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

Matthew Wing
and the LUXE collaboration

- Introduction
- Strong-field QED
- LUXE experiment
- LUXE detector systems
- LUXE physics expectations
- Summary

CERN Detector Seminar — 2 June 2023

Introduction: LUXE fills the vacuum

- The vacuum is the state with the lowest energy.
- It consists of vacuum fluctuations or virtual particles.
- Coupling to virtual particles affects physical particle processes.
- Want to understand how (strong) fields create pairs in vacuum.
  - Matter created out of “nothing”.

- What is strong-field QED and why is it interesting ?
- What is the LUXE experiment and what will it measure ?
- What are the the key technologies and detector systems that will allow us to measure strong-field QED processes at LUXE.

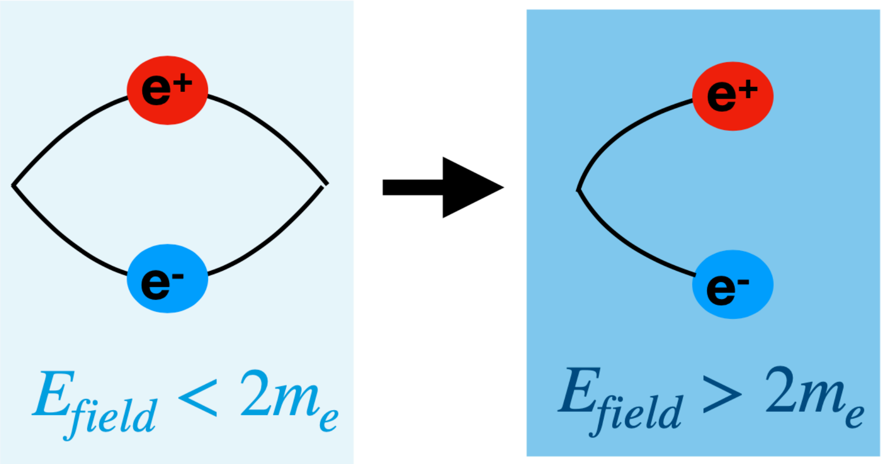
LUXE

LASER Und XFEL Experiment

Strong-field QED

Strong-field QED

- QED is one of the most thoroughly tested theories with measurements and perturbative calculations performed to high precision.
- The region of strong fields is less well-known, although they are present:
    - ➡ In magnetars and other astrophysical phenomena.
    - ➡ In atomic and laser physics.
    - ➡ In high-energy colliders, e.g. ILC or CLIC.
- LUXE will investigate the strong-field regime, where QED becomes non-perturbative.
- Characterised by the Schwinger critical field.



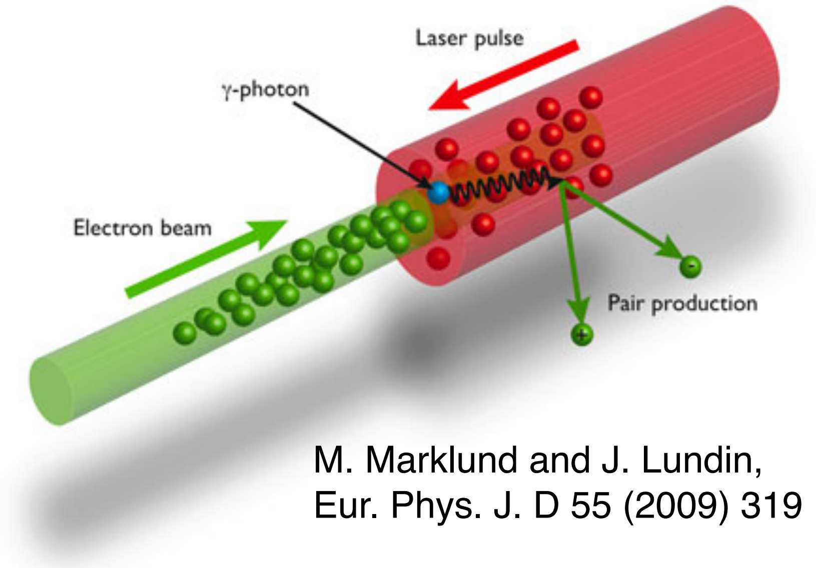
$$E_{\mathrm{crit}} = \frac{mc^2}{e\lambda\!\!\!^{-}_C} = \frac{m^2c^3}{e\hbar}$$

$$= 1.3 \times 10^{16} \ \mathrm{V/cm}$$

- Fluctuating vacuum (time > λ_C) stimulated by high field to produce real pair creation.

Strong-field QED in the laboratory

- Existing fields, e.g. lasers, orders of magnitude too small compared to E_{crit}.
- But non-linear quantum effects observable with relativistic probes.
  - Fields $O(E_{crit})$ in particle rest frame



M. Marklund and J. Lundin,
Eur. Phys. J. D 55 (2009) 319

- In the laboratory, reach fields at Schwinger limit in the rest frame of highly relativistic particles.
  - Use multi-GeV electrons and multi-TW laser.

Strong-field QED parameters

- Intensity parameter:

$$\xi = \frac{m_e E_L}{\omega_L E_{\text{crit}}}$$

- Measure of coupling between probe and laser field (also square root of laser intensity).
- *ξ ≥ 1*: non-perturbative regime

- Quantum parameters:

$$\chi_e = (1 + \cos\theta)\frac{E_e E_L}{m_e E_{\text{crit}}}$$

$$\chi_\gamma = (1 + \cos\theta)\frac{E_\gamma E_L}{m_e E_{\text{crit}}}$$

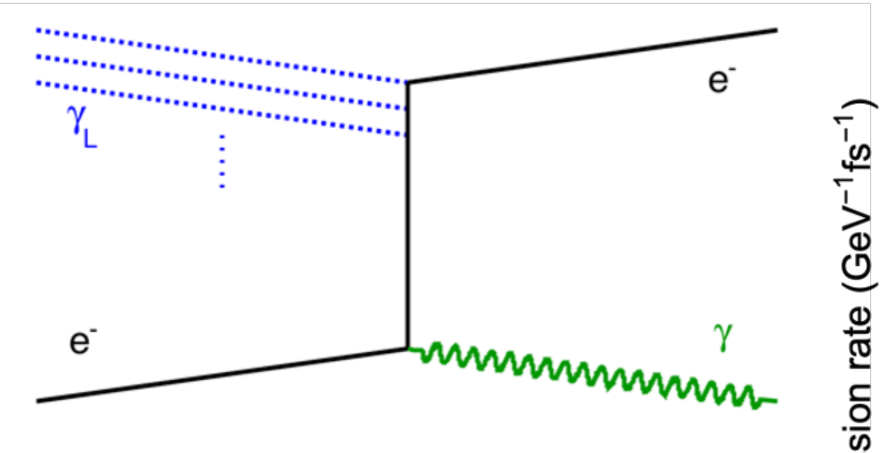
- Ratio of laser field and Schwinger critical field.
- *χ ≥ 1*: non-linear quantum effects become probable (e.g. pair production).

- Energy parameter:

$$\eta = \frac{\chi}{\xi} = (1 + \cos\theta)\frac{\omega_L E_{e/\gamma}}{m_e^2}$$

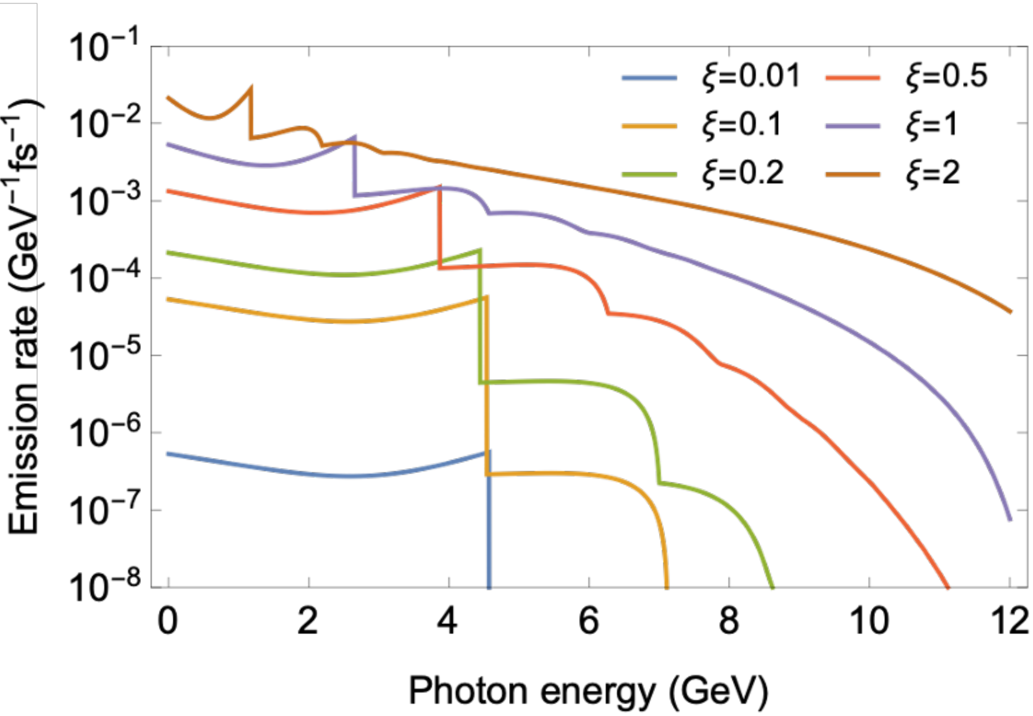
E_L :	Laser field
E_{crit} :	Schwinger critical field
ω_L :	Laser frequency
θ :	e/γ – laser crossing angle
$E_{e/\gamma}$:	Probe electron/photon energy

Non-linear Compton scattering



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

16.5 GeV electron, 800 nm laser, 17.2° crossing angle



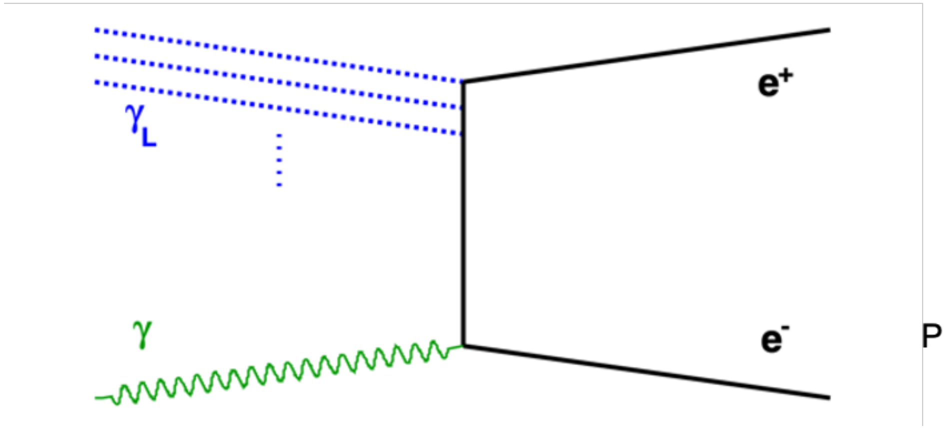
In strong fields, electrons obtain larger effective mass, $m_* = m_e (1+\xi^2)^{½}$

- Compton edge shifts as function of ξ.
- Higher harmonics appear, i.e. interaction with n laser photons.

Strong-field QED: $$E_{\text{edge}}(\xi) = E_e \frac{2n\eta}{2n\eta + 1 + \xi^2}$$

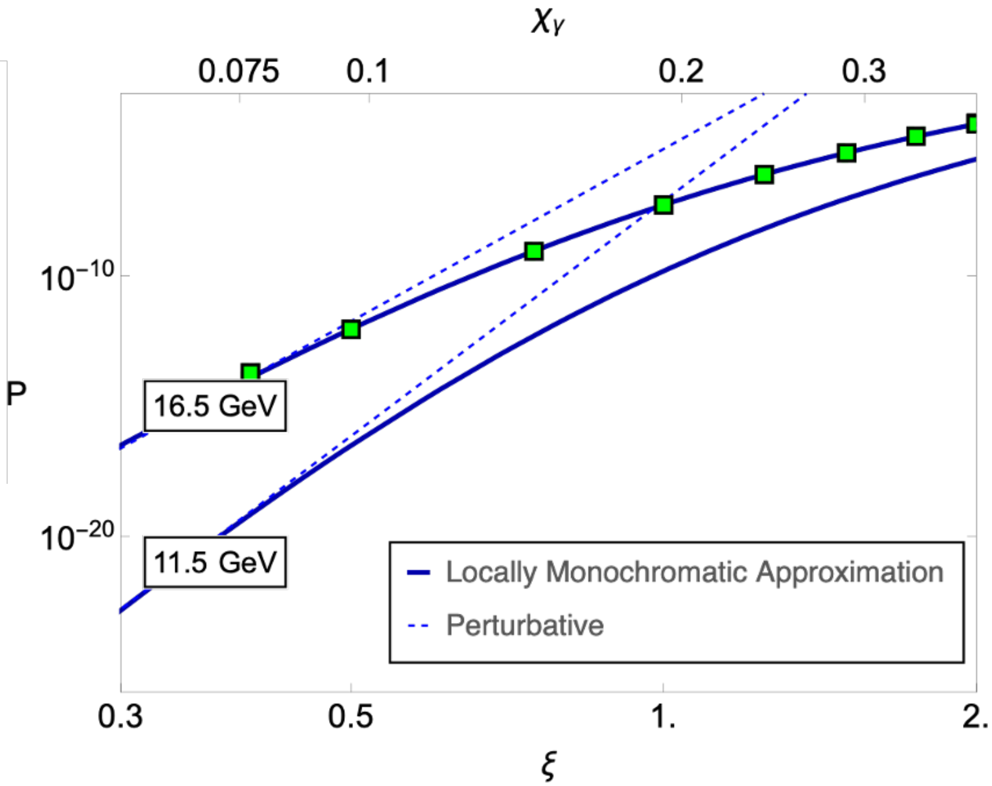
Classical limit: $$E_{\text{edge}}(\xi) = E_e \frac{2n\eta}{1 + \xi^2}$$

Non-linear Breit–Wheeler pair production



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

- Photon from Compton scattering or secondary beam.

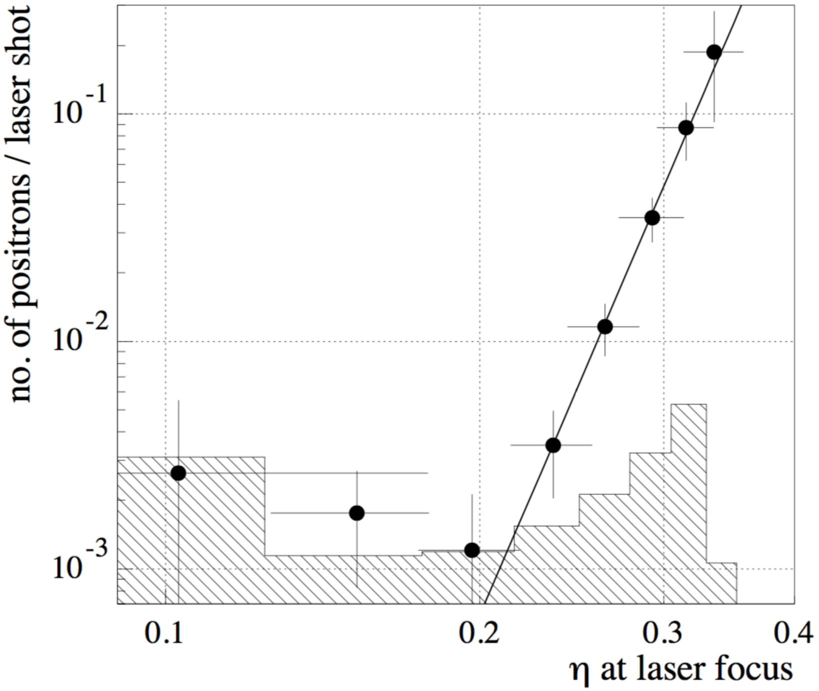


Perturbative regime: power law $\quad \xi \ll 1 \quad : \quad R_{e^+} \propto \xi^{2n} \propto I^n$

Non-perturbative regime $\quad \xi \gg 1 \quad : \quad R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$

E144 experiment at SLAC

- Pioneering experiment, E144, at SLAC in the 1990s.
- Used 1 TW laser and 46.6 GeV electron beam.
- Reached $\chi \sim 0.25$, $\xi \sim 0.4$.
- Observed process $e^- + n\gamma_L \rightarrow e^- + e^+ + e^-$
- Observed start of ξ^{2n} power law, but not departure from it.

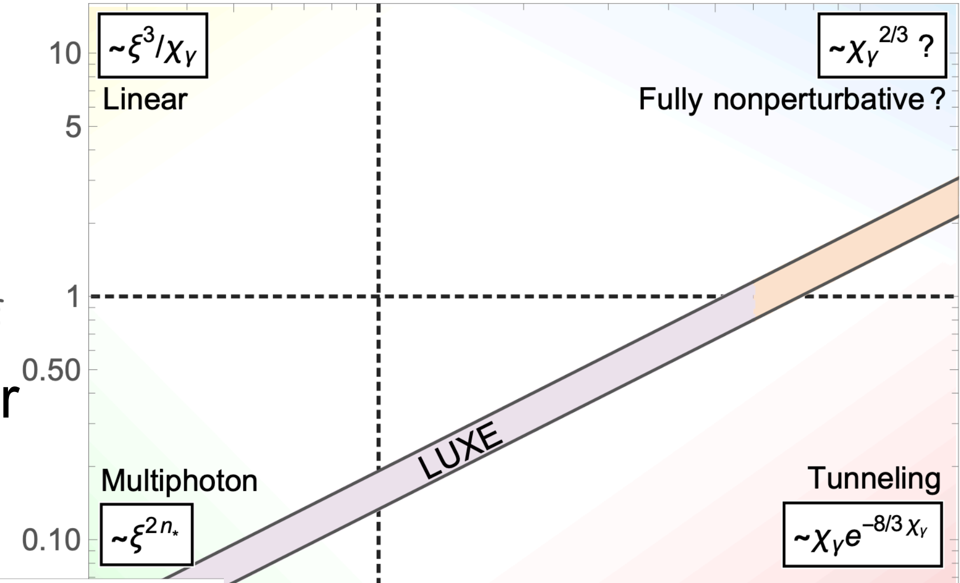


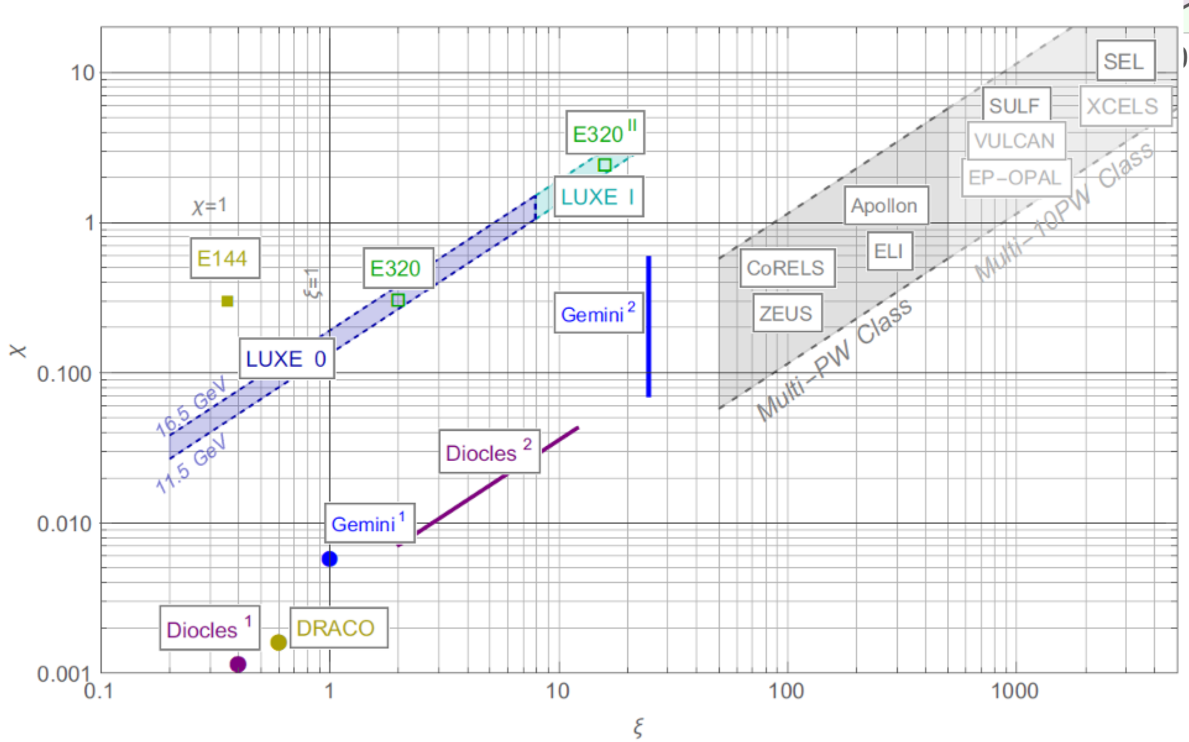
$\eta \sim \xi$

E144 Coll., C. Bamber et al., Phys. Rev. D 60 (1999) 092004;
T. Koffas, “Positron production in multiphoton light-by-light scattering”, PhD thesis, University of Rochester (1998), SLAC-R-626.

Strong-field QED parameter space

- Determined by particle beam energy and laser intensity.
- LUXE will precisely map parameter space in transition region.





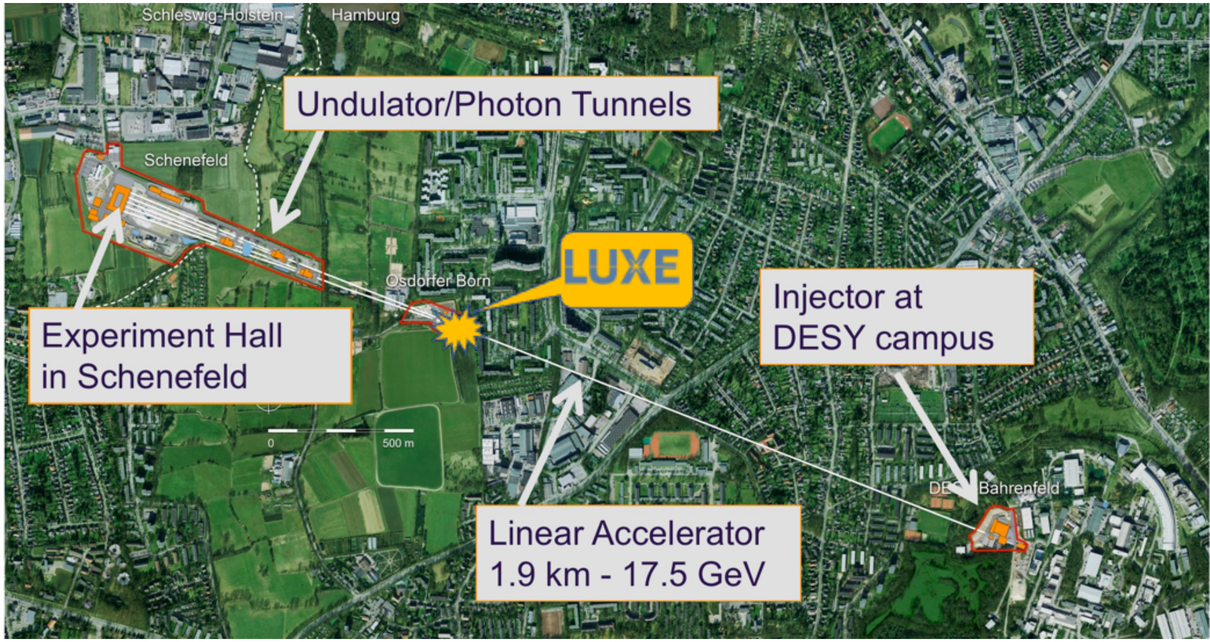
- E320: new experiment at SLAC.
- Gemini: laser wakefield experiments at RAL.
- ELI, etc. future high-power lasers.

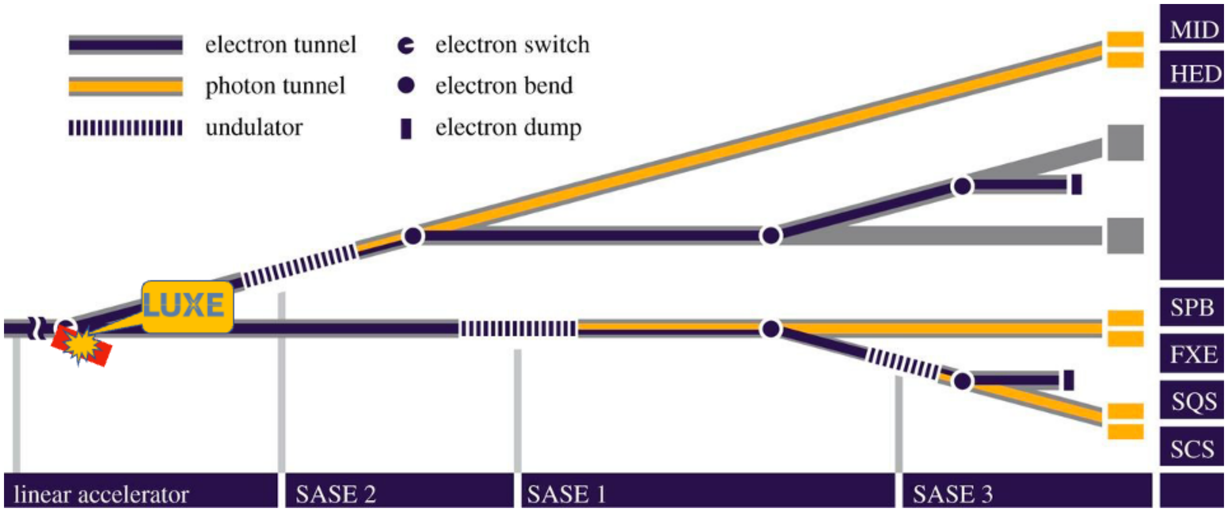
LUXE experiment

LUXE at European XFEL

EuXFEL electron beam:

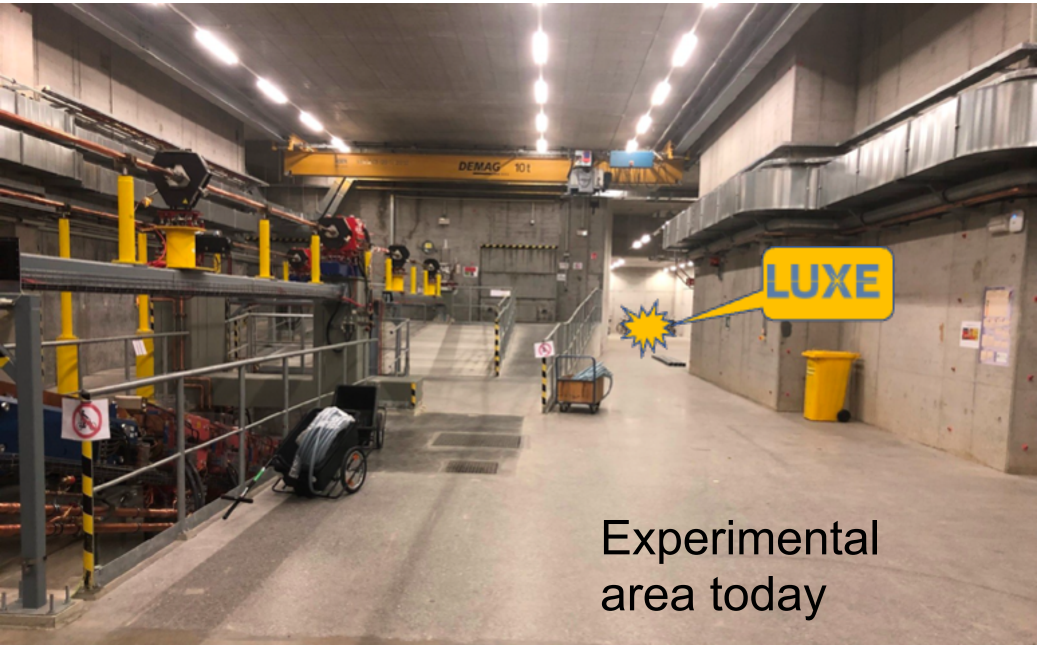
- Energy: 16.5 GeV
- Bunch: 1.5 × 10^9 e^-
- Repetition rate: 10 Hz
- Use 1 of 2700 bunches per train



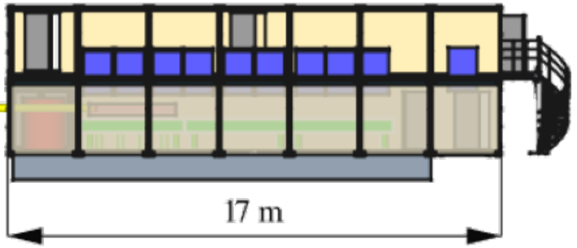


- Use electron beam before undulators
- Extract bunch to area planned for second fan
- No impact on photon science programme

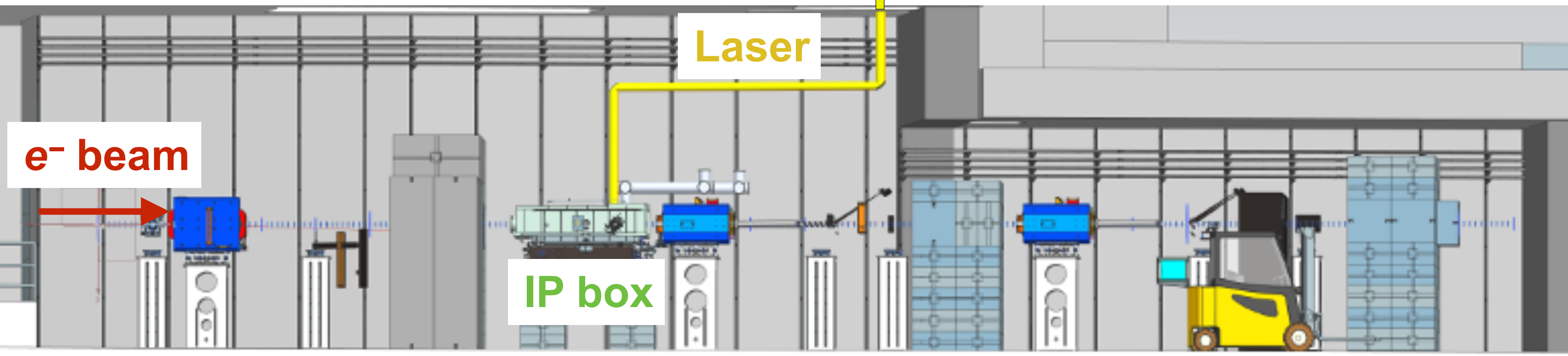
LUXE experimental area



Experimental area today



Laser room



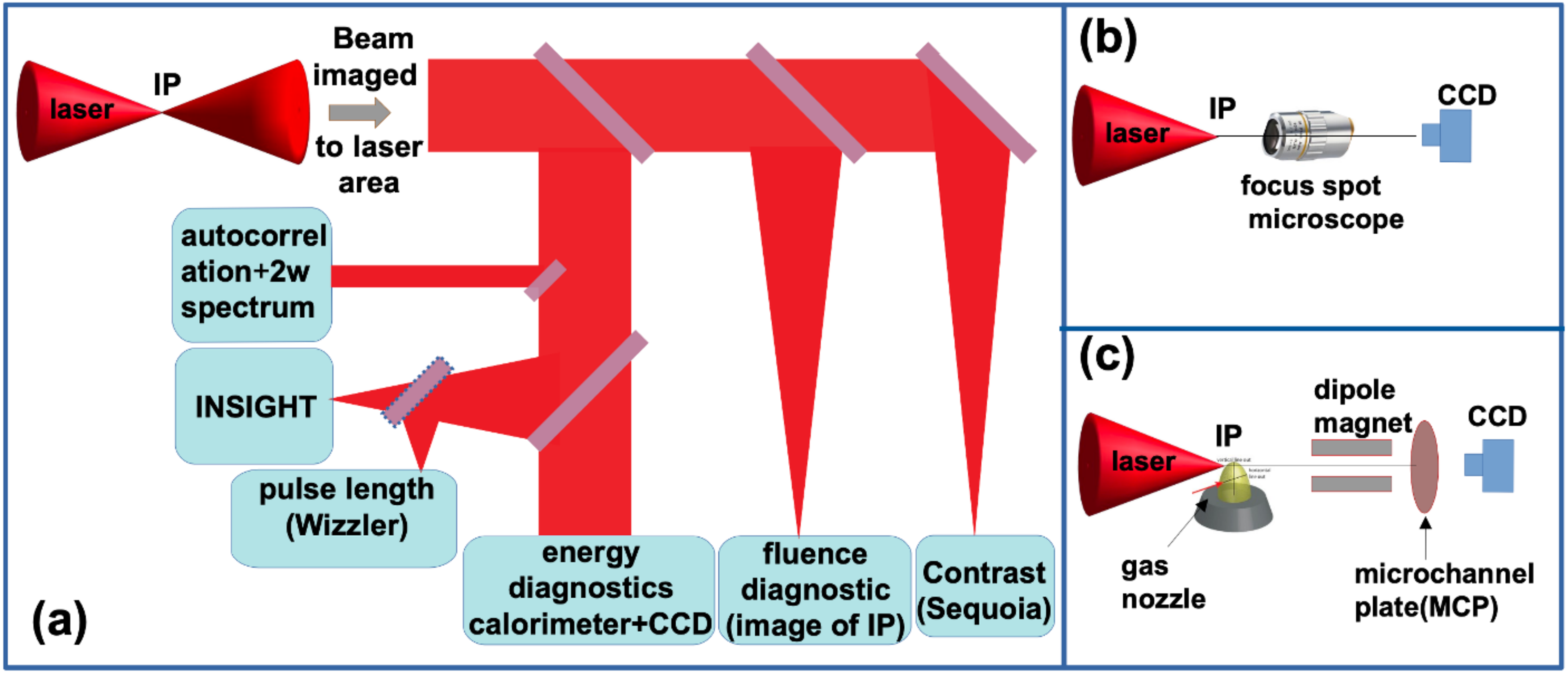
LUXE laser

Wavelength (energy)	800 nm (1.55 eV)
Power	40 / 350 TW
Pulse length	30 fs
Spot size	> 3 µm
Peak intensity	$13.3 / 120 \times 10^{19}$ W/cm^2
Peak intensity parameter ξ	7.9 / 23.6
Peak quantum parameter χ	1.5 / 4.5

- Repetition rate, 1 − 10 Hz
- Crossing angle, 17°

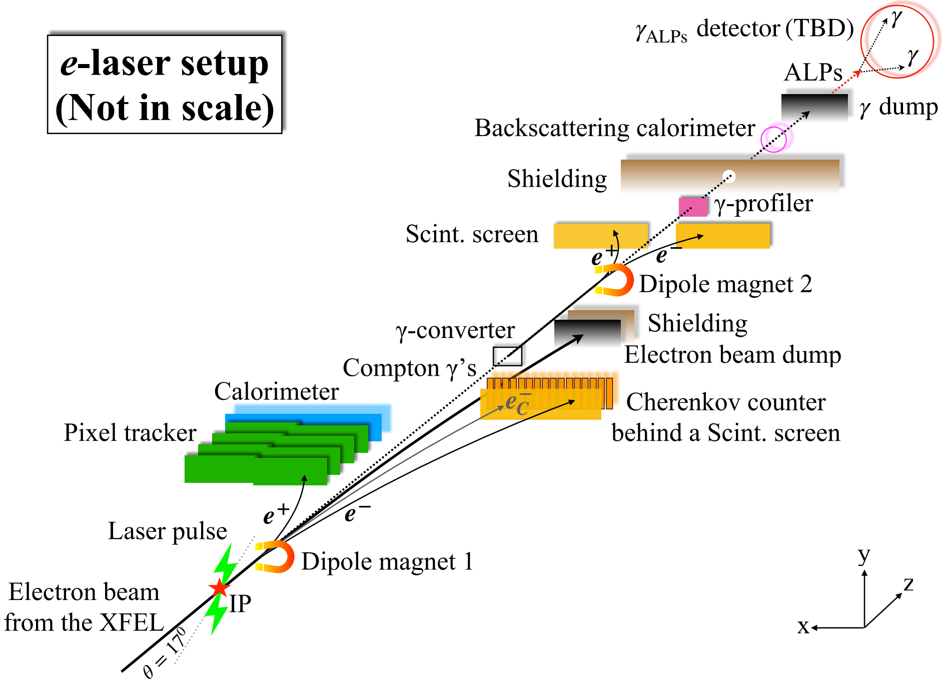
- Phases:
  - Phase-0 with a 40 TW laser (JETI40, Jena or new)
  - Upgrade to 350 TW laser for Phase-1

Laser diagnostics



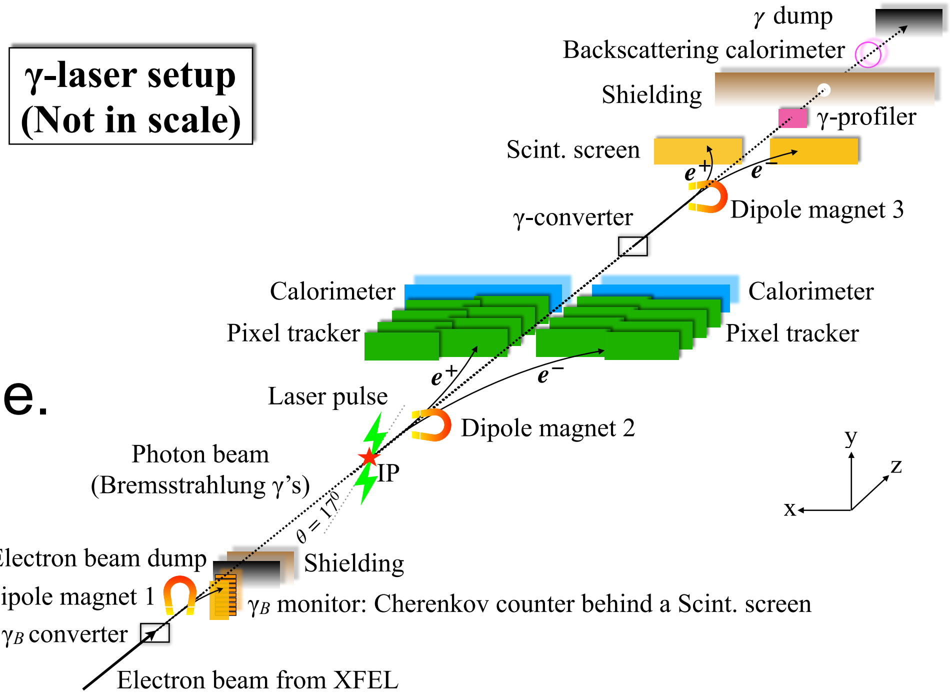
- Need to characterise energy, pulse length, spot size.
  - Diagnostics in IP chamber and in laser clean room.
- Uncertainty on laser intensity impacts physics results.
- Goal: < 5% uncertainty on laser intensity, 1% shot-to-shot uncertainty.

Experiment layout



- Two data-taking modes:
  - Electron–laser collisions
  - Photon–laser collisions: unique to LUXE

- Similar but different layouts.
- Many of the detectors are the same.
- Several challenges.

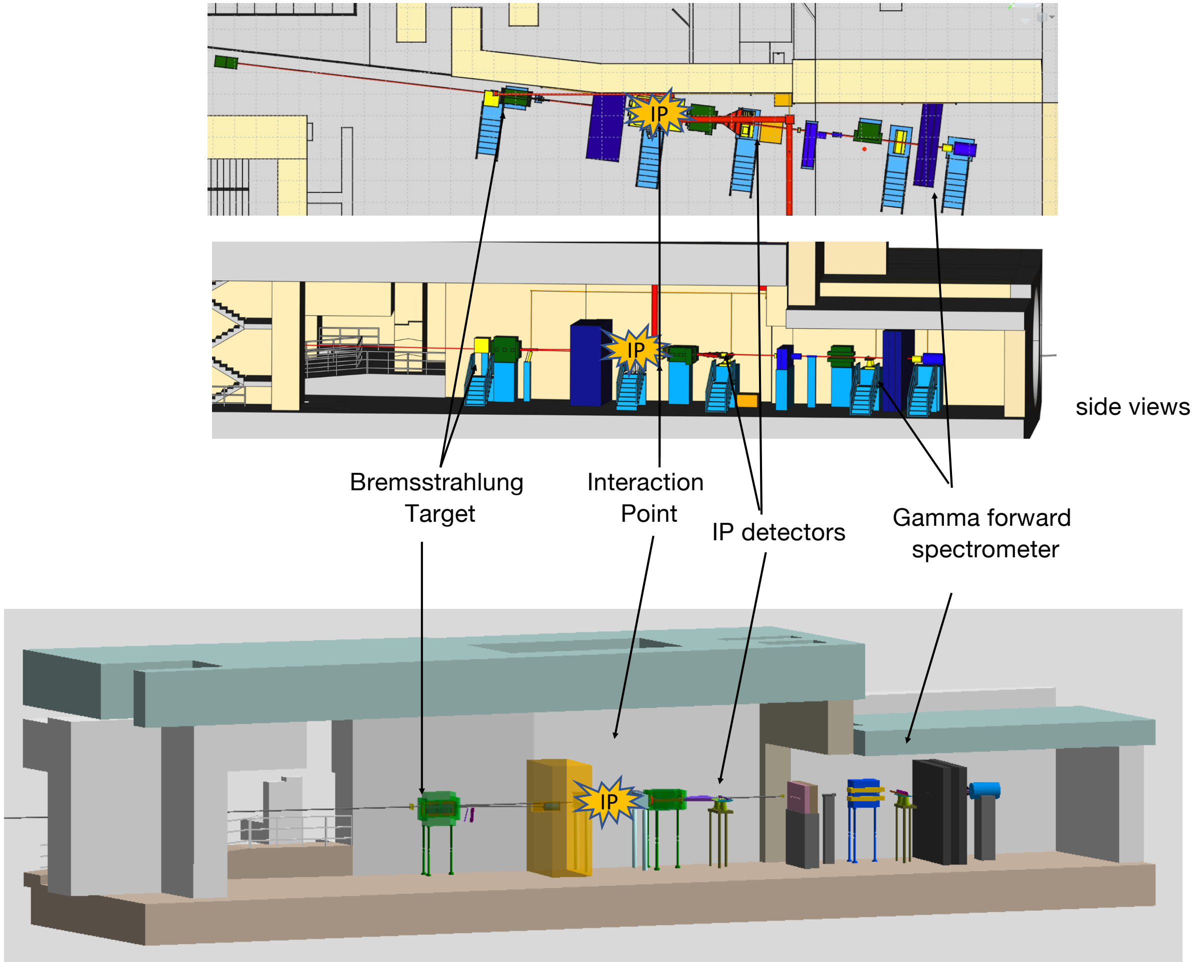


Layout — more engineering-like

CAD:

top view of experimental area

side views of experimental area



Bremsstrahlung Target

Interaction Point

IP detectors

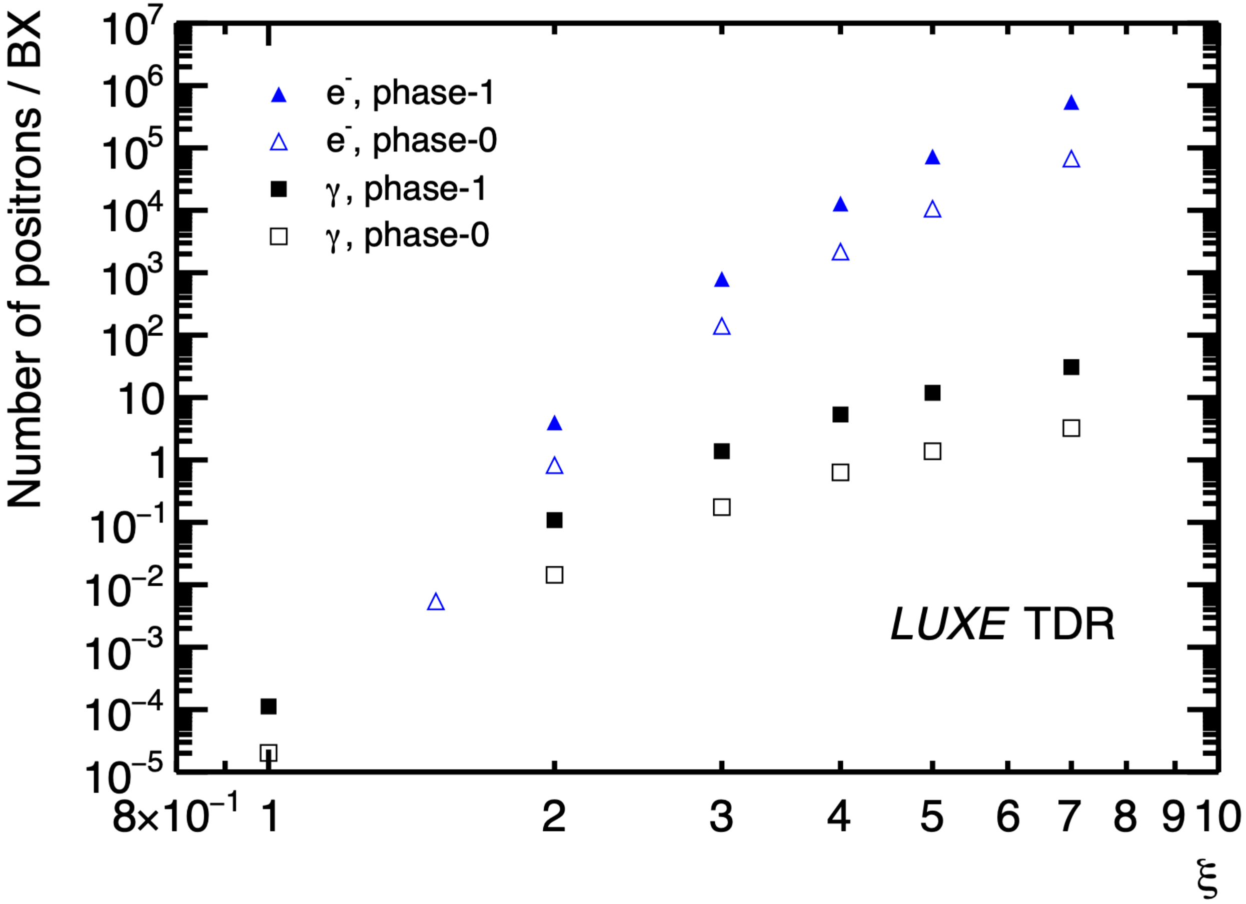
Gamma forward spectrometer

Full Geant4 simulation:

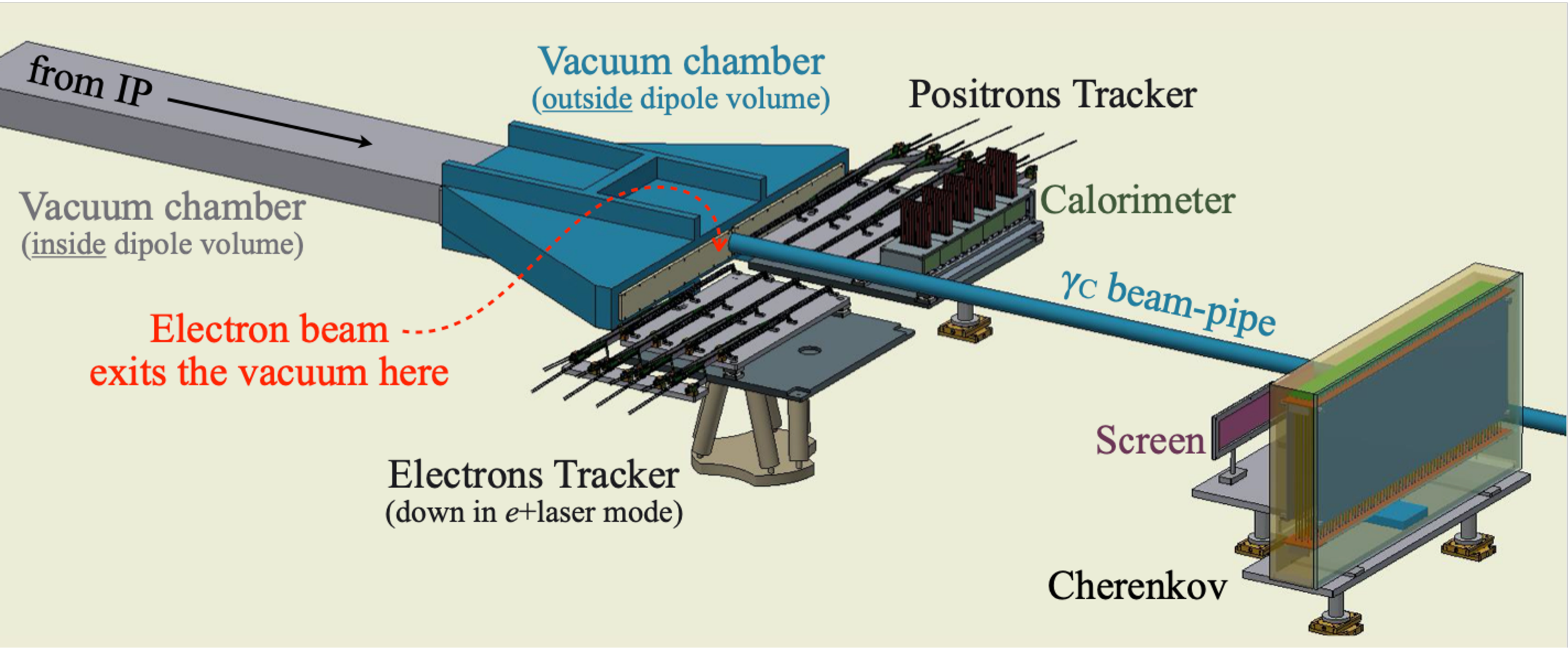
LUXE detectors

Detector requirements and challenges

- We want to detect electrons, positrons and photons in the *O(GeV)* range.
  - Measure fluxes and energy spectra.
- Detector technology to cater for varying fluxes of signal and background.
  - Fluxes vary between ~10^{-4} (e^+) and 10^9 (e^- and γ).



IP detectors

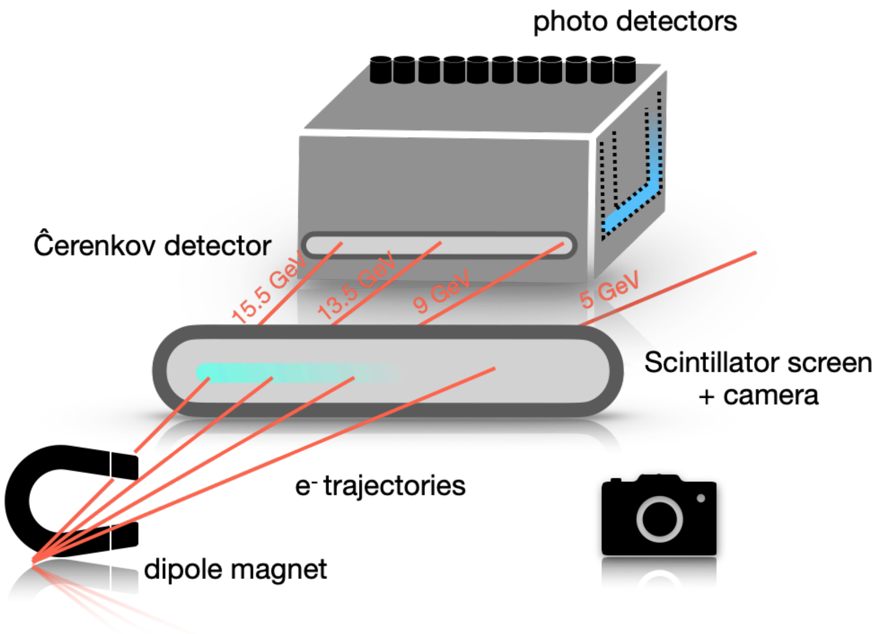


- Two complementary detector technologies per measurement:
  - Different sensitivities, cross calibration, reduction of systematic uncertainties.

Overview of electron/positron detectors

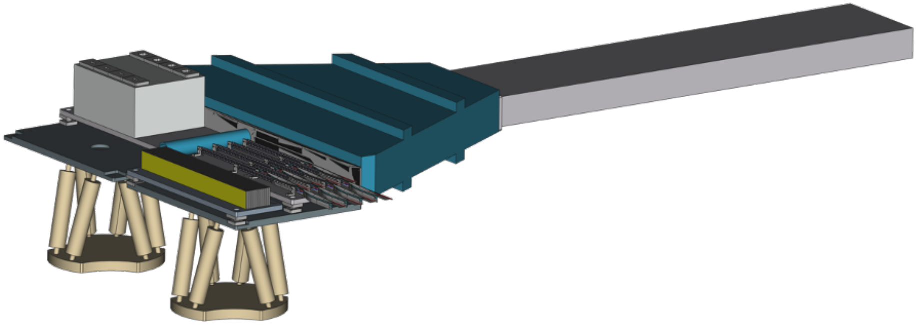
- High-flux regions
  - Scintillation screens
  - Cherenkov detectors

High rate tolerance,
large dynamic range.



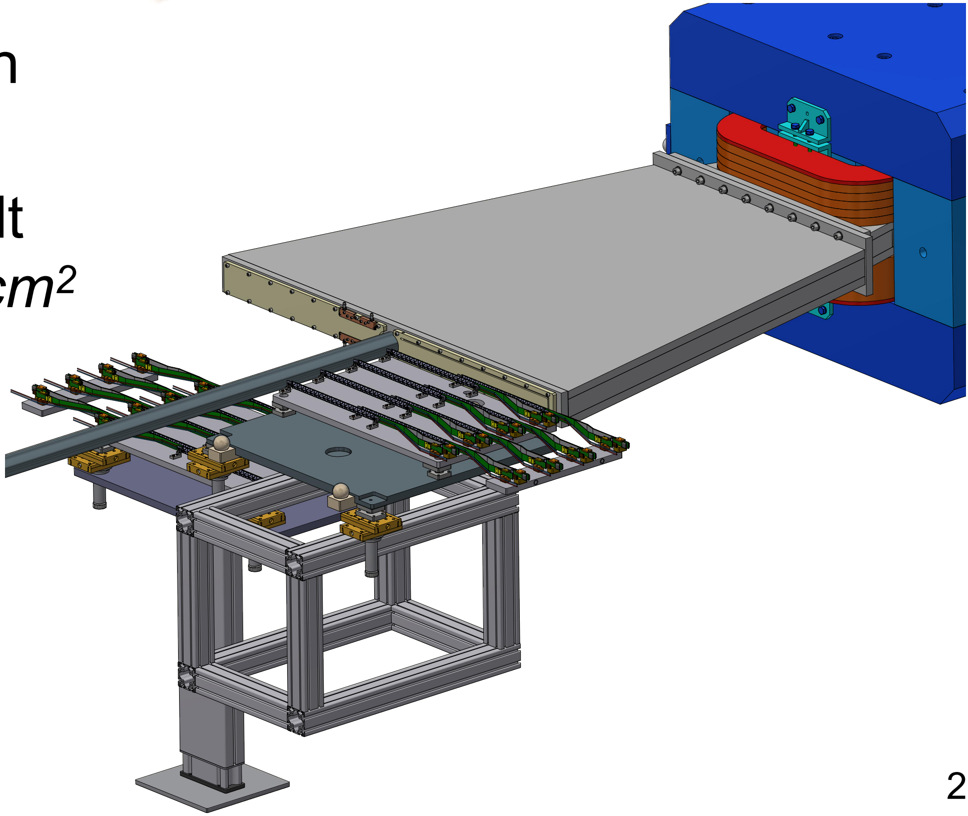
- Low-flux regions
  - Silicon pixel detectors
  - High granularity calorimeters

High signal efficiency,
high resolution.



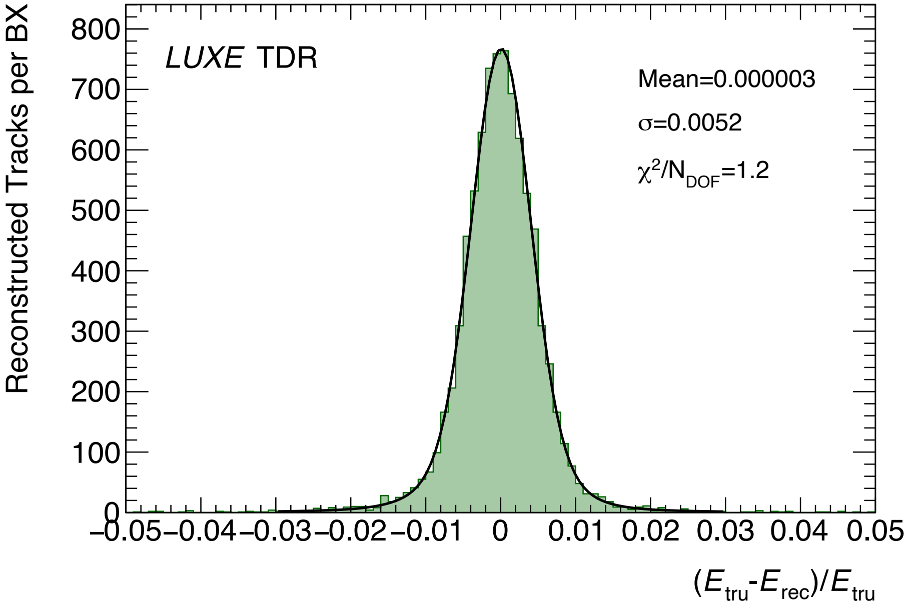
Positron detector — pixel tracker

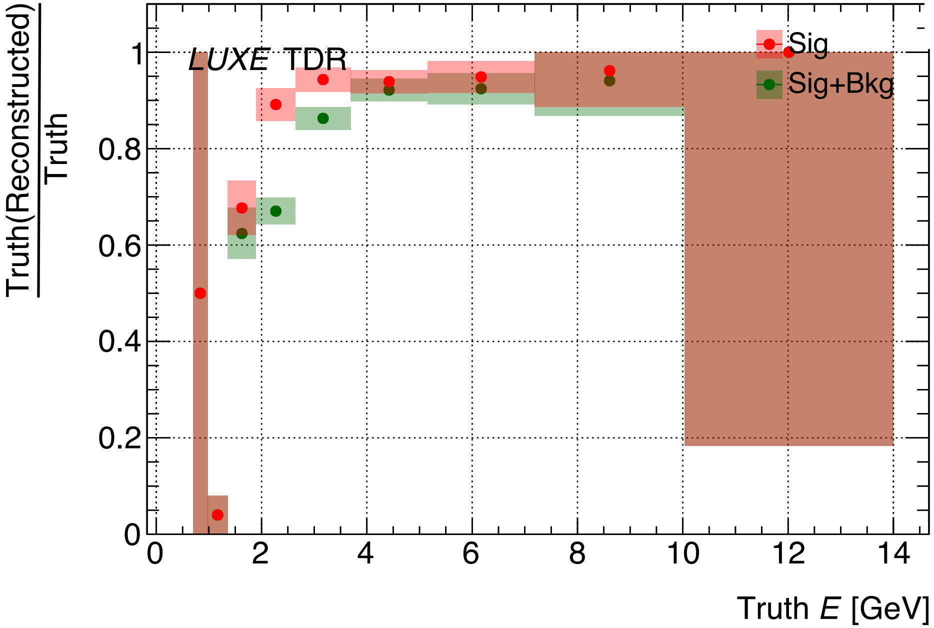
- Pixel tracker:
  - Based on ALICE ALPIDE pixel chips.
  - Pixel size *27 × 29* μm^2 with position resolution of ~ *5* μm.
- Consists of 4 layers each of which has 2 staves.
  - Each stave is *27 × 1.5* cm^2 built from 9 ALPIDE chips, *3 × 1.5* cm^2

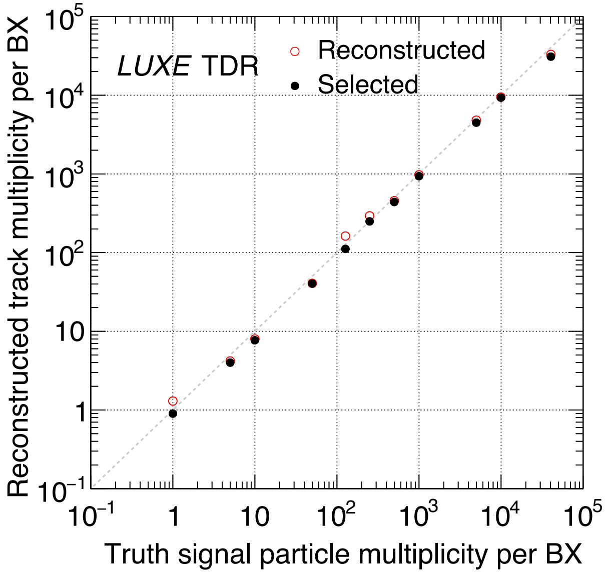


Pixel tracker performance

- Expected performance:
  - Energy resolution < 1%.
  - Good tracking efficiency.
  - Good linearity for different signal track multiplicities.

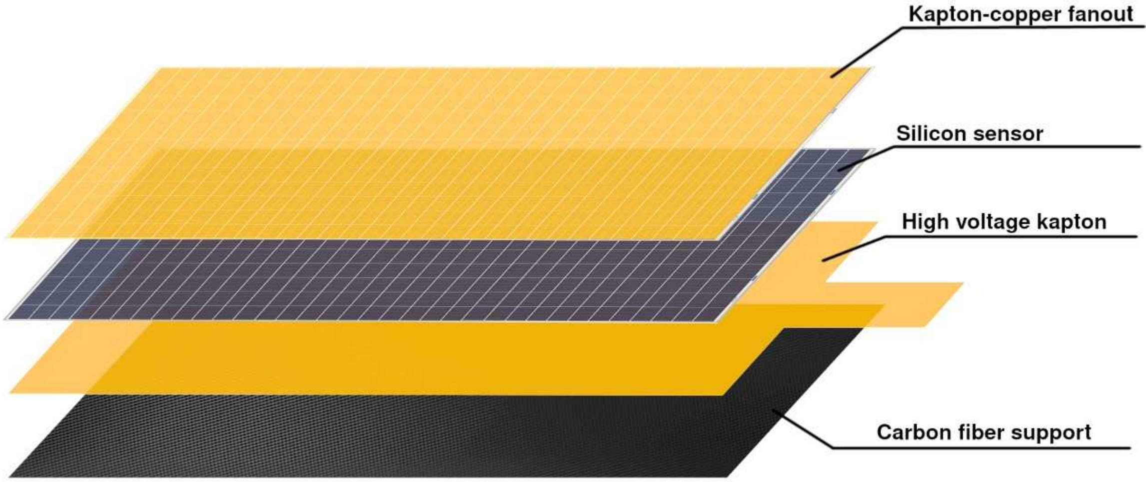






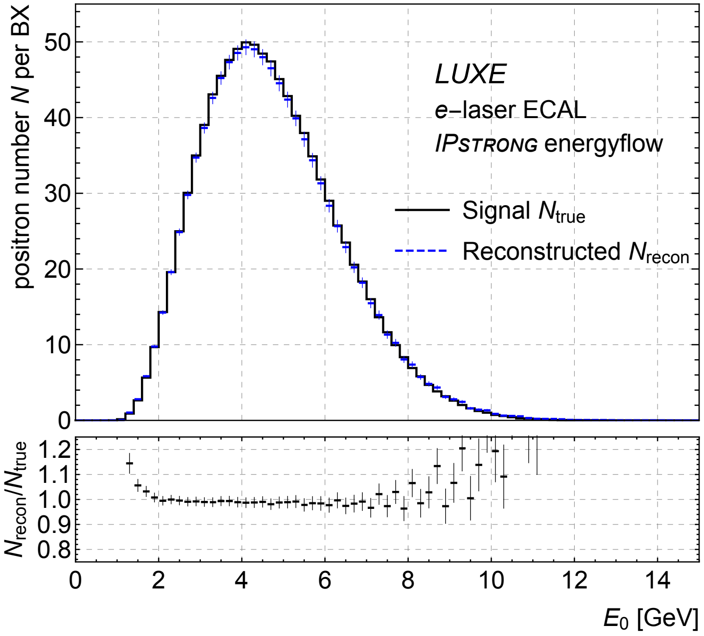
Positron detector — calorimeter

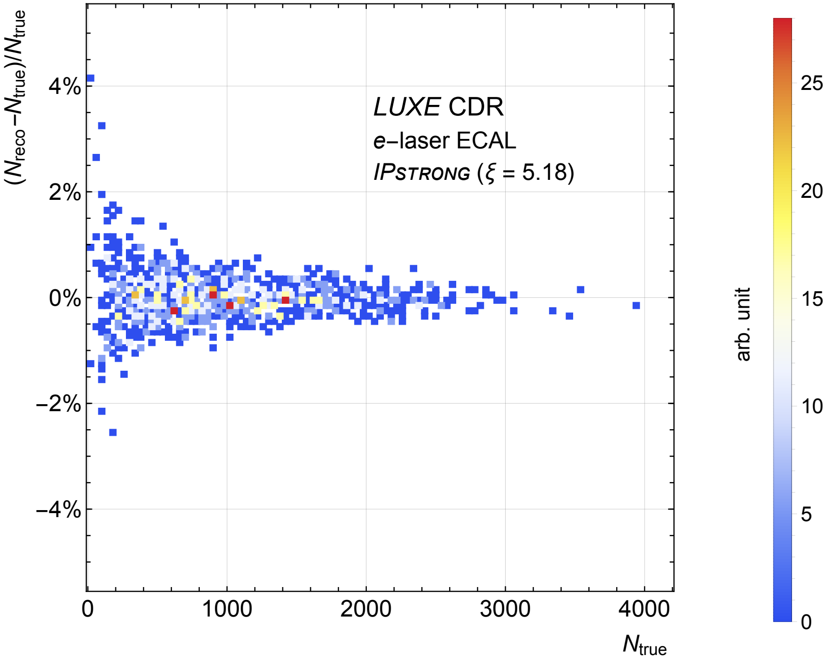
- High granularity, compact, sampling calorimeter.
  - Based on technology developed by (LC) FCAL collaboration.
  - Studies with 20 layers of 3.5 mm tungsten; baseline 10 layers @ 3.5 mm and 5 layers @ 7 mm.
  - Read out by FLAME ASIC (developed for FCAL).
  - Silicon sensors of 9 × 9 cm^2 with pads 5.5 × 5.5 mm^2.
  - A complete detector plane is 6 adjacent sensors.
  - Energy resolution of $\sigma/E = 20\%/(E\,/\,\text{GeV})^{1/2}$, position resolution ~750μm.

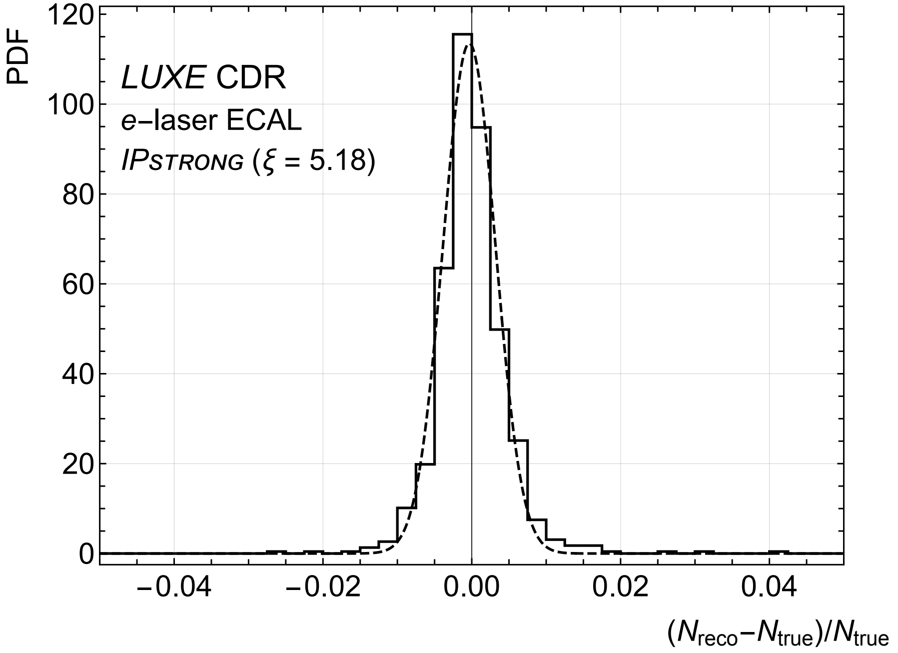


Calorimeter reconstruction

- Number of particles determined by comparing calorimetric energy with energy expected from cluster position.
- Good reconstruction for particle multiplicities of 1000.

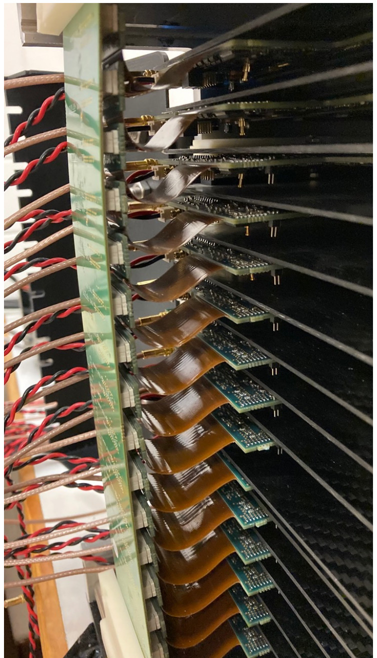






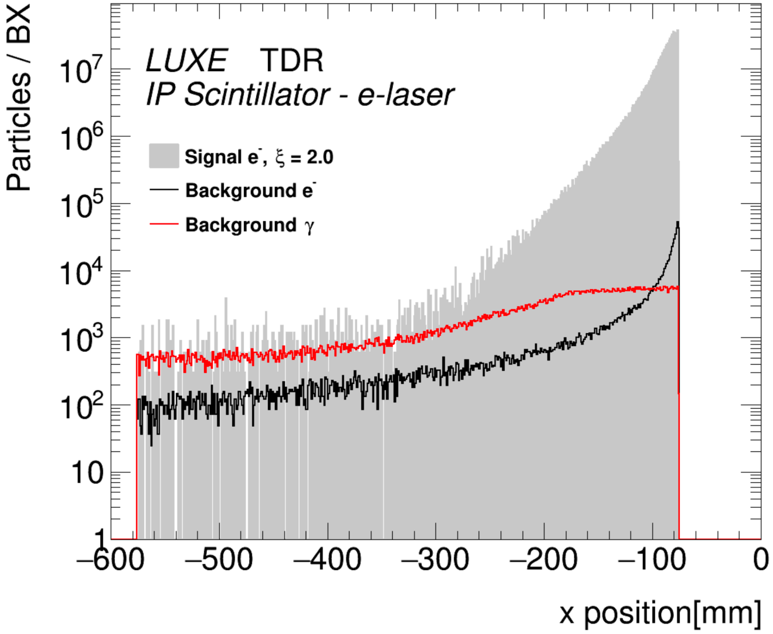
Electron calorimeter in γ–laser collisions

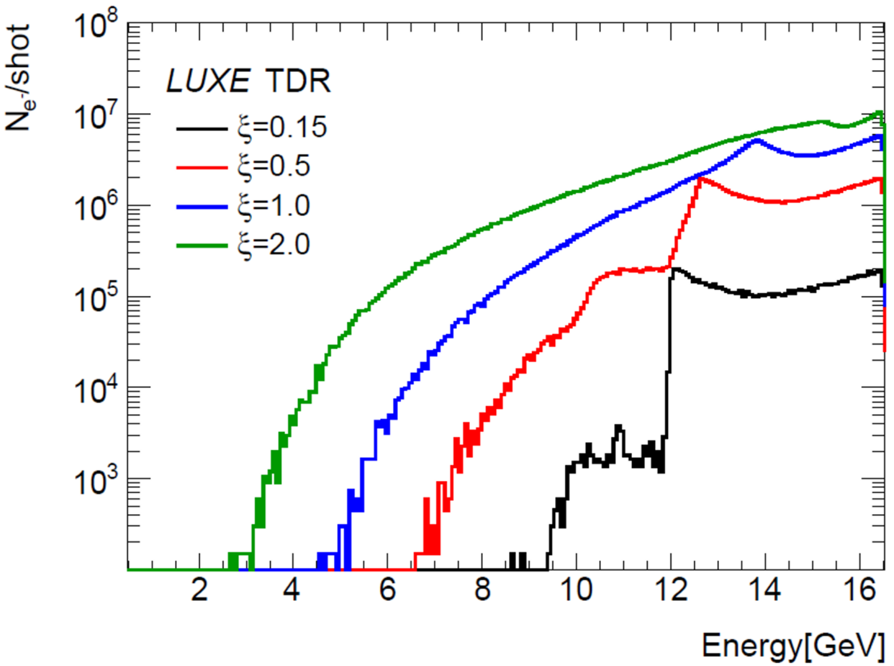
- To measure electrons in γ–laser collisions as rate is much lower.
- Use a silicon–tungsten electromagnetic calorimeter based on developments from CALICE collaboration.
  - Reference design for ILC concept.
  - 7 tungsten plates of 2.8 mm and 8 of 4.2 mm thickness.
  - Sensors are the same structure as other calorimeter
  - Pads directly connected to SKIROC2a ASIC.



High-rate electron detector — scintillation screen

- A scintillation screen and camera (with filter) is inexpensive, flexible and simple with good position resolution.
- Scintillator: GadOx; camera: CMOS/CCD.
- As a spectrometer, position gives energy.

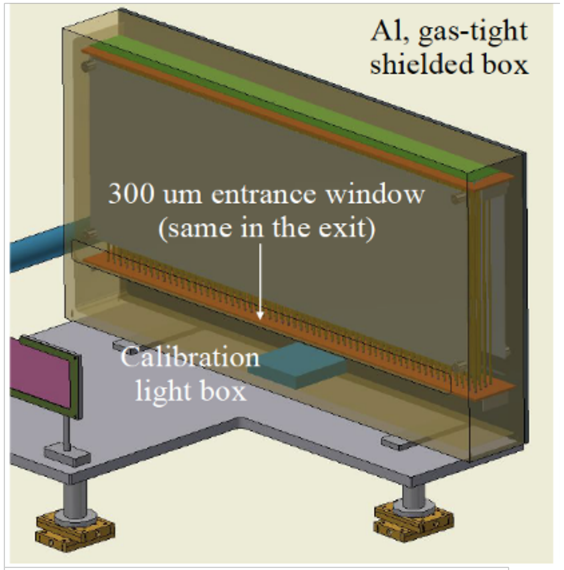




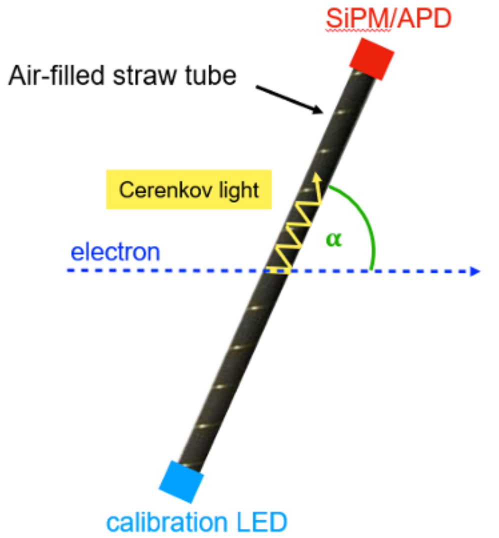
- Minimally affects electrons en route to Cherenkov detector.
- Good signal-to-background.
- Similar systems used in accelerators.

High-rate electron detector — Cherenkov

- Finely segmented (∅ = 4 mm) air-filled channel (reflective tubes as light guides).
  - Charged particles create Cherenkov light.
- Air: low refractive index
  - Reduce light yield.
  - Suppress backgrounds (Cherenkov threshold 20 MeV).

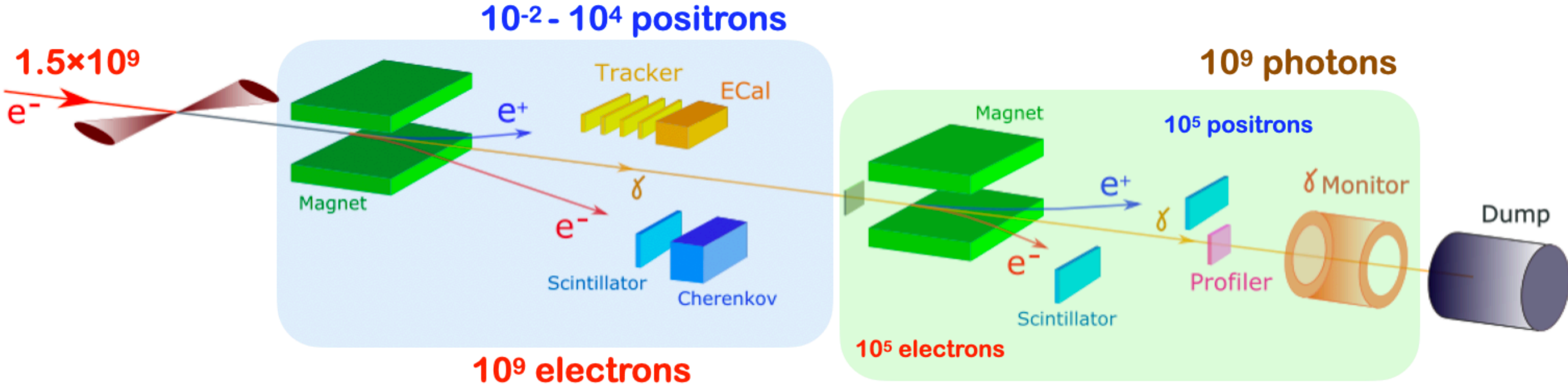



Straw prototype



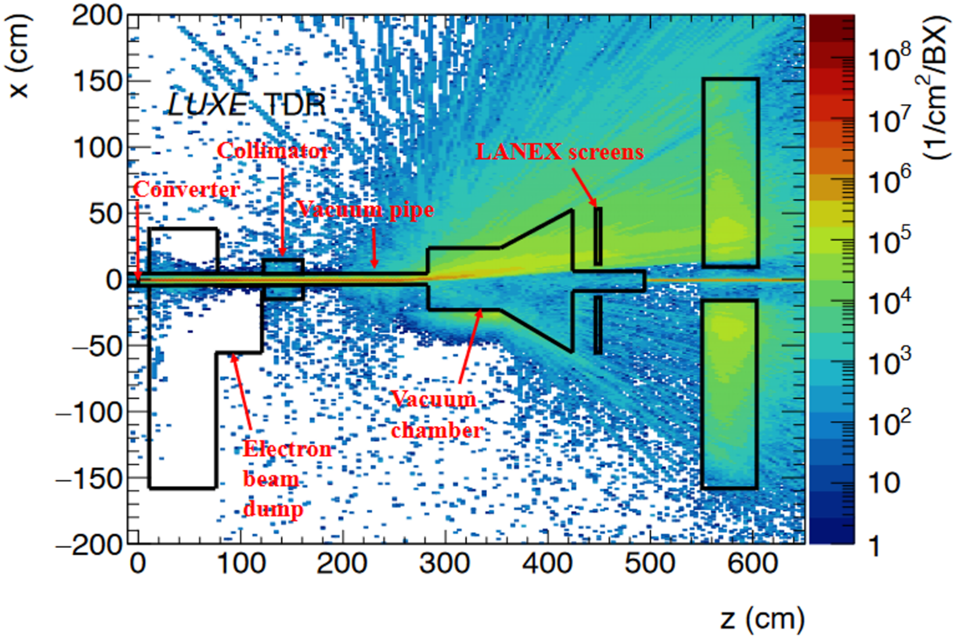
Overview of photon detectors

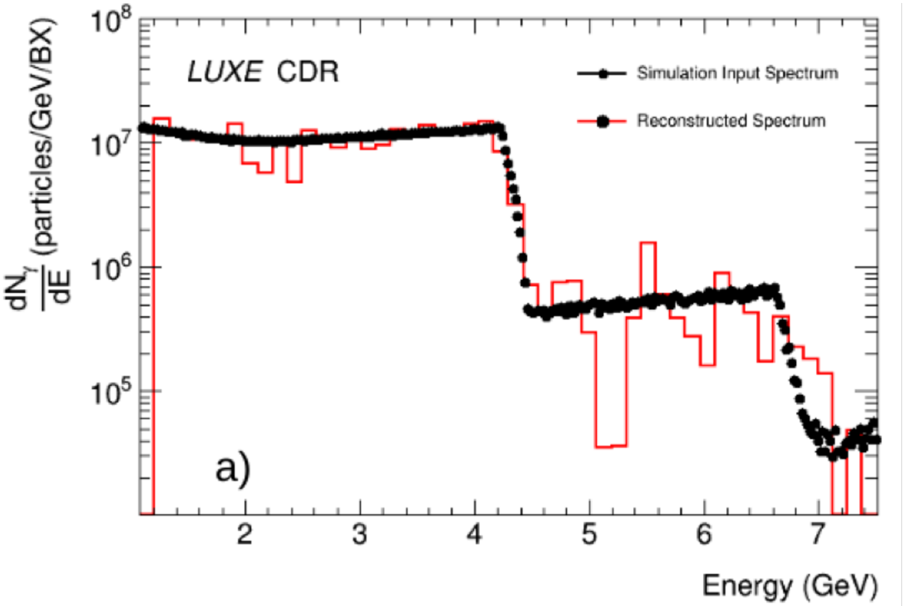
- Want to measure 10^9 photons summing up to TeV energies.
- Have three complementary systems:
  - Gamma-ray spectrometer where a fraction are converted to e^+e^- pairs.
  - Gamma-ray profiler which uses radiation-hard sapphire.
  - Gamma-flux monitor which relies on backscattering from photon dump.



Gamma-ray spectrometer

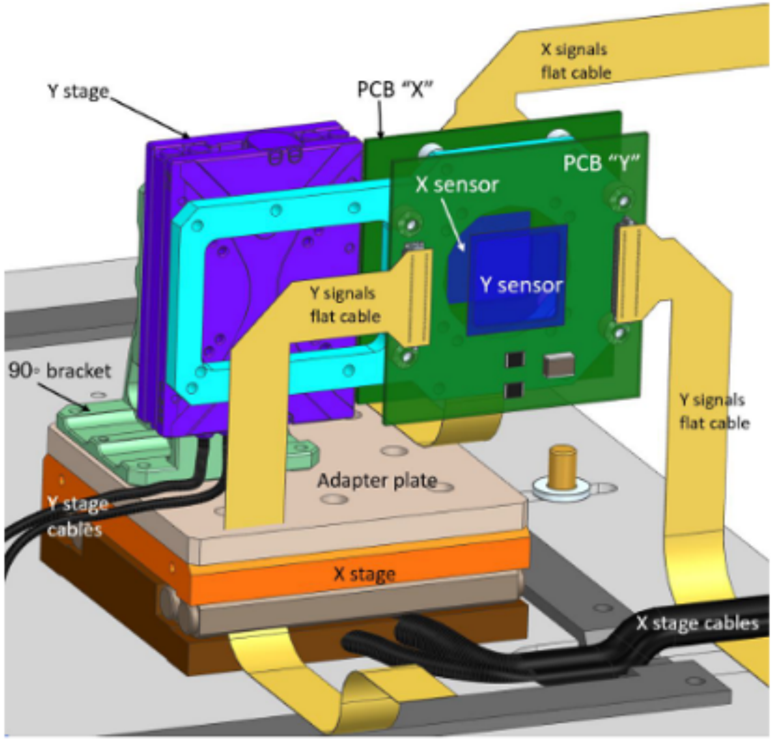
- Aim: to measure photon spectrum.
    - Measure e^+e^- pairs after photons pass through target.
    - Spectrometer with scintillation screens and CCD cameras.
    - Good energy resolution ($\delta E/E < 2\%$).
    - Non-invasive (>*99%* photons propagate through).

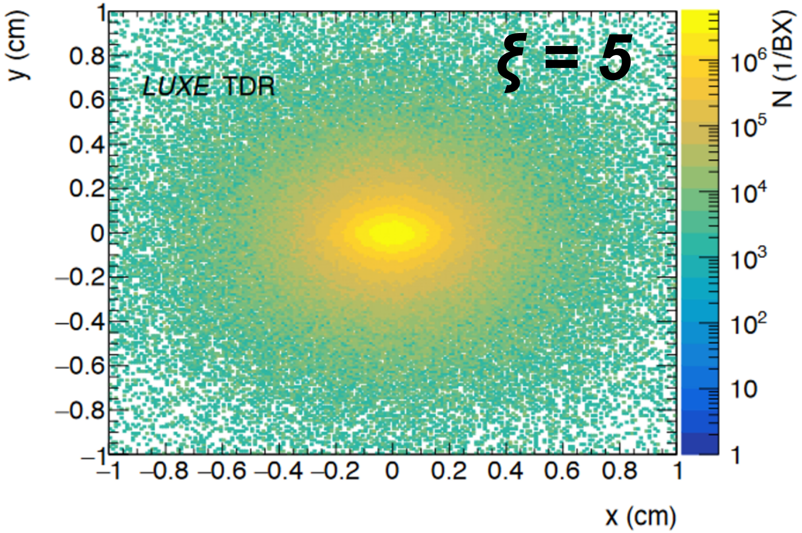


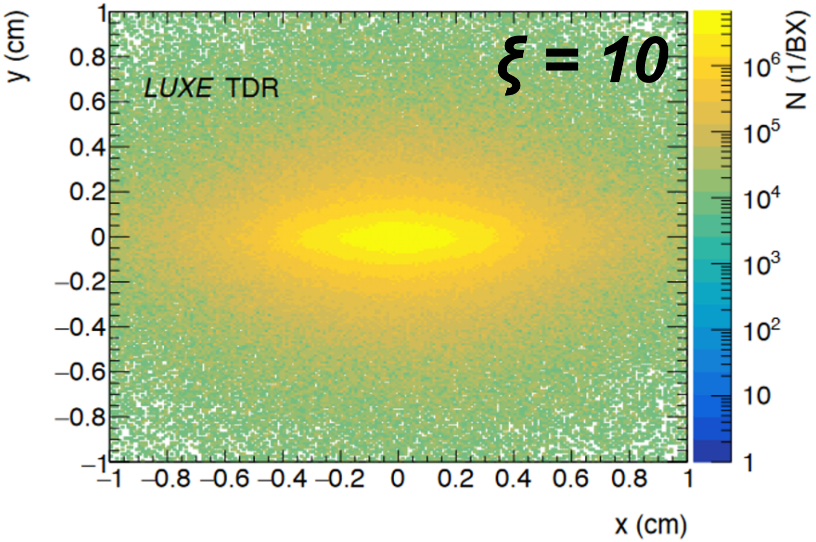


Gamma-ray profiler

- Two sapphire strip detectors movable with micron precision perpendicular to beam.
  - Photon beam location and shape
  - Precision measurement of laser intensity.
- Two detectors 2 × 2 cm² (100 μm thick) with 100 μm strip pitch should guarantee <5% precision in laser intensity.

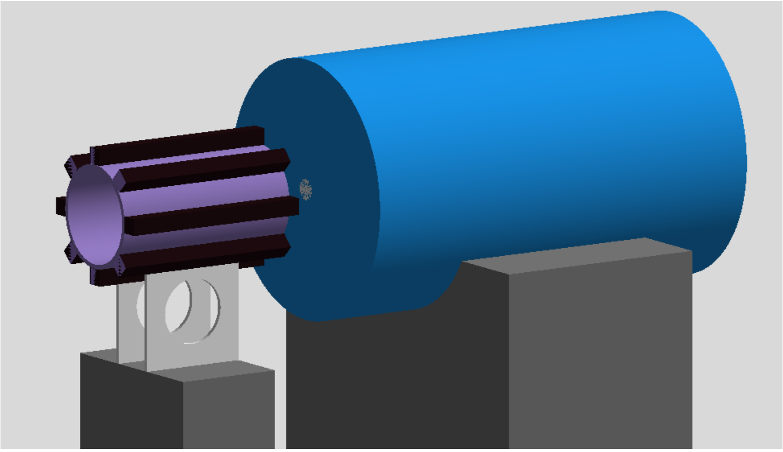


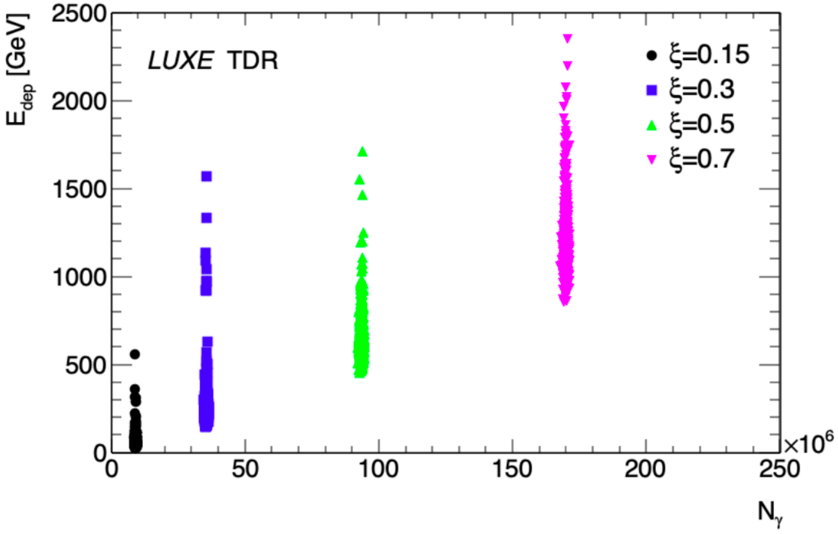


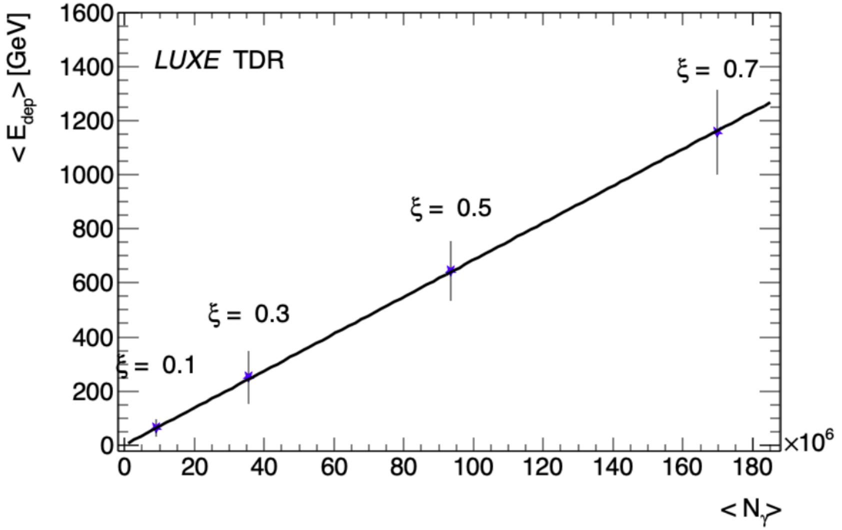


Gamma flux monitor

- Measure energy flow of particles back-scattered from photon beam dump.
- Gamma flux monitor:
  - Consists of lead glass blocks, *3.8 × 3.8 × 45 cm^3*.
  - Use modules planned for HERA-B.







Data handling

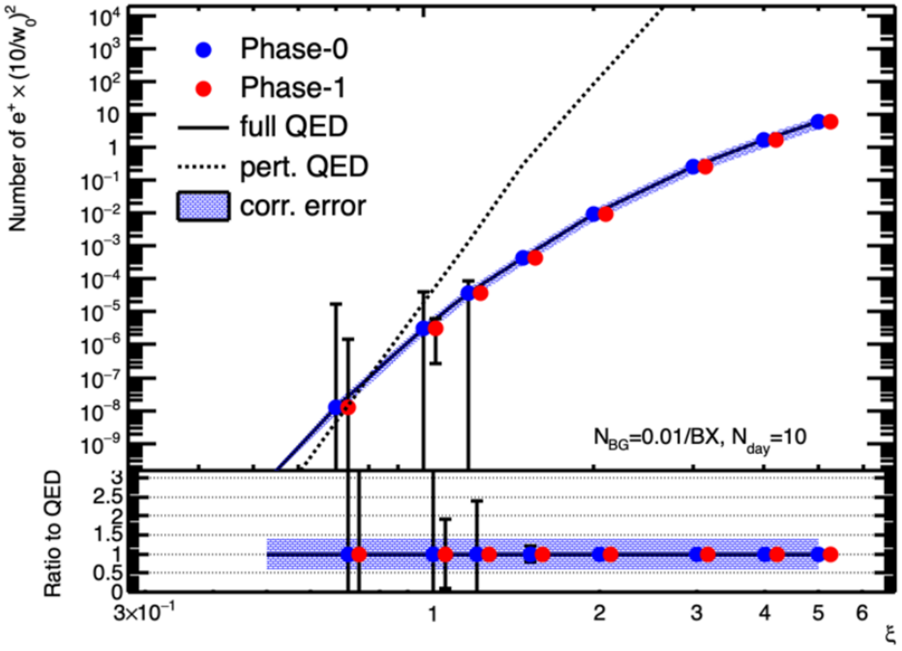
- Data handling should be “straightforward”: low frequency, modest rates.
  - Maximum data-taking frequency 10 Hz.
    - 1 Hz collision data, up to 9 Hz background.
  - Typical maximum rate per sub-detector O(10 MB/s).
- Need ~ 1 PC per sub-detector.
- All data is kept — no physics trigger.
- Should be able to use known/off-the-shelf solutions for control and synchronisation.
- Should be able to use/adapt existing software for data acquisition.

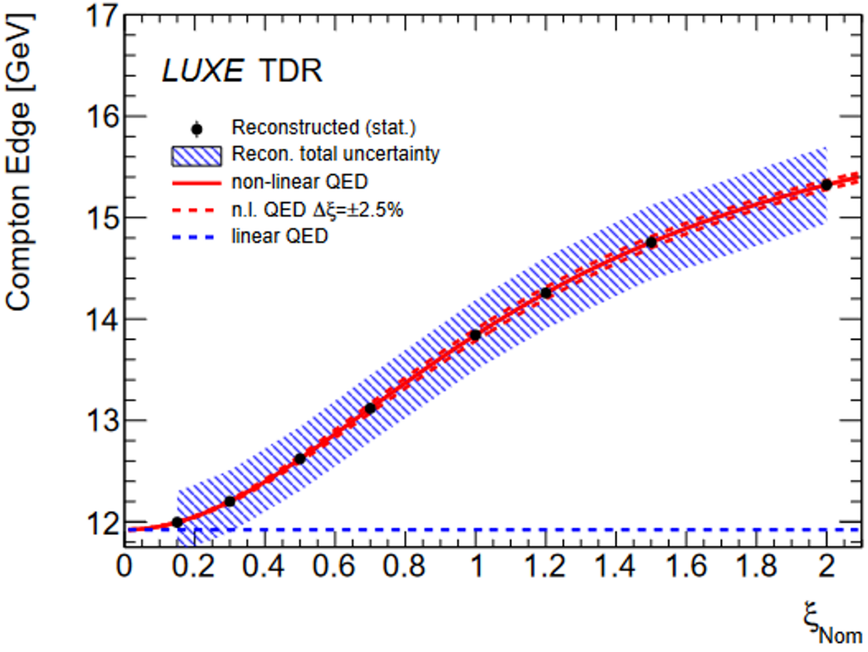
Systematic uncertainties — particle detection

- Low multiplicities (e^+e^- pair production):
  - Efficiencies for individual particles < 2 − 3% (cross-checks and in-situ calibration).
  - Linearity of response < 2% based on current tests.
  - Background: statistical uncertainty based on 9 Hz data, significant at low ξ.
- High multiplicities (Compton):
  - Linearity of response < 2% for Cherenkov (and scintillator) based on test beam and experience from other experiments.
  - Calibration < 2% based on test-beam calibration.
  - Background (for scintillators): constrain in situ.
- Energy scales (all):
  - Calibration/knowledge of magnetic field ~ 1%.
  - Alignment of < 50 μm results in < 0.5% uncertainty.

LUXE physics expectations

Expected results



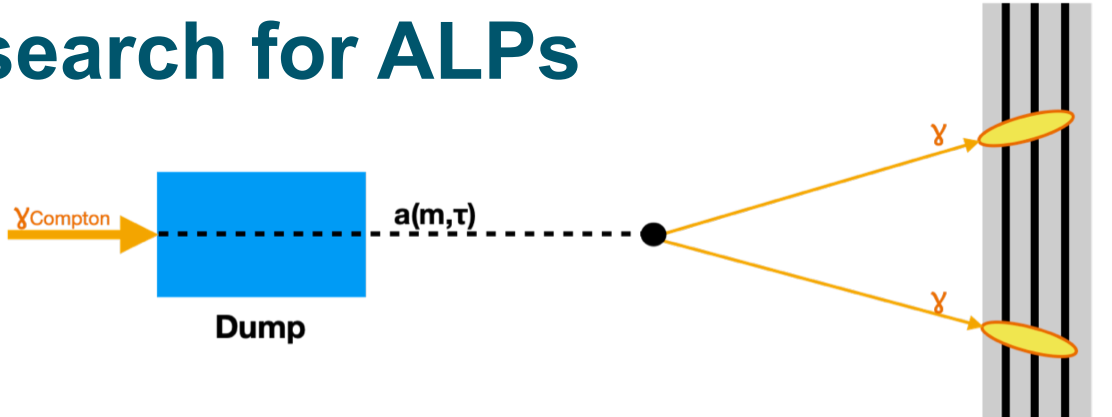


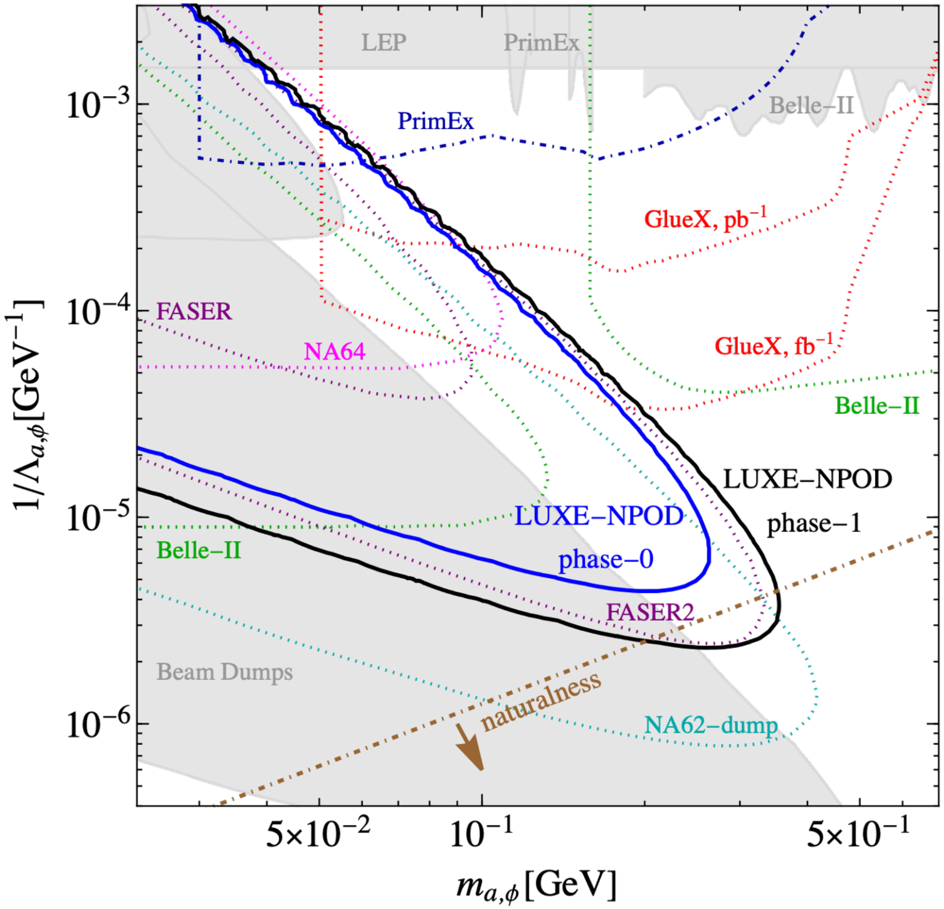
- Number of Breit–Wheeler pairs produced in *γ*–laser collisions.
- Assume 10 days of data taking and 0.01 background events/BX.
- 40% correlated uncertainty illustrates effect of uncertainty on *ξ*.

- Compton edge position as a function of *ξ* in *e*–laser collisions.
- Assuming 1 hour data taking, no background.
- Illustrative 2% energy scale uncertainty.

Detectors for BSM search for ALPs

- ~1 m long detector, ~2.5 m after photon dump.





- Search for axion-like particles or milli-charged particles.
- High-flux photon beam offers great potential.
  - ➡ Sensitivity competitive with other experiments ongoing and planned.
  - ➡ Detector still to be decided.

LUXE-NPOD: Z. Bai et al., *Phys. Rev.* **D 106** (2022) 115034, arXiv:2107.13554.

Final words

LUXE status and planning

- LUXE initiated in 2017.
- Officially recognised as a DESY experiment in November 2022.
- About 20 institutes.
- Could be ready for data taking in 2026.
- TDR to be published soon.

CDR: H. Abramowicz et al.,
Eur. Phys. J. ST **230** (2021) 2445,
arXiv:2102.02032.

https://luxe.desy.de

Summary

- LUXE is an exciting new experiment to investigate QED in uncharted territory.
- These strong fields occur in many areas of science and must be investigated in the laboratory.
- Searches for beyond the Standard Model signatures are also possible utilising the large photon flux.
- A number of challenges for the detectors although we have solutions that we are confident in. (BSM detectors are more open).
  - Large rate differences depending on beam parameters.
- Hope experiment will start taking data in 2026.
- Open to new ideas and collaborators.