

# LUXE: A new experiment to study non-perturbative QED

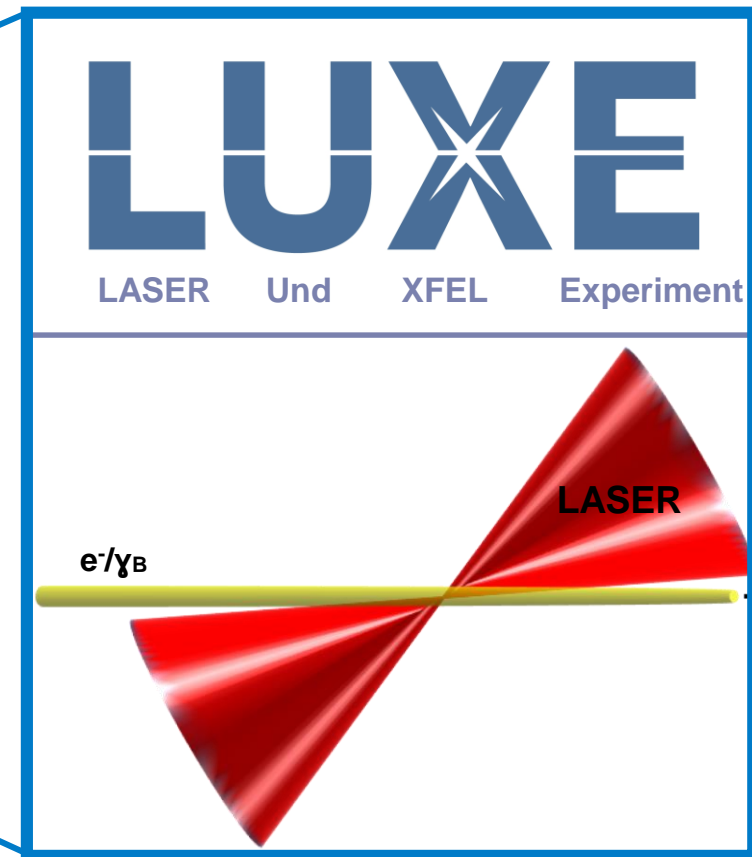
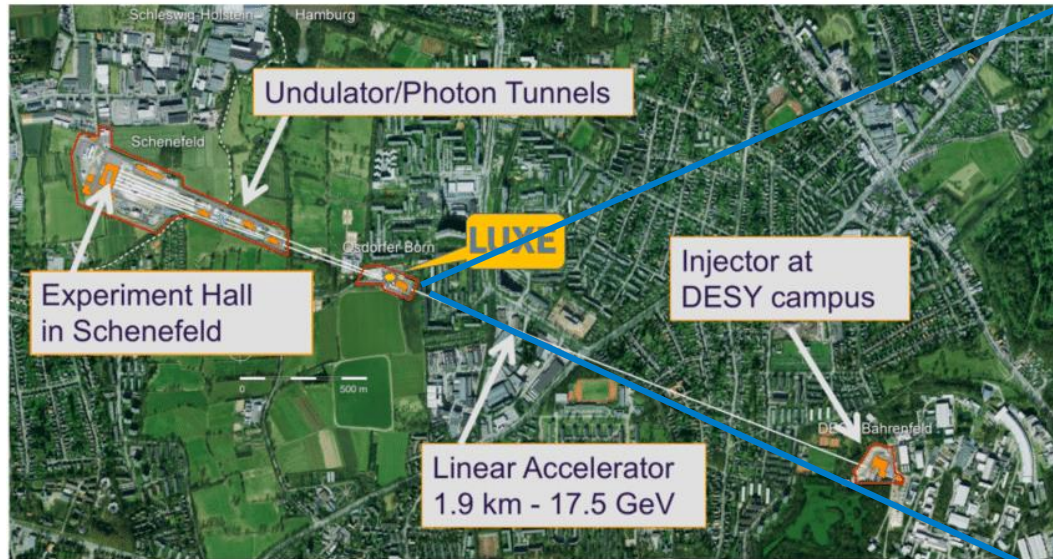
Ruth Jacobs (DESY)

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?

## More documentation?

LUXE CDR: [arXiv:2102.02032](https://arxiv.org/abs/2102.02032)

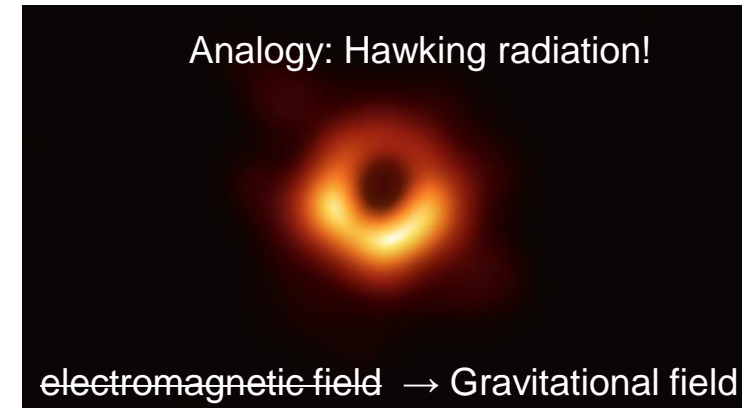
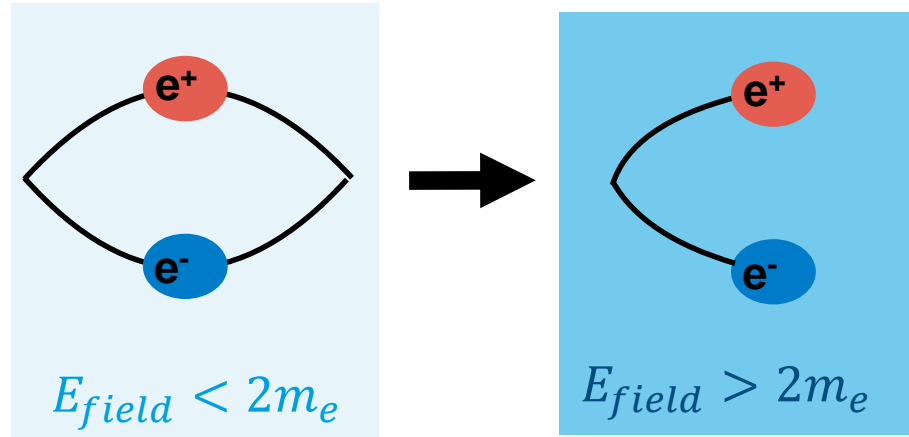
LUXE website: <https://luxede.desy.de>

# 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:  $\mathcal{E}_{cr} = 1.32 \cdot 10^{18} \text{ V/m}$ )

**Field energy:**

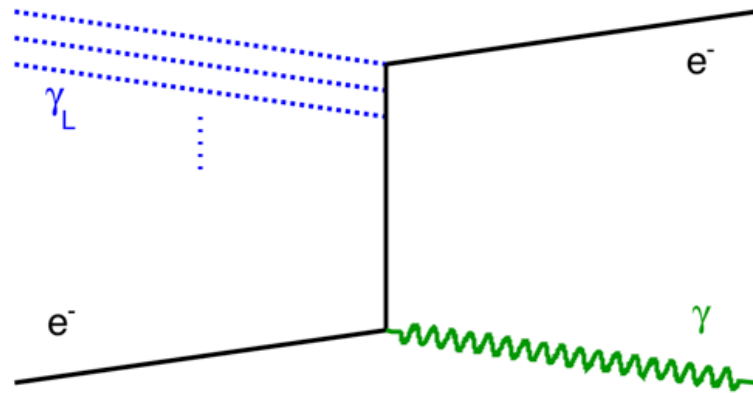
$$E_{field} = \frac{e\mathcal{E}}{m_e}$$



- 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!**

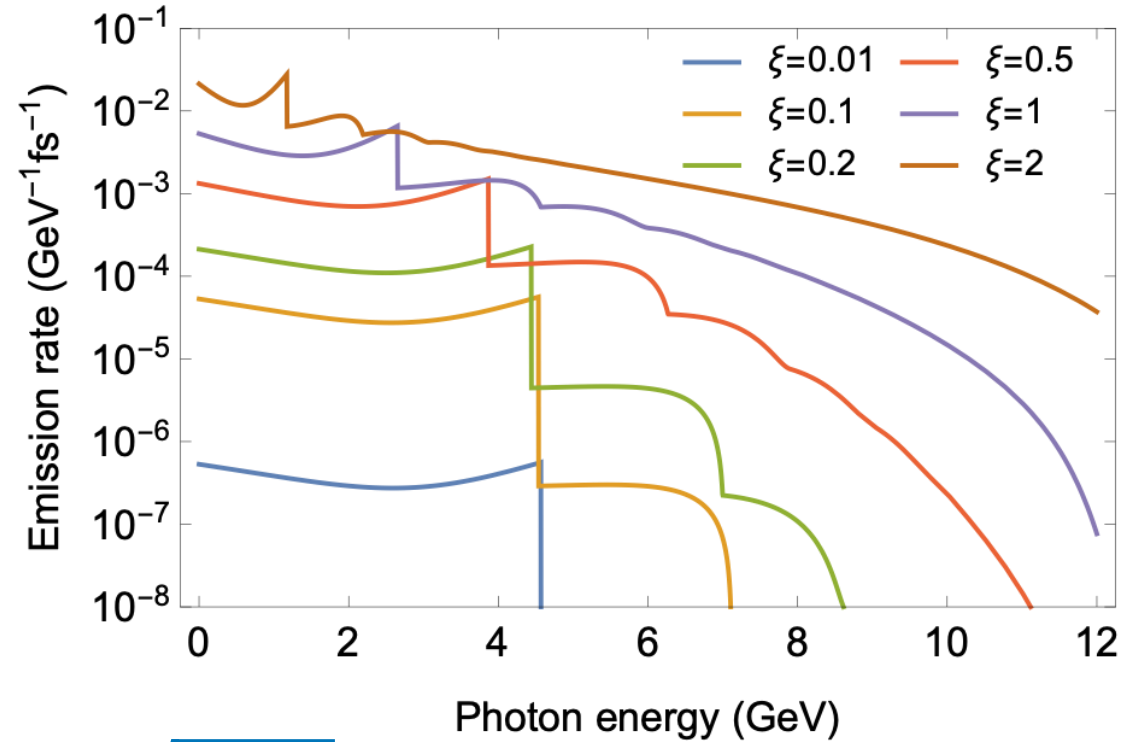
# Non-linear Compton scattering



**Non-linear Compton Scattering**

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

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

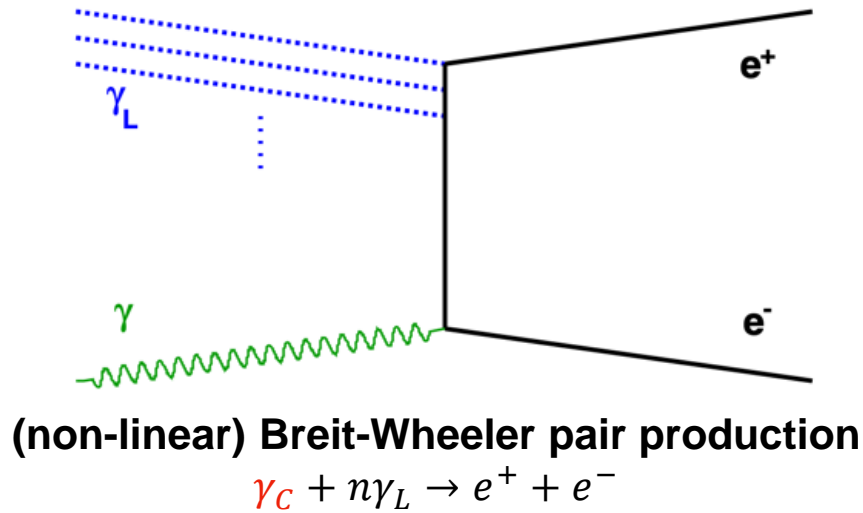


- in strong fields, electron obtains larger effective mass  $m_* = m_e \sqrt{1 + \xi^2}$   
 → Compton edge shifts with **laser intensity**  $\xi$   
 → higher harmonics ( $n$ -th order: interaction with  $n$  laser photons)
- theoretical prediction for QED:  $E_{edge}(\xi) = E_e \frac{2n\eta}{2n\eta + 1 + \xi^2}$  (energy parameter  $\eta_{LUXE} = 0.192$ )
- Note: Non-linear Compton scattering has a classical limit:  $E_{edge}(\xi) = E_e \frac{2n\eta}{1 + \xi^2}$   
 → QED deviation from classical determined by **quantum non-linearity parameter**  $\chi$ !

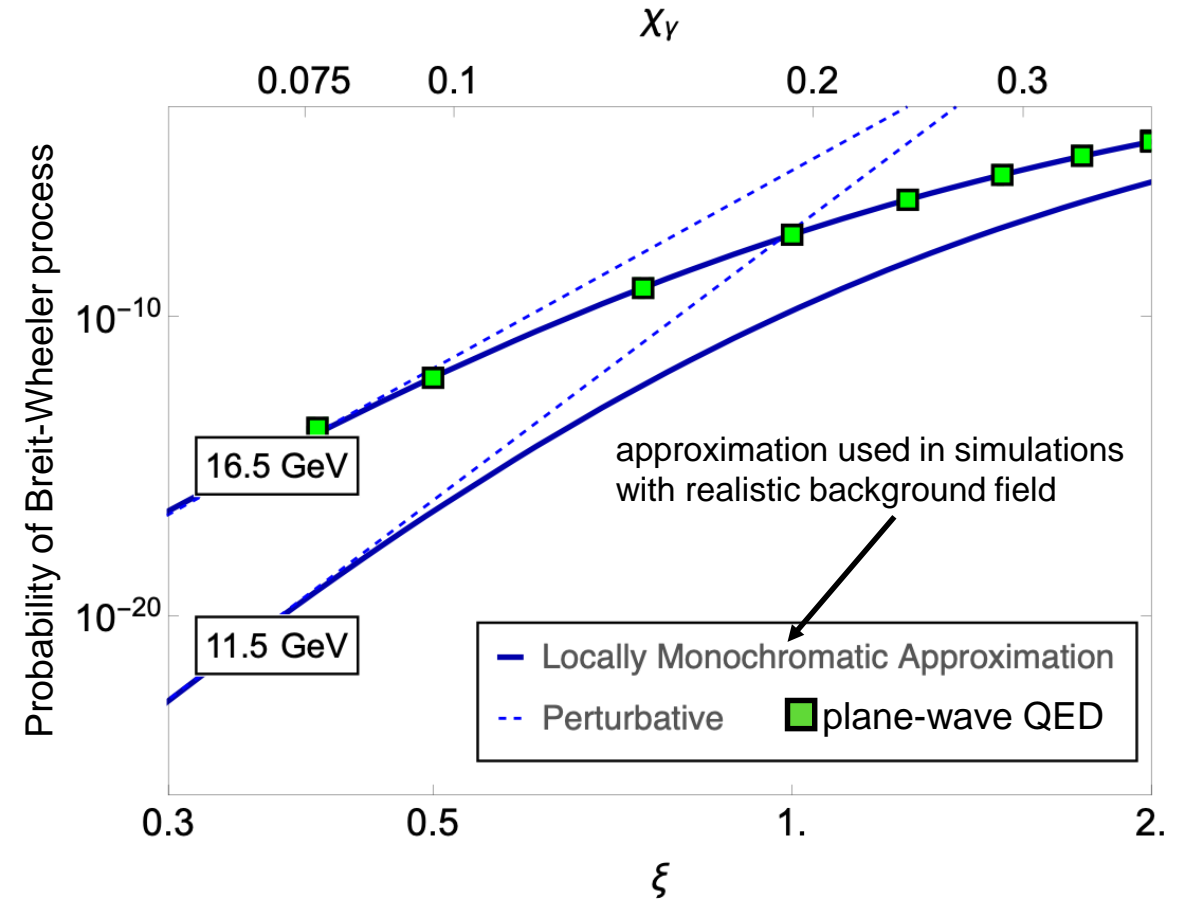
**SFQED parameter relation:**

$$\eta = \chi / \xi$$

# Breit-Wheeler pair production



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



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

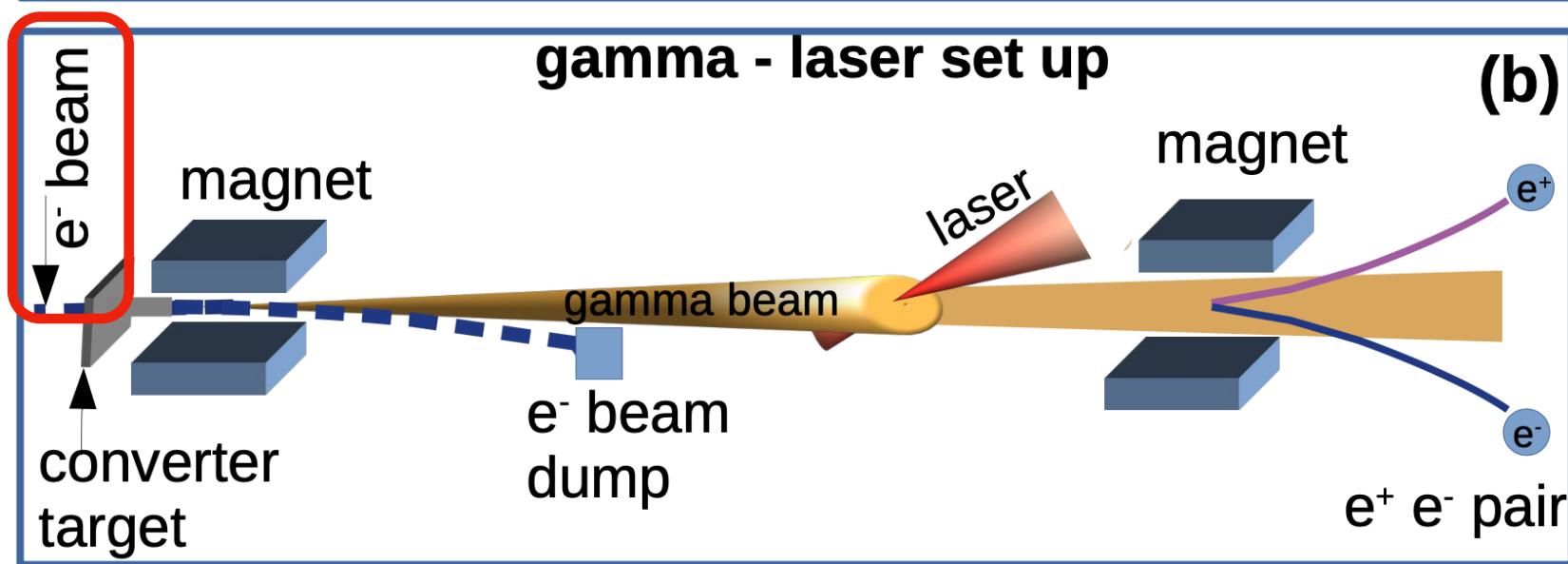
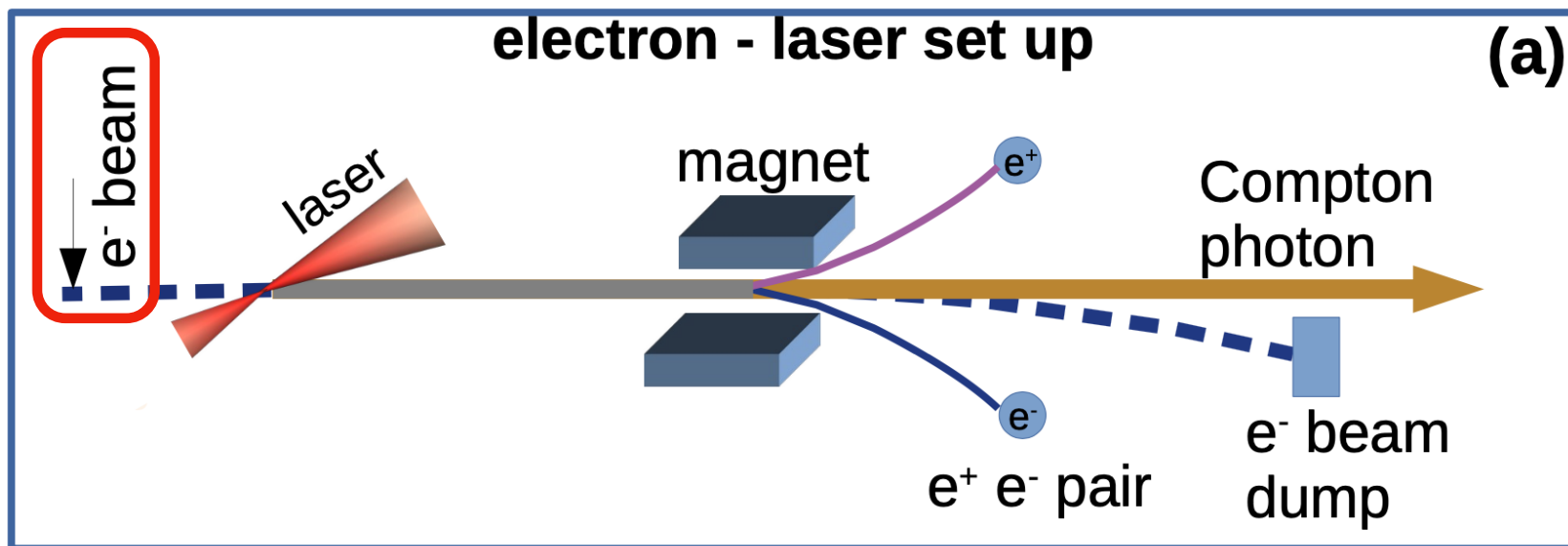
Perturbative regime  
 → power law

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

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 <sup>19</sup> W/cm <sup>2</sup> ]	13.3 / 120

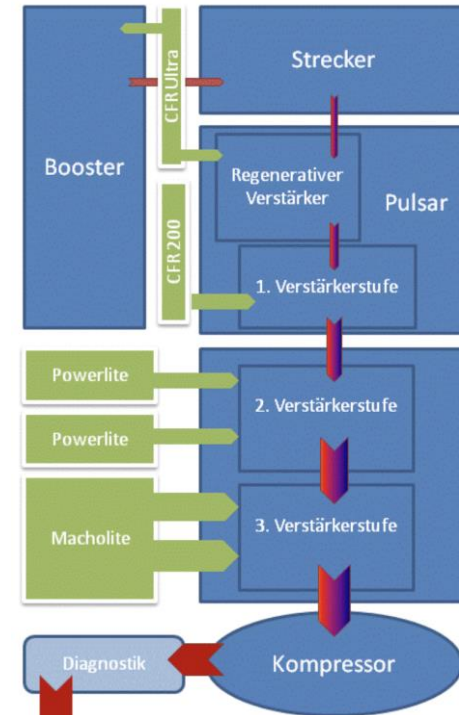
Laser intensity:

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

$E_L$ : laser energy (J)

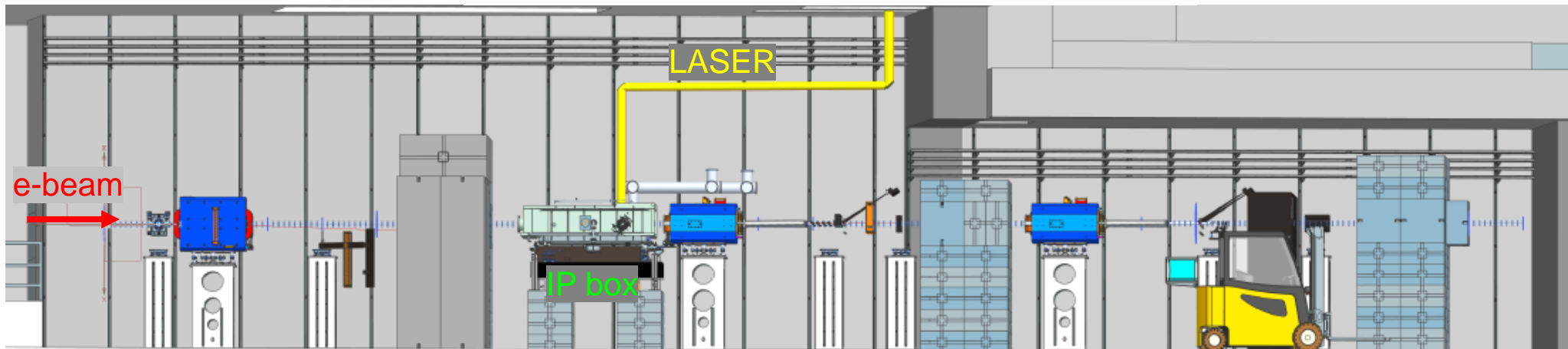
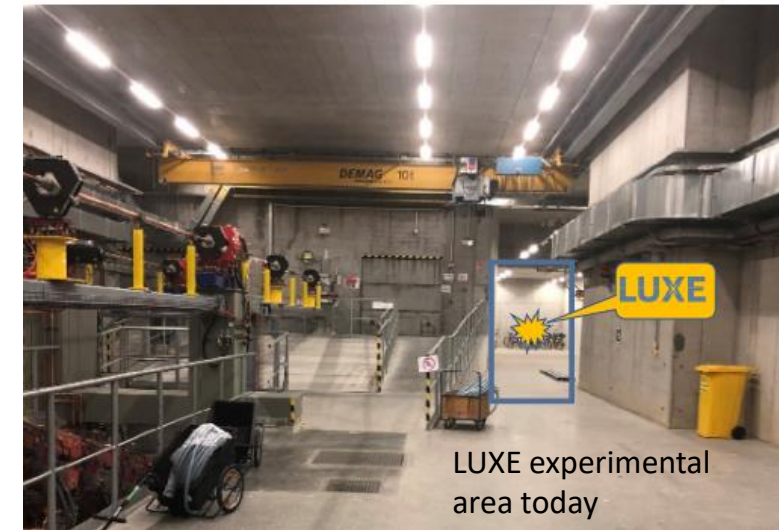
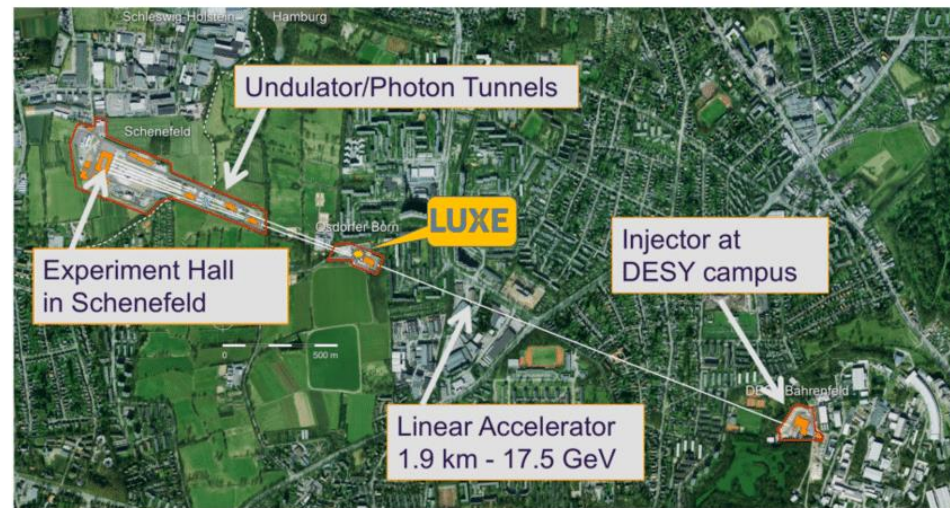
$\Delta t$ : pulse length (s)

$\pi d^2$ : focus area (m<sup>2</sup>)



- for LUXE Phase-0: existing 40TW JETI40 (Jena) laser will be used (alternatively: custom LASER)
- LUXE Phase-1: upgrade to 350TW laser system
- thanks to electron boost, don't need to push limits of current state-of-the-art of laser intensity
- BUT: need exceptional shot-to-shot stability!  
→ precision LASER diagnostics

# LUXE beamline

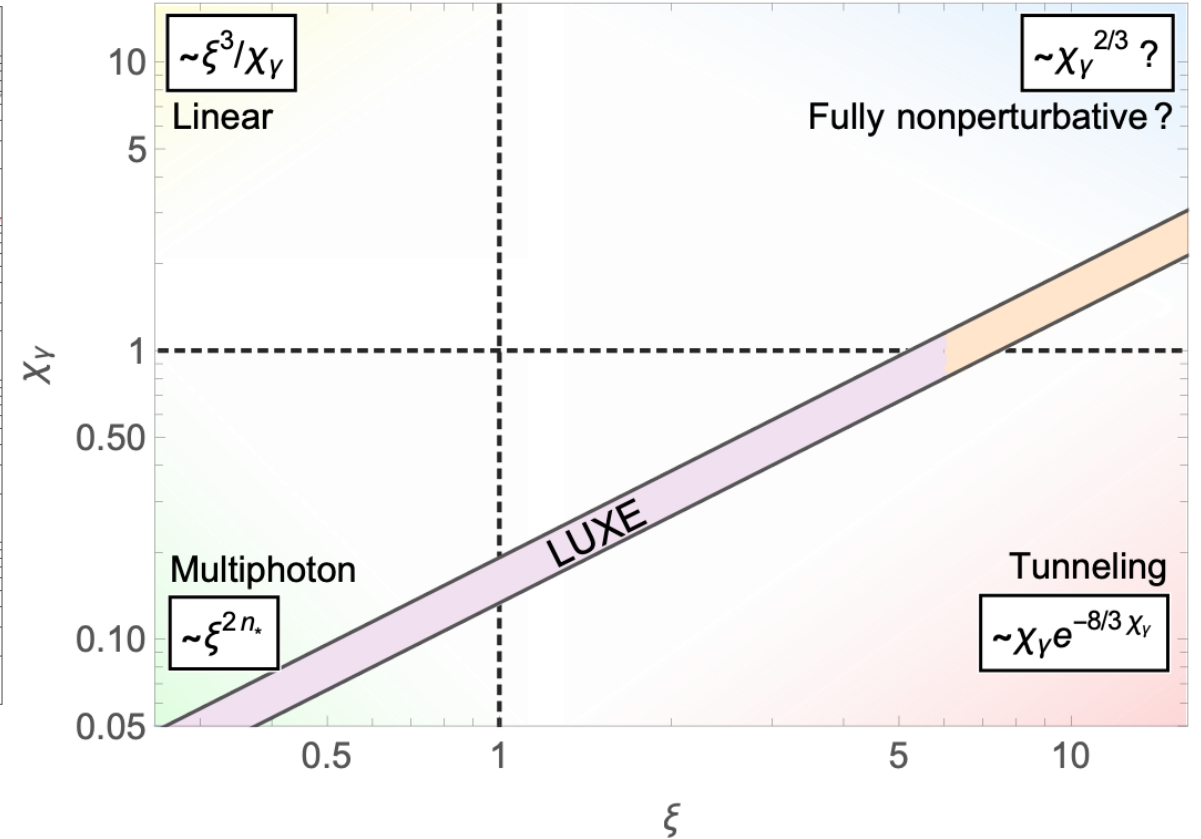
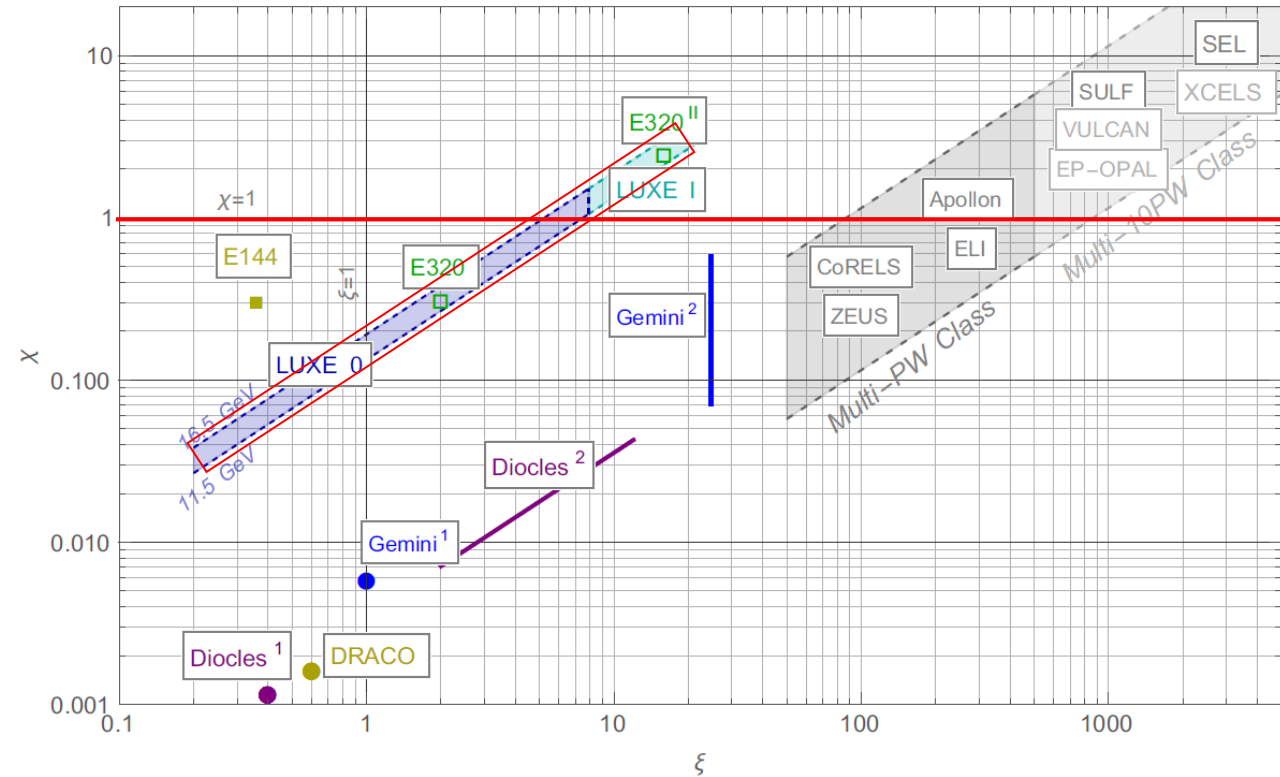


- LUXE uses high-quality 16.5 GeV Eu.XFEL electron beam before undulators
- Experiment location: Existing annex for future second Eu.XFEL fan(~2030's+) → Unique possibility to build and operate LUXE before that!
- Extract 1 bunch (out of 2700 bunches) per XFEL train for LUXE → design goal: transparent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

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

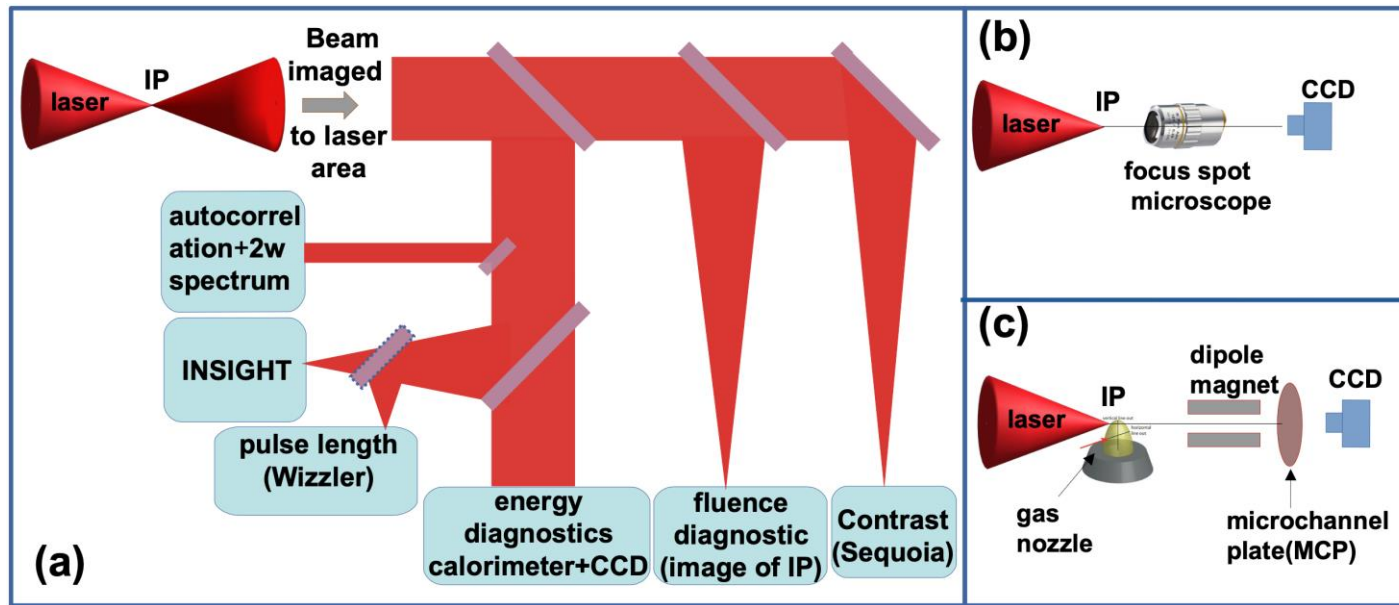


# LUXE in Strong-Field QED Parameter Space

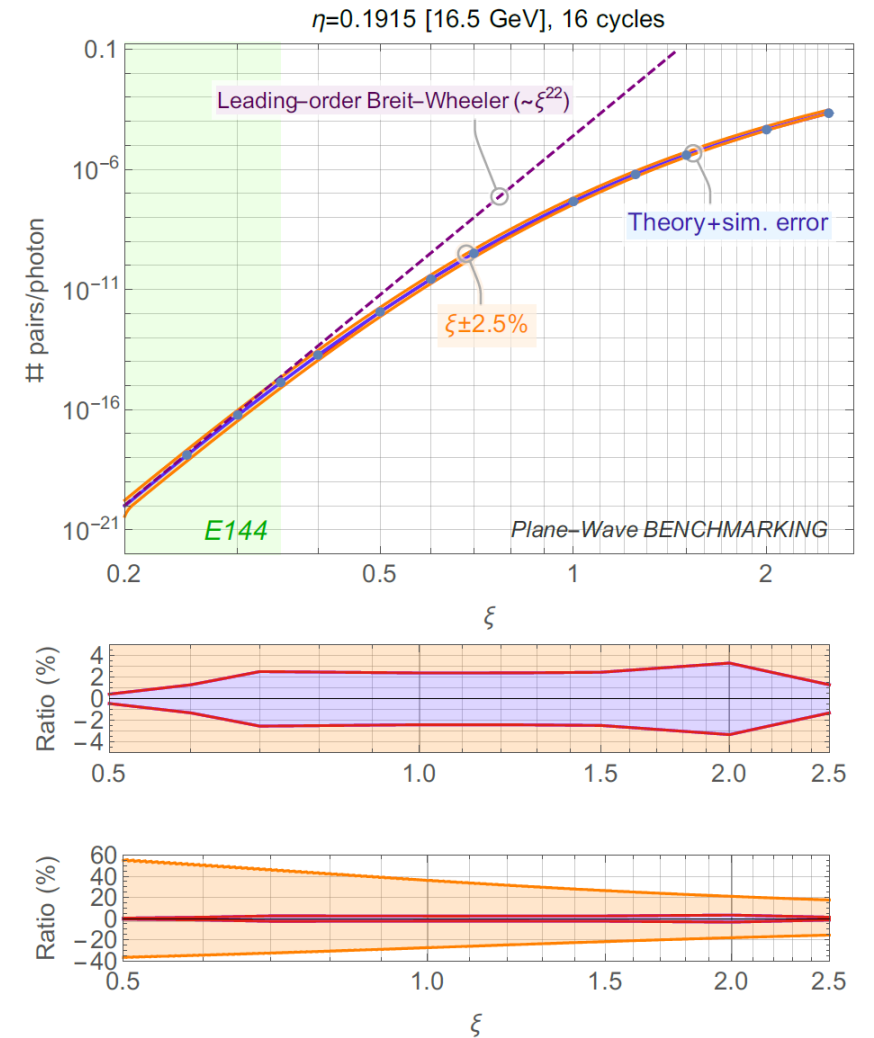


- experimental reach in SF QED parameter space ( $\xi, \chi$ )  
→ mainly determined by: particle beam energy, LASER intensity
- Previous experiment: E144 (SLAC e-laser collisions, 1990's) reached power-law regime, but not departure  
→ LUXE will have 3 orders of magnitude more powerful laser!
- LUXE unique ability: precision mapping of SF-QED parameter space in transition regime  
→ possible by varying the laser spot size systematically and continuous data-taking

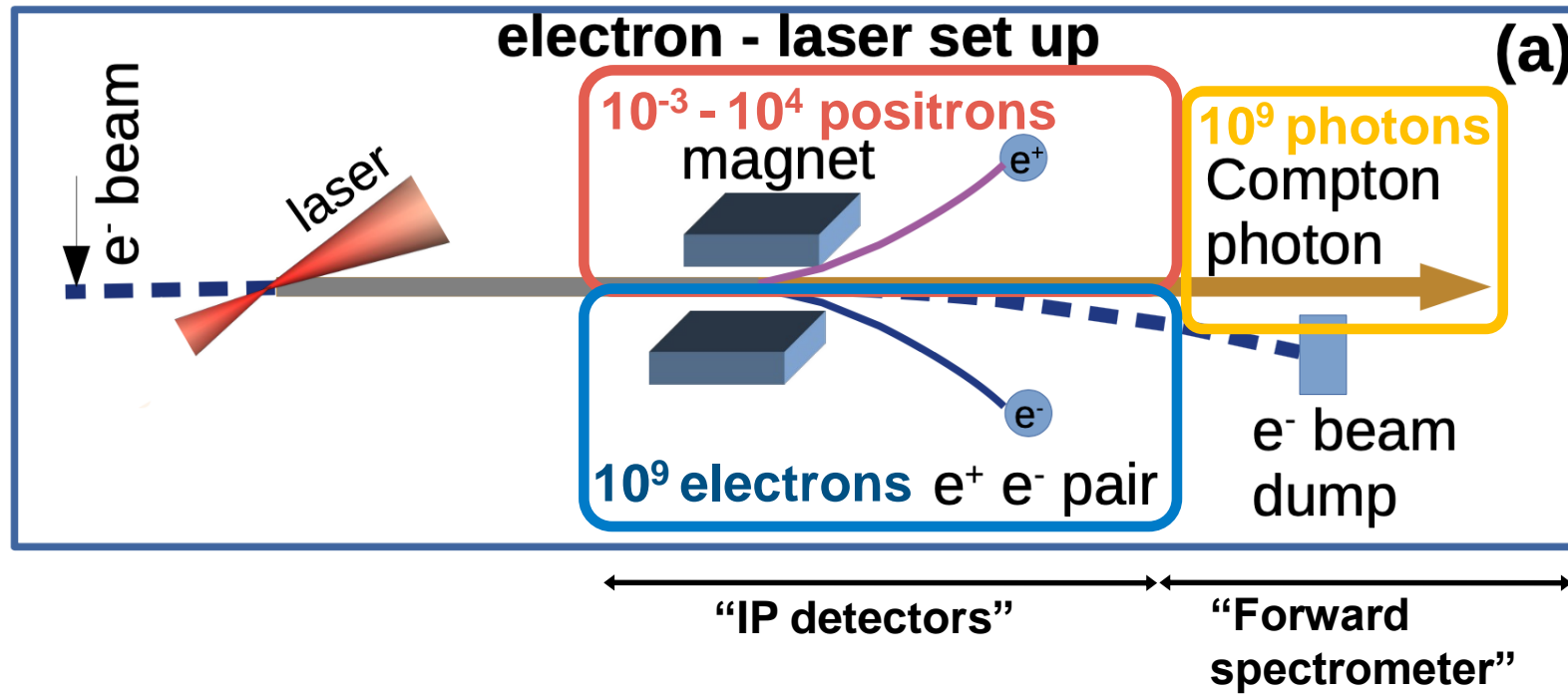
# Laser Diagnostics



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



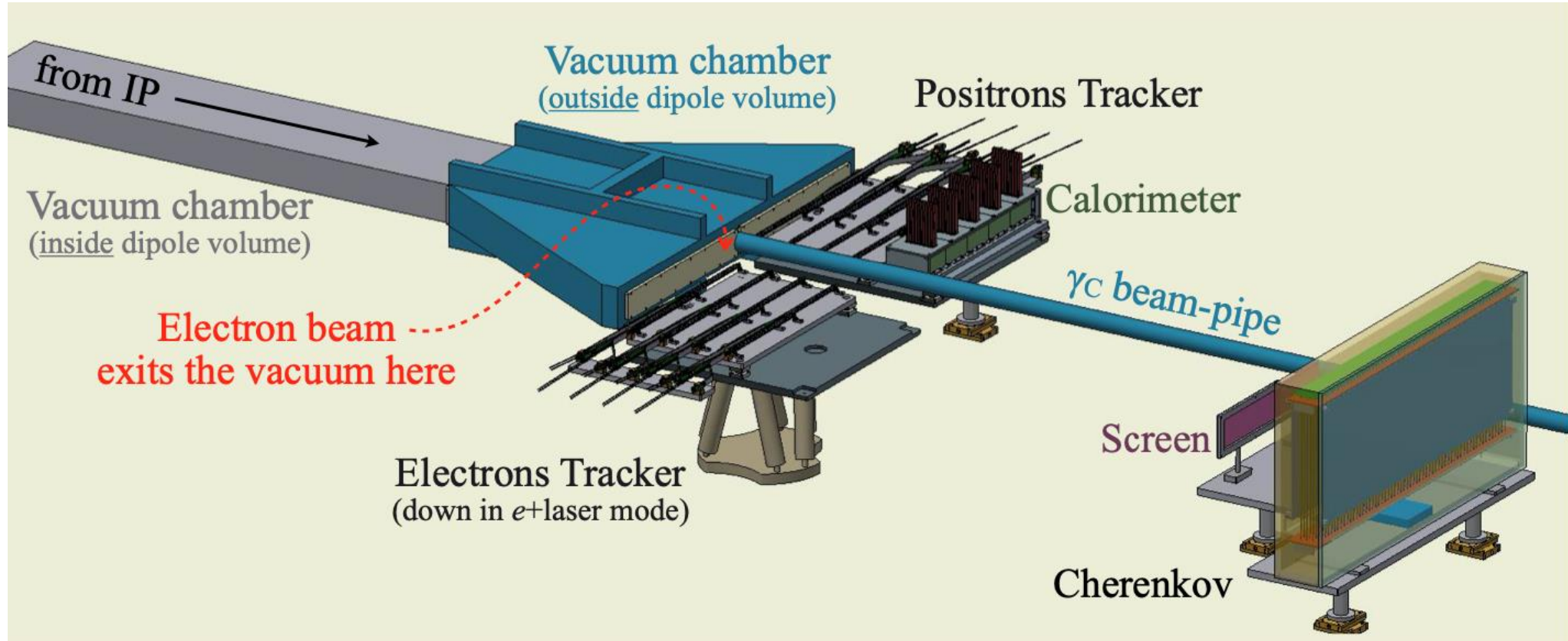
# Particle Detectors



- Goal: Detection of electrons, positrons and photon fluxes and energy spectra
- Particle fluxes vary between  $\sim 0.01$   $e^+$  and  $10^9$  ( $e^-$  and  $\gamma$ ) per laser shot!
- use technologies adapted to respective fluxes of signal and background
- LUXE: testbed for new detector technologies (& software) for future colliders!

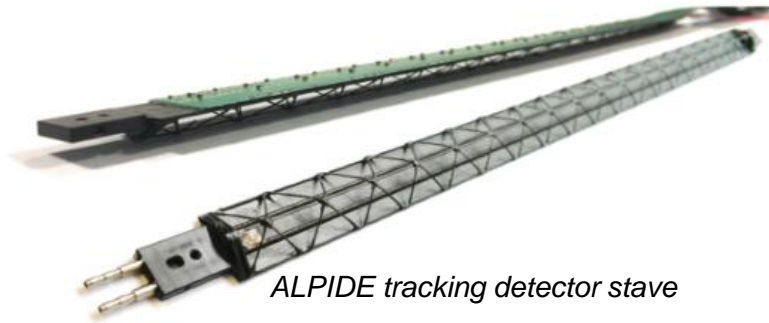
# Electron & Positron Detectors

Plot by N. Tal-Hod



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

# Positron Detection System



ALPIDE tracking detector stave



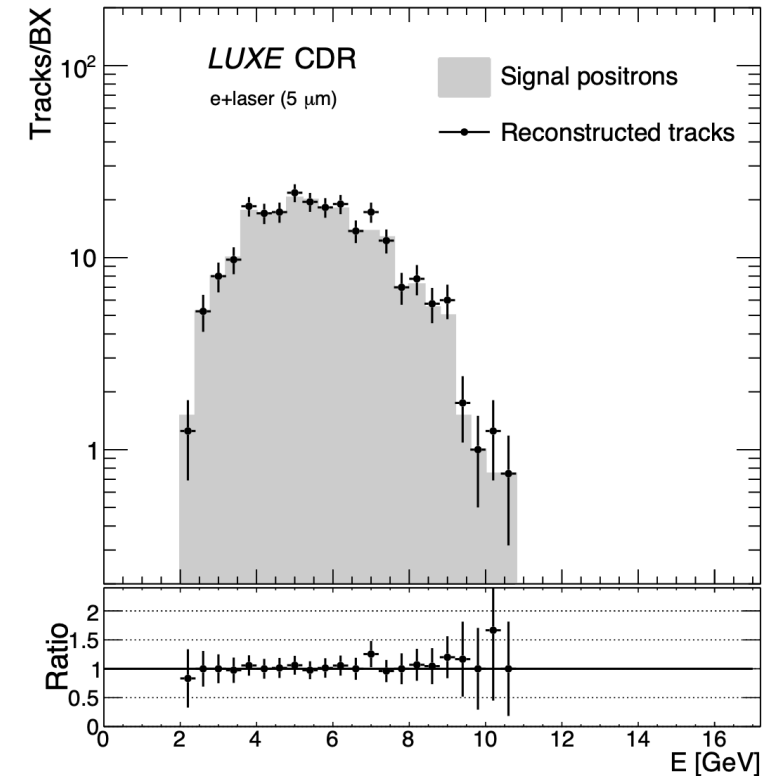
High-granularity ECAL layer

## Silicon Pixel Tracker:

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

## GaAs – Si High-granularity Calorimeter:

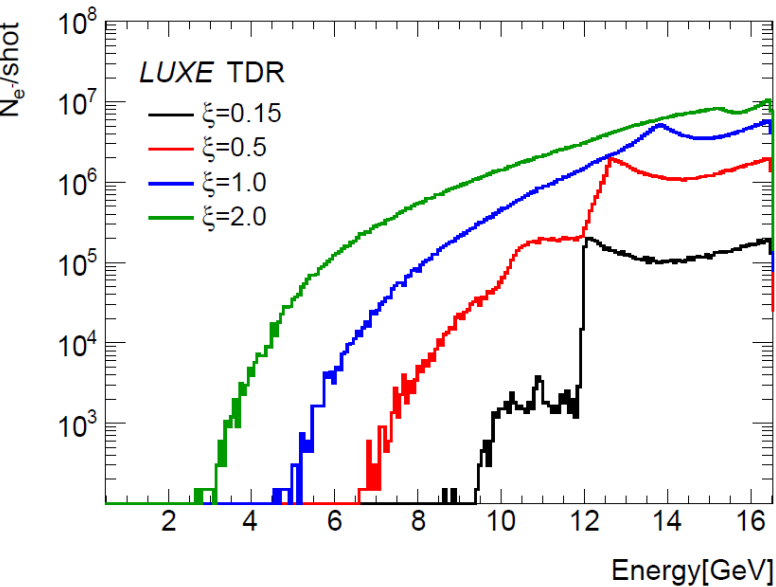
- 20-layer sampling calorimeter – high granularity: independent energy measurement through shower and position
- shower medium: 3.5mm Tungsten plates ( $1X_0$ ), active medium: Silicon sensors ( $5 \times 5 \text{ cm}^2$ , 320  $\mu\text{m}$  thick)
- read out by FLAME ASIC (developed for FCAL)



**Positron detectors: High signal efficiency, high resolution!**



# Electron Detection System

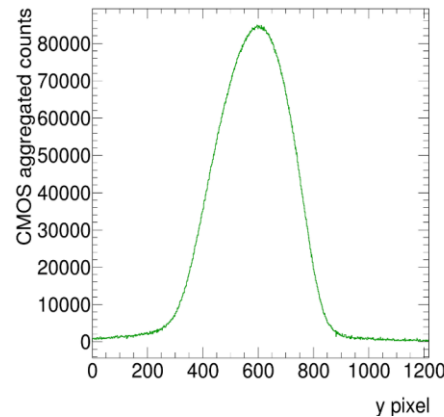
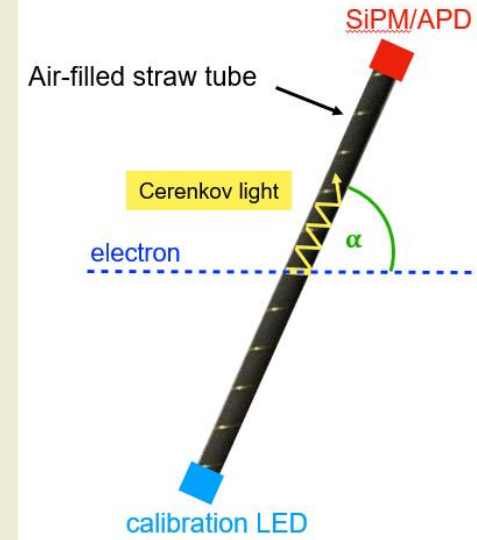
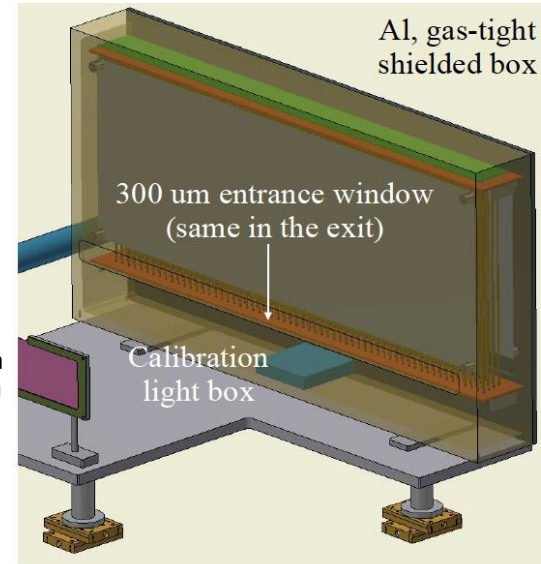
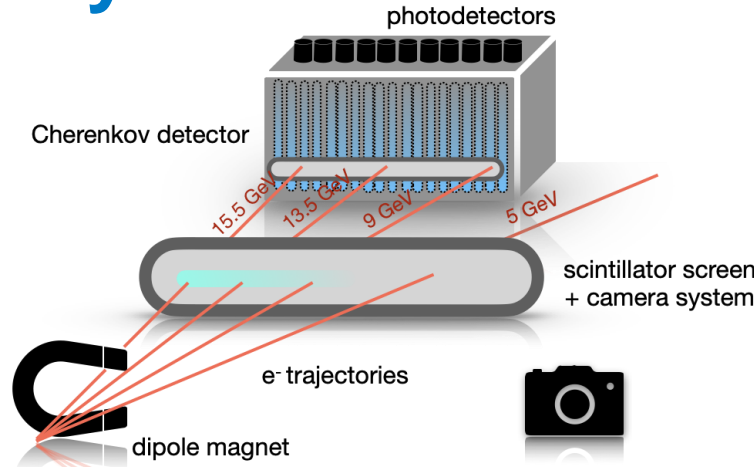


## Scintillator screen (LANEX):

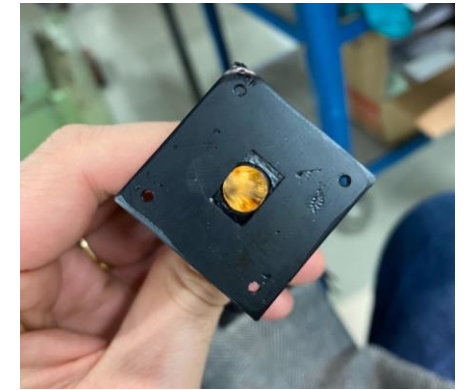
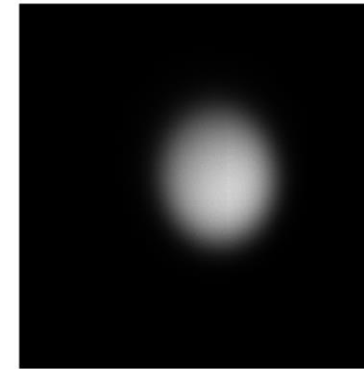
- camera takes pictures of scintillation light
- resolution of full system  $\sim 500\mu\text{m}$

## Cerenkov detector:

- finely segmented ( $\phi = 4\text{mm}$ ) Air-filled channel (reflective tubes as light guides)  $\rightarrow$  charged particles create Cerenkov light
- Active medium Air: low refractive index - reduce light yield, suppress backgrounds (Cerenkov threshold 20 MeV)



Beam spot imaged on Scint. Screen

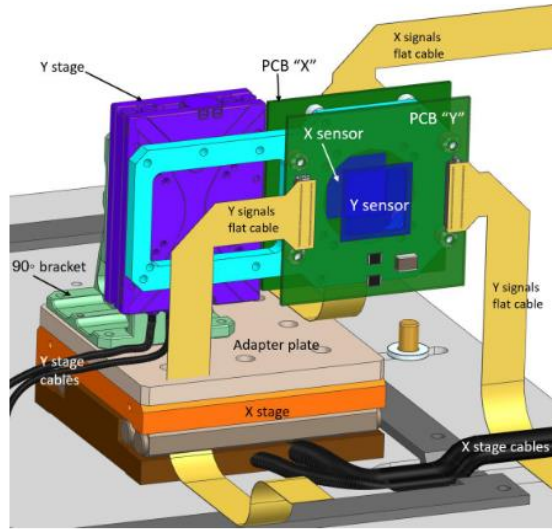


Straw prototype

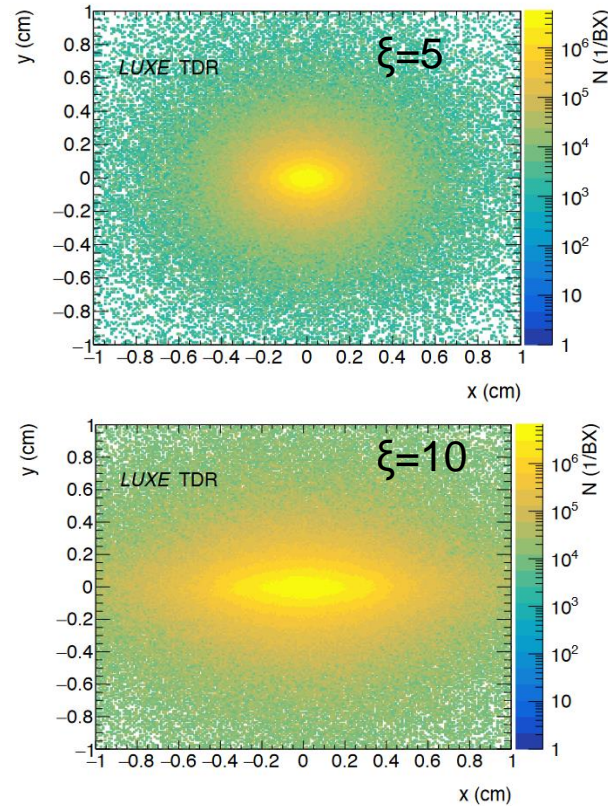
**Electron detectors: High rate tolerance, large dynamic range!**

( $\rightarrow$  talk by A. Athanassiadis, today 18:15, session T98)

# Photon Detection System

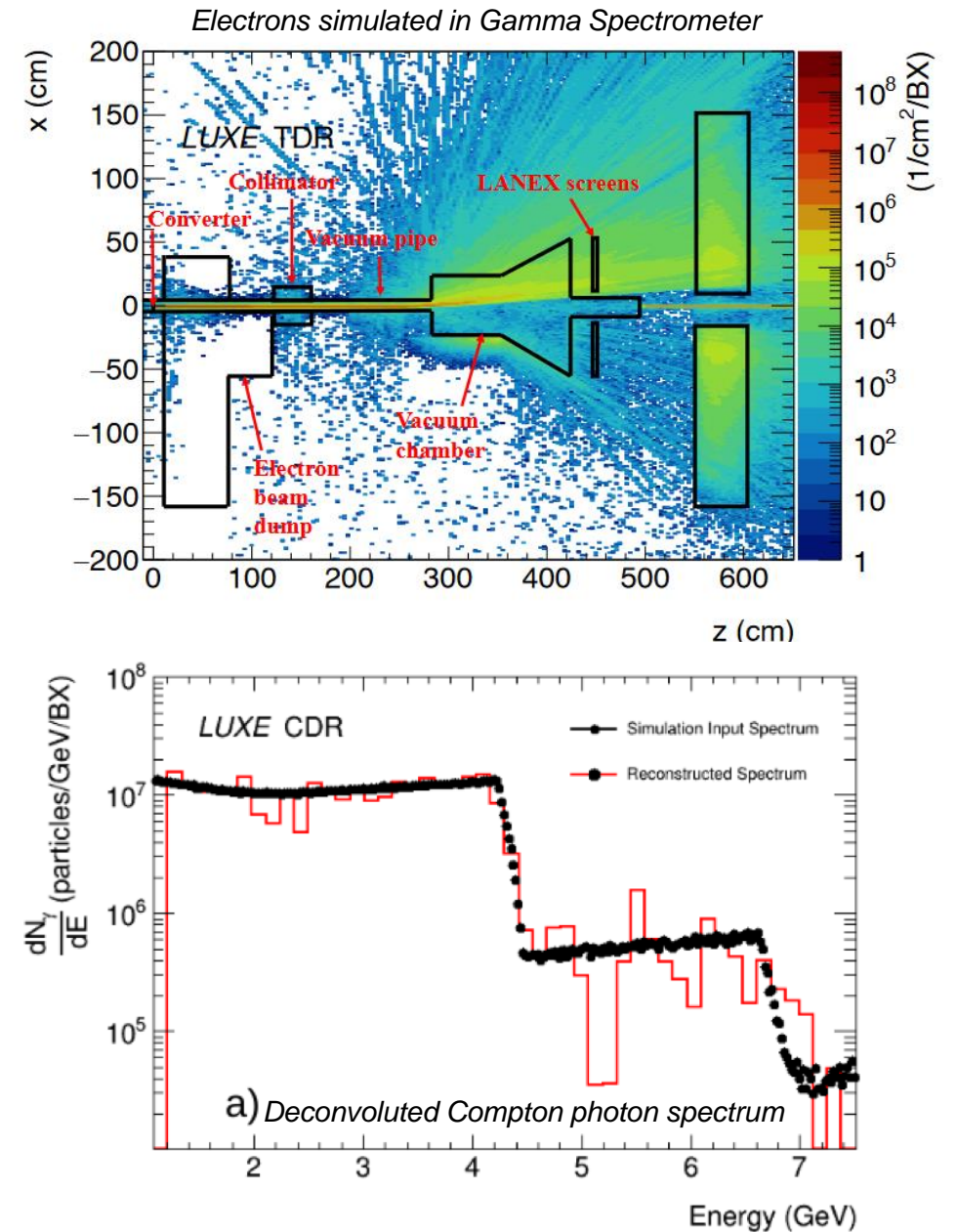


Gamma Beam Profiler



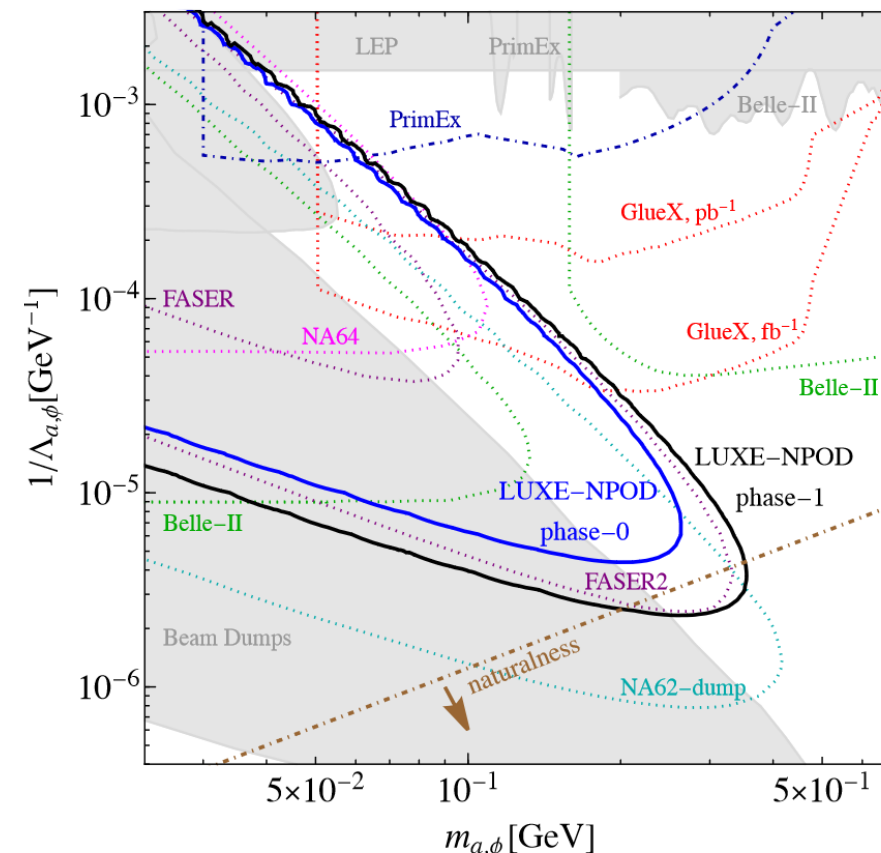
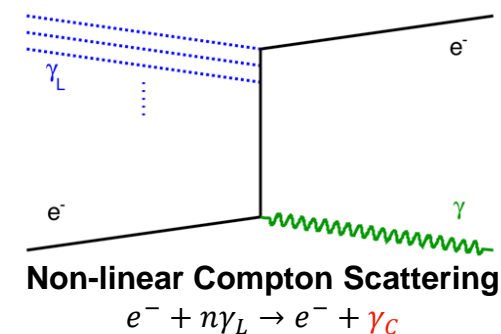
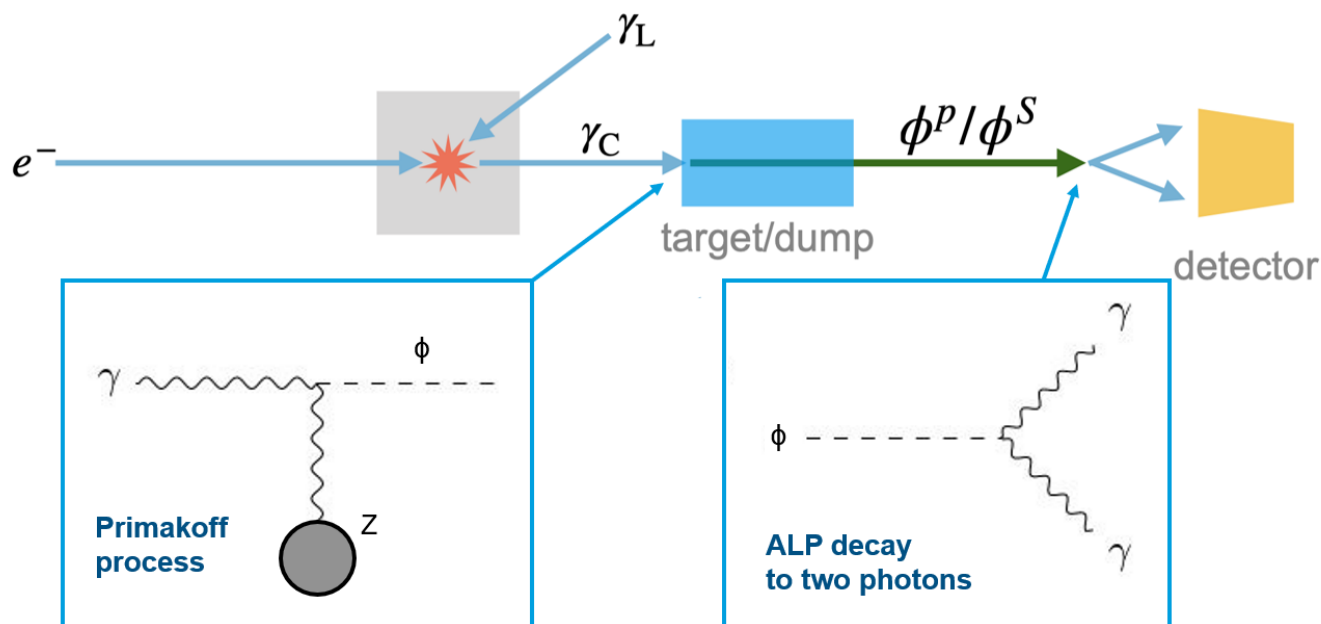
## Gamma detector technologies:

- Gamma profiler (sapphire strips)  
→  $\gamma$  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



# Bonus: LUXE BSM Searches (LUXE-NPOD)

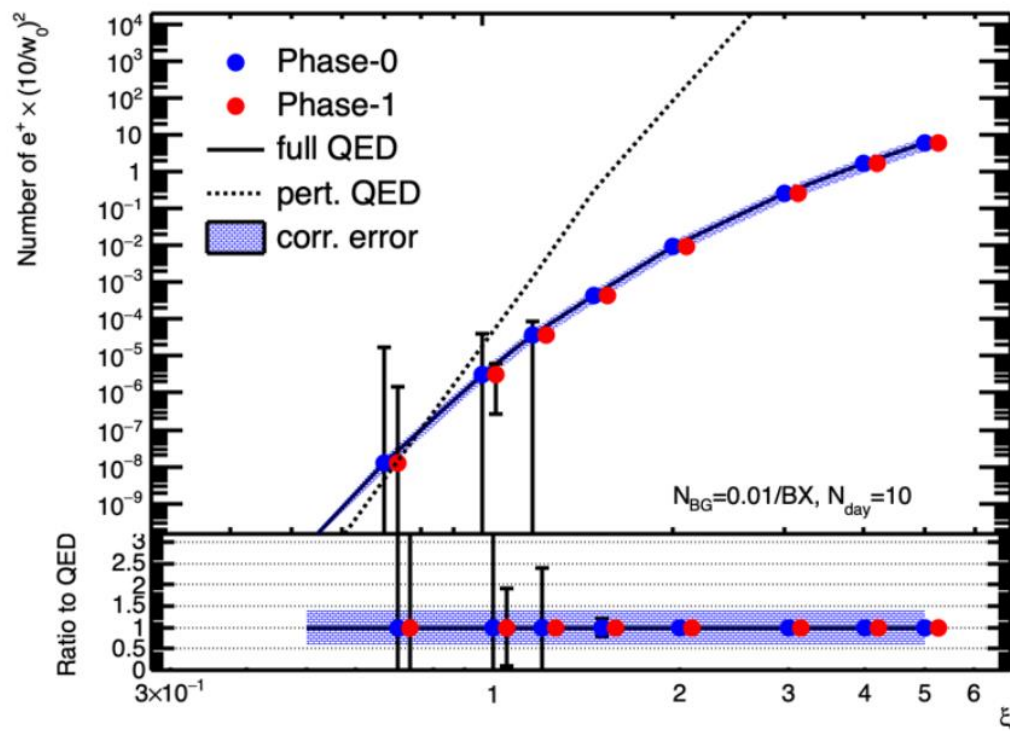
- LUXE will produce a high-intensity photon beam through Compton Scattering  
 → produce e.g. axion-like (ALPs) in photon beam-dump  
 → detect via new particle decay to two photons
- Production of new particles also possible in primary electron/LASER interaction
- Conceptual design of photon detector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



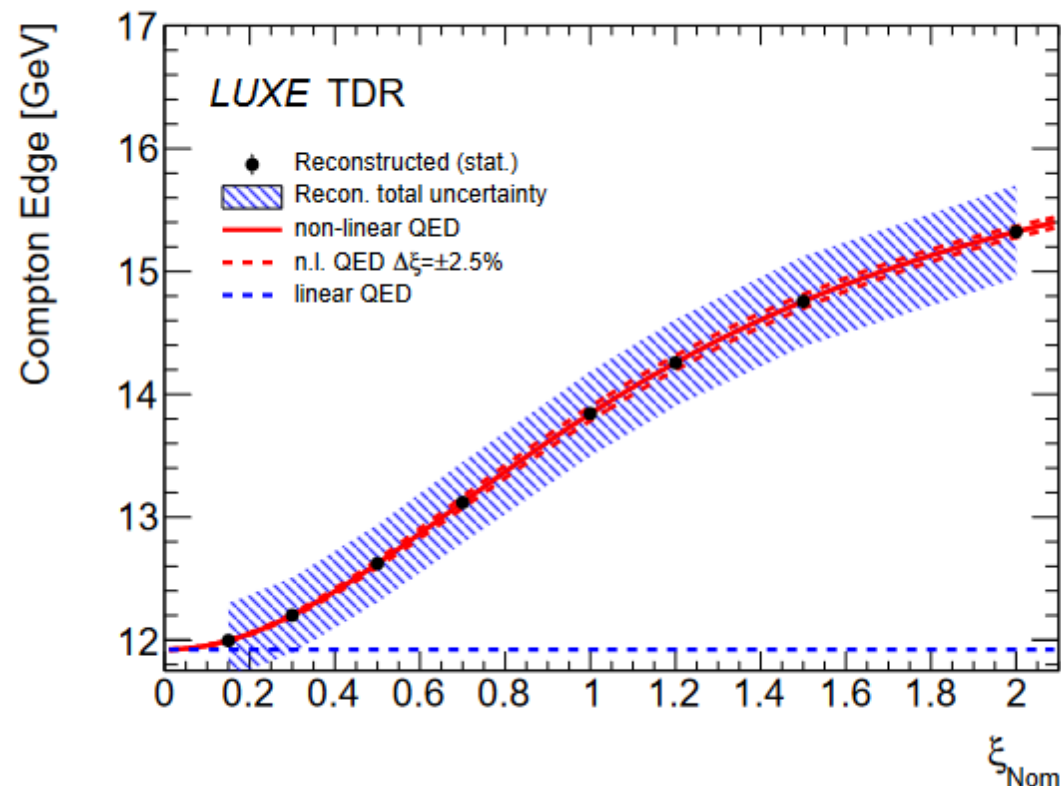
**LUXE-NPOD sensitivity to sub-GeV ALPs competitive with other experiments ongoing and in planning**



# Expected Results



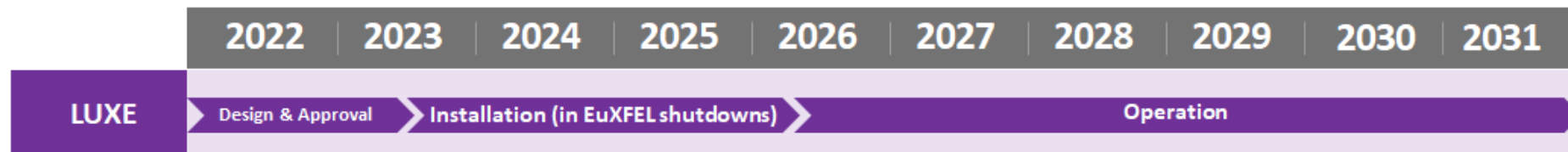
- Number of Breit-Wheeler pairs produced in photon-Laser collisions
- assuming 10dy of data-taking and 0.01 background events/bunch crossing
- 40% correlated uncertainty to illustrate effect of uncertainty on  $\xi$



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

# LUXE Status & Planning

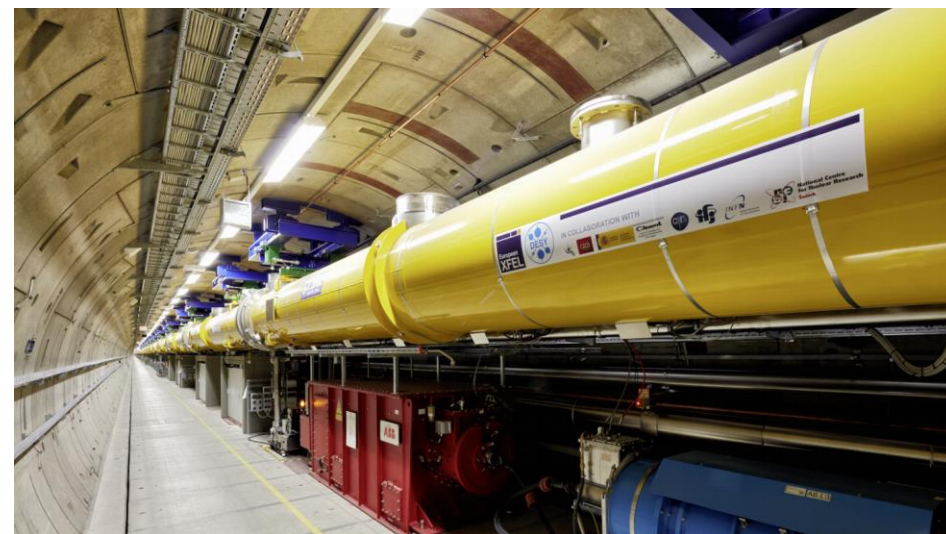
- LUXE initiated in 2017
- 2022: international collaboration of ~20 institutional members, significant contributions by external partners
- approval process at DESY and EuXFEL is progressing
- experiment funding: pursuing several options
- foresee four-year construction period to start of data-taking  
→ depending on approval time-scale, could be in 2026
- extensive material on technical design and planning available  
→ consolidate into TDR soon!





# 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 in 2025 during extended shutdown planned for European XFEL
  - Very diverse detector technologies, optimized for LUXE physics goals
  - Ideal testbed for new technologies for future colliders



**LUXE: exciting window of opportunity for a near-term new particle physics experiment**  
**Open to new collaborators!**

## Contact

Deutsches Elektronen-  
Synchrotron DESY

[www.desy.de](http://www.desy.de)

Ruth Jacobs

FHR

[ruth.magdalena.jacobs@desy.de](mailto:ruth.magdalena.jacobs@desy.de)

# 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

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

**Note:**

$\mathcal{E}_L$ : Laser field

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

$\theta$ : Laser - probe crossing angle

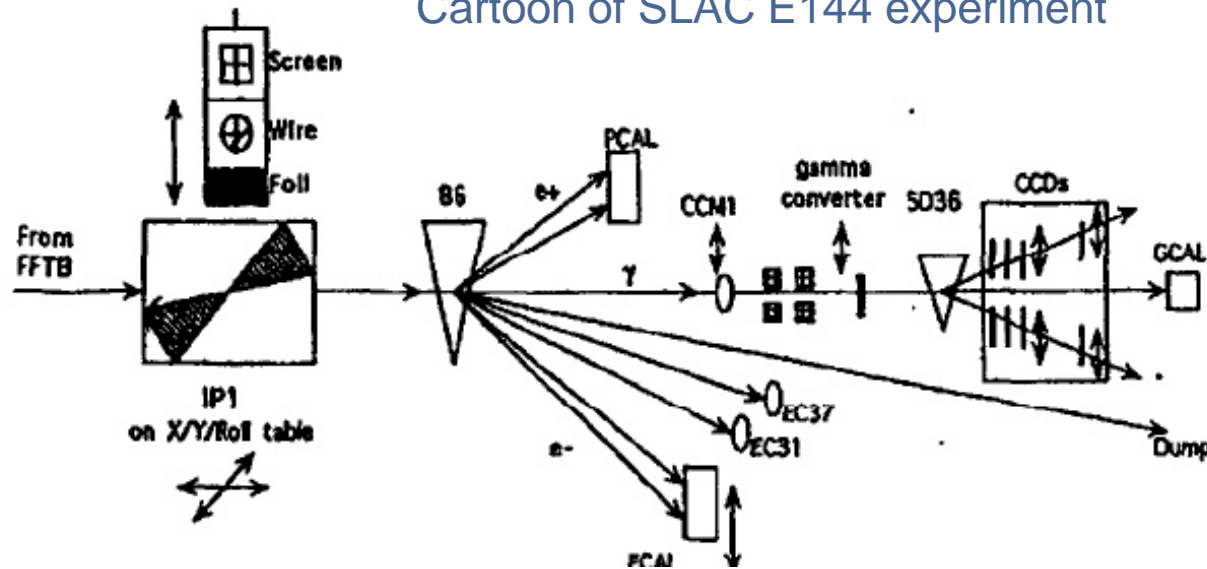
$\omega_L$ : Laser frequency

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

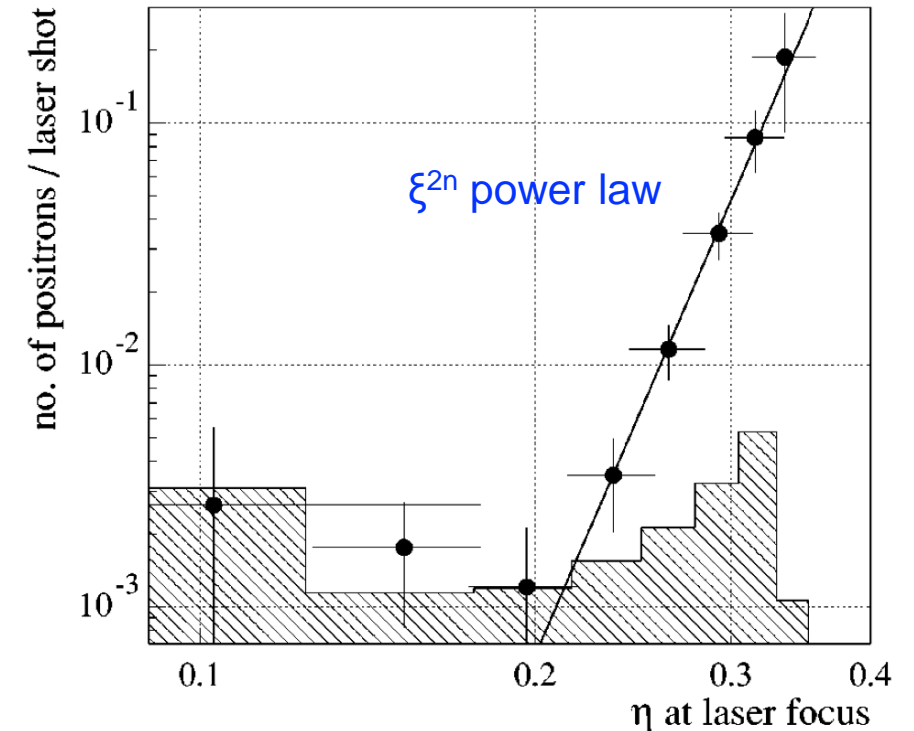
**Different combinations of  $\xi$  and  $\chi$  result in different types of non-linear behavior!**

# 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  $\chi \leq 0.25$ ,  $\xi < 0.4$
- observed process  $e^- + n\gamma_L \rightarrow e^- e^+ e^-$
- observed start of the  $\xi^{2n}$  power law, but not departure

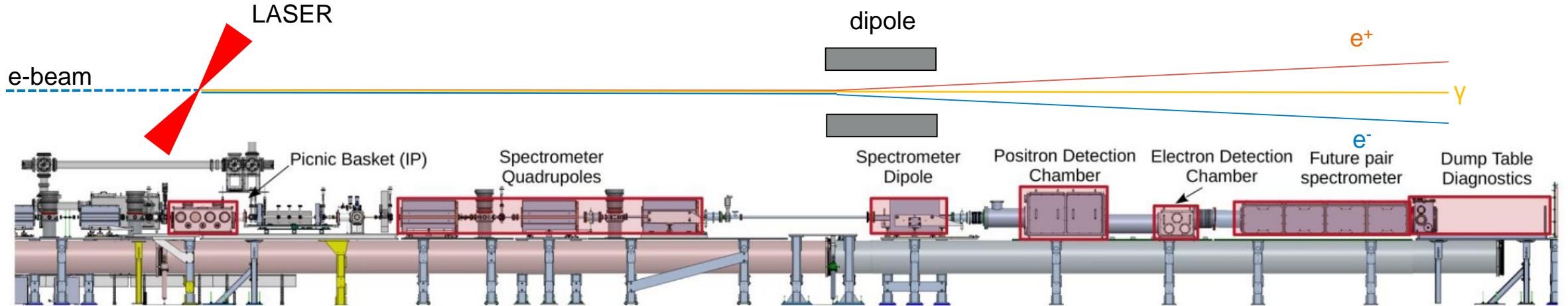


**LUXE : Three orders of magnitude more powerful laser than E144, will enter non-perturbative regime**

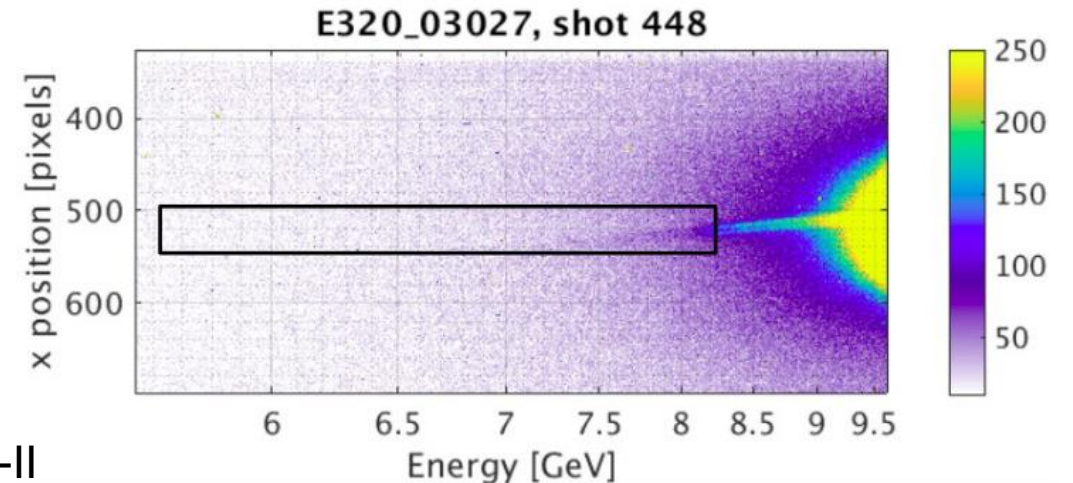


# E-320 experiment at SLAC

[Link](#) to E320 overview by S. Meuren

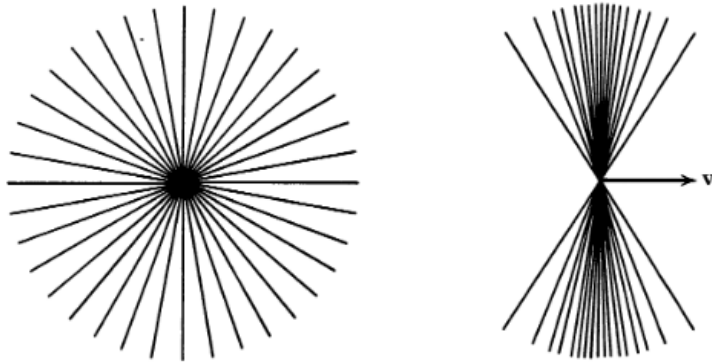


- E320: ongoing SF-QED experiment at SLAC using 13 GeV electron beam (FACET-II) and 16 TW optical Laser
- first electron-LASER collisions in 2022
- By design: similar parameter reach as LUXE (after Laser and Detector upgrades)
- Main differences to LUXE:
  - electron-Laser collision mode only
  - E-320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



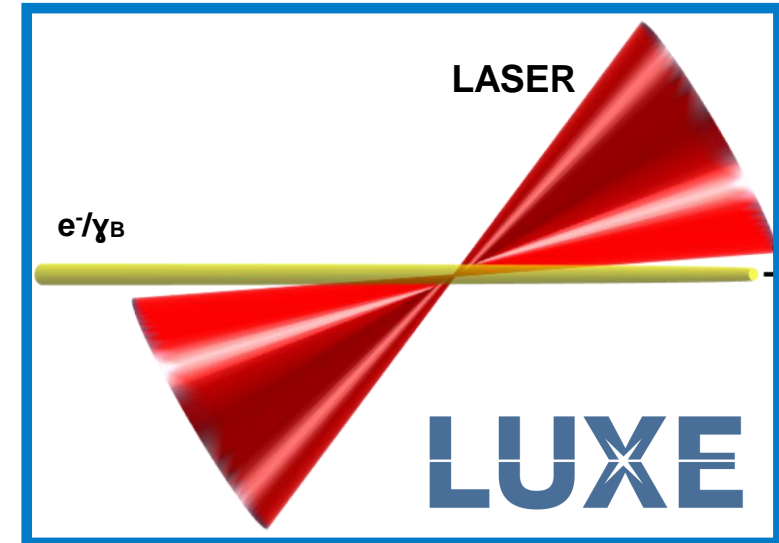
# SFQED with relativistic probes

- 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

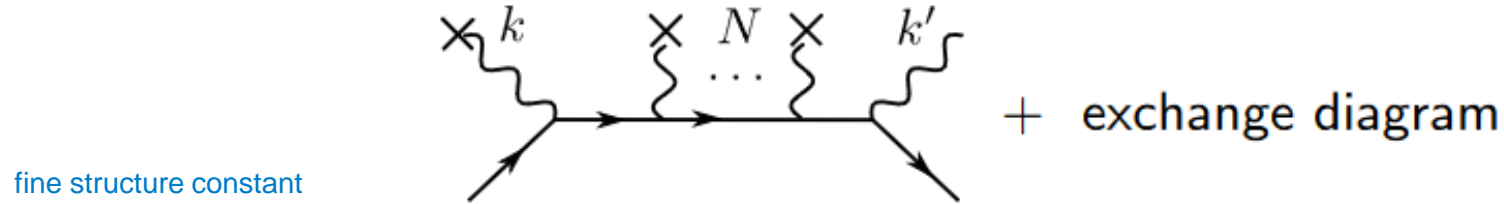
$$\mathcal{E}_{rest\ fr.} = \gamma \mathcal{E}_{lab\ fr.}$$



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

# Compton scattering in strong fields

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

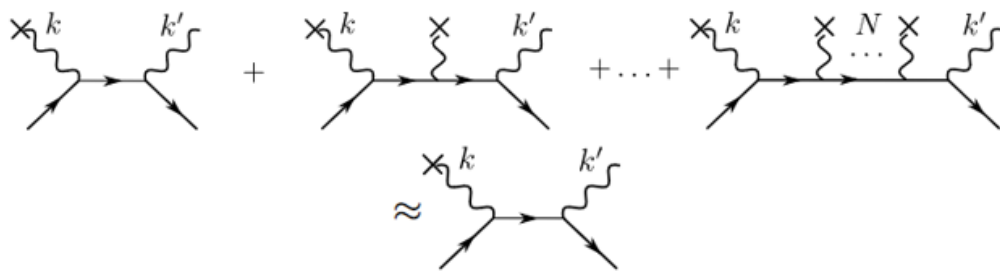


fine structure constant

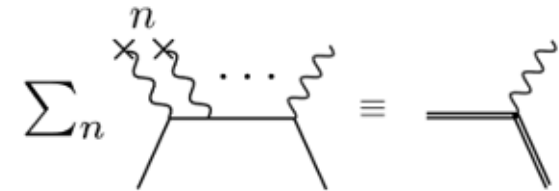
Probability  $P \sim \alpha \left( \frac{eA_0}{m} \right)^{2N} = \alpha \xi^{2N}$

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

'Classical nonlinearity / intensity parameter',  $\xi$ .



**"weak" field  $\xi < 1$**



'Nonlinear' Compton scattering

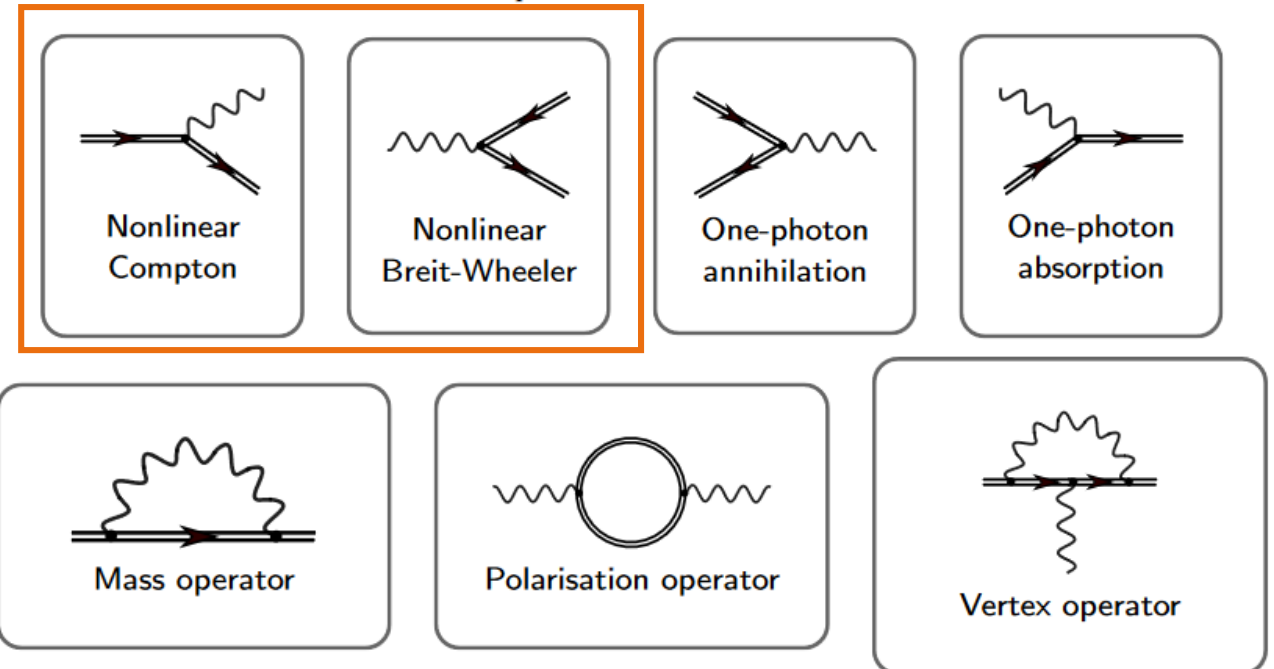
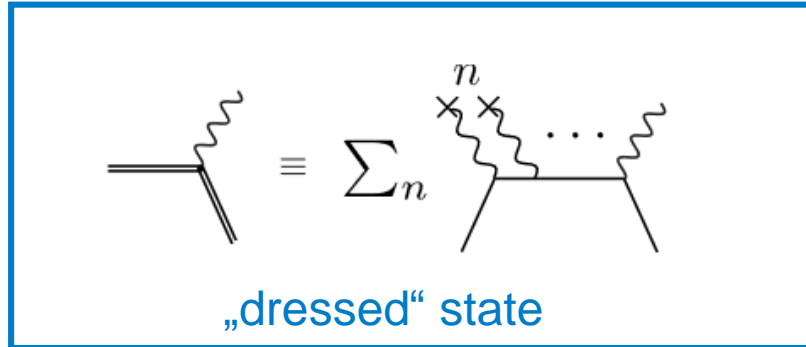
**strong field:  $\xi \geq 1$**

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

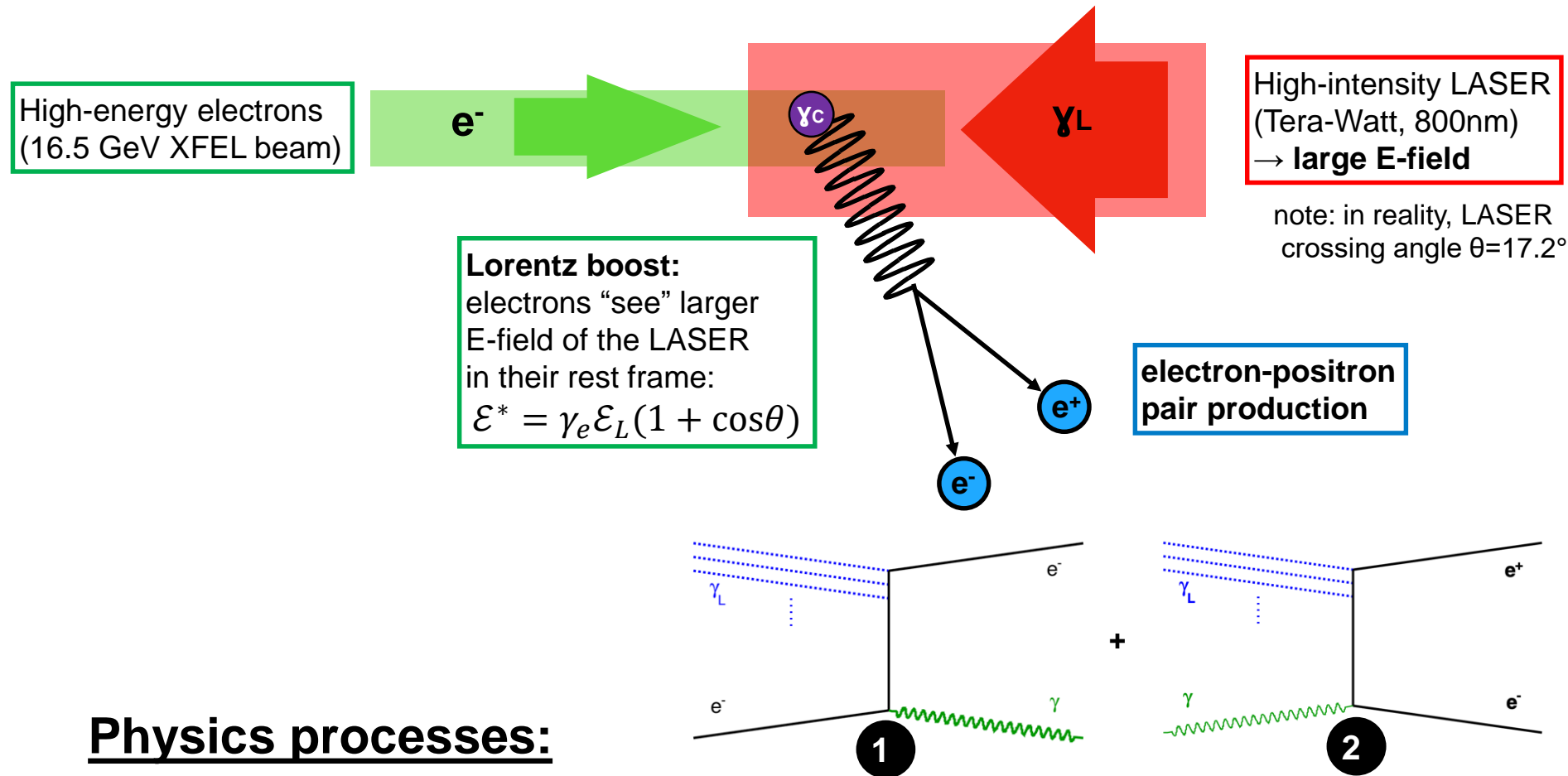
# The Furry picture

- 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 ( $\alpha \ll 1$ )

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



# LUXE: Electron + LASER collisions

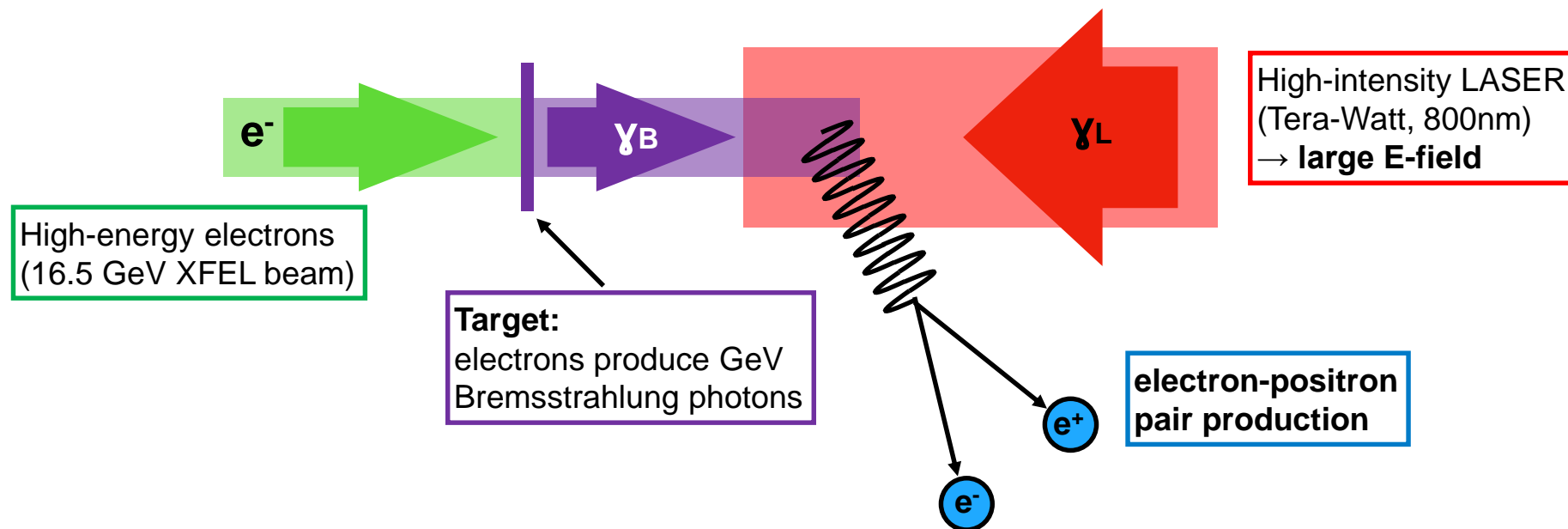


## Physics processes:

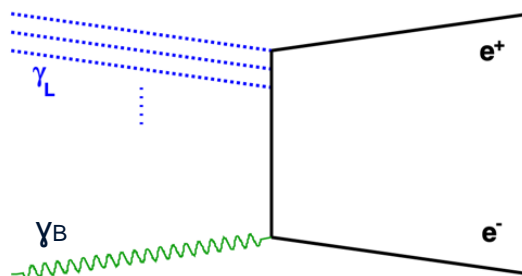
- 1 Non-linear Compton Scattering:  $e^- + n\gamma_L \rightarrow e^- + \gamma_C$
- 2 Non-linear Breit-Wheeler pair production:  $\gamma_C + n\gamma_L \rightarrow e^+ + e^-$



# LUXE: Photon + LASER collisions



## Physics process:

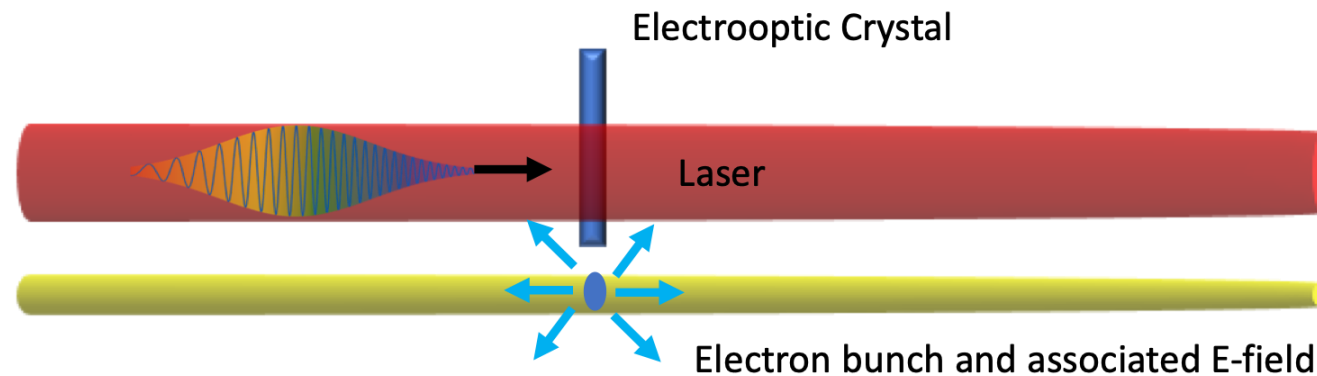


Non-linear Breit-Wheeler pair production :  $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

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

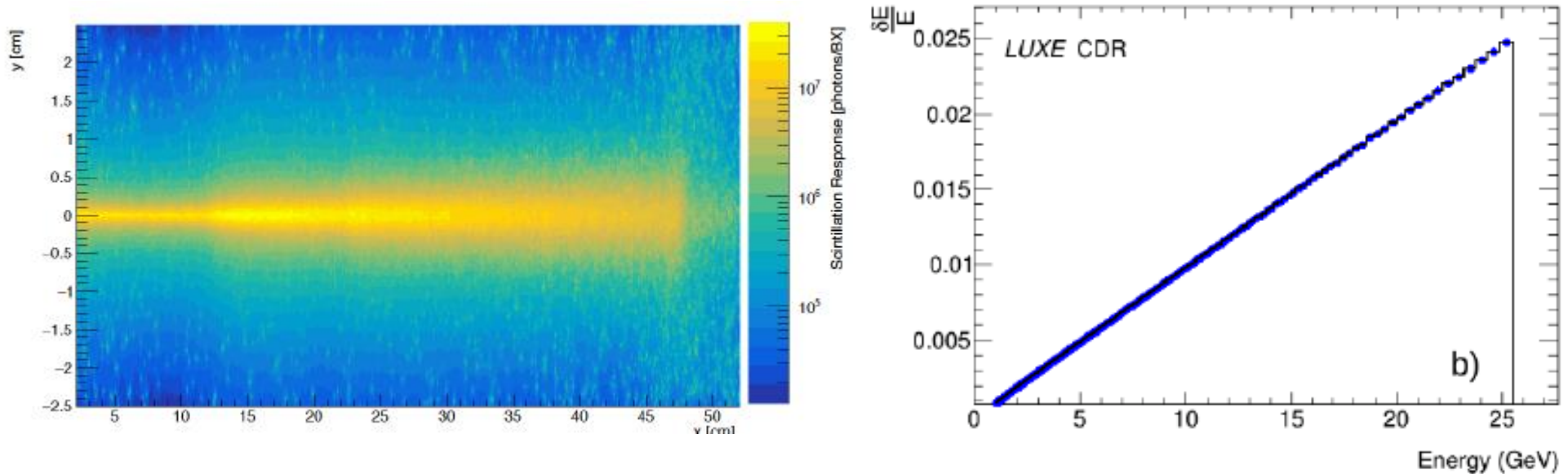
# Synchronization

- 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 synchronization system  
→ synchronization of two RF signals to <13fs
- synchronise the XFEL.EU master clock oscillator to the oscillator of the JETI40  
→ already used across XFEL to synchronize LASERS and accelerator  
→ fine-tune repetition rate via piezo-elements controlling LASER cavity size
- stability against temperature variations: isolation and active feedback loops
- spatial overlap: beam pointing monitoring systems for both electron and LASER beam



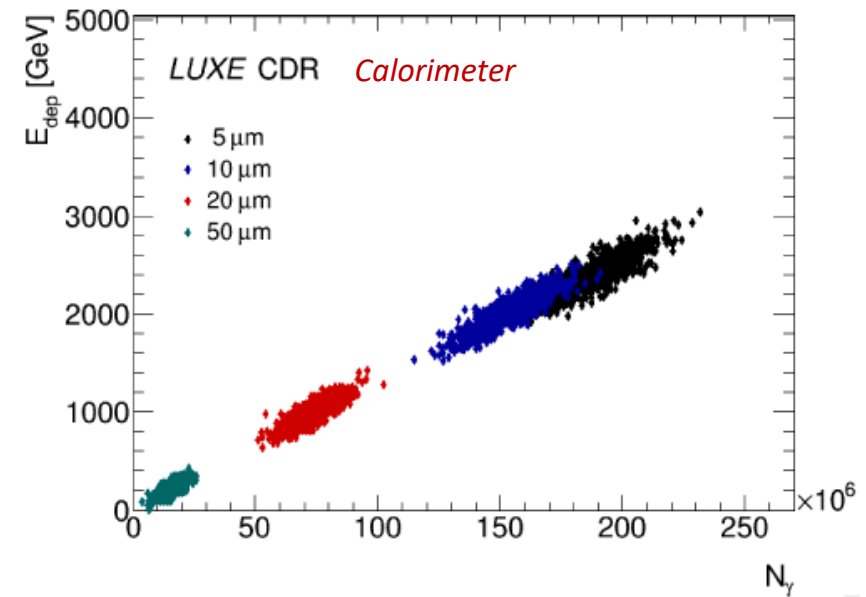
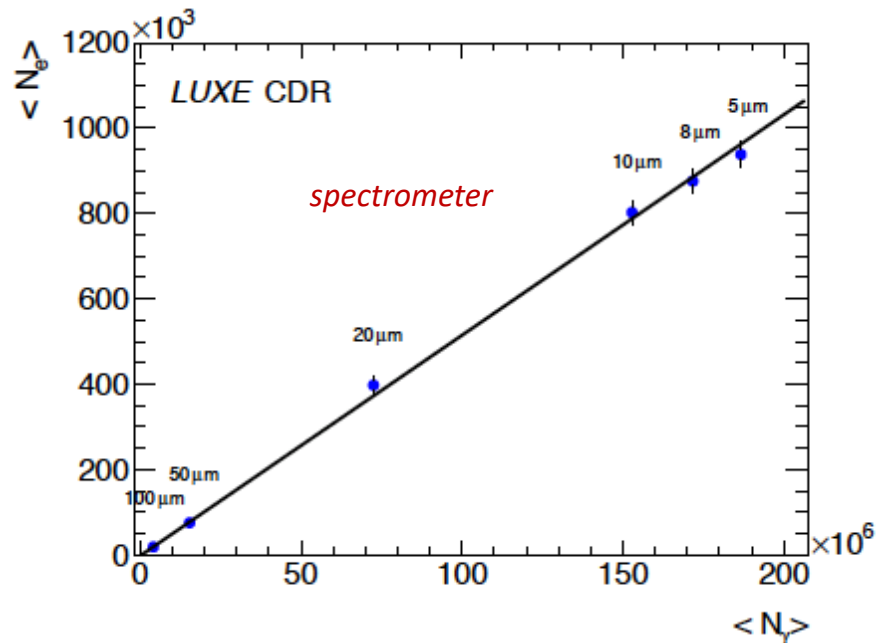
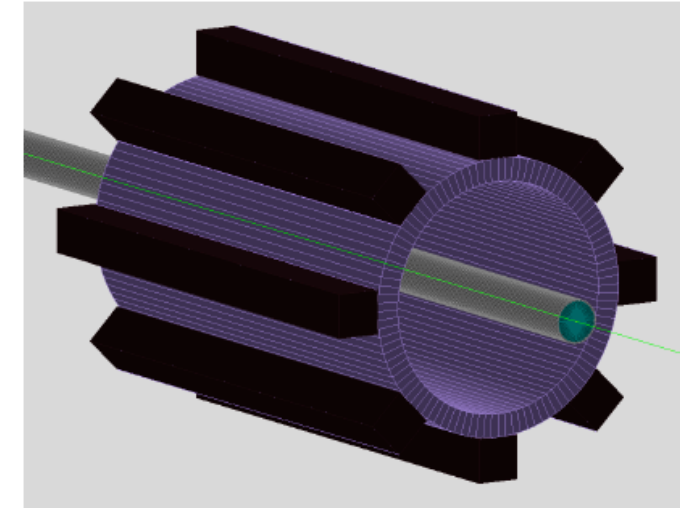
# Forward Spectrometer Detectors

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



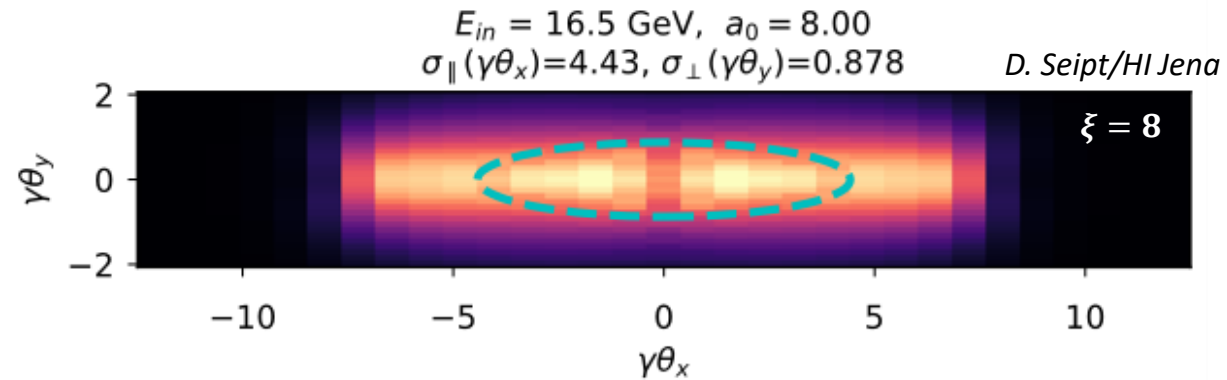
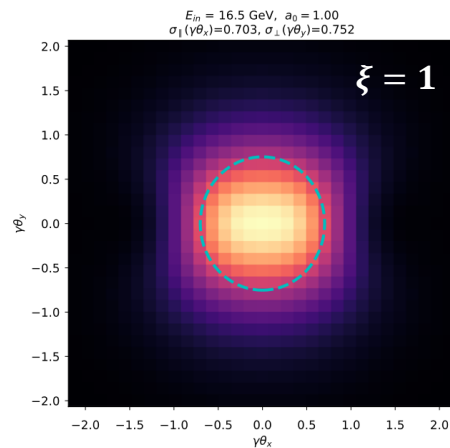
# Backscattering Calorimeter

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



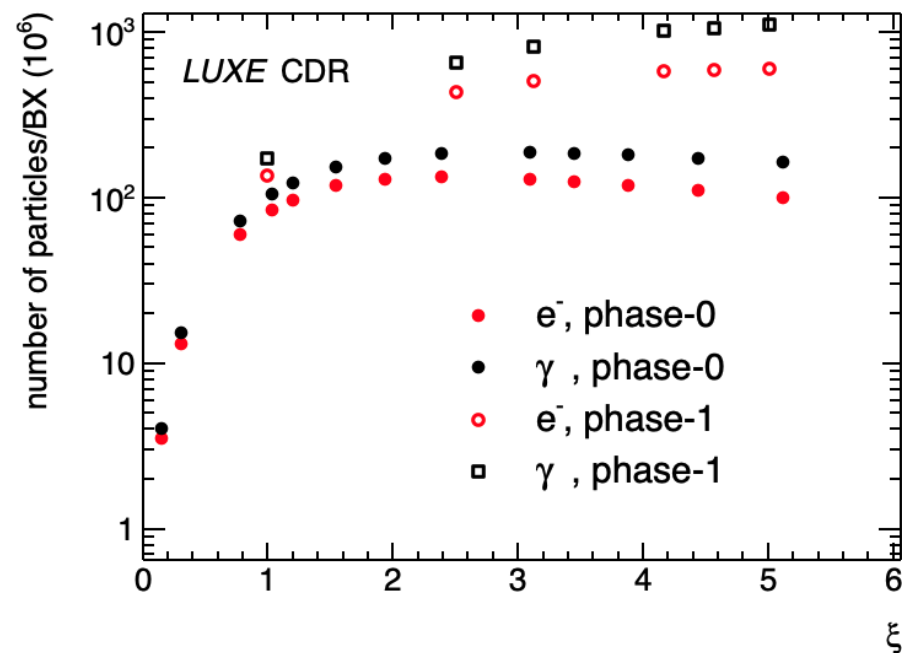
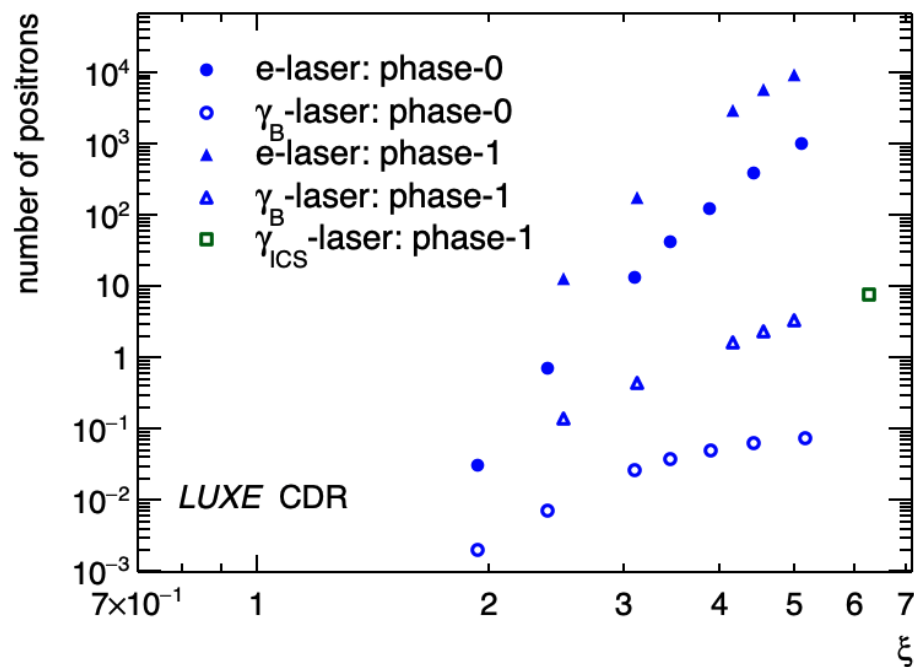
# Gamma Profiler

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



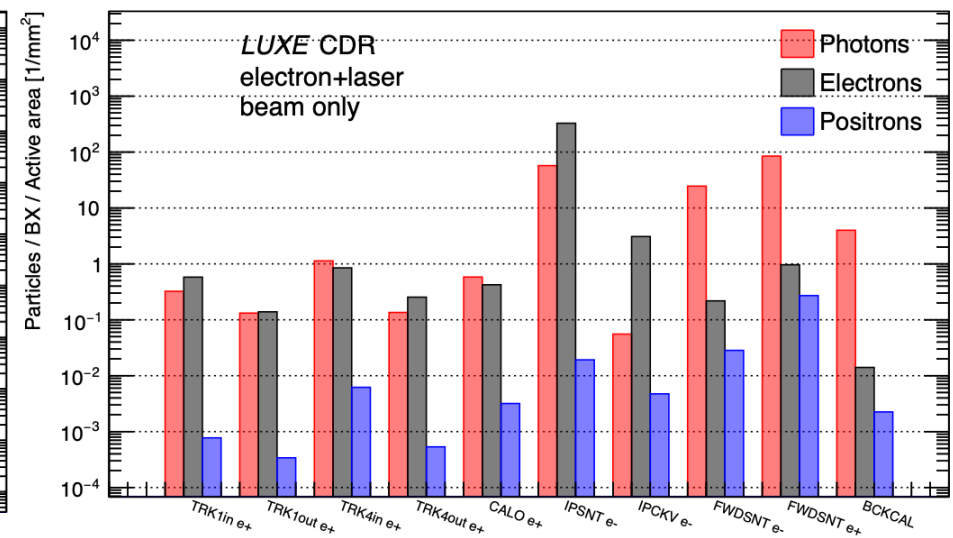
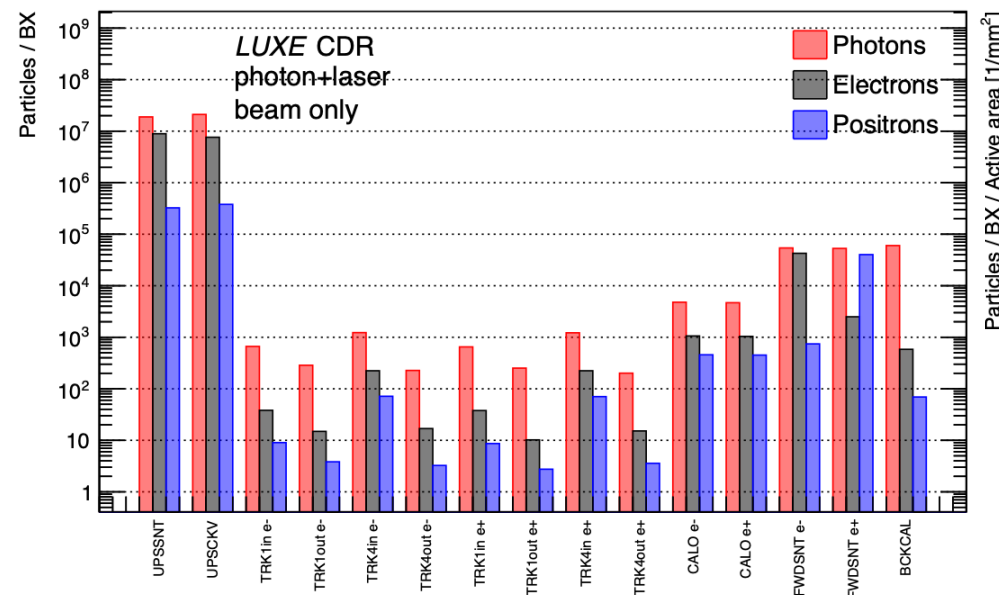
- Measurement of  $5 \mu\text{m}$  provides constraint:  $\frac{\delta\xi}{\xi} < 1\%$  for  $\xi > 2$

# Particle rates

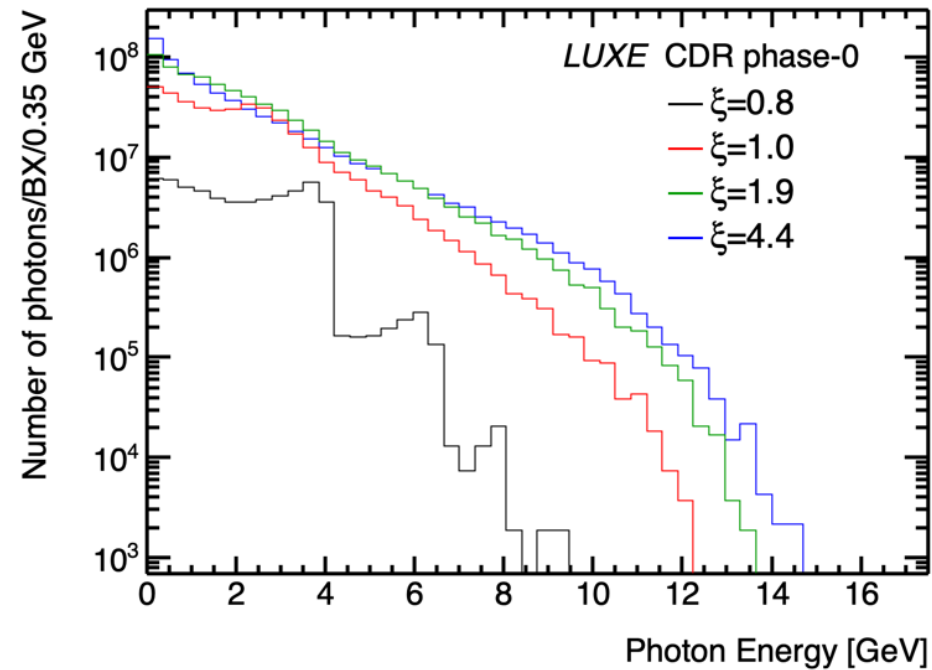
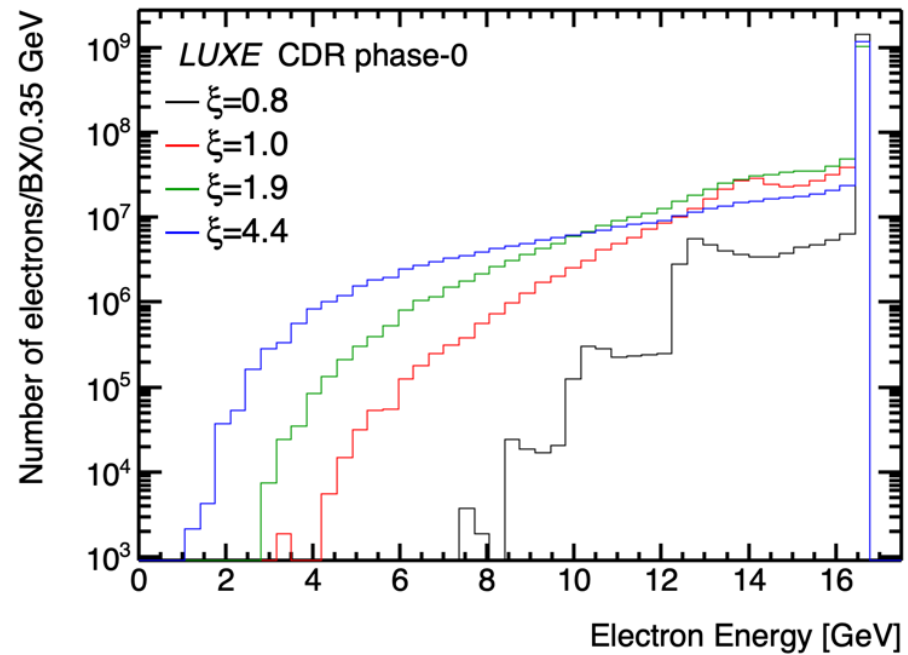




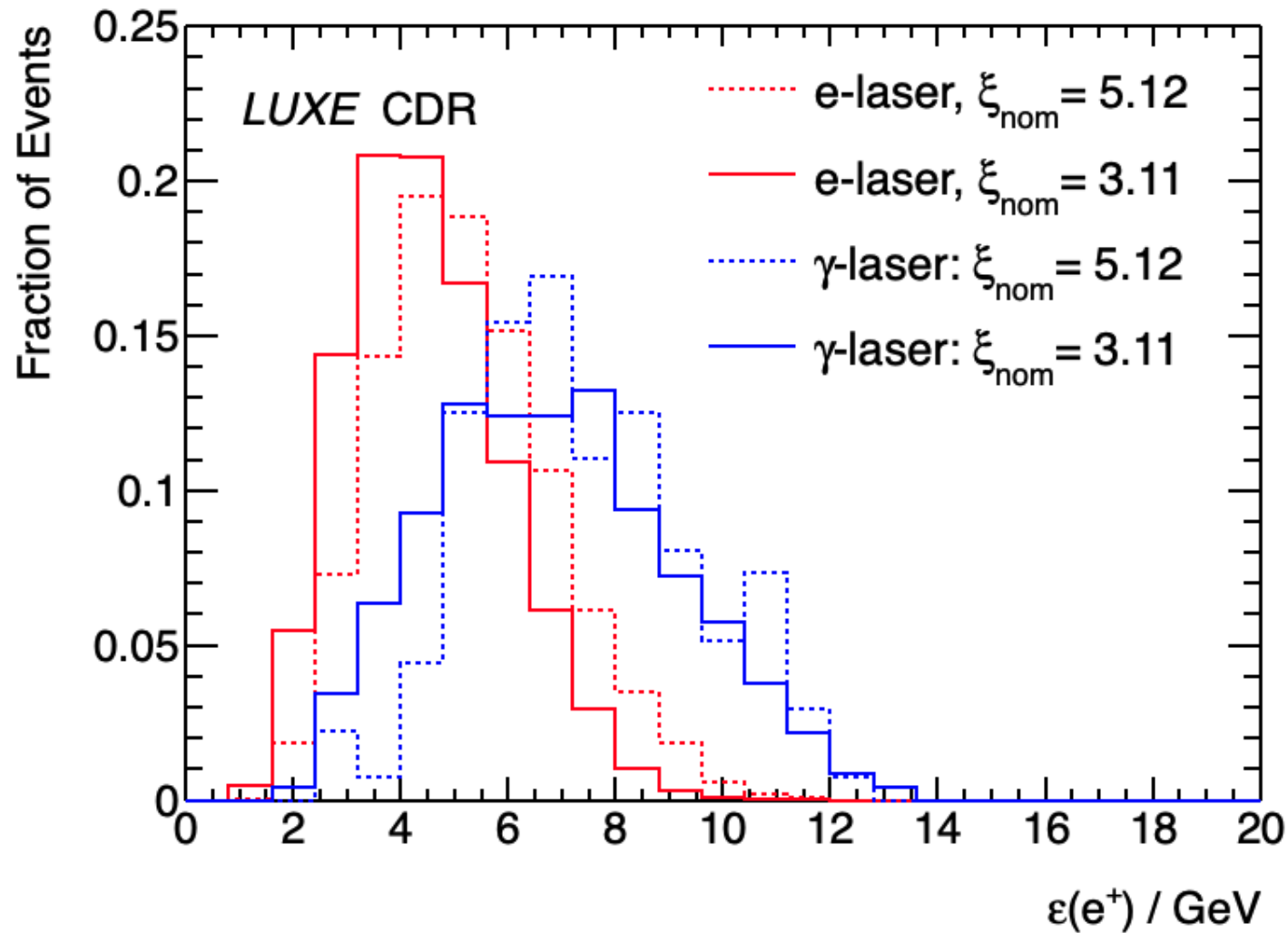
# Beam Background rates



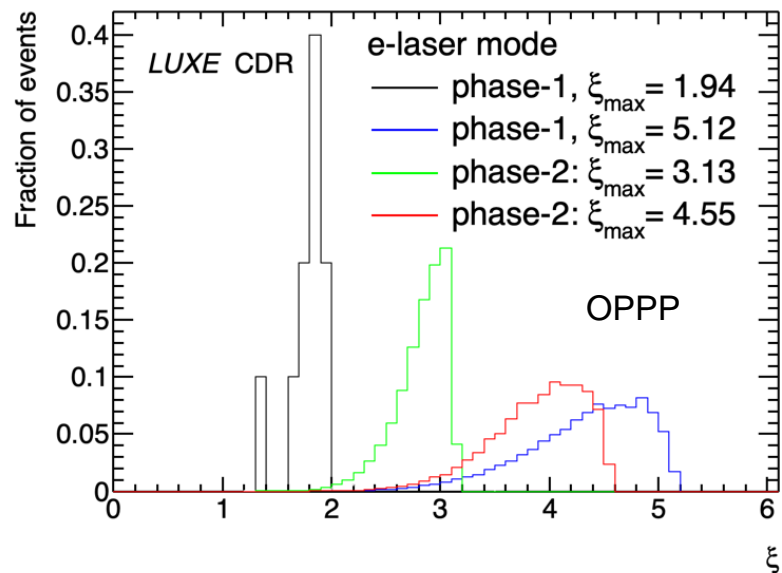
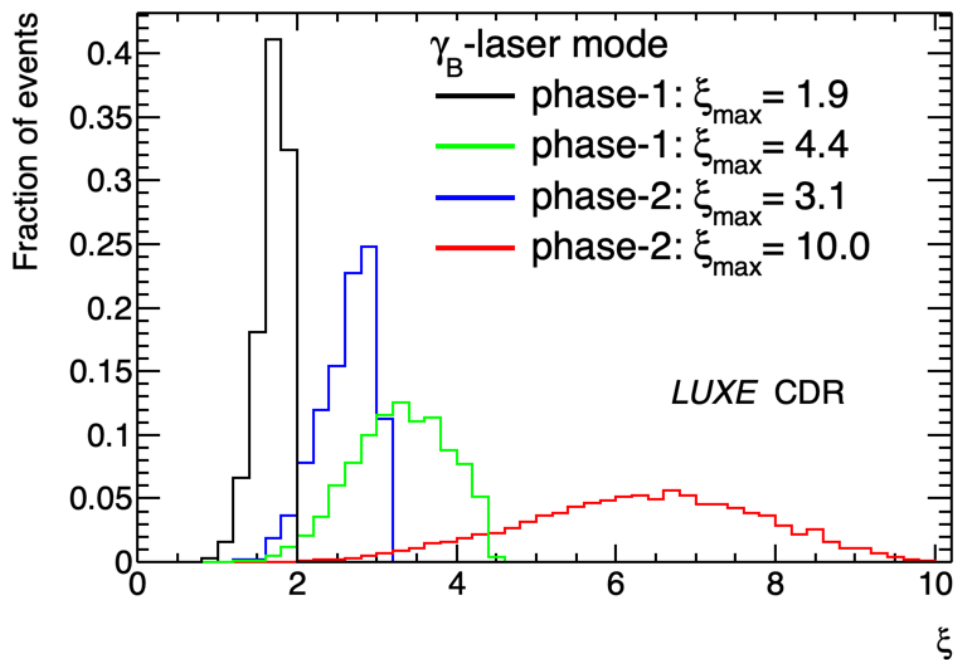
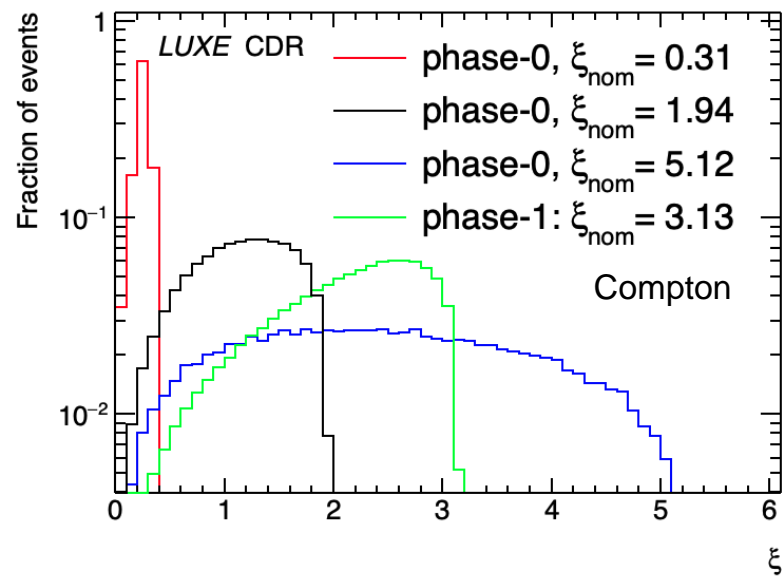
# e+LASER Spectra



# Positron Spectra

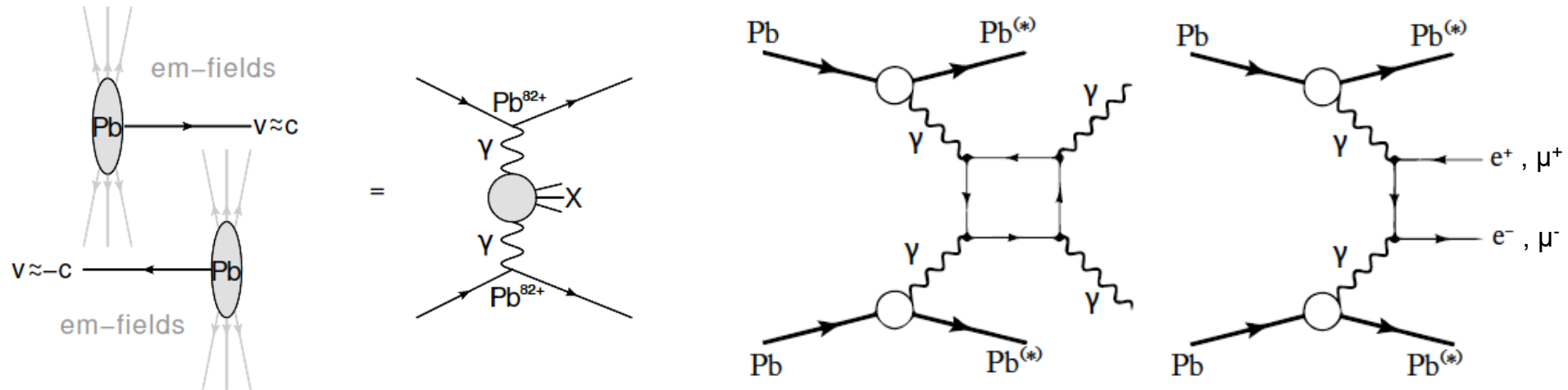


# xi distributions



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

- LHC: photon-photon interaction in ultra-peripheral heavy-ion collisions (UPC)  
→ e.g.  $\gamma\gamma \rightarrow \gamma\gamma$ ,  $\gamma\gamma \rightarrow \mu\mu$
- 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



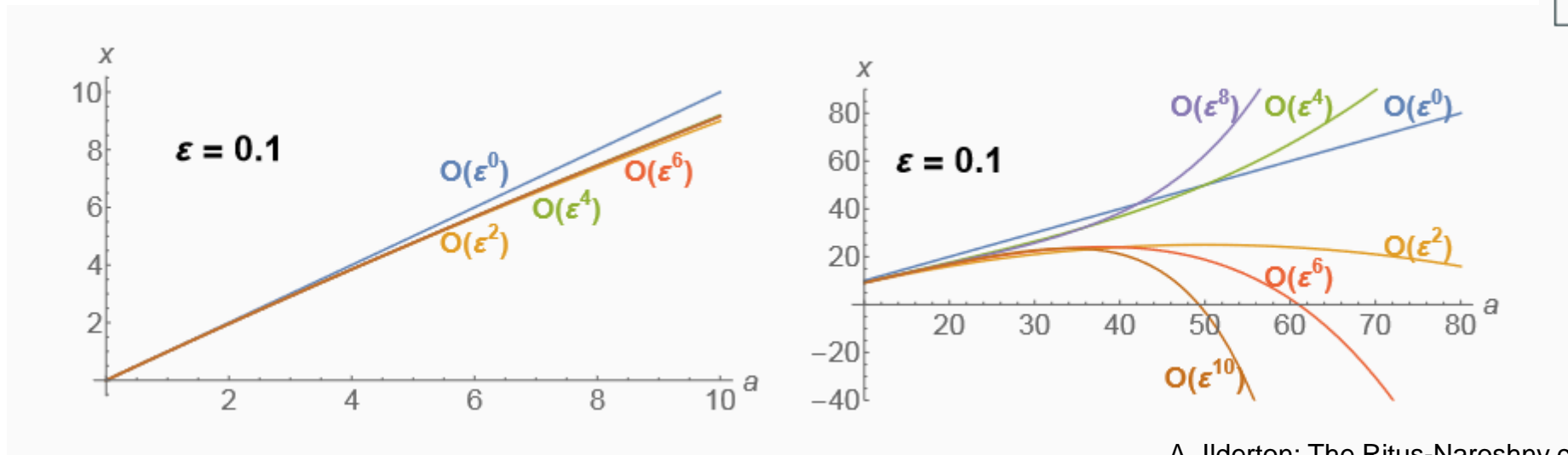
Figures from: arXiv:2010.07855v3  
(Also a nice review to read, if you want to know more!)



# Ritus-Naroshny Conjecture

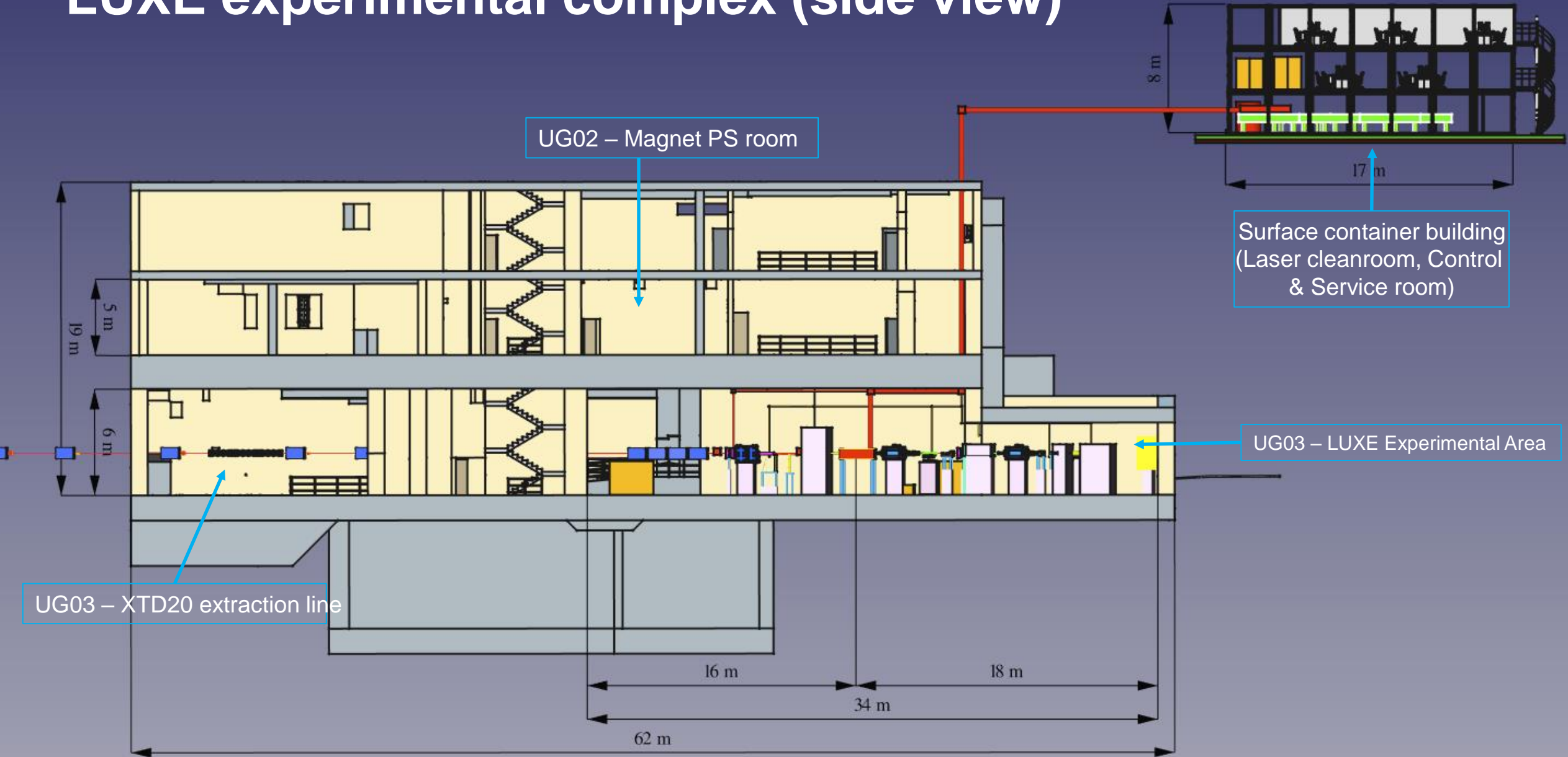
- Ritus-Naroshny Conjecture: in the vicinity of sufficiently strong fields, the Furry expansion breaks down  
→ perturbative QED coupling  $\alpha$  is modified by the field strength:  $\alpha \rightarrow \alpha \chi^{2/3}$
- Conjecture interpreted to hold for any „locally constant“ background  
(field constant over formation length scale of physics process)

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



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

# LUXE experimental complex (side view)



# LUXE experimental complex (top view)

