LUXE: A NEW EXPERIMENT TO STUDY NON-PERTURBATIVE QED

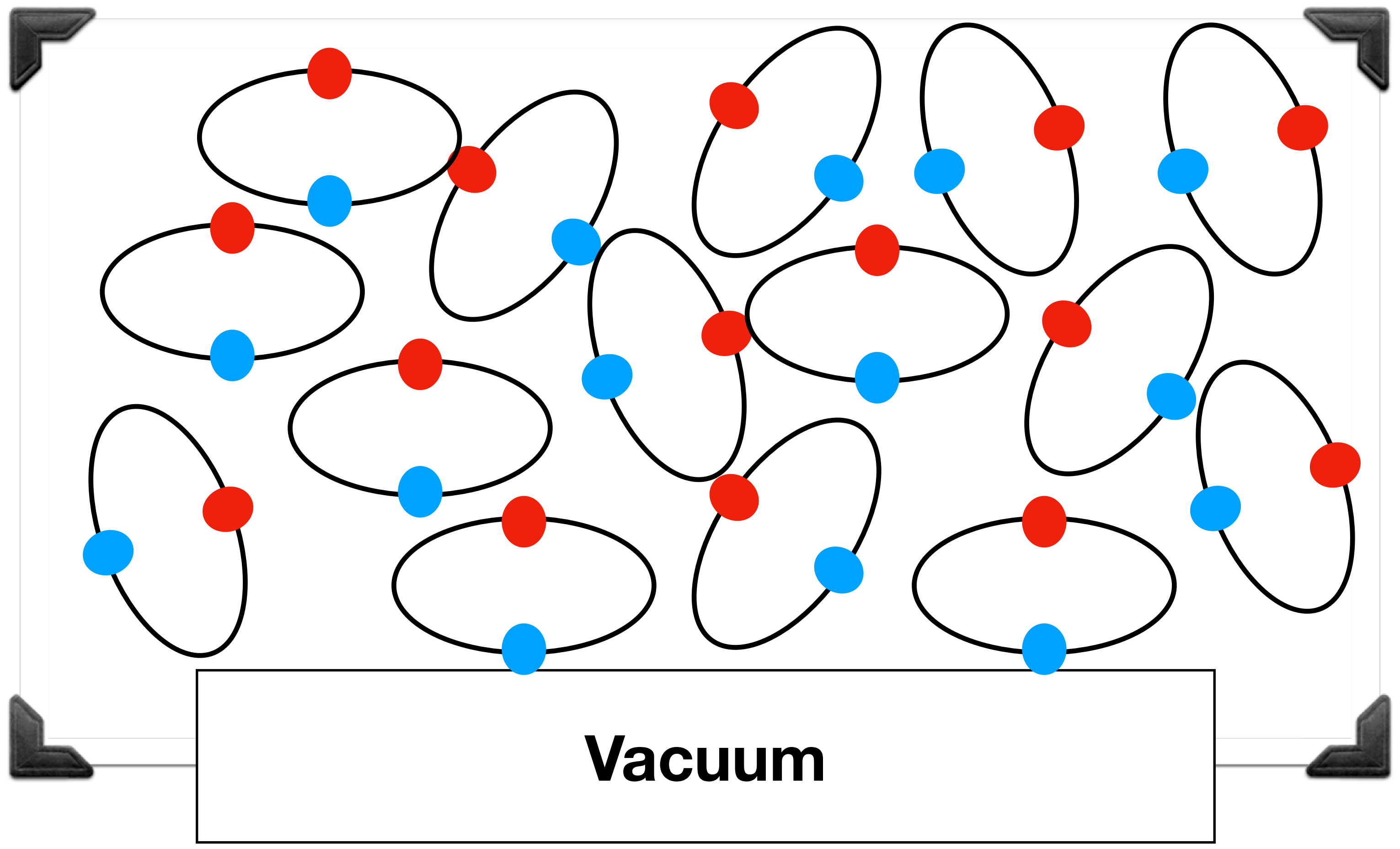
LOUIS HELARY (DESY) ON BEHALF OF LUXE

LES RENCONTRES DE PHYSIQUE DE LA VALLÉE D'AOSTE — MARCH 6TH - 12TH 2022 — LA THUILE

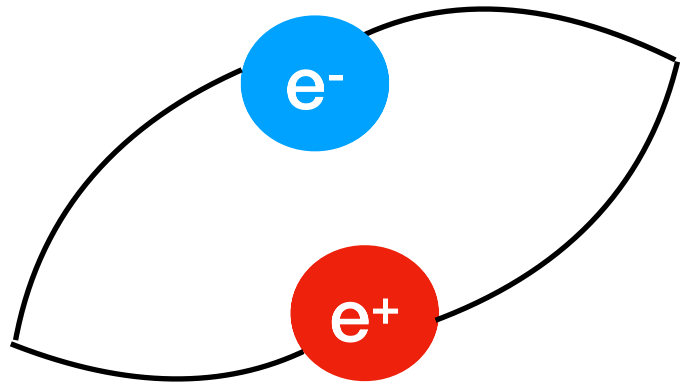
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

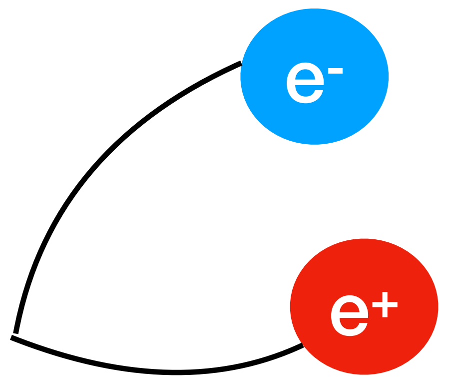
INTRODUCTION: QED, VACUUM AND STRONG FIELD QED

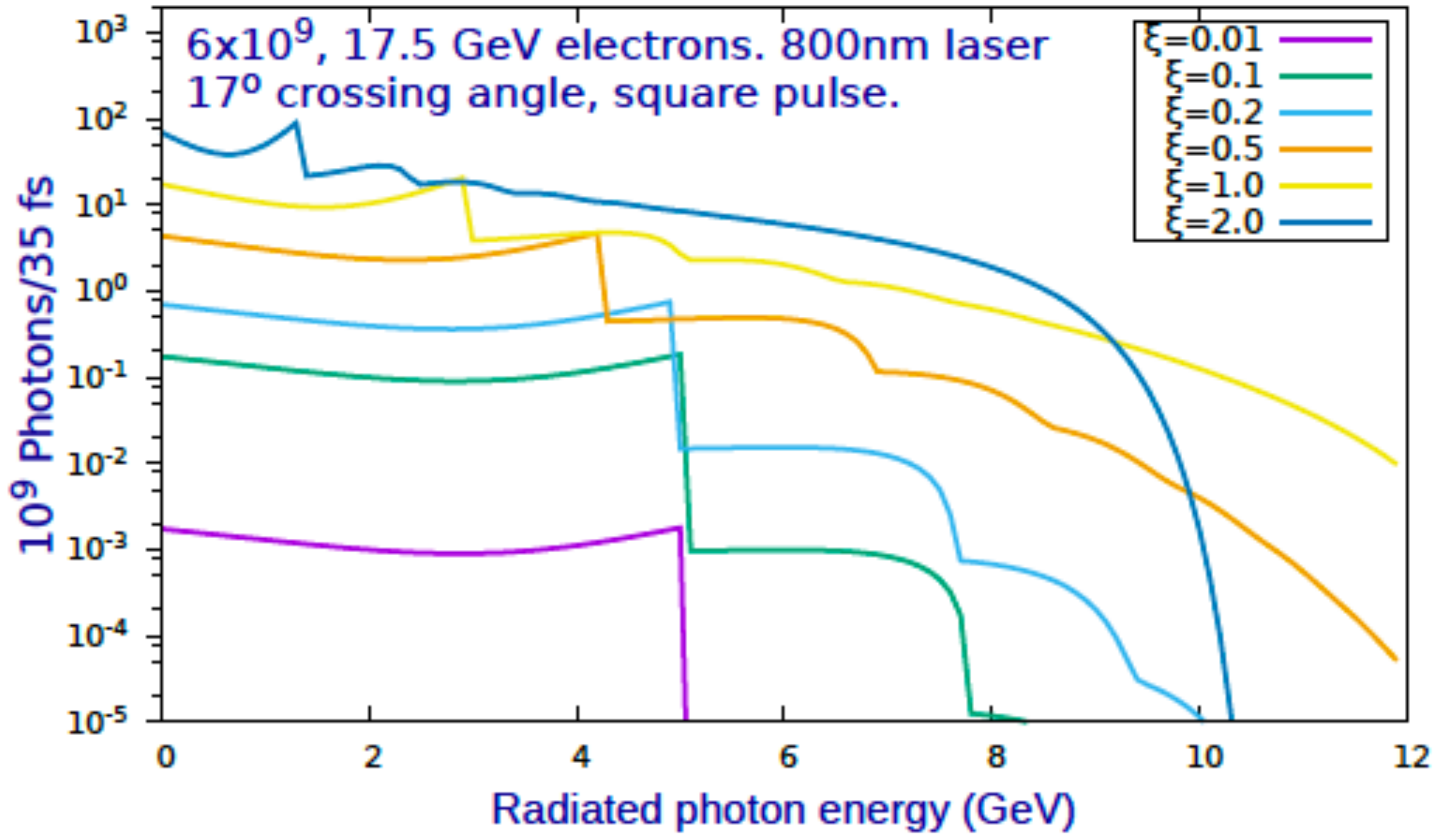
- QED: one of the most well-tested physics theory!
  - Calculation in QED based on perturbative theory of α_{EM}.
    - Prediction electron (g-2) precision better than 1 part in a trillion!
- Vacuum:
  - Virtual particles that can be charged and couple to fields.
  - Quantum fields: average is zero, 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 $\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}$ V/m



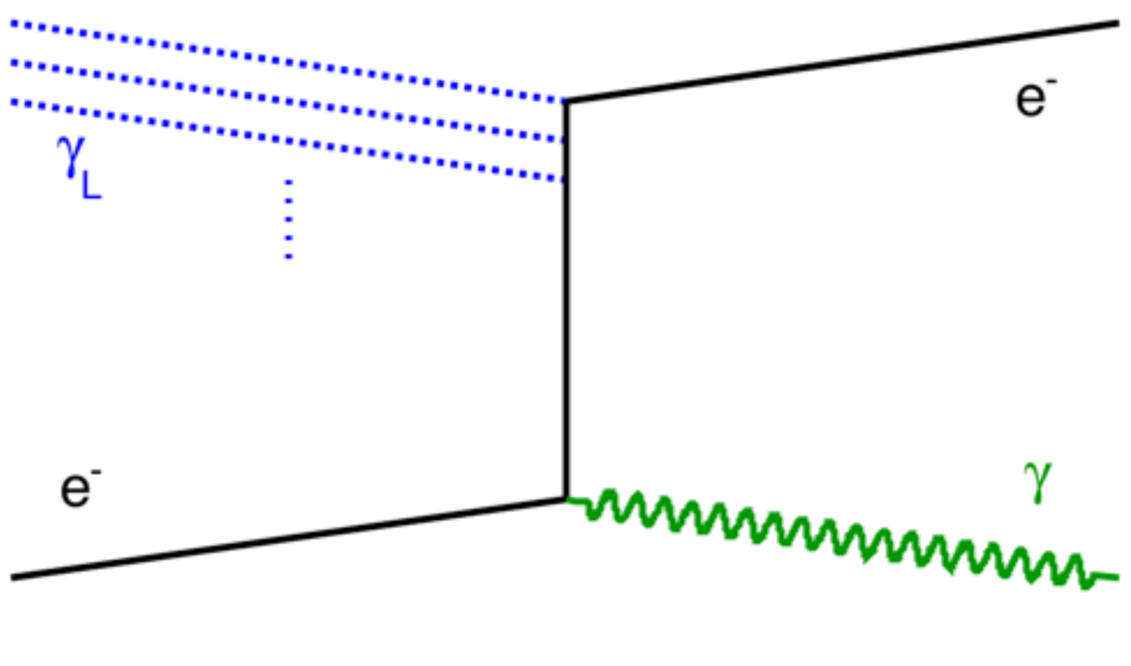




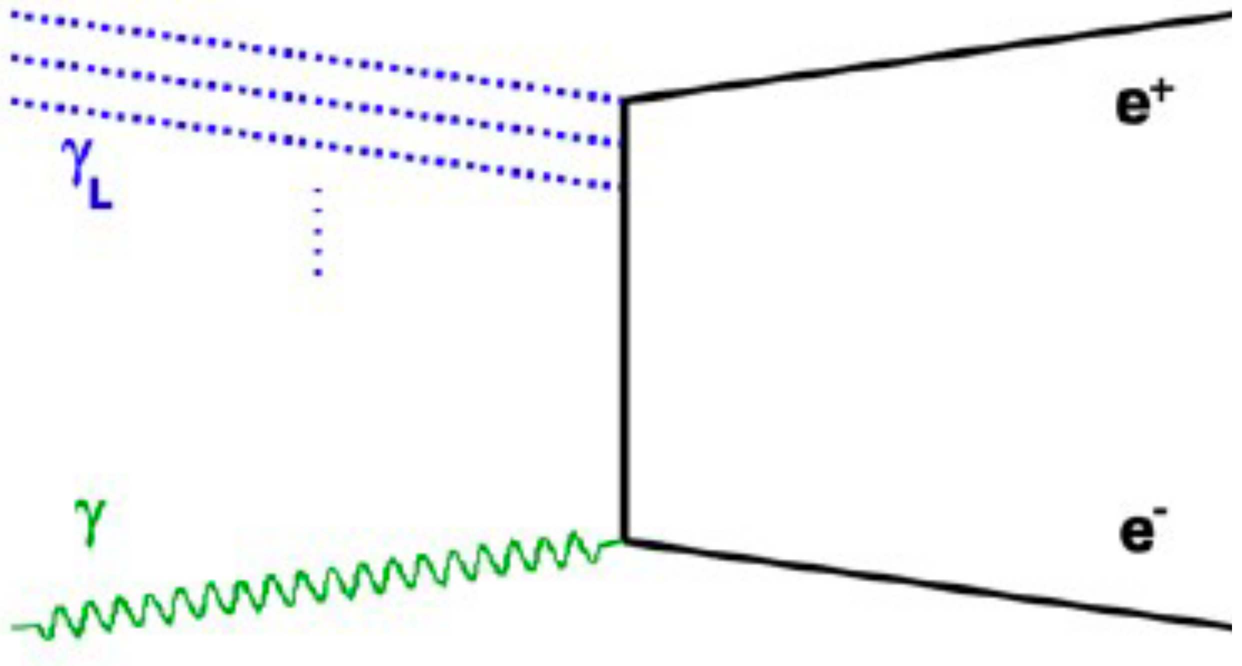
  - QED becomes non perturbative above Schwinger-limit
    → Strong field QED (SFQED)!
- Experimental consequences:
  - **Field-induced ("Breit-Wheeler") Pair Creation**
  - **Modified Compton Spectrum.**
- Non-perturbative and SFQED never been reached in a clean environment, accessible by LUXE!
  - Experimentally reached by colliding highly boosted electrons with high-intensity laser!

INTRODUCTION: SFQED PROCESSES AND PREDICTIONS

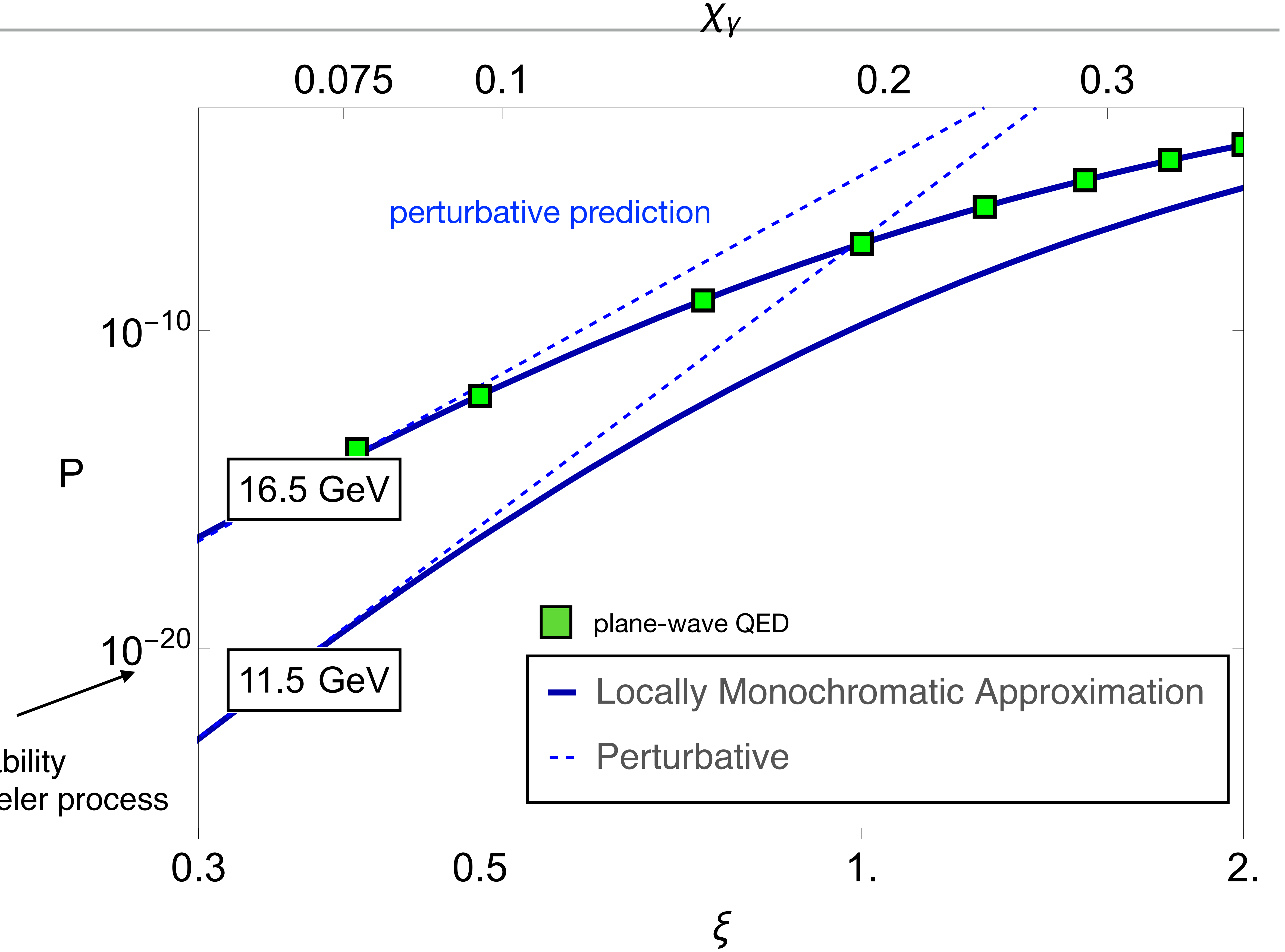
- Processes sensitive to in LUXE:



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.

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

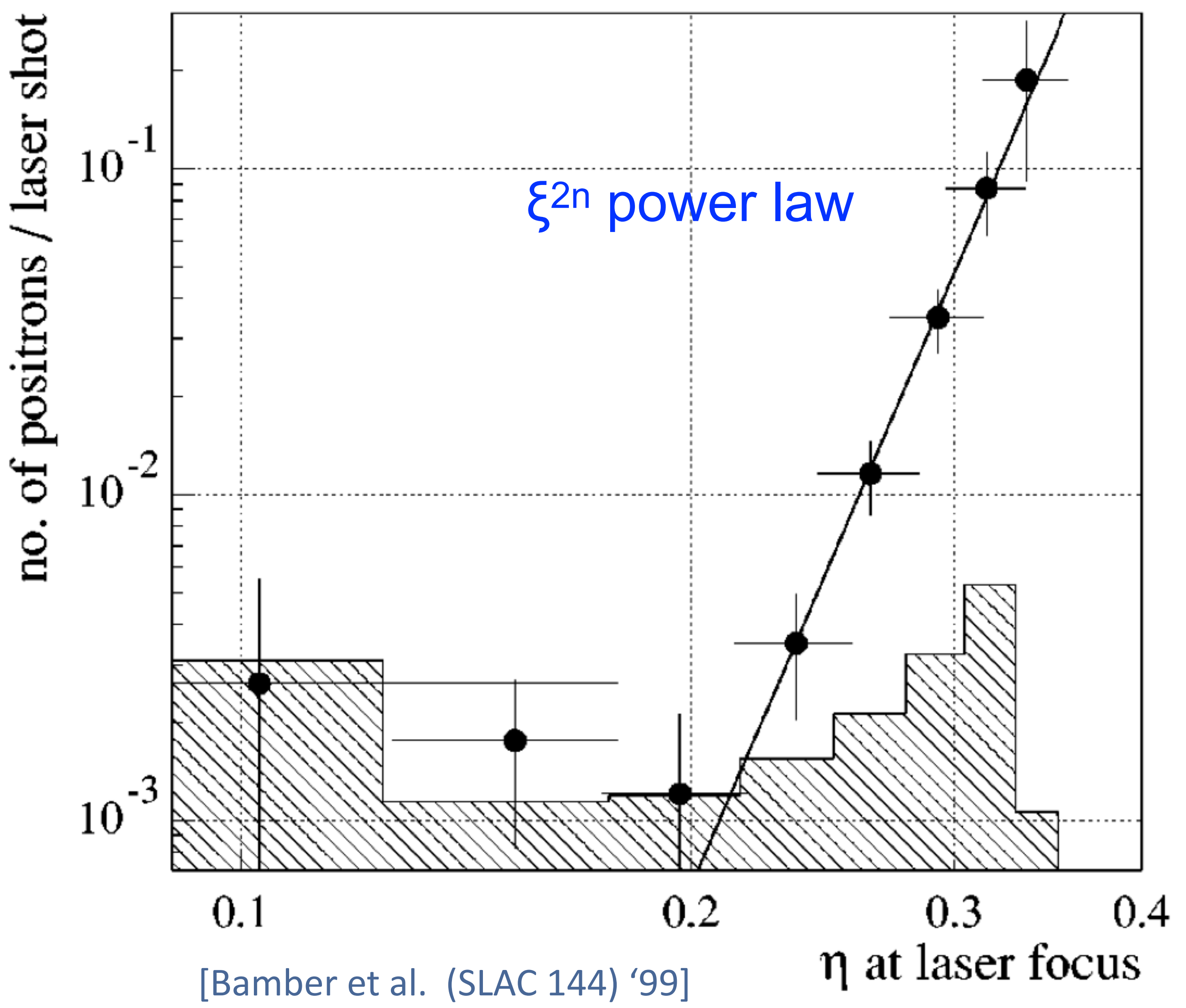
- Predictions:

$\boxed{\xi \ll 1:}$ $R_{e^+} \propto \xi^{2n} \propto I^n$ — Perturbative regime, rate follows power law

$\boxed{\xi \gg 1:}$ $R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$ — Non-perturbative regime, departure from power law (valid for low X values)

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

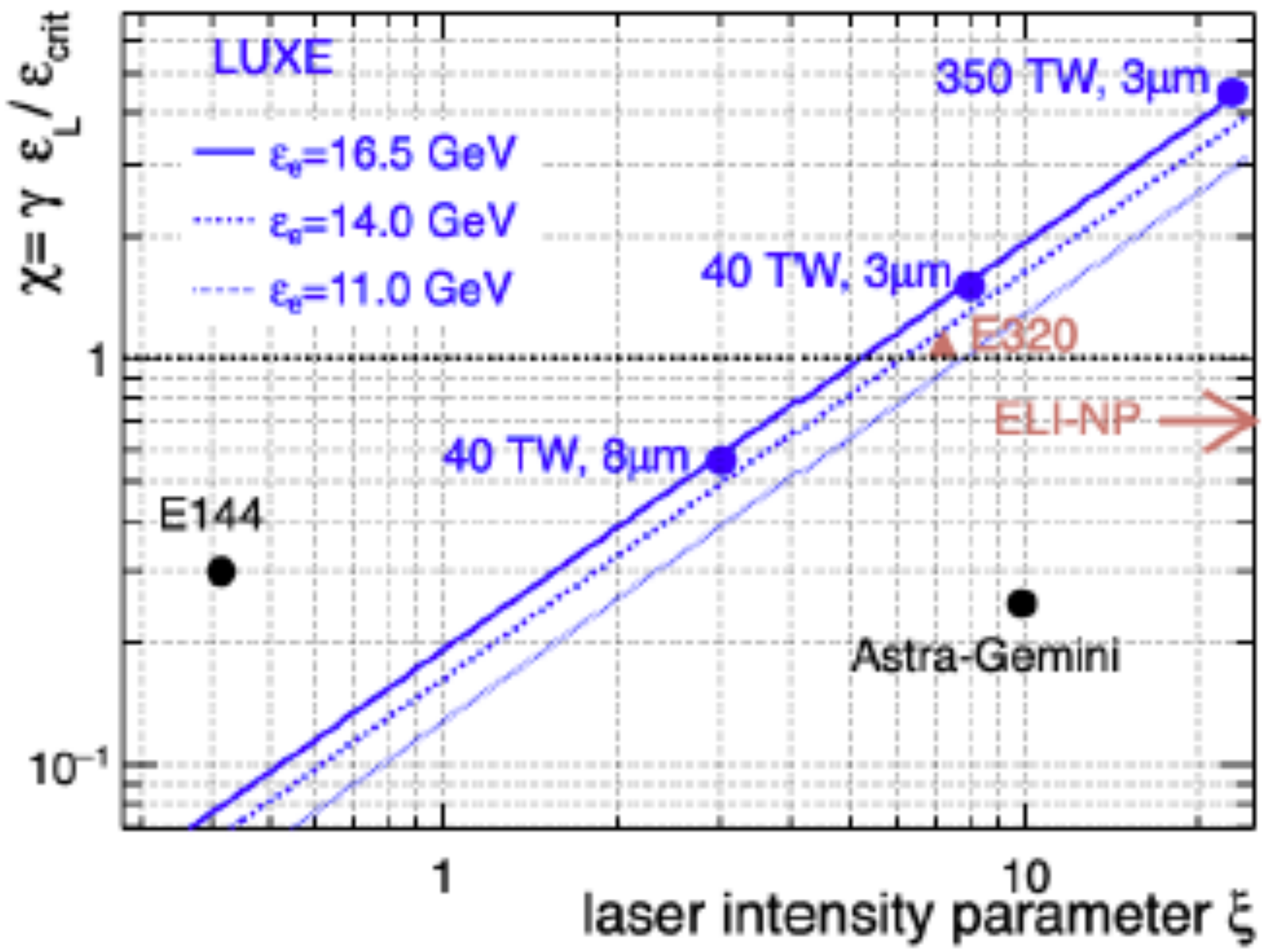


$\eta \sim \xi$

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

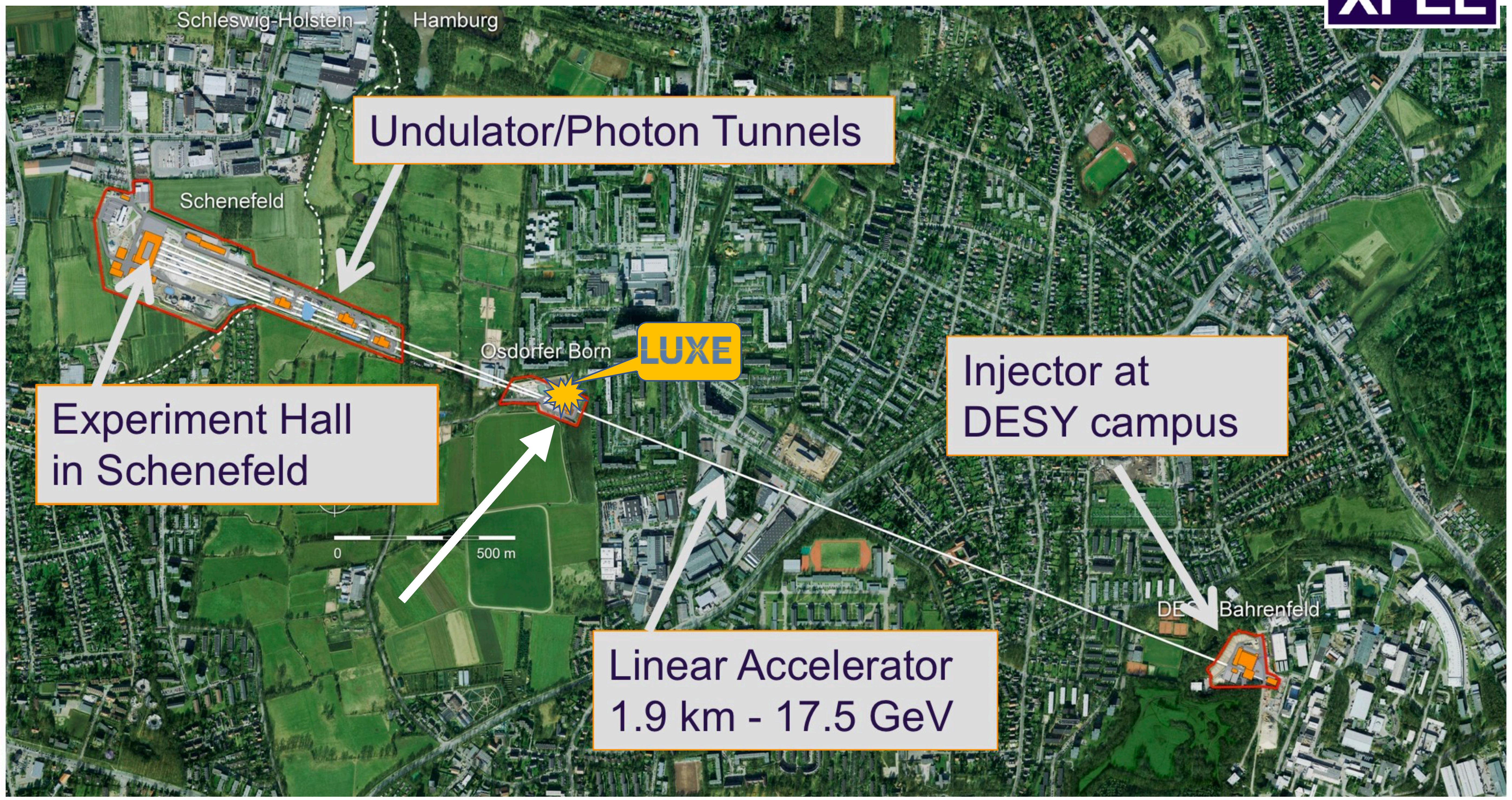
- Nowadays multiple experiments proposed worldwide to observe SFQED:
  - Accelerator based: SLAC-E320 (US), LUXE (DE)
  - Laser plasma wakefield accelerator: Astra Gemini (UK), ELI-NP (RO)
  - Others: crystal based experiment, heavy ions…

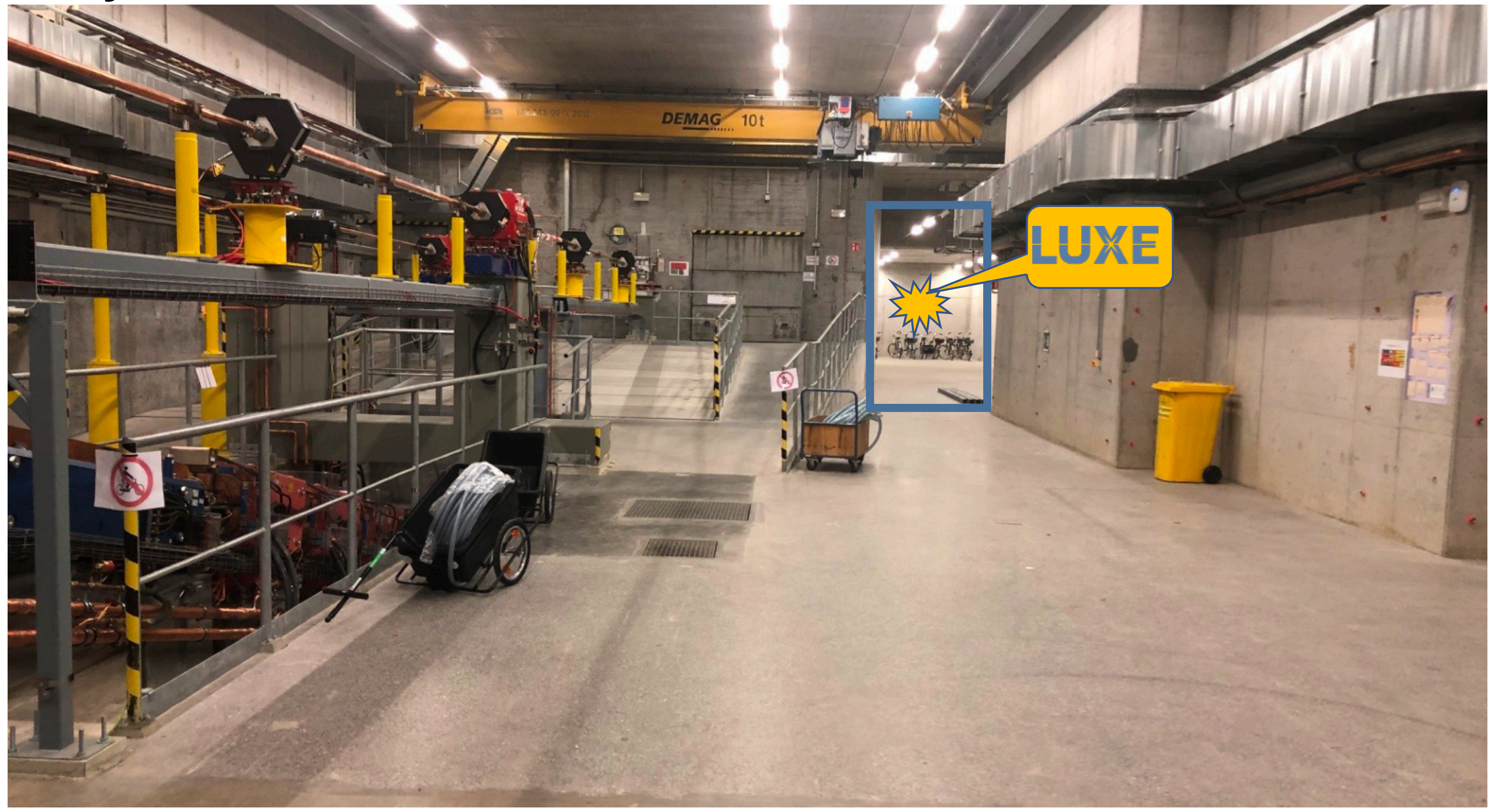
- Luxe allow to measure with precision large part of ξ vs X phase space.
  - Observation of non perturbative regime in clean vacuum environment.
    - Only experiment proposed to directly explore photon-laser interactions.

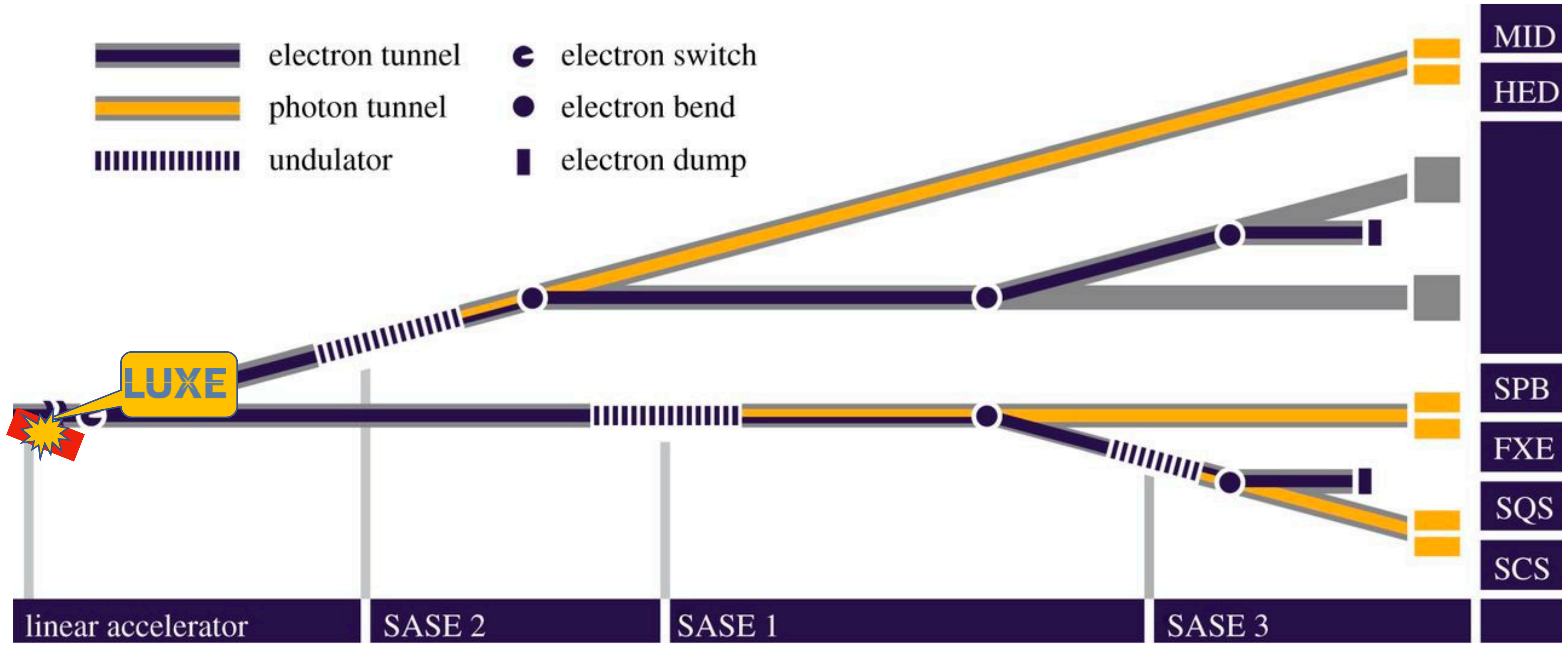


- Main Luxe scientific goals:
  - Observe and measure in detail SFQED:
    - Measure electron rate as a function of laser intensity.
    - Measure Compton edges.
  - Study BSM physics.

- 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.







LUXE IN SITU

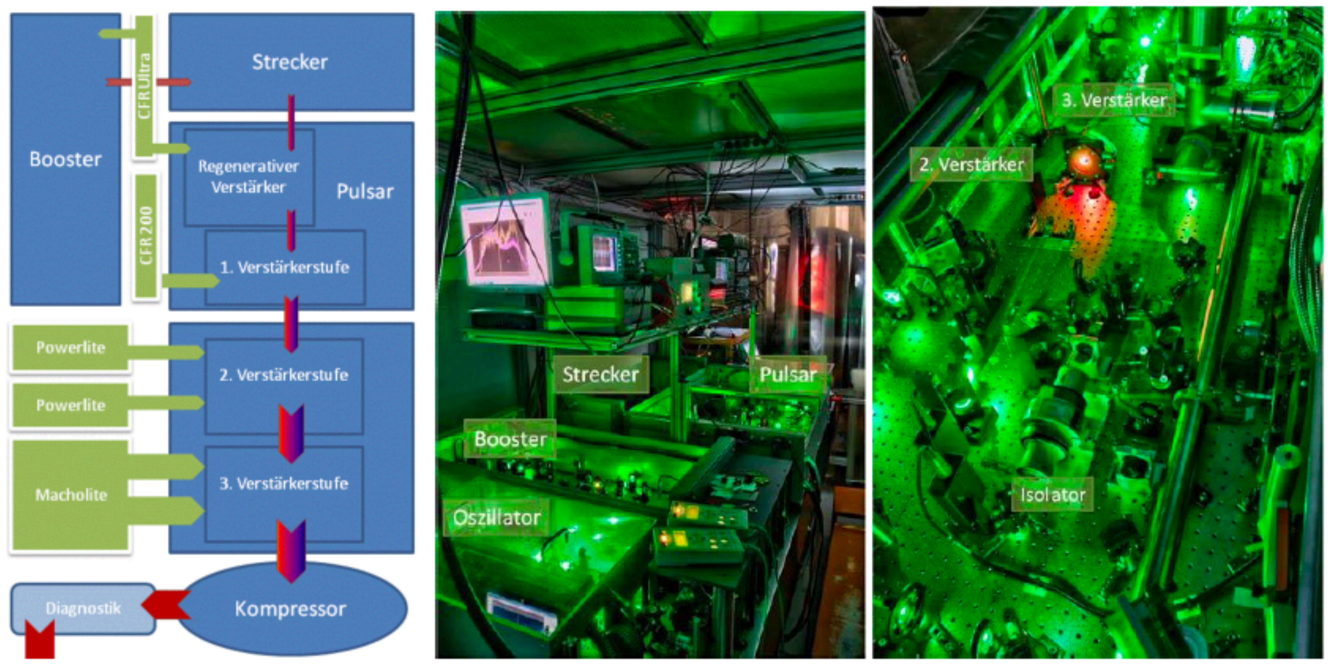
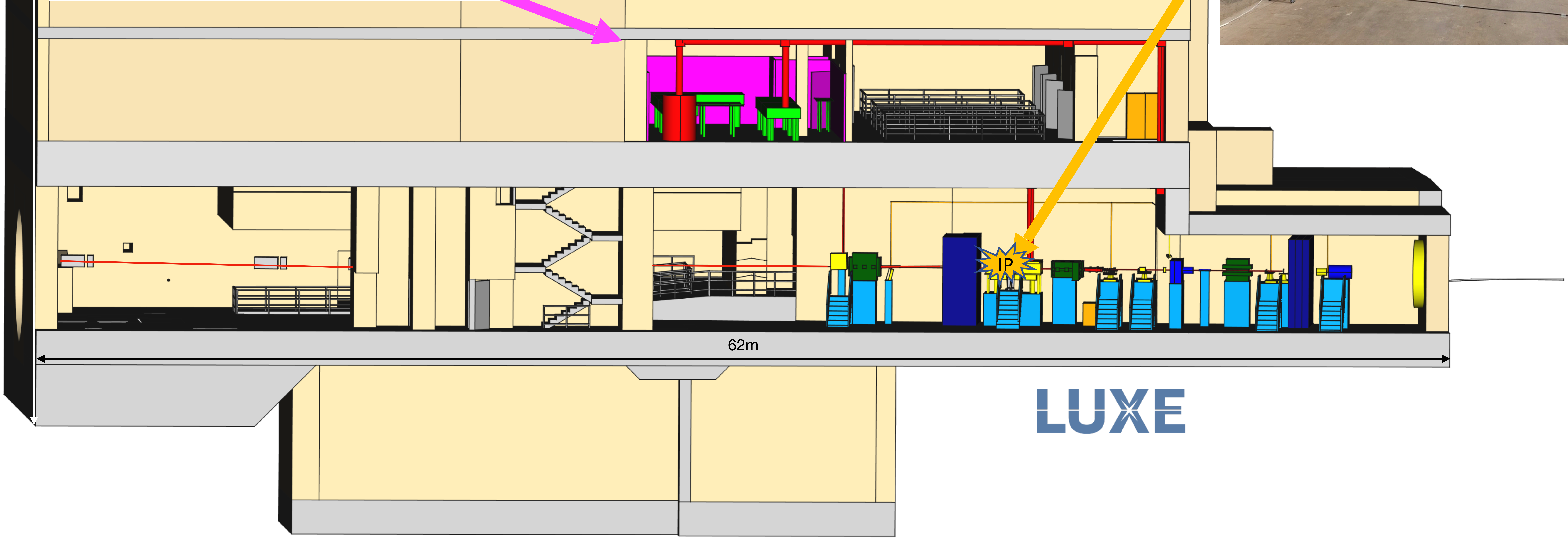
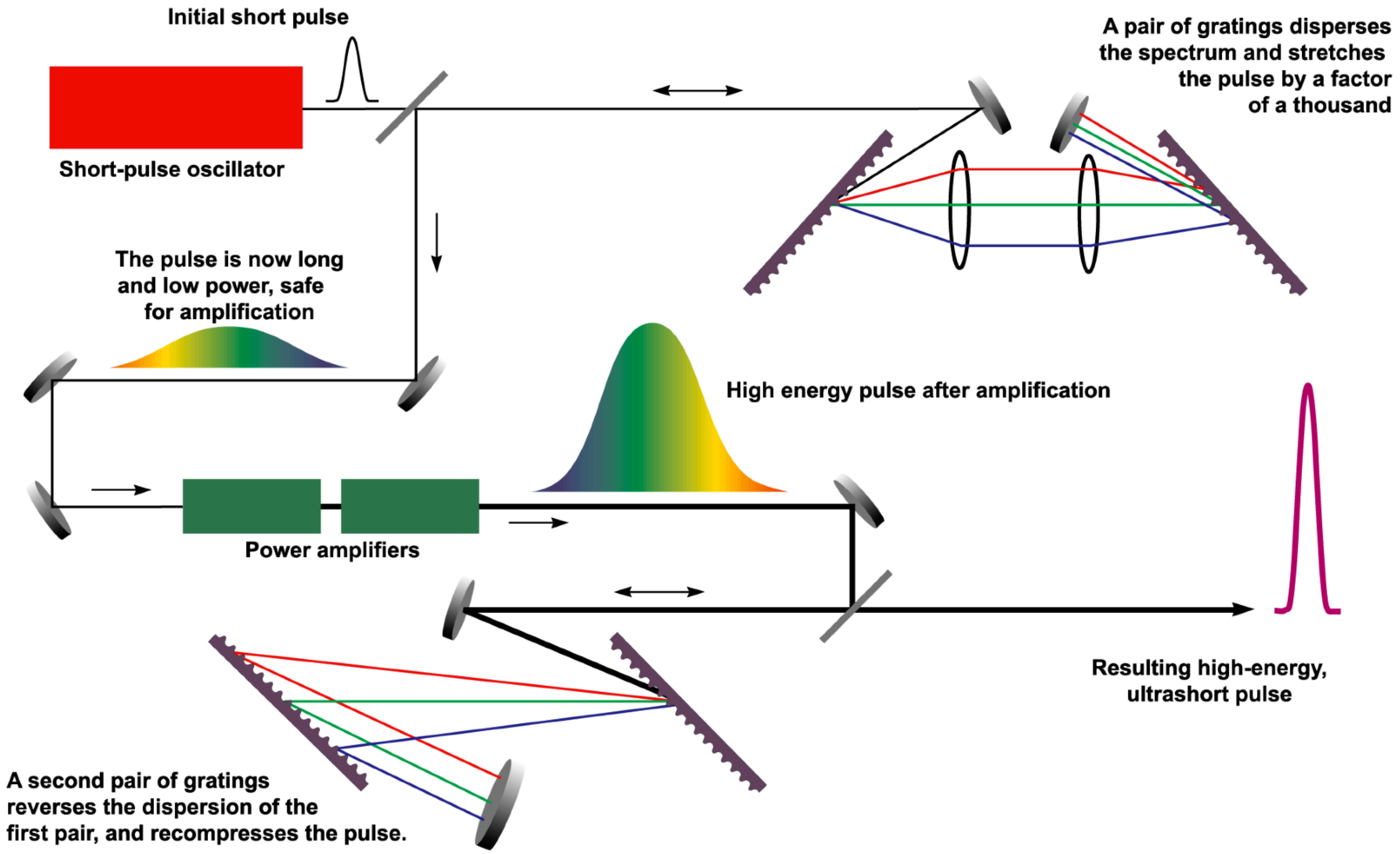


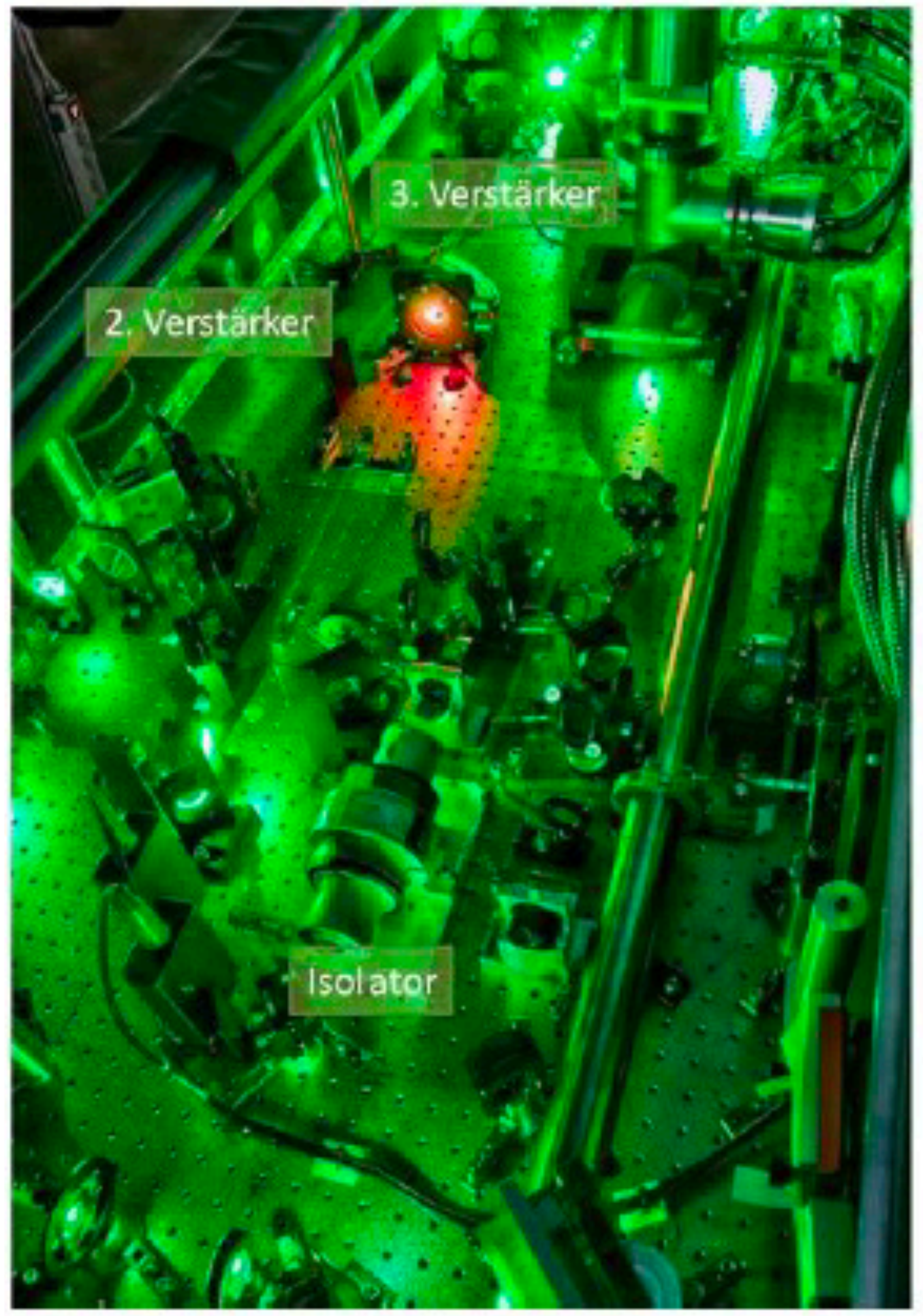
Figure 22. Schematic of the JETI system highlighting major assemblies. Current Installation of JETI-40 at the University of Jena. Front-end is shown in centre and power amplifiers right.



LASER

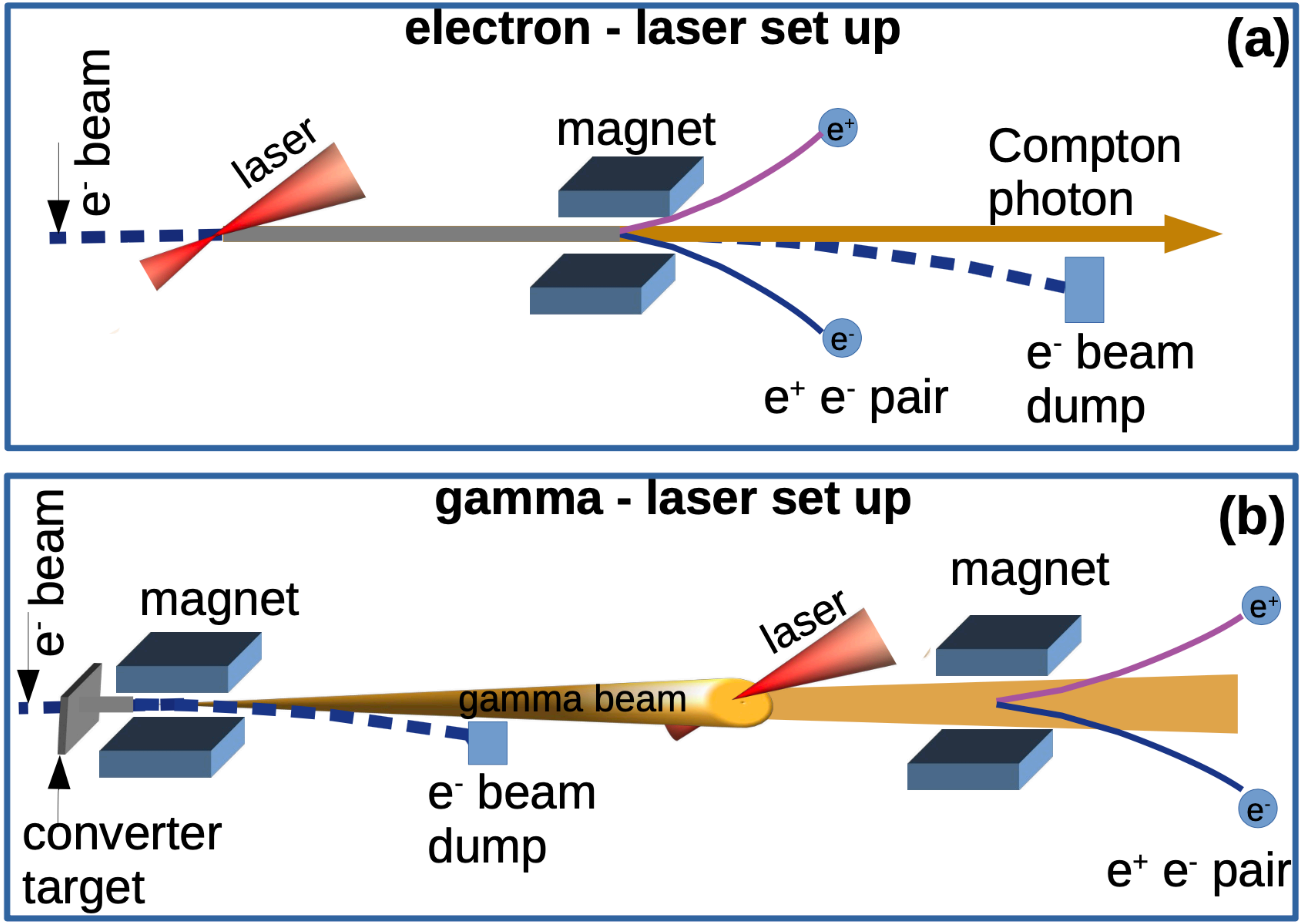
- Chirped Pulse Amplification (CPA) technique
- Ti:Sa laser with 800 nm wavelength (E=1.55 eV).
- Two phases:
  - In phase 0 uses JETI40 (Jena custom 40 TW laser).
  - In phase I will use commercial 350 TW laser.
- Laser parameters:
  - Repetition rate: 1Hz.
  - Pulse length 30 fs
- Laser characterisation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



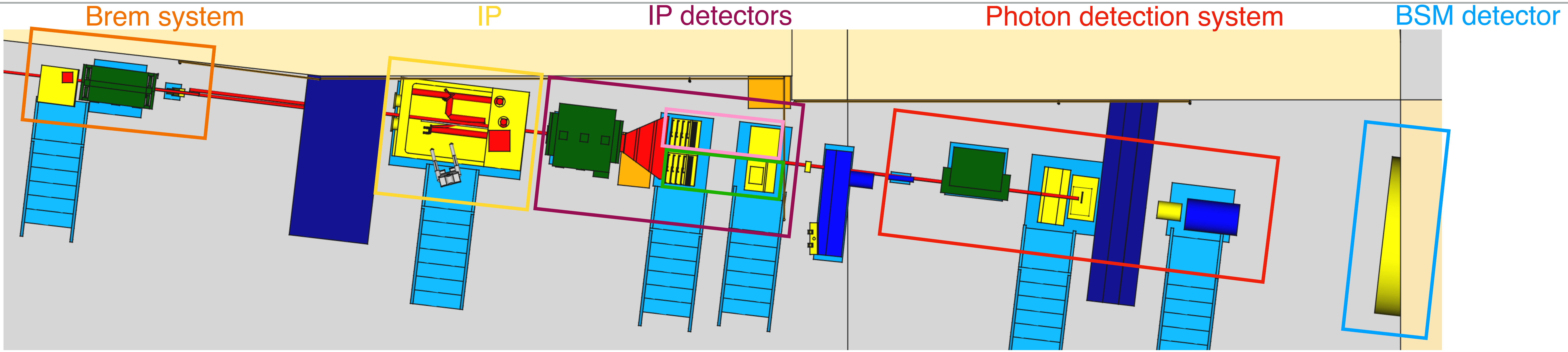


Parameter	Phase 0	Phase 0	Phase I
Laser power	40 TW		350 TW
Laser energy after compression [J]	1.2		10
Percentage of laser in focus [%]	50		
Laser focal spot size w_0 [μm]	>8	>3	>3
Peak intensity [10^{19} W/cm2]	1.9	13.3	120
Peak intensity parameter ξ	3.0	7.9	23.6
Peak quantum parameter X E_{beam}=16.5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

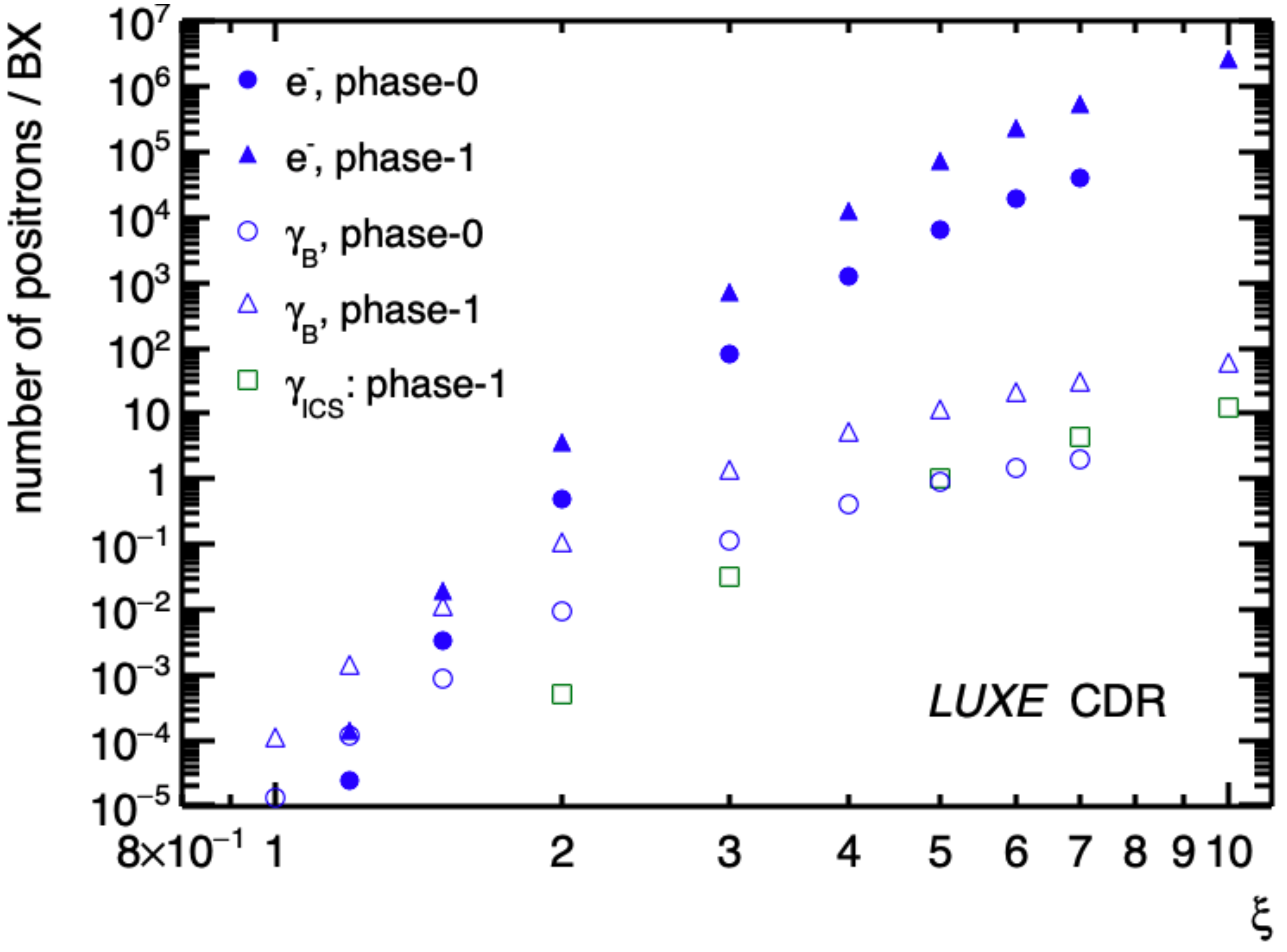
DATA TAKING MODES



RATES PER BUNCH CROSSING

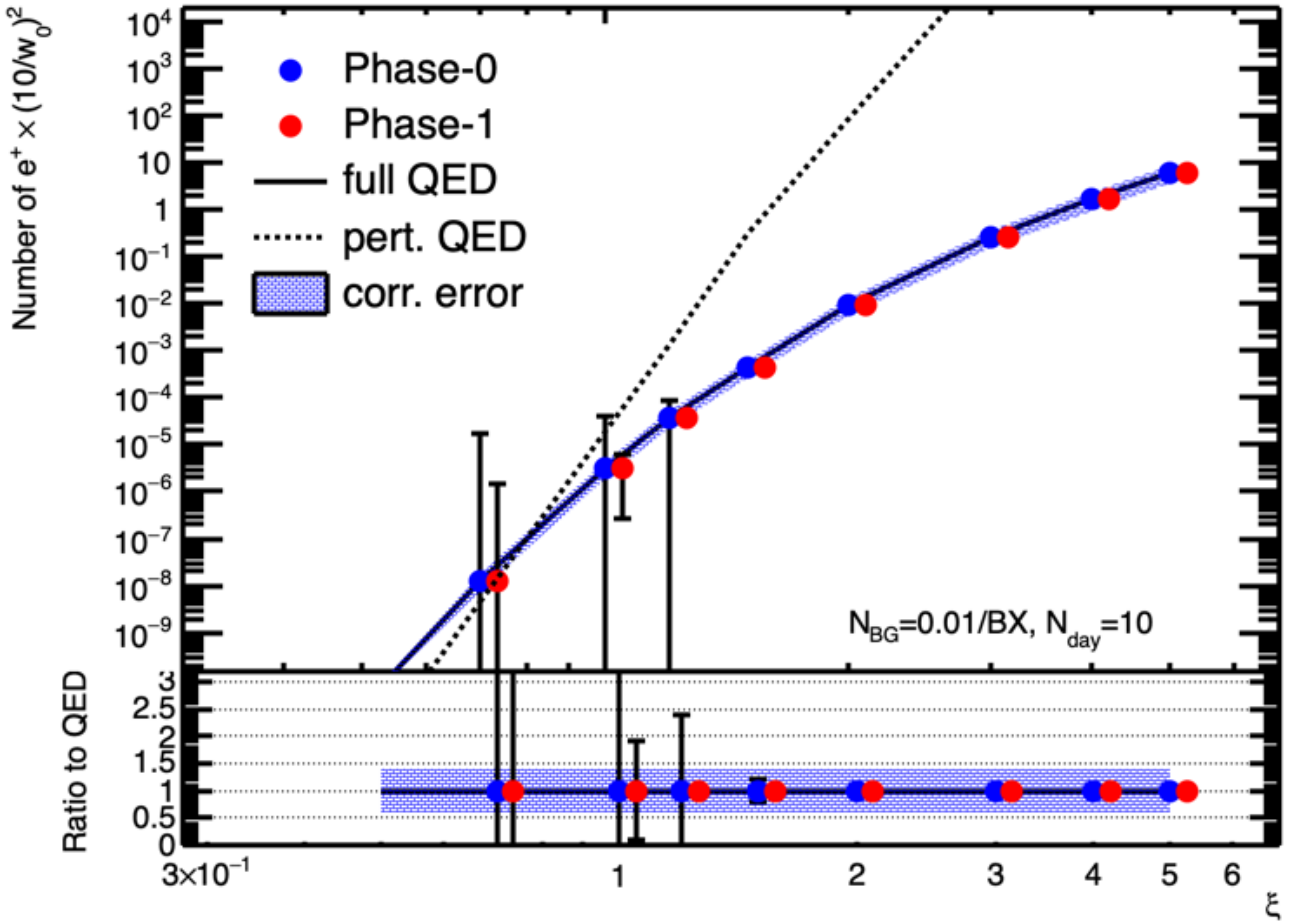


- Electron-laser:
  - Signal pairs created: 10^{-5} to 10^{6}.
  - Background particles flux and detectors used:
    - e^- side: up to 10^{9} particles, Cherenkov, and scintillating screen.
    - e^+ side: up to 10^{3} particles, calorimeter and tracker.
- Gamma-laser:
  - Signal pairs created: 10^{-5} 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.

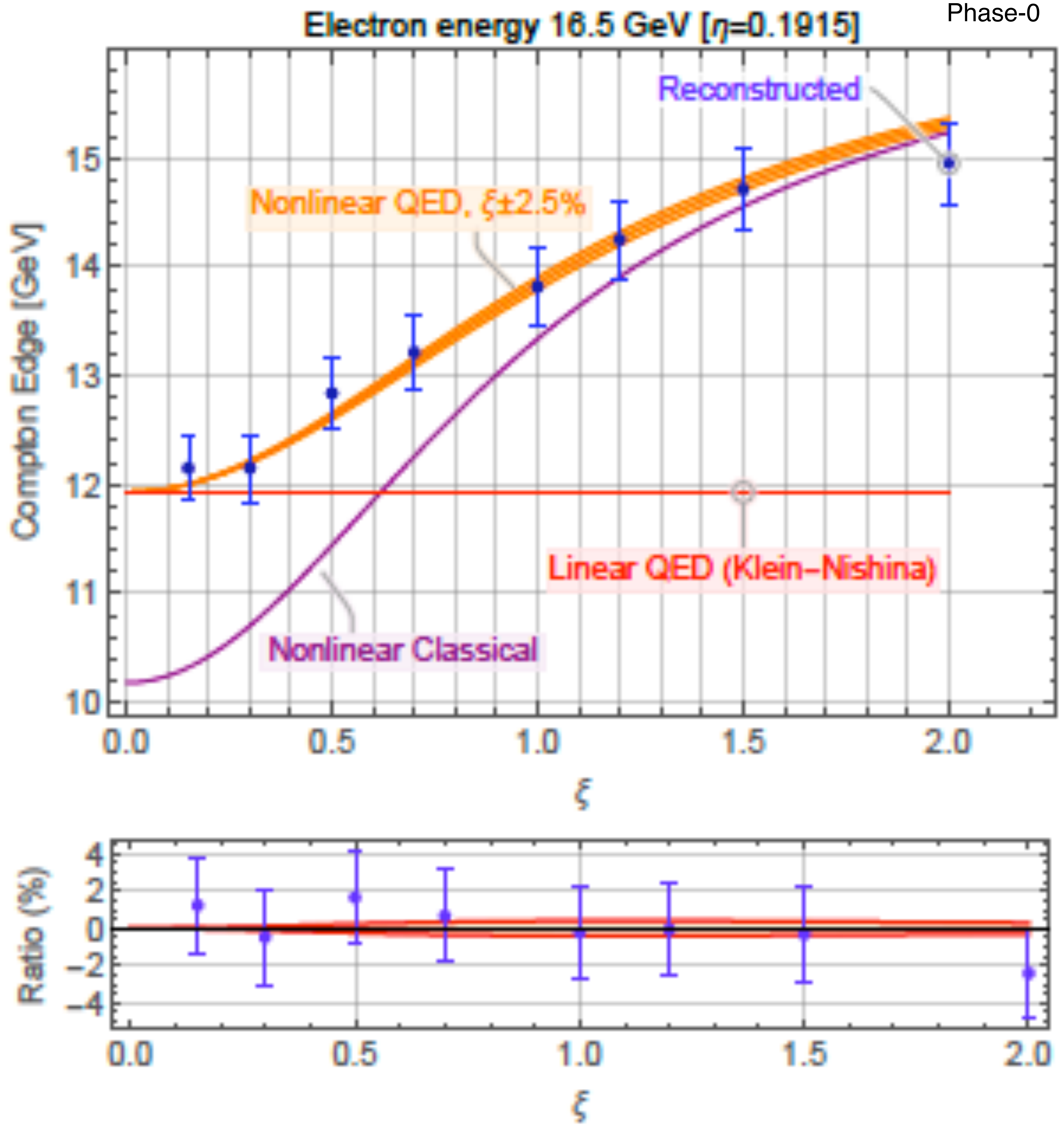


WHAT DO WE WANT TO MEASURE?

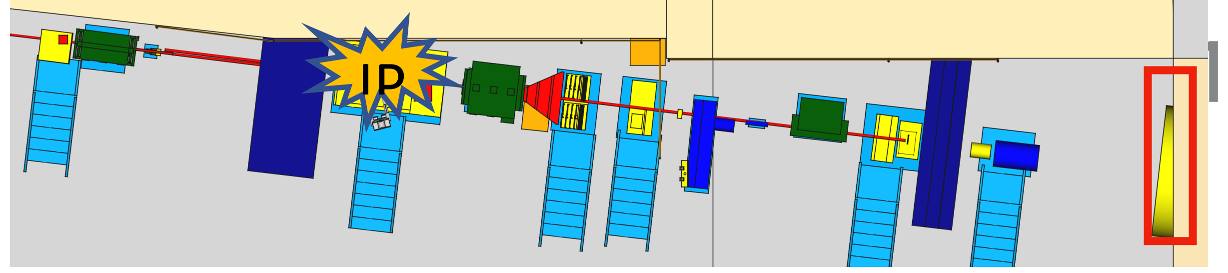
- Measure number of electrons per laser shot and Compton edges position.
  - Data measurements allow to discriminate theory!



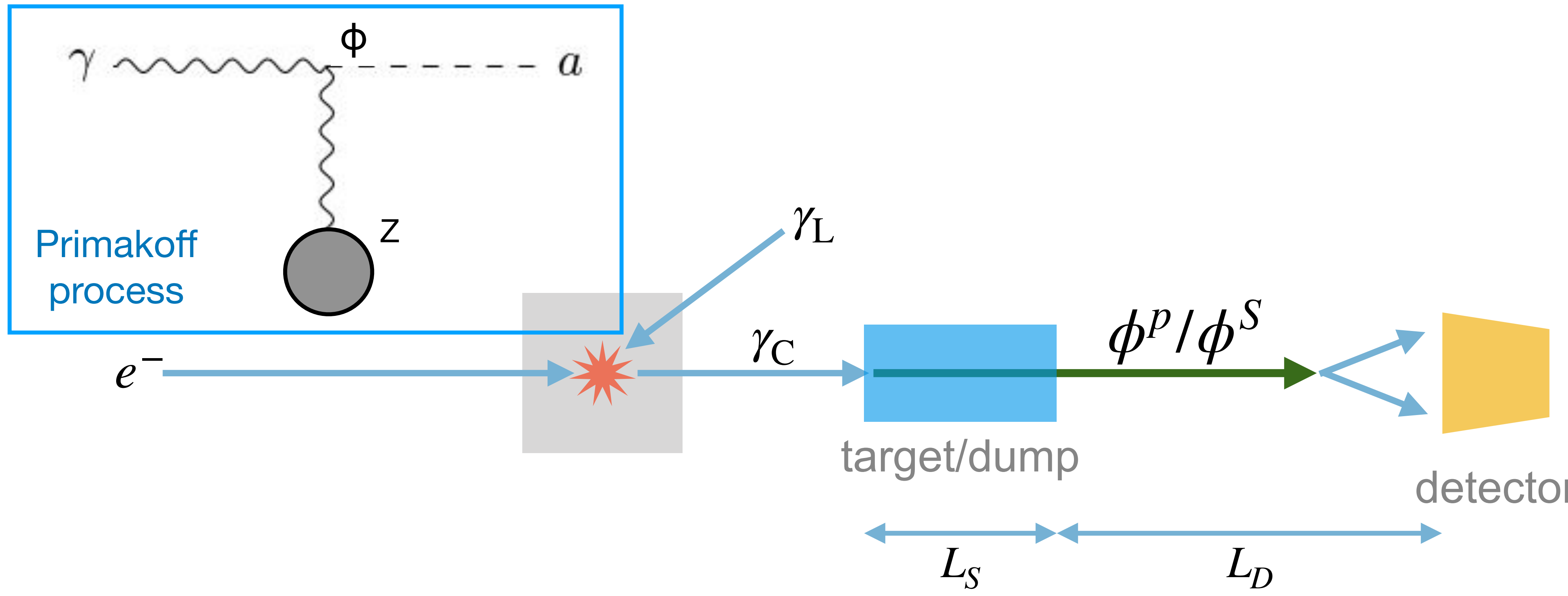
Phase-0



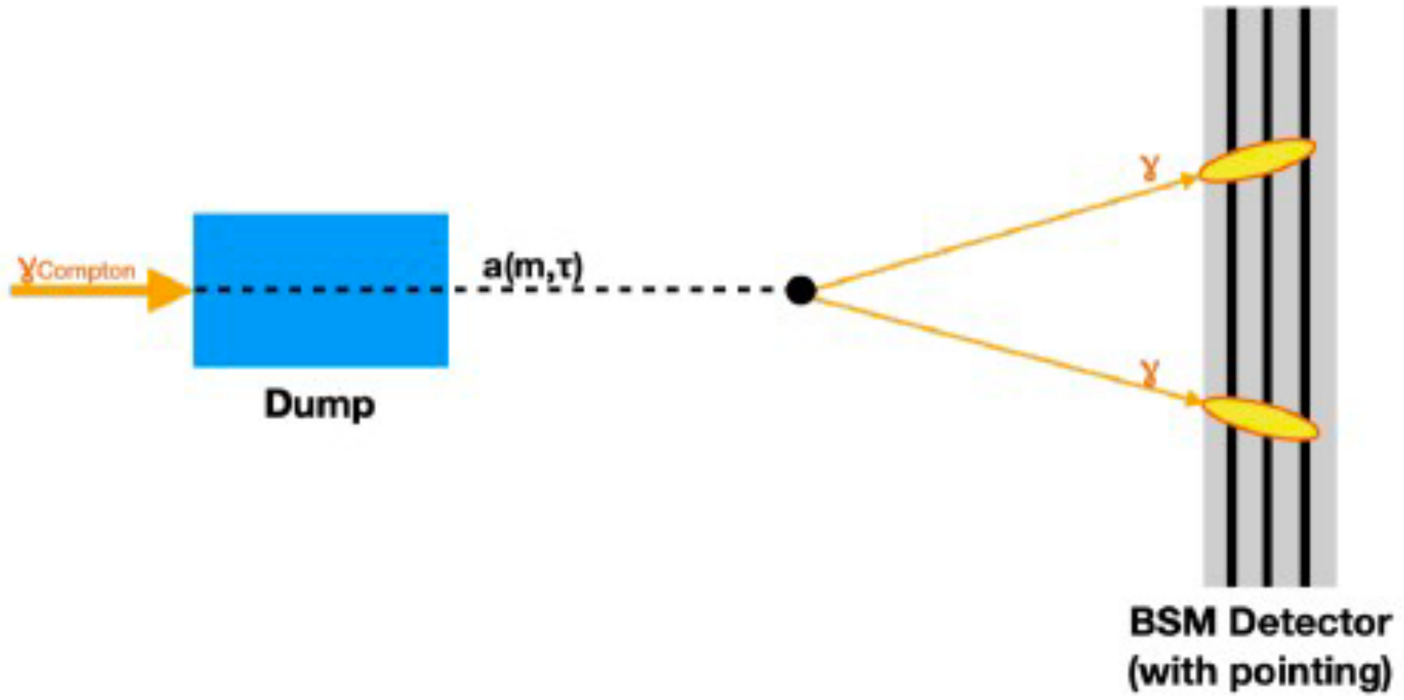
https://arxiv.org/pdf/2107.13554.pdf

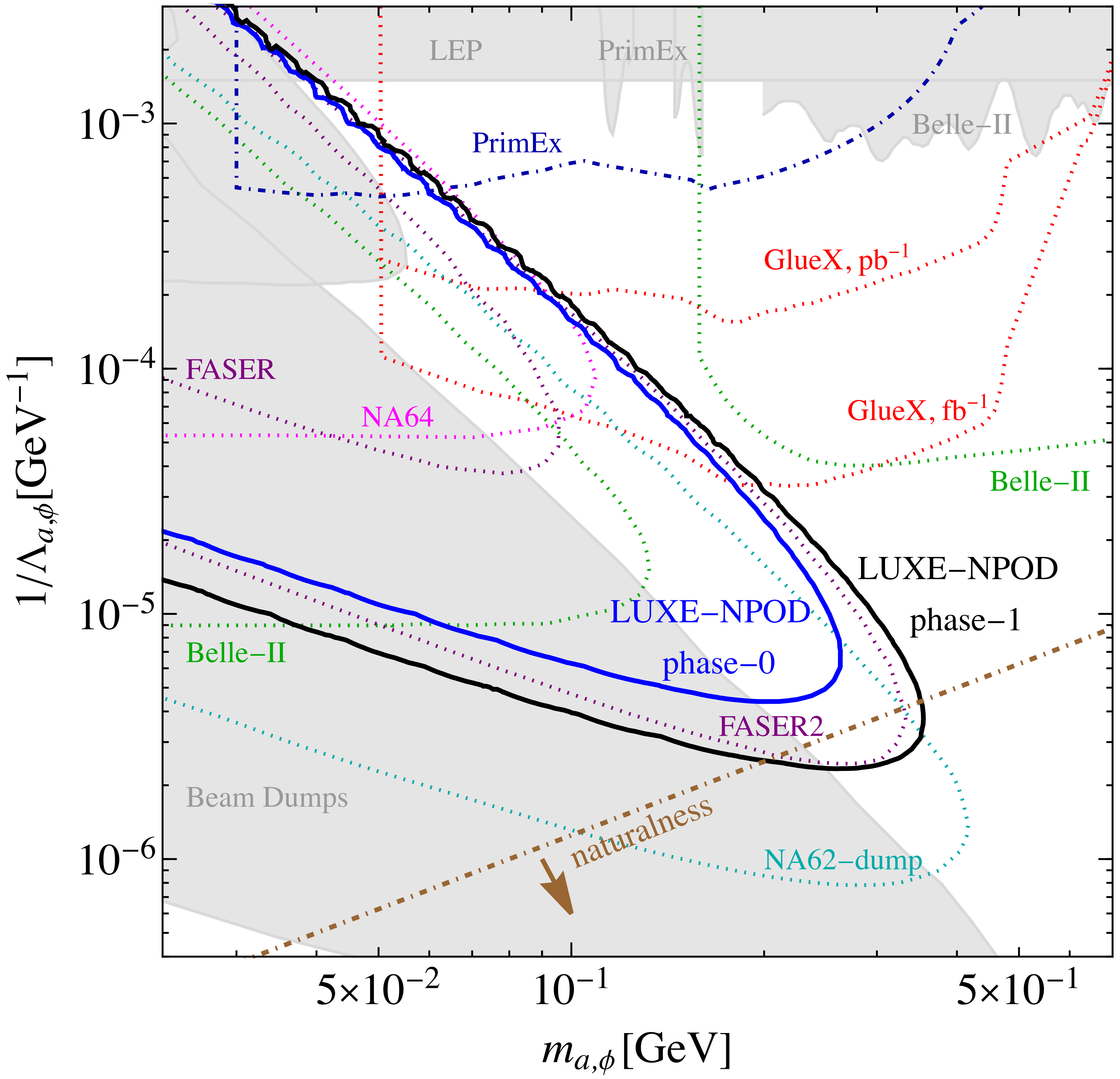


- Explore sensibility to BSM theories.
  - Axion-like particles (ALPs) produced in dump.
  - New neutral particles produced at IP.
  - Milli-charged particles



- For ALPs:
  - sensitive to masses m(a)~100 MeV.
  - decay to photons after some lifetime τ.
  - Place detector behind dump.
  - Could use calorimeter with good pointing resolution to constrain decay point.

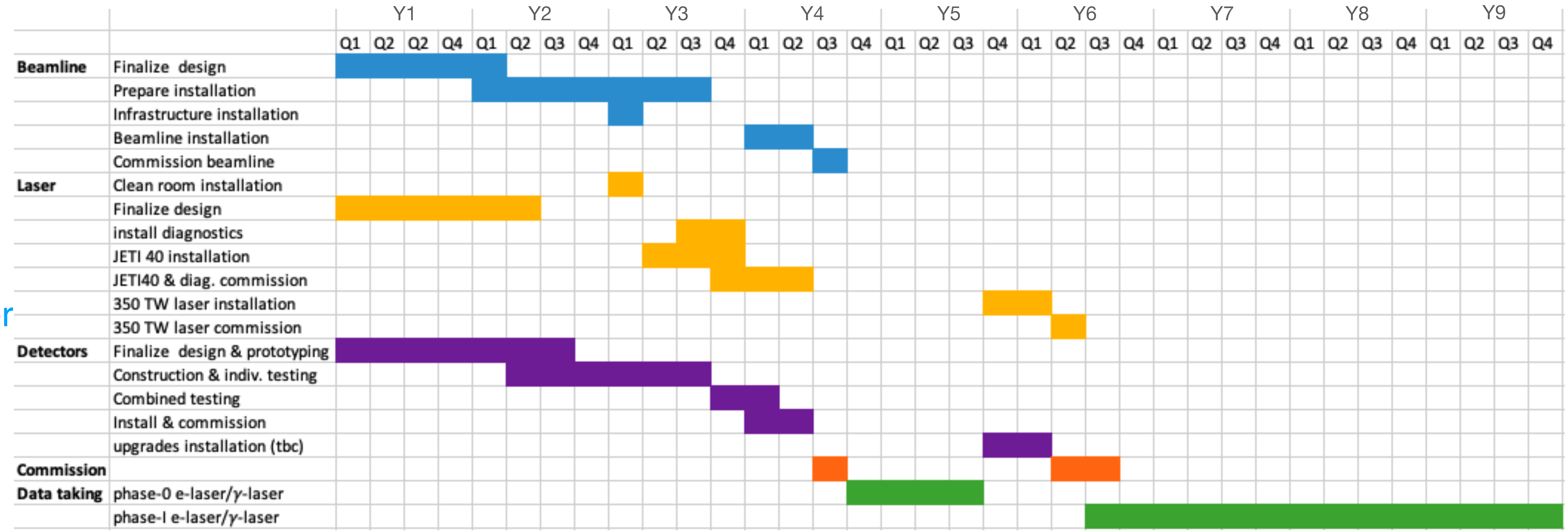




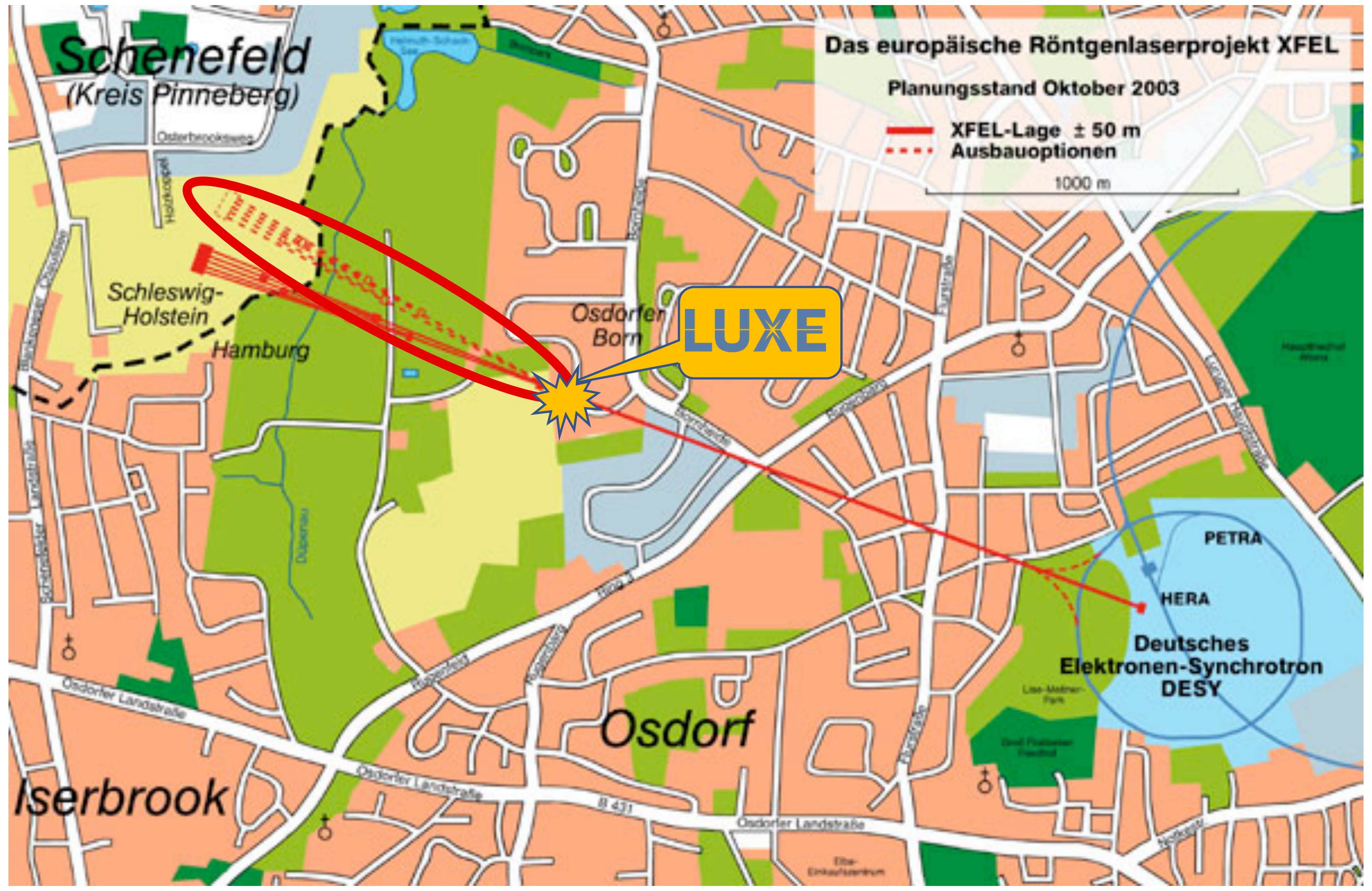
- First sensitivity show very competitive results!
  - After just 1 year of data.

ONE WORD ON THE PLANNING

- CDR released in 2021.
  - Now working toward TDR for 2022.
- Experiment should extend over a decade (design to end).
  - XFEL to reclaim tunnel for extension of facility in the future.

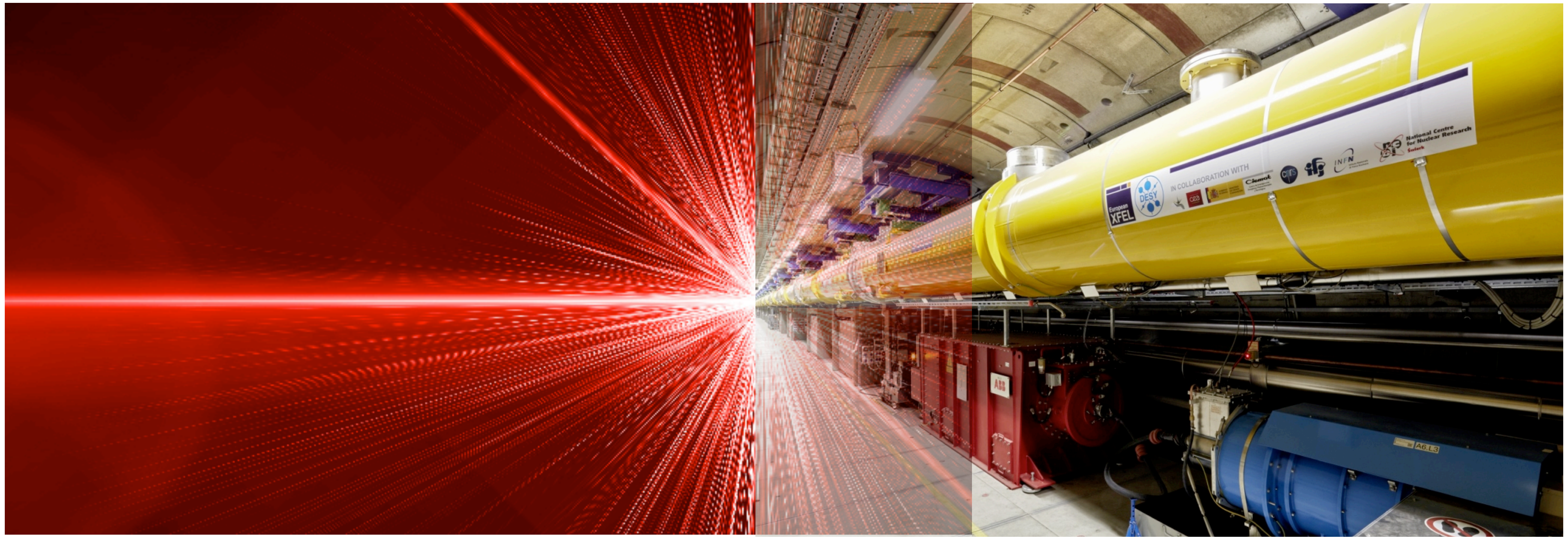


- In parallel of review continue detector R&D, and experiment planification.
  - Plan to perform multiple test-beam campaign in the future.

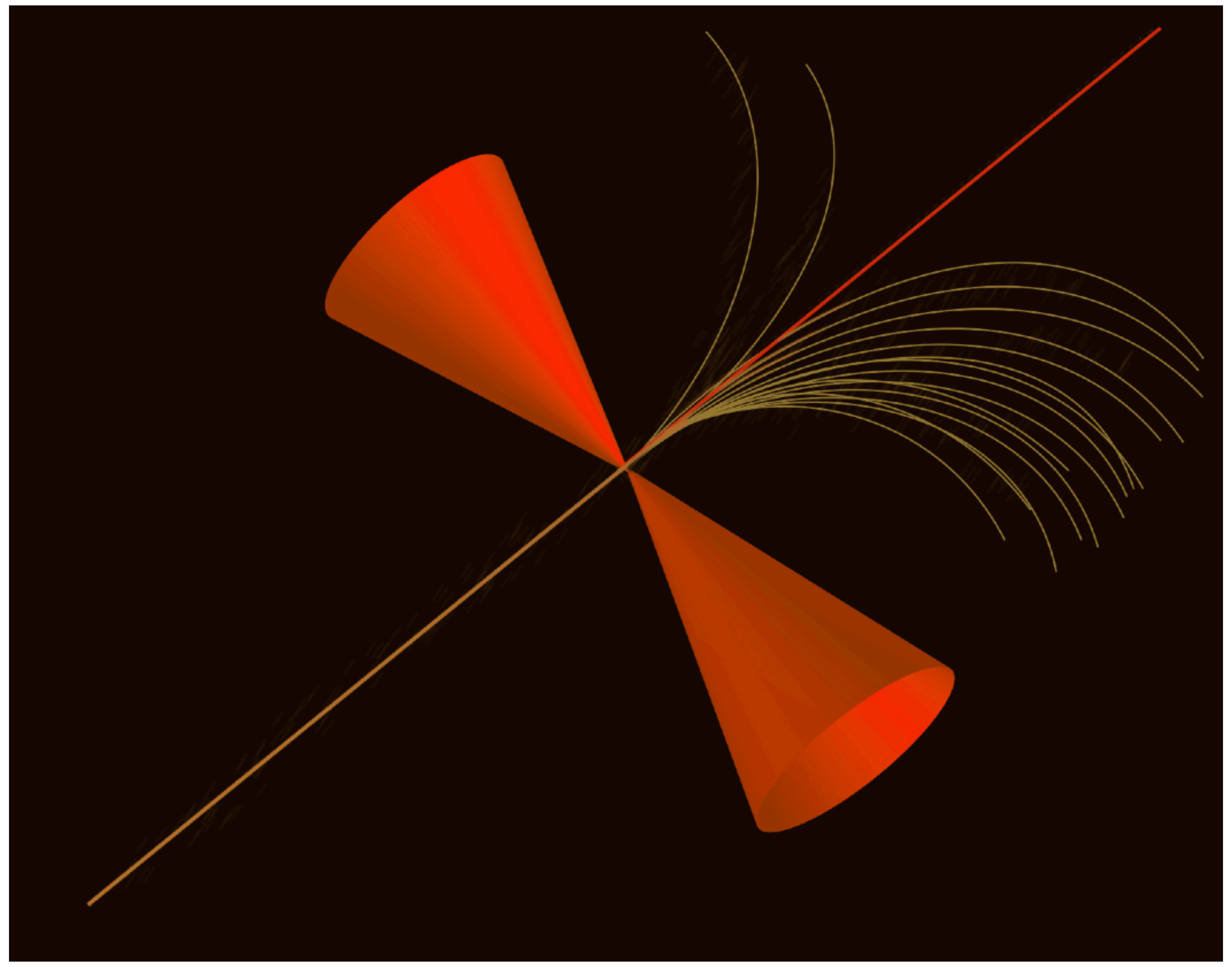


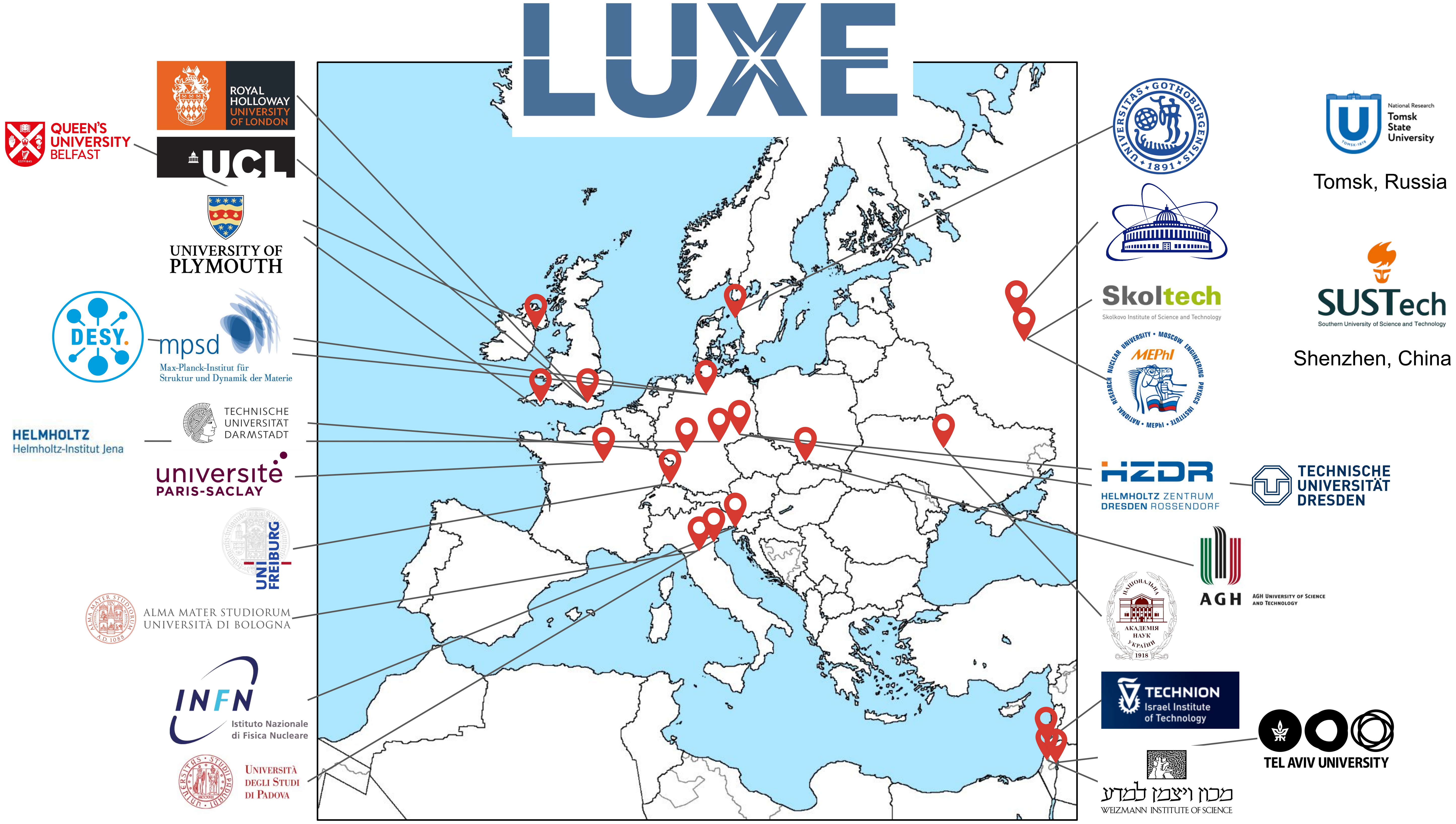
CONCLUSIONS

- 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!
    - 10^{-5} to 10^{9} per laser shot.
  - 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.



THANK YOU FOR YOUR ATTENTION!





Conceptual Design Report for the LUXE Experiment

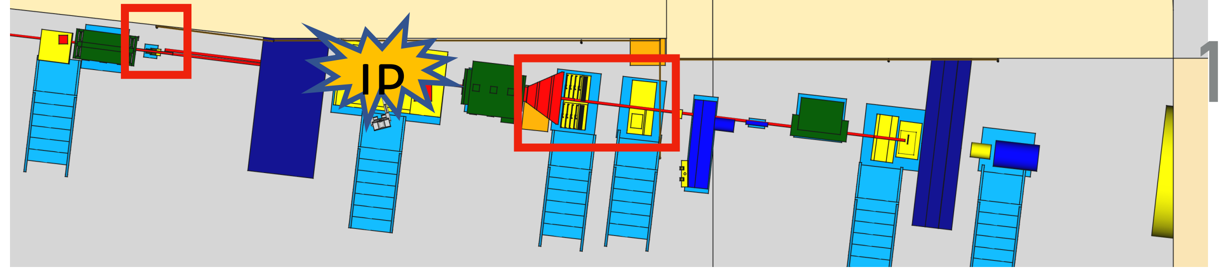
H. Abramowicz[1], U. Acosta[2,3], M. Altarelli[4], R. Aßmann[5], Z. Bai[6,7], T. Behnke[5], Y. Benhammou[1], T. Blackburn[8], S. Boogert[9], O. Borysov[5], M. Borysova[5,10], R. Brinkmann[5], M. Bruschi[11], F. Burkart[5], K. Büßer[5], N. Cavanagh[12], O. Davidi[6], W. Decking[5], U. Dosselli[13], N. Elkina[3], A. Fedotov[14], M. Firlej[15], T. Fiutowski[15], K. Fleck[12], M. Gostkin[16], C. Grojean[*5], J. Hallford[5,17], H. Harsh[18,19], A. Hartin[17], B. Heinemann[†5,20], T. Heinzl[21], L. Helary[5], M. Hoffmann[5,20], S. Huang[1], X. Huang[5,15,20], M. Idzik[15], A. Ilderton[21], R. Jacobs[5], B. Kämpfer[2,3], B. King[21], H. Lahno[10], A. Levanon[1], A. Levy[1], I. Levy[22], J. List[5], W. Lohmann[‡5], T. Ma[23], A.J. Macleod[21], V. Malka[6], F. Meloni[5], A. Mironov[14], M. Morandin[13], J. Moron[15], E. Negodin[5], G. Perez[6], I. Pomerantz[1], R.Pöschl[24], R. Prasad[5], F. Quéré[25], A. Ringwald[5], C. Rödel[26], S. Rykovanov[27], F. Salgado[18,19], A. Santra[6], G. Sarri[12], A. Sävert[18], A. Sbrizzi[§28], S. Schmitt[5], U. Schramm[2,3], S. Schuwalow[5], D. Seipt[18], L. Shaimerdenova[29], M. Shchedrolosiev[5], M. Skakunov[29], Y. Soreq[23], M. Streeter[12], K. Swientek[15], N. Tal Hod[6], S. Tang[21], T. Teter[18,19], D. Thoden[5], A.I. Titov[16], O. Tolbanov[29], G. Torgrimsson[3], A. Tyazhev[29], M. Wing[5,17], M. Zanetti[13], A. Zarubin[29], K. Zeil[3], M. Zepf[18,19], and A. Zhemchukov[16]

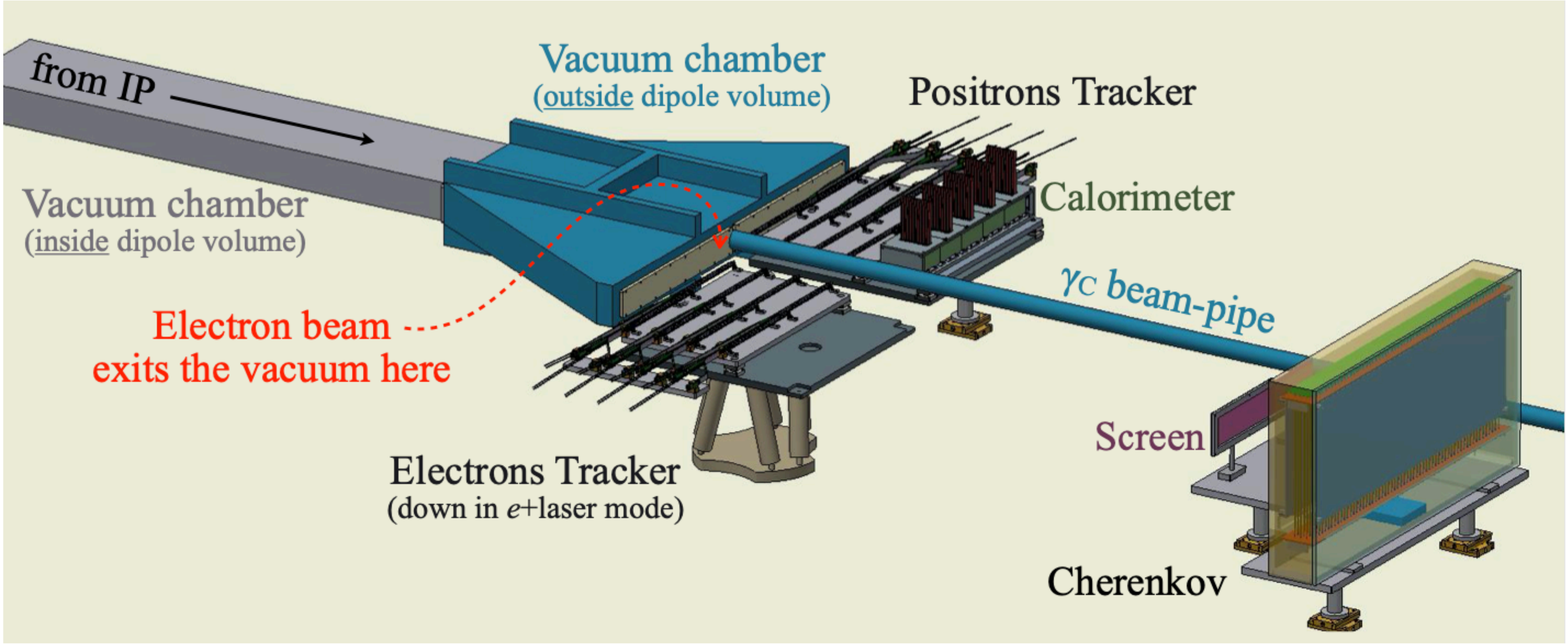
More informations:

- CDR, published by European Physics Journal ST: Eur.Phys.J.ST 230 (2021) 11, 2445-2560
- LUXE: https://luxe.desy.de/
- NPOD paper: https://arxiv.org/pdf/2107.13554.pdf

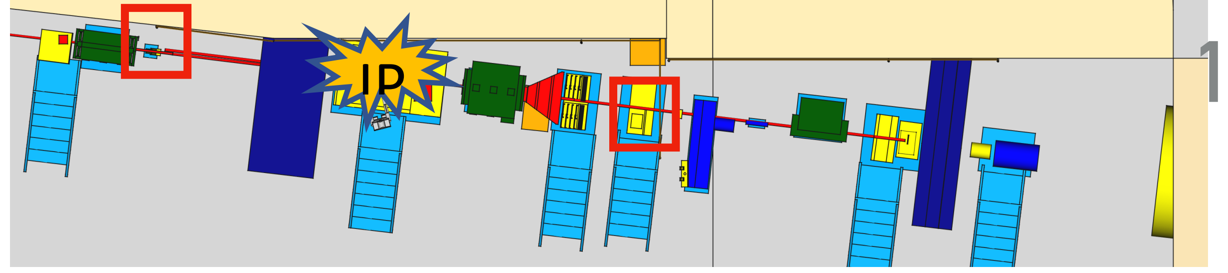
BACK-UP

DETECTOR AT THE IP



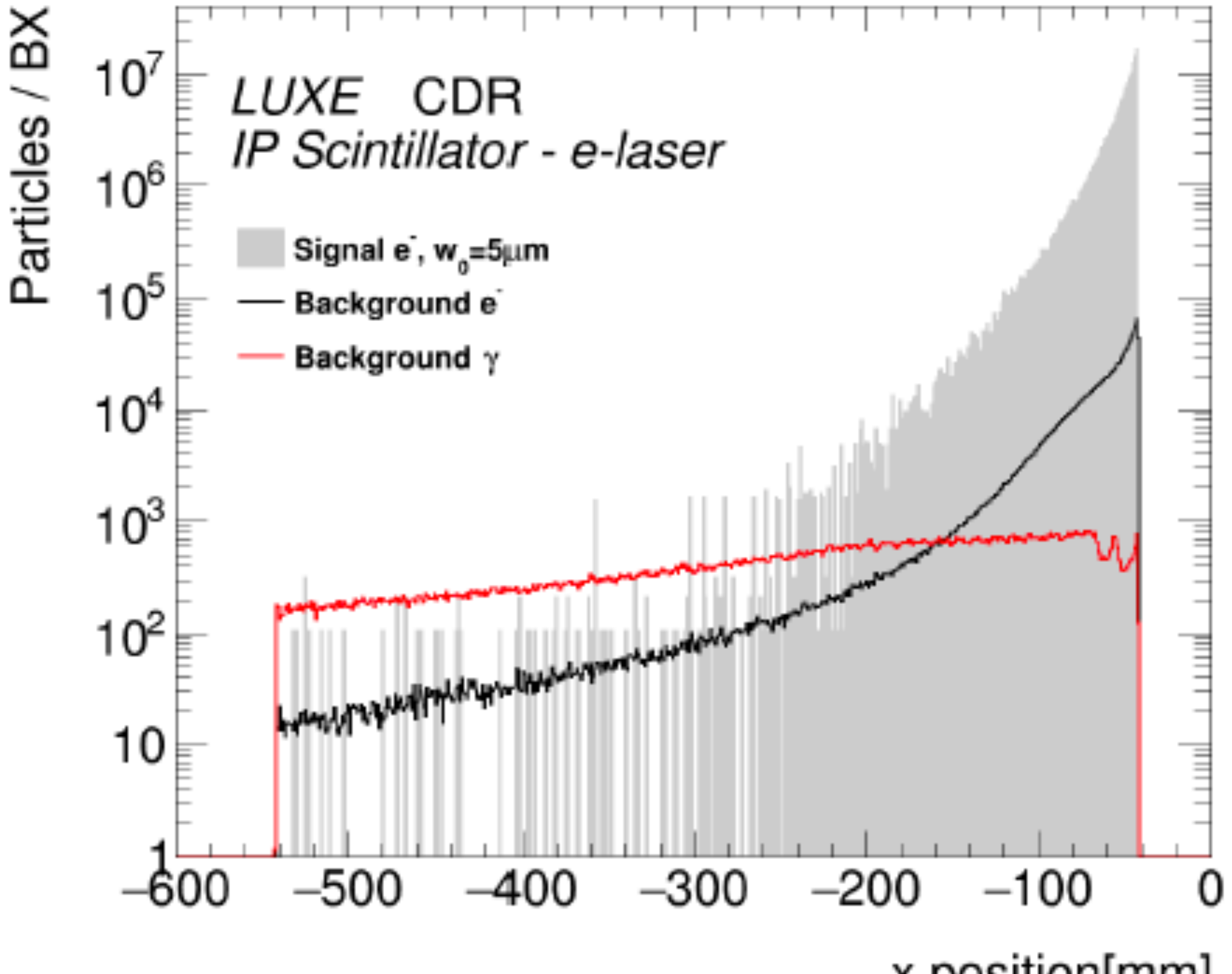


CHERENKOV AND SCINTILLATOR SCREEN (E-LASER: IP DETECTOR ELECTRON SIDE | GAMMA-LASER: BREM TARGET)



- Scintillator screen with camera:
  - Position of particles on screen determine energy (thanks to the magnetic field).
    - Signal/background ~100
      - Used for instance at AWAKE at CERN

- Cherenkov detector:
  - Developed for ILC polarimetry.
    - Use low refractive gas index (such as Ar) and optical filter to reduce light yield.
      - Fine segmentation (1.5mm) to resolve Compton edges
        - Signal/background>1000
        - Not sensitive to electron <20 MeV.



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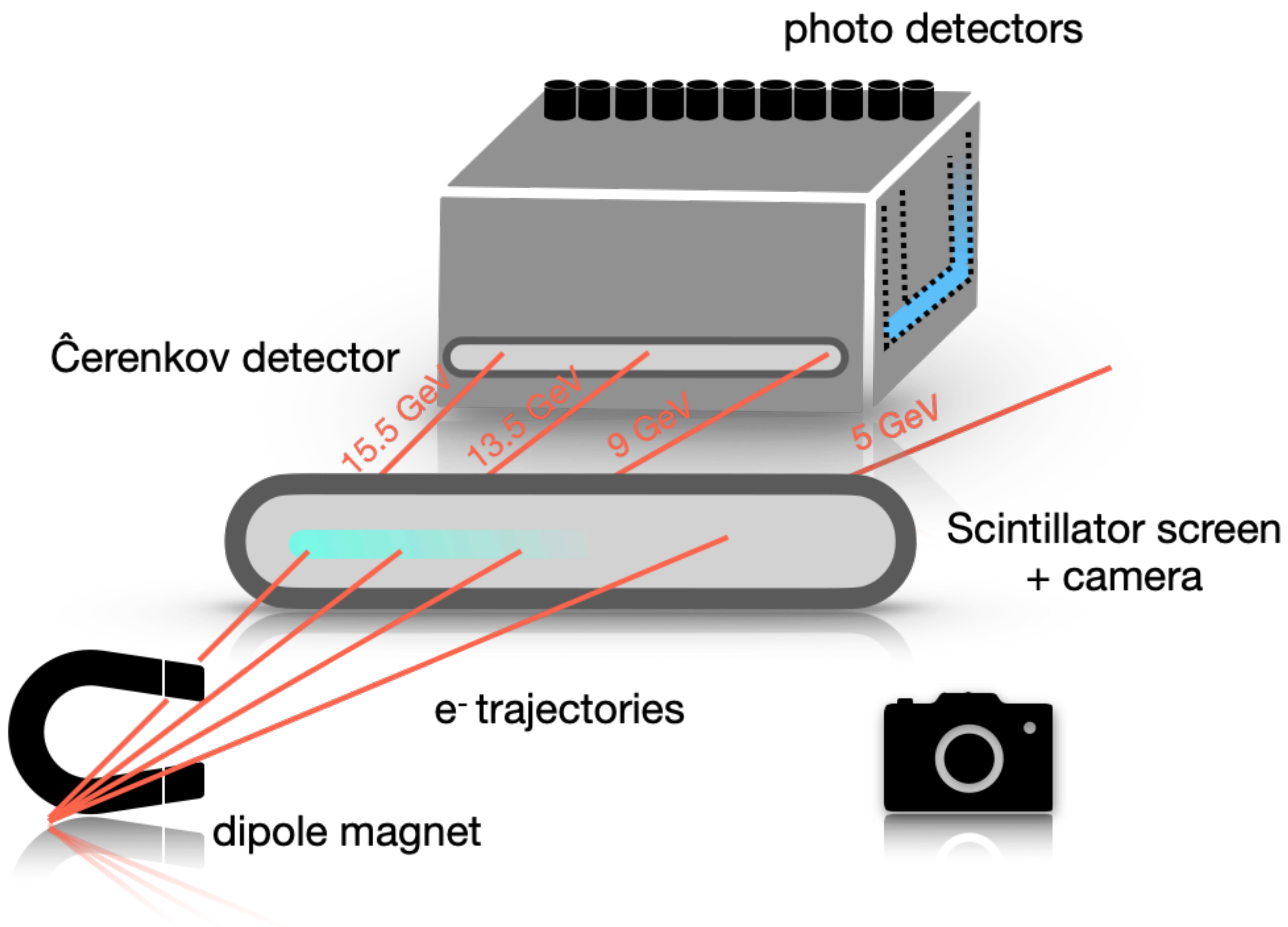
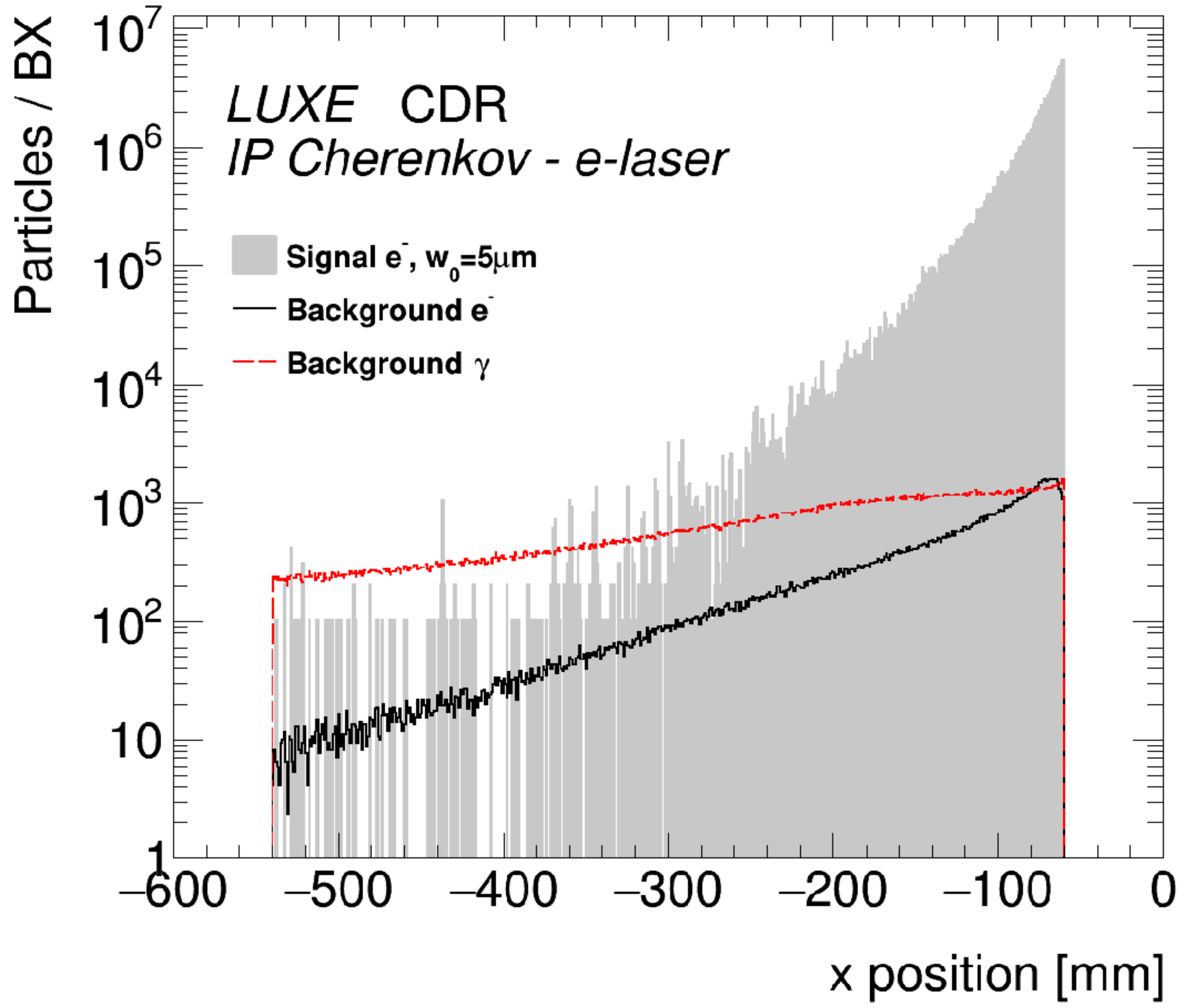
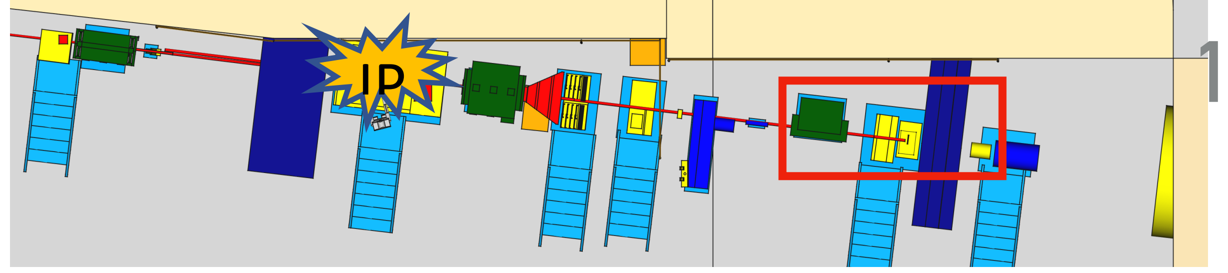
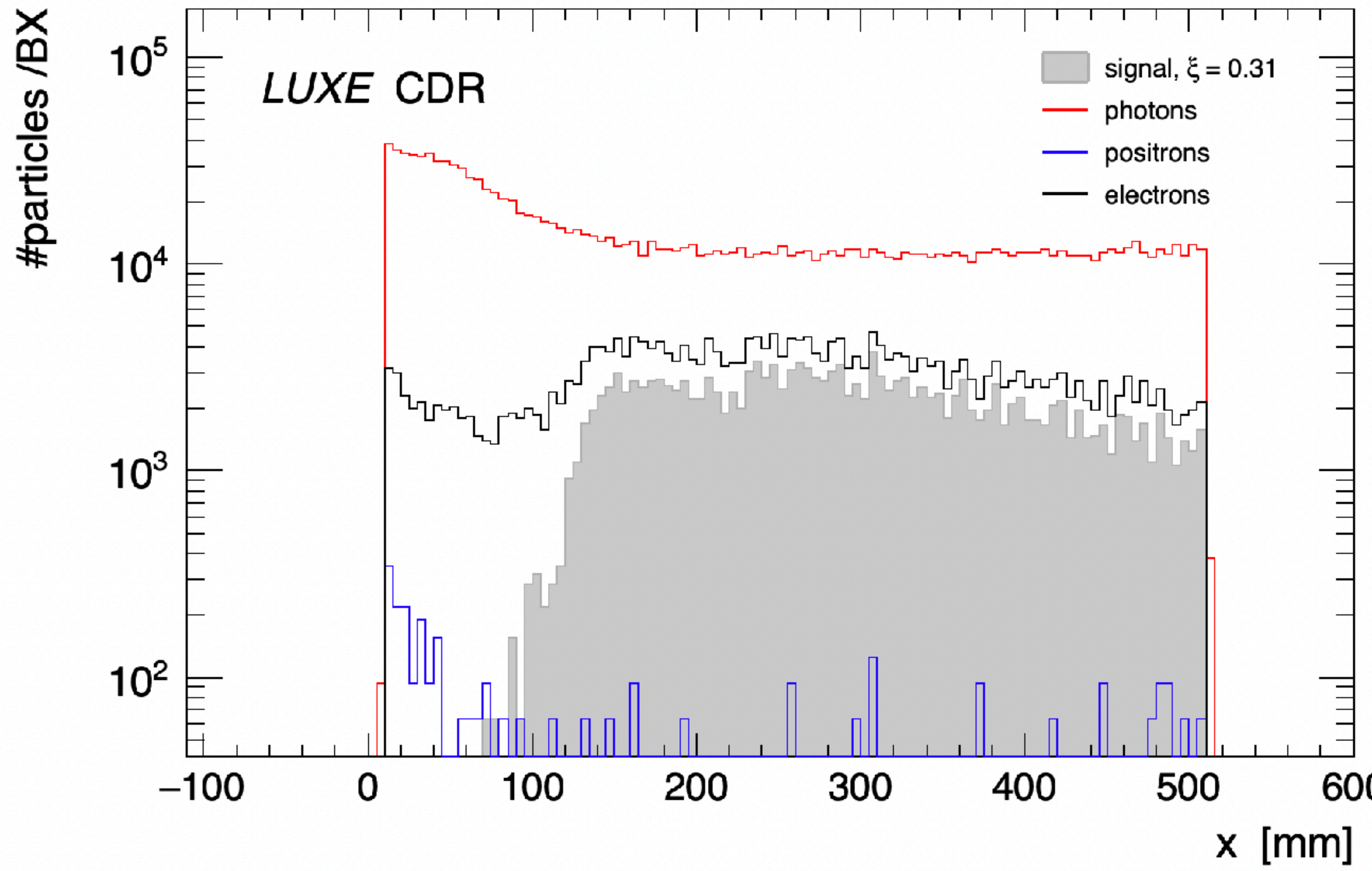


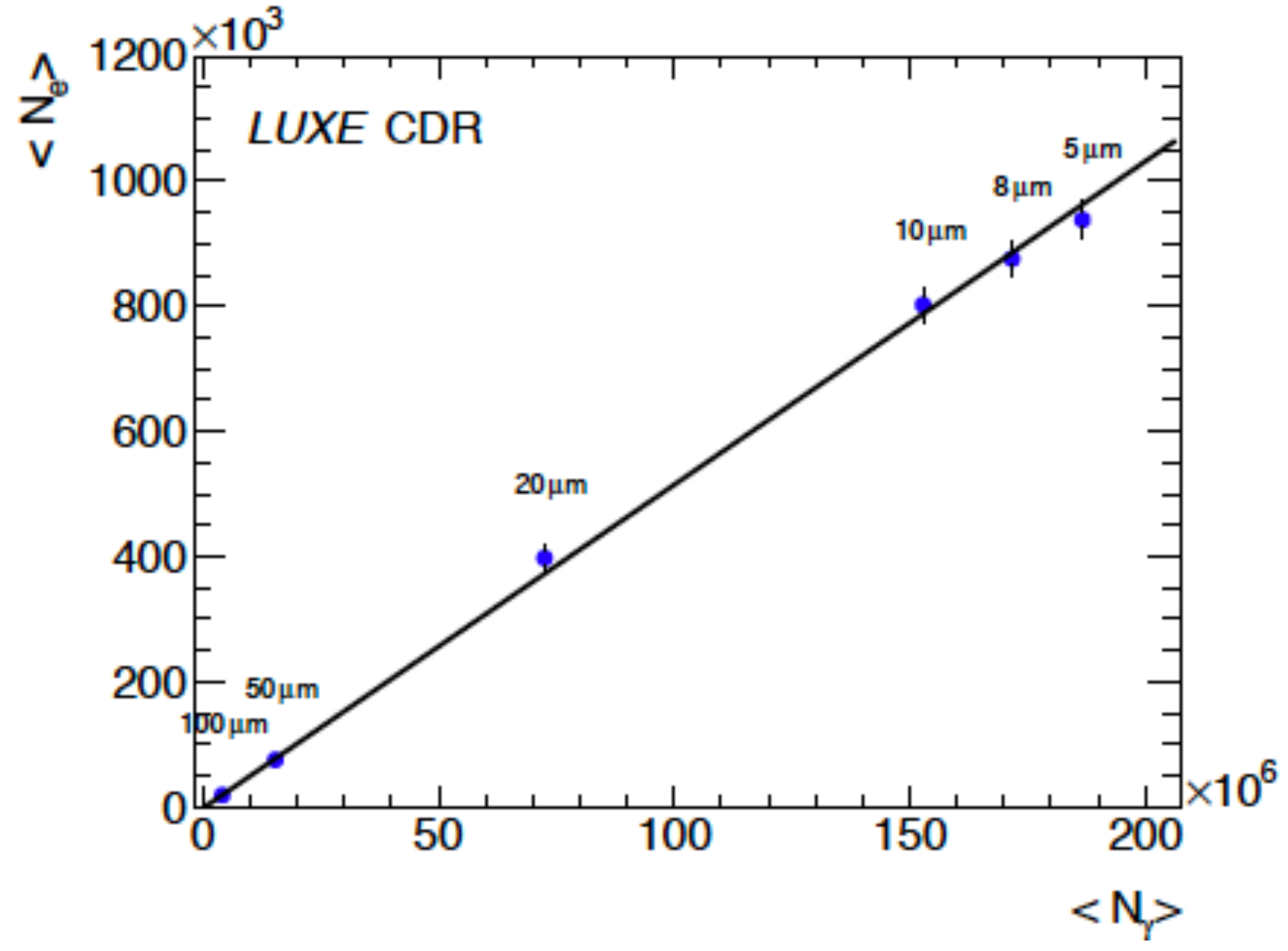


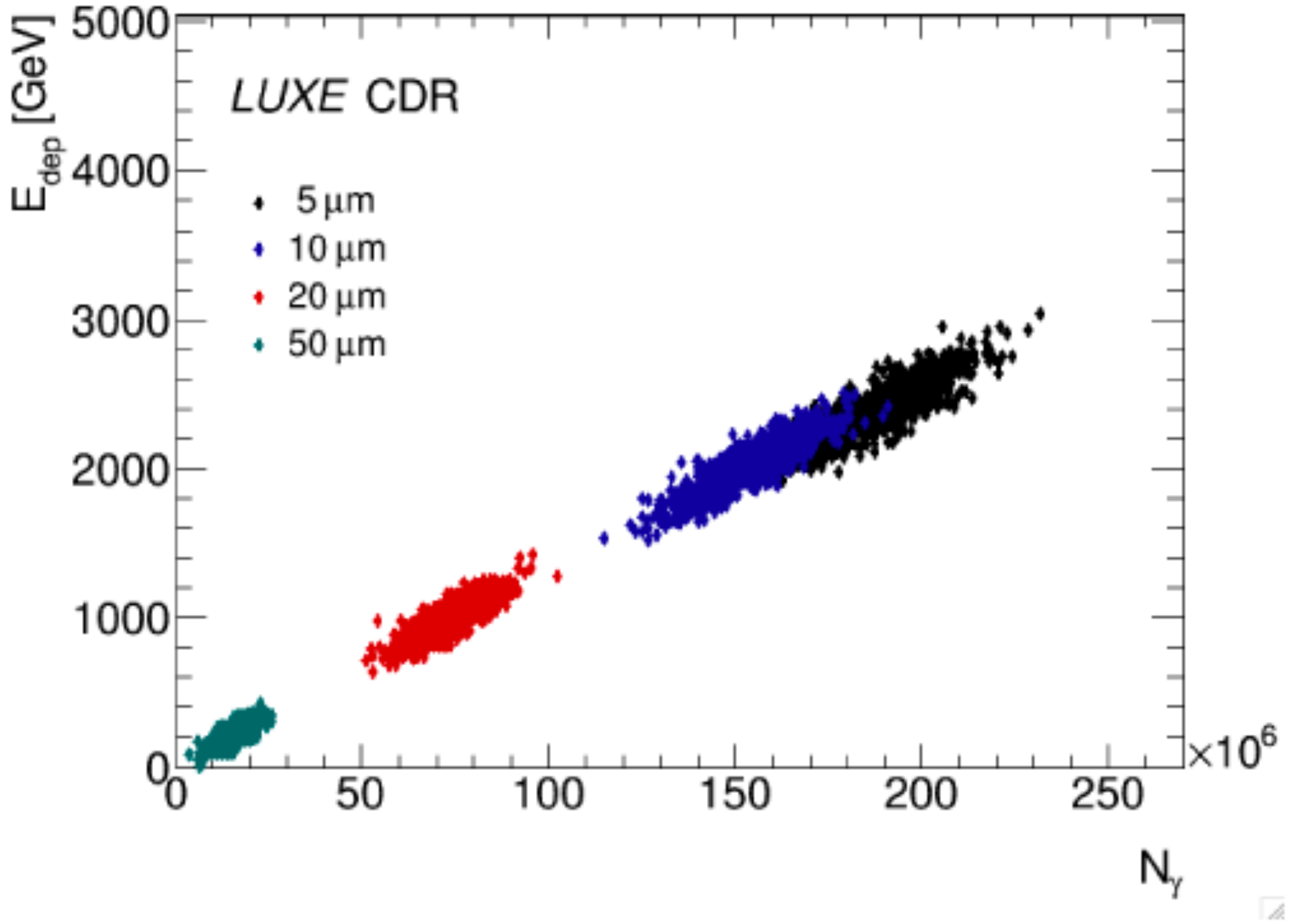


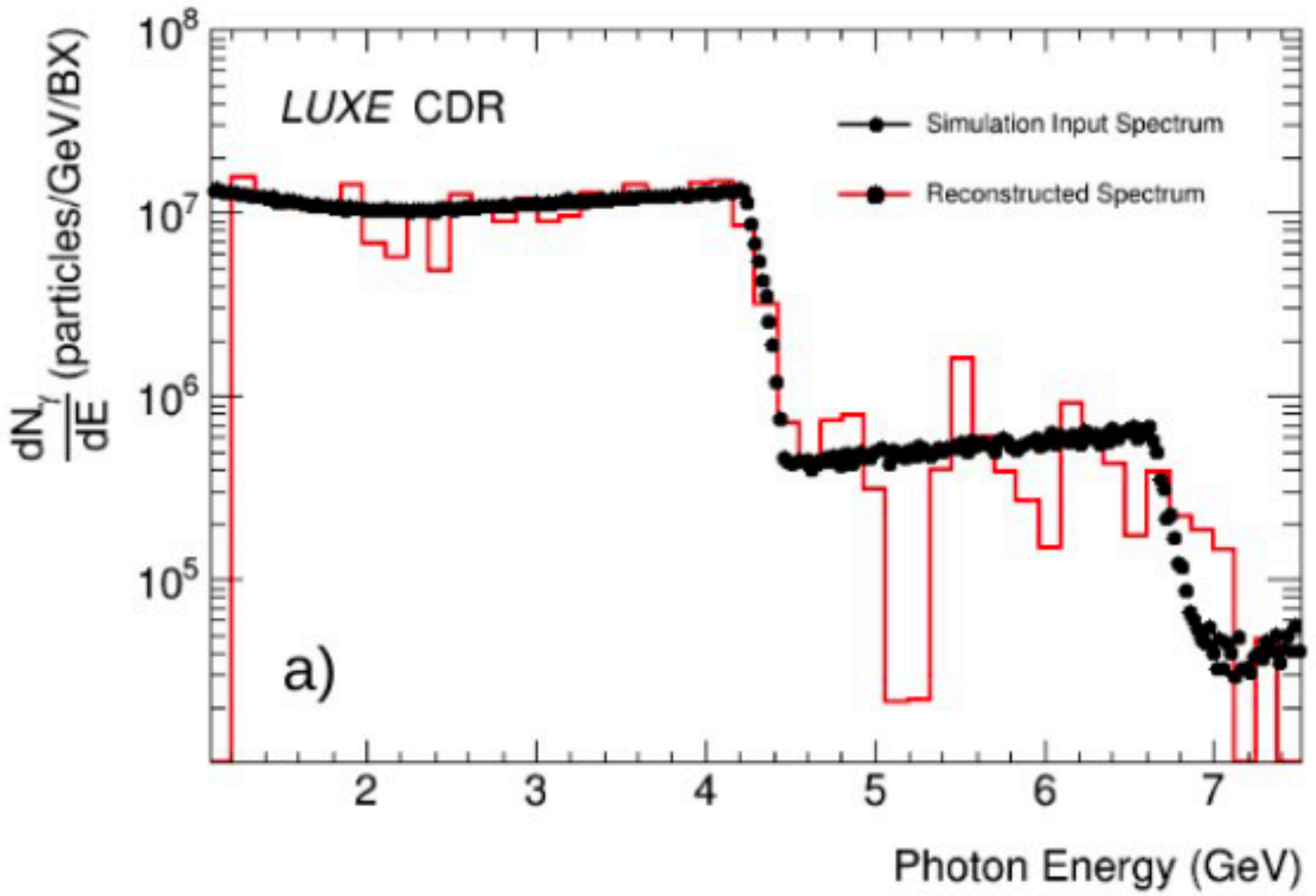
PHOTON DETECTION SYSTEM (END OF BEAMLINE IN BOTH MODES)

- Three detector technologies
  - Spectrometer with scintillator screens behind converter
    - Measure flux and energy spectrum.
      - Alternative way to reconstruct Compton edges!
  - Backscattering calorimeter using lead glass blocks from HERMES.
    - Measure flux.
  - Gamma profiler (sapphire sensors)
    - Measure location.
      - If use polarized laser, expect angular spectrum of photons to depend on ξ.

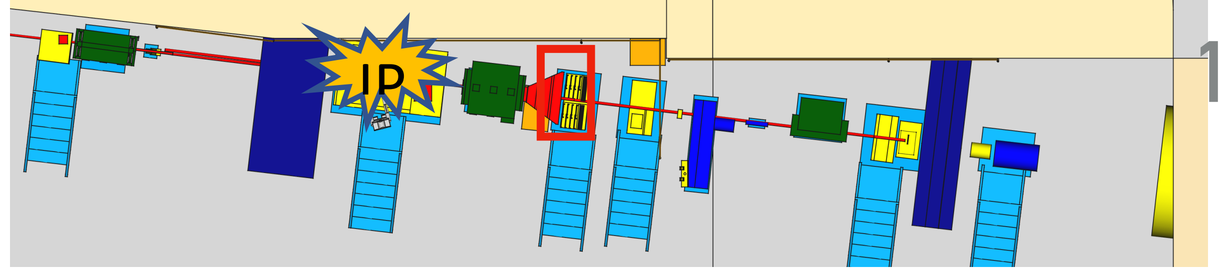




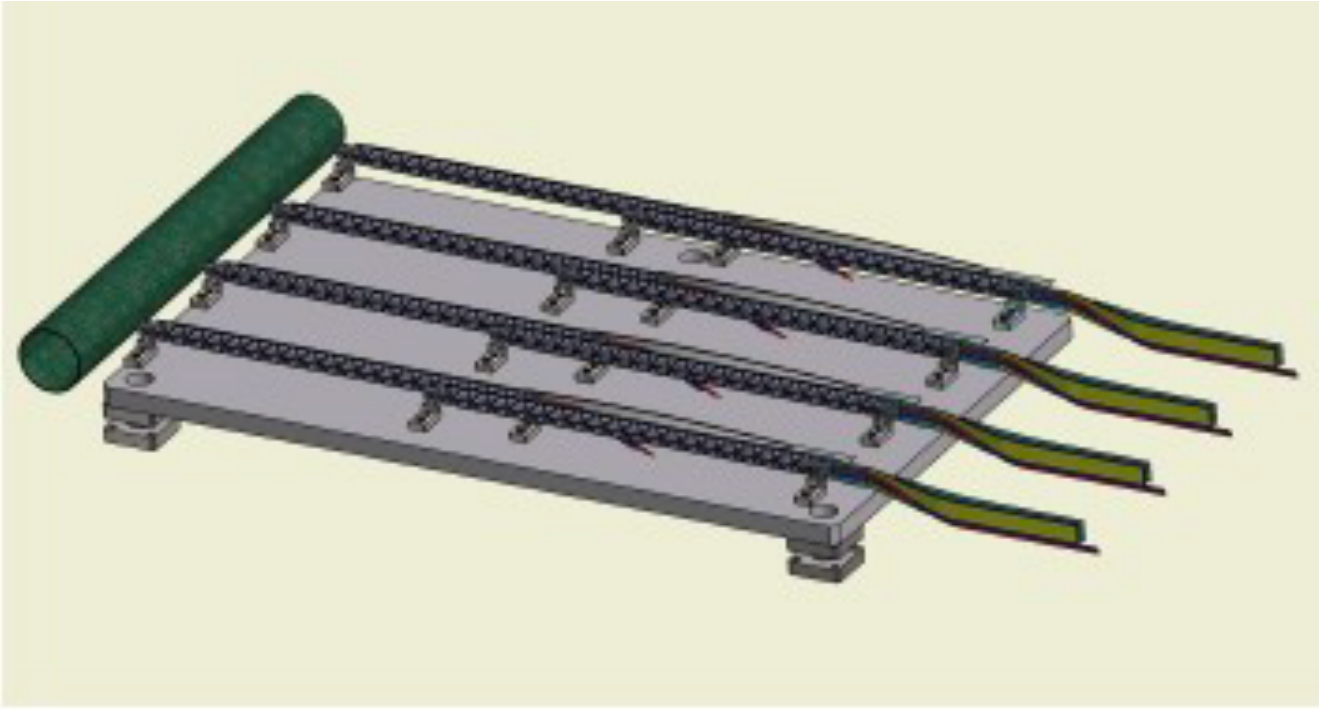


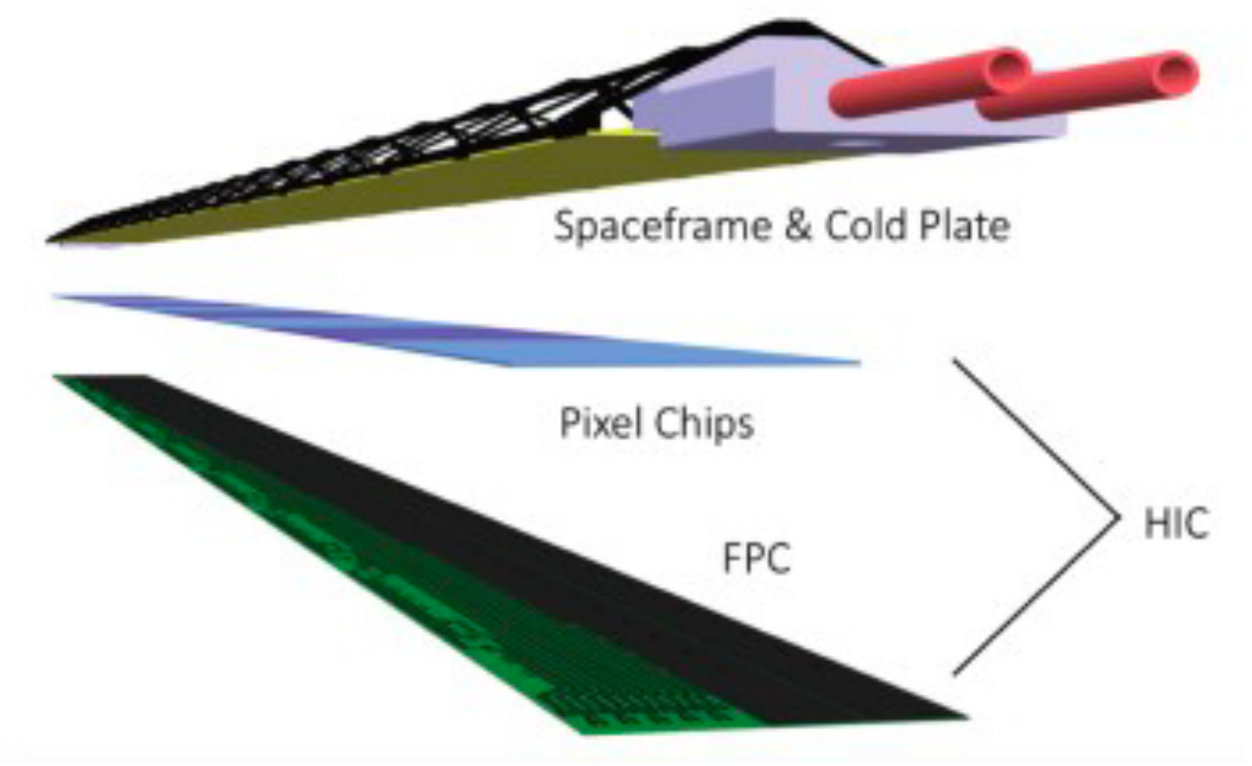


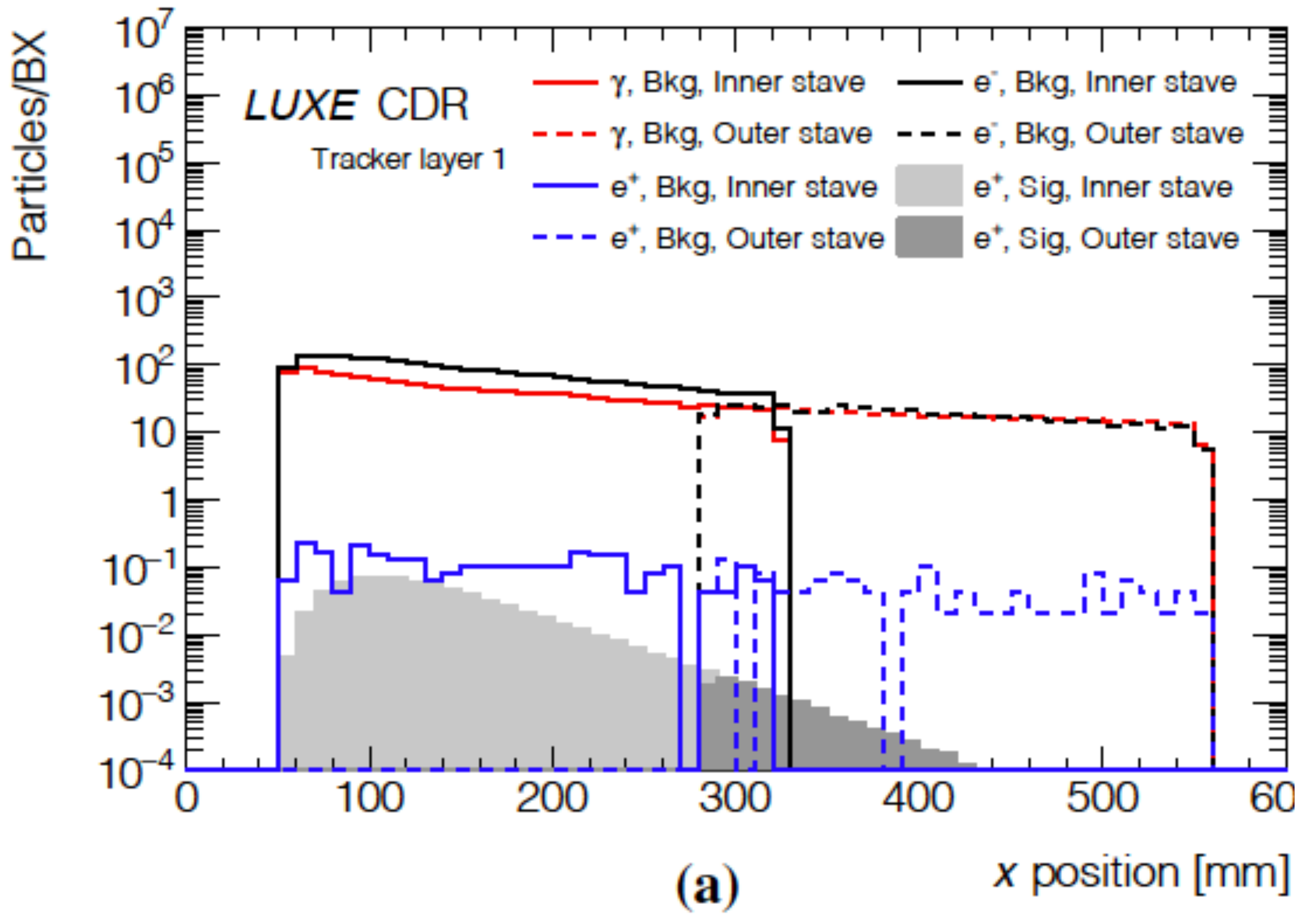
TRACKER (E-LASER: IP DETECTOR POSITRON SIDE | GAMMA-LASER: IP DETECTOR BOTH SIDES)



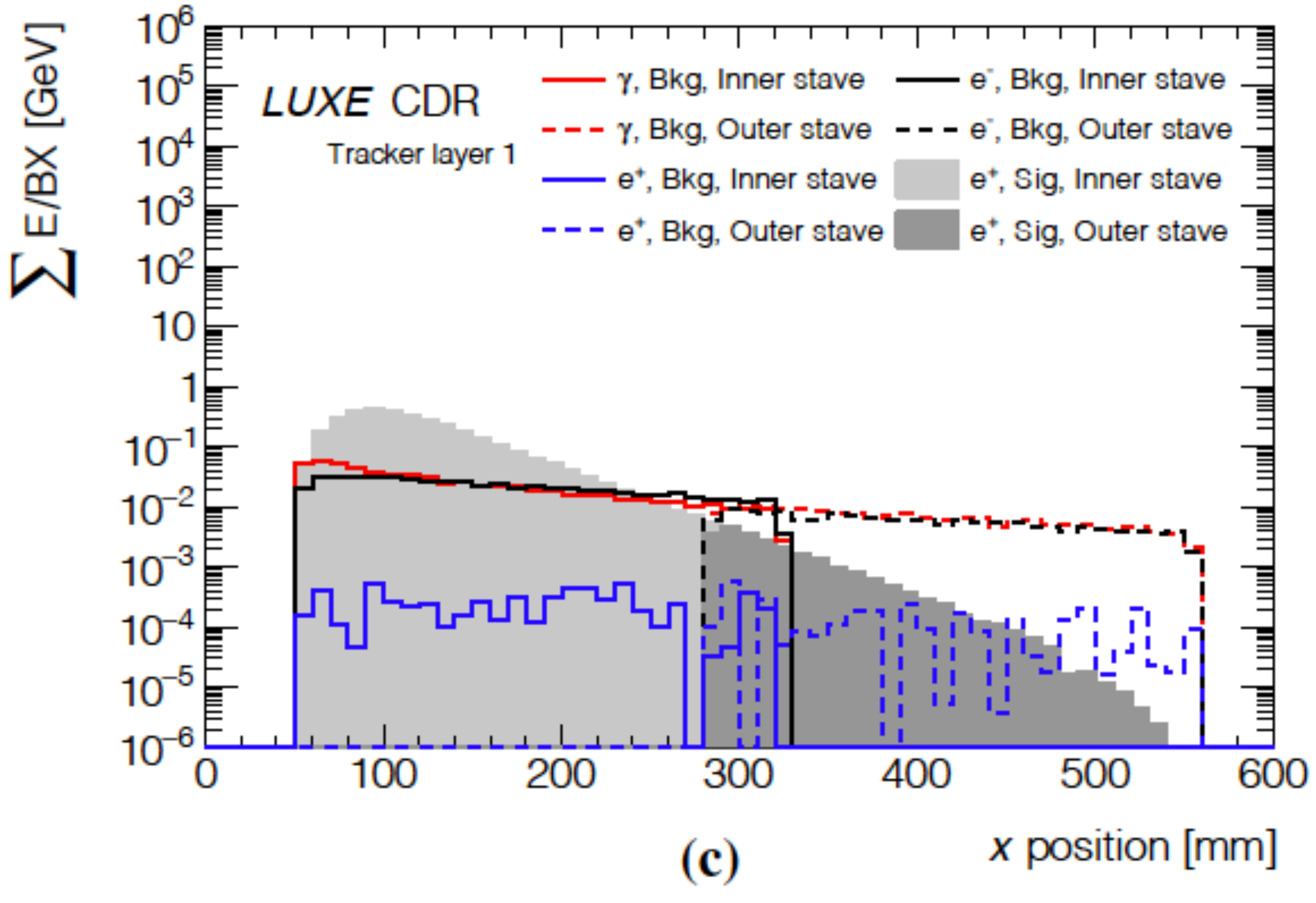
- Use four layers of ALPIDE silicon pixel sensors.
  - Developed for ALICE tracker upgrade.
    - Pitch size: 27 x 29 μm^2 => spatial resolution ~5 μm
- Using tracking algorithm:
  - Background: <0.1 event per bunch crossing
  - Good energy reconstruction



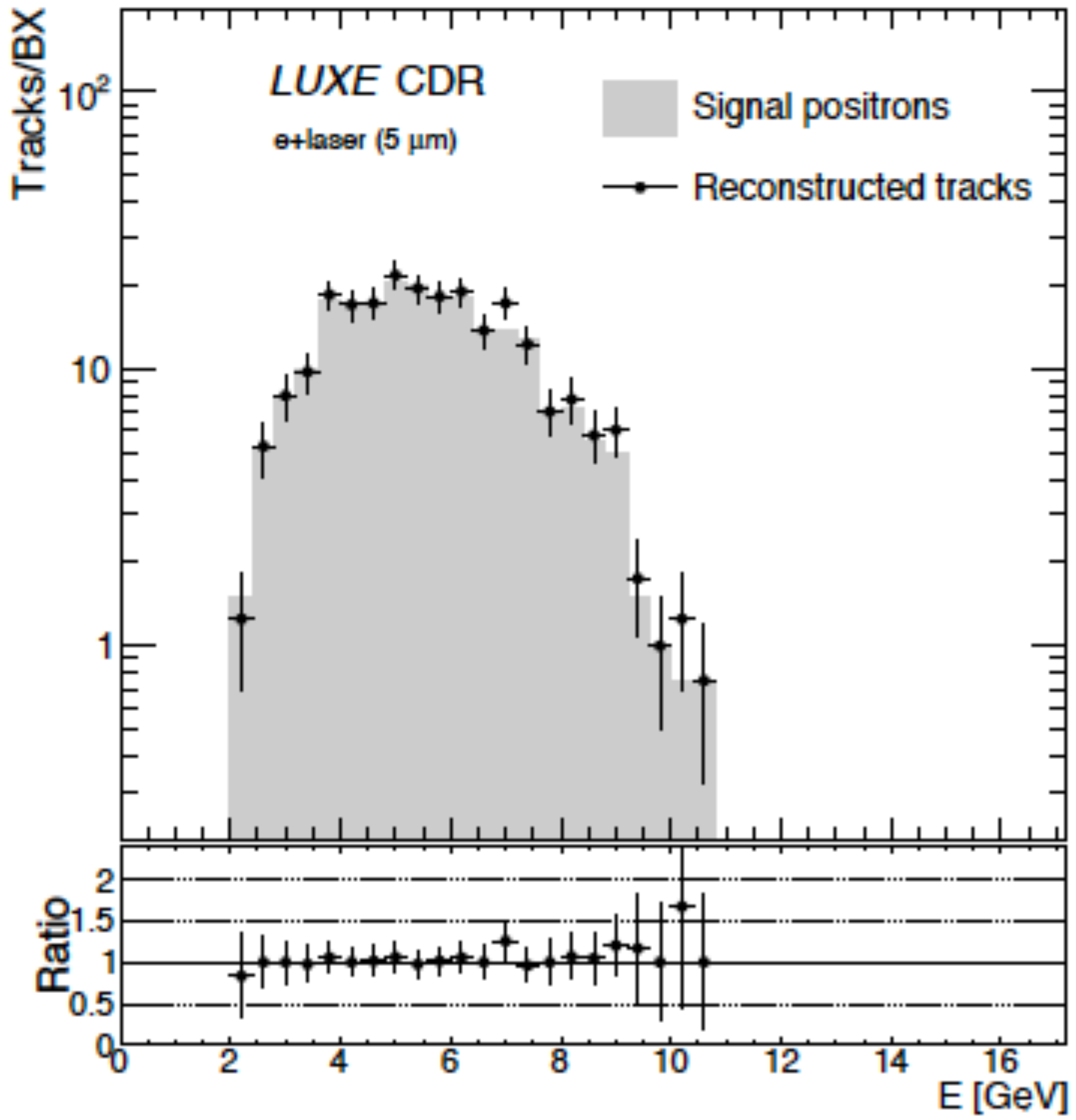


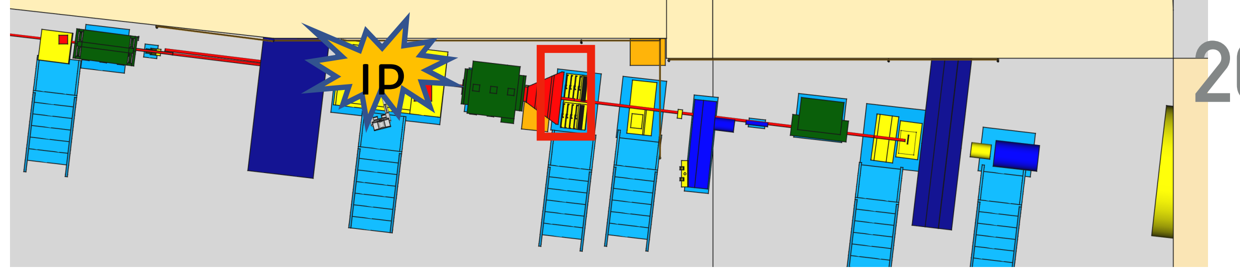


(a)

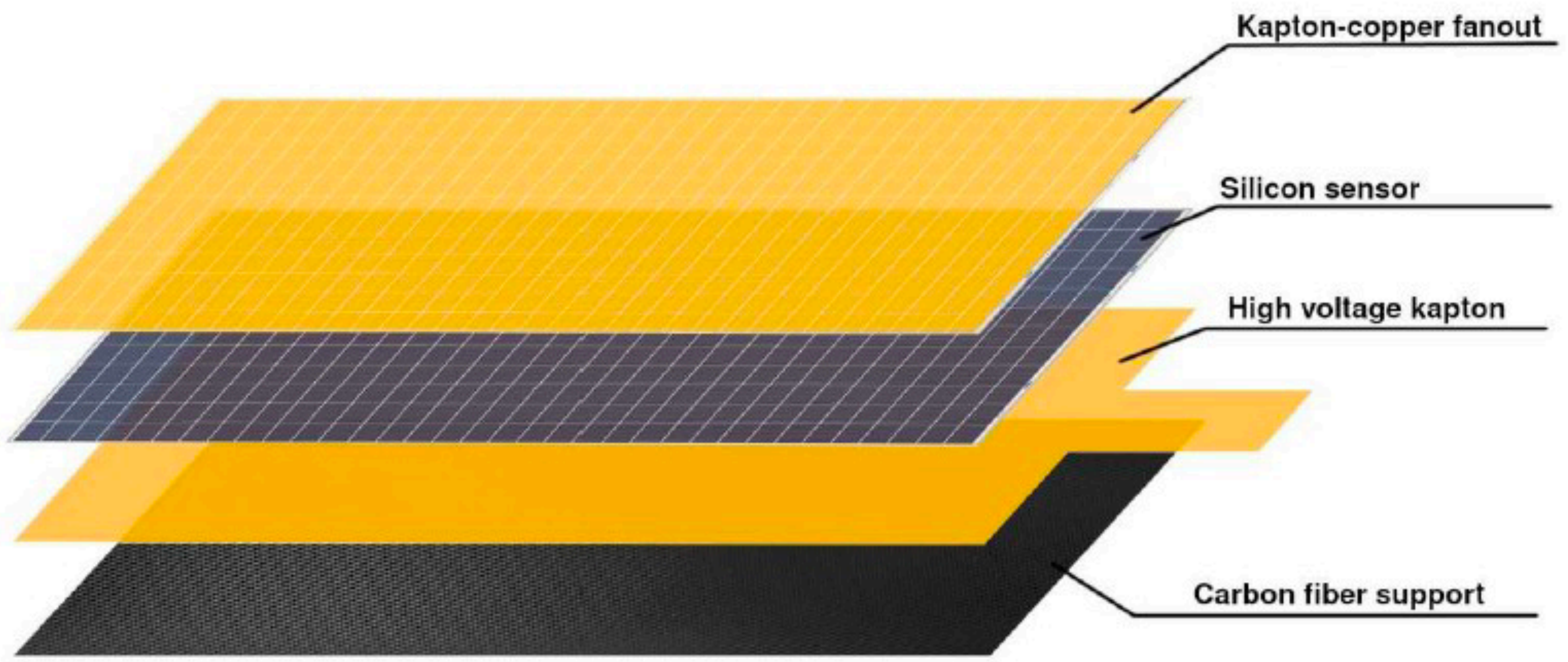


(c)

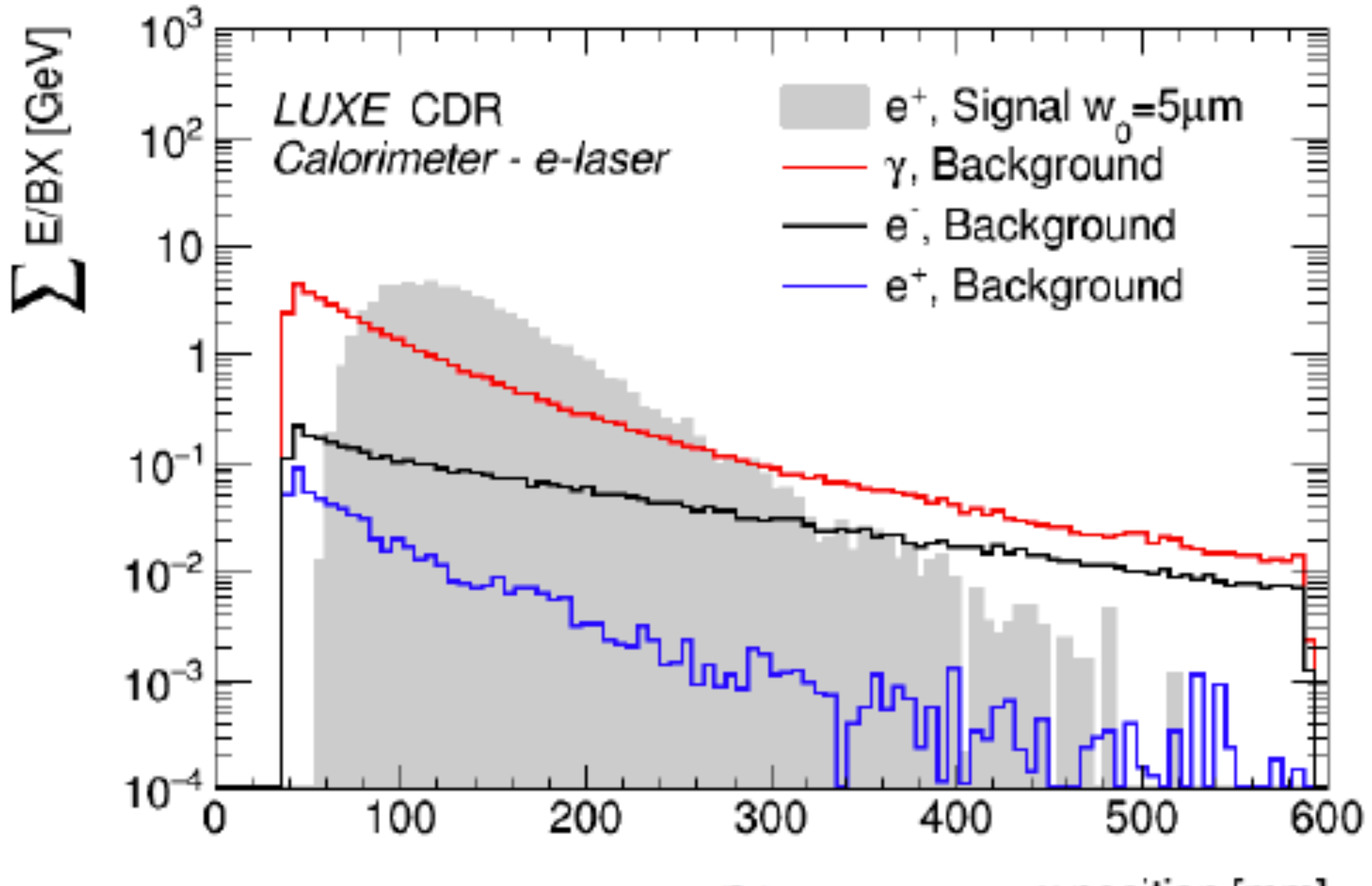




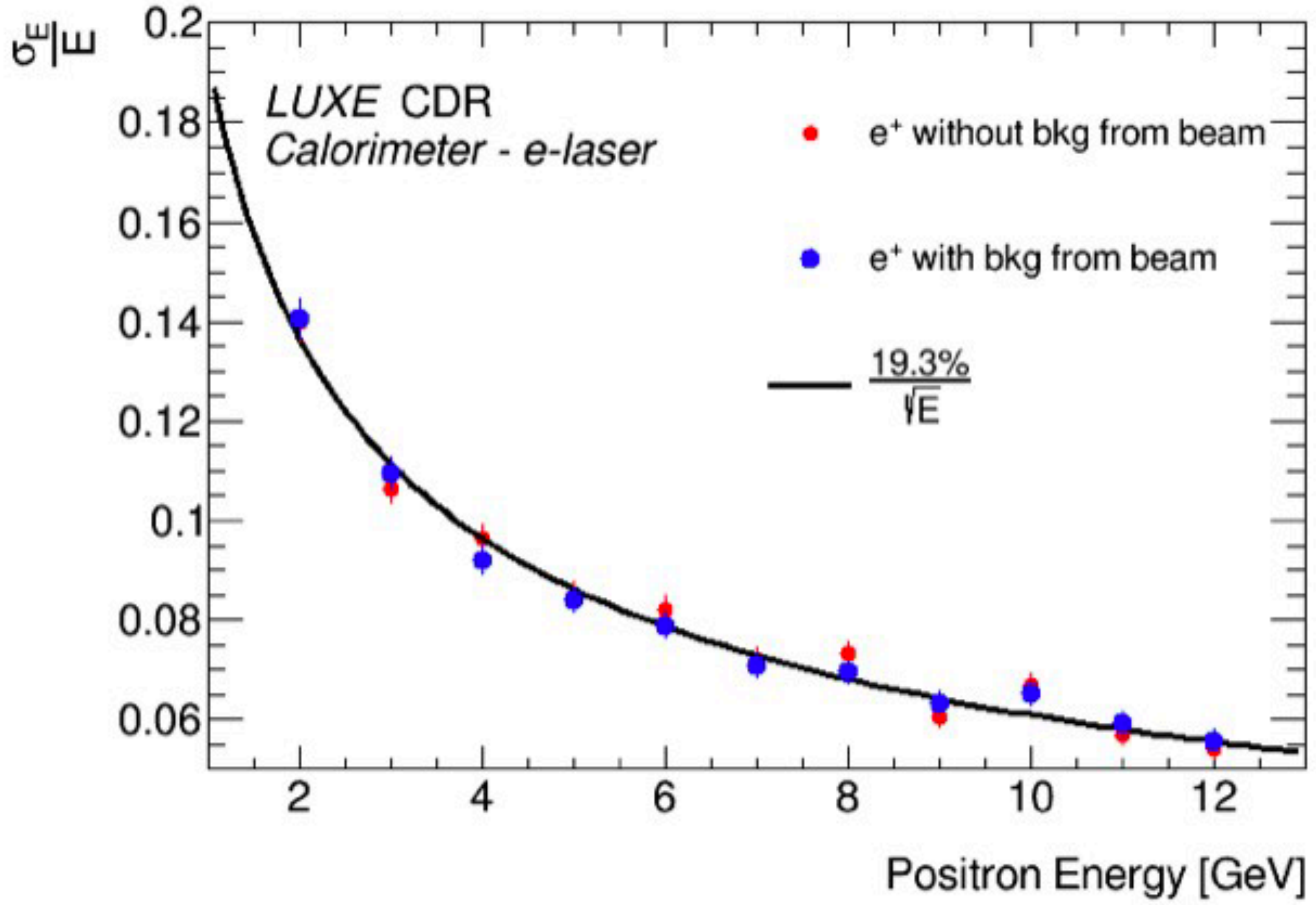
- High granularity Calorimeter developed for ILC FCAL
  - 20 layers of 3.5 mm thick tungsten plates
  - Silicon or GaAs sensors (5x5 cm² pads, 320 µm thick), Moliere radius 8 mm
  - Readout via FLAME ASIC (developed for FCAL)

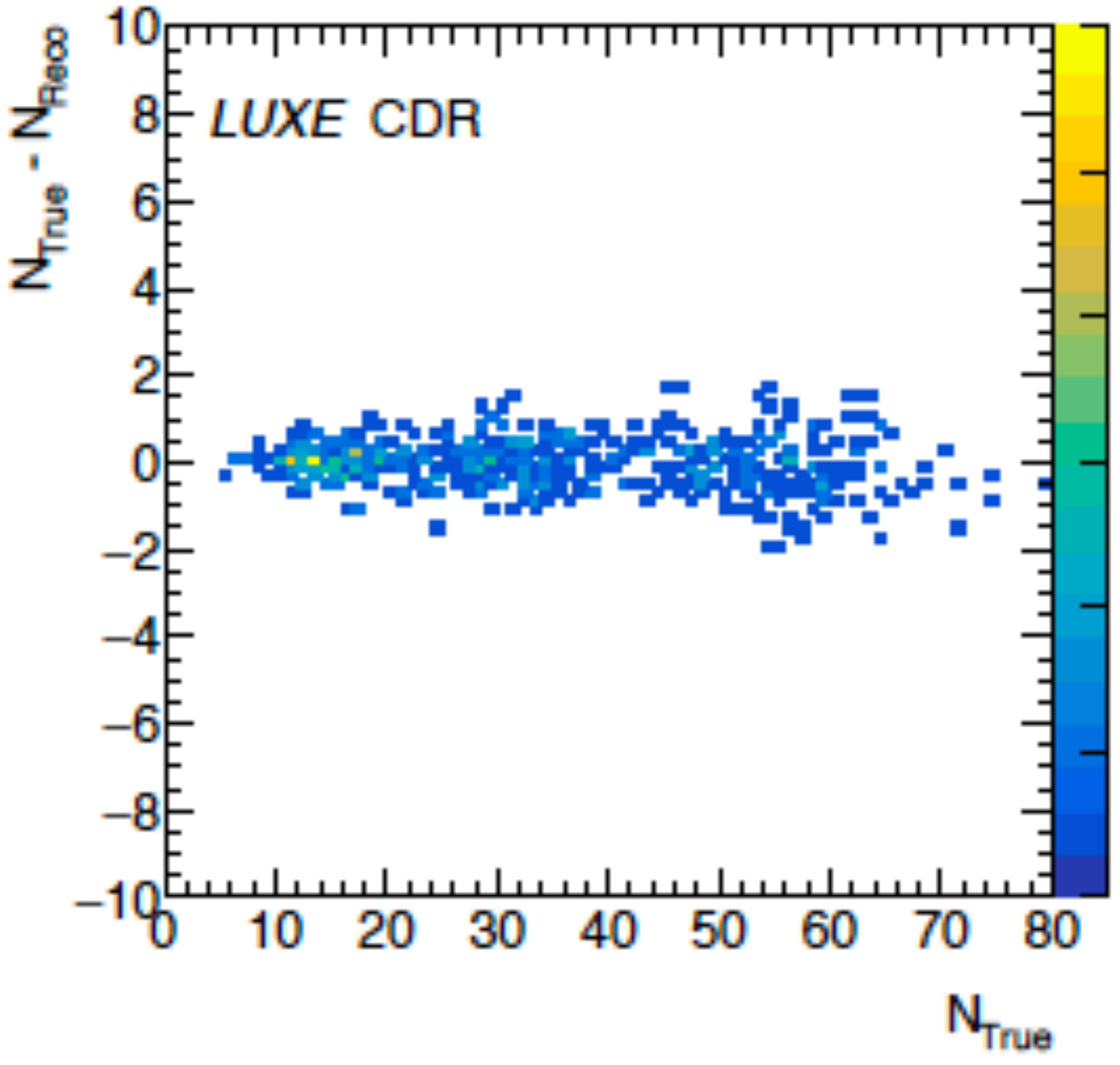


- Resolution:
  - Energy $\frac{\sigma_E}{E} = \frac{19.3\%}{\sqrt{E/GeV}}$, position: $\sigma_x = 0.78\ mm$
  - Independent measure of energy via position and calorimetry => $N_{particle}$

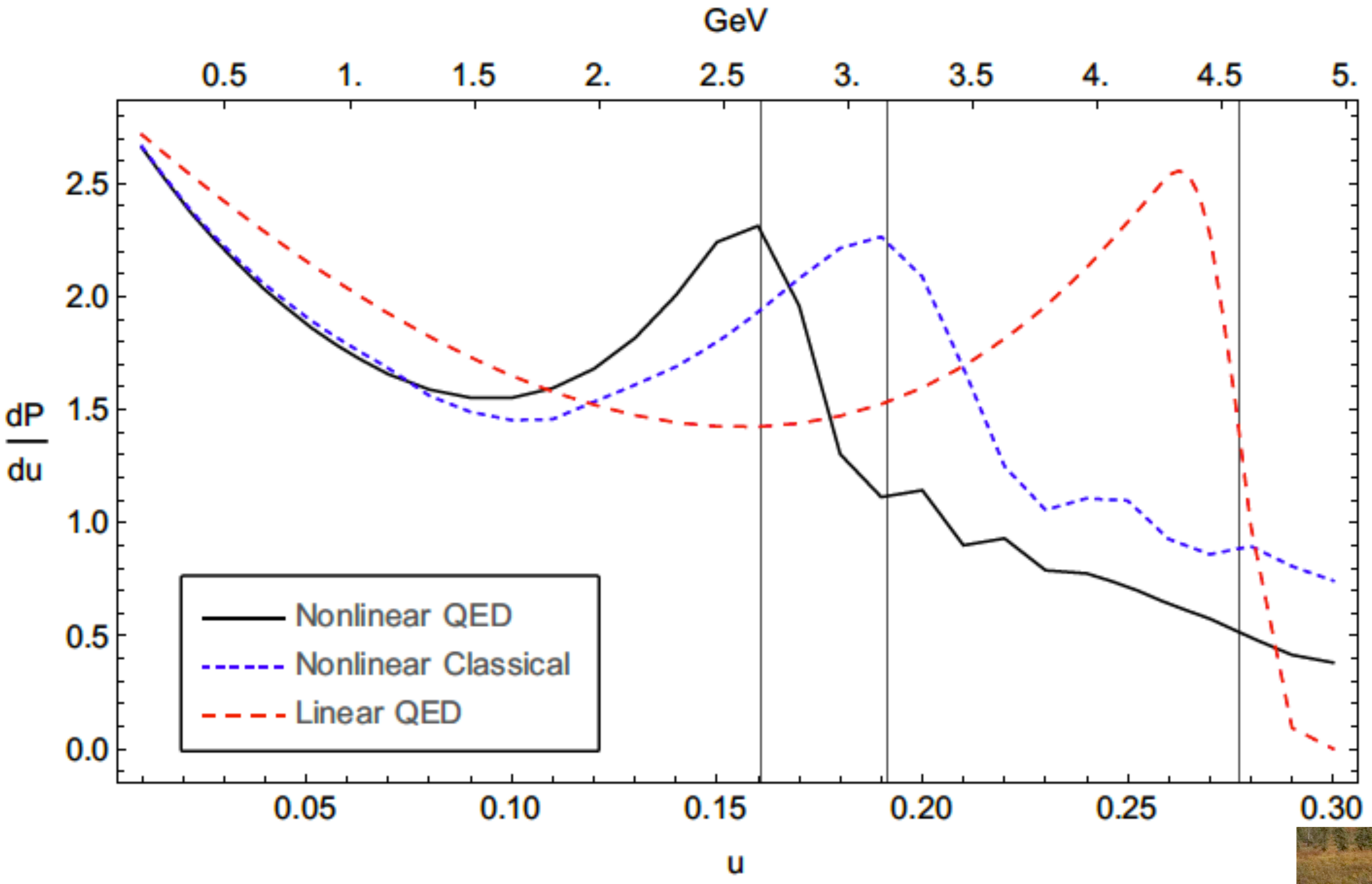


(b)



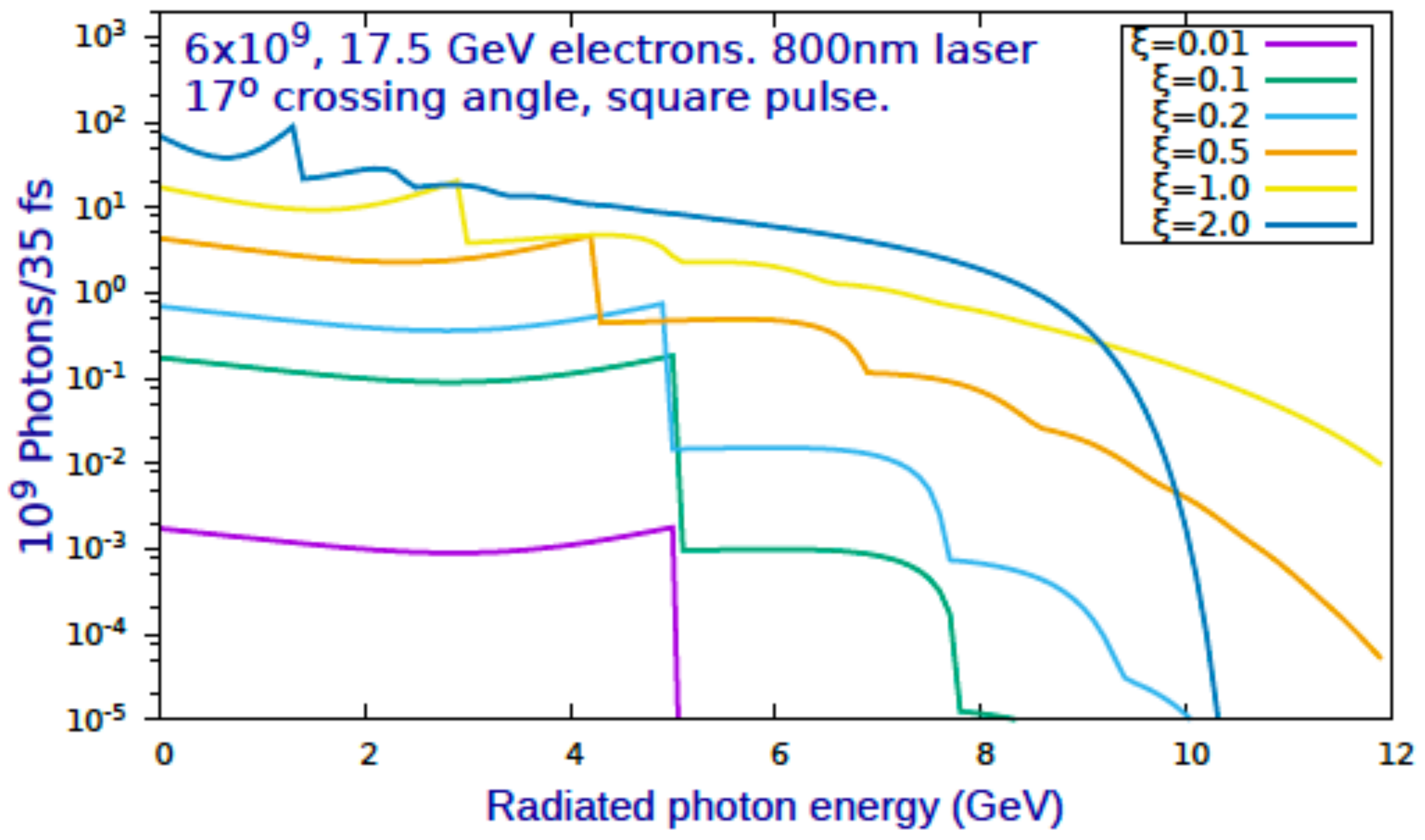


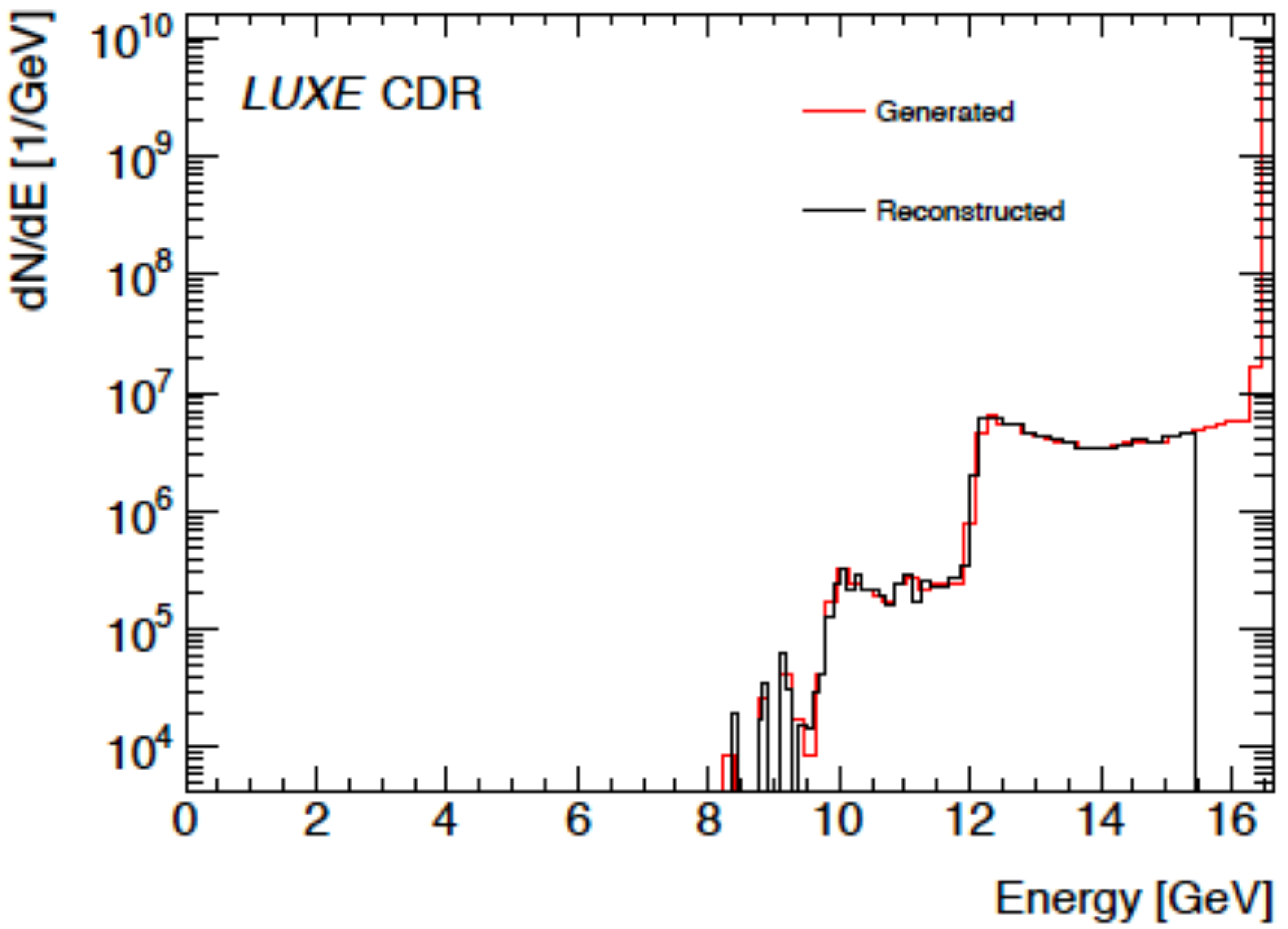
COMPTON EDGES



WHAT DO WE WANT TO MEASURE?

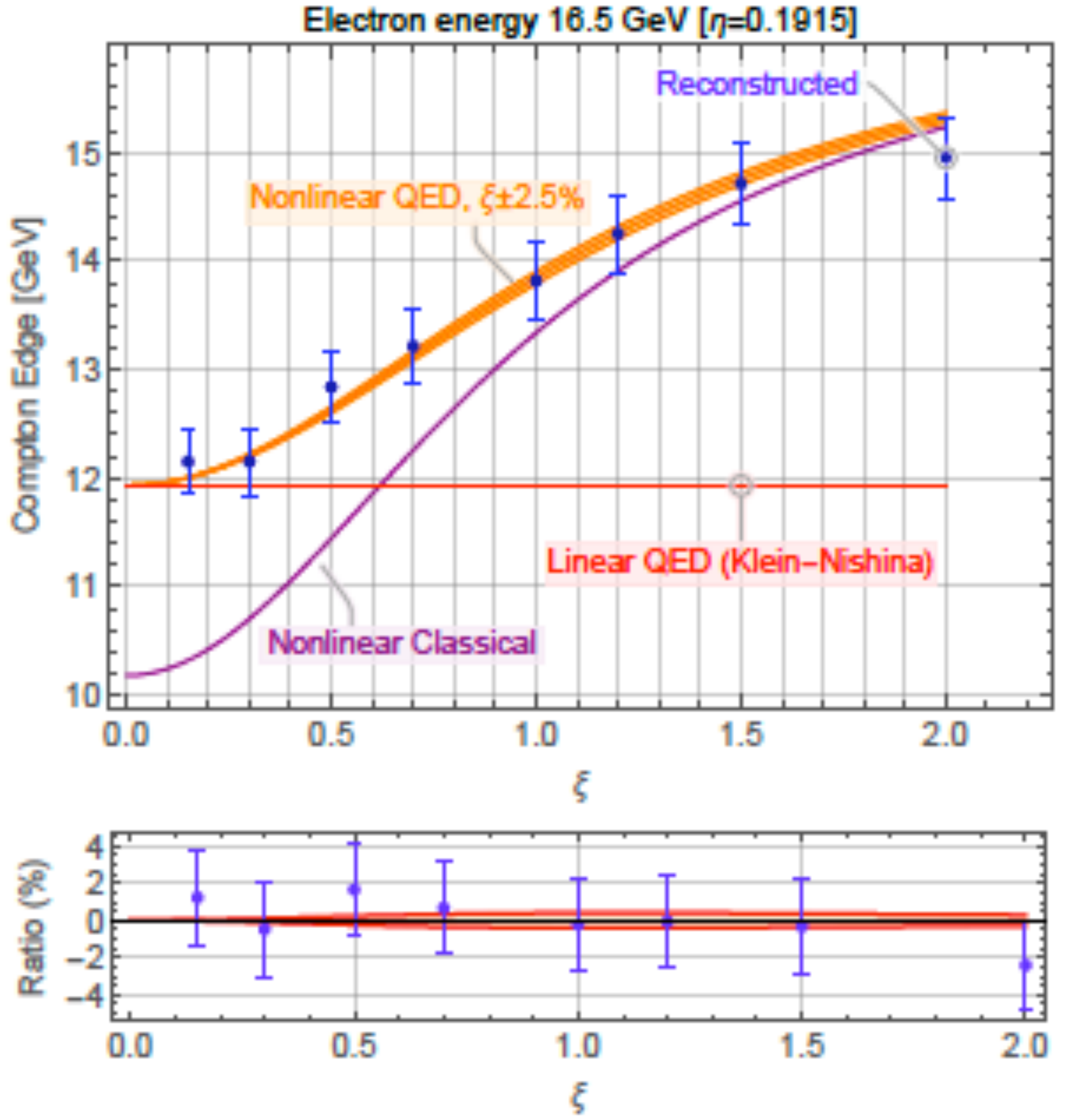
- Need to measure Compton edges, as they will be shifted to lower energies in SFQED!



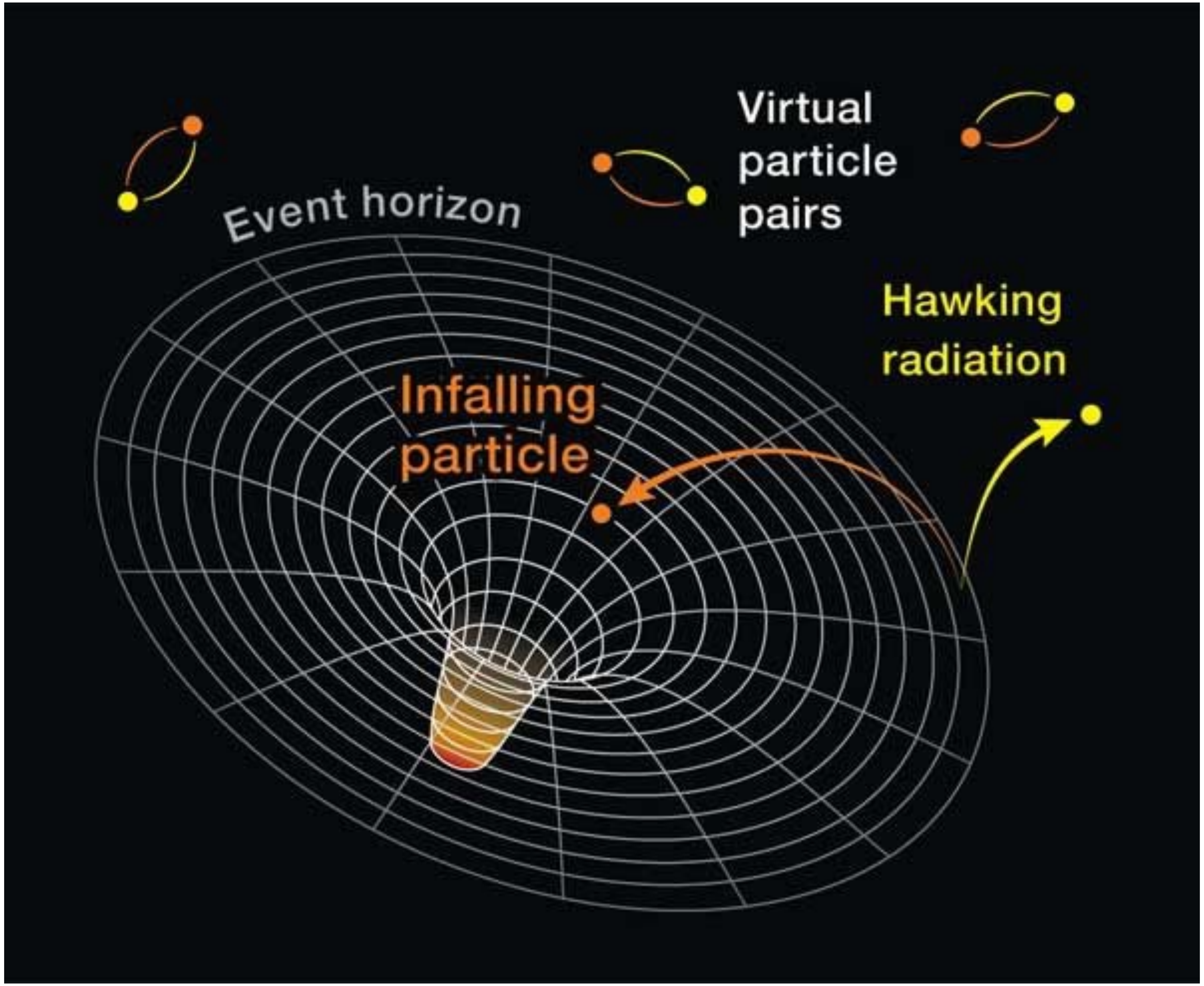


- Electron energy spectrum to reconstruct Edges using **Finite Impulses Response Filter** (FIR) technique.
- Compare result to theory prediction in phase 0:

Phase-(



BLACK HOLE EQUIVALENT



LUXE may be “the closest we can get” to probing Hawking radiation in the lab

LASER STABILITY

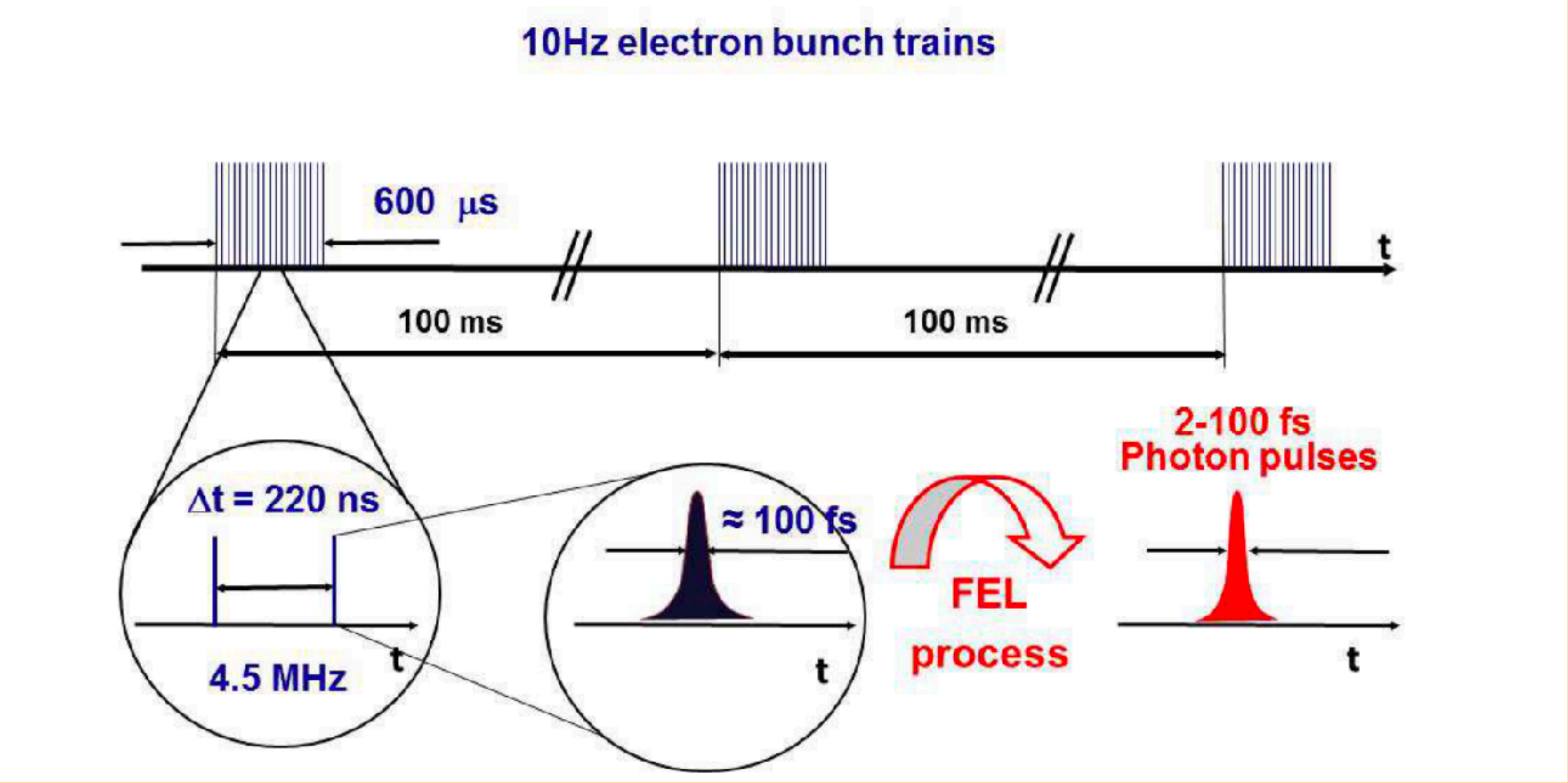


Figure 1: X-ray burst structure at the European X-ray free electron laser.

- **LOI Luxe requirements:**
  - 35 fs laser pulse width
  - 130 fs electron pulse length
- **machine (electrons) stability**

→ BAM diagnostics & feedback, last BAM at end of LINAC (1932m) → **10-15 fs** (rms)

- **laser oscillator stability**

→ optical synchronization → **<10 fs** *(rms)*

Parameter	Value XFEL.EU	Assumed Values for LUXE
Beam Energy [GeV]	$\lesssim 17.5$	16.5
Bunch Charge [nC]	$\lesssim 1.0$	0.25
Number of bunches/train	2700	1
Repetition Rate [Hz]	10	10
Spotsize at the IP [μm]	–	5
Bunch length [μm]	30–50	30–50
Normalised projected emittance [mm mrad]	1.4	1.4

- **laser stability**
  - amplification stages → additional drift measurement and compensation recommended!
  - beam transport to IP (mainly drifts) → option: additional fiber link to IP for drift measurement and compensation