

The Strong-Field QED Experiment LUXE at the European XFEL



Detector Challenges for the LUXE Experiment

Thomas Schörner (DESY) for the LUXE Collaboration
Lepton-Photon Conference 2023, Melbourne, 18 July 2023

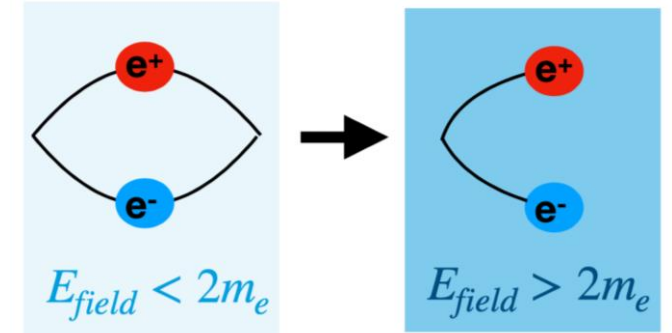
Strong-Field QED in a Nutshell

Aim of LUXE: extend QED knowledge into “strong-field” regime beyond “Schwinger limit” (increasing α_{EM} , begin of non-pert. effects)

Important regime – role in astrophysical phenomena, magnetars, atomic & laser physics, high-energy colliders ...

Schwinger limit characterized by “critical field”
→ e^+e^- pairs torn apart (real and observable)

$$E_{\text{crit}} = \frac{mc^2}{e\chi_c} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} \text{ V/cm}$$



Intensity parameter:

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

E_L : Laser field
 E_{crit} : Schwinger critical field
 ω_L : Laser frequency

- Relates laser field to critical field
- Measure of coupling between probe and laser field (also square root of laser intensity).
- $\xi \geq 1$: non-perturbative regime

Only chance (and LUXE concept) to reach E_{crit} : high-intensity lasers → 10^{14} V/m
• Additional 10^4 V/m through collision with high-energy electrons or photons (Lorentz factor)

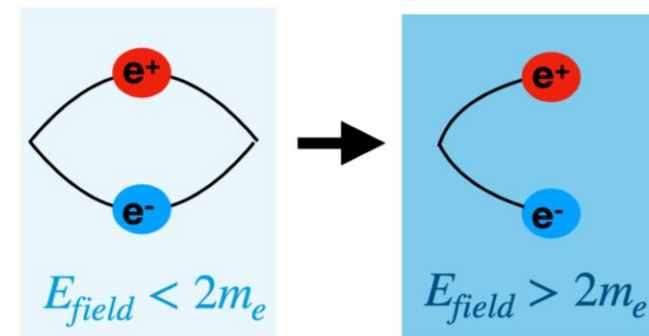
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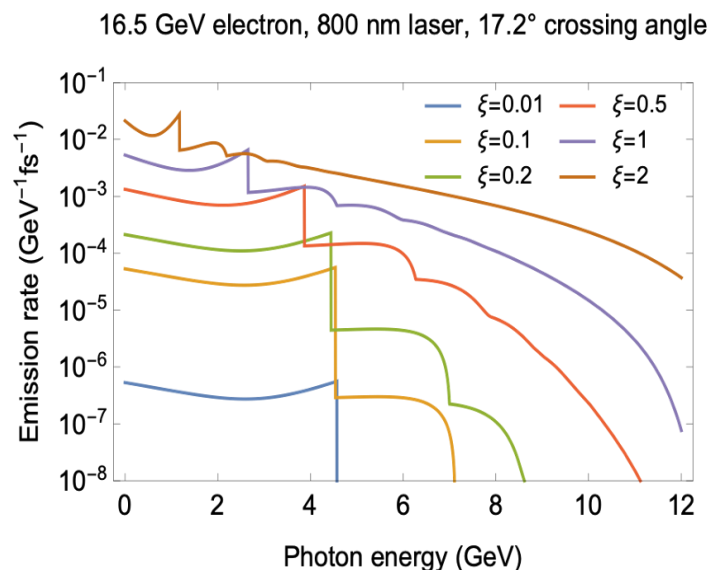
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Non-linear Compton scattering
(measure Compton e^- / γ spectrum)

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

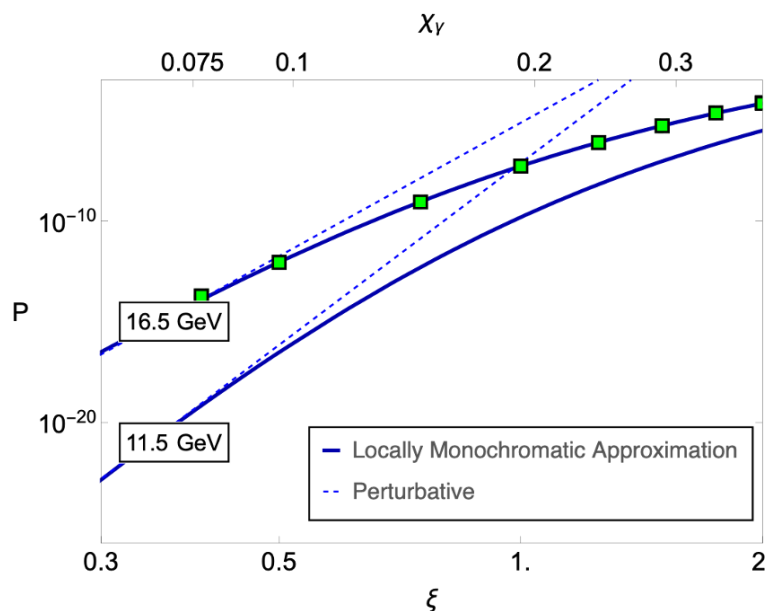
Compton edge shifts with intensity parameter ξ ;
measure $e_c + \gamma$
(spectra, rates)



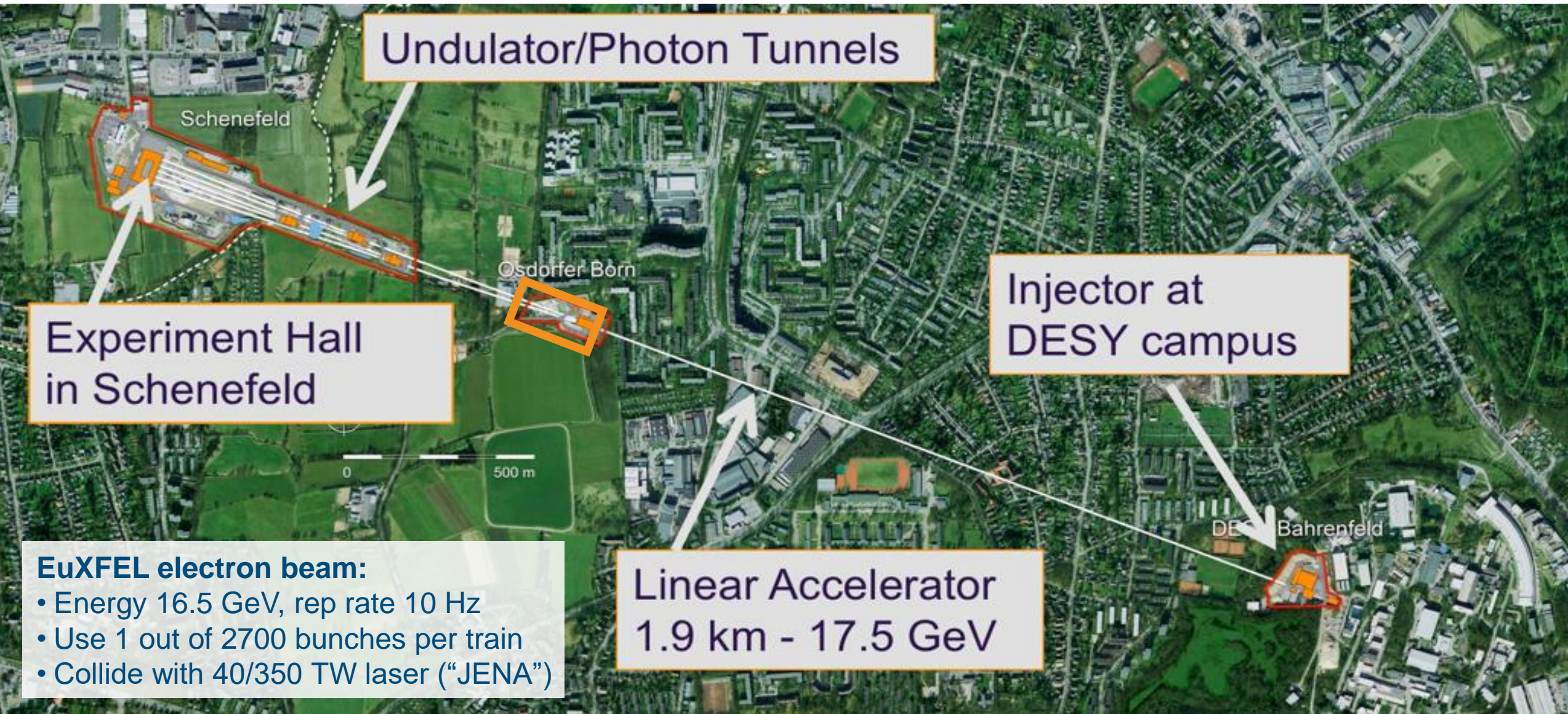
Search for Breit-Wheeler pair creation
(main measurement – e^+ counting vs ξ)

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

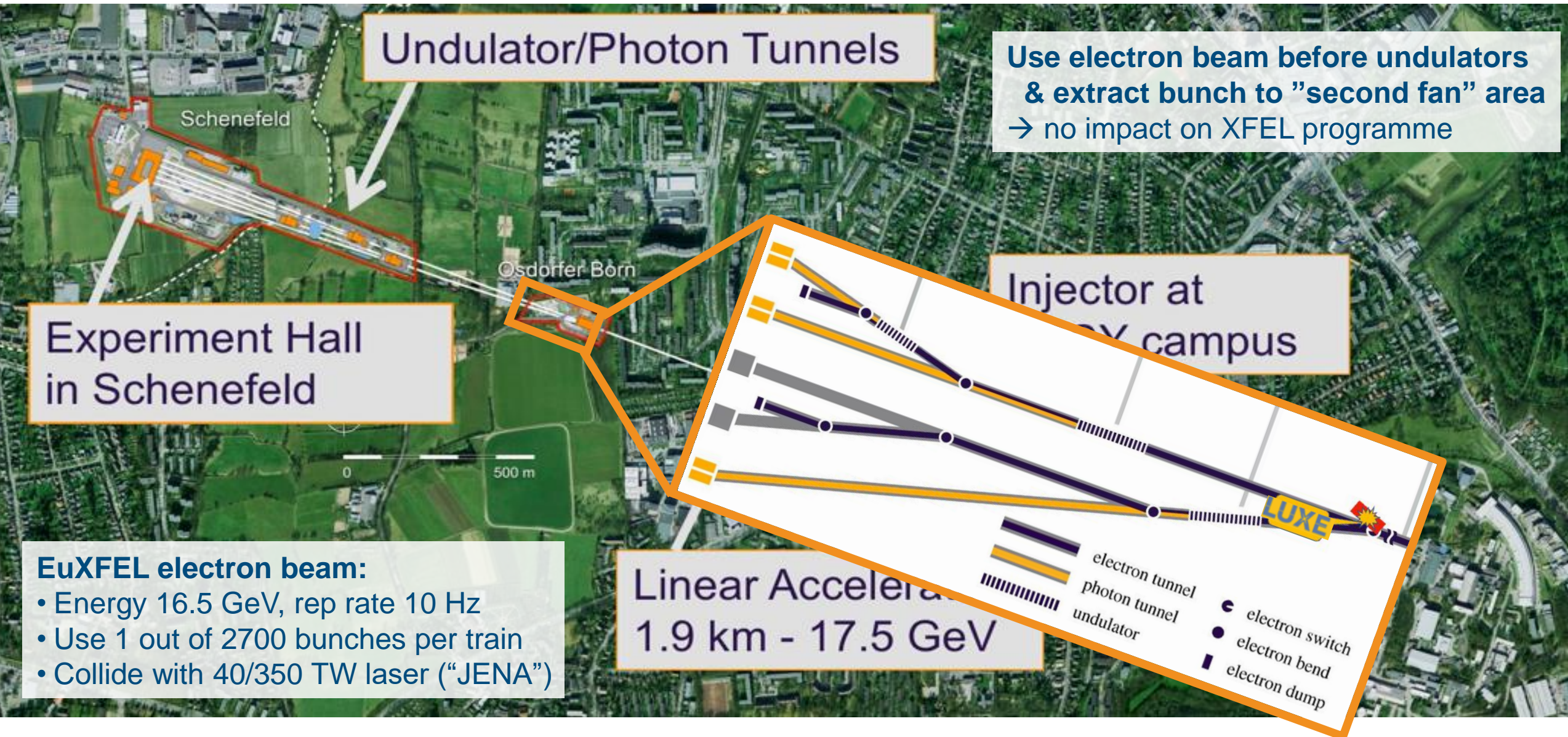
Non-pert. region:
expect deviation from
power law $\sim \xi^{2n}$;



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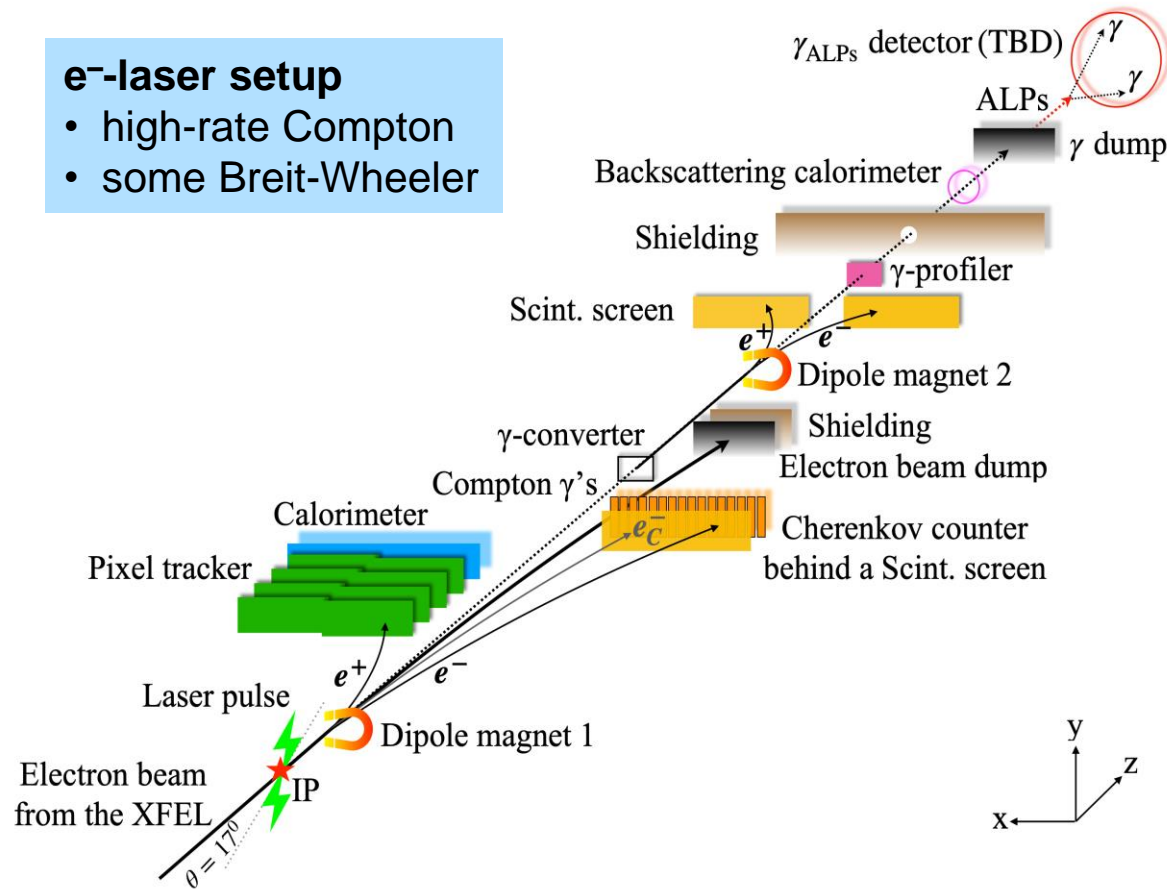


The LUXE Experiment

Two data-taking modes: electron-laser collisions (\rightarrow high-rate Compton) AND photon-laser collisions via Bremsstrahlung (low-rate Breit-Wheeler pair creation, unique to LUXE)

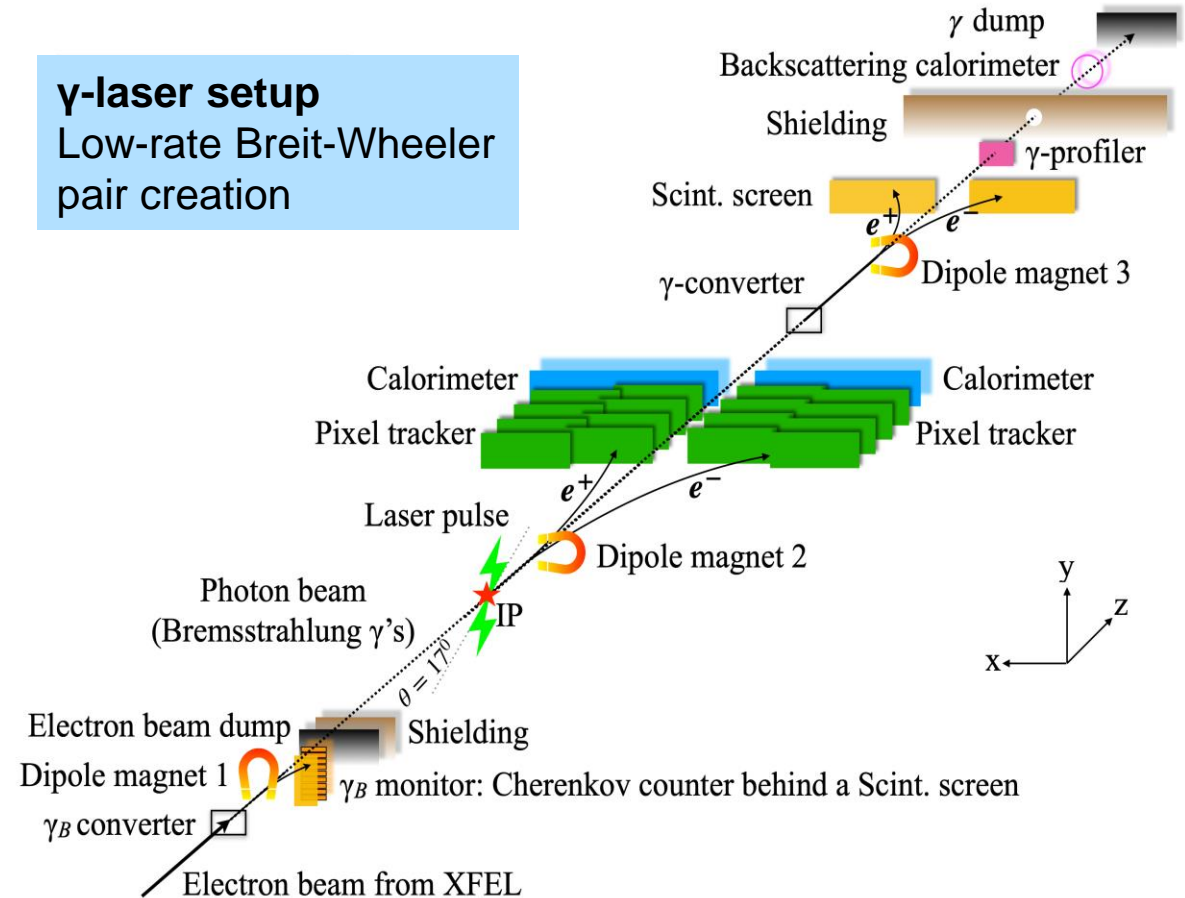
e⁻-laser setup

- high-rate Compton
- some Breit-Wheeler



γ -laser setup

Low-rate Breit-Wheeler pair creation



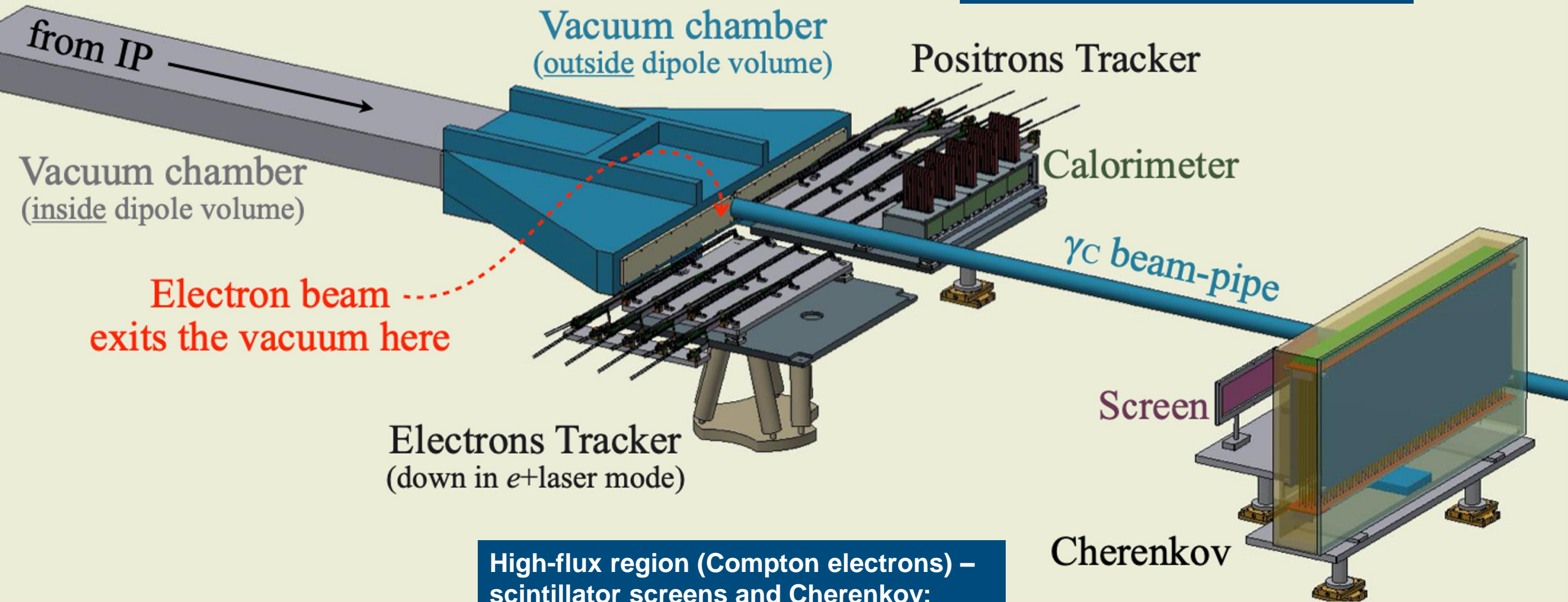
Need varied detector technologies to cater for varying fluxes of signal and background e^+ , e^- , γ

- Master large range of rates between $\sim 10^{-4}$ (e^+) and 10^9 (e^- and photons) per bunch crossing

LUXE Detectors

Detectors for electrons and positrons close to the IP
Flexible electron side (Compton versus Breit-Wheeler)

Low-flux region (Breit-Wheeler positrons) – pixel tracker and high-granularity calorimeters: high efficiency, high resolution



High-flux region (Compton electrons) –
scintillator screens and Cherenkov:
high rate tolerance, large dynamic range

LUXE e^+e^- Detectors

IP detectors for electrons and positrons

Low-flux region: pixels and calorimeters

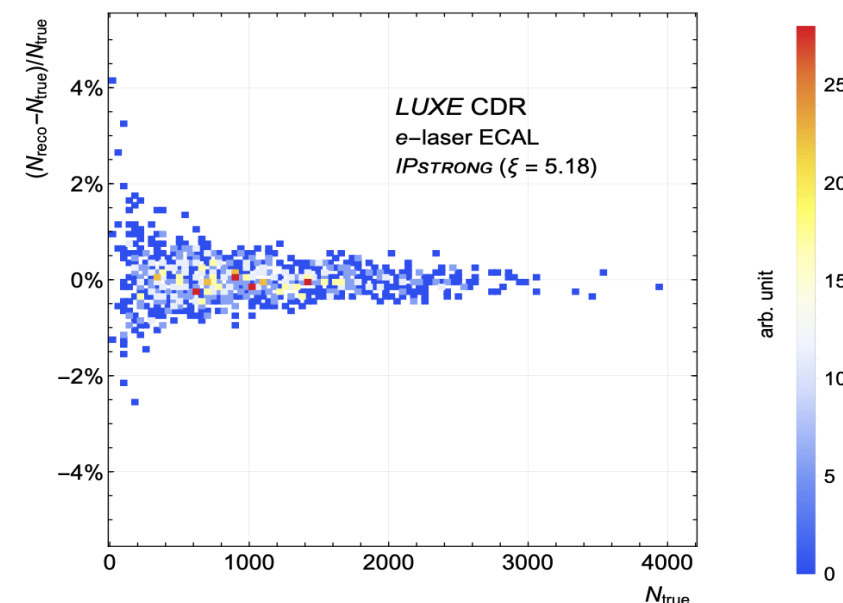
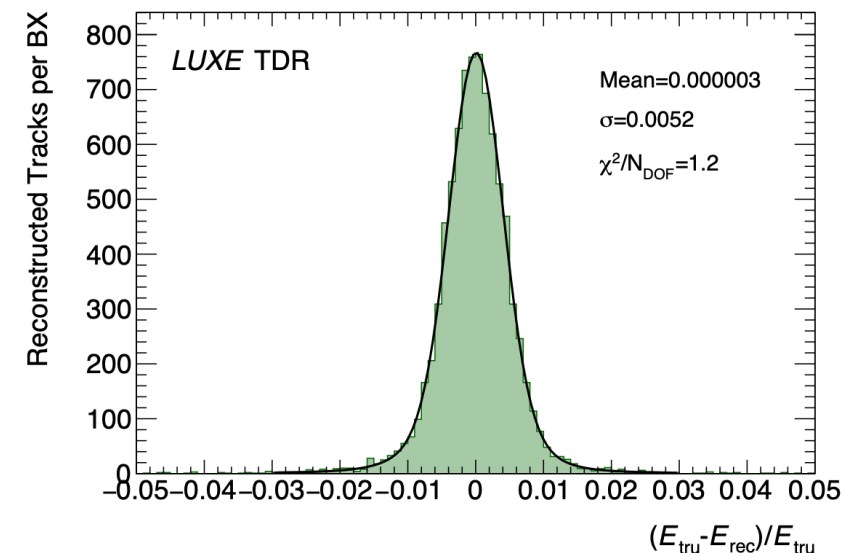
Pixel tracker: 4 layers with 2 staves each

- Staves built from 9 ALPIDE chips (ALICE, $3 \times 1.5 \text{ cm}^2$)
- Pixel size $27 \times 29 \mu\text{m}^2$ with position resolution of $\sim 5 \mu\text{m}$ (plot).
- Good linearity for all track multiplicities (\rightarrow positron counting!!!)
- Good efficiency and energy resolution ($< 1\%$);

High granularity, compact, sampling calorimeter (FCAL technology)

- Plan: 20 layers of 3.5 mm tungsten, interleaved with (15 layers of?) silicon sensors of $9 \times 9 \text{ cm}^2$ with pads $5.5 \times 5.5 \text{ mm}^2$.
- Number of particles (positrons) determined by comparing calorimetric energy with energy expected from cluster position – works well for particle multiplicities up to 1000.
- Energy resolution of $\sigma/E = 20\%/(E / \text{GeV})^{1/2}$, position resolution $\sim 750 \mu\text{m}$.

Note: probably different choice (CALICE Si-W) for electrons



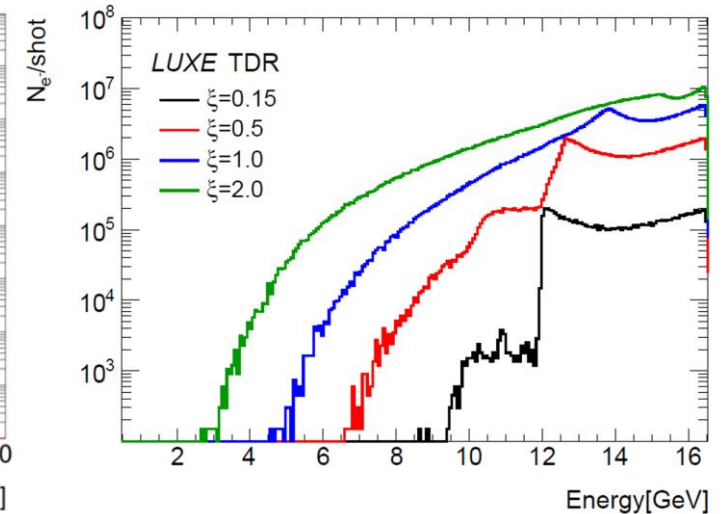
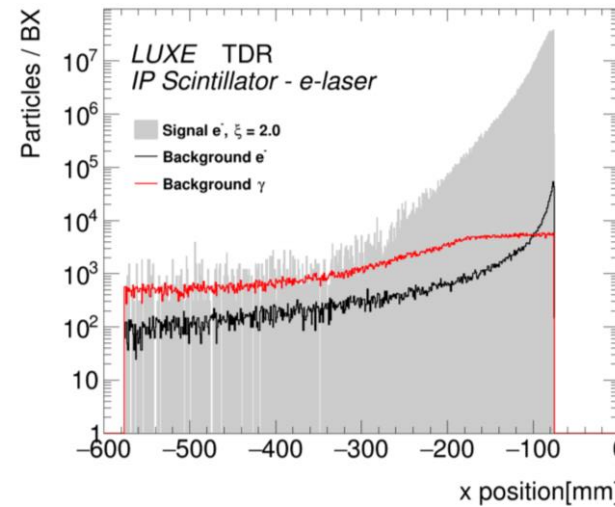
LUXE e^+e^- Detectors

IP detectors for electrons and positrons

High-flux region: scintillators and Cherenkov

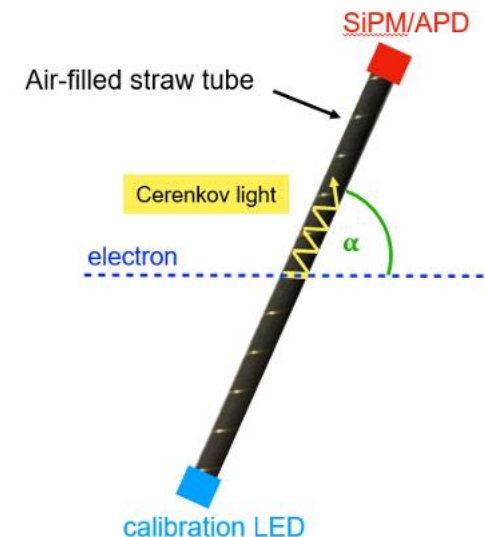
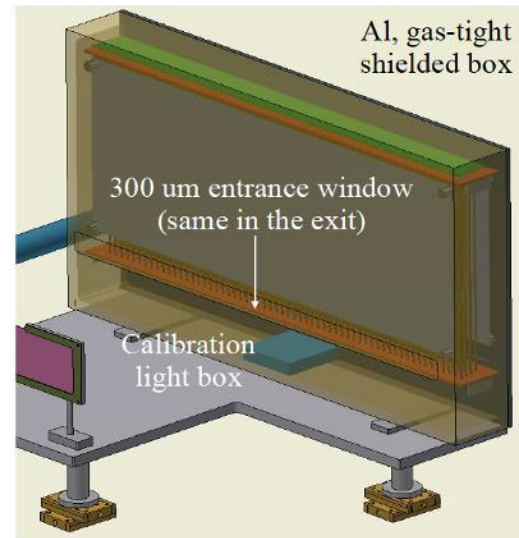
Scintillator screen and camera with filter

- Inexpensive, flexible, simple, good position resolution, good signal-to-background ratio.
- Scintillator: GadOx; camera: CMOS/CCD.
- Acts as a spectrometer: position gives energy (note varying Compton e^- spectra for different ξ)
- Minimally affects electrons *en route* to Cherenkov detector



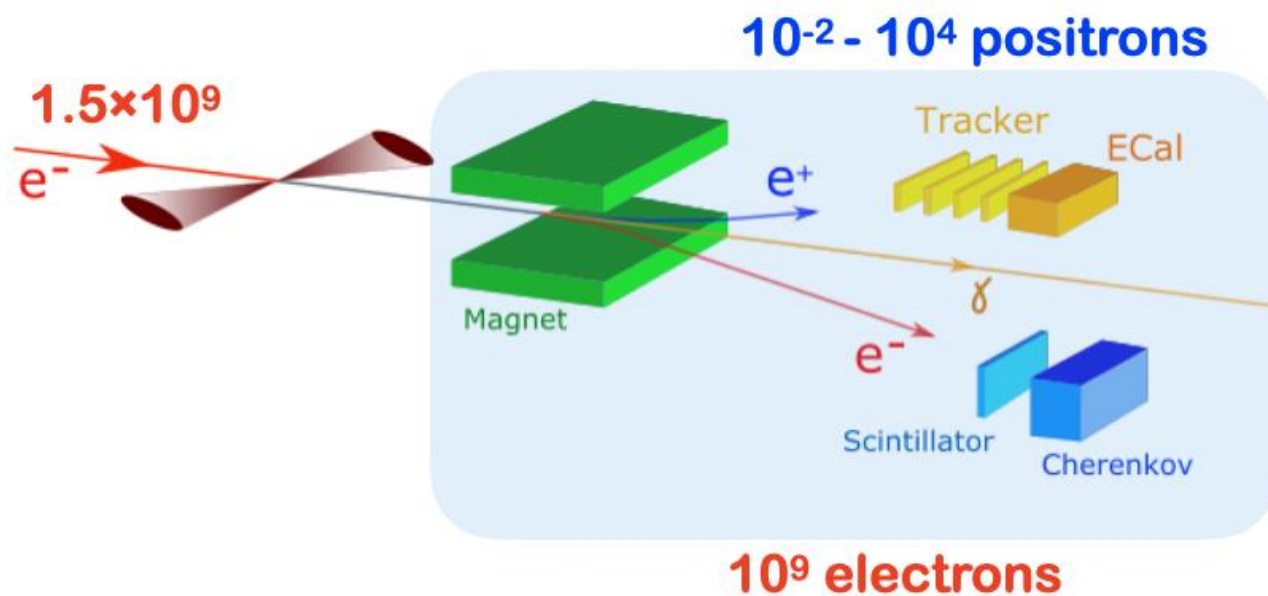
Cherenkov detector

- Charged particles create Cherenkov light in finely segmented ($\varnothing = 4$ mm) air-filled reflective tubes acting as light guides
- Air: low refractive index \rightarrow reduces light yield, suppress backgrounds (Cherenkov threshold 20 MeV).



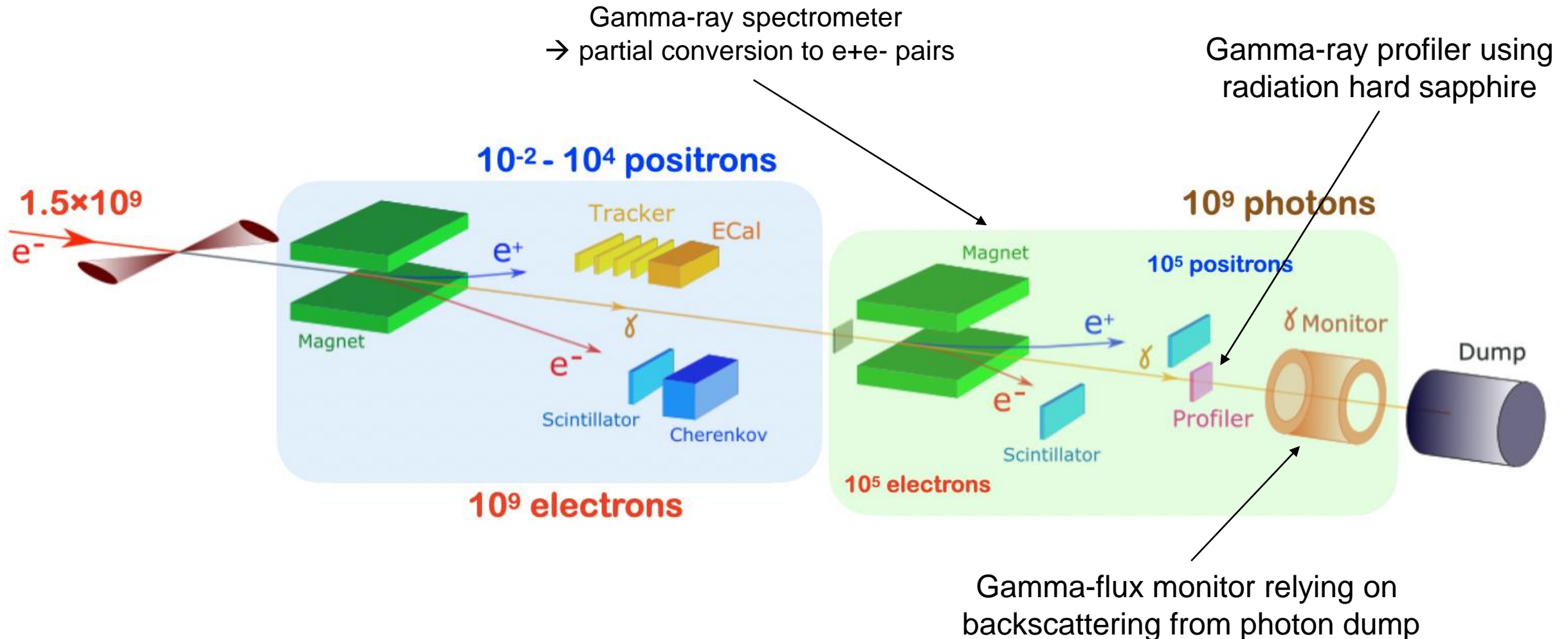
LUXE Photon Detectors

The e^+e^- a system just discussed



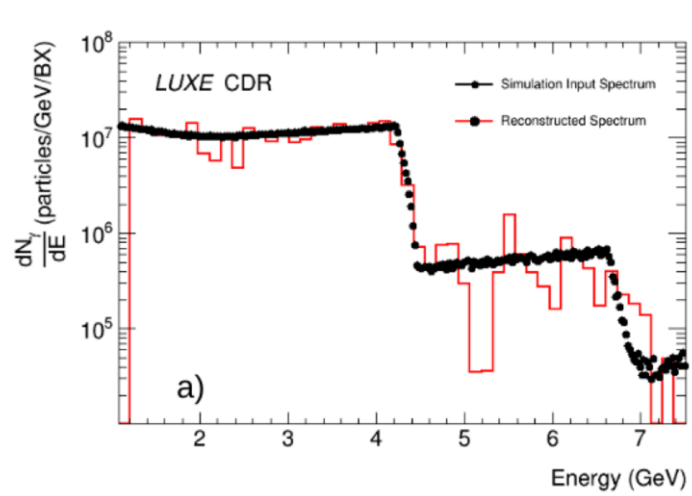
LUXE Photon Detectors

Challenge: measuring 10^9 photons / BX summing up to TeV energies. Three complementary systems to characterise the photon, measure their spectrum and learn about intensity parameter ξ .



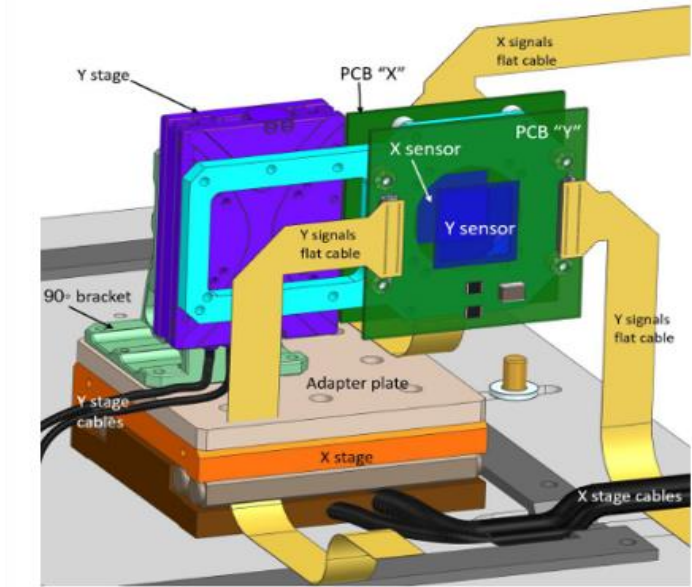
LUXE Photon Detectors

Aim: measuring 10^9 photons (Compton, Bresstrahlung) summing up to TeV energies

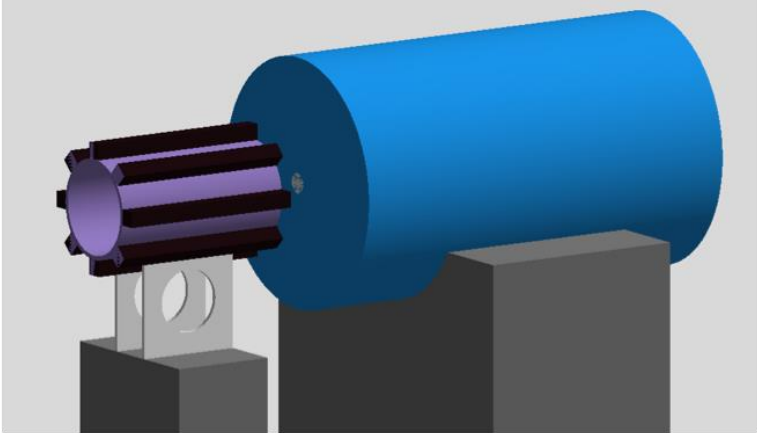
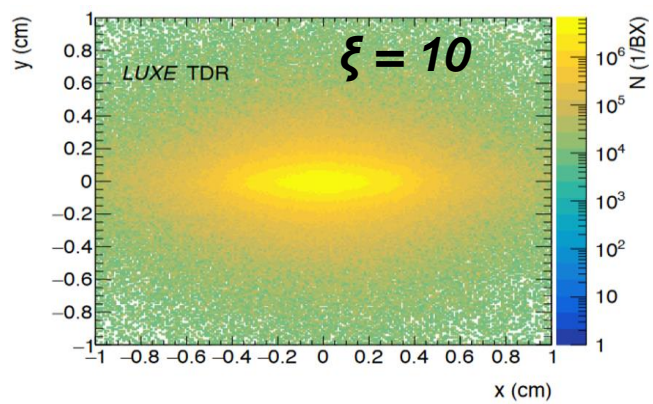


Gamma-ray spectrometer: measure γ spectrum using e^+e^- pairs after photon target (scintillation screens & CCD cameras).

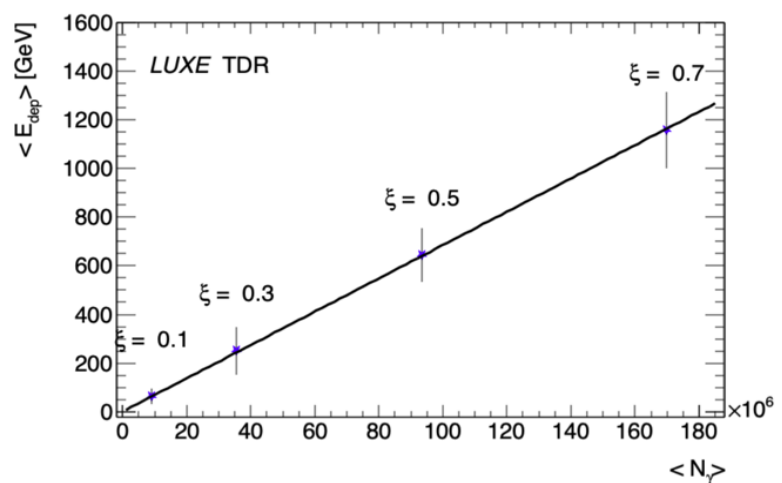
- Good energy resolution ($\delta E/E < 2\%$)
- non-invasive – $>99\%$ of all photons propagate through.



Gamma-ray profiler: two movable sapphire strip detectors → photon beam location and shape; precision measurement of laser intensity.



Gamma-flux monitor: measure energy flow of particles back-scattered from photon beam dump (lead glass blocks) → “luminosity measurement” (ξ)



Data Handling and Systematic Uncertainties

Off-the-shelf DAQ, existing / extendable software; systematics studied → can be handled

Data handling – straight forward:

- Low data-taking frequency < 10 Hz, 1 Hz collision data, up to 9 Hz background
- Maximum rate per sub-detector O(10 MB/s) → 1 PC per sub-detector

All data are kept – no physics trigger

Should be able to use **known / off-the-shelf solutions** for control, synchronisation; use / adapt existing software for DAQ

Systematic uncertainties – particle detection:

- At low multiplicities (pair production):
 - Efficiencies for individual particles < 2-3% (cross-checks and in-situ calibration)
 - Linearity of response <2% (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 (test beam & experience)
 - Calibration <2% (test beam)
 - Background (for scintillators): constrain in situ
- Energy scales (all):
 - Calibration / knowledge of magnetic field ~1%
 - Alignment of <50 μm results in <0.5% uncertainty

Summary

LUXE will provide exciting new opportunities!

Strong field QED occurs in many areas – LUXE can investigate this uncharted territory!
Searches for BSM signatures are also possible utilising large photon fluxes.

LUXE started in 2017, now ~100 collaborators from ~20 international institutes, hosted at DESY & EU XFEL

A number of challenges for the detectors although we have solutions that we are confident in (BSM detectors are more open).

- TDR out soon!
- Hope: start of taking data in 2026.

Open to new ideas and collaborators!



Thank you!

Thanks to F. Meloni, M. Wing

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

<https://luxe.desy.de>

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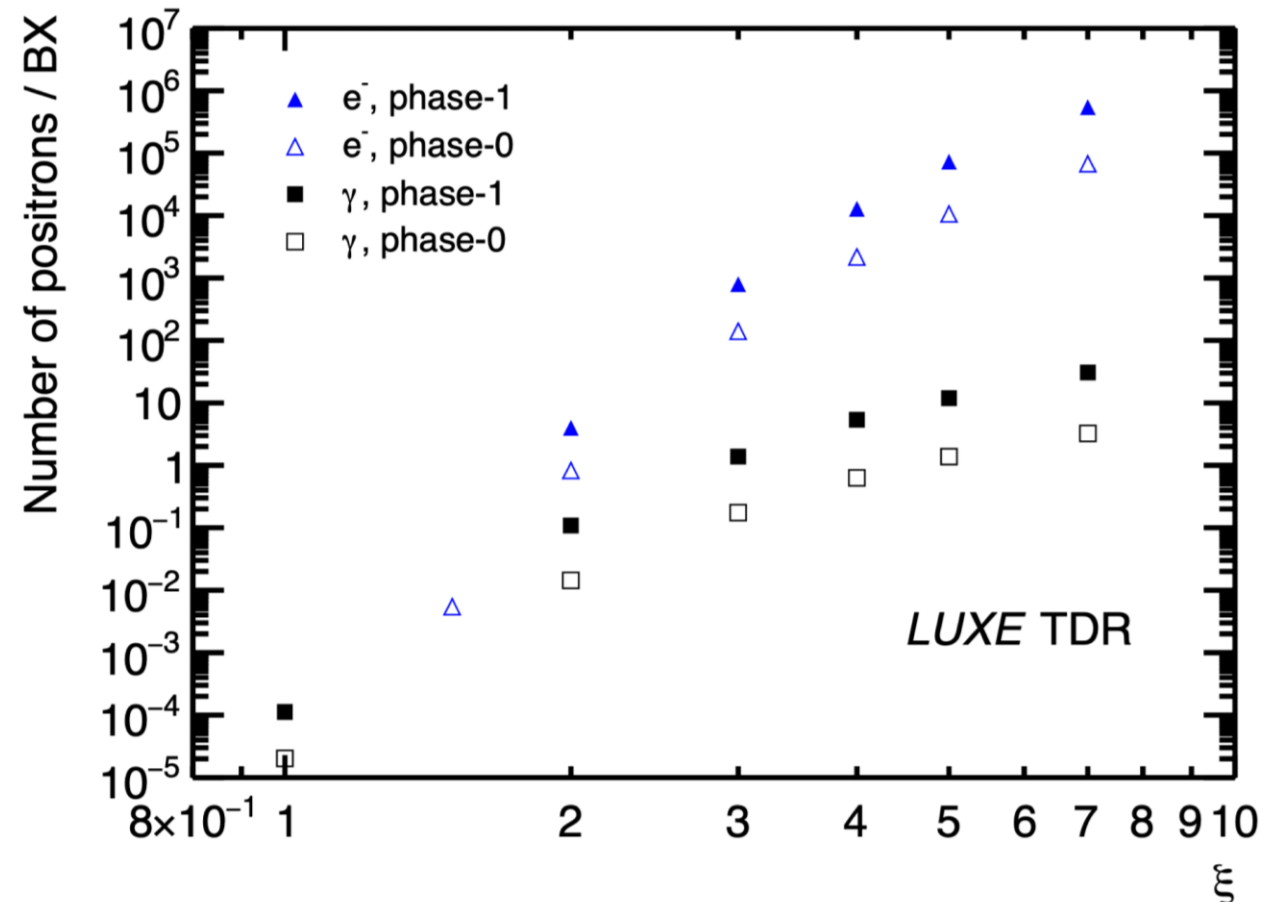
Backup

LUXE Detectors – the Challenge

Detect electrons, positrons and photons in the O(GeV) range, and measure their fluxes and energies.

Need varied detector technologies to cater for varying fluxes of signal and background

- Fluxes vary between $\sim 10^{-4}$ (e^+) and 10^9 (e^- and photons) per bunch crossing

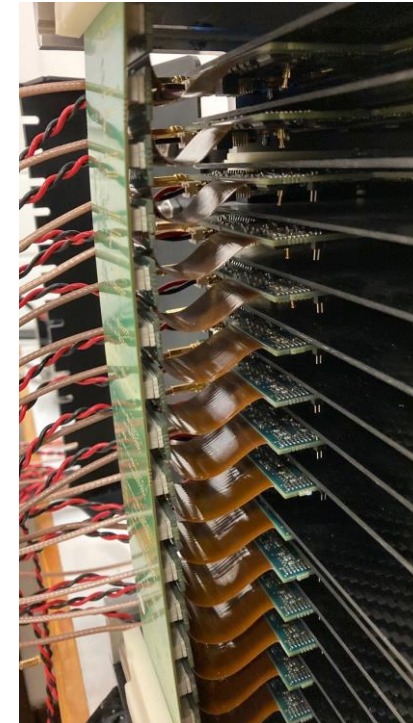


LUXE Detectors: Electron Calorimeters

... for gamma-laser collisions (lower rate – calorimeters instead of scintillators and Cherenkov)

Use a silicon-tungsten electromagnetic calorimeter based on developments from the CALICE collaboration

- Reference design for the 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



Strong-Field QED

Parameters

- Intensity parameter:

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

- Quantum parameters:

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

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

- Energy parameter:

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

- Measure of coupling between probe and laser field (also square root of laser intensity).
- $\xi \geq 1$: non-perturbative regime
- Ratio of laser field and Schwinger critical field.
- $\chi \geq 1$: non-linear quantum effects become probable (e.g. pair production).

E_L : Laser field

E_{crit} : Schwinger critical field

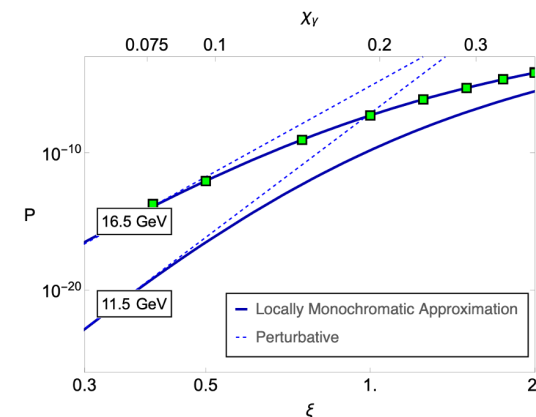
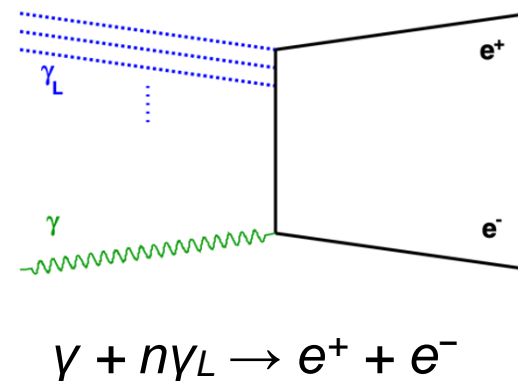
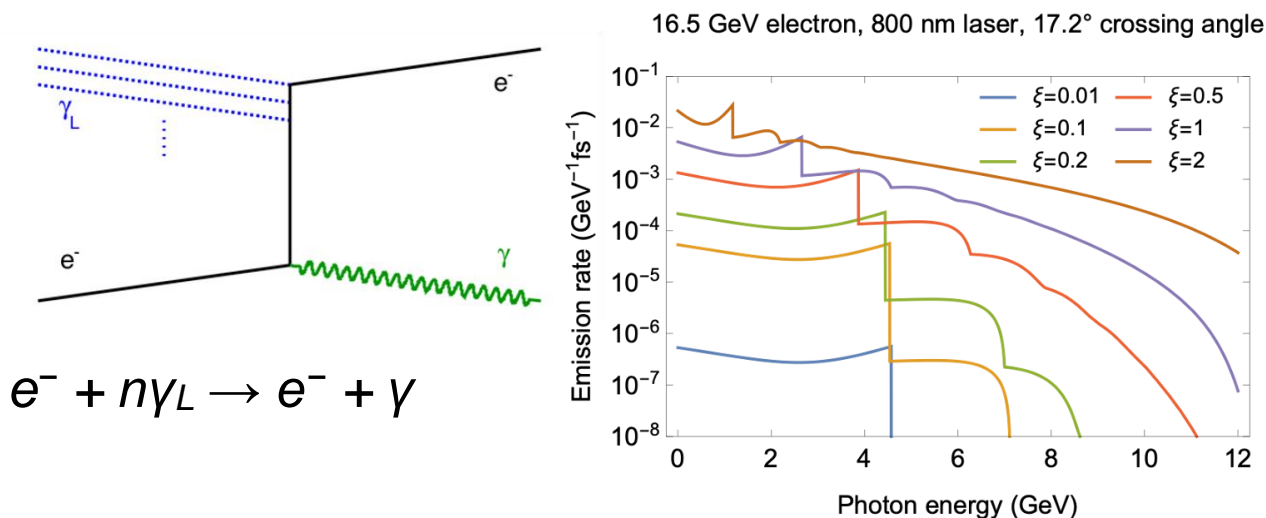
ω_L : Laser frequency

θ : e/γ – laser crossing angle

$E_{e/\gamma}$: Probe electron/photon energy

Strong-Field QED

Non-linear Compton scattering and Breit-Wheeler pair production



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

- 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:

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

Photon from Compton scattering or secondary beam.

Perturbative regime: power law

$$\xi \ll 1 : R_{e^+} \propto \xi^{2n} \propto I^n$$

Non-perturbative regime

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