The LUXE experiment and prospects for Super-LUXE at FCC-ee

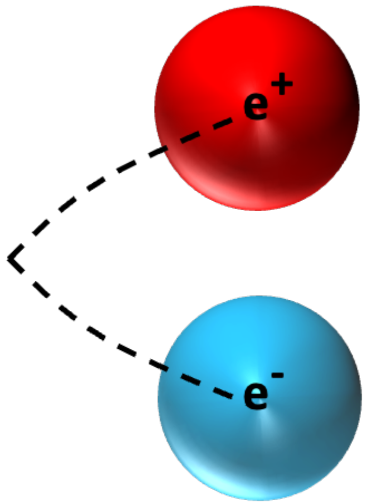
Matthew Wing
and the LUXE collaboration

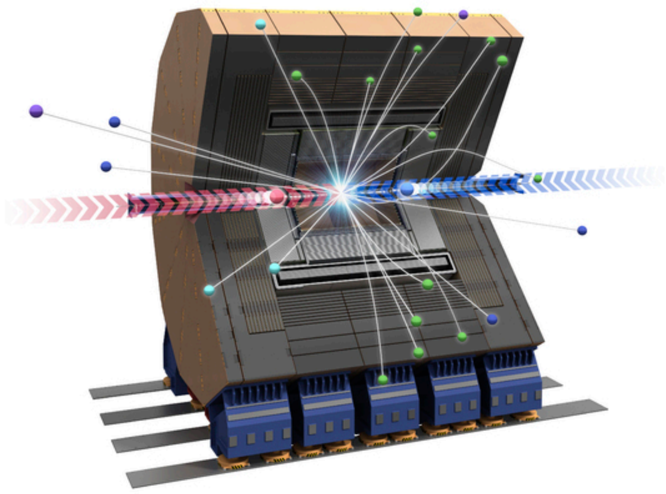
- Strong-field QED
- LUXE experiment
- LUXE physics expectations
- And “LUXE” at new facilities
- Summary

Non-collider science opportunities at FCC-ee — 23 August 2024

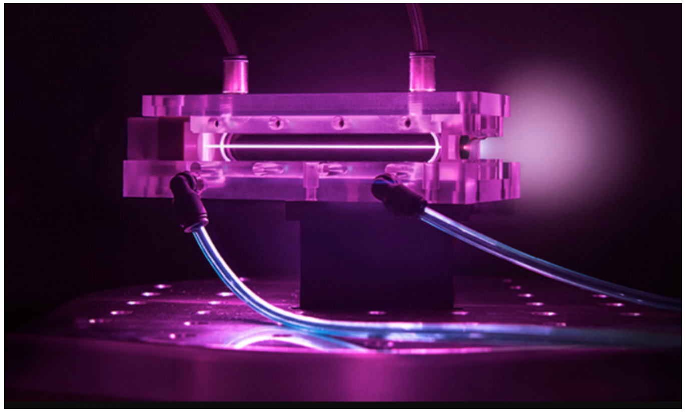
Why do we care about strong-field QED ?

Fundamental science

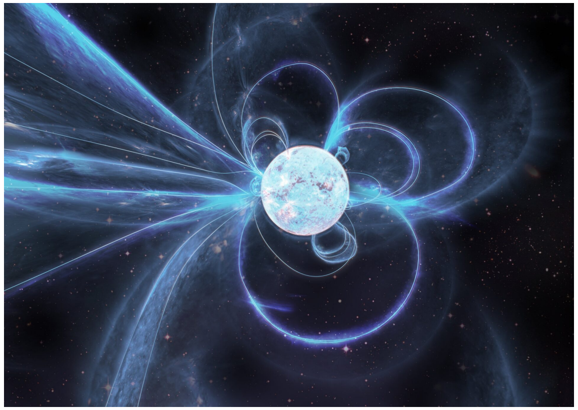




Higgs factories

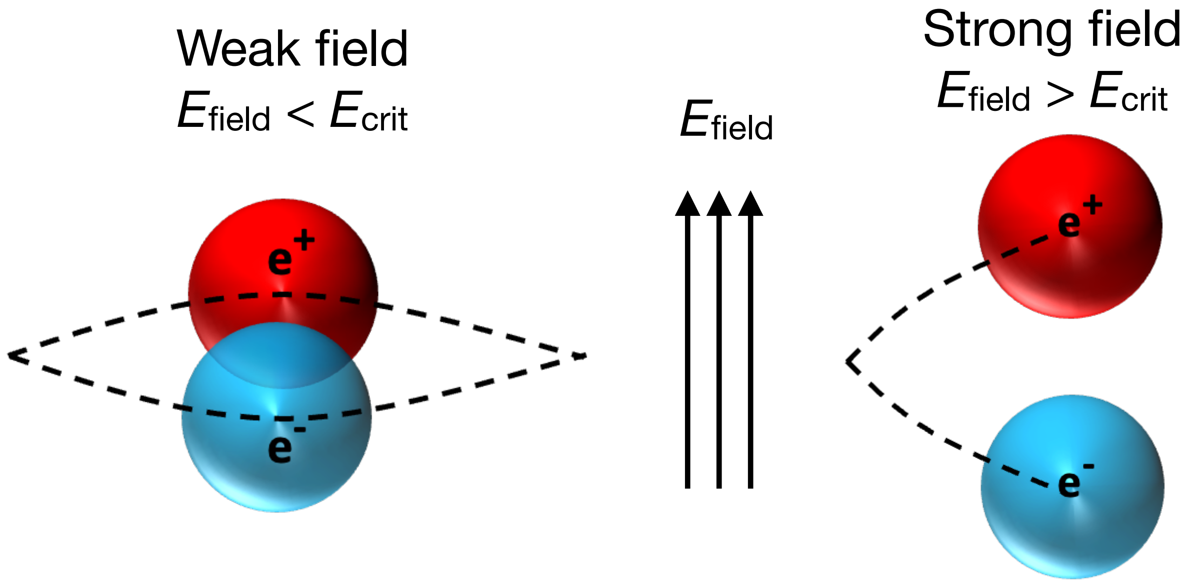


Laser physics and novel accelerators



Neutron stars, black holes, etc.

Introduction: Strong-field QED



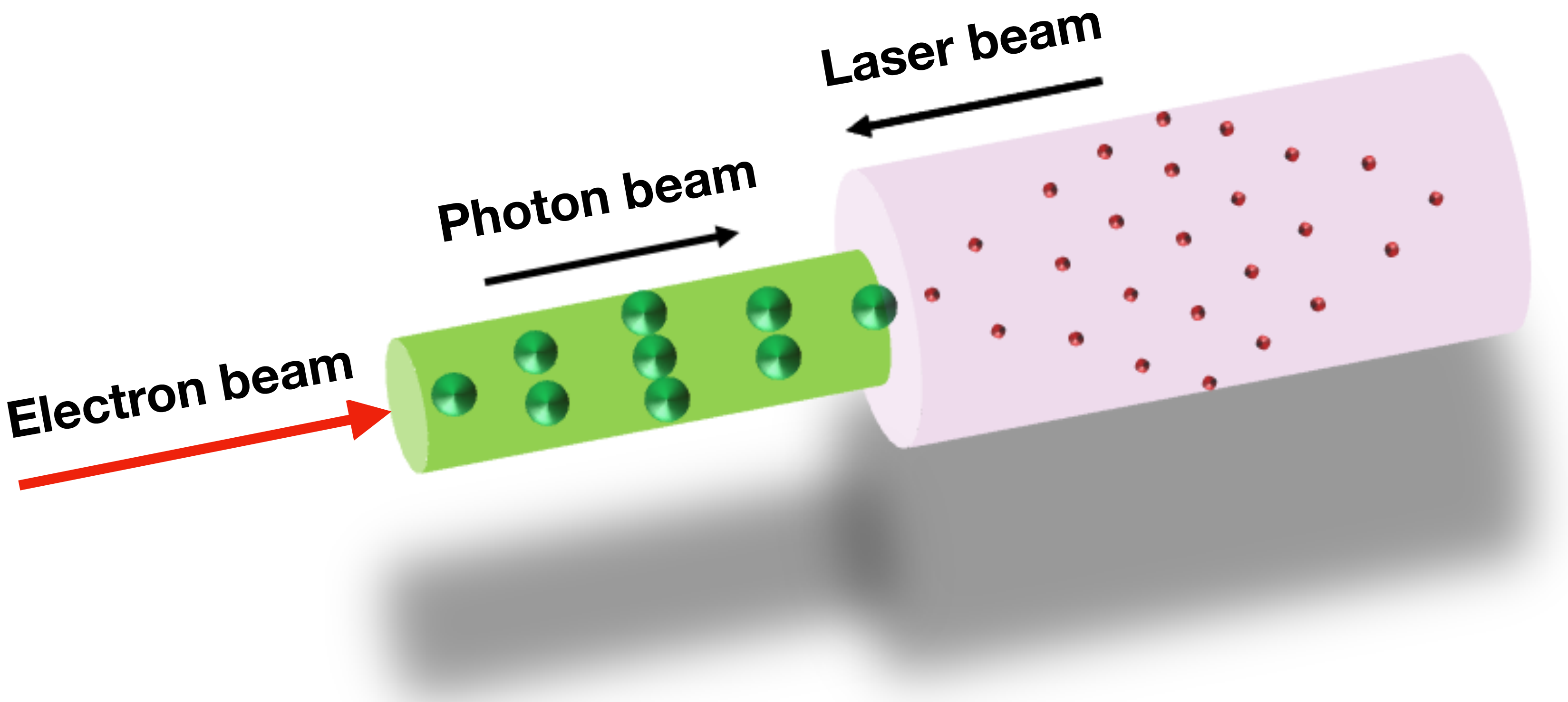
Critical field or Schwinger limit:

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

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

Introduction: Strong-field QED

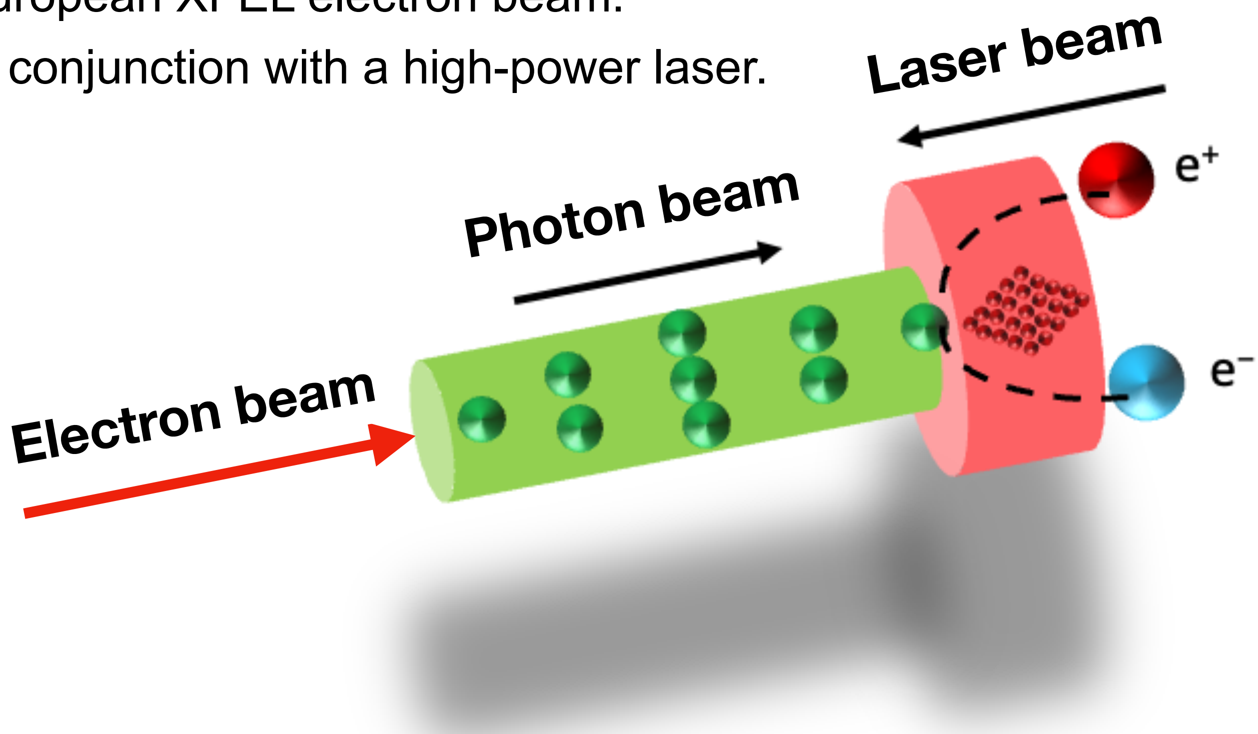
Laboratory frame



- Critical field can be reached with relativistic length contraction.

Introduction: Strong-field QED

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

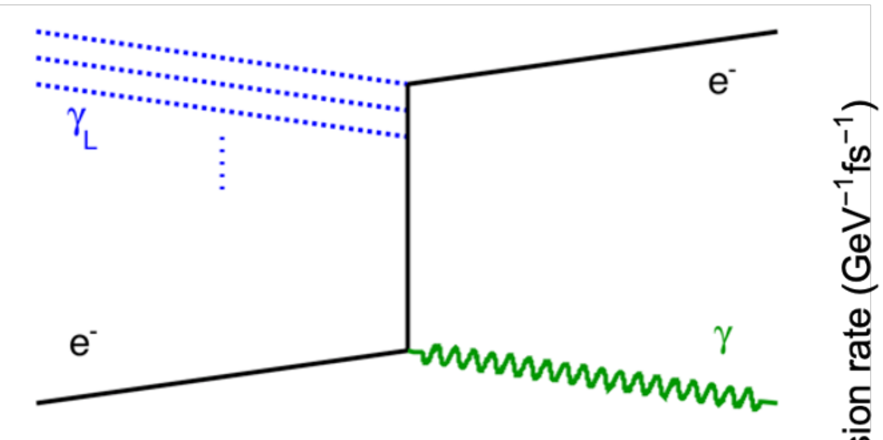


Boosted frame

- Critical field can be reached with relativistic length contraction.

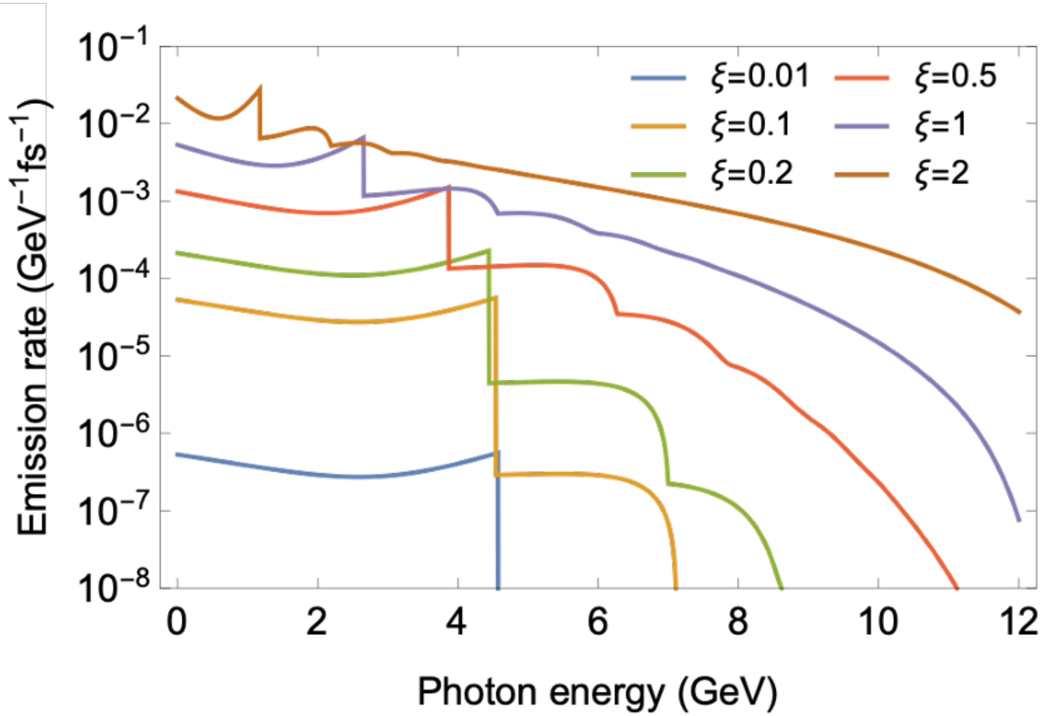
- Investigate QED in new parameter space
  - E.g. transition to non-linear QED.
  - With high precision and control.

Non-linear Compton scattering



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

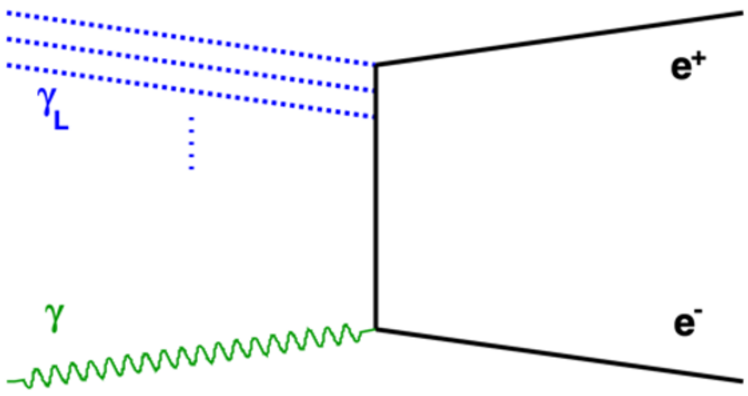
16.5 GeV electron, 800 nm laser, 17.2° crossing angle



In strong fields:

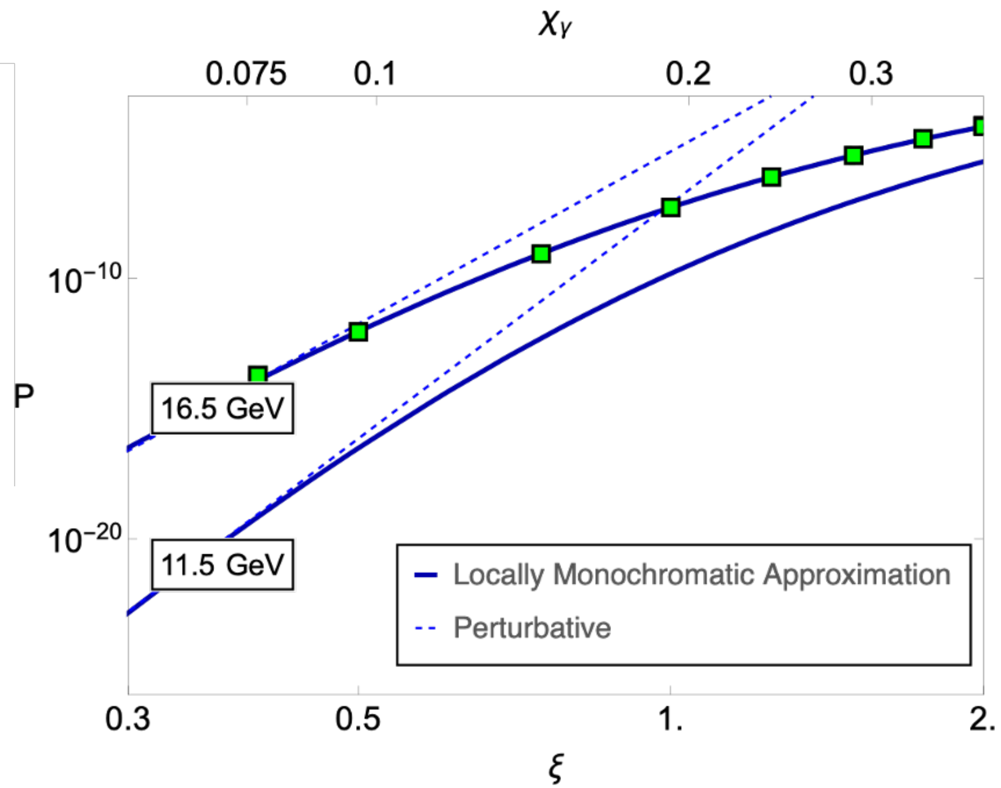
- Compton edge shifts as function of ξ (square root of laser intensity).
- Higher harmonics appear, i.e. interaction with n laser photons.

Non-linear Breit–Wheeler pair production



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

- Photon from Compton scattering or secondary beam.



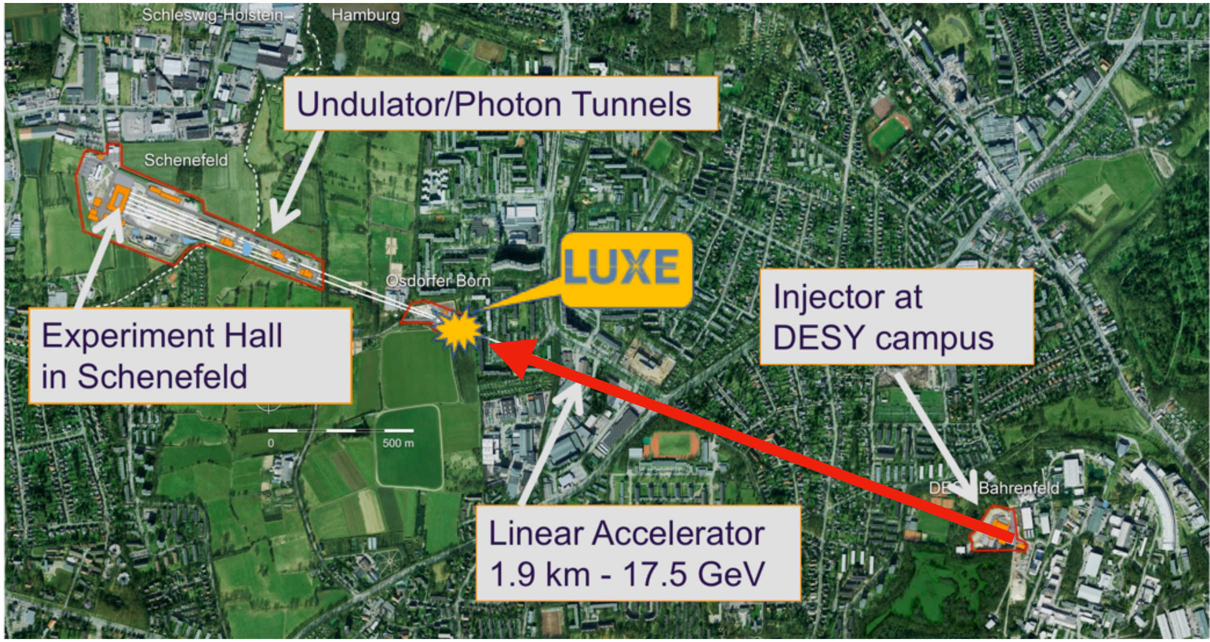
Perturbative regime: power law $\xi \ll 1 \quad : \quad R_{e^+} \propto \xi^{2n} \propto I^n$

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

LUXE at European XFEL

EuXFEL electron beam:

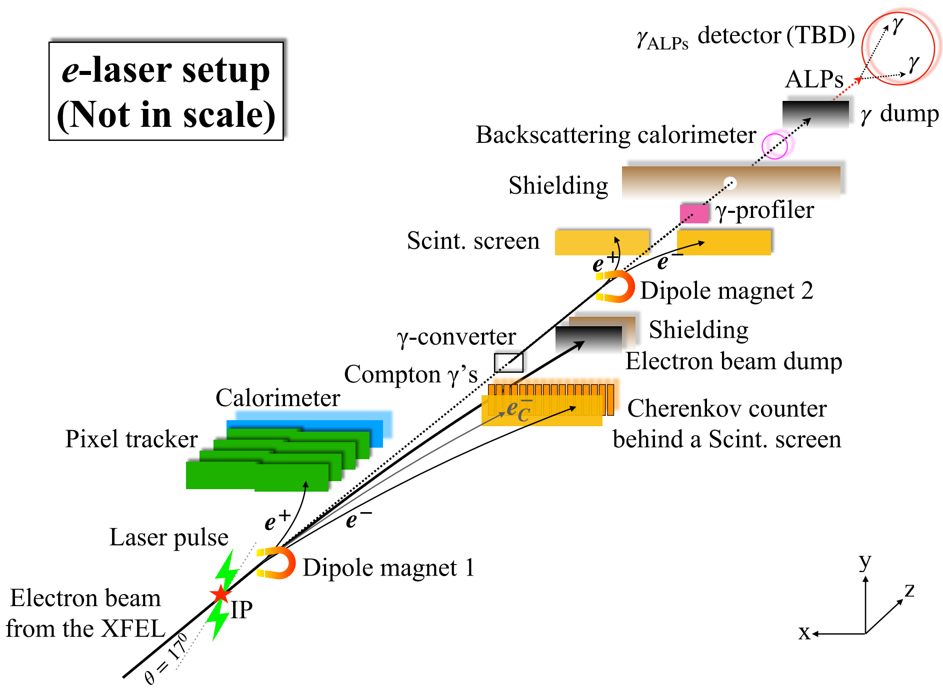
- Energy: *16.5 GeV*
- Bunch: *1.5 × 10⁹ e⁻*
- Repetition rate: *10 Hz*
- Use 1 of 2700 bunches per train
- Use electron beam before undulators
- Extract bunch to area planned for second fan
- No impact on photon science programme



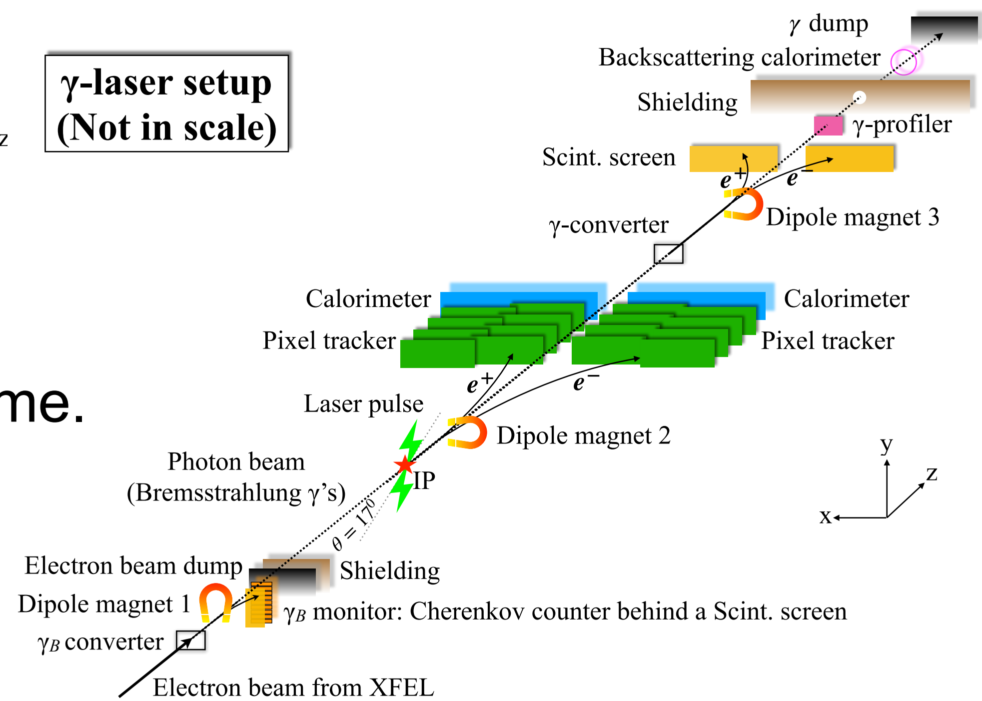
Laser parameters:

Wavelength (energy)	800 nm (1.55 eV)
Power	40 / 350 TW
Peak intensity	$13.3 / 120 \times 10^{19}$ W/cm^2
Peak intensity parameter ξ	7.9 / 23.6
Peak quantum parameter χ	1.5 / 4.5

Experiment layout



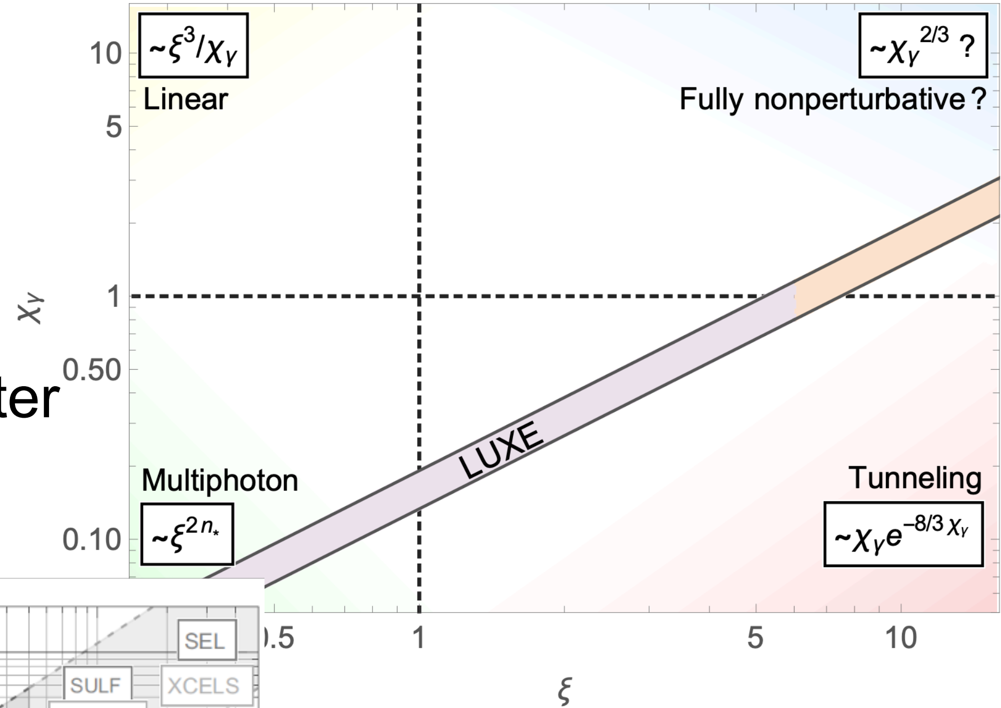
- Two data-taking modes:
  - Electron–laser collisions
  - Photon–laser collisions: unique to LUXE

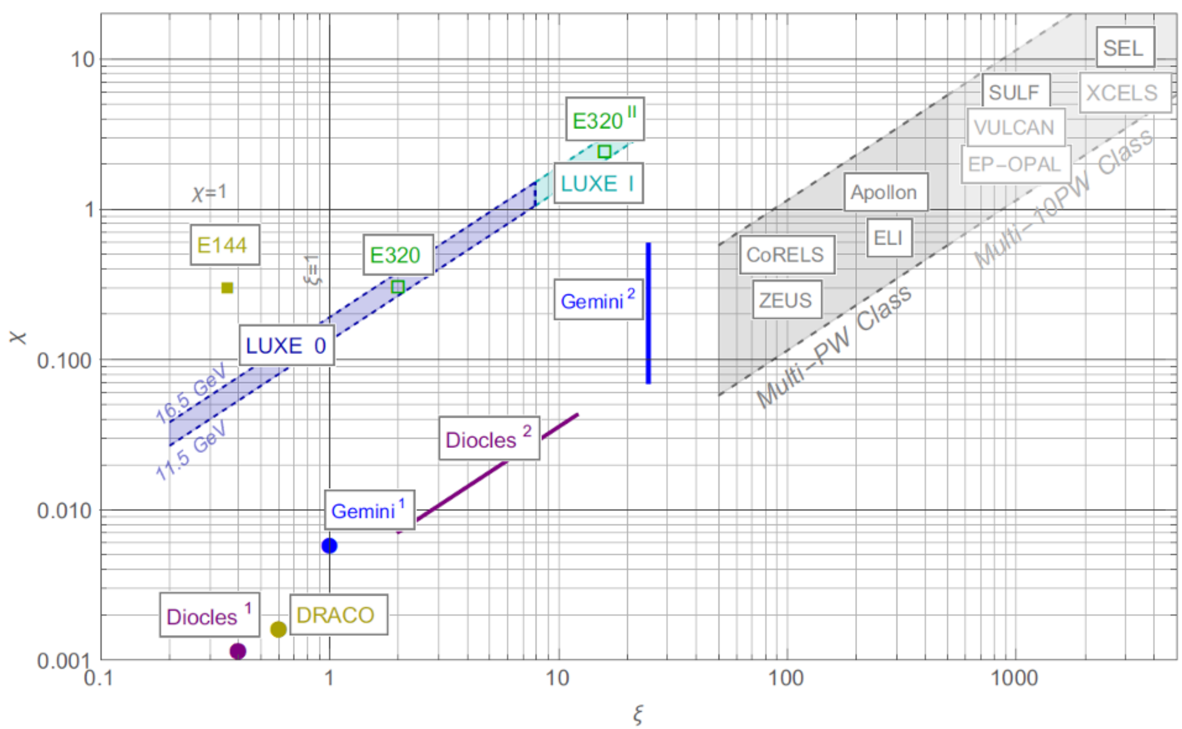


- Similar but different layouts.
- Many of the detectors are the same.
- Several challenges.

Strong-field QED parameter space

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

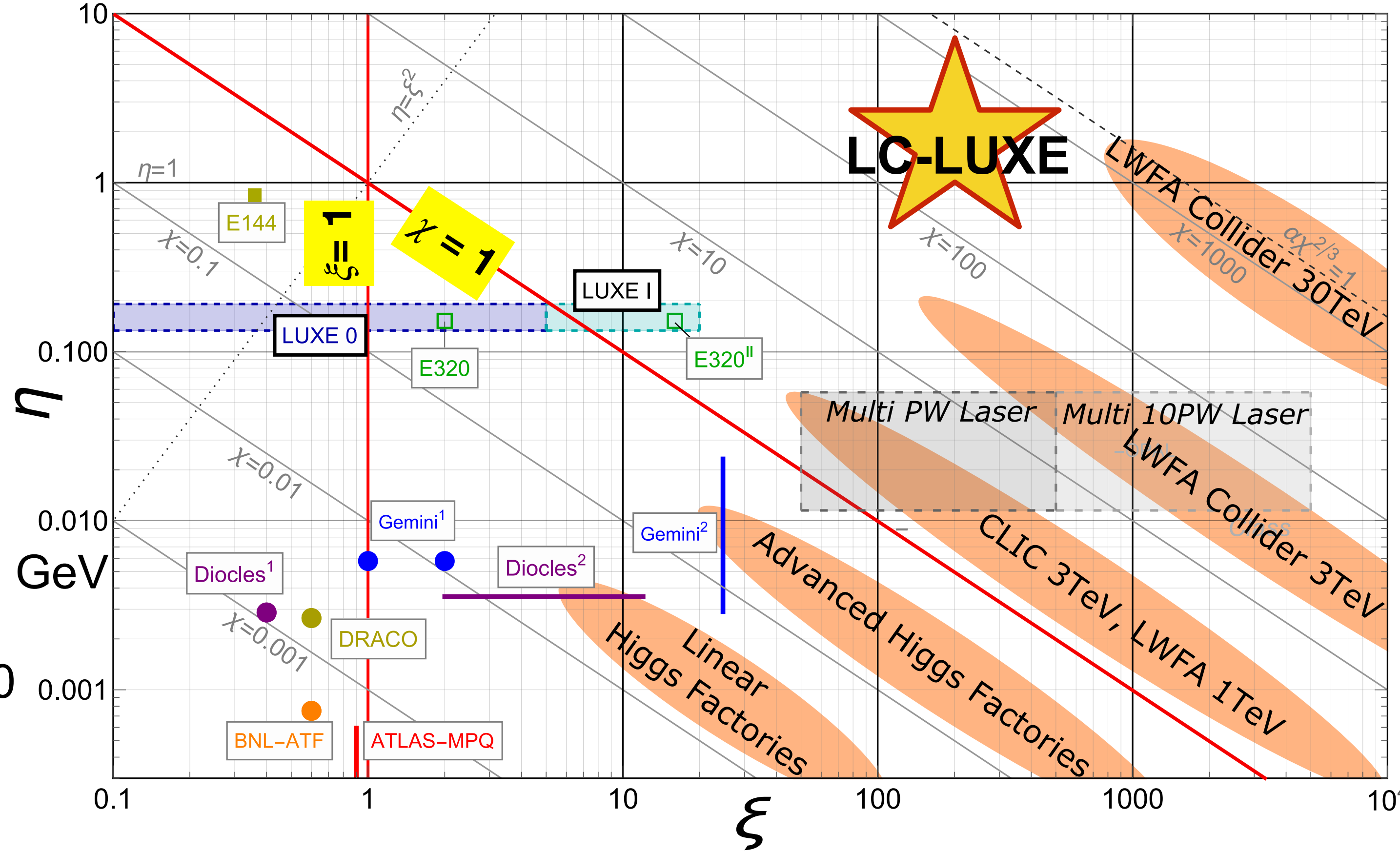




- E320: new experiment at SLAC.
- Gemini: laser wakefield experiments at RAL.
- ELI, etc. future high-power lasers.

LUXE at linear colliders: strong-field QED

$$\chi = \eta\xi$$



LC-LUXE:

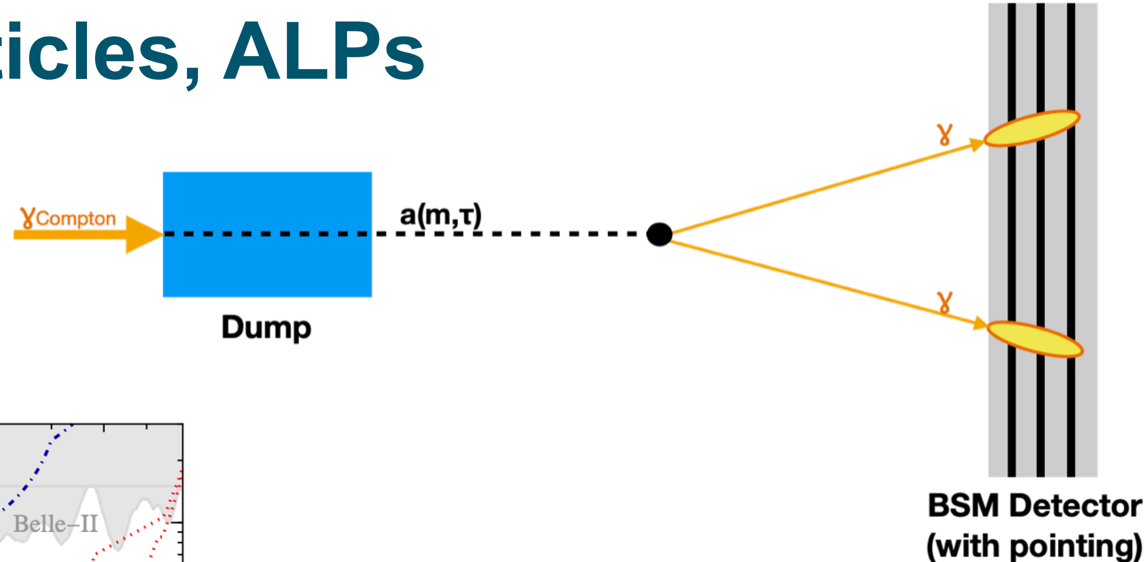
- 16.5 → 125 → 500 GeV means
- χ ~ 0.4 → 30 →120

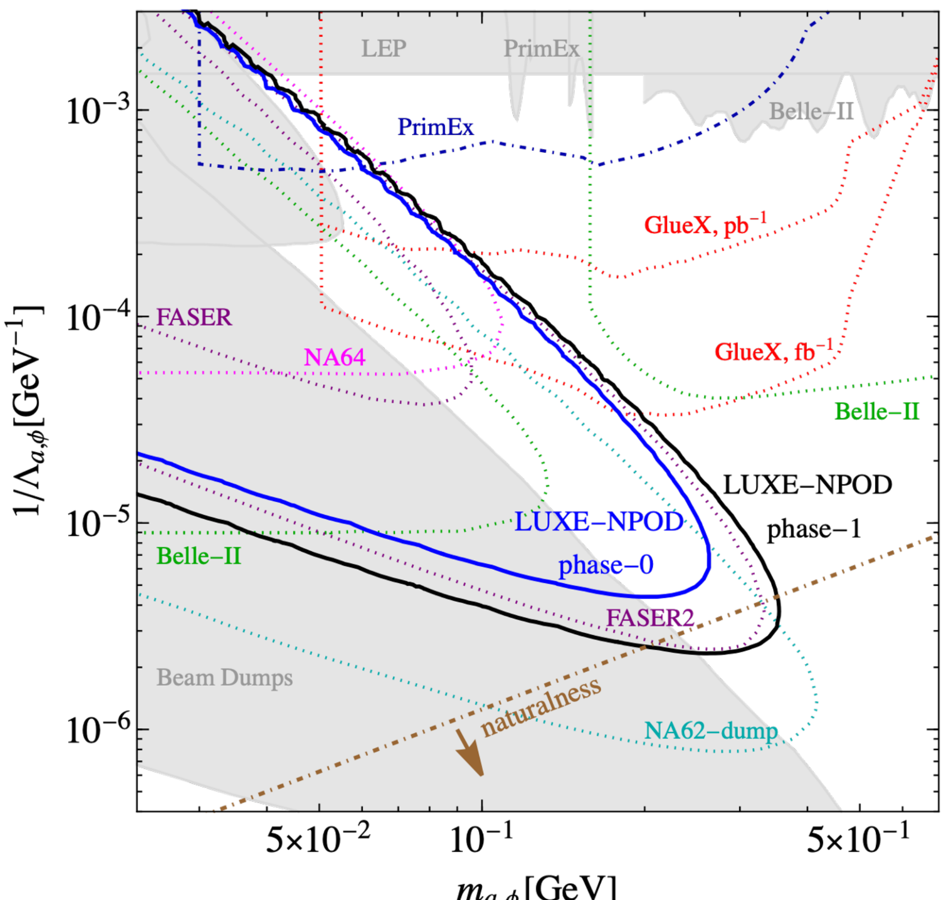
- Higher energy leads to extension in parameter space.
- FCC-ee electron energies would probe similarly high strong-field QED parameters.

J. List, talk at LCWS 2023

Search for new particles, ALPs

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



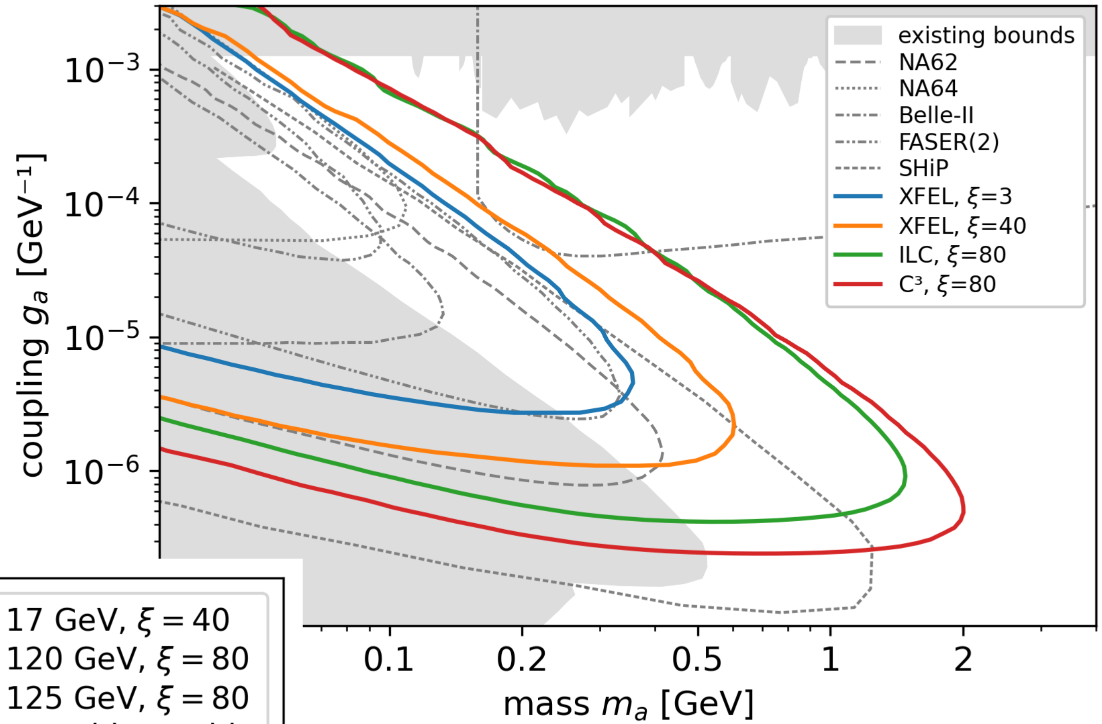


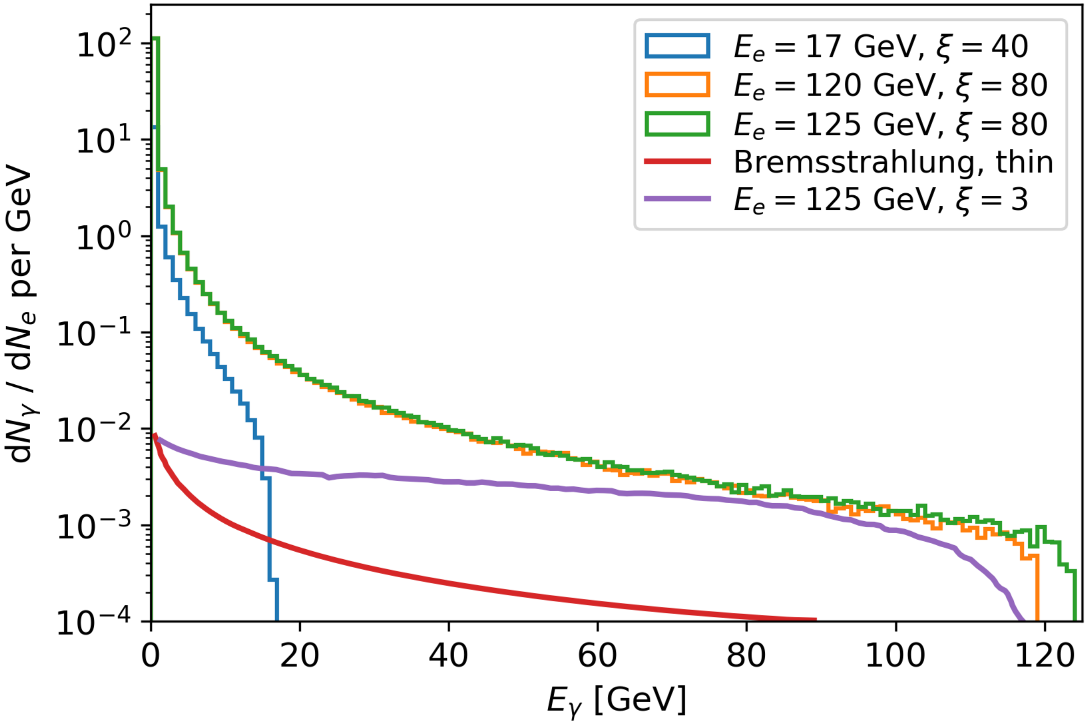
- Search for axion-like particles or milli-charged particles.
- High-flux photon beam offers great potential.
  - ➡ Sensitivity competitive with other experiments ongoing and planned.

LUXE-NPOD: Z. Bai et al., *Phys. Rev.* **D 106** (2022) 115034, arXiv:2107.13554.

Search at high-energy facilities

- Higher effective luminosity and higher beam energy extends sensitivity to ALPs.
- Also optimise laser intensity parameter.





Significant extension for linear collider facilities.

I. Schulthess, SLAC FPD seminar

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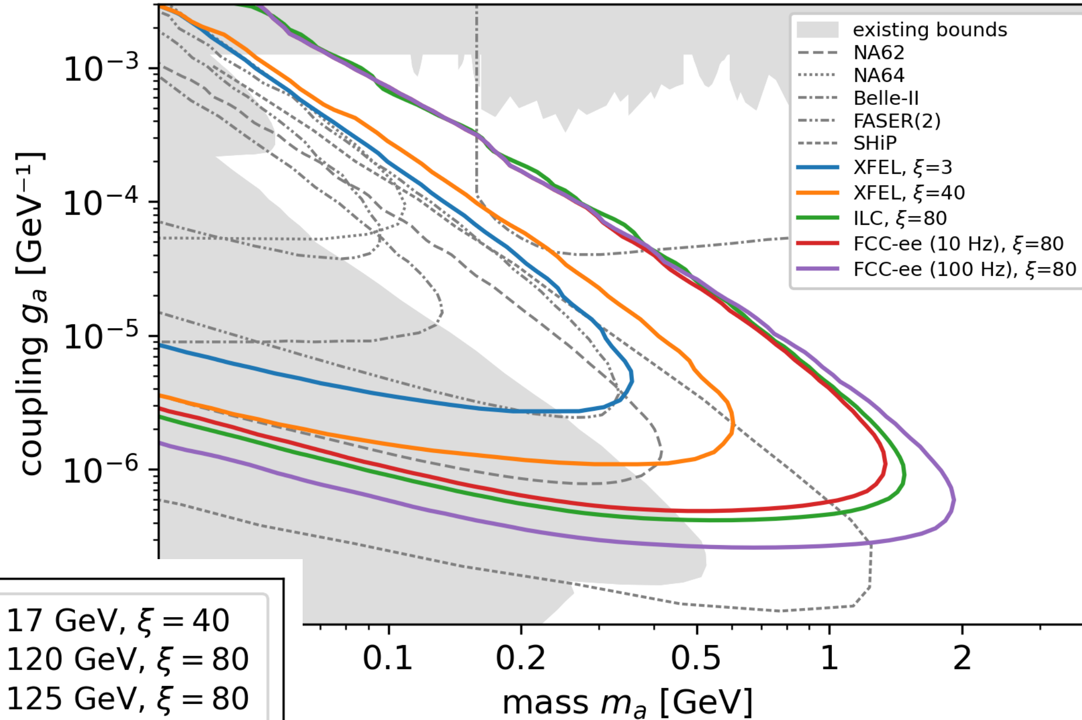
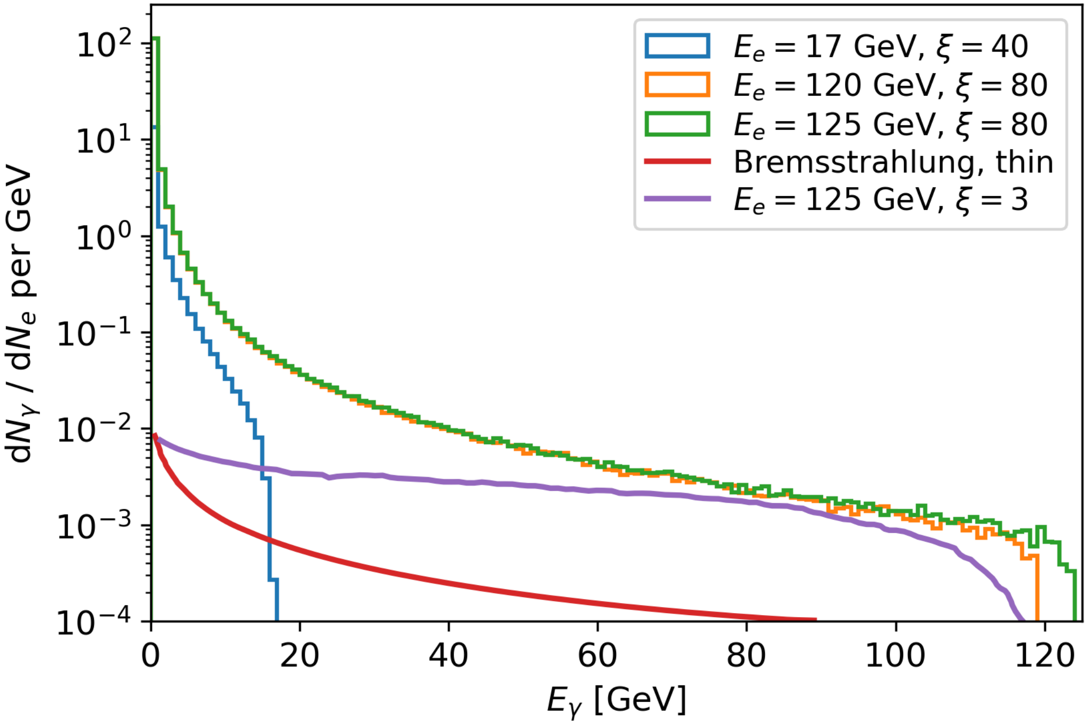




Significant extension for linear collider facilities.

I. Schulthess, SLAC FPD seminar

Summary

- **LUXE is an exciting new experiment to investigate QED in uncharted territory.**
  - High precision measurements — large samples, controlled systematics.
  - Measure over a broad range of quantum parameters, in particular the transition region to non-linear QED.
- **In principle future facilities with high-energy electron beams can incorporate a Super-LUXE into their design.**
  - FCC-ee can extend the strong-field QED parameters.
  - FCC-ee can extend the sensitivity to ALPs.
  - Some optimisation possible (?) for circulating beams.

LUXE TDR, arXiv:2308.00515,
to be published in EPJ-ST

Back-up

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 accepted by Eur. Phys. J.
- Experiment could be realised quite quickly.

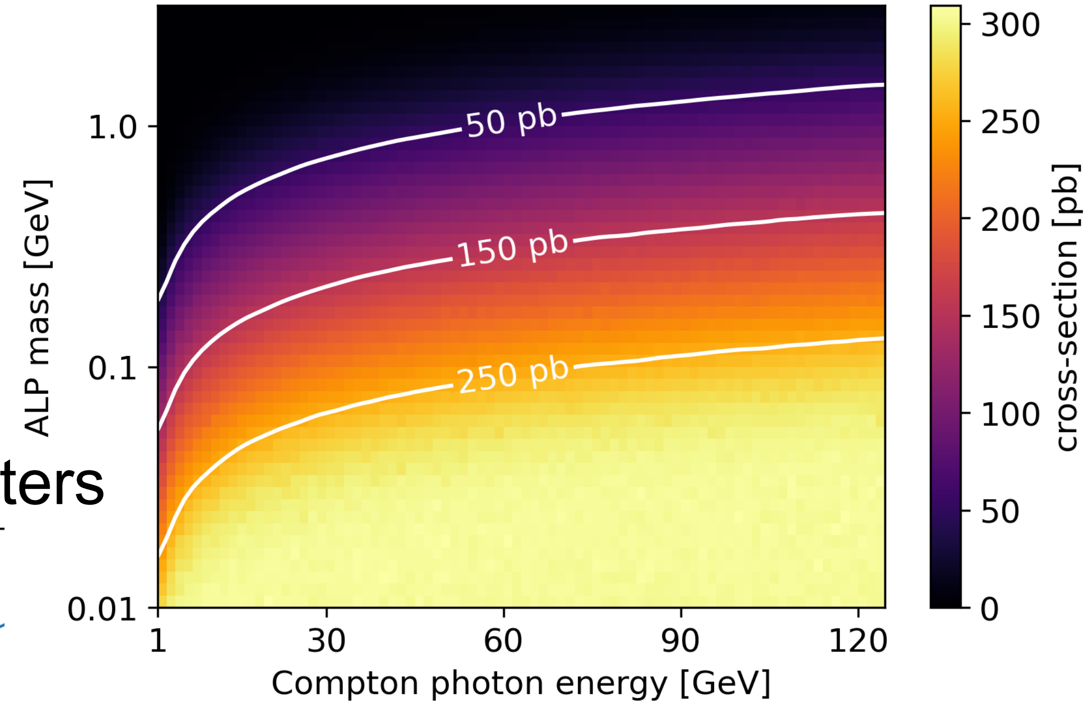
	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LUXE	Design & Approval			Installation (in EuXFEL shutdowns)			Operation			

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

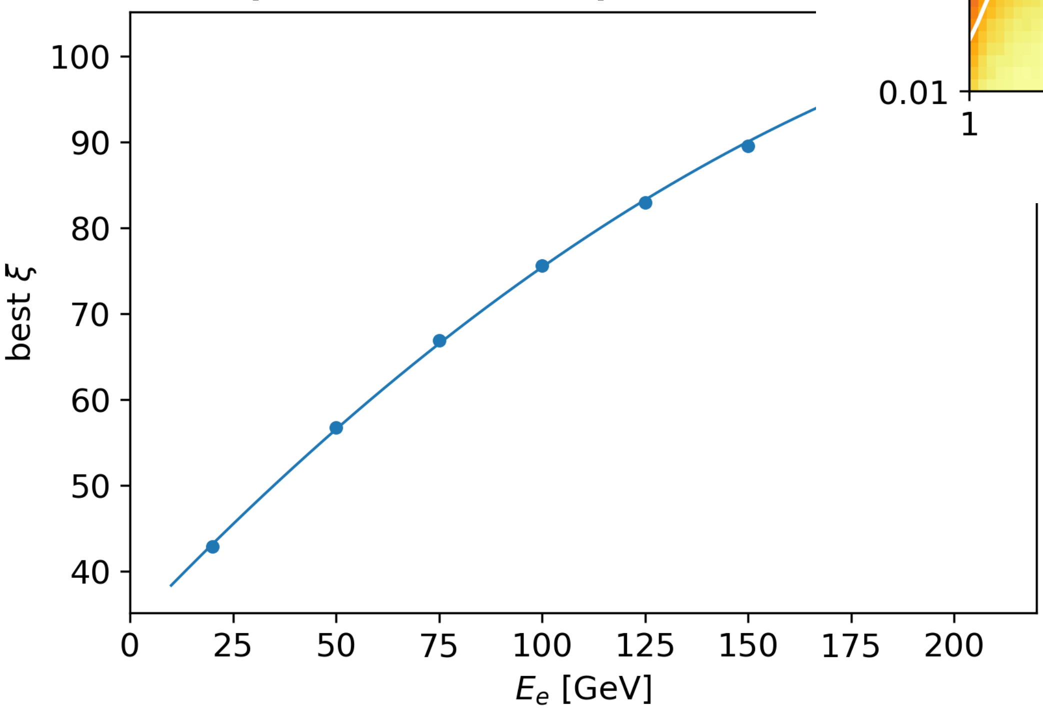
TDR: H. Abramowicz et al., arXiv:2308.00515.

https://luxe.desy.de

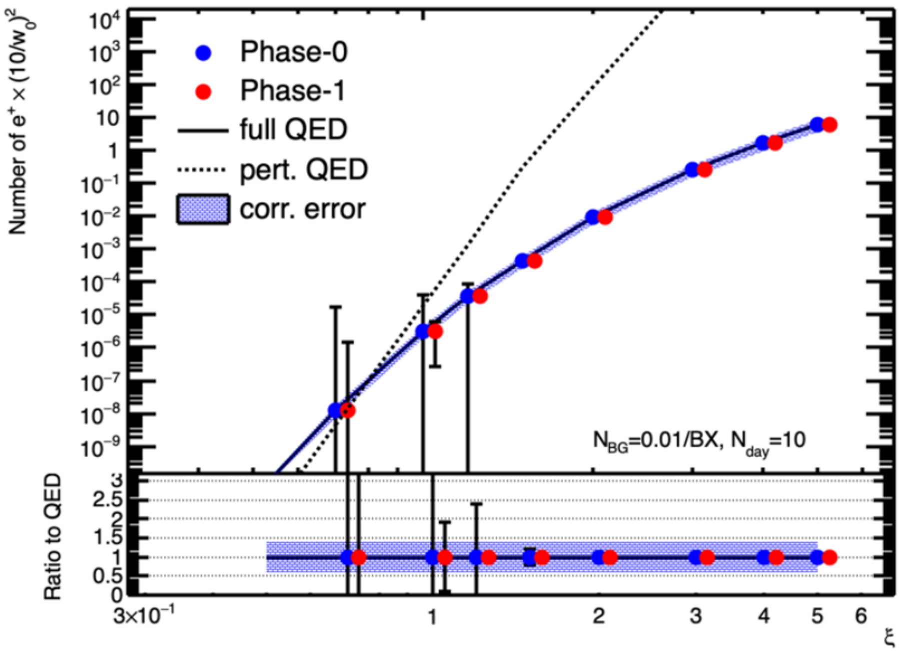
Production cross section

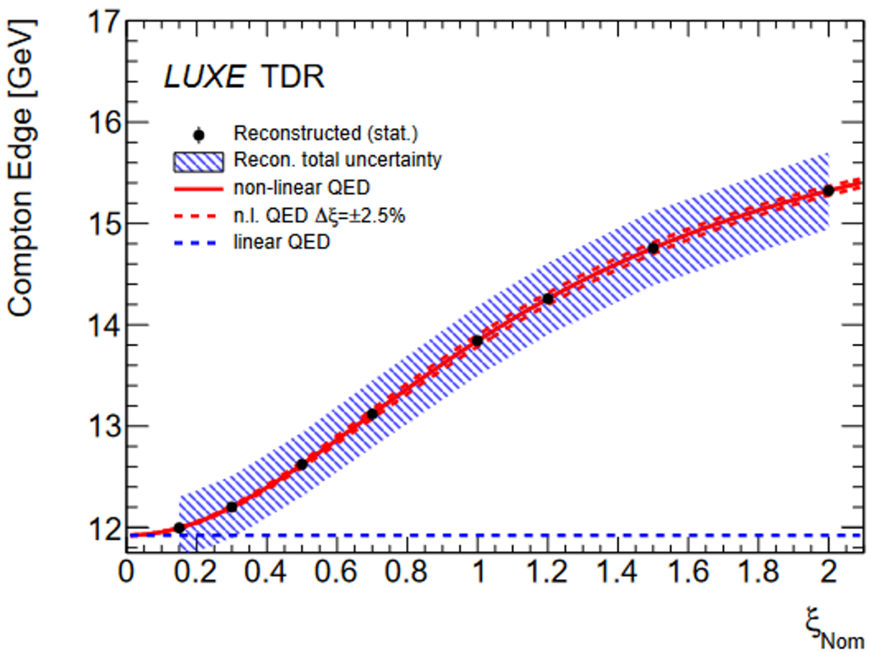


Optimal laser parameters



Expected results



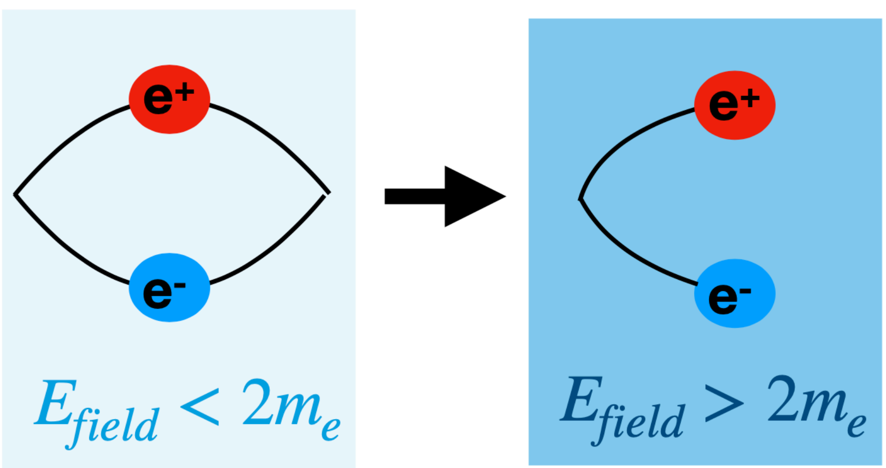


- Number of Breit–Wheeler pairs produced in γ–laser collisions.
- Assume 10 days of data taking and 0.01 background events/BX.
- 40% correlated uncertainty illustrates effect of uncertainty on ξ.

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

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.



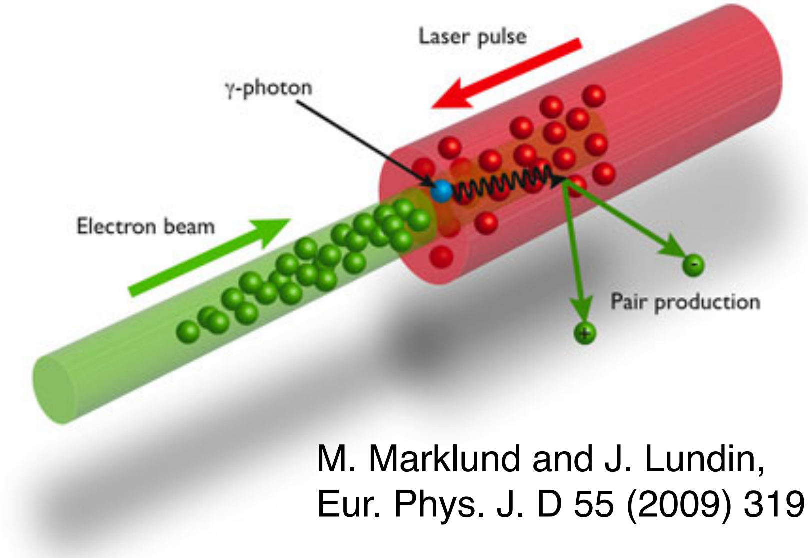
$$E_{crit} = \frac{mc^2}{e\lambda\!\!\!^{-}_C} = \frac{m^2c^3}{e\hbar}$$

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

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

Strong-field QED in the laboratory

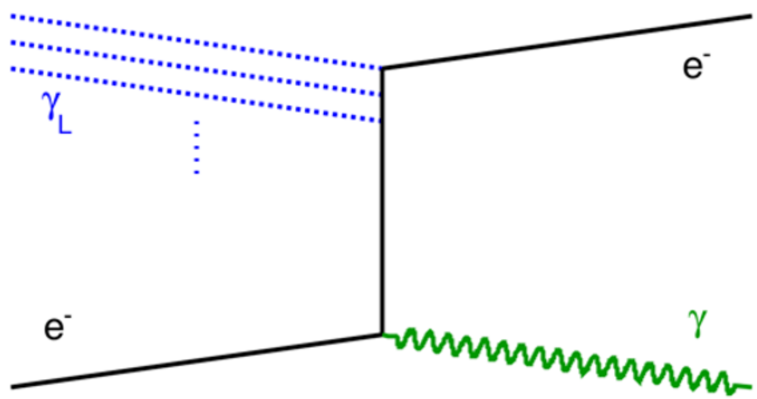
- Existing fields, e.g. lasers, orders of magnitude too small compared to E_{crit}.
- But non-linear quantum effects observable with relativistic probes.
  - Fields $O(E_{crit})$ in particle rest frame



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

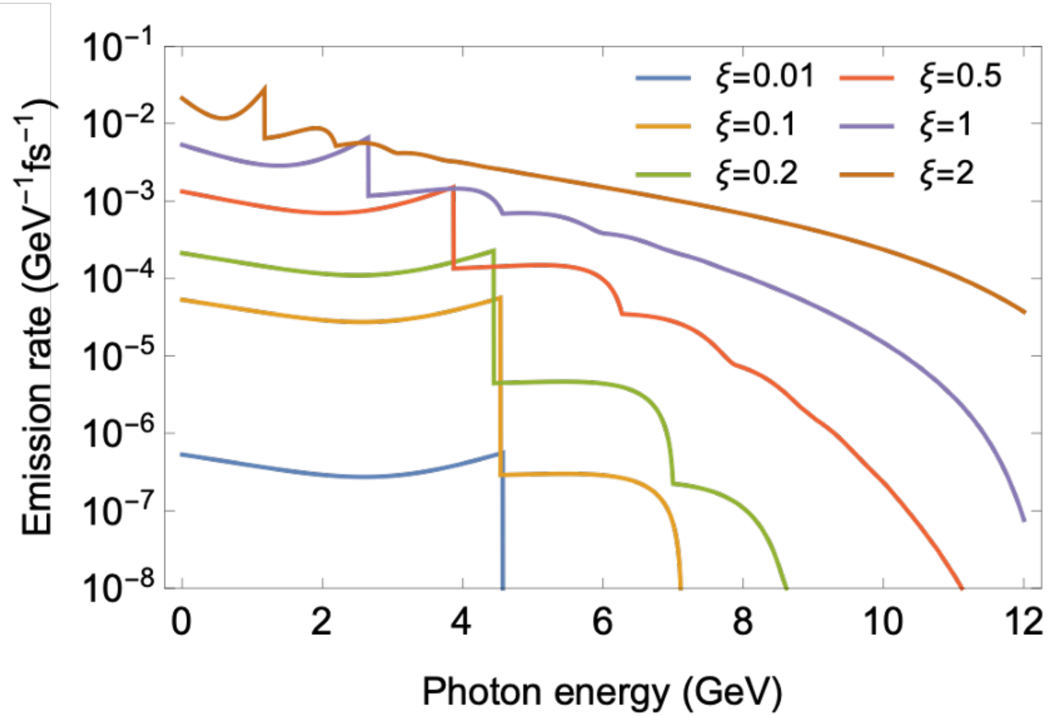
- In the laboratory, reach fields at Schwinger limit in the rest frame of highly relativistic particles.
  - Use multi-GeV electrons and multi-TW laser.

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, $m_* = m_e\,(1+\xi^2)^{½}$

- Compton edge shifts as function of ξ (square root of laser intensity).
- 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: $$E_{\mathrm{edge}}(\xi) = E_e \frac{2n\eta}{1 + \xi^2}$$

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).
- $\xi \geq 1$: 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.
- $\chi \geq 1$: non-linear quantum effects become probable (e.g. pair production).

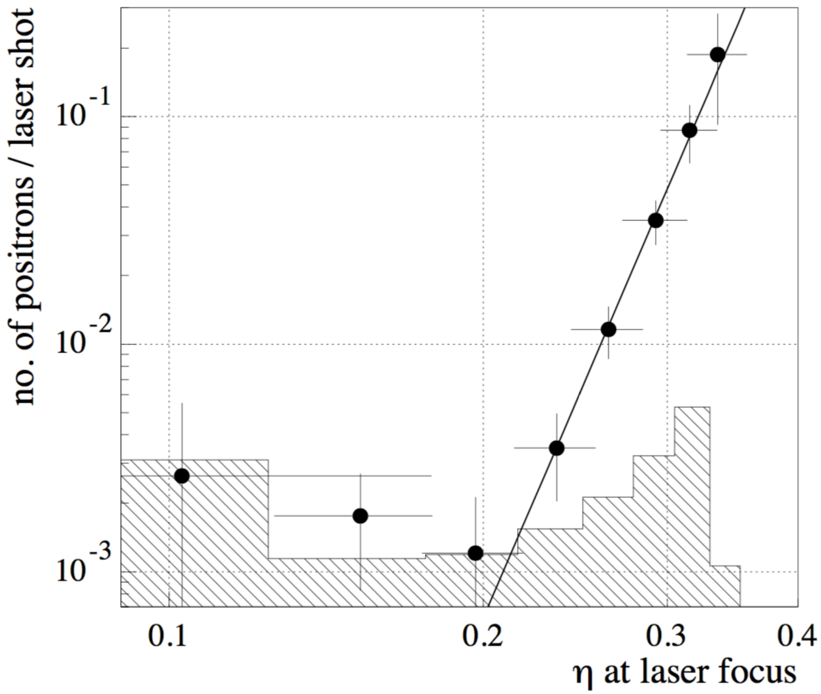
- Energy parameter:

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

E_L :	Laser field
E_{crit} :	Schwinger critical field
ω_L :	Laser frequency
θ :	e/γ – laser crossing angle
$E_{e/\gamma}$:	Probe electron/photon energy

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
  $e^- + n\gamma_L \rightarrow e^- + e^+ + e^-$
- Observed start of ξ^{2n} power law, but not departure from it.



$\eta \sim \xi$

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.

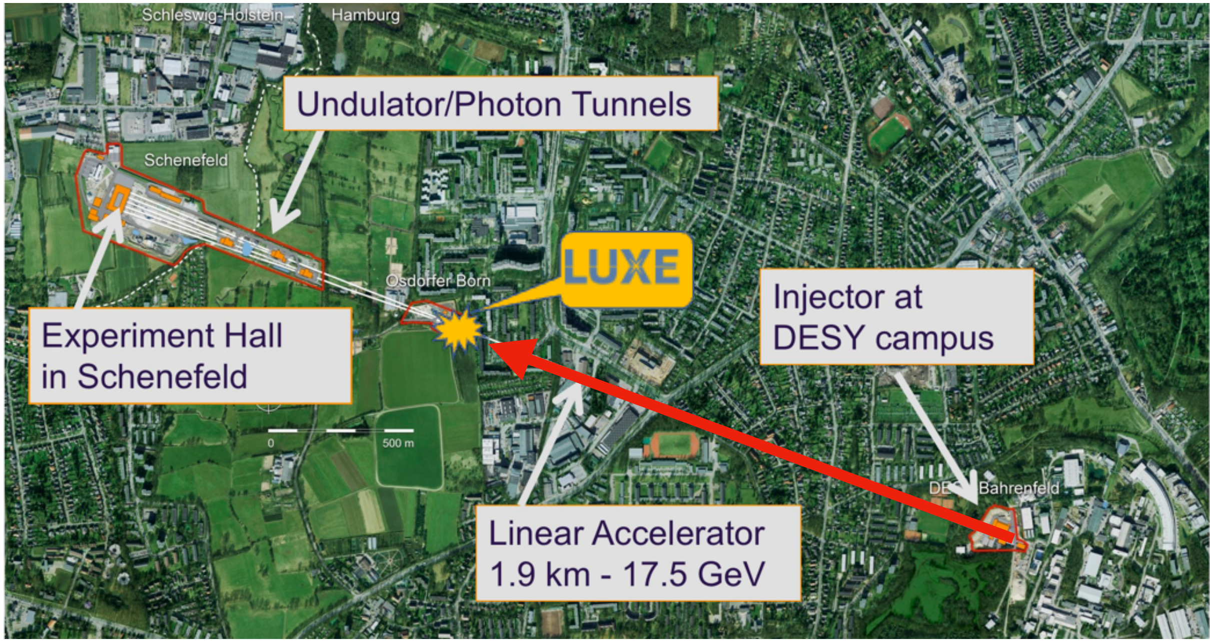
Data handling

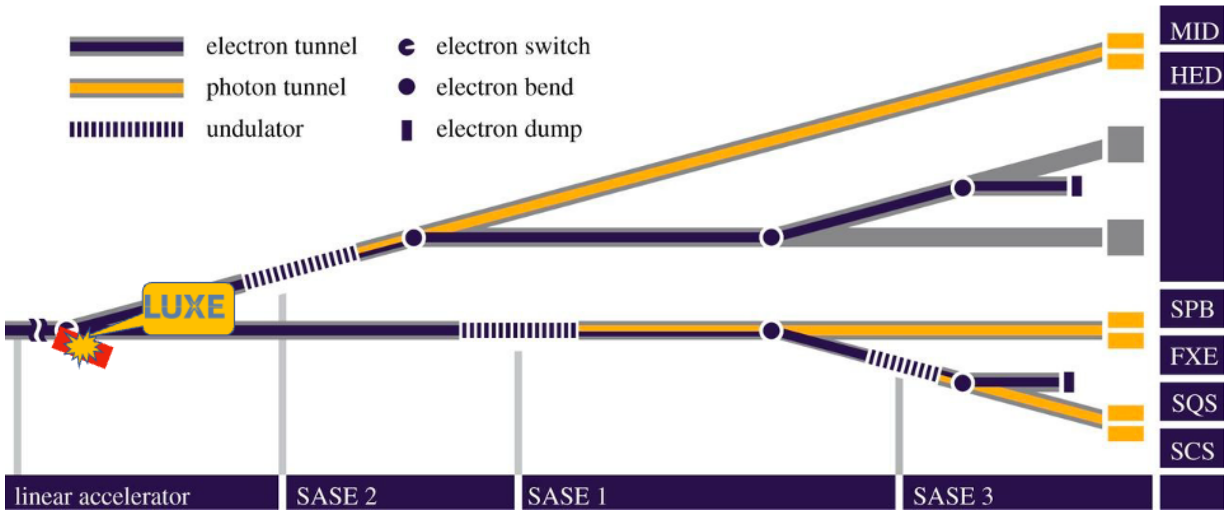
- Data handling should be “straightforward”: low frequency, modest rates.
  - Maximum data-taking frequency 10 Hz.
    - 1 Hz collision data, up to 9 Hz background.
  - Typical maximum rate per sub-detector O(10 MB/s).
- Need ~ 1 PC per sub-detector.
- All data is kept — no physics trigger.
- Should 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 at European XFEL

EuXFEL electron beam:

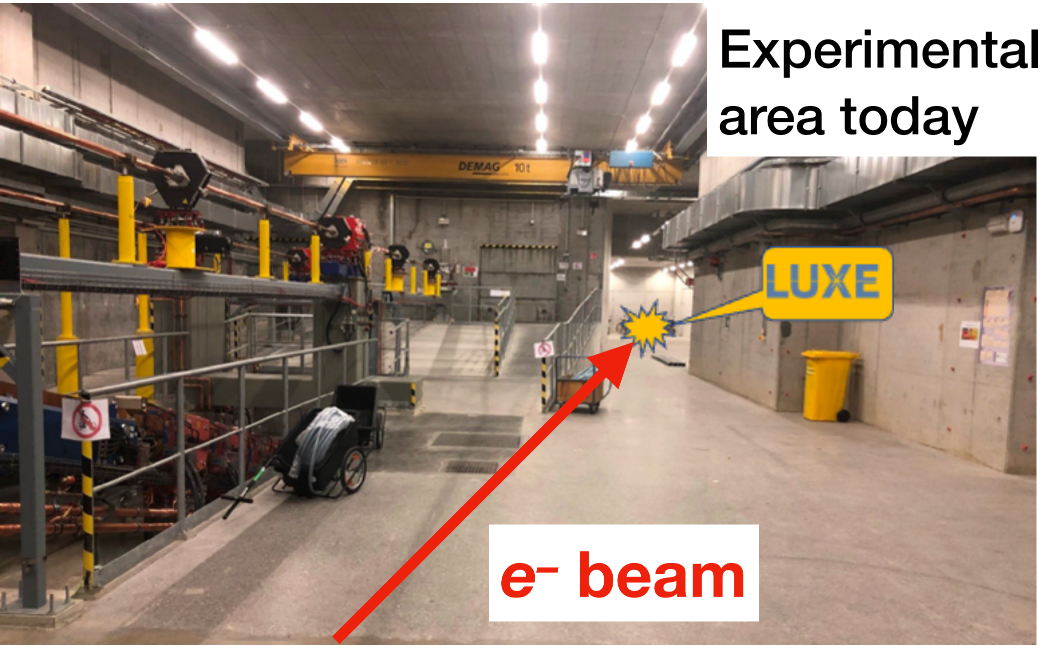
- Energy: *16.5 GeV*
- Bunch: *1.5 × 10⁹ e⁻*
- Repetition rate: *10 Hz*
- Use 1 of 2700 bunches per train



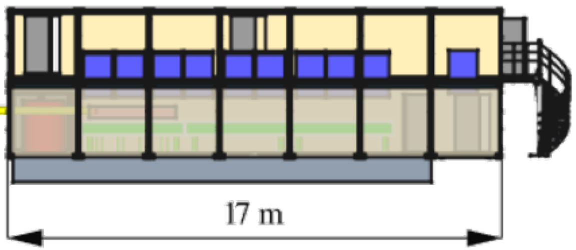


- Use electron beam before undulators
- Extract bunch to area planned for second fan
- No impact on photon science programme

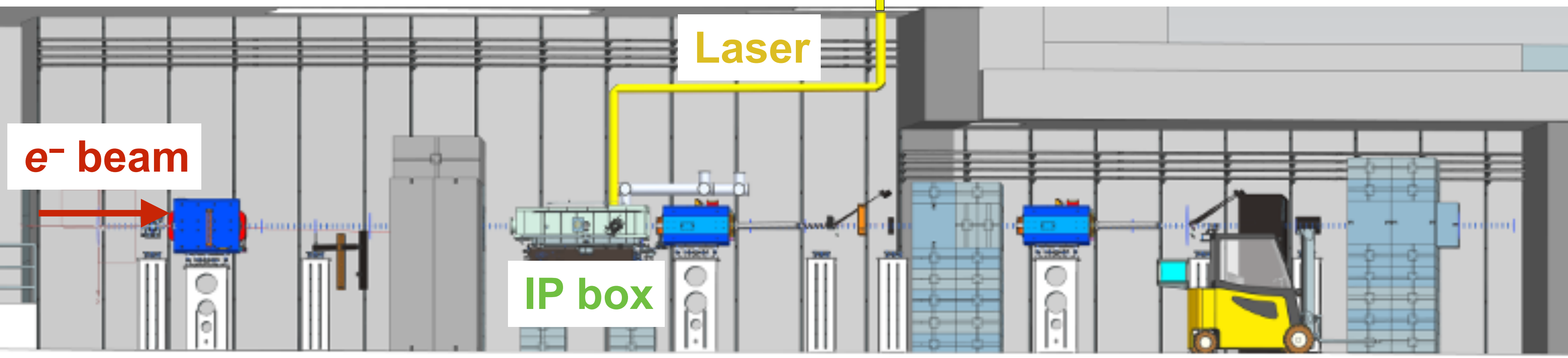
LUXE experimental area



Experimental area today



Laser room



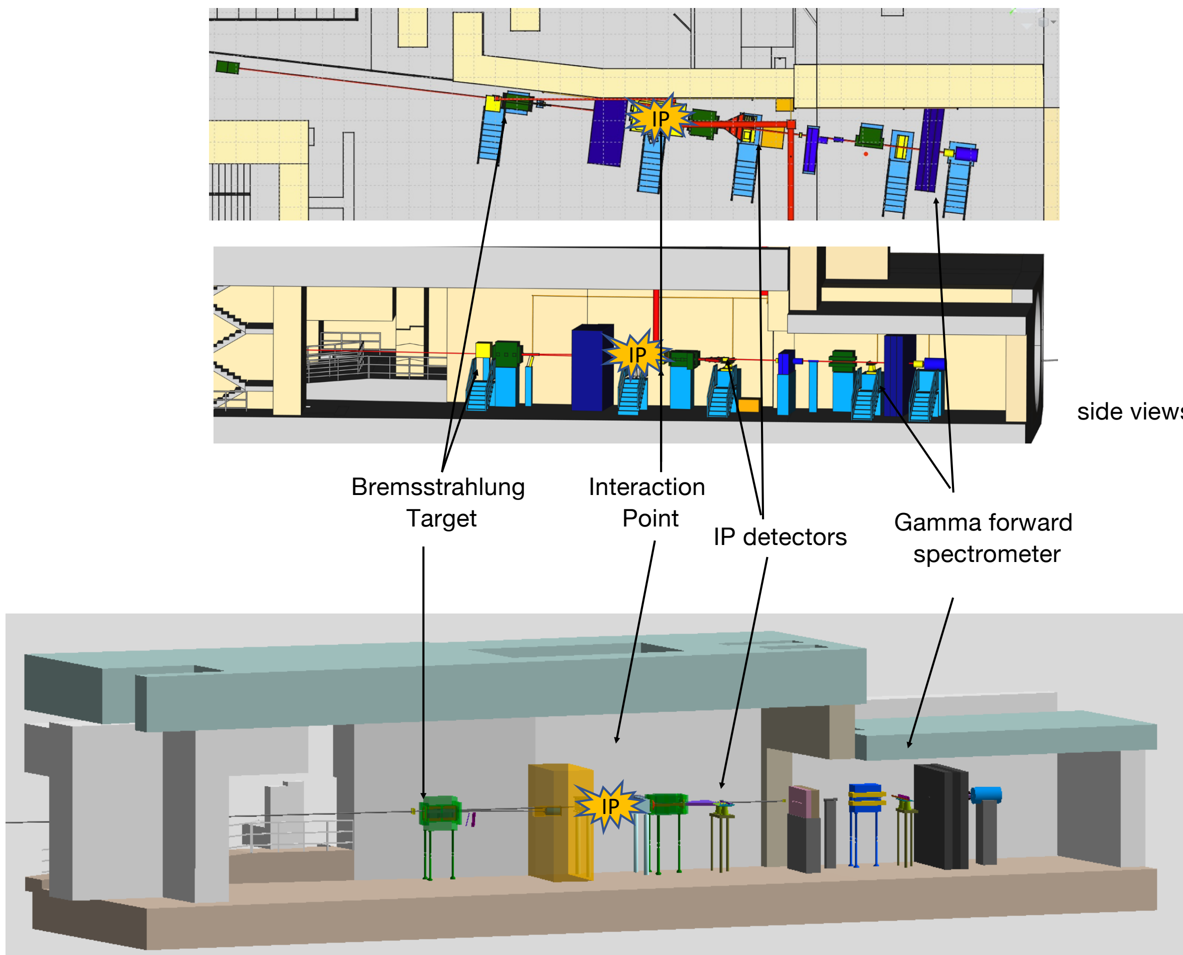
Layout — more engineering-like

top view of experimental area

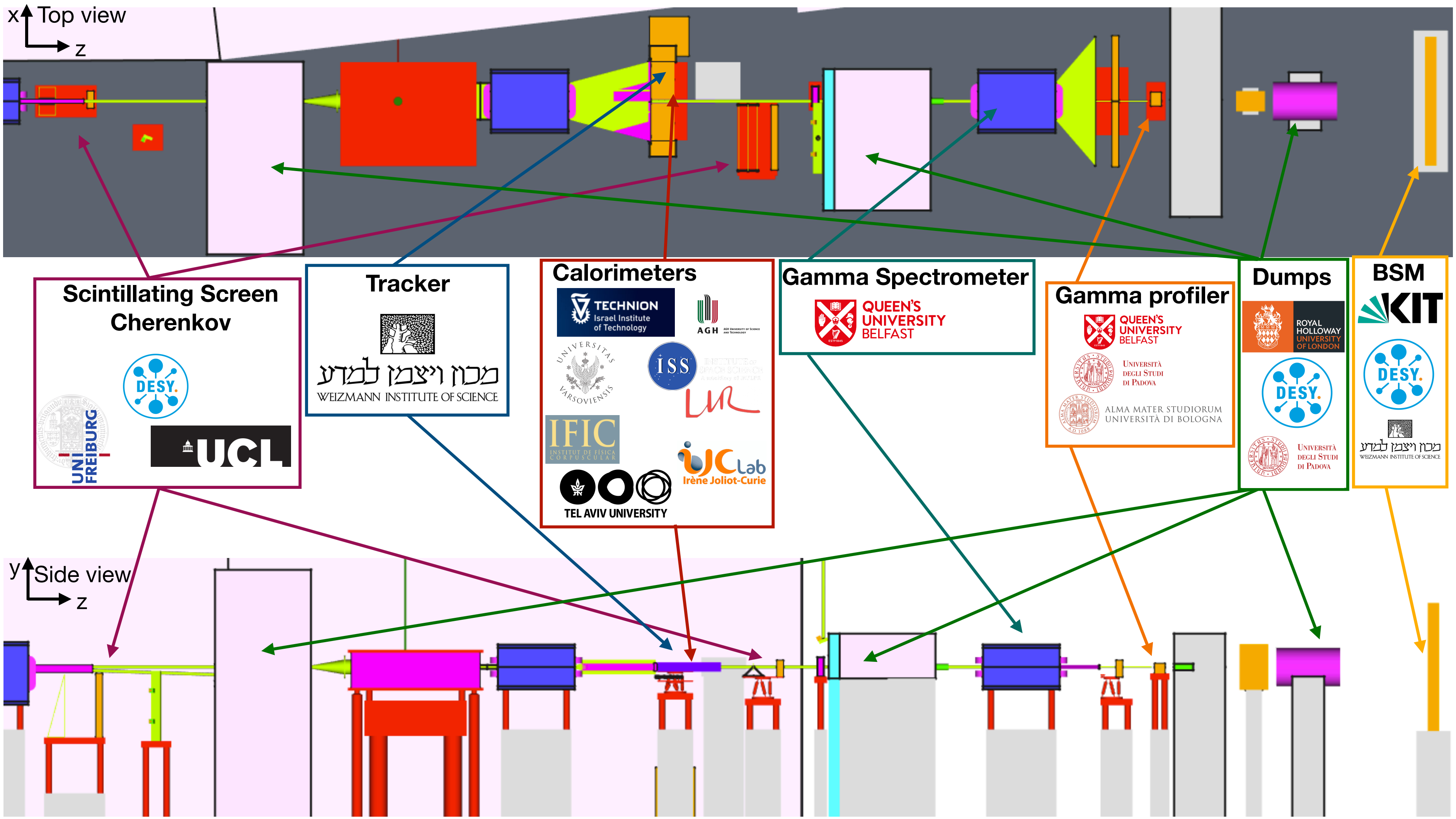
CAD:

side views of experimental area

Full Geant4 simulation:



LUXE status and planning



LUXE laser

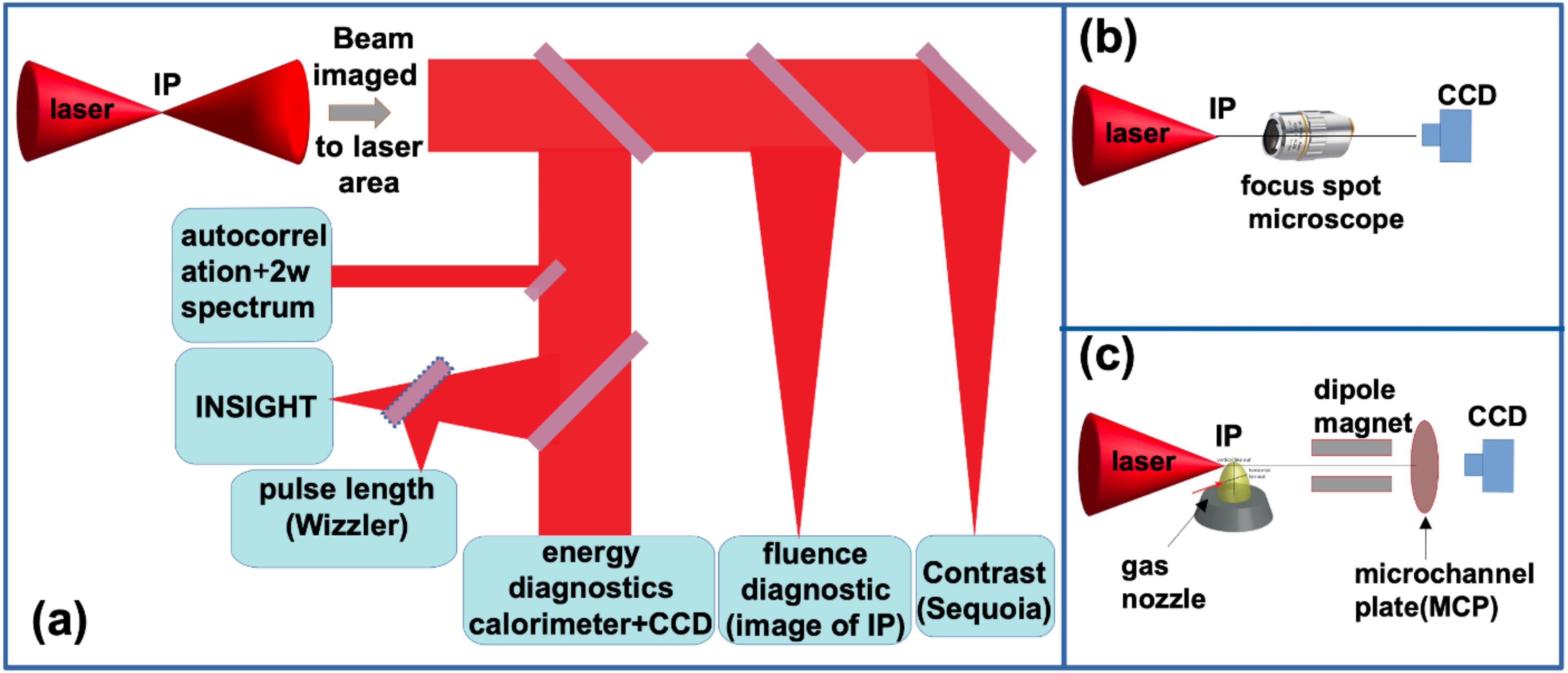
Wavelength (energy)	800 nm (1.55 eV)
Power	40 / 350 TW
Pulse length	30 fs
Spot size	> 3 μm
Peak intensity	13.3 / 120 × 10^{19} W/cm^2
Peak intensity parameter ξ	7.9 / 23.6
Peak quantum parameter χ	1.5 / 4.5

- 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, Jena or new)
  - Upgrade to *350 TW* laser for Phase-1

Laser diagnostics

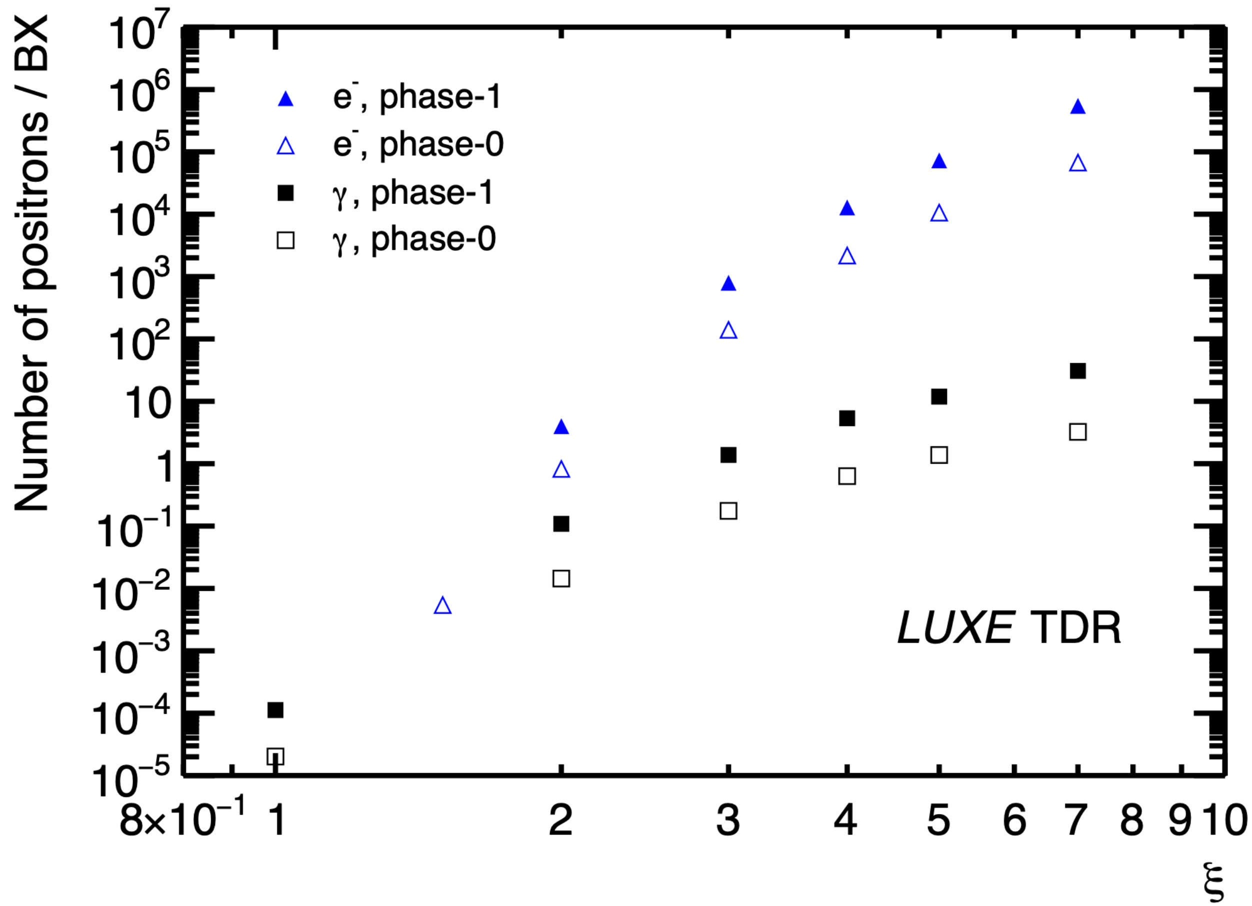


- Need to characterise energy, pulse length, spot size.
  - Diagnostics in IP chamber and in laser clean room.
- Uncertainty on laser intensity impacts physics results.
- Goal: < 5% uncertainty on laser intensity, 1% shot-to-shot uncertainty.

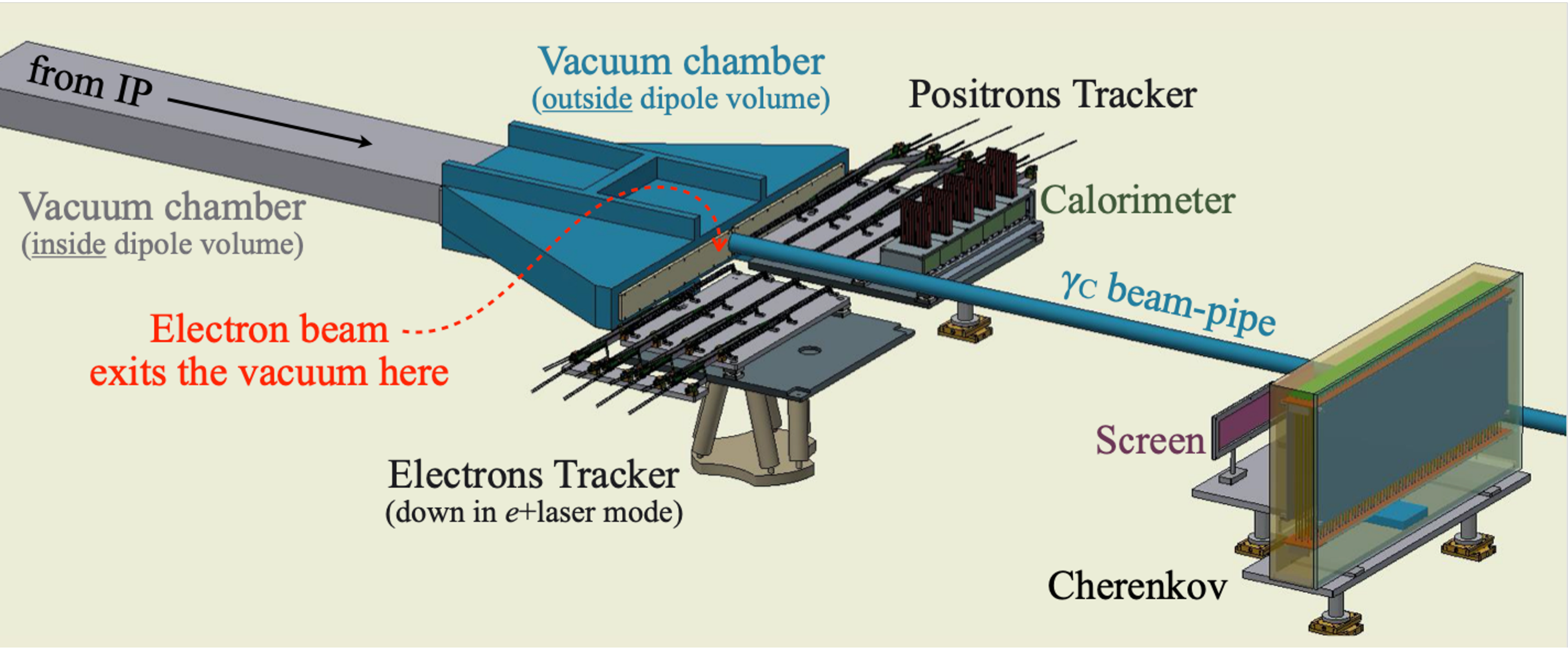
Detector requirements and challenges

- 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 γ).



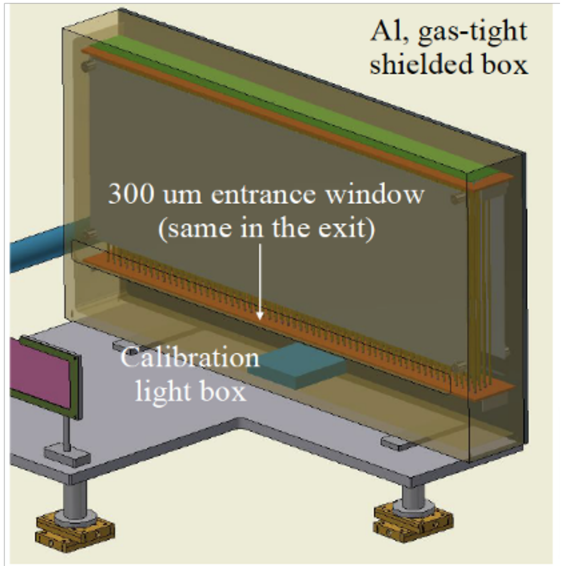
IP detectors

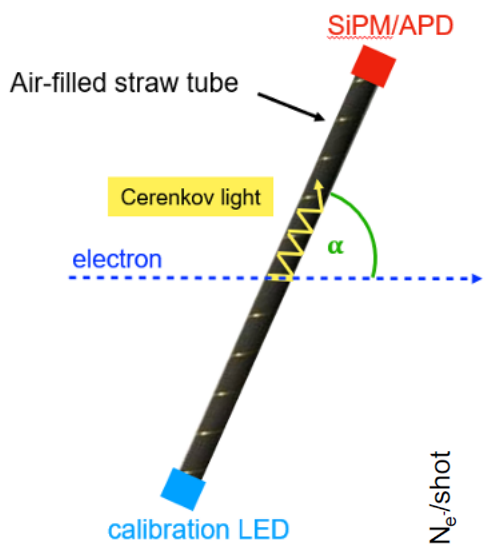


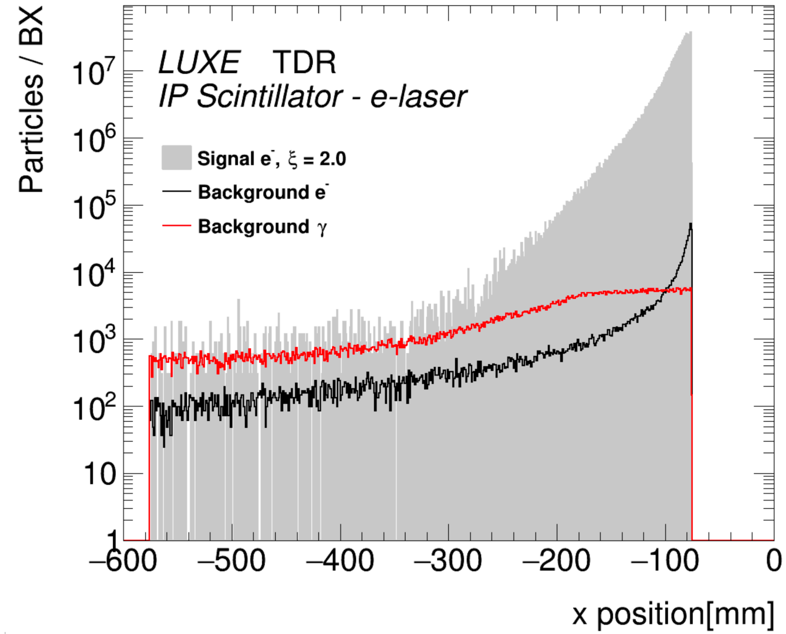
- Two complementary detector technologies per measurement:
  - Different sensitivities, cross calibration, reduction of systematic uncertainties.
- In-situ measurements of beam backgrounds when laser not on.

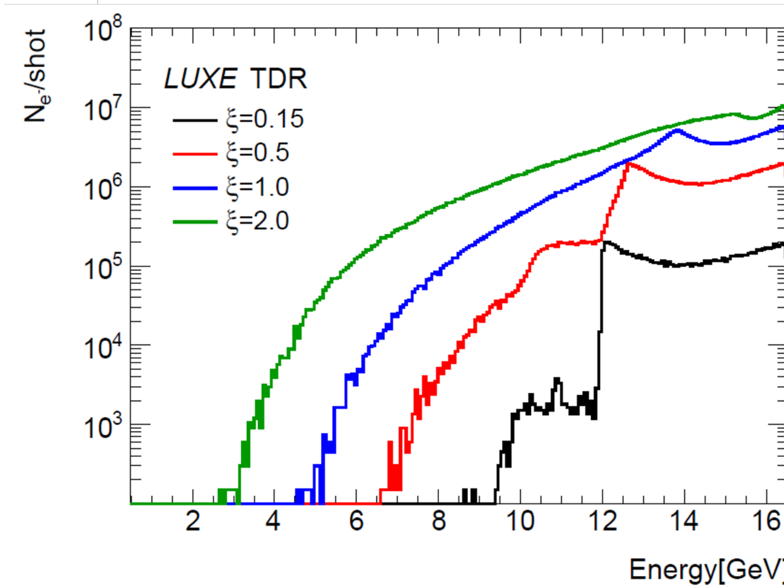
High-rate electron detectors

- A scintillation screen and camera is inexpensive, flexible and simple with good position resolution.





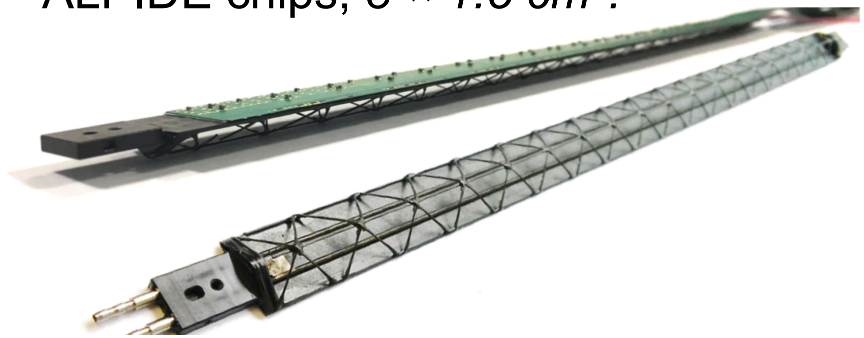


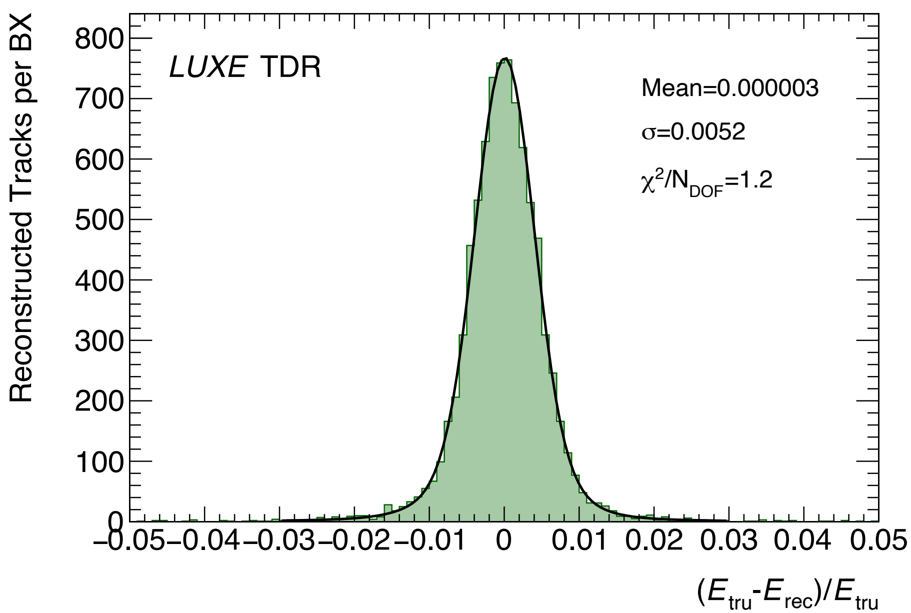


- Finely segmented (∅ = *4 mm*) air-filled channel (reflective tubes as light guides).
  - Charged particles create Cherenkov light.
  - Recent tests at E320.

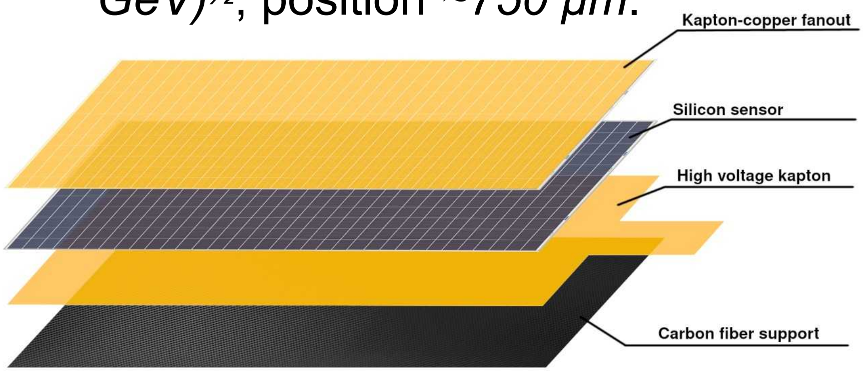
Positron detectors

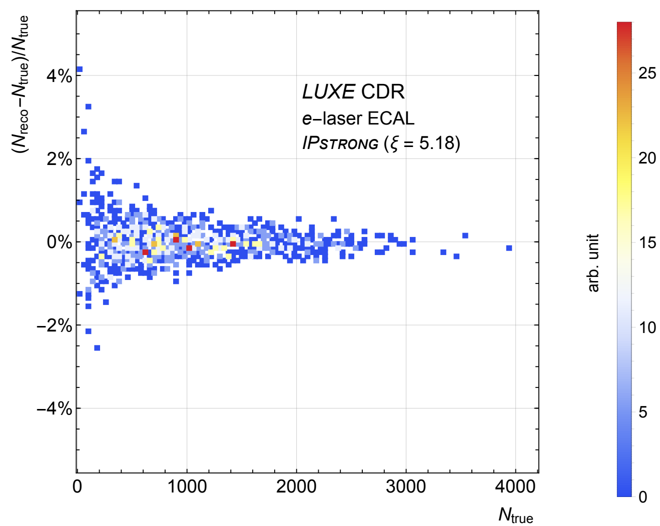
- Pixel tracker:
  - 4 layers each of which has 2 staves.
  - Each stave is *27 × 1.5 cm²* built from 9 ALPIDE chips, *3 × 1.5 cm²*.





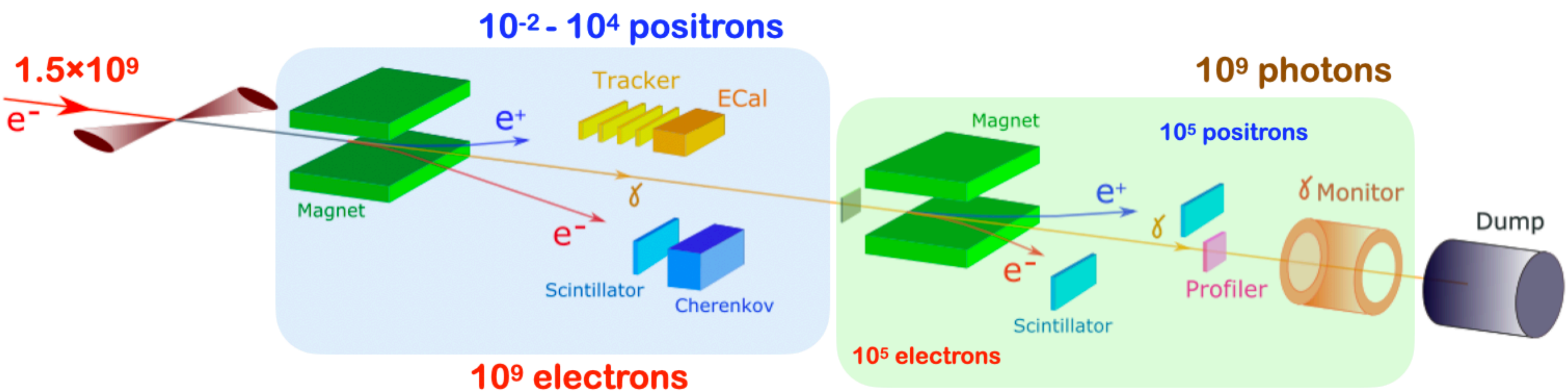
- High granularity, compact, sampling calorimeter.
  - Based on technology developed by (LC) FCAL collaboration.
  - 20 layers of 3.5 mm tungsten.
  - Energy resolution $\sigma/E = 20\%/(E/\mathrm{GeV})^{1/2}$, position *~750 μm*.





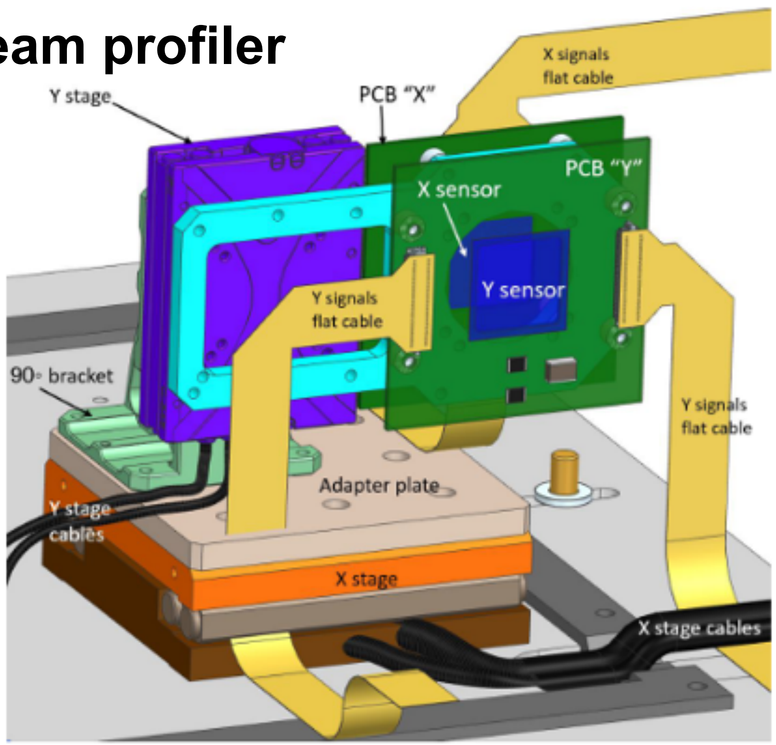
Overview of photon detectors

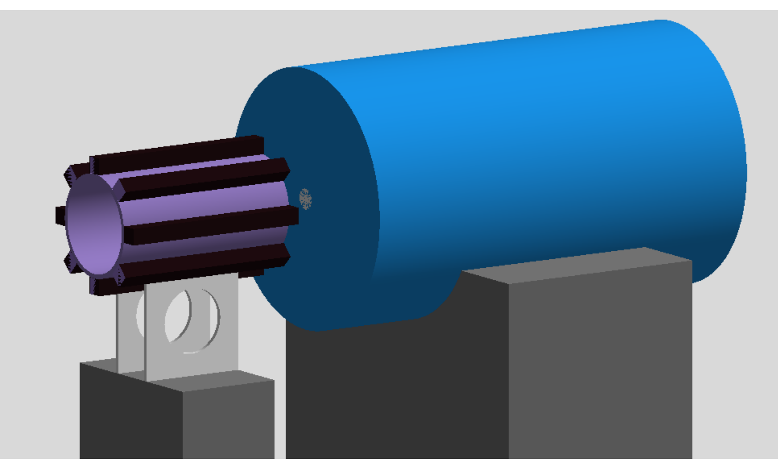
- Want to measure *10⁹* photons summing up to TeV energies.
- Have three complementary systems:
  - Gamma-ray spectrometer where a fraction are converted to e^+e^- pairs.
  - Gamma-ray profiler which uses radiation-hard sapphire.
  - Gamma-flux monitor which relies on backscattering from photon dump.



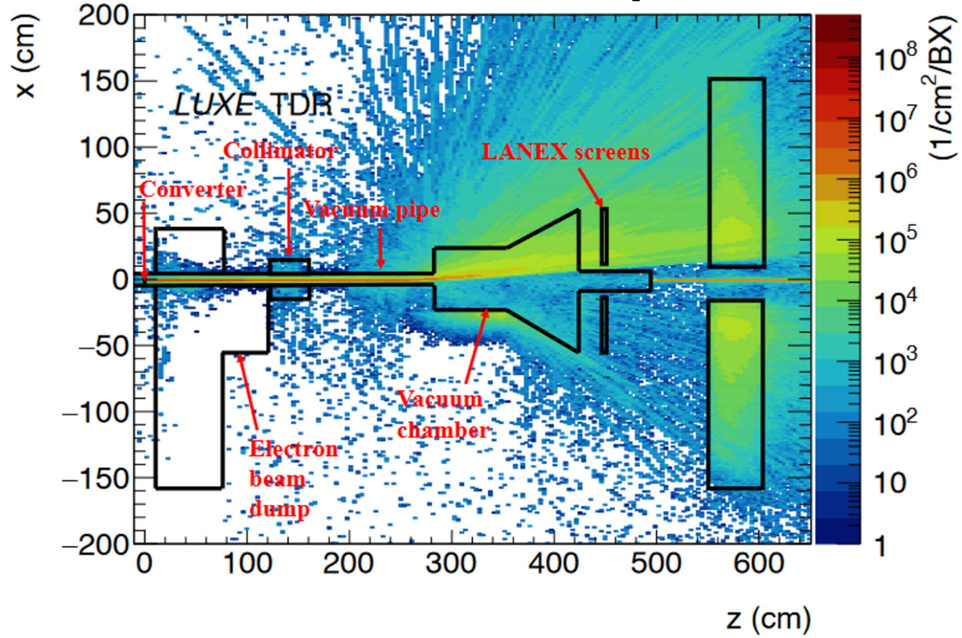
Gamma-ray detectors

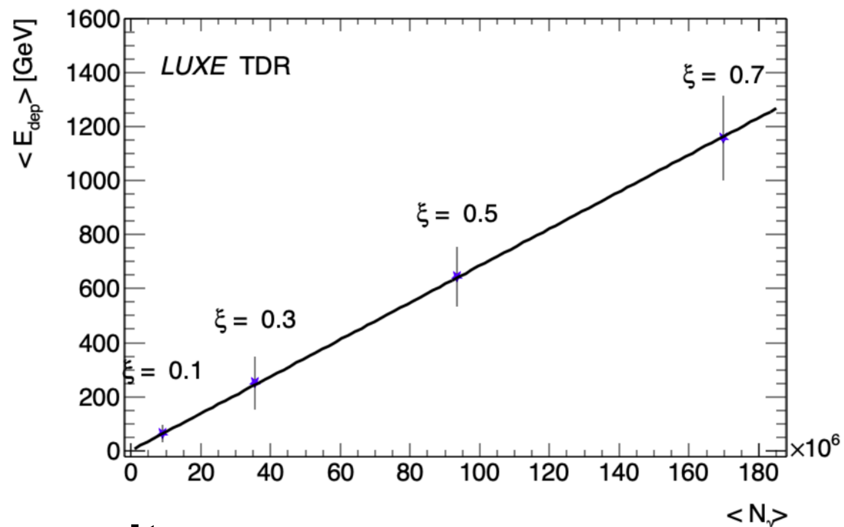
Beam profiler





Spectrometer



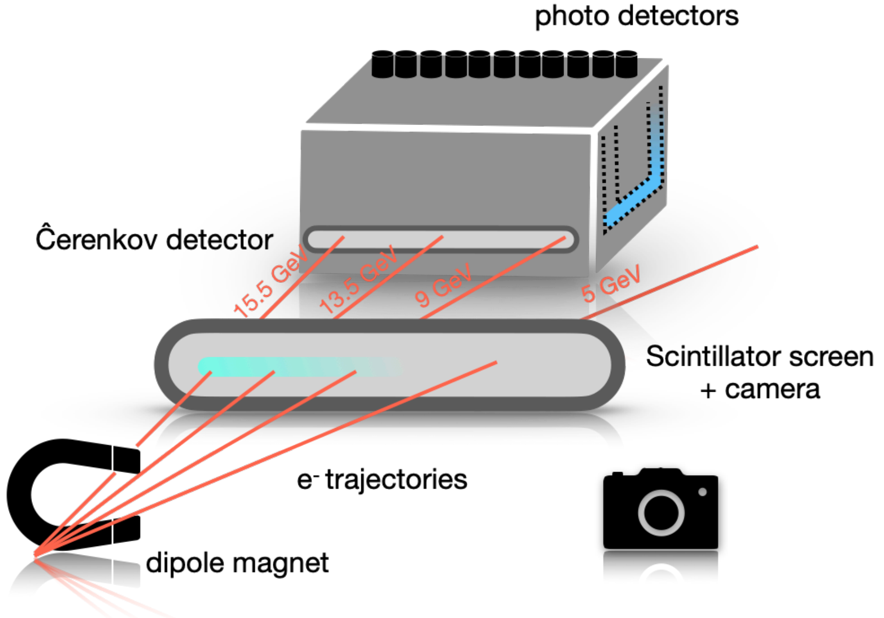


Flux monitor

Overview of electron/positron detectors

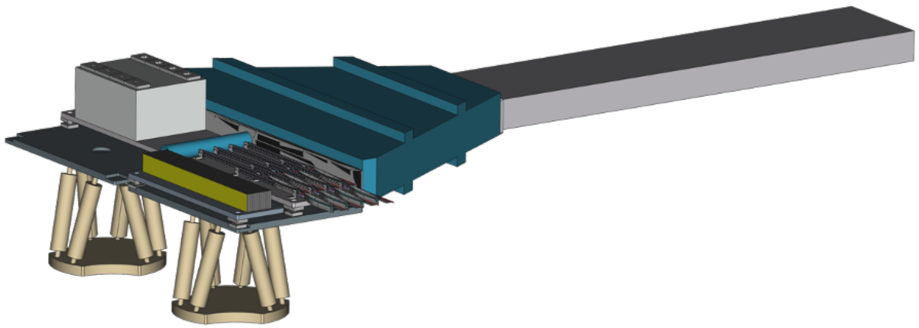
- High-flux regions
  - Scintillation screens
  - Cherenkov detectors

High rate tolerance,
large dynamic range.



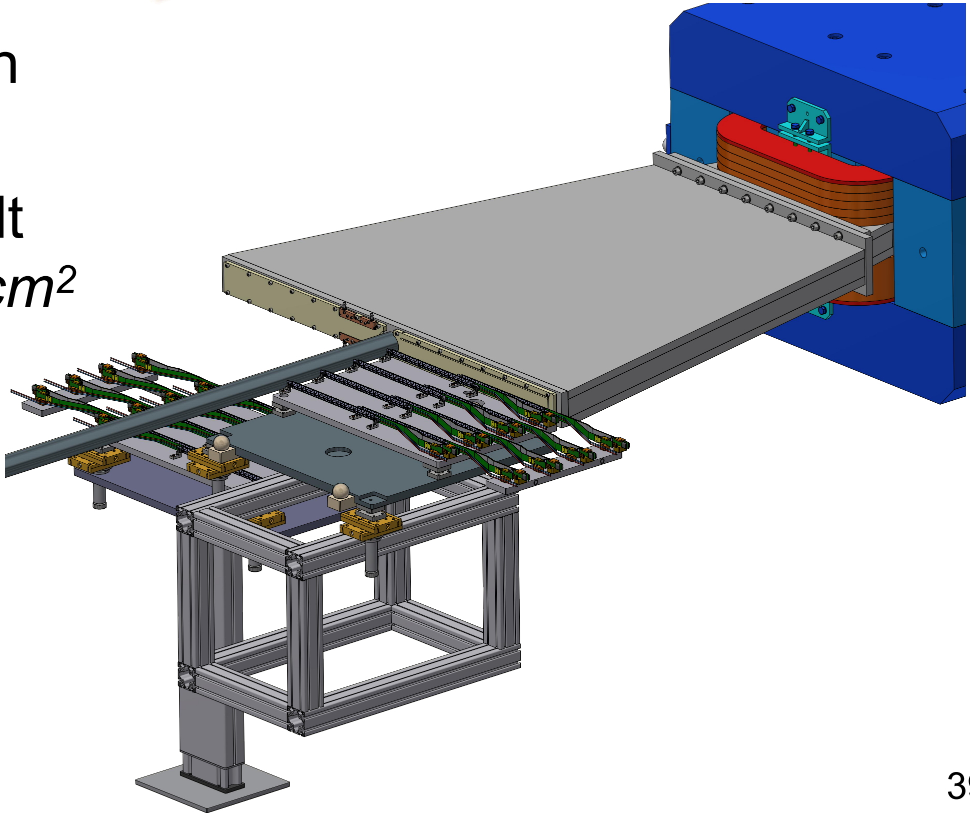
- Low-flux regions
  - Silicon pixel detectors
  - High granularity calorimeters

High signal efficiency,
high resolution.



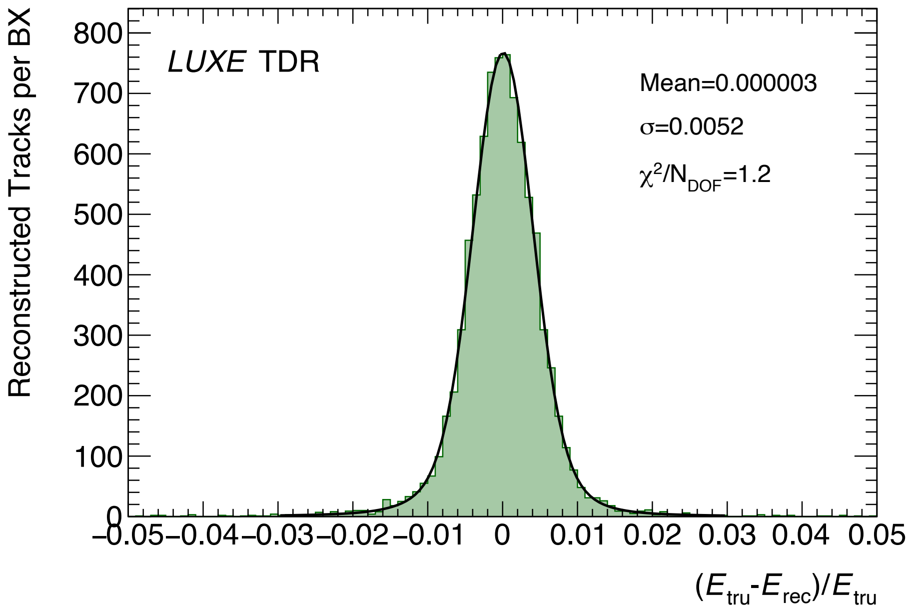
Positron detector — pixel tracker

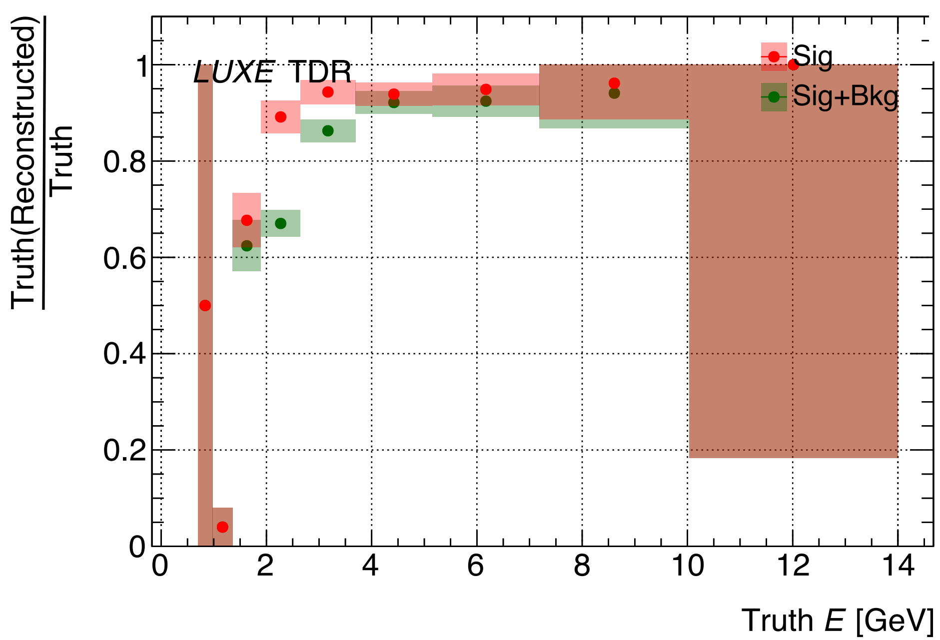
- Pixel tracker:
  - Based on ALICE ALPIDE pixel chips.
  - Pixel size *27 × 29 μm²* with position resolution of ~ *5 μm*.
- Consists of 4 layers each of which has 2 staves.
  - Each stave is *27 × 1.5 cm²* built from 9 ALPIDE chips, *3 × 1.5 cm²*

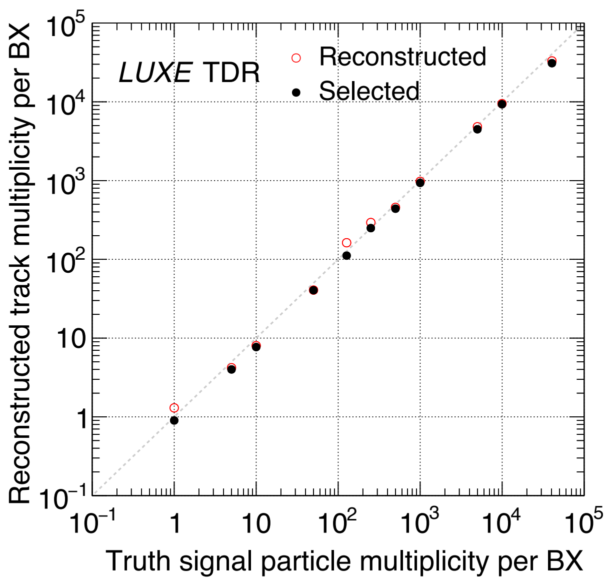


Pixel tracker performance

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

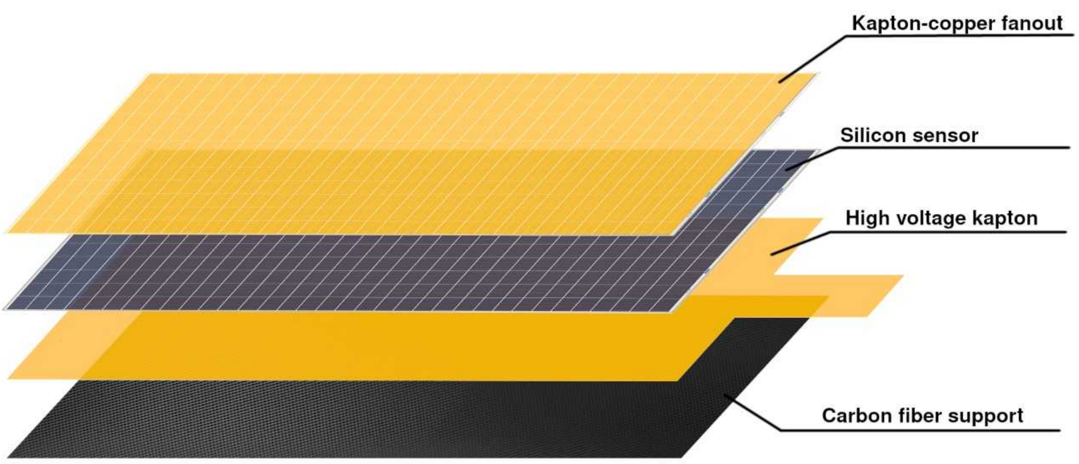


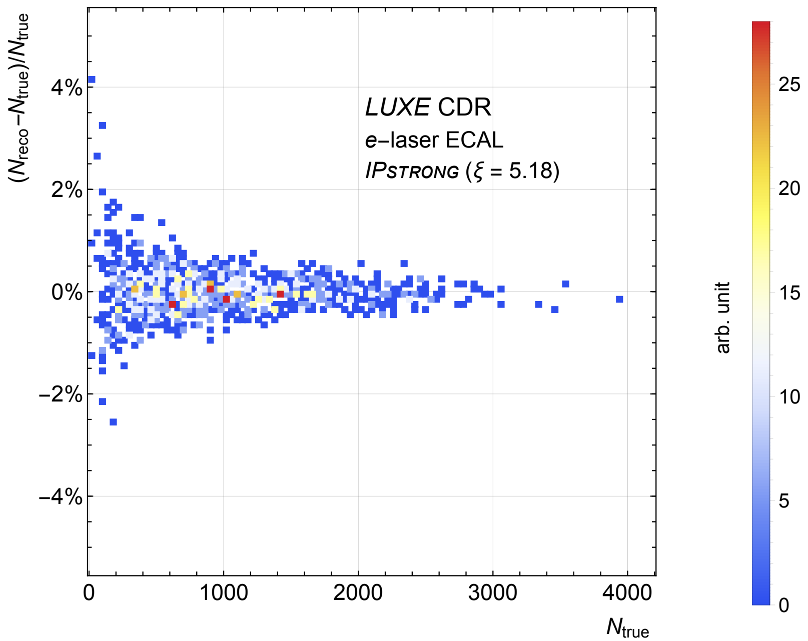




Positron detector — calorimeter

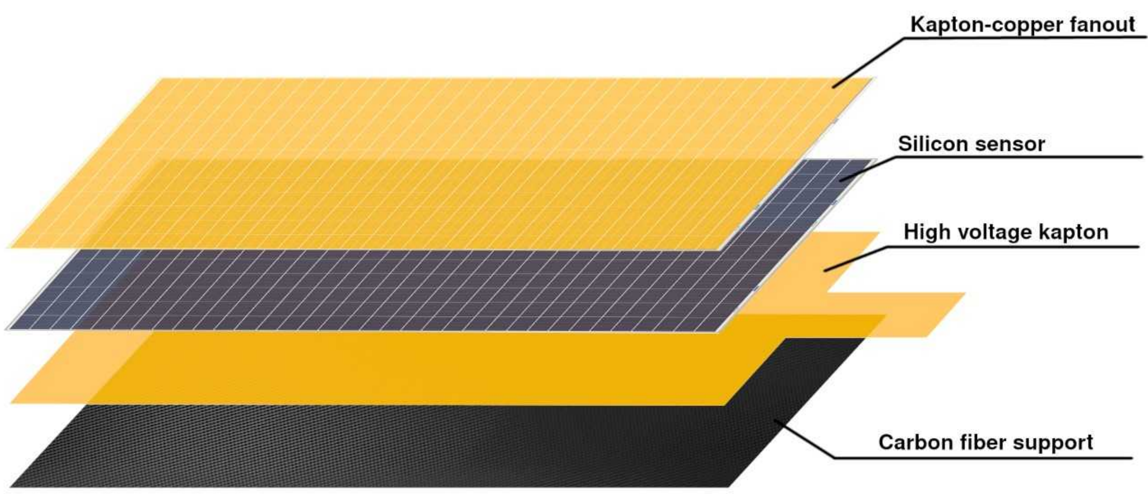
- High granularity, compact, sampling calorimeter.
  - Based on technology developed by (LC) FCAL collaboration.
  - Studies with 20 layers of 3.5 mm tungsten; baseline 10 layers @ *3.5 mm* and 5 layers @ *7 mm*.
  - Silicon sensors of $9 \times 9\ cm^2$ with pads $5.5 \times 5.5\ mm^2$; a complete detector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





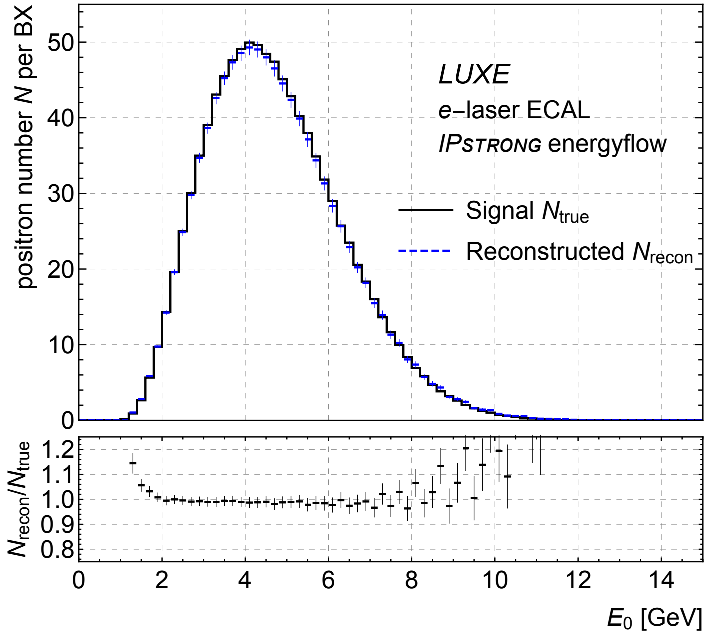
Positron detector — calorimeter

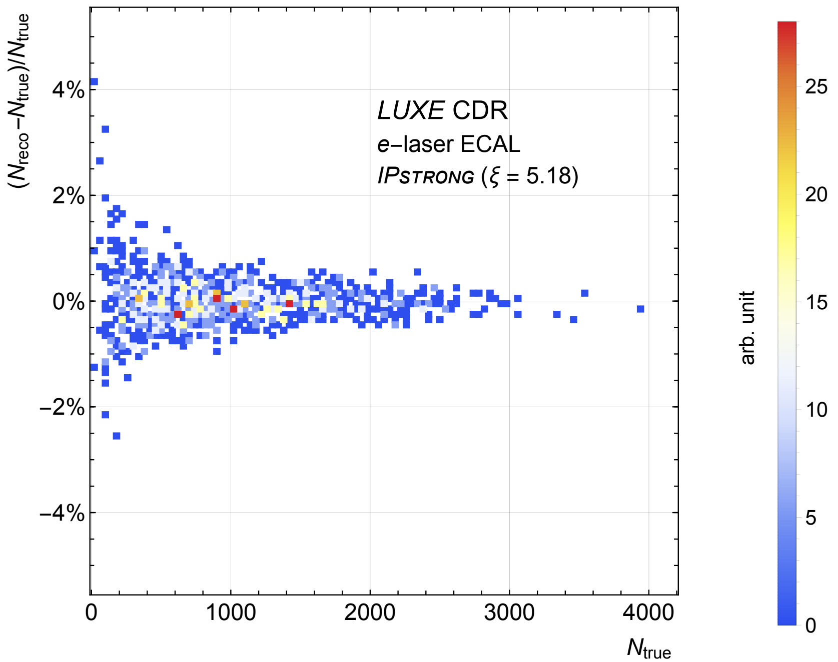
- High granularity, compact, sampling calorimeter.
  - Based on technology developed by (LC) FCAL collaboration.
  - Studies with 20 layers of 3.5 mm tungsten; baseline 10 layers @ 3.5 mm and 5 layers @ 7 mm.
  - Read out by FLAME ASIC (developed for FCAL).
  - Silicon sensors of $9 \times 9\ cm^2$ with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

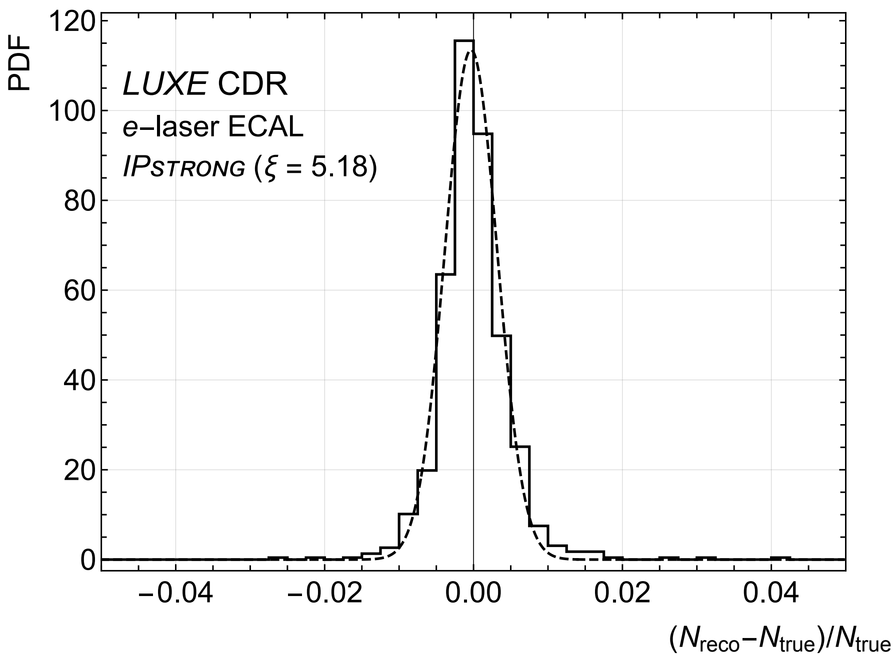


Calorimeter reconstruction

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

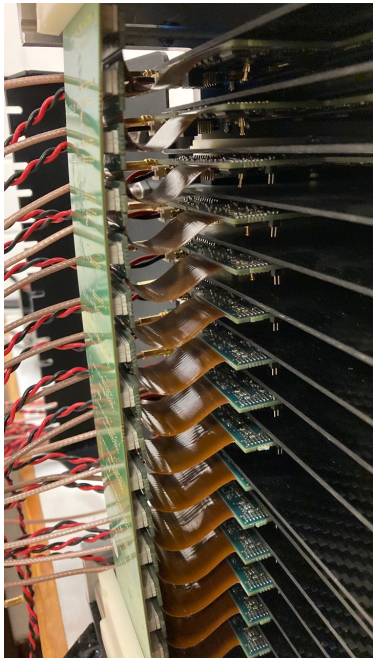






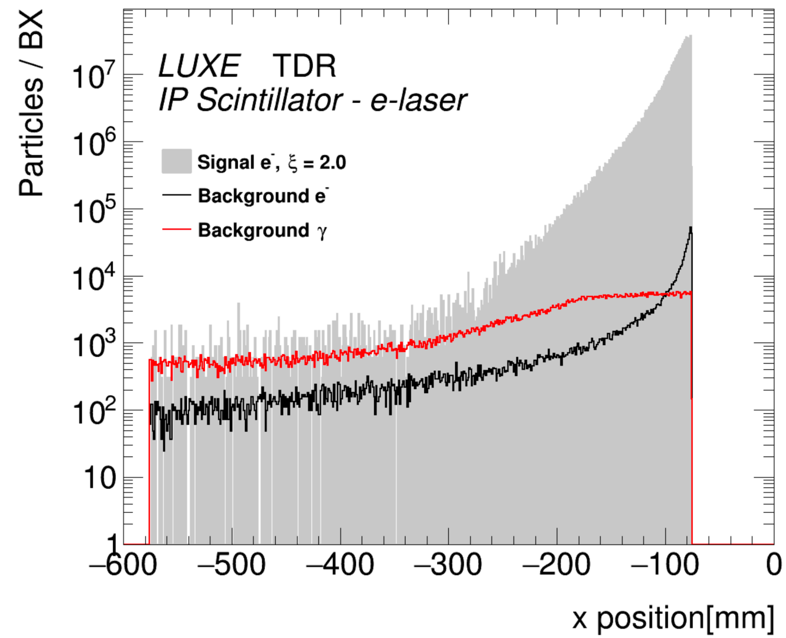
Electron calorimeter in γ–laser collisions

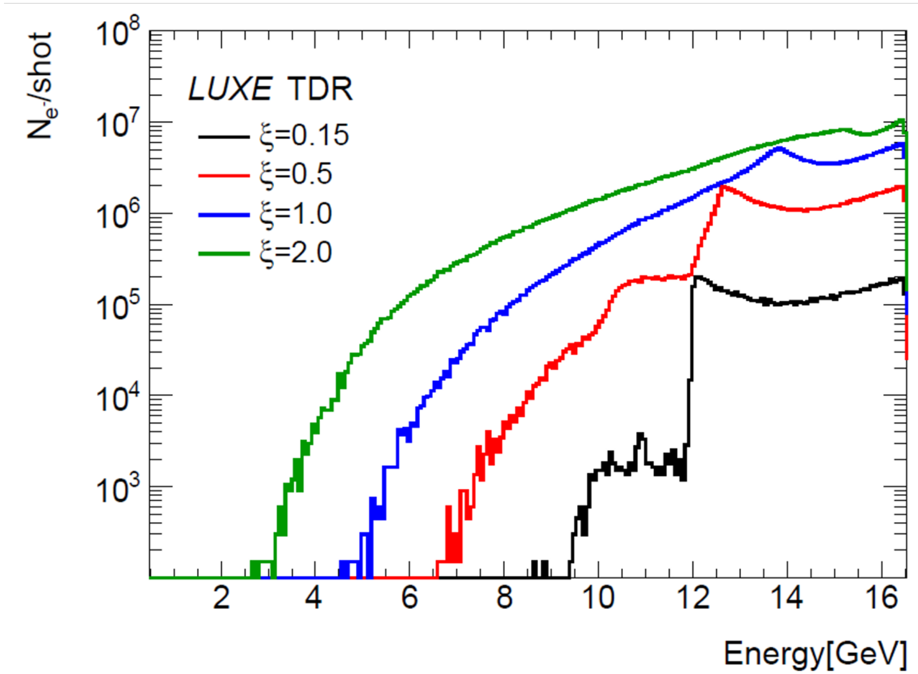
- To measure electrons in *γ*–laser collisions as rate is much lower.
- Use a silicon–tungsten electromagnetic calorimeter based on developments from CALICE collaboration.
  - Reference design for ILC concept.
  - 7 tungsten plates of *2.8 mm* and 8 of *4.2 mm* thickness.
  - Sensors are the same structure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

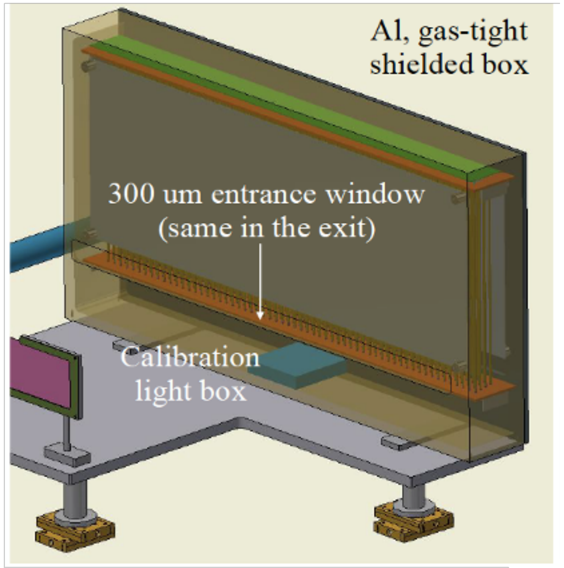




- Minimally affects electrons en route to Cherenkov detector.
- Good signal-to-background.
- Similar systems used in accelerators.

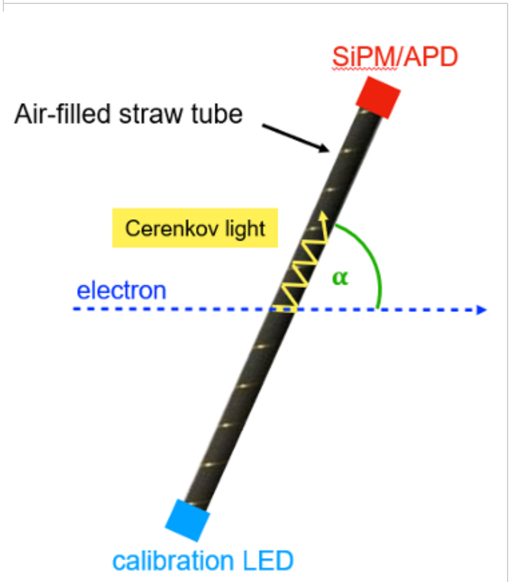
High-rate electron detector — Cherenkov

- 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*).



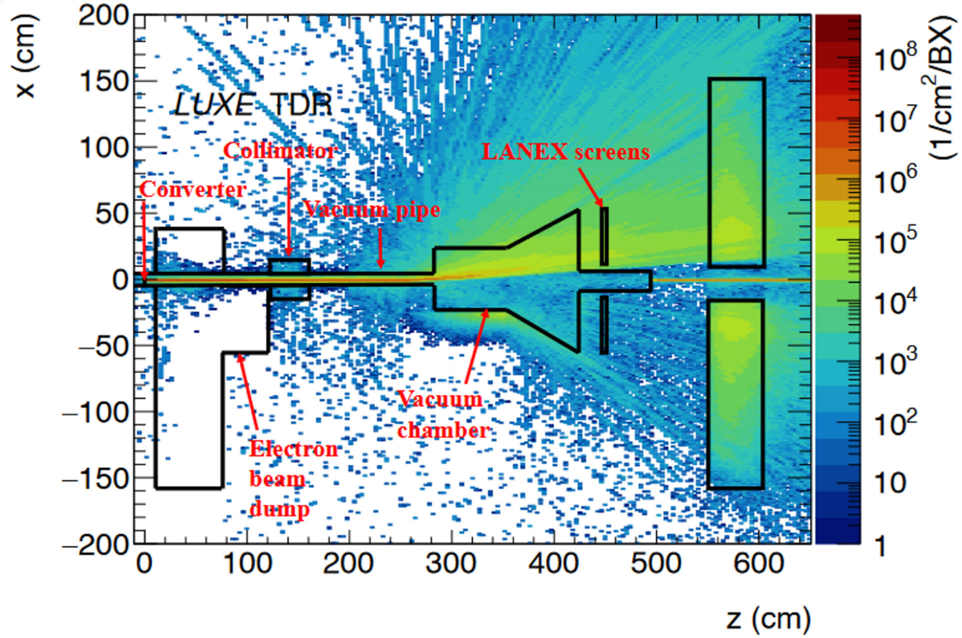
- Beam tests and R&D ongoing.
- Also deploy at E320.

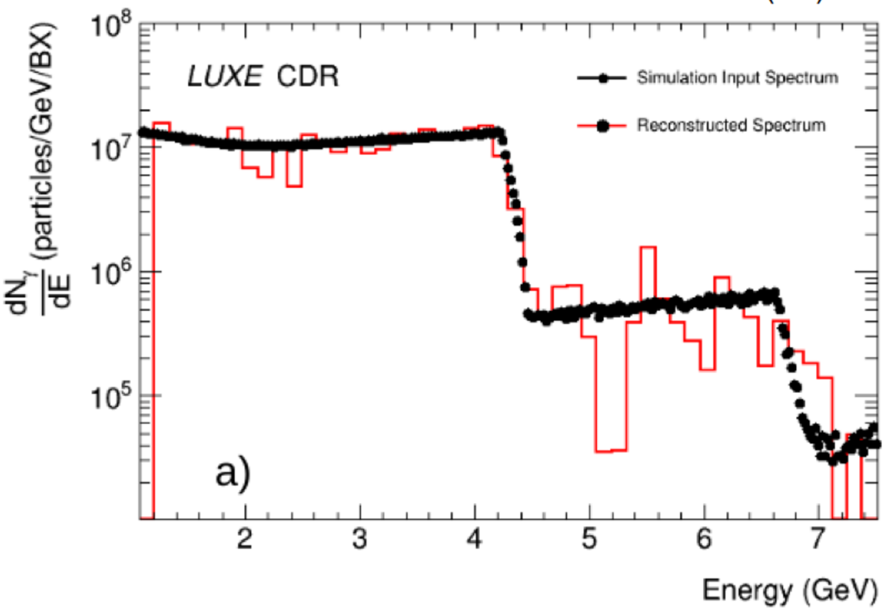
Straw prototype



Gamma-ray spectrometer

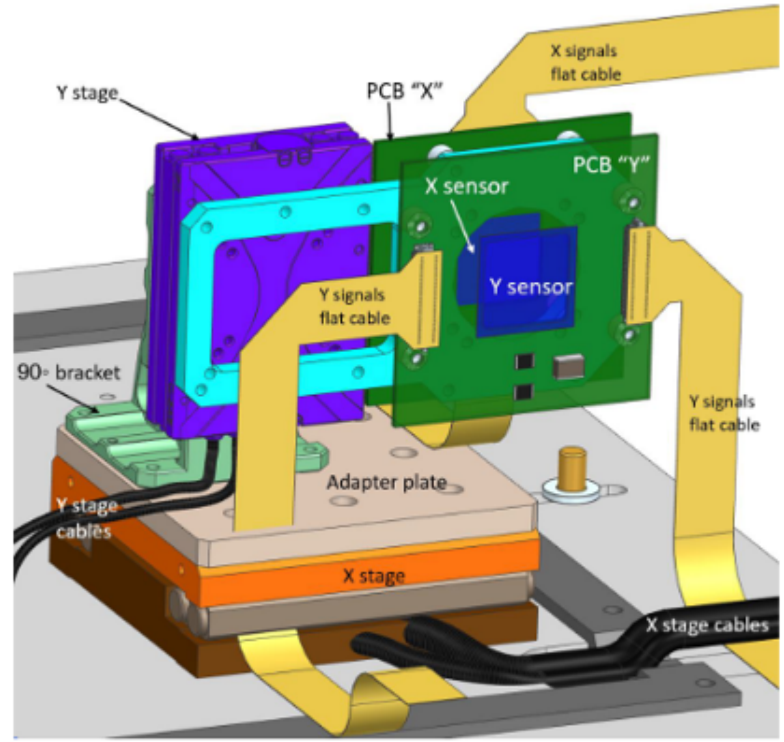
- Aim: to measure photon spectrum.
  - Measure e^+e^- pairs after photons pass through target.
  - Spectrometer with scintillation screens and CCD cameras.
  - Good energy resolution ($\delta E/E < 2\%$).
  - Non-invasive (*>99%* photons propagate through).

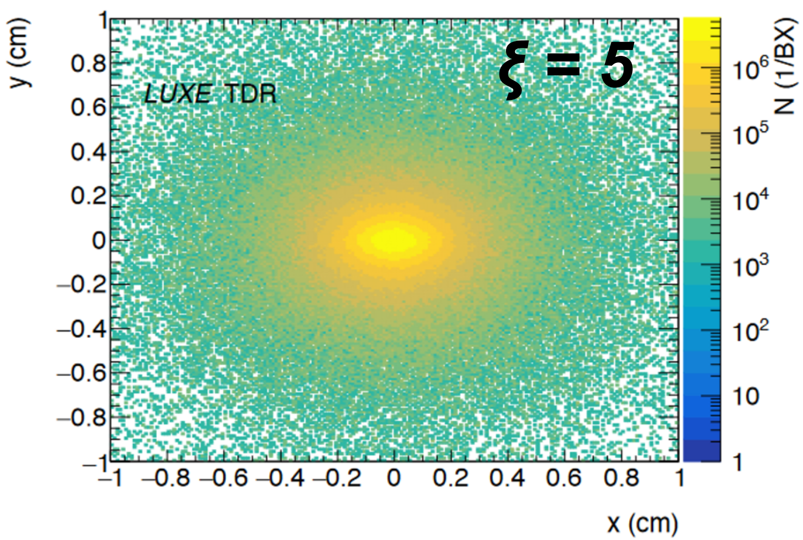


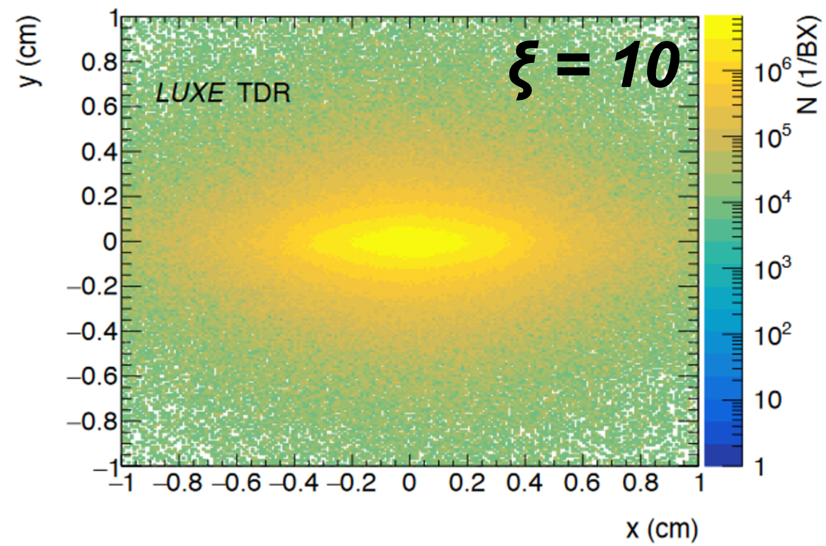


Gamma-ray profiler

- 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.

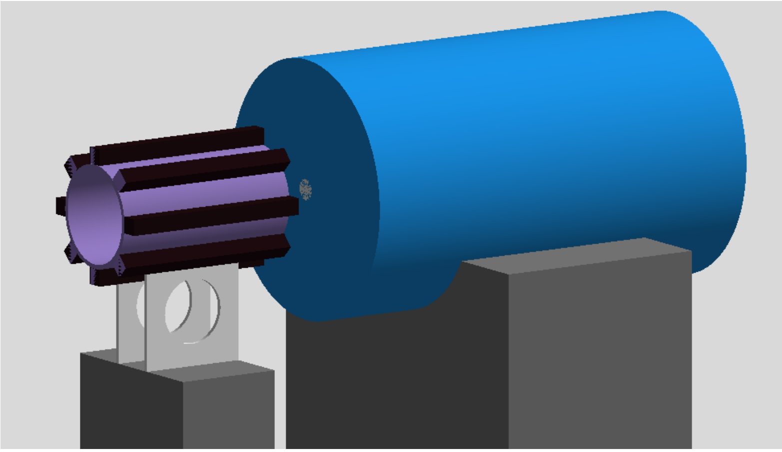


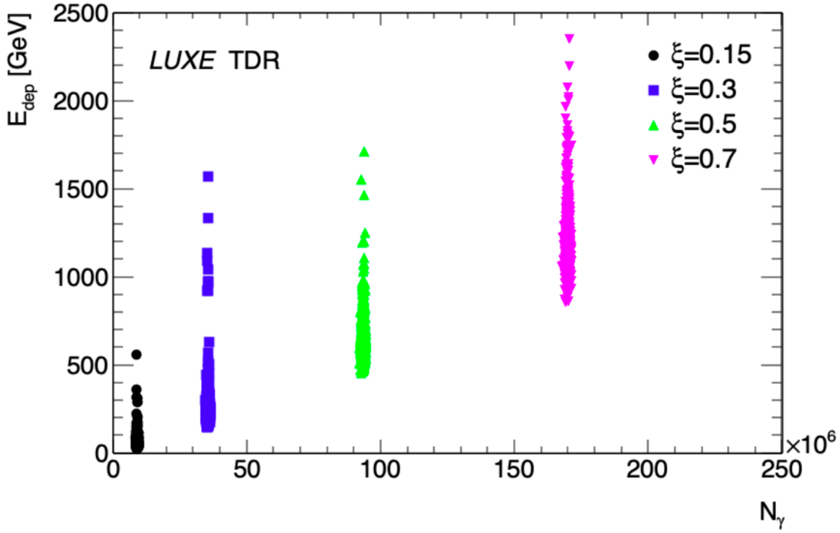


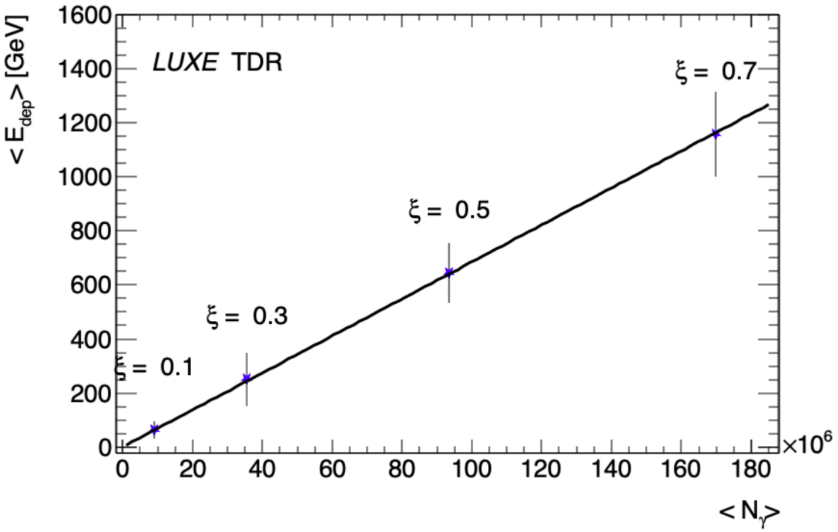


Gamma flux monitor

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