Strong-field QED project LUXE at the European XFEL

For the LUXE Collaboration
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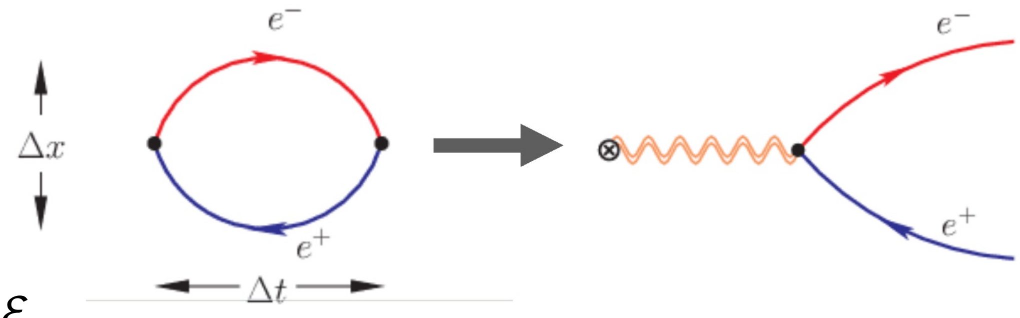
- Physics Motivation
- Physics Content
- Design of the experiment

Strong Field QED

QED is the most stringently tested theory – what is the interest of exploring it further?
- stringent tests are in the perturbative regime
- the strong-field QED explores the non-perturbative regime yet not tested experimentally



$$E_{field} = \frac{\mathcal{E}}{m_e}$$

$E_{field} < 2m_e$

$E_{field} > 2m_e$
$\Delta x \geq \lambda_C$

In constant $\mathcal{E}$ field this happens when

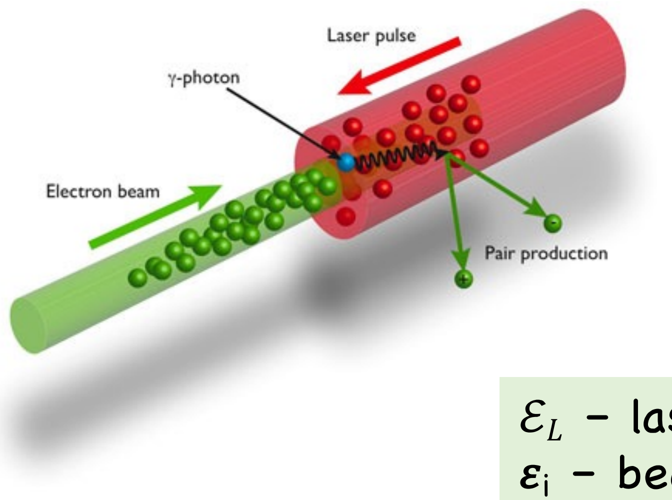
$$\mathcal{E}_{crit} = \frac{m_e^2 c^3}{\hbar e} = 1.32 \times 10^{18} V/m.$$

$\mathcal{E}_{crit}$ - **Schwinger limit**

Strong fields occur in
- magnetars
- black holes (albeit in gravitational field)
- the field of heavy ions
- future e+e- colliders

light-matter interactions under extreme conditions important for
- ultra-relativistic plasma dynamics
- highly non-linear effects
- novel beam sources (compact in space and ultra-short in time)

SFQED in electron-laser interactions



- There are still no lasers achieving the Schwinger limit (by orders of magnitude)
- Boost the field by Lorentz factor
- Use high-energy electron beam

$\mathcal{E}_L$ – laser field in rest frame of beam particle
ε_i – beam energy; θ – crossing angle, ω_L – laser wavelength

ξ – classical non-linearity parameter

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

ξ - work done over λ_e in units of $\hbar\omega_L$
(~number of laser photons interacting)
ξ^2 - measure of laser intensity

χ – quantum non-linearity parameter

$$\chi_i = \frac{\varepsilon_i}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}(1+\beta\cos\theta)$$

χ – work done over λ_e in units of $m_e c^2$

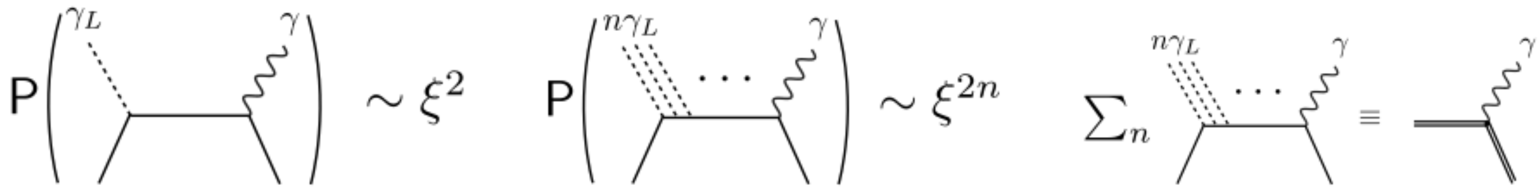
η – energy parameter

$$\eta_i = \frac{\omega_L \varepsilon_i}{m_e^2}(1+\beta\cos\theta)$$

$$\eta_i = \frac{\chi_i}{\xi}$$

Physics processes

Compton scattering

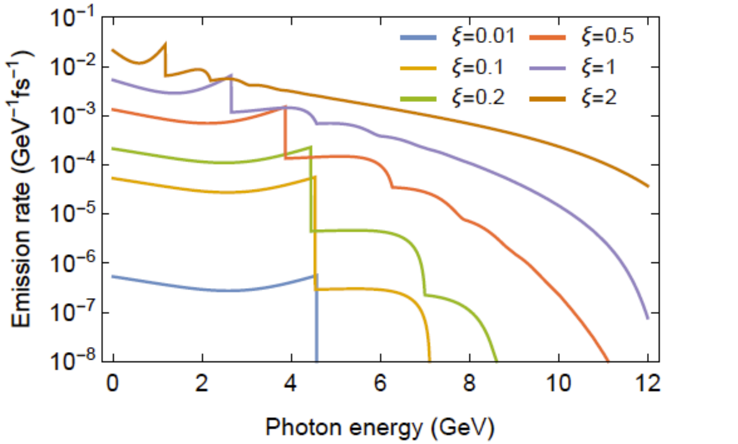


$\xi < 1$

$\xi < 1$, $n\gamma$, perturbative non-linear

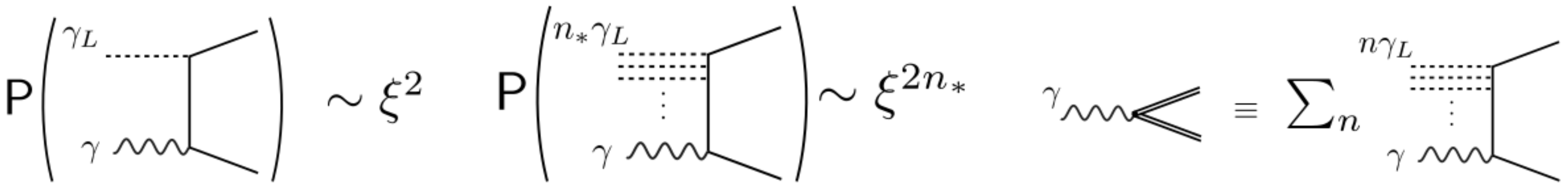
$\xi > 1$, non – perturbative

Compton edge is moving



$m \to m\sqrt{1+\xi^2}$, "Kibble mass", all-order effect when $\xi \not\ll 1$

Breit-Wheeler pair creation



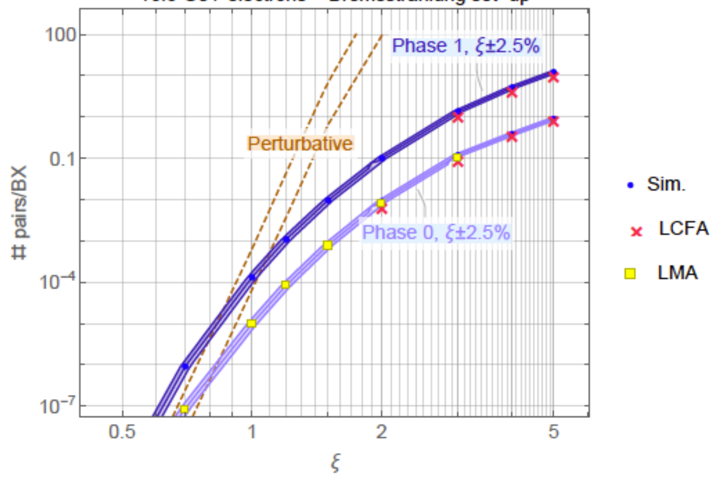
$\xi < 1$

$2m_e^2\eta_\gamma \geq 4m_e^2(1+\xi^2)$

$\xi < 1$, perturbative non-linear

$$n_* = \left\lceil \frac{2(1+\xi^2)}{\eta_\gamma} \right\rceil$$

$\xi > 1$, non – perturbative



Consult A. Fedotov et al., Phys. Rep. 1010 (2023) 1

LUXE experimental setup

European XFEL electron beam:

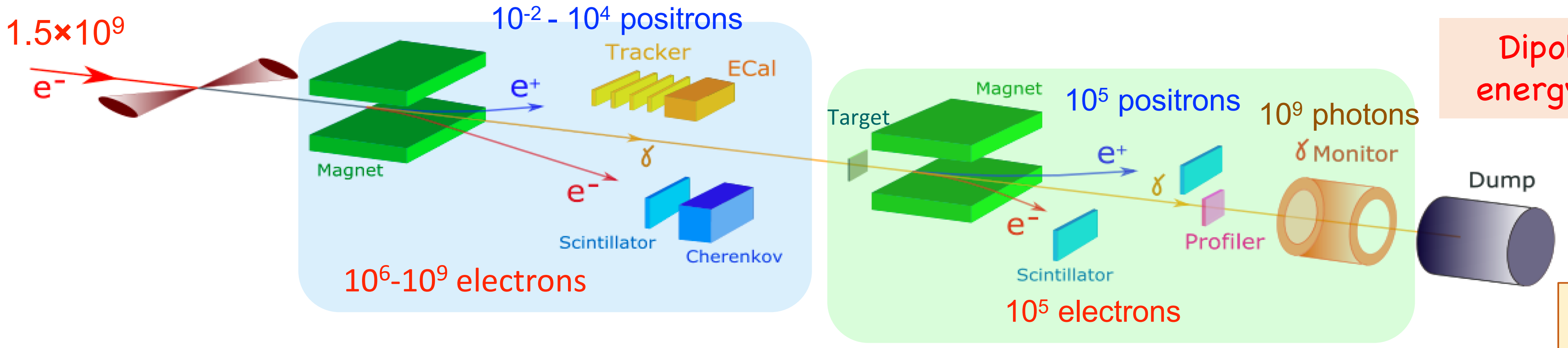
- Energy 16.5 GeV (possible 10 GeV, 14 GeV)
- Use one out of 2700 bunches per train
- Repetition rate 10 Hz
- Focusing down to $\sigma_{x,y}$: 5 – 10 μm
- Generate photon beam for γ laser interactions

Laser:

- Laser wavelength = 800 nm (1.55 eV)
- Repetition rate 1 Hz
- Pulse duration 25-30 fs
- Power:
  - Phase 0: 40 TW, (1.3×10^{20} W/cm^2, ξ = 7.9)
  - Phase 1: 350 TW, (1.2×10^{21} W/cm^2, ξ = 23.6)

LUXE setup contains two (+1 BSM) detector subsystems

- Electron positron detection system
- Photon detection system



Dipoles correlate energy and position

BSM physics with photons
3rd detector subsystem
Yet to be designed

Simulation of physics – Ptarmigan (by T. Blackburn from Uni of Gothenburg)
Detectors performance – GEANT4

Why LUXE?

First experiment to observe non-linear physics E144 at SLAC in 1990s

- used 1 TW laser and 46.6 GeV e-beam
- reached $\chi \leq 0.25$, $\xi < 0.4$, observed pair production
- observed start of the ξ^{2n} power law

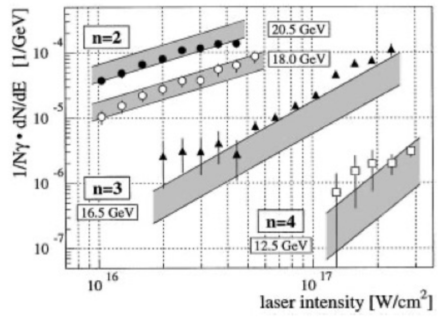


FIG. 5. The normalized yield of scattered electrons of energies corresponding to $n = 2$, 3, and 4 infrared laser photons per interaction versus the intensity of the laser field at the interaction point. The bands represent a simulation of the experiment, including 30% uncertainty in laser intensity and 10% uncertainty in N_γ.

C. Bula et al. PRL (1996)

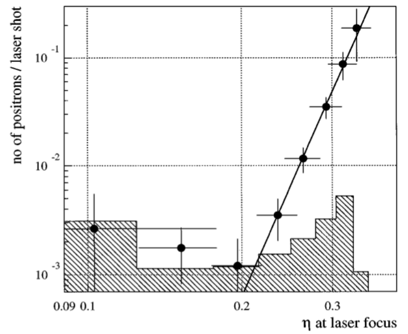
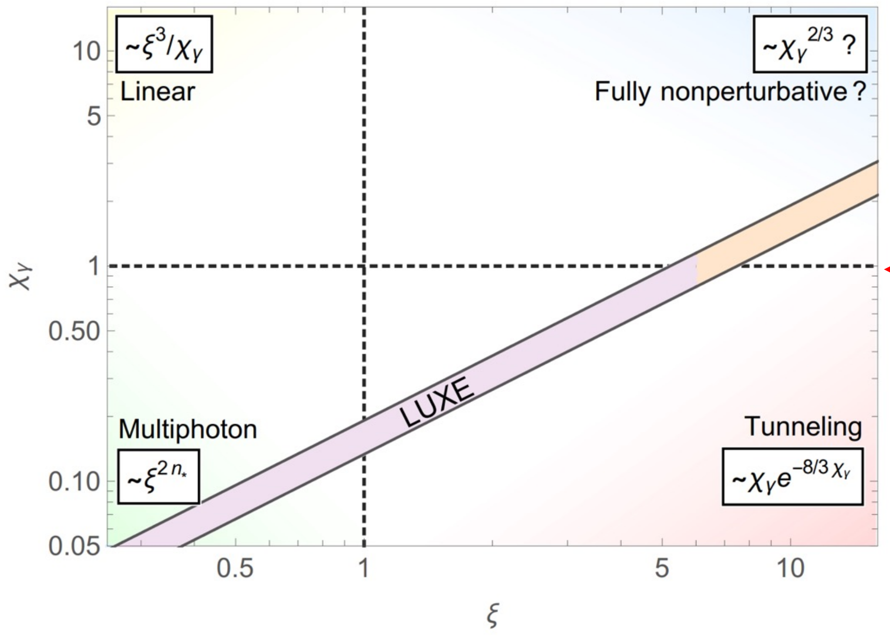
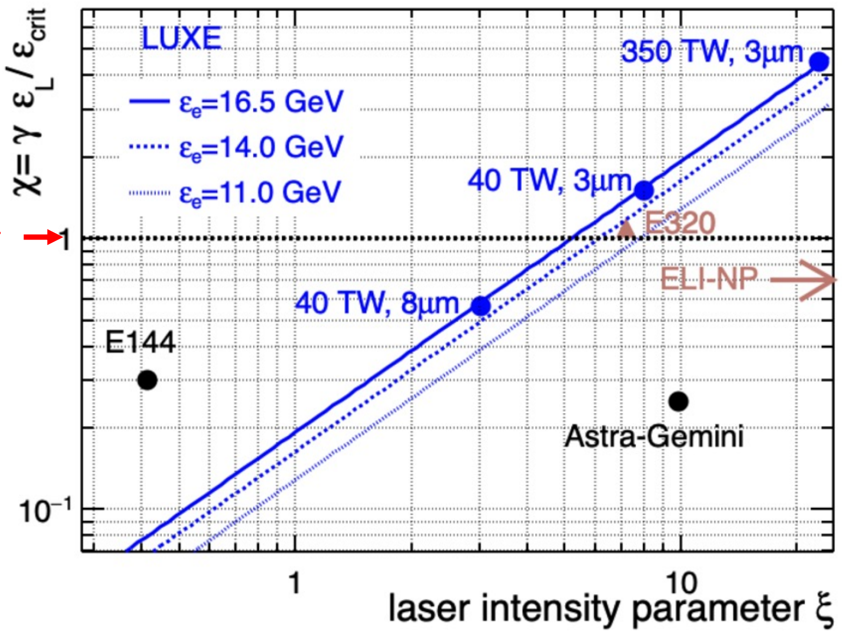


FIG. 4. Dependence of the positron rate per laser shot on the laser field-strength parameter η. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.

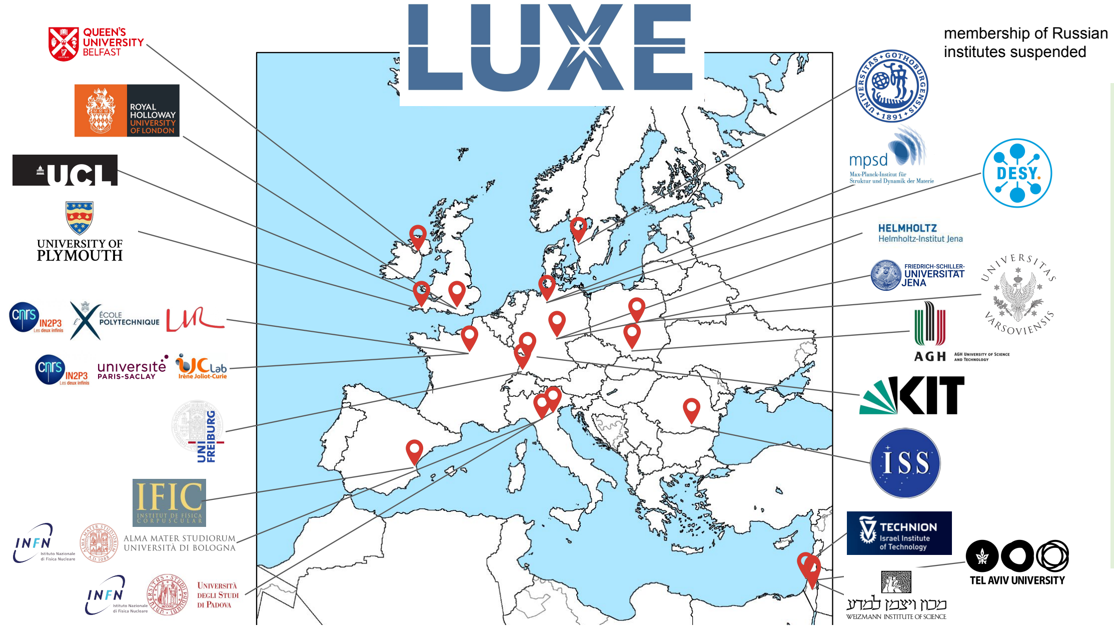
C. Burke et al. PRL (1997)



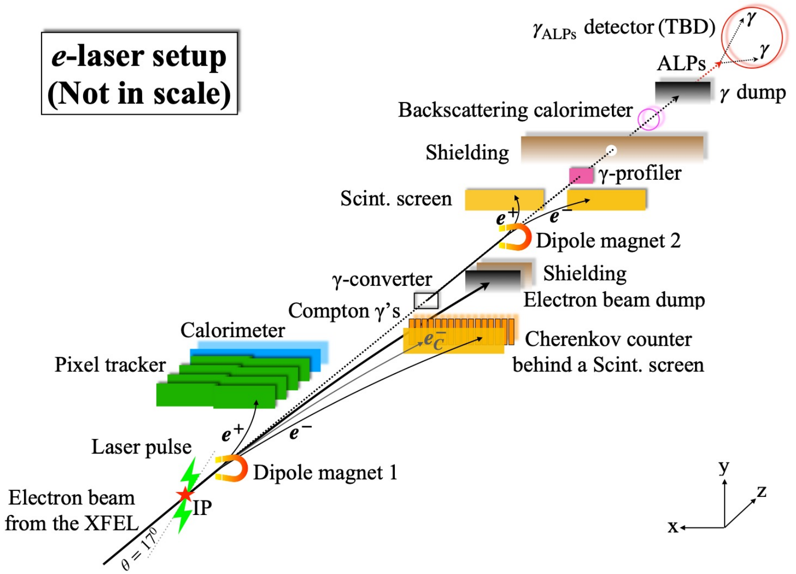
← Schwinger limit →

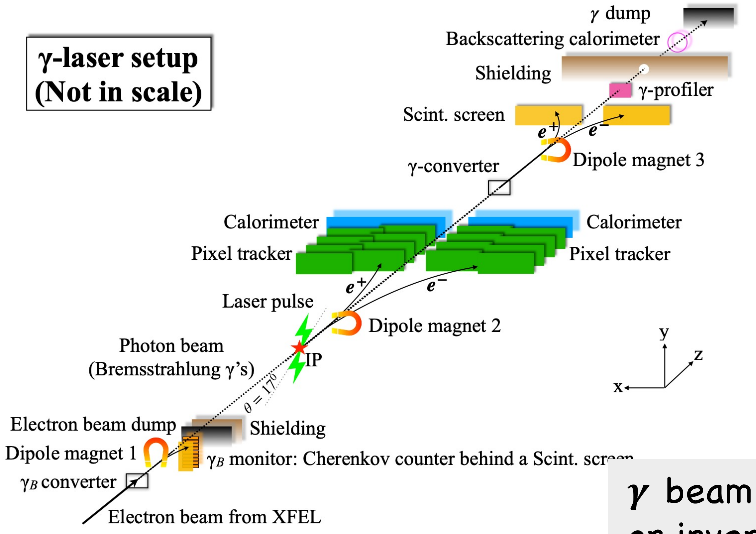


More about LUXE



- LUXE is an international collaboration of 22 institutes
- Interdisciplinary (particle and laser physicists)
- Published CDR (EPJ ST 230 (2023) 2445 – passed CD0 (mission of DESY)
- Drafted TDR (to be published soon) – passed CD1 (technically sound)
- Next stage – demonstrate funding
- Expected to come online 2026 and complete program 2030

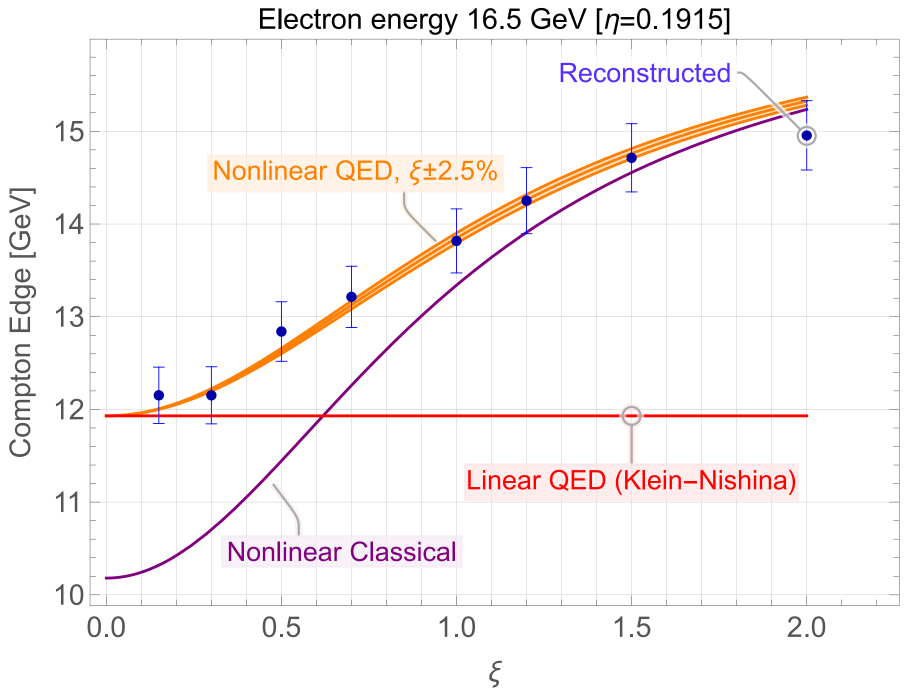




γ beam from bremsstrahlung or inverse Compton scattering

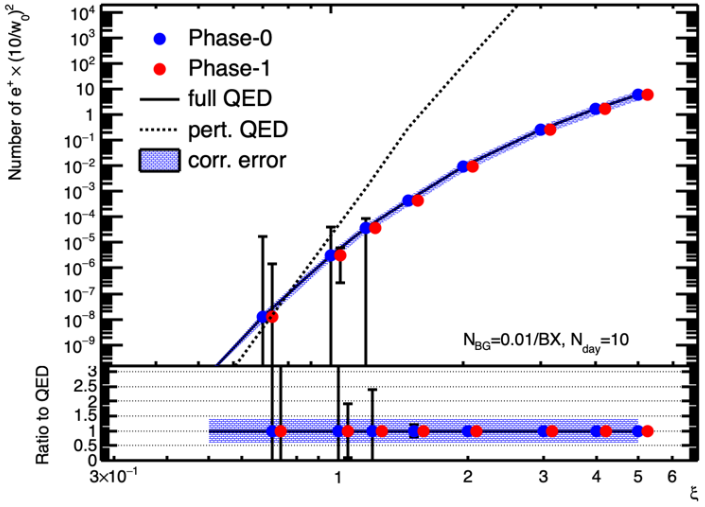
LUXE goals

Compton edge for e⁻



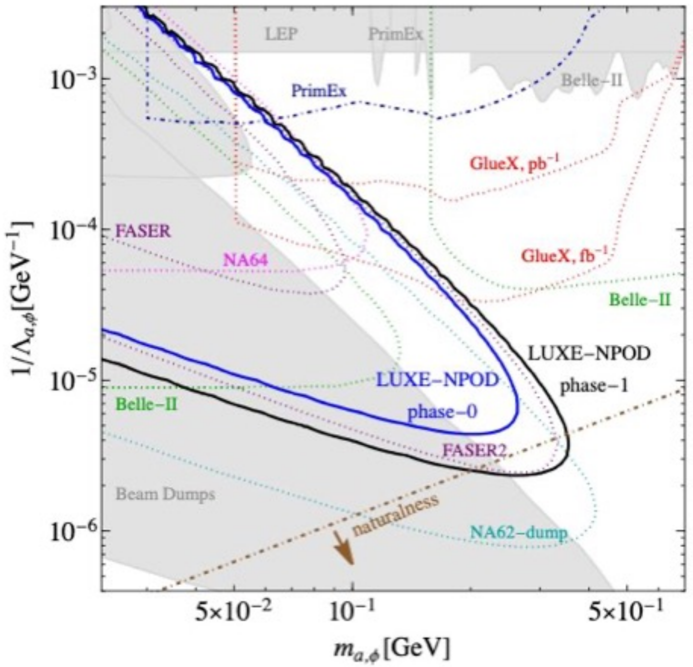
25 cycles

Breit-Wheeler positrons



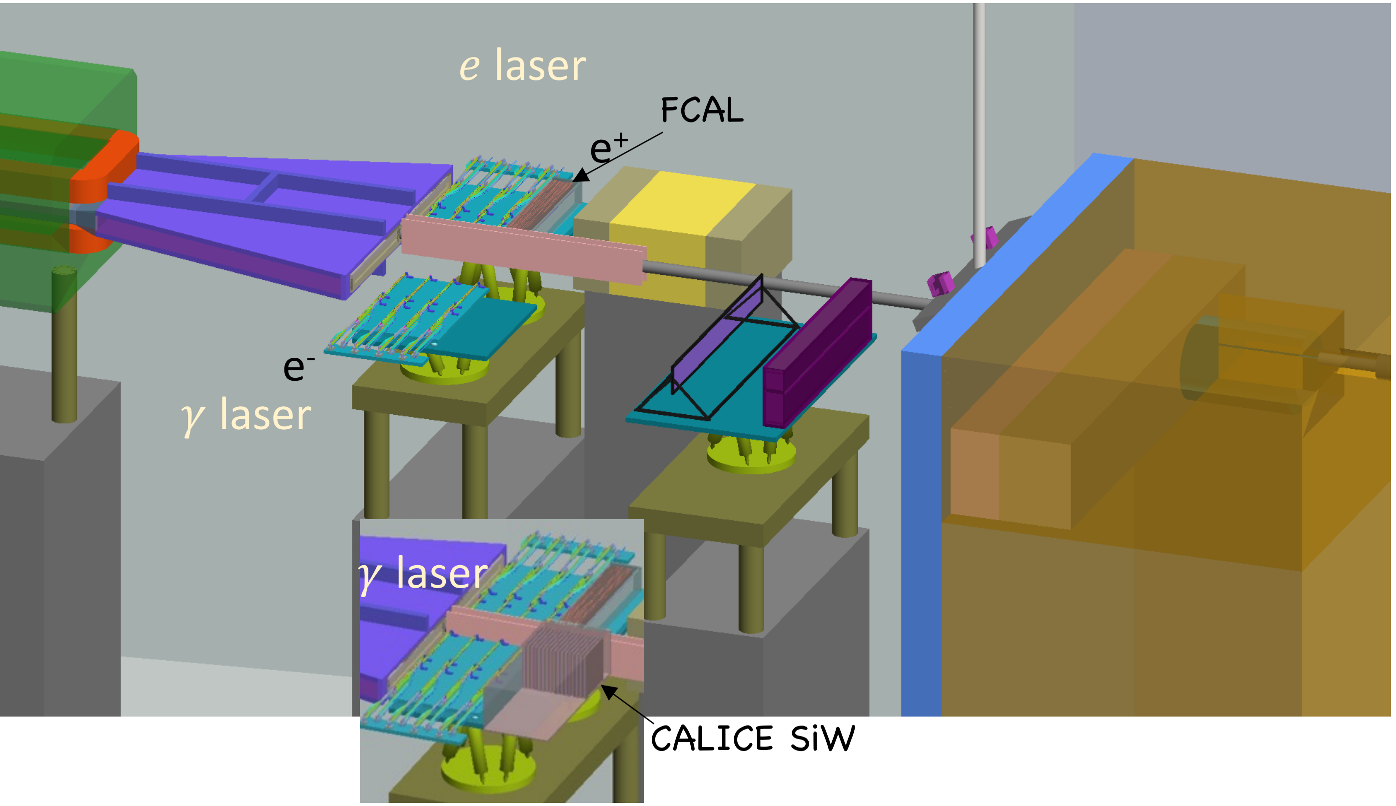
10 days of running statistics only

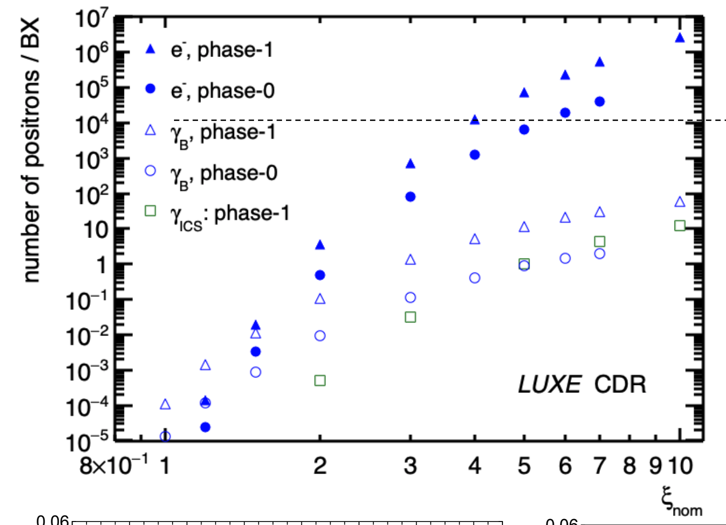
Search for ALPs

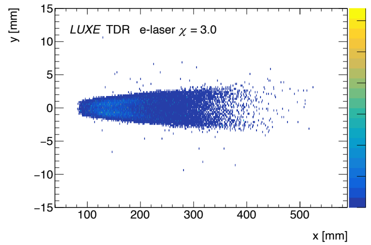


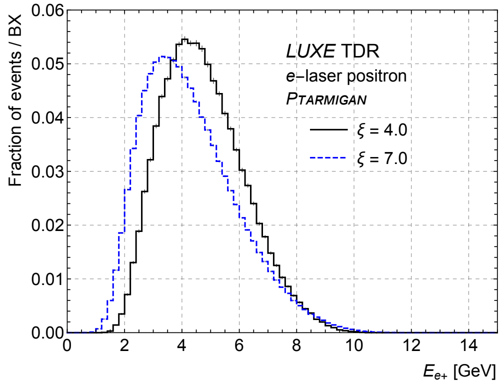
about 1 year

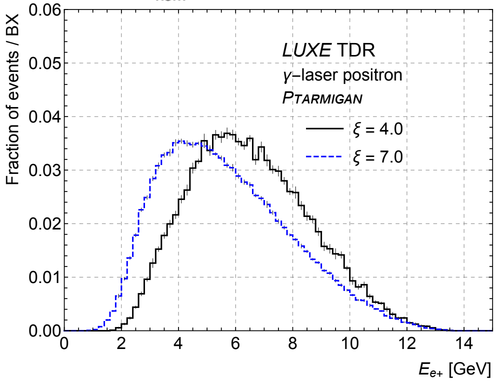
Positron detection











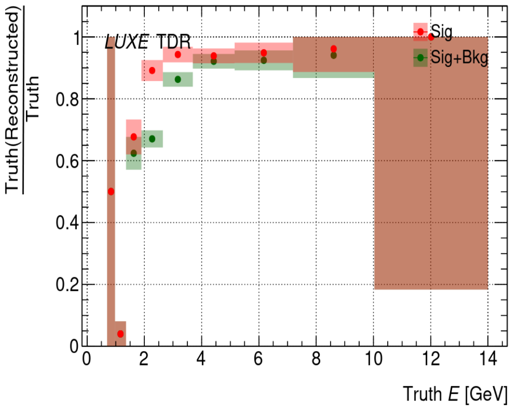
Geometry:
Tracker – located at 4 m from IP, volume 50x1.5x30 cm^3, 5 cm from beamline, 4 layers (ALICE staves with ALPIDE chip)
ECAL-P – located 4.3 m from IP, volume 53x5.2x9 cm^3, 5 cm from beamline, 20 layers of Si/W (FCAL design)
ECAL-E – behind the tracker on the electron side in γ laser mode (CALICE SiW)

Positron spectra - expected performance

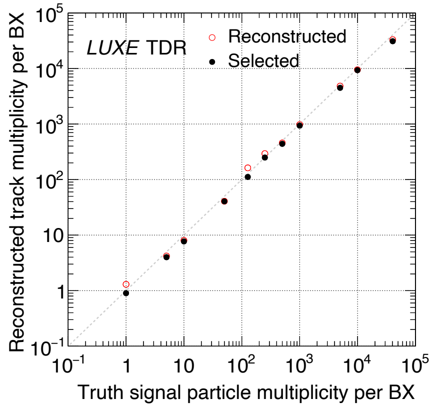
Tracker
- Pixel size: 27 x 29 μm^2, spatial resolution ~5 μm
- Track reconstruction efficiency is above 95%
- Energy resolution < 1%, independent of energy

ECALP
- $1X_0$ W/1mm gap for 320 μm Si, 5x5 mm^2 pads
- Small Molière radius, high spatial resolution of local
- Energy resolution $21\%/(E[GeV])^{1/2}$

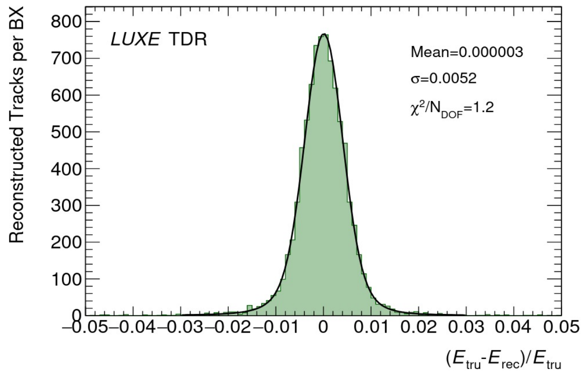
efficiency for 1000p/BX

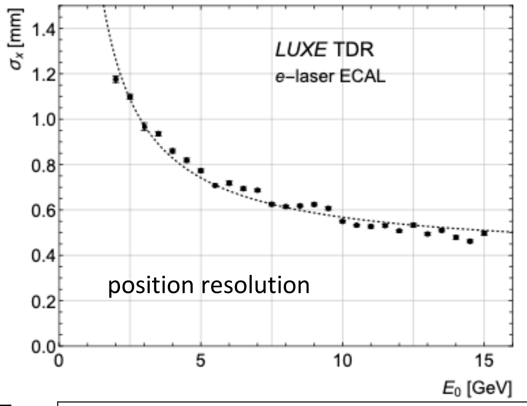


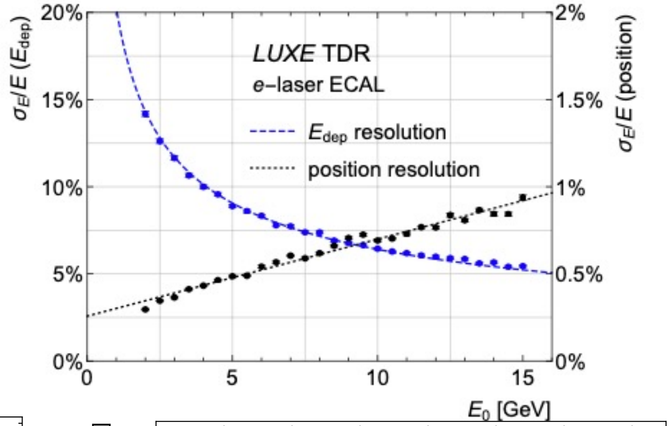
multiplicity/BX

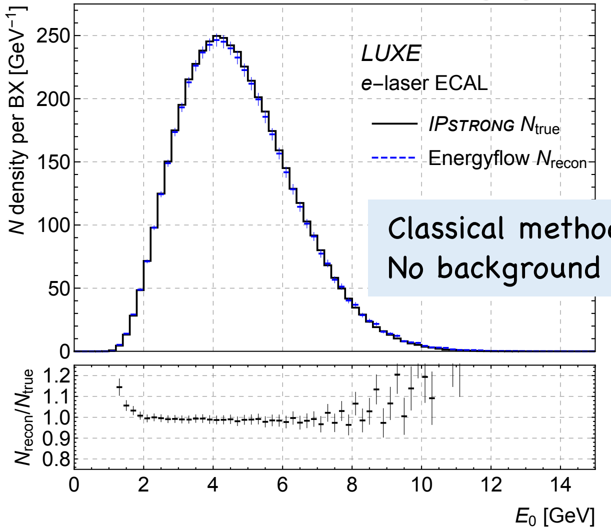


Energy resolution

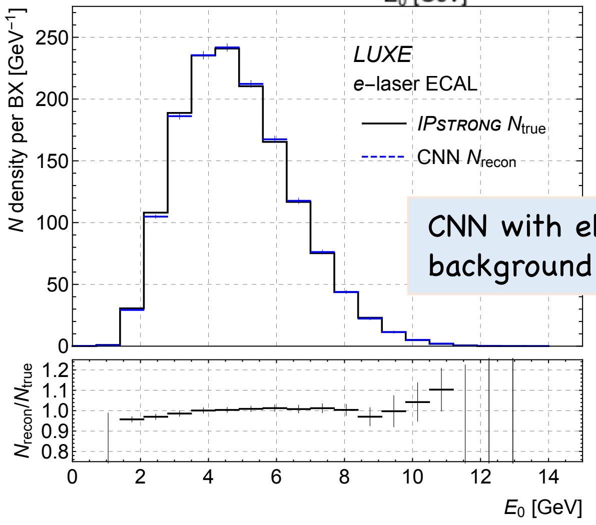








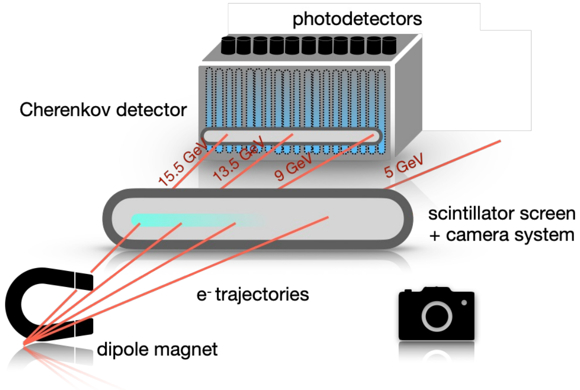
Classical method
No background

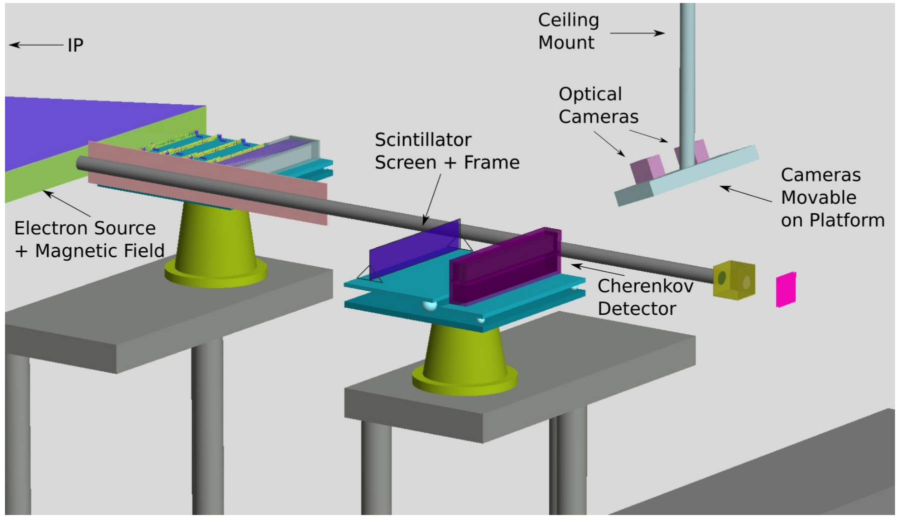


CNN with elmg background

Compton electron detection

- Expected event rate: up to 10^9 electrons
- Chosen technologies:
  - Scintillator screen
  - Cherenkov gas detector



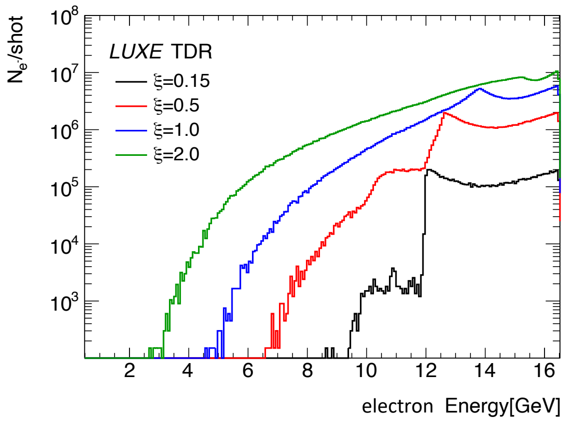


Scintillator screen

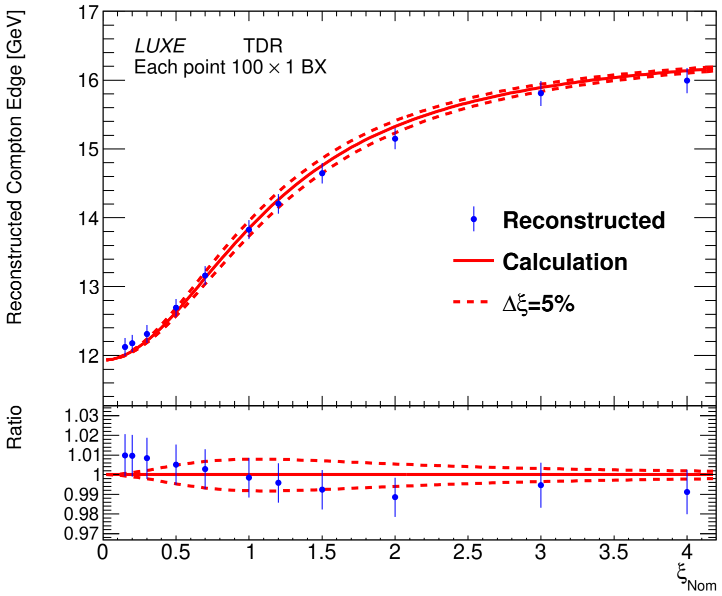
- Technology is widely used for laser monitoring
- High resolution CMOS camera takes pictures of the screen as it emits the light
- Scintillator: Tb-Doped Gadolinium Oxysulfide (GadOx) screen
- Radiation hard (up to 10 MGy)

Performance

- Signal/background ~100
- Position resolution <0.5 mm (~50 MeV)
- Sufficiently high dynamic range (40dB)
- Successfully tested with electron beam



FIR – finite impulse response filter



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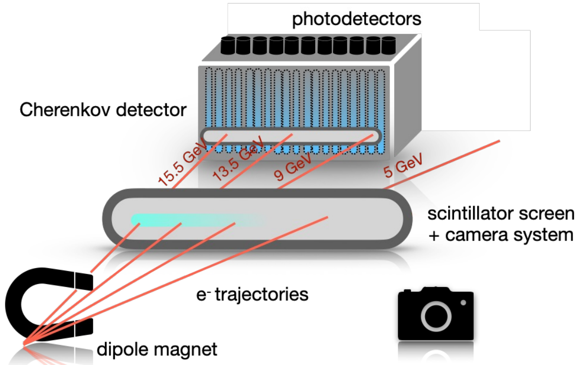
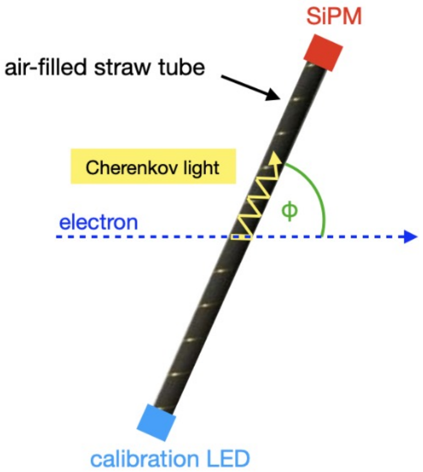
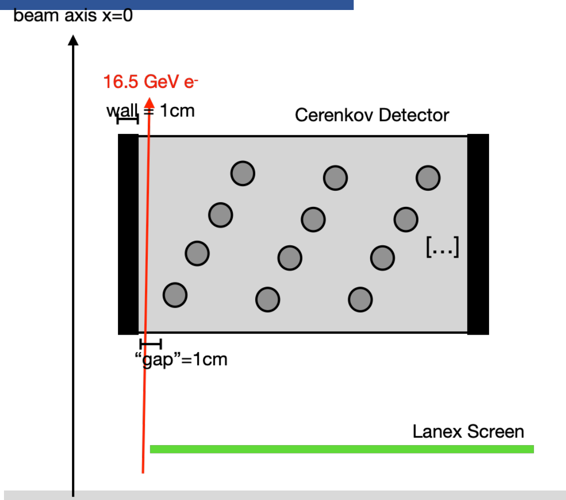






240 straws of R = 2 mm in 4 layers

Gaseous Cherenkov detector;

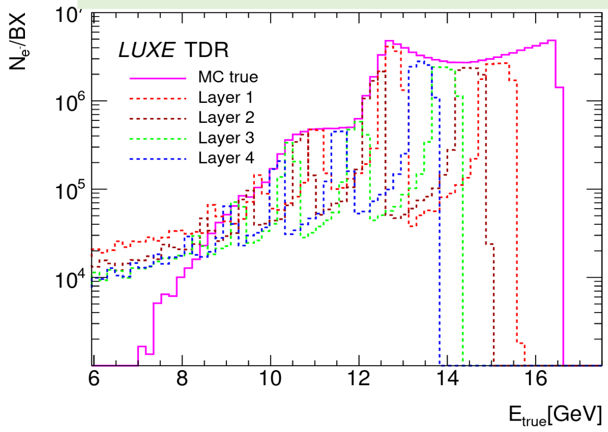
- Vertical reflective straw tubes with SiPMs and/or APDs
- Low refractive index gas (air, n=1.0028), possibly optical filter to reduce light yield;
- Fine segmentation to resolve kinematic edges in Compton spectra

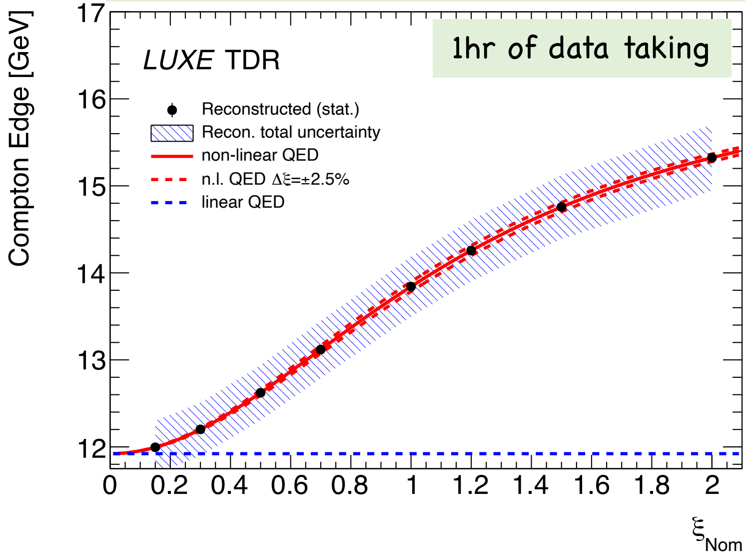
FIR – finite impulse response filter

Performance

- Signal/background >1000
- Not sensitive to electrons <20 MeV or photon background
- Successfully tested with electron beam

Electrons spectrum reconstructed from straw layers

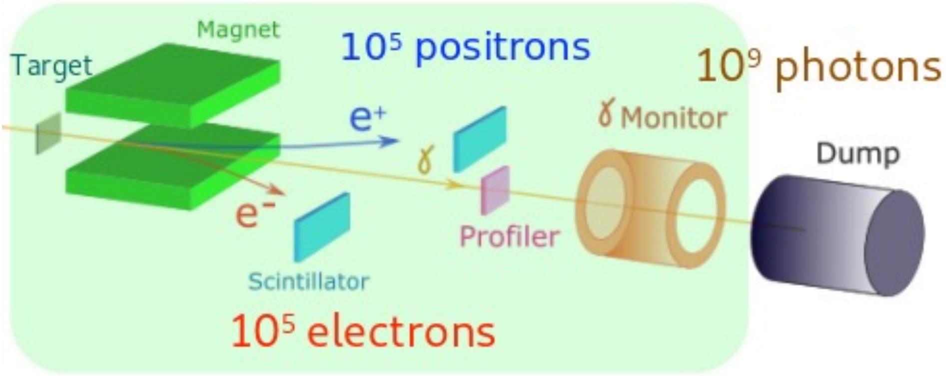




Photon detection system

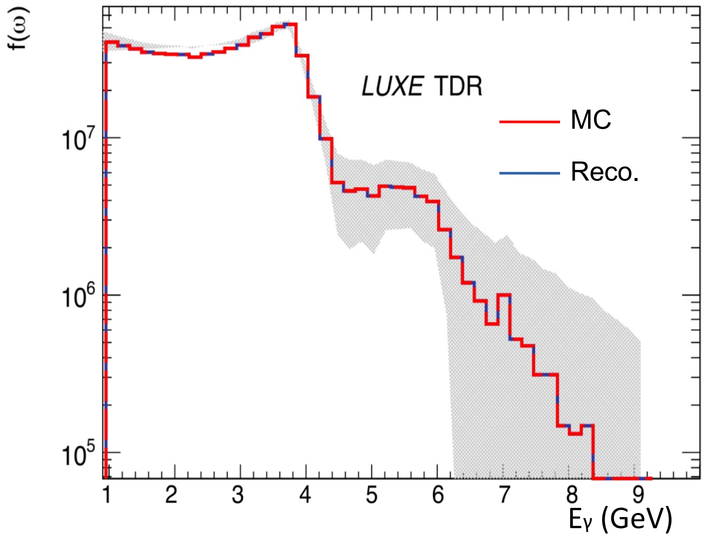
High number of photon

- up to 10^9 photons/BX
- summing up to TeV energies



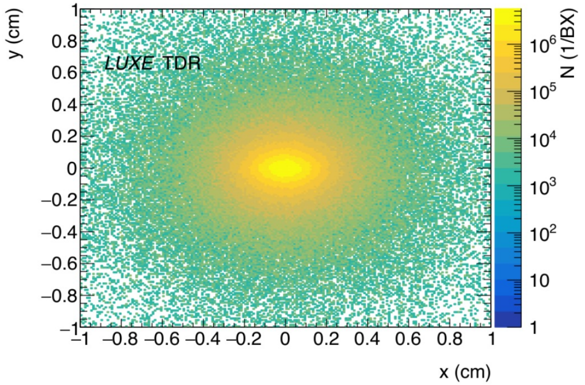
Photon spectrometer

- tungsten converter target
- dipole magnet
- 2 scintillator screens
- deconvolution of e^+,e^- spectra



Gamma profiler

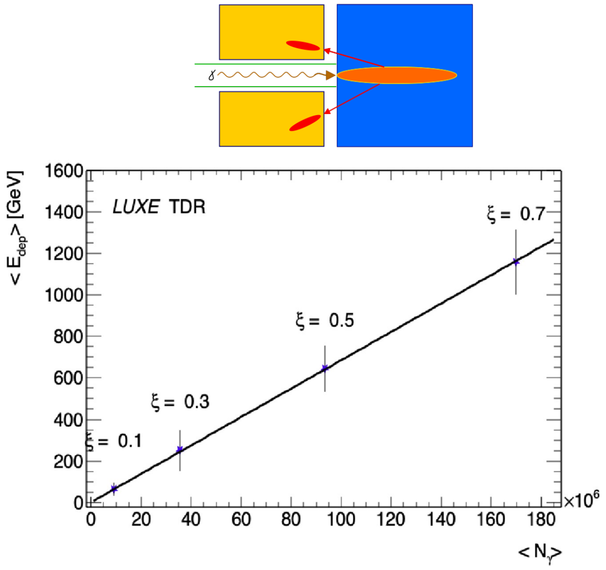
- two sapphire strip detectors
- spatial asymmetry



transverse profile of photon beam depends on laser intensity (ξ)

Photon flux monitor

- 8 lead glass blocks, 3.8×3.8×45 cm^3
- on cylinder with R = 120 mm
- energy backscattered from dump



Summary

- LUXE will explore strong-field QED in new regime by colliding electrons from the European XFEL with powerful laser
- Experimental design geared towards achieving physics goals with particular focus on minimising systematics
- Opportunity to expand physics program to search for BSM
- Opportunity to apply detector technologies otherwise developed for future colliders
- Very attractive time frame (start sometime in 2026 and complete program by 2030)
- Standing invitation to join the LUXE project