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


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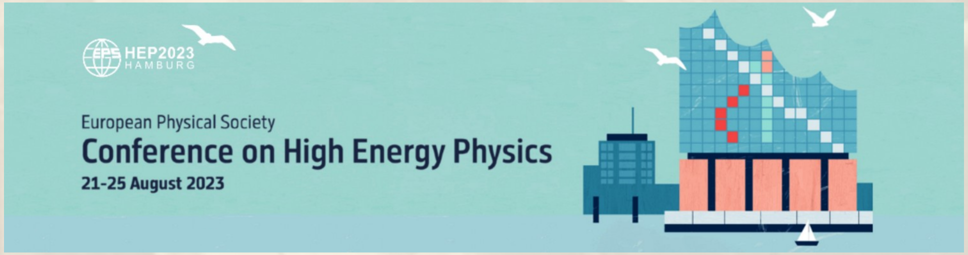
on behalf of LUXE collaboration


LUXE

WEIZMANN INSTITUTE OF SCIENCE



# Outline

- New experiment proposed at DESY and Eu.XFEL
- Study QED in Strong Field regime

**More on LUXE physics:**

Talk: Evan Ranken

Talk: Nicolo Trevisani

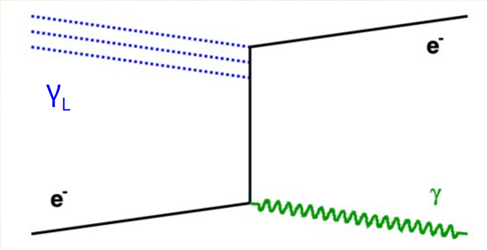
* LUXE TDR: arXiv:2308.00515
* LUXE website: https://luxe.desy.de

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

# LUXE: Physics processes

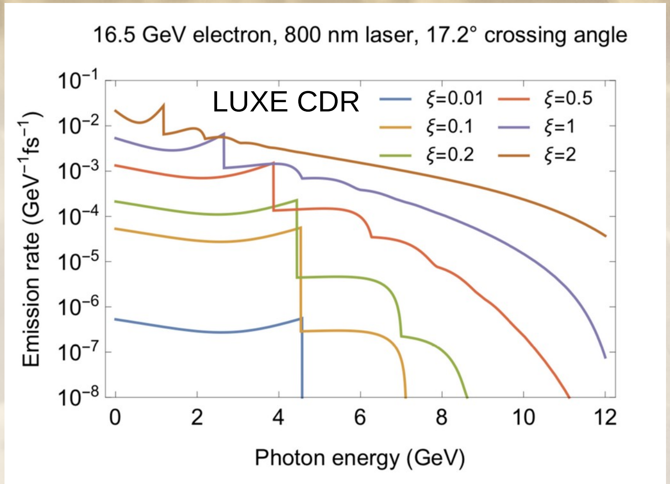
## Non-linear Compton Scattering:

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




**Observables:**

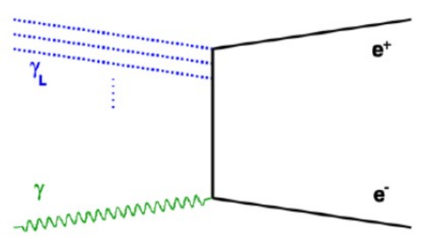
- Shift of first kinematic edge because of increase of electron effective mass: $m^* = m\sqrt{1+\xi}$;
- Position of other kinematic edges;
- Intensity of nγ scattering.



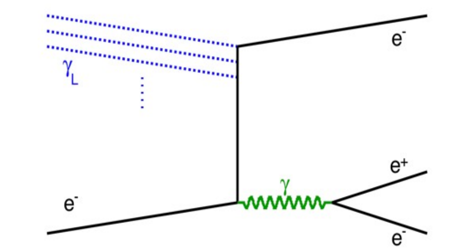

## Pair production:

non-linear Breit-Wheeler and trident

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




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




Generating incident photon:

- Compton photons inside the same laser pulse => largest rate
- Bremsstrahlung photons produced upstream => highest E
- Inverse Compton scattering upstream (E=9 GeV)

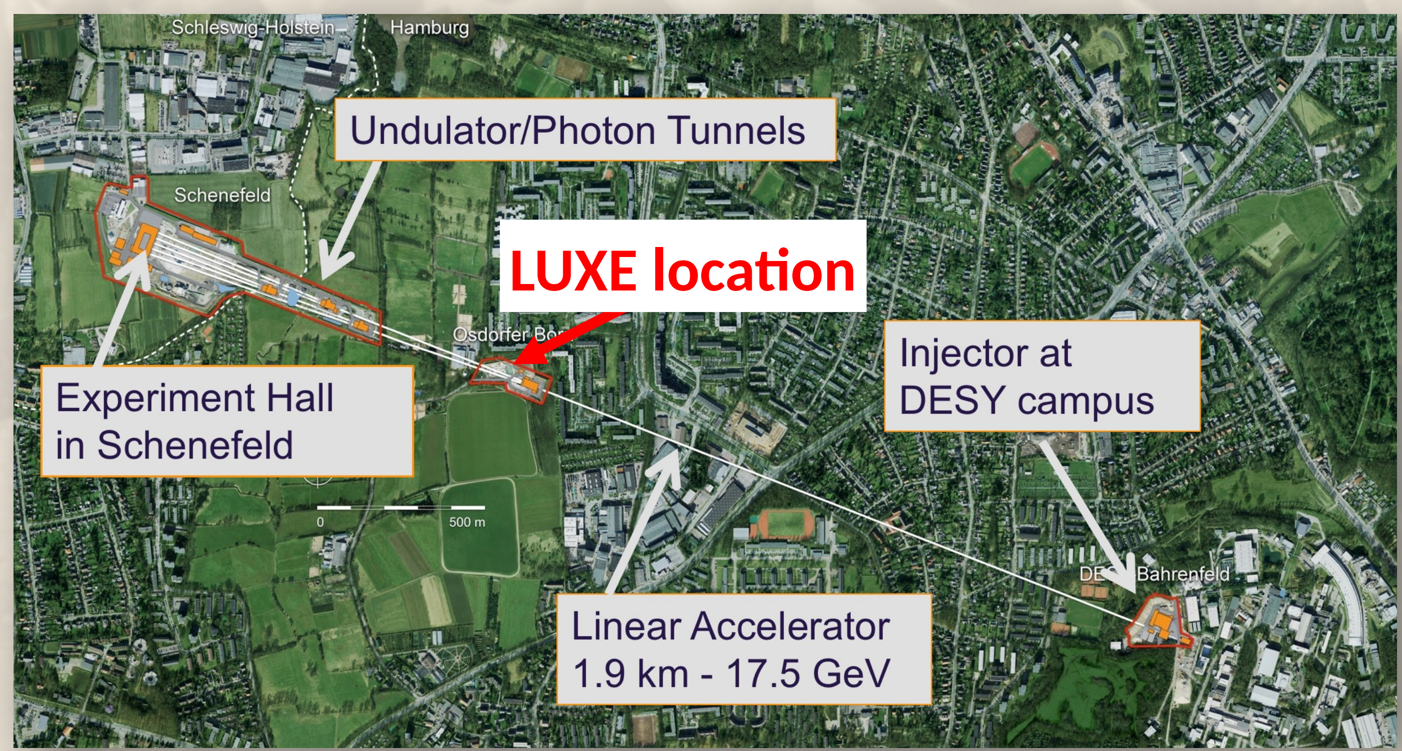
# Electron Beam at European XFEL

**LUXE experiment will study Strong Field QED in collisions of high power laser with:**

- XFEL electron beam;
- High energy photon beam produced by XFEL electrons in bremsstrahlung or ICS.

## <u>Eu XFEL:</u>

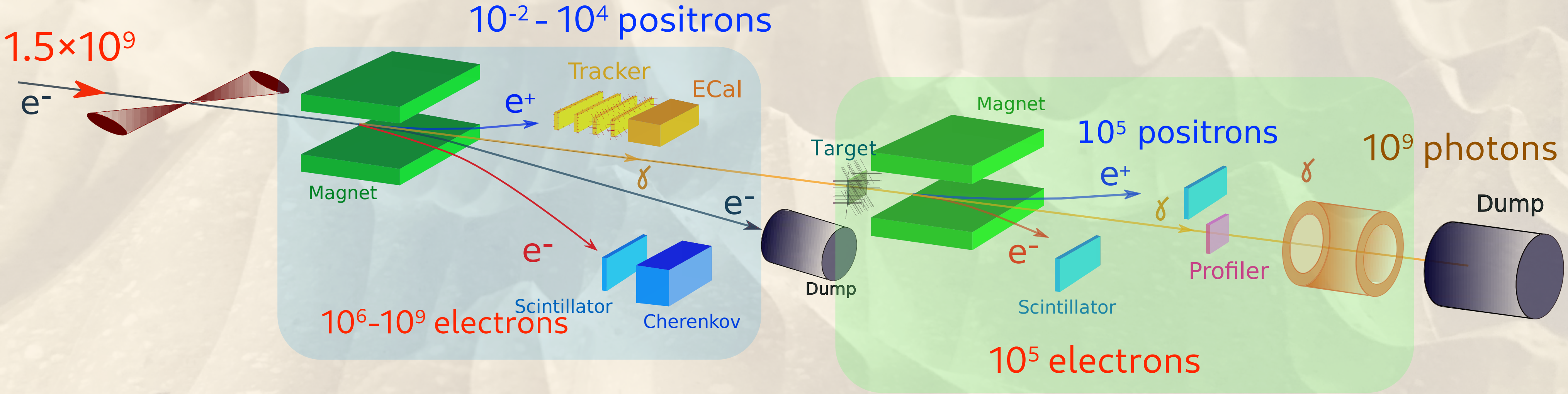
- Linear electron accelerator
- Operates since 2017
- Used to generate X-ray photons
- Energy 16.5 GeV (possible 10 GeV, 14 GeV, 17.5 GeV);
- Repetition rate 10 Hz;
- LUXE uses one out of 2700 bunches per train;
- Focusing down to $\sigma_{x,y}$: 5 - 20 μm;
- Typically $1.5\times10^9$ e- per bunch.



# LUXE setup

**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.

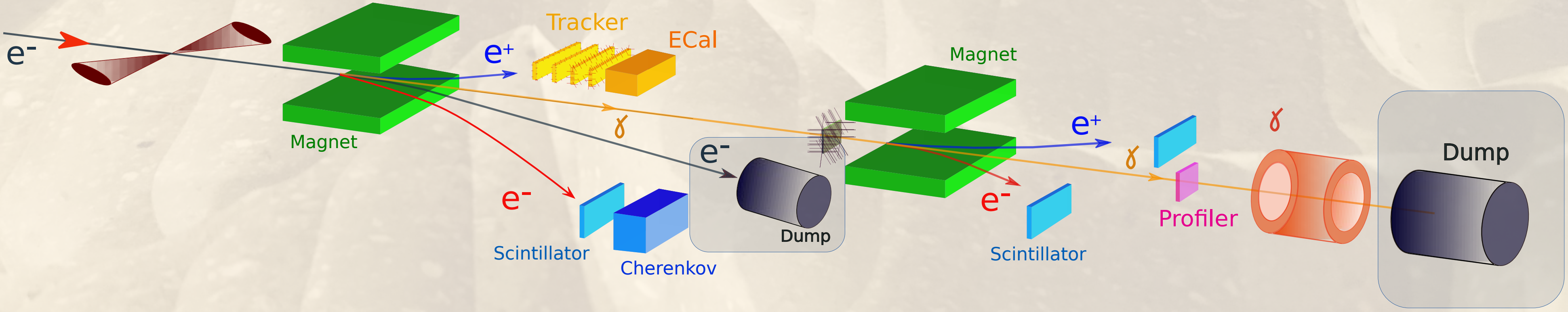
# LUXE setup

There are 3 beam dumps in the experimental area (two are highlighted) located few meters away from the detectors:

- They are sources of substantial background composed of e-, e+, photons and neutrons;
- Additional radiation load on the detectors and electronics:

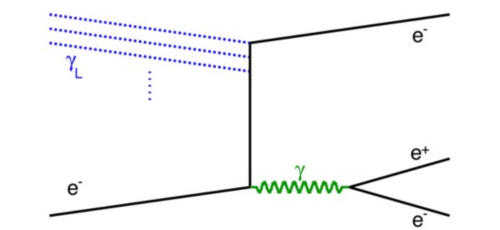
**Studies to optimize shielding and beam dumps design:**

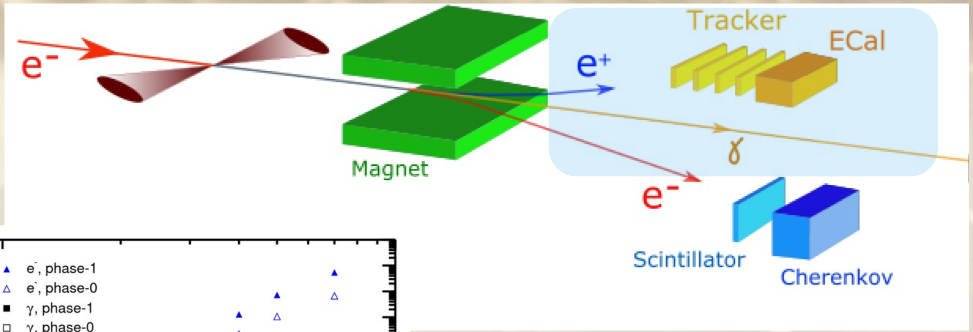
- Reduce the flux of particles in backward direction;
- Shielding to protect detectors from scattered particles;
- Consider timing to cut the background;
- Detailed study of neutron fluxes both in Geant4 and FLUKA simulations.

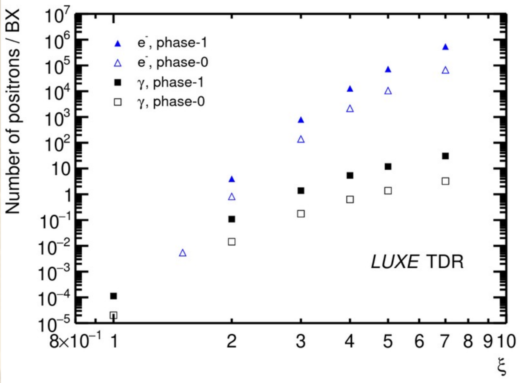


# Positron Detection

Study e+e- pair production

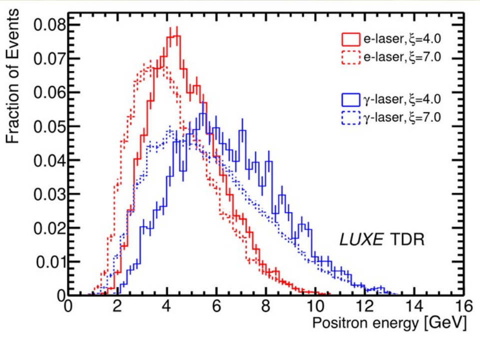


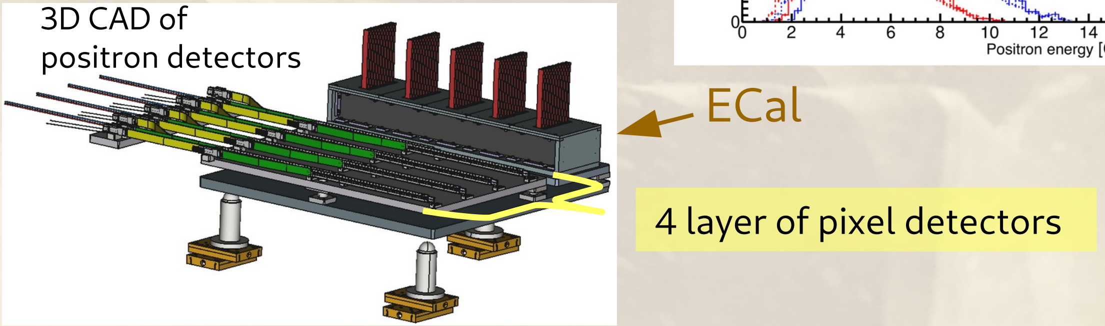

**Expected event rates per laser shot**

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




**Spectrometer:**

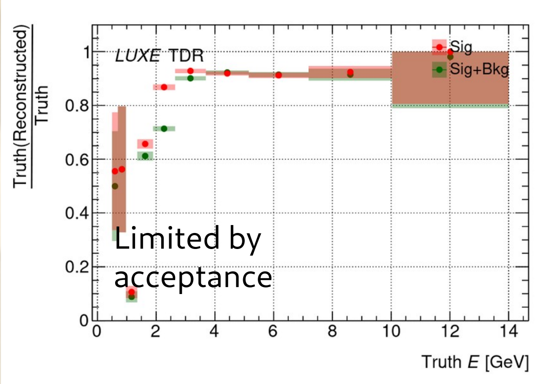
- Magnet: 1 T – 1.5 T of ~1.3 m;
- 4 layers of silicon pixel detectors;
- Compact electromagnetic calorimeter.



# Tracker

- ALPIDE silicon pixel sensors: 15 x 30 mm$^2$;
- Sensors developed for ALICE Inner Tracking System (currently in operation);
- 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.

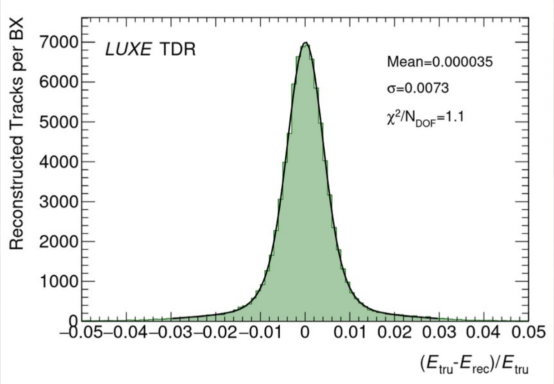
Reconstruction efficiency for events with 10k positrons




**Performance in MC simulation**

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

Energy resolution

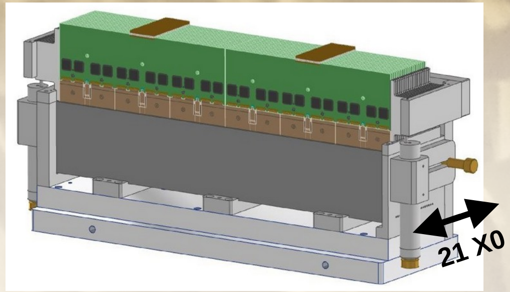


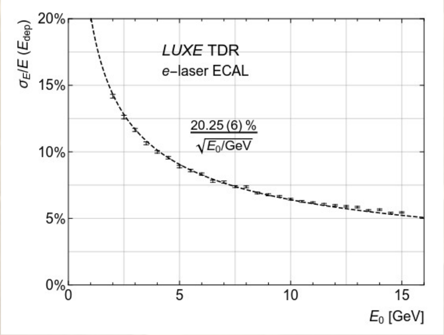

Developing reconstruction algorithms for high multiplicity events based on ML and Quantum Computers: Talk: Yee Chinn Yap

Poster: Annabel Kropf

# Electromagnetic Calorimeter

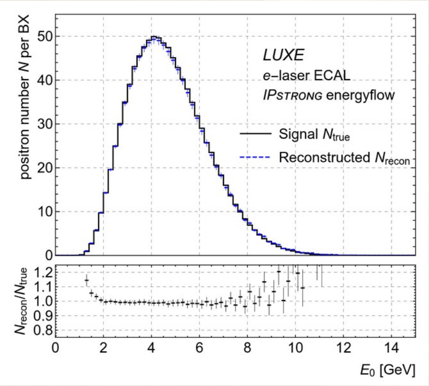
- Ultra compact design developed by FCAL collaboration;
- Sampling calorimeter: 21 layers of 3.5 mm thick tungsten absorber plates (21 X0)
- Silicon sensors (5.5 x 5.5 $mm^2$ pads, 320 μm thick), installed in 1 mm gap between absorbers;
- Small Molière radius, high spatial resolution of local energy 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.

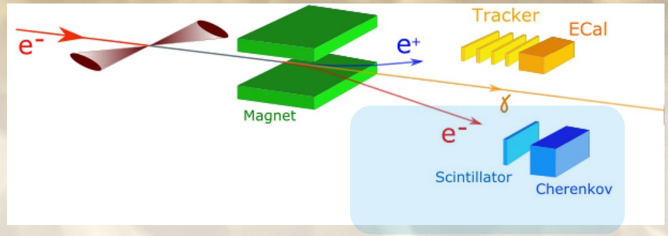



## Special algorithm for high multiplicity events

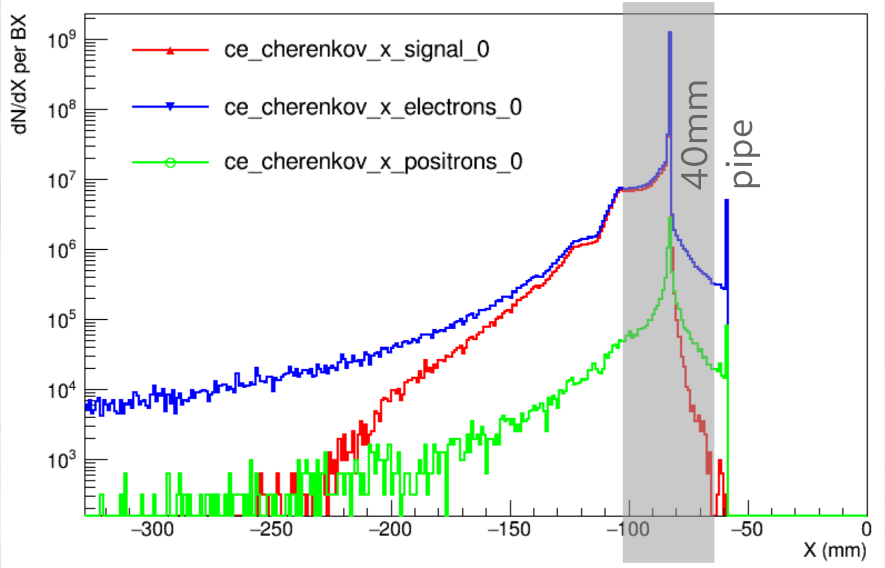
capable of reconstructing spectra and number of particles based on distribution of deposited energy

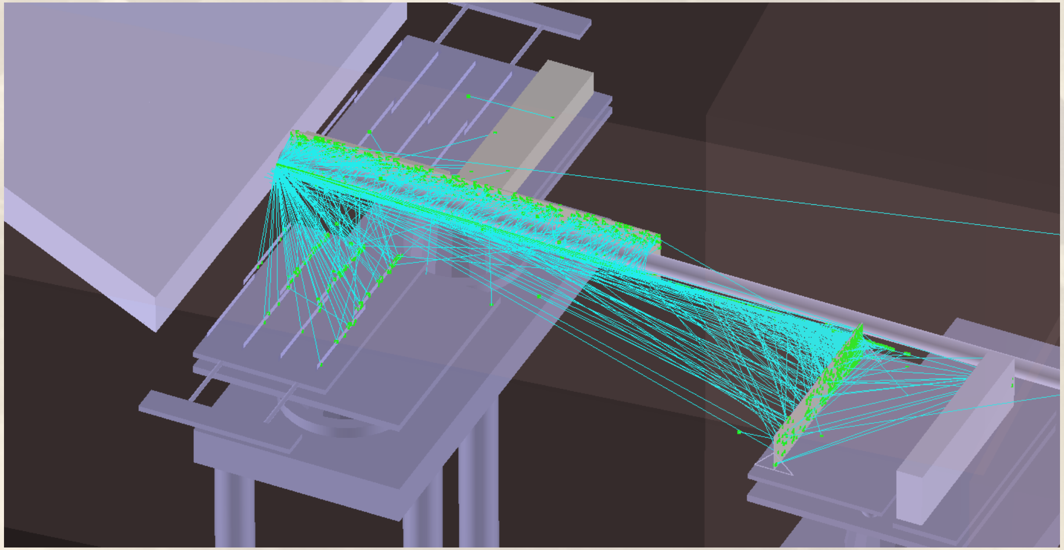
# Electron Detectors Setup

- Electrons after Compton scattering have continuous spectrum ranging from 16.5 GeV down to lowest energies within acceptance of the magnet;
- Beam pipe cannot be used;
- After exiting from the vacuum chamber electrons propagate in the air;
- Generate extra background.




Simulated 100k electrons of 16.5 GeV.
Background particles hitting detectors and shielding

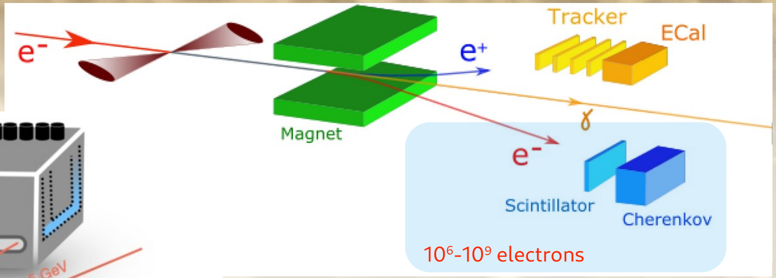


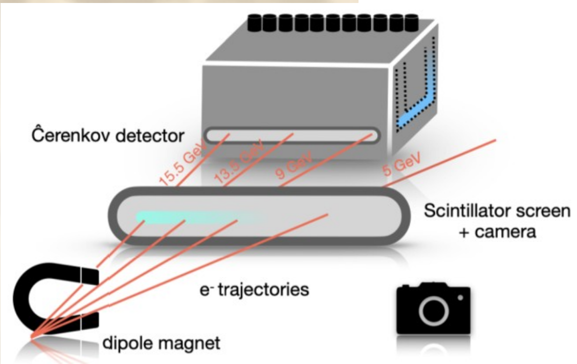



# Electron Detection

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

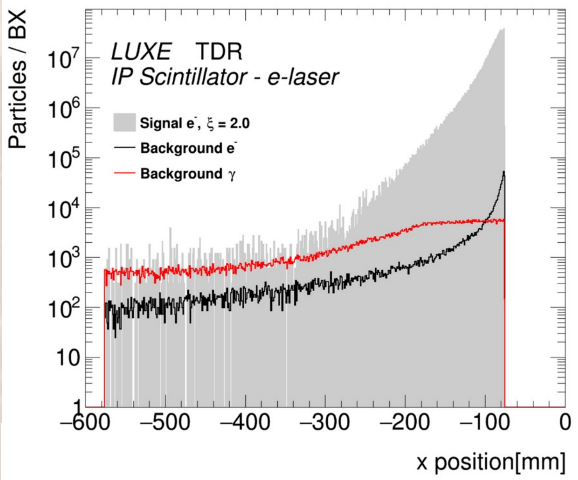
More in EPS [talk: Antonios Athanassiadis]



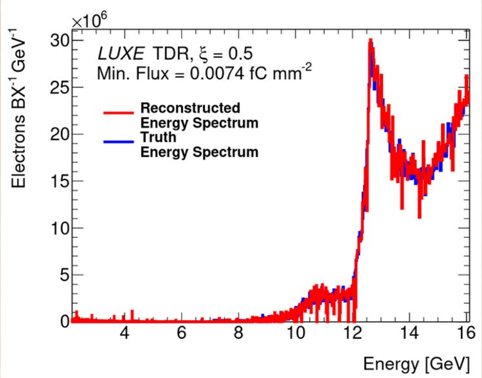

## Scintillator Screen

- High resolution CMOS camera takes pictures of scintillatior screen as it emits the light;
- Scintillator: Tb-Doped Gadolinium Oxysulfide (GadOx) screen;
- Radiation hard (up to 10 MGy).



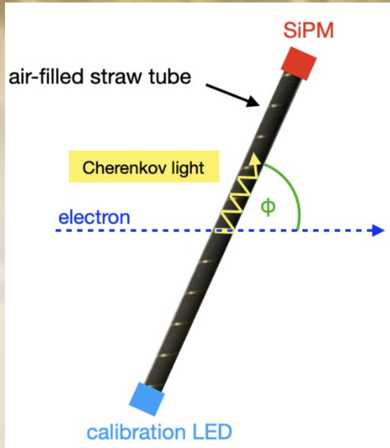

**Performance**

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

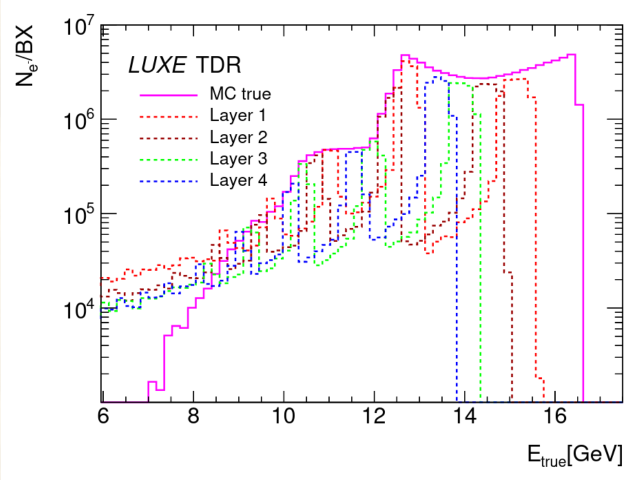


# Cherenkov Detector

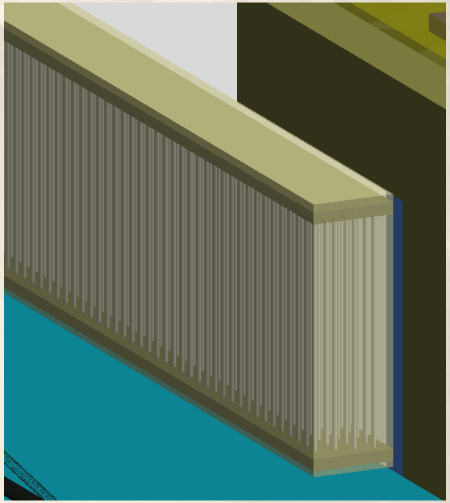
- Gaseous Cherenkov detector;
- Low refractive index gas (air, n=1.0028), possibly optical filter to reduce light yield;
- Fine segmentation to resolve kinematic edges in Compton spectra
- Not sensitive to electrons <20 MeV and photon background;
- Signal/background >1000;
- The concept was successfully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



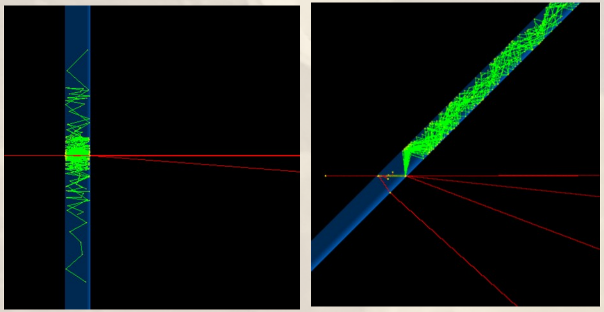

Electrons spectrum reconstructed from the layers of straws with Cherenkov light measurement




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



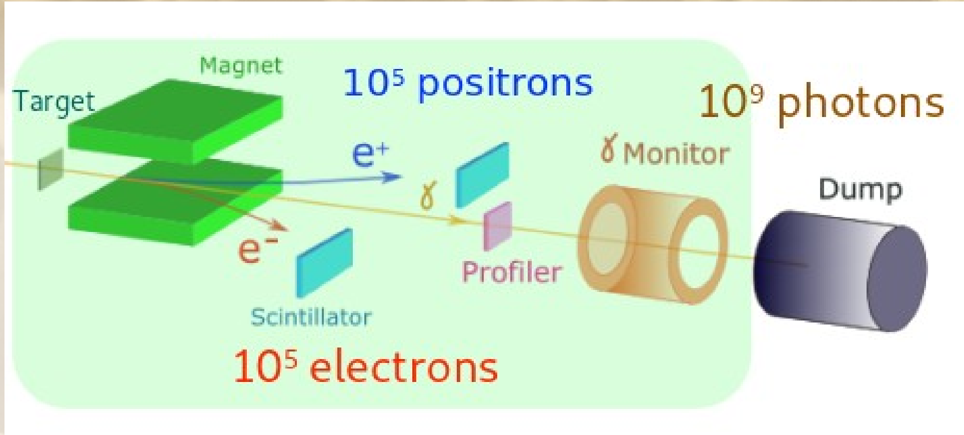
Geant4 simulation of Cherenkov light in the straw with φ = 90º and 45º.



# Photon Detection System

**High number of photon:**

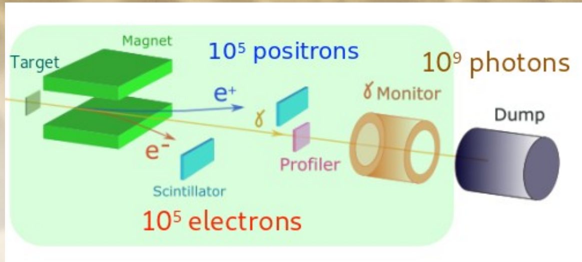
- up to $10^9$ photons;
- summing up to TeV energies;
- Confined in the cone ~0.2 mrad.




**Three subsystems:**

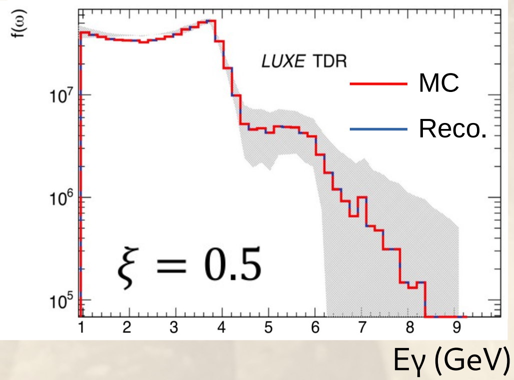
- Photon spectrometer
  - Measure photon energy spectrum and flux.
- Gamma profiler made of sapphire strip sensors:
  - Measure transverse profile of the beam.
- Backscattering calorimeter:
  - Measure flux.

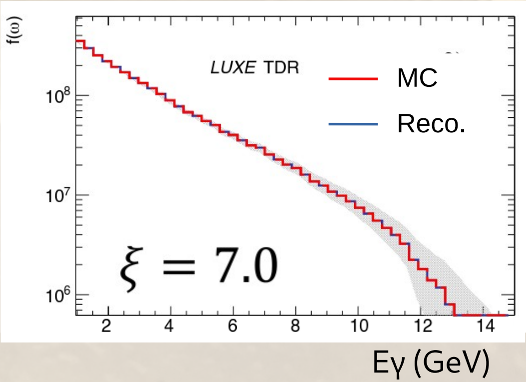
# Photon Spectrometer




- Tungsten convertor target (10 μm) generates $10^4$ - $10^5$ electron/positron pairs;
- Dipole magnet: 1.4 T, 1.3 m;
- Electrons and positrons are detected 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;

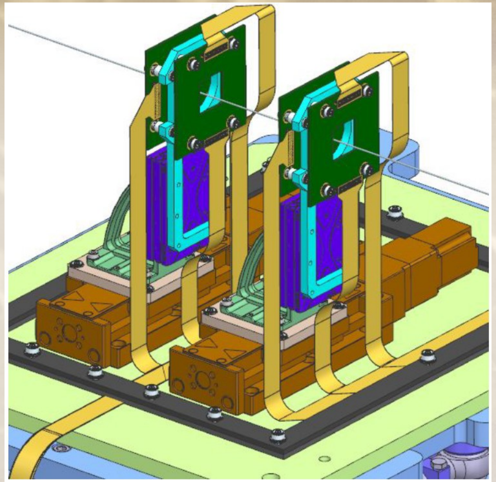
Reconstructed photon spectrum for different laser intensity



# Gamma Beam Profiler

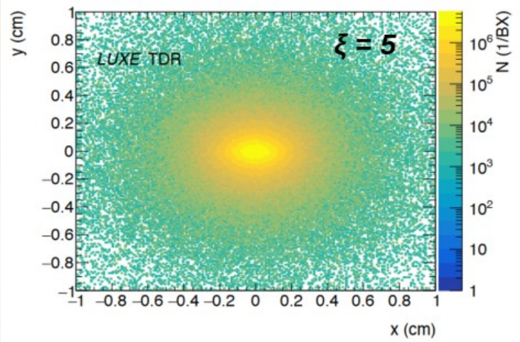
For linearly polarized laser the asymmetry in transverse profile of photon beam depends on laser intensity (ξ).

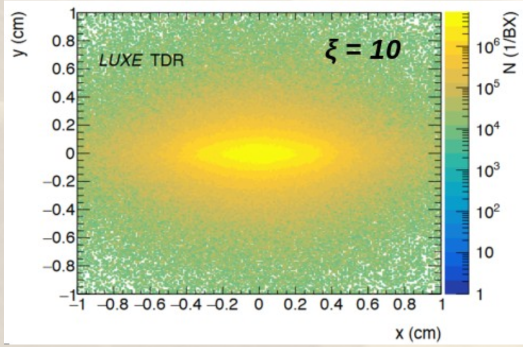


**Design:**

- Two sapphire strip detectors placed on a table movable with micron precision in both directions perpendicular to beam 11.5 m from the IP;
- 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.

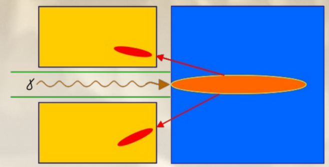
- Spatial distributions of the Compton photons hitting sapphire sensor for different laser intensities;
- Laser polarization results in x/y asymmetry.
- Measure laser intensity with 2.5% precision.



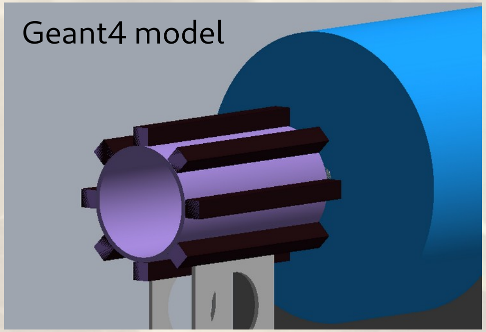



# Photon Flux Monitor

For ξ > 1, Nγ > $10^8$ / BX



- 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.

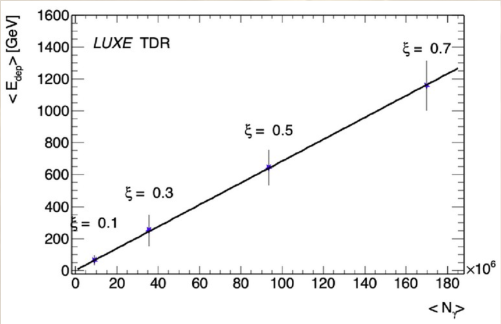
## Performance in simulation:

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

## Performance in beam test:

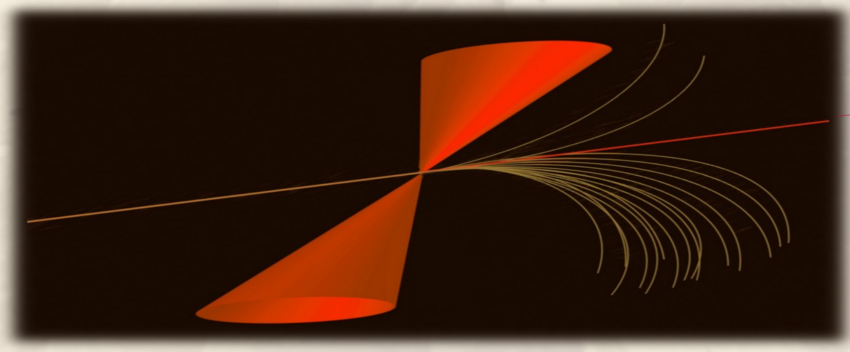
- Three prototypes: lead glass block coupled to PMT.
- Electron beam 60 MeV, up to 25 pC (~$10^8$ e-).
- Good agreement between measurements and beam charge provided by the beam monitor.

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