# LUXE status and prospects

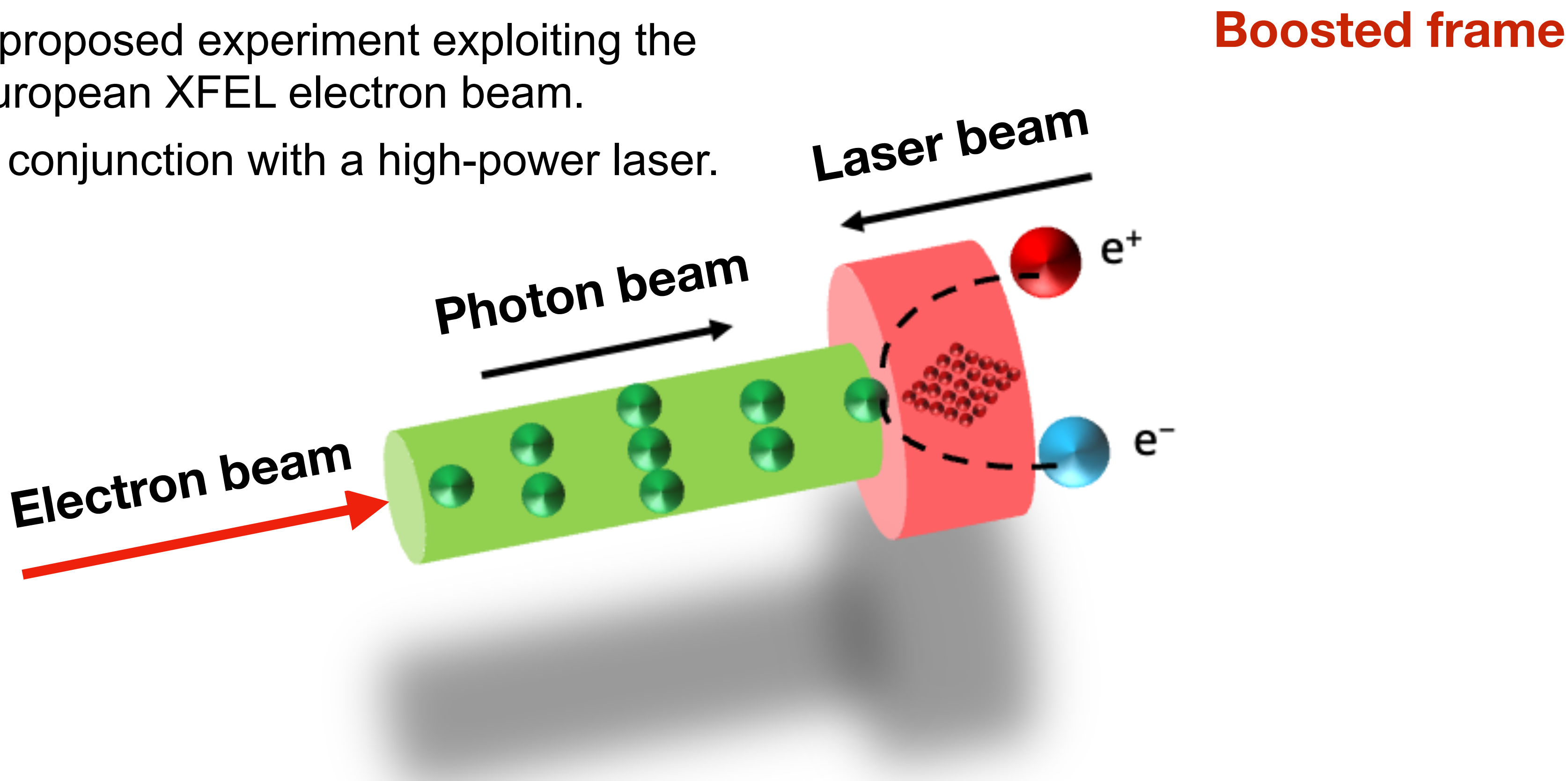
Matthew Wing
for the LUXE collaboration

- Strong-field QED physics
- LUXE experiment
- LUXE physics expectations
- Status and new developments

ExHILP 2025 — ELI Beamlines Facility, 1–5 September 2025

# Introduction: Strong-field QED

- LUXE: **L**aser **U**nd **X**FEL **E**xperiment
  - A proposed experiment exploiting the European XFEL electron beam.
  - In conjunction with a high-power laser.




- Critical field can be reached with relativistic length contraction.
- Relativistically boosted field $\chi = \gamma \, E_L / E_{\rm crit}$

- Investigate QED in new parameter space
  - E.g. transition to non-linear 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).
- *ξ ≥ 1*: non-perturbative regime

- **Quantum parameters:**

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

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

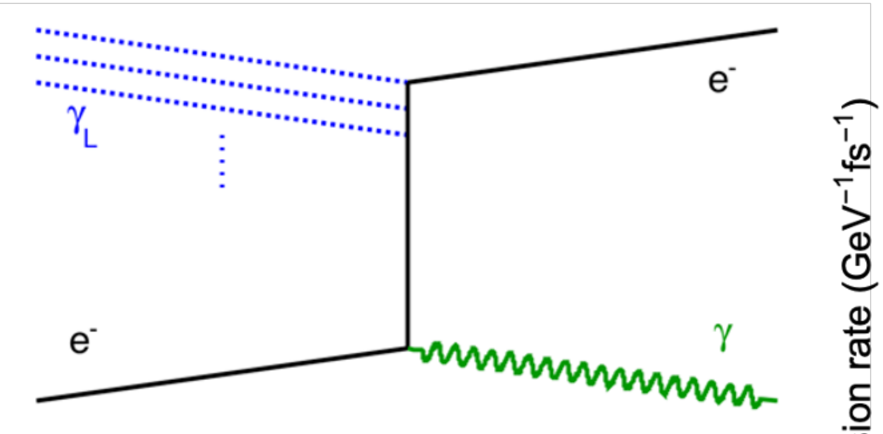
- Ratio of laser field and Schwinger critical field.
- *χ ≥ 1*: non-linear quantum effects become probable (e.g. pair production).

- **Energy parameter:**

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

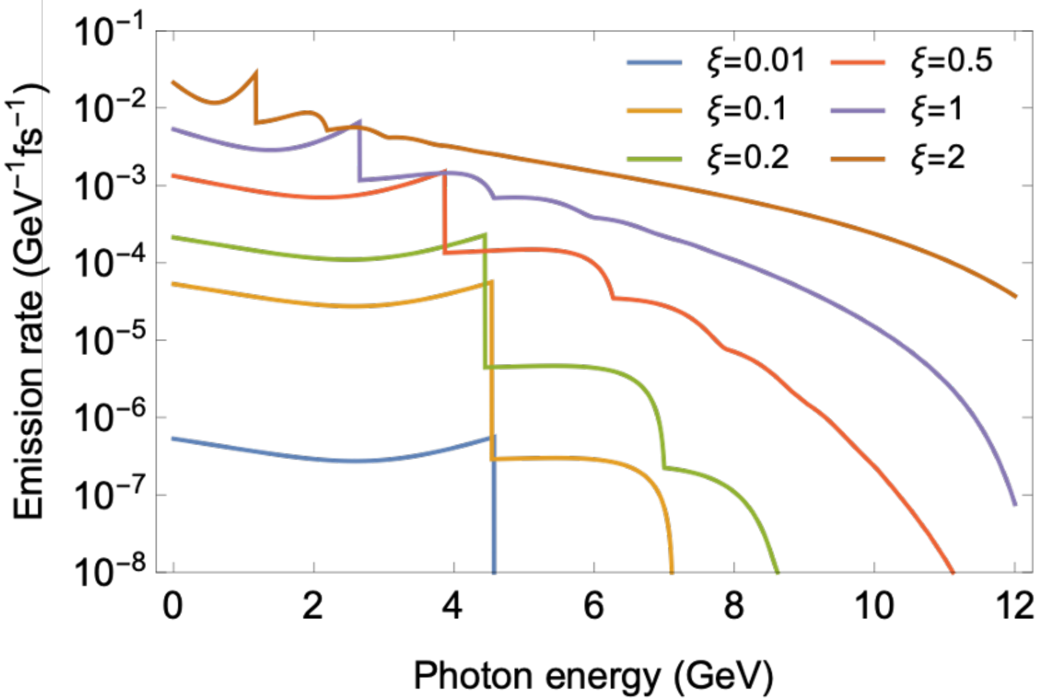
| | |
|---|---|
| $E_L$ : | Laser field |
| $E_{\text{crit}}$ : | Schwinger critical field |
| $\omega_L$ : | Laser frequency |
| $\theta$ : | $e/\gamma$ – laser crossing angle |
| $E_{e/\gamma}$ : | Probe electron/photon energy |

# Non-linear Compton scattering




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

16.5 GeV electron, 800 nm laser, 17.2° crossing angle



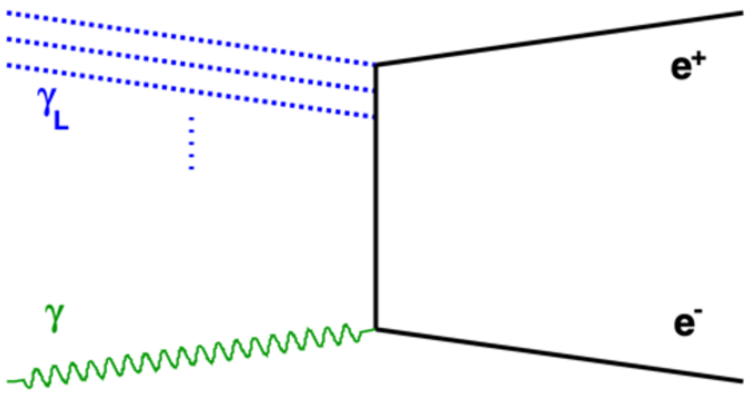

In strong fields, electrons obtain larger effective mass, $m_* = m_e (1+\xi^2)^{1/2}$

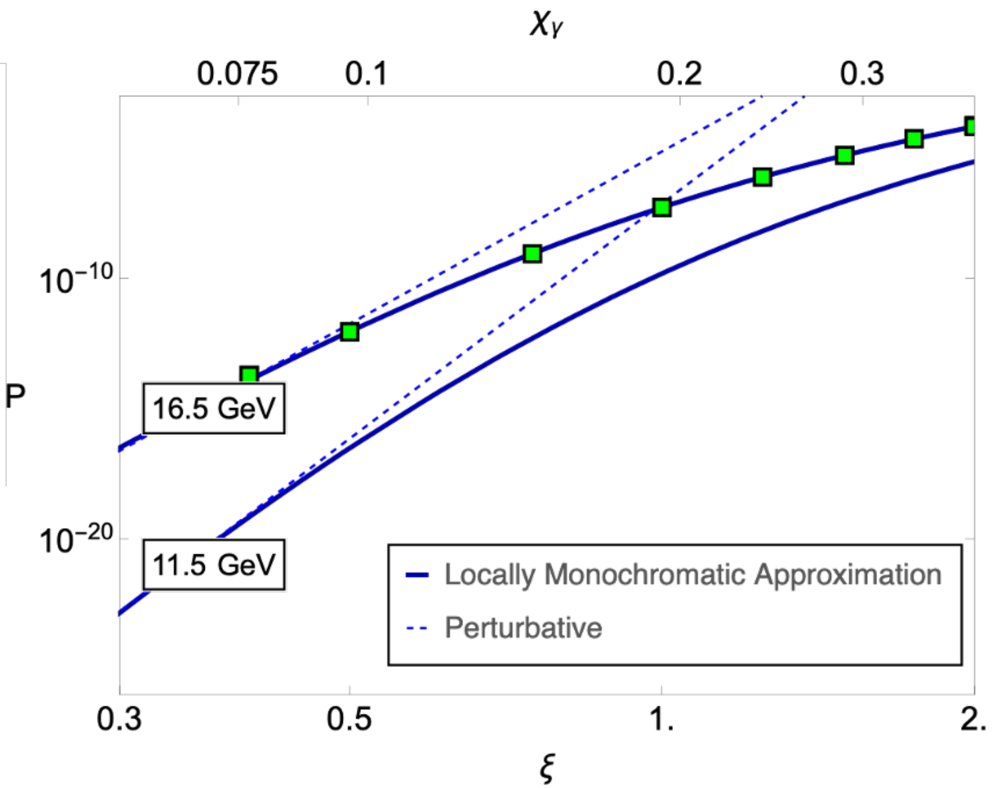
- Compton edge shifts as function of $\xi$.
- Higher harmonics appear, i.e. interaction with $n$ laser photons.

Strong-field QED: $$E_{\mathrm{edge}}(\xi) = E_e \frac{2n\eta}{2n\eta + 1 + \xi^2}$$

Classical limit: $$E_{\mathrm{edge}}(\xi) = E_e \frac{2n\eta}{1 + \xi^2}$$

# Non-linear Breit–Wheeler pair production




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

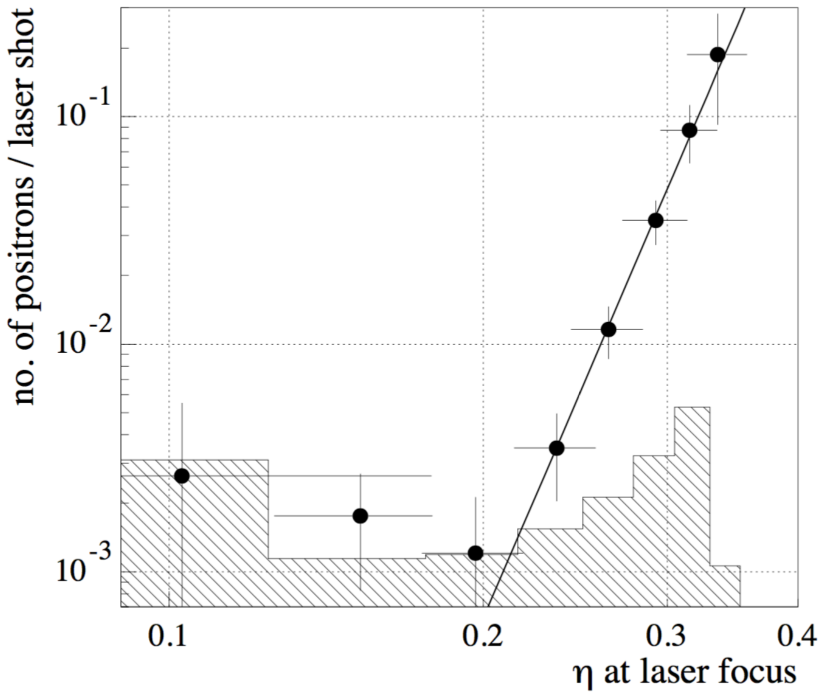
- Photon from Compton scattering or secondary beam.

Perturbative regime: power law $\quad \xi \ll 1 \quad : \quad R_{e^+} \propto \xi^{2n} \propto I^n$

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

# E144 experiment at SLAC

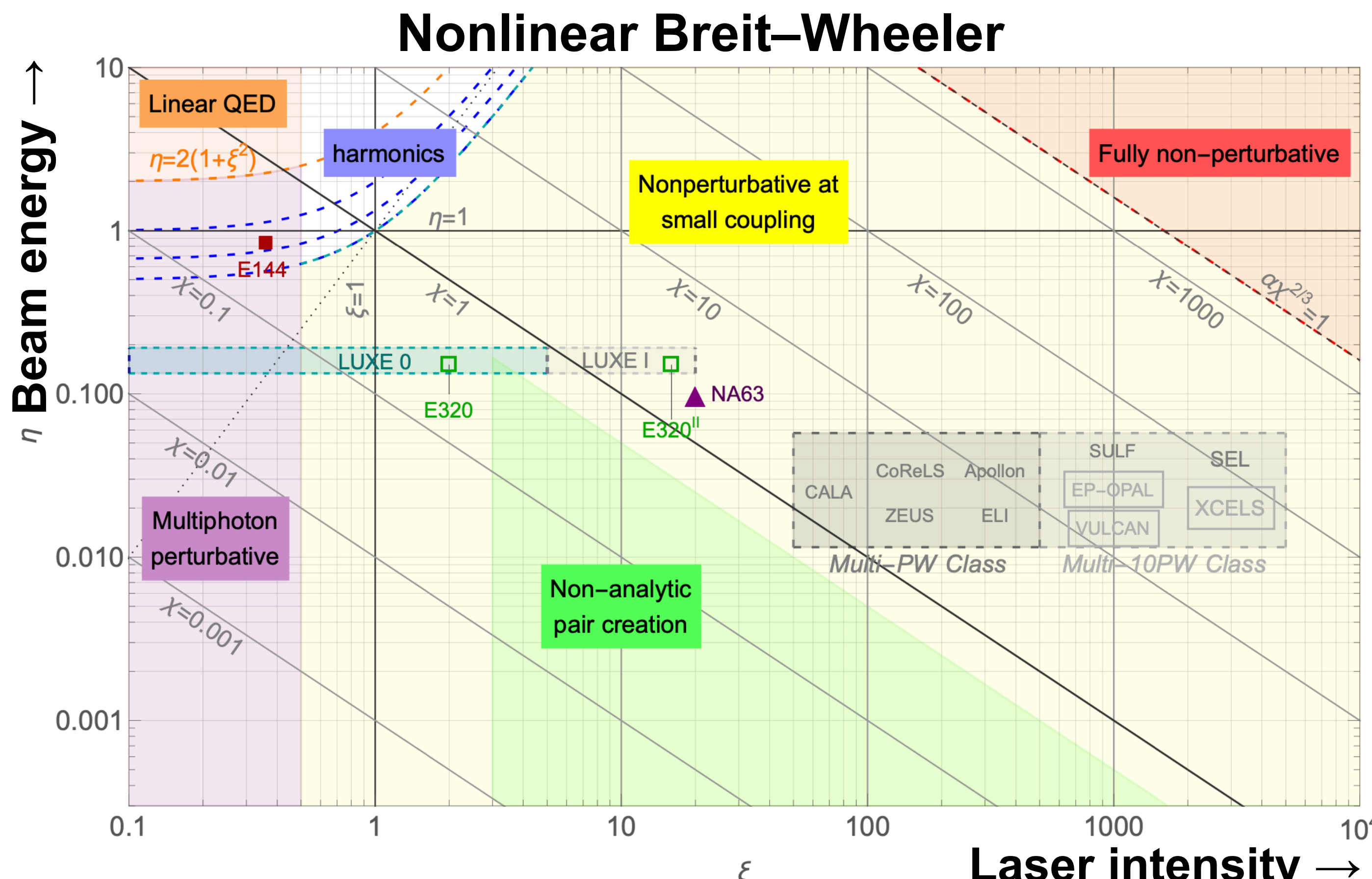
- Pioneering experiment, E144, at SLAC in the 1990s.
- Used 1 TW laser and 46.6 GeV electron beam.
- Reached $\chi$ ~ *0.25, $\xi$ ~ 0.4*.
- Observed process
  $e^- + n\gamma_L \rightarrow e^- + e^+ + e^-$
- Observed start of $\xi^{2n}$ power law, but not departure from it.




η ~ ξ

E144 Coll., C. Bamber et al., Phys. Rev. D 60 (1999) 092004;
T. Koffas, "Positron production in multiphoton light-by-light scattering", PhD thesis, University of Rochester (1998), SLAC-R-626.

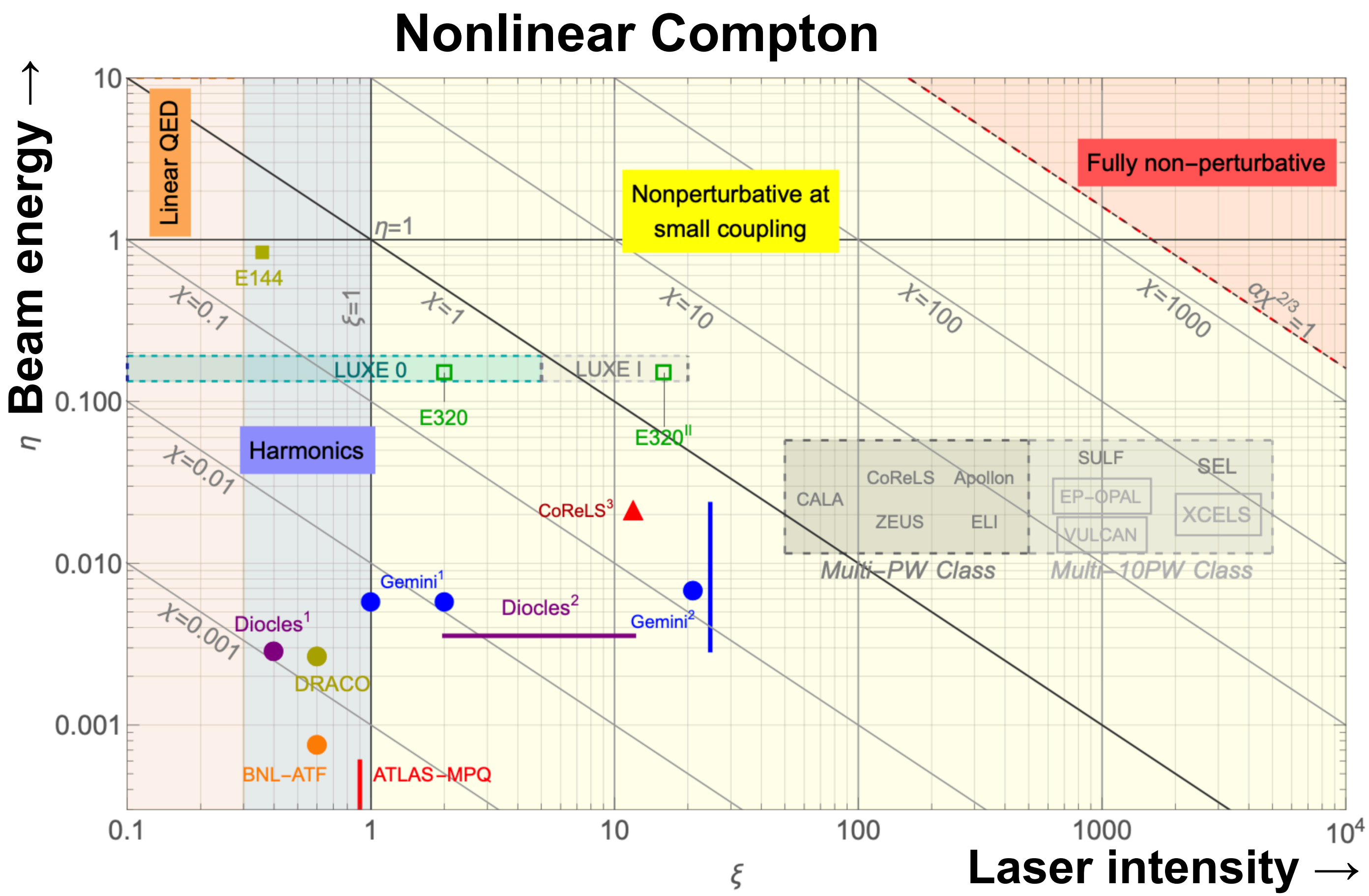
# Strong-field QED parameter space




Credit: B. King

- Determined by particle beam energy and laser intensity.
- LUXE will precisely map parameter space in transition region.
- E320: new experiment at SLAC.
- ELI, etc. future high-power lasers.

# Strong-field QED parameter space




Credit: B. King

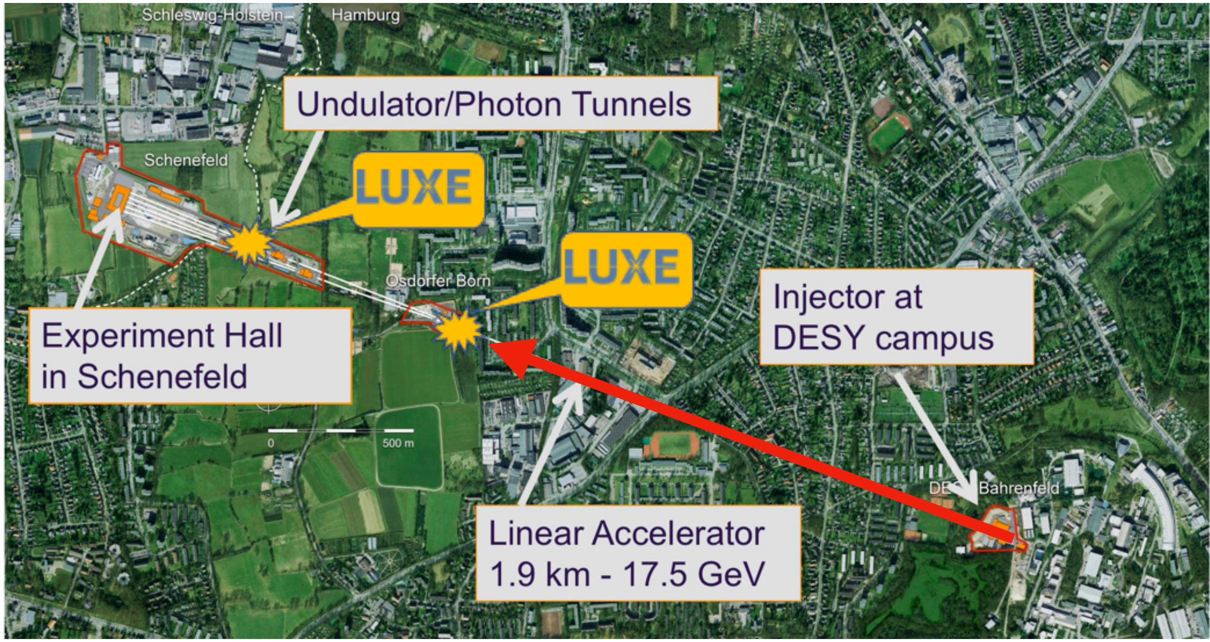
- Determined by particle beam energy and laser intensity.
- LUXE will precisely map parameter space in transition region.
- + more high-power laser facilities.

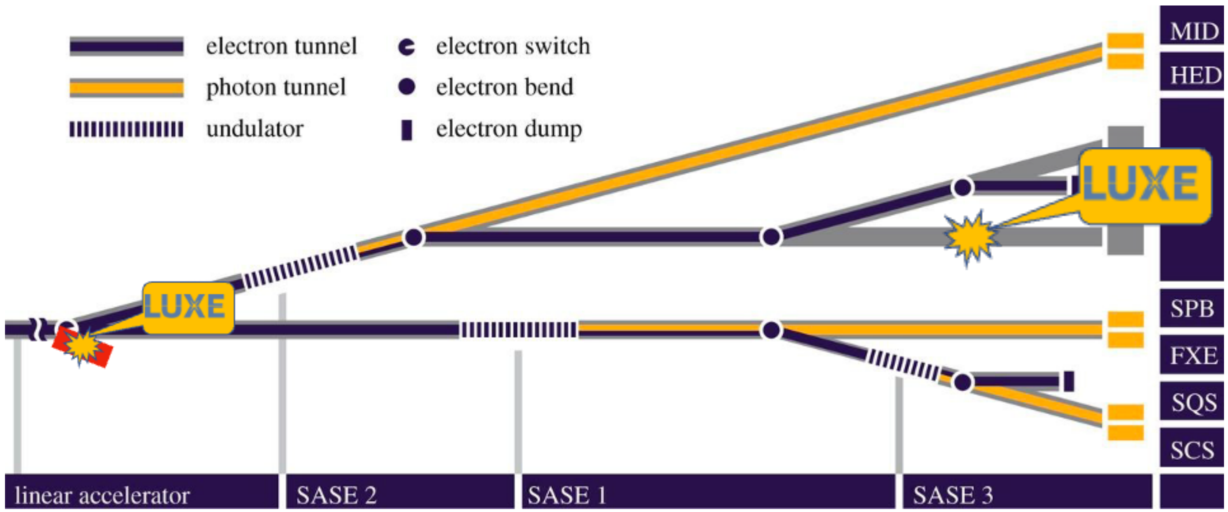
# LUXE experiment

# LUXE at European XFEL

EuXFEL electron beam:

- Energy: *16.5 GeV*
- Bunch: *1.5 × 10⁹ e⁻*
- Repetition rate: *10 Hz*
- Use 1 of 2700 bunches per train




- Use electron beam without undulation
- No impact on photon science programme
- Exact location under development

# LUXE laser

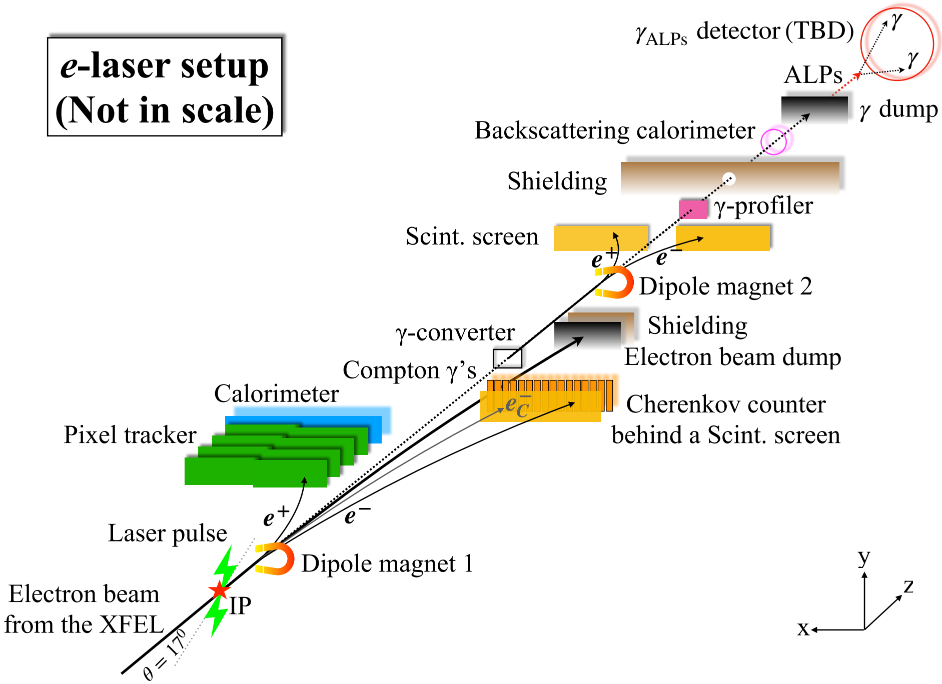
| | |
|---|---|
| Wavelength (energy) | 800 nm (1.55 eV) |
| Power | 40 / 350 TW |
| Pulse length | 30 fs |
| Spot size | > 3 μm |
| Peak intensity | 13.3 / 120 × $10^{19}$ W/cm$^2$ |
| Peak intensity parameter $\xi$ | 7.9 / 23.6 |
| Peak quantum parameter $\chi$ | 1.5 / 4.5 |

- Repetition rate, *1 − 10 Hz*
- Crossing angle, *17°*


- Goal: < 5% uncertainty on laser intensity, 1% shot-to-shot uncertainty.

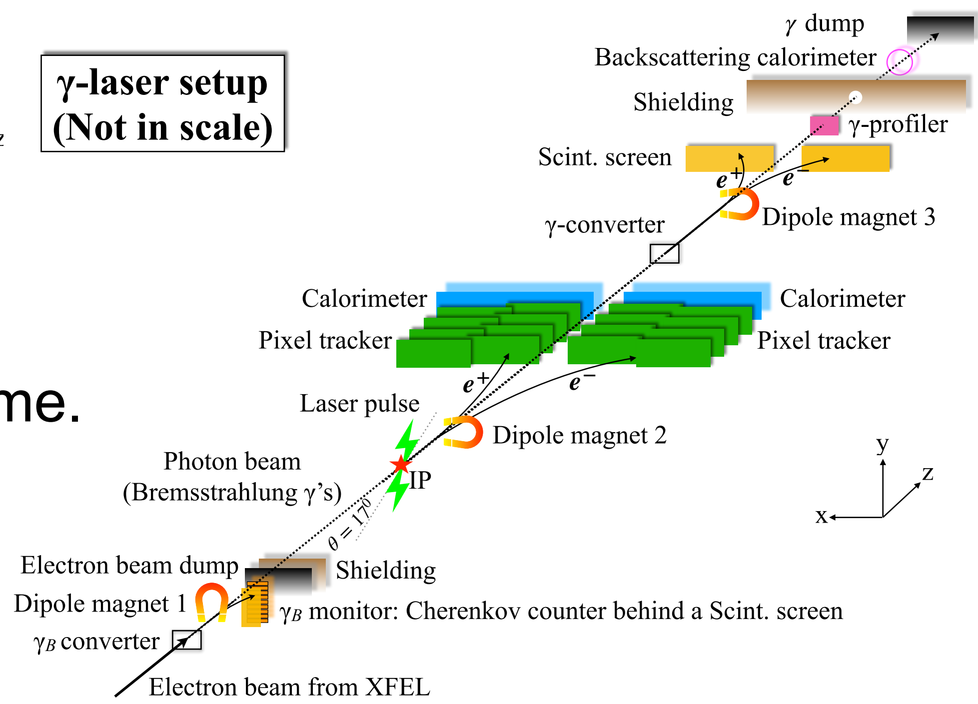
- Phases:
  - Phase-0 with a *40 TW* laser (JETI40)
  - Upgrade to *350 TW* laser for Phase-1
  - Potential for higher-power ?

# Experiment layout




- Two data-taking modes:
  - Electron–laser collisions
  - Photon–laser collisions: unique to LUXE

- Similar but different layouts.
- Many of the detectors are the same.
- Several challenges.

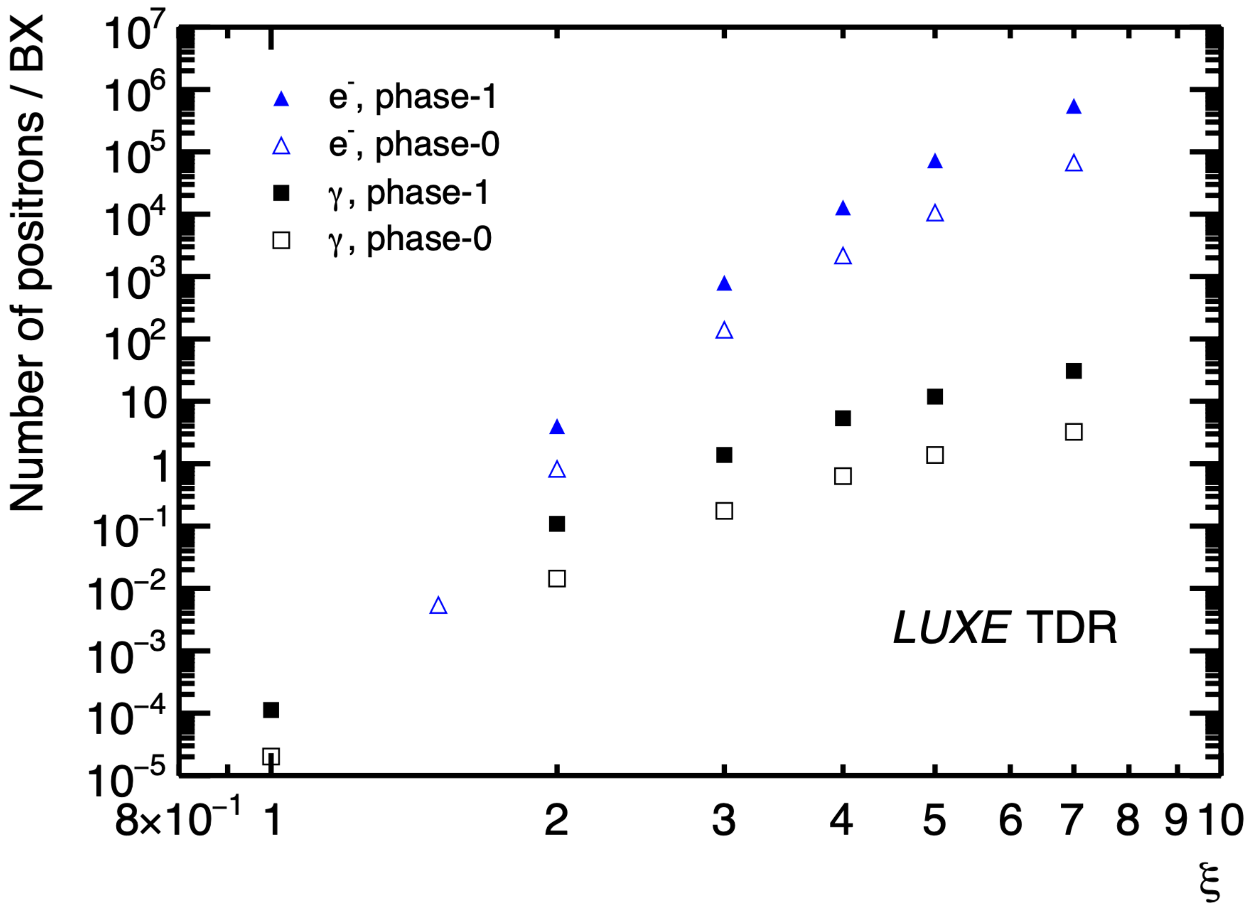



**Note programme to search for axion like particles (ALPs) too.**

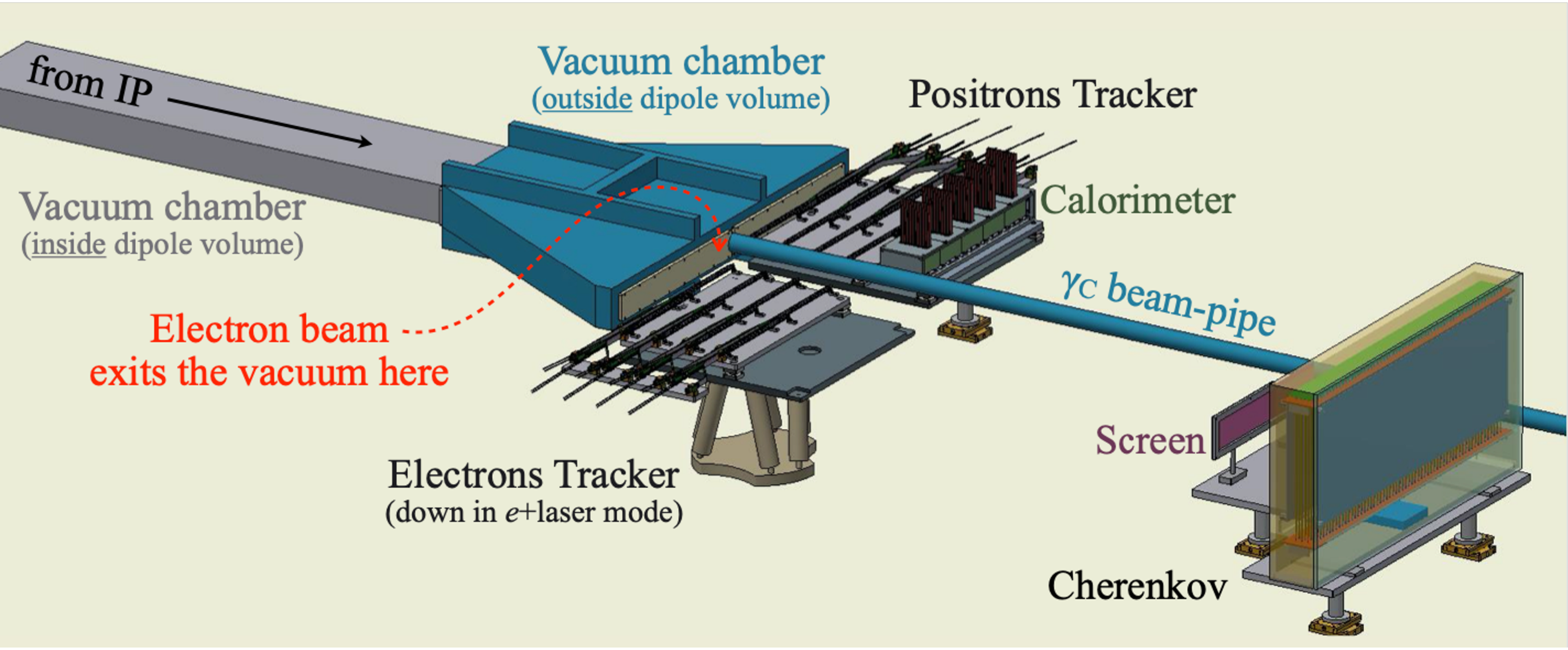
# Detector requirements and challenges

- 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 ~$10^{-4}$ ($e^+$) and $10^9$ ($e^-$ and $\gamma$).



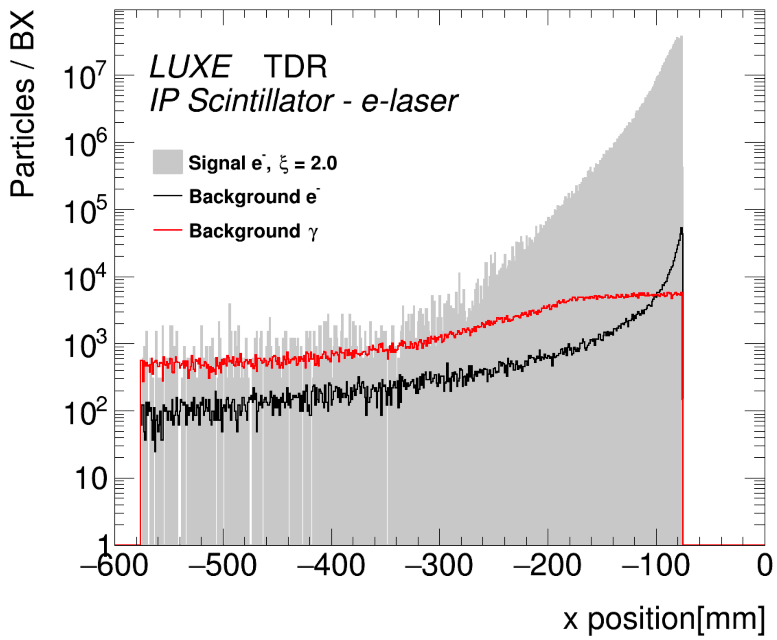
# IP detectors

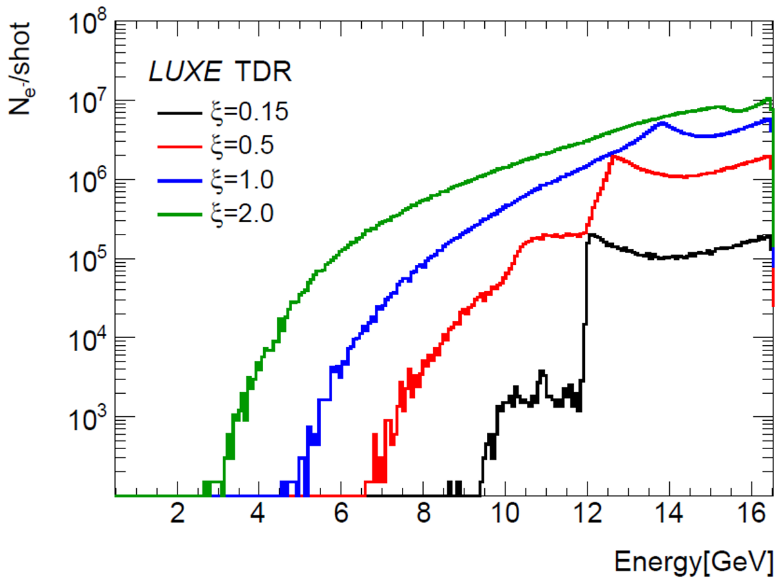



- Two complementary detector technologies per measurement:
  - Different sensitivities, cross calibration, reduction of systematic uncertainties.
- In-situ measurements of beam backgrounds when laser not on.

# High-rate electron detectors

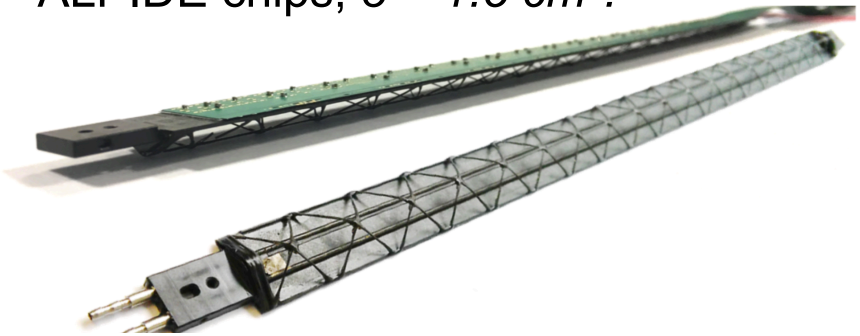
- A scintillation screen and camera is inexpensive, flexible and simple with good position resolution.
- Cherenkov straw detectors have smaller low-energy background.
- Tests done with E320 experiment at FACET-II beamline in SLAC.

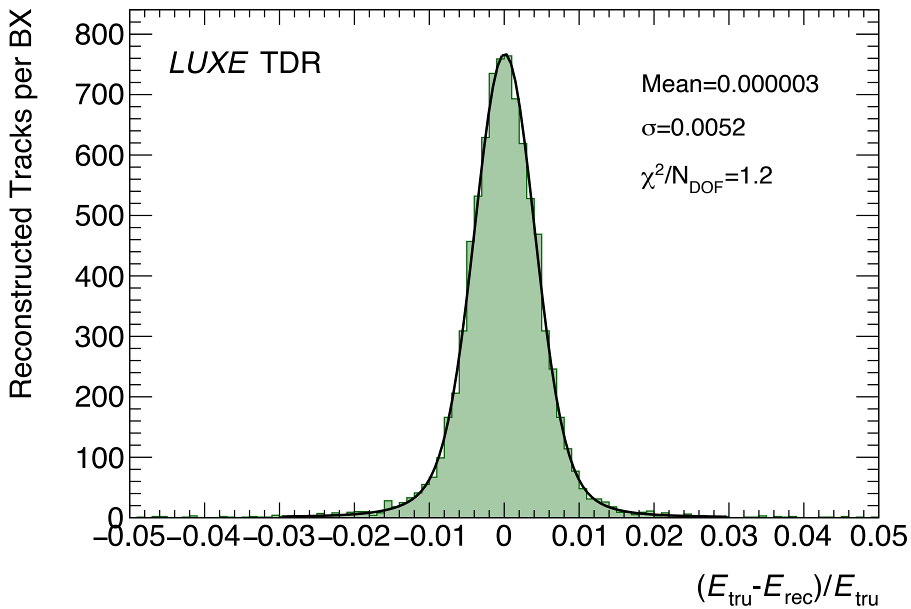


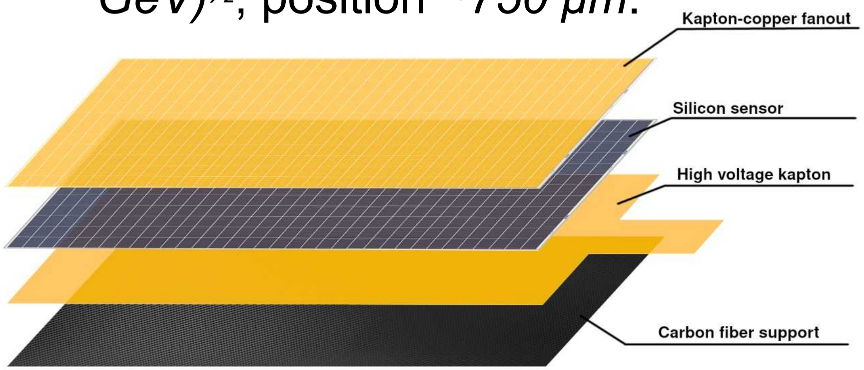
# Positron detectors

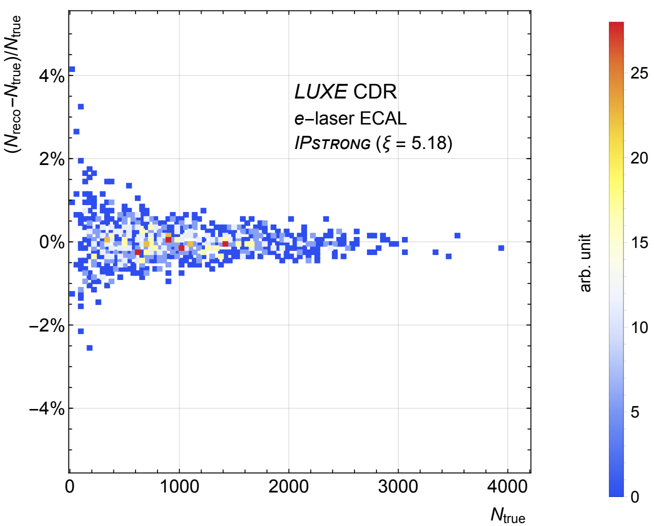
- Pixel tracker:
  - 4 layers each of which has 2 staves.
  - Each stave is *27 × 1.5 cm²* built from 9 ALPIDE chips, *3 × 1.5 cm²*.





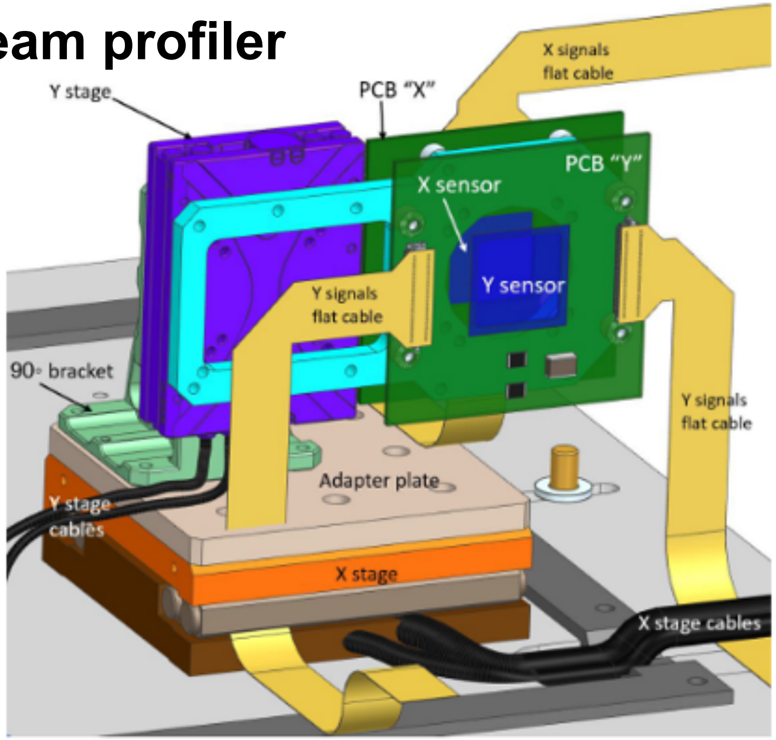

- High granularity, compact, sampling calorimeter.
  - Based on technology developed by (LC) FCAL collaboration.
  - 20 layers of 3.5 mm tungsten.
  - Energy resolution $\sigma/E = 20\%/(E/\mathrm{GeV})^{1/2}$, position *~750 µm*.



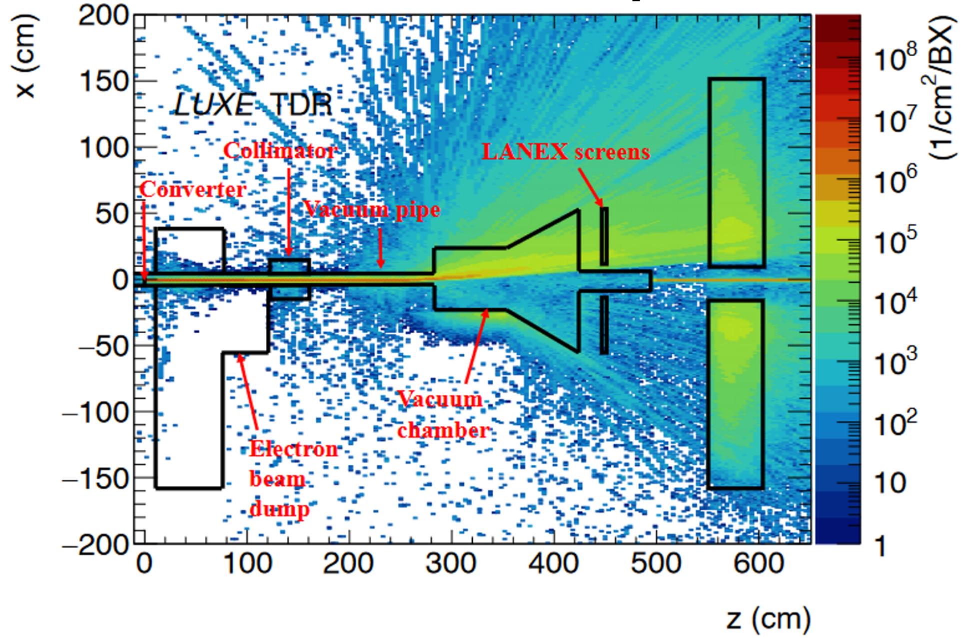



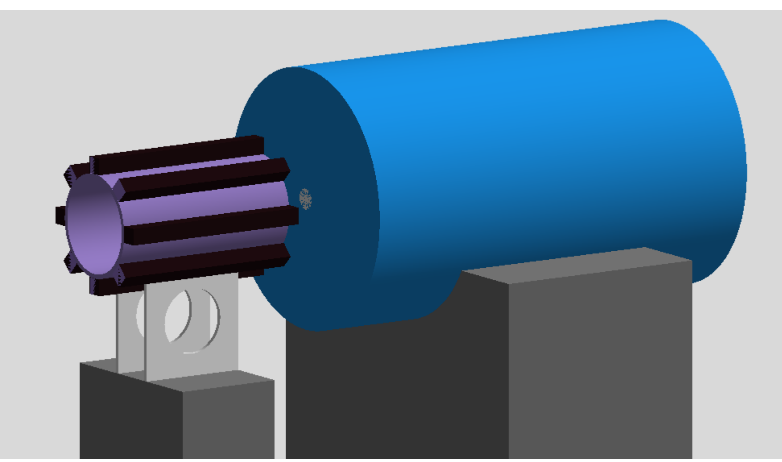
# Gamma-ray detectors

## Beam profiler




## Spectrometer



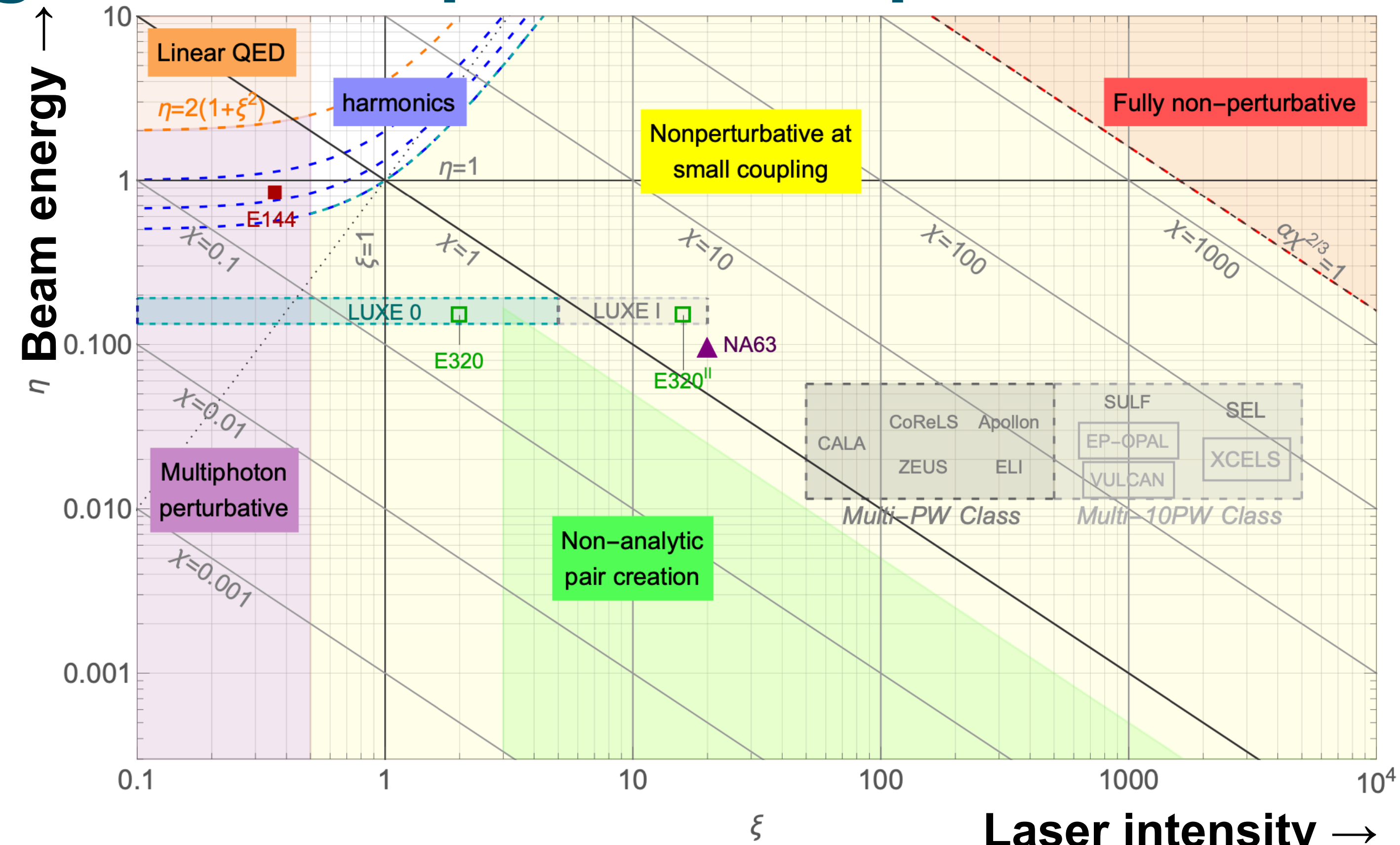



Also doing tests of beam-dump calorimeter at FLASHForward.

## Flux monitor

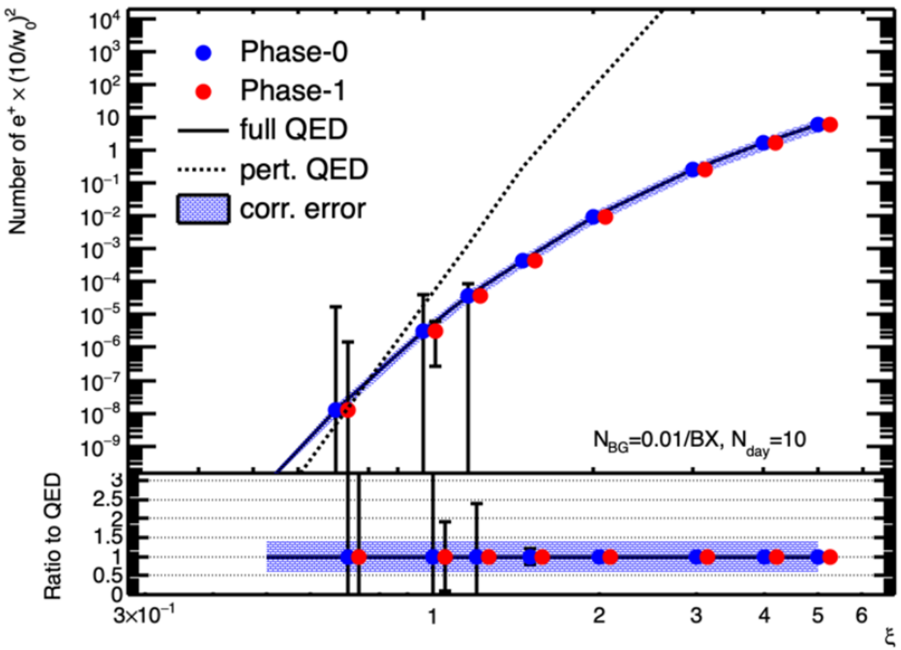
# LUXE physics expectations

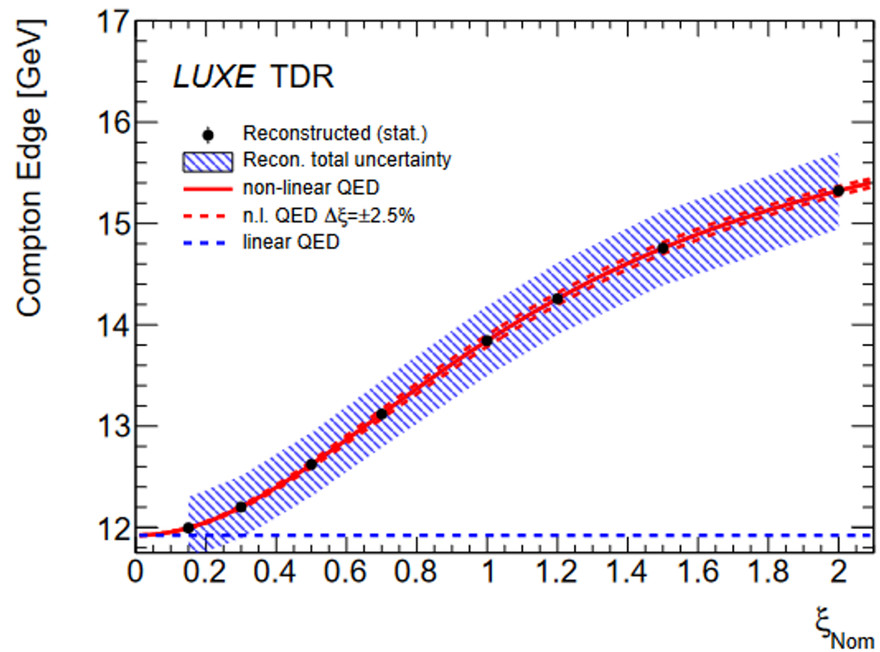
# Strong-field QED parameter space




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

# Expected results



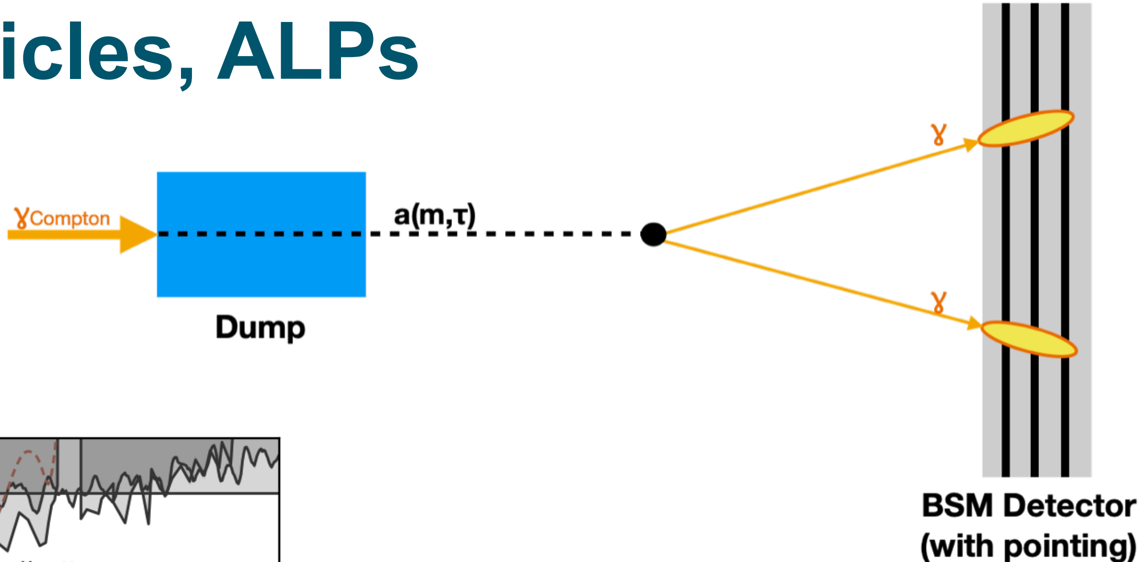



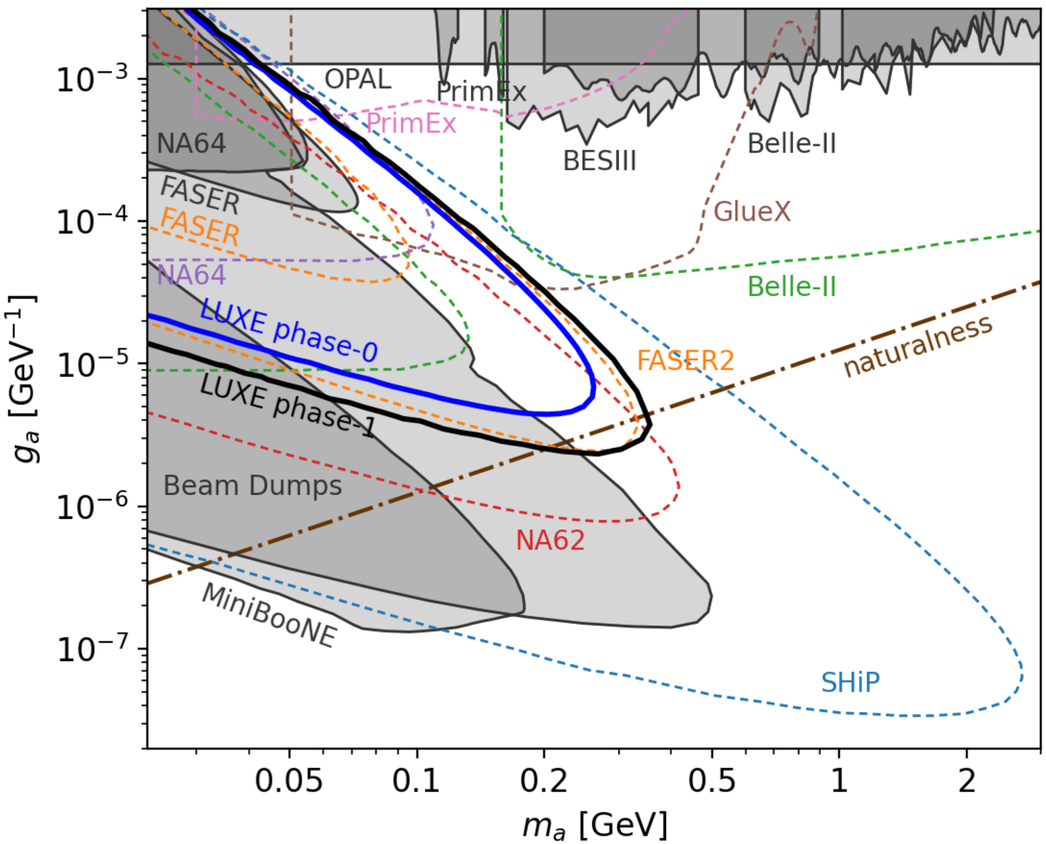

- Number of Breit–Wheeler pairs produced in *γ*–laser collisions.
- Assume 10 days of data taking and 0.01 background events/BX.
- 40% correlated uncertainty illustrates effect of uncertainty on *ξ*.

- Compton edge position as a function of *ξ* in *e*–laser collisions.
- Assuming 1 hour data taking, no background.
- Illustrative 2% energy scale uncertainty.

# Search for new particles, ALPs

- *~1 m* long detector, *~2.5 m* after photon dump.




- 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, arXiv:2107.13554.

# Status and new developments

# LUXE status and planning

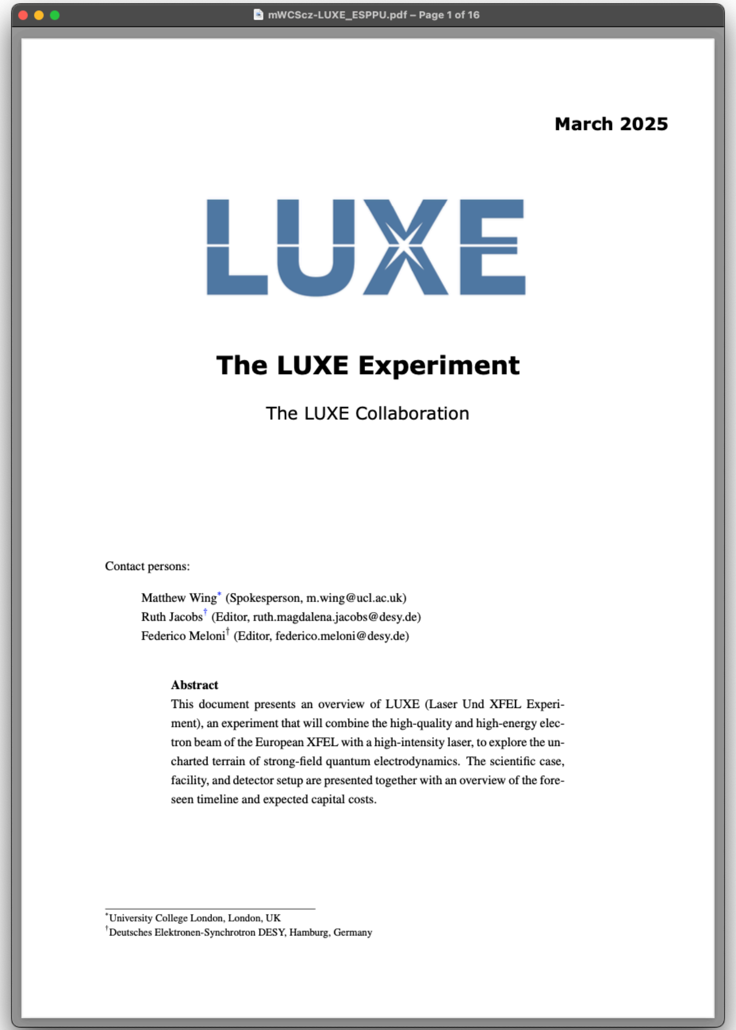
- LUXE initiated in 2017.
- Officially recognised as a DESY experiment in November 2022.
- About 20 institutes; 100 people.
- Technical Design Report published by Eur. Phys. J.
- Experiment could be realised quite quickly.
  - **Could be taking data by end of decade.**


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

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

https://luxe.desy.de

# European particle physics strategy



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March 2025

LUXE

**The LUXE Experiment**

The LUXE Collaboration


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**Abstract**

This document presents an overview of 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. The scientific case, facility, and detector setup are presented together with an overview of the foreseen timeline and expected capital costs.



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## Input to the European Strategy for Particle Physics: Strong-Field Quantum Electrodynamics


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**Abstract**

This document sets out the intention of the strong-field QED community to carry out, both experimentally and numerically, **high-statistics parametric studies of quantum electrodynamics in the non-perturbative regime**, at fields approaching and exceeding the critical or 'Schwinger' field of QED ($\boldsymbol{F_{\text{qed}} = m^2c^3/e\hbar \approx 1.3 \times 10^{18}}$ V/m). In this regime, several exotic and fascinating phenomena are predicted to occur that have never been directly observed in the laboratory. These include Breit-Wheeler pair production, vacuum birefringence, and quantum radiation reaction. This experimental program will also serve as a stepping stone towards studies of elusive phenomena such as elastic scattering of real photons and the conjectured perturbative breakdown of QED at extreme fields. State-of-the-art high-power laser facilities in Europe and beyond are starting to offer unique opportunities to study this uncharted regime at the intensity frontier, which is highly relevant also for the design of future multi-TeV lepton colliders. However, a transition from qualitative observational experiments to quantitative and high-statistics measurements can only be performed with large-scale collaborations and with systematic experimental programs devoted to the optimisation of several aspects of these complex experiments, including detector developments, stability and tolerances studies, and laser technology.


https://arxiv.org/abs/2504.00873

https://arxiv.org/abs/2504.02608

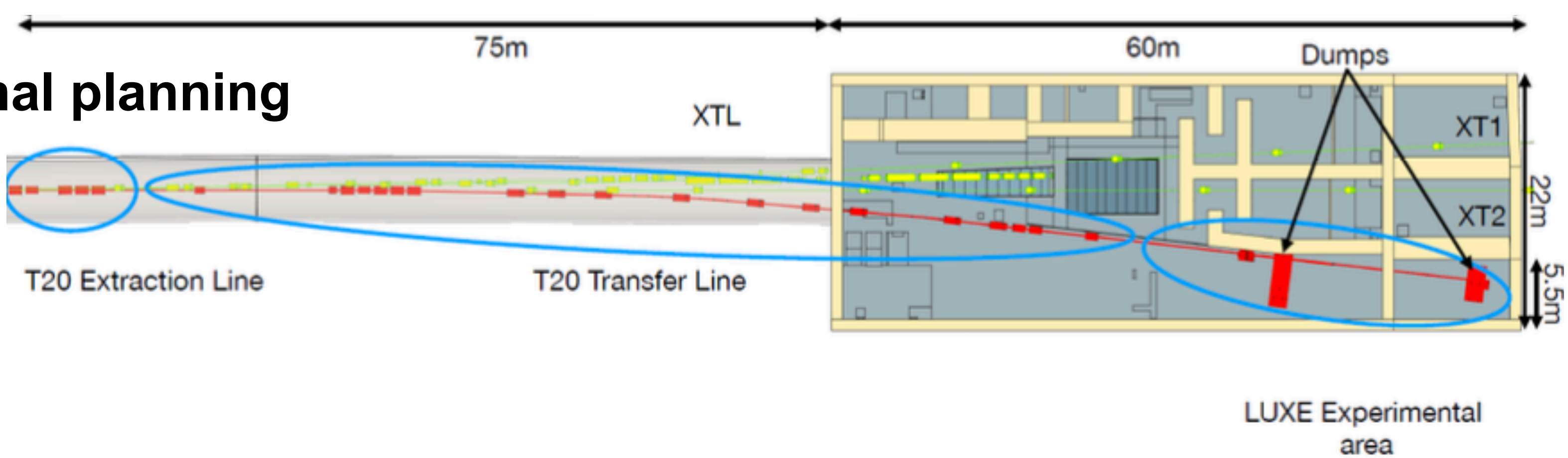
# ELBEX and LUXE

AN ELECTRON BEAMLINE AT THE European-XFEL

## ELBEX

- Goal: prepare installation of a beamline to extract *16.5 GeV* electron beam and provide to users: LUXE, plasma, test-beam.
- Funding: Horizon Europe INFRA-DEV-01 (4.3 M€ total over 5 years).
- Partners: EuXFEL (infrastructure), INFN Padova (dumps), CSIC Valencia (diagnostics), Manchester (beamline, plasma optimisation).
- Kick-off meeting in January and ramping up.

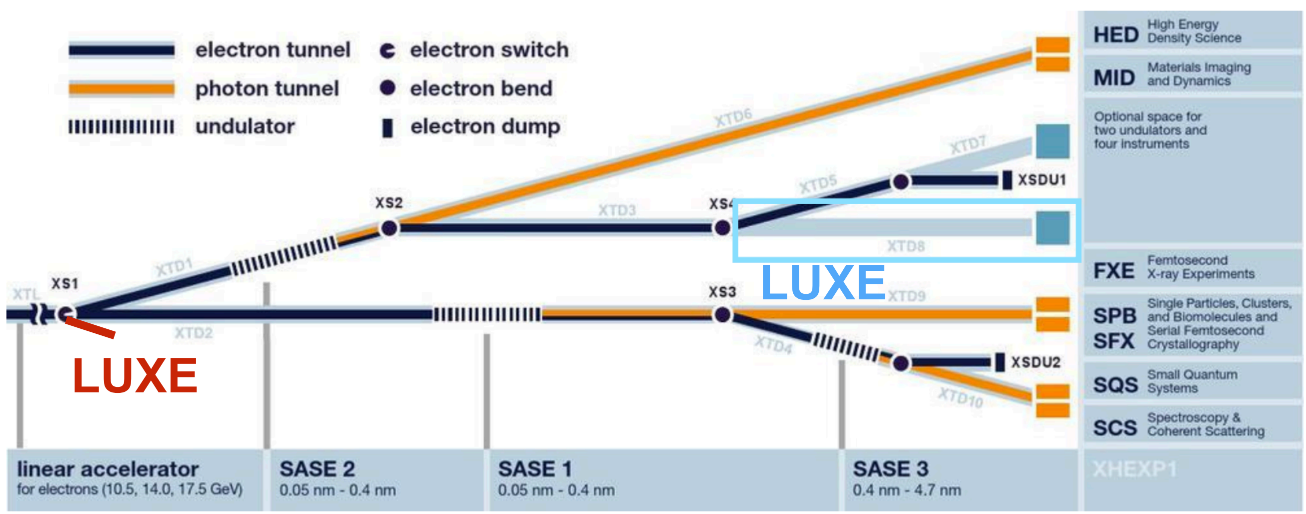
**Original planning**




Funded by the European Union

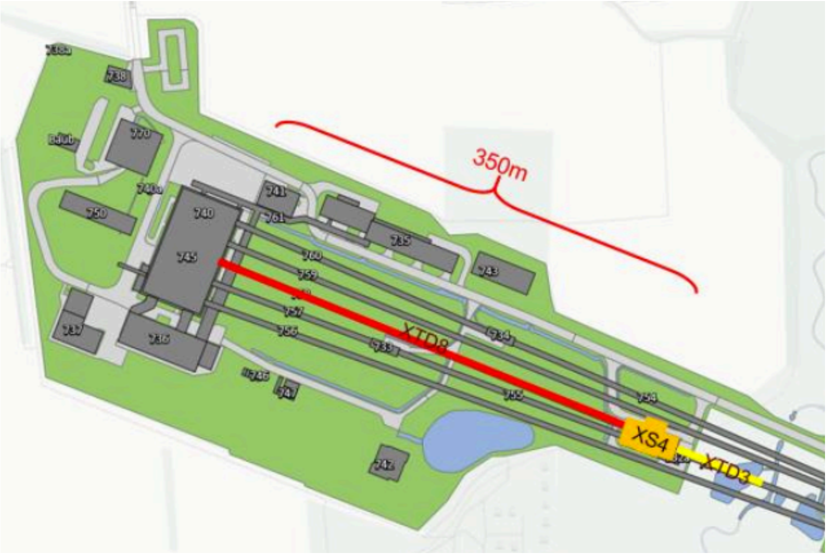
# ELBEX new location ?

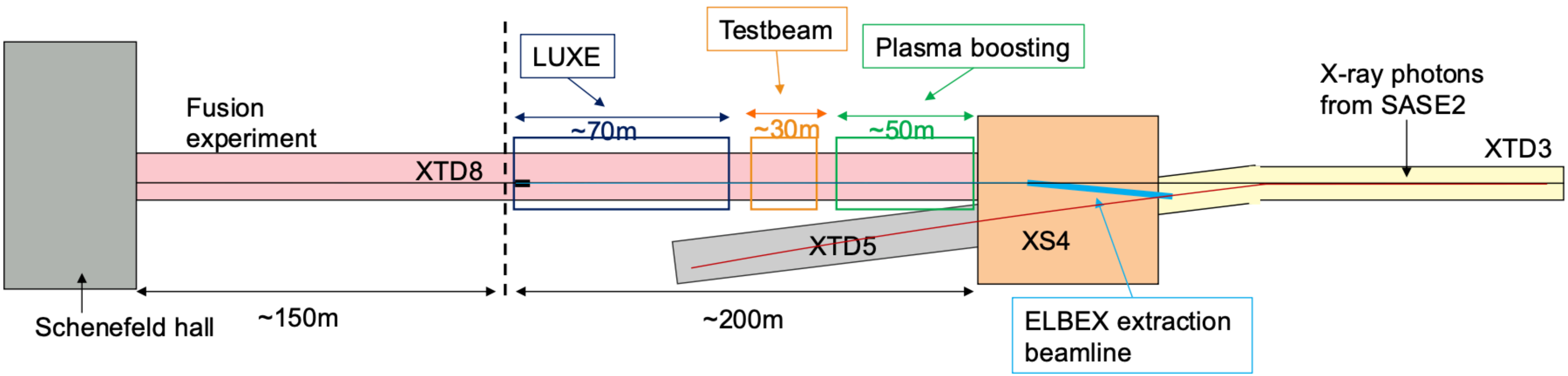
- Opportunity to move ELBEX in the EuXFEL fan (XS1 → XTD8).
- EuXFEL is planning laser-based fusion experiments with X-ray beams and petawatt laser.
- For LUXE:
  - Advantage of improved access and more longitudinal space.
  - Exploring potential co-use of laser.
  - Extract electron beam in XTD3/XS4 and share beamline with X-rays.
- Work needed for beamline design, design of experiment, etc. but advantages look significant.



# ELBEX users in XTD8

- Plasma boosting, ~ 50 m.
- Test-beam, ~ 30 m.
- LUXE, ~ 70 m.
- Beamline services, ~ 25 m.
- ELBEX + users, total ~ 175 m ⇒ 175 m for fusion experiments.




**A very promising location and facility → being studied**

# LUXE status

- The ELBEX beamline is essential for LUXE and a boost to the project.
- On lasers:
  - We have the possibility to use the JETI40 laser from Jena for start-up experiments.
  - We are looking at the possibility of a petawatt laser for experiments.
- We have LUXE institutes who will provide detectors and expertise.
- The possible new location poses challenges and re-design work, but:
  - Access, space and co-use of laser are strong positives.
  - Pursuing this possibility.

# Summary

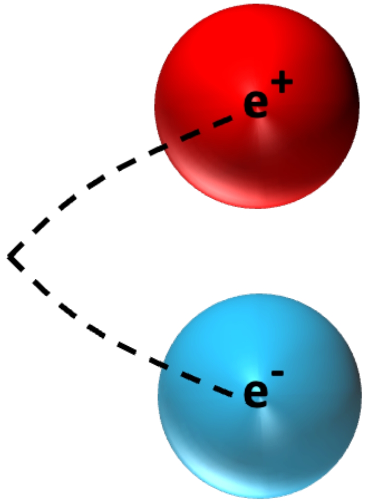
- **LUXE is an exciting new experiment to investigate QED in uncharted territory.**
- What makes LUXE unique and compelling ?
  - The exquisite initial electron beam.
  - 24/7 running.
  - *e*–laser and *γ*–laser modes.
  - Comprehensive suite of detectors.
  - Strong collaboration with a broad range of expertise.
- High precision measurements — large samples, controlled systematics.
- Measure over a broad range of quantum parameters, in particular the transition region to non-linear QED.
- Serious confrontation of experiment and theory.

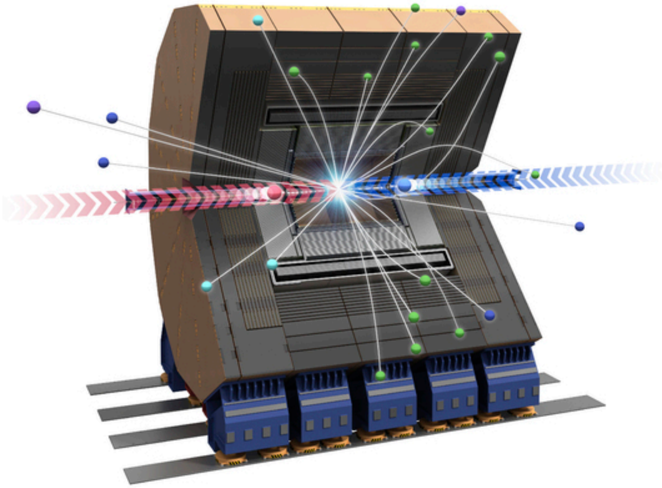
**Thanks to**
**A. Athanassiadis, L. Helary, L. Hendriks,**
**R. Jacobs, B. King, I. Schulthess, M. Zepf**
**and the LUXE collaboration**

# Back-up

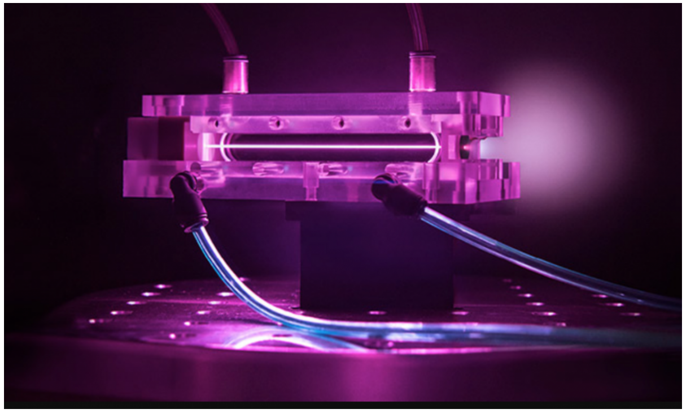
# Why are we interested in strong-field QED ?

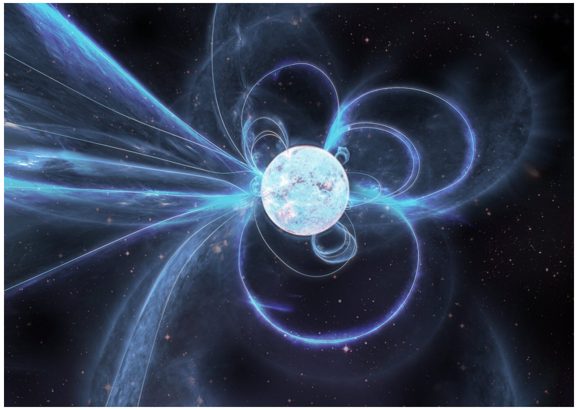
**Fundamental science**



**Higgs factories**



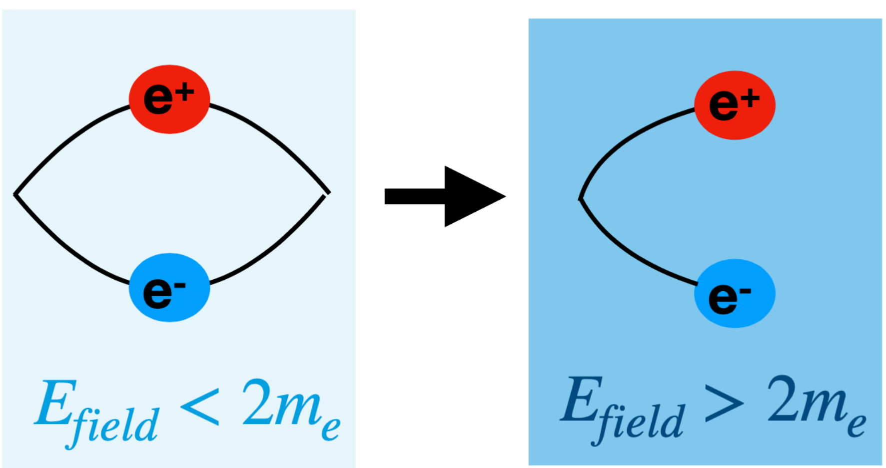


**Laser physics and novel accelerators**

**Neutron stars, black holes, etc.**

# Strong-field QED

- QED is one of the most thoroughly tested theories with measurements and perturbative calculations performed to high precision.
- The region of strong fields is less well-known, although they are present:
  - ➡ In magnetars and other astrophysical phenomena.
  - ➡ In atomic and laser physics.
  - ➡ In high-energy colliders, e.g. ILC or CLIC.
- LUXE will investigate the strong-field regime, where QED becomes non-perturbative.
- Characterised by the Schwinger critical field.

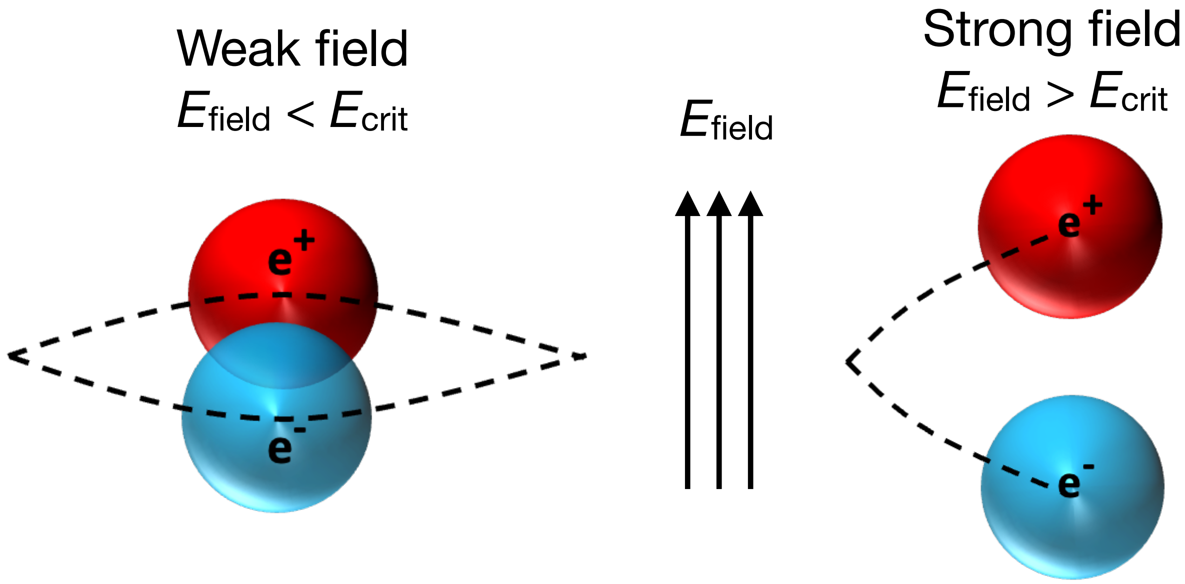



$$E_{\text{crit}} = \frac{mc^2}{e\lambda\!\!\!^{-}_C} = \frac{m^2c^3}{e\hbar}$$

$$= 1.3 \times 10^{16} \;\; \text{V/cm}$$

- Fluctuating vacuum (time > $\lambda_C$) stimulated by high field to produce real pair creation.

# Introduction: Strong-field QED

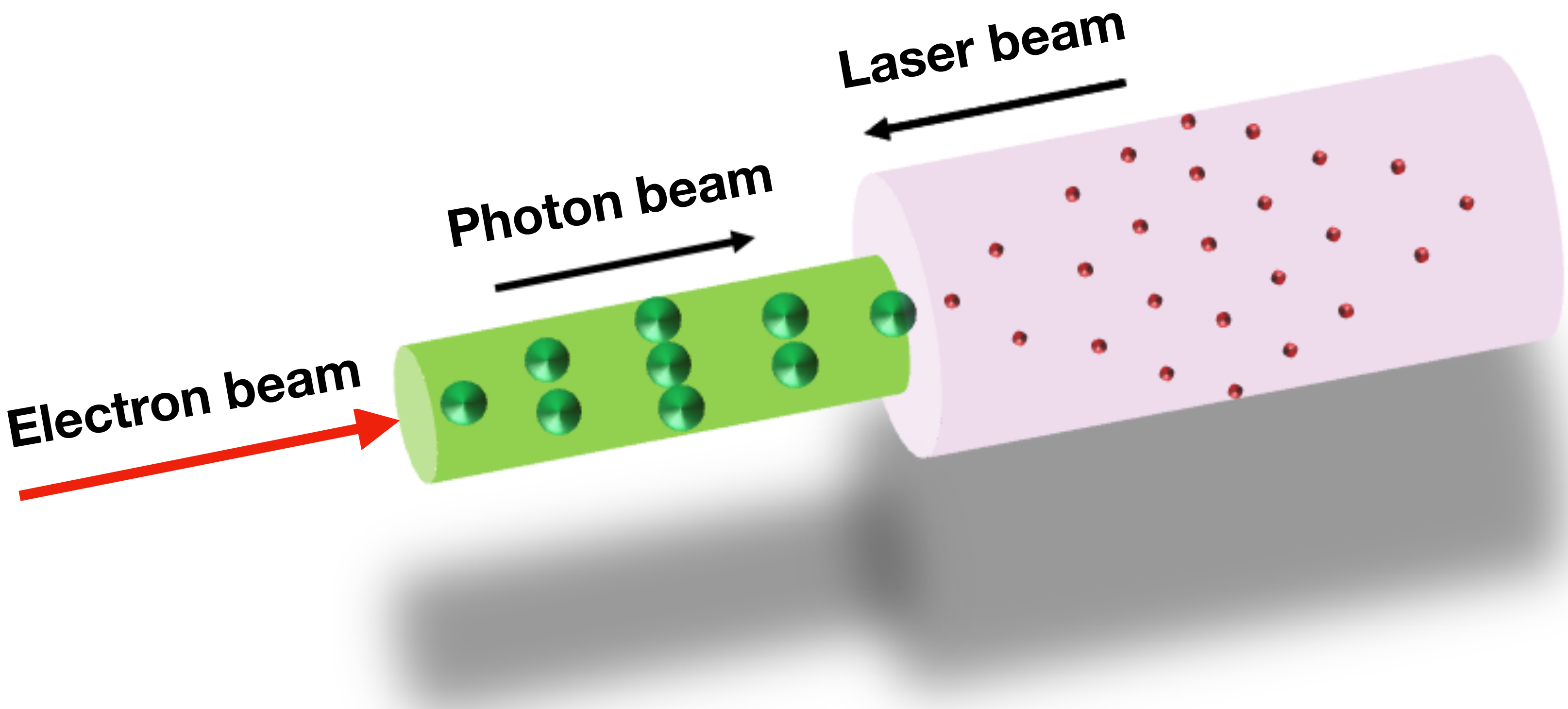



Critical field or Schwinger limit: $E_{\text{crit}} = \frac{mc^2}{e ƛ_C} = \frac{m^2 c^3}{e\hbar} = 1.3 \times 10^{16}$ V/cm

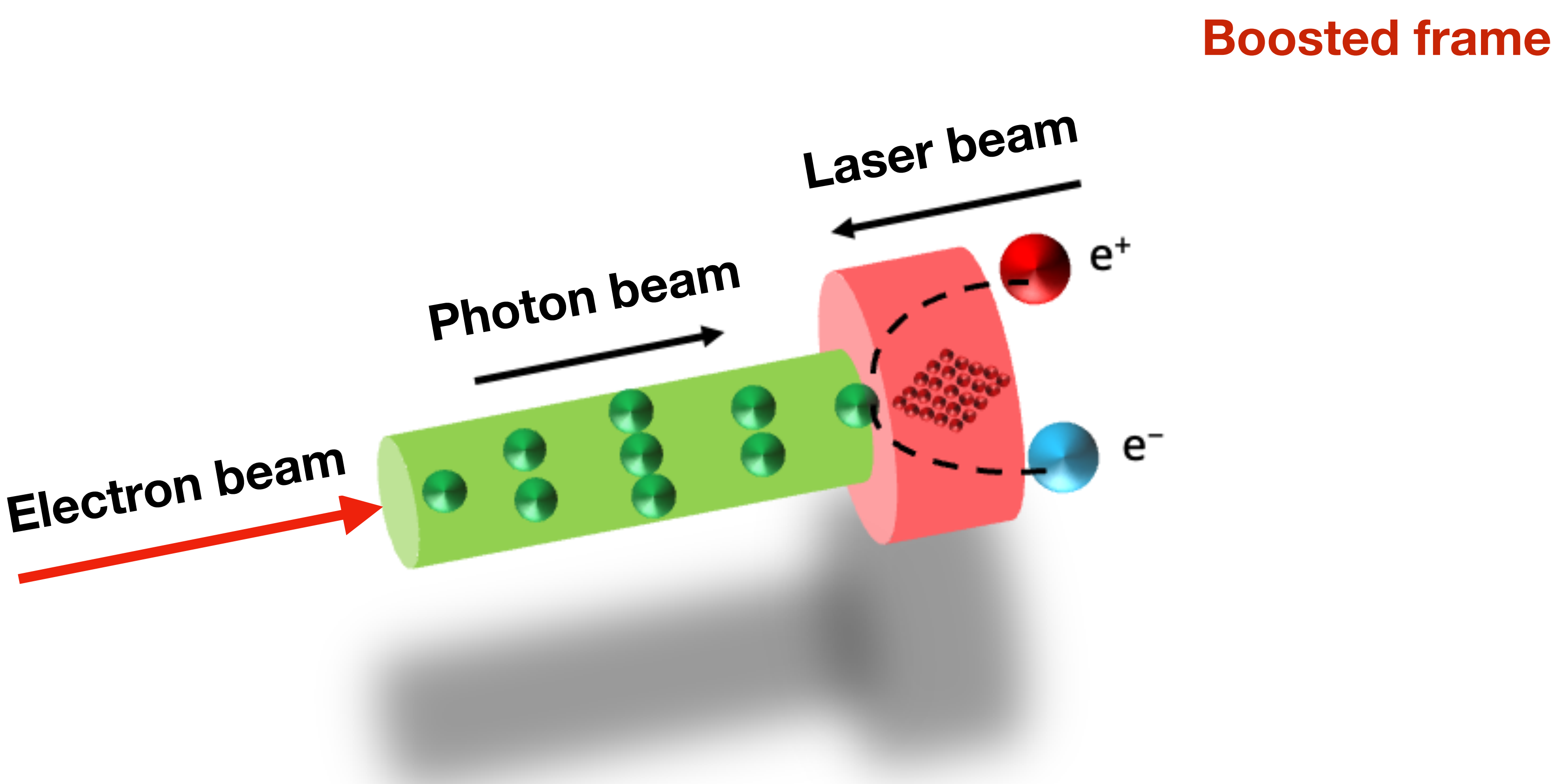
**Never achieved to date ! 10,000× greater than world's largest lasers.**

# Introduction: Strong-field QED

Laboratory frame



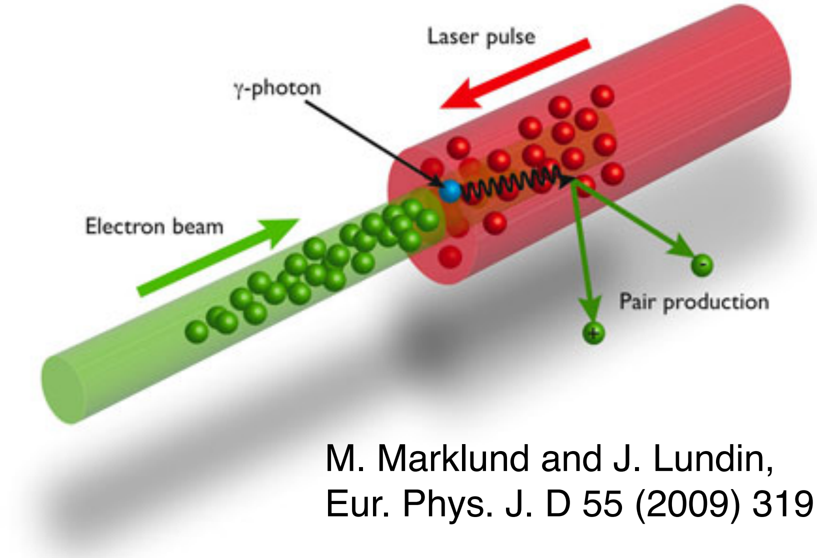
# Introduction: Strong-field QED




- Critical field can be reached with relativistic length contraction.
- Relativistically boosted field $\chi = \gamma\ E_L / E_{\text{crit}}$

# Strong-field QED in the laboratory

- Existing fields, e.g. lasers, orders of magnitude too small compared to $E_{crit}$.
- But non-linear quantum effects observable with relativistic probes.
  - Fields $O(E_{crit})$ in particle rest frame




M. Marklund and J. Lundin, Eur. Phys. J. D 55 (2009) 319

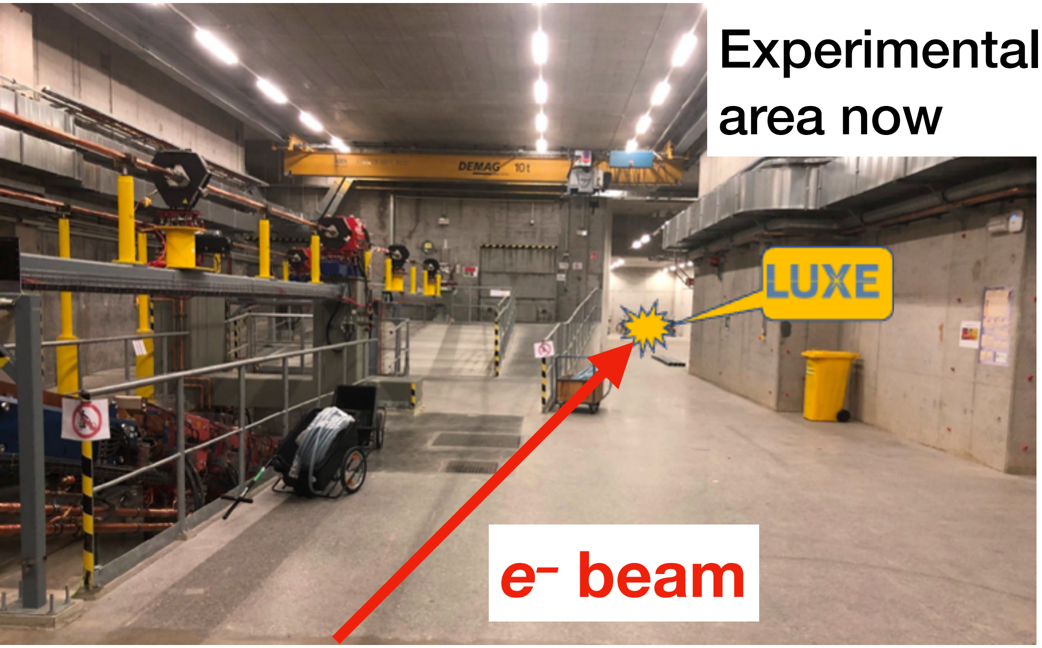
- In the laboratory, reach fields at Schwinger limit in the rest frame of highly relativistic particles.
  - Use multi-GeV electrons and multi-TW laser.

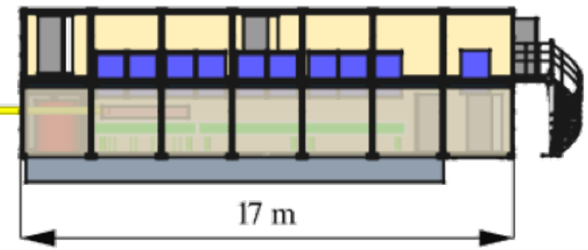
# Data handling

- 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 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.

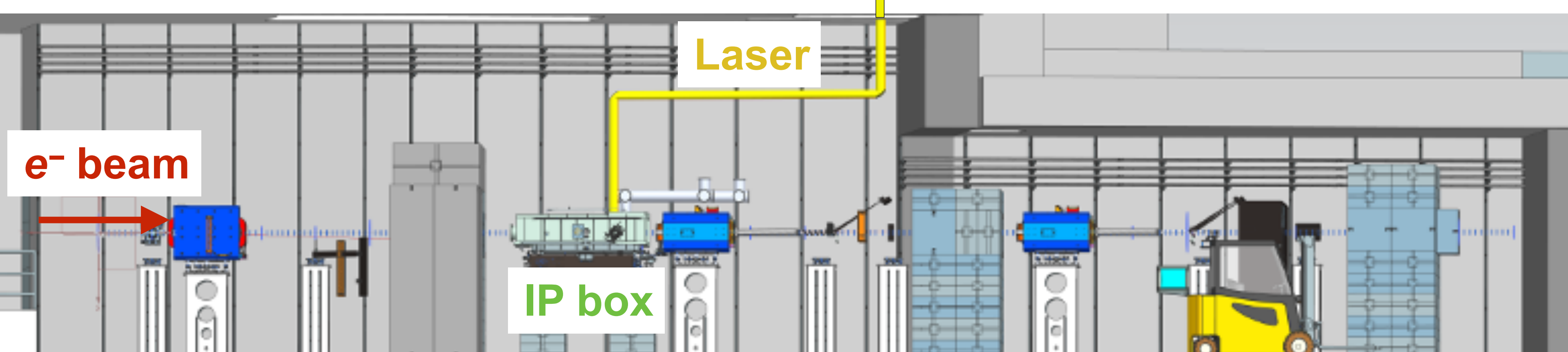
# LUXE experimental area

Experimental area now

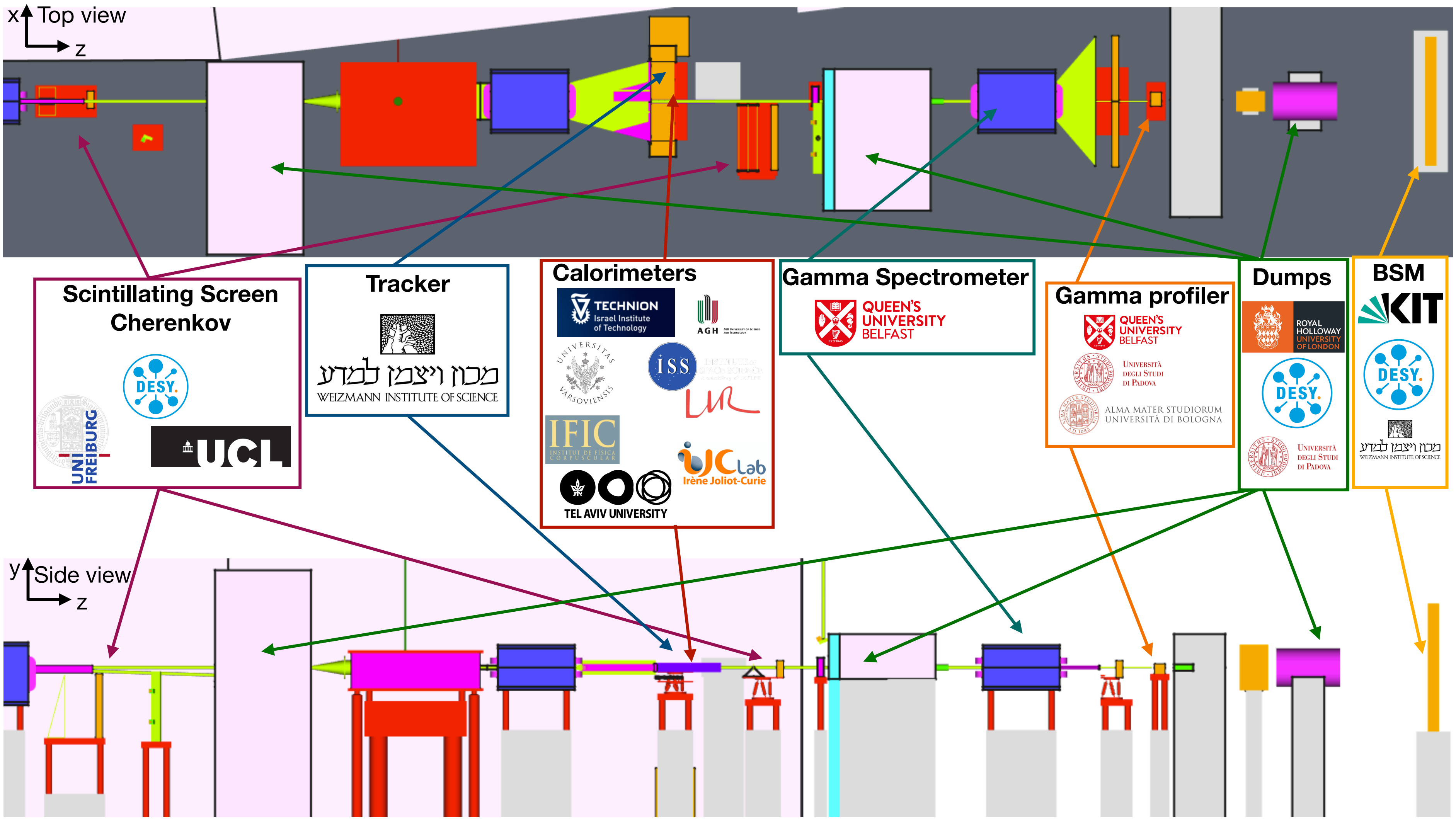



Laser room



# LUXE status and planning



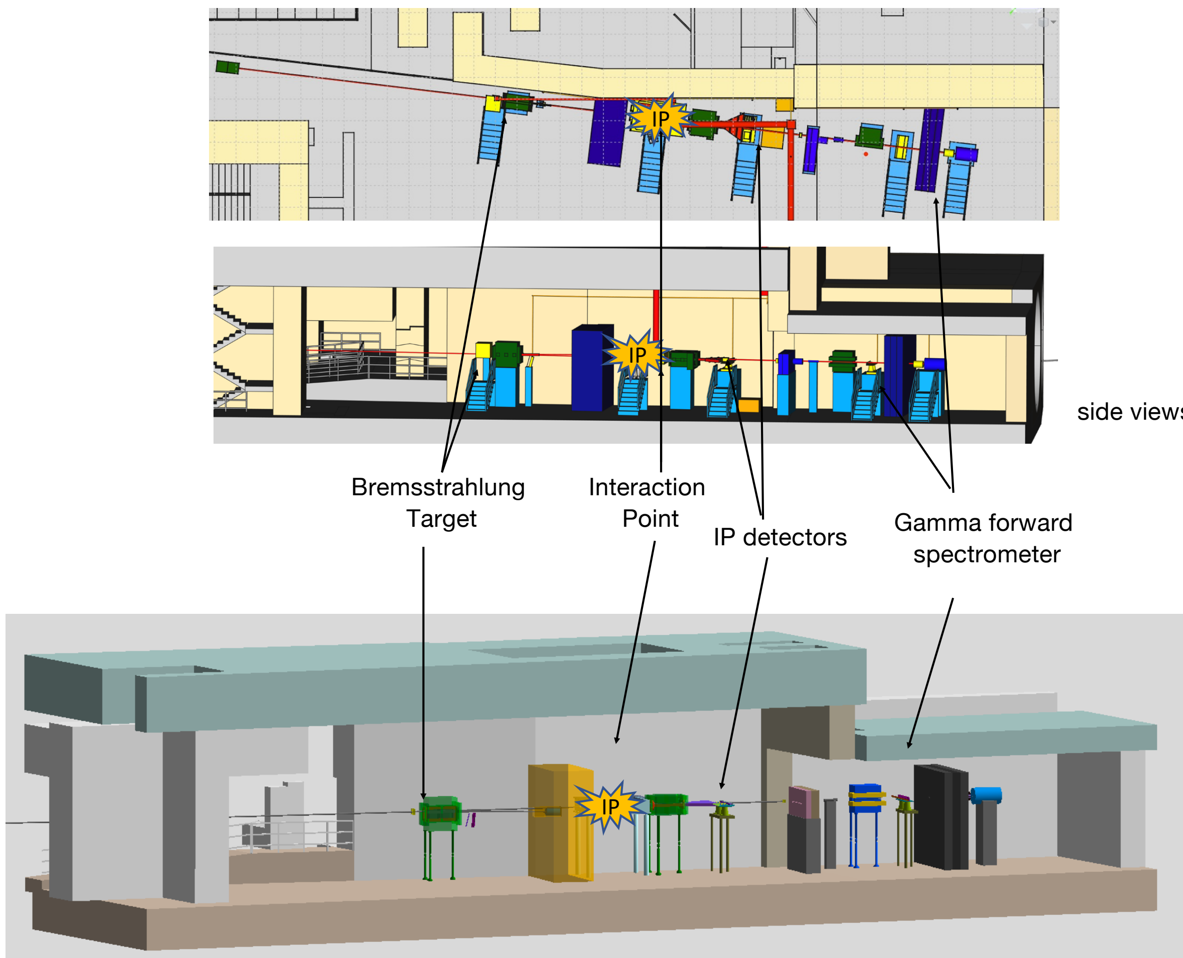
# Layout — more engineering-like

top view of experimental area

CAD:

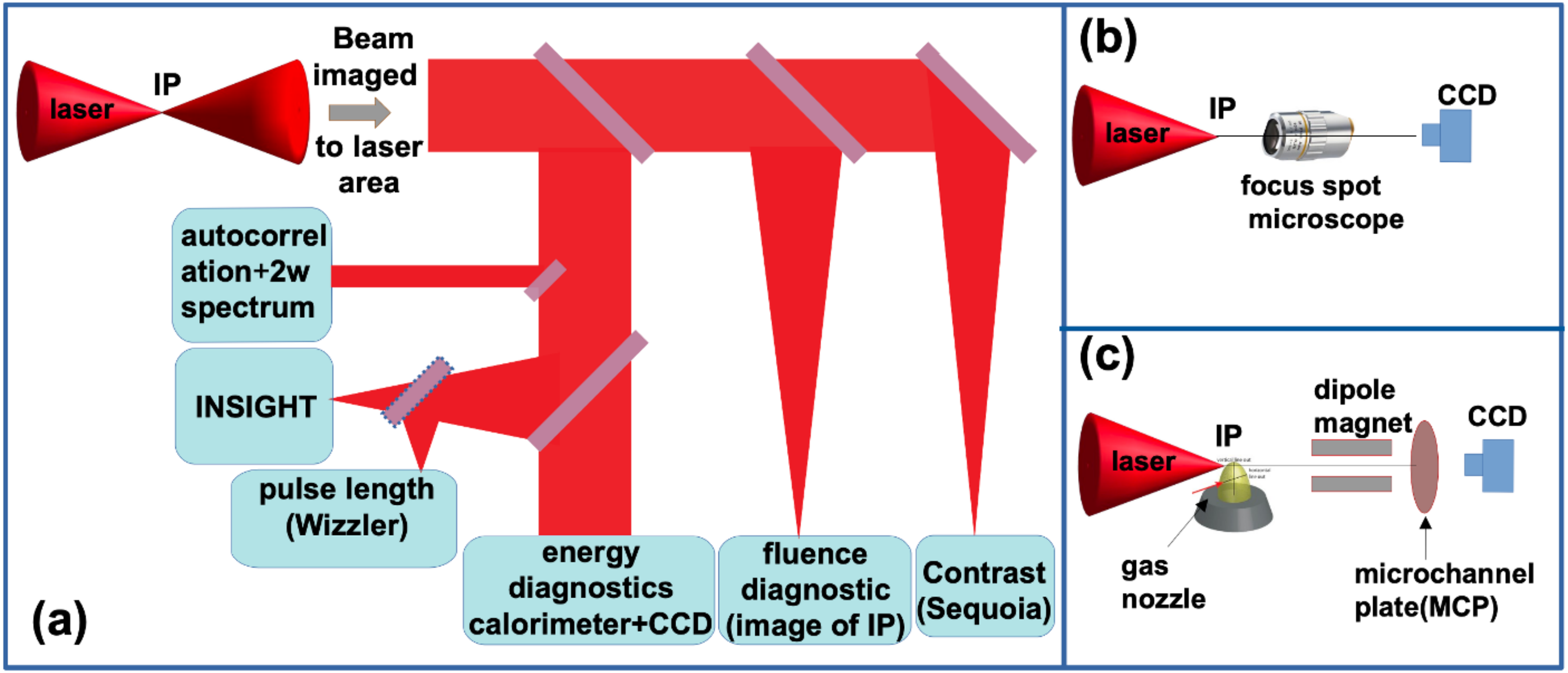
side views of experimental area

Full Geant4 simulation:




**Advanced design that fits into hall at end of ELBEX beamline.**

# Laser diagnostics

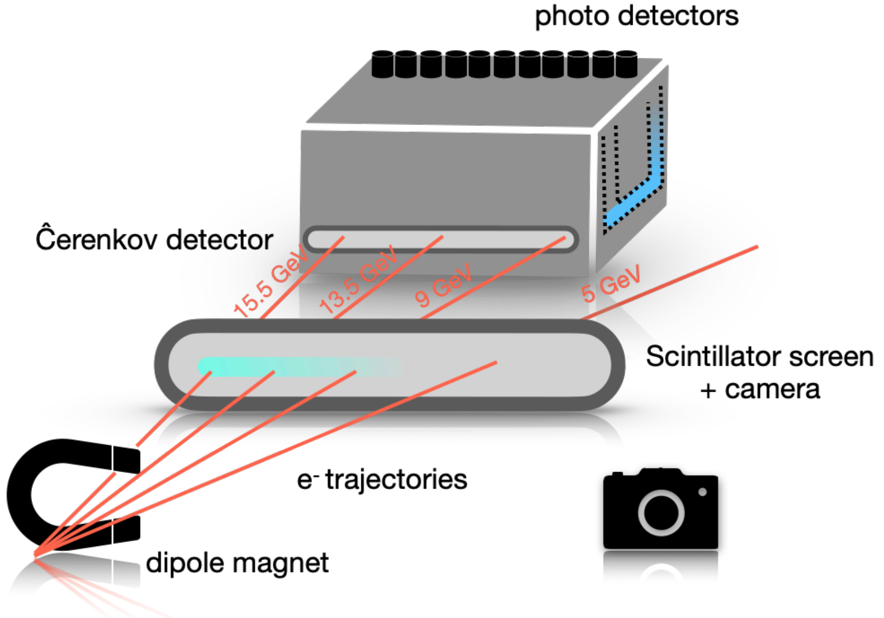



- Need to characterise energy, pulse length, spot size.
  - Diagnostics in IP chamber and in laser clean room.
- Uncertainty on laser intensity impacts physics results.
- Goal: < 5% uncertainty on laser intensity, 1% shot-to-shot uncertainty.

# Overview of electron/positron detectors

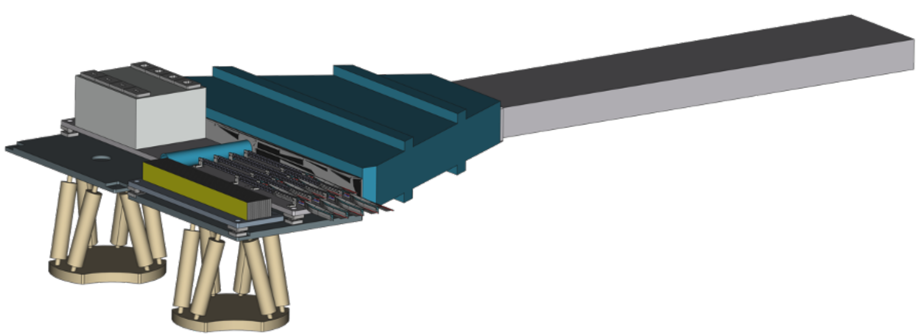
- High-flux regions
  - Scintillation screens
  - Cherenkov detectors

High rate tolerance,
large dynamic range.



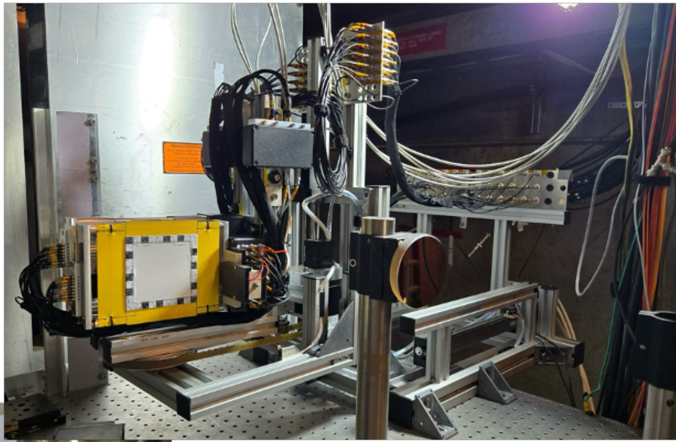

- Low-flux regions
  - Silicon pixel detectors
  - High granularity calorimeters

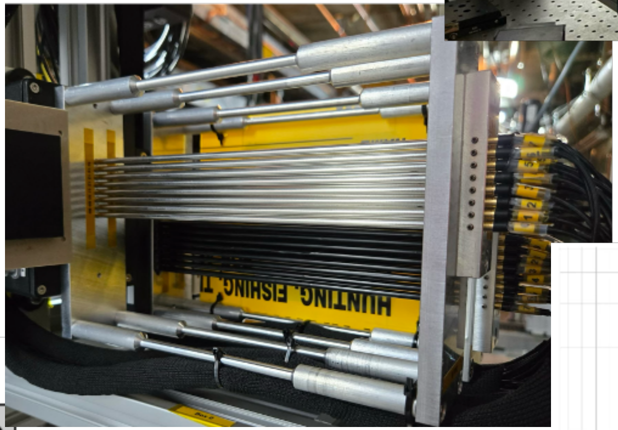
High signal efficiency,
high resolution.

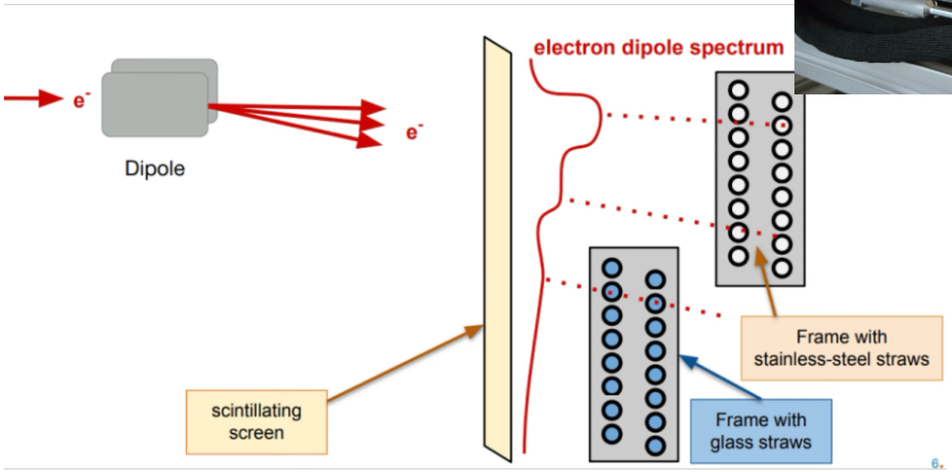


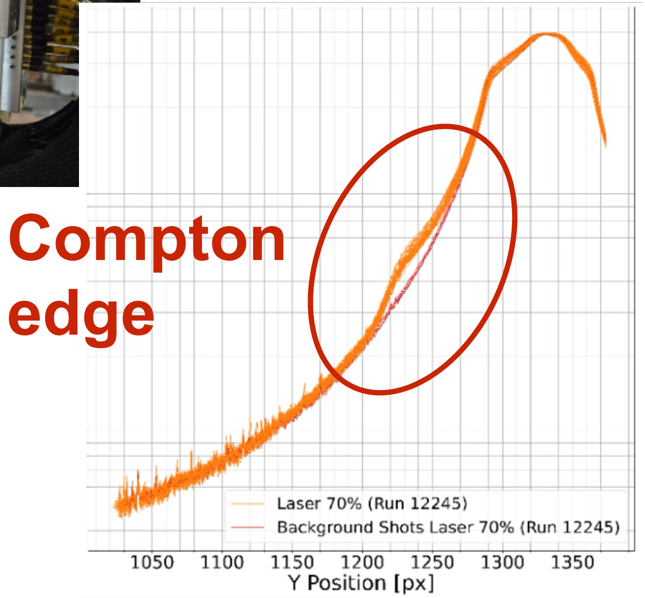
# High-rate electron detectors @E320

- Unique opportunity to install in FACET-II in 2024.
- Collected data with electrons (*10 GeV, 1.6 nC*) and laser (*10 TW*).
- Measured Compton spectrum with $\xi \sim 1 \ldots 5$.



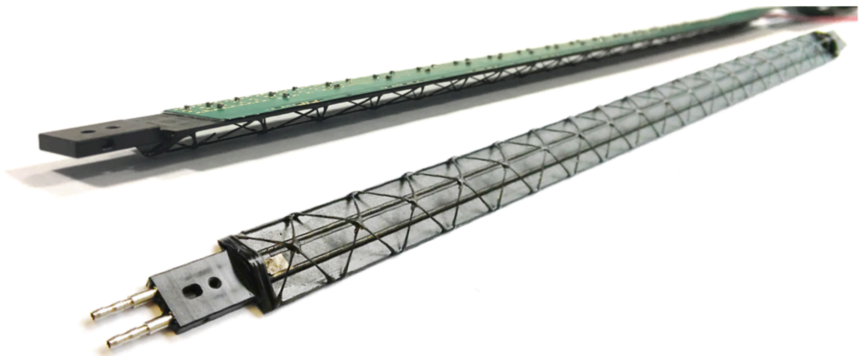


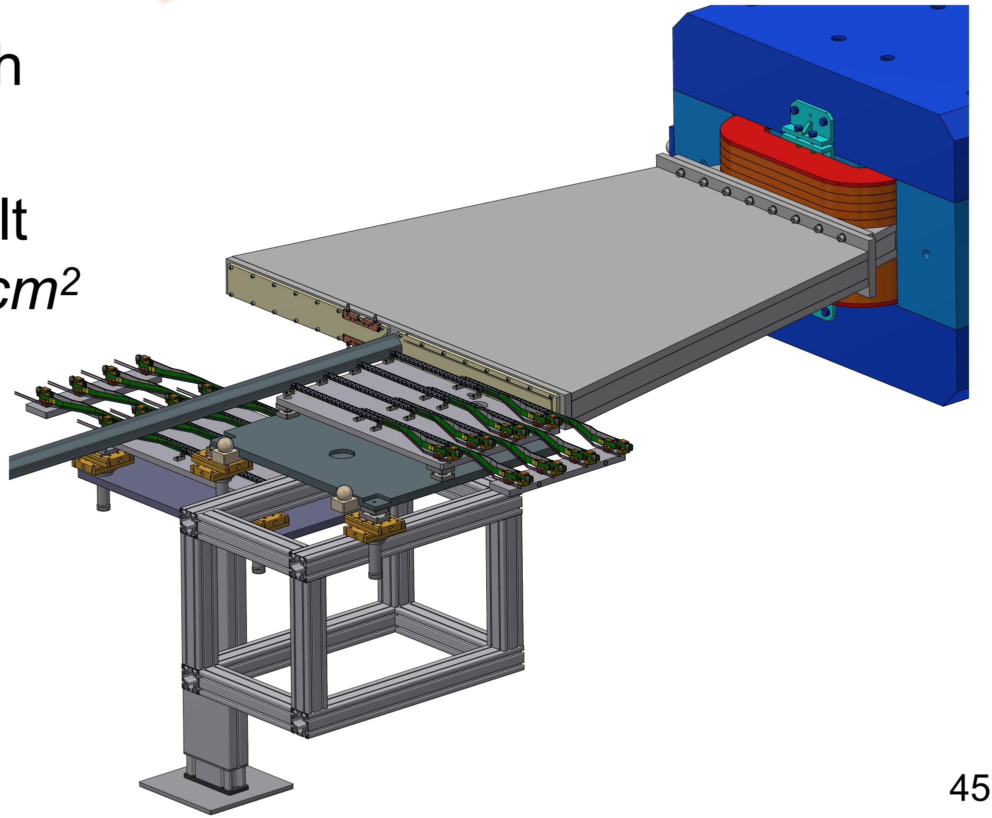


# Positron detector — pixel tracker

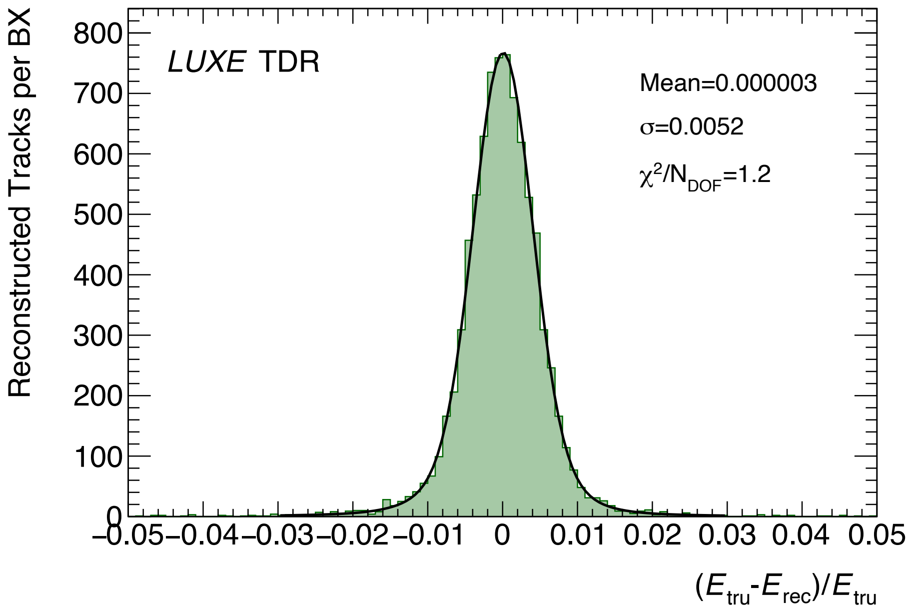
- Pixel tracker:
  - Based on ALICE ALPIDE pixel chips.
  - Pixel size *27 × 29 μm²* with position resolution of ~ *5 μm*.
- Consists of 4 layers each of which has 2 staves.
  - Each stave is *27 × 1.5 cm²* built from 9 ALPIDE chips, *3 × 1.5 cm²*

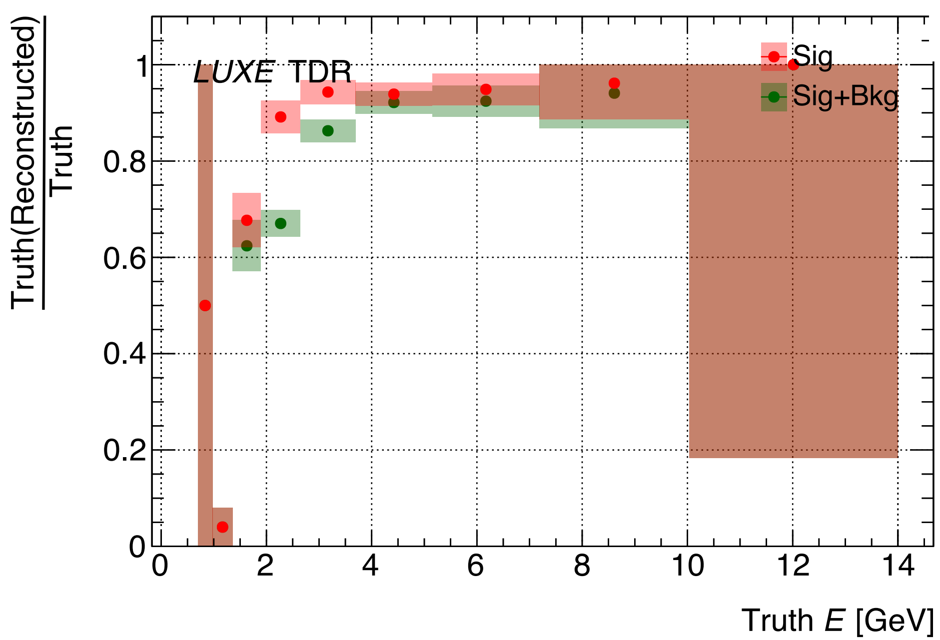


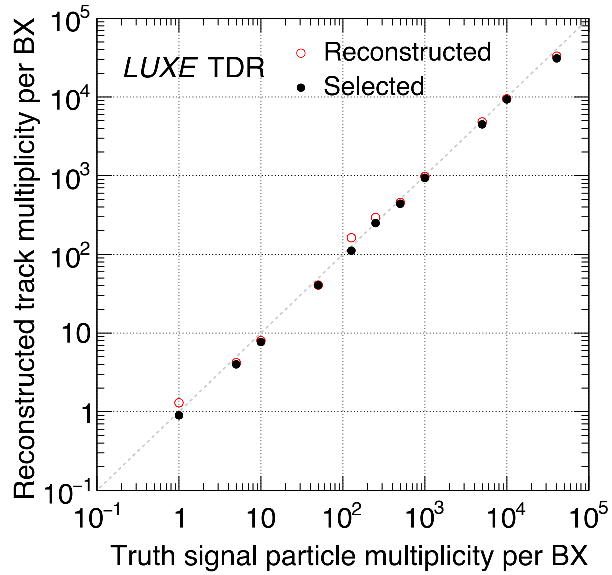


# Pixel tracker performance

- Expected performance:
  - Energy resolution < 1%.
  - Good tracking efficiency.
  - Good linearity for different signal track multiplicities.

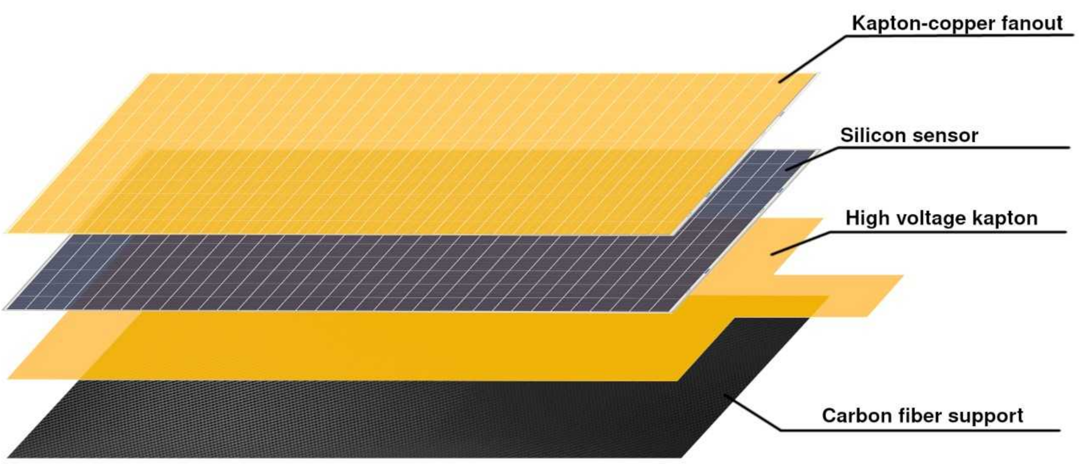


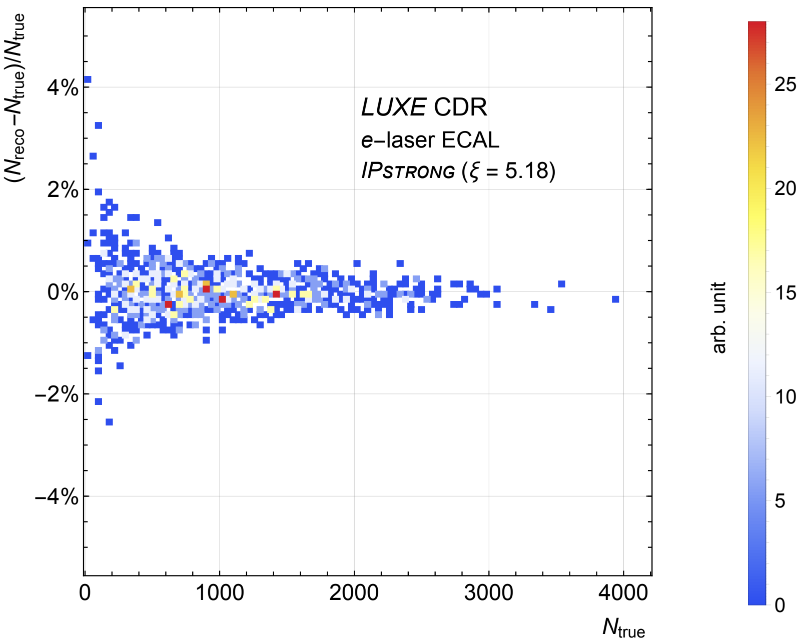



# Positron detector — calorimeter

- High granularity, compact, sampling calorimeter.
  - Based on technology developed by (LC) FCAL collaboration.
  - Studies with 20 layers of 3.5 mm tungsten; baseline 10 layers @ *3.5 mm* and 5 layers @ *7 mm*.
  - Silicon sensors of $9 \times 9\ cm^2$ with pads $5.5 \times 5.5\ mm^2$; a complete detector plane is 6 adjacent sensors.
  - Energy resolution $\sigma/E = 20\%/(E/GeV)^{1/2}$, position ~*750 μm*.



# Positron detector — calorimeter

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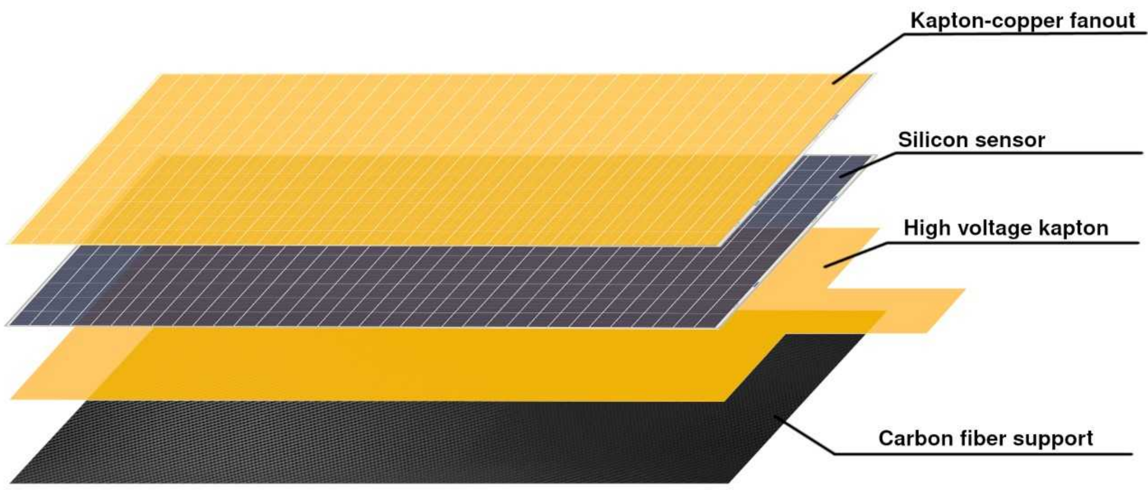
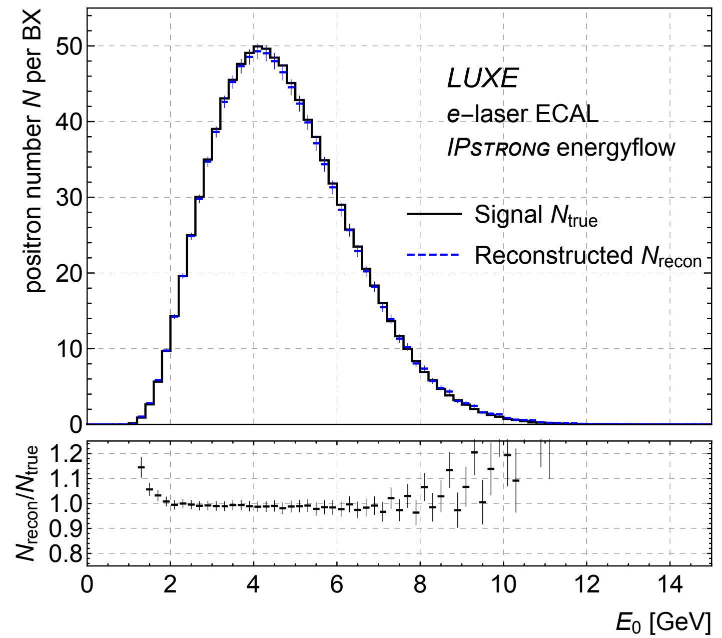
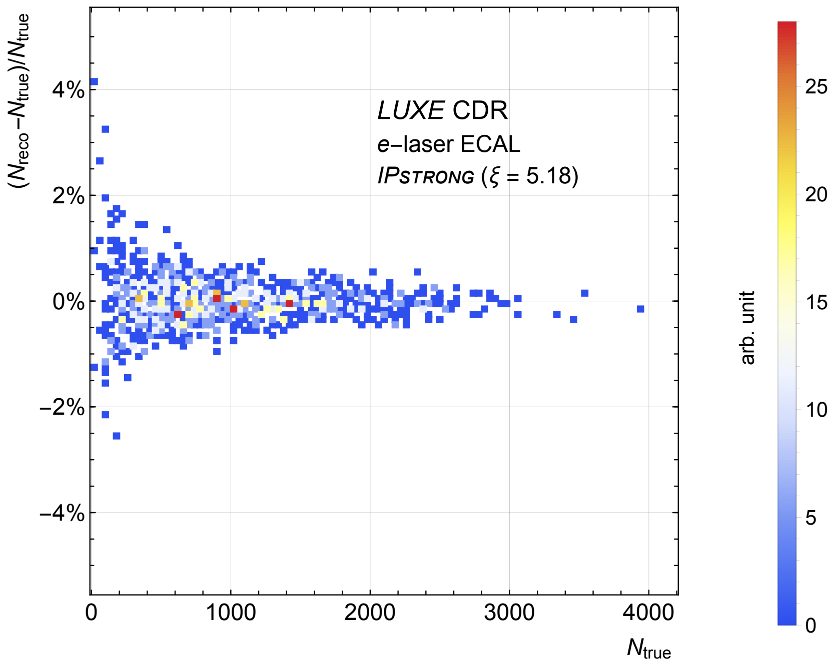
  - Based on technology developed by (LC) FCAL collaboration.
  - Studies with 20 layers of 3.5 mm tungsten; baseline 10 layers @ 3.5 mm and 5 layers @ 7 mm.
  - Read out by FLAME ASIC (developed for FCAL).
  - Silicon sensors of 9 × 9 $cm^2$ with pads 5.5 × 5.5 $mm^2$.
  - A complete detector plane is 6 adjacent sensors.
  - Energy resolution of $\sigma/E = 20\%/(E\ /\ GeV)^{1/2}$, position resolution ~750μm.

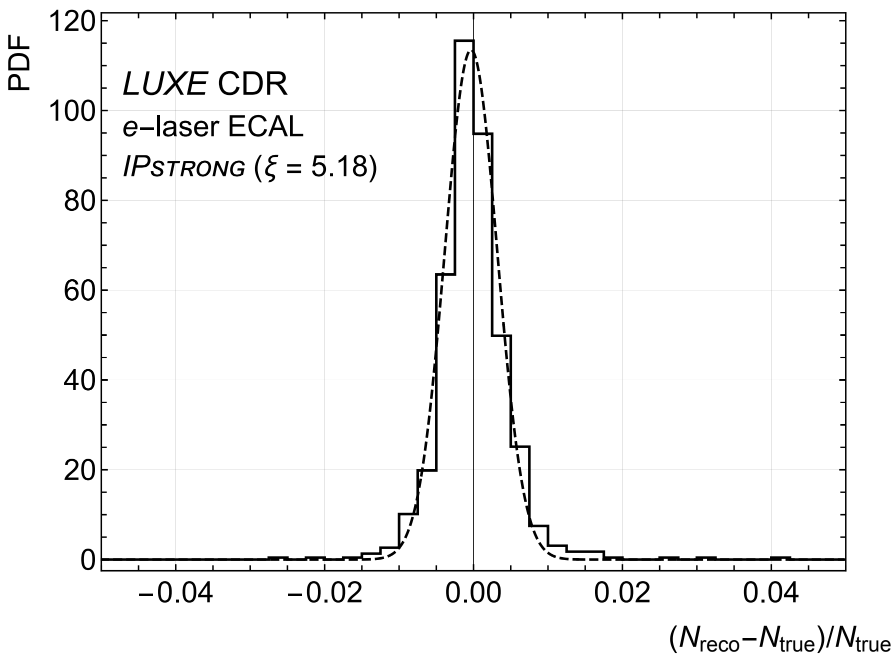


# Calorimeter reconstruction

- Number of particles determined by comparing calorimetric energy with energy expected from cluster position.
- Good reconstruction for particle multiplicities of 1000.

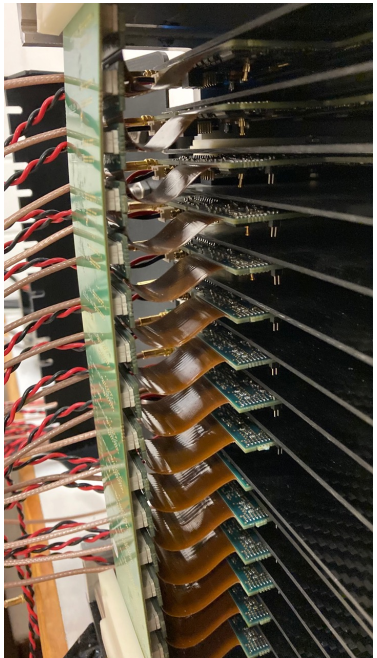


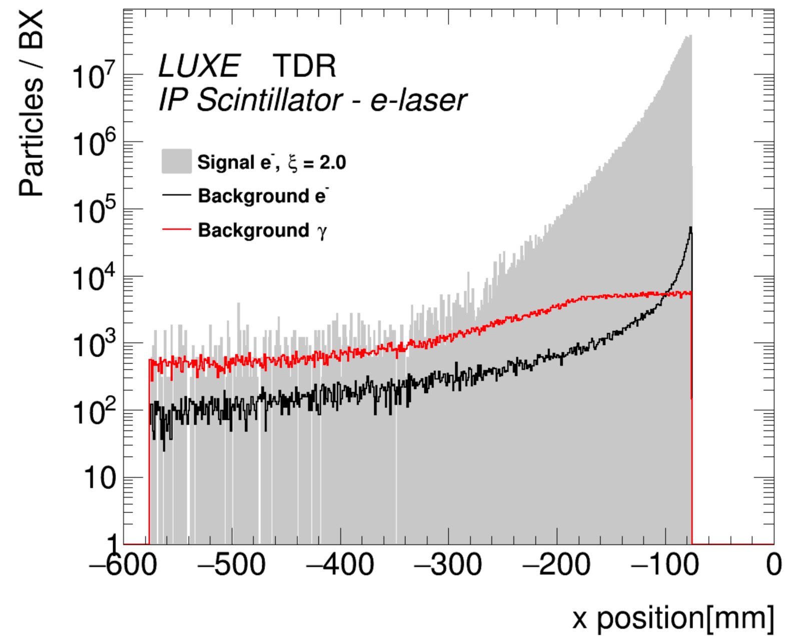
# Electron calorimeter in γ–laser collisions

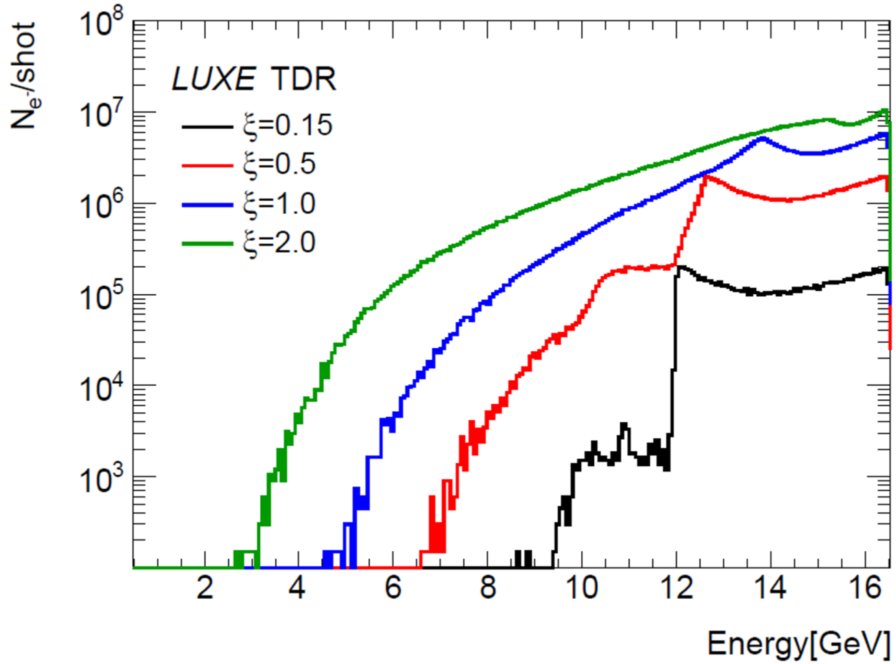
- To measure electrons in γ–laser collisions as rate is much lower.
- Use a silicon–tungsten electromagnetic calorimeter based on developments from CALICE collaboration.
  - Reference design for ILC concept.
  - 7 tungsten plates of *2.8 mm* and 8 of *4.2 mm* thickness.
  - Sensors are the same structure as other calorimeter
  - Pads directly connected to SKIROC2a ASIC.



# High-rate electron detector — scintillation screen

- A scintillation screen and camera (with filter) is inexpensive, flexible and simple with good position resolution.
- Scintillator: GadOx; camera: CMOS/CCD.
- As a spectrometer, position gives energy.

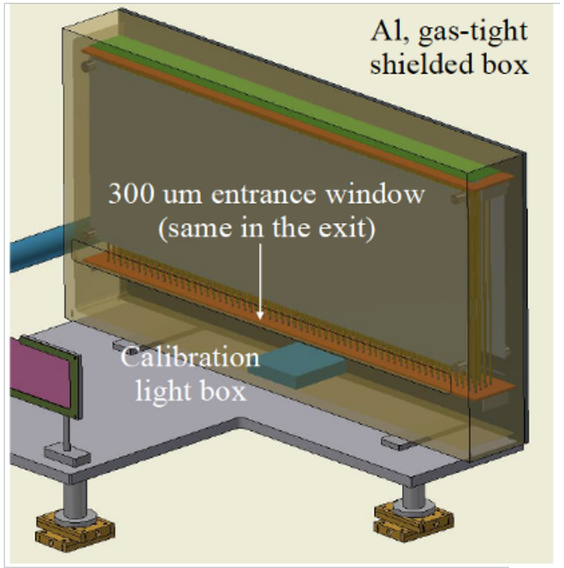



- Minimally affects electrons en route to Cherenkov detector.
- Good signal-to-background.
- Similar systems used in accelerators.

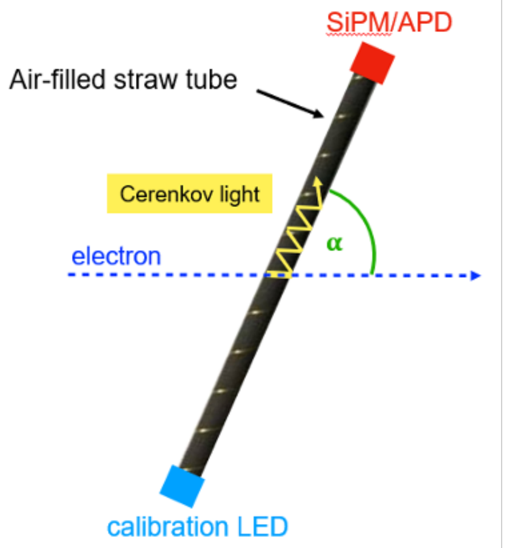
# High-rate electron detector — Cherenkov

- Finely segmented (∅ = *4 mm*) air-filled channel (reflective tubes as light guides).
  - Charged particles create Cherenkov light.
- Air: low refractive index
  - Reduce light yield.
  - Suppress backgrounds (Cherenkov threshold *20 MeV*).



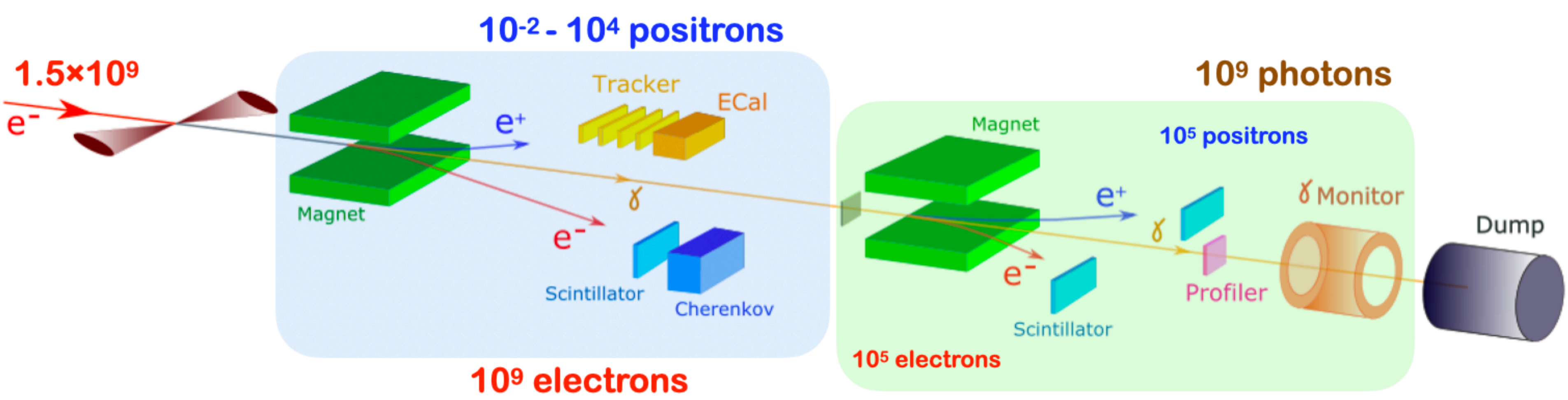

- Beam tests and R&D ongoing.
- Also deploy at E320.

Straw prototype



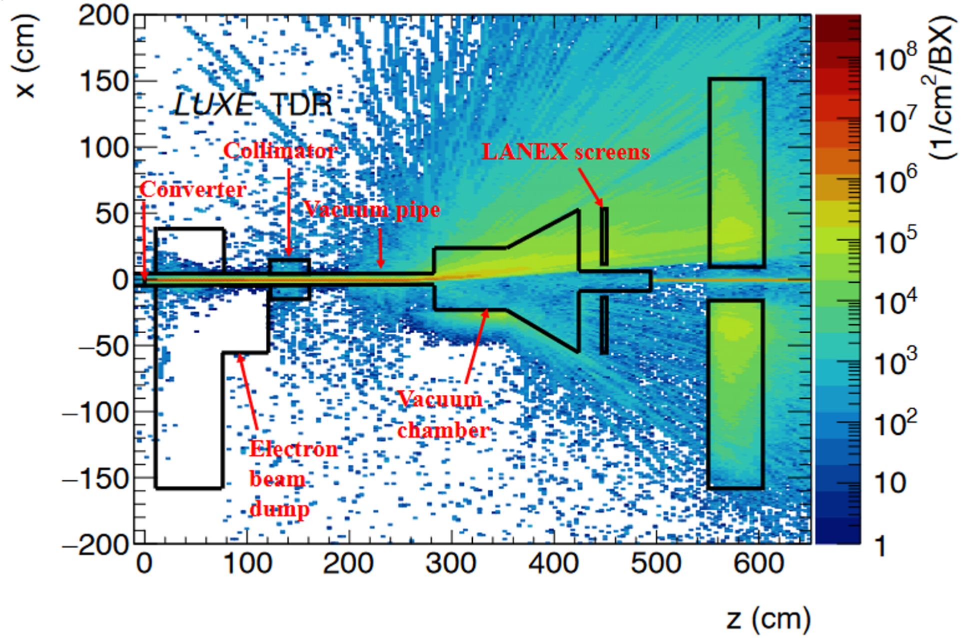
# Overview of photon detectors

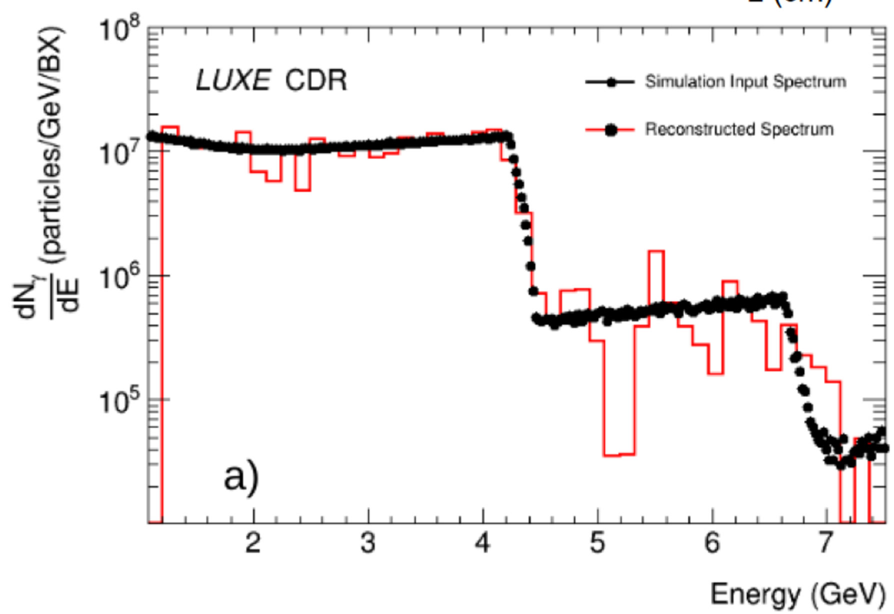
- Want to measure *$10^9$* photons summing up to TeV energies.
- Have three complementary systems:
  - Gamma-ray spectrometer where a fraction are converted to $e^+e^-$ pairs.
  - Gamma-ray profiler which uses radiation-hard sapphire.
  - Gamma-flux monitor which relies on backscattering from photon dump.



# Gamma-ray spectrometer

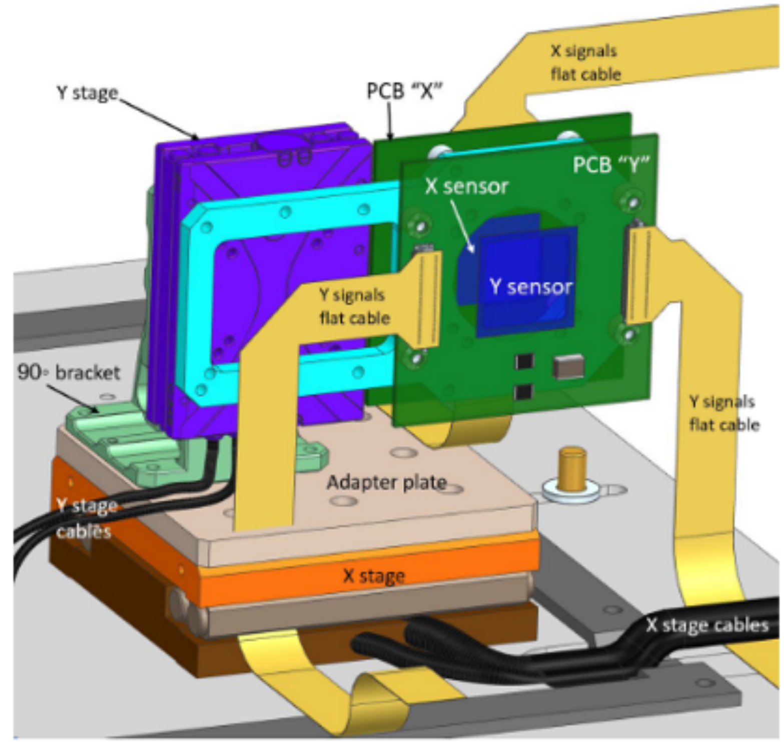
- Aim: to measure photon spectrum.
  - Measure $e^+e^-$ pairs after photons pass through target.
  - Spectrometer with scintillation screens and CCD cameras.
  - Good energy resolution ($\delta E/E < 2\%$).
  - Non-invasive (>*99%* photons propagate through).

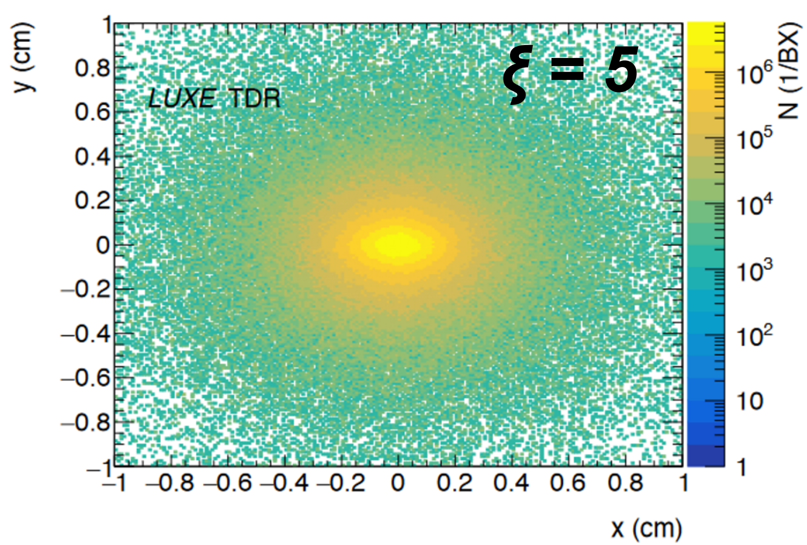


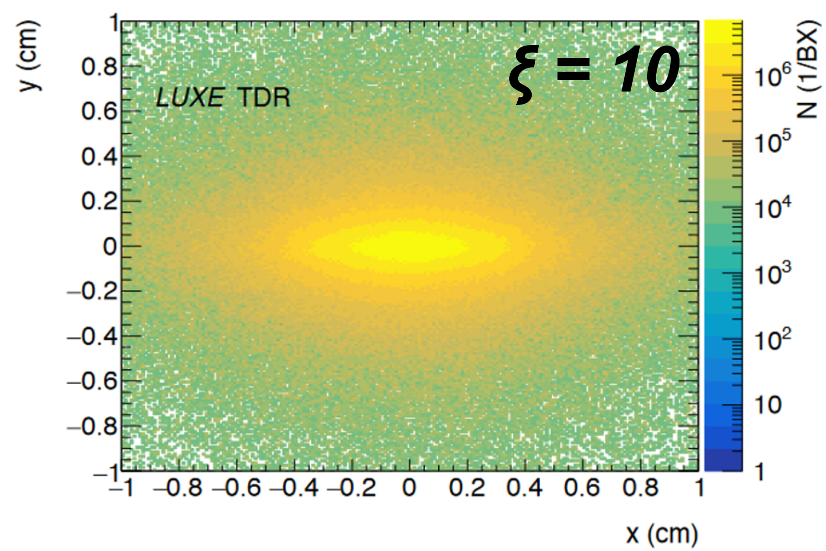



# Gamma-ray profiler

- Two sapphire strip detectors movable with micron precision perpendicular to beam.
  - Photon beam location and shape
  - Precision measurement of laser intensity.
- Two detectors 2 × 2 cm² (100 μm thick) with 100 μm strip pitch should guarantee <5% precision in laser intensity.

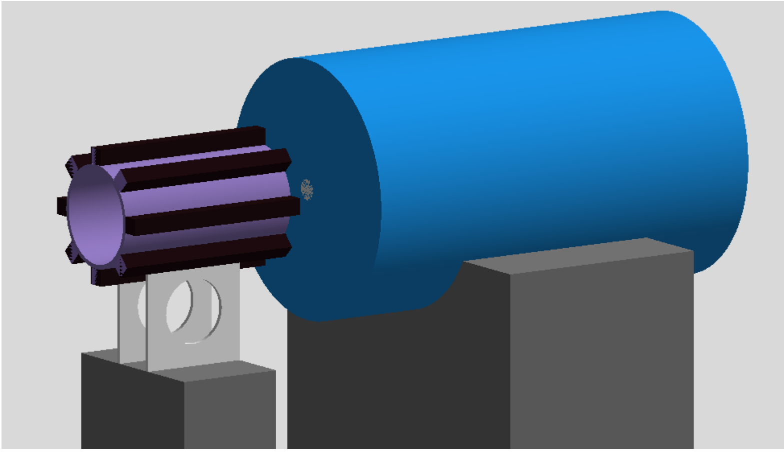


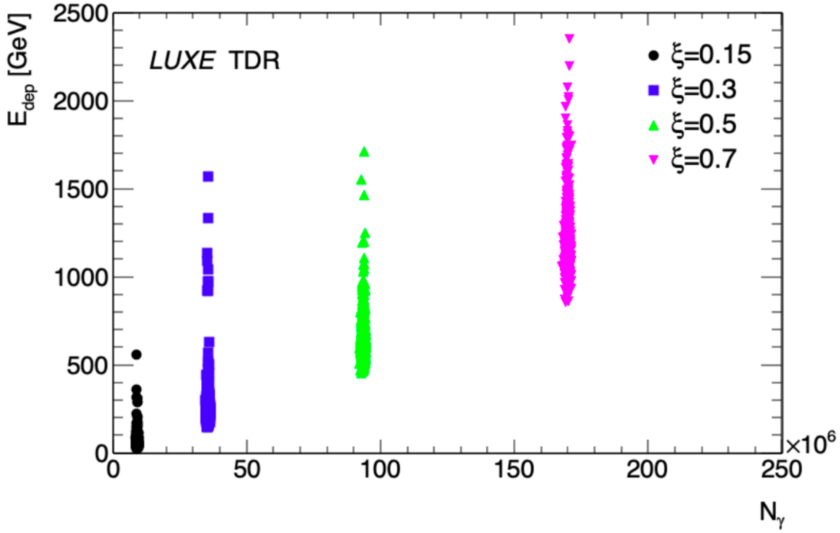



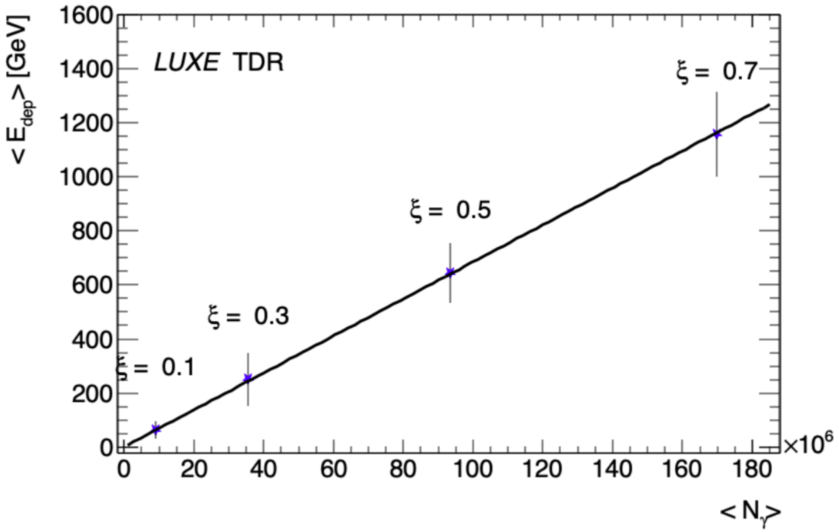



# Gamma flux monitor

- Measure energy flow of particles back-scattered from photon beam dump.
- Gamma flux monitor:
  - Consists of lead glass blocks, *3.8 × 3.8 × 45 cm³*.
  - Beam tests ongoing at FLASHForward.





# Systematic uncertainties — particle detection

- 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 $\xi$.
- 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 ~ 1%.
  - Alignment of < *50 μm* results in < 0.5% uncertainty.