LUXE ELECTRON, POSITRONS (AND PHOTONS) DETECTORS

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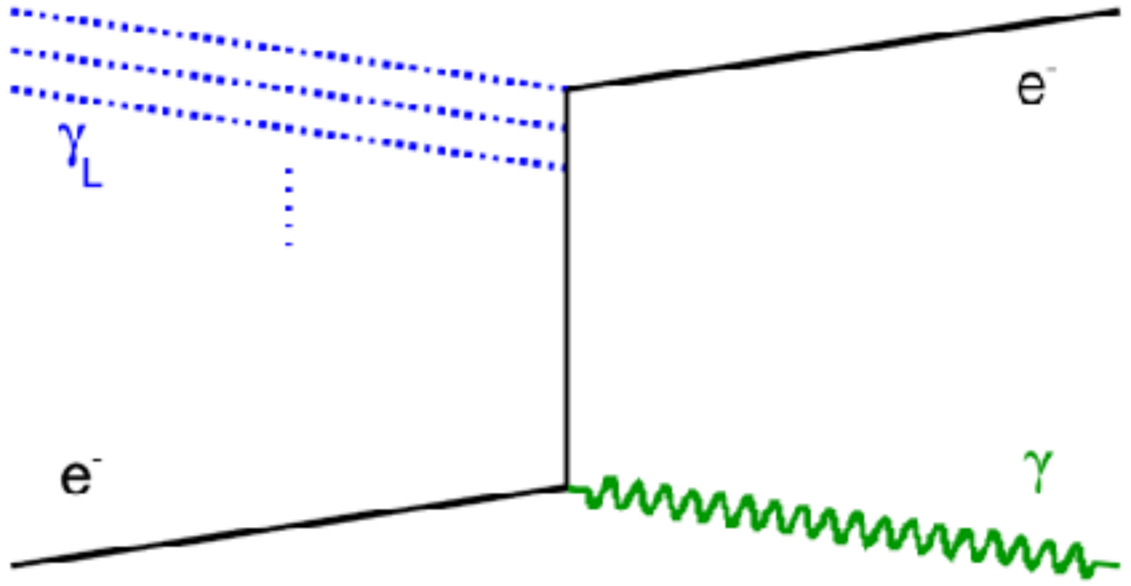
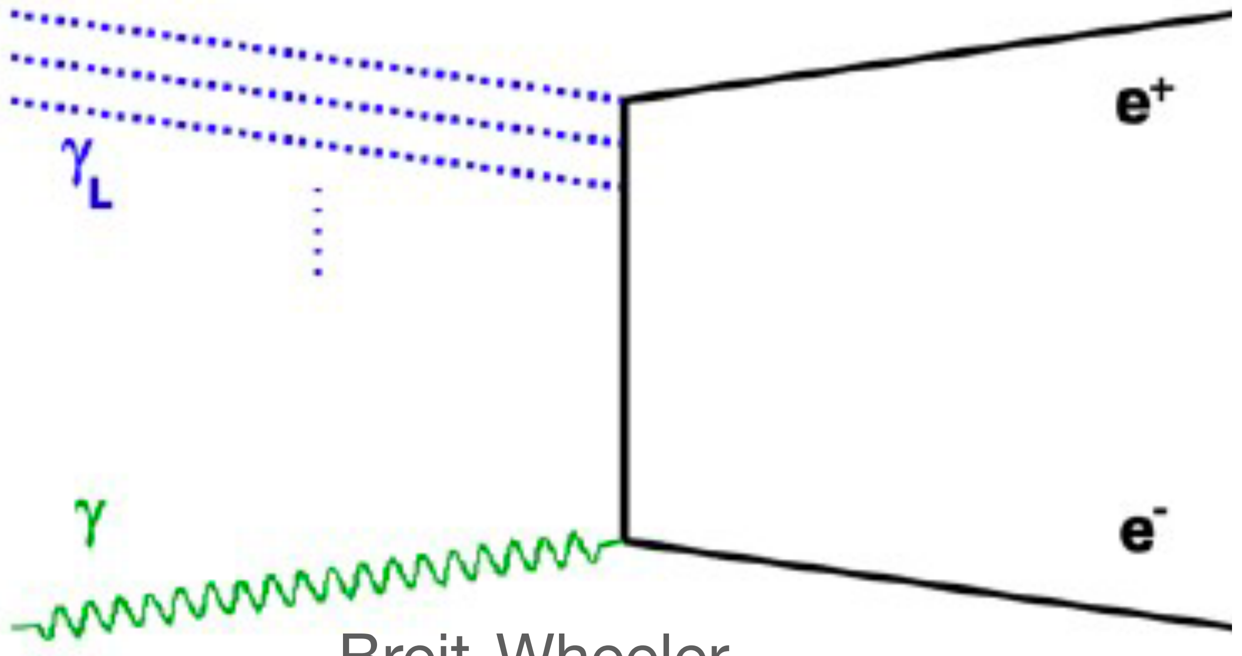
2ND FCC POLARIZATION WORKSHOP, SEPTEMBER 22TH 2022

INTRODUCTION: SFQED PROCESSES AND PREDICTIONS

- Processes sensitive to in LUXE:



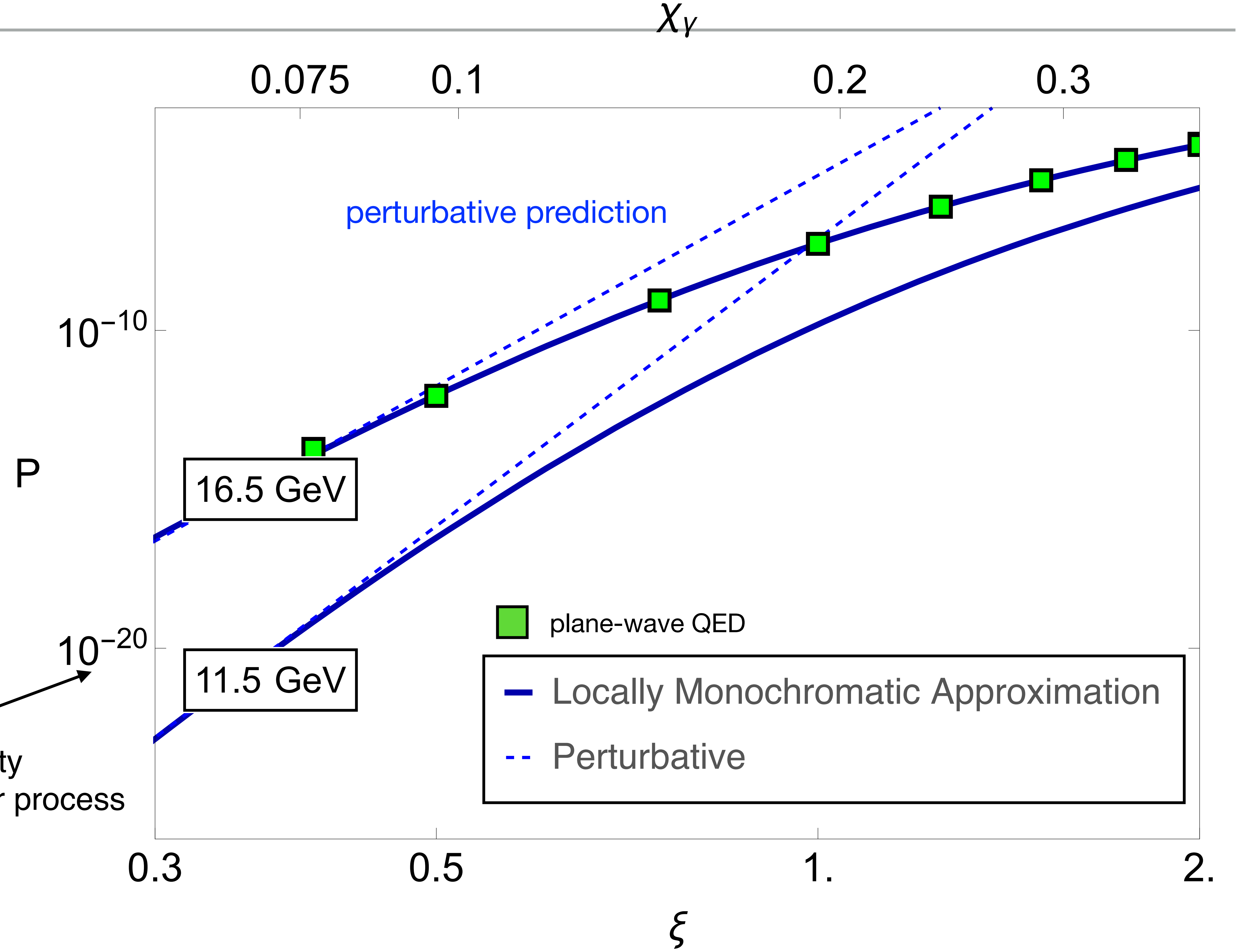
non-linear Compton scattering



Breit-Wheeler

- Parameters used in SFQED:
  - ξ = Measure of e-Laser coupling and Laser intensity.
  - X^2 = fraction of Laser energy transferred to electron beam.

$$\xi = \frac{e\varepsilon_L}{m_e \omega_L c} \propto I_{Laser} \qquad \chi \approx \gamma \frac{\varepsilon_L}{\varepsilon_{crit}} \propto \sqrt{I_{Laser}}\, E_{beam}$$



probability
of Breit-Wheeler process

- Predictions:

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

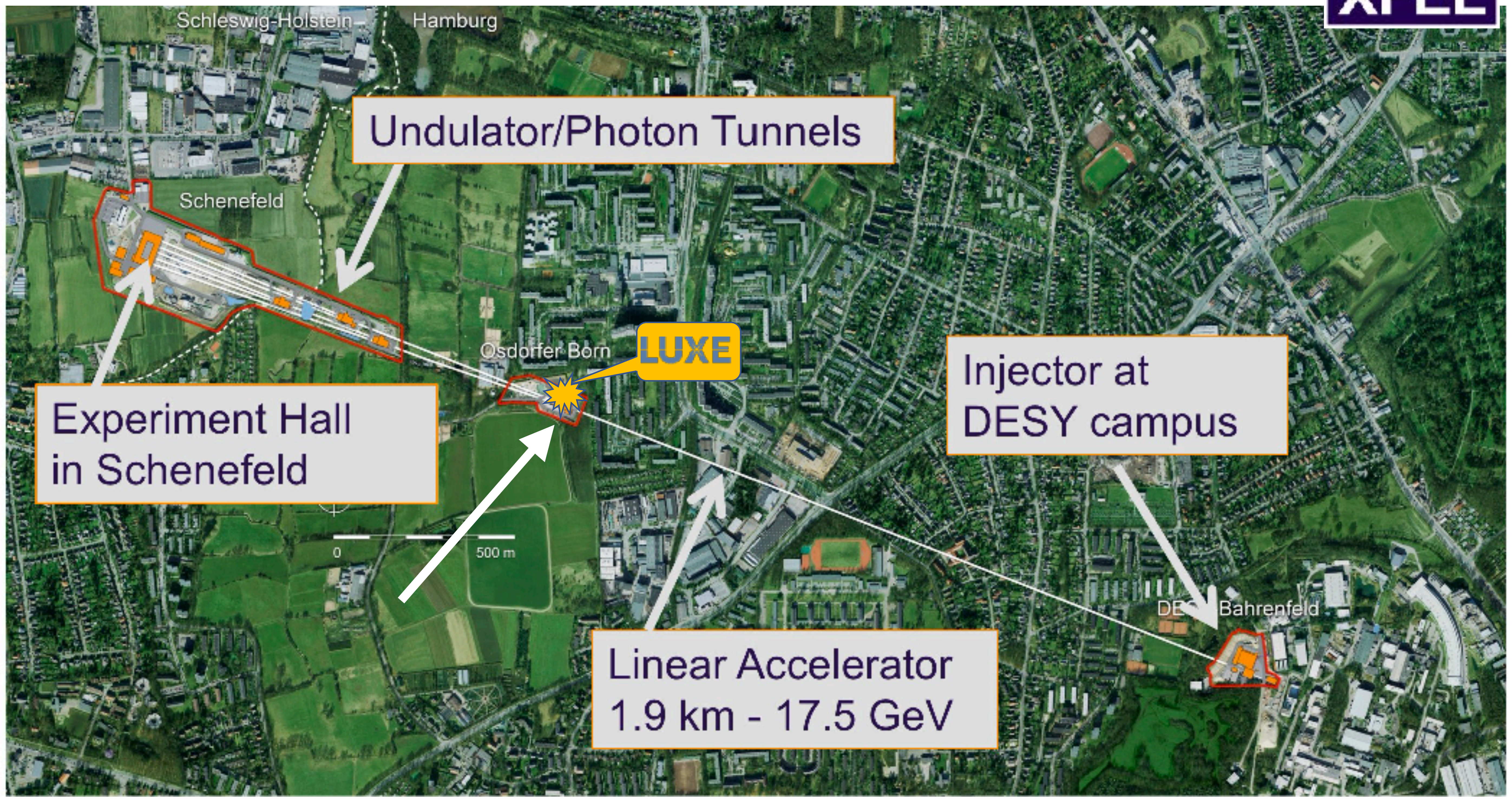
Perturbative regime, rate follows power law

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

Non-perturbative regime, departure from power law
(valid for low X values)

- Main Luxe scientific goals:
  - Demonstrate SFQED by interacting high power laser (>40 TW) with high energy electron beams (16.5 GeV).
    - Measure positron rate as a function of laser intensity.
    - Measure Compton edges.
      - Position of edges different as function of ξ parameter.

- European XFEL:
  - Running since 2017.
  - Provide X-ray photons to 6 experiments.
    - Electron through undulator:
      - SASE (self-amplified spontaneous emission).
  - Linear electron accelerator.
    - 2700 electron bunches at 10 Hz.
      - Aim to run at 16.5 GeV with 1.5e9 e-/bunch.
- Experiment will be located XS1 shaft in Orsdorfer Born.
  - Built for XFEL extension (beyond 2030).
- Experiment will have no impact on photon science,
  - Only use 1 of the 2700 bunches.

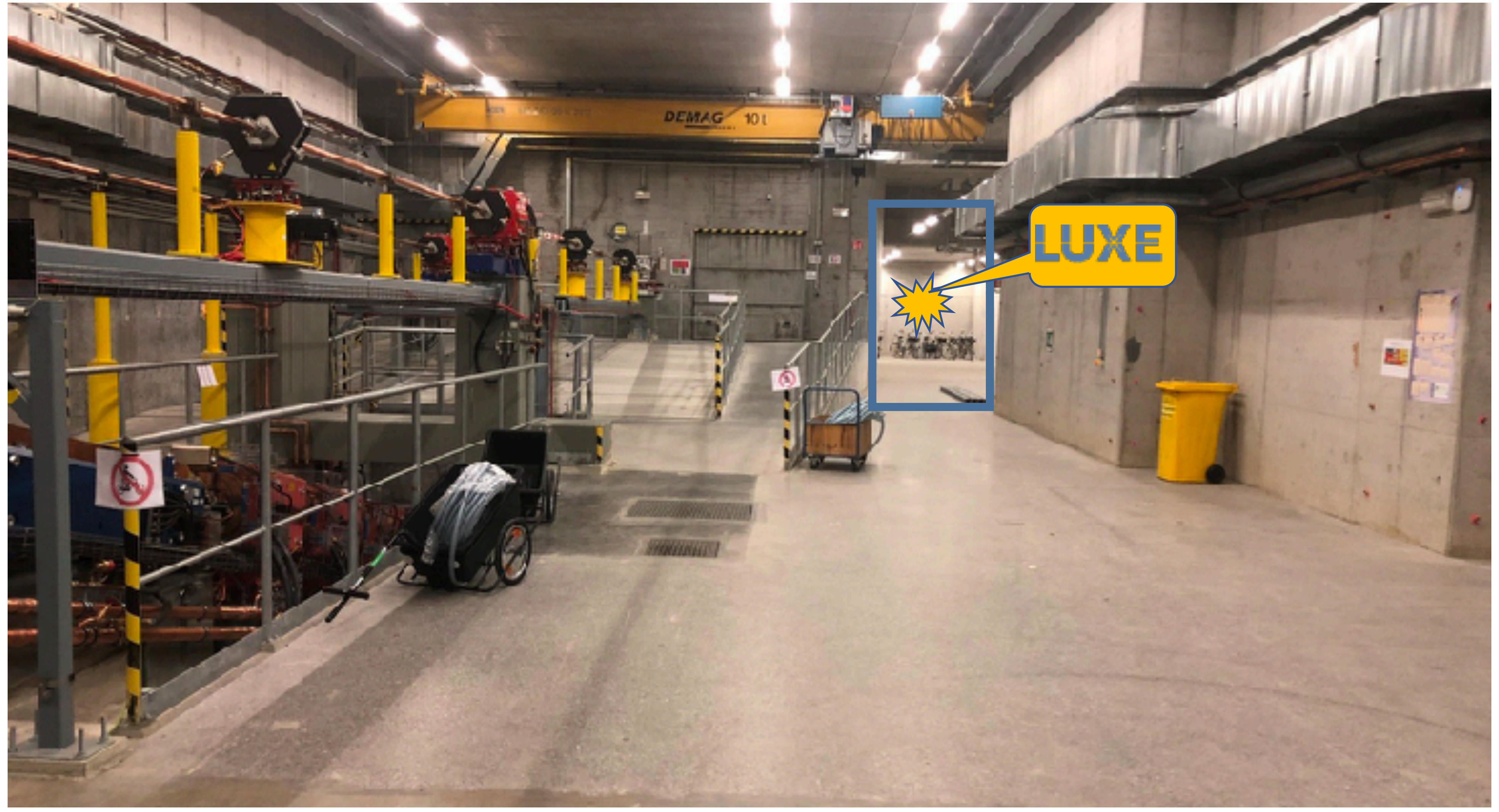


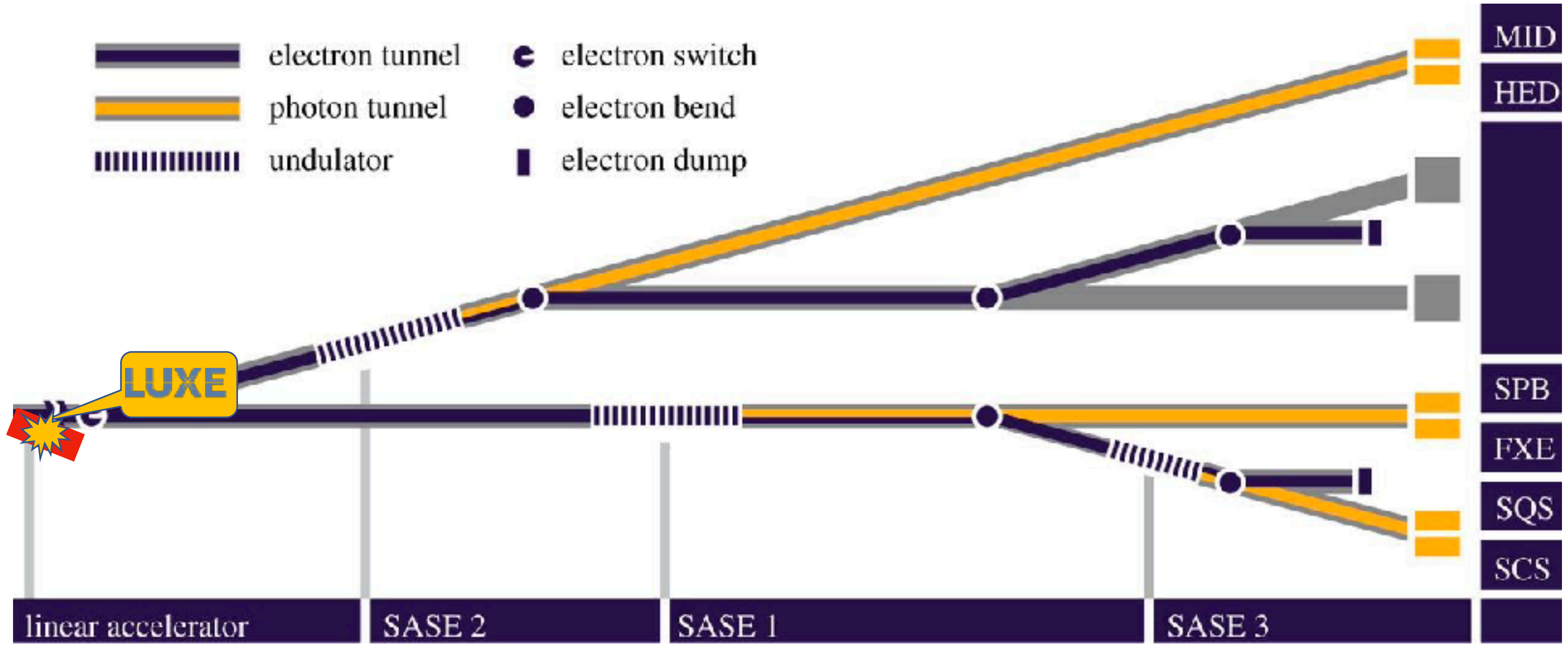
Undulator/Photon Tunnels

Injector at DESY campus

Experiment Hall in Schenefeld

Linear Accelerator 1.9 km - 17.5 GeV

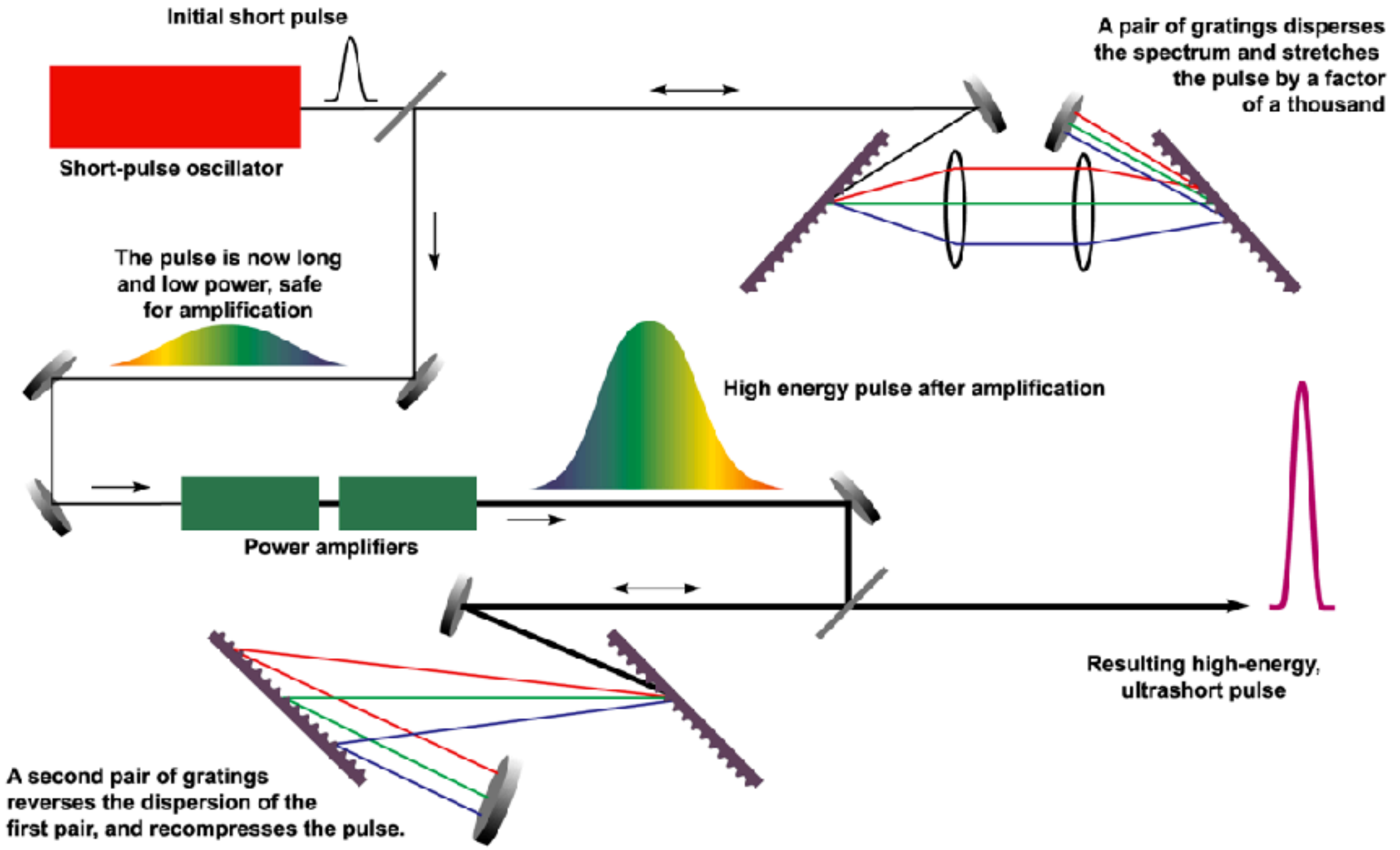


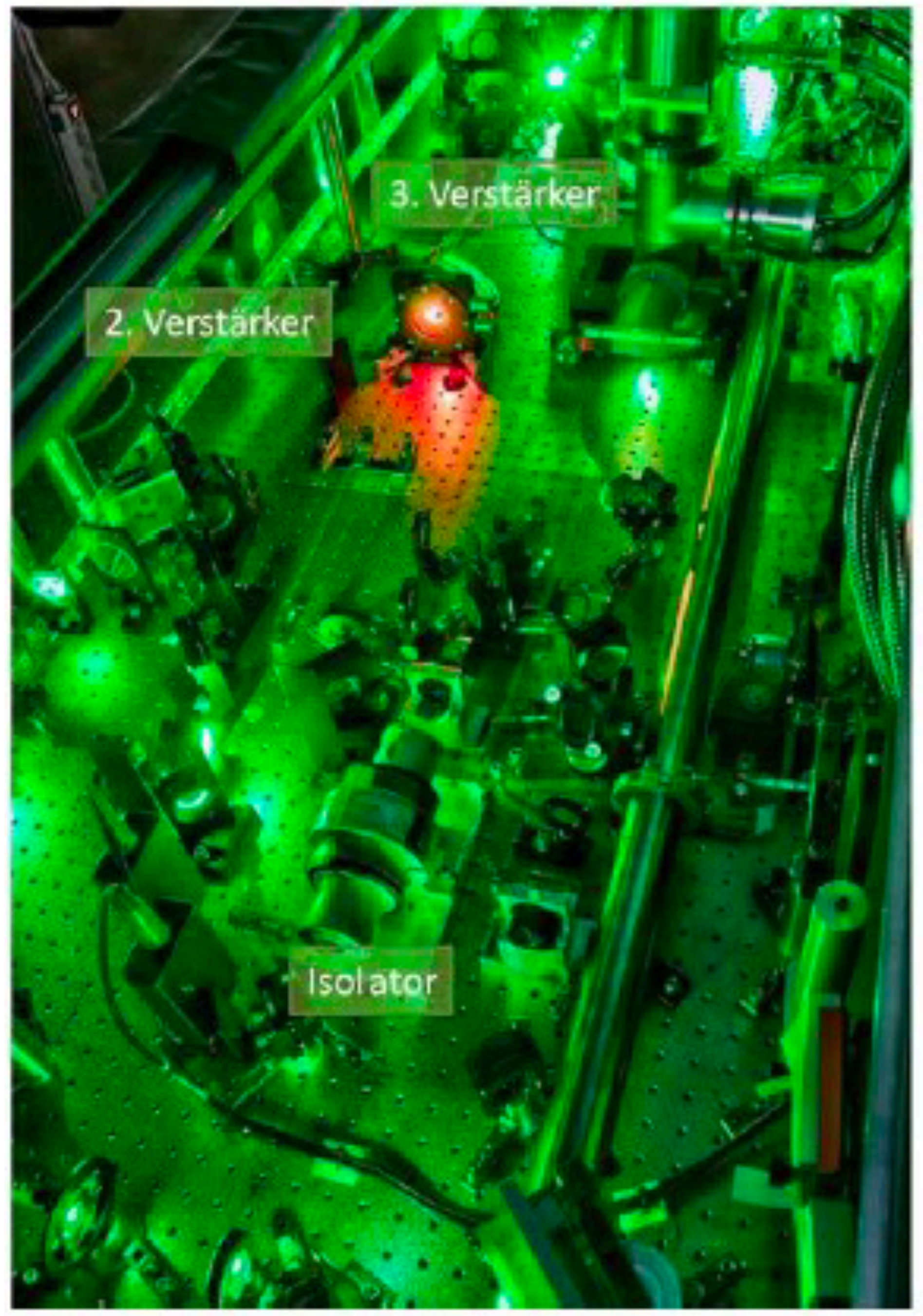


LASER

See talk from GianLuca Sarri yesterday

- Chirped Pulse Amplification (CPA) technique
- Ti:Sa laser with 800 nm wavelength (E=1.55 eV).
- Two phases:
  - In phase 0 uses JETI40 (Jena custom 40 TW laser).
  - In phase I will use commercial 350 TW laser.
- Laser parameters:
  - Repetition rate: 1Hz.
  - Pulse length 30 fs
- Laser characterisation quantities: energy, pulse length, spot size
  - ≤ 5% uncertainty on Laser intensity, 1% shot-to-shot uncertainty





Parameter	Phase 0	Phase 0	Phase I
Laser power	40 TW		350 TW
Laser energy after compression [J]	1.2		10
Percentage of laser in focus [%]	50		
Laser focal spot size w_0 [μm]	>8	>3	>3
Peak intensity [10^{19} W/cm2]	1.9	13.3	120
Peak intensity parameter ξ	3.0	7.9	23.6
Peak quantum parameter X E_{beam}=16.5 GeV	0.56	1.5	4.5

LUXE IN SITU

High power Laser

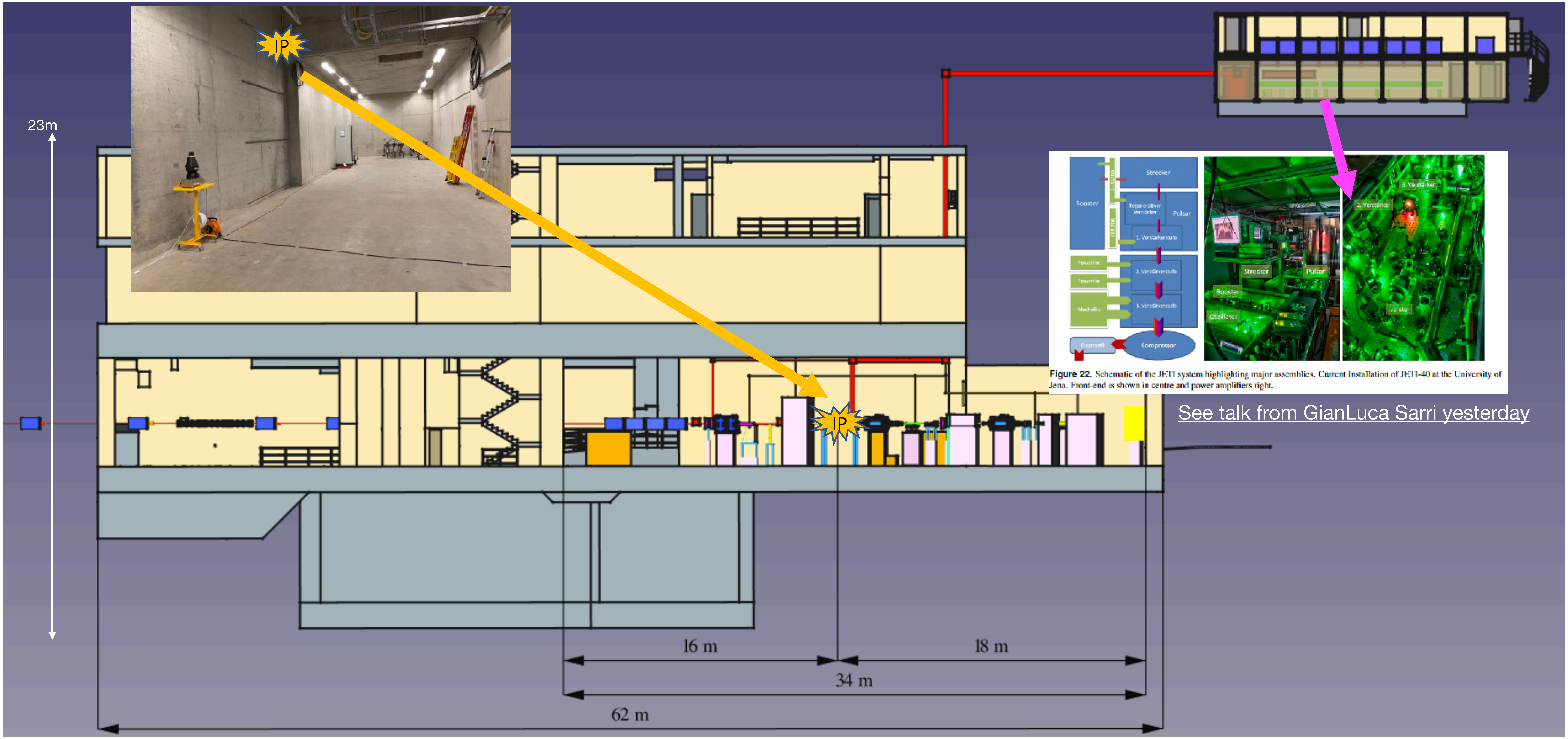
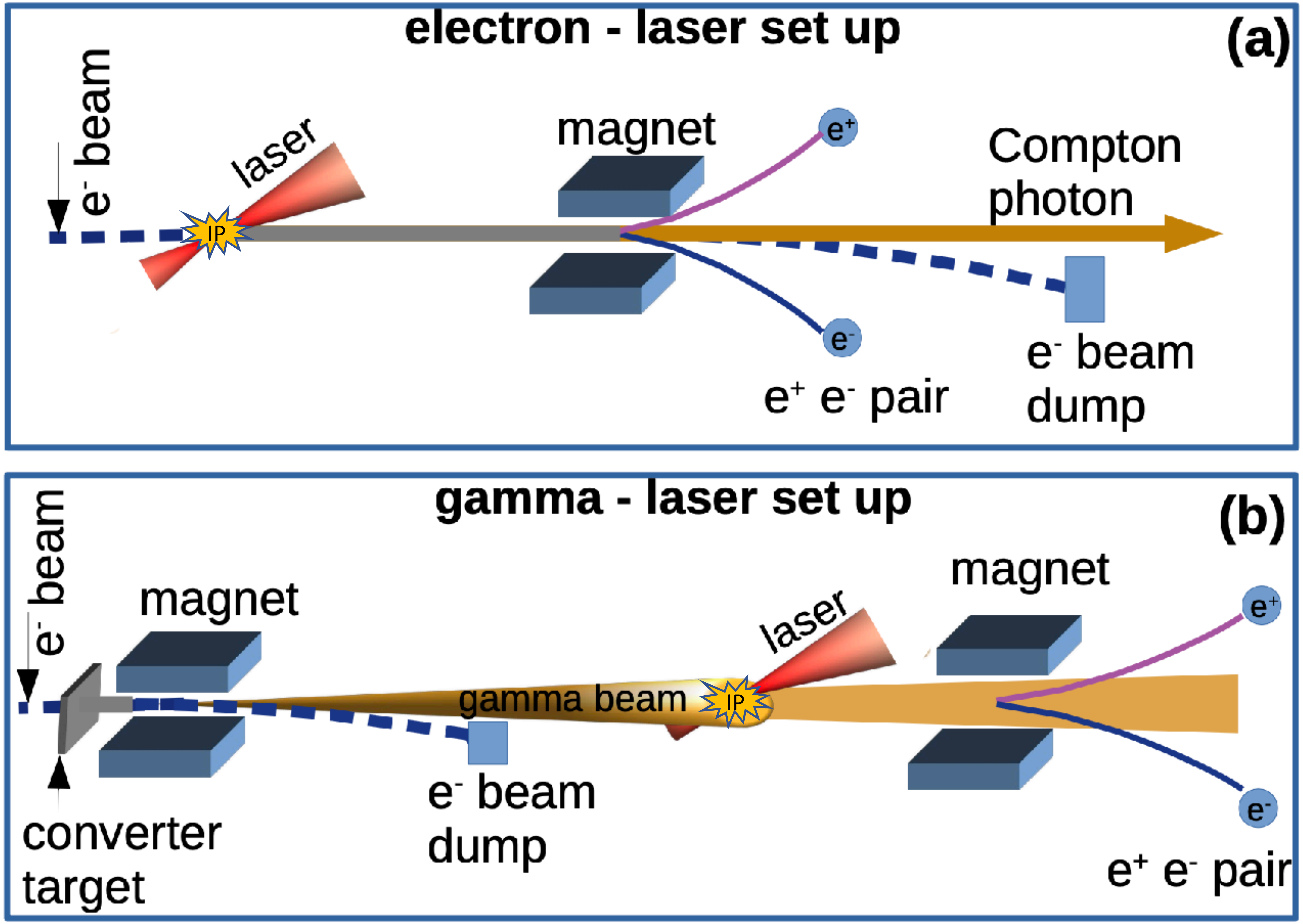


Figure 22. Schematic of the JETI system highlighting major assemblies. Current Installation of JETI-40 at the University of Jena. Front-end is shown in centre and power amplifiers right.

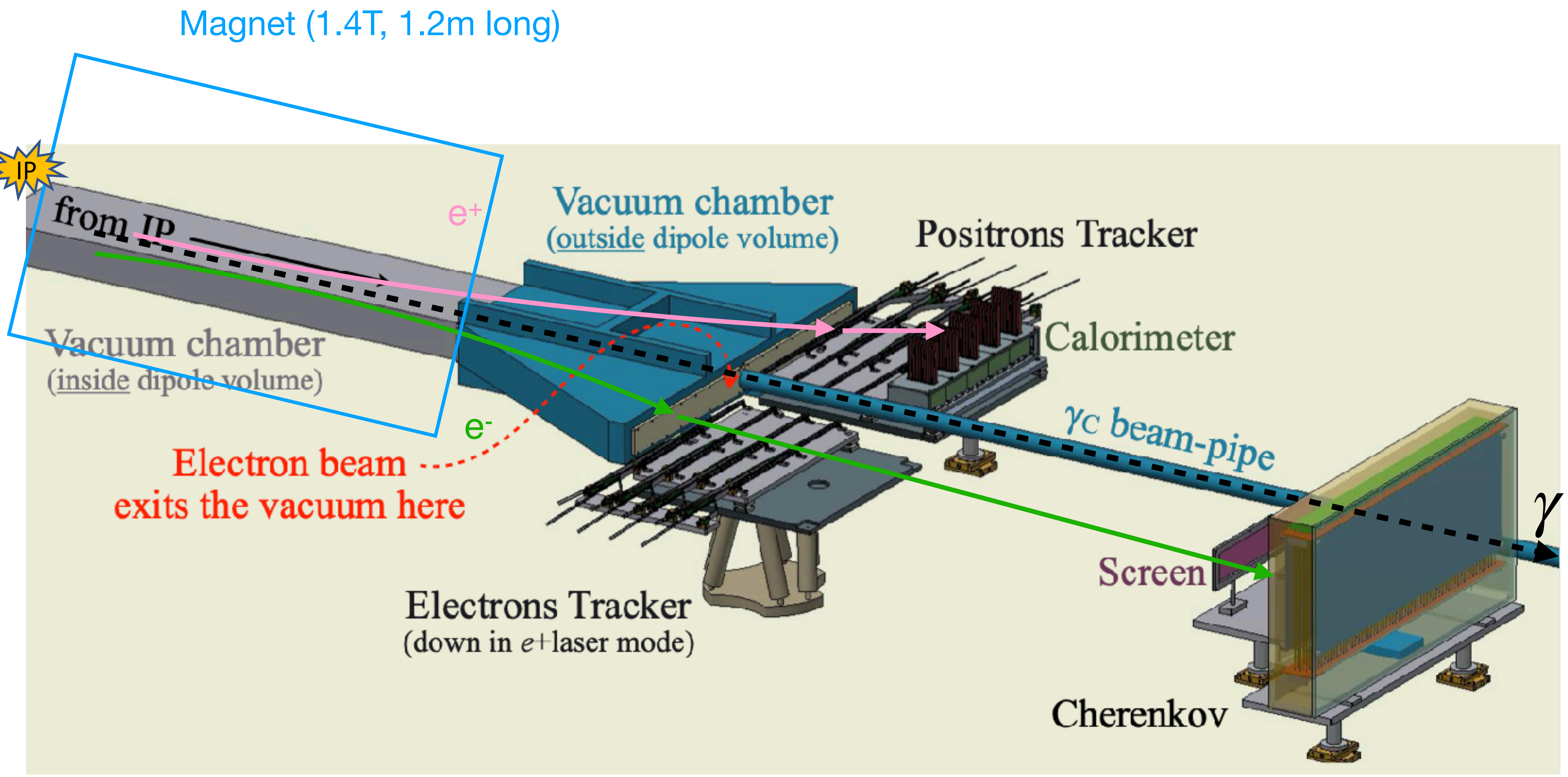
See talk from GianLuca Sarri yesterday

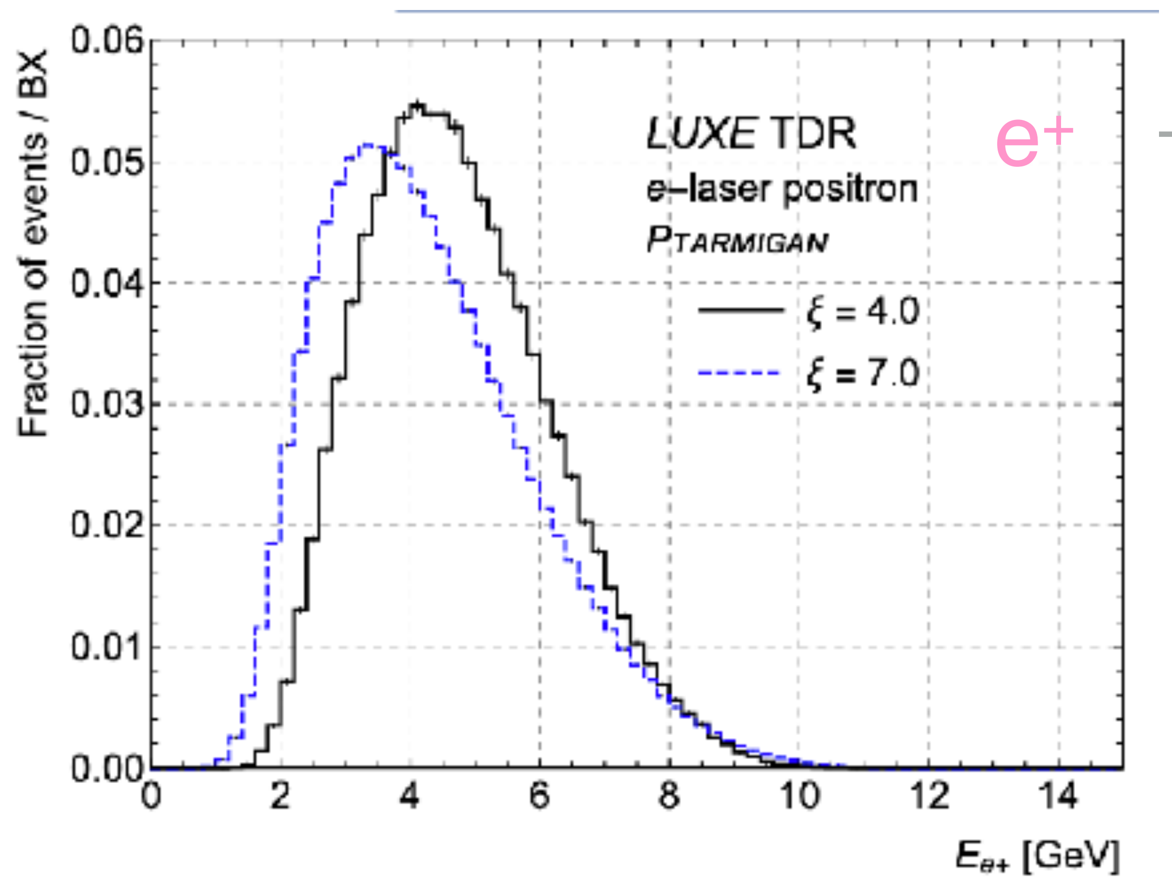
DATA TAKING MODES

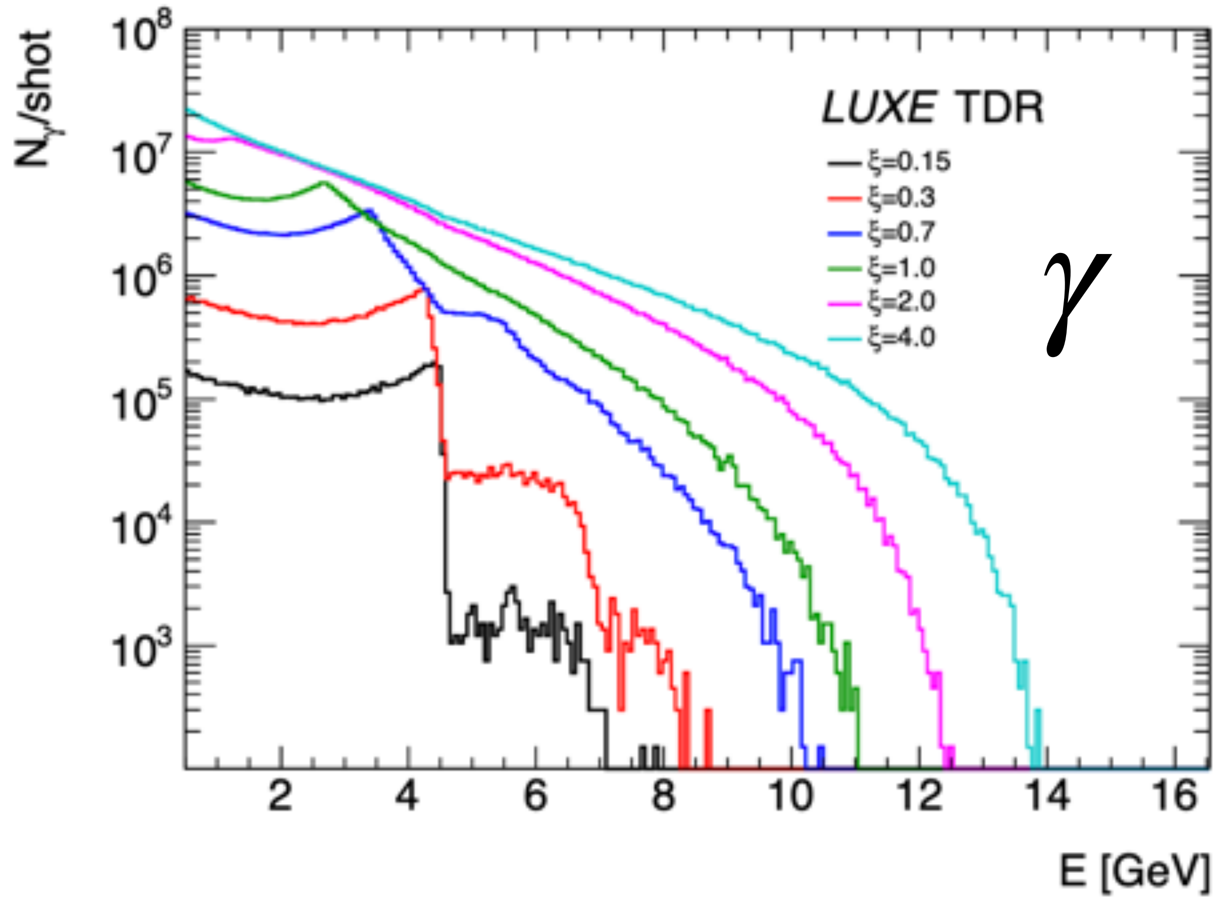


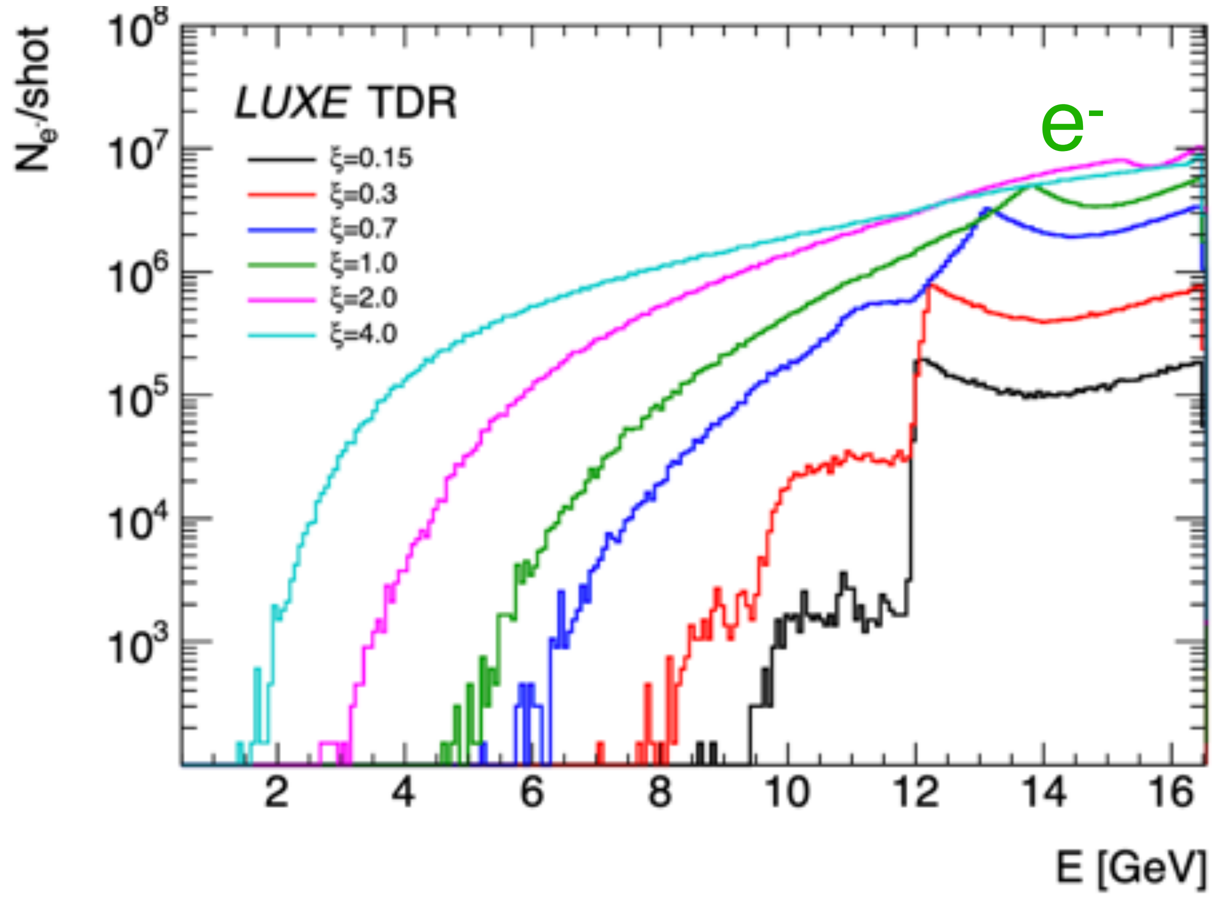
Mostly be talking about this mode!

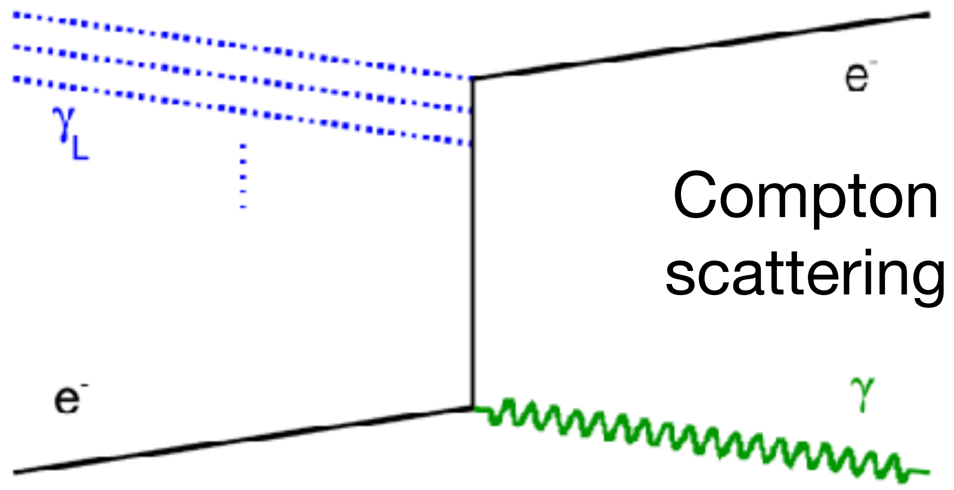
DETECTION SYSTEMS AFTER THE INTERACTION POINT



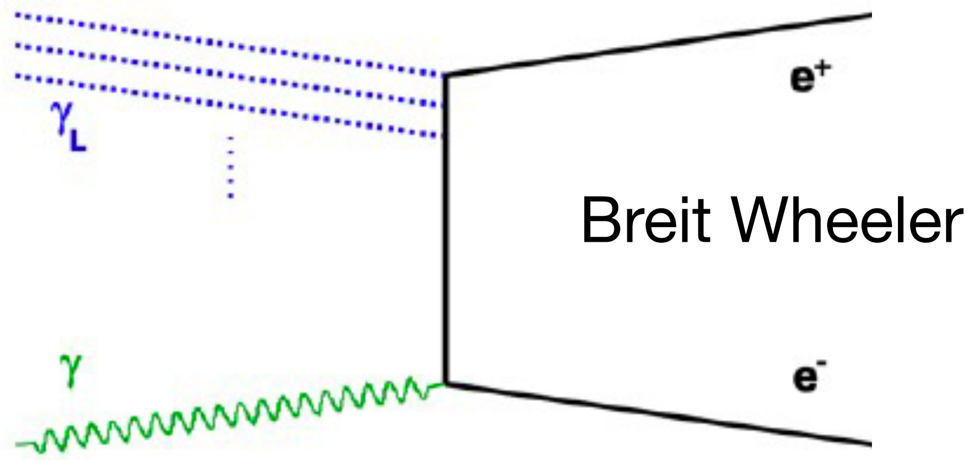






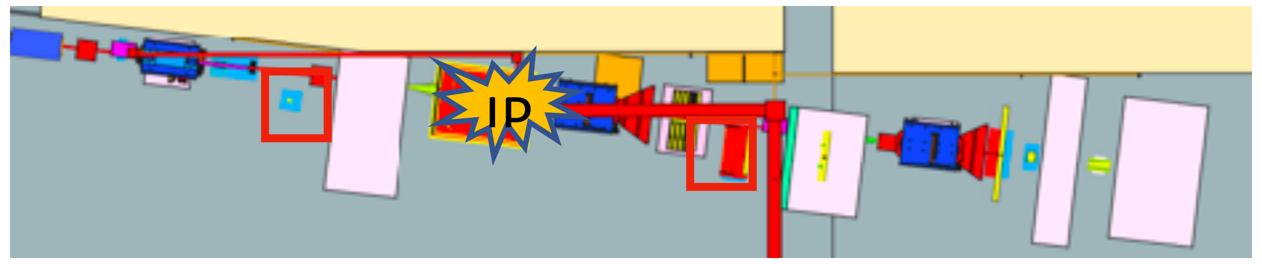


Compton scattering

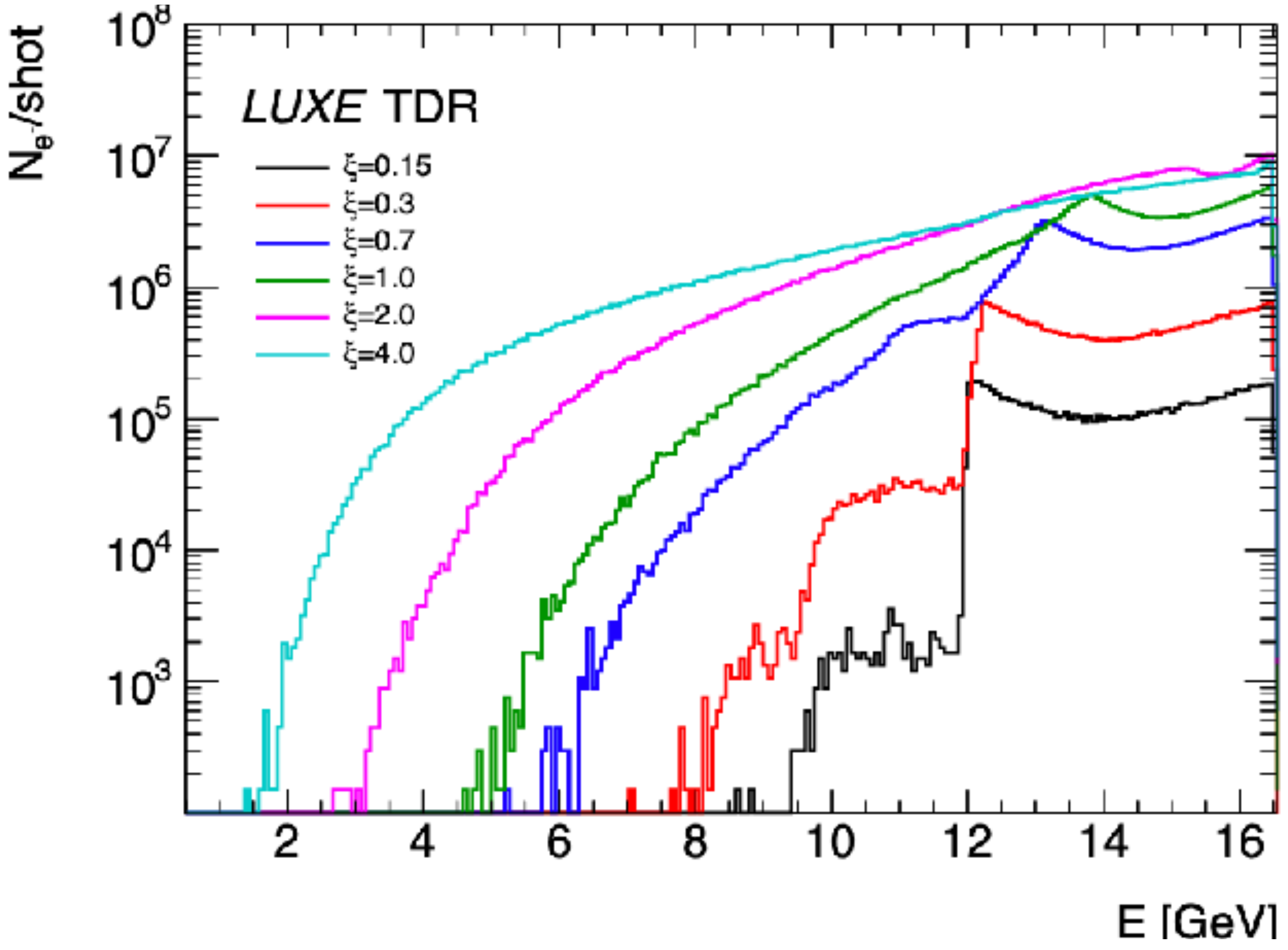


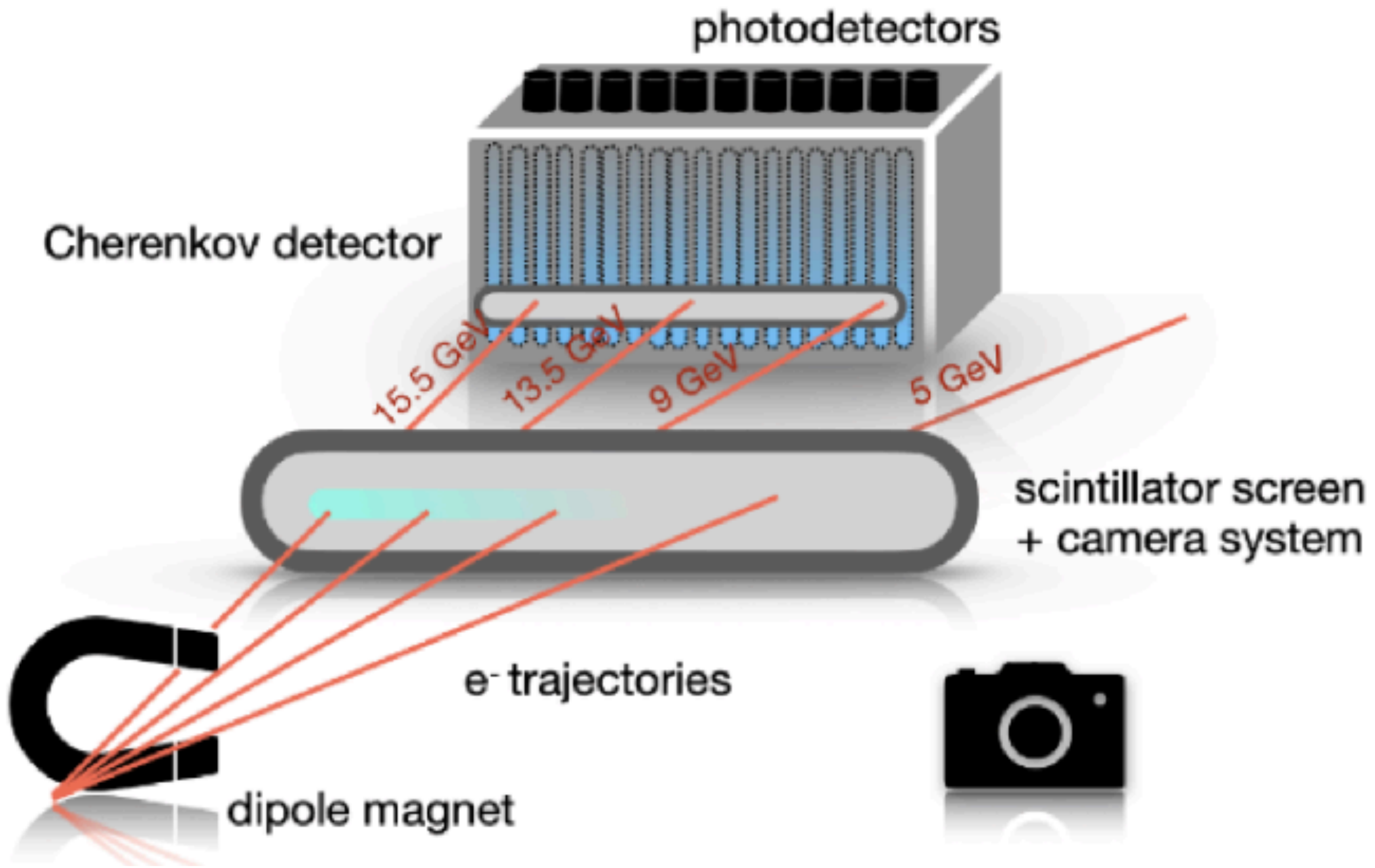
Breit Wheeler

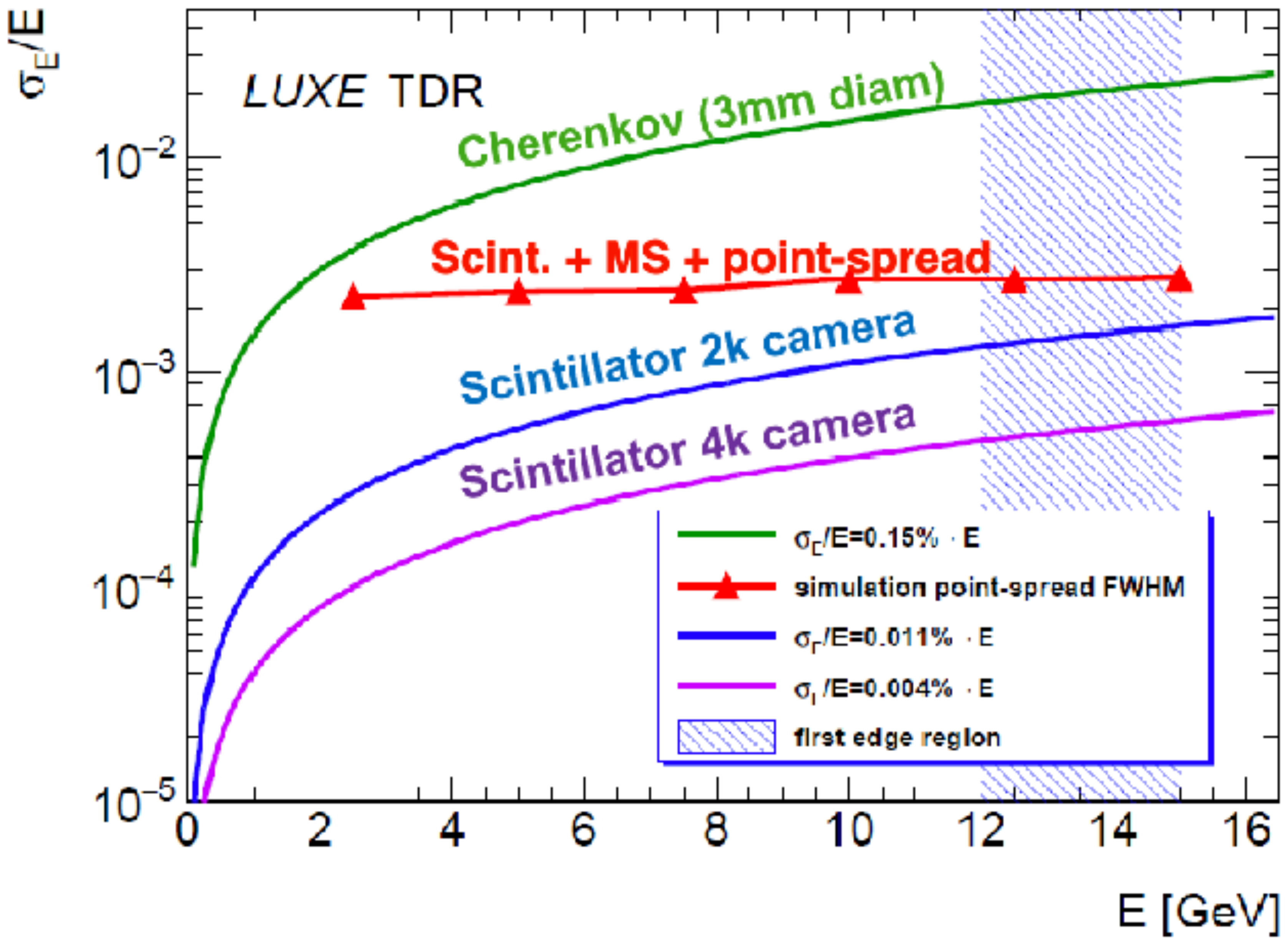
ELECTRON SIDE: HIGH FLUX PARTICLE DETECTORS: (E-LASER: IP DETECTOR ELECTRON SIDE | GAMMA-LASER: BREM TARGET)



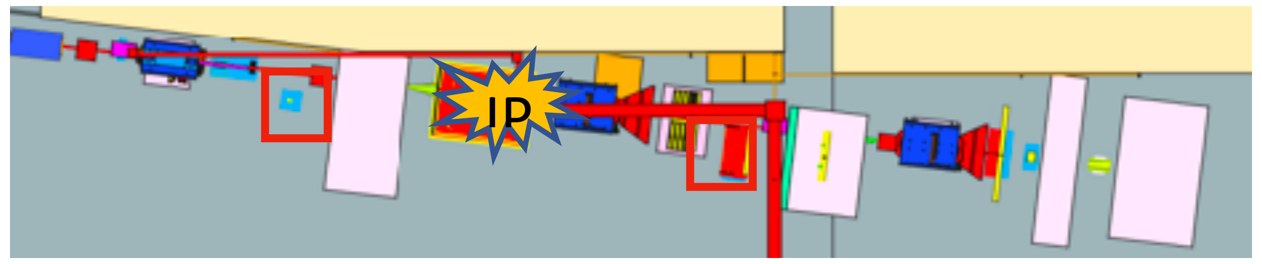
- Mesure particles on electron side of spectrometer.
  - Energy measurement come from position of hit after dipole spectrometer.
  - Use two different systems Cherenkov detector and Scintillating screens with camera.
  - Require good energy resolution: less than 2% in first edge region.
  - Good linearity: less than 1% uncertainty on electron rate.
  - Large dynamic range to cover ~10^3 to 10^8 particles.
  - Good background rejection







ELECTRON SIDE: HIGH FLUX PARTICLE DETECTORS: SCINTILLATING SCREEN (E-LASER: IP DETECTOR ELECTRON SIDE | GAMMA-LASER: BREM TARGET)



- Scintillating screen with camera.
  - Used for instance at AWAKE at CERN
  - 310 µm Tb-doped GaDOx (emitting 543 nm light, ~600 µs decay time).
  - Use two types of precision optical cameras (4k: 4096 x 2160 pixels, 2k: 1920 x 1200 pixels).

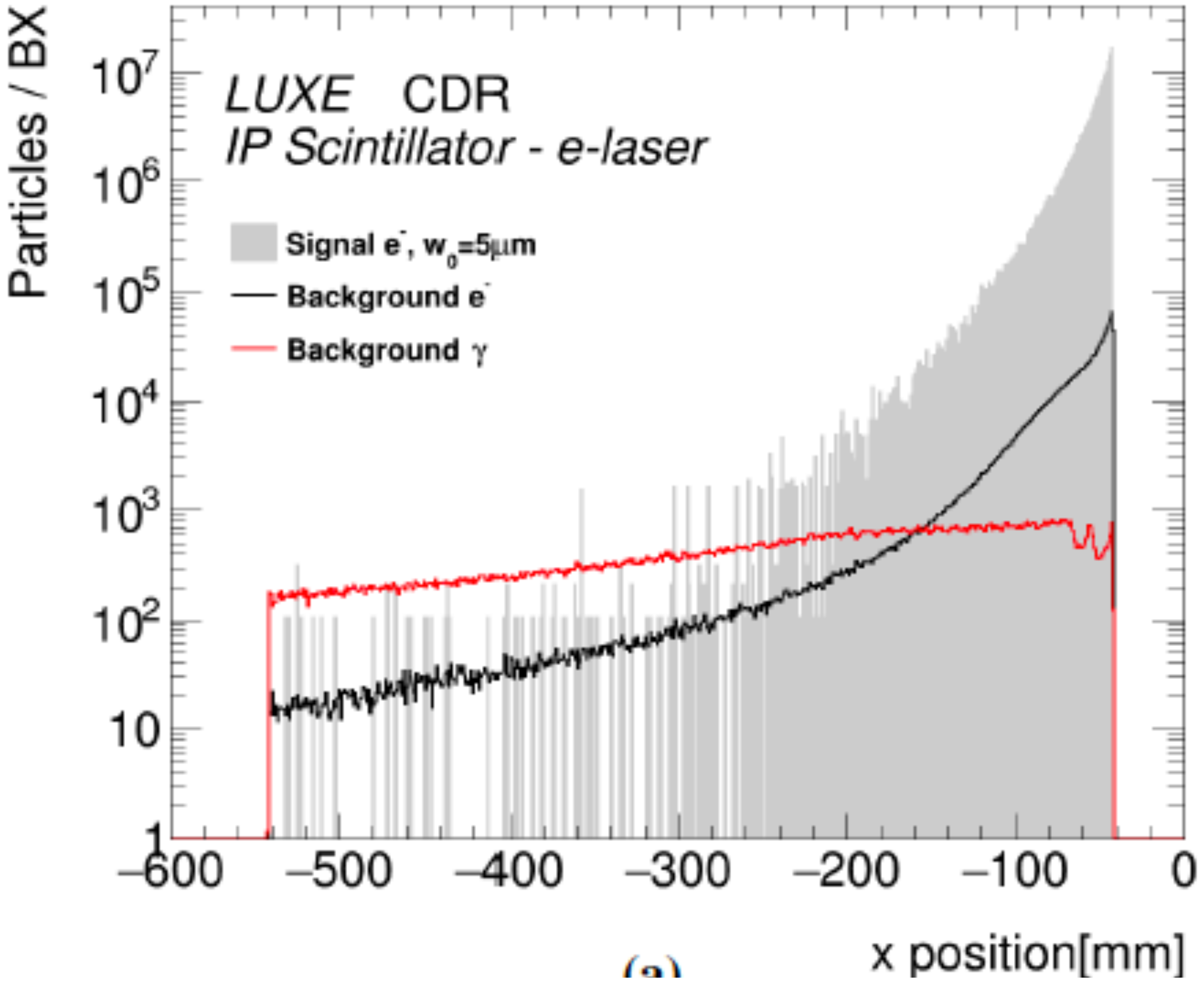
  - Require good energy resolution: less than 2% in first edge region:
    - Excellent position resolution (σ4k=50 µm, σ2k= 140 µm)
    - Finer resolution for high-energy electron range (smaller separation in dipole)

  - Good linearity: less than 1% uncertainty on electron rate.
    - Calibration light sources, and in-situ calibration
  - Large dynamic range to cover ~10^3 to 10^8 particles.

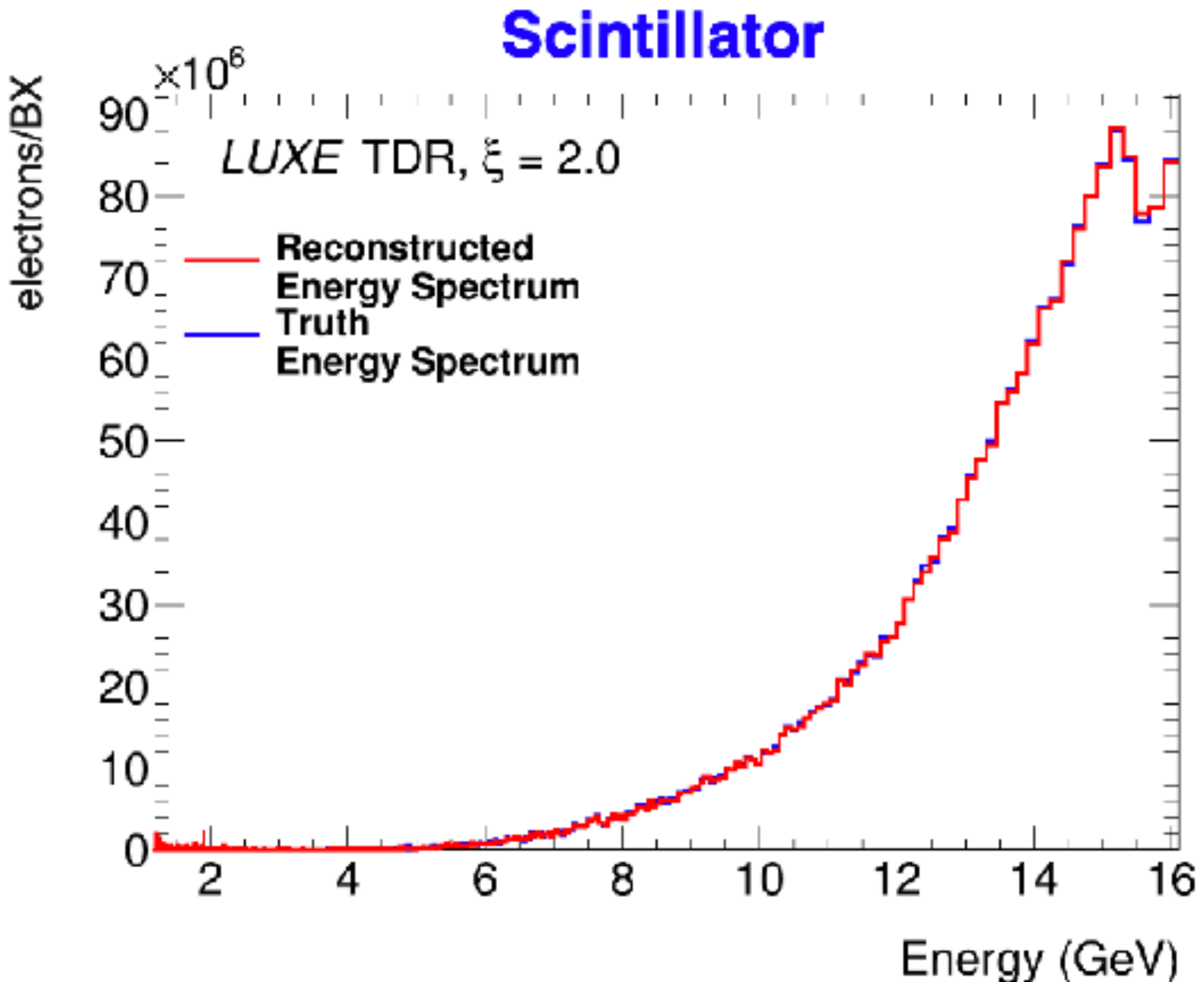
  - Good background rejection:
    - Signal/background ~100

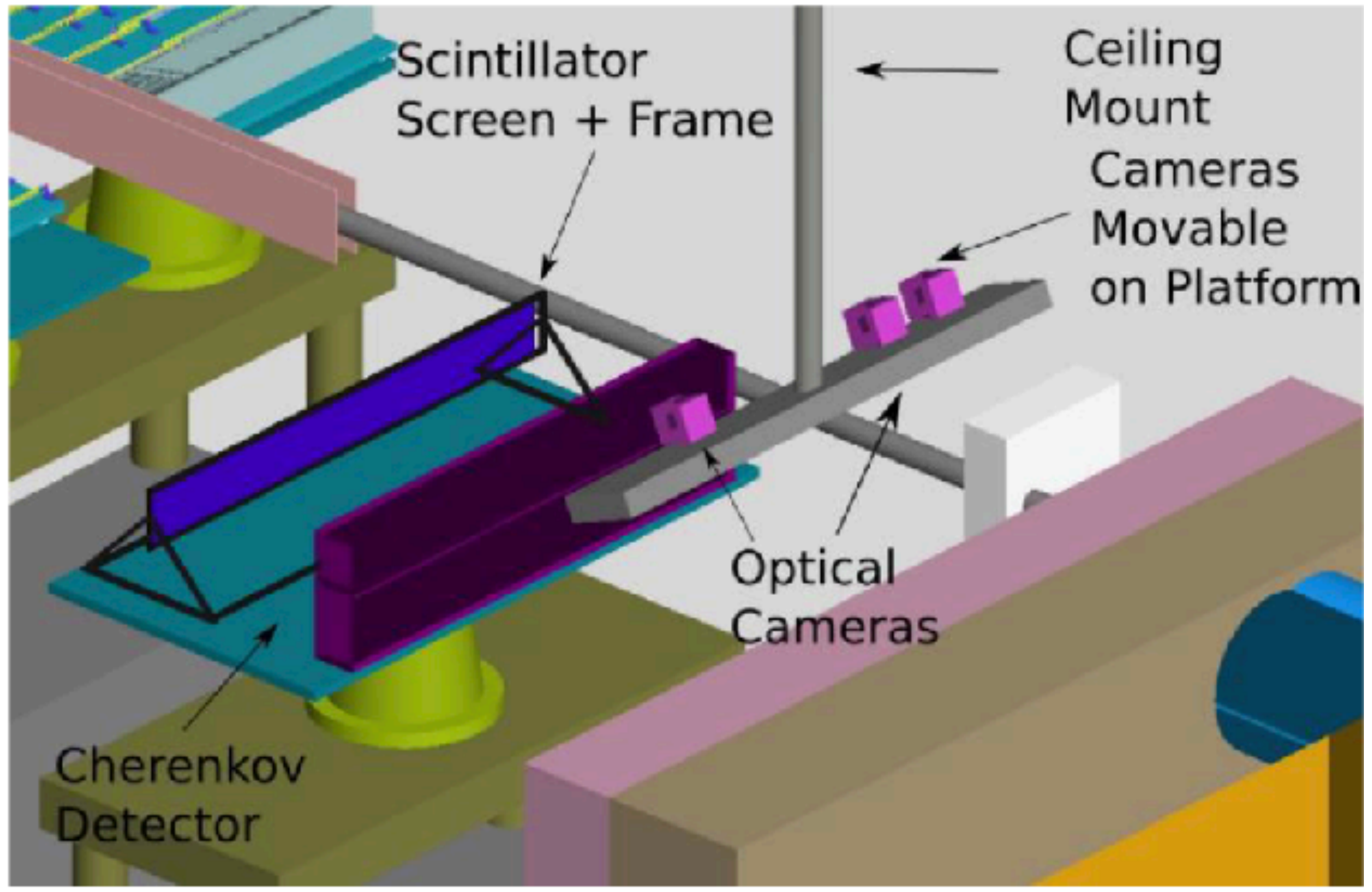
  - Cameras deported to ceiling on movable platform to reduce radiations exposure.

  - Energy reconstructed from luminosity of spot at given position on the screen.
    - Measure Compton Spectrum.

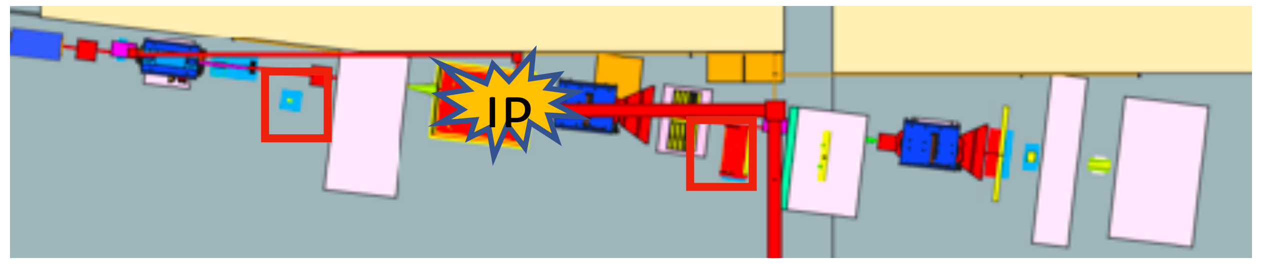


(a)

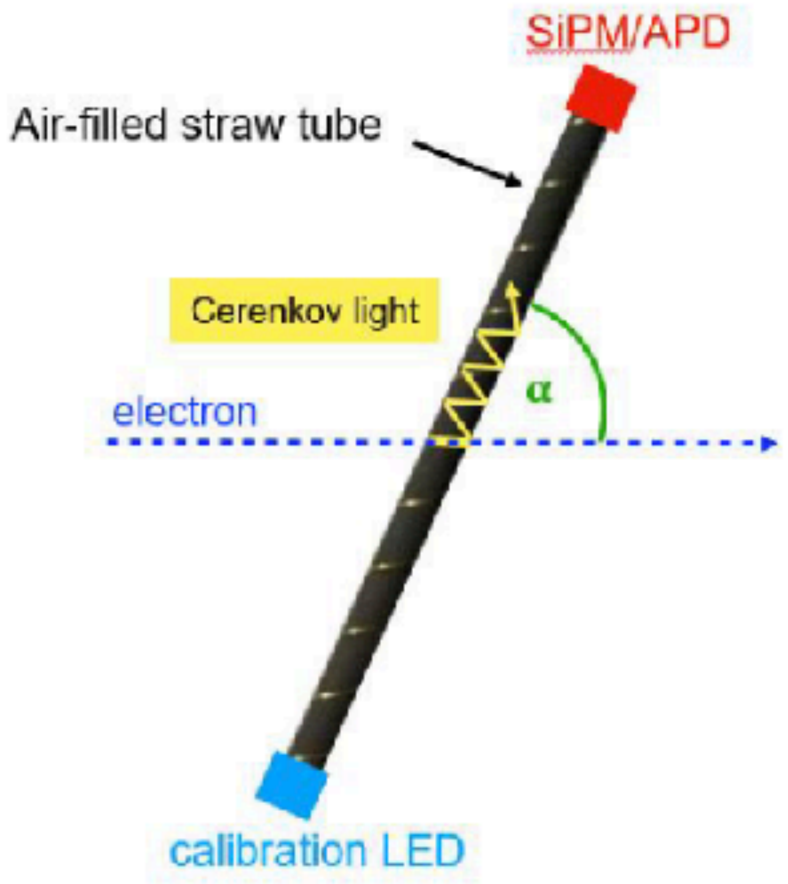


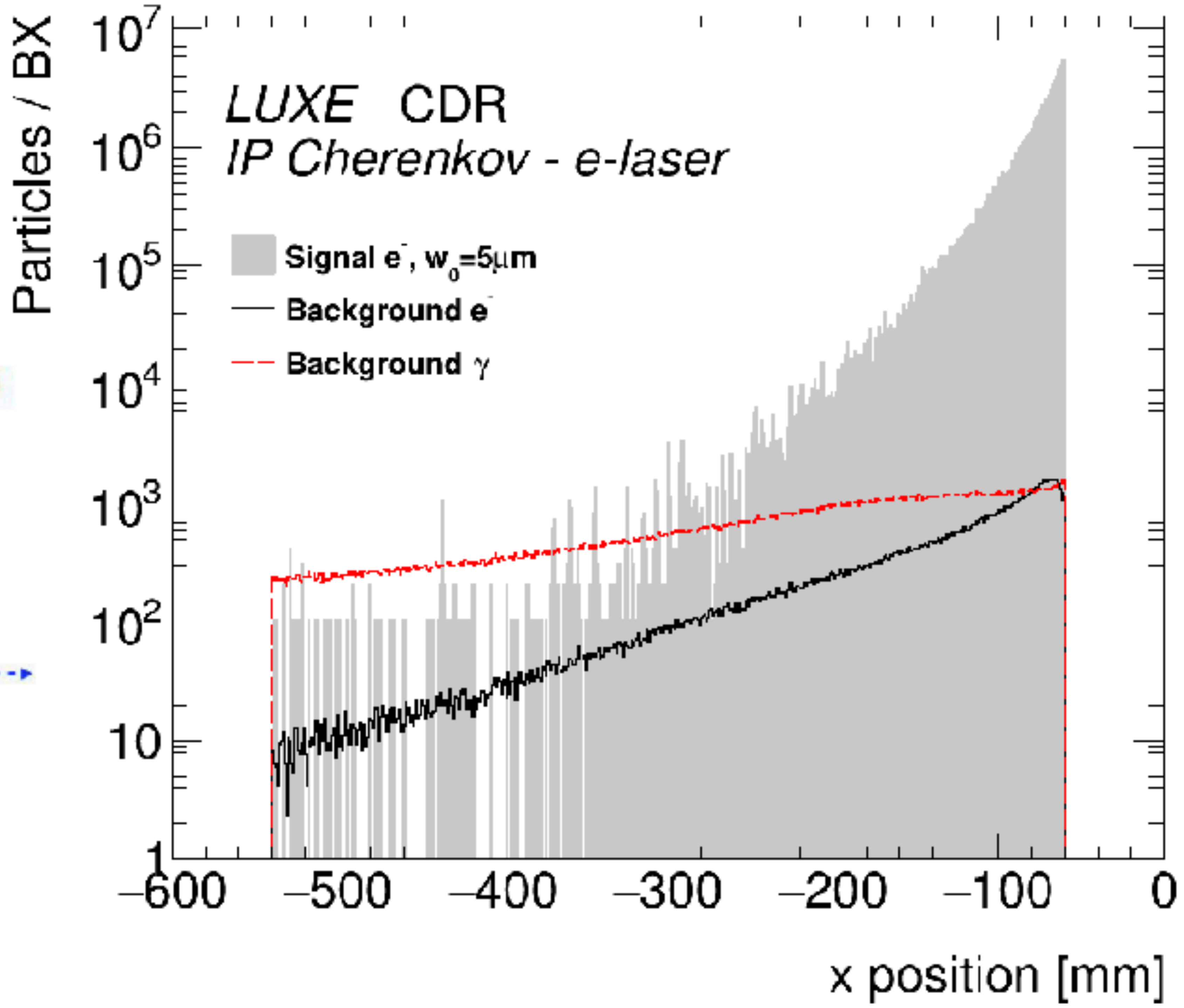


ELECTRON SIDE: HIGH FLUX PARTICLE DETECTORS: CHERENKOV (E-LASER: IP DETECTOR ELECTRON SIDE | GAMMA-LASER: BREM TARGET)

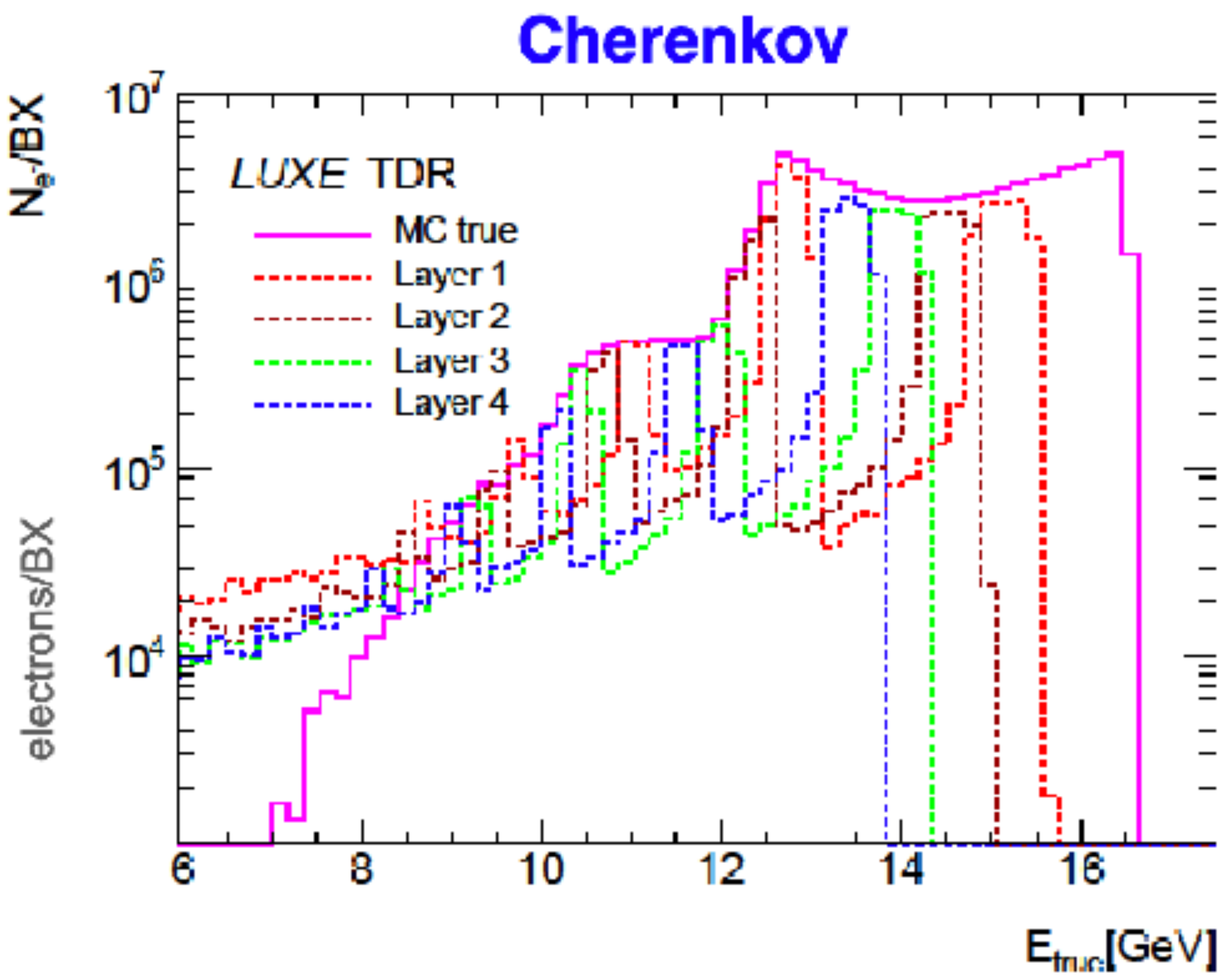


- Cherenkov detector:
  - Started development from ILC polarimetry prototype (See Jenny talk earlier).
    - Use metal straws (light guide) filled with air(low refractive index) to reduce light yield.
    - Spatially segmented detector: 2x 100 parallel straw channels

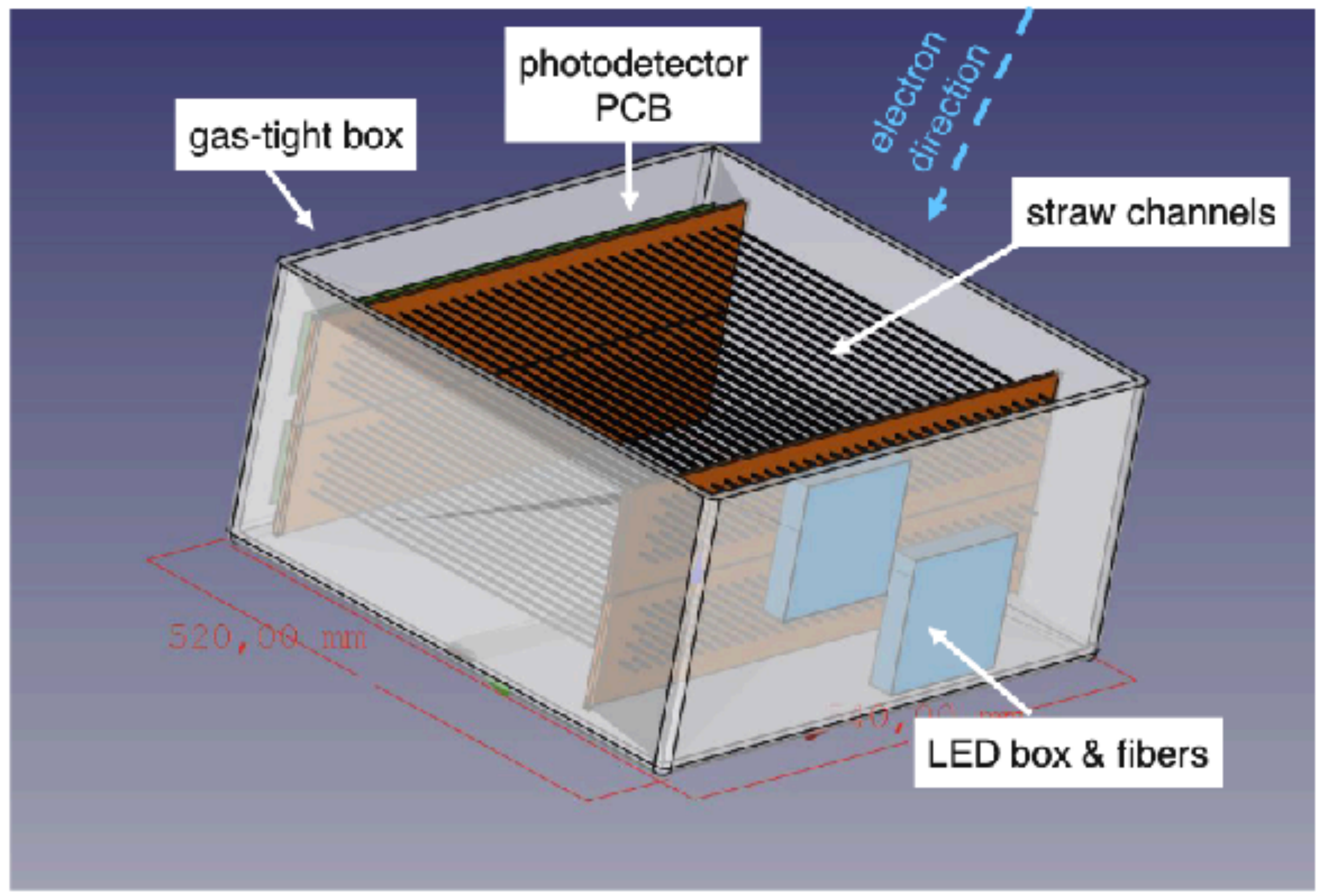




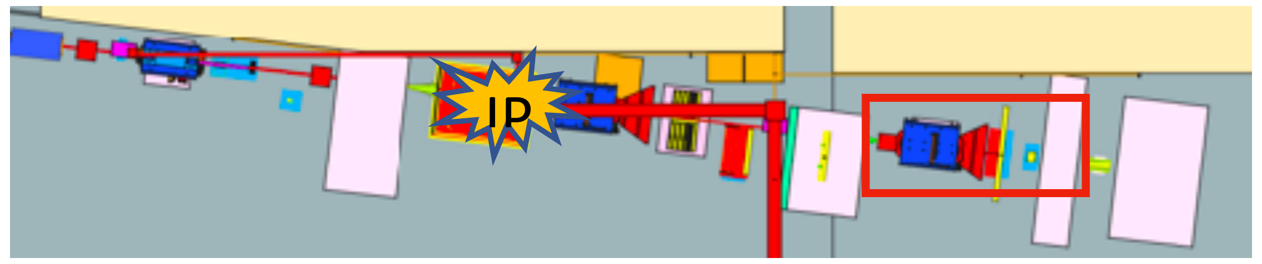
- Require good energy resolution: less than 2% in first edge region.
  - Fine segmentation ((Ø~3mm)) to resolve Compton edges.
- Good linearity: less than 1% uncertainty on electron rate.
  - Calibration light sources, and in-situ calibration.
- Large dynamic range to cover ~10^3 to 10^7 particles.
  - Plan to use dual readout system (SiPM and APD)
- Good background rejection
  - Signal/background>1000
  - Not sensitive to electron <20 MeV.
- Energy spectrum estimated from light yield in each tube and unfolded to account for overlapping geometry.
  - Measure Compton Spectrum.



Perspective view (rotated)



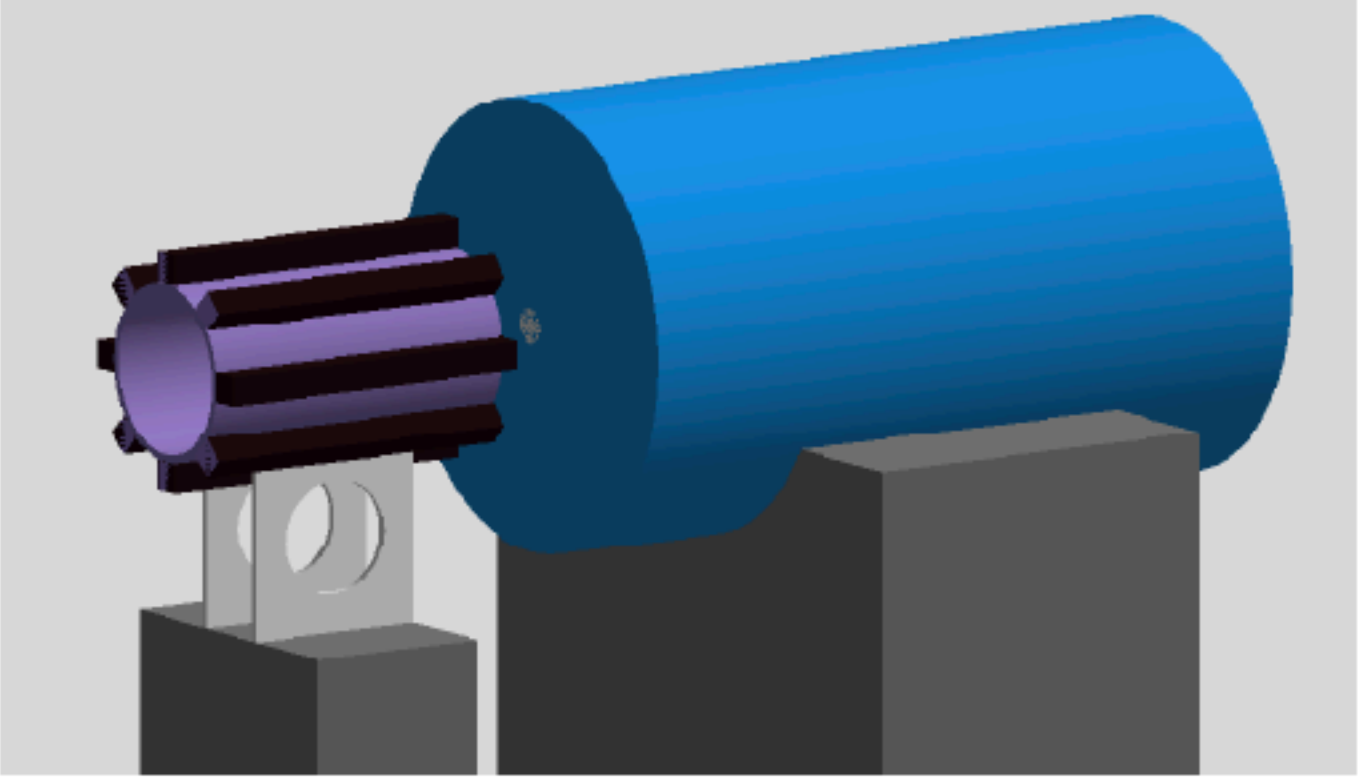
PHOTON DETECTION SYSTEM (END OF BEAMLINE IN BOTH MODES)



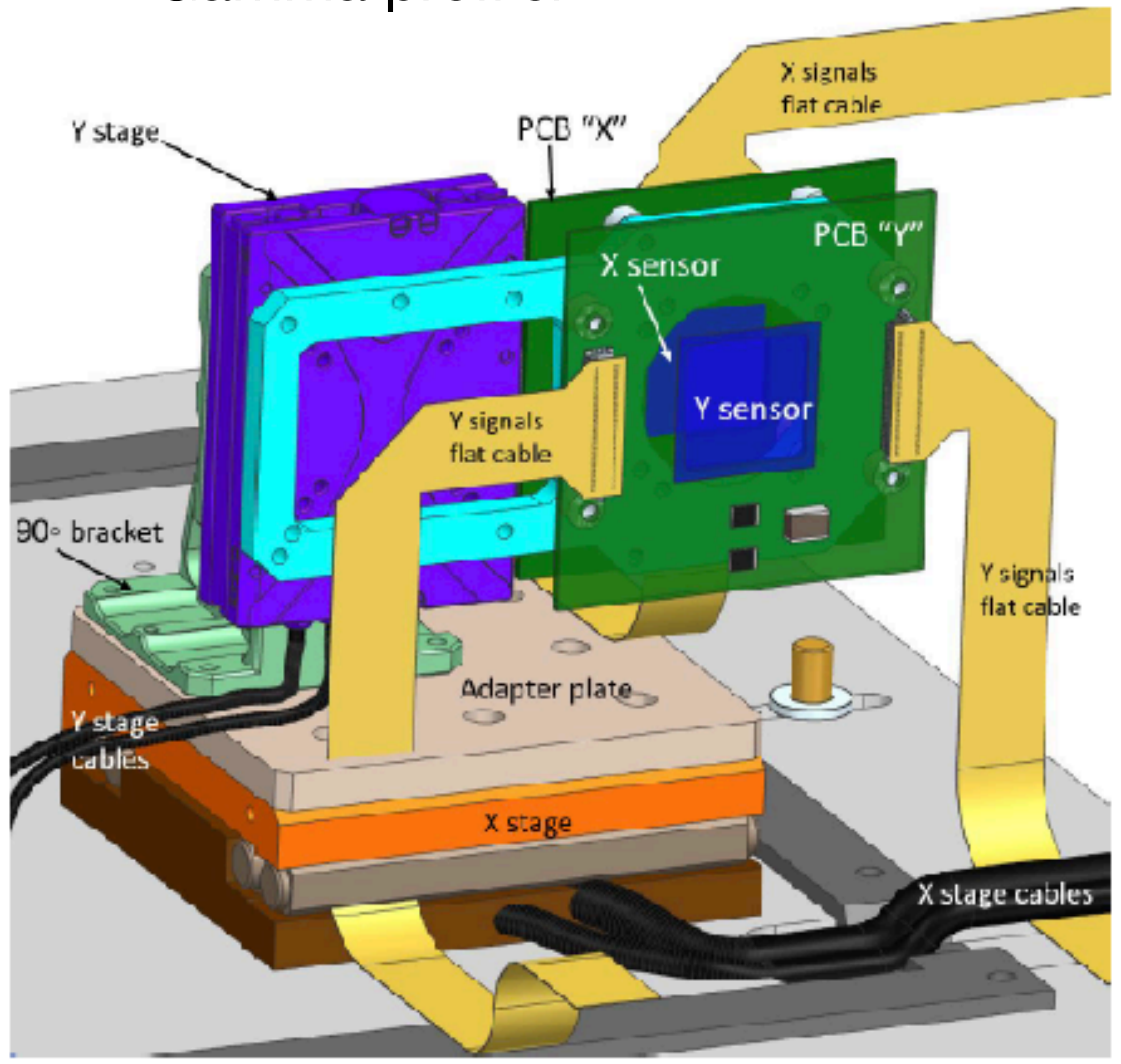
- Three detector technologies:
  - Backscattering calorimeter using lead glass blocks readout by PMTs placed before dump.
    - Measure integrated flux of photons produced in the experiment (~luminometer).
  - Gamma profiler (sapphire sensors)
    - Measure location of photon beam and profile.
      - If use polarized laser, expect angular spectrum of photons to depend on ξ.
  - Gamma spectrometer (see next slide).

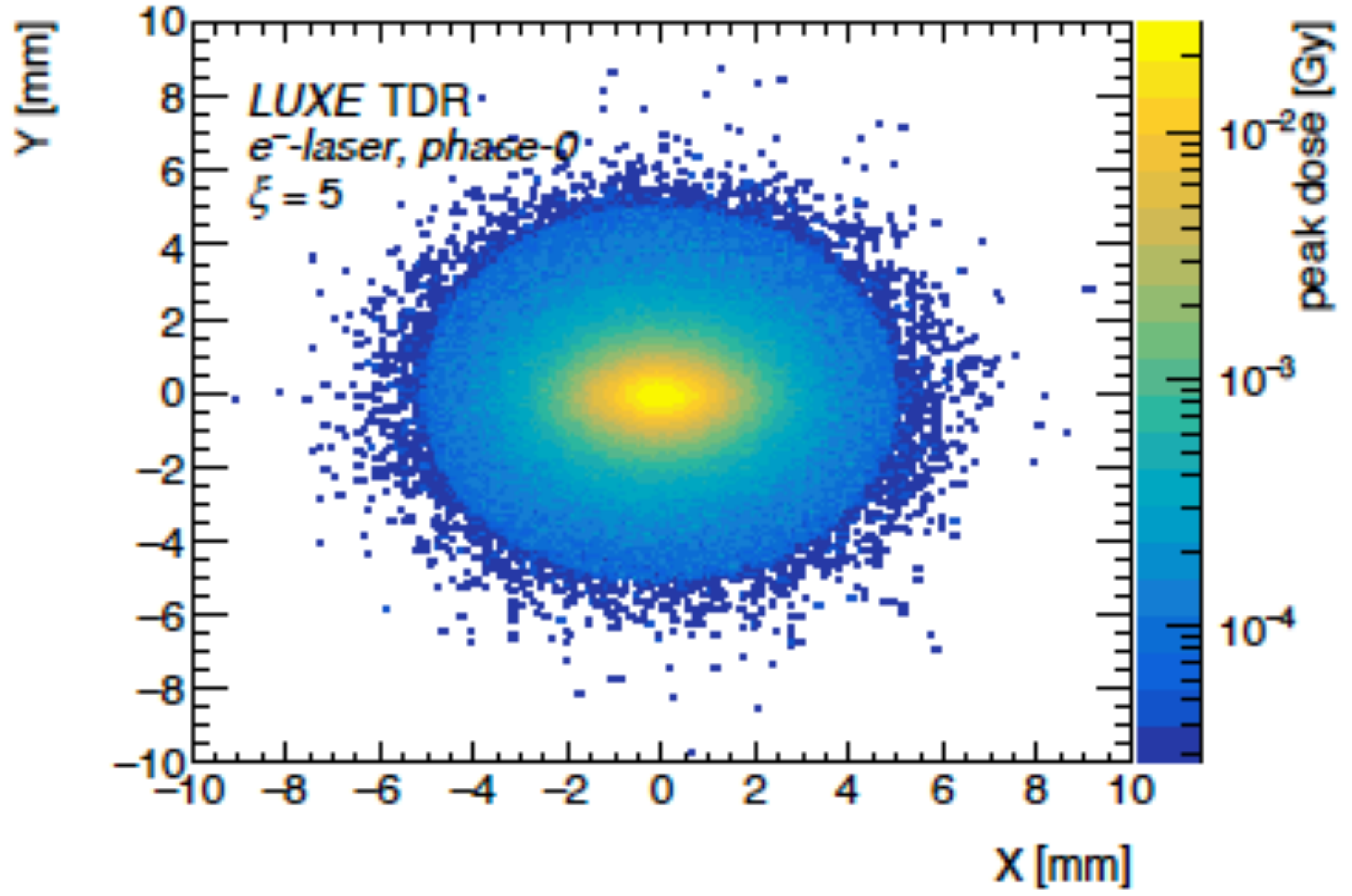
Final γ dump

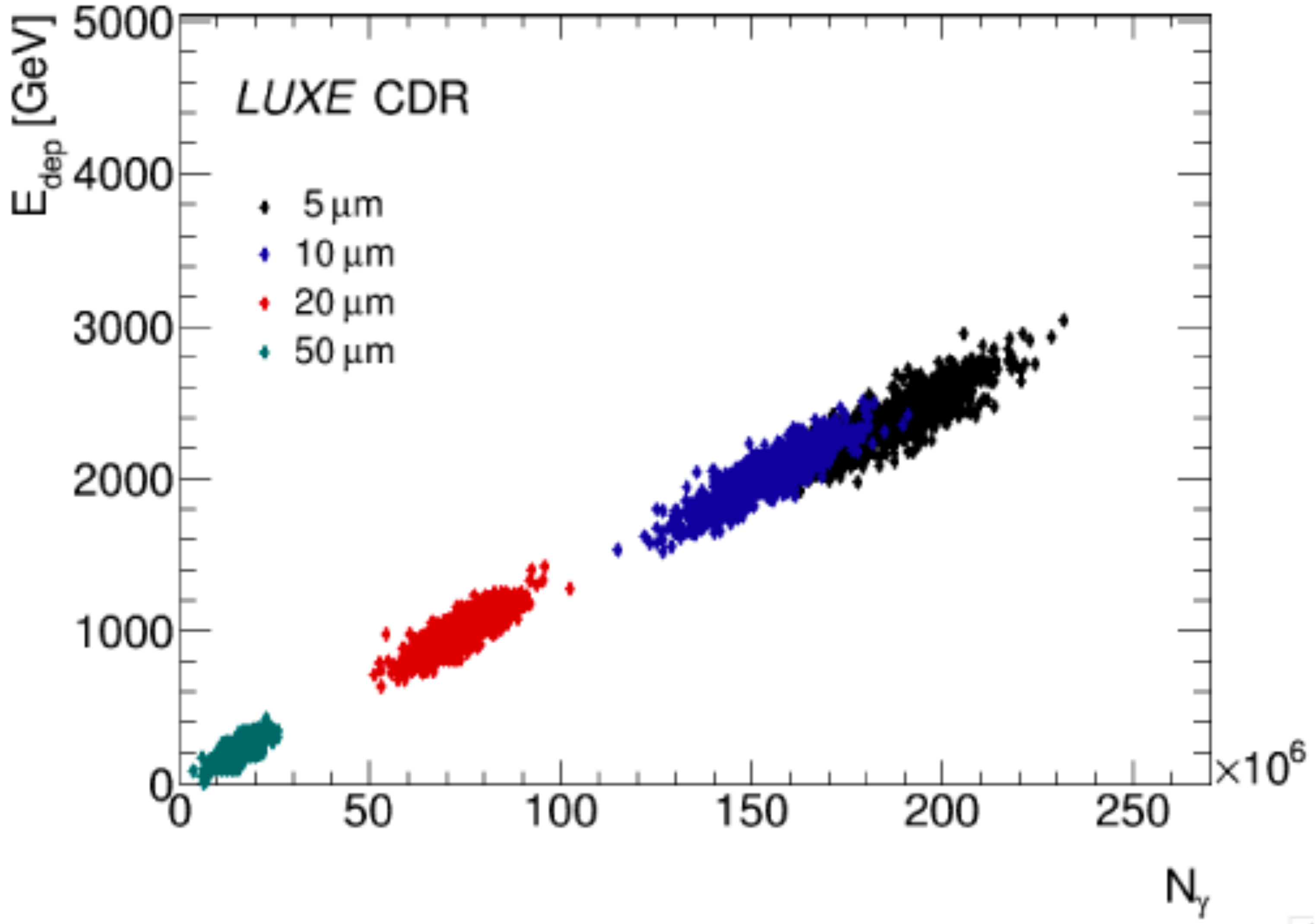
Calorimeter



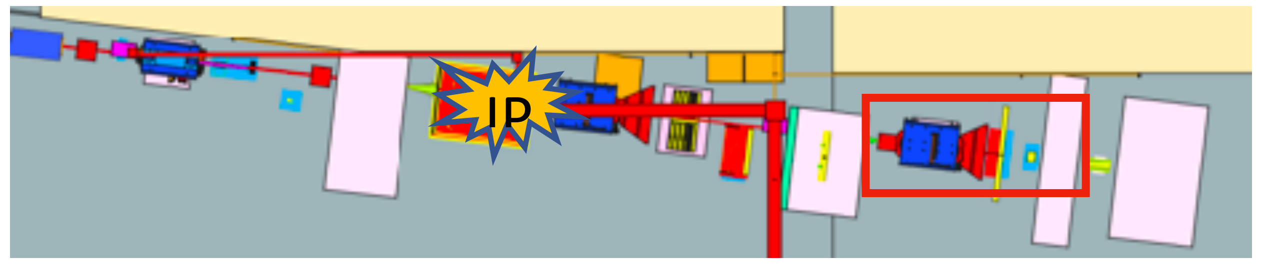
Gamma profiler



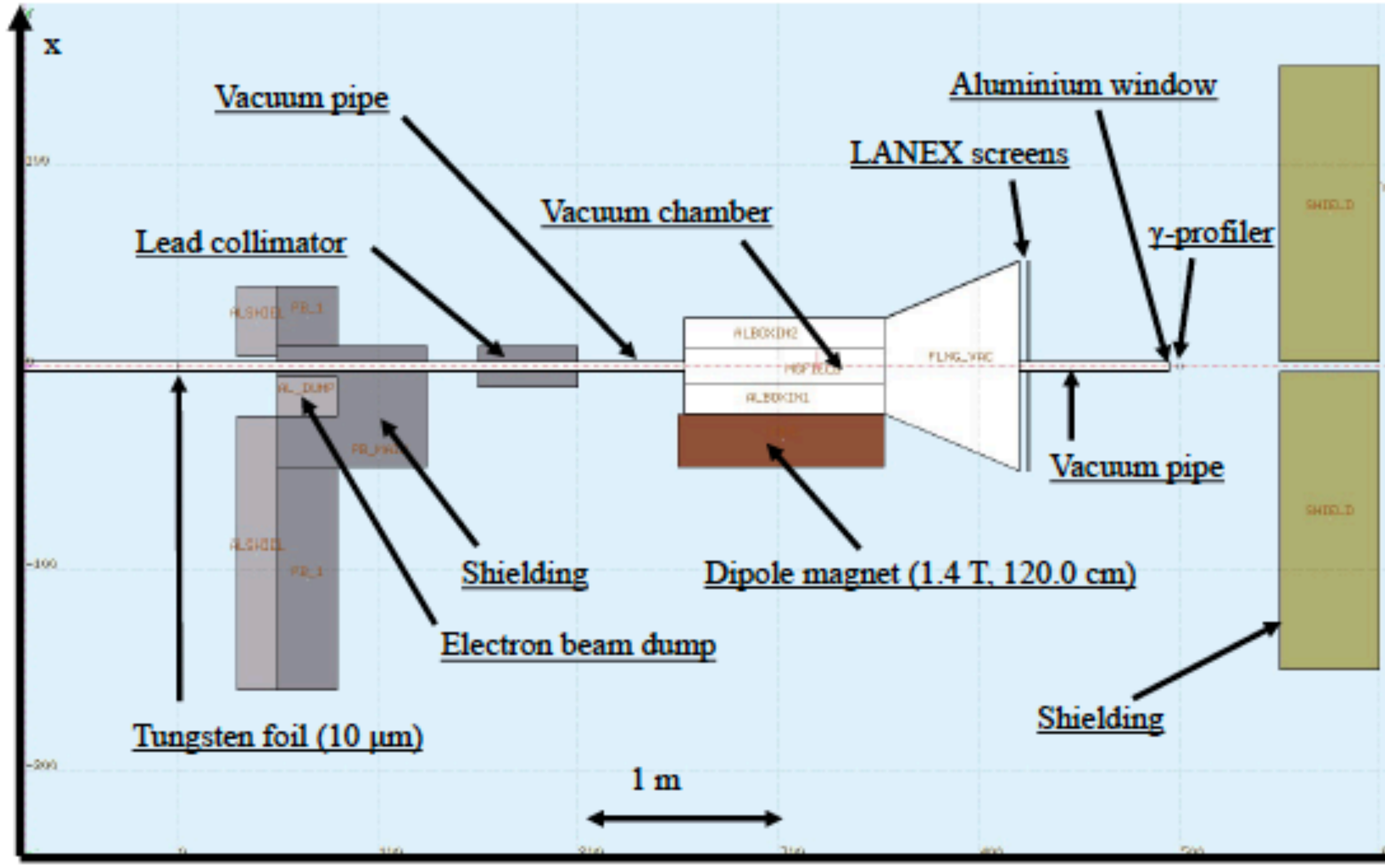




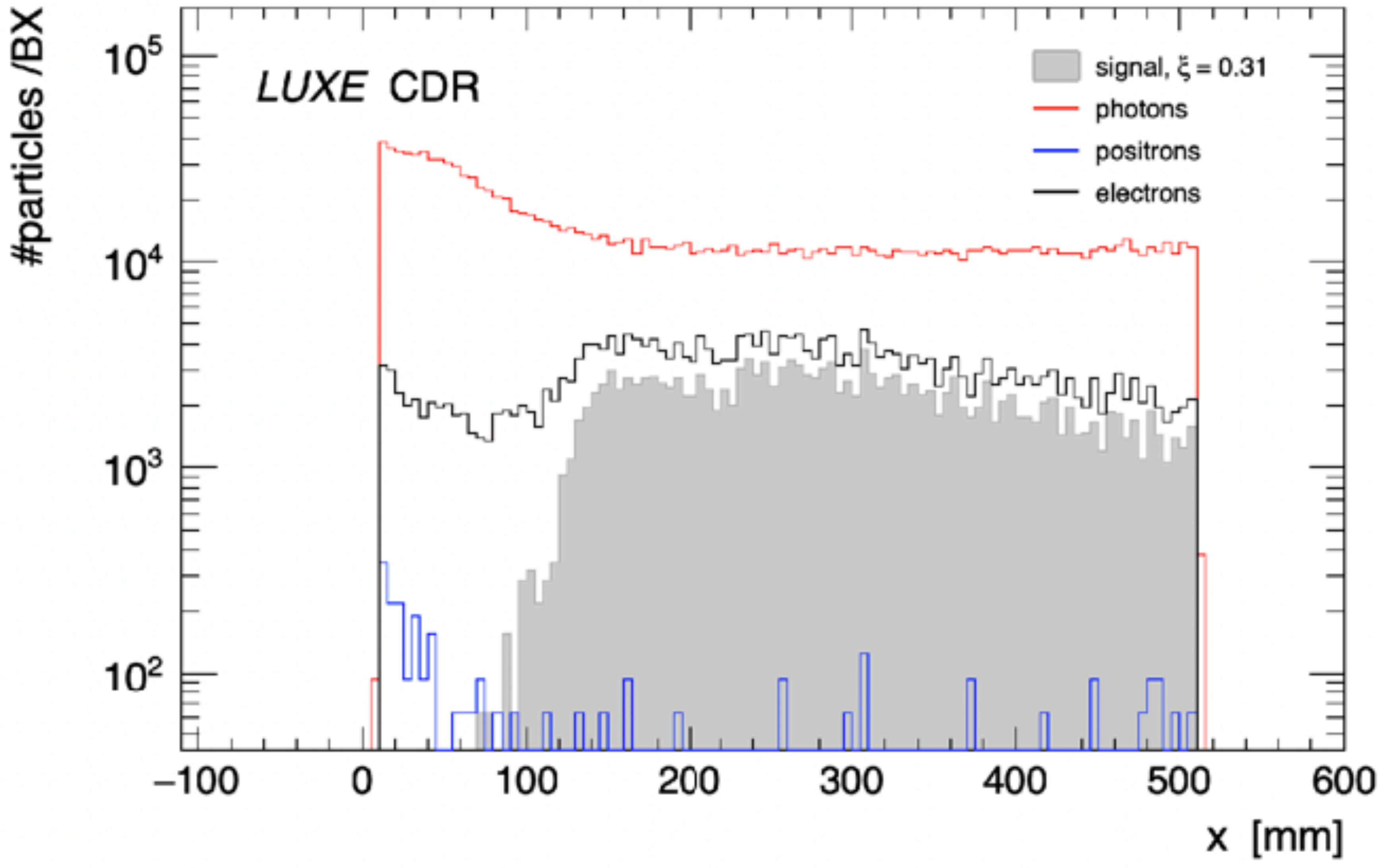
PHOTON DETECTION SYSTEM - GAMMA SPECTROMETER (END OF BEAMLINE IN BOTH MODES)



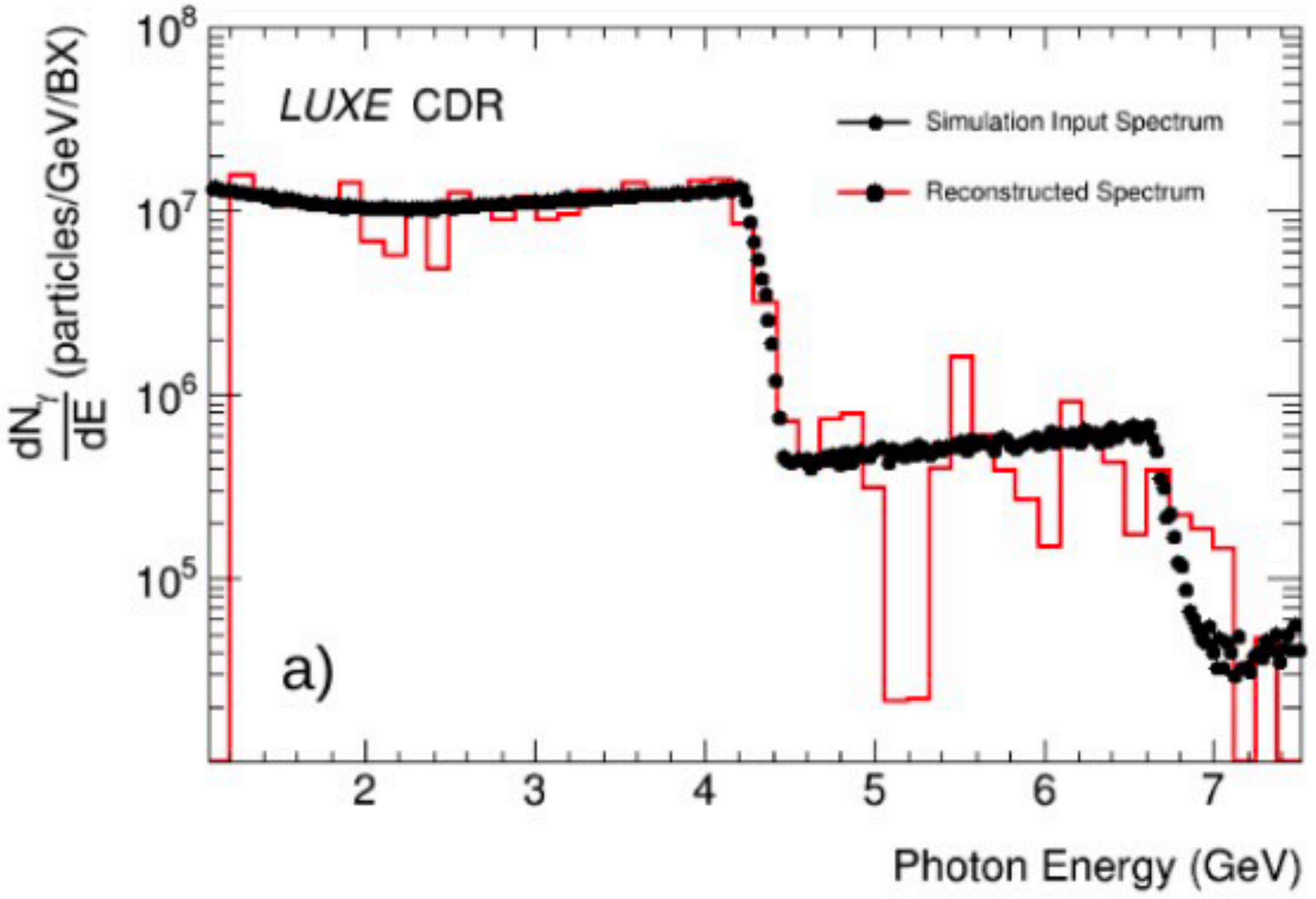
- Gamma spectrometer:
  - Measure the spectrum and yield of electron-positron pairs generated from the gamma-ray beam through a converter target.
  - Electrons positrons energy measured using LANEX screens located after dipole spectrometer magnet, and readout by amplified CCD camera.
  - Deconvolution of the particle spectra using Bethe-Heitler cross-section to obtain photon energy spectrum!
    - Alternative method to measure Compton Spectrum.



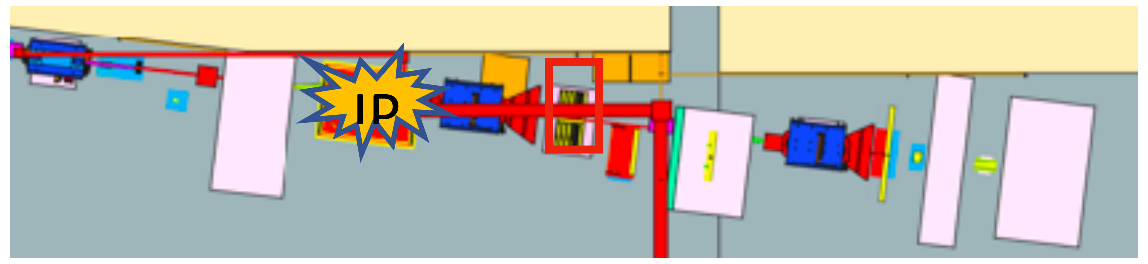
Electron side of gamma spectrometer



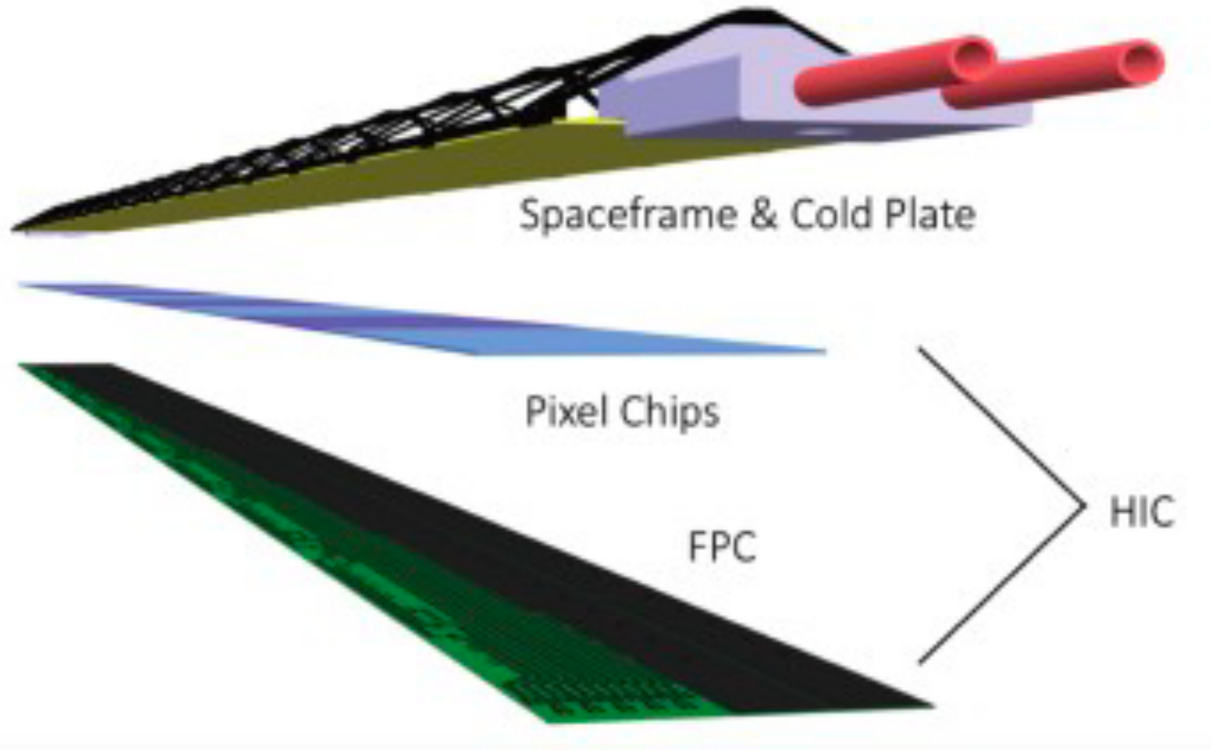
Deconvoluted gamma energy spectrum

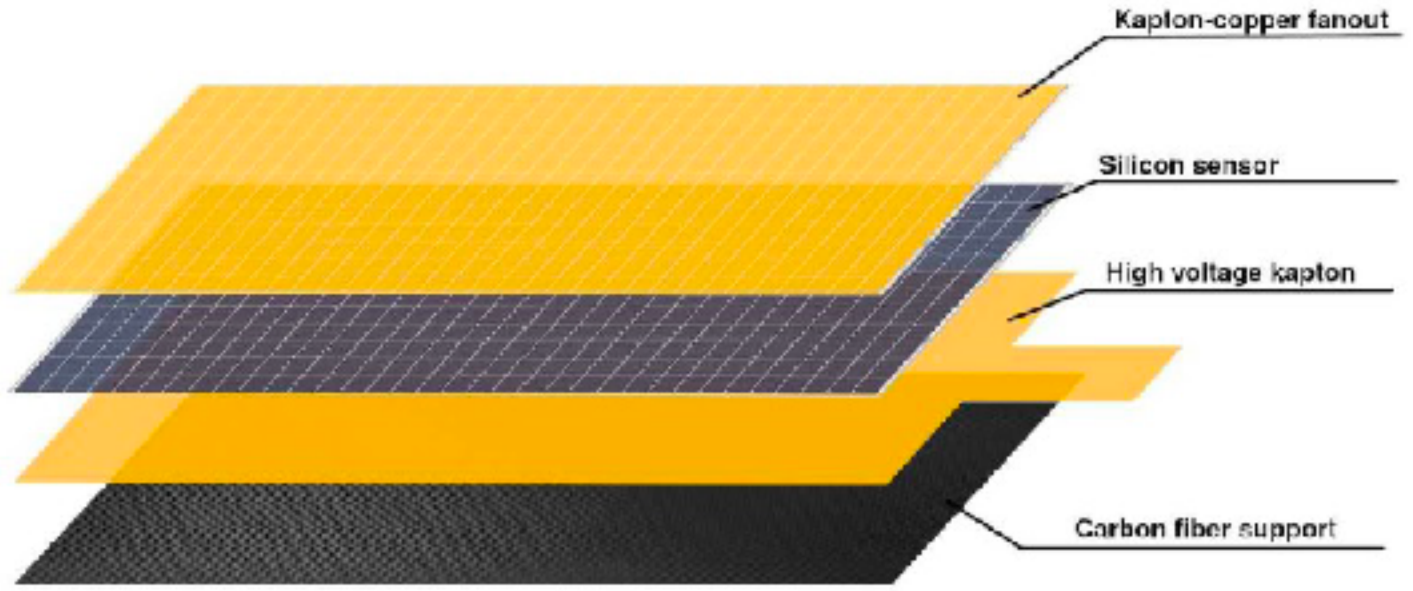


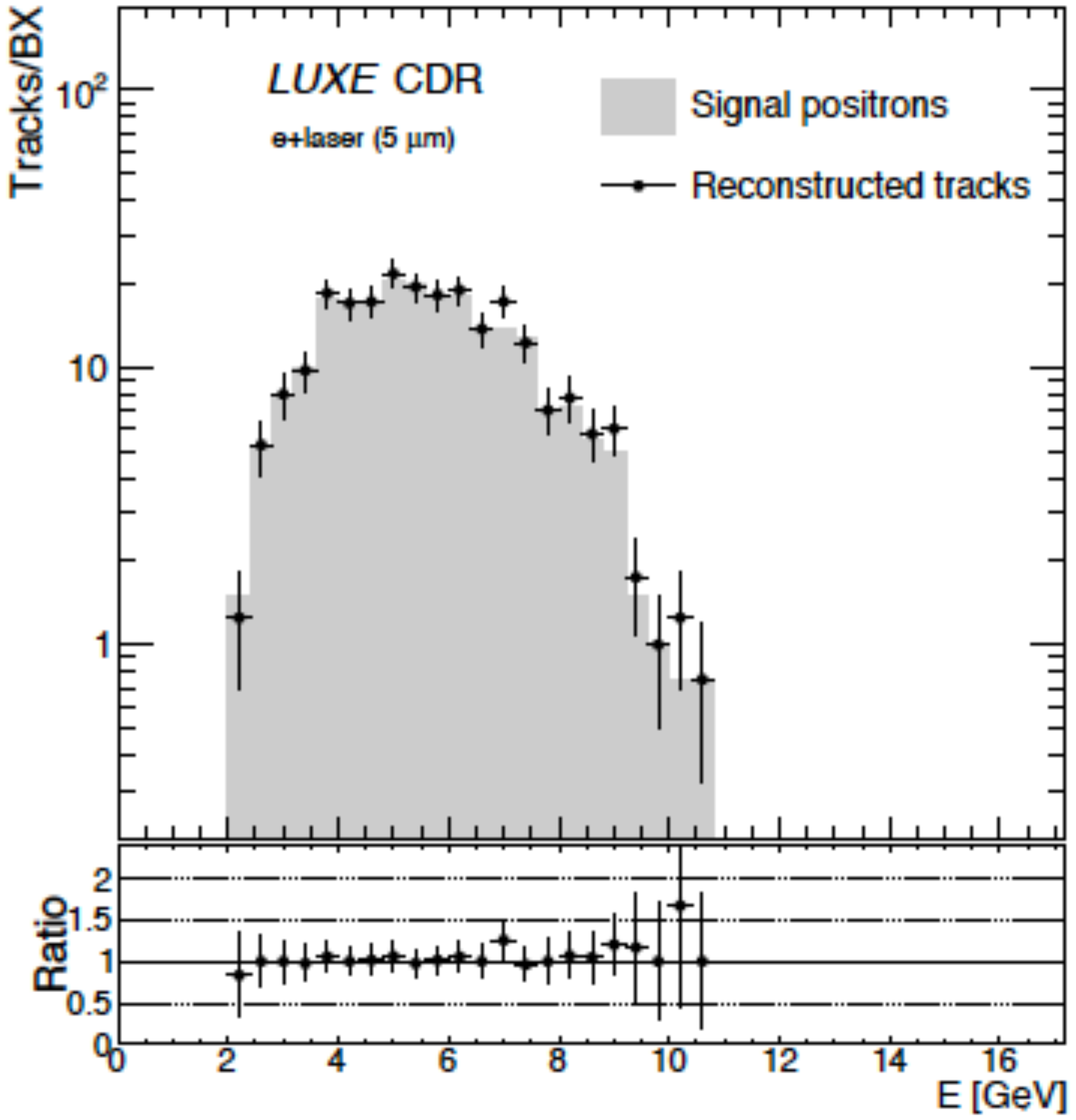
POSITRON SIDE: LOW FLUX DETECTOR: TRACKER AND CALORIMETERS (E-LASER: IP DETECTOR POSITRON SIDE | GAMMA-LASER: IP DETECTOR BOTH SIDES)



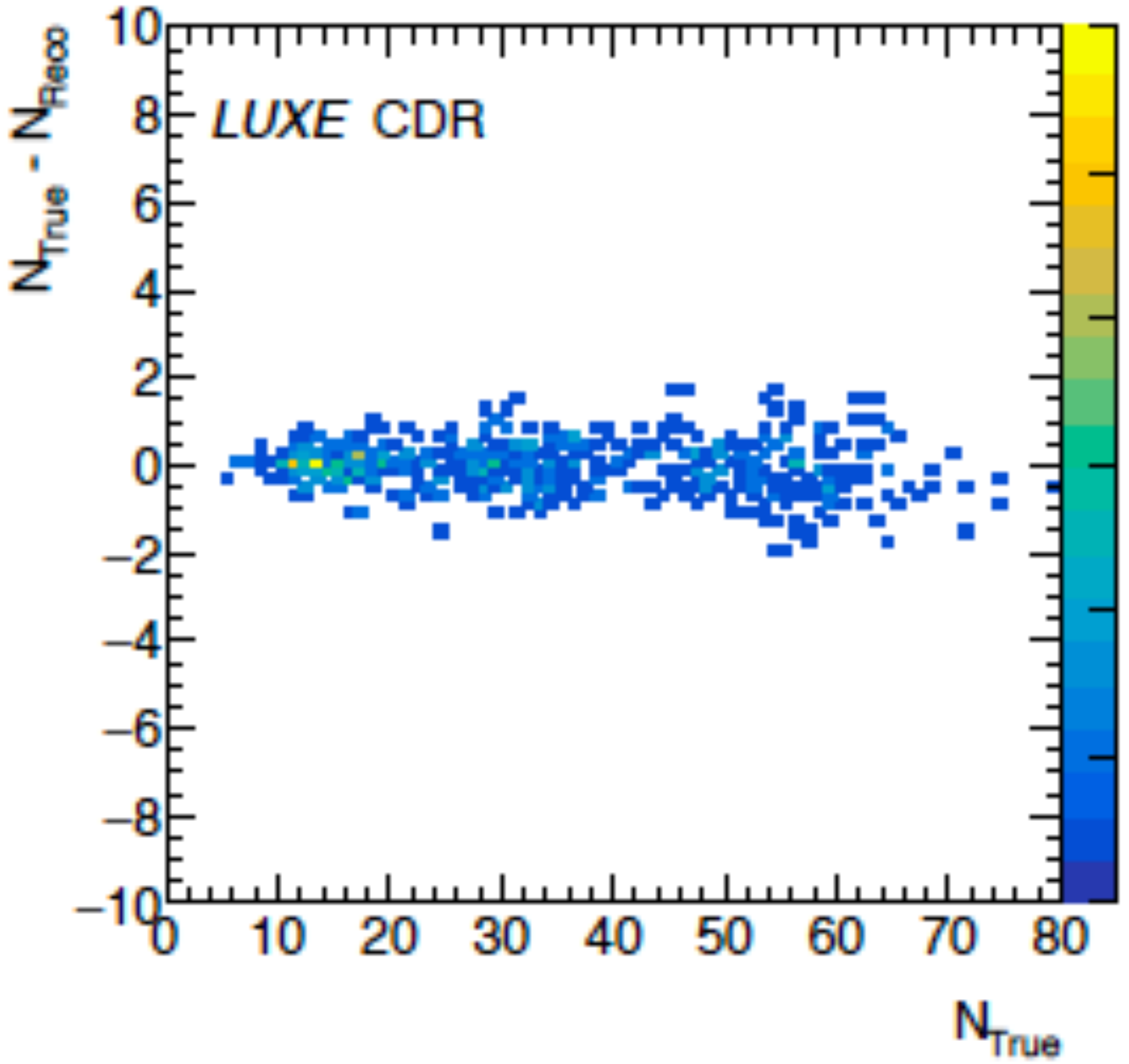
- Tracker: Use four layers of ALPIDE silicon pixel sensors.
  - Developed for ALICE tracker upgrade.
    - Pitch size: 27 x 29 µm² => spatial resolution ~5 µm
  - Using tracking algorithm:
    - Background: <0.1 event per bunch crossing
    - Good energy reconstruction







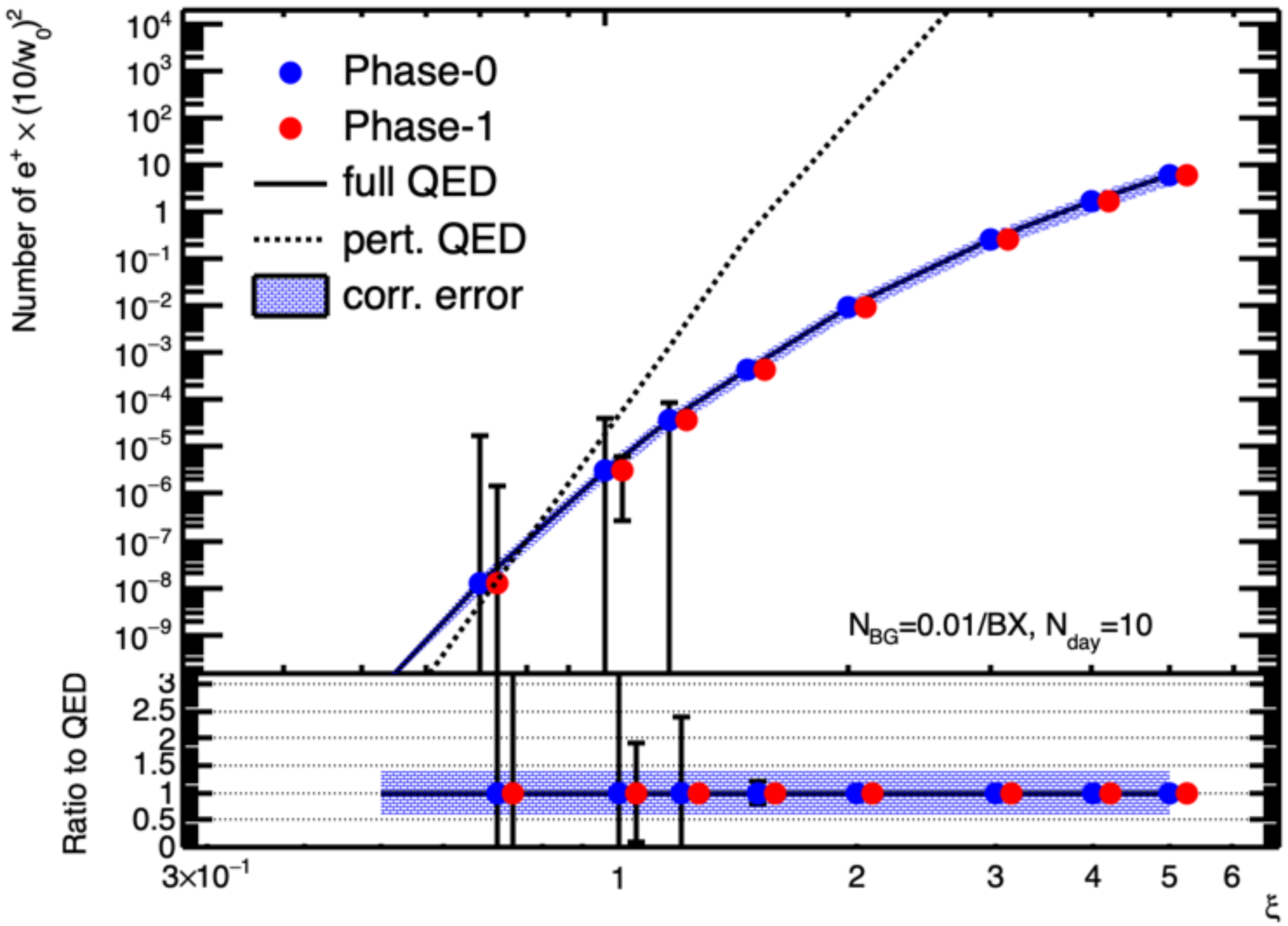
- High granularity Calorimeter developed for ILC FCAL
  - Developed for ILC FCAL
    - 20 layers of 3.5 mm thick tungsten plates
    - Silicon sensors (5x5 cm² pads, 320 µm thick)/
    - Readout via FLAME ASIC (developed for FCAL)
  - Resolution:
    - Energy $\frac{\sigma_E}{E} = \frac{19.3\%}{\sqrt{E/GeV}}$, position: $\sigma_x = 0.78\ mm$
    - Independent measure of energy via position and calorimetry => $N_{particle}$
      - Very important for high ξ runs where number of pairs can be very high!

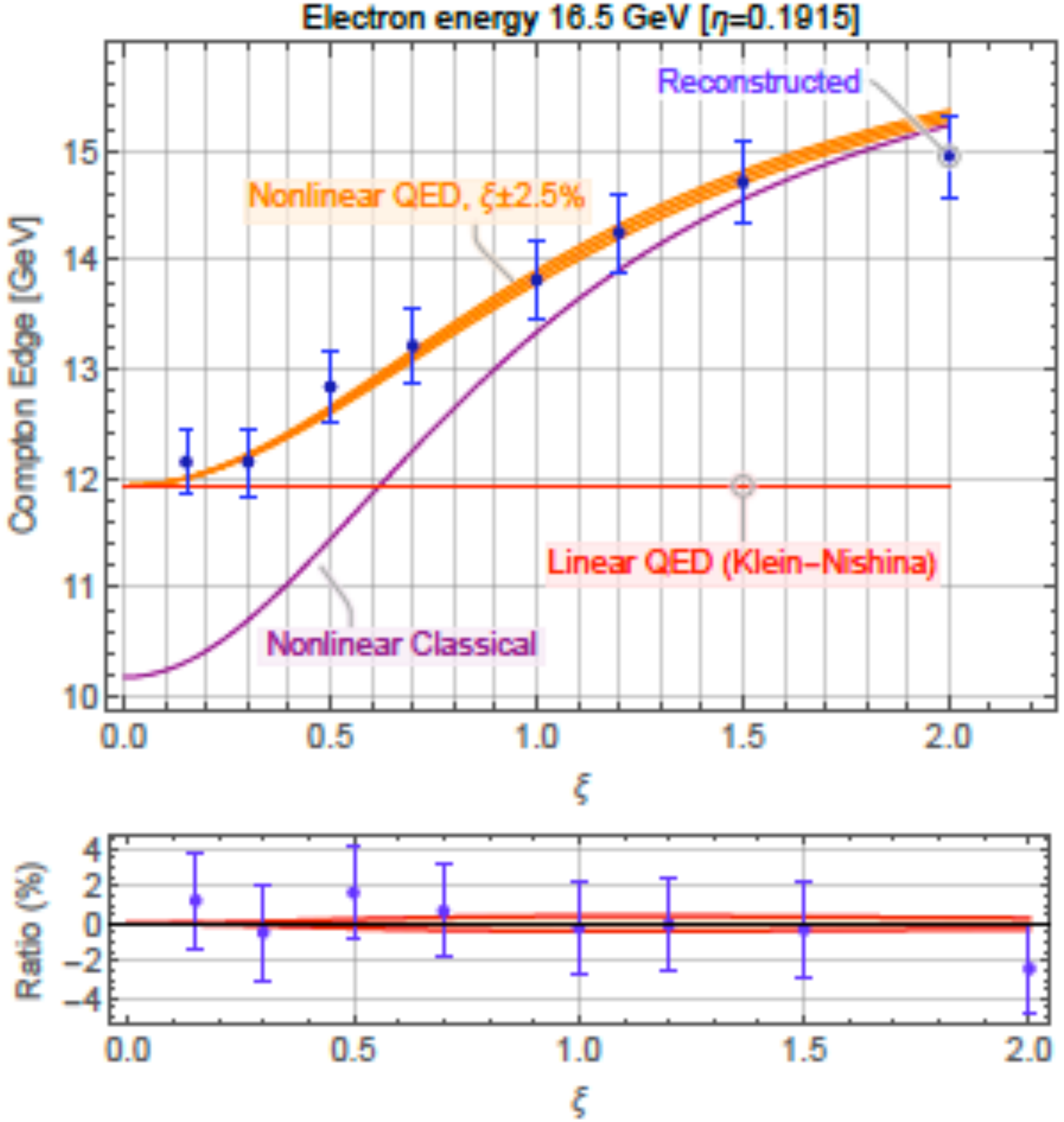


PUTTING EVERYTHING TOGETHER

- Breit-Wheeler process:
  - Estimated from low flux detectors (tracker, calorimeters) by measuring number of positrons created per laser shot.

- Non-linear Compton scattering:
  - Measure electrons energy distribution from Cherenkov detector and scintillating screen at IP.
  - Measure photons energy spectrum from gamma spectrometer.
  - Determine edge positions using Finite Impulse Response Filter technique.



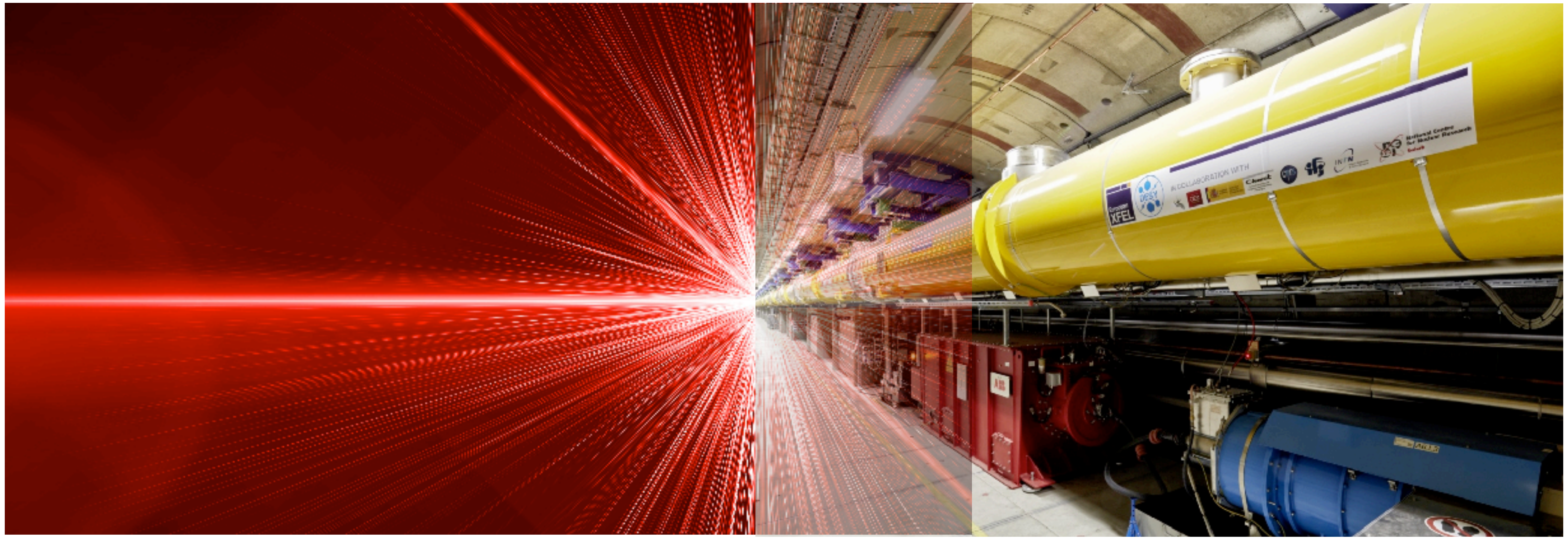


CONCLUSIONS

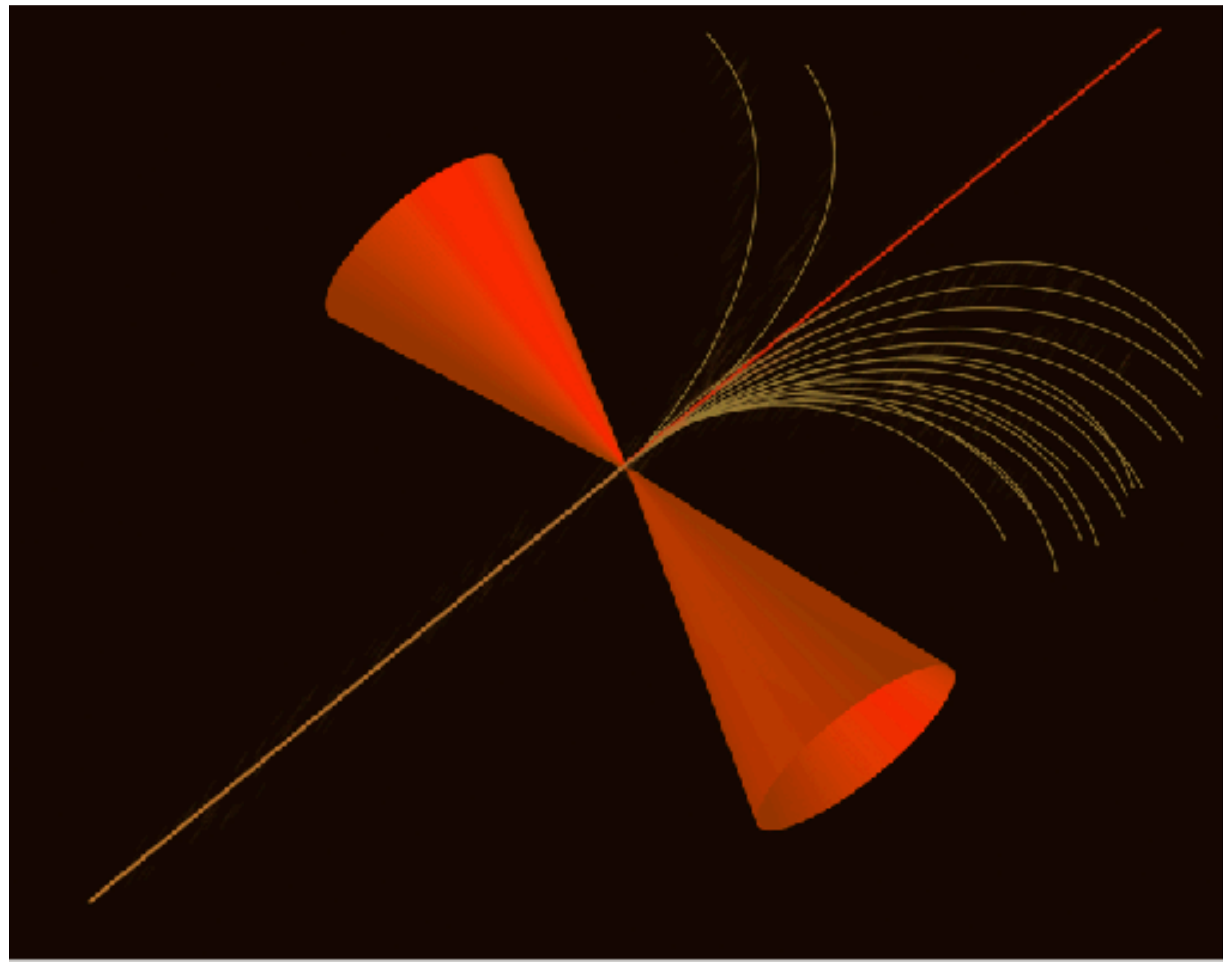
- The LUXE experiment will allow to measure QED in uncharted regime!
  - Might expect some surprises there!

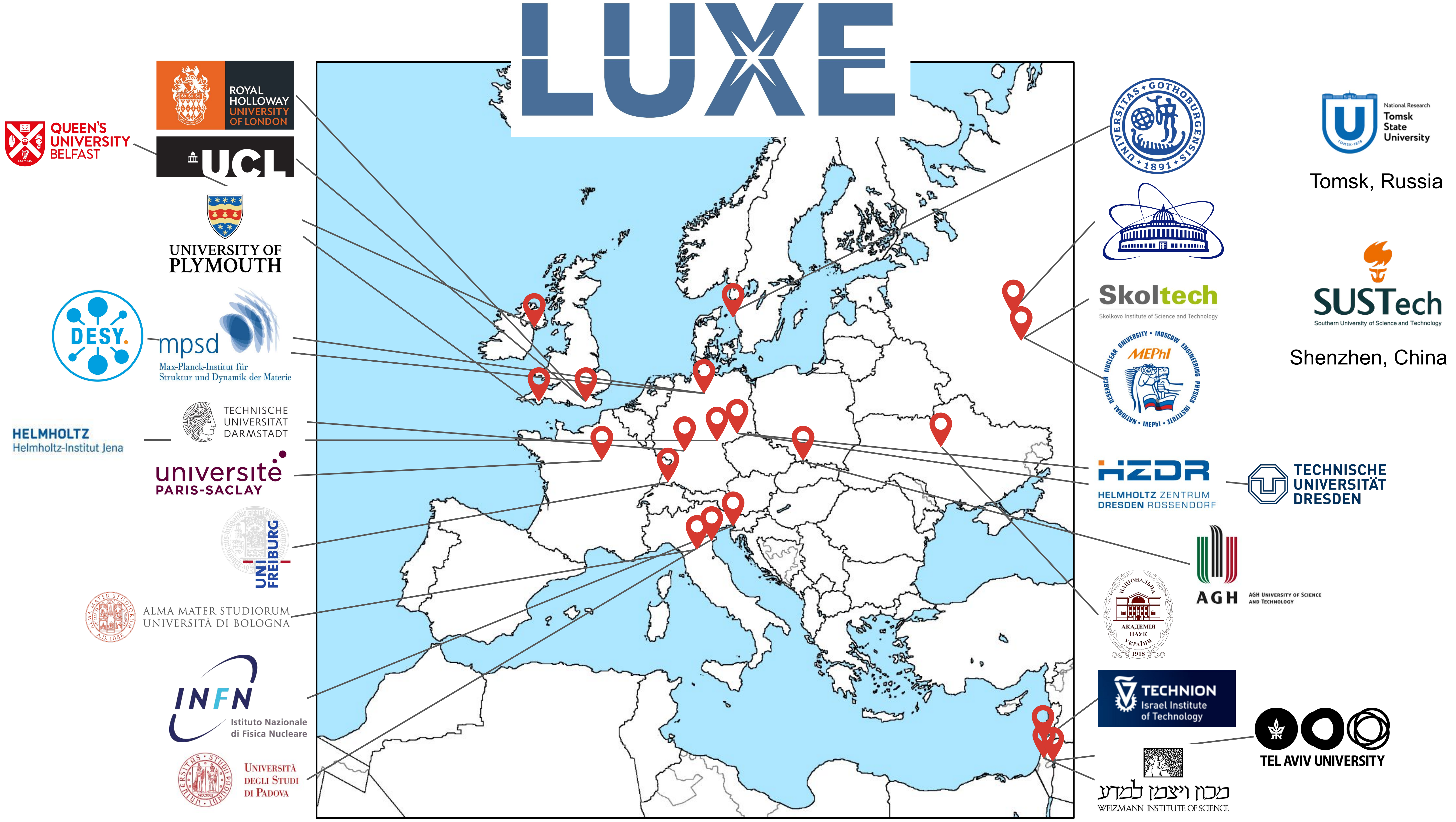
- Synergy experiment between particle physics and Laser physics!
  - Experiment planing to function on established technology to cope with challenging rate to measure!
  - Innovative development for Laser control system, and Laser diagnostics underway.

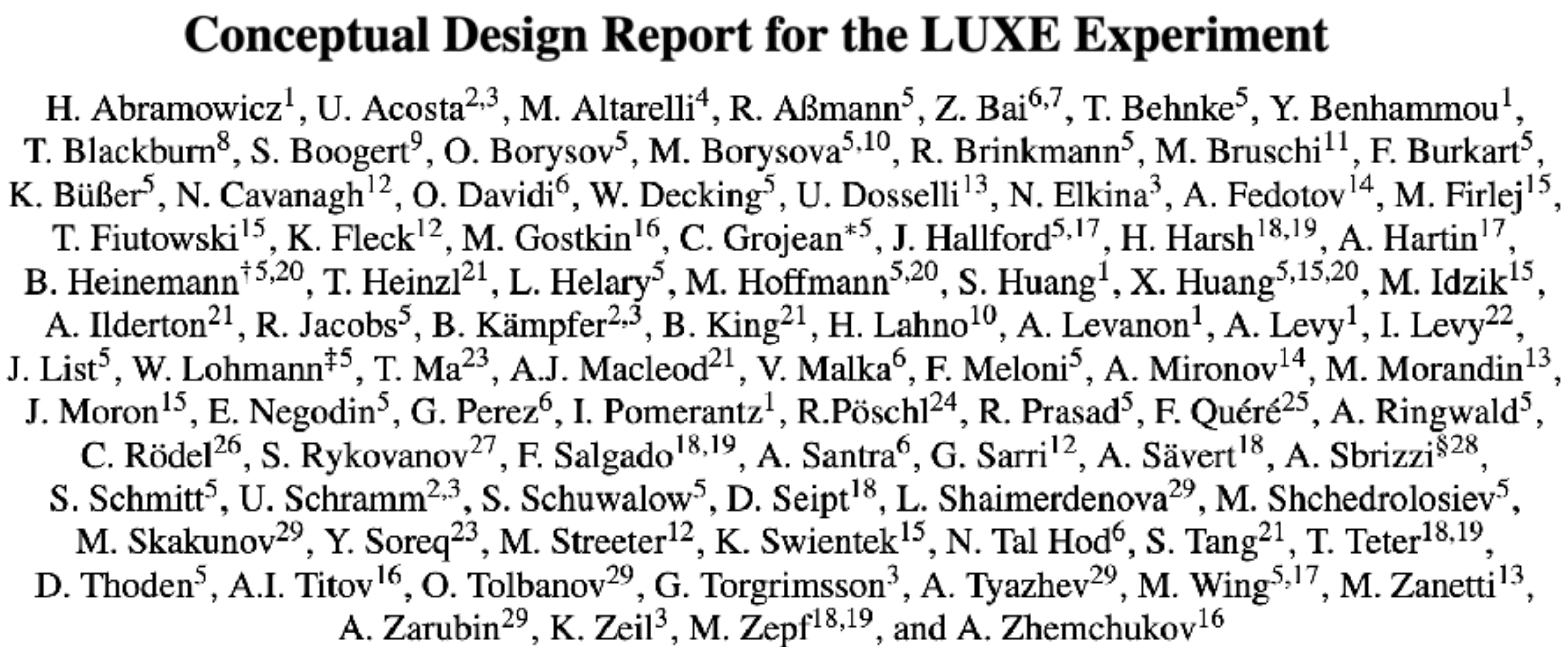
- LUXE CDR is now out, working on the TDR for 2022!
  - Still lot of works to do before the experiment can be running.



BACKUP







Conceptual Design Report for the LUXE Experiment

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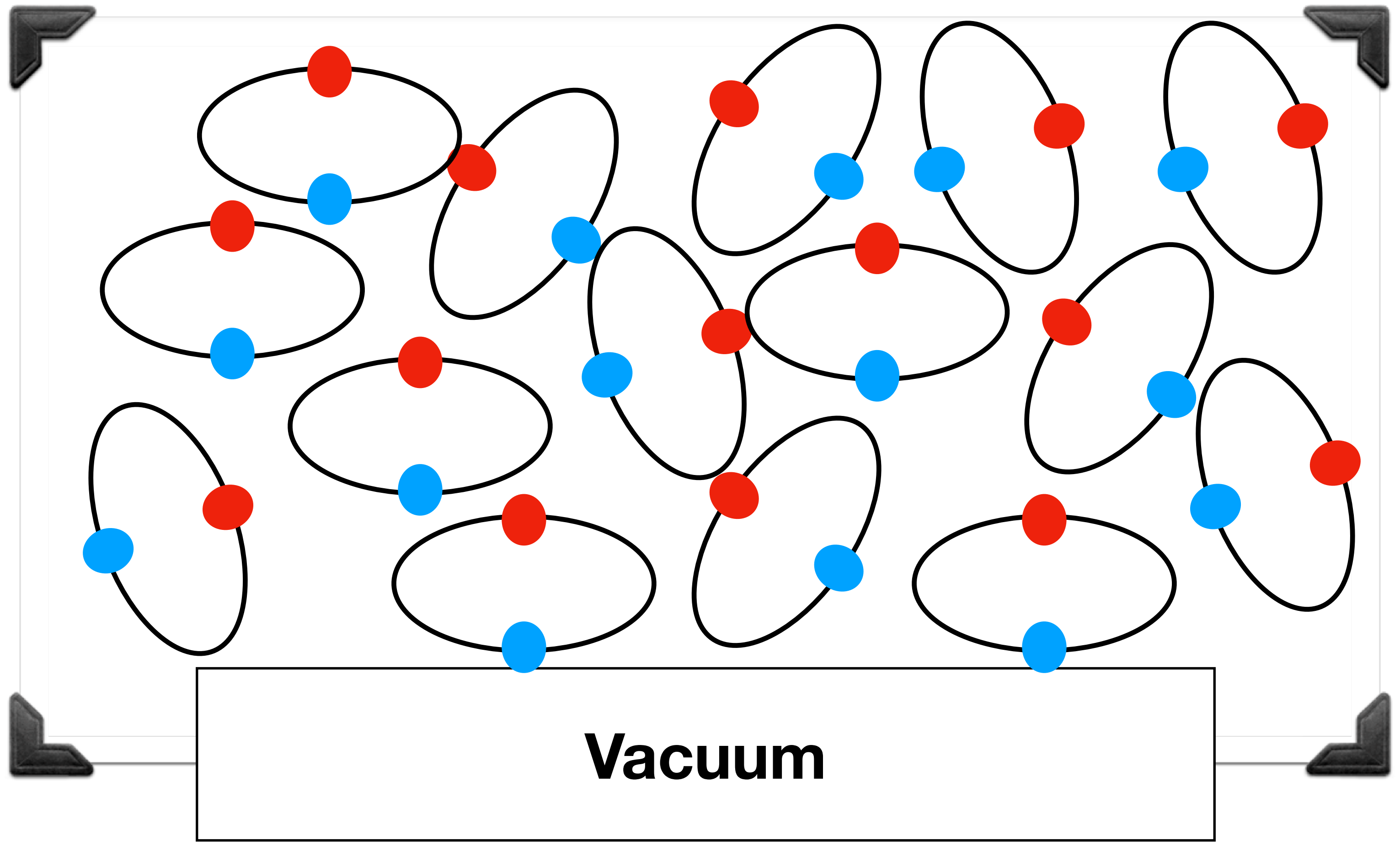
More informations:

- CDR, published by European Physics Journal ST: Eur.Phys.J.ST 230 (2021) 11, 2445-2560
- LUXE: https://luxe.desy.de/

INTRODUCTION: QED, VACUUM AND STRONG FIELD QED



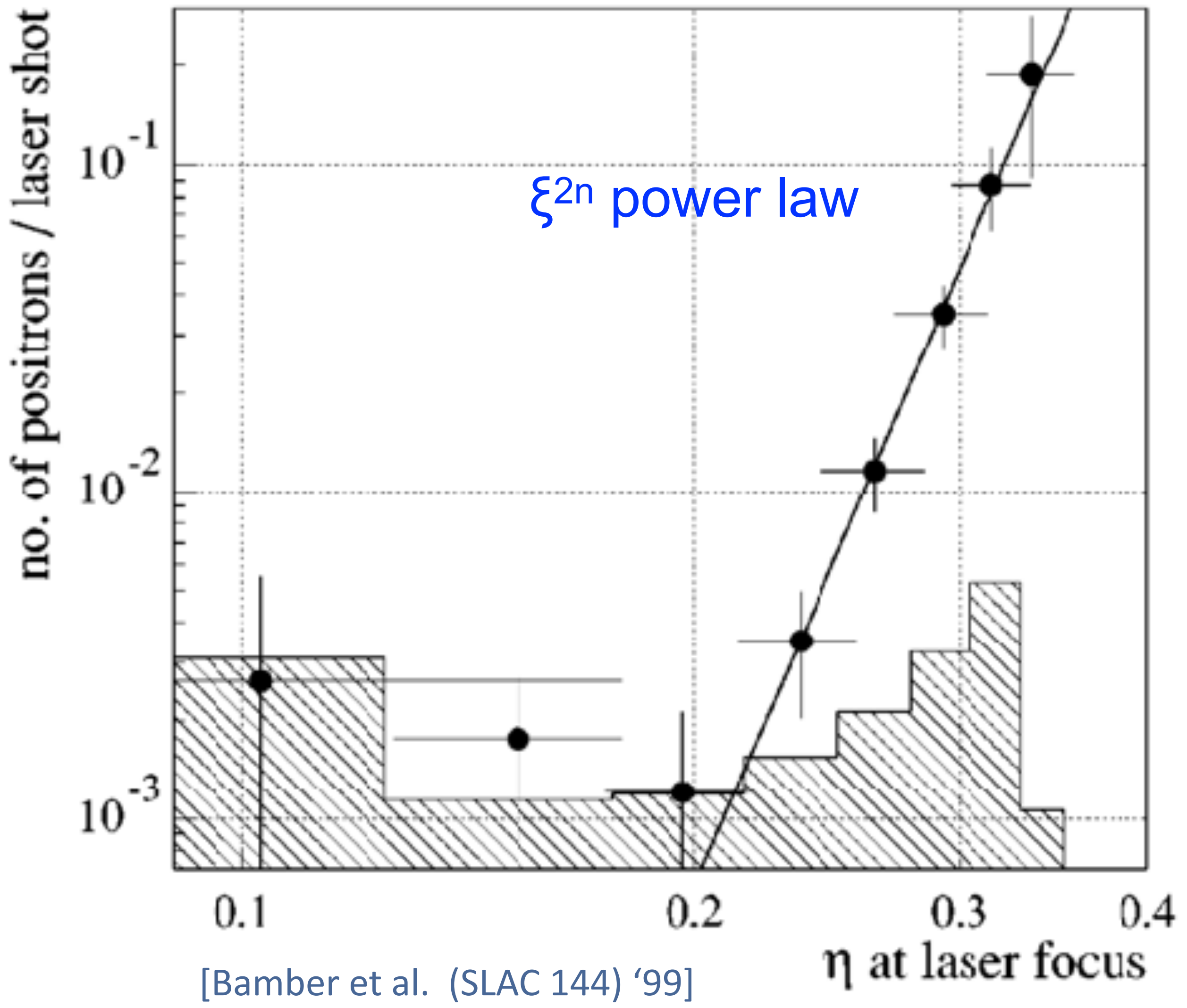
- QED: one of the most well-tested physics theory!
  - Calculation in QED based on perturbative theory of α_{EM}.
    - Prediction electron (g-2) precision better than 1 part in a trillion!
- Vacuum:
  - Virtual particles that can be charged and couple to fields.
  - Quantum fields: average is zero, but variance is not!
  - Physical particle travel in vacuum affected by interactions with these.
- If one apply a strong electromagnetic field on a vacuum:
  - $W_{field} < 2\ m_e$ $\quad$ $W_{field} > 2\ m_e$, with: $W_{field} = \frac{\varepsilon e}{m_e}$ and $\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}$

  - QED becomes non perturbative above Schwinger-limit
    → Strong field QED (SFQED)!
- Experimental consequences:
  - **Field-induced ("Breit-Wheeler") Pair Creation**
  - **Modified Compton Spectrum.**

- Non-perturbative and SFQED never been reached in a clean environment, accessible by LUXE!
  - Experimentally reached by colliding highly boosted electrons with high-intensity laser!

INTRODUCTION: SFQED STATE OF THE ART

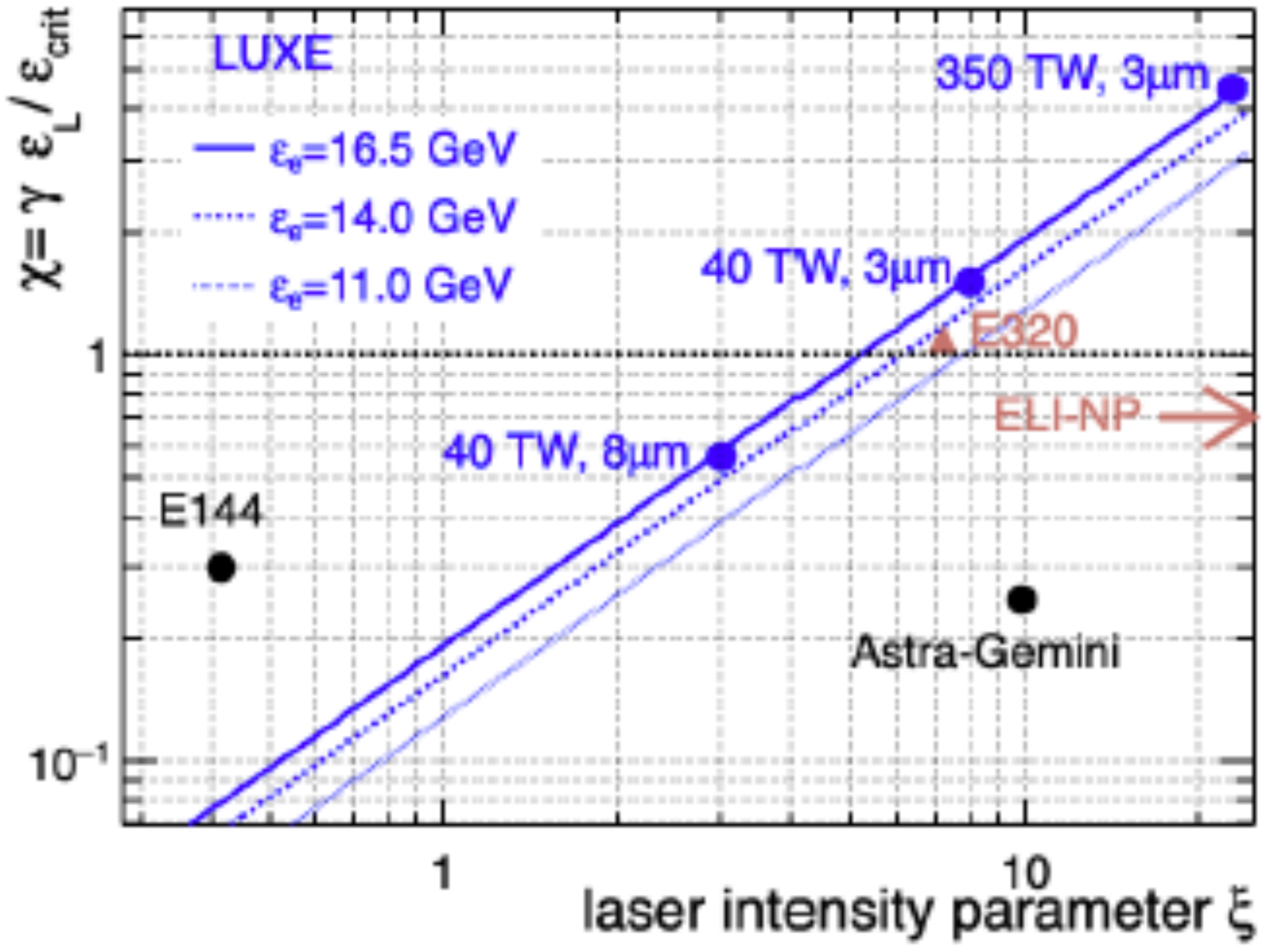
- Historically SFQED studied first in 1990's at SLAC E144 (experiment)
  - 1TW laser with $I_{Laser}=10^{18}$ W/cm^2
  - e- beam: 46.6 GeV
  - reached $\xi<0.4$, $\chi \leq 0.25$
  - observed multi-photon interaction: $e^- + n\gamma_L \rightarrow e^-e^+e^-$ process
  - observed start of the ξ^{2n} power law, but not departure



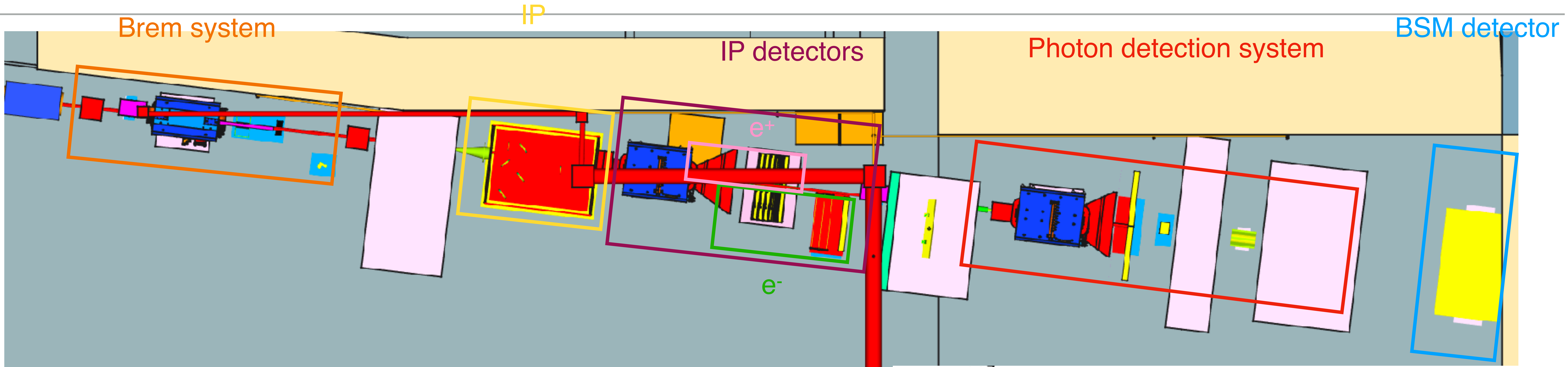
[Bamber et al. (SLAC 144) '99]

η~ ξ

- Nowadays multiple experiments proposed worldwide to observe SFQED:
  - Accelerator based: SLAC-E320 (US), LUXE (DE)
  - Laser plasma wakefield accelerator: Astra Gemini (UK), ELI-NP (RO)
  - Others: crystal based experiment, heavy ions…
- Luxe allow to measure with precision large part of ξ vs X phase space.
  - Observation of non perturbative regime in clean vacuum environment.
    - Only experiment proposed to directly explore photon-laser interactions.
- Main Luxe scientific goals:
  - Demonstrate SFQED
    - Measure electron rate as a function of laser intensity.
    - Measure Compton edges.
      - Position of edges different as function of ξ parameter.
  - Study BSM physics.



RATES PER BUNCH CROSSING



- Electron-laser:
  - Signal pairs created: 10^{-4} to 10^{6}.
  - Background particles flux and detectors used:
    - e^- side: up to 10^9 particles, Cherenkov, and scintillating screen.
    - e^+ side: up to 10^3 particles, calorimeter and tracker.
- Gamma-laser:
  - Signal pairs created: 10^{-5} to 10.
  - Background particles flux and detectors used:
    - e^- side: up to 10 background particles, calorimeter and tracker.
    - e^+ side: up to 10 particles, calorimeter and tracker.
    - Brem target: 10^6 particles, Cherenkov, and scintillating screen.
- In both setups: Photon detection system up to 10^9 photons to detect uses:
  - scintillating screen, beam profiler, backscattering calorimeter.