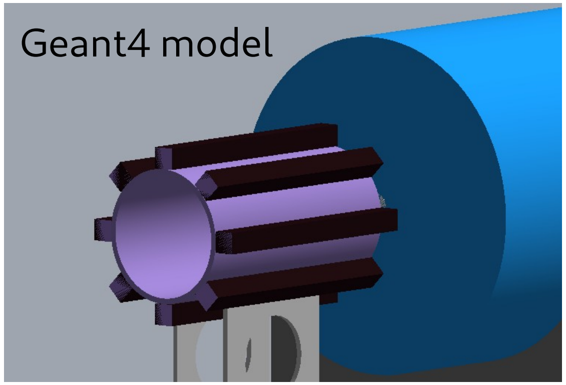
- Almost linear dependence of the deposited energy and the number of incident photons.
- Estimated uncertainty is 3-10%

Performance in beam test:

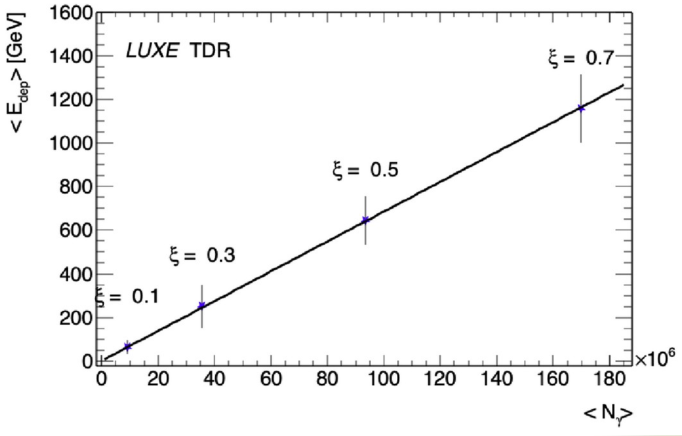
- Three prototypes: lead glass block coupled to PMT.
- Electron beam 60 MeV, up to 25 pC (~10^8 e-).
- Good agreement between measurements and beam charge provided by the beam monitor.

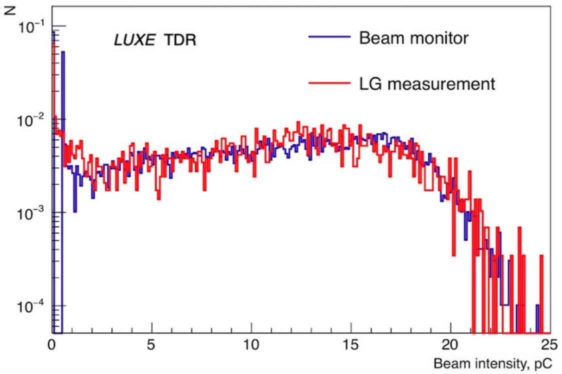
For $\xi > 1$, $N\gamma > 10^8$ / BX





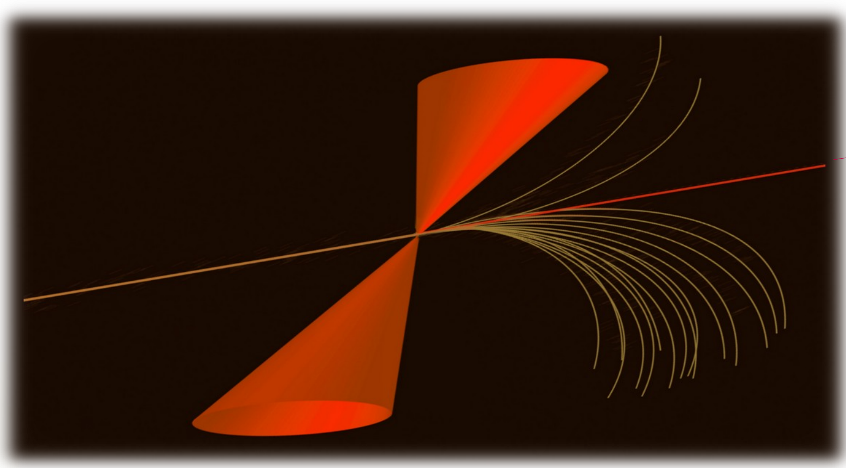
Detector response obtained in Geant4 simulations





Summary

- LUXE experiment presents an exciting opportunity to explore QED in new regime using European XFEL and high power laser
- Designed detector systems will allow LUXE to achieve physics goals in experimental measurements
- The design of the experiment allows its operation without interference with main EU.XFEL program
- The review of LUXE technical design completed in 2022 received positive DESY Physics Review Committee feedback
- Goal is installation in 2025 during extended shutdown planned for European XFEL



Thanks for your attention

Backup

LUXE participants