High-rate electron detectors to study Compton scattering in non-perturbative QED

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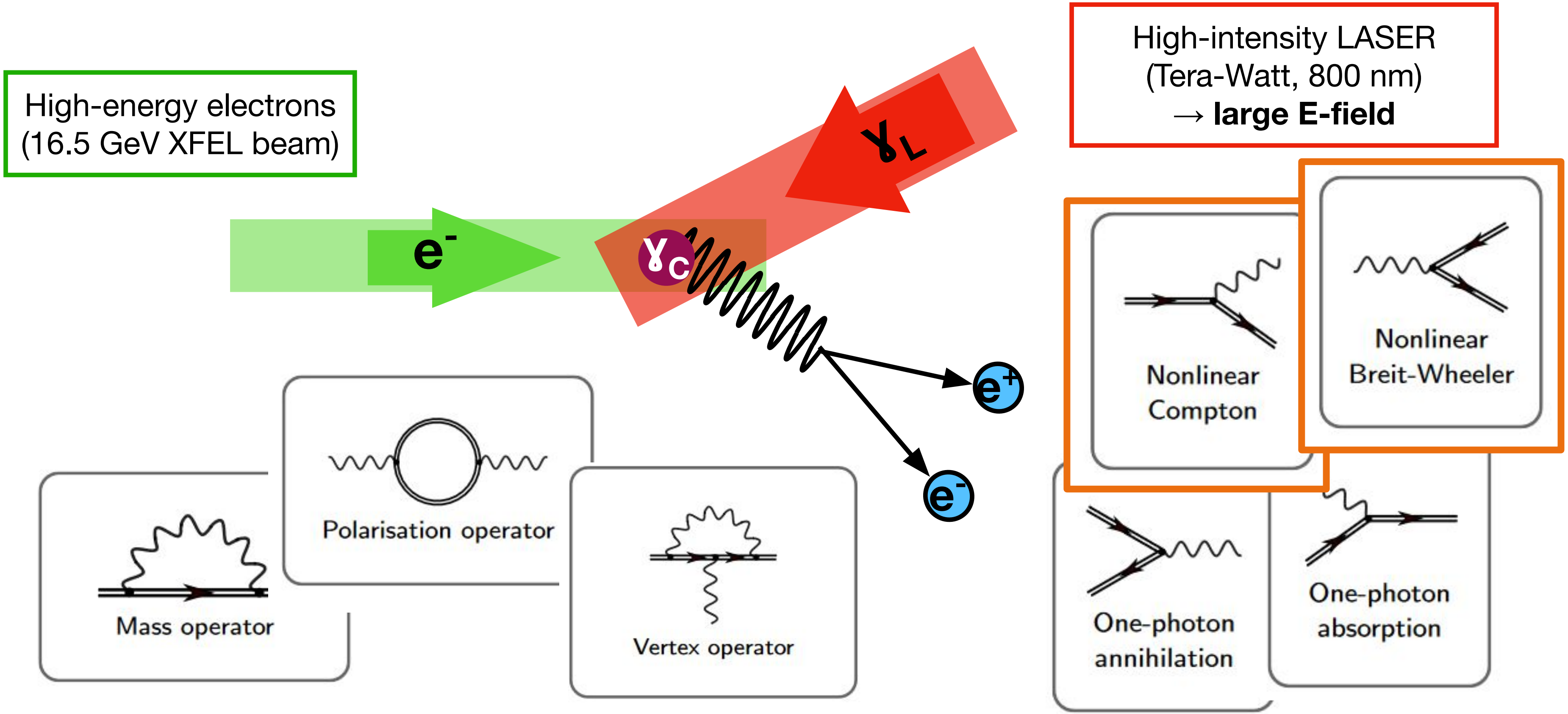
Detector R&D Retreat 2024, 19.01.2024

HELMHOLTZ LUXE FTX Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG CLUSTER OF EXCELLENCE QUANTUM UNIVERSE DESY.

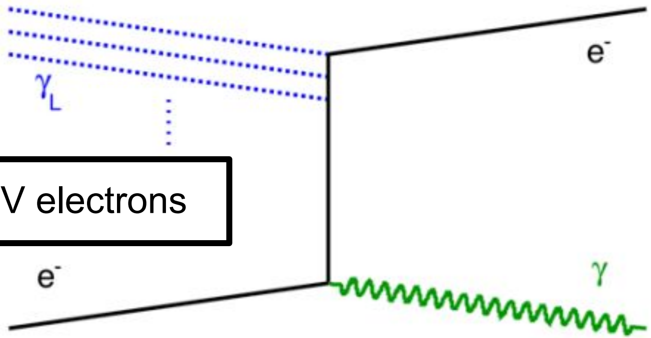
LUXE - Laser Und XFEL Experiment



LUXE - Laser Und XFEL Experiment

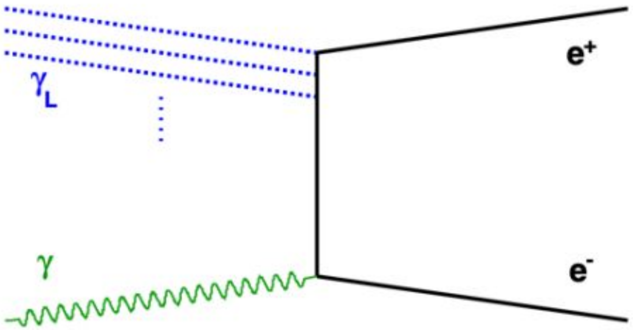
High intensity laser

16.5 GeV electrons



Non-linear Compton Scattering

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



Breit-Wheeler pair production

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

Goal of LUXE

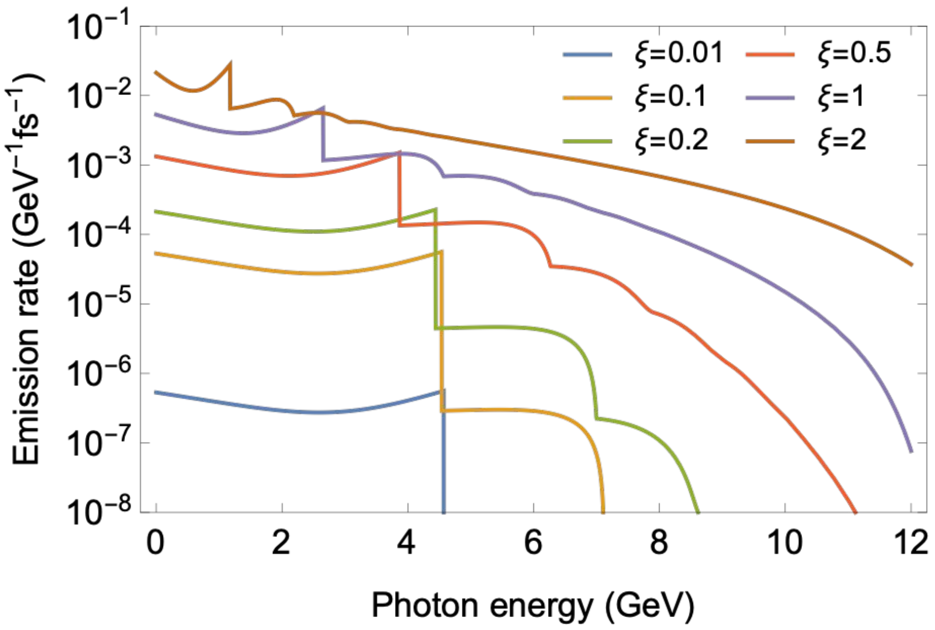
- Measure particle interactions in strong-field QED regime for different laser intensity values ξ

$$\xi = \frac{m_e}{\omega_L} \sqrt{I/I_{\mathrm{cr}}}$$

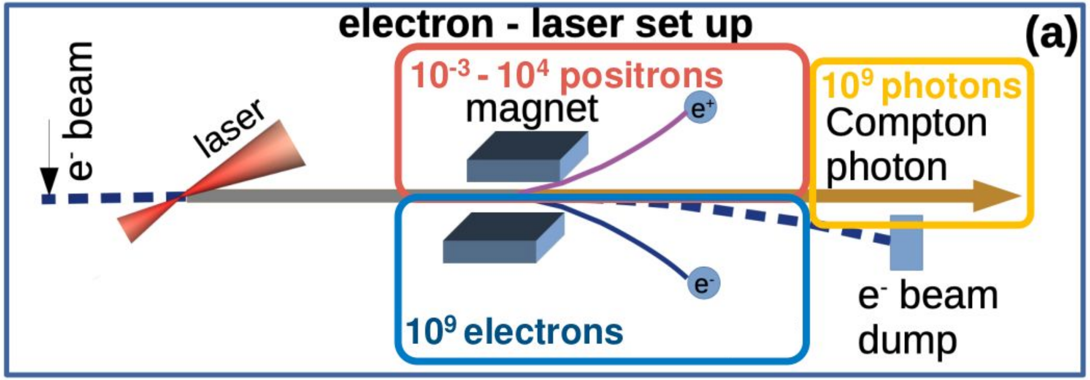
- Example measurement: compton energy spectra

→ Small shift in Compton edge

→ High number of electrons expected



Challenges of LUXE

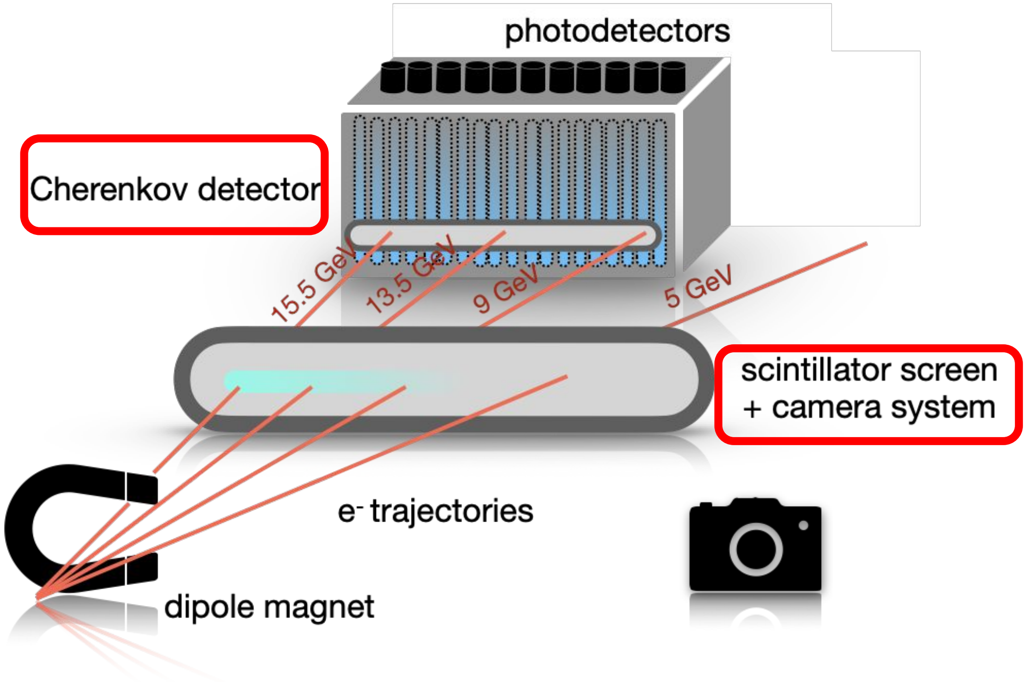


- Goal: Detection of electron, positron and photon fluxes and energy spectra
- Wide range of technologies that are adapted specifically for the rates and particle types
- LUXE foresees two complementary detector technologies per location

→ Cross-calibration possible

→ Low systematic uncertainties

The Electron Detection System (EDS)



- Behind dipole: Electrons will be fanned out with respect to their energy

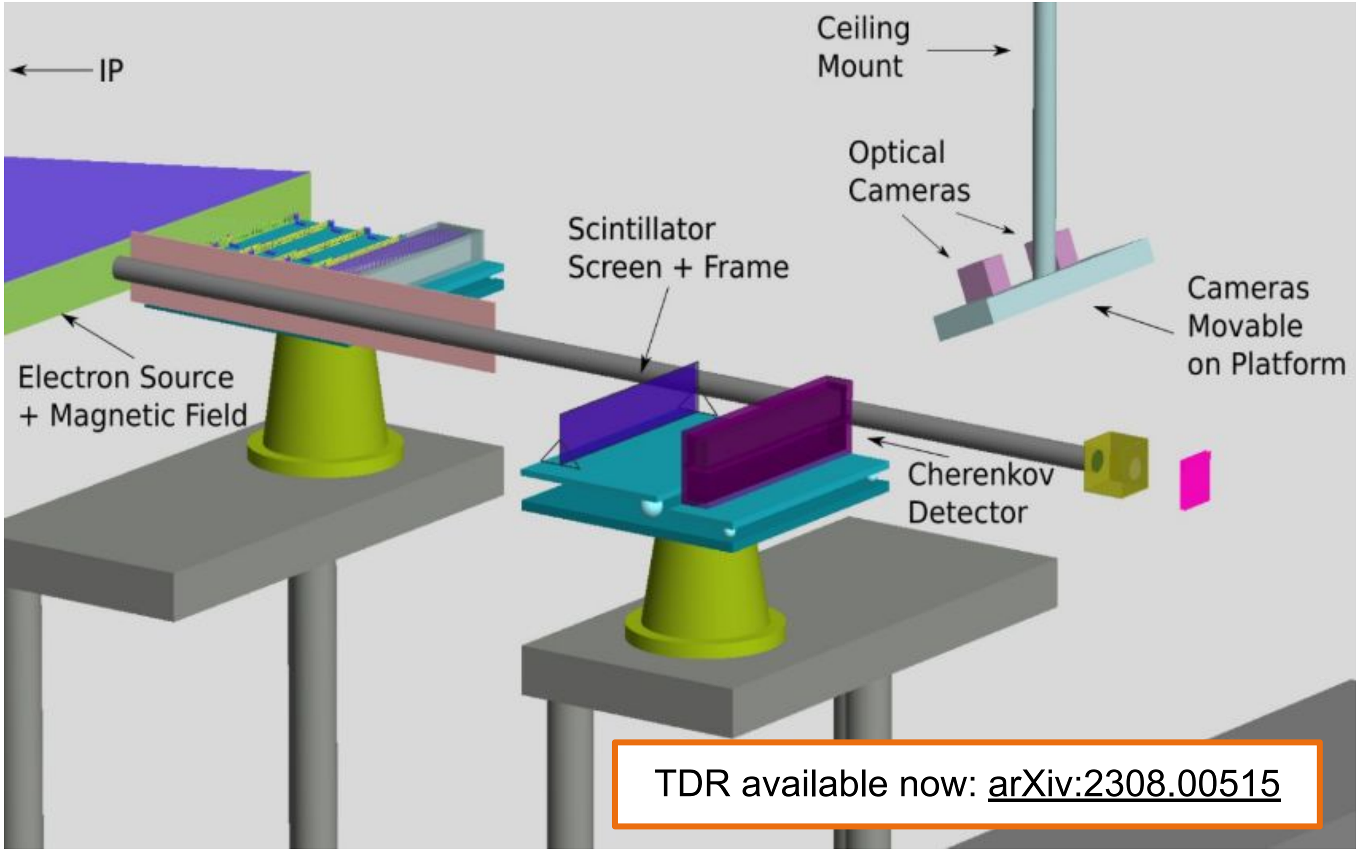
- Scintillator screen and camera with **ΔE/E < 1%** and **Δx ~ 500 μm**

  → Light yield proportional to number of electrons

- Segmented Cherenkov detector with **ΔE/E ~ 2%** and **Δx ~ 3 mm**

  → Stainless-steel tubes aligned in a grid perpendicular to beam axis

The Electron Detection System (EDS)

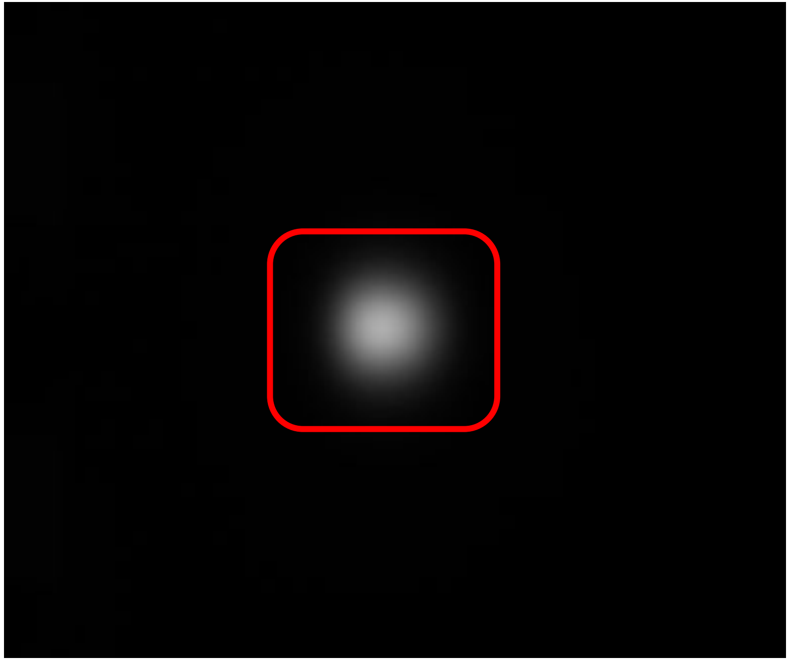


TDR available now: arXiv:2308.00515

The scintillator screen and camera system

Reconstruction algorithm

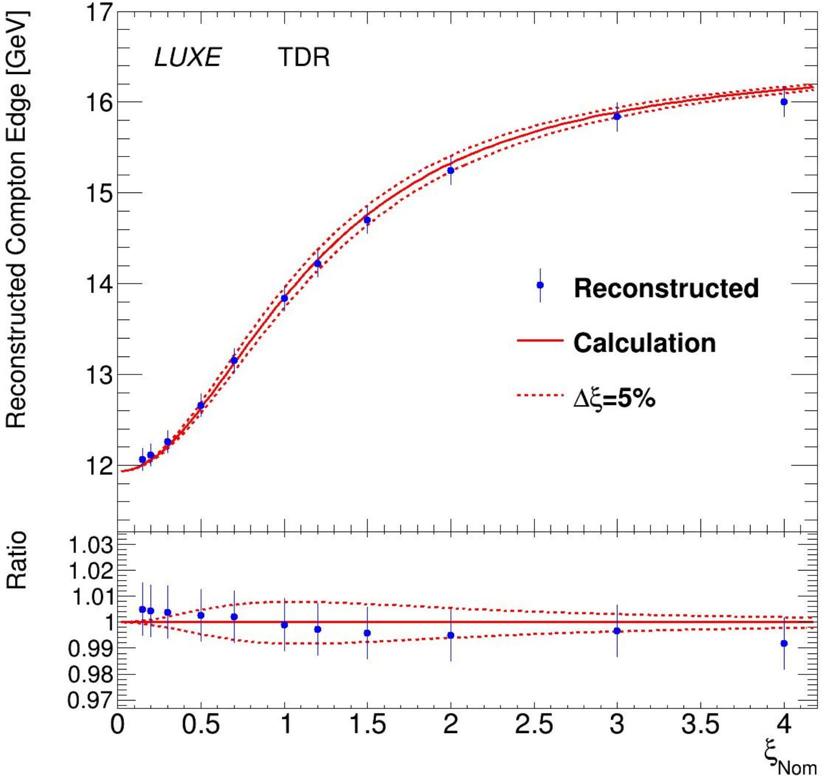
- If electron passes screen
  - Light emitted and recorded by camera
  - Position on screen in relation to electron energy
- Camera data contains data about CMOS count/gray value per pixel
- Within area of interest $\rightarrow$ Obtain mean and standard deviation from a gaussian fit



The scintillator screen and camera system

Reconstruction algorithm - Simulation

- Take peak of edge, compare to theoretical expectation
- Generally good results, could be better in the low-ξ and high-ξ
- Only for ξ < 0.5 reconstructed edge points lie outside Δξ = 5%



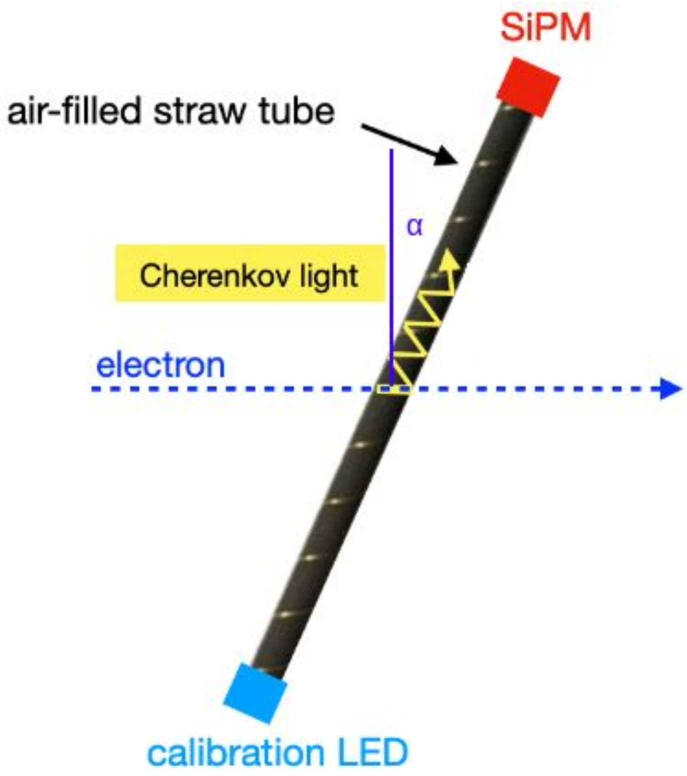
The Cherenkov detector

Basic idea

- Reflective, air filled straws aligned next to each other

- Cherenkov light produced by electrons is reflected towards Silicon-Photomultipliers (SiPMs)

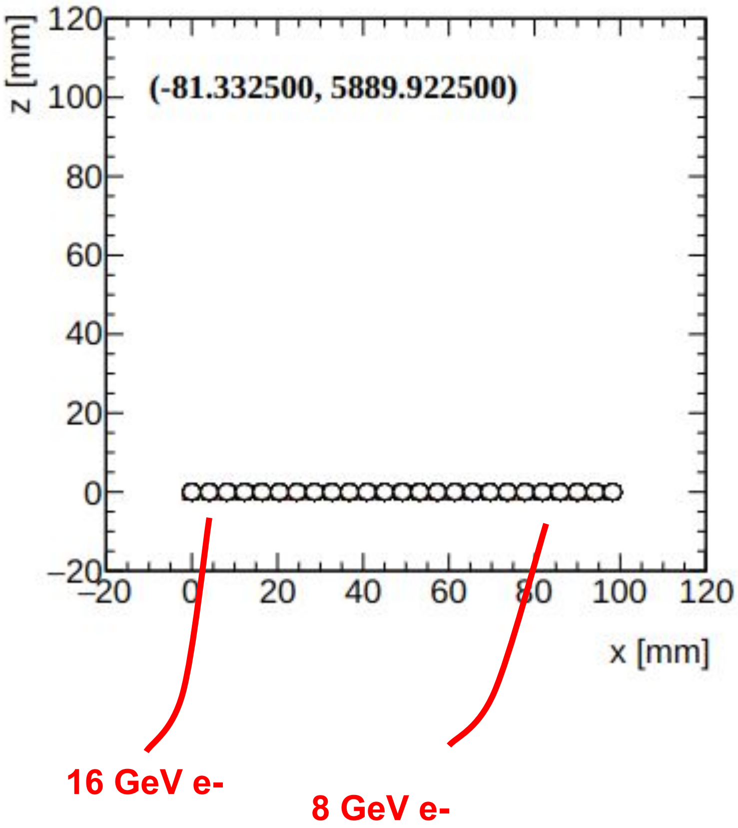
- Many parameters have to be optimized:
  - Straw dimensions, material, reflectivity and angle α
  - SiPM dimensions and characteristics



The Cherenkov detector

Reconstruction algorithm

- Single row of straws

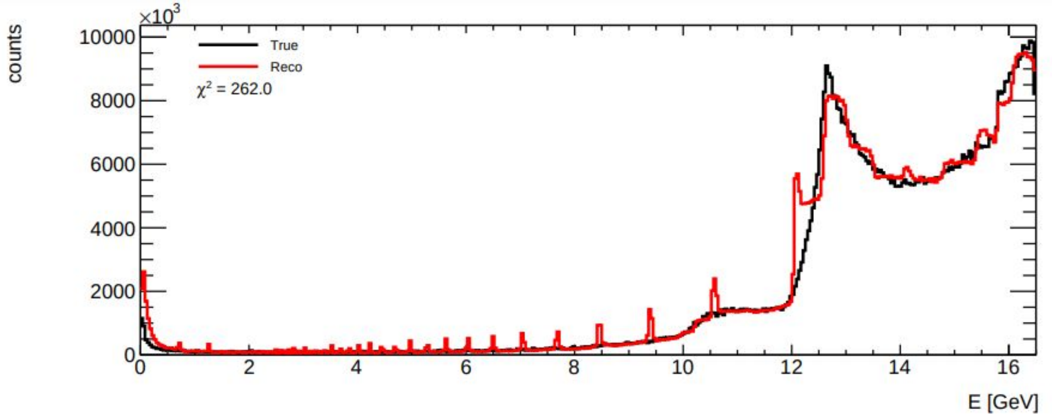


The Cherenkov detector

Reconstruction algorithm

- Single row of straws

- Compton energy reconstruction via finite-impulse-response-filter method



- Convolution between
  - Compton edge position $$R_d(i) = \sum_{k=-N}^{k=N} h_d(k) \cdot g_d(i-k)$$
  - Gaussian filter $$h_d(k) = -k \exp -\frac{k^2}{2\sigma^2}$$

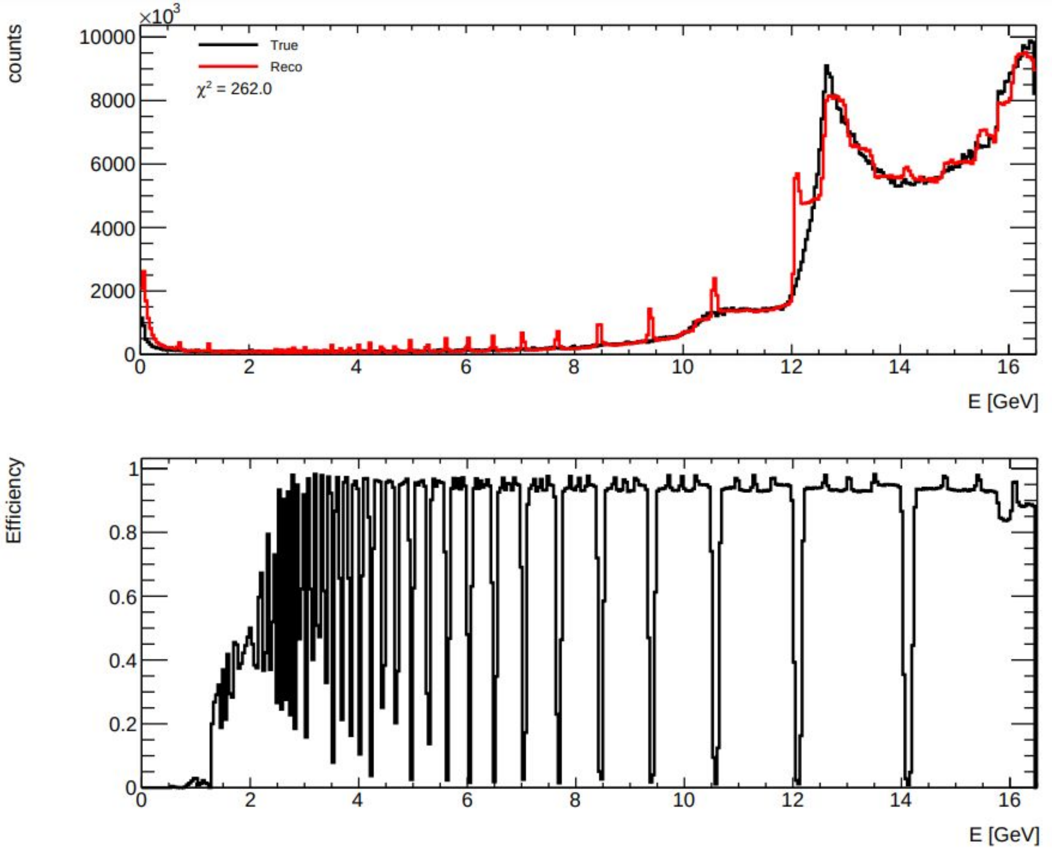
The Cherenkov detector

Reconstruction algorithm

- Single row of straws

- Peak structure in Compton energy fit

- Electron detection efficiency drops periodically



The Cherenkov detector

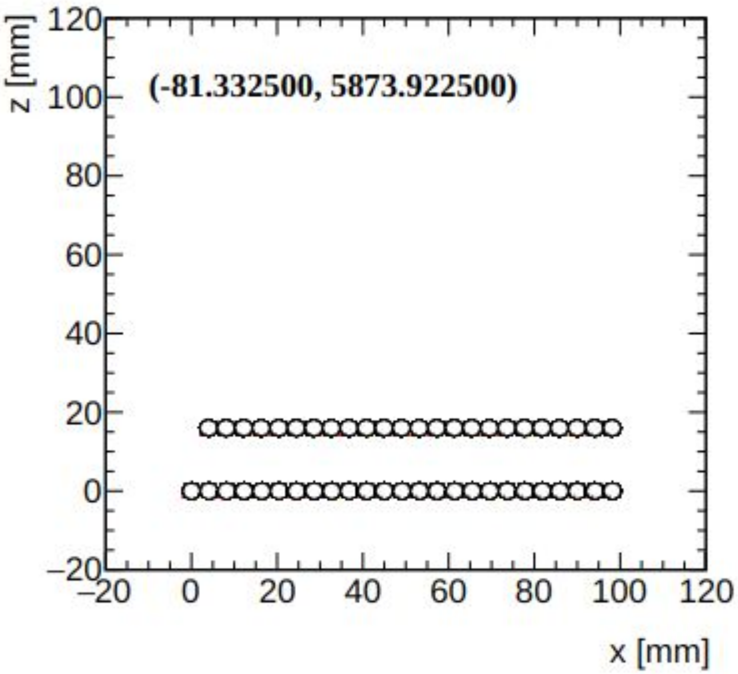
Reconstruction algorithm

- Single row of straws

- Peak structure in Compton energy fit

- Electron detection efficiency drops periodically

→ Second row of straws

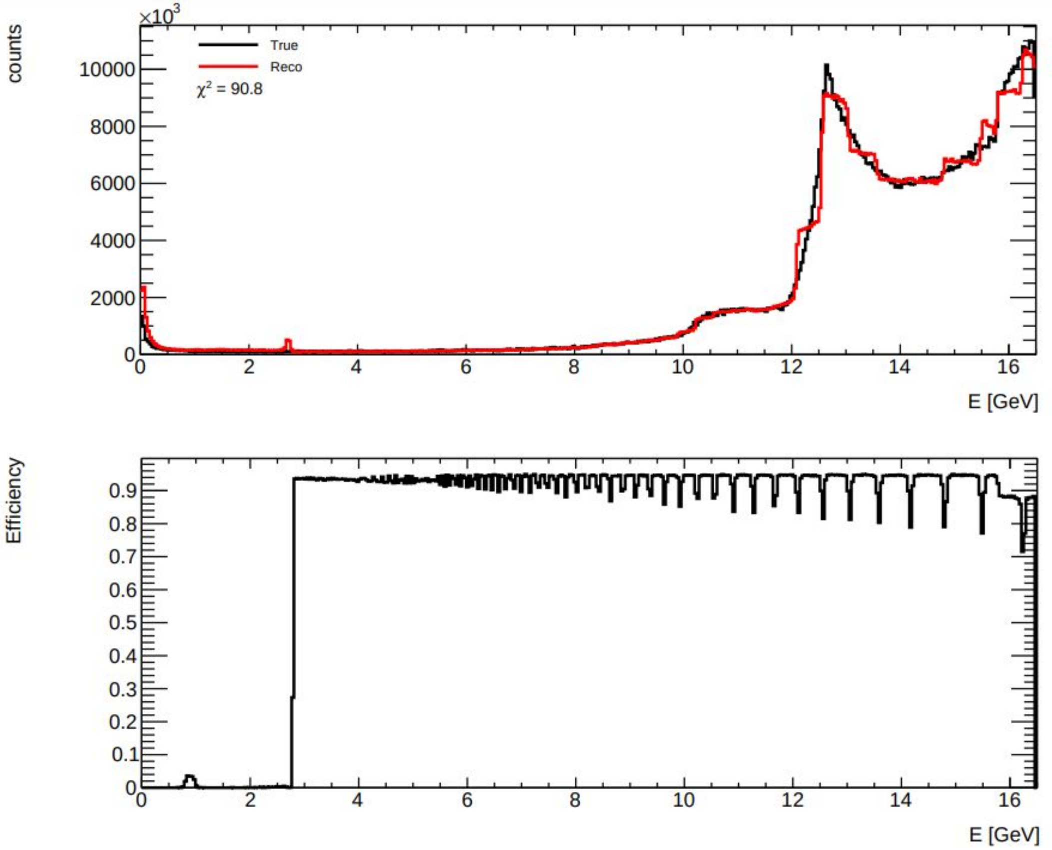


The Cherenkov detector

Reconstruction algorithm

- Single row of straws
- Peak structure in Compton energy fit
- Electron detection efficiency drops periodically

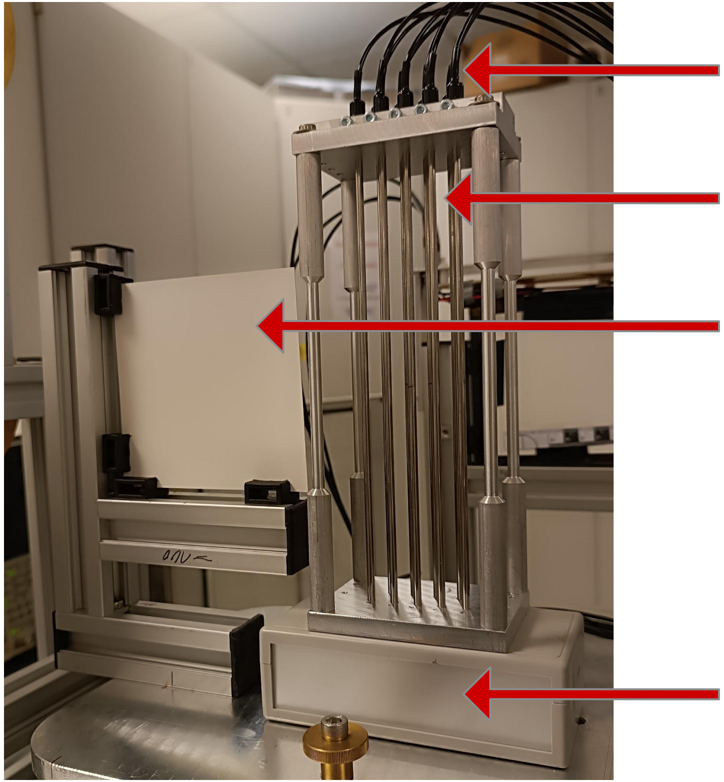
→ Second row of straws recovers this effect partially



The EDS prototype

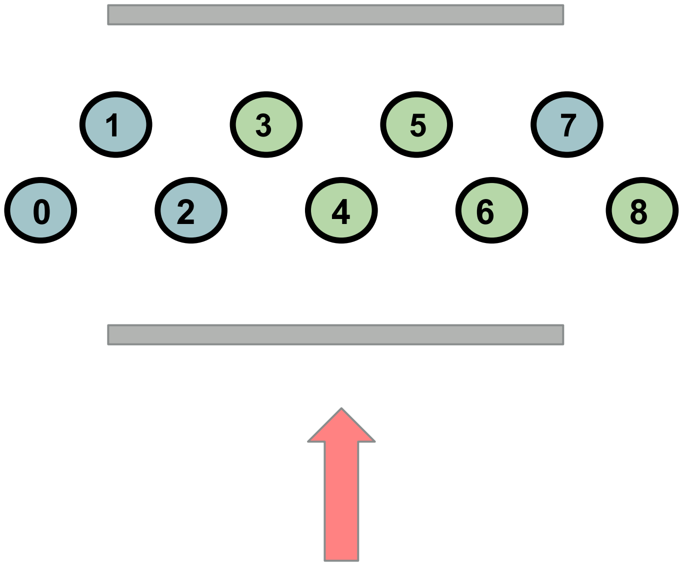
Setup

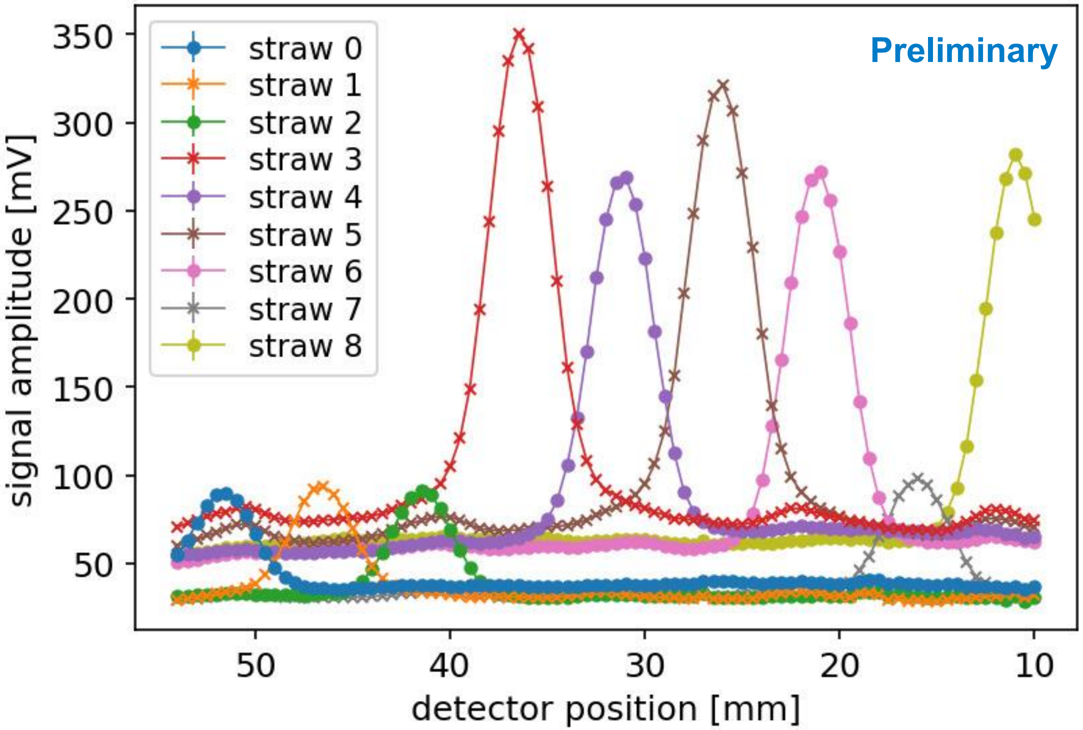
- Straws with 3 mm inner diameter
- SiPMs from Hamamatsu and Onsemi
- Screens with different light yield or resolution
- Straws and screen movable (left-right, tilting)



The EDS prototype

Testbeam results

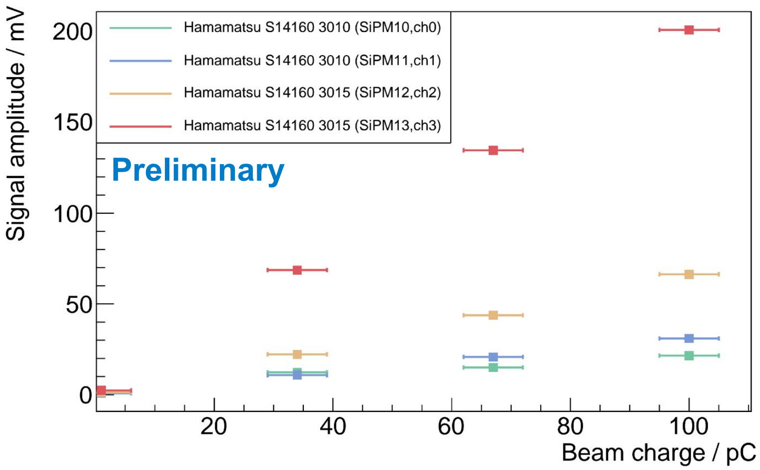




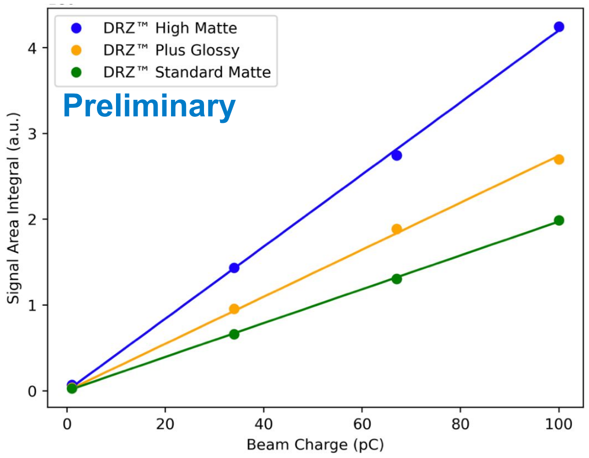
The EDS prototype

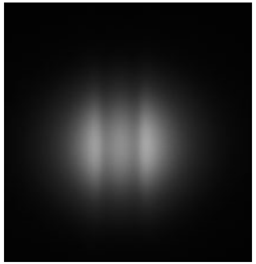
Testbeam results

Light yield measured in different straws



Light yield measured of different screens





Beam spot with straw in front imaged on Scint. Screen

- First testbeam results from on-campus facility ARES
- Various beam parameters under test (bunch charge, electron energy, stability,...)
- Analysis ongoing → BUT: Linear responses achievable

Future plans

- Evaluation of recent testbeam measurements

  → At <u>ARES</u> facility at DESY

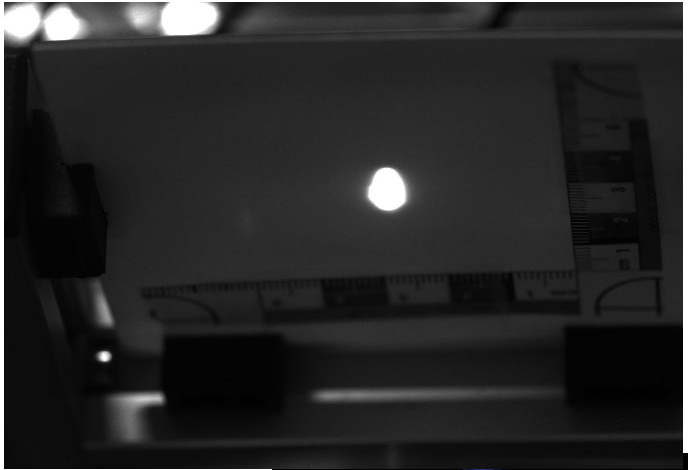
  → 1 pC - 100 pC electron beam with 150 MeV

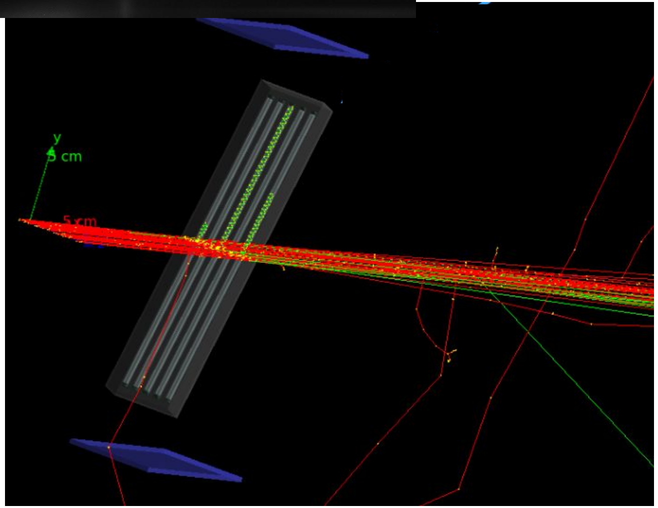
- Extended simulation studies

- Data acquisition for camera readout and analysis

- Design and construction of a 16 channel prototype

- Physics measurement at the E320 experiment at SLAC





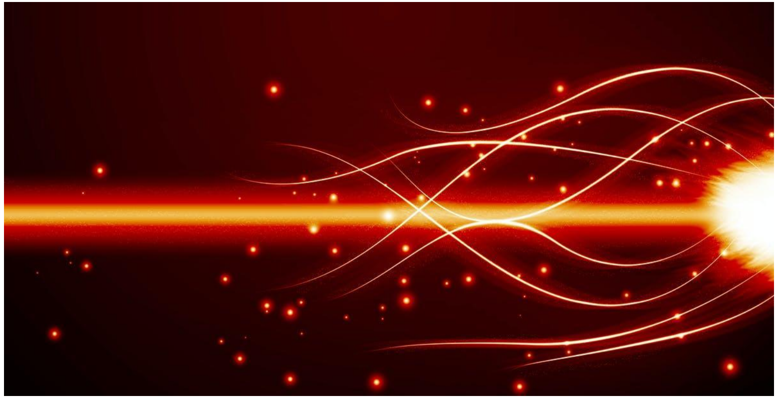
Conclusion

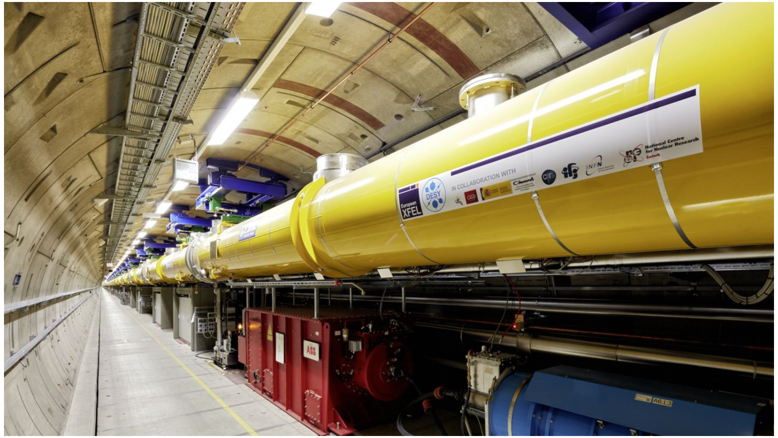
- LUXE will explore the regime of non-perturbative strong-field QED

- Due to the redundant detector setups, high-resolution measurements will be achieved.

- The concept of the electron detection system is a suitable system.

- Simulation, testbeam and laboratory studies will pave the way for the high-rate electron detector.



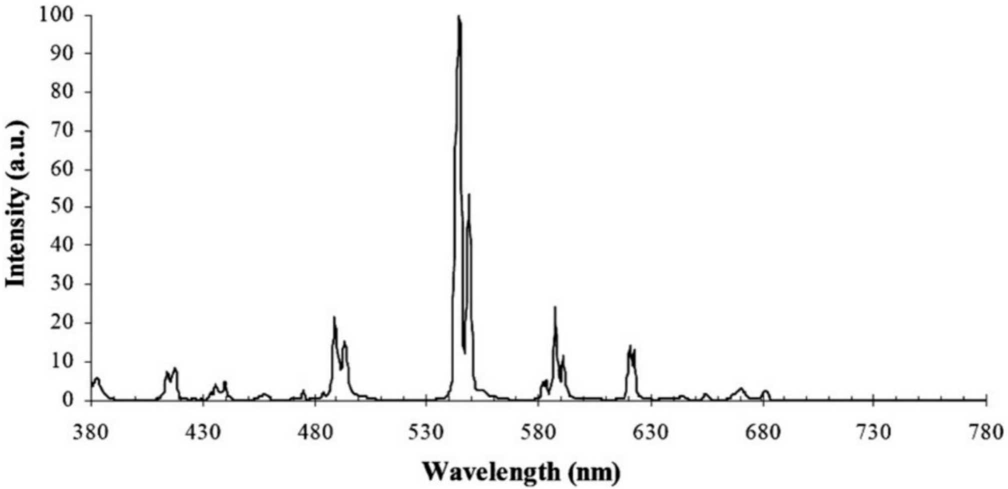


Backup

The scintillator screen and camera system

Screen Properties

- Gadolinium Oxysulfide doped with Terbium
- High number of emitted photons (543 nm)
- Linear behaviour
- Decay constant ~ 600 μs
- Radiation-hard (up to 100 MGy)



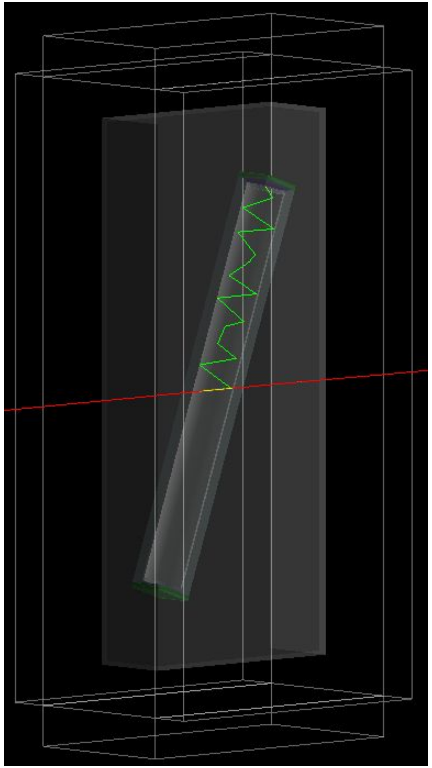
Camera Properties

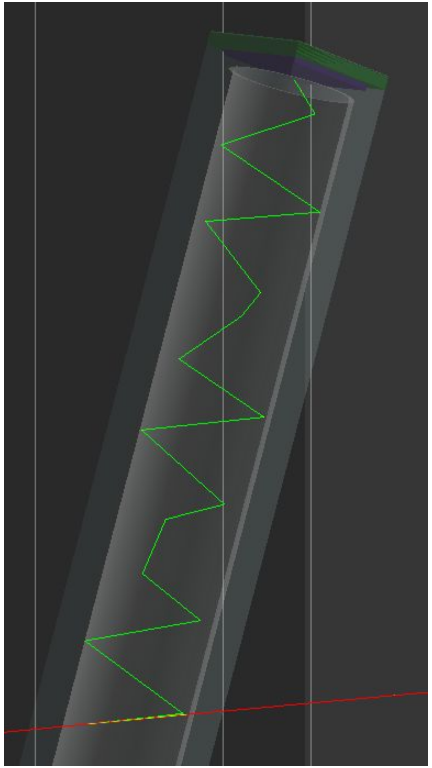
- Basler cameras with 2K and 4K resolution
- Monochromatic CMOS sensors
- Optical filters to accept light of 543 nm
- 70% quantum efficiency

The Cherenkov detector

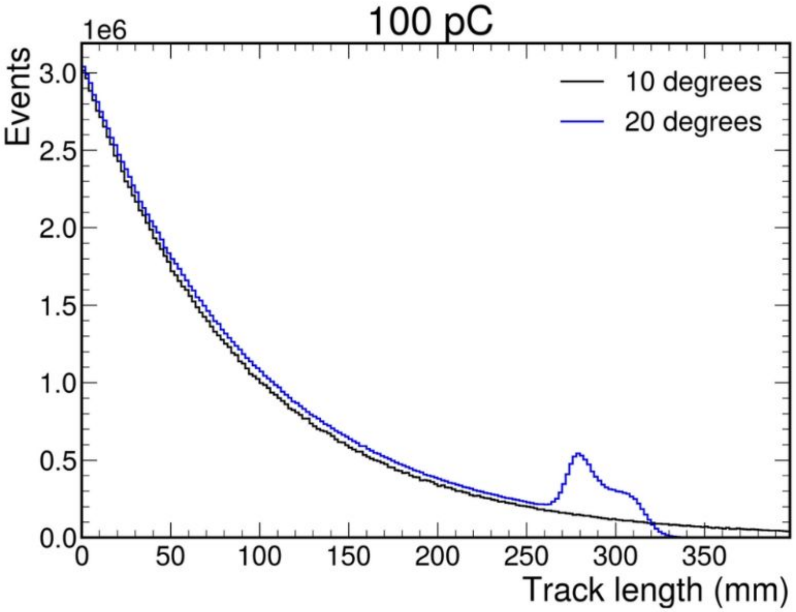
Simulation studies

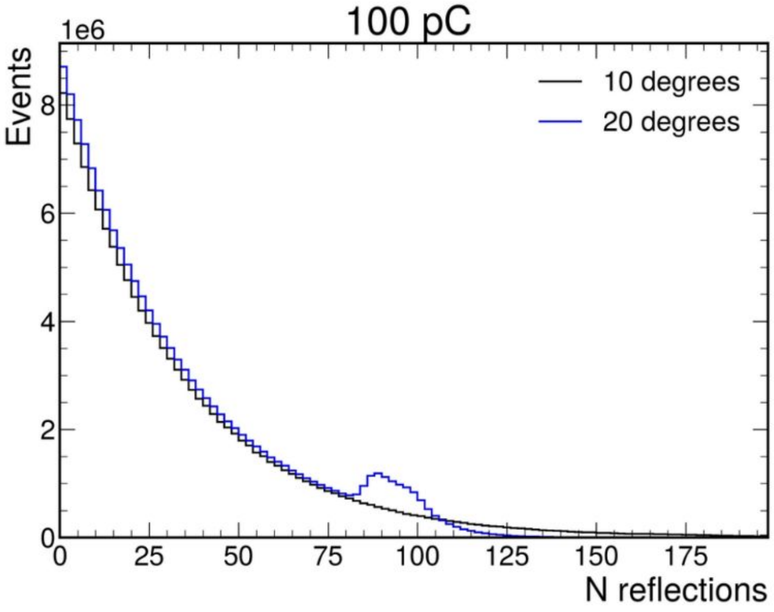
- GEANT4 used to simulate electron interactions, detector design and materials
- Cherenkov light and optical properties simulated
- Straw parameters e.g. **dimensions**, **reflectivity** or the **angle** are considered





The Cherenkov detector





- Optical effects can be studied in detail
- Here: For an angle of 20° → Higher probability of photons reaching the end of the tube