LUXE: A new experiment to study non-perturbative QED

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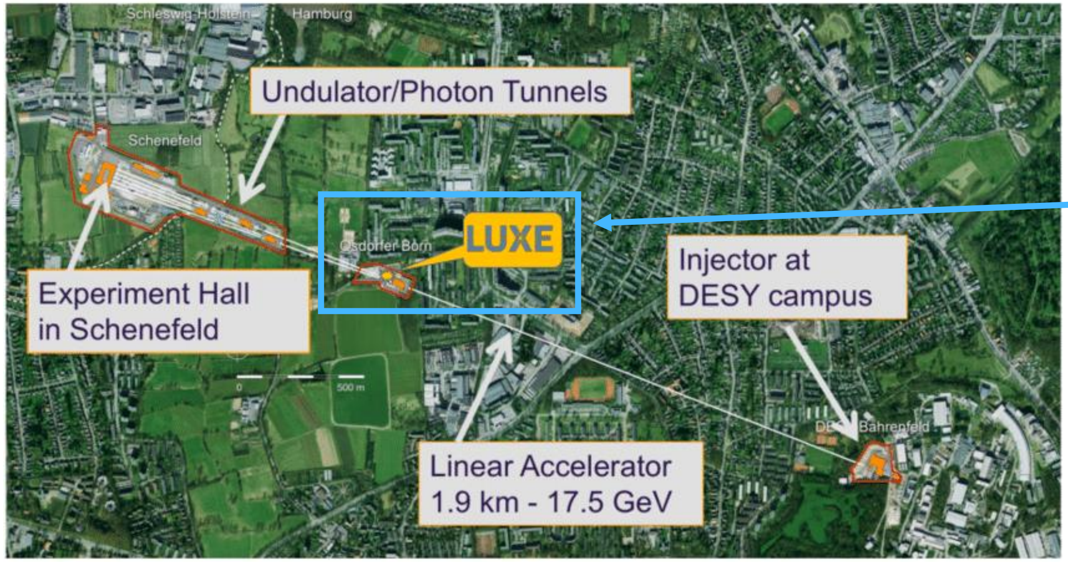
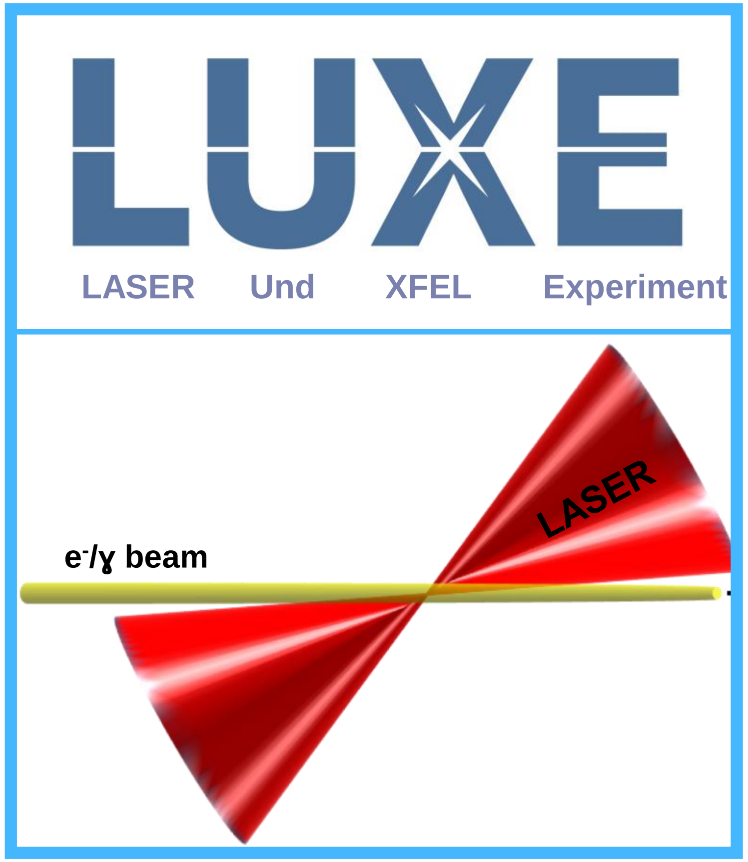
DPG Frühjahrstagung Dresden
22.03.2023

HELMHOLTZ

Overview





What is the LUXE experiment?

- proposed new experiment at DESY Hamburg & Eu.XFEL
- collisions between XFEL electron beam and high-intensity laser
  → probe (strong-field) QED in uncharted regime

What will be covered today?

1) What is strong-field QED and why is it interesting?

2) What does LUXE add to SFQED experiment landscape?

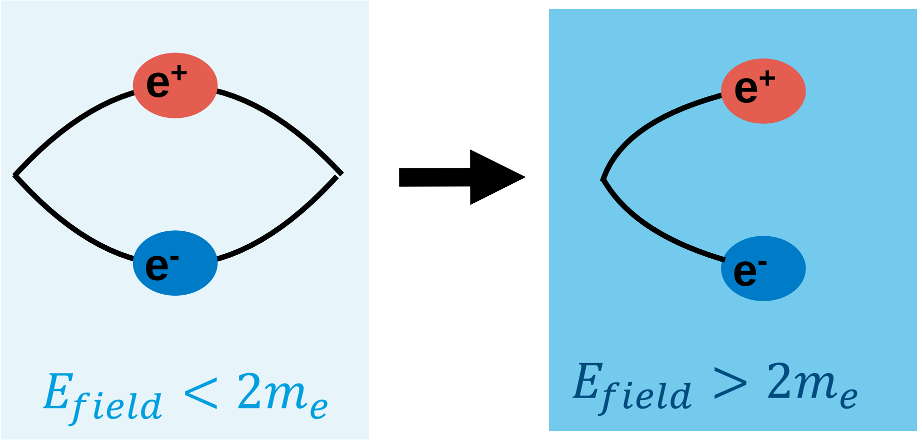
3) What are key technologies to reach LUXE's physics goals?

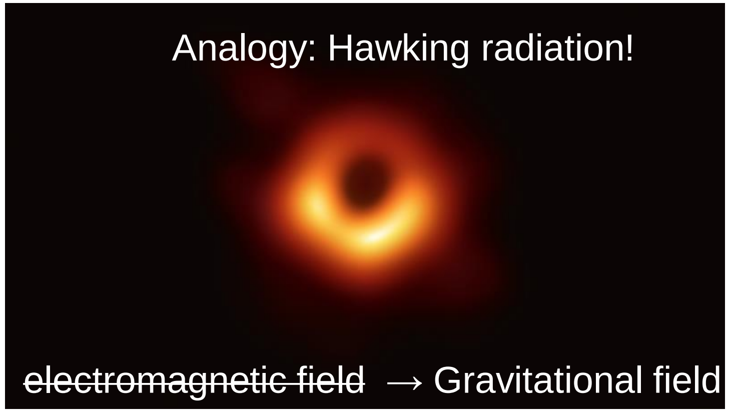
Strong-Field QED (SFQED)

- QED is one of the most well-tested theories in physics → based on perturbative calculations
- LUXE will probe QED in non-perturbative strong-field regime
- strong external field: work by field over Compton wavelength > rest mass of virtual particle
  → Schwinger-Limit
- Schwinger critical field: $\mathcal{E}_{cr} = \frac{m_e^2 c^3}{e\hbar}$ (e.g. for electrical field: $\mathcal{E}_{cr} = 1.32 \cdot 10^{18}\, V/m$)

Field energy:

$$E_{field} = \frac{e\mathcal{E}}{m_e}$$

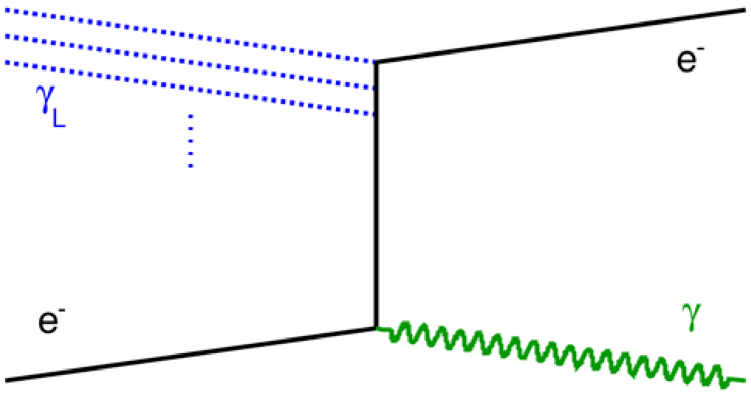




- Schwinger effect: creation of e^+e^- pair from vacuum in constant field
  → existing fields orders of magnitude too small compared to $\mathcal{E}_{cr}$, effect unobservable… but:

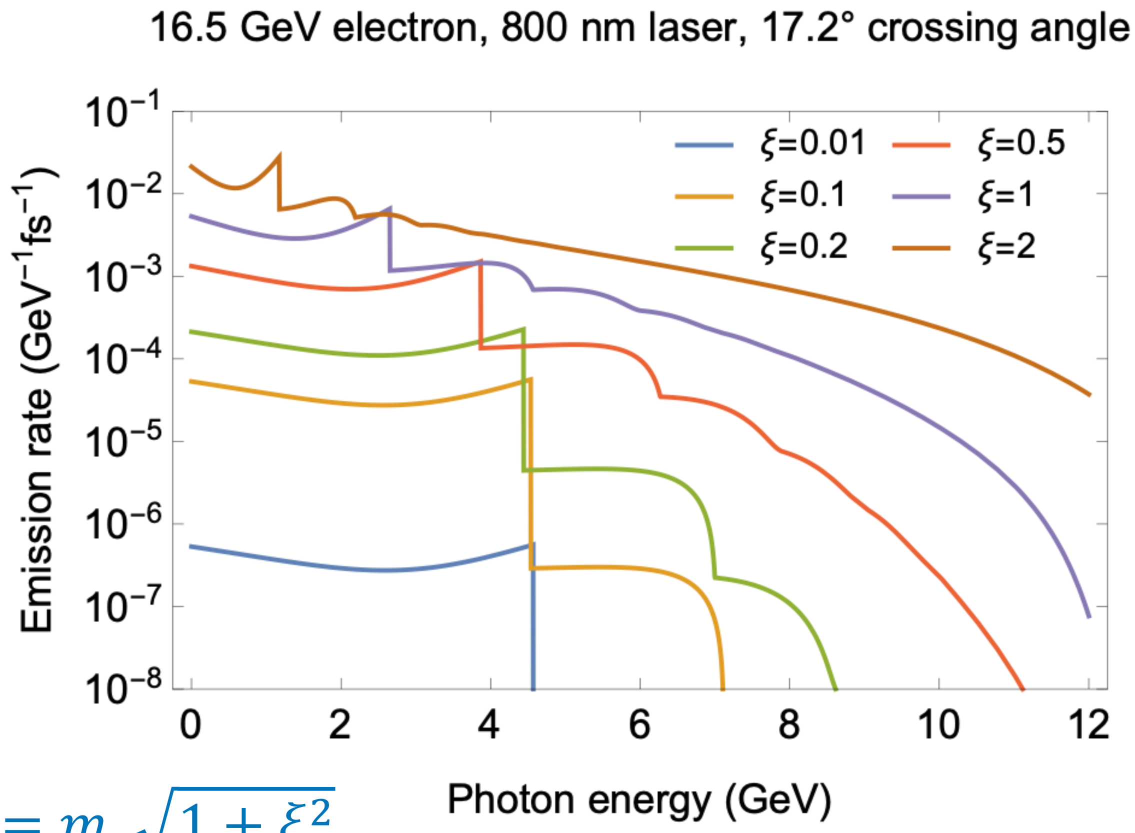
Non-linear quantum effects accessible in fields below $\mathcal{E}_{cr}$ with relativistic probe particles
→ fields $\mathcal{O}(\mathcal{E}_{cr})$ in particle rest frame!

Non-linear Compton scattering



Non-linear Compton Scattering

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



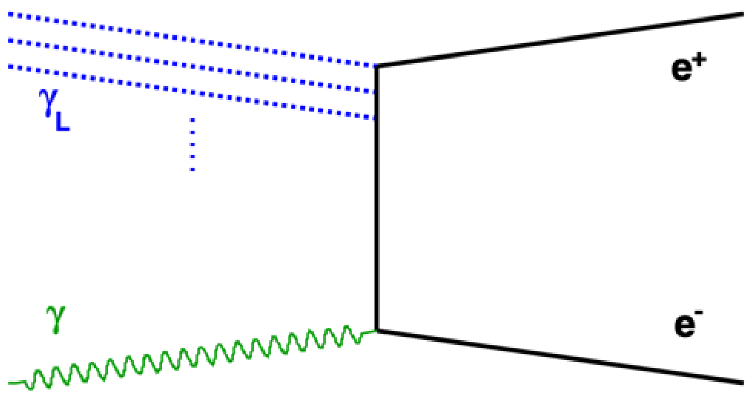
- in strong fields, electron obtains larger effective mass $m_* = m_e\sqrt{1+\xi^2}$
  →Compton edge shifts with laser intensity parameter ξ
  →n-th order harmonics (interaction with n laser photons)

- Note: Non-linear Compton scattering has a classical limit
  → deviation between non-linear QED and non-linear classical Compton: quantum non-linearity parameter χ

- Parameters ξ and χ determined by laser intensity and electron beam energy

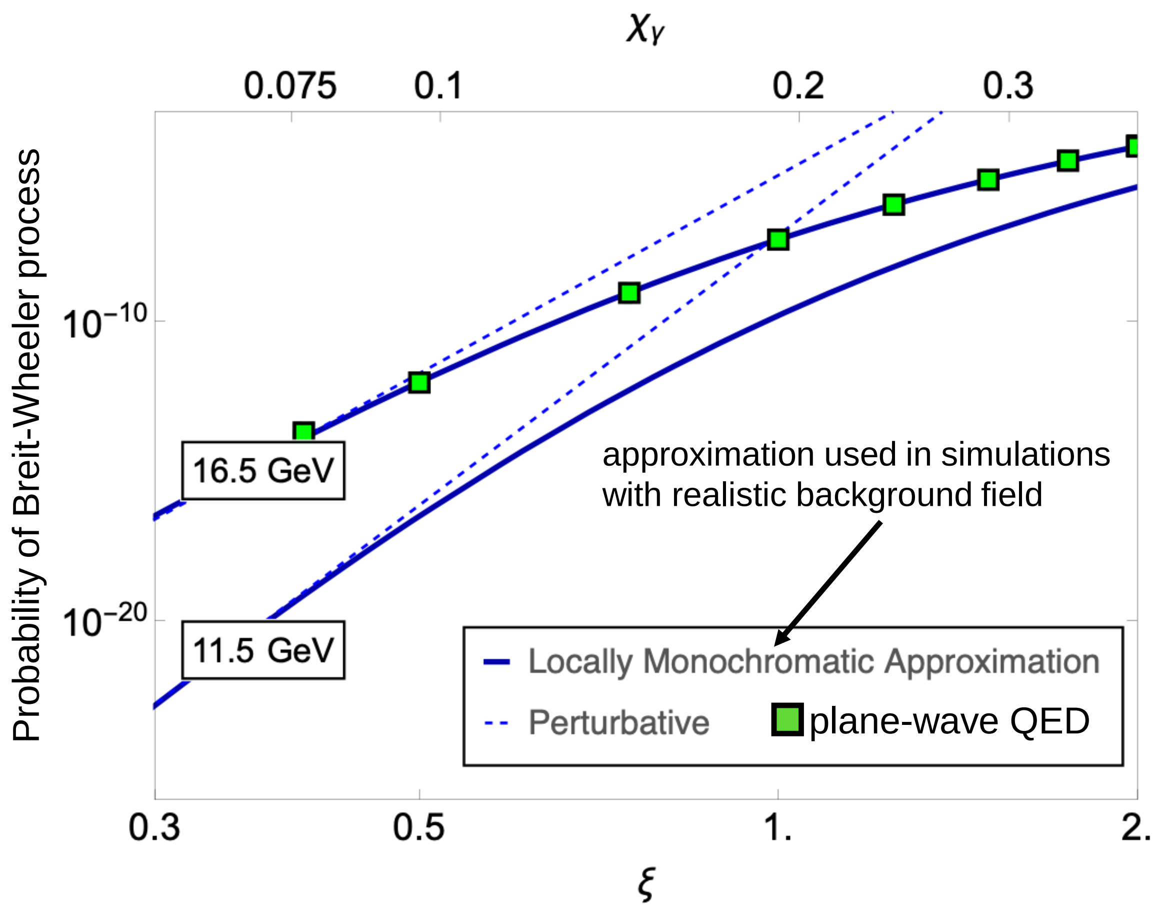
Different combinations of ξ and χ result in different types of non-linear behavior!

Breit-Wheeler pair production



(non-linear) Breit-Wheeler pair production

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



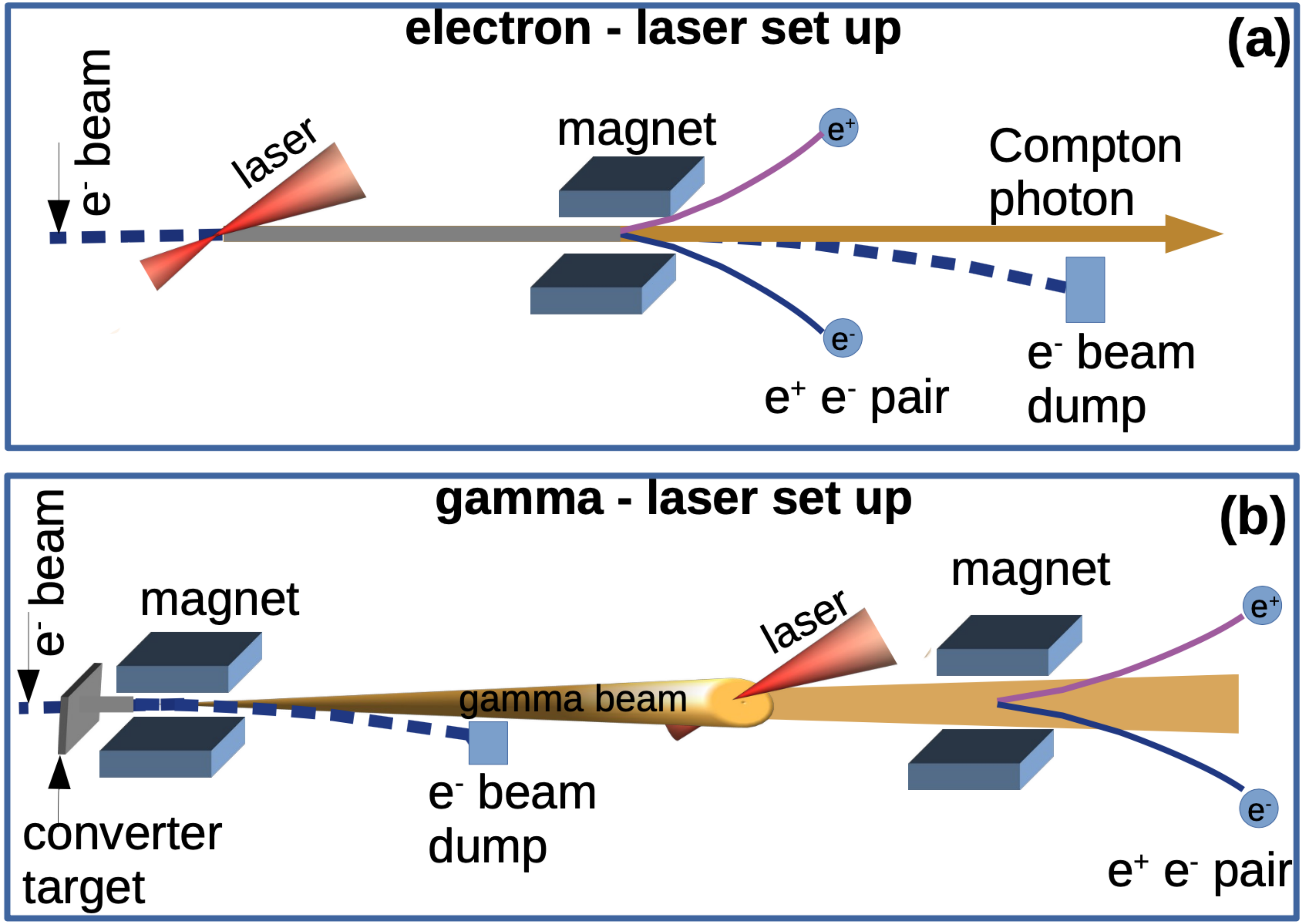
- initial photon from Compton scattering or secondary beam
- Note: this process has no classical limit (energy threshold)! → purely quantum, requires $\chi \sim \mathcal{O}(1)$!

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

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

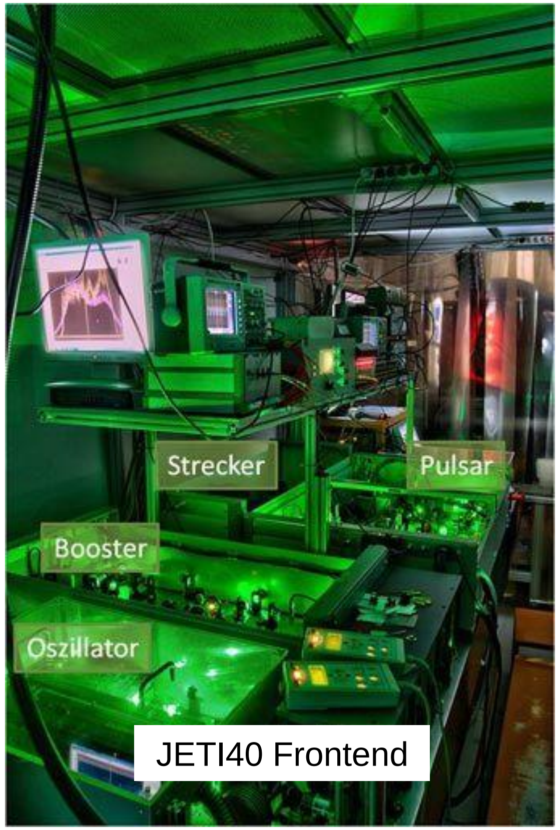
LUXE: first experiment to measure Breit-Wheeler pair production with real photons!

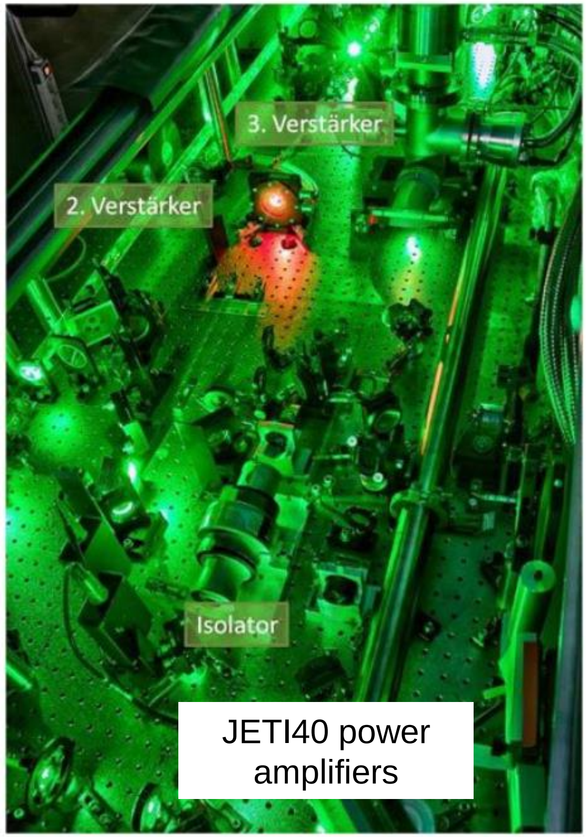
LUXE experimental setup(s)



Unique in LUXE!

The LUXE laser





LUXE basic Laser parameters	
active medium	Ti:Sa
wavelength (energy)	800nm (1.55eV)
crossing angle	17.2°
pulse length	30fs
spot size	≥3μm
power	40TW / 350TW
peak intensity [10^{19} W/cm^2]	13.3 / 120

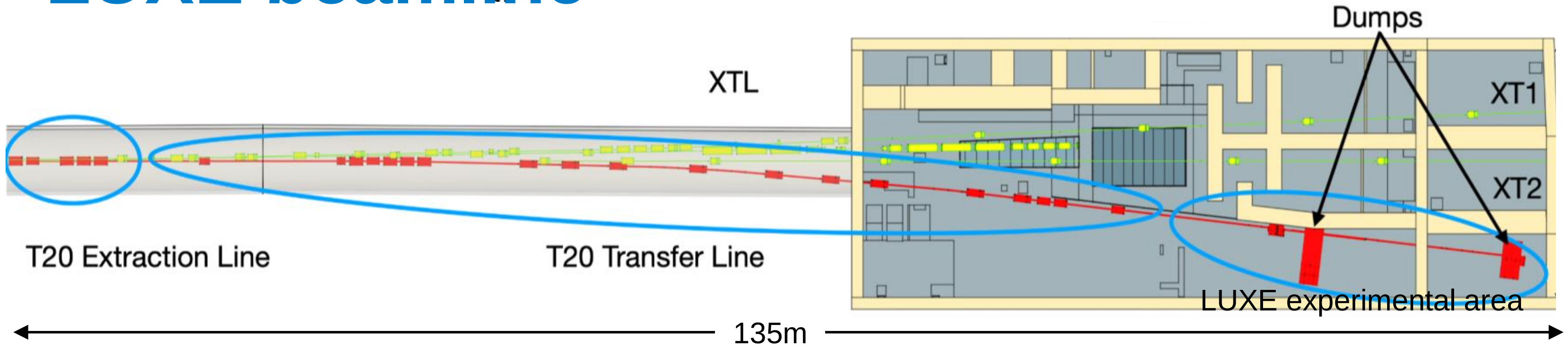
Laser intensity:

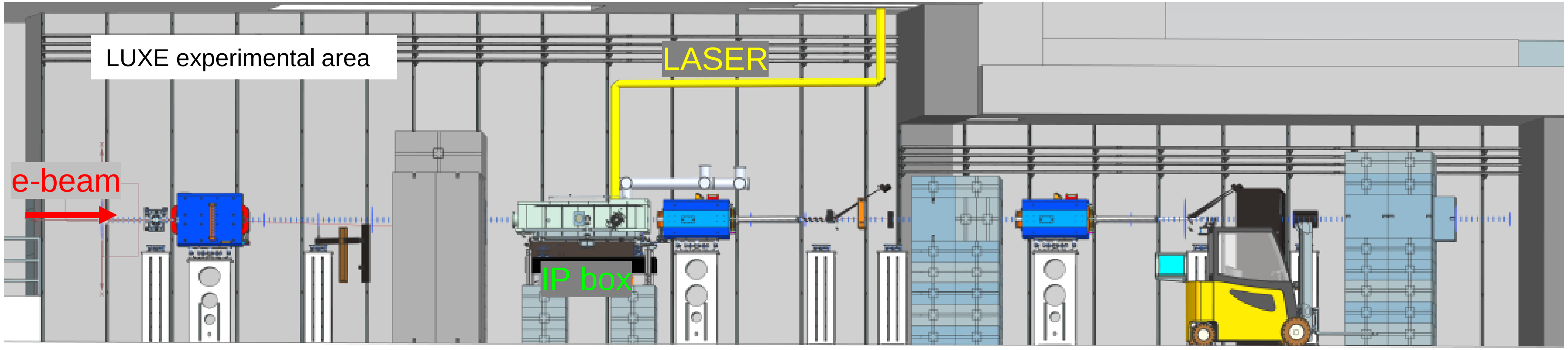
$$I = \frac{E_L}{\Delta t \pi d^2}$$

E_L: laser energy (J)
Δt: pulse length (s)
πd^2 : focus area (m^2)

- high-intensity Ti:Sa laser system (chirped pulse amplification)
- LUXE Phase-0: existing 40TW system (JETI40, Jena) or custom laser, Phase-1: upgrade to 350TW
  → scan SFQED parameter space: variable laser spot size
- electron boost: current state-of-the-art in laser intensity is sufficient
  → need exceptional shot-by-shot stability!

LUXE beamline

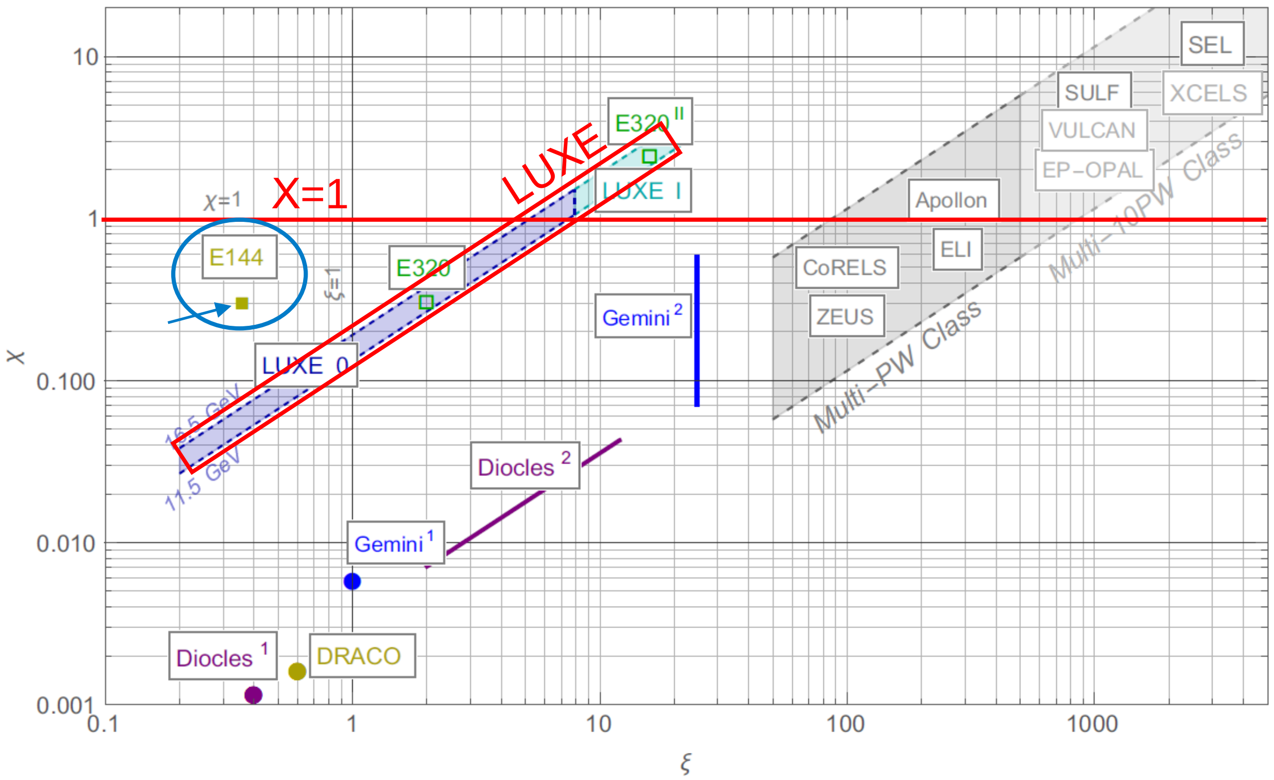


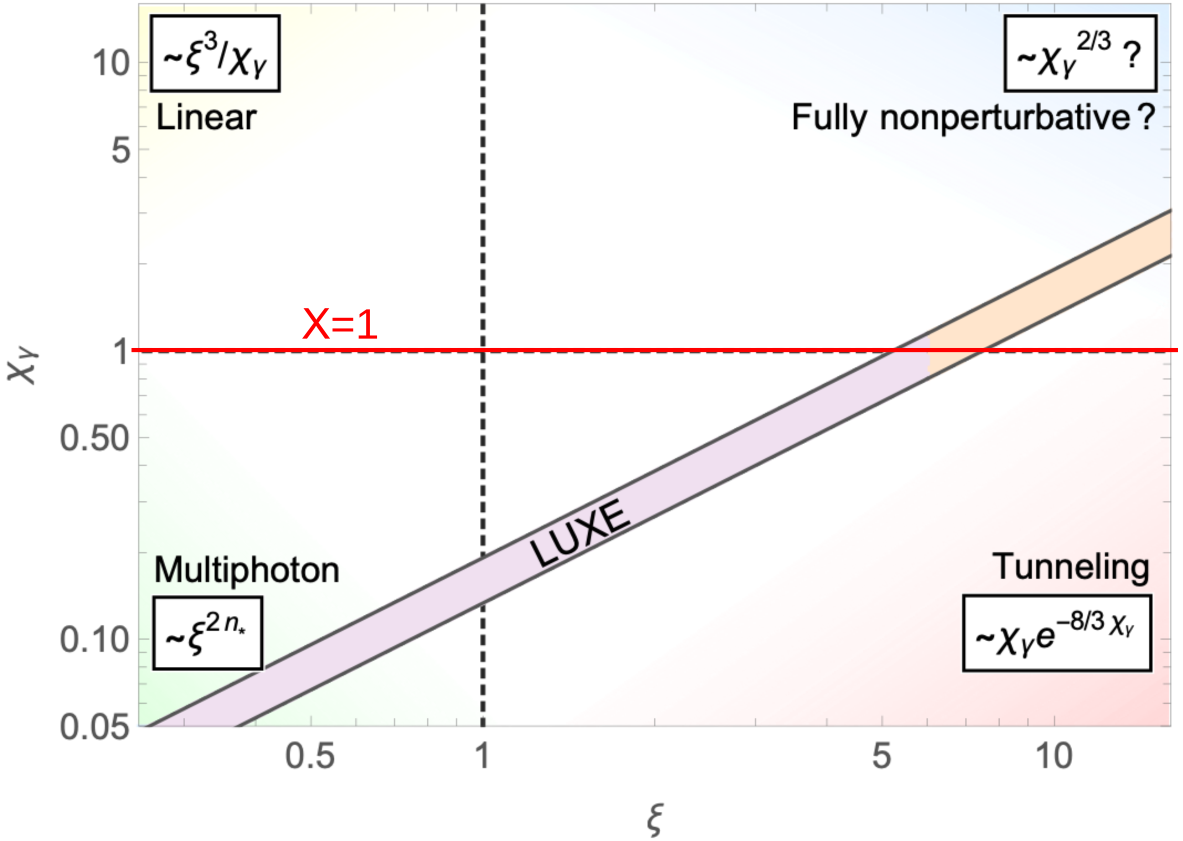


- LUXE uses high-quality 16.5 GeV EuXFEL electron beam before undulators
- experiment location exists: annex for future second EuXFEL fan(~2030's+)
  → unique possibility to build and operate LUXE before that!
- extract 1 bunch (out of 2700 bunches) per XFEL train for LUXE
  → design goal: transparent to XFEL photon science!

XFEL e^- Beam Properties important for LUXE	
Energy	16.5 GeV
#electrons/bunch	$1.5 \cdot 10^9$
repetition rate	10 Hz

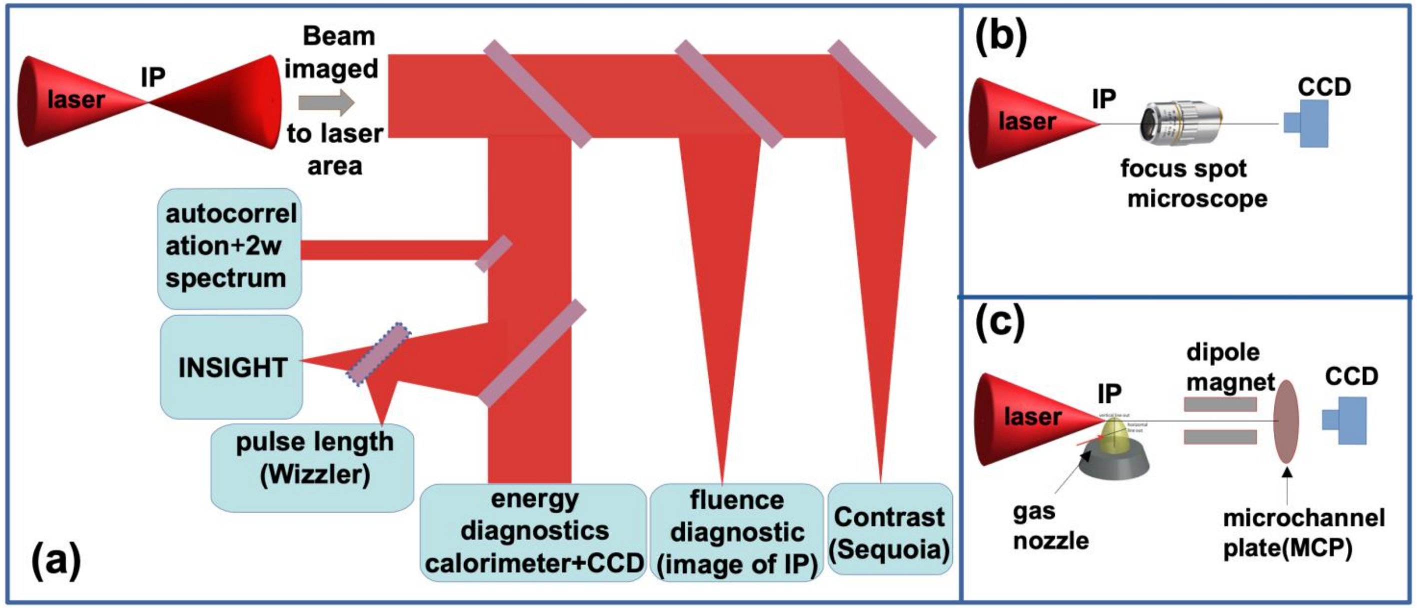
LUXE in Strong-Field QED Parameter Space

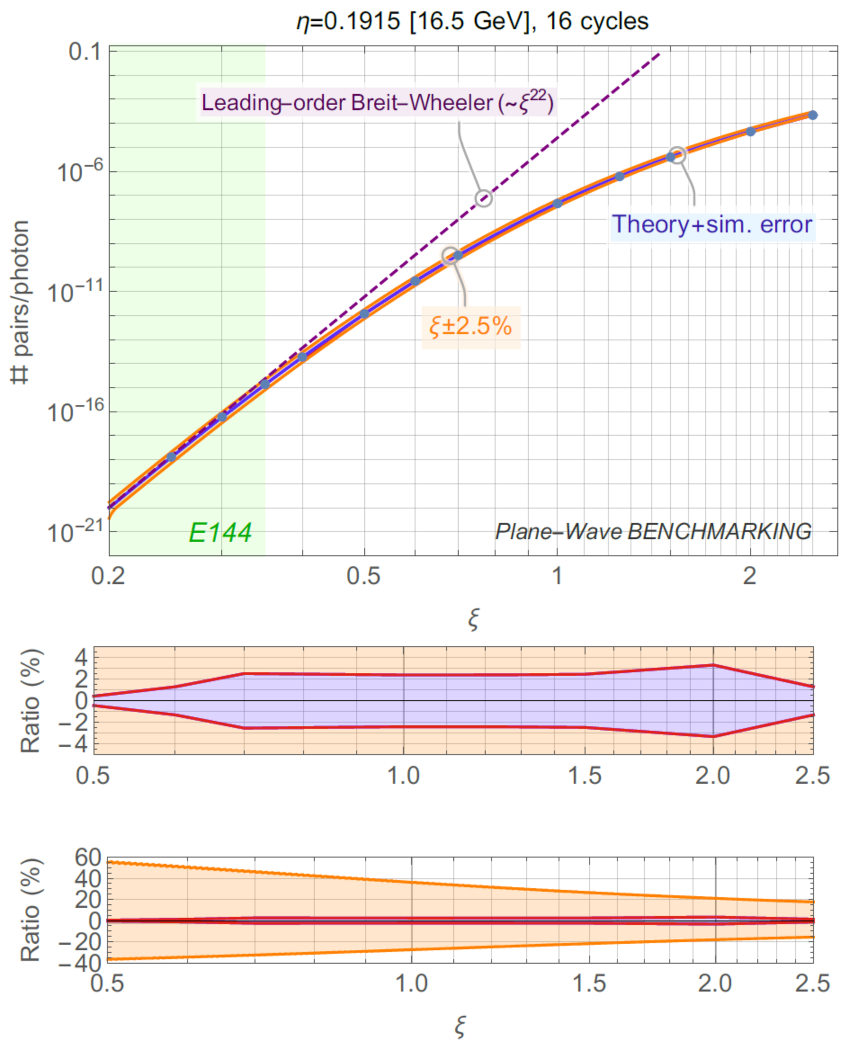




- experimental reach in SF QED parameter space (ξ, χ)
  → mainly determined by: particle beam energy, LASER intensity
- predecessor: E144 (SLAC e-laser collisions, 1990's) reached power-law regime, but not departure
  → LUXE: three orders of magnitude more powerful laser
- LUXE unique ability: continuous data-taking with variable laser spot size
  → precision mapping of SFQED parameter space in transition regime

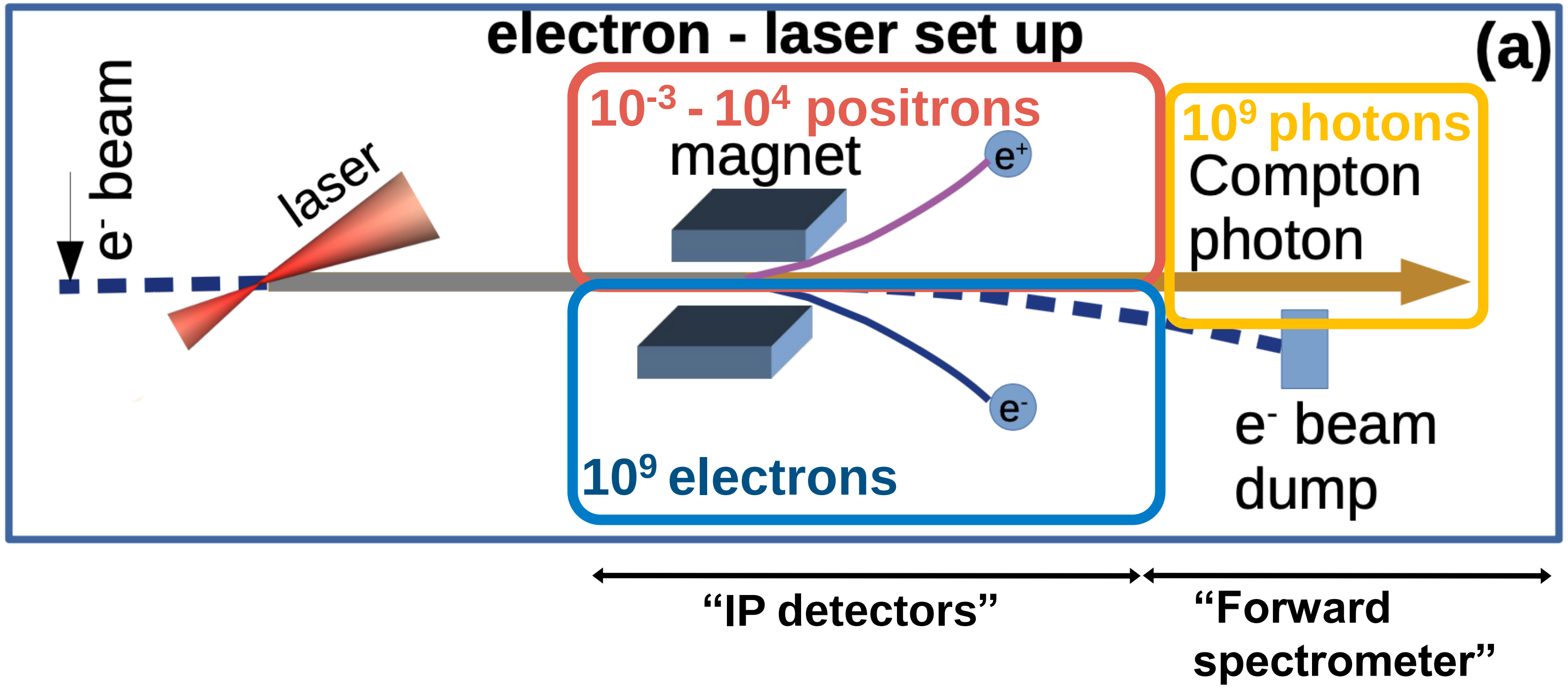
Laser Diagnostics





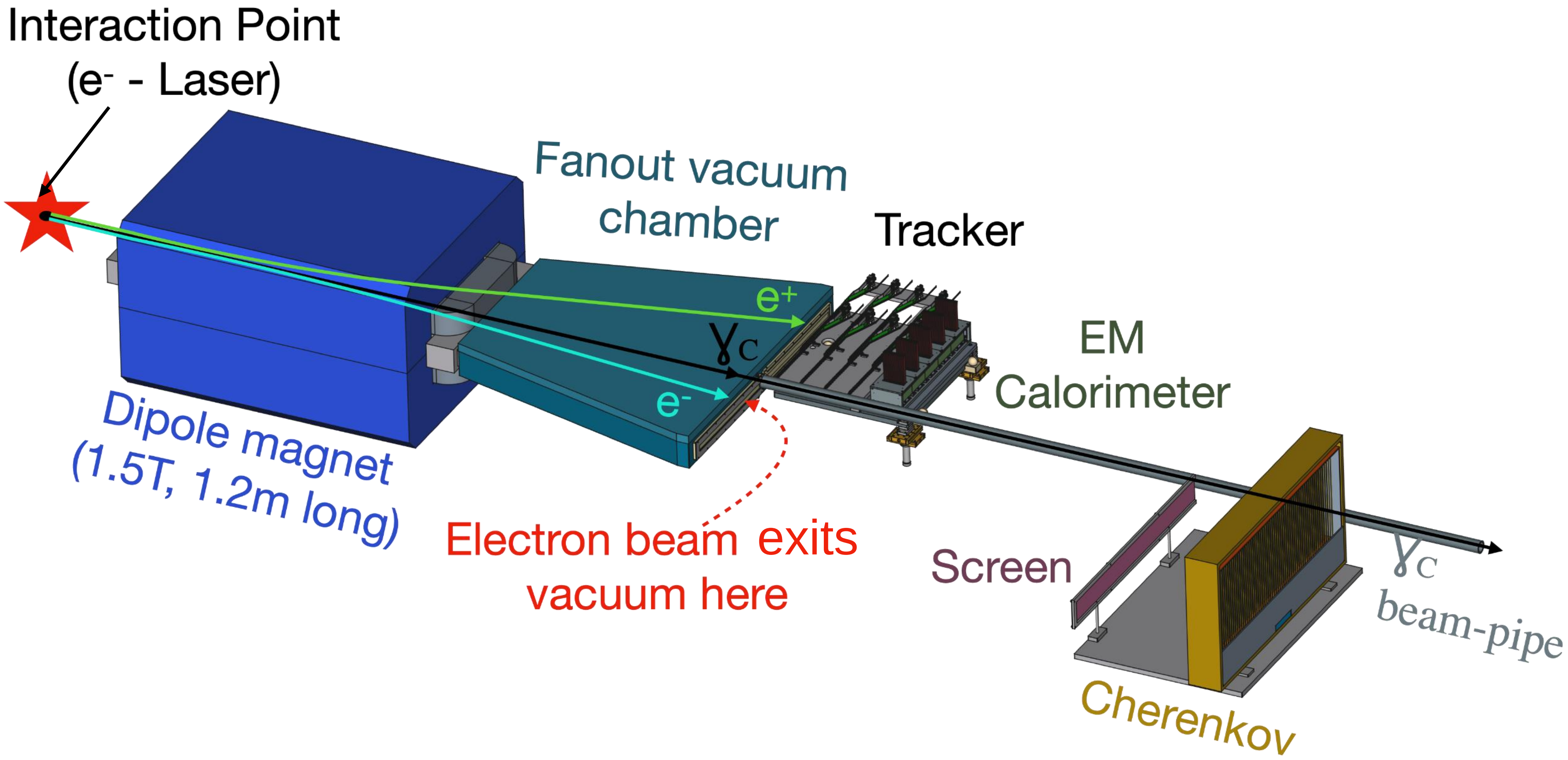
- LASER characterization quantities: energy, pulse length, spot size
- many (partially redundant) measurements planned
- LASER intensity uncertainty has a large impact on sensitivity!
- goal: ≤ 5% absolute uncertainty on LASER intensity, ≤ 1% shot-to-shot uncertainty

LUXE Particle Detectors



- goal: detection of electrons, positrons and photon fluxes and energy spectra
- particle fluxes vary between ~0.001 e^+ and 10^9 (e^- and ɣ) per laser shot!
- use technologies adapted to respective fluxes of signal and background

LUXE IP Detectors



Two complementary detector technologies per measurement
→ cross-calibration, reduction of systematic uncertainties

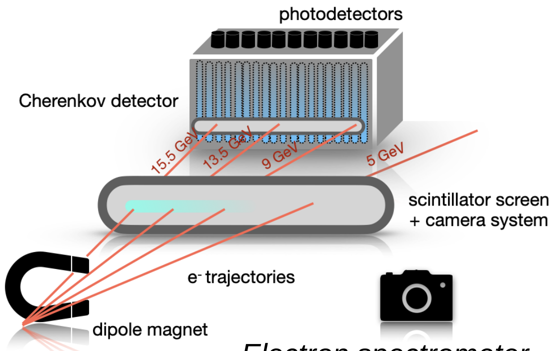
LUXE Particle Detectors

- e^+: Si pixel tracker,
  high-granularity Si-W calorimeter
  → high signal efficiency, momentum resolution

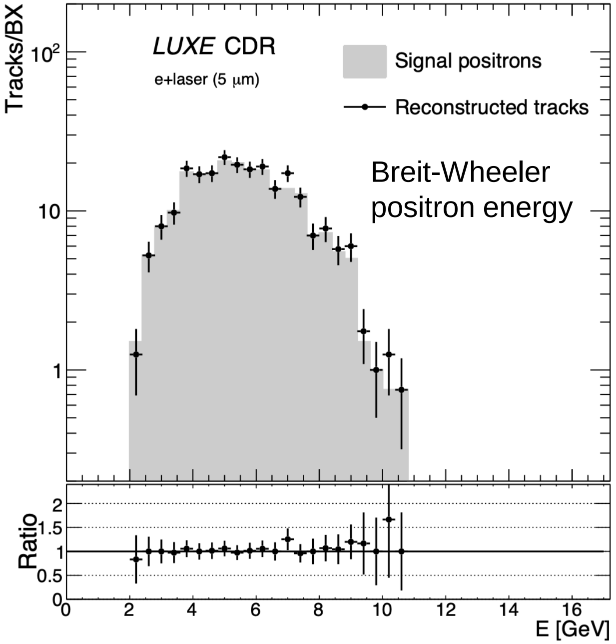
- e^-: scintillation screen & camera system,
  Cherenkov detectors
  → high rate tolerance, background rejection

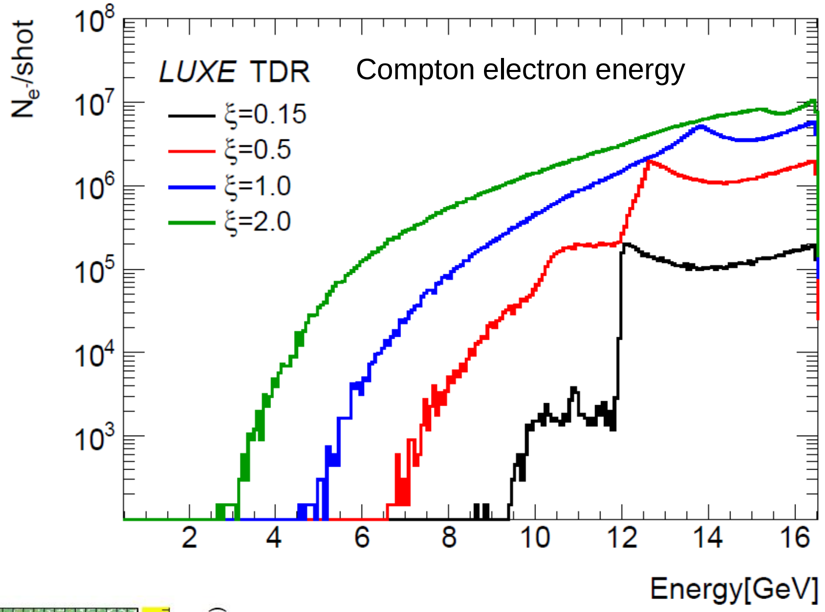
- γ: sapphire strip beam profiler,
  conversion spectrometer
  lead-glass flux monitors
  → complementary ξ measurement

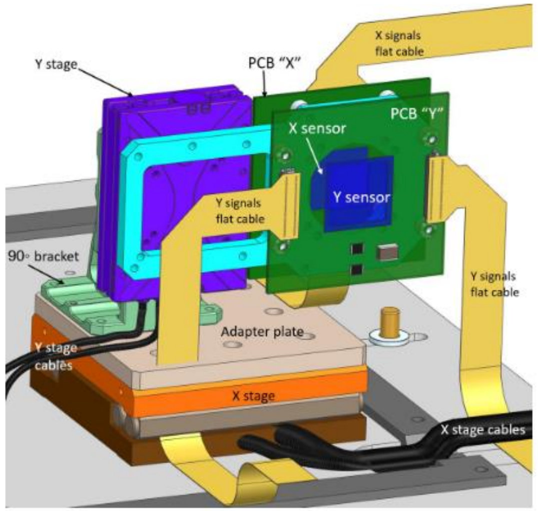
ALPIDE tracking detector stave



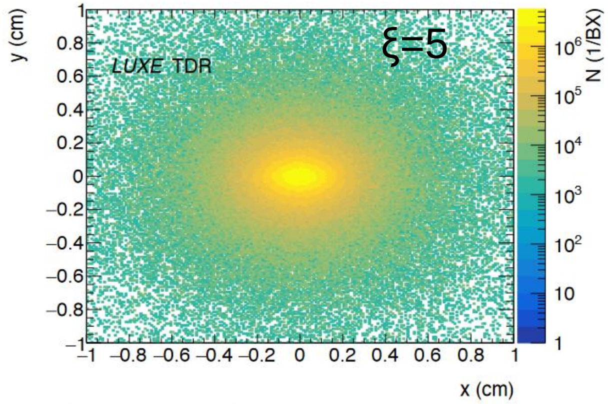
Electron spectrometer

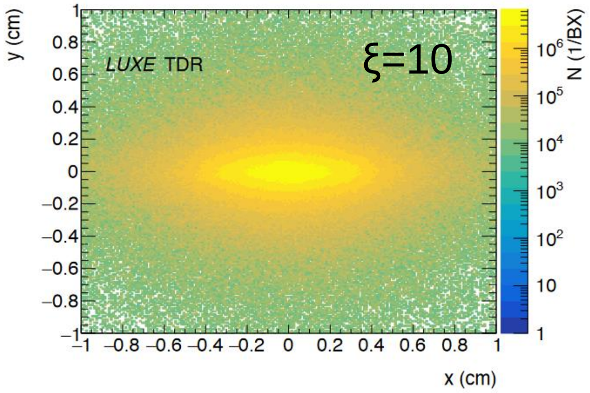






Gamma Beam Profiler





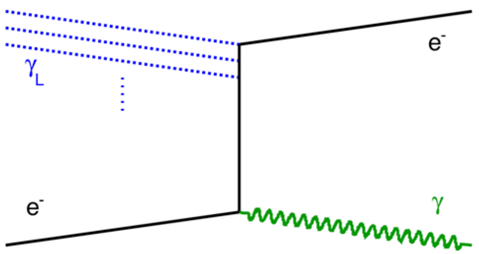
Talk by A. Athanassiadis
T98: today, 18:15

LUXE: interesting near-term application for new detector technologies

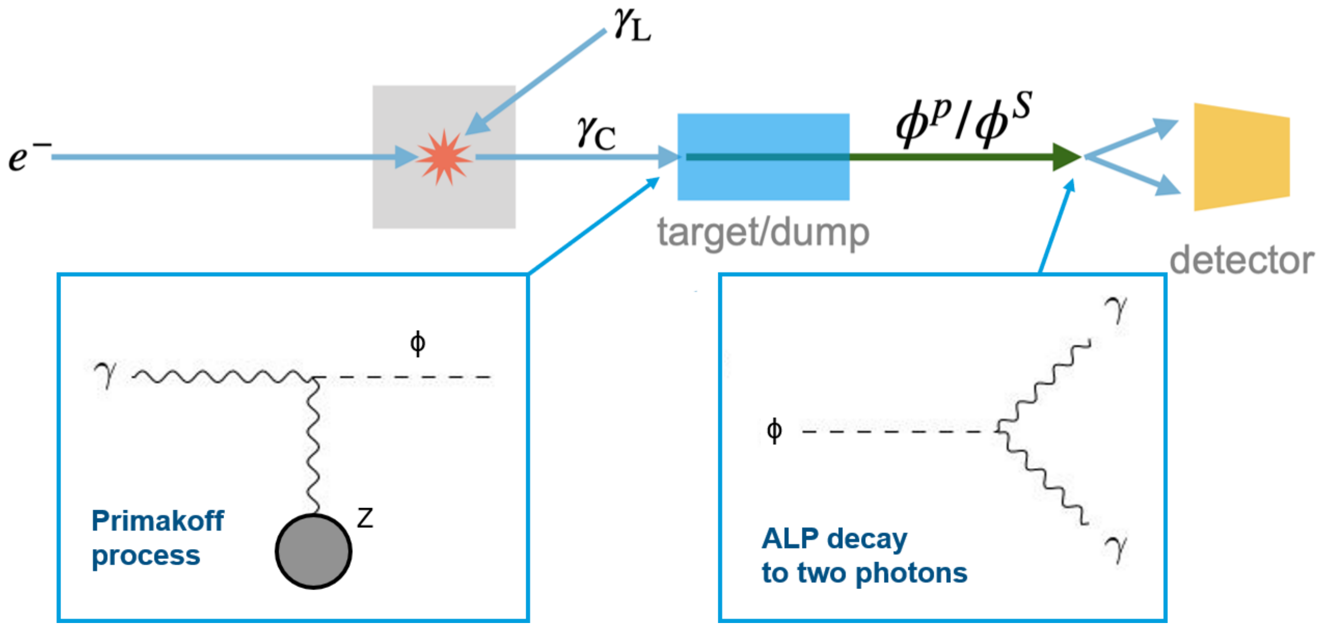
arXiv:2107.13554

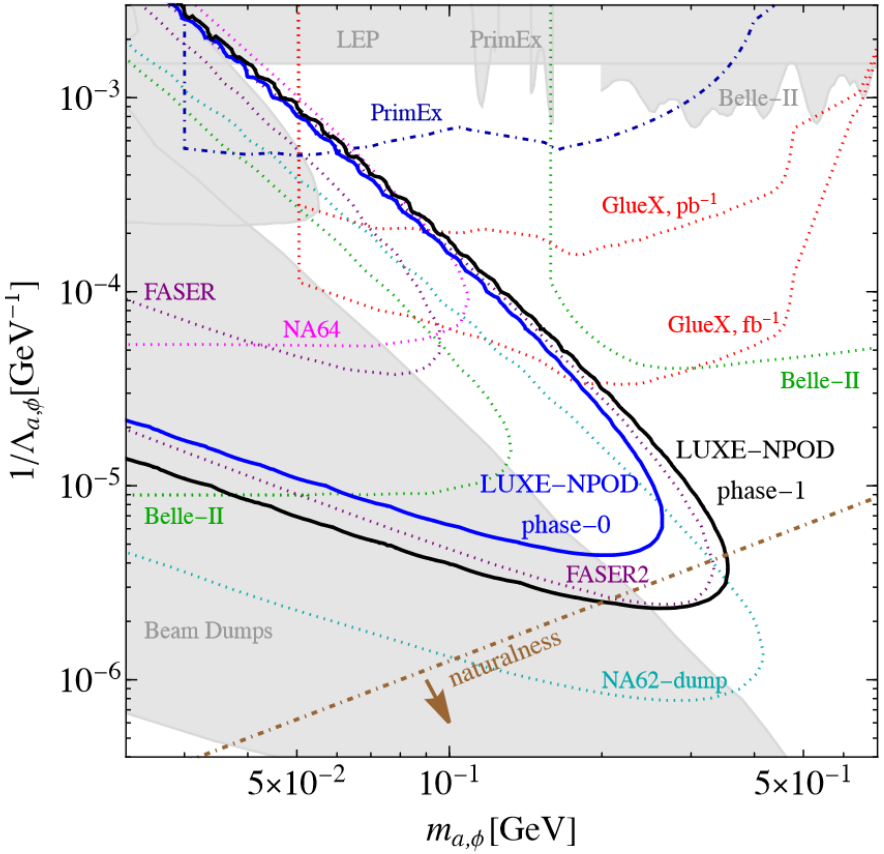
Bonus: LUXE BSM Searches (LUXE-NPOD)

- LUXE will produce a high-intensity photon beam through Compton Scattering
  → produce e.g. axion-like (ALPs) in photon beam-dump
  → detect via new particle decay to two photons
- production of new particles also possible in primary electron/LASER interaction
- conceptual design of photon detector with pointing capabilities ongoing
  → similar technologies applicable as e.g. in SHiP



Non-linear Compton Scattering
$e^- + n\gamma_L \rightarrow e^- + \gamma_C$





LUXE-NPOD sensitivity to sub-GeV ALPs competitive with other experiments ongoing and in planning

CDR: *EPJST.* **230**, 2445–2560 (2021)

LUXE Status & Planning

- LUXE initiated in 2017
- 2023: international collaboration of ~20 institutional members,
  → significant contributions by external partners
- approval process at DESY and EuXFEL is progressing
- experiment funding: pursuing several options
- foresee staged construction in EuXFEL shutdowns:
  → depending on approval time scale, earliest data-taking
  could start in 2026
- extensive material on technical design and planning available
  → consolidation into TDR ongoing

Summary

- LUXE will explore QED in uncharted regime
  - observe transition from perturbative to non-perturbative QED
  - directly observe pair production from real photons
  - complementary approach to other ongoing SFQED experiments
  - search for BSM physics with photon beam dump

- goal: installation starting in 2025 during extended shutdown planned for European XFEL
  - very diverse detector technologies, optimized for LUXE physics goals
  - ideal testbed for new technologies e.g. for future colliders

More documentation?

LUXE CDR: arXiv:2102.02032

LUXE website: https://luxe.desy.de

LUXE: exciting window of opportunity for a near-term new particle physics experiment

Open to new collaborators!

Contact

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Backup

SFQED parameters

Intensity parameter:

$$\xi = \sqrt{4\pi\alpha}\left(\frac{\mathcal{E}_L}{\omega_L m_e}\right) = \frac{m_e \mathcal{E}_L}{\omega_L \mathcal{E}_{cr}}$$

- measure of coupling between probe and Background (laser) field (also: square root of laser intensity)
- $\xi \geq 1$: non-perturbative regime

Note:

$\mathcal{E}_L$: Laser field
$\mathcal{E}_{cr}$: Schwinger critical field

θ: Laser - probe crossing angle

ω_L: Laser frequency

$E_{e/\gamma}$: probe electron (photon) energy

Quantum parameters:

$$\chi_e = (1+\cos\theta)\frac{E_e}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

$$\chi_\gamma = (1+\cos\theta)\frac{E_\gamma}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

- ratio of background laser field and Schwinger critical field
- $\chi \geq 1$: non-linear quantum effects become probable (e.g. pair production)

Energy Parameter

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

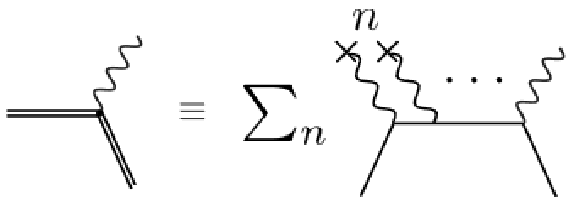
- (dimensionless) energy of collision between probe particle and background

Different combinations of ξ and χ result in different types of non-linear behavior!

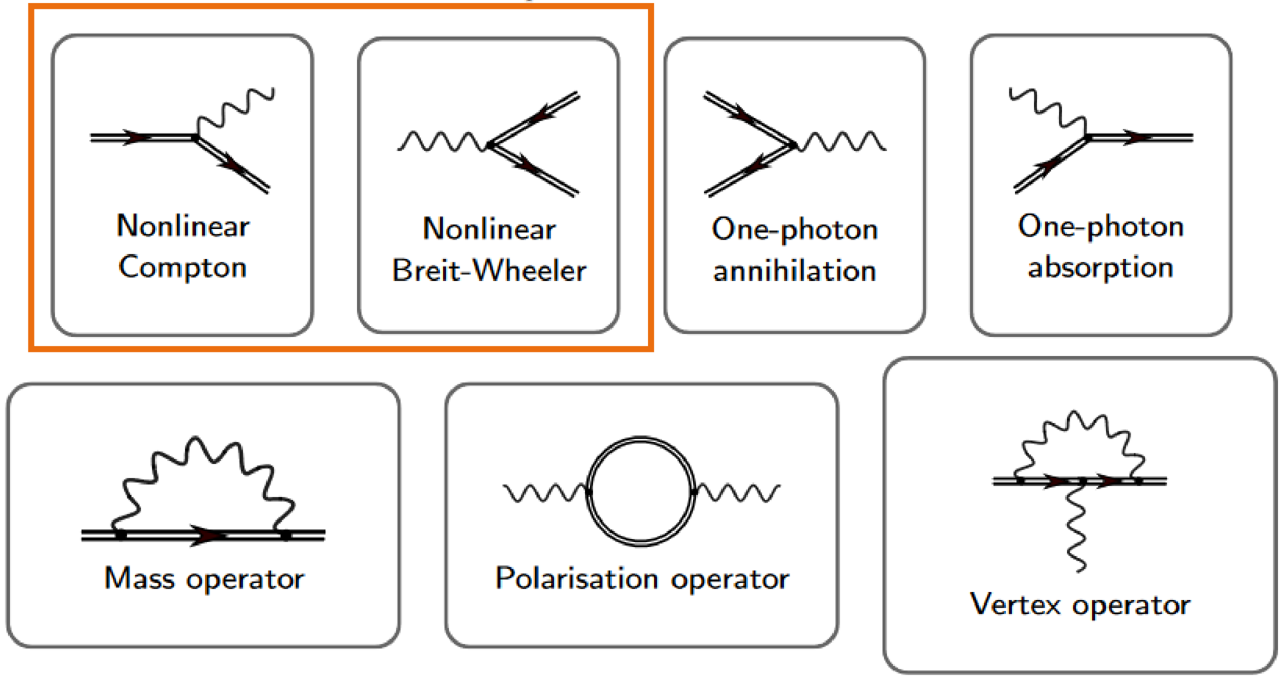
The Furry picture

- How to do calculations? Solve equations of motion (Dirac equation) in field background
  → analytical solutions exist in plane wave background („Volkov wave functions")
- derive Feynman rules for „dressed" states („Furry expansion")
  → treat background exactly, particle scattering perturbatively ($\alpha \ll 1$)

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\left(i\not{D} - m\right)\psi}_{\text{'unperturbed'}} \underbrace{-e\bar{\psi}\not{A}\psi}_{\text{interaction}},$$



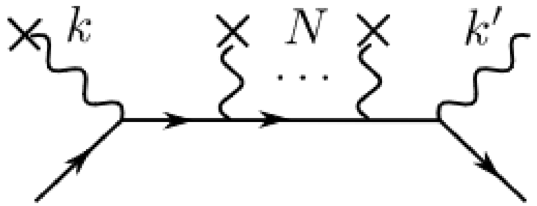
„dressed" state



Compton scattering in strong fields

[Link](#) to QU lecture by Ben King
Review paper: A. Fedotov et al, 2203.00019 [arXiv:hep-ph]

- Consider Compton scattering in plane-wave background field: $A(x) = A_0 \sin(k \cdot x)$



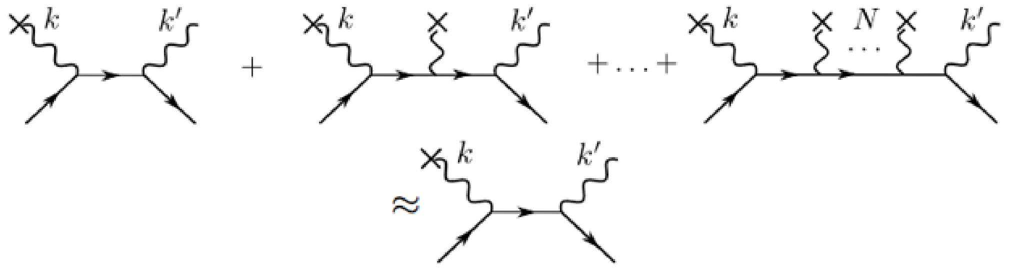
$+$ exchange diagram

fine structure constant

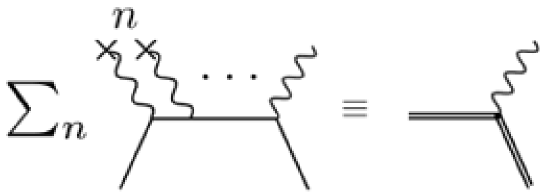
Probability $P \sim \alpha \left(\frac{eA_0}{m}\right)^{2N} = \alpha\xi^{2N}$

$$\xi = \frac{eA_0}{m}$$

'Classical nonlinearity / intensity parameter', ξ.



"weak" field $\xi < 1$



'Nonlinear' Compton scattering

strong field: $\xi \geq 1$

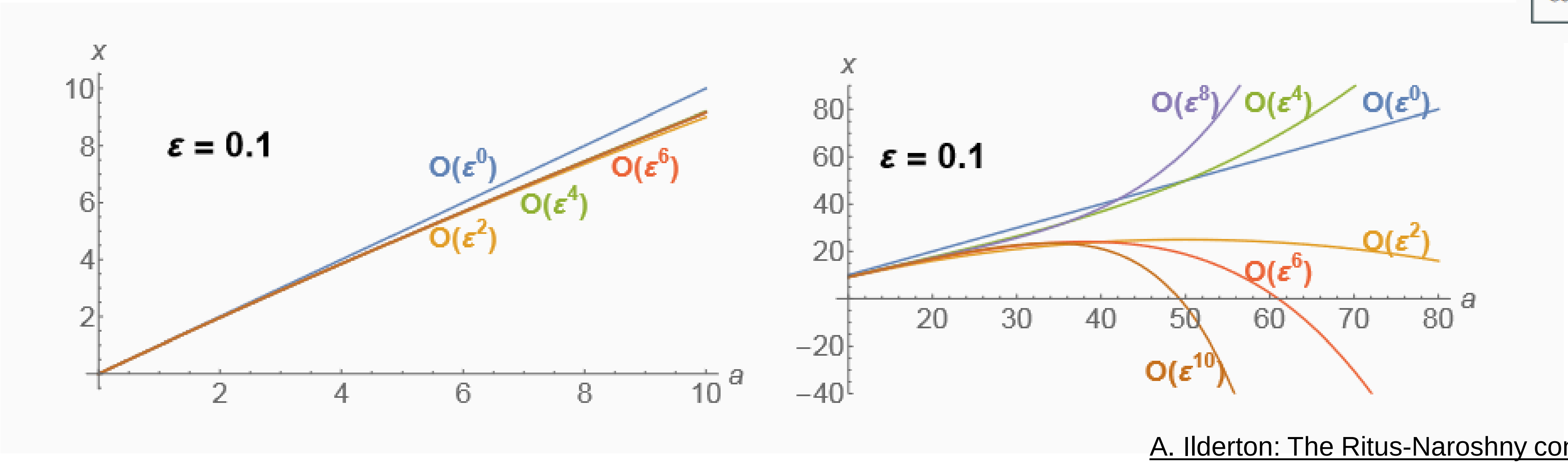
Strong field ($\xi \geq 1$): Need to take into account all order diagrams!

Ritus-Naroshny Conjecture

- Ritus-Naroshny Conjecture: in the vicinity of sufficiently strong fields, the Furry expansion breaks down
  $\rightarrow$ perturbative QED coupling α is modified by the field strength: $\alpha \rightarrow \alpha\chi^{2/3}$

- Conjecture interpreted to hold for any „locally constant“ background
  (field constant over formation length scale of physics process)

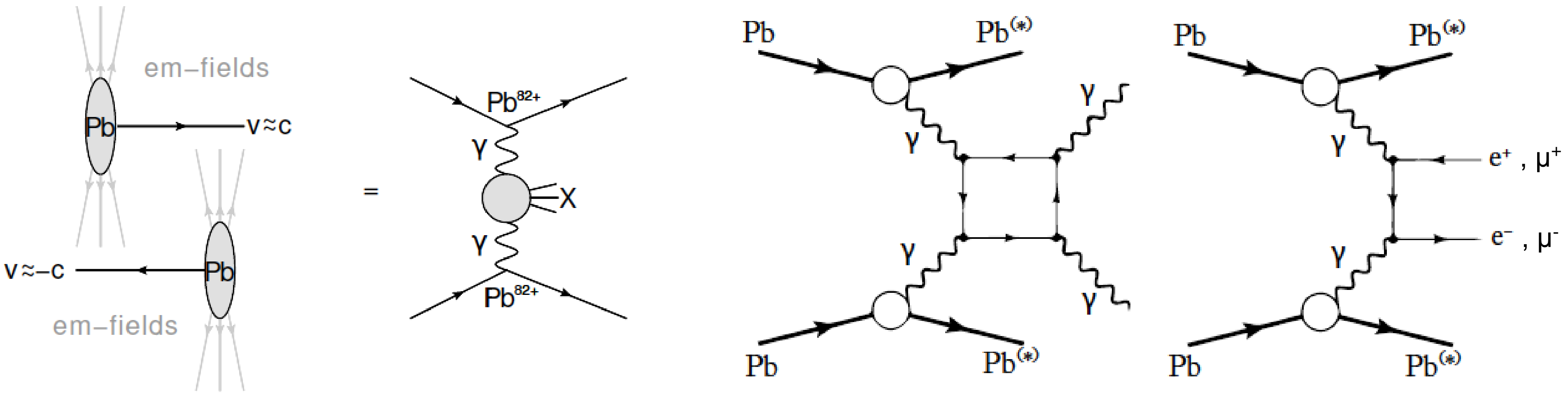
$$a \leftrightarrow a_0,\ \varepsilon^2 \leftrightarrow \alpha$$



A. Ilderton: The Ritus-Naroshny conjecture: A tutorial

How does LUXE relate to LHC light-by-light scattering?

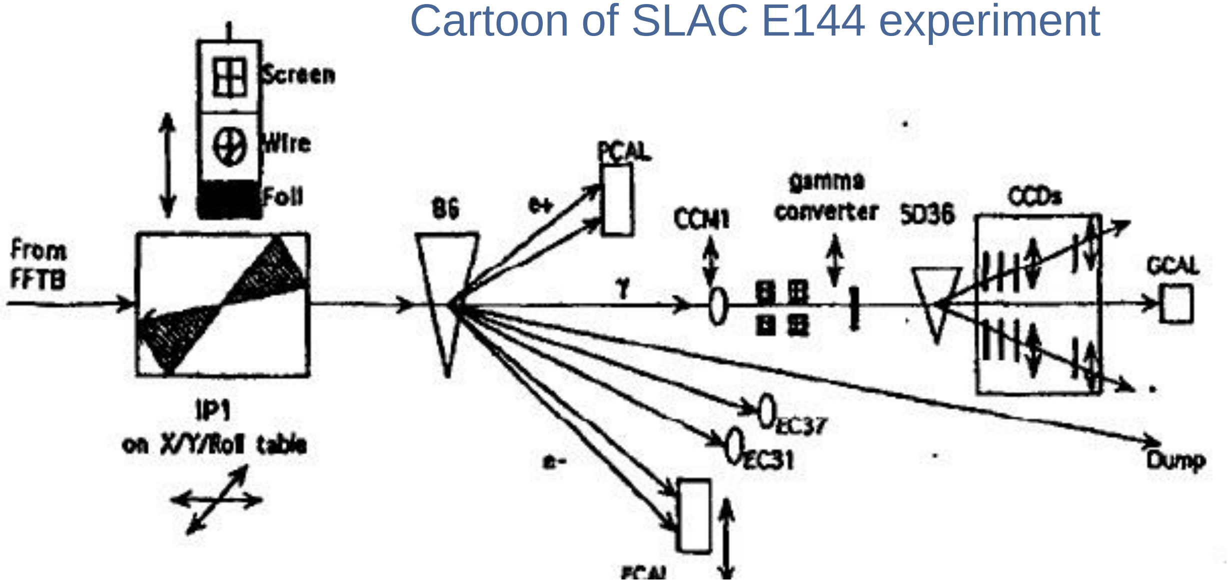
- LHC: photon-photon interaction in ultra-peripheral heavy-ion collisions (UPC)
  → e.g. $\gamma\gamma \to \gamma\gamma$, $\gamma\gamma \to \mu\mu$
- UPC: fields above the Schwinger limit can be reached in the lab
- main difference to LUXE: in UPC, EM field is extremely short-lived, cannot travel over macroscopic distances
- this regime is still covered by linear perturbative QED

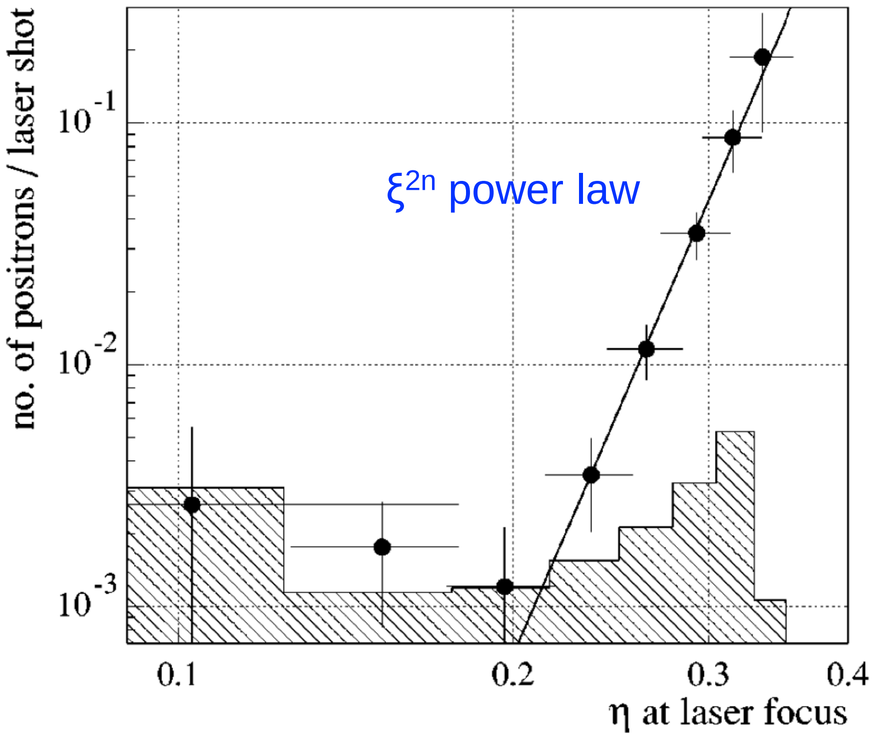


Figures from: arXiv:2010.07855v3
(Also a nice review to read, if you want to know more!)

E144 experiment at SLAC

Cartoon of SLAC E144 experiment



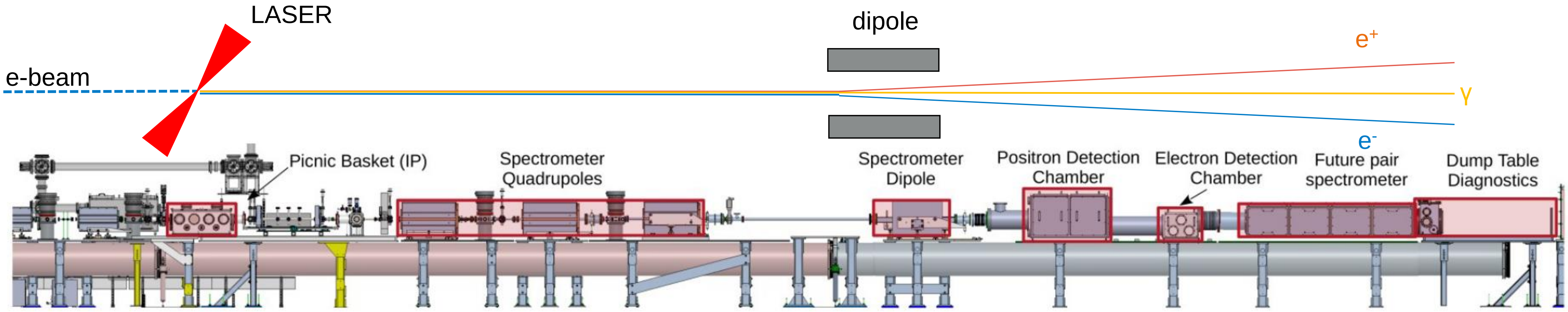


- E144: SLAC experiment in 1990's using 46.6 GeV electron beam (e+LASER only!)
- reached χ ≤ 0.25, ξ<0.4
- observed process $e^- + n\gamma_L \rightarrow e^-\ e^+e^-$
- observed start of the ξ^{2n} power law, but not departure

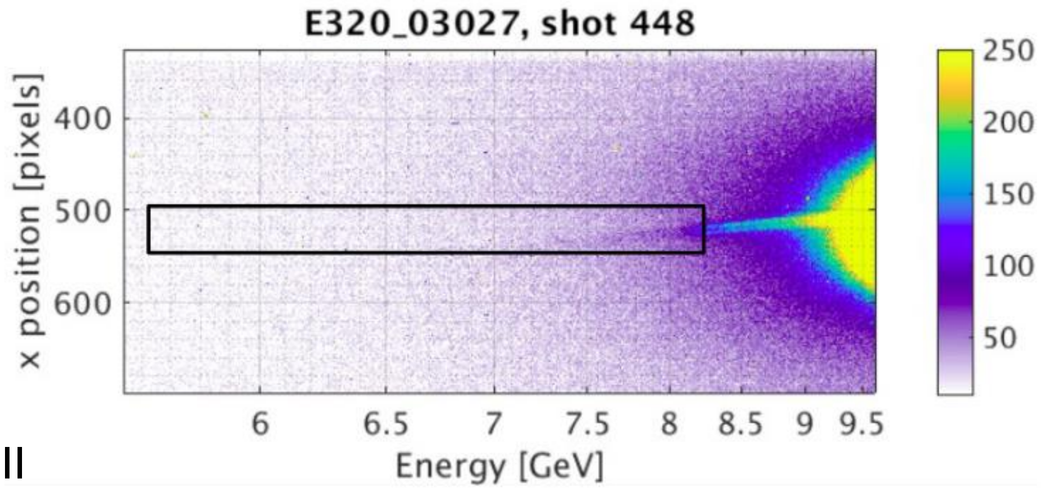
LUXE : Three orders of magnitude more powerful laser than E144, will enter non-perturbative regime

E-320 experiment at SLAC

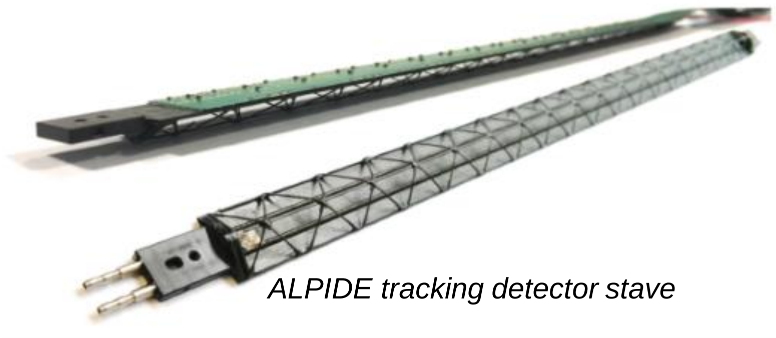
Link to E320 overview by S. Meuren



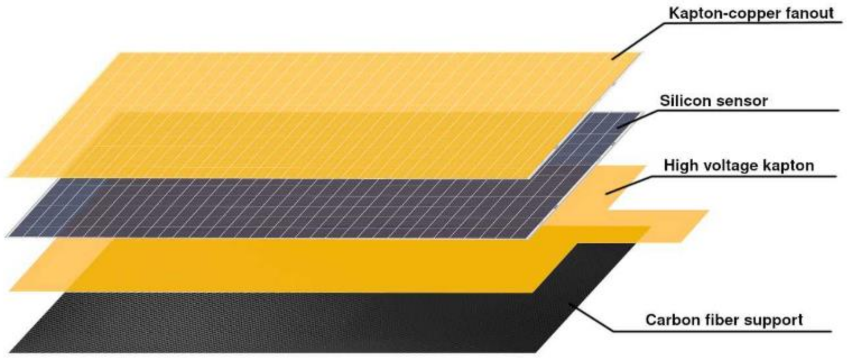
- E320: ongoing SF-QED experiment at SLAC using 13 GeV electron beam (FACET-II) and 16 TW optical Laser
- first electron-LASER collisions in 2022
- By design: similar parameter reach as LUXE (after Laser and Detector upgrades)
- Main differences to LUXE:
  - electron-Laser collision mode only
  - E-320 data-taking time limited due to other users of FACET-II



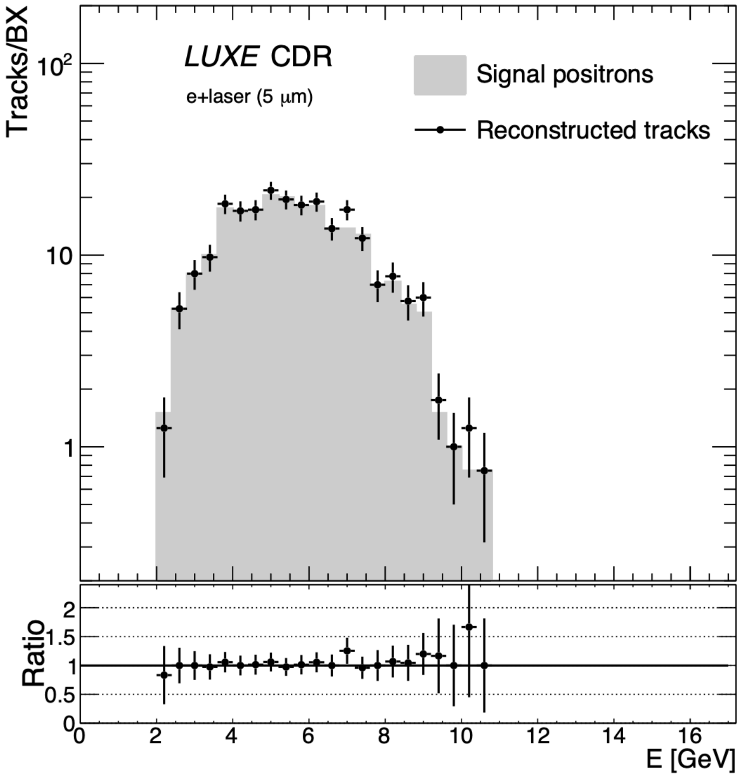
Positron Detection System



ALPIDE tracking detector stave



High-granularity ECAL layer



Silicon Pixel Tracker:

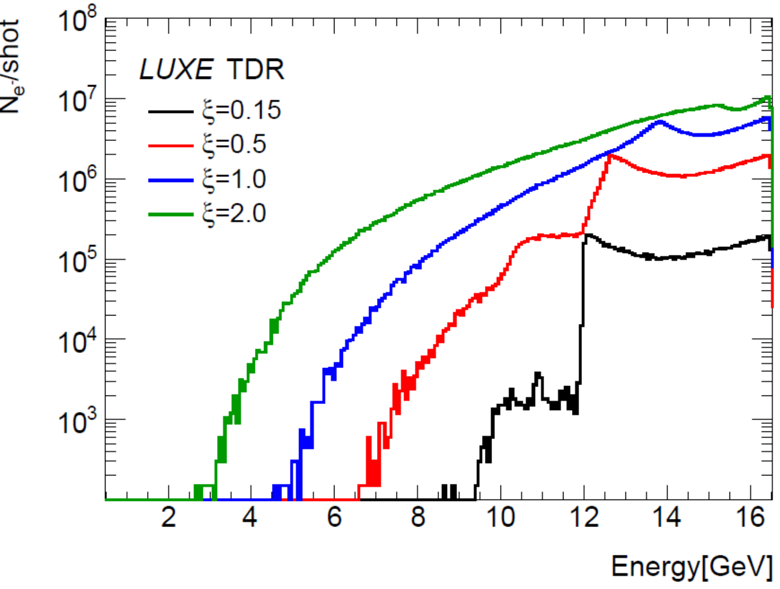
- four layers of ALPIDE silicon pixel sensors → developed for ALICE pixel tracker upgrade
- pitch size (27 x 29 μm), 5 μm resolution
- tracking: $\varepsilon > 98\%,\ \frac{\delta p}{p} \approx 0.3\%$
- very small background (<0.1 event / bunch crossing)

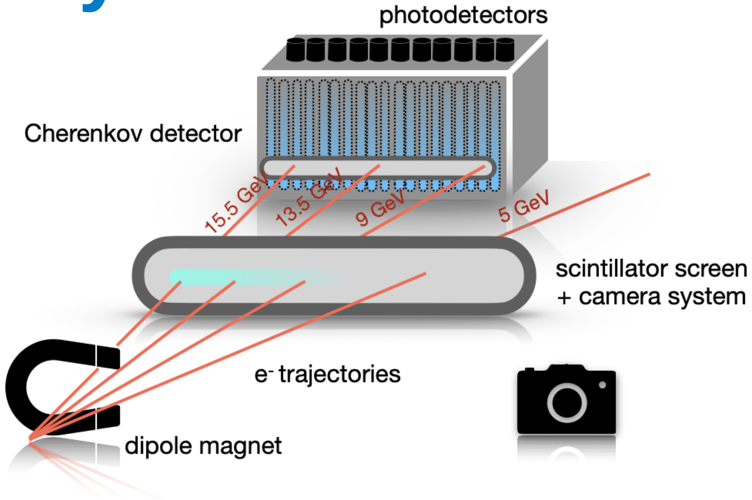
GaAs – Si High-granularity Calorimeter:

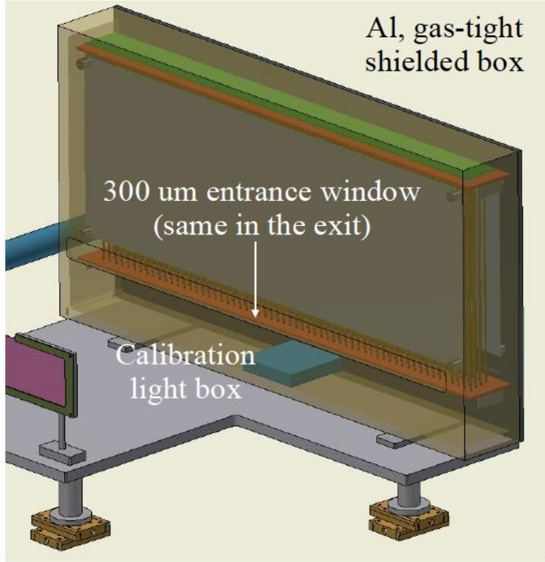
- 20-layer sampling calorimeter – high granularity: independent energy measurement through shower and position
- shower medium: 3.5mm Tungsten plates ($1X_0$), active medium: Silicon sensors ($5x5cm^2$, 320μm thick)
- read out by FLAME ASIC (developed for FCAL)

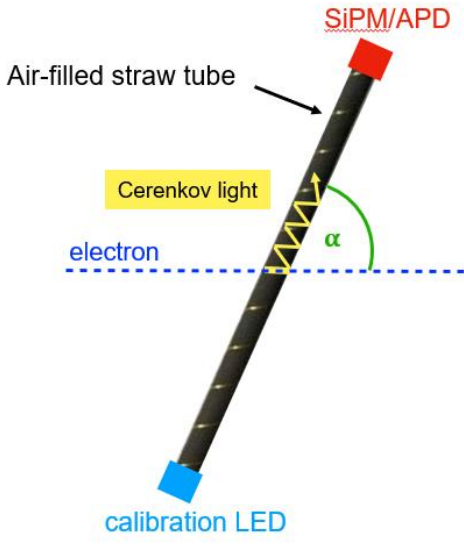
Positron detectors: High signal efficiency, high resolution!

Electron Detection System



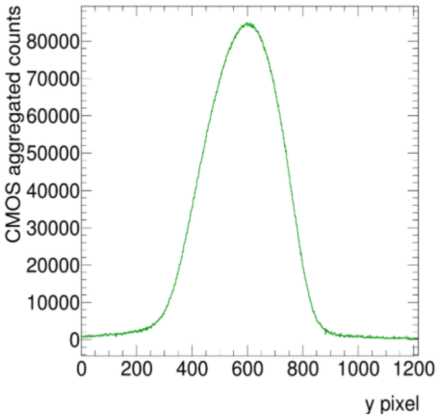


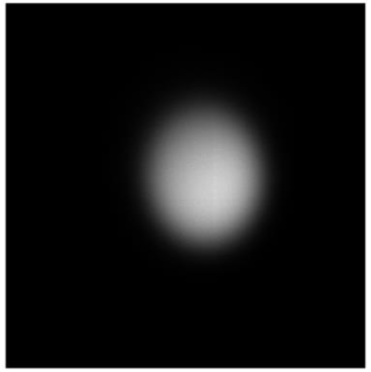




Scintillator screen (LANEX):

- camera takes pictures of scintillation light
- resolution of full system ~500µm





Beam spot imaged on Scint. Screen

Straw prototype

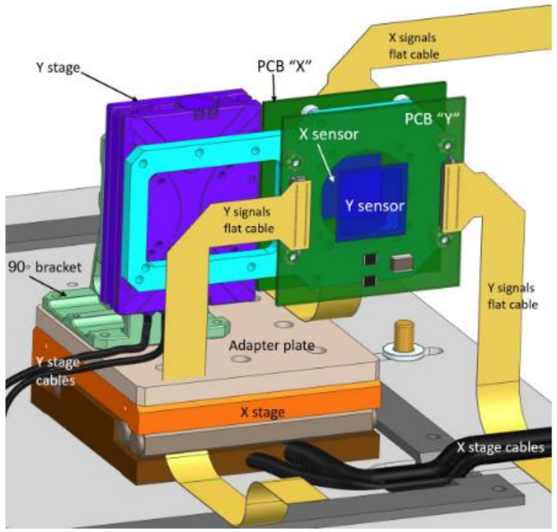
Cerenkov detector:

- finely segmented $(\emptyset = 4mm)$ Air-filled channel (reflective tubes as light guides) → charged particles create Cherenkov light
- Active medium Air: low refractive index - reduce light yield, suppress backgrounds (Cherenkov threshold 20 MeV)

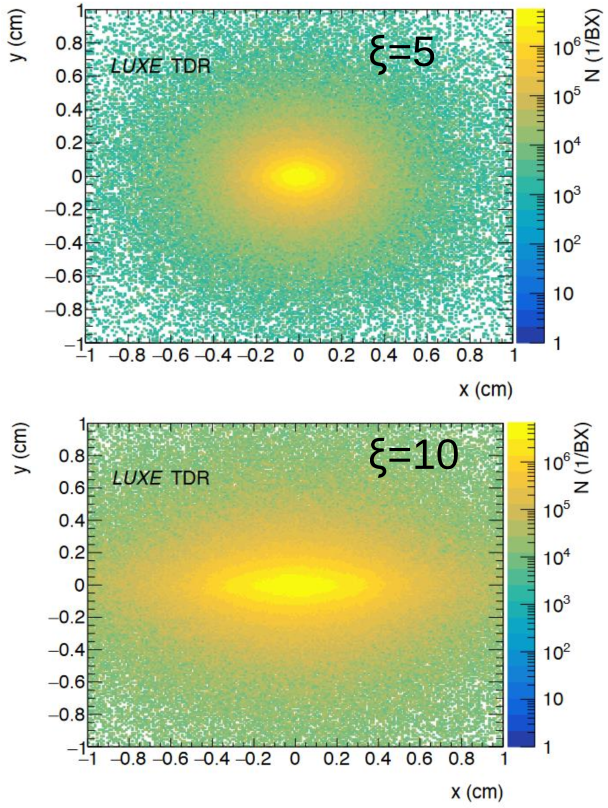
Electron detectors: High rate tolerance, large dynamic range!

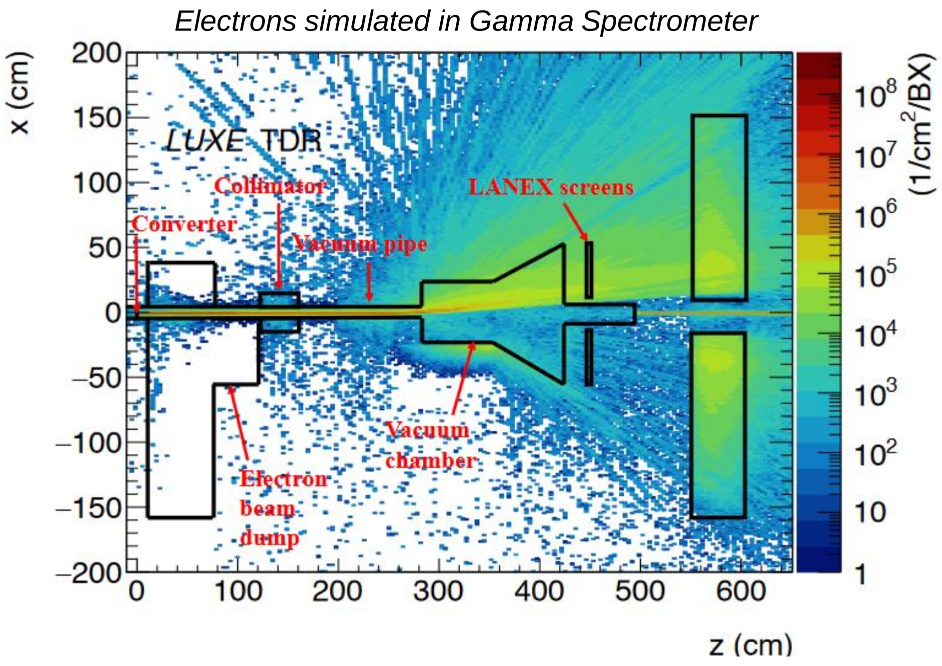
(→ talk by A. Athanassiadis, today 18:15, session T98)

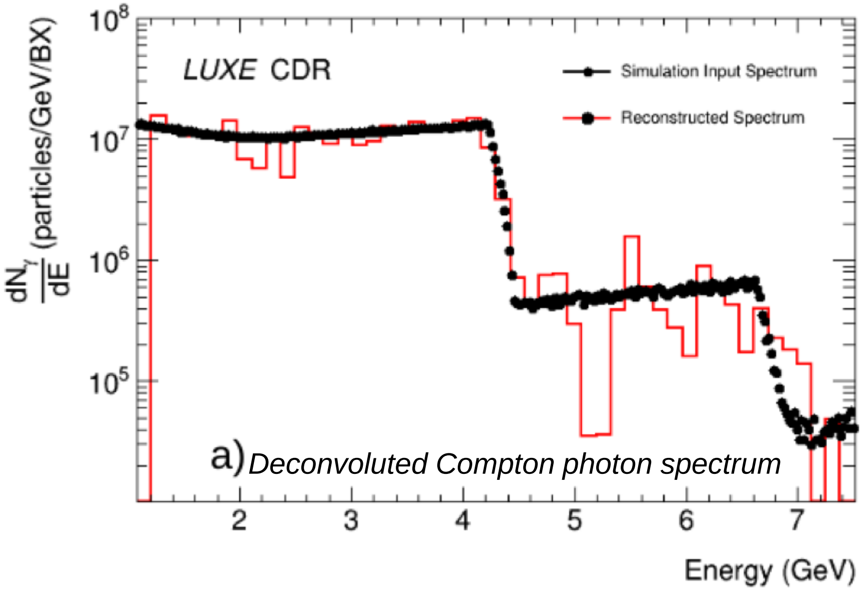
Photon Detection System



Gamma Beam Profiler





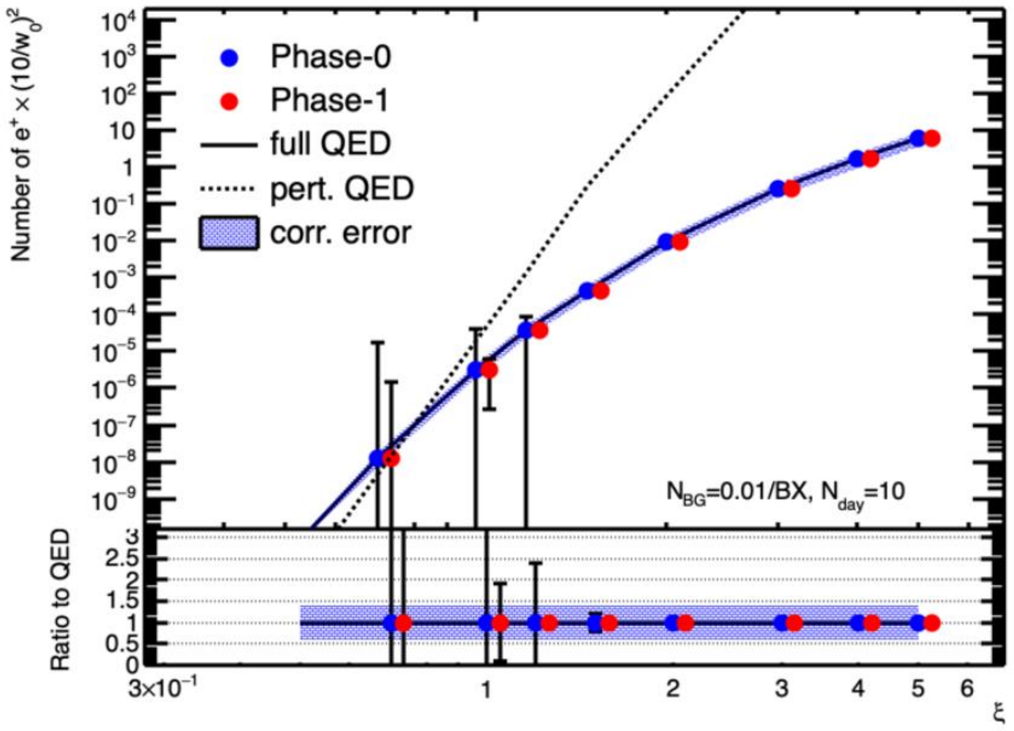


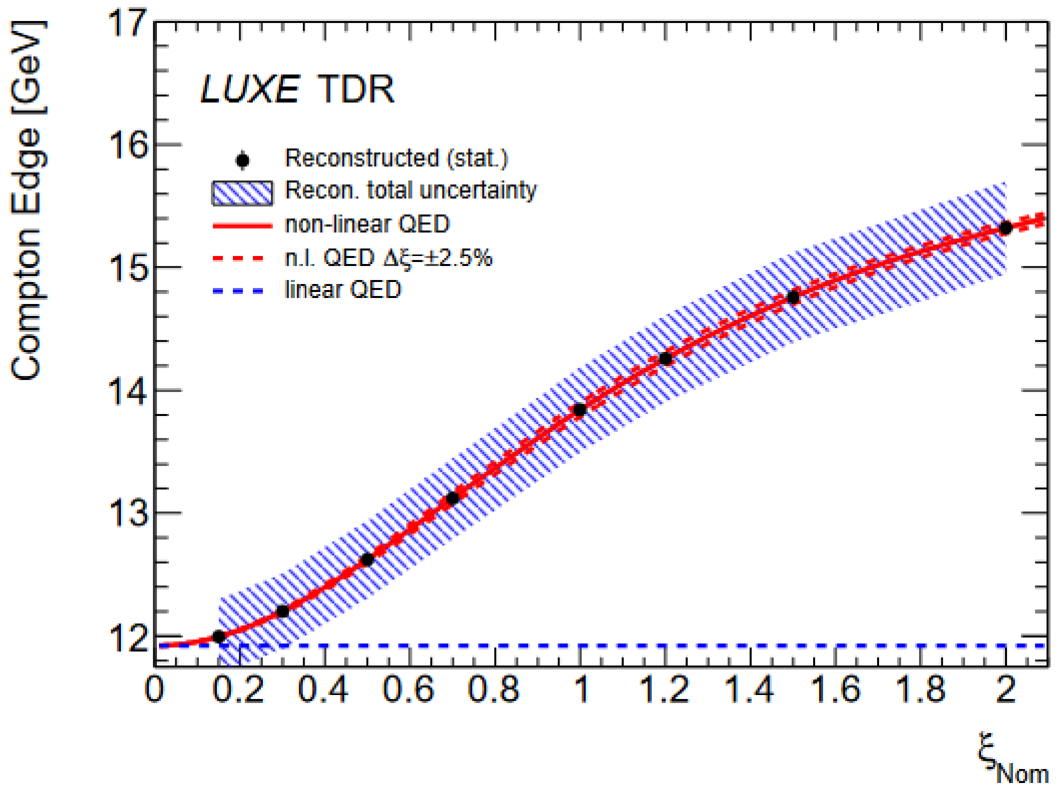
Gamma detector technologies:

- Gamma profiler (sapphire strips)
  → ɣ beam location and shape
  → precision measurement of Laser intensity
- Gamma spectrometer with scintillator screens behind converter
  → flux, energy spectrum ($\frac{\delta E}{E} < 2\%$)
- Gamma dump backscattering calorimeter → photon flux

Photon detectors: Precision measuremen of ξ, complementary to Laser diagnostics

Expected Results



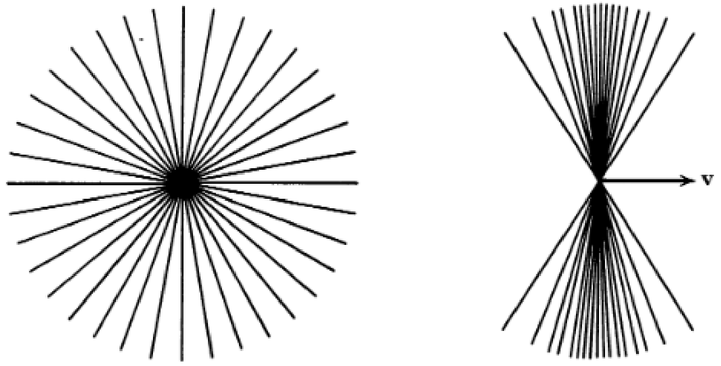


- Number of Breit-Wheeler pairs produced in photon-Laser collisions
- assuming 10dy of data-taking and 0.01 background events/ bunch crossing
- 40% correlated uncertainty to illustrate effect of uncertainty on ξ

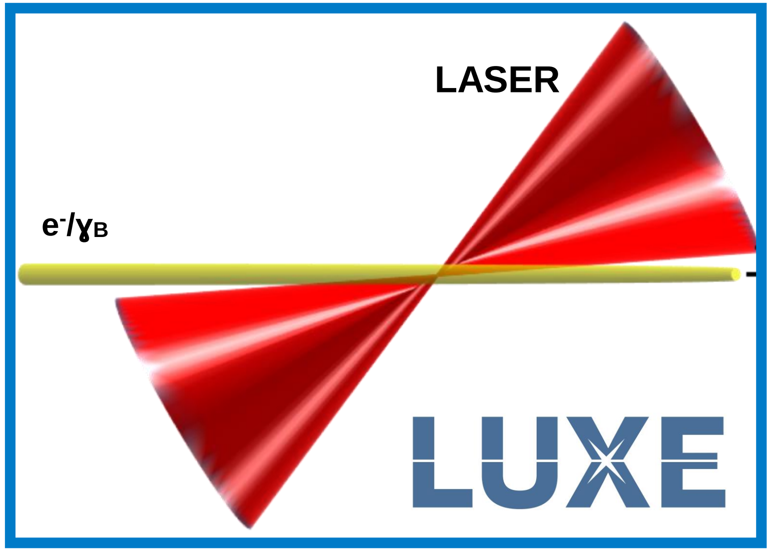
- Compton edge position as function of ξ in electron-laser collisions
- assuming 1h data-taking, no background
- 2% energy scale uncertainty to illustrate impact

SFQED with relativistic probes

- In the lab: reach fields at Schwinger limit in the rest frame of highly relativistic probe particles
  → LUXE: 16.5 GeV electrons + multi-TW optical LASER



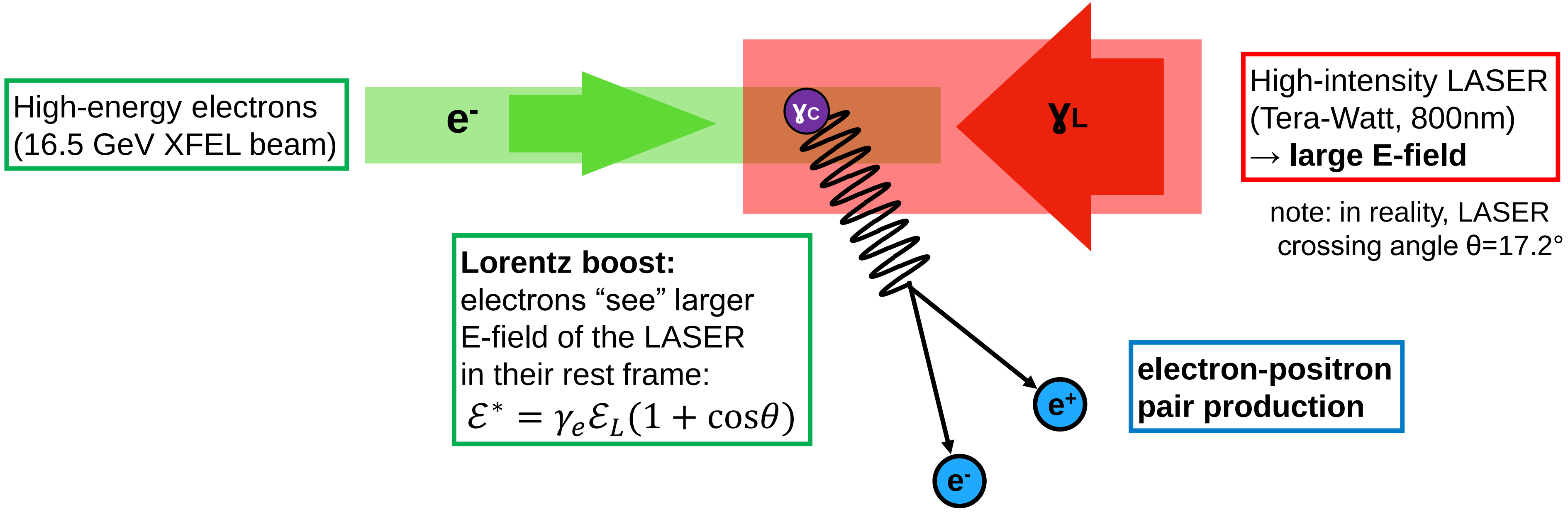
J. D. Jackson, *Classical Electrodynamics* 3rd. Edition



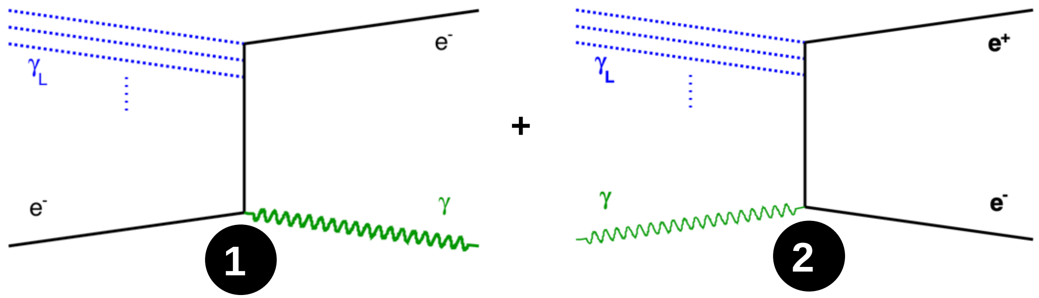
$$\mathcal{E}_{rest\ fr.} = \gamma \mathcal{E}_{lab\ fr.}$$

- Important consequence of having a relativistic probe:
  → any field background can be approximated as a plane wave

LUXE: Electron + LASER collisions



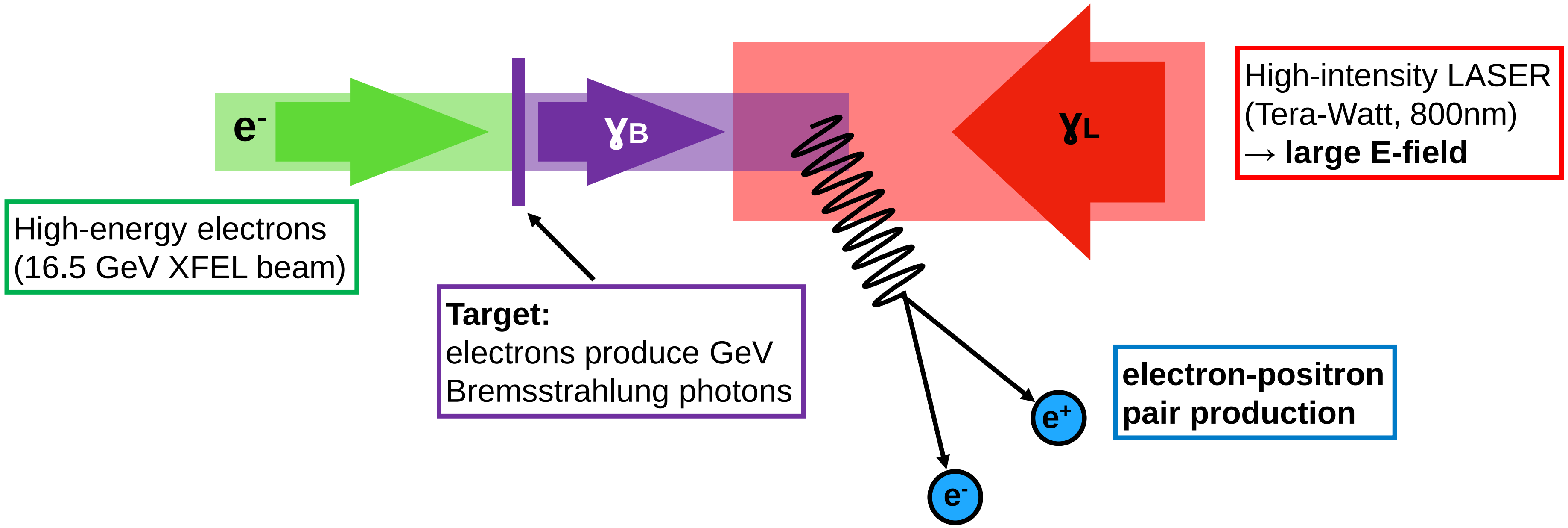
Physics processes:



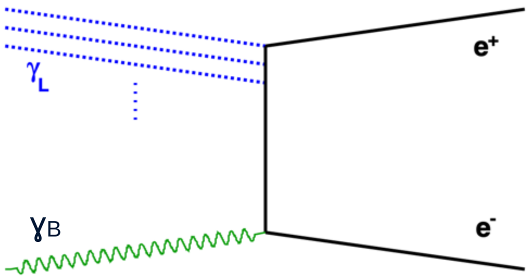
1. **Non-linear Compton Scattering:** $e^- + n\gamma_L \rightarrow e^- + \gamma_C$
2. **Non-linear Breit-Wheeler pair production :** $\gamma_C + n\gamma_L \rightarrow e^+ + e^-$

LUXE main goal: Measure positron rate as function of LASER intensity

LUXE: Photon + LASER collisions



Physics process:

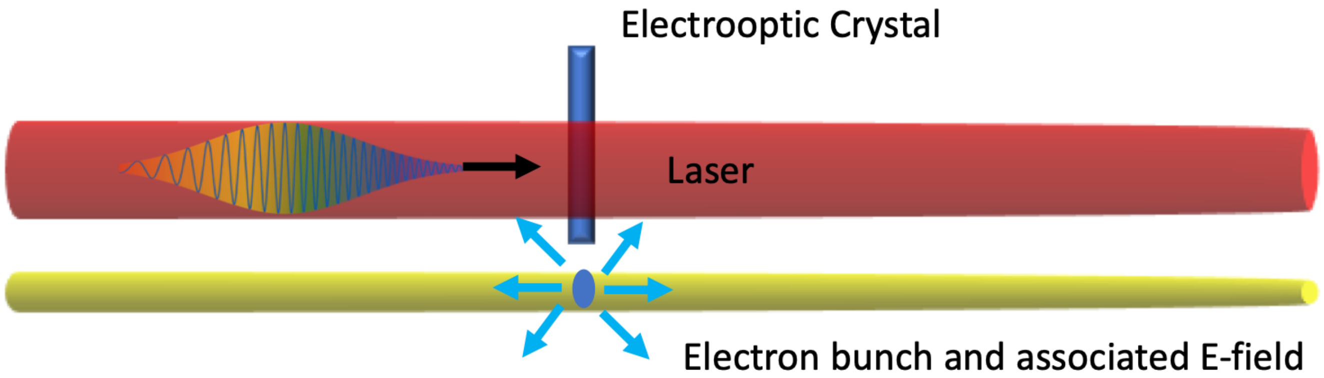


Non-linear Breit-Wheeler pair production : $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

LUXE: first SF-QED experiment to probe directly photon-photon interaction

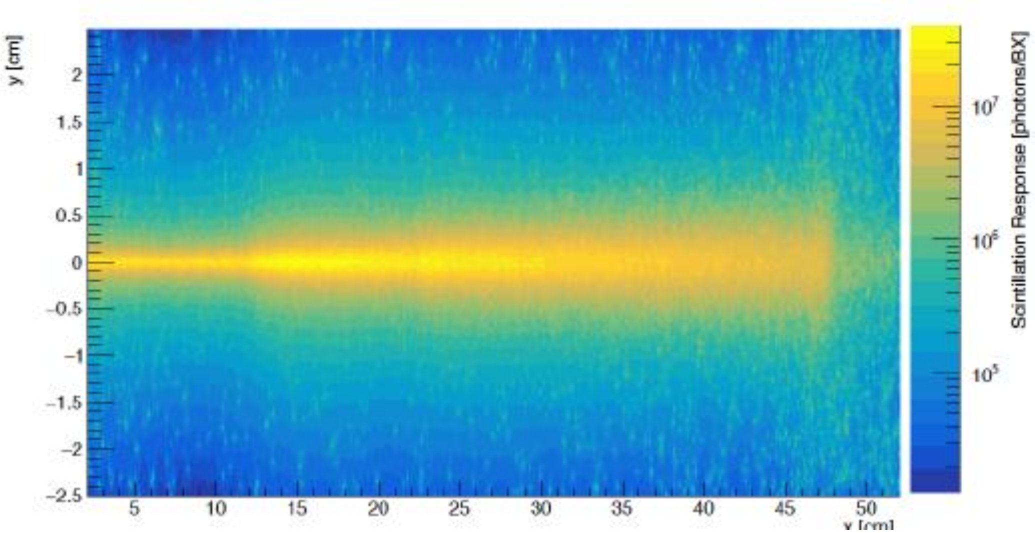
Synchronization

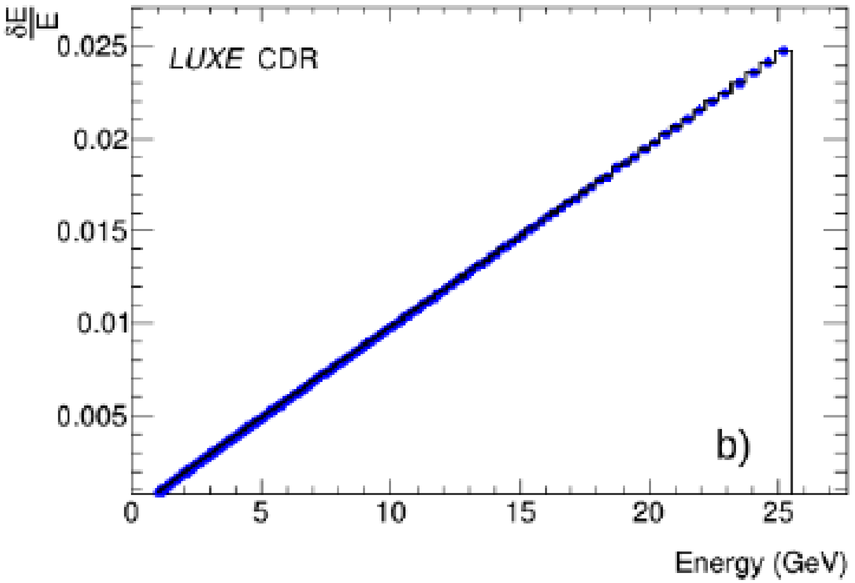
- critical: spatial and temporal overlap of electron beam and LASER
- temporal overlap requirement (30fs LASER pulse, >100fs electron bunch)
  → at least half the pulse width (50fs)
- XFEL developed world-leading syncronization system
  → sychronization of two RF signals to <13fs
- synchronise the XFEL.EU master clock oscillator to the oscillator of the JETI40
  → already used across XFEL to sychronize LASERS and accelerator
  → fine-tune repetition rate via piezo-elements controling LASER cavity size
- stability against temperature variations: isolation and active feedback loops
- spatial overlap: beam pointing monitoring sytems for both electron and LASER beam



Forward Spectrometer Detectors

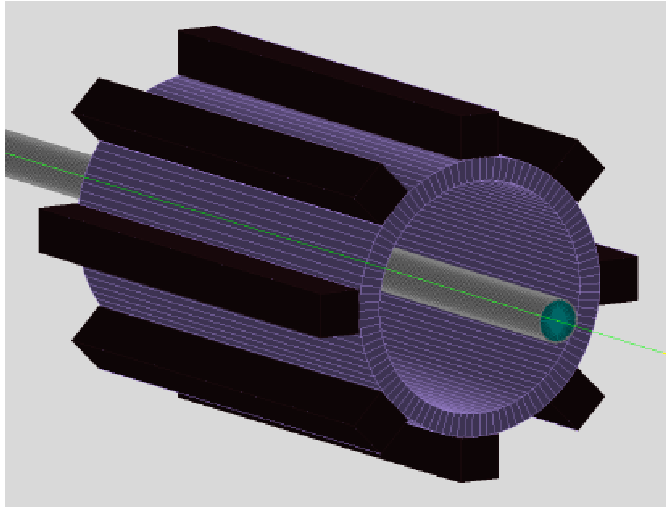
- **Up to 10^9 photons per bunch crossing with ~GeV energies**
- **Energy spectrum measurement**
  - Spectrometer with scintillators behind converter
  - Energy resolution <2%

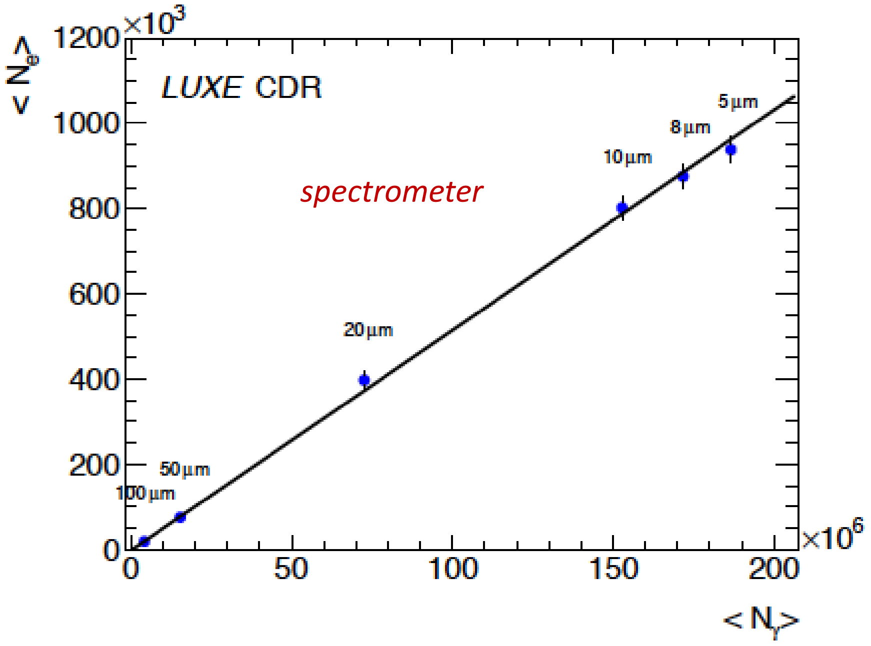


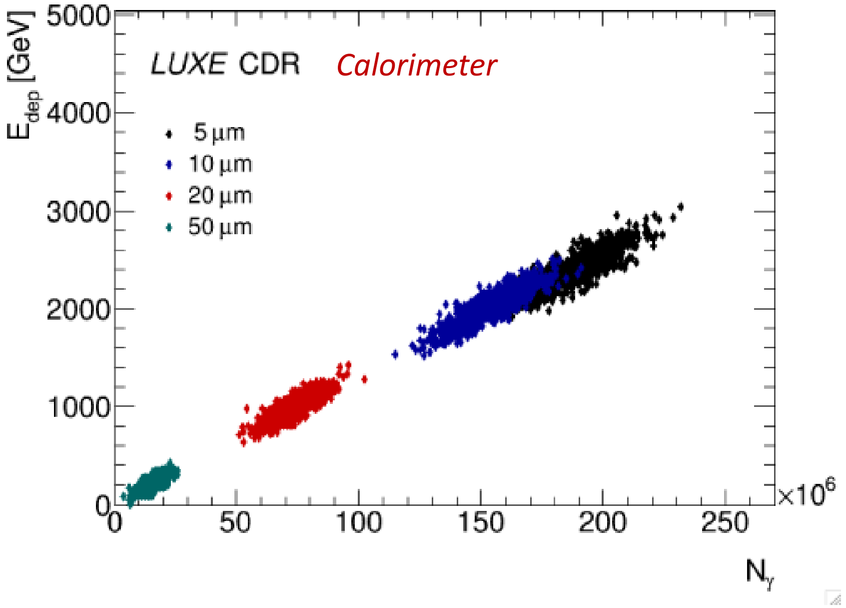


Backscattering Calorimeter

- **Up to 10^9 photons per bunch crossing with ~GeV energies**
- **Flux measured with**
  - Spectrometer
  - Backscattering calorimeter (lead glass blocks)

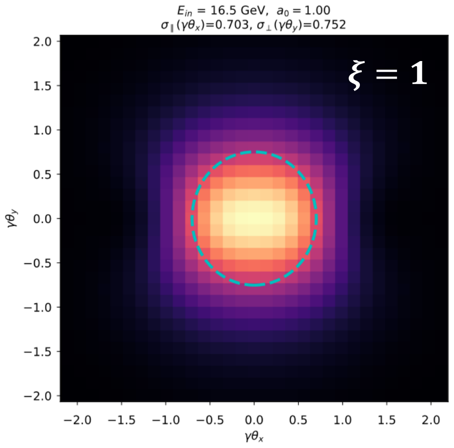


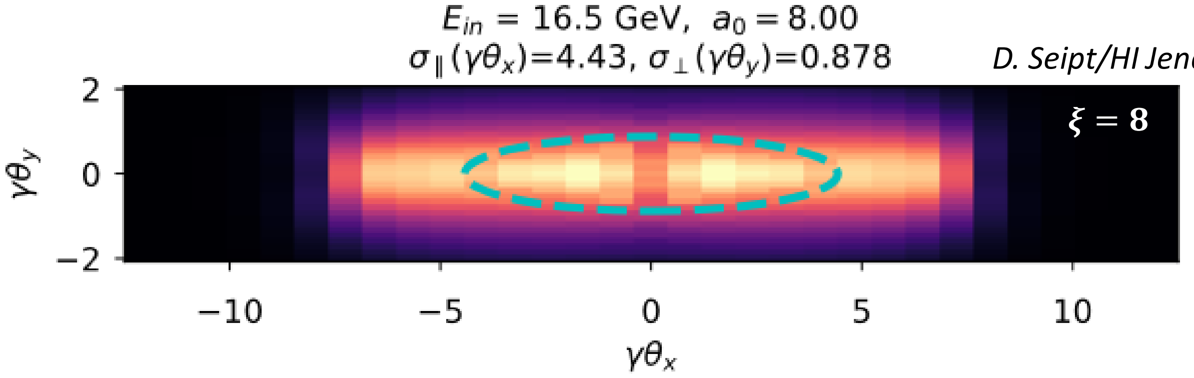




Gamma Profiler

- **When using polarized laser, expect angular spectrum of photons to depend on ξ for $\xi > 1$ and distance from IP of 6m:**
  - Parallel: $\sigma_{||} = \xi \times\ 180\ \mu$m, Perpendicular: $\sigma_{||} = 180\ \mu$m
  - Ellipticity is independent measure of laser intensity parameter ξ

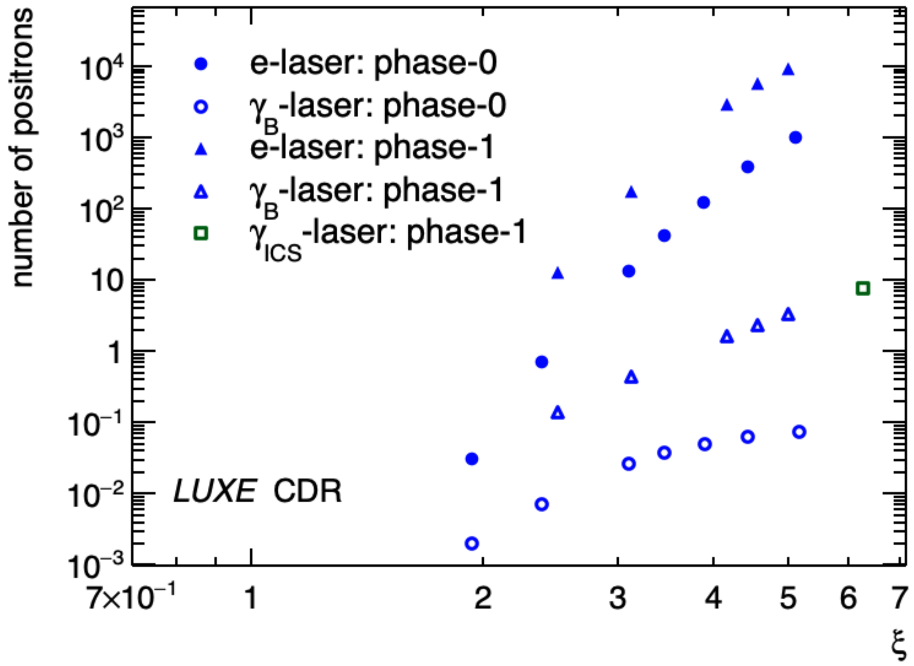


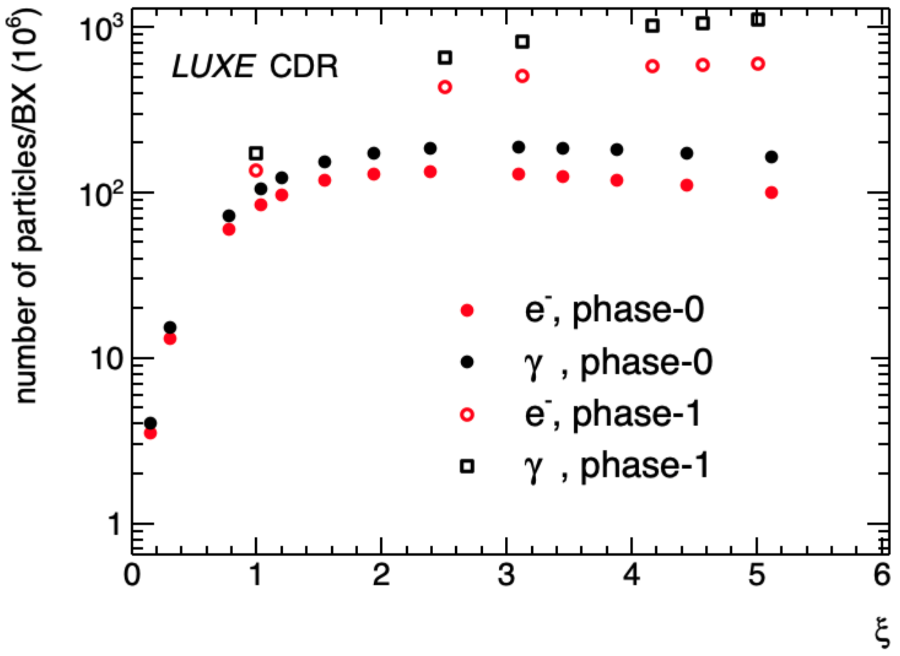


D. Seipt/HI Jena

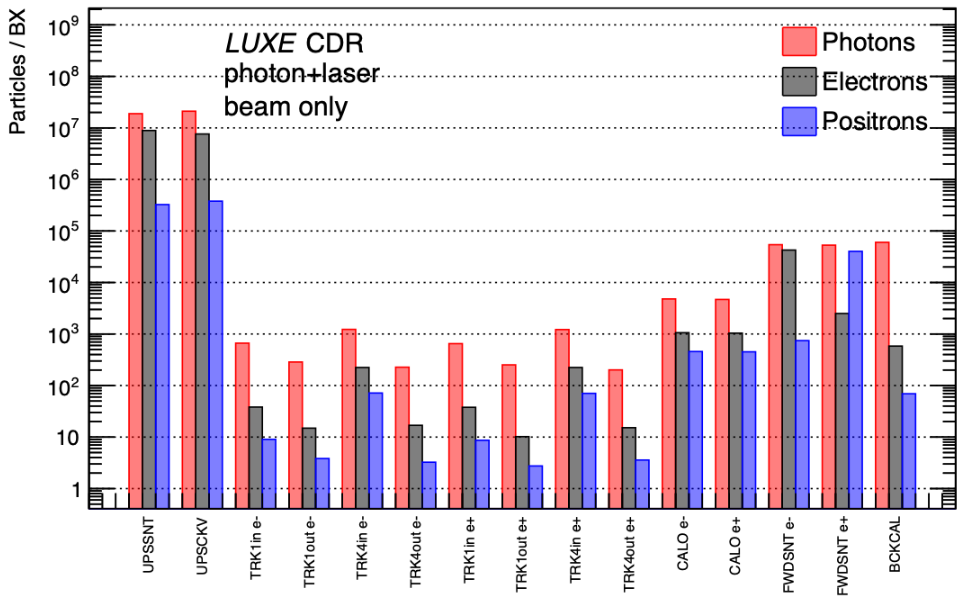
- **Measurement of 5 μm provides constraint: $\frac{\delta\xi}{\xi} < 1\%$ for ξ>2**

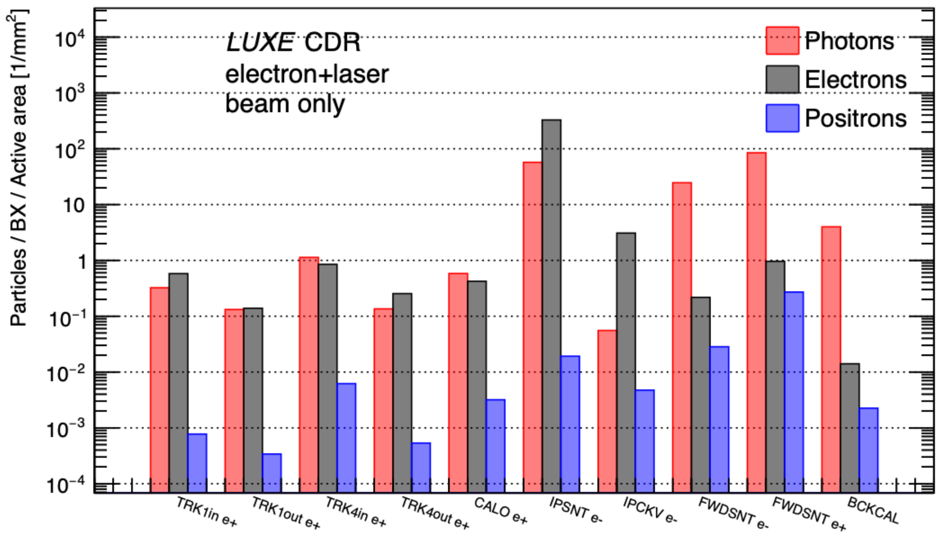
Particle rates



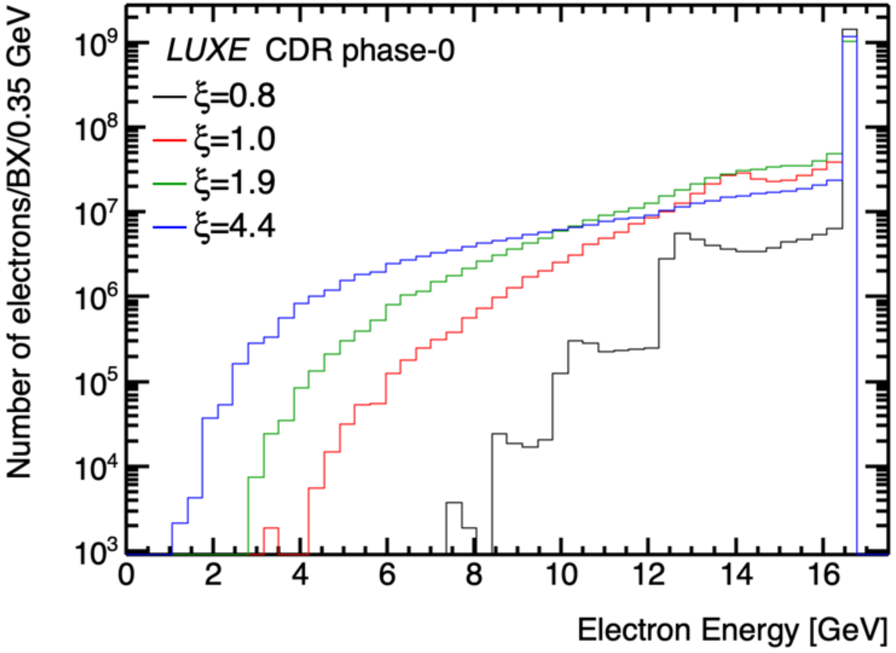


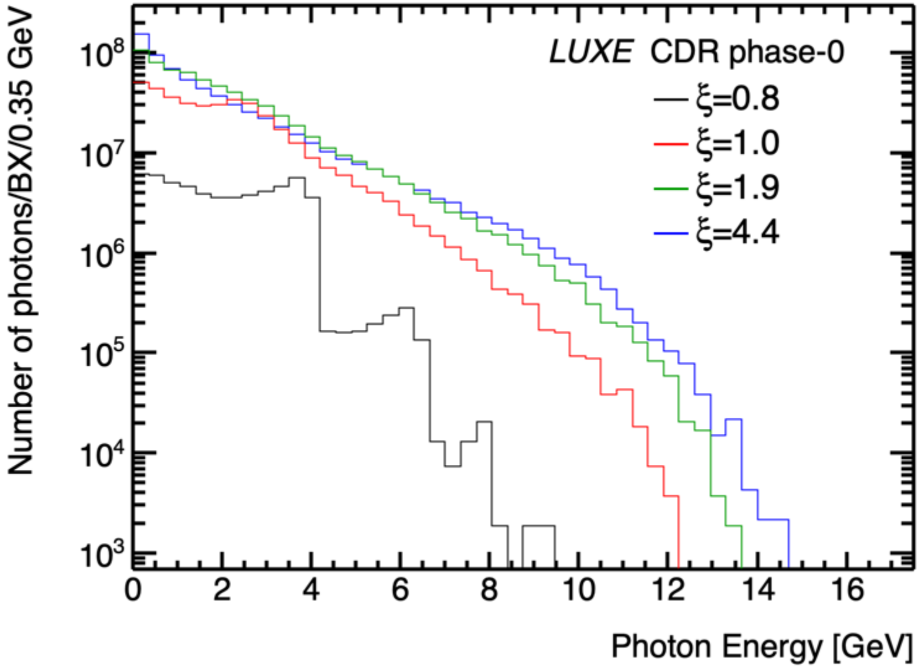
Beam Background rates



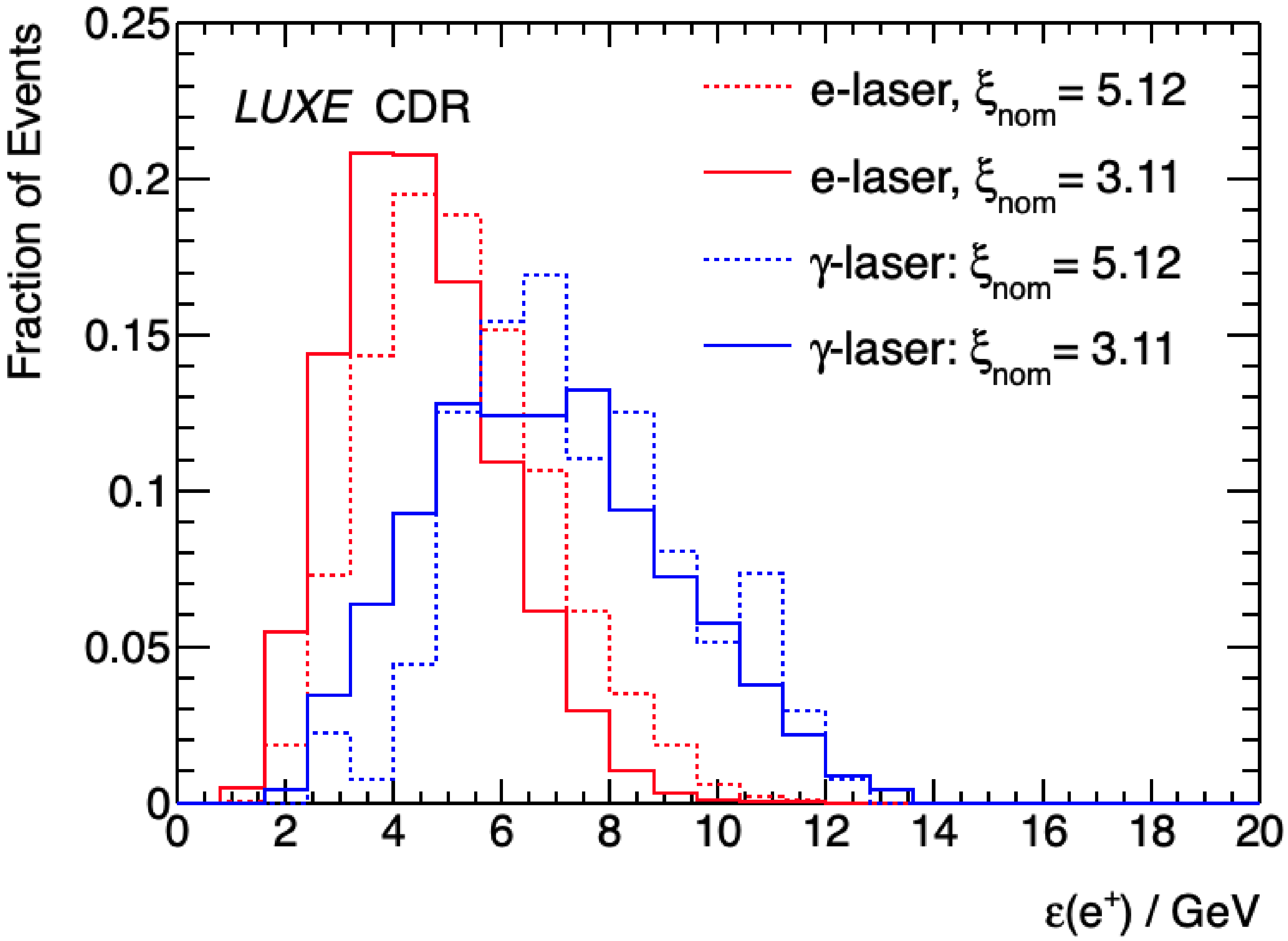


e+LASER Spectra

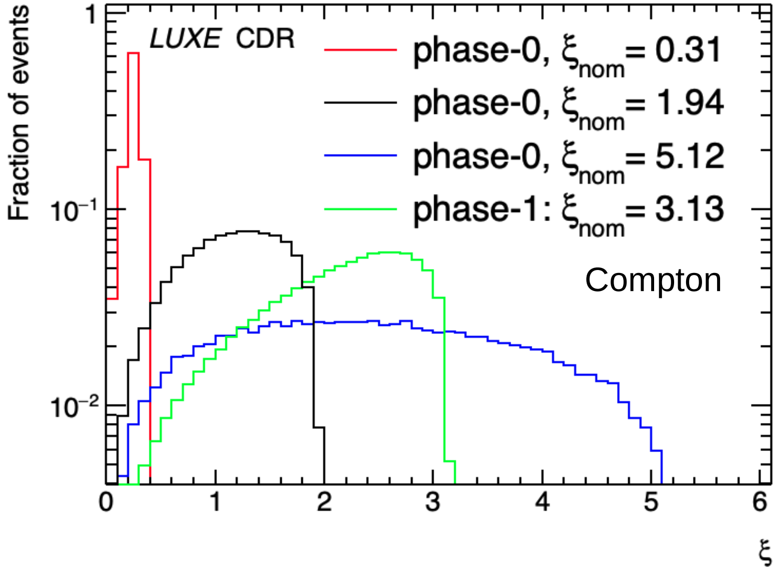


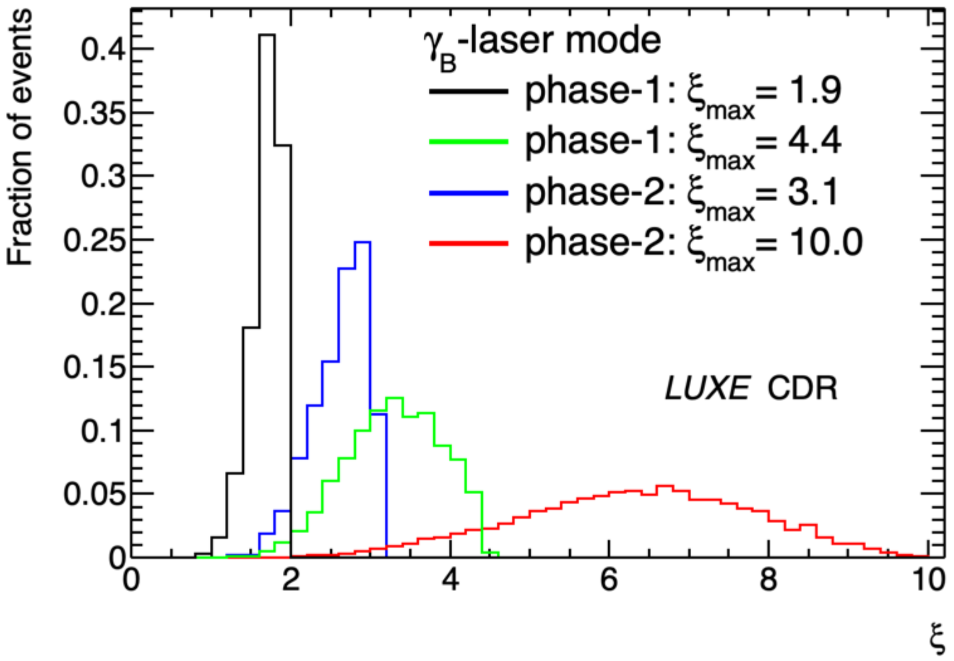


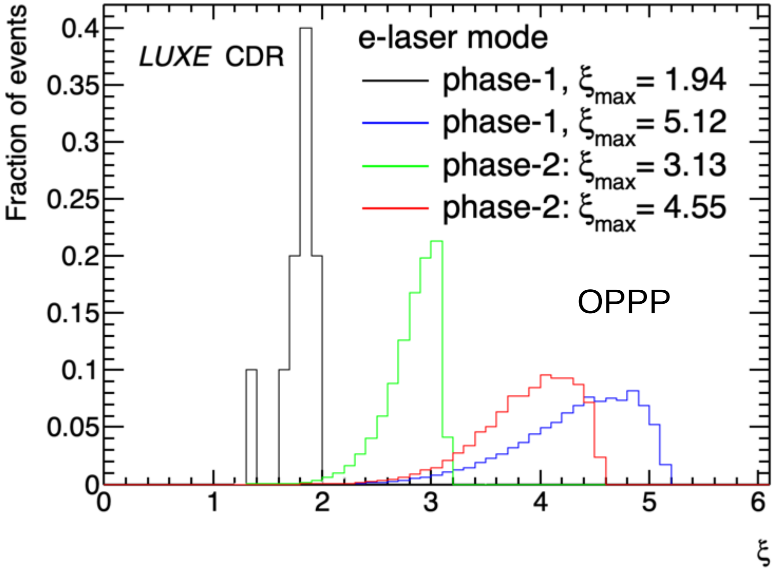
Positron Spectra



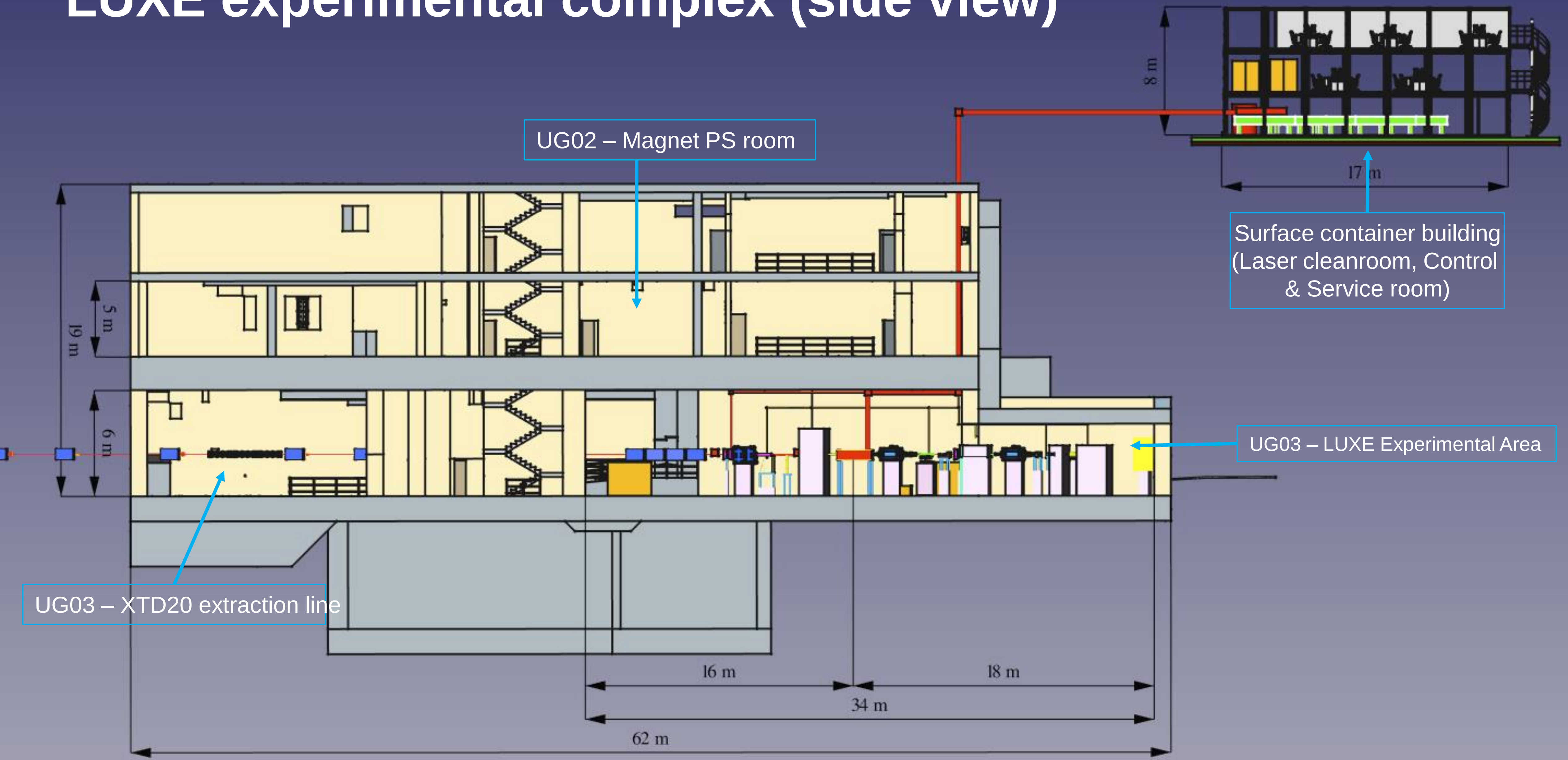
xi distributions







LUXE experimental complex (side view)



LUXE experimental complex (top view)