Experimental Prospects at LUXE: a new non-perturbative QED experiment colliding laser pulses and the EU.XFEL electron beam

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New Vistas in Photon Physics in Heavy-Ion Collisions

19.09.22-22.09.22

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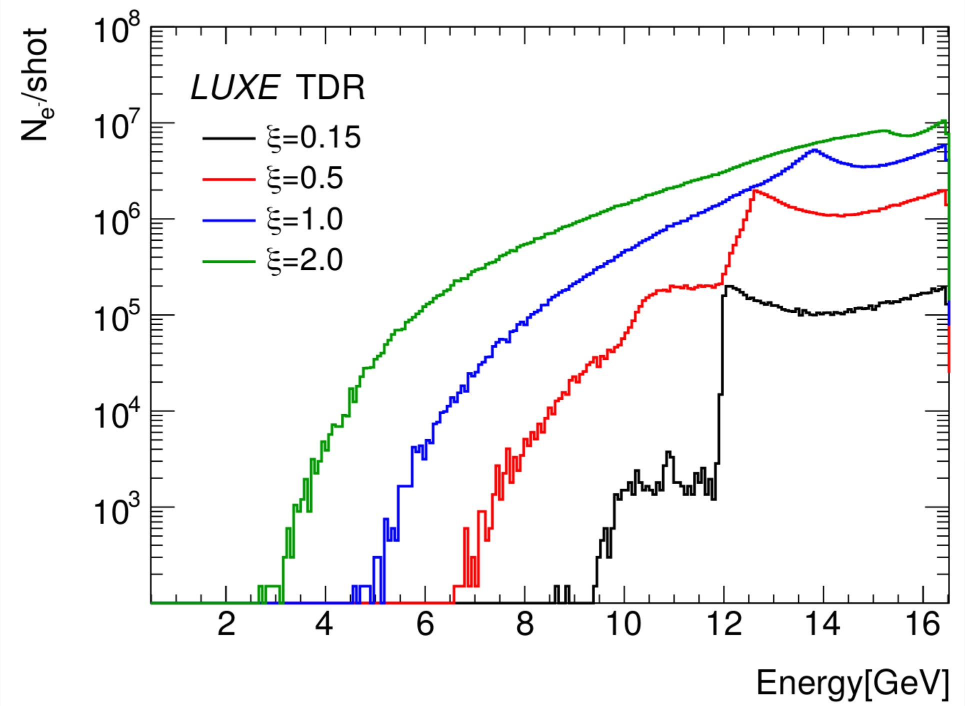
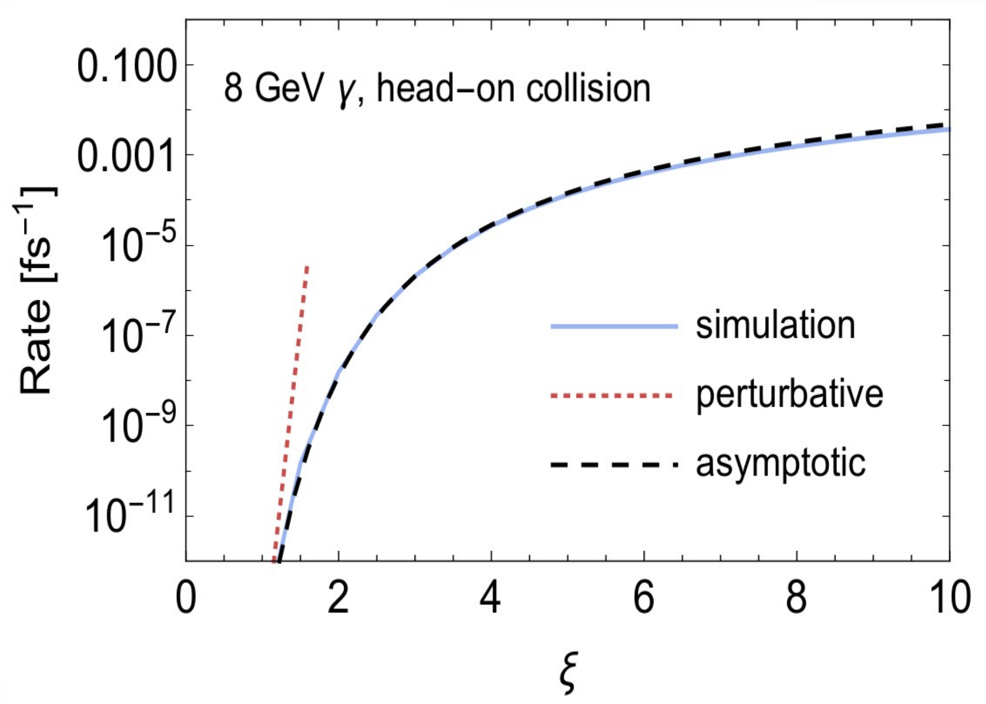
Theory

- See talk by Daniel Seipt https://indico.cern.ch/event/1139676/contributions/5049498/ 22.09.22, 09:30
  - LUXE wants to probe deep into ξ, χ and measure precisely the transition from QED to SFQED
    - ‘Compton Edge’ energy spectrum feature dependent on ξ
    - Huge range in probability of multiphoton Breit-Wheeler for changing ξ
    - Measurement down to very low rates presents considerable detection challenge





Simulated expected rates for each of the two interactions. Left shows the energy spectra of electrons after radiating through non-linear Compton scattering. Right shows the changing rate of multiphoton Breit-Wheeler, beside an extrapolation for the perturbative solution at low ξ.

Laser Und Eu.XFEL

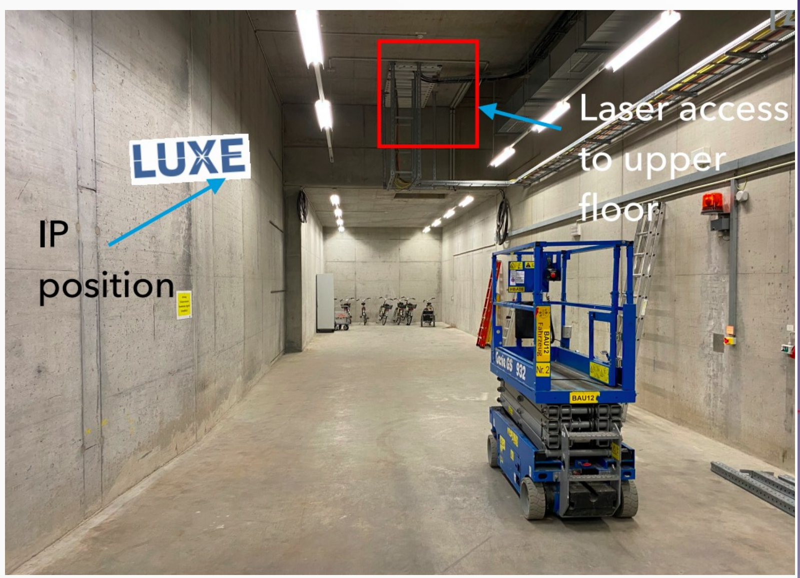
- Ti:Sa lasers used in phase-0, phase-1 of LUXE, with 40TW, 350TW pulses
- Param. ξ controlled with optical focussing, allows for detailed scan
- XFEL is a high-quality high-energy electron linear accelerator in the west of Hamburg
- Bunches typically used for high-energy photon science
- LUXE takes only one bunch of 2,700 at 10Hz; 1Hz signal, 9Hz for background
- XFEL's world-leading synchronisation system used to time the collision of ~30fs laser pulse

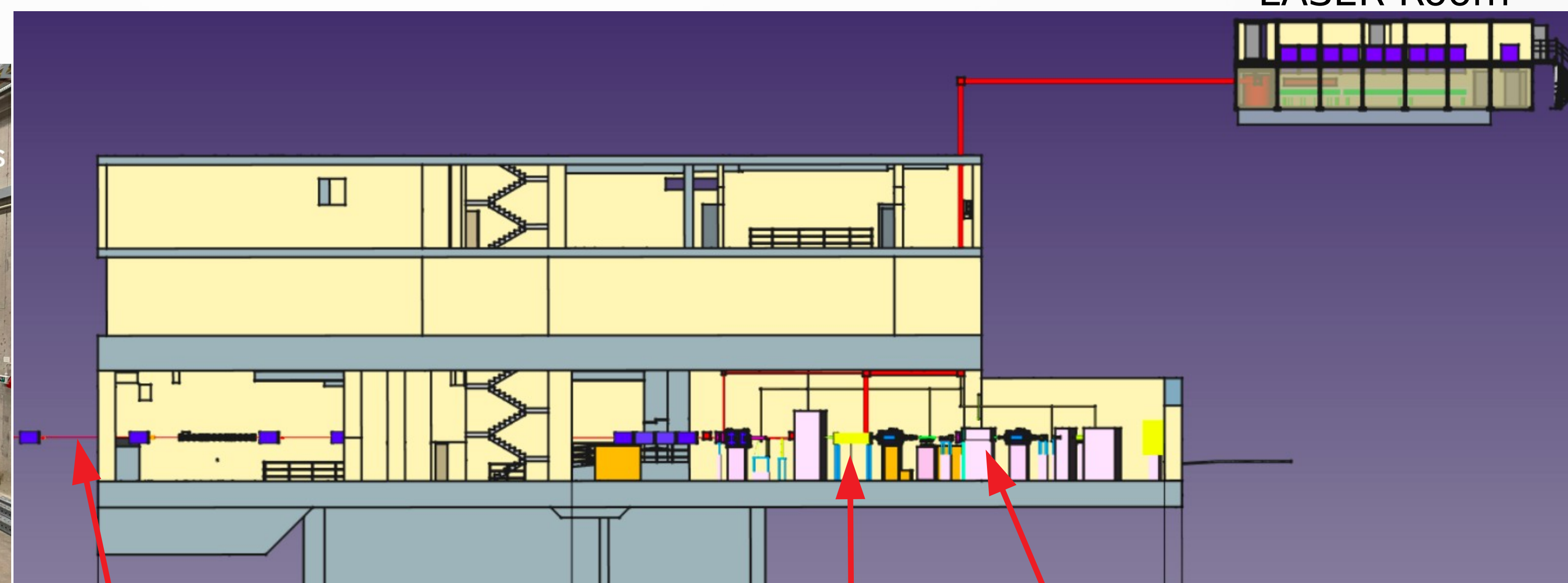
Parameter	Value
Beam Energy [GeV]	16.5
Bunch Charge [nC]	0.25
Bunch Population [e^-]	1.5×10^9
Bunches / Bunch Train	2700
Bunch Train Frequency [Hz]	10
Spot-size at the IP [μm]	5-20
Bunch Length [μm]	5-10
Normalised Projected Emittance [mm mrad]	1.4
Energy Spread $\delta E/E$ [%]	0.1
Bunch Length [fs]	50

Typical beam parameters for the XFEL electron beam at the site of LUXE.

In the Cavern…

- Concrete chamber already exists beamline will be outfit with kicker + focussing magnets, an interaction chamber and array of detectors; laser is piped through to IP from a laser clean-room to be constructed on the surface
- XFEL operates nearly all year, giving up to $\sim 10^7$ seconds of data per year
- LUXE runs independently, accumulating statistics over period of many years

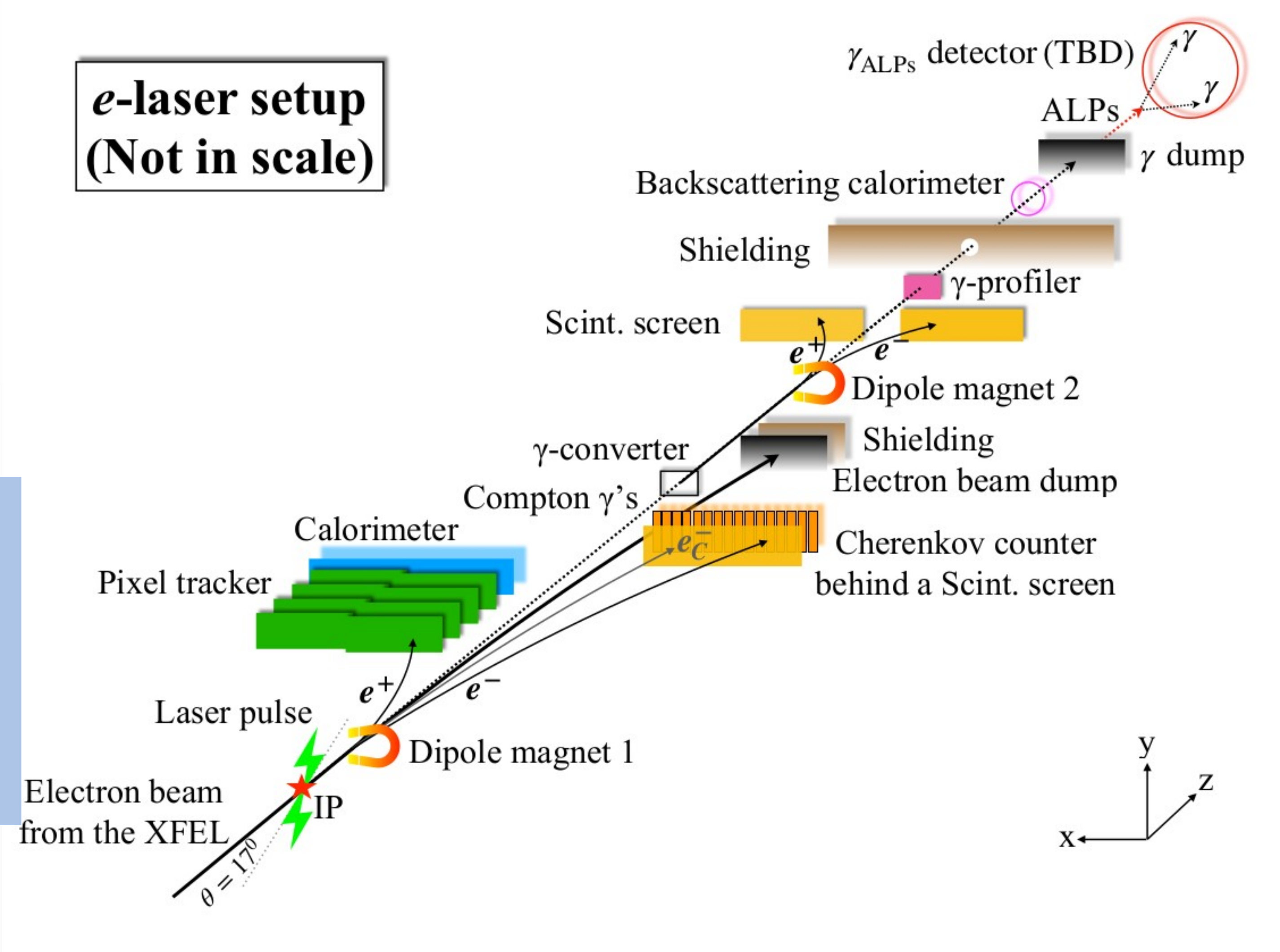




Detector Outline

- High energy incident particles radiate boosted daughters
- Resulting particles separated by magnetic field
- For charged particles, results in energy-dependent planar fan for use in magnetic spectrometry

<u>Key Detection challenges:</u>
a. ~10GeV electrons, in rates 10^7-10^9
b. ~10GeV photons, in rates 10^7-10^9 + directly measuring beam shape
c. ~5GeV positrons, in rates 10^{-2}-10^6 + in high background environment



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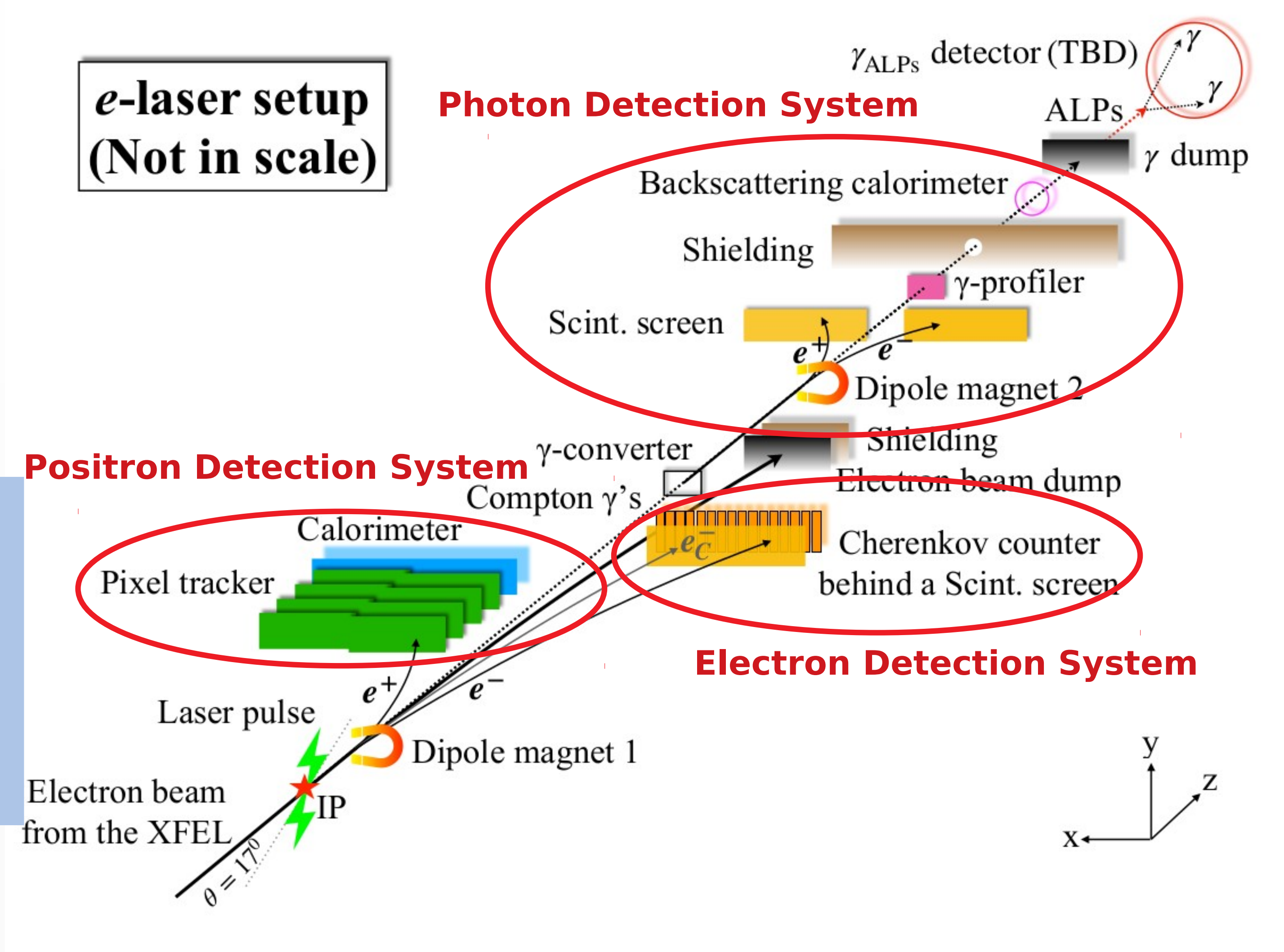

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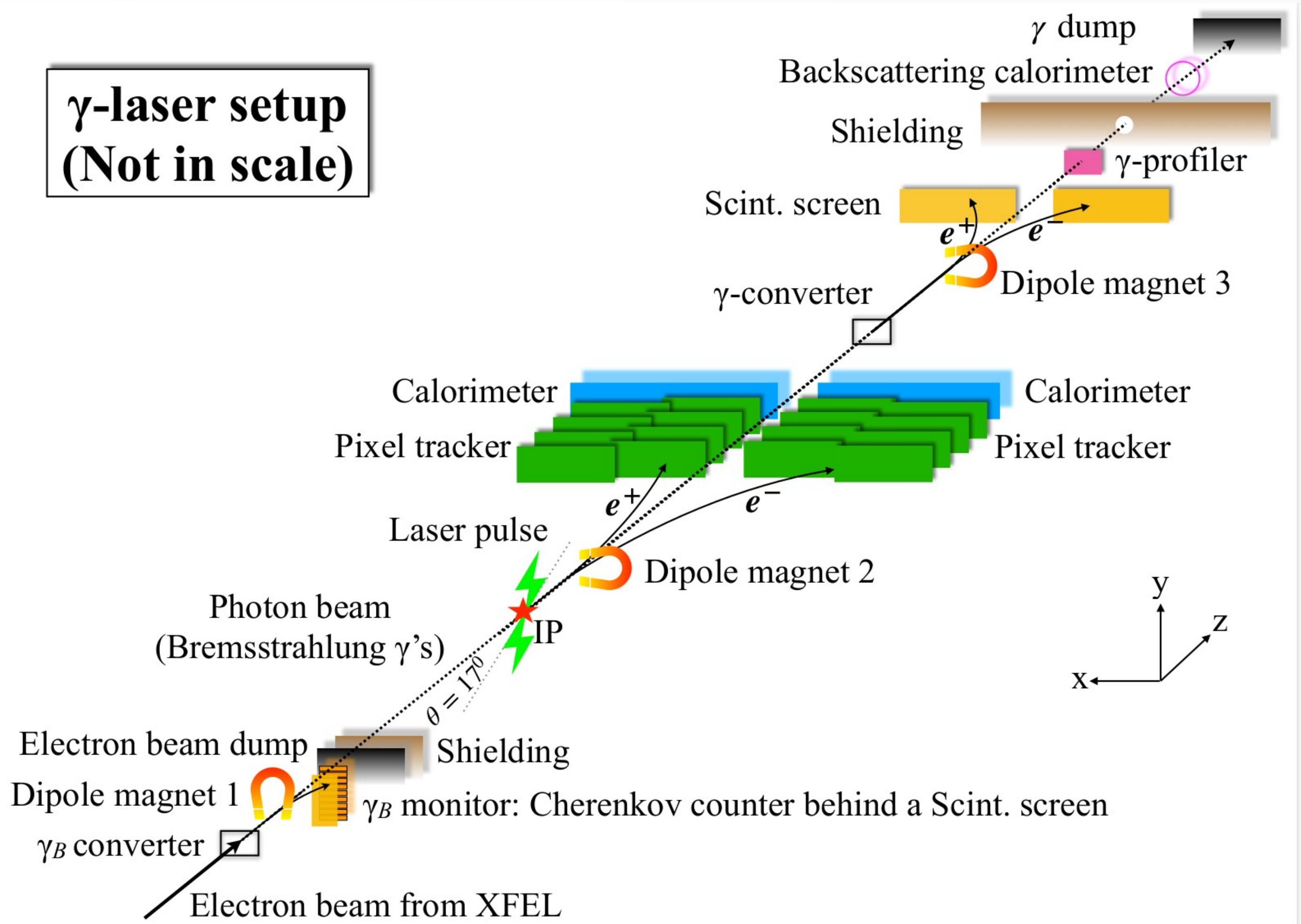
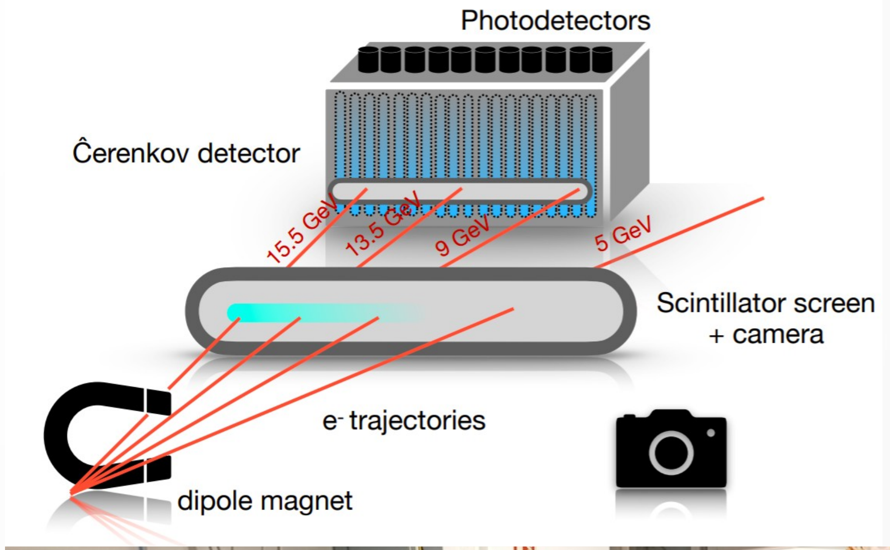
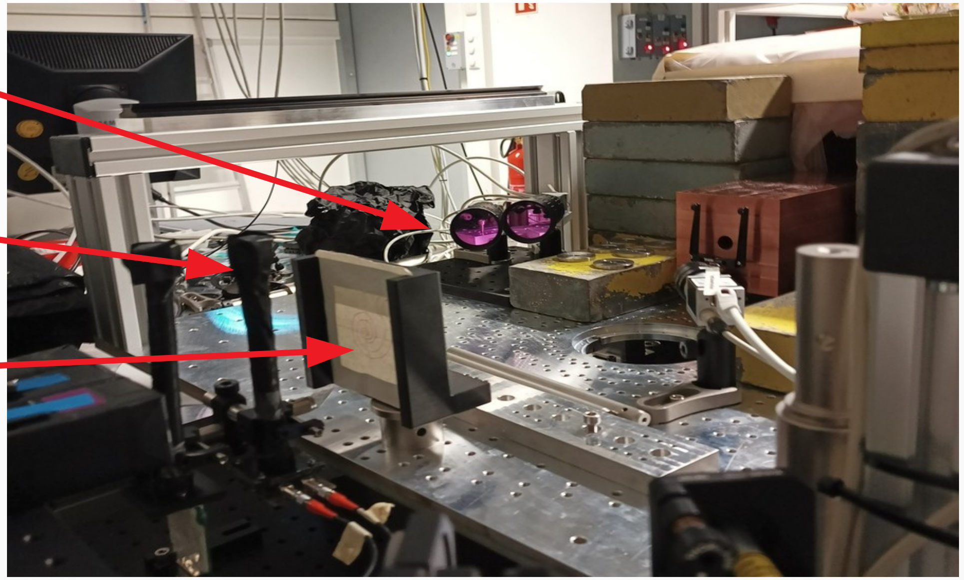
<u>Key Detection challenges:</u>
a. ~5GeV electrons, in rates 10^{-3}-10^{2} in a high-background environment
b. ~10GeV photons, in rates 10^{7}-10^{8} + directly measuring beam shape
c. ~5GeV positrons similar to electrons



Electron Detection System

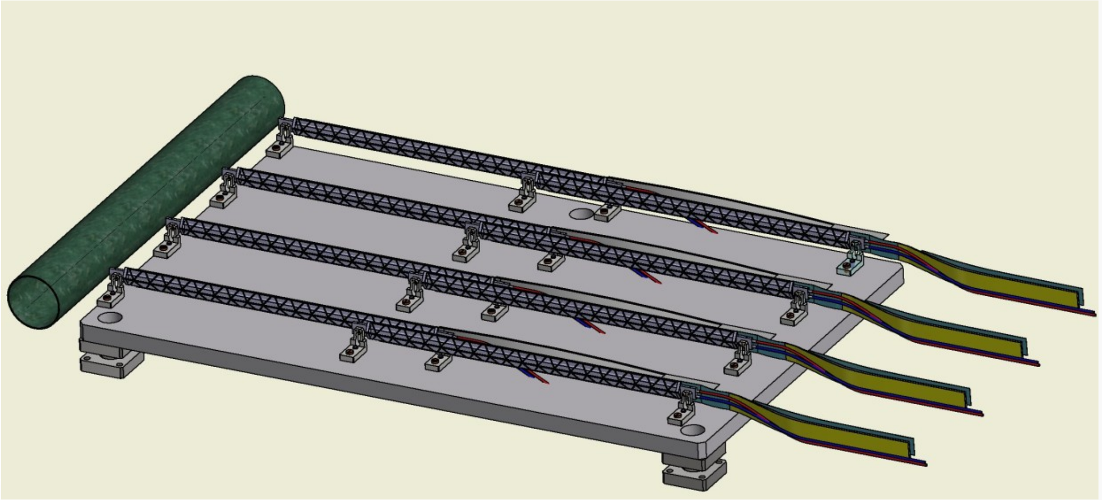
- Composed of two parts: a <u>Scintillator Screen & Camera spectrometer</u>, and a <u>Gas Cherenkov Detector</u>
- Both use only the position of charge flux for magnetic spectrometry
- The screen and camera offer fine position → energy resolution for low cost / complexity
- The Cherenkov Detector, with several hundred air-filled straws, excludes all non-charged background & charged bkg with E<20 MeV
- Prototypes have been constructed and tested with beam in DESY

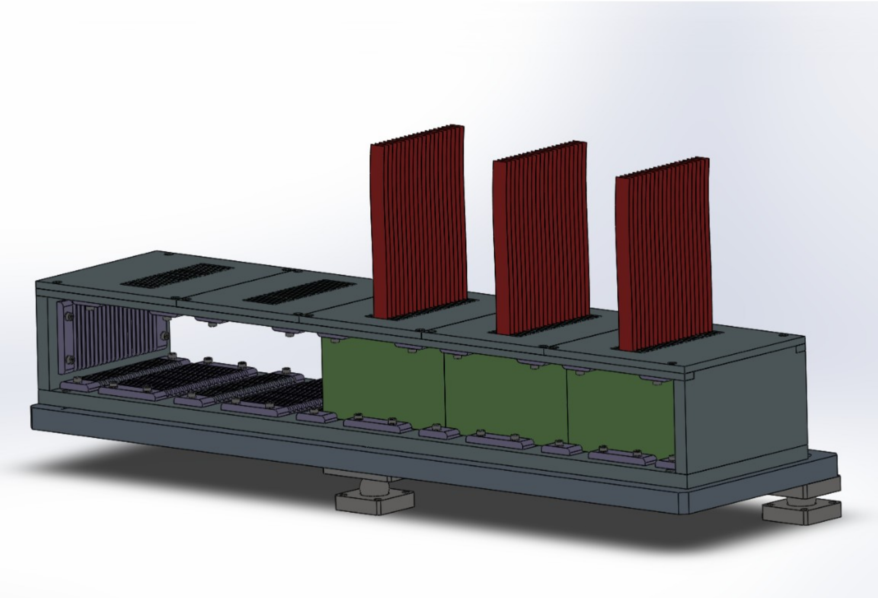




Positron Detection System

- Positrons are tracked and reconstructed by a Silicon Tracker detector, with Sampling calorimeter directly measuring track energy
- Pixel tracker based on ALICE SPD alpide layers; high efficiency, position resolution (~5 μm) and use of reconstruction algorithms – including QC – allows high-quality resolution of tracks and rejection of background
- Compact ECAL is a Sampling Calorimeter uses Tungsten plates to absorb & shower, then detected by pixelated layers of Si or GaAs
- MC performance: ~20% track energy resolution, track resolution of ~0.8mm
- (Some portion of) system replicated to detect electrons in γ-laser mode





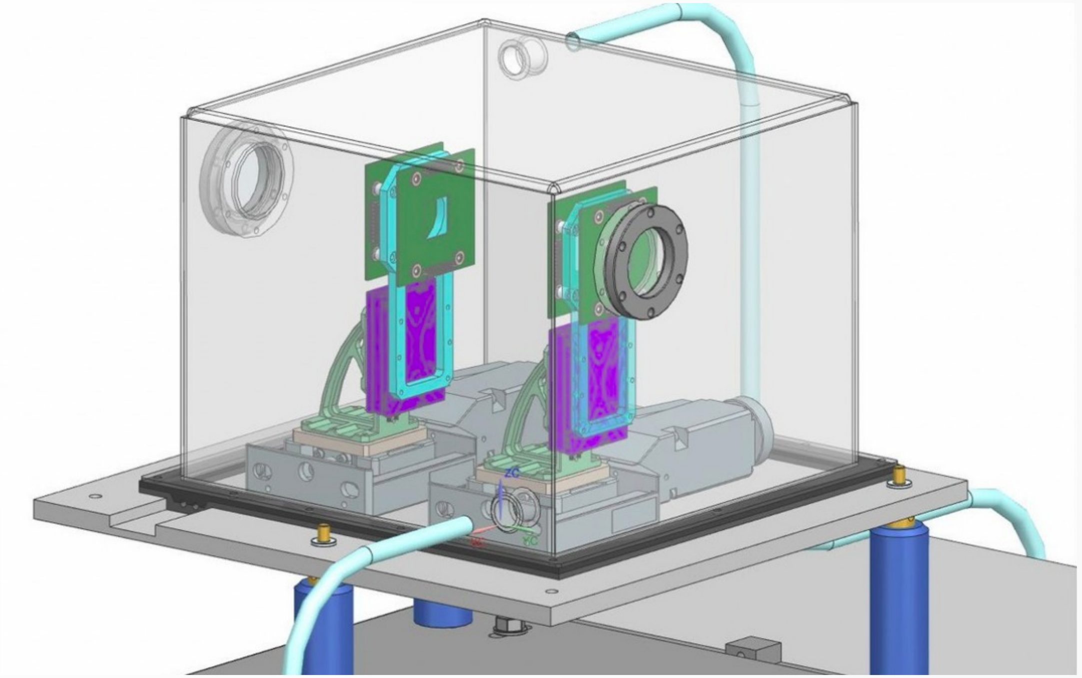
Photon Detection System

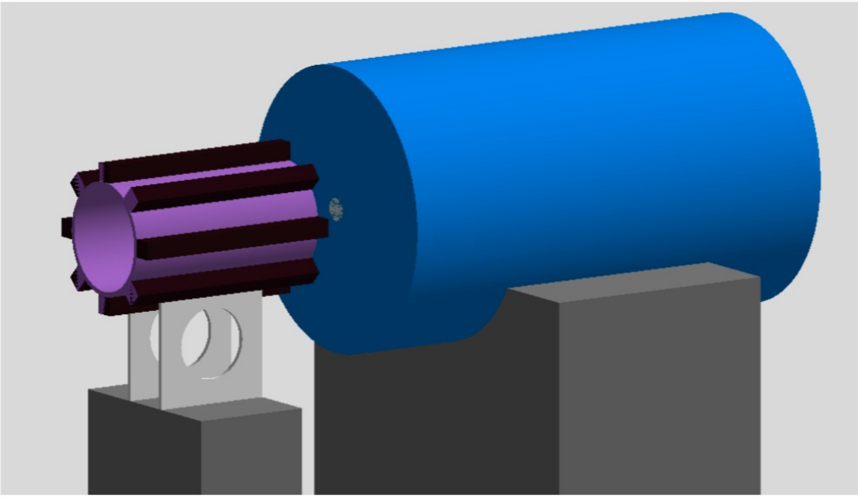
Photon Beam Energy Spectrum: Gamma Spectrometer,

Beam Flux Profile: Gamma Beam Profiler

Total energy flux: Backscattering Calorimeter

- Gamma spectrometer target converts ~1% of photons to e^- / e^+ pairs; these are measured in a magnetic spectrometer scintillator screen & camera system similar to e-laser IP region
- Sapphire microstrip lattice charge-collection detector boasts radiation hardness and down to 5 micron resolution
- Cherenkov light from photon backscatters from dump in lead-glass blocks detected by Photo-Multiplier Tubes



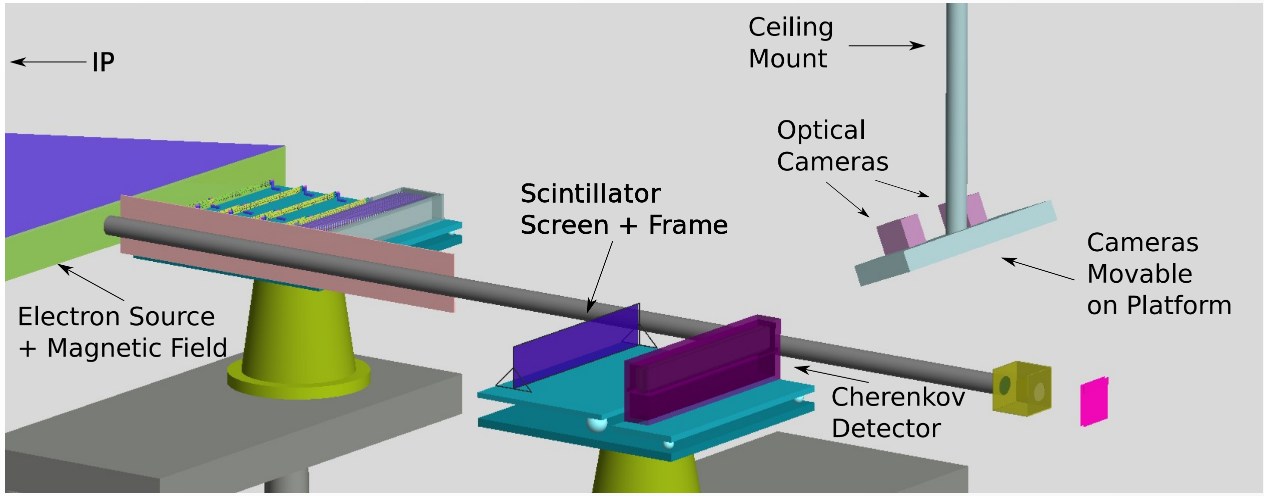


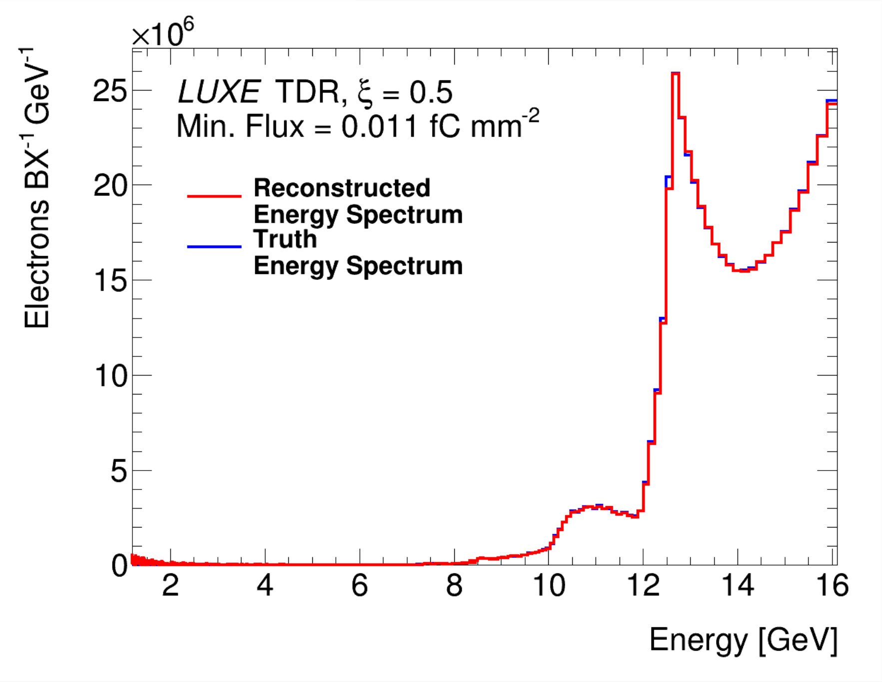
Detector Highlights - Scintillator

- The physics observables of the Compton Edge position and rate / BX of positrons are key

- Scintillator Screen & Camera system has a complete simulation + reconstruction process figured out (largely implemented in geant4)

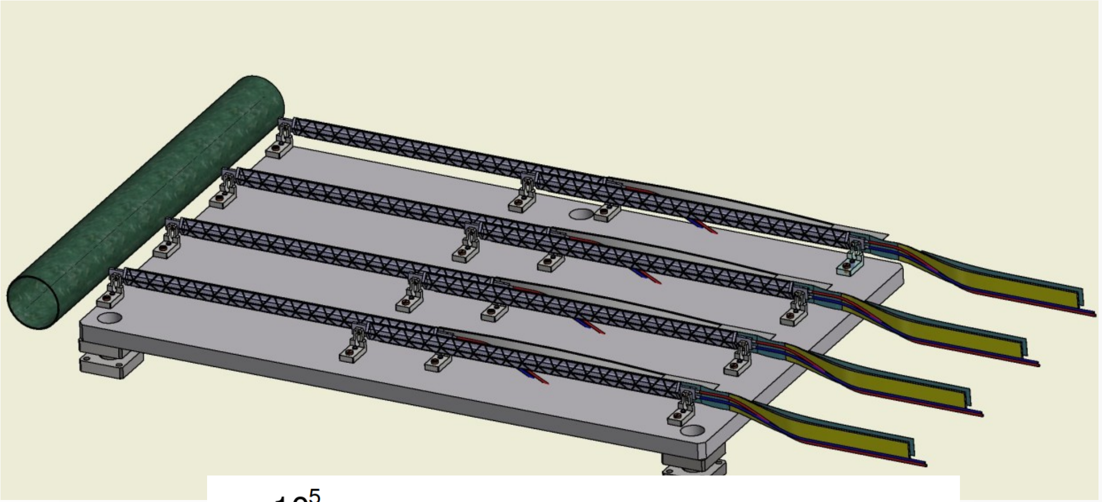
- Screen resolution down to ~100 μm → 0.1% E uncertainty; one-shot reco vs truth integral difference <0.5%; final edge position uncertainty dependent on B-field, ~1%

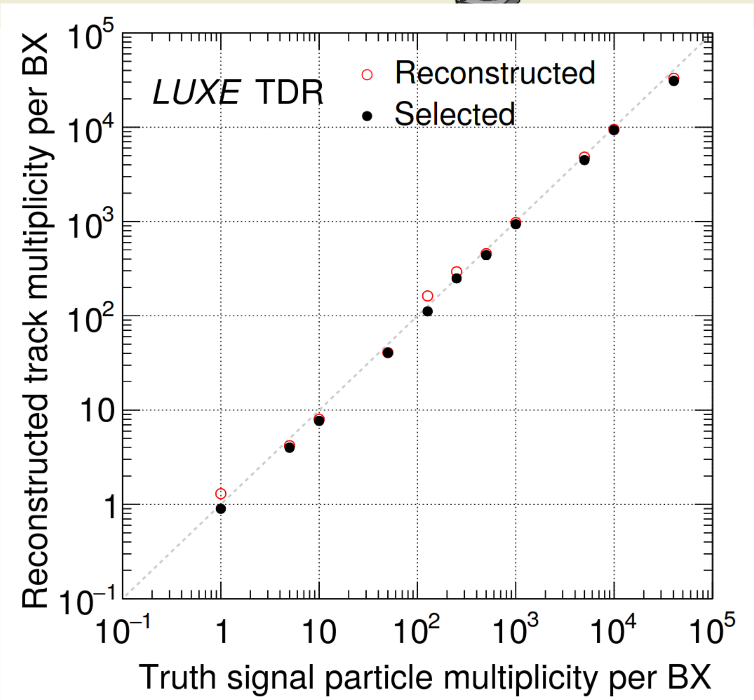




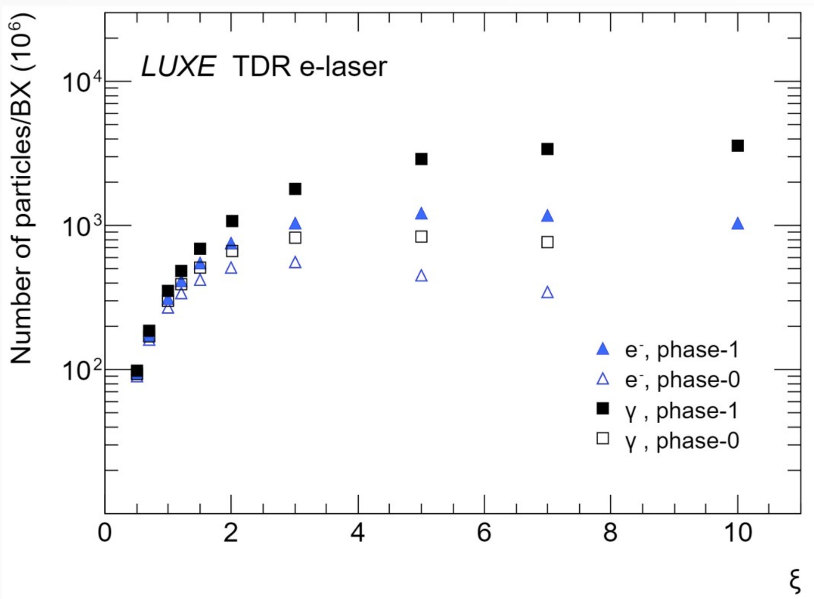
Detector Highlights - Tracker

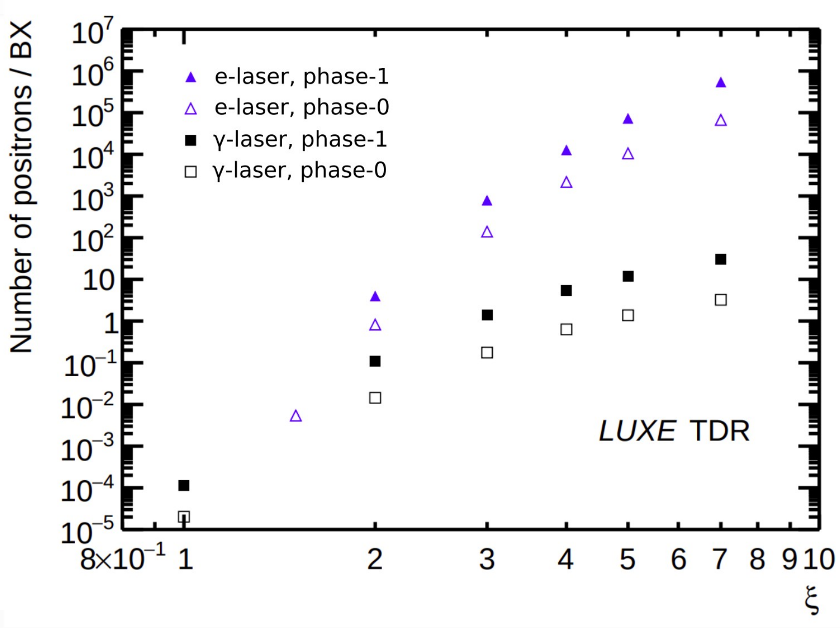
- The physics observables of the Compton Edge position and rate / BX of positrons are key
- Tracker simulation + reconstruction generates tracks, digitizes hits, reconstructs + selects signal, rejecting background
- Tracking efficiency is high, largely unaffected by uncertainties, leads to good signal reco and confidence of measurement down to 10^{-3} positrons / BX (rejection power > 10^{-3})

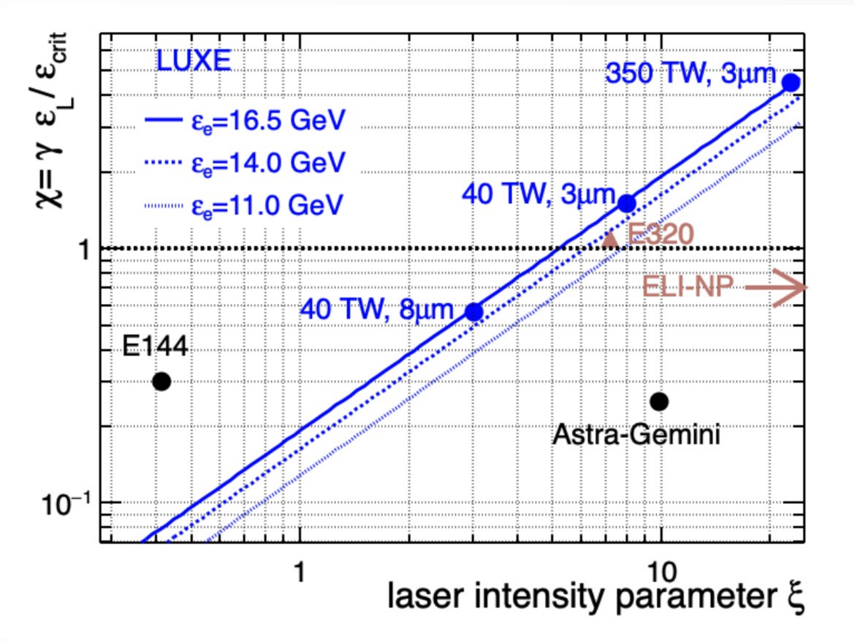




Expected Results







- Left: the numbers of electrons scattered and photons radiated per bunch crossing in the e-laser mode of LUXE for changing ξ parameter. Center: The numbers of positrons (and electrons in a pair) created per bunch crossing in the e-laser and γ-laser modes, for changing ξ parameter. Beam energy assumed at 16.5 GeV. Right: the parameter space in ξ, χ, spanned by LUXE

Summary / Status

- LUXE plans to study SFQED by observing collisions between intense laser pulses and GeV-energy electrons or photons from the EU.XFEL
- Opportunity to explore further into strong-fields than ever before, and to do so accumulating the statistics to make high-quality measurements of the transition from QED to SFQED
- To do this requires a suite of detectors designed to measure each of electrons, positrons and photons, with challenging ranges of flux and interfering background
- Internal DESY Critical Decision approval / review process ongoing
- Technical Design Report is awaiting release, Conceptual Design Report completed: https://arxiv.org/abs/2102.02032, *Eur. Phys. J. Spec. Top.* 230, 2445–2560 (2021)

Thanks for listening and get in touch if you find LUXE interesting!

Backup

LASER

- Chirped-Amplification technique provides the most intense electric-fields achievable today in the lab
- LUXE plans two phases, phase-0 using an existing 40 TW laser Ti:Sa (JETI40) in Jena
- Phase-1 needs custom-built 350 TW Ti:Sa laser, of pulse frequency 1Hz
- Intensity at interaction point dictated by power but also by optical focussing, allowing for scan in ξ
- Laser diagnostics give an independent measurement of ξ achieved shot-to-shot
- Goal is 5% absolute uncertainty, 1% shot-to-shot relative uncertainty

Laser parameters	phase-0	phase-1
Fraction of ideal Gaussian intensity in focus (%)	50	
Laser central wavelength (nm)	800	
Laser pulse duration (fs)	25-30	
Laser focal spot waist w_0 (μm)	≥ 3	
Laser repetition rate (Hz)	1-10	
Electron-laser crossing angle (rad)	0.35	
Laser energy after compression (J)	1.2	10
Laser power (TW)	40	350
Peak intensity in focus ($\times 10^{20}$ W/cm^2)	< 1.33	≤ 12
Dimensionless peak intensity, ξ	< 7.9	< 23.6

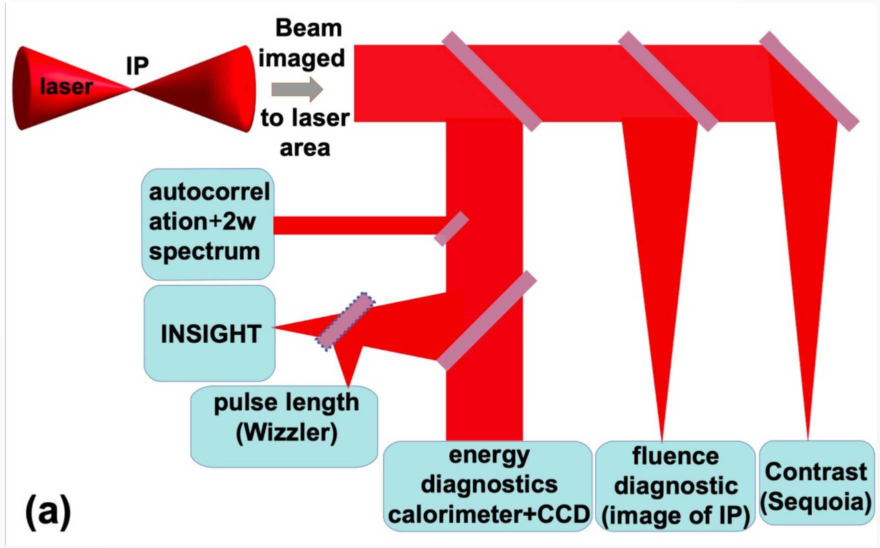
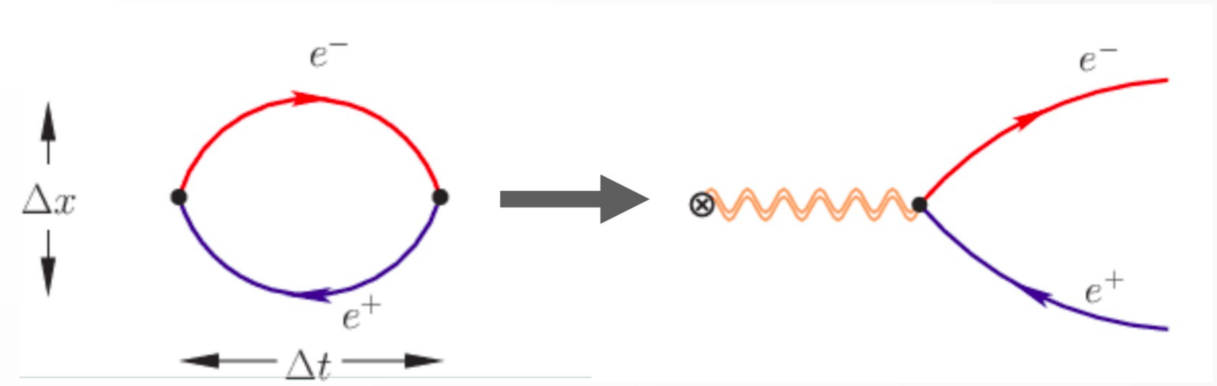
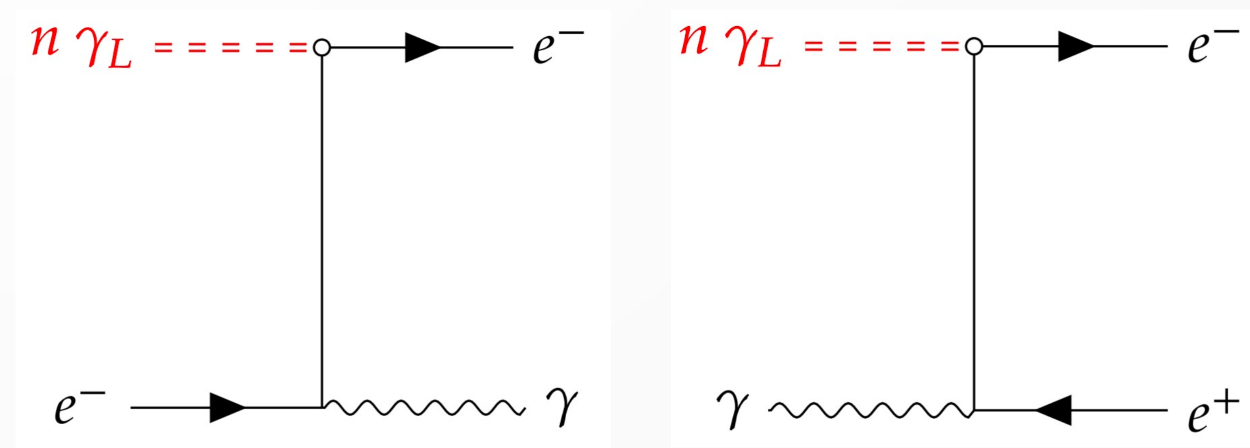


Illustration of several laser diagnostic shot-to-shot measurements

Theory

- Conventional QED works very well at low energies / intensities
- At higher field strengths, approaching Schwinger limit, Strong Electric fields can ‘boil the vacuum’ in process similar to Hawking radiation
- LUXE (LASER Und XFEL Experiment) intends to reach the SFQED regime with collision of high-energy particles with a powerful laser pulse
- The rates and kinematics of resultant particles are measured, and so the behaviour of SFQED reconstructed





The two interactions of interest: Non-Linear Compton Scattering (left), Multiphoton Breit-Wheeler Process (right). The two can occur immediately after one another, in a ‘trident’ process

Theory

- Electric field can be characterised with unitless ξ, χ parameters
- LUXE wants to probe deep into ξ, χ, but also measure precisely the transition from QED to SFQED
  - Compton energy spectrum features shifting kinematic edge dependent on ξ
  - Huge range in probability of multiphoton Breit-Wheeler for changing ξ
- Measurement down to very low rates presents a considerable detection challenge

$$E_{Schwinger} \equiv m_e^2 c^3 / e\hbar = 1.32 \times 10^{18}\ Vm^{-1}$$

$$\xi = \frac{eE_L}{m_e \omega_L c} = \frac{m_e E_L c^2}{\omega_L E_{Schw.} \hbar}$$

$$\chi = \frac{E_p}{E_{Schw.}} = \frac{p}{m_e} \frac{E_L}{E_{Schw.}} (1 + \beta cos(\theta))$$

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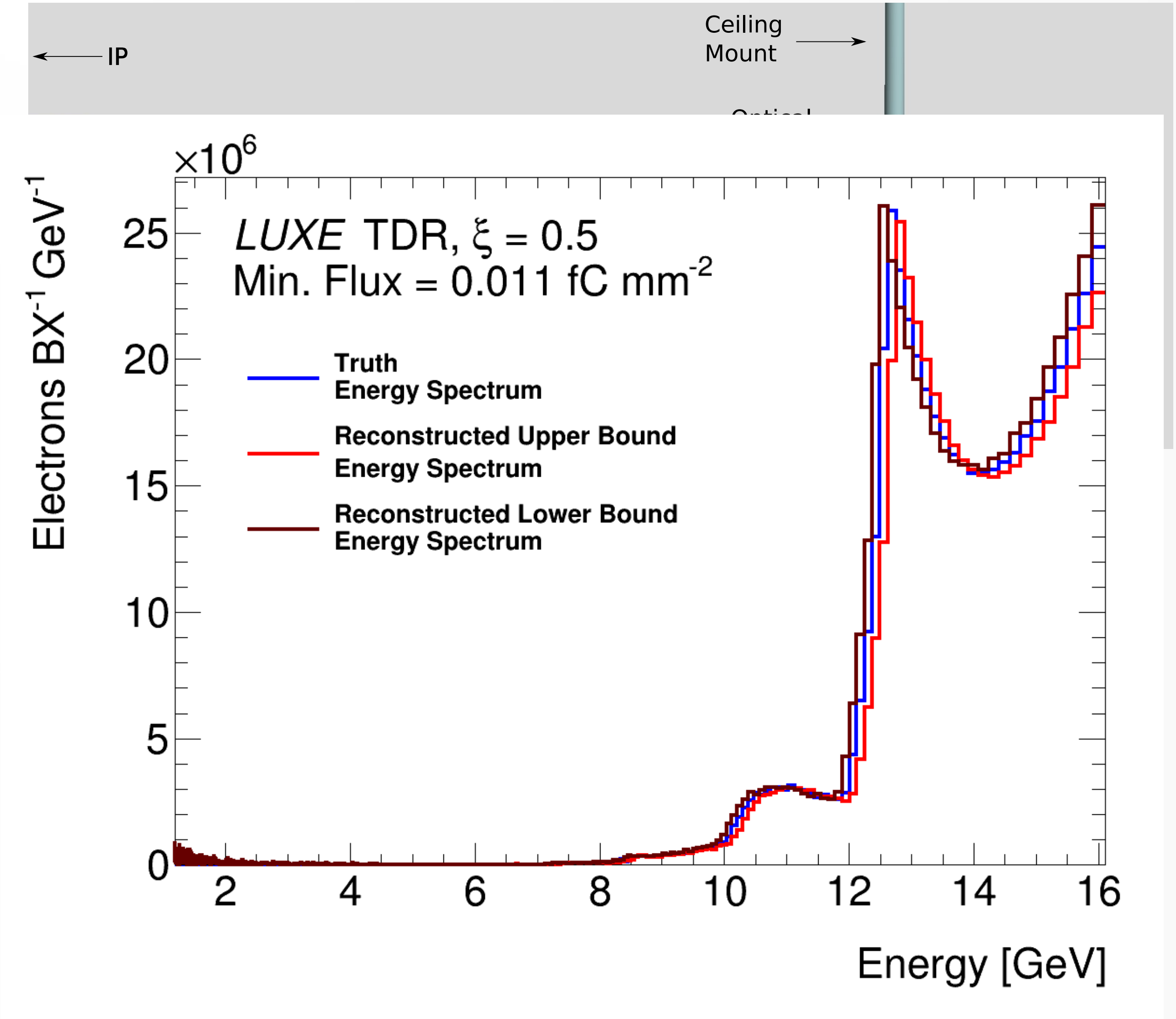
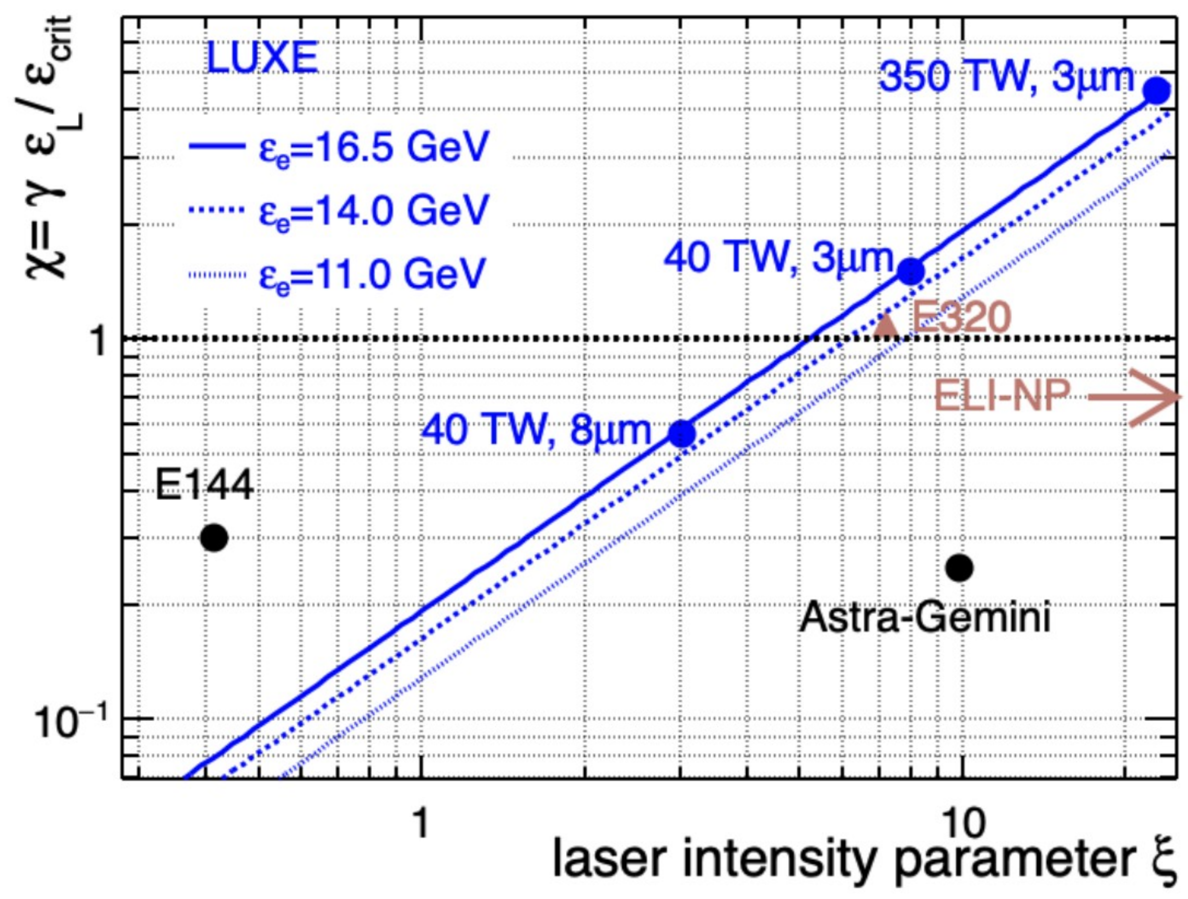
- The physics observables of the Compton Edge position and rate / BX of positrons are key
- Scintillator Screen & Camera system has a complete simulation + reconstruction process figured out (largely implemented in geant4)
- Screen resolution down to ~100 µm → 0.1% E uncertainty; one-shot reco vs truth integral difference <0.5%; final edge position uncertainty dependent on B-field, <1%



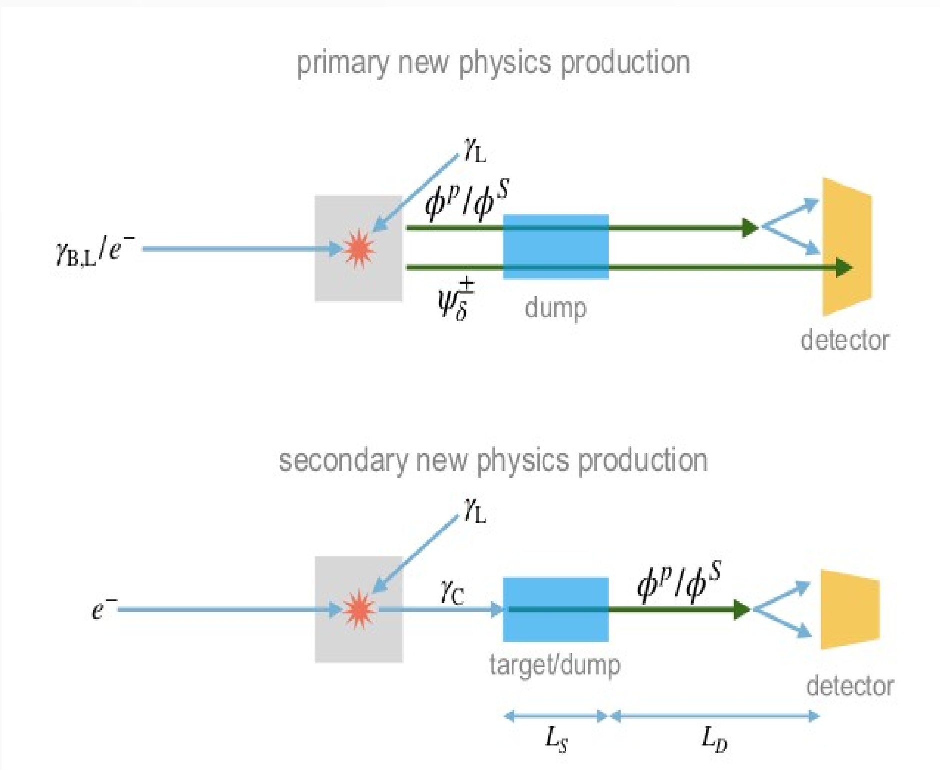
Expected Results

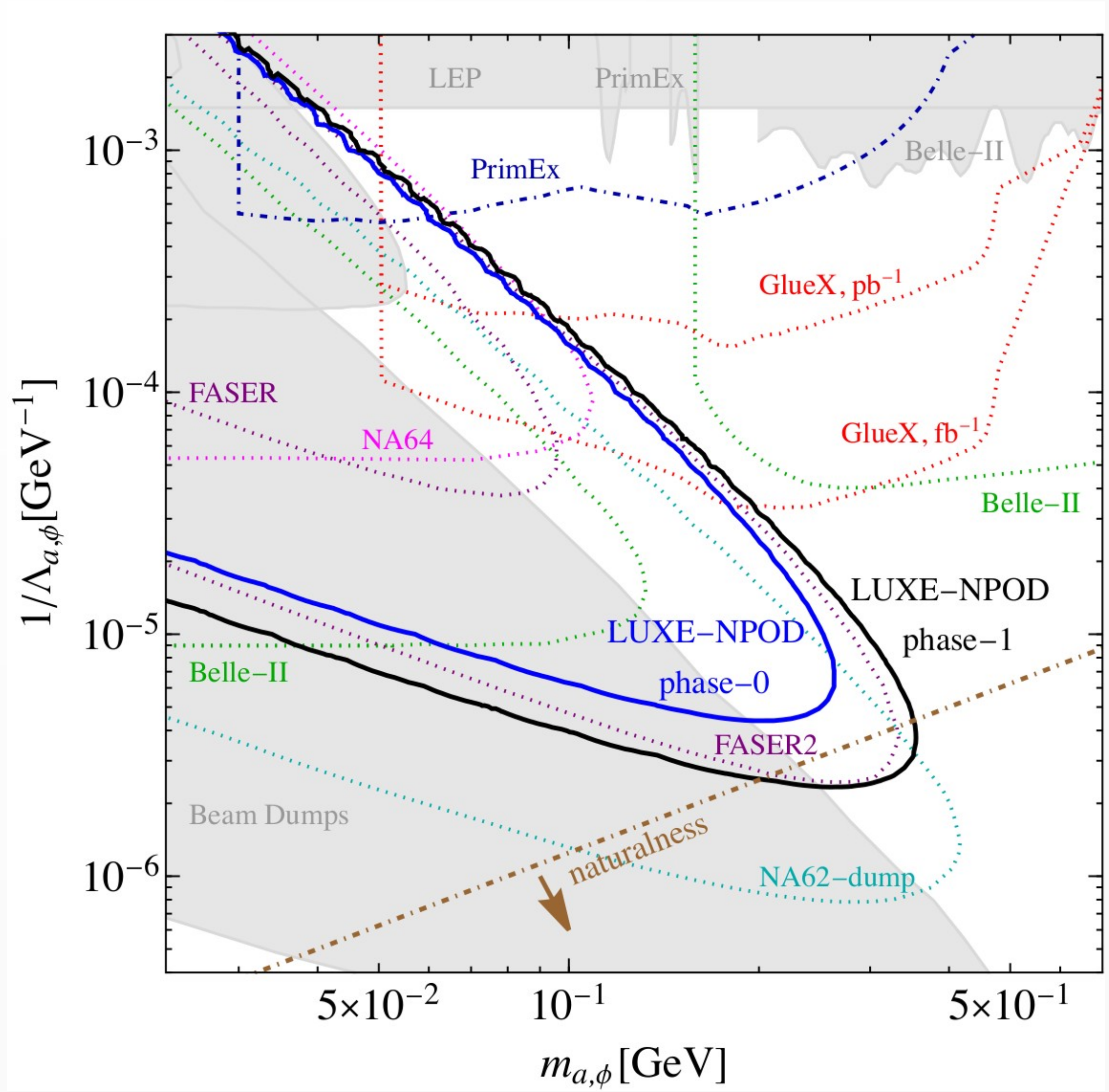
- E144 observed e- / e+ at SLAC in the 90s, 46.6 / 49.1 GeV e- beam & max. laser intensity = 5.0 x 10^{17} W/cm^2, achieved χ ~0.25, ξ<0.4
- ELI-NP (Extreme Light Infrastructure) will provide extremely intense laser up to 10^{23}–10^{24} W/cm^2
- E320 may reach milestone of χ = 1.0
- LUXE offers the possibility of the highest values of χ yet reached, with the infrastructure and time to accumulate statistics for high-quality measurements of strong electric fields & the nature of the regime transition



BSM Searches

- Due to high-energy high-flux photon source, in either running mode, searches BSM can be made in a beam-dump experiment
- ALPs and mCPs are searched for, and it's expected LUXE can carve out a slice of parameter-space



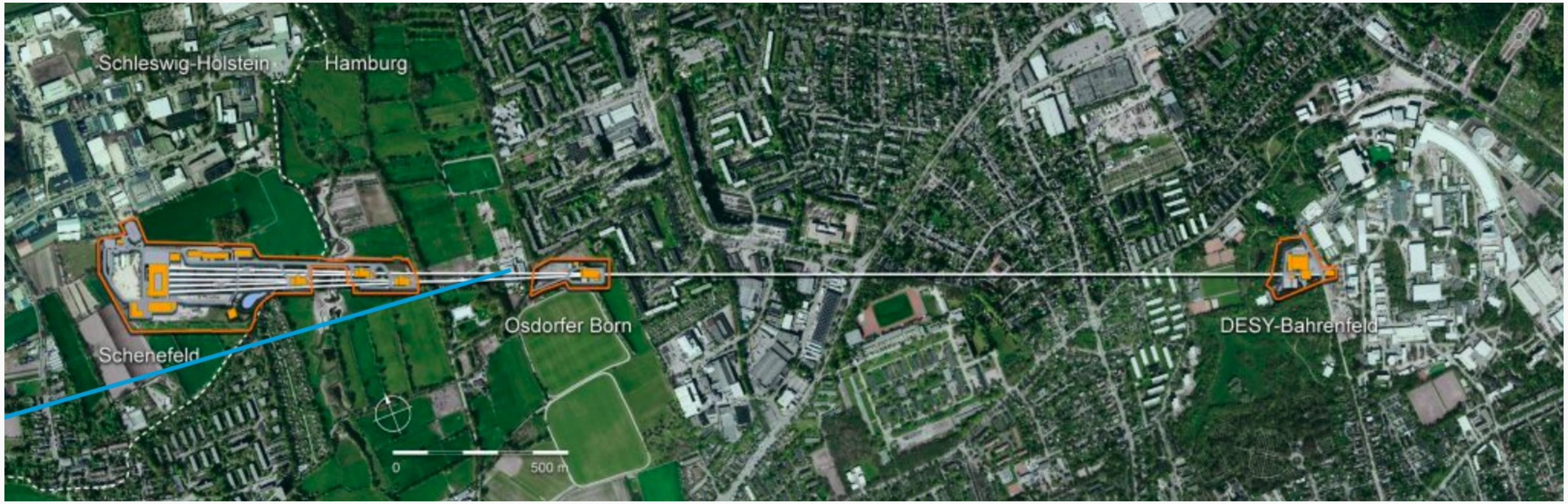


Simulation…

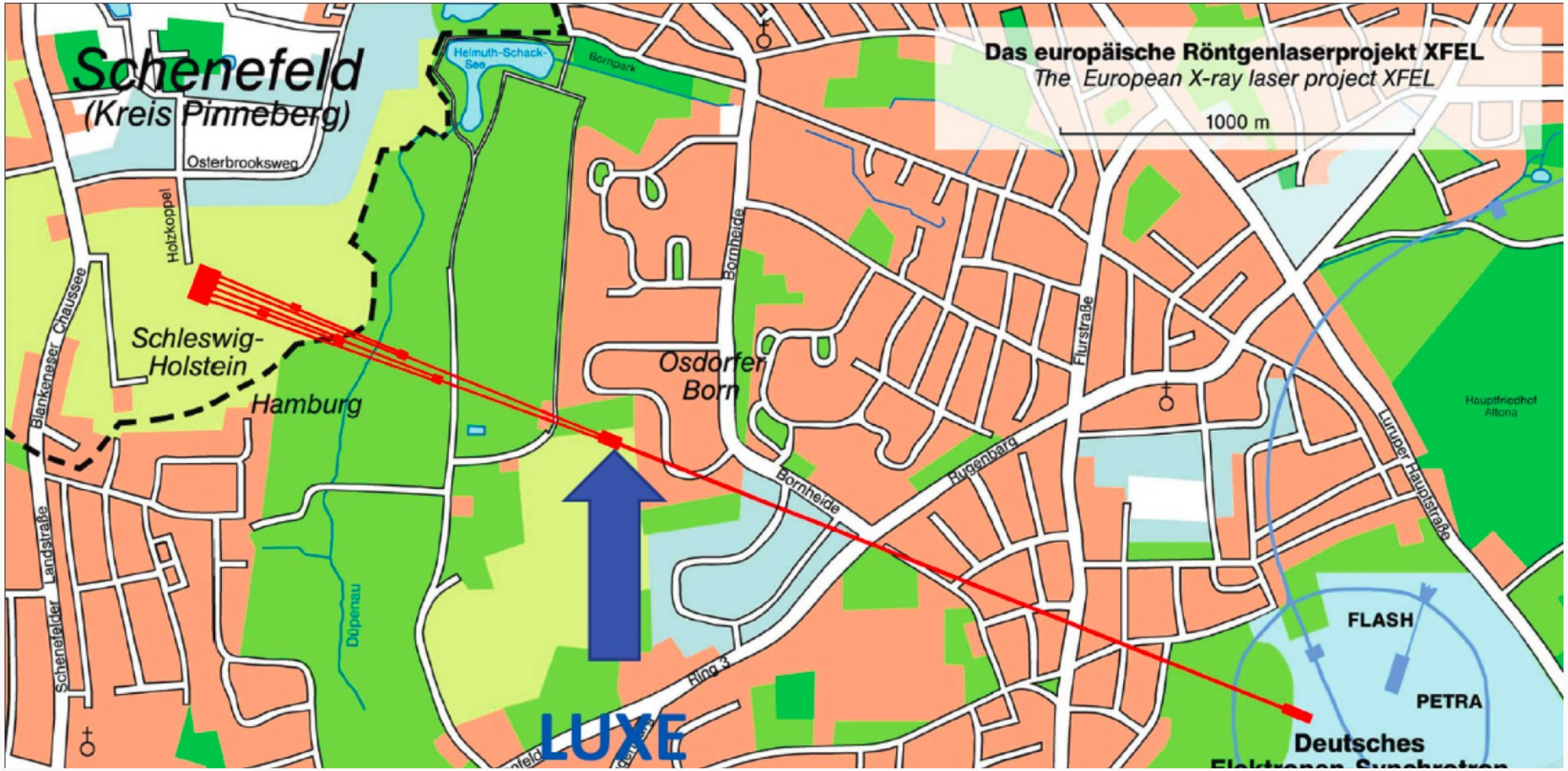
- Ptarmigan (https://github.com/tgblackburn/ptarmigan) is the program we use to generate the results of SFQED interactions in the interaction point
- Geant4 & FLUKA are used to estimate background and harmful radiation levels in the experimental chamber
- Geant4 and some small parameterisations are used for individual detector simulation and reconstruction

LUXE Running Modes

- Electron bunches from the XFEL accelerator collide with laser in an e-laser mode
- Photons generated from the e^- bunches used in photon-photon collisions in a γ-laser mode
- These photons are generated through bremsstrahlung or Inverse-Compton-Scattering, where the laser is split and interacts with the bunch first upstream, giving effective monochromatic photon source ~ 8.4 GeV and possibility of measuring polarisation effect on pair creation



XFEL



Das europäische Röntgenlaserprojekt XFEL
The European X-ray laser project XFEL
1000 m
Schenefeld
(Kreis Pinneberg)
Osterbrooksweg
Holzkoppel
Blankeneser Chaussee
Schleswig-
Holstein
Hamburg
Osdorfer
Born
Bornheide
Flurstraße
Rugenbarg
Luruper Hauptstraße
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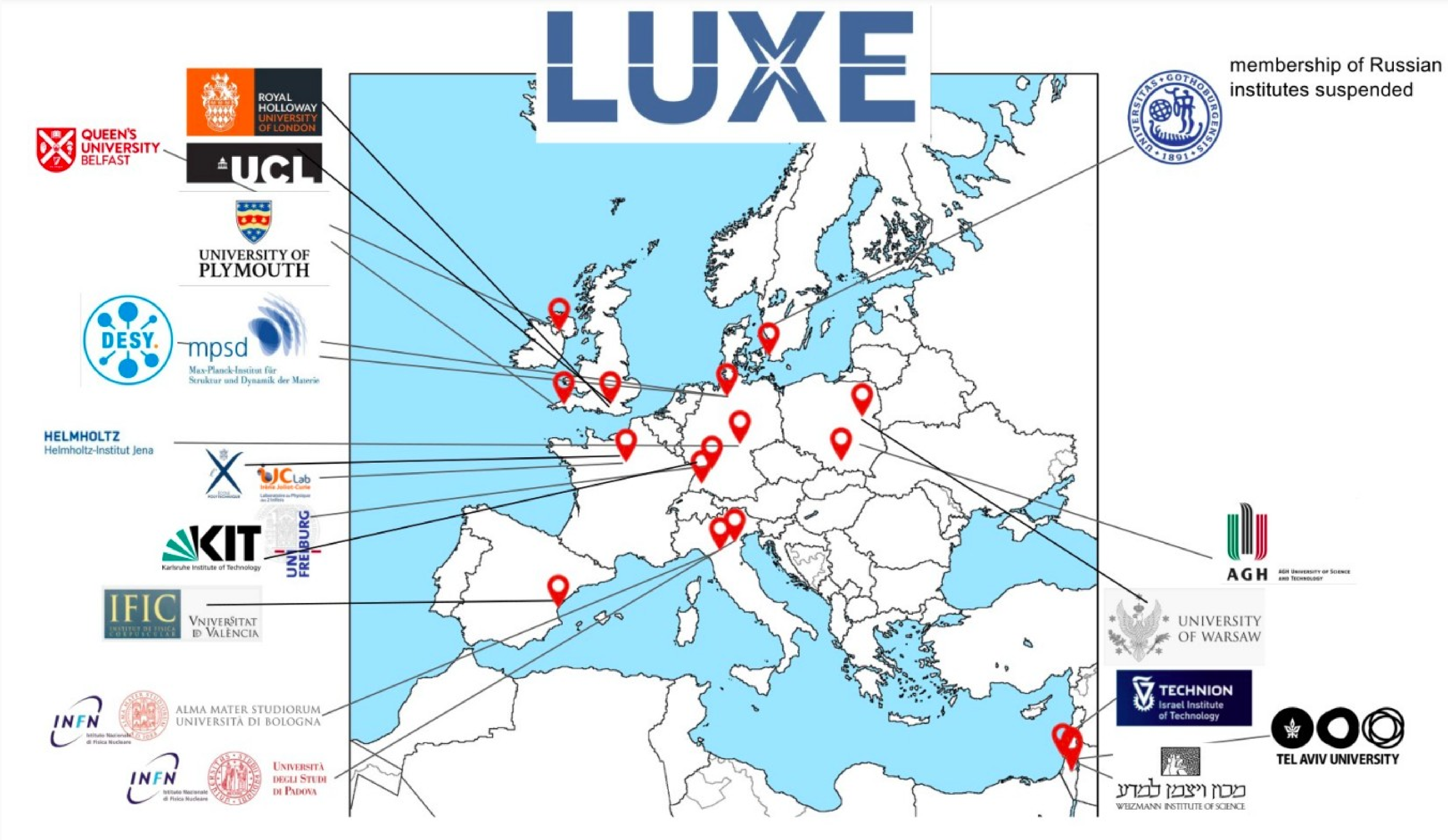
FLASH
PETRA
Deutsches
LUXE


LUXE
membership of Russian institutes suspended
ROYAL HOLLOWAY UNIVERSITY OF LONDON
QUEEN'S UNIVERSITY BELFAST
UCL
UNIVERSITY OF PLYMOUTH
DESY.
mpsd
Max-Planck-Institut für Struktur und Dynamik der Materie
HELMHOLTZ
Helmholtz-Institut Jena
IJCLab
KIT
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INFN
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
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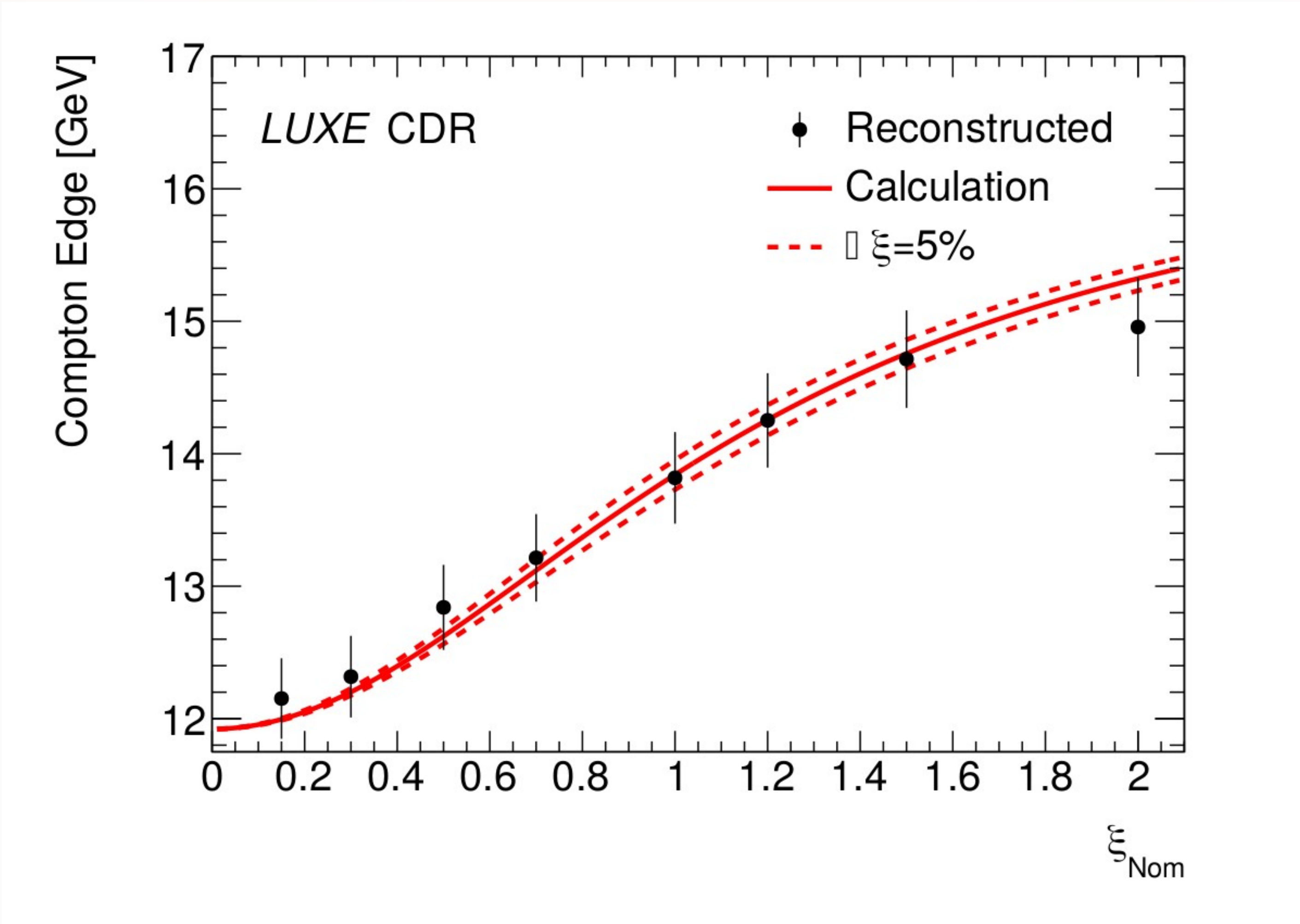

Compton electron edge upper kink position from simulated analysis as a function of the nominal ξ value. The red solid line shows the theoretical prediction. The dashed lines show the impact of a 5% uncertainty on the laser intensity. The black circles show the anticipated data result based on the analysis. The uncertainty shown is dominated by an energy scale uncertainty of 2.5%, a statistical uncertainty corresponding to 1 h of data taking is also included but negligible.