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

Antonios Athanassiadis[1,2], John Hallford[1,3], Louis Helary[1], Luke Hendriks[1,3], Ruth Magdalena Jacobs[1], Jenny List[1], Gudrid Moortgat-Pick[2], Evan Ranken[1], Stefan Schmitt[1], Matthew Wing[1,3]

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[1] Deutsches Elektronen-Synchrotron (DESY)
[2] Universität Hamburg
[3] University College London (UCL)

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

LUXE - Laser Und XFEL Experiment

- New experiment at DESY Hamburg to probe non-perturbative **strong-field** QED regime (SFQED)

High intensity laser

16.5 GeV electrons

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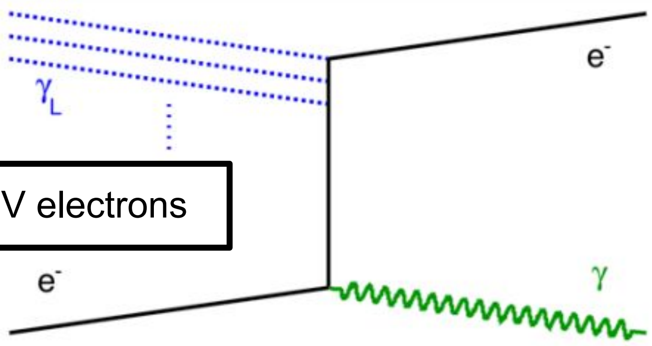

Non-linear Compton Scattering

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

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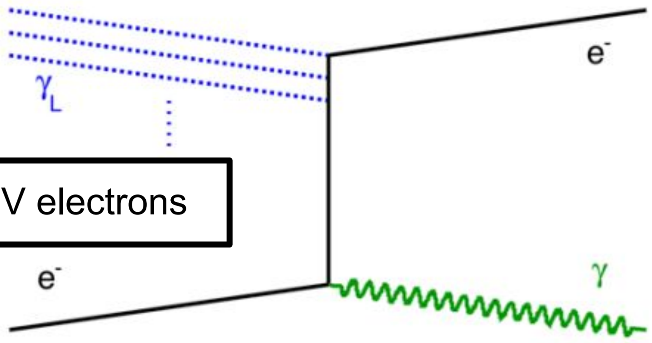

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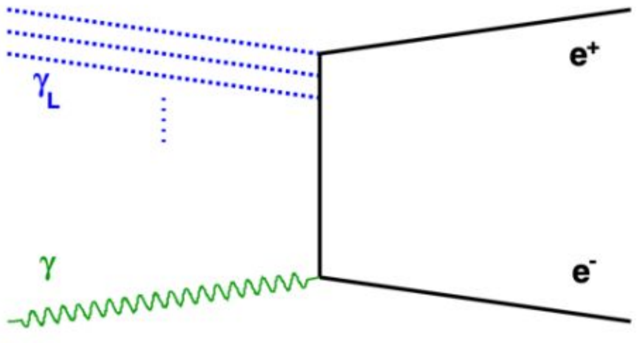

Breit-Wheeler pair production

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

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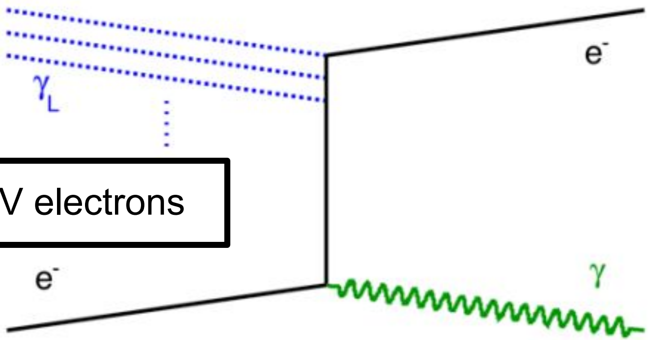

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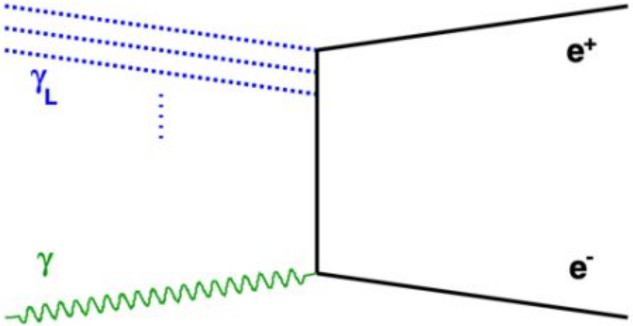

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Goal of LUXE

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

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

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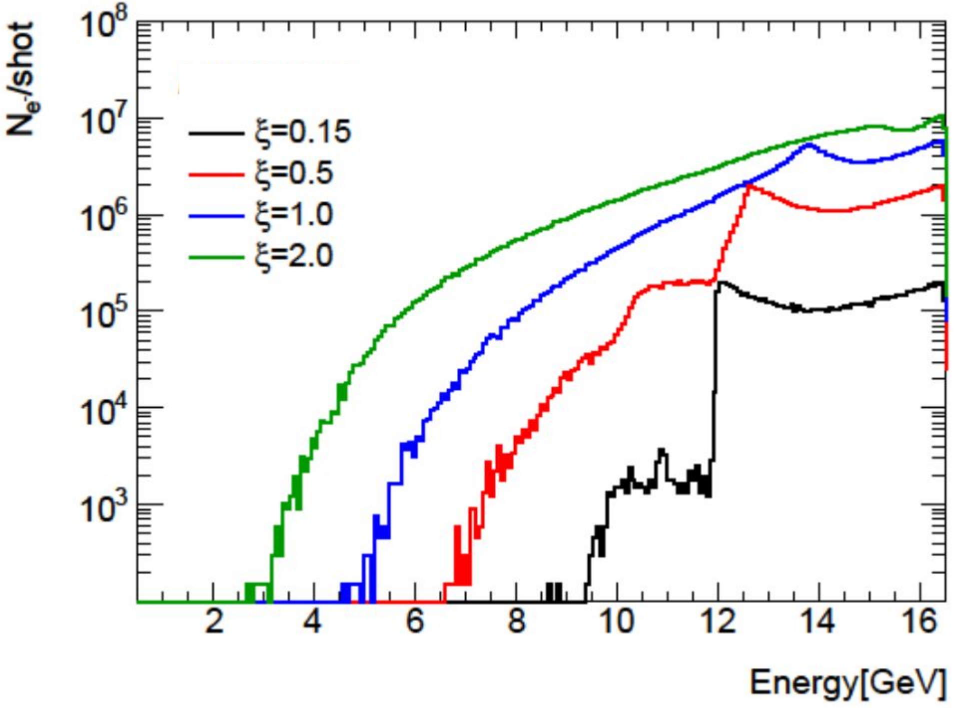
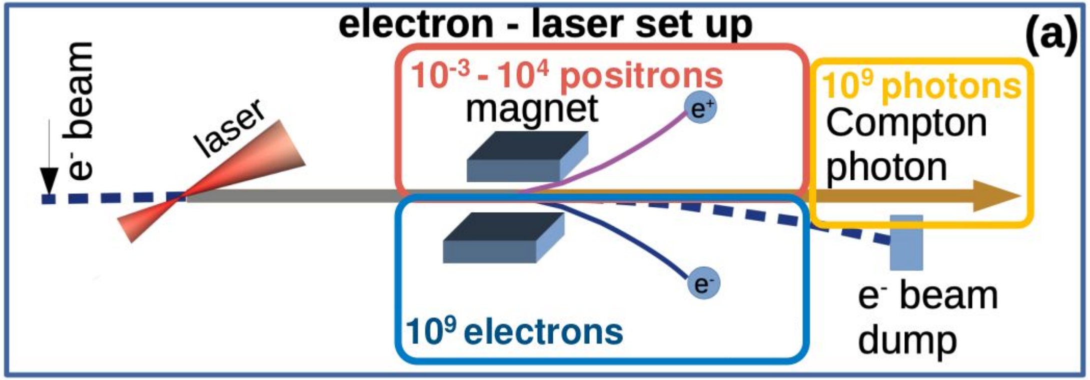
- Example measurement: compton electron energy spectra

➤ Small shift in Compton edge

➤ High number of electrons expected



Challenges of LUXE



- Wide range of technologies that are adapted specifically for the rates and particle types

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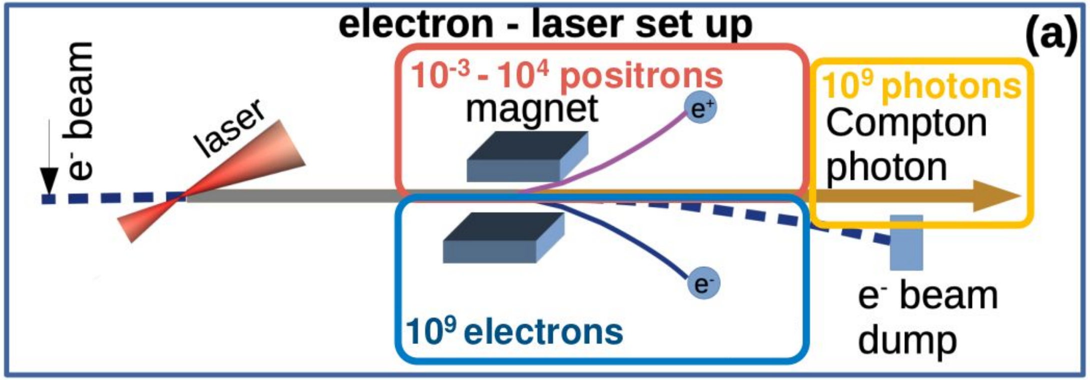
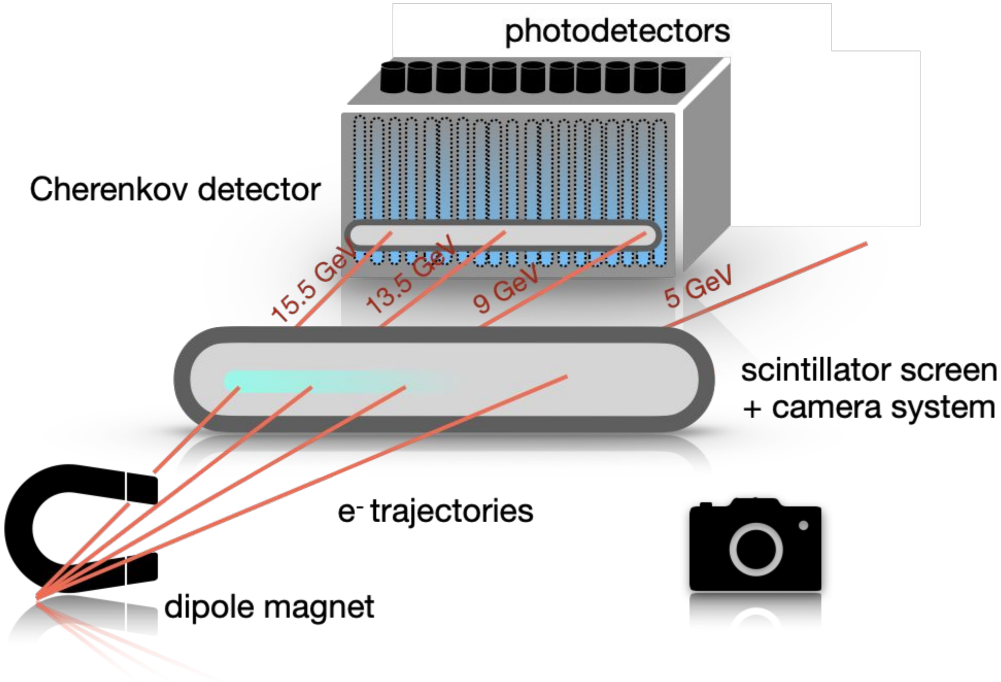


- Wide range of technologies that are adapted specifically for the rates and particle types

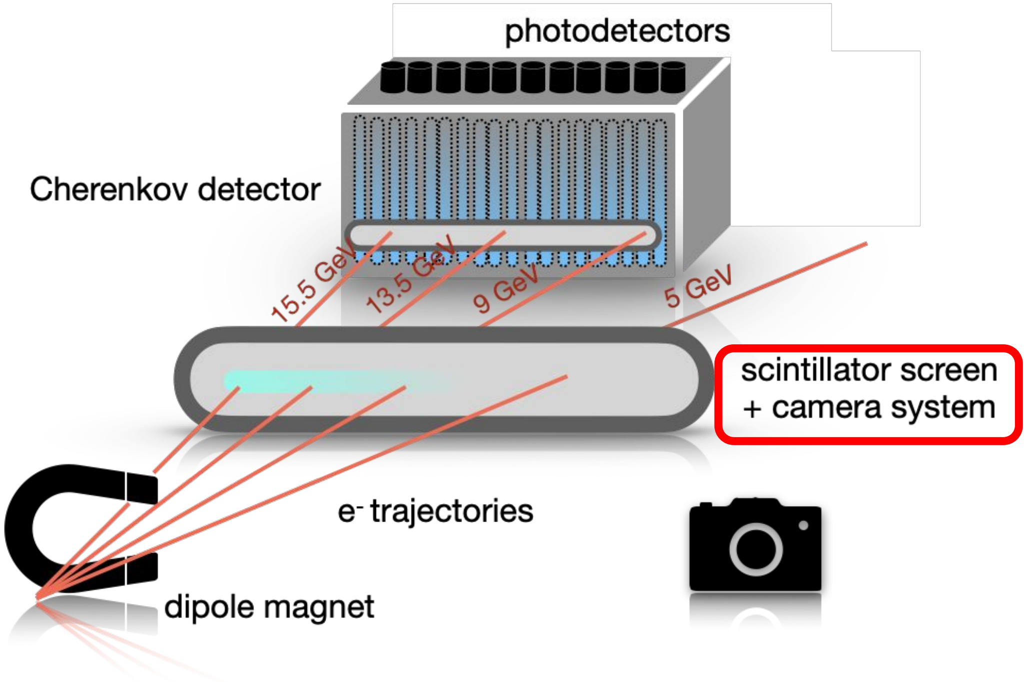
- LUXE foresees two complementary detector technologies per location
  - Cross-calibration possible
  - Low systematic uncertainties

The Electron Detection System



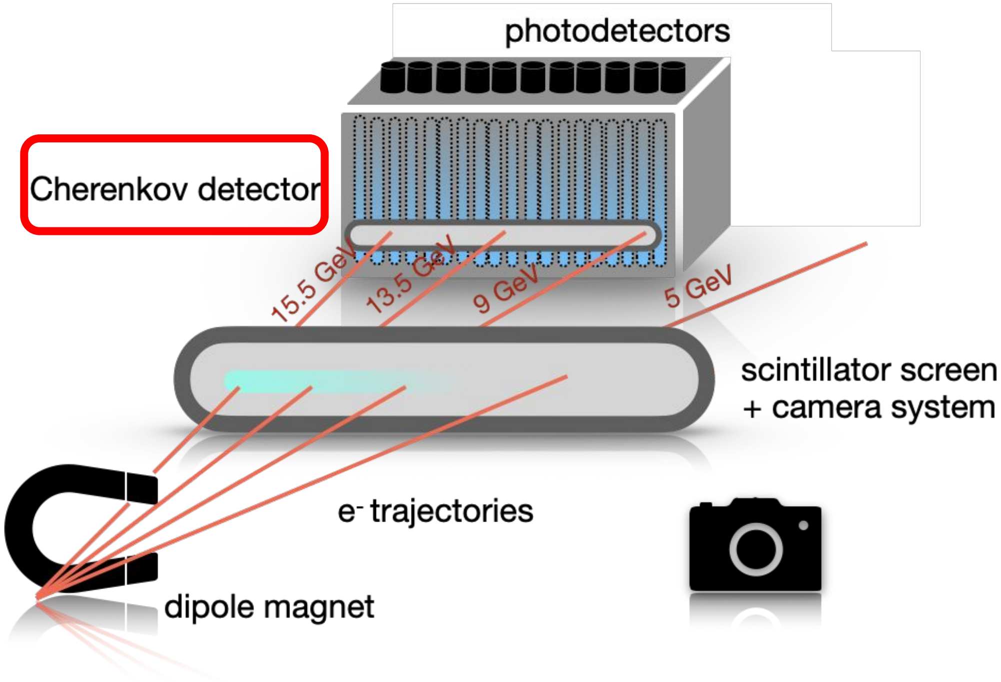
- Behind dipole: Electrons will be fanned out with respect to their energy

The Electron Detection System



- Behind dipole: Electrons will be fanned out with respect to their energy
- Scintillator screen and camera with $\Delta E/E < 1\%$ and $\Delta x \sim 500\mu m$
  - ➤ Light yield proportional to number of electrons

The Electron Detection System

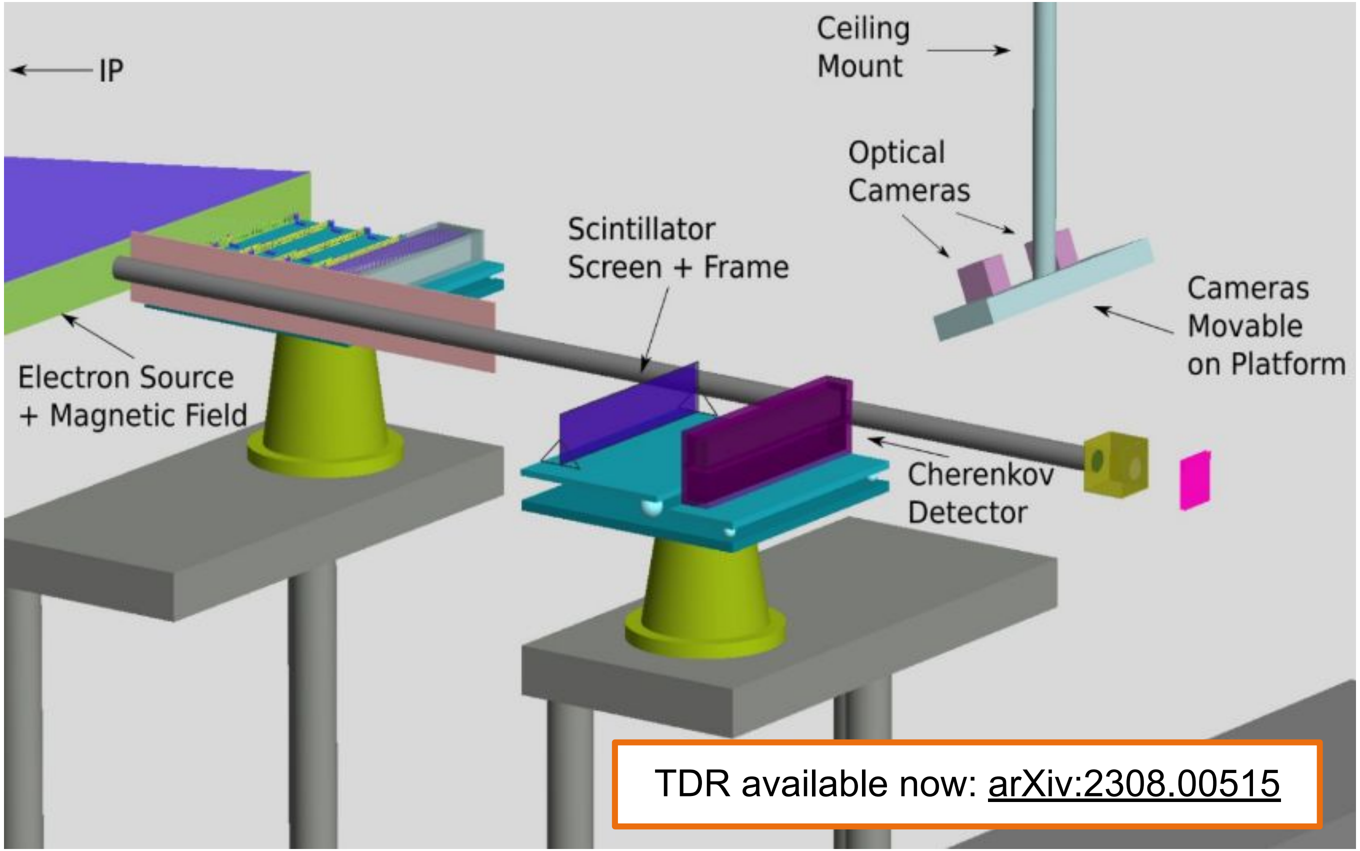


- Behind dipole: Electrons will be fanned out with respect to their energy

- Scintillator screen and camera with $\Delta E/E < 1\%$ and $\Delta x \sim 500\mu m$
  - Light yield proportional to number of electrons

- Segmented Cherenkov detector with $\Delta E/E \sim 2\%$ and $\Delta x \sim 3mm$
  - Stainless-steel tubes aligned in a grid perpendicular to beam axis

The Electron Detection System

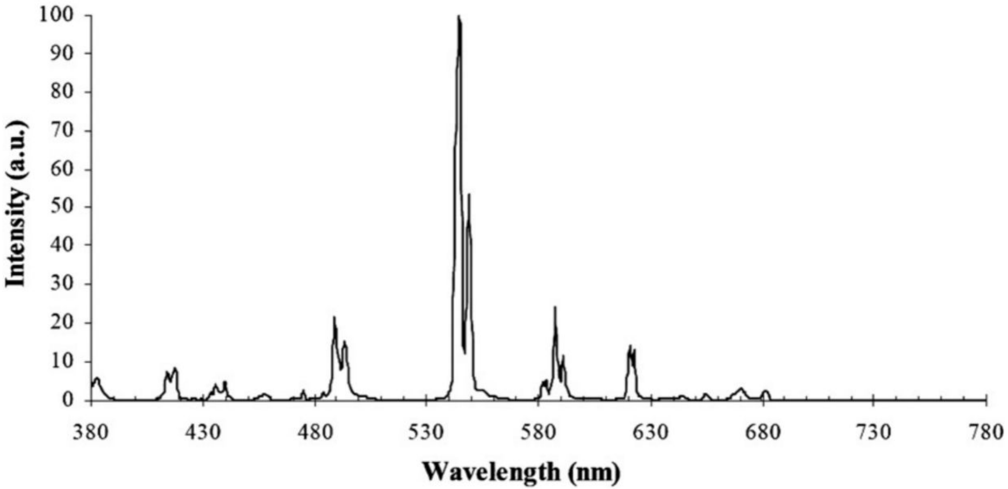


TDR available now: arXiv:2308.00515

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)



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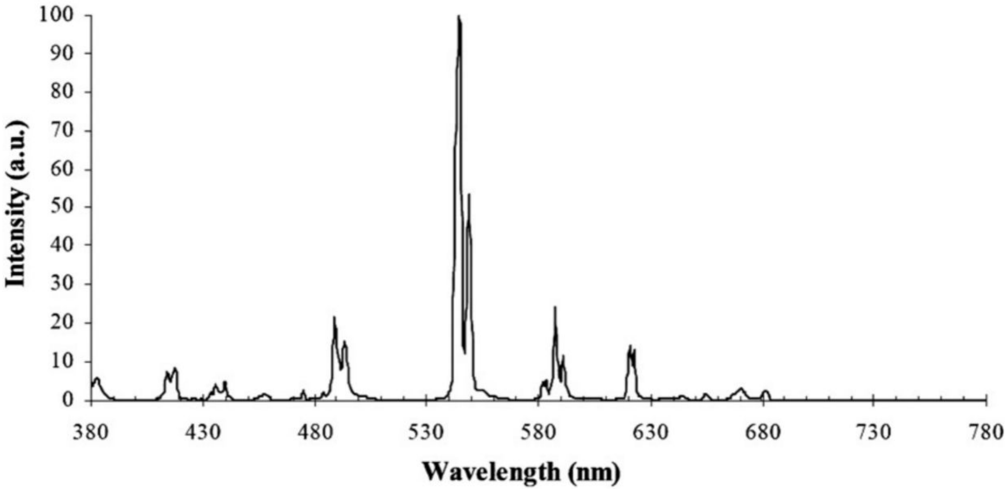


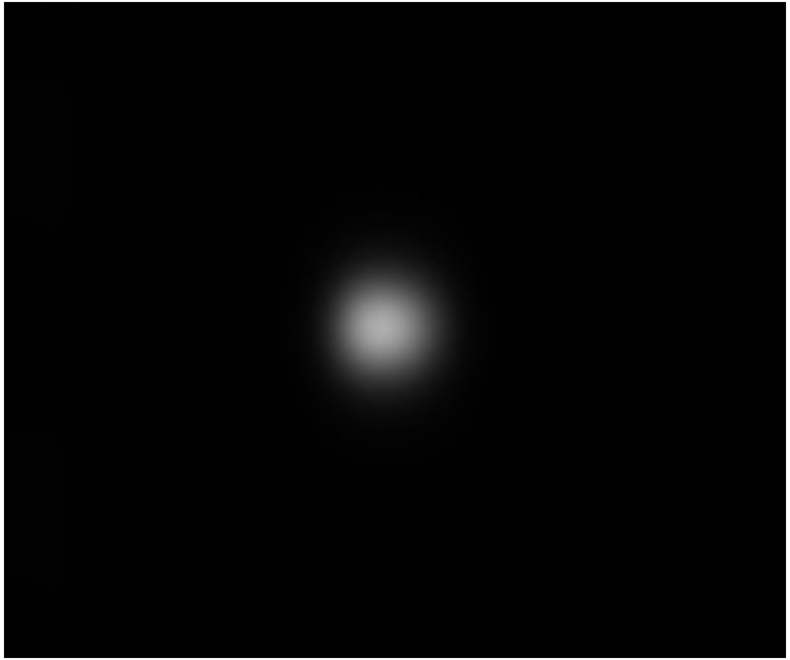
Camera Properties

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

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



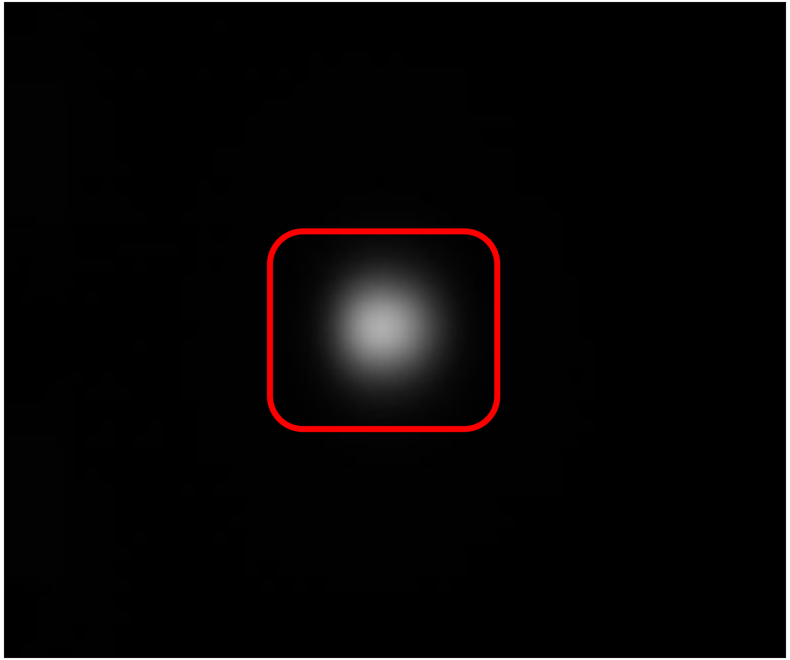
The scintillator screen and camera system

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

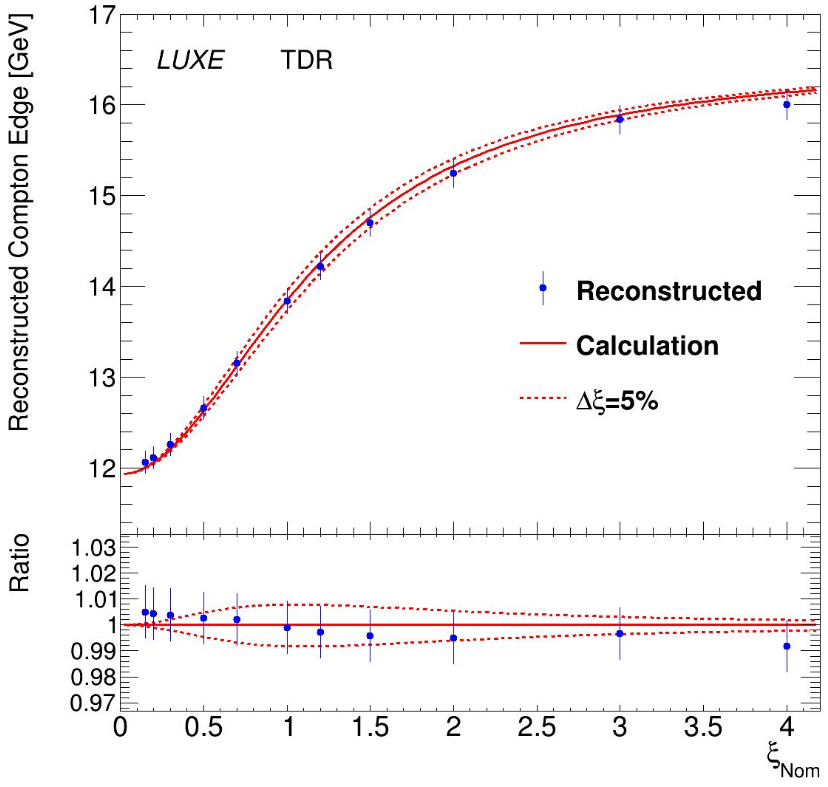
- Within area of interest ➤ Obtain mean and standard deviation from a gaussian fit



The scintillator screen and camera system

Reconstruction algorithm - Simulation

- Take peak of edge, compare to theoretical expectation



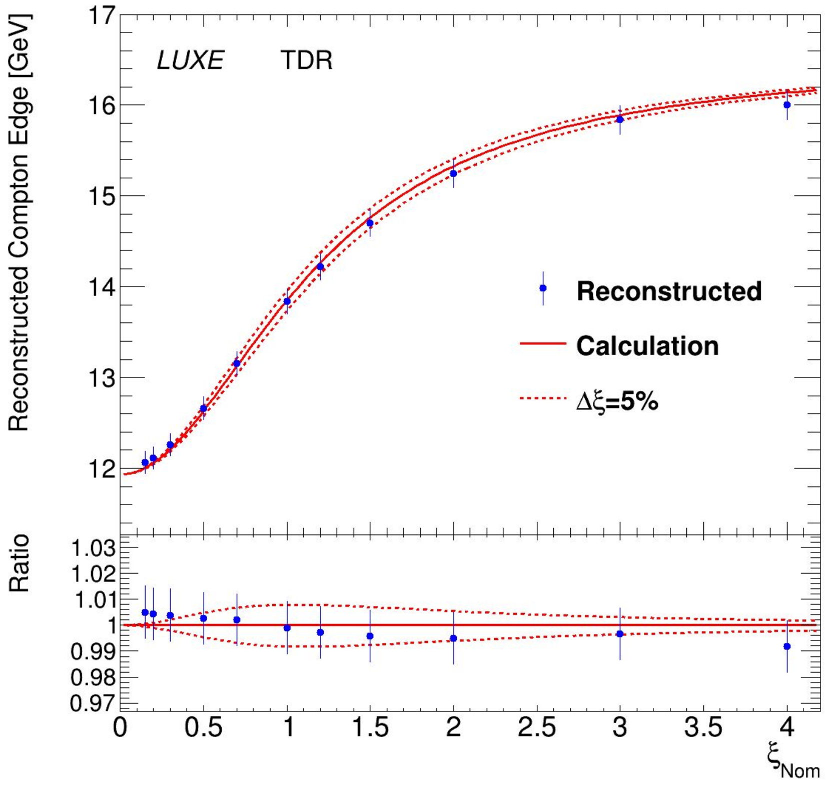
The scintillator screen and camera system

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%

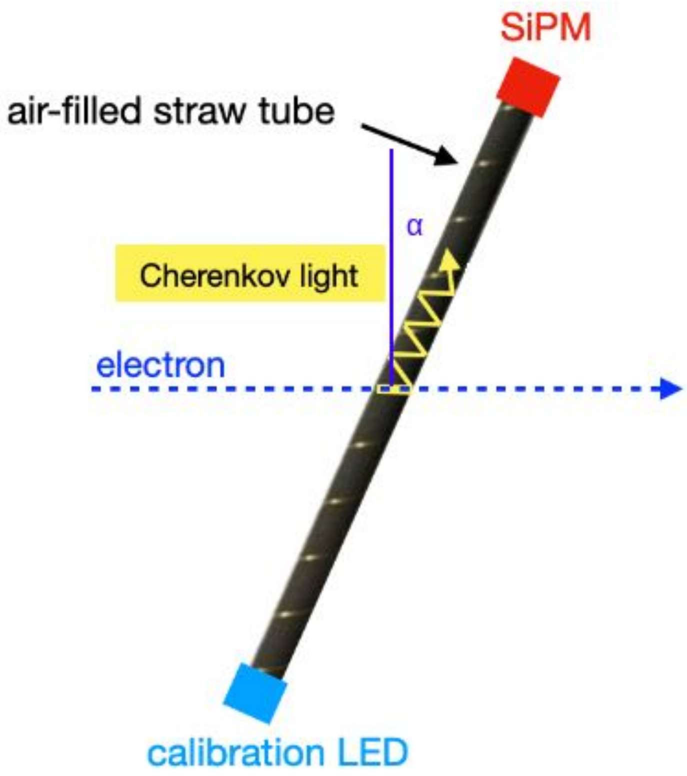


The Cherenkov detector

Basic idea

- Reflective, air filled straws aligned in a grid

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



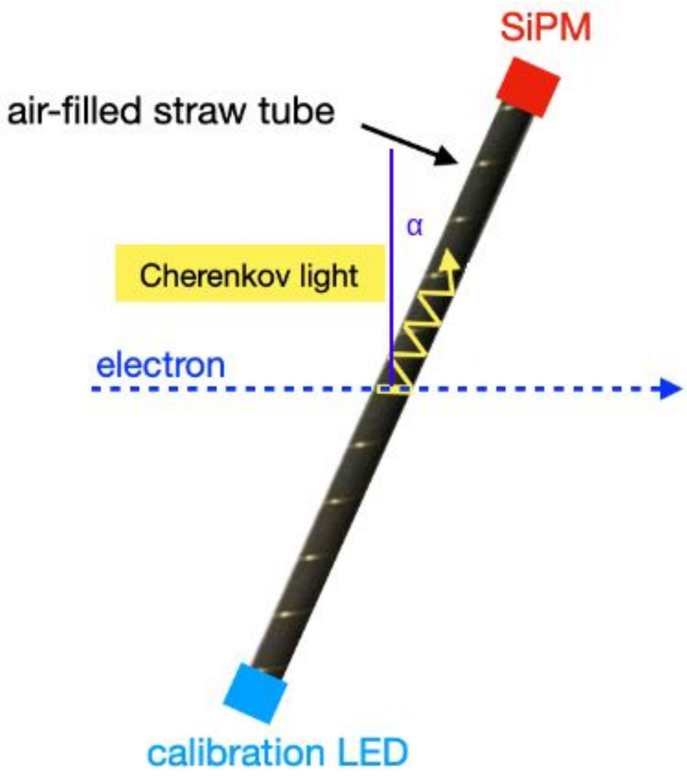
The Cherenkov detector

Basic idea

- Reflective, air filled straws aligned in a grid

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

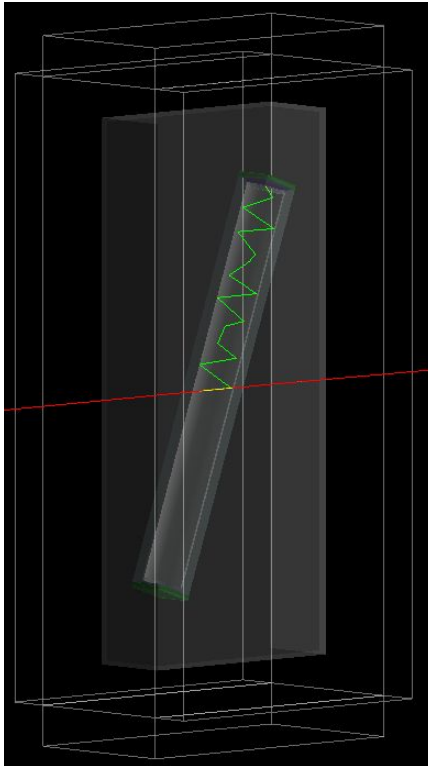
- Many parameters have to be optimized:
  - Straw dimensions, material, reflectivity and angle α
  - SiPM dimensions and characteristics

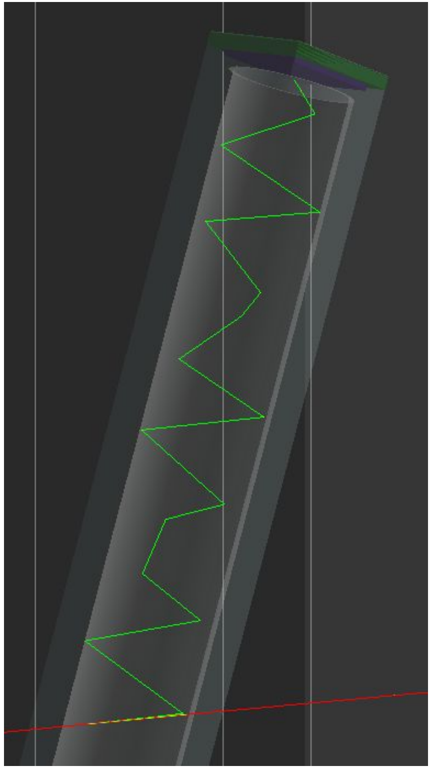


The Cherenkov detector

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





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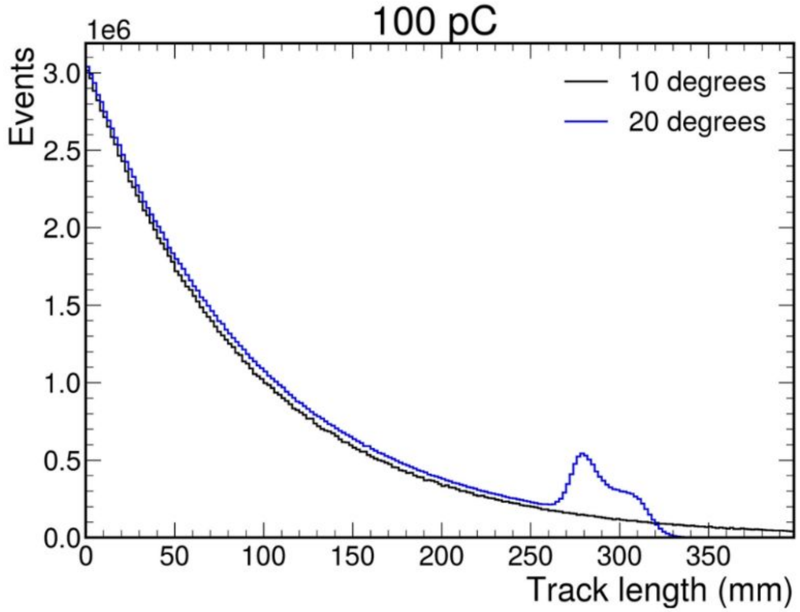
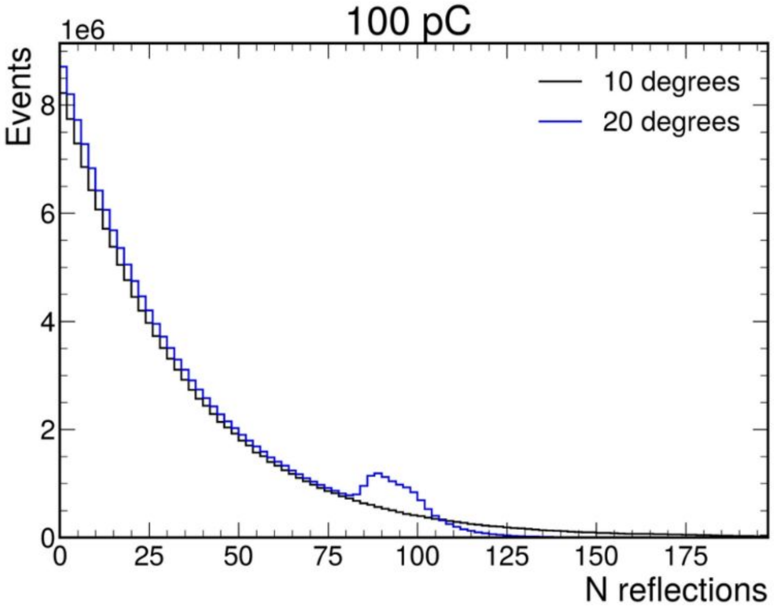


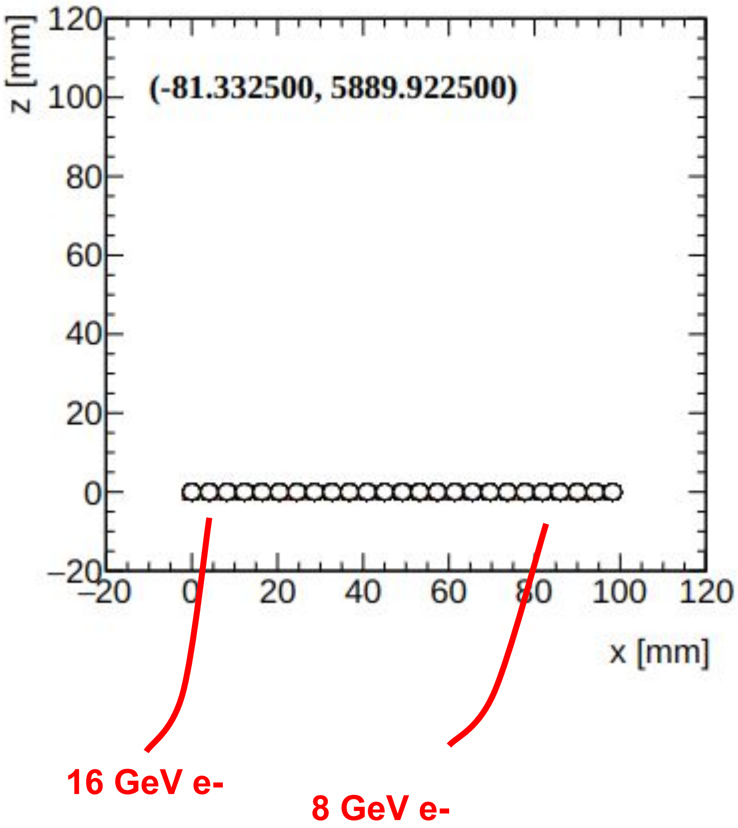


- Optical effects can be studied in detail
- Here: For an angle of 20° ➤ Higher probability of photons reaching the end of the tube

The Cherenkov detector

Reconstruction algorithm

- Single row of straws



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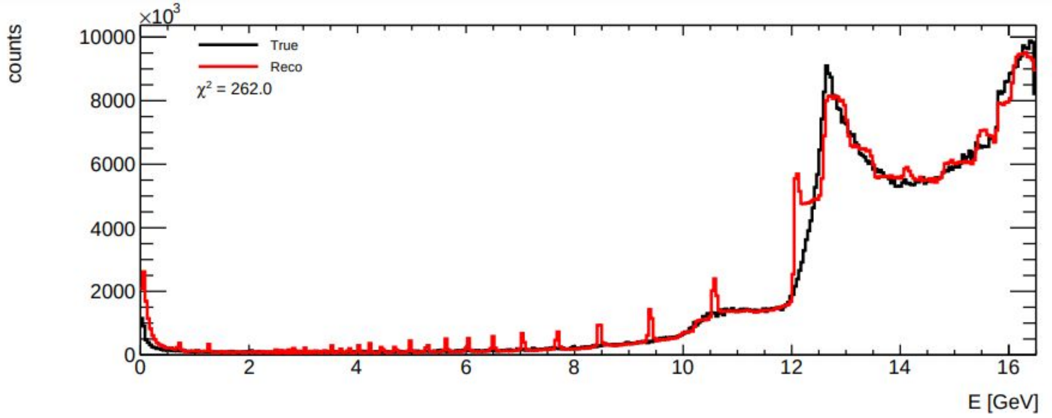


- Compton energy reconstruction via finite-impulse-response-filter method

- Convolution between
  - Compton edge position

$$R_d(i) = \sum_{k=-N}^{k=N} h_d(k) \cdot g_d(i-k)$$

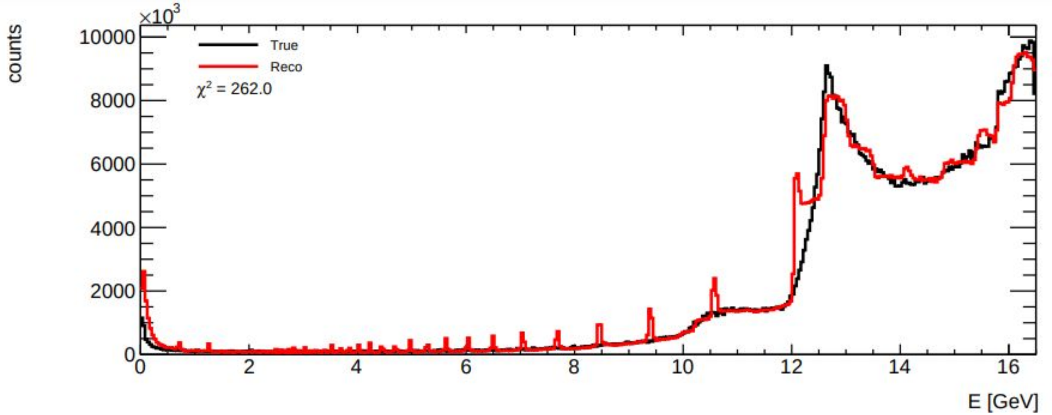
  - Gaussian filter

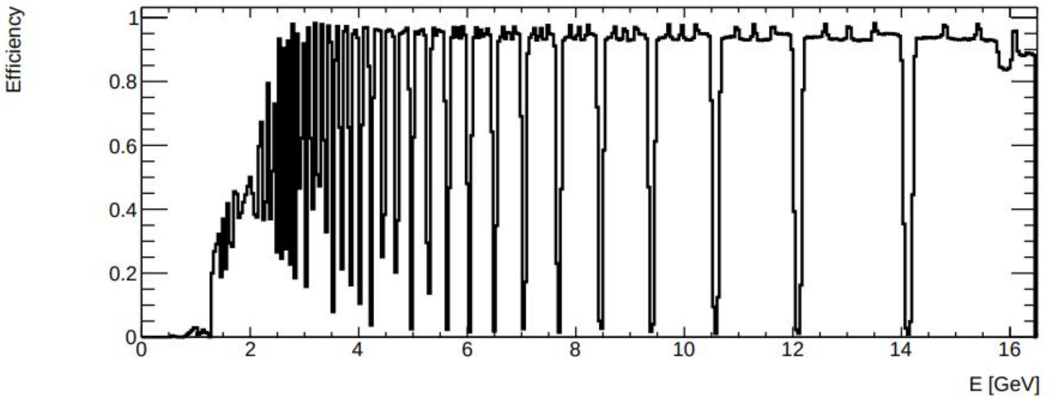
$$h_d(k) = -k \exp - \frac{k^2}{2\sigma^2}$$

The Cherenkov detector

Reconstruction algorithm

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





The Cherenkov detector

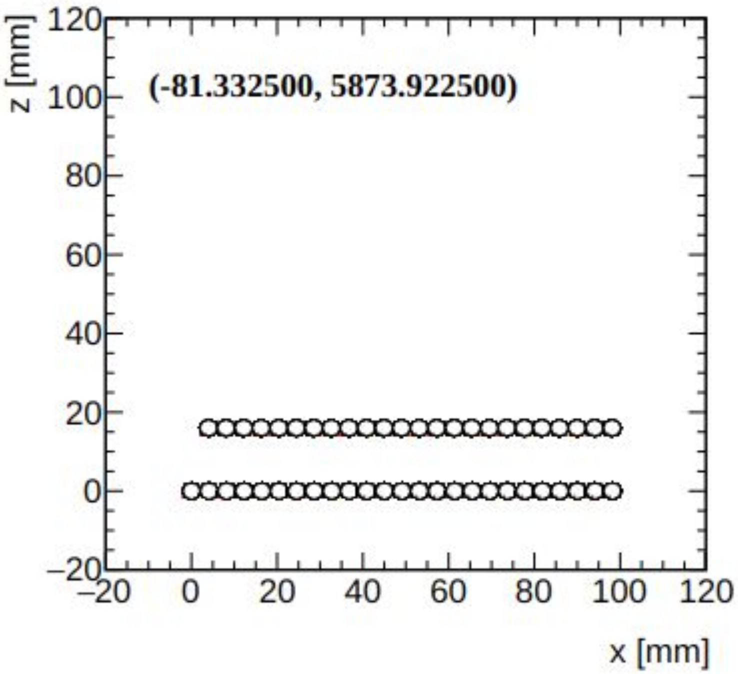
Reconstruction algorithm

- Single row of straws

- Peak structure in Compton energy fit

- Electron detection efficiency drops periodically

➤ Second row of straws

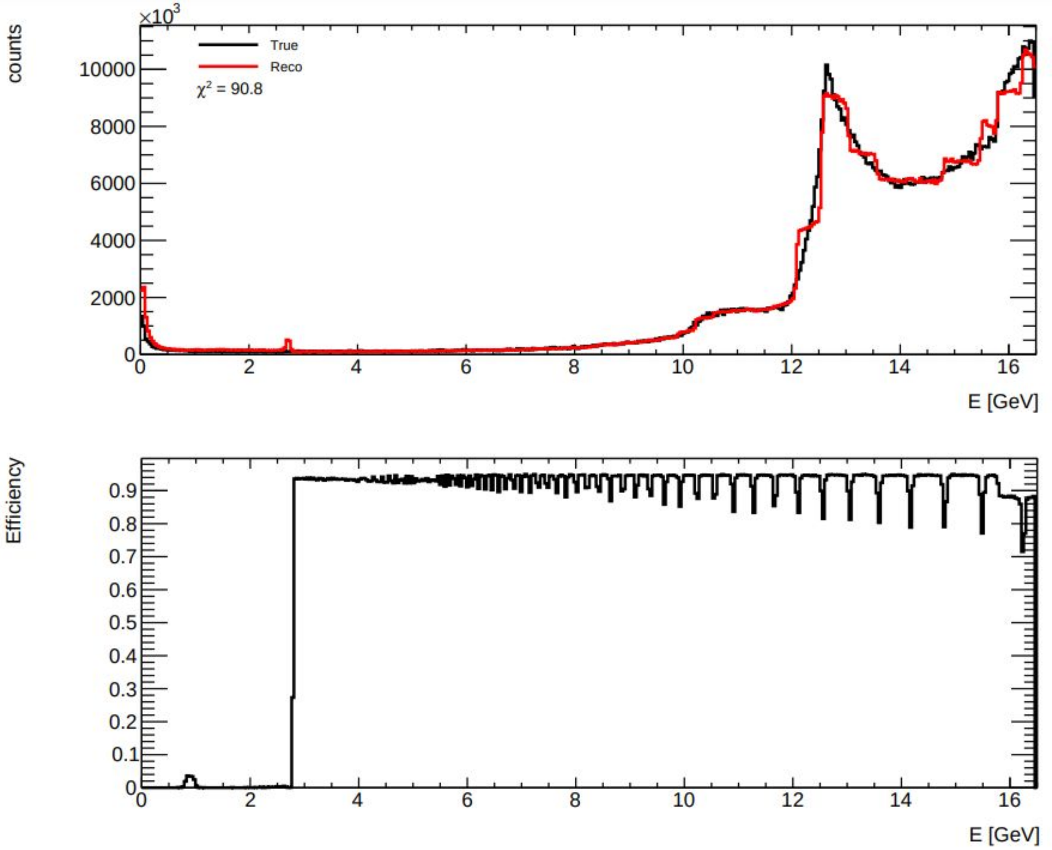


The Cherenkov detector

Reconstruction algorithm

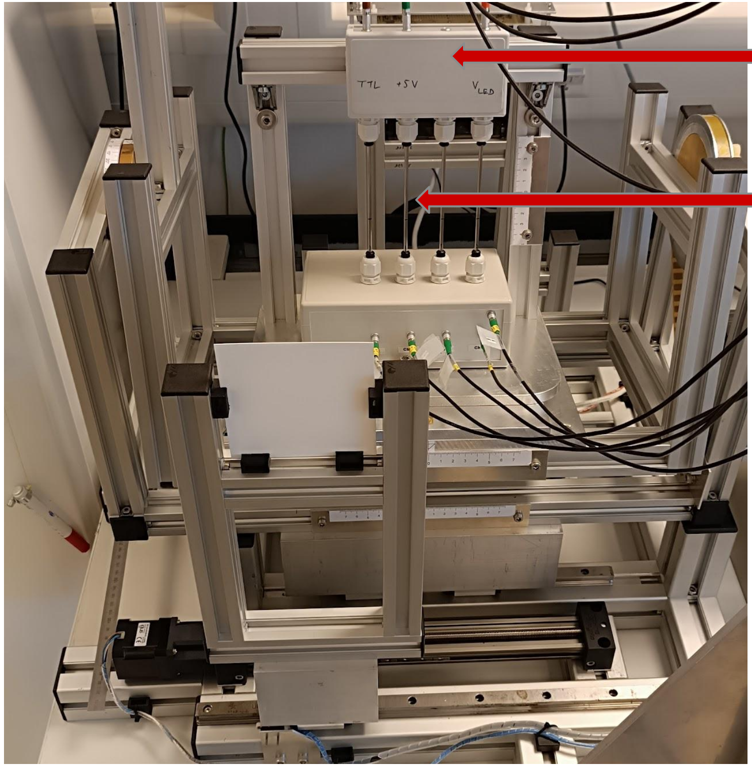
- Single row of straws
- Peak structure in Compton energy fit
- Electron detection efficiency drops periodically

➤ Second row of straws recovers this effect partially



The first prototype detector

- Straws with 0.1 mm thickness



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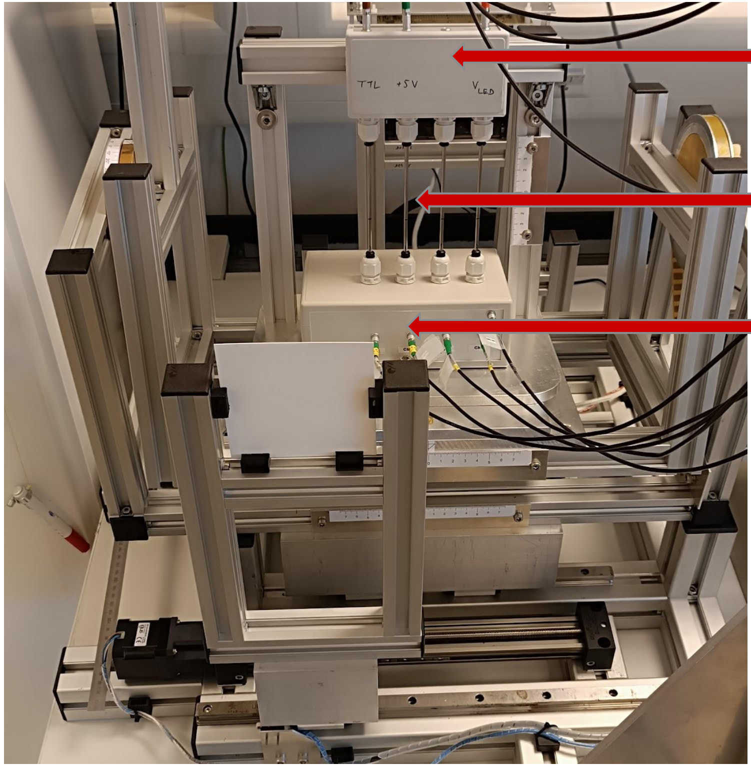

Calibration LEDs

Straws

Box with SiPMs

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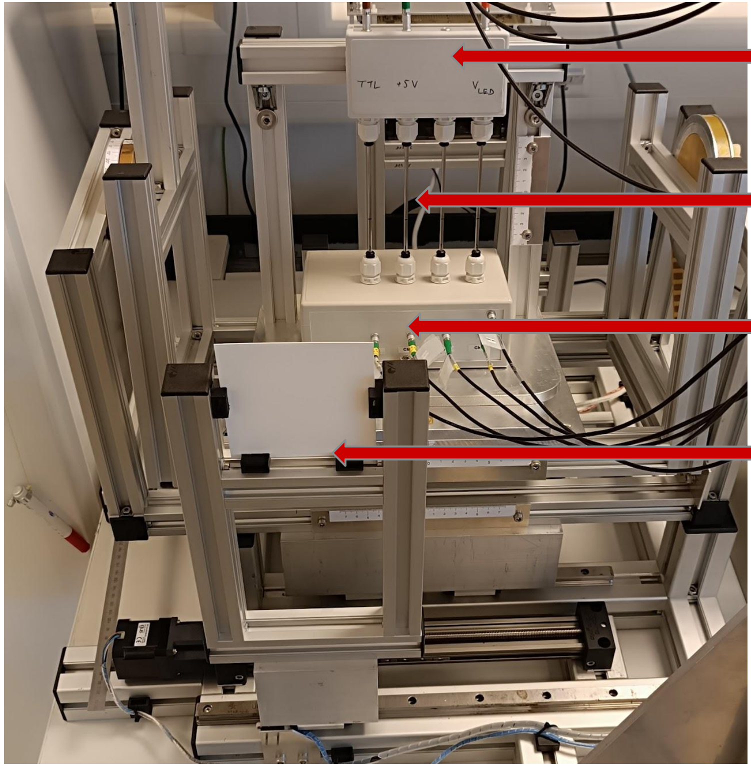
- Screens with different light yield or resolution



Calibration LEDs

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Box with SiPMs

Screen

The first prototype detector

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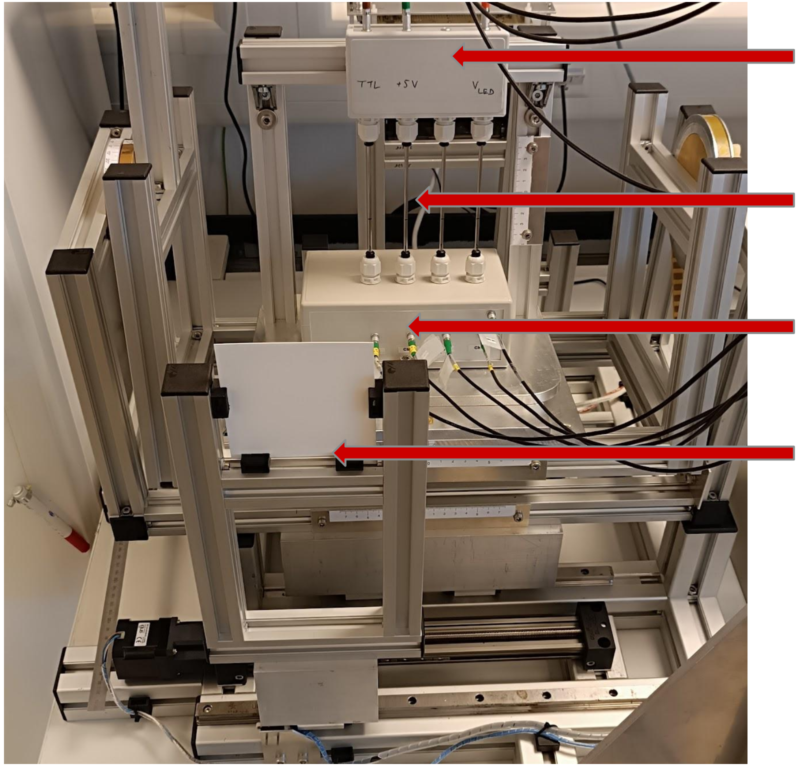
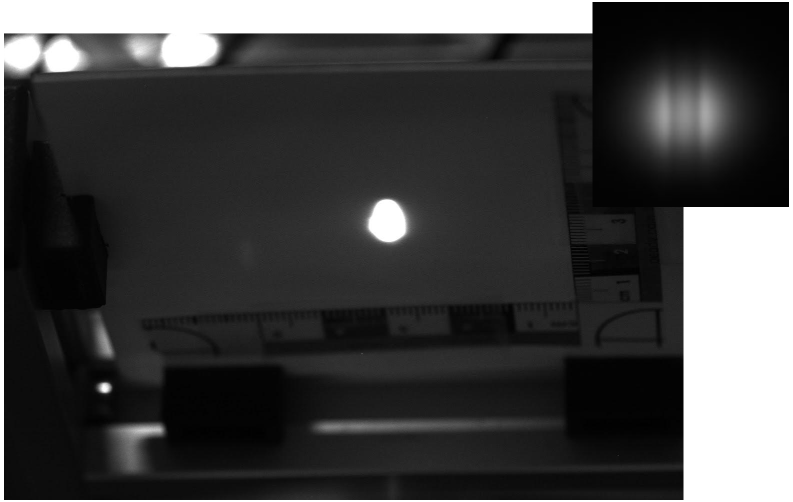
- Screens with different light yield or resolution
- Straws and screen movable (left-right, tilting)



Future plans

- Evaluation of recent testbeam measurements
  - At ARES facility at DESY
  - 1 pC - 100 pC electron beam with 150 MeV



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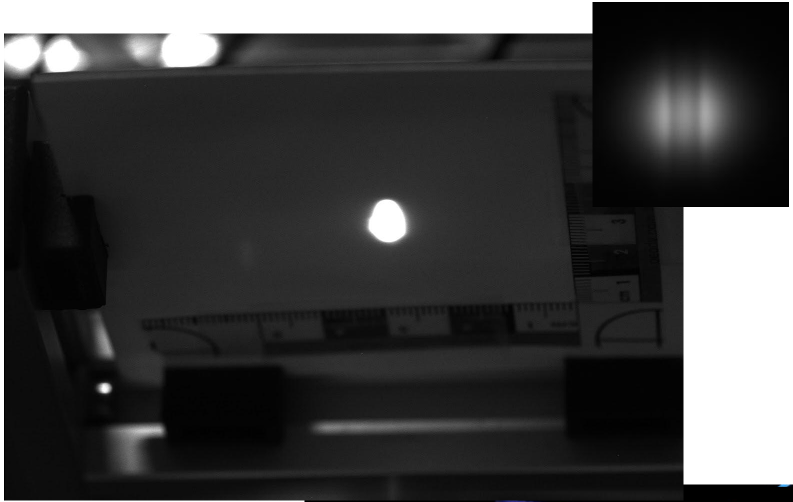

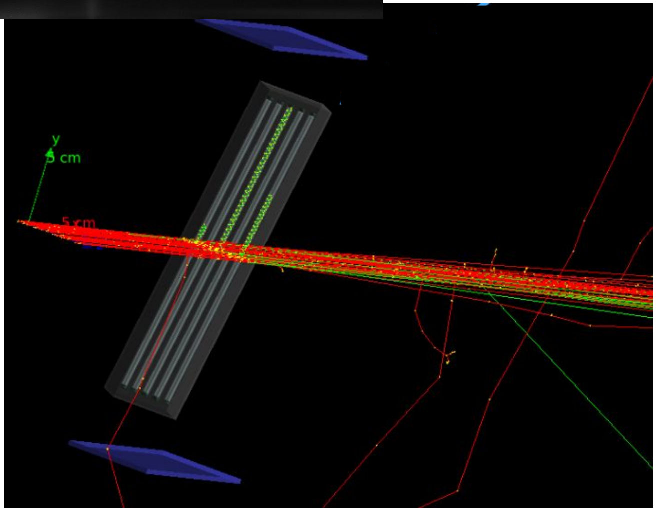

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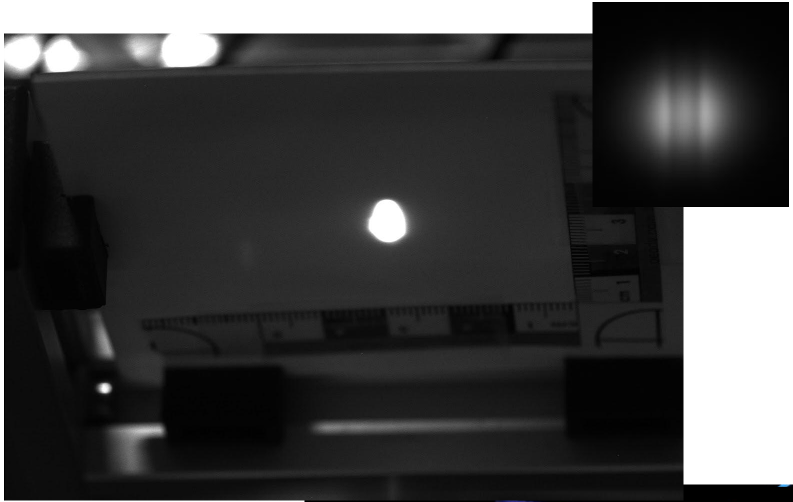
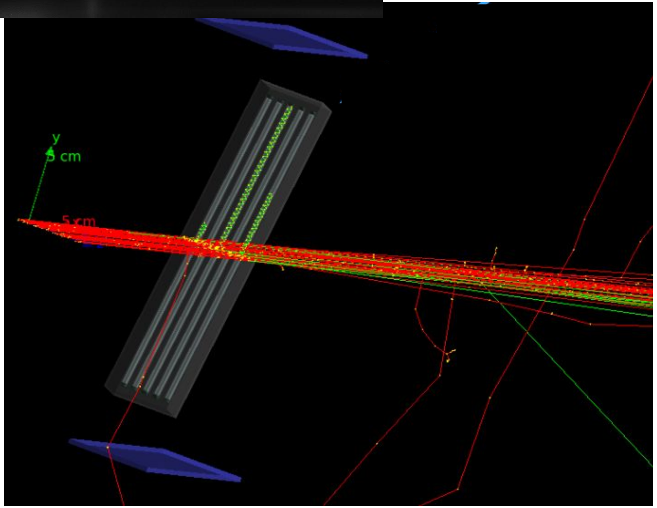
  - 1 pC - 100 pC electron beam with 150 MeV
- Extended simulation studies
- Data acquisition for camera readout and analysis
- Construction of a 16/32 channel prototype





Conclusion

- LUXE demands many requirements on the detectors in order to measure the effects of 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.

Thank you

For more details, have a look at other contributions about LUXE at EPS-HEP:	
Detector Challenges at LUXE by Oleksandr Borysov	Quantum algorithms for tracking by Yee Chinn Yap
New physics at LUXE by Nicolo Trevisani	Quantum annealers for tracking by Annabel Kropf
LUXE: a new experiment to study non-perturbative QED by Evan Altair Ranken	