The LUXE Detector Systems and their Synergies with E320

SLAC FPD Seminar

Antonios Athanassiadis, on behalf of the LUXE collaboration
11th of June 2024

Deutsches Elektronen-Synchrotron DESY

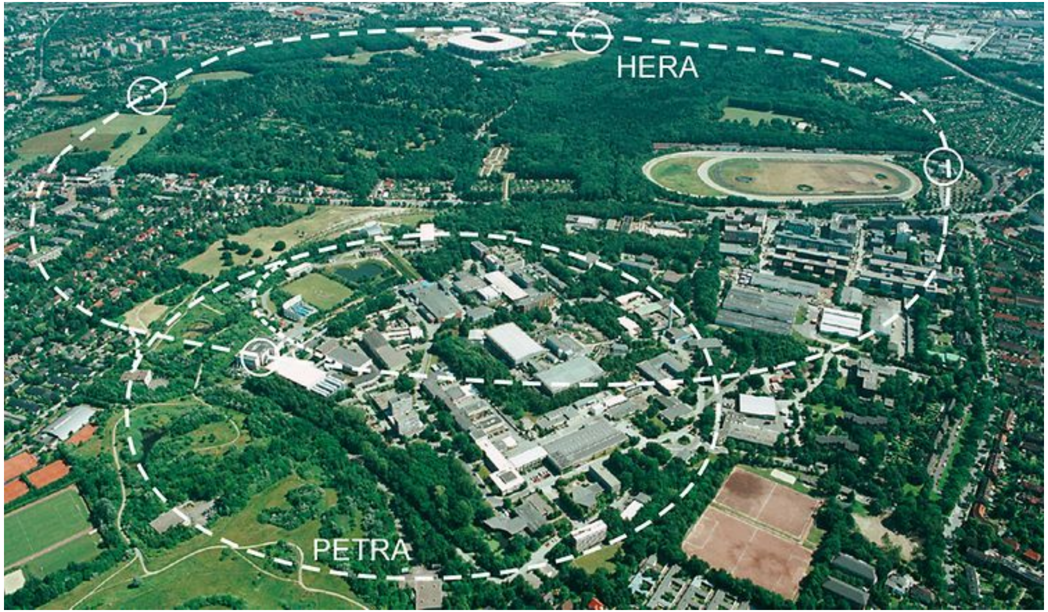
About DESY

Deutsches Elektronen-Synchrotron

- In operation since 1964
- Discovery of the gluon at HERA
- Many accelerator facilities active
- DESY II, PETRA, Eu.XFEL, FLASH,...

Four fields of research

- Particle accelerators
- Particle physics
- Photon science
- Astrophysics

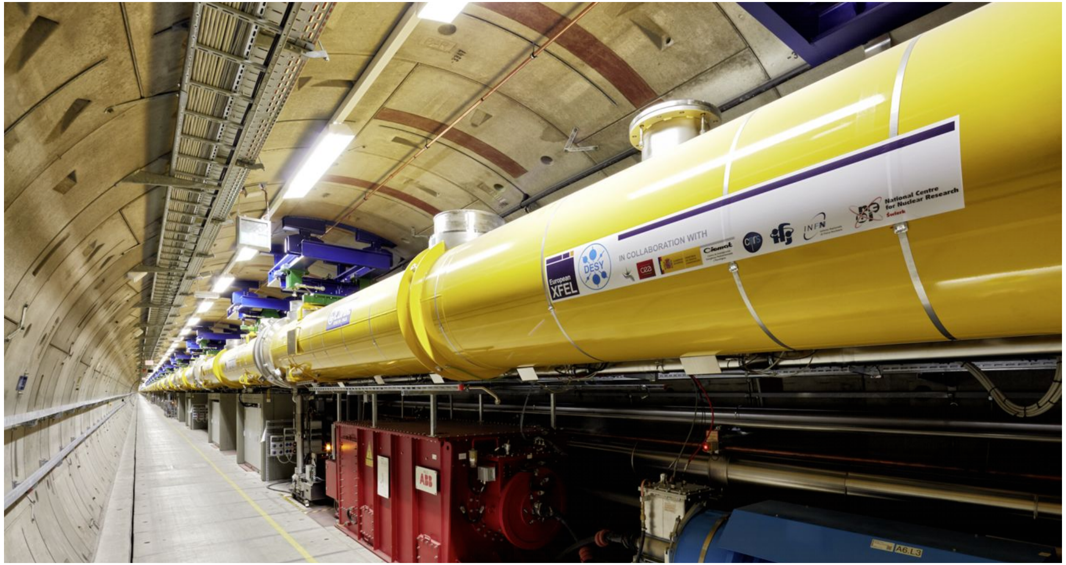


What is LUXE?

New experiment at DESY Hamburg & Eu.XFEL to probe strong-field QED – An uncharted regime

LUXE

LASER Und XFEL Experiment



In this seminar:

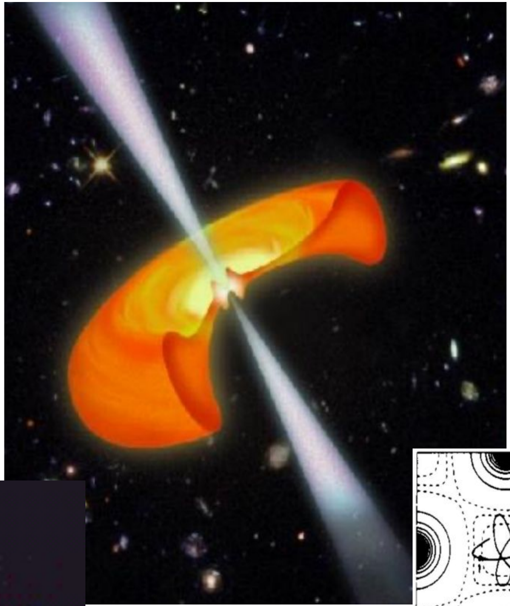
- What is strong-field QED?
- What are the features of LUXE?
- What are the key technologies?
- What are the synergies to E320?

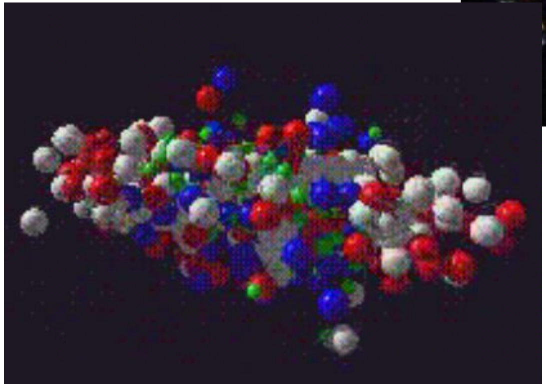
CDR: arXiv:2102.02032 TDR: arXiv:2308.00515

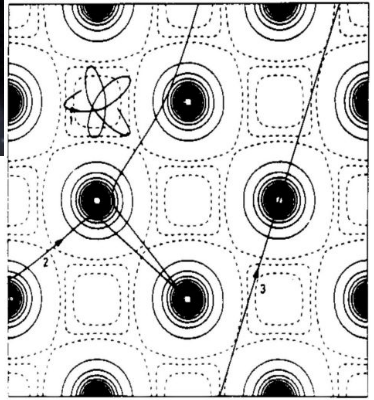
What is strong-field QED and why is it interesting?

Where do we obtain strong fields?

- Magnetars
  (Neutron stars with B > 10^{10} T)
- Heavy ion collisions
- Strong lasers → γγ - collisions
- Beam-beam effects
- Crystals ([NA63](NA63))

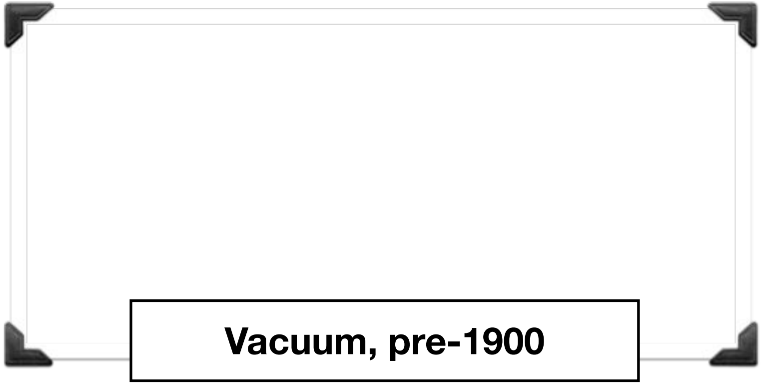




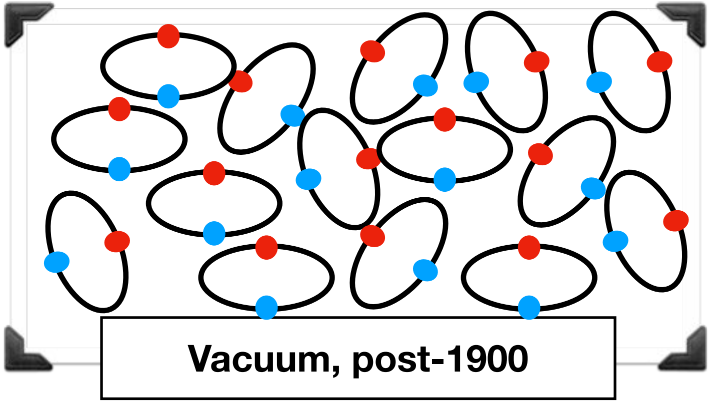


QED and the vacuum

Emptiness

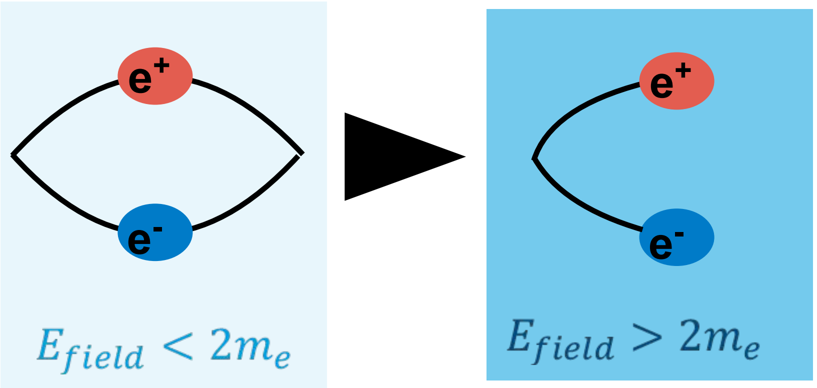


Virtual particles with an average value of zero but non-zero variance



The Quantum Electrodynamics is one of the most well-tested physics theories!

Strong-field QED



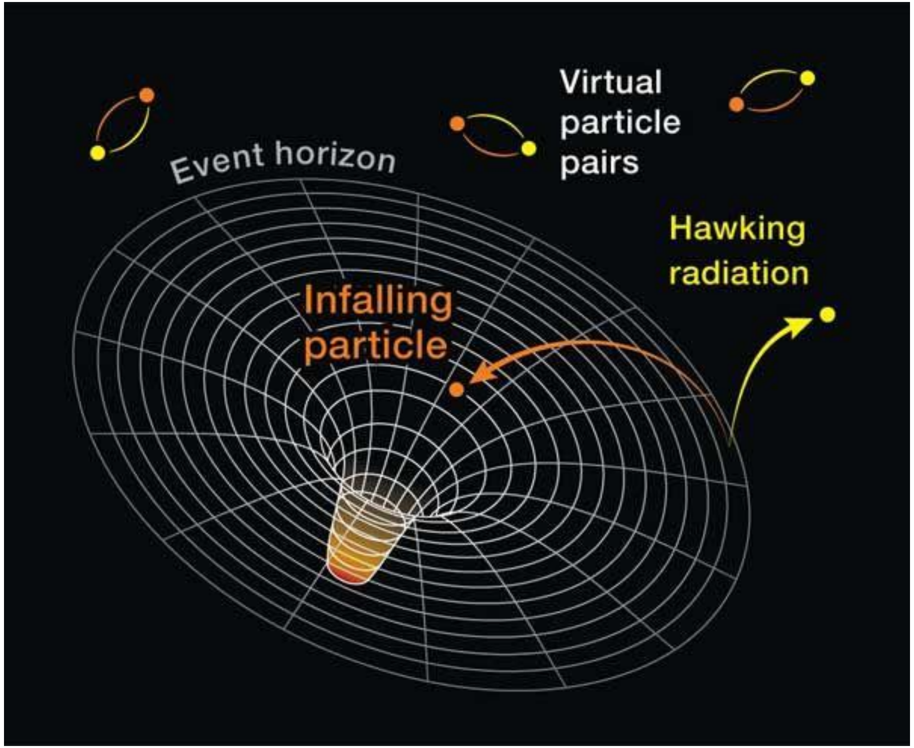
QED non-linear when field polarized

- If work of ext. field > rest mass of pair
  → Schwinger-Limit ε_{cr}
  → Field-induced Breit-Wheeler pair creation
- Existing fields are too small
  → BUT el. field not lorentz invariant

$$\mathcal{E}_{cr} = \frac{m_e^2 c^3}{e\hbar} = 1.32 \cdot 10^{18}\, V/m$$

$$\mathcal{E}_{rest\ fr.} = \gamma \mathcal{E}_{lab\ fr.}$$

Hawking radiation analogy

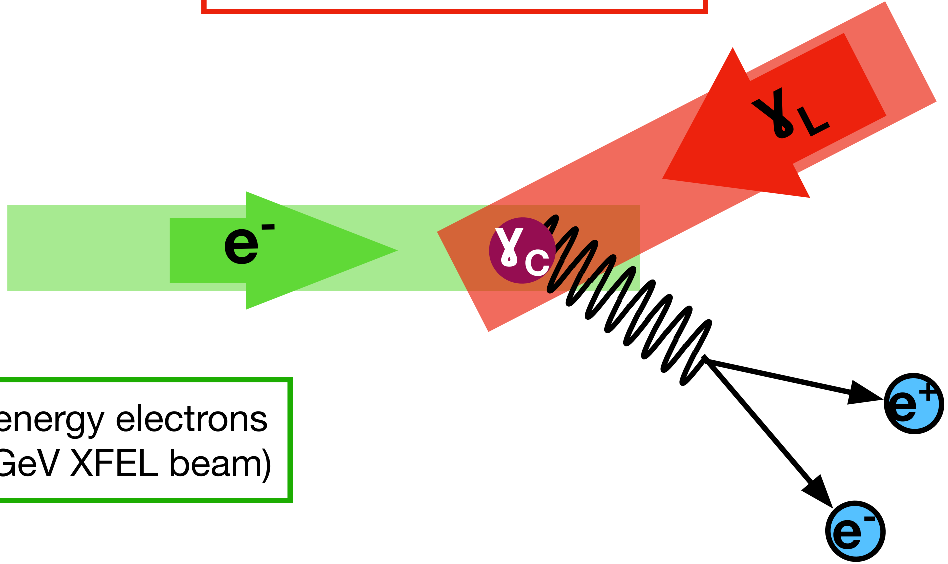


Particle-antiparticle pair production in vicinity of strong gravitational vs. electromagnetic field!

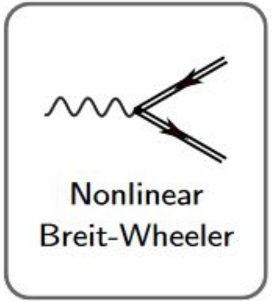
Strong-fields with relativistic probes

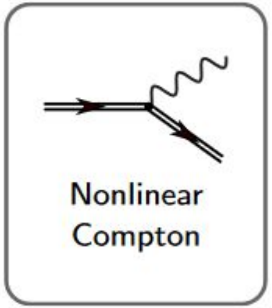
Electron-Laser collisions

High-intensity LASER
(Tera-Watt, 800nm)
→ **large E-field**



High-energy electrons
(16.5 GeV XFEL beam)





Strong-fields with relativistic probes

Gamma-Laser collisions

High-intensity LASER
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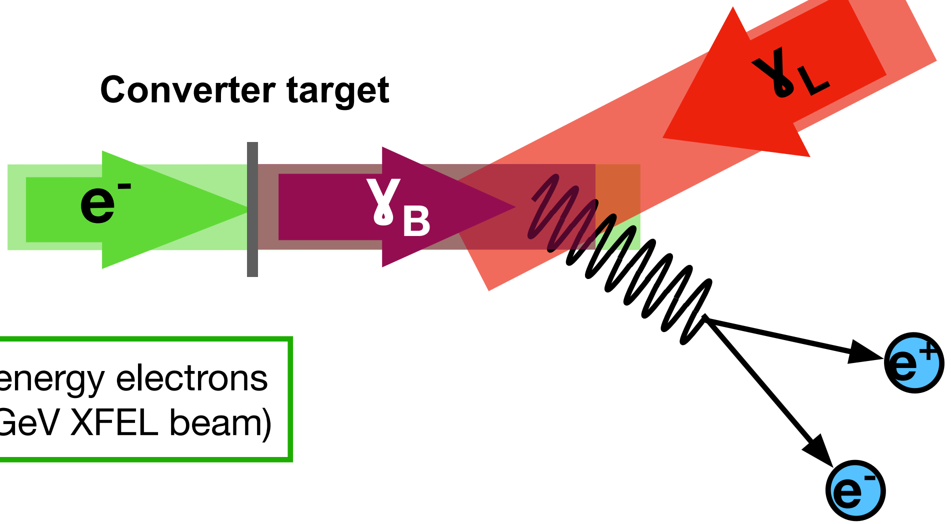
→ **large E-field**



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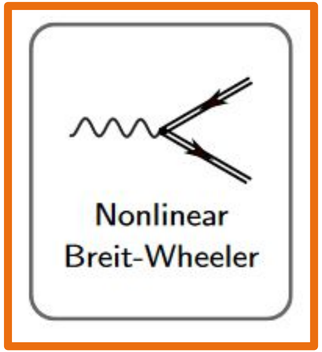
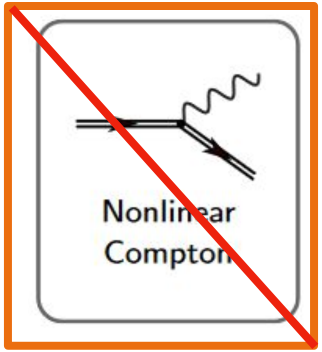
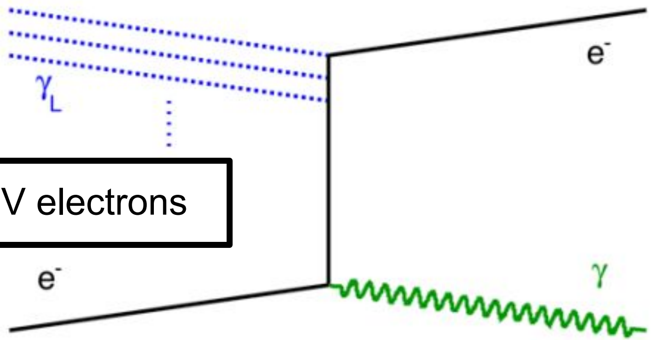




Strong-fields with relativistic probes

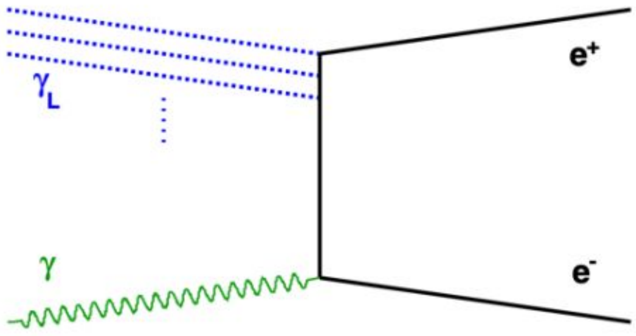
High intensity laser

16.5 GeV electrons



Non-linear Compton Scattering

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



Breit-Wheeler pair production

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

Important parameters

ξ is probe-background coupling

- Here: ξ ~ laser intensity
- ξ > 1 → non-perturbative regime

$$\xi = \frac{m_e \mathcal{E}_L}{\omega_L \mathcal{E}_{cr}}$$

χ is background field to ε_{cr} ratio

- Here: χ ~ laser energy transfer
- χ > 1 → non-linear quantum effects

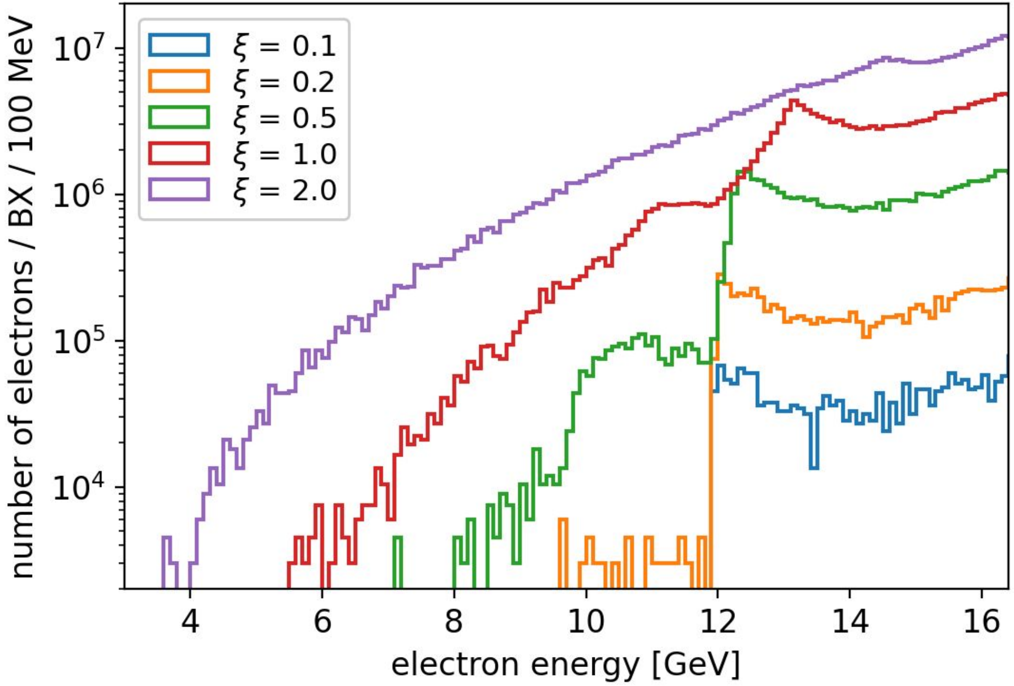
$$\chi_e = (1 + \cos\theta) \frac{E_e}{m_e} \frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

η is dimensionless energy of collision

$$\eta = \frac{\chi}{\xi}$$

Different combinations of ξ and χ result in different types of non-linear behavior

Non-linear Compton scattering



Within strong fields

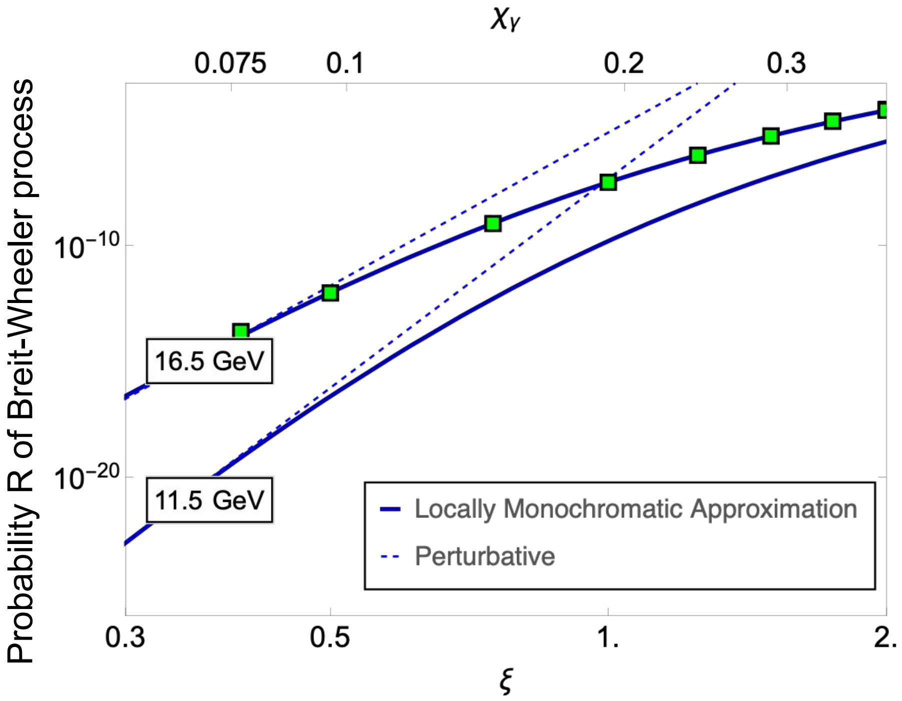
- Electron obtains larger eff. mass
  → Compton edge shift with ξ
  → Higher harmonics appear

Goal at LUXE: Verify predictions

Breit-Wheeler pair production

ξ << 1
→ Perturbative regime $R_{e^+} \propto \xi^{2n}$

ξ >> 1
→ Exponential law $R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$



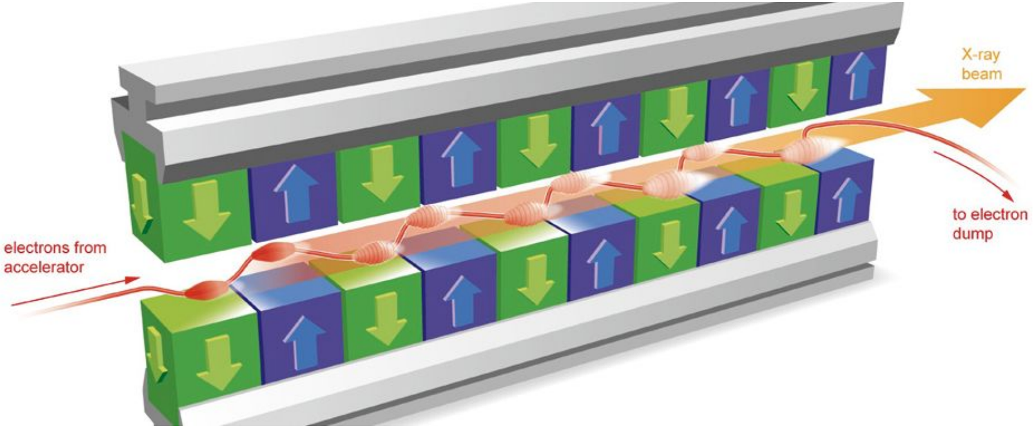
LUXE will be the first experiment to measure Breit-Wheeler pairs with real photons

Features of the LUXE experiment

The European XFEL

European X-Ray-Free-Electron-Laser

- In operation since 2017
- Linear electron accelerator
    - 1.9 km
    - 17.5 GeV max.
    - 2700 bunches at 10 Hz
- X-Ray photons for 6 instruments
    - Self-amplified spontaneous emission
    - 0.25 keV – 25 KeV



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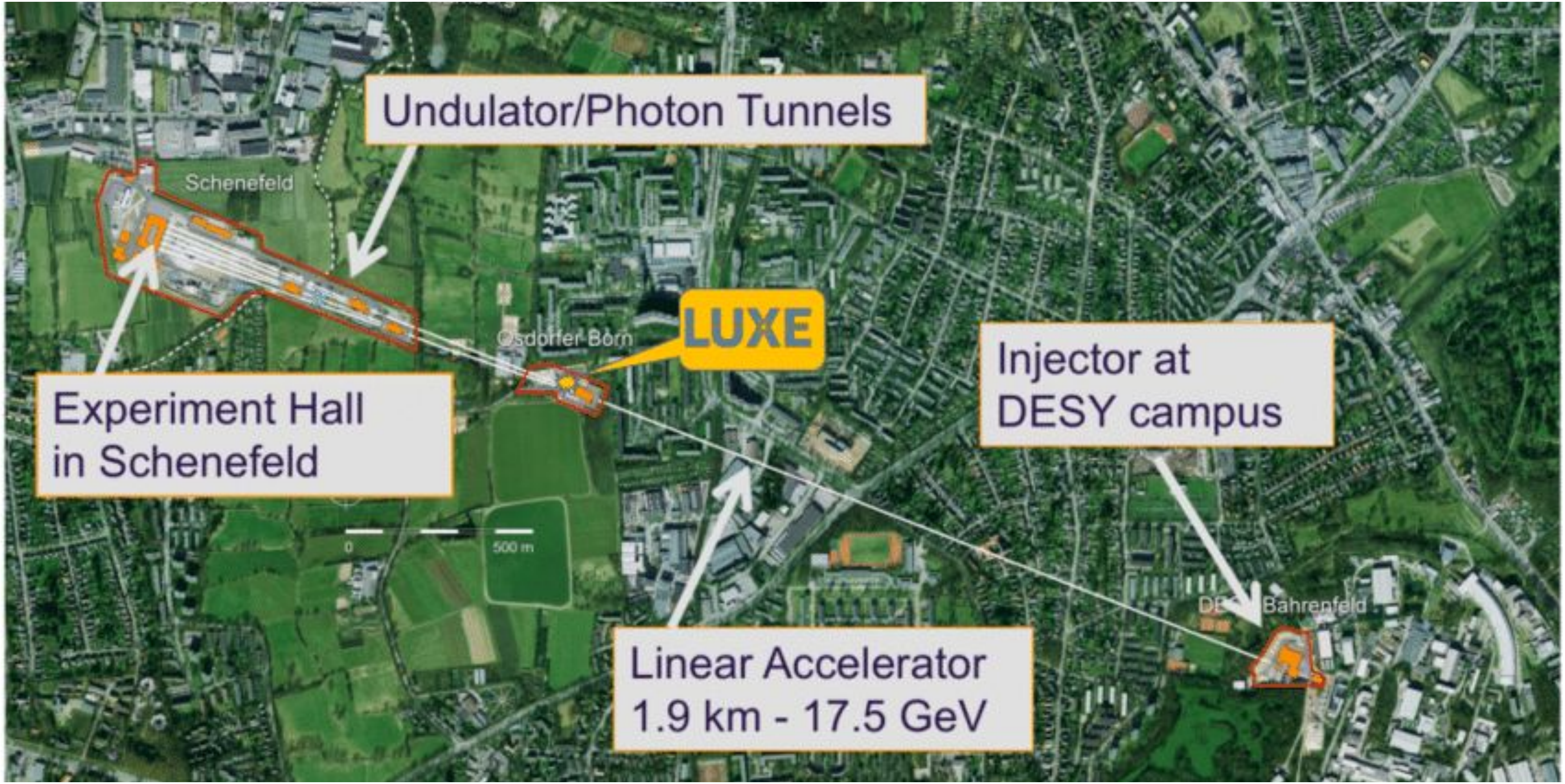
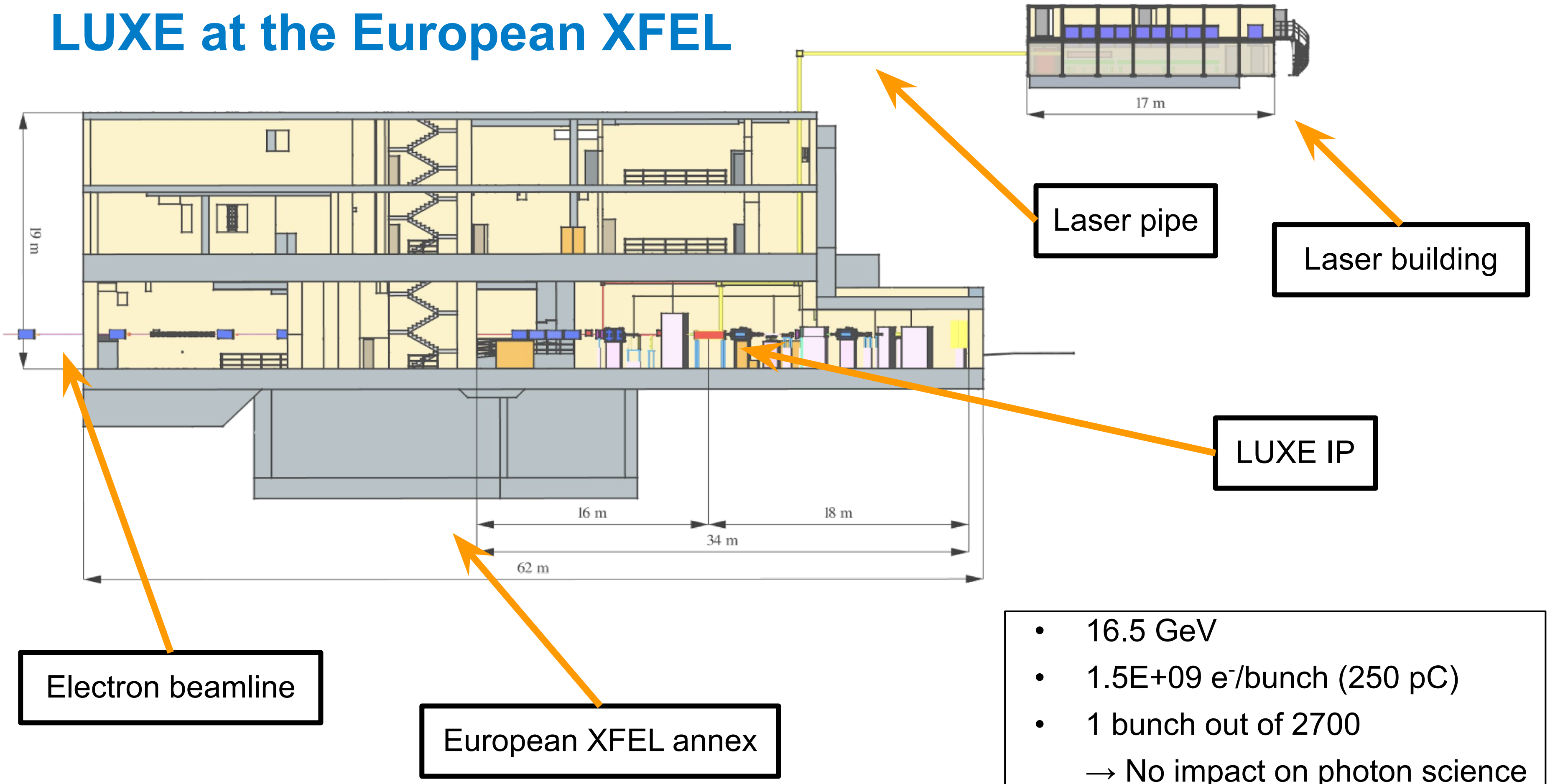
Accelerator performance

- $(\sigma_x , \sigma_y) = (9.3 , 8.1)$ µm
- Pulse length: 1…130 fs
- Shot to shot position: ~1µm
- Energy variation <0.1%

LUXE at the European XFEL



LUXE at the European XFEL

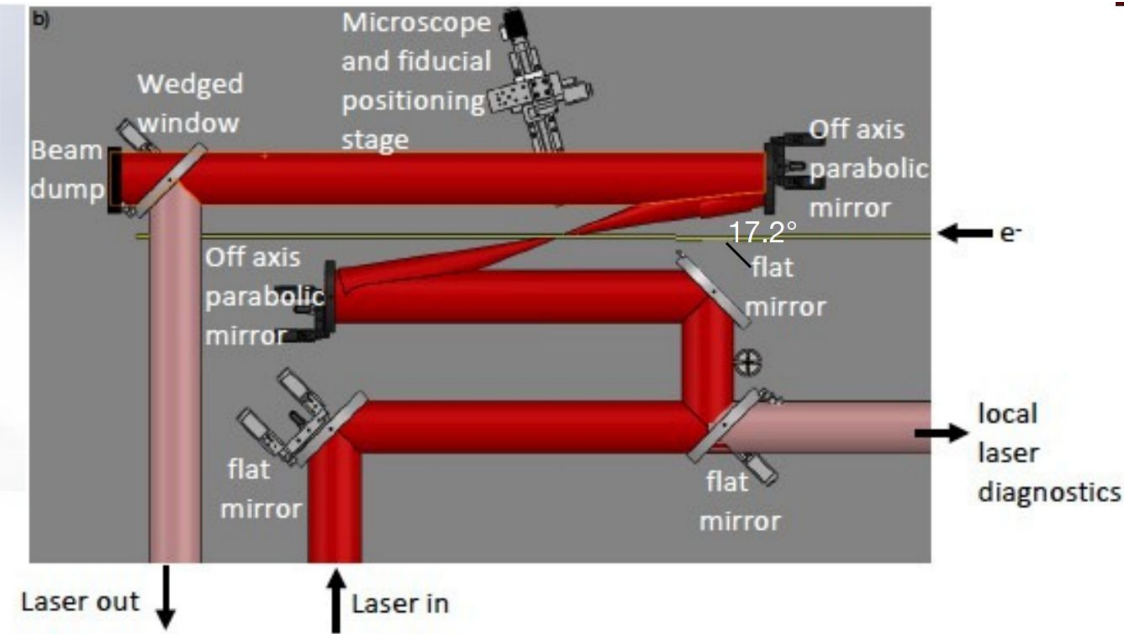


- 16.5 GeV
- 1.5E+09 e⁻/bunch (250 pC)
- 1 bunch out of 2700

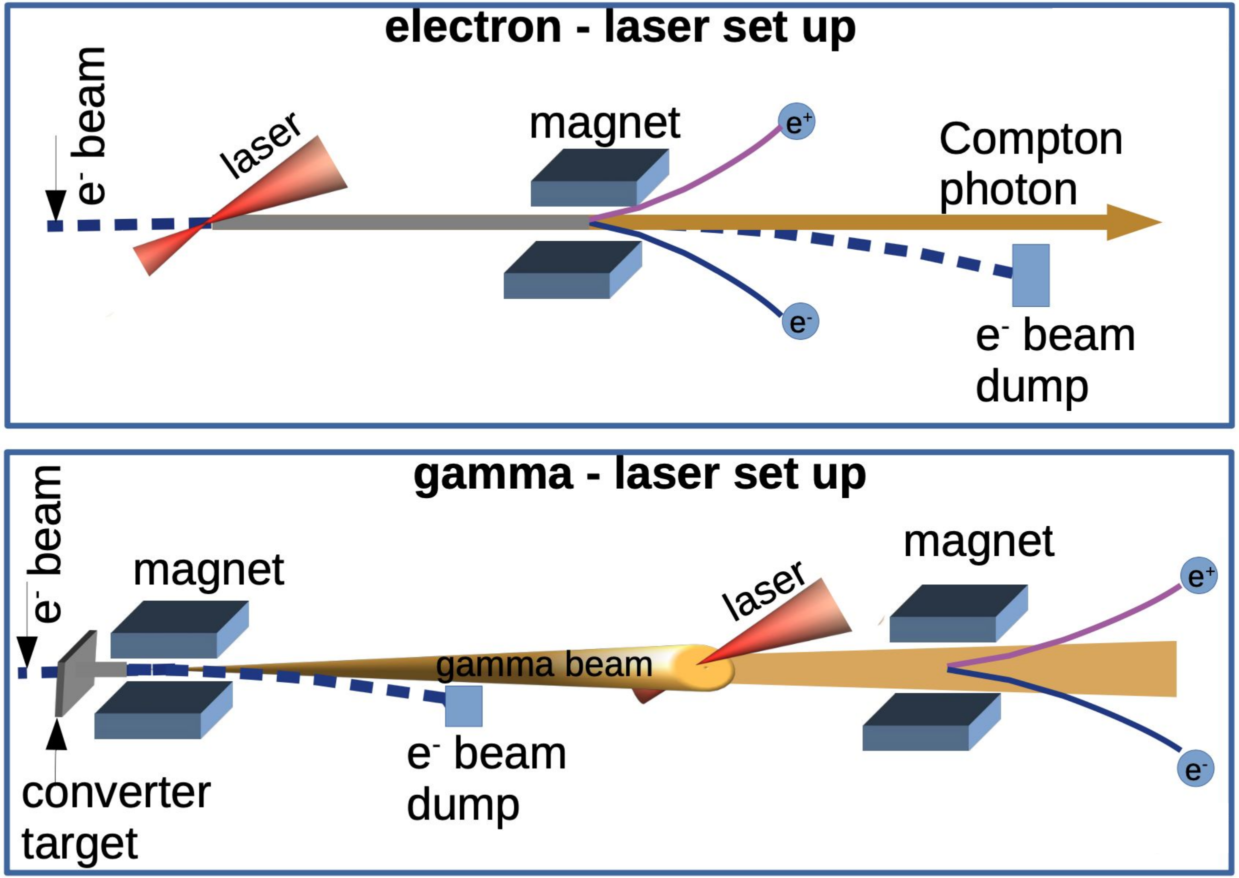
→ No impact on photon science

The LUXE laser

Laser parameters:	
Active medium	Ti:Sa
Wavelength	800 nm
Crossing angle at IP	17.2°
Pulse length	30 fs
Spot size	> 3 μm
Power	40 - 350 TW
Peak intensity	13 - 120 $*10^{19}$ W/cm^2

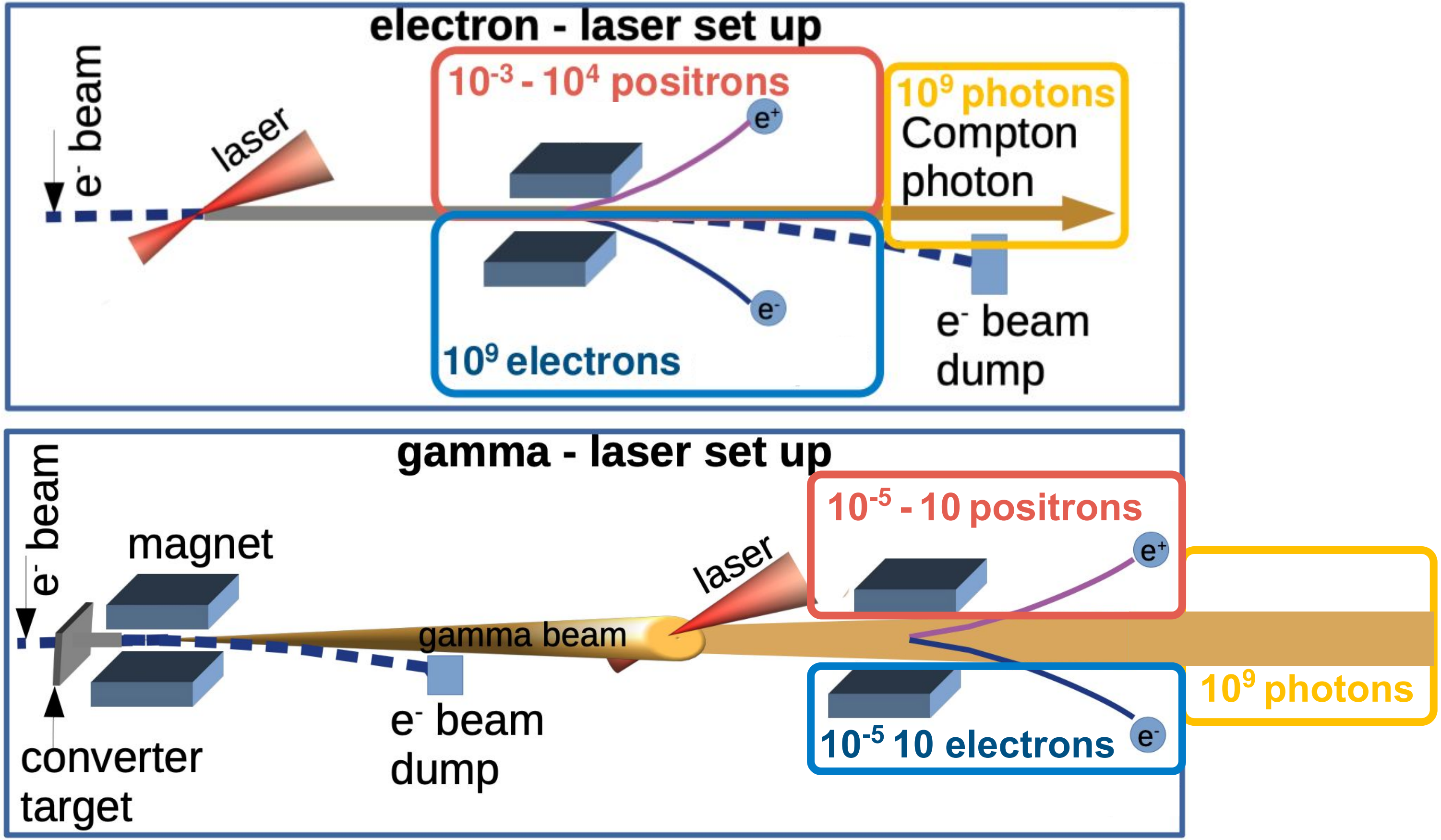


LUXE experimental setup(s)



Unique in LUXE!

LUXE experimental setup(s)



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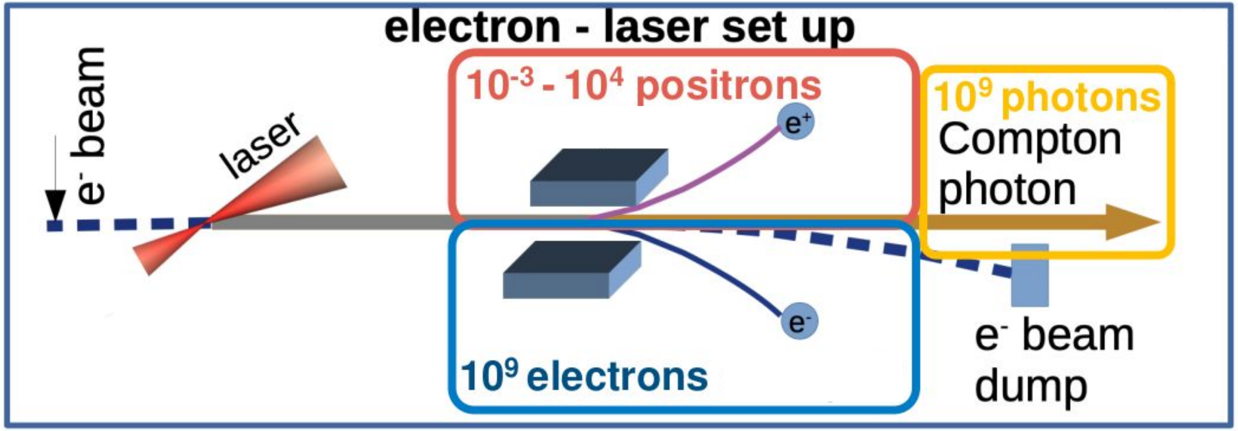


Goal: Flux and energy measurements of e-, e+, γ

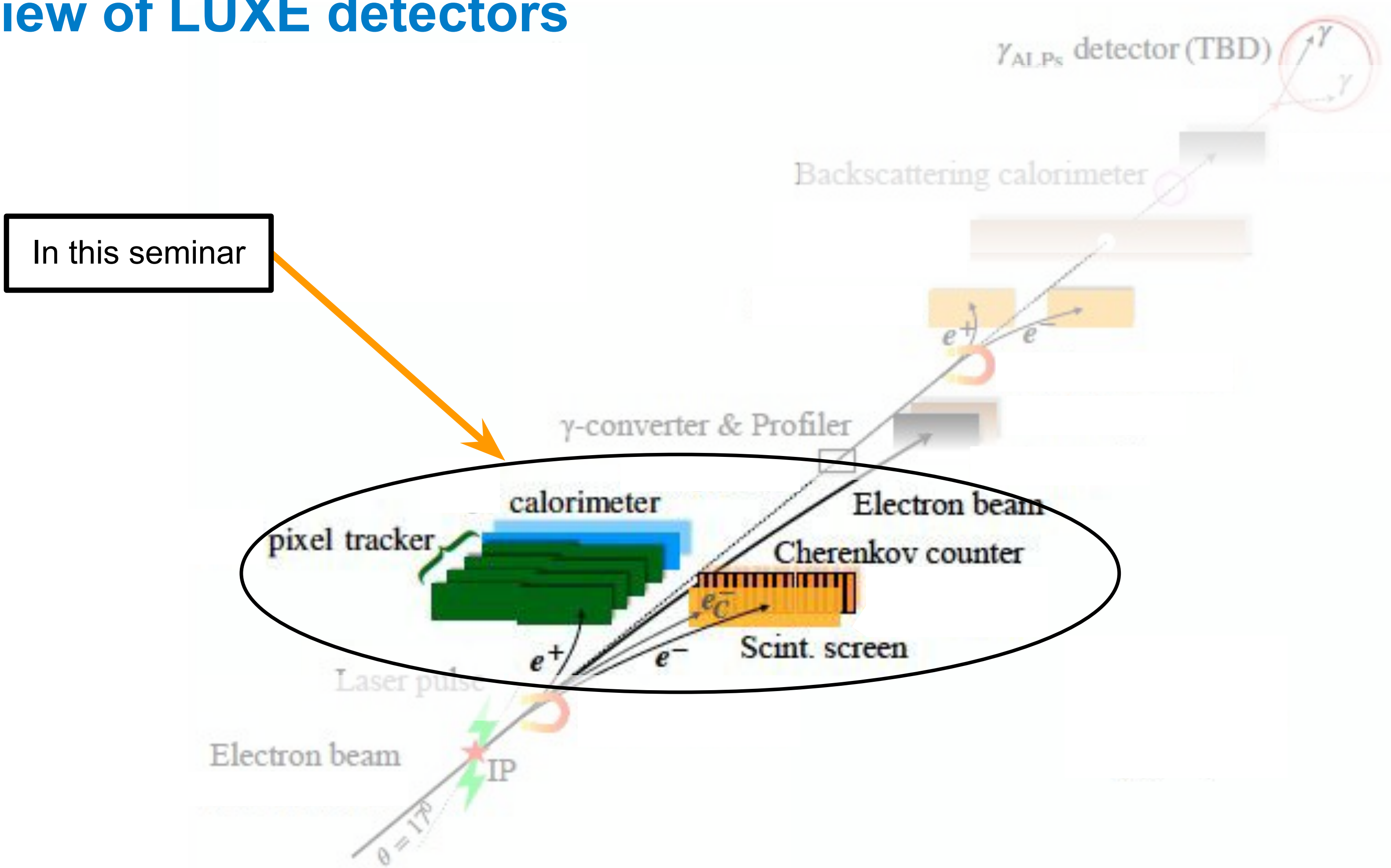
- Testbed for a wide range of novel technologies
- Two complementary detector technologies per location

  → Cross-calibration possible

  → Low systematic uncertainties

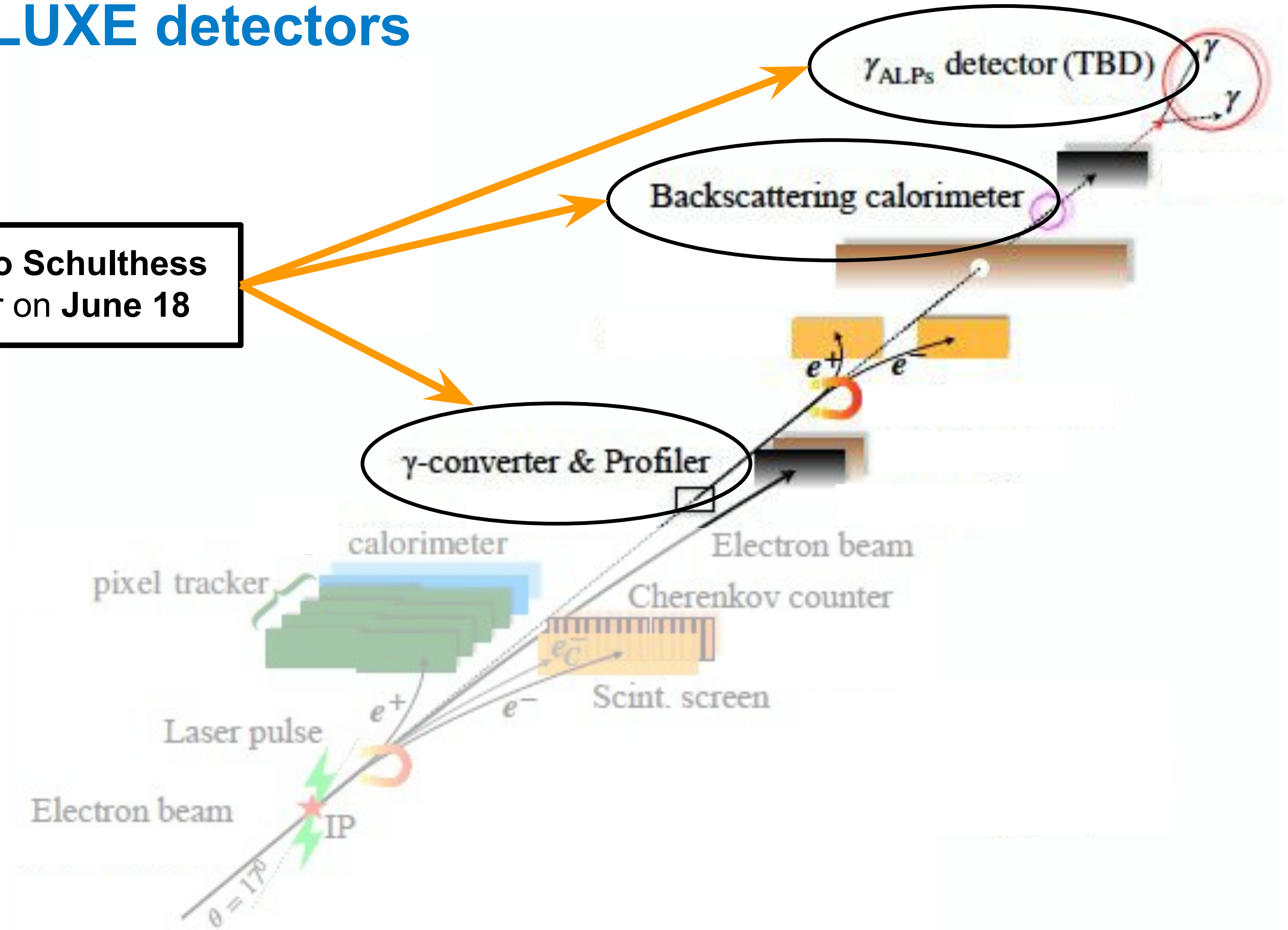
Technologies and detectors

Overview of LUXE detectors

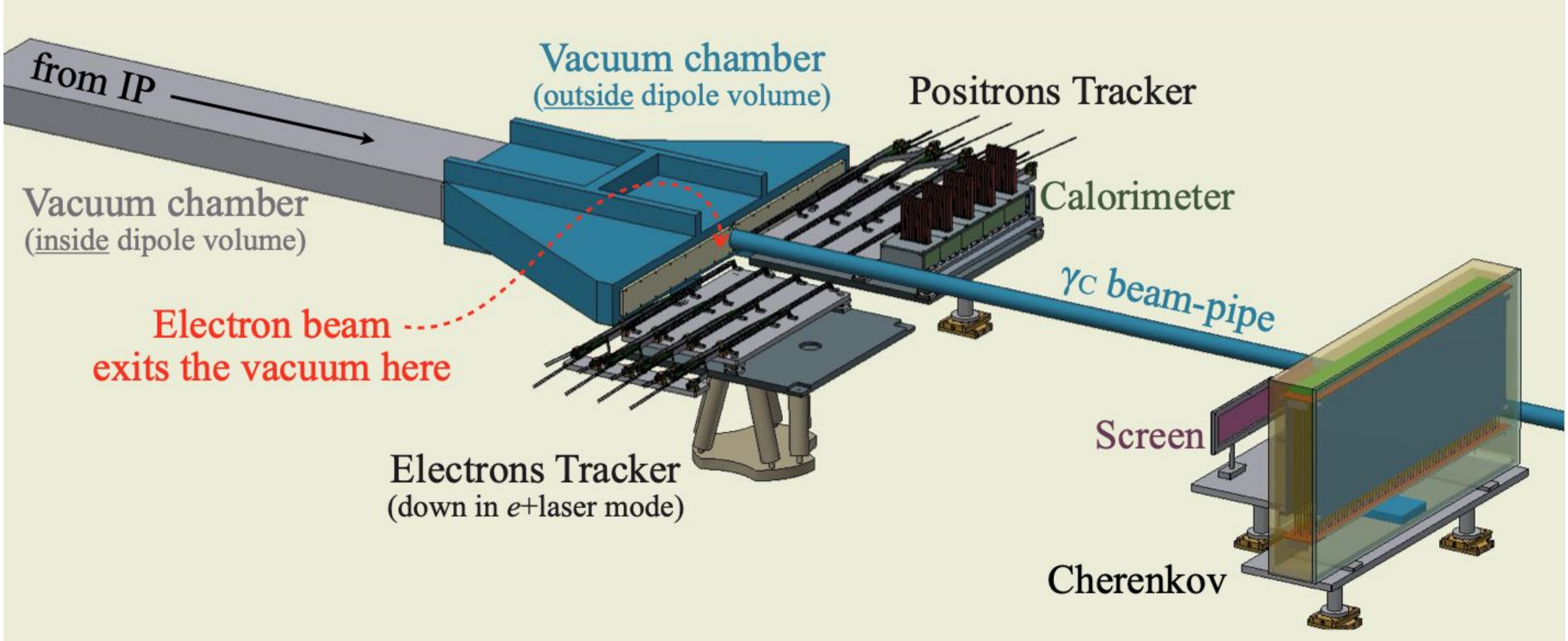


Overview of LUXE detectors

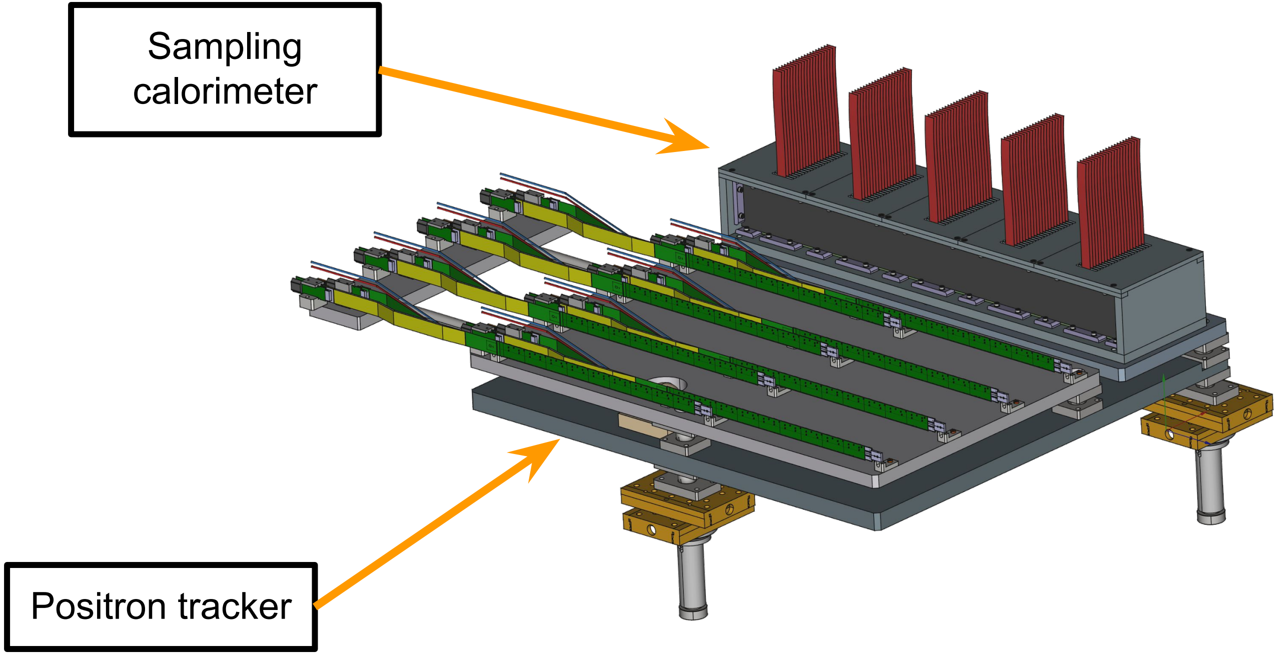
Discussed by **Ivo Schulthess** in FPD seminar on **June 18**



Electron & Positron detectors



Positron Detection System

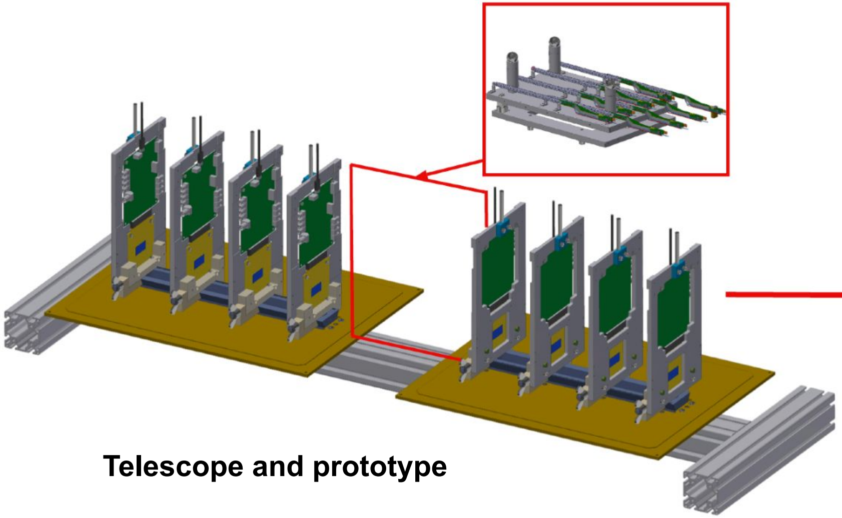


Positron Detection System

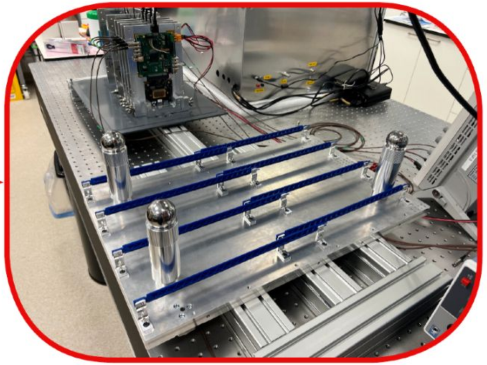
Positron tracker

- Silicon pixel tracker of ALPIDE type
- Pitch size: 27x29 μm²
- Resolution: 5 μm
- Efficiency: 98%

ALPIDE tracking detector stave



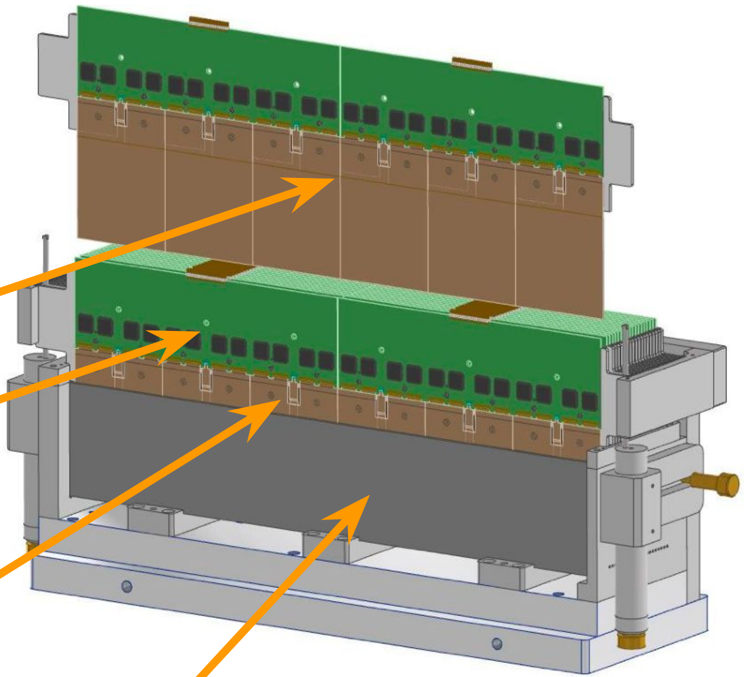
Telescope and prototype



Positron Detection System

Sampling calorimeter

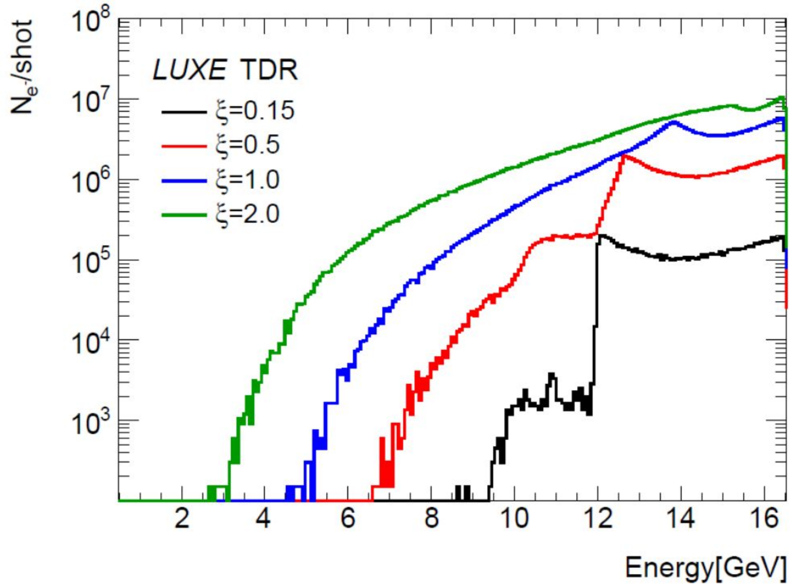
- Forward Calorimeter for ILC
- 20-layer with high granularity
  → Energy and position measurement
- 3.5 mm tungsten and 320 µm silicon

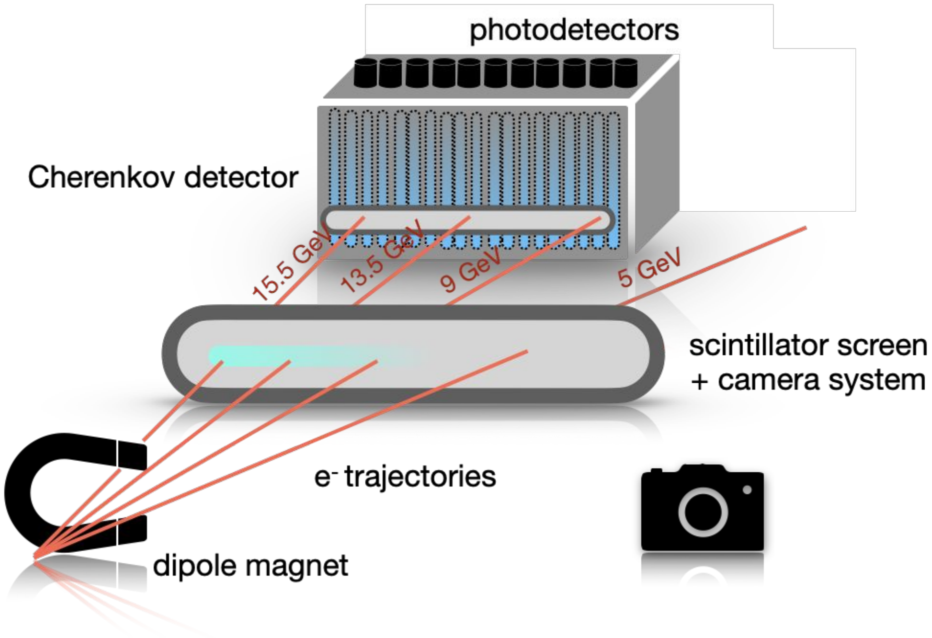


Electron Detection System

Scintillating screen and Cherenkov counter

- Scintillator screen & camera system
  → 500 µm position resolution
- Cherenkov counter system
  → 4 mm channel segmentation





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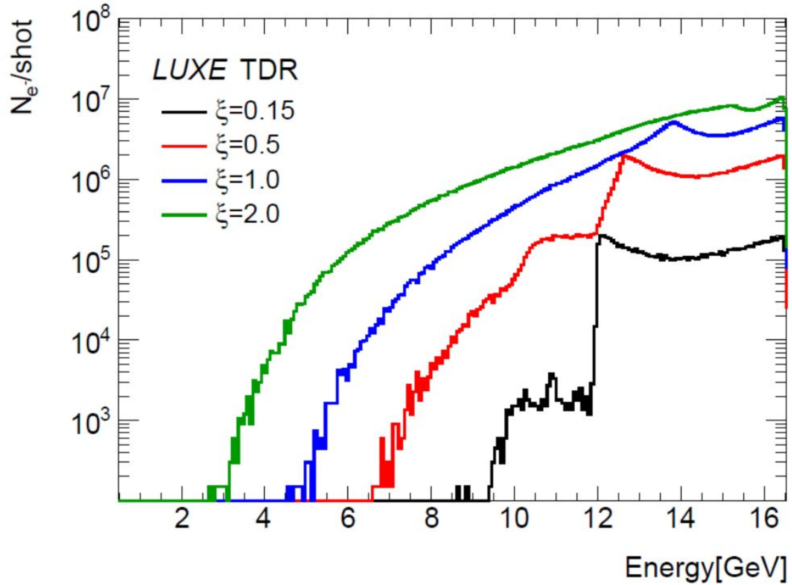

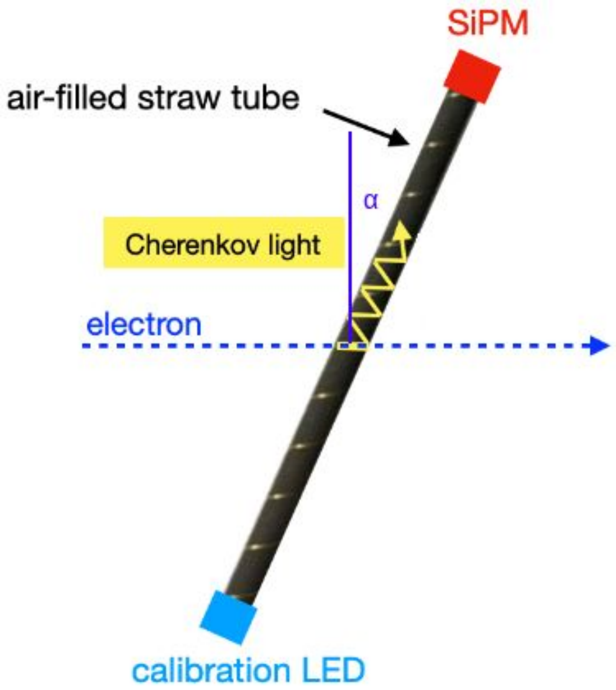

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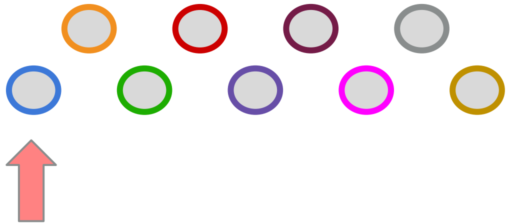
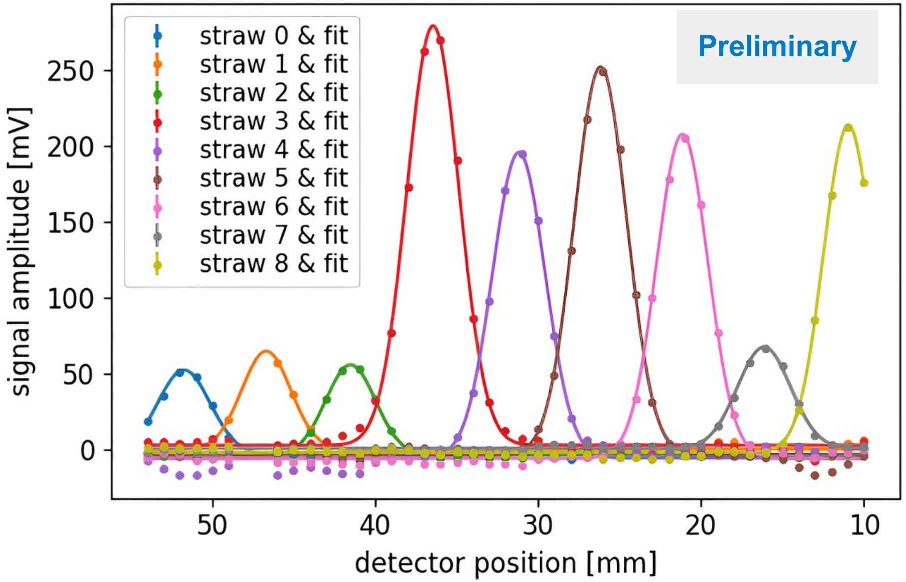
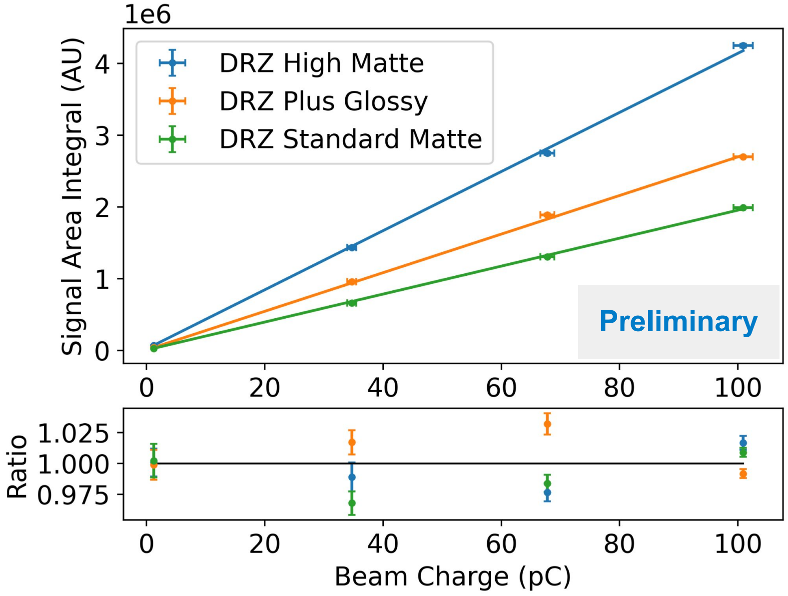




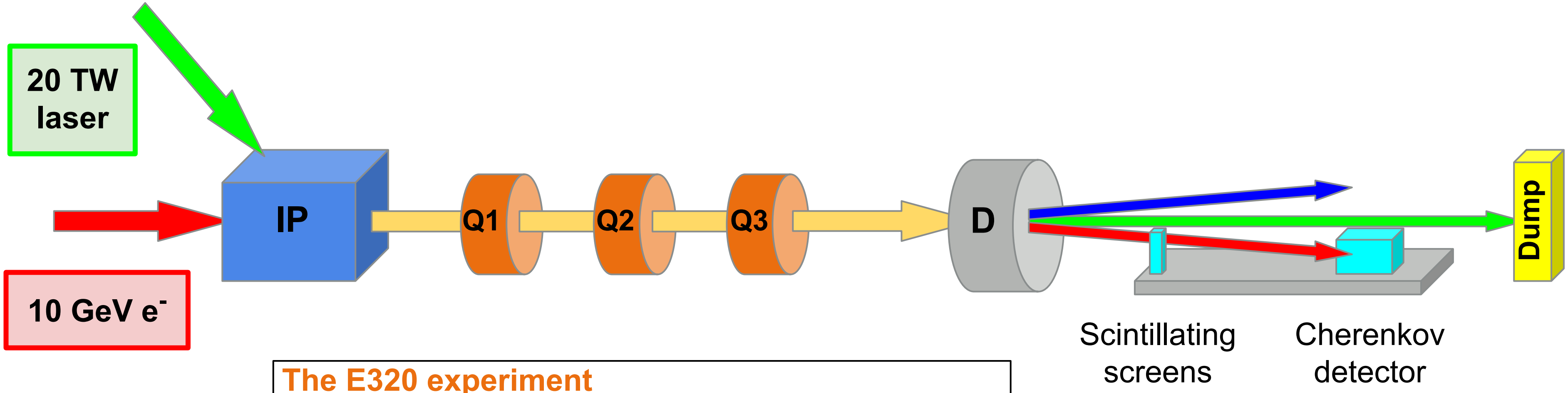
Light yield measured in detector at different straw positions



Light yield measured of different screens

Synergies with E320

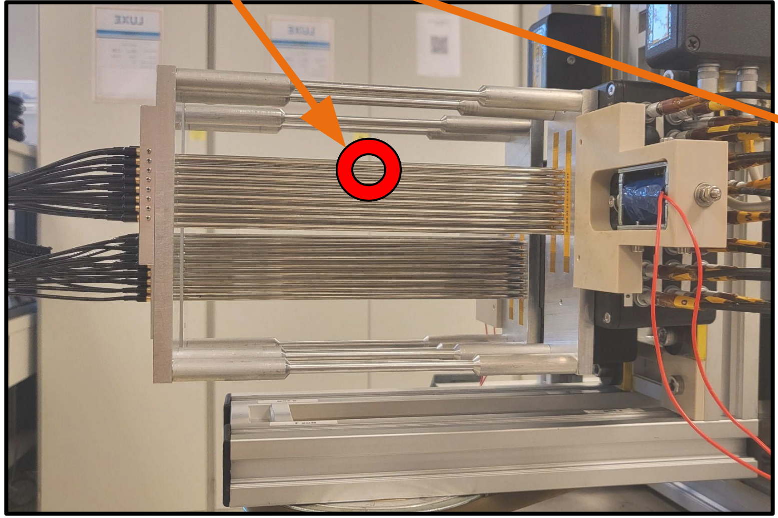
Synergies between LUXE and E320

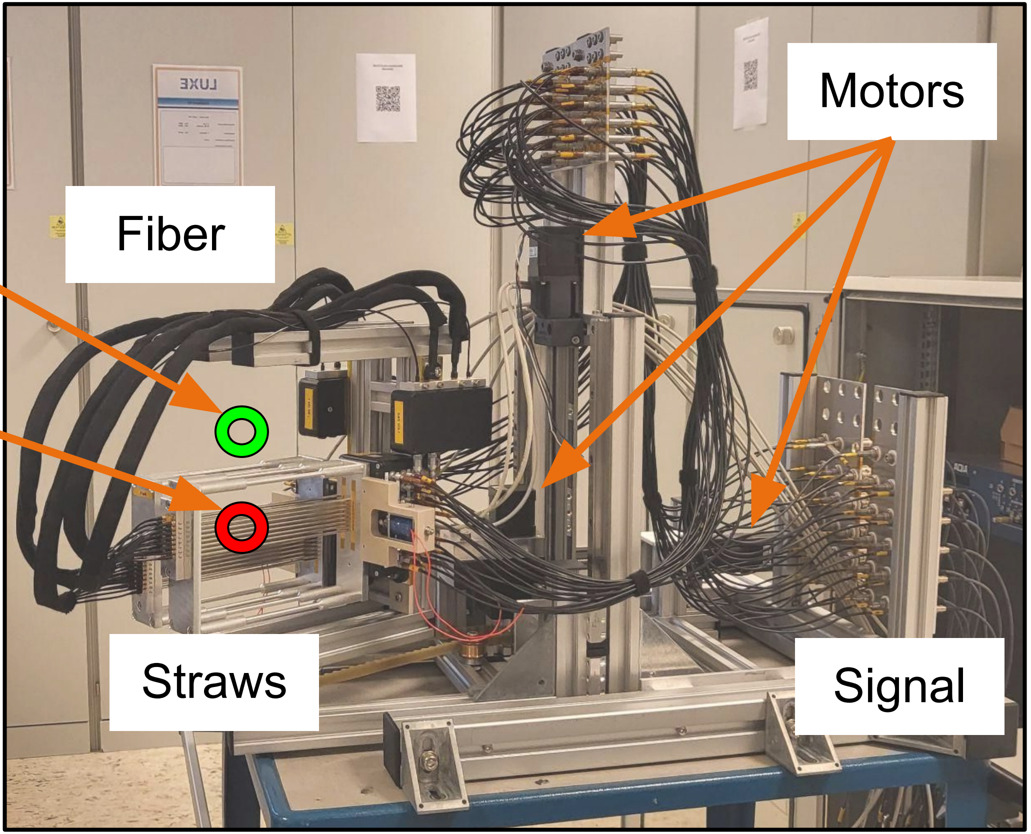


The E320 experiment

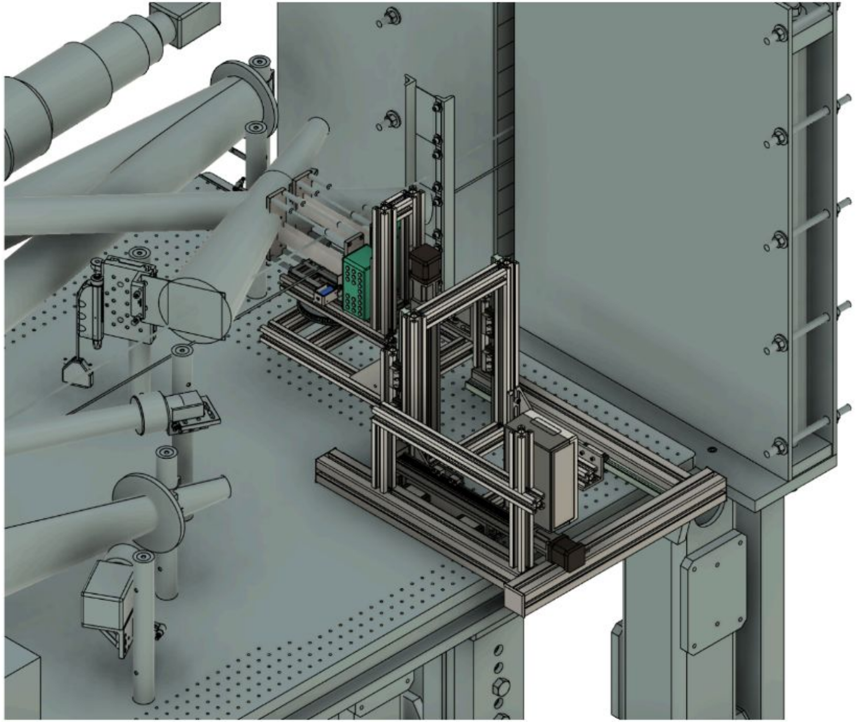
- 10…13 GeV electron beam with 1.5 nC
- 20 TW laser
- $\xi \sim 3 \ldots 5$ (10)
- 0.26 T dipole magnet → e-/e+ vertical fan out
- In-air experimental area before dump
  → Scintillating screens & cameras
  → LUXE Cherenkov detector

Synergies between LUXE and E320

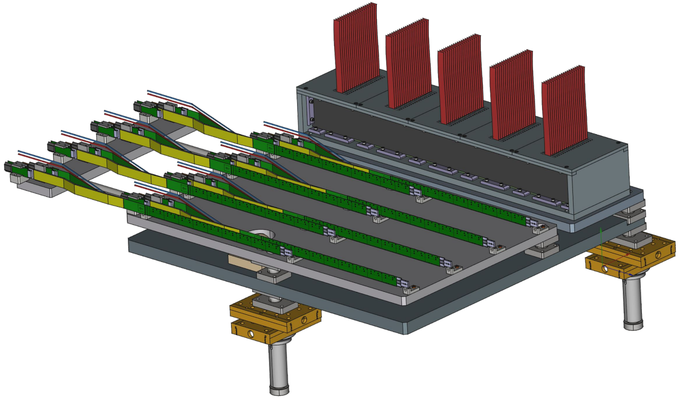




Synergies between LUXE and E320

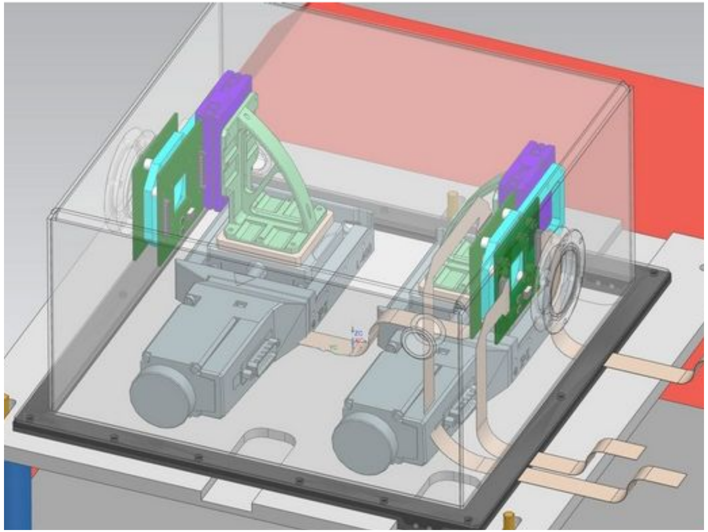


Synergies between LUXE and E320



Future collaborations

- Electron Detection System measurements of Compton electrons after shutdown
- Positron Tracker (WIS) installation this summer
- Gamma Beam Profiler (INFN) installation in discussion



Conclusion

LUXE will explore the regime of strong-field QED

First observation of real Breit-Wheeler pairs

Many different detector technologies optimized for precision measurements

E320 successfully probes strong-fields
→ Synergies will be used for development and further physics exploration

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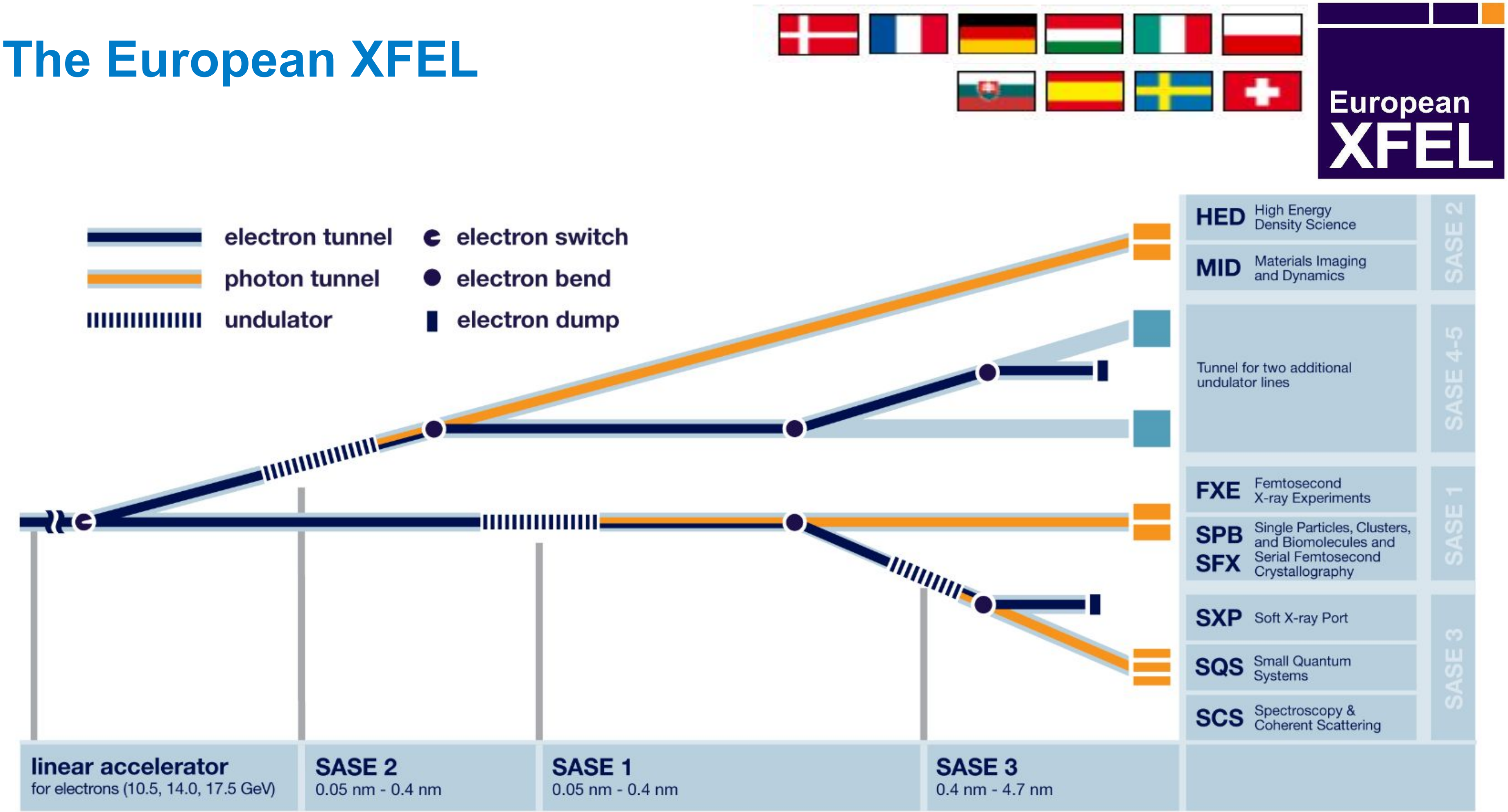
Contact

Deutsches Elektronen-Synchrotron (DESY) | Antonios Athanassiadis (FH-FTX)

www.desy.de | antonios.athanassiadis@desy.de

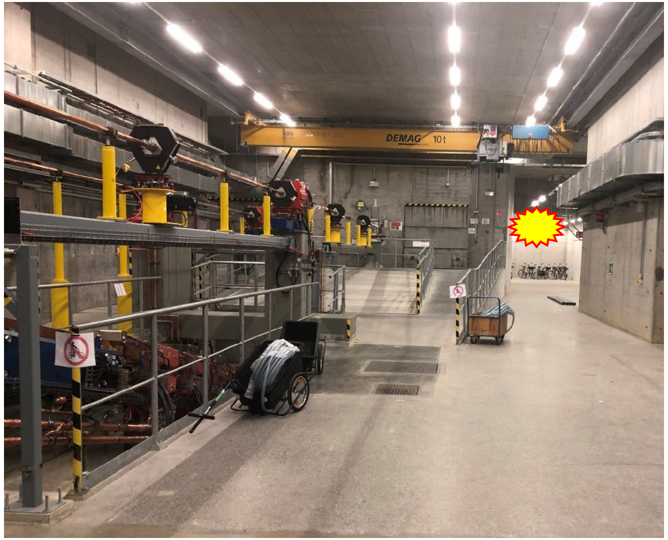
Backup

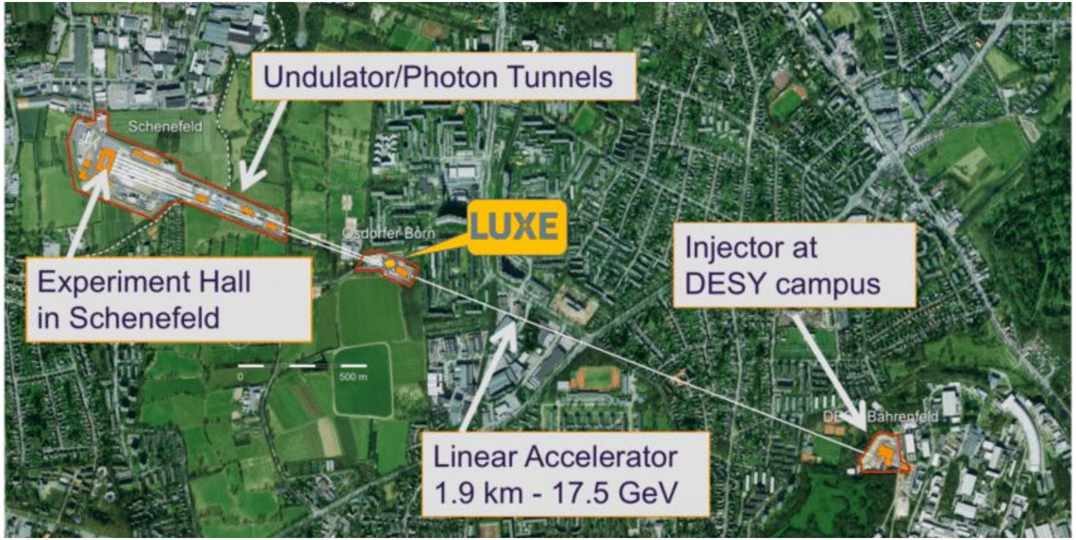
The European XFEL



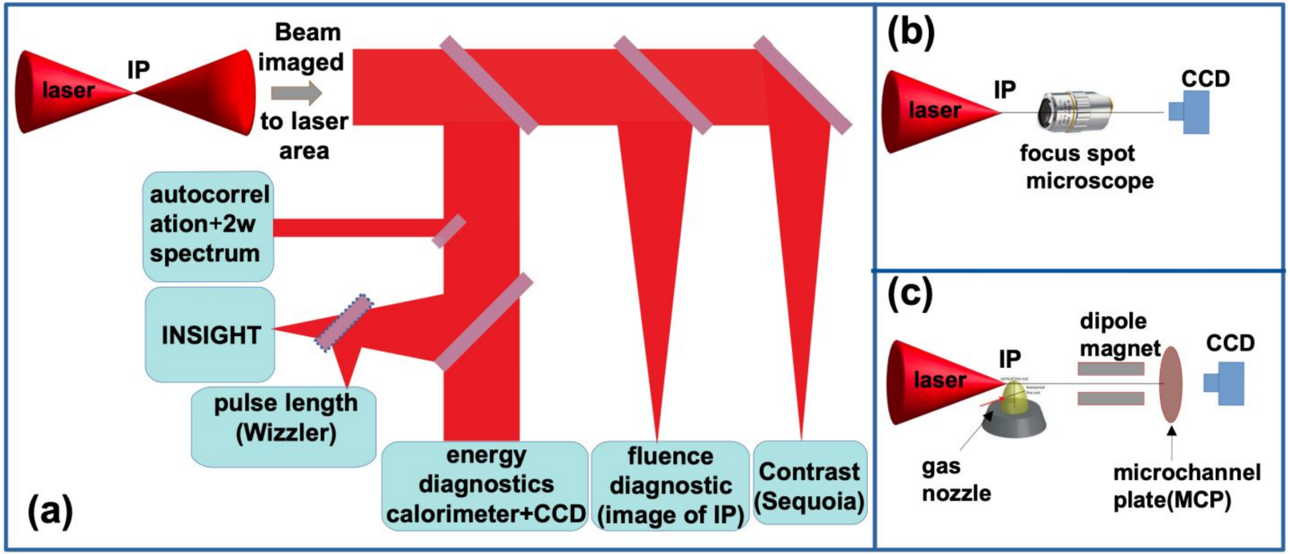
LUXE at the Eu.XFEL

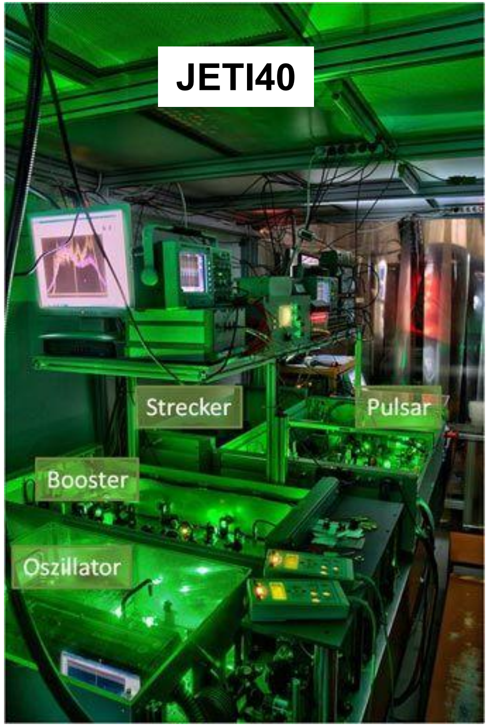
- Experiment will be located in the annex (built for later XFEL upgrade)
- No impact on photon science → Only one out of 2700 bunches used
- Aim to run at 16.5 GeV with $1.5*10^9$ electrons/bunch (250 pC) and 130 fs pulse width



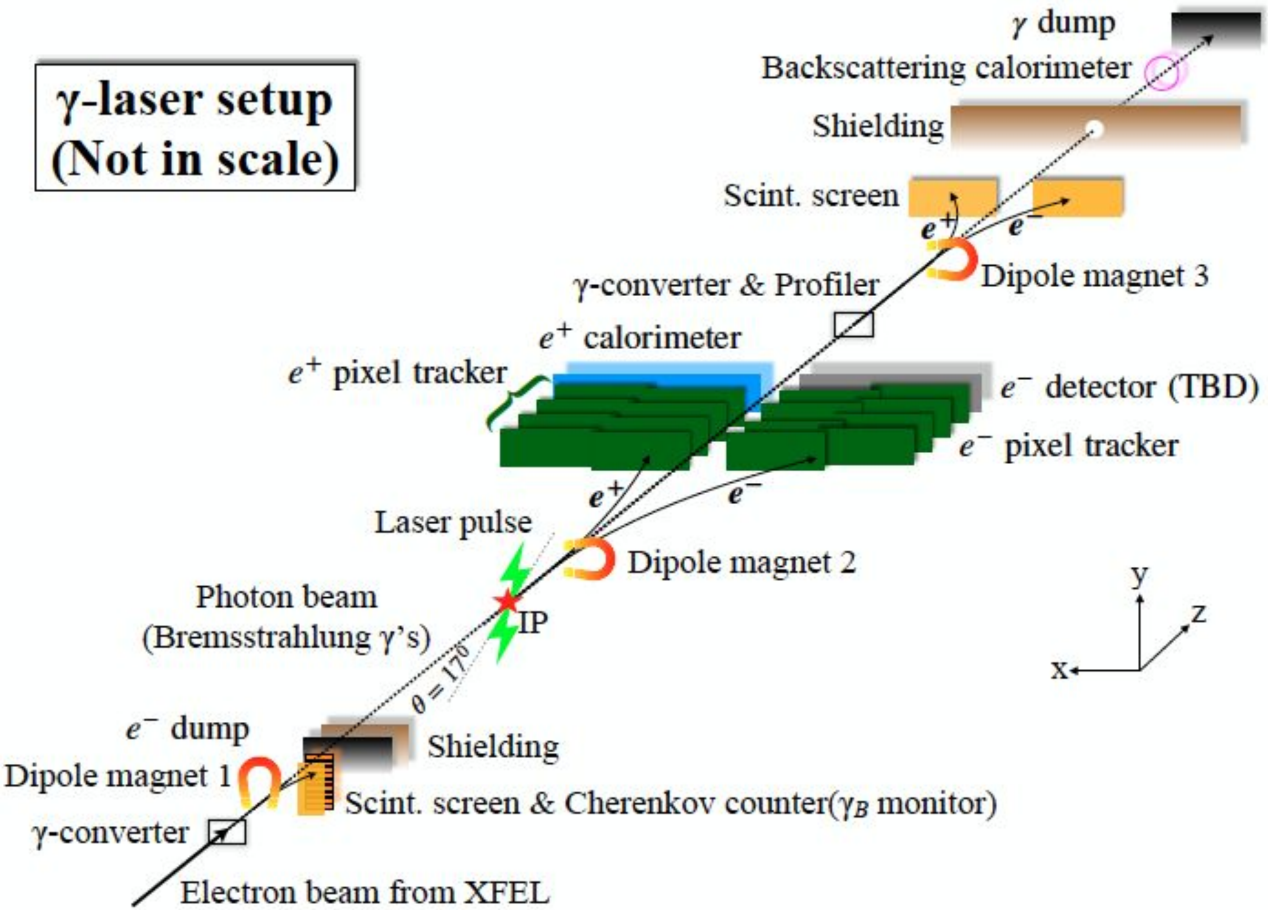


The LUXE laser



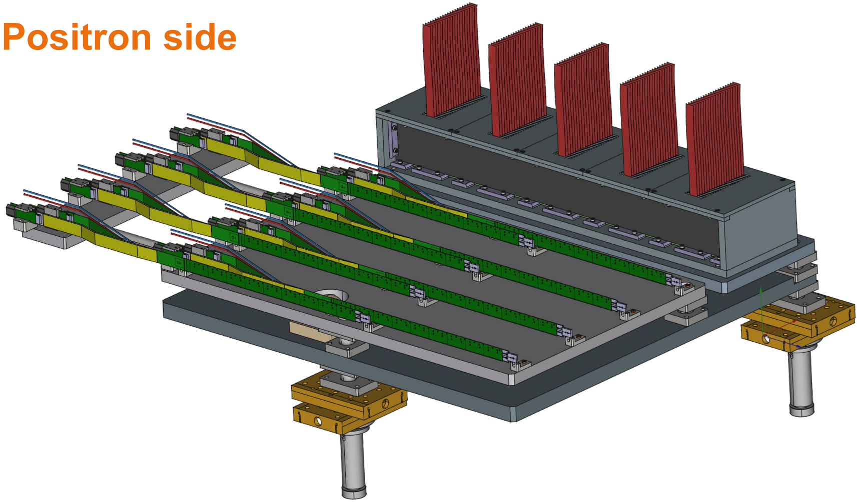


LUXE phase-1 detectors



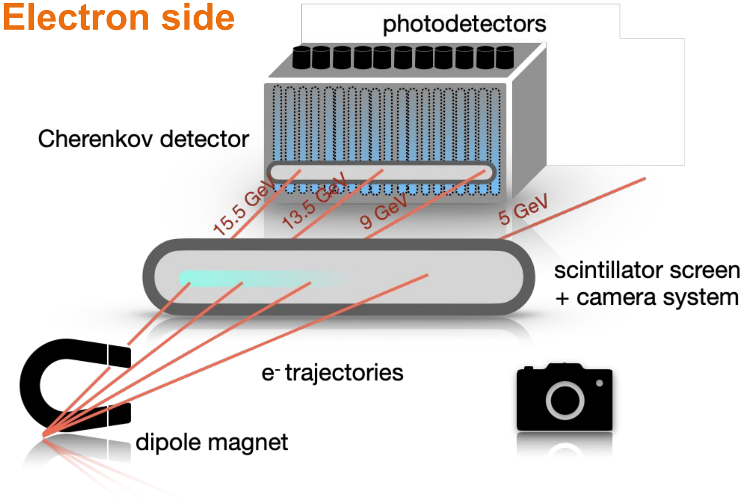
The Positron and Electron Detection System

Positron side



- Four-layer silicon pixel tracker (ALPIDE) with $\Delta E/E \sim 0.3\%$ and $\Delta x \sim 5\mu m$
- Highly granular electromagnetic calorimeter (Sampling silicon tungsten) with $\Delta E/E \sim 19.3\% / \sqrt{E}$ and $\Delta x \sim 780\mu m$

Electron side



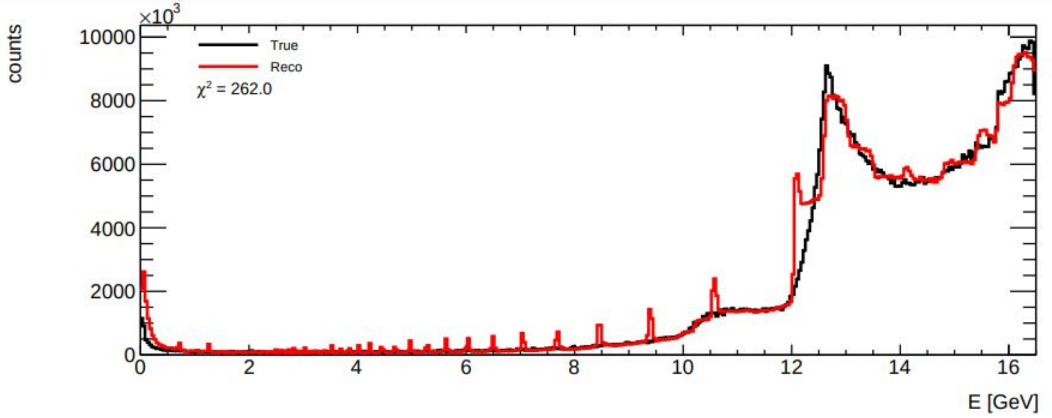
- Scintillator screen and camera with $\Delta x \sim 500\mu m$
- Segmented Cherenkov detector with $\Delta E/E \sim 2\%$ and $\Delta x \sim 3mm$

The Cherenkov detector

Reconstruction algorithm

- Single row of straws

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



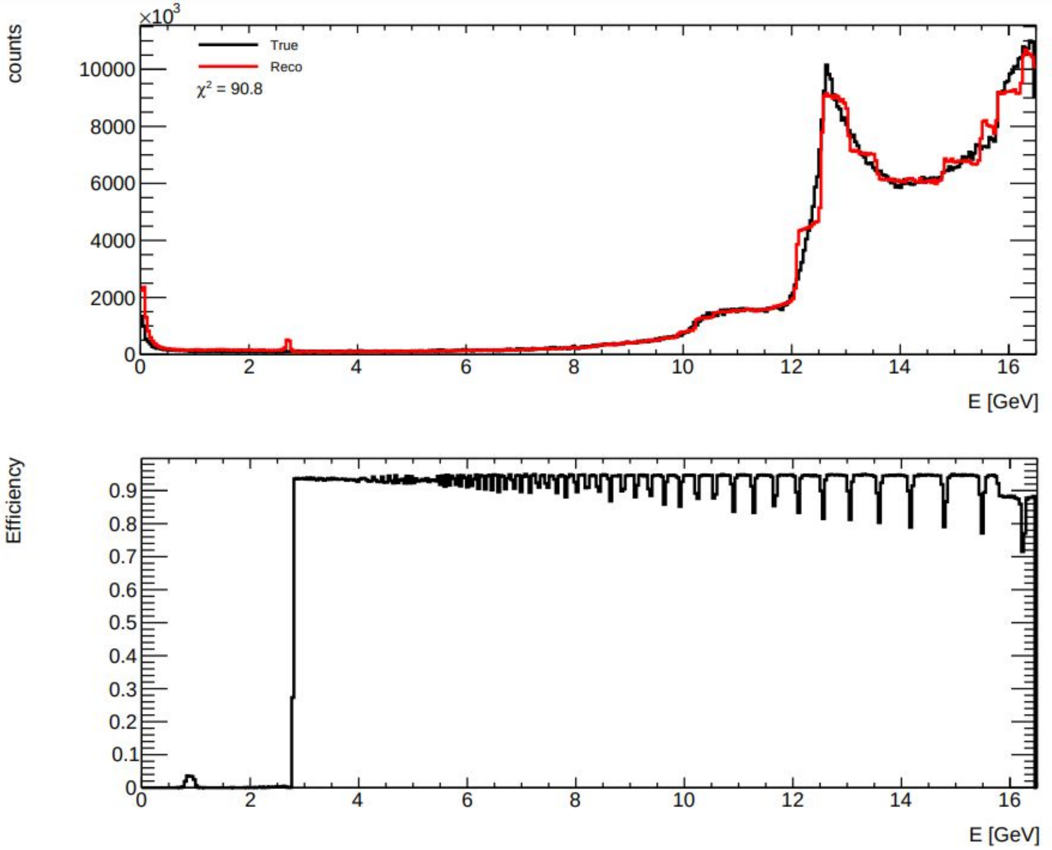
- Convolution between
  - Compton edge position $$R_d(i) = \sum_{k=-N}^{k=N} h_d(k) \cdot g_d(i-k)$$
  - Gaussian filter $$h_d(k) = -k \exp -\frac{k^2}{2\sigma^2}$$

The Cherenkov detector

Reconstruction algorithm

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

➤ Second row of straws recovers this effect partially



The Photon Detection System

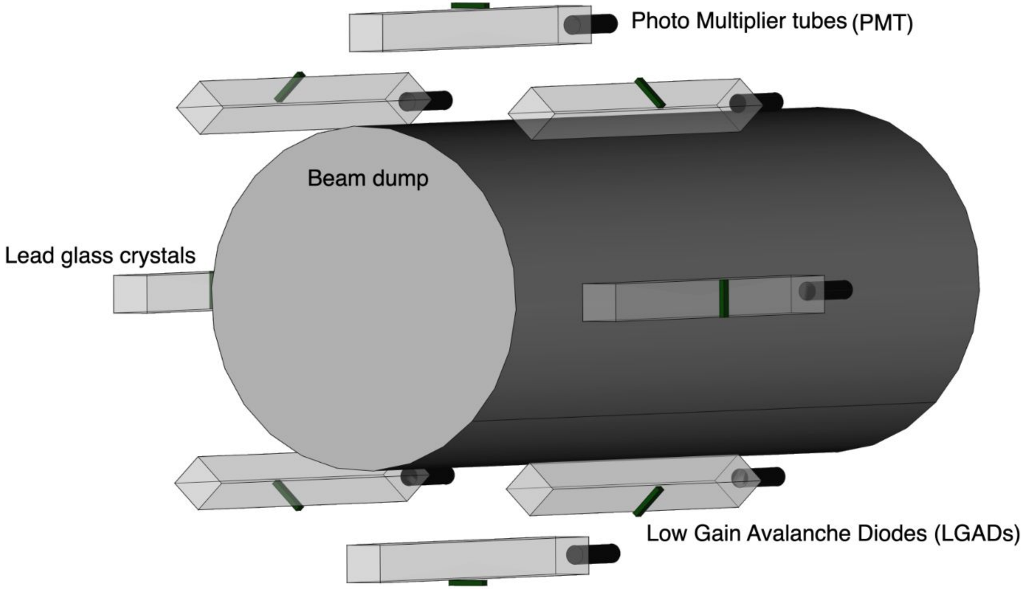
Backscattering calorimeter

- Gamma beam dump surrounded by TF-101 lead glass crystals with PMTs/LGADs used to measure particle fluxes and impact positions

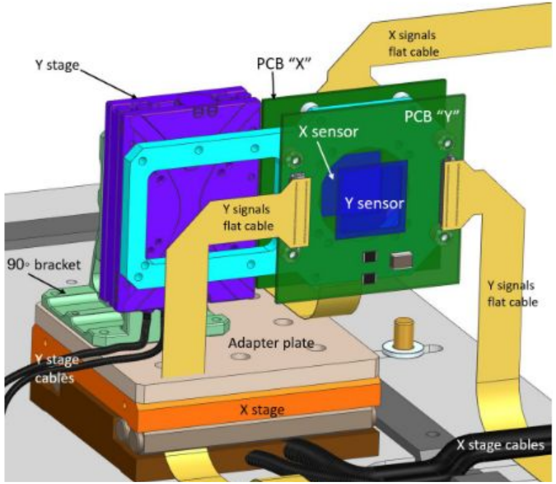
- Preliminary GEANT4 simulation studies on the detector geometry ongoing

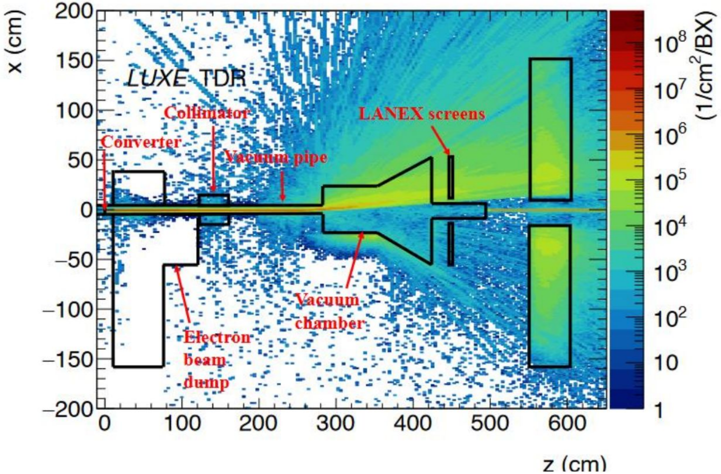
- PIER seed grant proposal is currently being reviewed
  - Across-campus collaboration possible

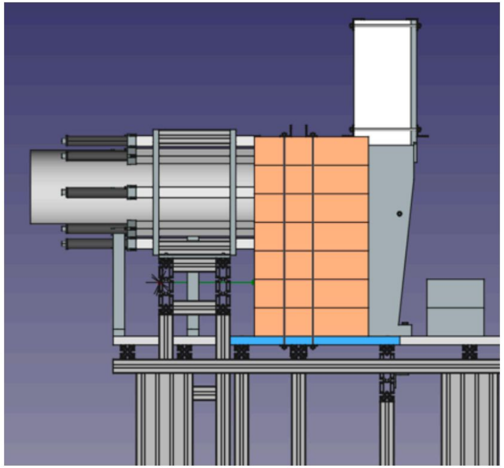
- Testbeam with conceptual detector idea at DESY



Gamma Detection System (GDS)







Gamma profiler (sapphire strips)

- Measure profile of ɣ beam using sapphire strips
- Prototype tested successfully in various high-rate facility

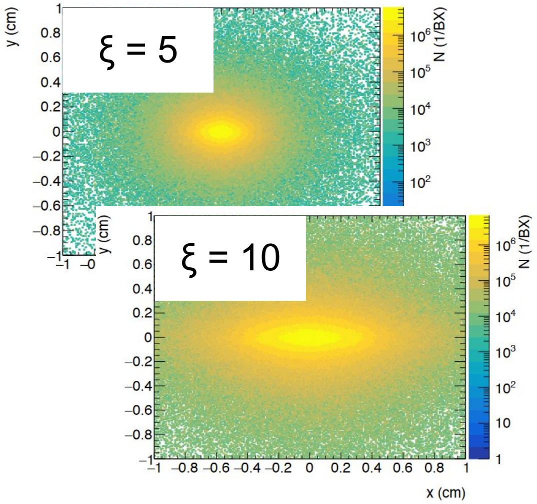
Gamma spectrometer

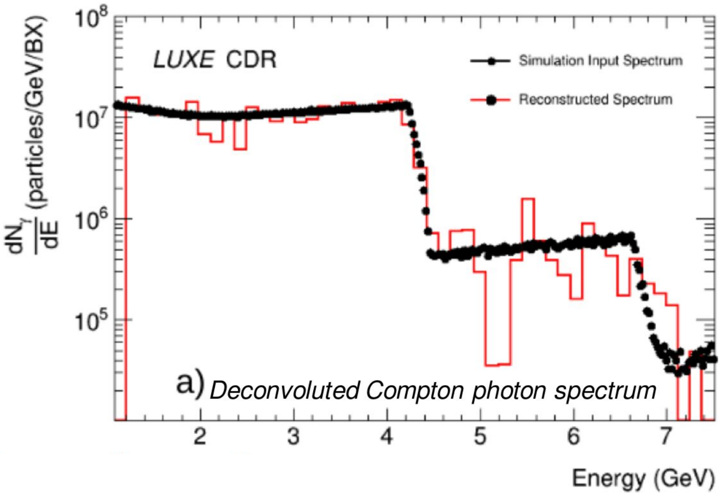
- Converter target + spectrometer magnet + scintillator screens
- Measure ɣ energy spectrum

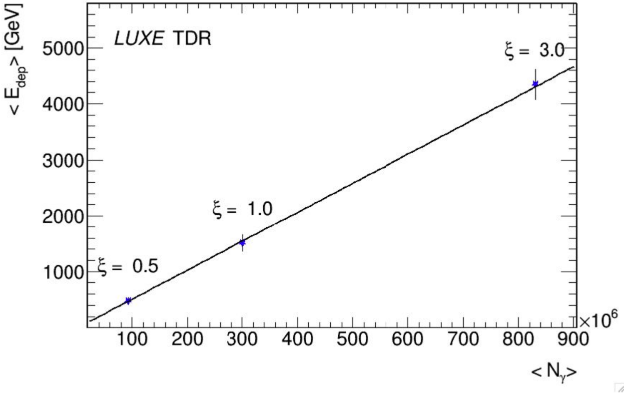
Gamma flux monitor

- crystal placed around beam dump
- Measure photon flux
- Proof of concept at FlashForward

Gamma Detection System (GDS)







Gamma profiler (sapphire strips)

- γ beam location and shape
- Precision measurement of laser intensity

Gamma spectrometer

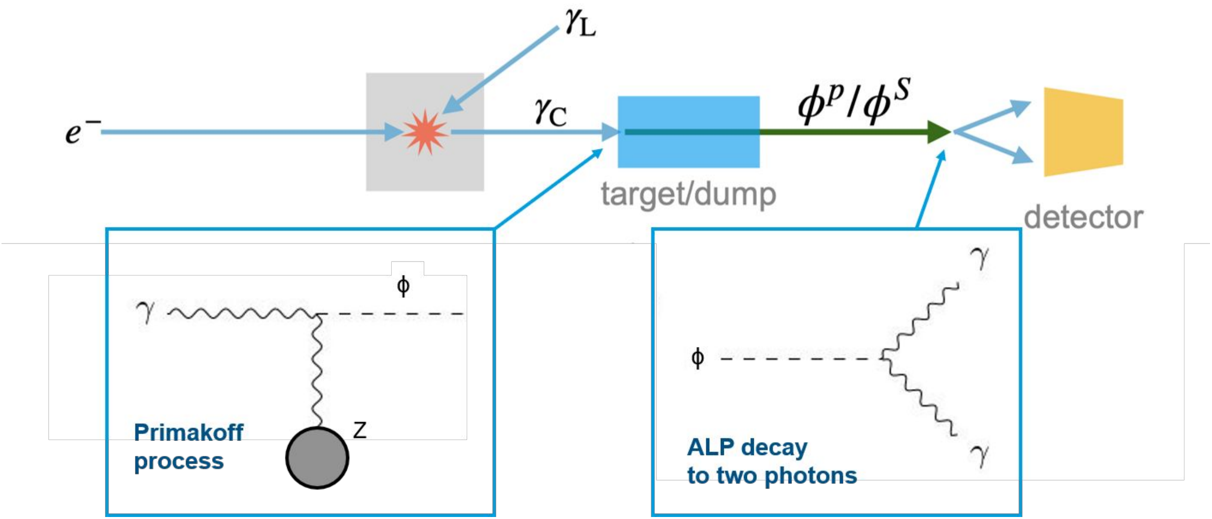
- Simulation-based reconstruction tested
- Energy resolution of $(\frac{\delta E}{E} < 2\%)$

Gamma flux monitor

- Precision 3-10% from first simulation-based study

LUXE BSM searches

- Sensibility to BSM theories:
  - New neutral particles produced at IP
  - Milli-charged particles
  - Axion-like particles (ALPs) produced in dump
- For ALPs:
  - sensitive to masses of ~ 100 MeV
  - decay to two photons after dump
  - Calorimeter with good pointing resolution to reconstruct decay point



LUXE status

- LUXE initiated in 2017 (A. Ringwald, B. Heinemann)
- 2022: international collaboration with ~20 institutional members

- **Nov 2022: LUXE officially recognized as a DESY experiment!**

- Four-year construction period → first data as early as 2027 (depending on approval time-scale)
- Extensive material on detailed design and planning available
  → TDR released in summer 2023!

Scintillator screen response

Rel. brightness	Standard	Plus	High
Manufacturer Website *	0.84	1	1.32
Best Fit	0.72	1	1.53

- Comparison of light yield at different bunch charges
  - ➨ Screens behave as expected

*http://www.mcio.com/Products/drz-screens.aspx