

LUXE: an experiment to study non-perturbative QED and search for new particles

Matthew Wing (UCL/DESY)
on behalf of the LUXE collaboration



- Introduction and motivation
- Strong-field QED physics
- LUXE experiment at European XFEL
- LUXE physics expectations
- Collaboration status and summary



KIT Particle Physics Colloquium — KIT, 2 July 2026



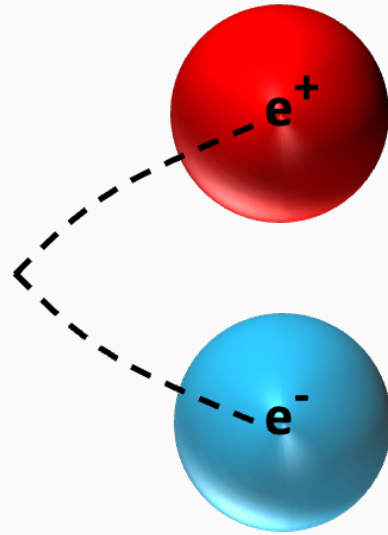
Introduction

- Quantum electrodynamics (QED) is the most precisely tested theory in modern physics.
 - But its predictions remain unexplored for extreme electromagnetic fields.
- When field strengths approach the Schwinger limit, QED enters a non-perturbative regime.
 - The quantum vacuum becomes unstable, spontaneously producing e^+e^- pairs.
 - Matter and antimatter created from pure light.
- Make high precision measurements and challenge theory in the transition from perturbative to non-perturbative regime and beyond.
- World-leading high-quality and high-energy European XFEL electron beam is key.
 - Complemented by precise diagnosis of laser pulse and suite of detectors.
 - LUXE experiment !

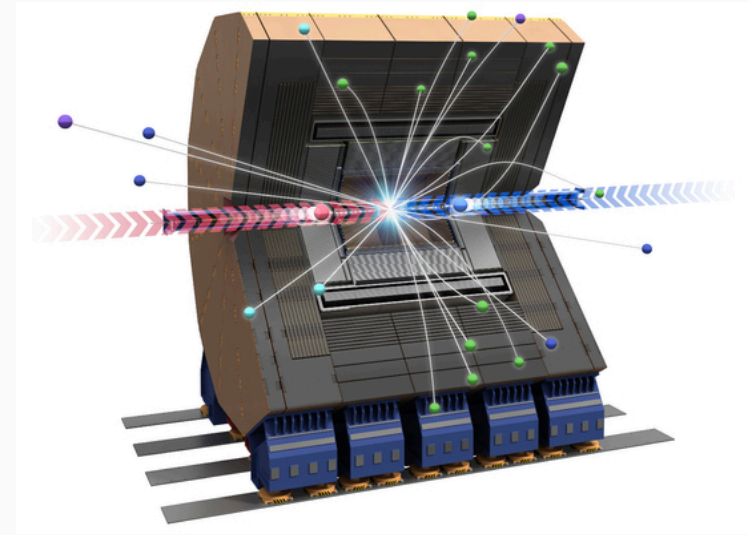


Why are we interested in strong-field QED ? **LUXE**

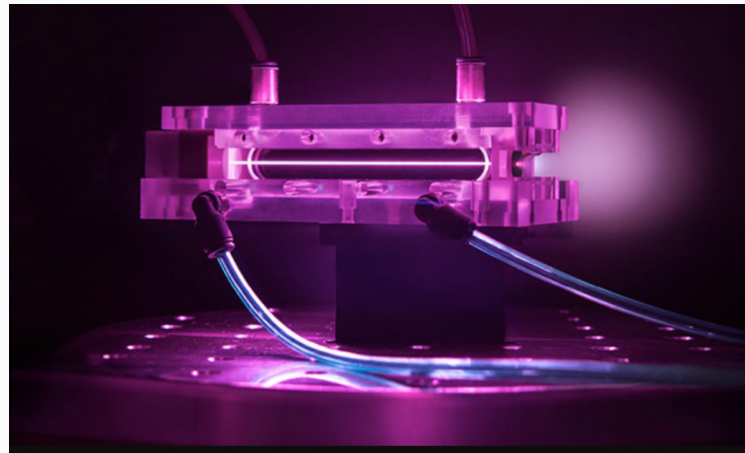
Fundamental science



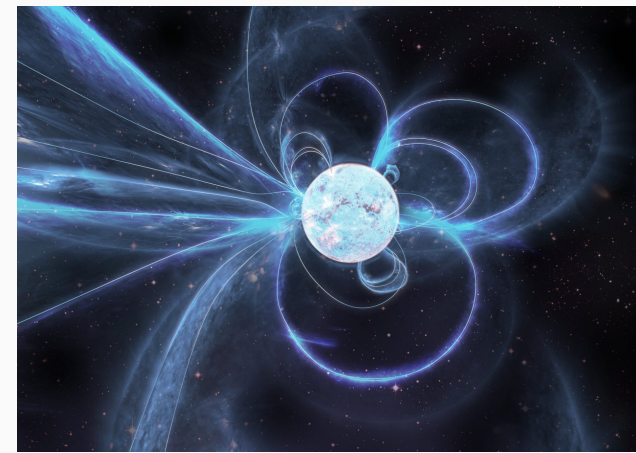
Higgs factories



Laser physics and novel accelerators

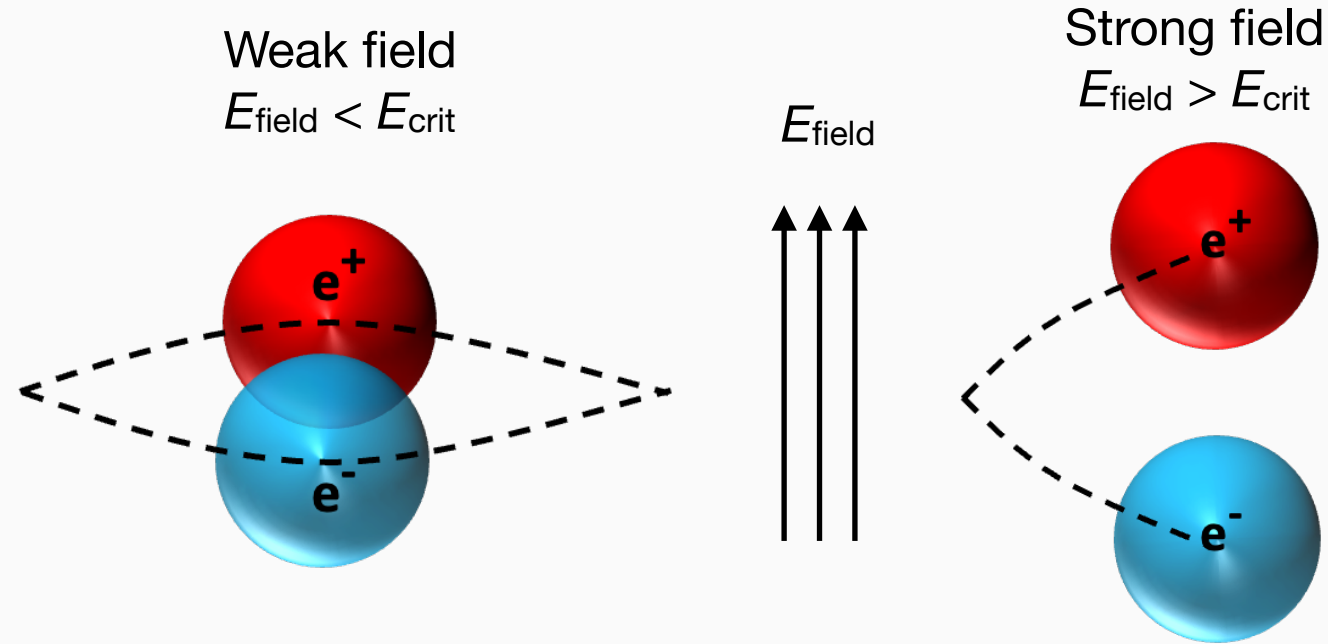


Neutron stars, black holes, etc.



Strong-field QED physics

Strong-field QED



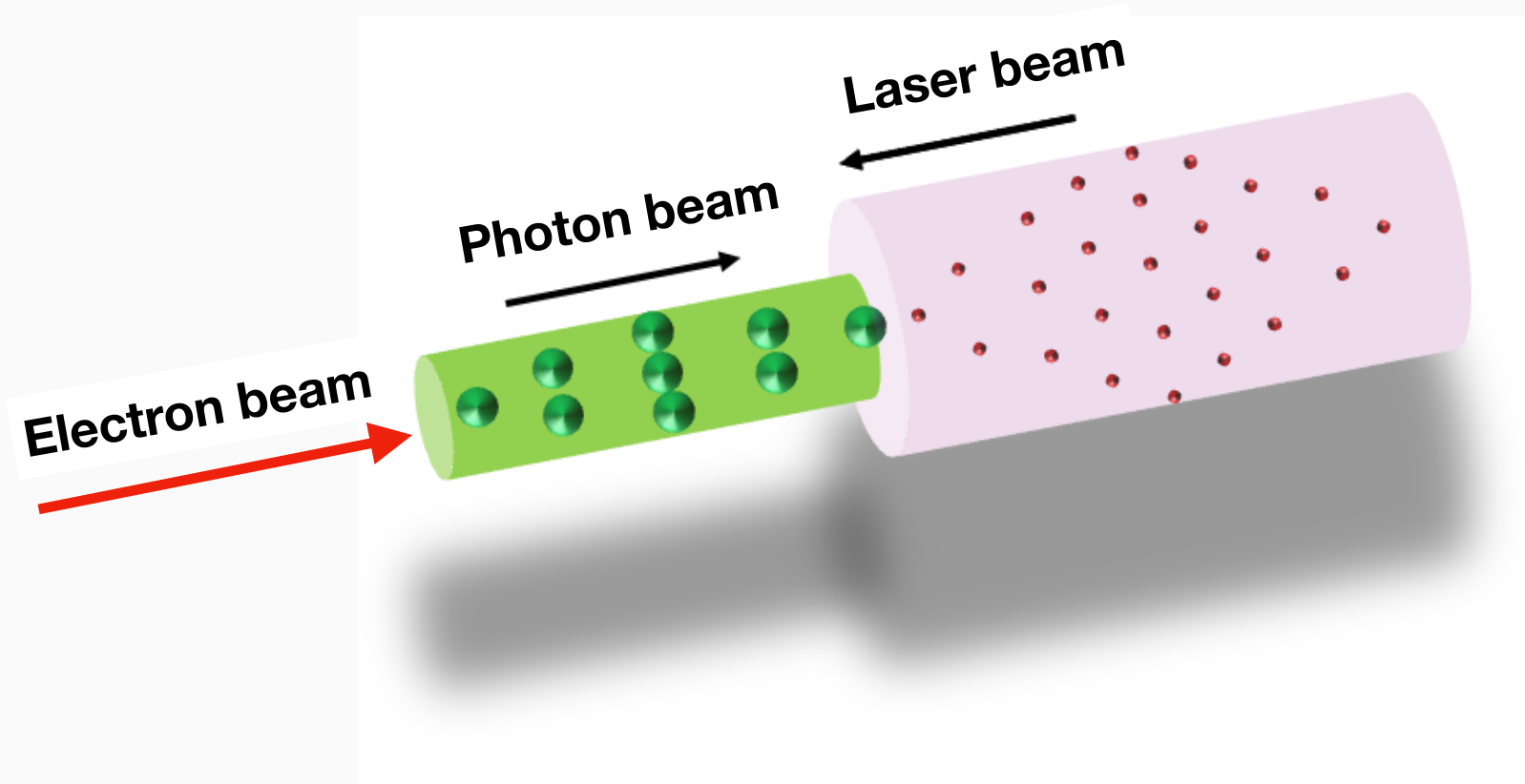
Critical field or
Schwinger limit:

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

10,000× greater than
world's largest lasers.

Exceeding the critical field

LUXE

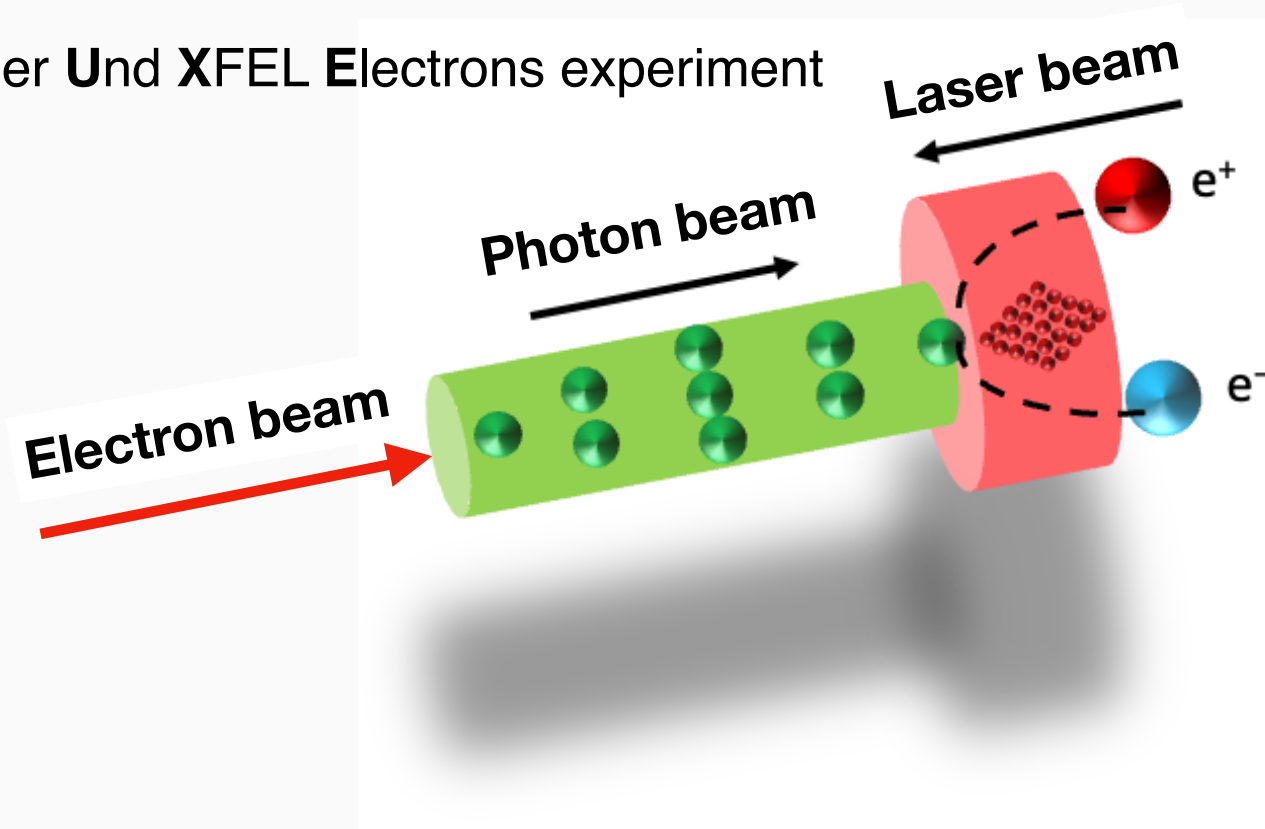


Laboratory
frame

- Critical field can be reached with relativistic length contraction.

Strong-field QED

- **LUXE**: Laser Und XFEL Electrons experiment



Boosted
frame

- Critical field can be reached with relativistic length contraction.
- Relativistically boosted field, $\chi = \gamma E_L / E_{\text{crit}}$
- Investigate QED in new parameter space
 - E.g. transition to nonlinear QED.
 - With high precision and control.

Strong-field QED parameters

- **Intensity parameter:**

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

- Measure of coupling between probe and laser field (also square root of laser intensity).

- **Quantum parameters:**

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

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

- Ratio of laser field and Schwinger critical field.

E_{crit} : Schwinger critical field

E_L : Laser field

ω_L : Laser frequency

θ : e/γ – laser crossing angle

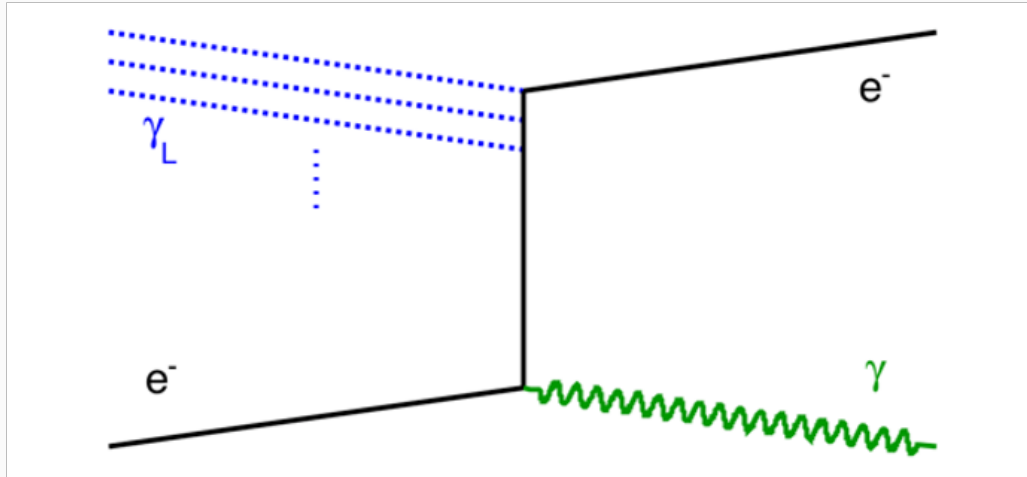
$E_{e/\gamma}$: Probe electron/photon energy

- **Energy parameter:**

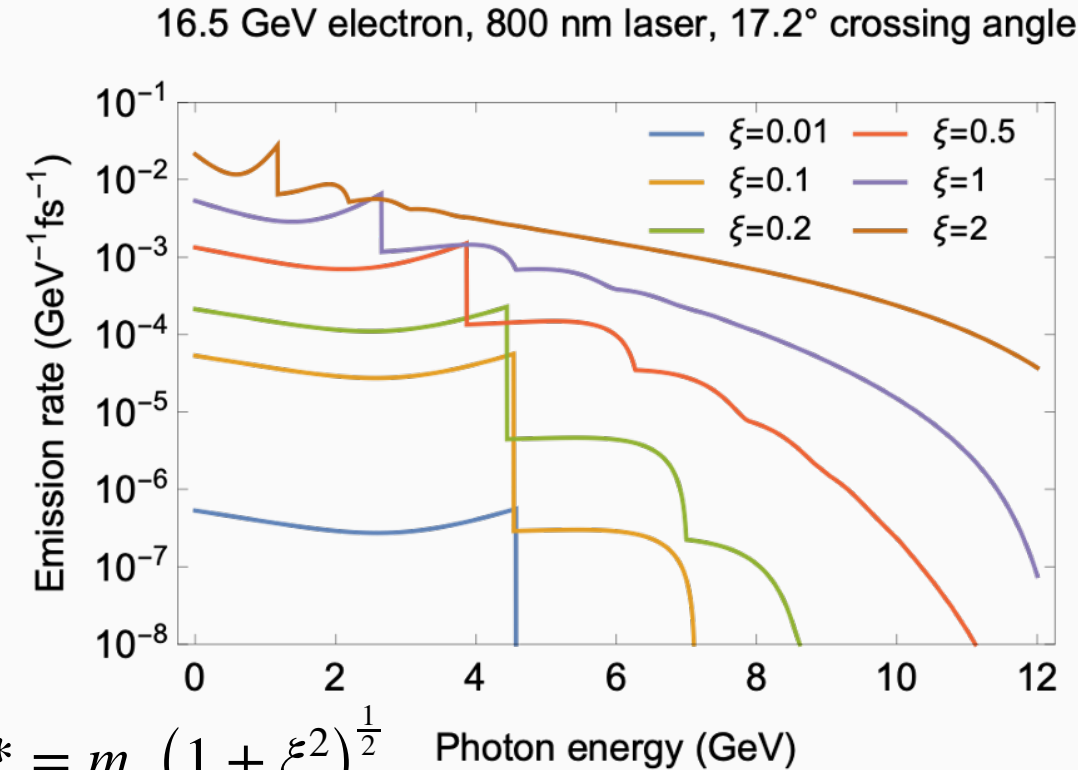
$$\eta = \frac{\chi}{\xi} = (1 + \cos \theta) \frac{\omega_L E_{e/\gamma}}{m_e^2}$$



Nonlinear Compton scattering



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



- In strong fields, electrons obtain larger effective mass, $m^* = m_e (1 + \xi^2)^{\frac{1}{2}}$
 - Compton edge shifts as a function of ξ .
 - Higher harmonics appear, i.e. interactions with n laser photons.



Strong-field
QED

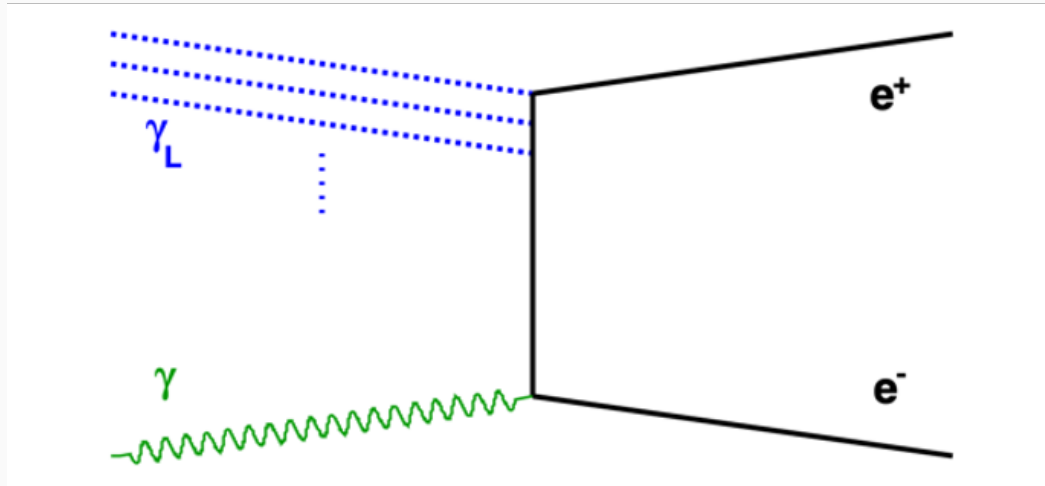
$$E_{\text{edge}}(\xi) = E_e \frac{2n\eta}{2n\eta + 1 + \xi^2}$$

Classical
limit

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

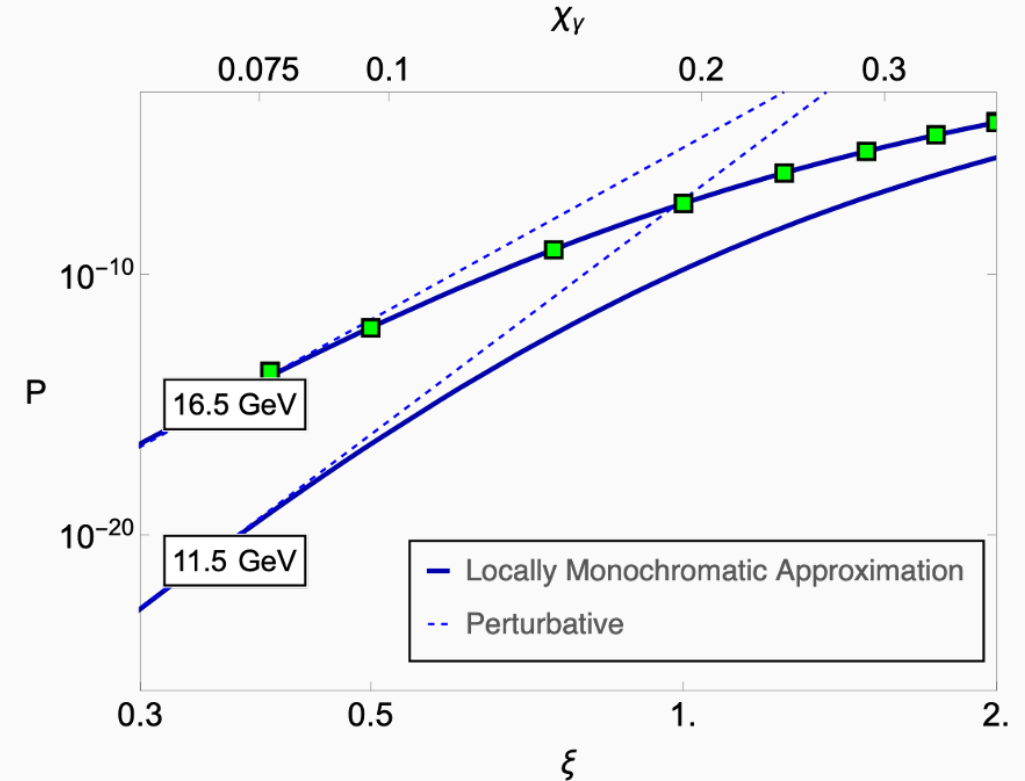


Nonlinear Breit–Wheeler pair production



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

Photon from Compton scattering or secondary beam.



Perturbative regime: power law

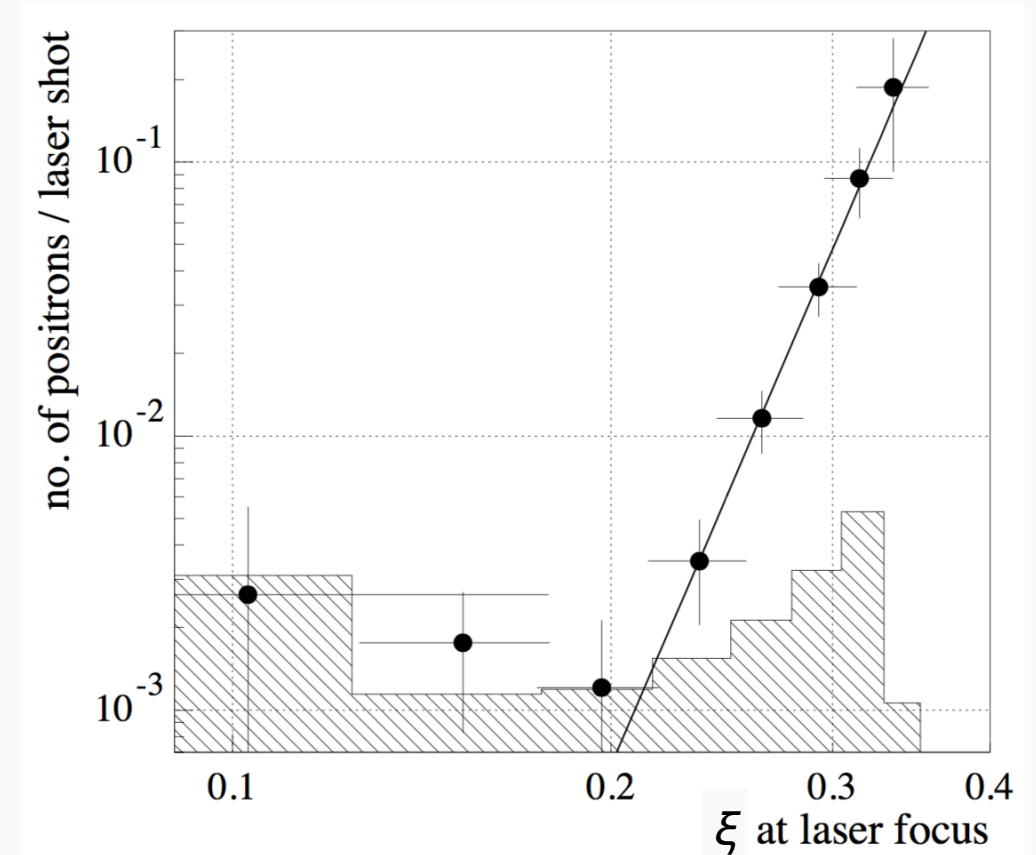
$$\xi \ll 1 : R_{e^+} \propto \xi^{2n} \propto I^n$$

Non-perturbative regime

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

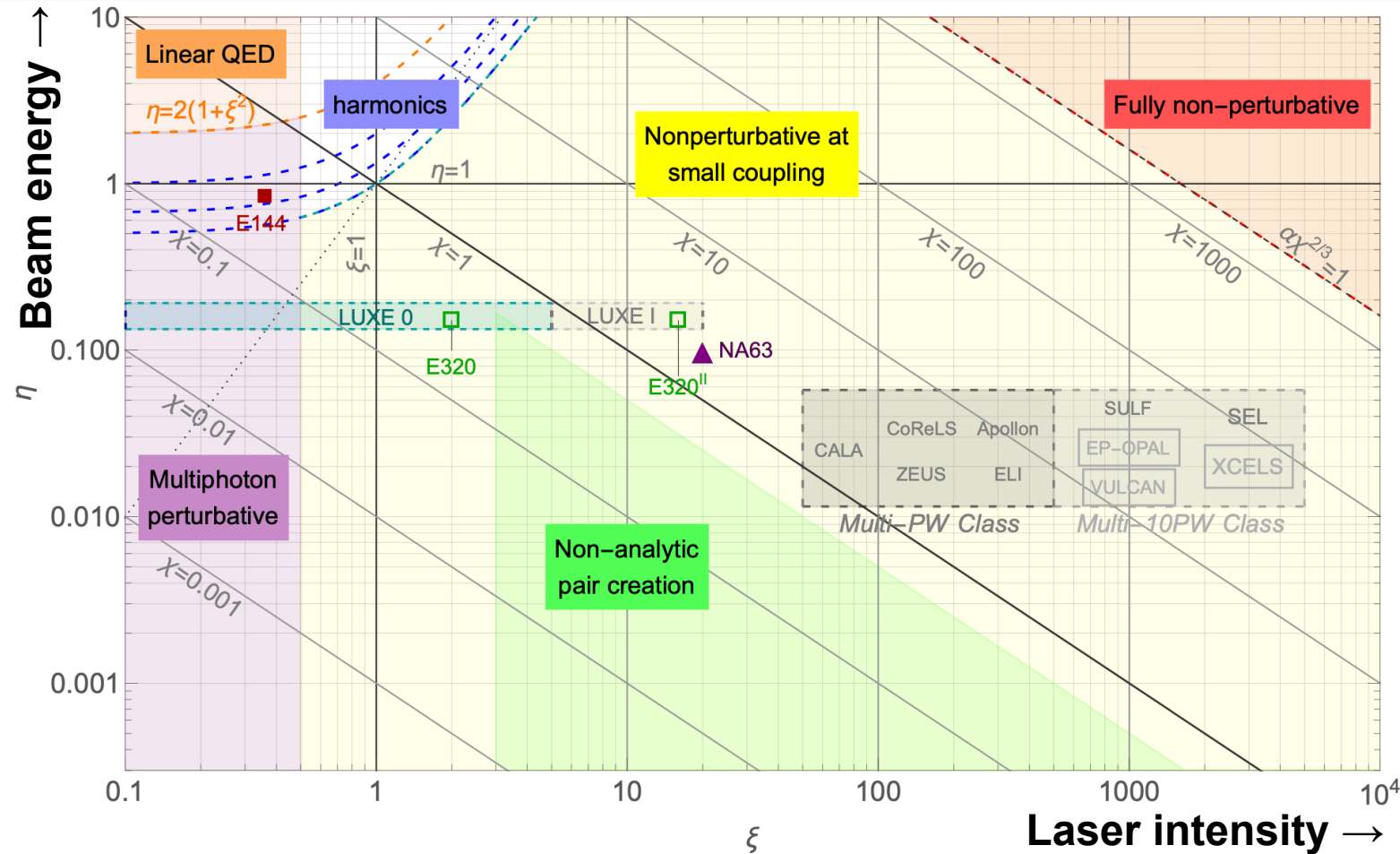
E144 experiment at SLAC

- Pioneering experiment, E144, at SLAC in the 1990s.
- Used 1 TW laser and 46.6 GeV electron beam.
- Reached $\chi \sim 0.25$, $\xi \sim 0.4$.
- Observed process $e^- + n\gamma_L \rightarrow e^- + e^+ + e^-$
- Measured about 100 positrons.
- Observed start of ξ^{2n} power law, but not departure from it.



Strong-field QED parameter space

Nonlinear Breit–Wheeler process

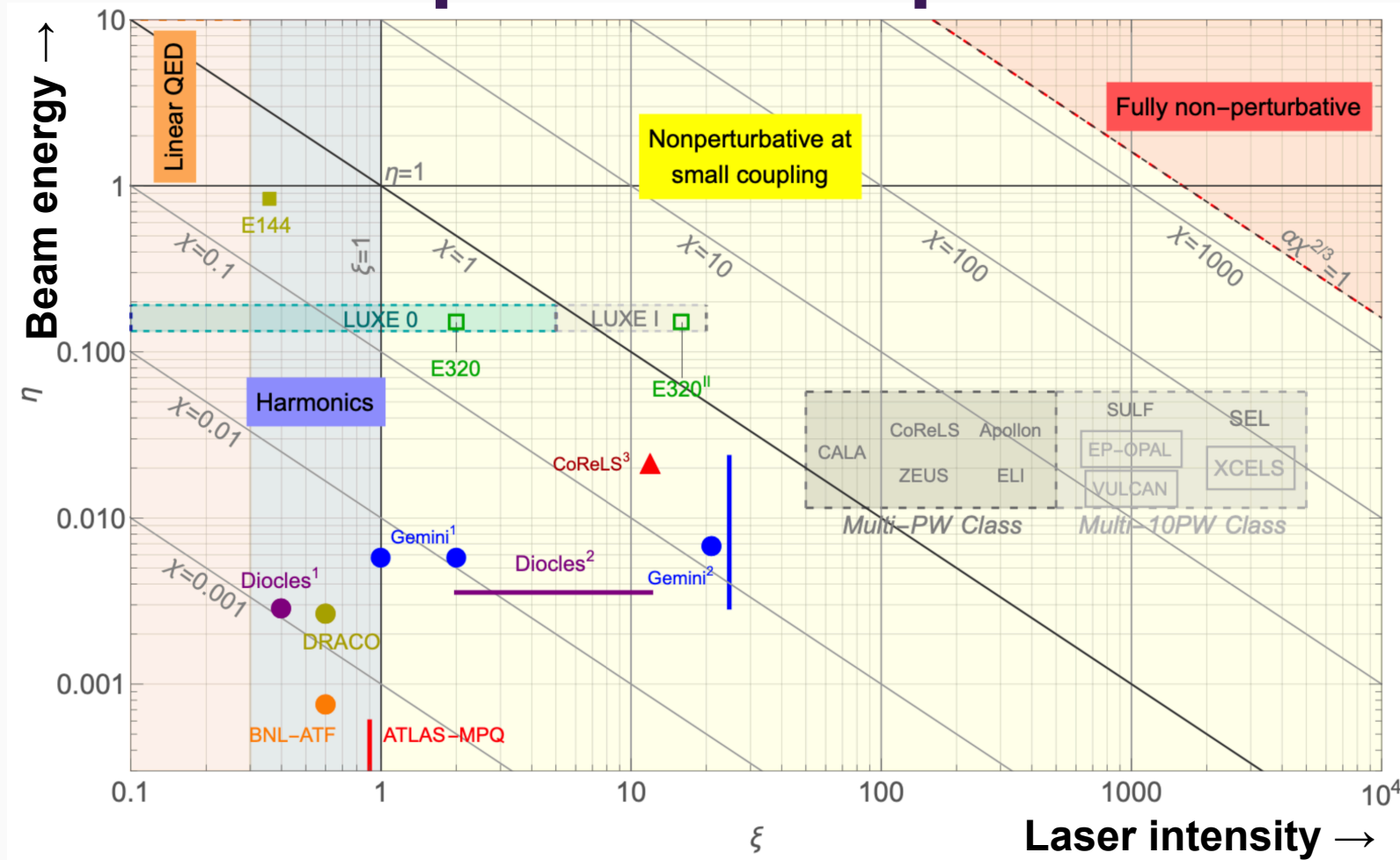


Credit: B. King:
G. Sarri et al., *Eur. Phys. J. Plus* **140** (2025) 1151.

- Determined by particle beam energy and laser intensity.
- LUXE will precisely map parameter space in transition region.

Strong-field QED parameter space

Nonlinear Compton process



Credit: B. King:
G. Sarri et al., *Eur. Phys. J. Plus* **140** (2025) 1151.

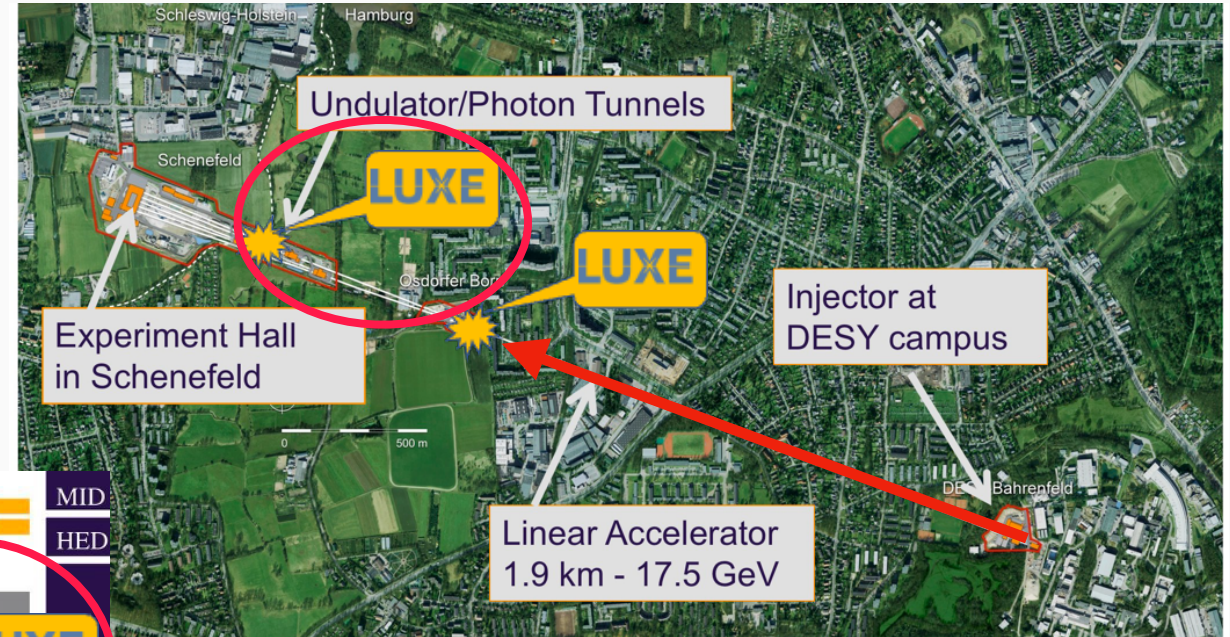
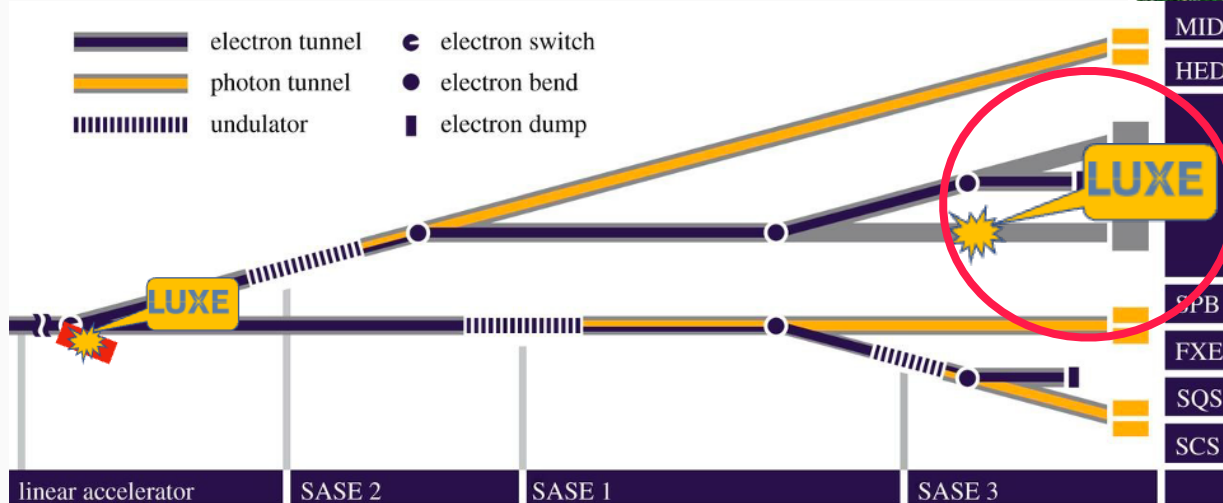
- Determined by particle beam energy and laser intensity.
- LUXE will precisely map parameter space in transition region.

LUXE experiment at European XFEL

LUXE at European XFEL

EuXFEL electron beam:

- Energy: 16.5 GeV (+ whatever provided)
- Bunch: $1.5 \times 10^9 e^-$
- Repetition rate: 10 Hz
- Use 1 of 2700 bunches per train

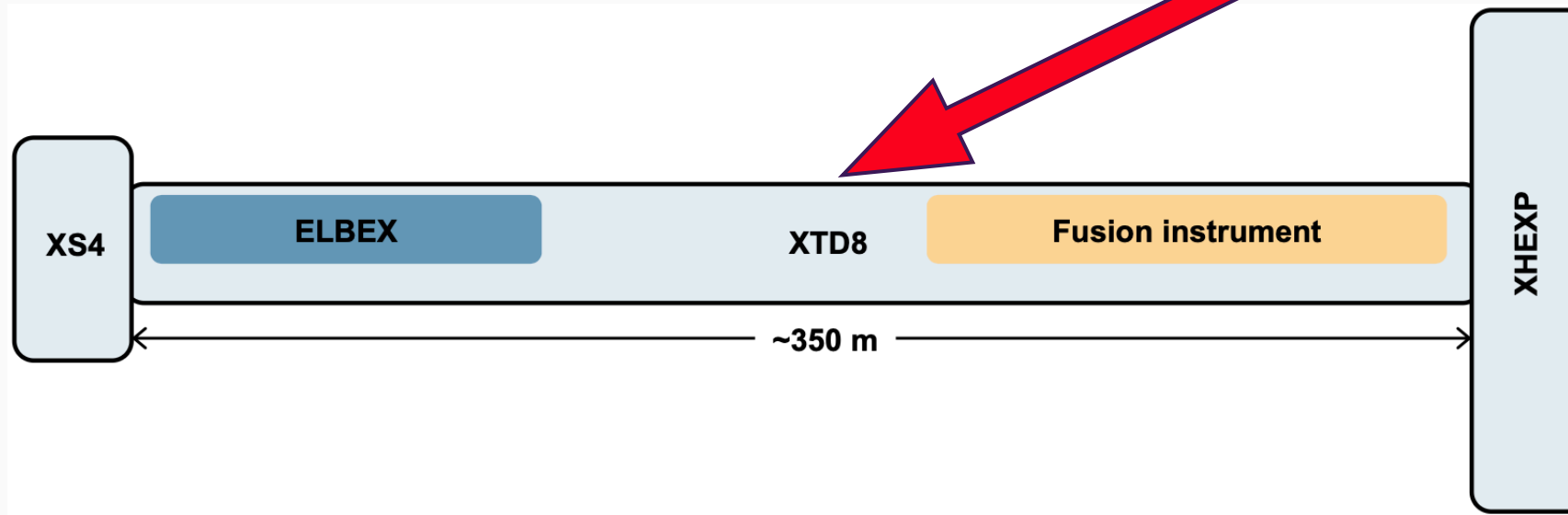
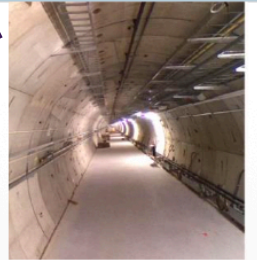
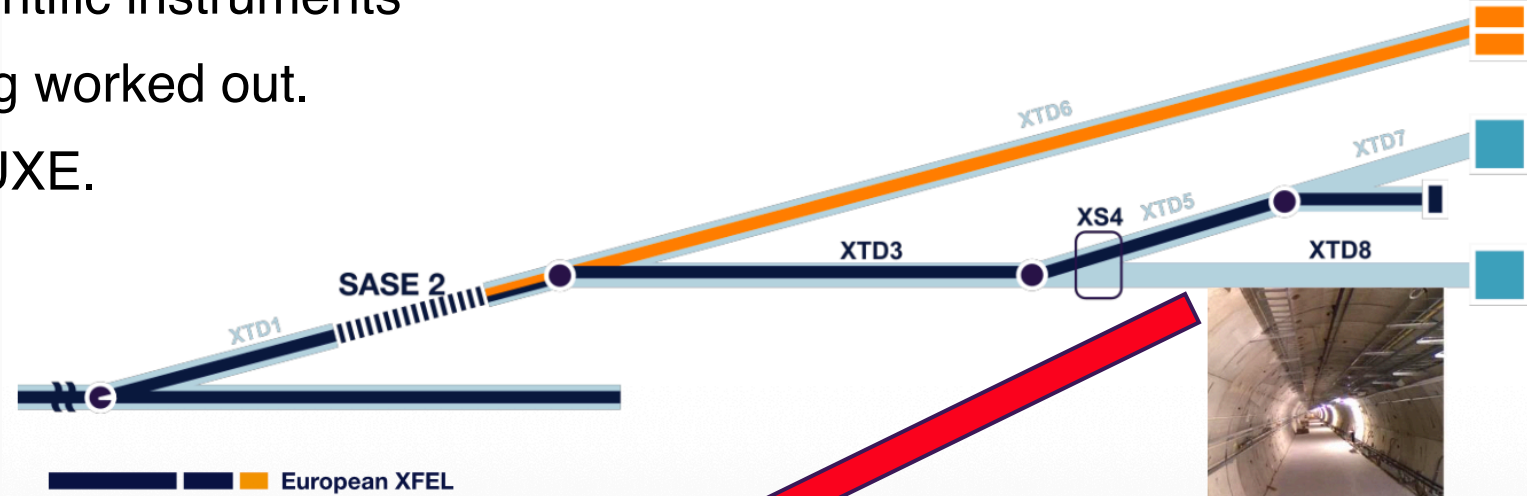


- Use electron beam without undulation
- Minimal impact on photon science programme.
- Minimal impact on fusion science programme.

LUXE at European XFEL

LUXE

- XTD8 — a tunnel section for scientific instruments
- Initial schematic and details being worked out.
- ELBEX: Electron beamline for LUXE.



LUXE at European XFEL

LUXE

- XTD8 — a tunnel section for scientific instruments
- Initial schematic and details being worked out.
- ELBEX: Electron beamline for LUXE.



LUXE laser

LUXE

Wavelength (energy)	800 nm (1.55 eV)
Power	40 / 350 TW
Pulse length	30 fs
Spot size	$> 3 \mu\text{m}$
Peak intensity	$13.3 / 120 \times 10^{19} \text{ W/cm}^2$
Peak intensity parameter ξ	7.9 / 23.6
Peak quantum parameter χ	1.5 / 4.5



- Repetition rate 1 – 10 Hz.
- Crossing angle, 17°
- Phases:
 - Phase-0 with a 40 TW laser (JETI40)
 - Upgrade to a 350 TW laser for Phase-1
 - Potential for higher power with fusion laser ?

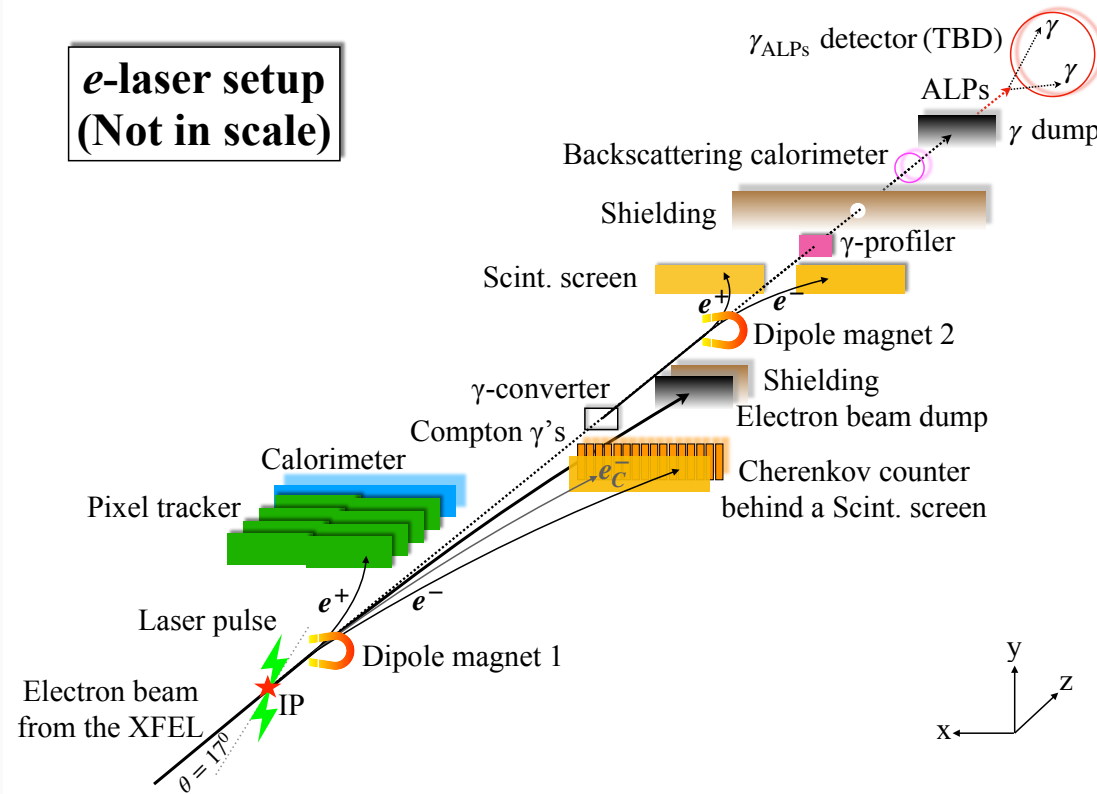


Goal:

- $< 5\%$ uncertainty on laser intensity
- 1% shot-to-shot uncertainty

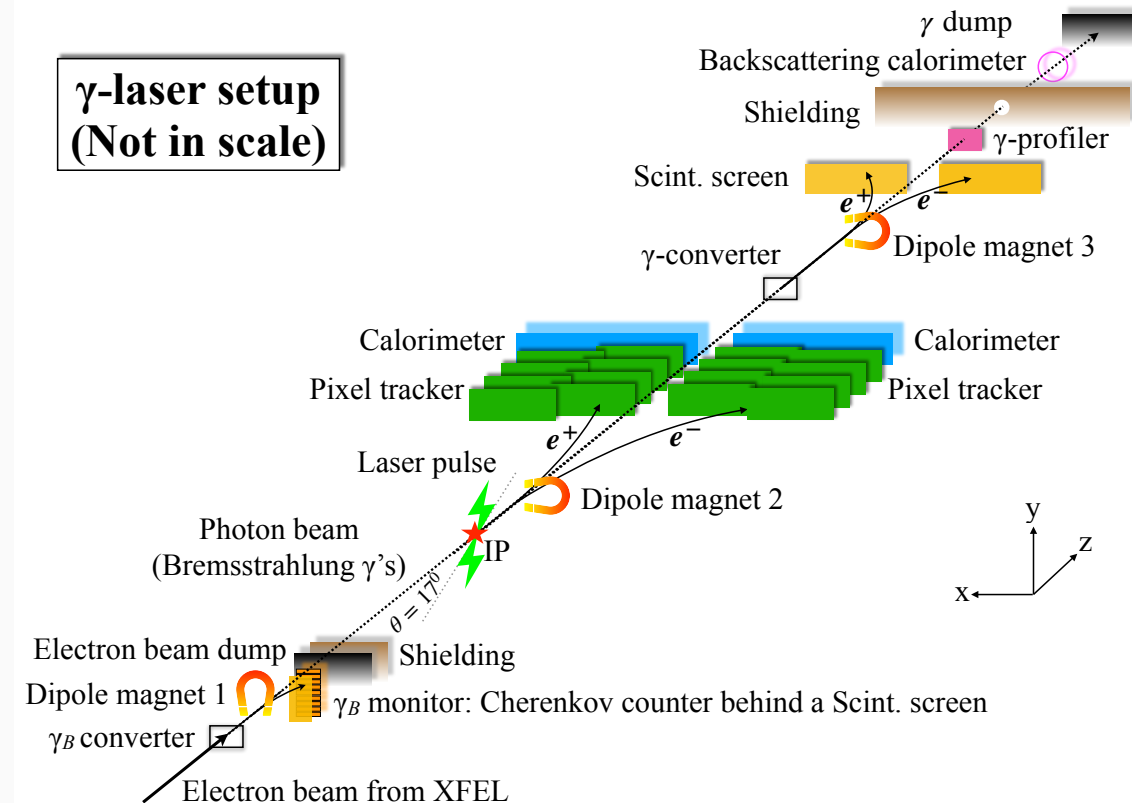
Experimental layout

***e*-laser setup
(Not in scale)**



Two data-taking modes

***γ*-laser setup
(Not in scale)**



- Similar but different layouts.
- Many of the detectors are the same.
- Note programme to search for axion like particles (ALPs) too.

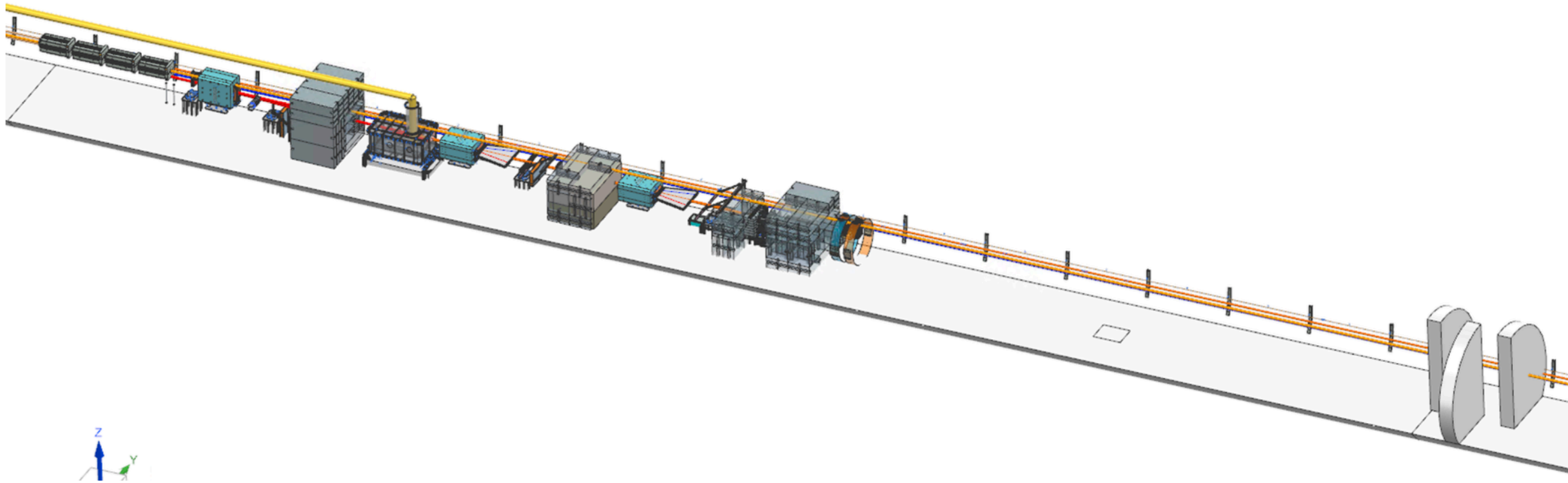
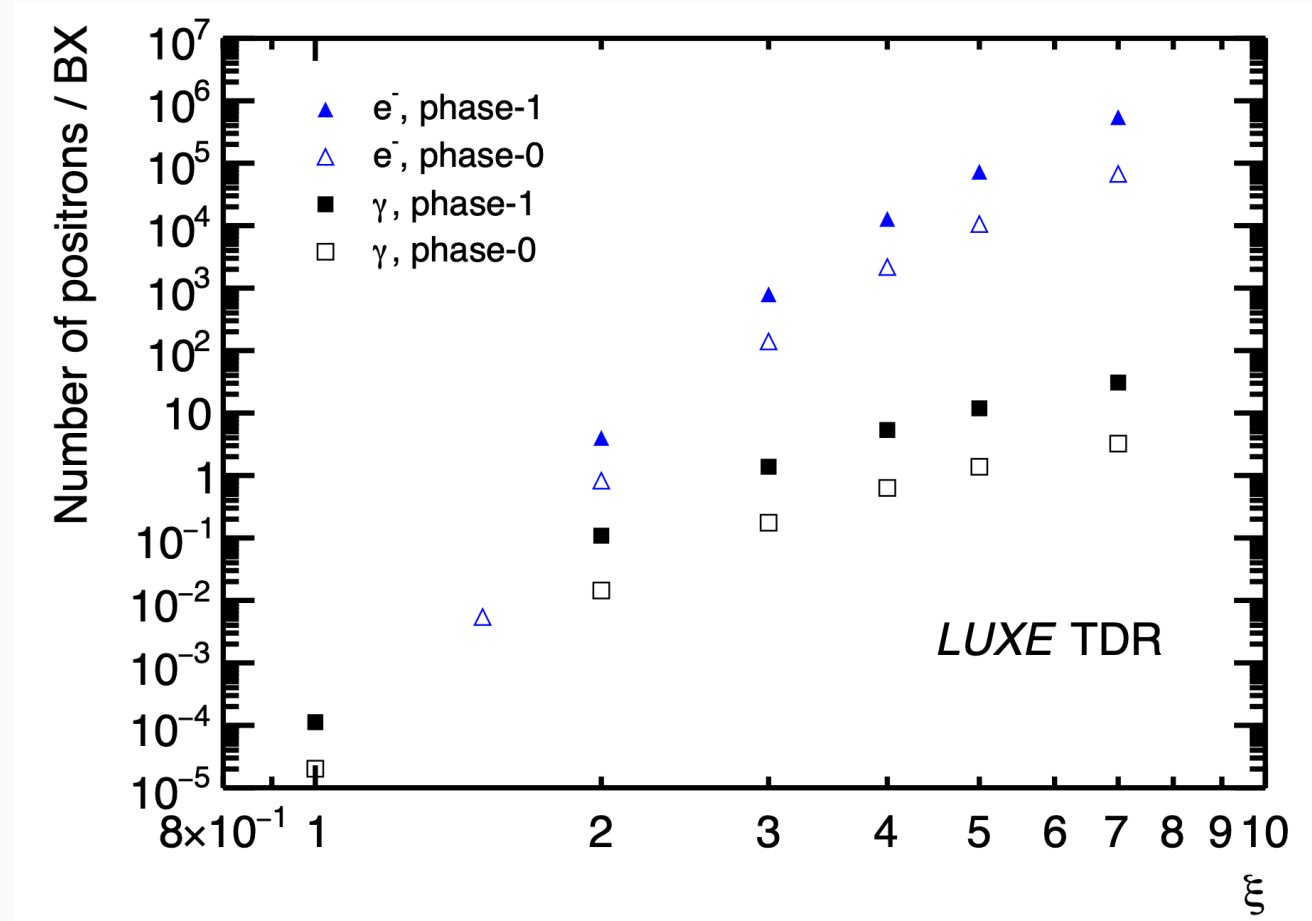


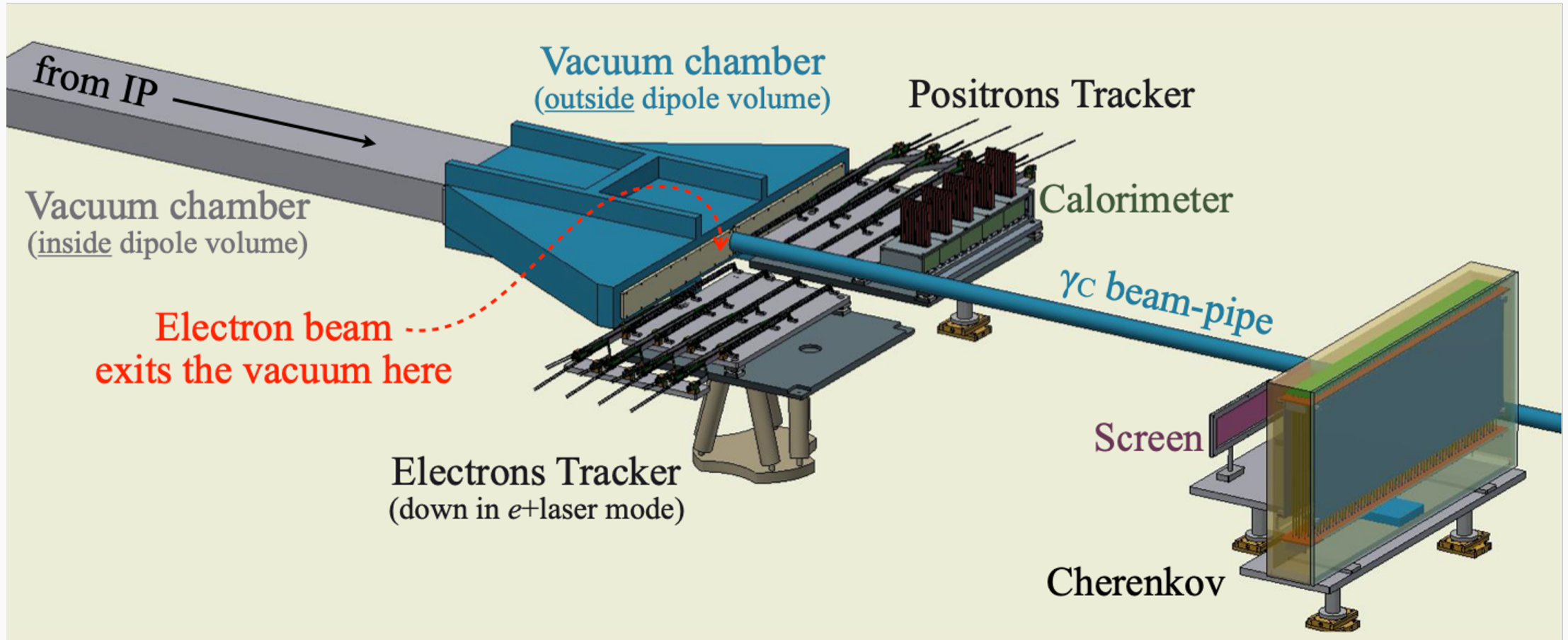
Figure 2.6: Conceptual placement of the LUXE experimental installations in the XTD8 tunnel.

Detector requirements and challenges

- Want to detect electrons, positrons and photons in the O(GeV) range.
 - Measure fluxes and energy spectra.
- Detector technology to cater for varying fluxes of signal and background.
 - Fluxes vary between $\sim 10^{-4}$ (e^+) and 10^9 (e^- and γ).



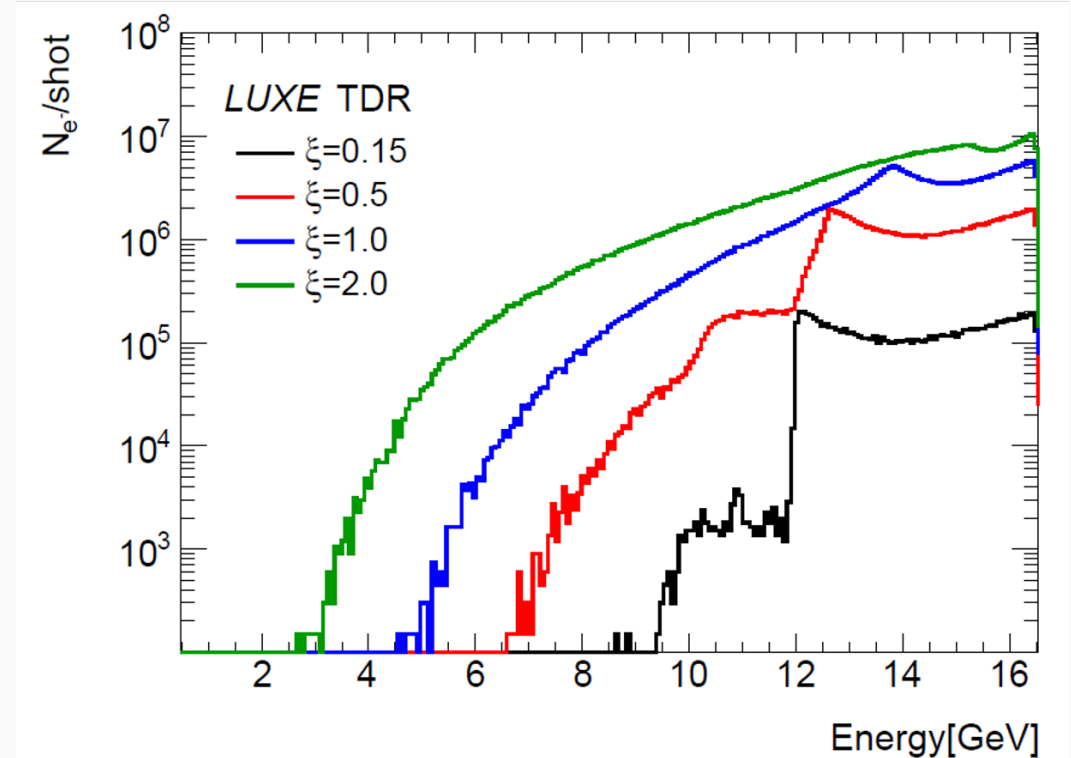
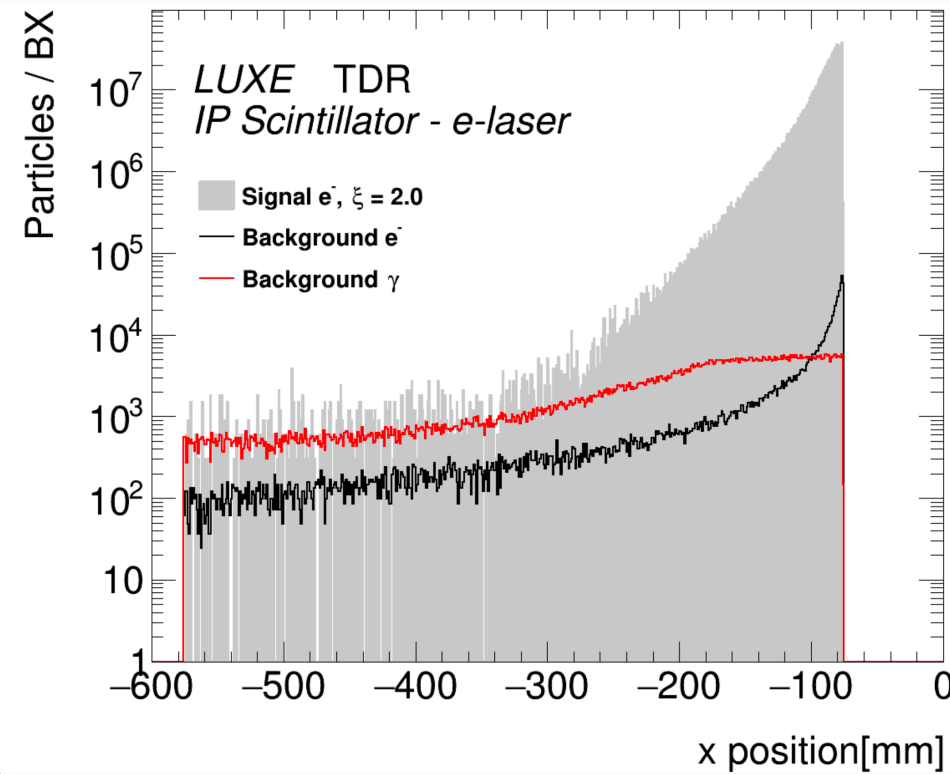
Detectors after the interaction point



- Two complementary detector technologies per measurement:
 - Different sensitivities, cross calibration, reduction of systematic uncertainties.
- In-situ measurements of beam back backgrounds when laser off.

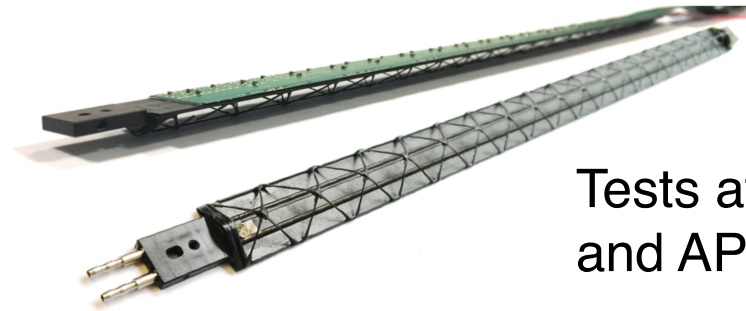
High-rate electron detectors

- A scintillator screen and camera is inexpensive, flexible and simple with good position resolution.
- Cherenkov straw detectors have small low-energy background.
- Simulations show good performance and reconstruction of important quantities.
- Tests done with ARES and E320 experiment at FACET-II beamline in SLAC.



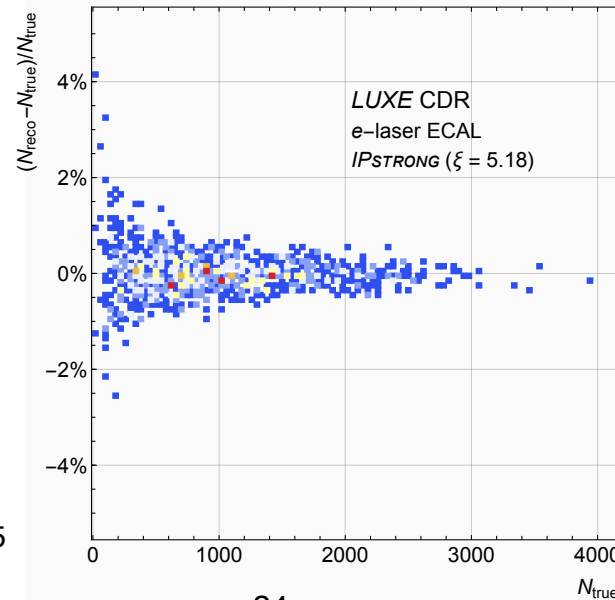
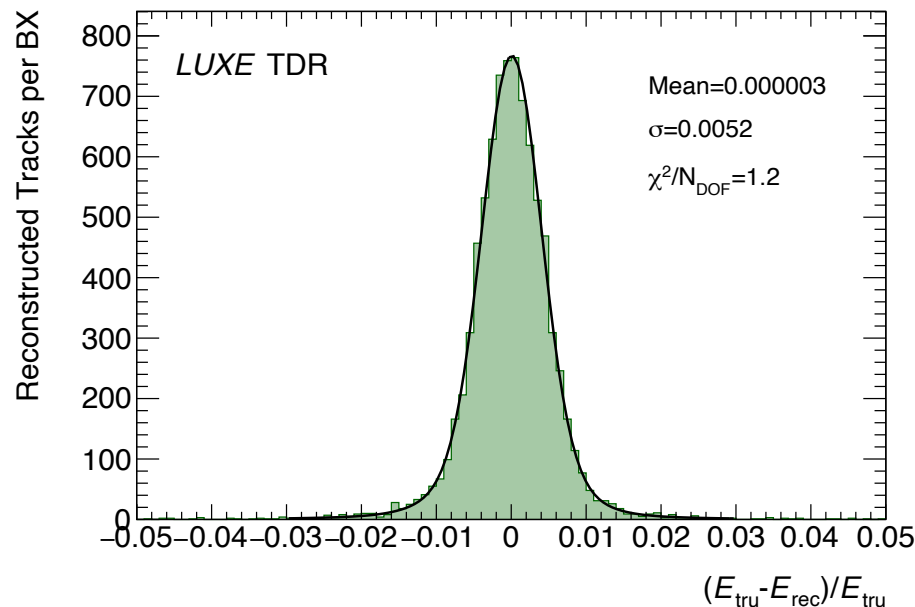
Positron detectors

- Pixel tracker:
 - 4 layers each of which has 2 staves.
 - Each stave is $27 \times 1.5 \text{ cm}^2$ built from 9 ALPIDE chips, $3 \times 1.5 \text{ cm}^2$.



Tests at E320, ELI-NP and APOLLON.

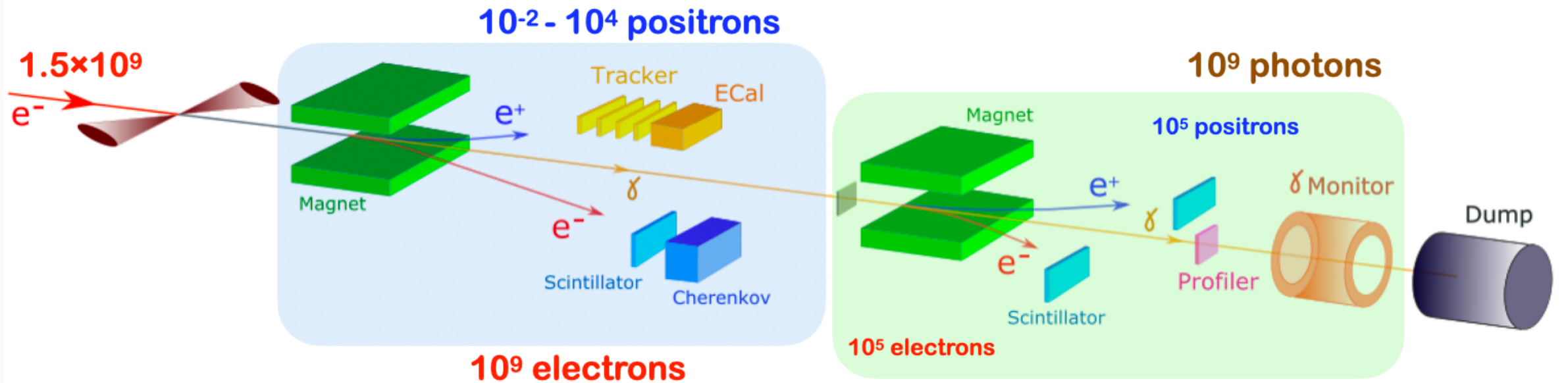
- High granularity, compact, sampling calorimeter.
 - Based on technology developed by (LC) FCAL collaboration and CALICE.
 - 20 layers of 3.5 mm of tungsten.
 - Energy resolution $\sigma/E = 20\%/(E/\text{GeV})^{1/2}$, position $\sim 750 \mu\text{m}$.



Tests at DESY test beam.



Photon detectors



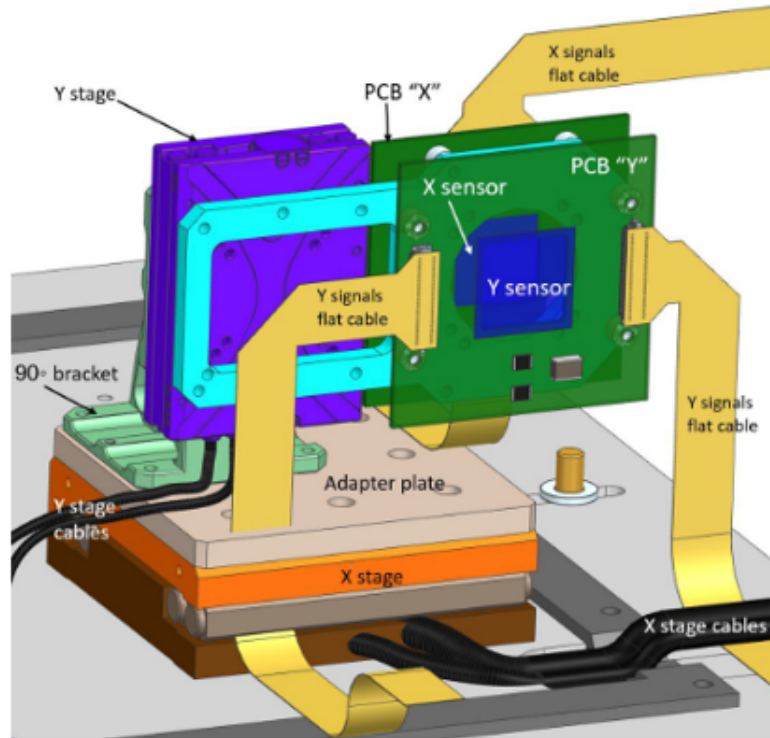
- Large flux (10^9) of high-energy photons.
- Have three complementary systems:
 - Gamma-ray spectrometer where a fraction are converted to e^+e^- pairs.
 - Gamma-ray profiler which uses radiation-hard sapphire.
 - Gamma-flux monitor which relies on backscattering from photon dump.

Gamma-ray detectors

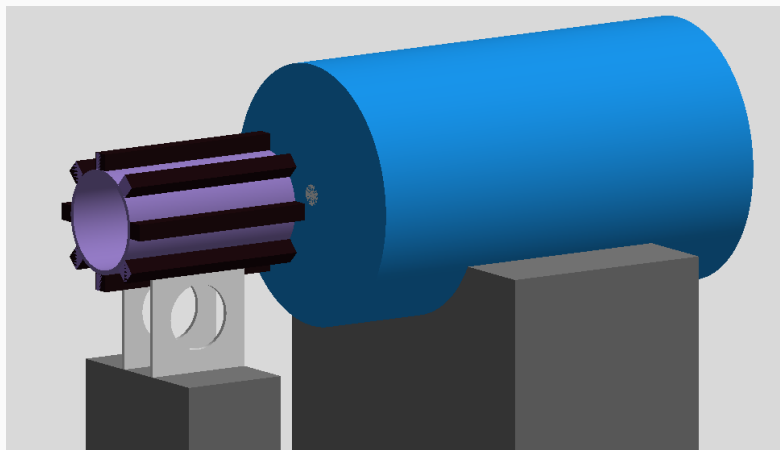
LUXE

Beam profiler

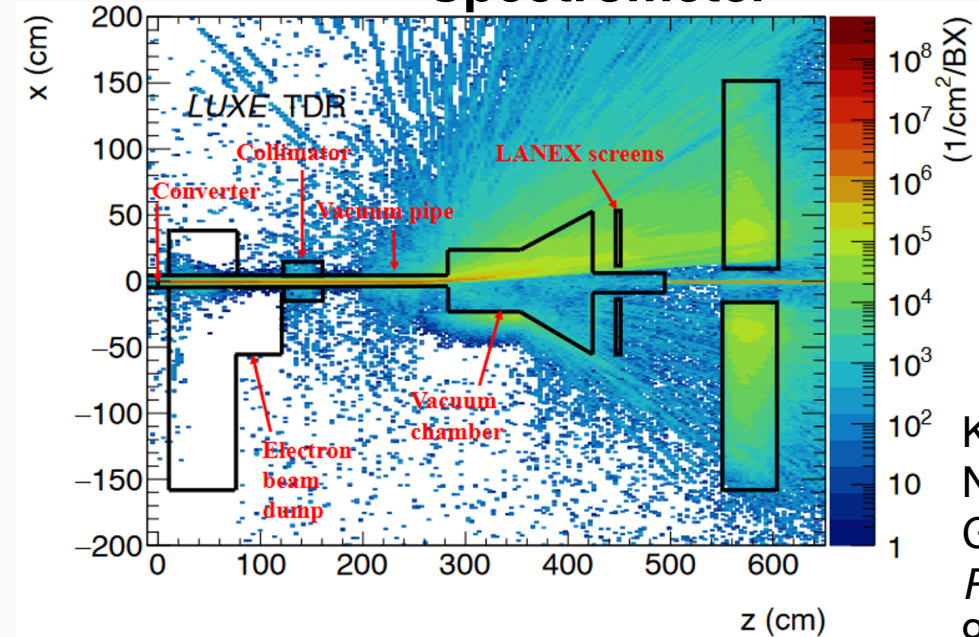
G. Avoni et al.,
*Nucl. Instrum.
Meth. A* **1068**
(2024) 169752.



Flux monitor



Spectrometer



K. Fleck,
N. Cavanagh &
G. Sarri, *Sci.
Rep.* **10** (2020)
9894.

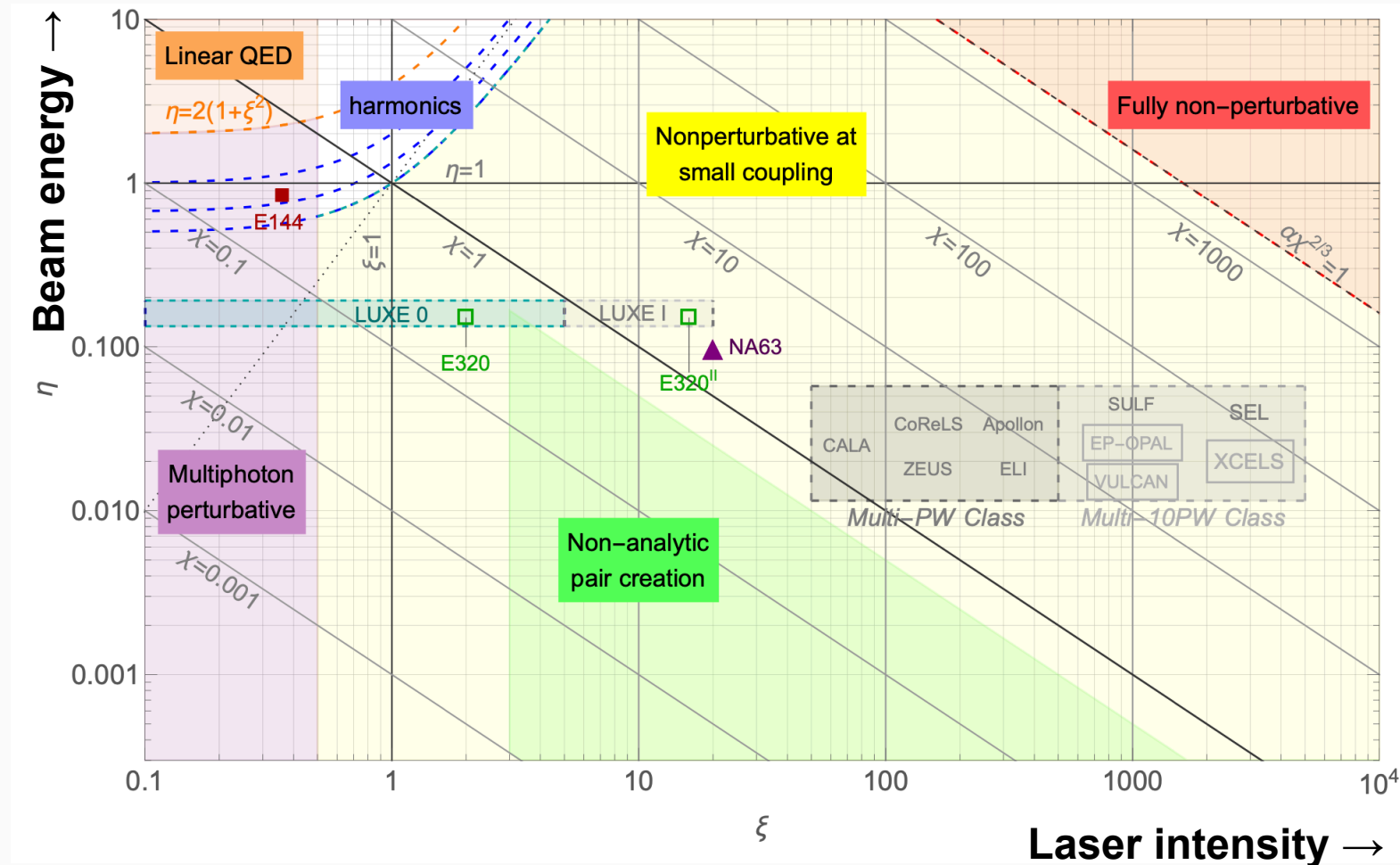
- Large flux of high-energy photons.
 - Measure photon energy spectrum.
 - Measure ξ .
 - Measure number of photons (luminosity).
- Also doing tests of flux monitor at FLASHForward.

A. Athanassiadis et al.,
arXiv:2508.17991.

UCL

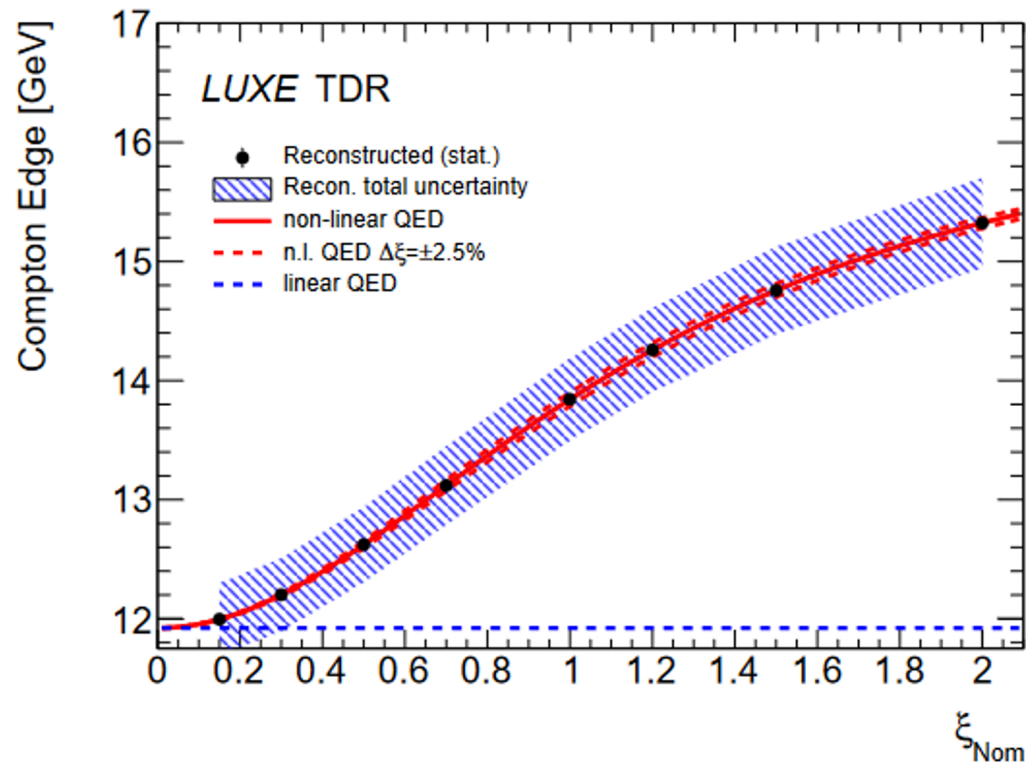
LUXE physics expectations

Strong-field QED parameter space

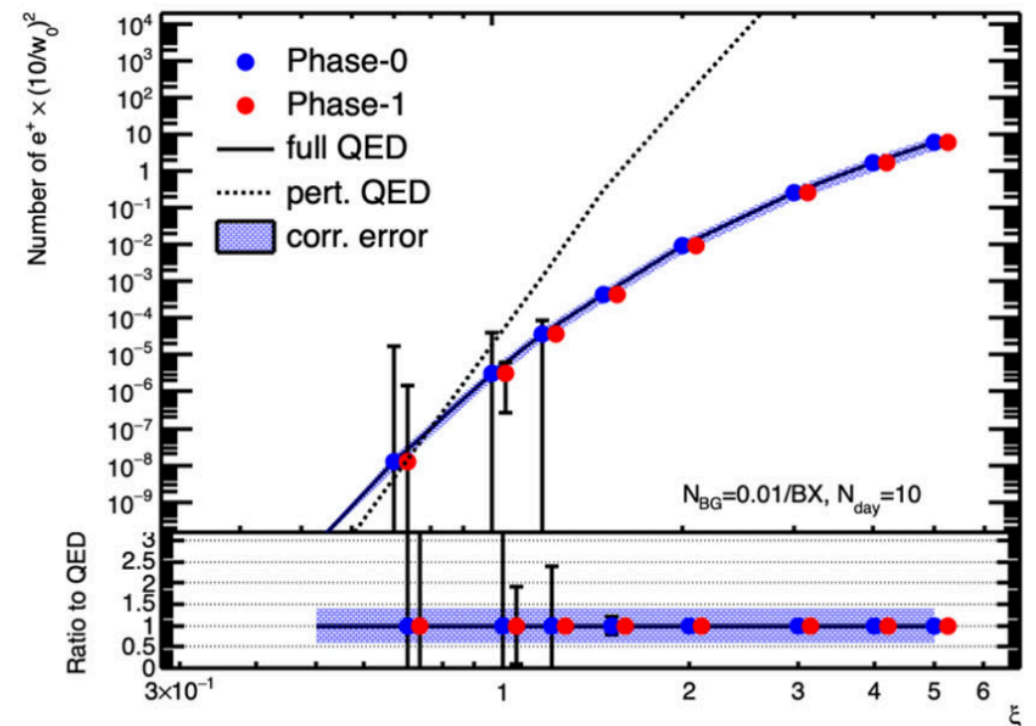


- Aim to map significant part of phase space.
 - Variation of key parameters.
 - Excellent detector systems, coverage and systematic understanding.

Expected LUXE results



- Compton edge position as a function of ξ in e -laser collisions.
- Can be done within 1 day of dedicated data taking.
- Illustrative 2% energy scale uncertainty.

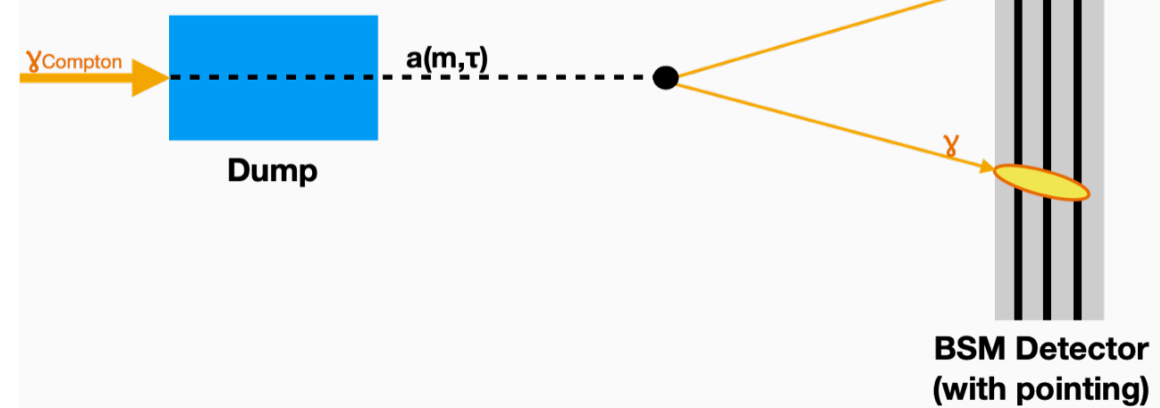
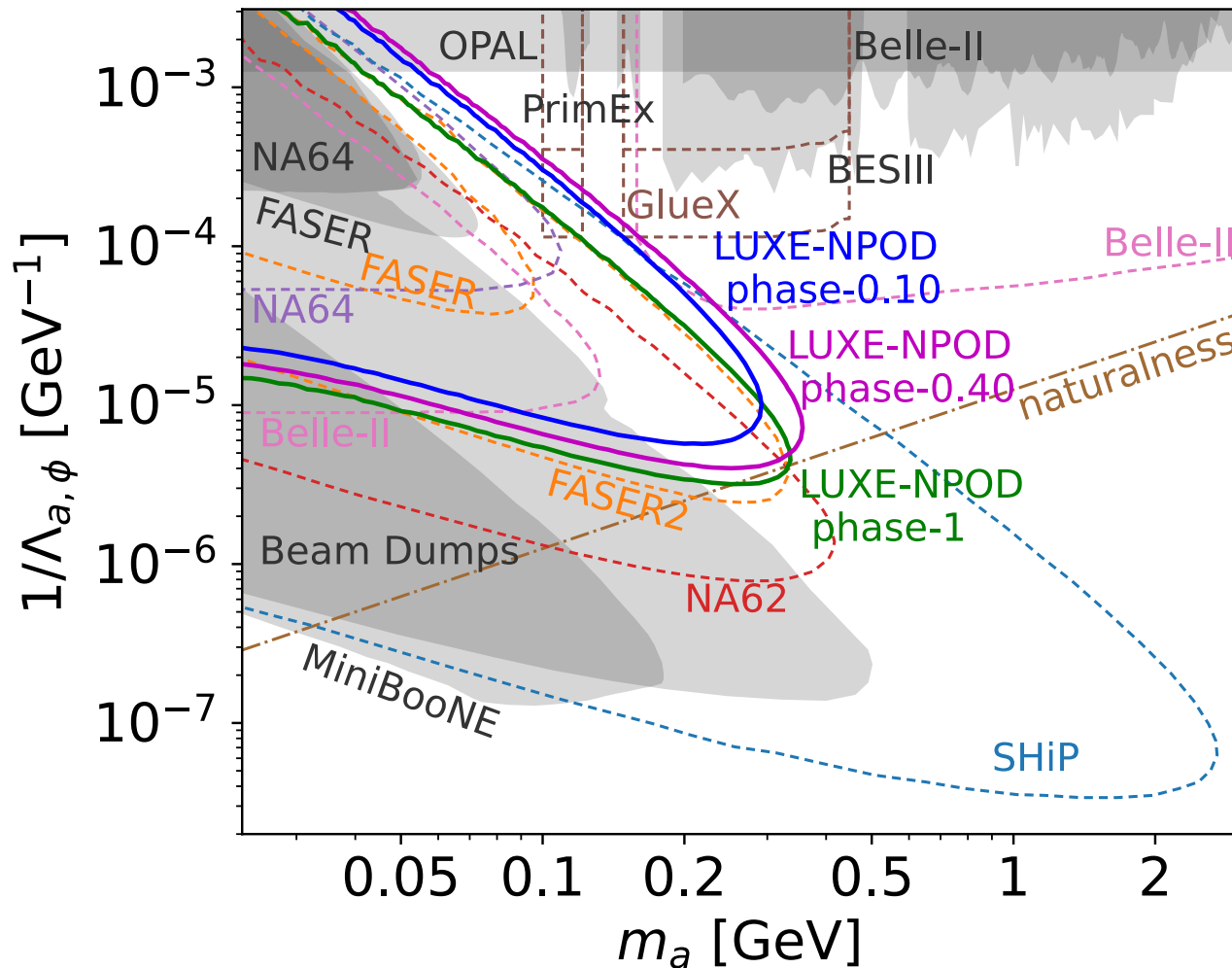


- Number of Breit–Wheeler pairs produced in γ -laser collisions.
- Assumed 10 days of data taking per point.
- 40% correlated uncertainty illustrates effects of uncertainty on ξ .

Search for new particles, ALPs

LUXE

Detector after photon dump: extra longitudinal space in XTD8 helpful.



- Search for axion-like particles or milli-charged particles.
- High-flux photon beam offers potential.
 - Should look asap !

LUXE-NPOD: Z. Bai et al., *Phys. Rev. D* **106** (2022) 115034.
M. Almanza Soto et al., *Phys. Rev. D* **112** (2025) 112014.

LUXE data taking



- LUXE's default planning is to take data when EuXFEL is delivering electrons, ~4000 hours.
- Variation in beam energy, e.g. 14 GeV, allows different η to be probed.
- Have two phases:
 - Phase-0 with a laser power of 40 TW.
 - Phase-1 with a laser power of 350 TW.
 - Variation of laser intensity to allow different ξ to be probed.
- Have two modes:
 - Electron–laser mode
 - Photon–laser mode.
- Would want 1 year of smooth data taking per phase and mode.
 - Gives > 4 years of data taking. Plus calibration, alignment, tests, changeover, etc., + very-high-power laser ?



Collaboration status



LUXE status

- LUXE initiated in 2017.
- Officially recognised as a DESY experiment in November 2022.
- About 20 institutes, 100 people.
- Technical Design Report published by European Physical Journal.
- Experiment could be realised quite quickly.
 - **Could be taking data by end of decade.**



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

TDR: H. Abramowicz et al.,
LUXE Coll., *Eur. Phys. J. ST* **233**
(2024) 1709, arXiv:2308.00515.



<https://luxede.desy.de>

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Abstract

Introduction

Physics opportunities and scientific goals

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References

Acknowledgements

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Appendices

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H. Abramowicz, U. Acosta, M. Altarelli, R. Aßmann, Z. Bai, T. Behnke, Y. Benhammou, T. Blackburn, S. Boogert, O. Borysov, M. Borysova, R. Brinkmann, M. Bruschi, F. Burkart, K. Büßer, N. Cavanagh, O. Davidi, W. Decking, U. Dosselli, N. Elkina, A. Fedotov, M. Firlej, T. Flutowski, K. Fleck, ... A. Zhemchukov

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Abstract

This Conceptual Design Report describes LUXE (Laser Und XFEL Experiment), an experimental campaign that aims to combine the high-quality and high-energy electron beam of the European XFEL with a powerful laser to explore the uncharted terrain of quantum electrodynamics characterised by both high energy and high intensity. We will reach this hitherto inaccessible regime of quantum physics by analysing high-energy electron-photon and photon-photon interactions in the extreme environment provided by an intense laser focus. The physics background and its relevance are presented in the science case which in turn leads to, and justifies, the ensuing plan for all aspects of the experiment: Our choice of experimental parameters allows (i) field strengths to be probed where the coupling to charges becomes non-perturbative and (ii) a precision to be achieved that permits a detailed comparison of the measured data with calculations. In addition, the high photon flux predicted will enable a sensitive search for new physics beyond the Standard Model. The initial phase of the experiment will employ an existing 40 TW laser, whereas the second phase will utilise an upgraded laser power of 350 TW. All expectations regarding the performance of the experimental set-up as well as the expected physics results are based on detailed numerical simulations throughout.

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Abstract

Introduction

Overview and scientific objectives

Laser and diagnostics

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Electromagnetic calorimeter

Scintillator screens and camera system

Cherenkov detector

Gamma ray spectrometer

Gamma beam profiler

Gamma flux monitor

Data acquisition, computing and simulation

Technical infrastructure

Data availability

Notes

References

Acknowledgements

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Author information

LUXE Collaboration, H. Abramowicz, M. Almanza Soto, M. Altarelli, R. Aßmann, A. Athanassiadis, G. Avoni, T. Behnke, M. Benettoni, Y. Benhammou, J. Bhatt, T. Blackburn, C. Blanch, S. Bonaldo, S. Boogert, O. Borysov, M. Borysova, V. Boudry, D. Breton, R. Brinkmann, M. Bruschi, F. Burkart, K. Büßer, N. Cavanagh, ... M. Zuffa

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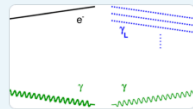
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Abstract

This Technical Design Report presents a detailed description of all aspects of the LUXE (Laser Und XFEL Experiment), an experiment that will combine the high-quality and high-energy electron beam of the European XFEL with a high-intensity laser, to explore the uncharted terrain of strong-field quantum electrodynamics characterised by both high energy and high intensity, reaching the Schwinger field and beyond. The further implications for the search of physics beyond the Standard Model are also discussed.

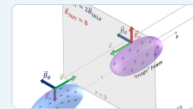
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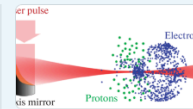
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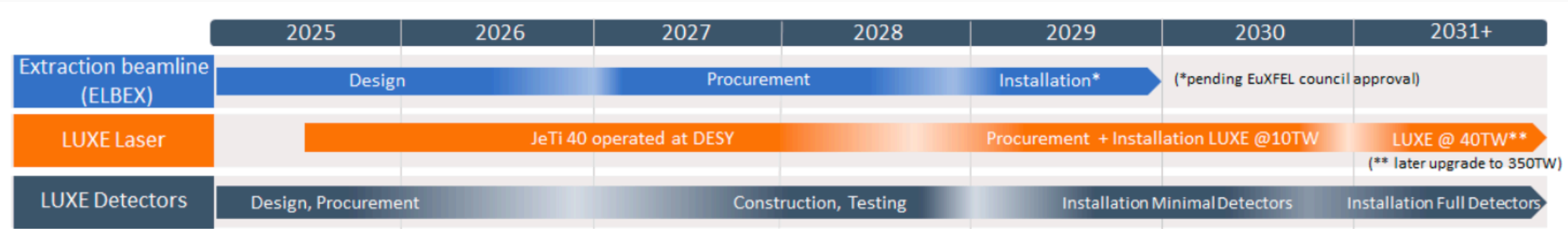


Figure 2.8: Timeline for the staged construction of the LUXE experiment.

Summary

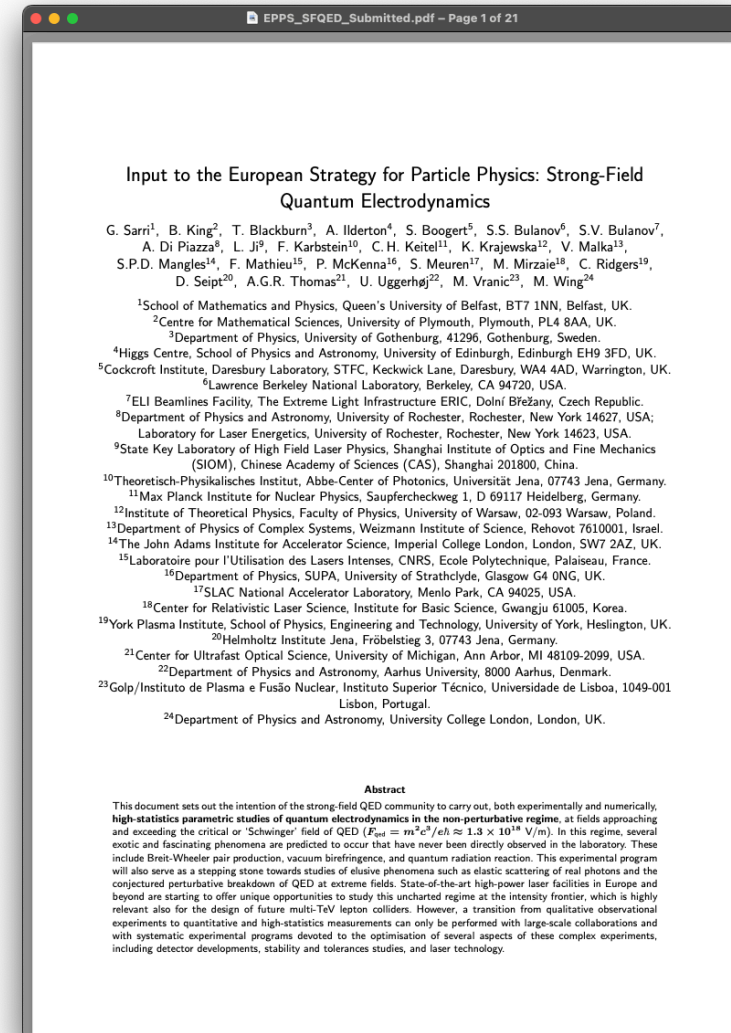
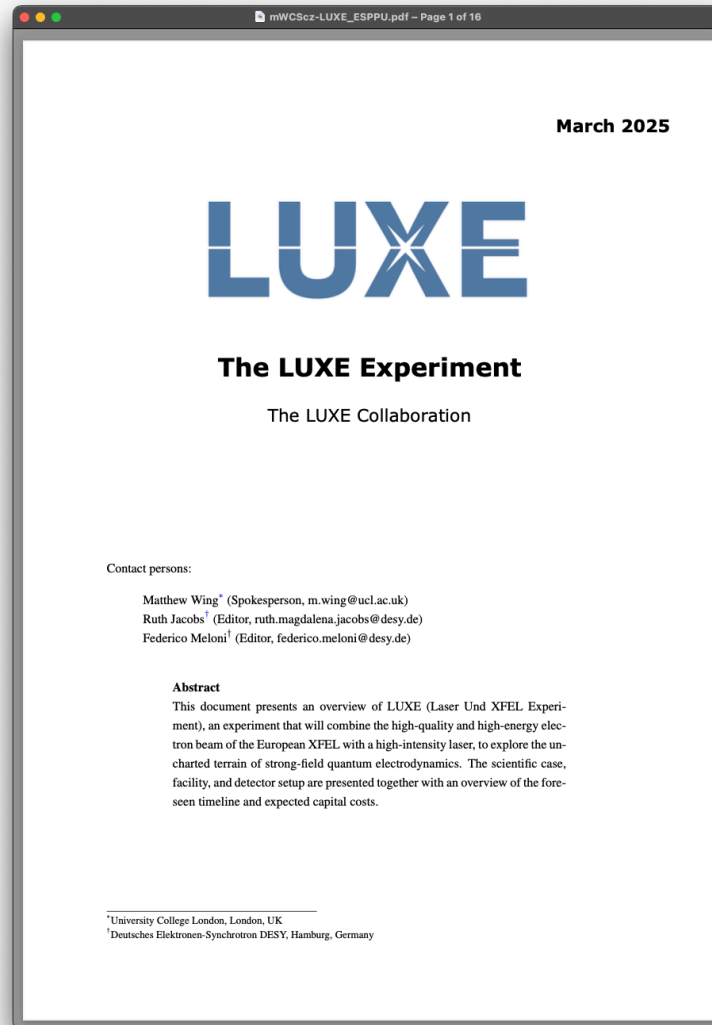
- **LUXE is an exciting new experiment planning to investigate QED in uncharted territory.**
 - An exquisite electron beam.
 - 24/7 running.
 - e-laser and γ -laser modes.
 - Comprehensive suite of detectors.
 - Strong collaboration with a broad range of expertise.
- Measure over a wide range of quantum parameters, e.g. transition to non-perturbative QED
 - High precision measurements — large samples and controlled systematics.
 - Serious confrontation of experiment and theory.
- Initial work shows new site, XTD8 tunnel, is suitable for LUXE.
 - Instruments as previously designed fit with (longitudinal) space for optimisation.
 - Working on detailed design to realise LUXE by end of the decade.



Backup

European particle physics strategy

LUXE

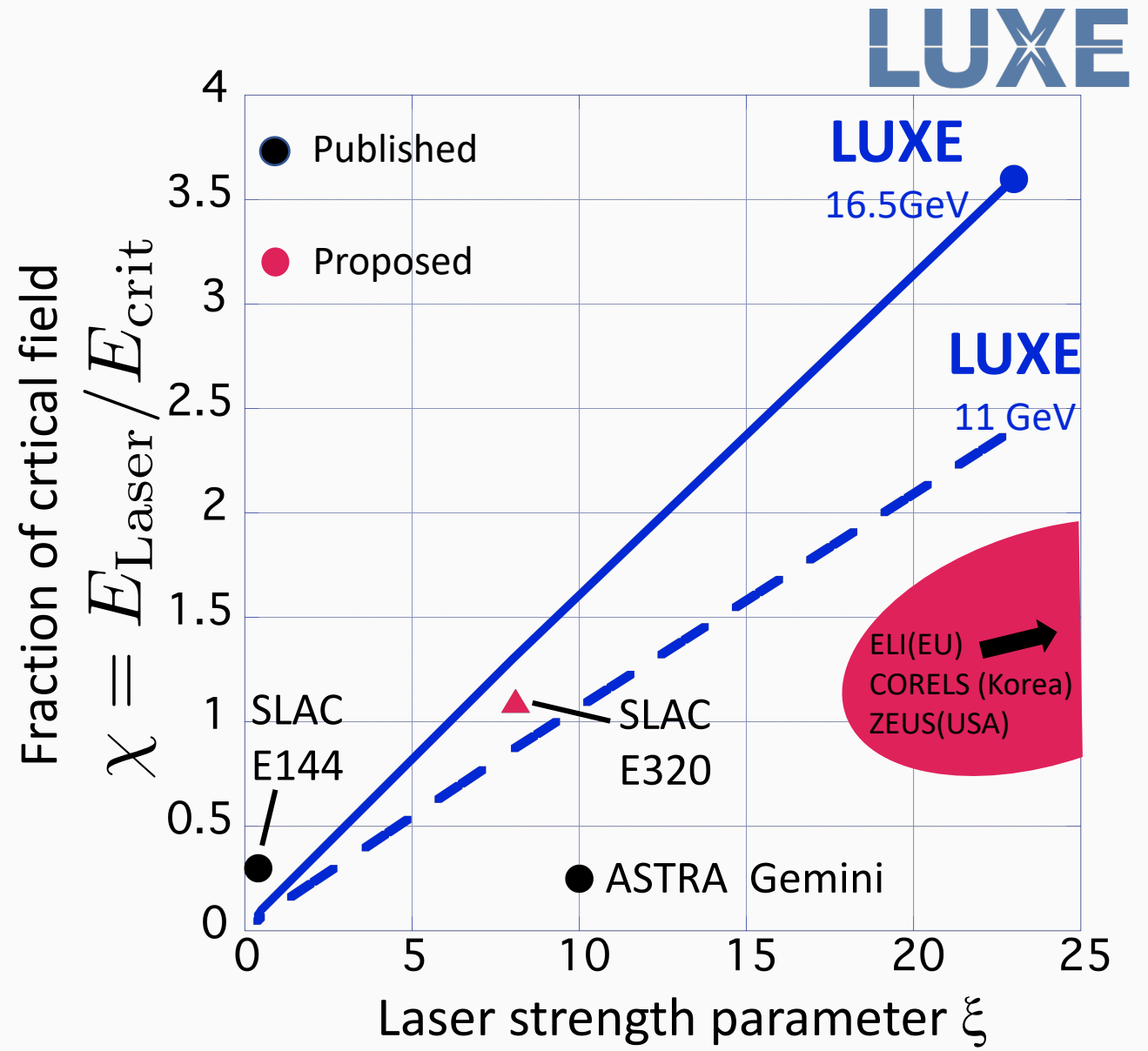
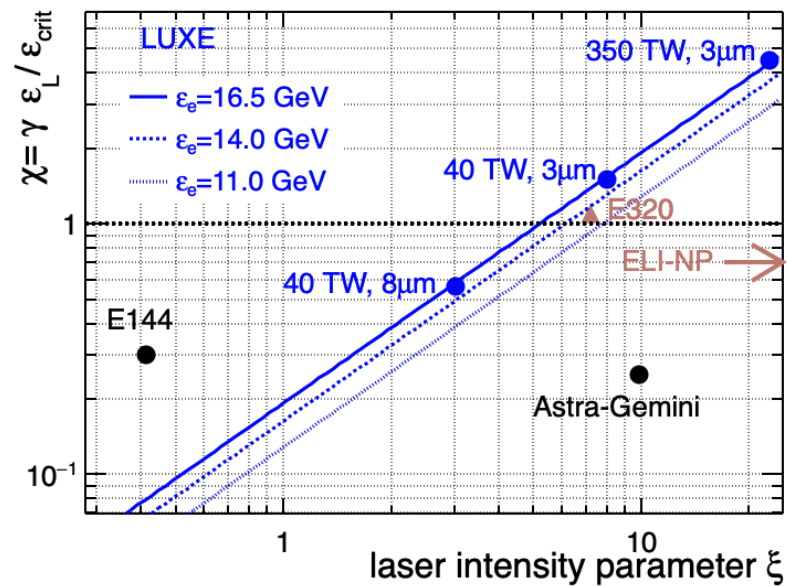
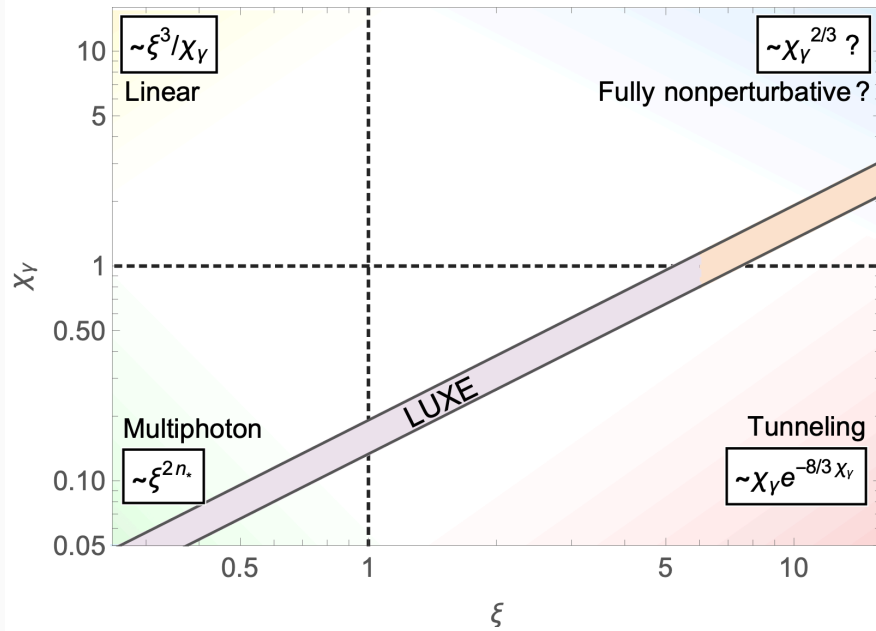


<https://arxiv.org/abs/2504.00873>

G. Sarri et al., *Eur. Phys. J. Plus*
140 (2025) 1151



QED parameter space



Systematic uncertainties

- Low multiplicities (e^+e^- pair production):
 - Efficiencies for individual particles $< 2 - 3\%$ (cross-checks and in-situ calibration).
 - Linearity of response $< 2\%$ based on 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) based on test beam and experience from other experiments.
 - Calibration $< 2\%$ based on test-beam calibration.
 - Background (for scintillators): constrain in situ.
- Energy scales (all):
 - Calibration/knowledge of magnetic field $\sim 1\%$.
 - Alignment of $< 50 \mu m$ results in $< 0.5\%$ uncertainty.

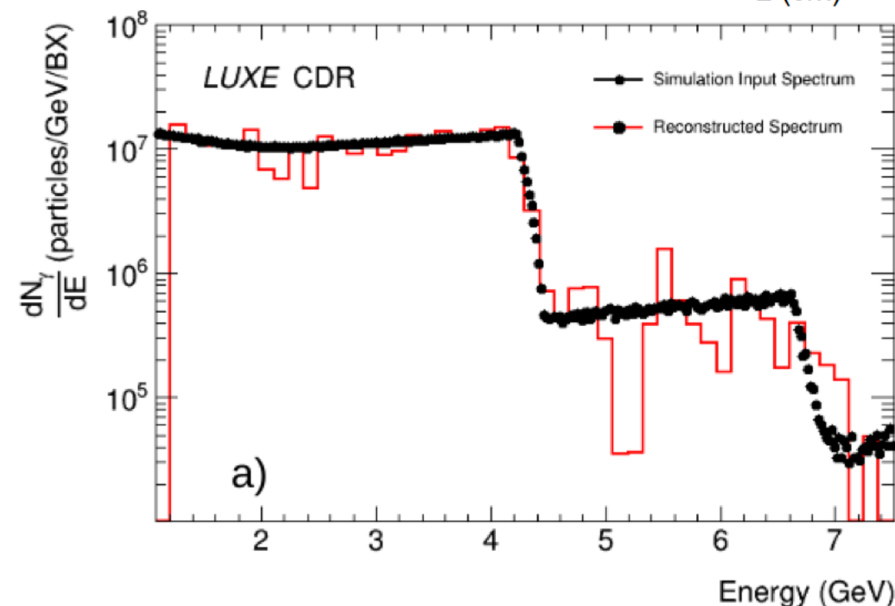
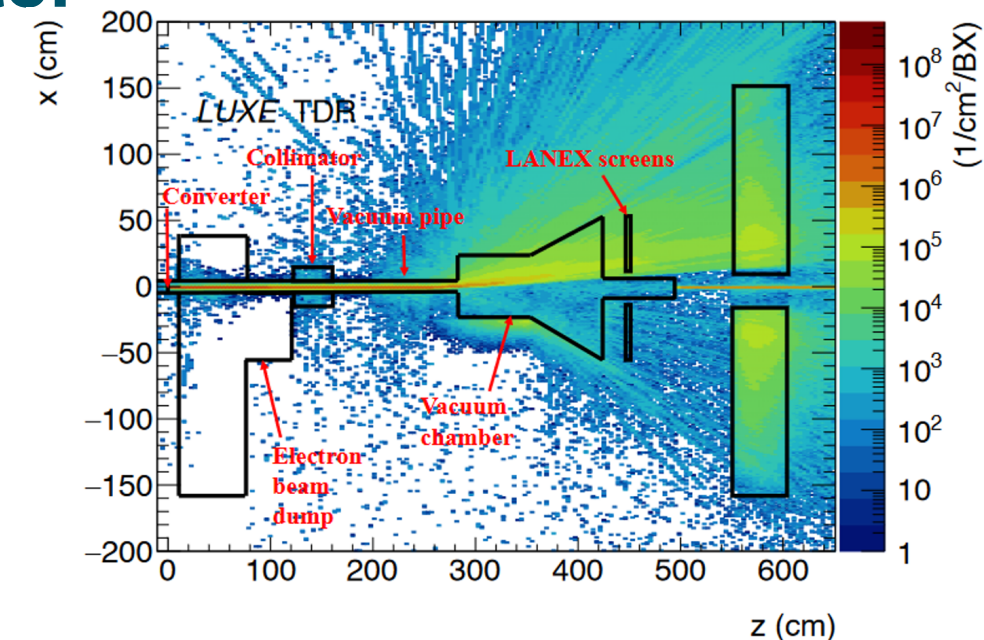


Data handling

- Data handling should be “straightforward”: low frequency, modest rates.
 - Maximum data-taking frequency 10 Hz.
 - 1 Hz collision data, up to 9 Hz background.
 - Typical maximum rate per sub-detector $O(10 \text{ MB/s})$.
- Need ~ 1 PC per sub-detector.
- All data is kept — no physics trigger.
- Should be able to use known/off-the-shelf solutions for control and synchronisation.
- Should be able to use/adapt existing software for data acquisition.

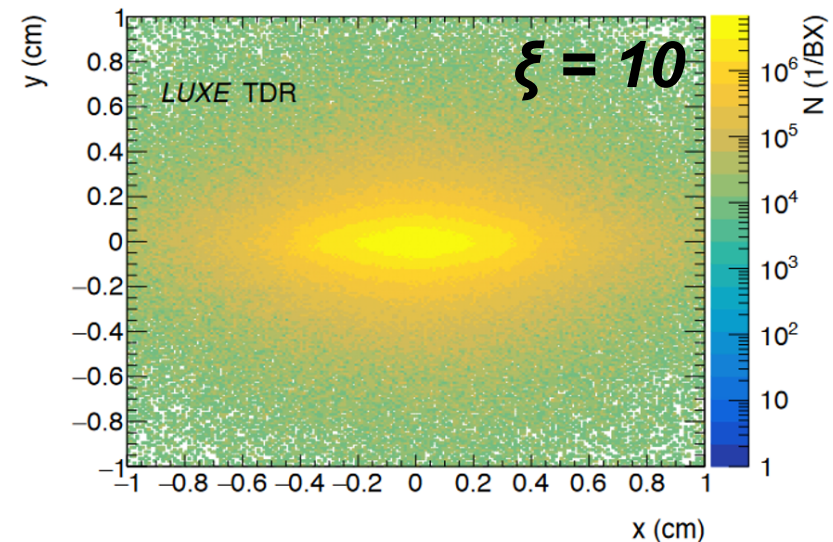
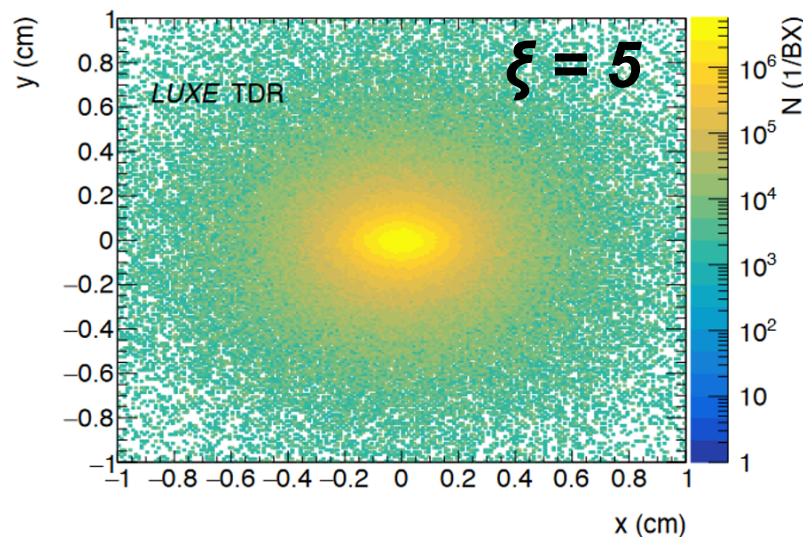
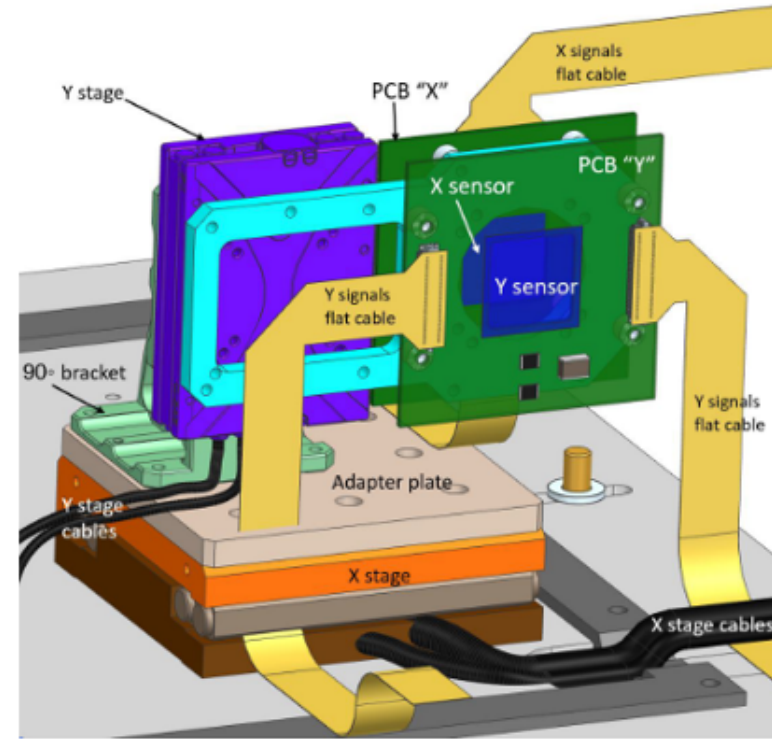
Gamma-ray spectrometer

- Aim: to measure photon spectrum.
 - Measure e^+e^- pairs after photons pass through target.
 - Spectrometer with scintillation screens and CCD cameras.
 - Good energy resolution ($\delta E/E < 2\%$).
 - Non-invasive (>99% photons propagate through).



Gamma-ray profiler

- Two sapphire strip detectors movable with micron precision perpendicular to beam.
 - Photon beam location and shape
 - Precision measurement of laser intensity.
- Two detectors $2 \times 2 \text{ cm}^2$ (100 μm thick) with 100 μm strip pitch should guarantee <5% precision in laser intensity.



Gamma flux monitor

- Measure energy flow of particles back-scattered from photon beam dump.
- Gamma flux monitor:
 - Consists of lead glass blocks, $3.8 \times 3.8 \times 45 \text{ cm}^3$.
 - Beam tests ongoing at FLASHForward.

