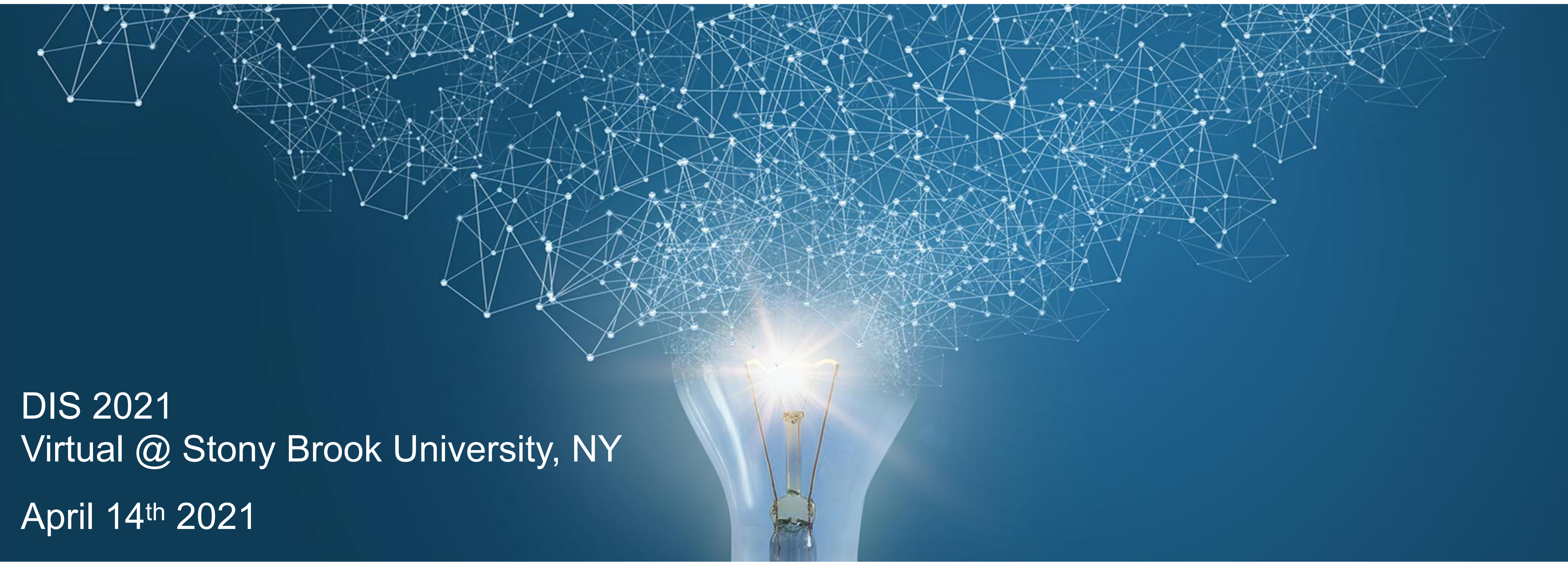
LUXE: A new experiment to study non-perturbative QED

Ruth Jacobs, for the LUXE Collaboration



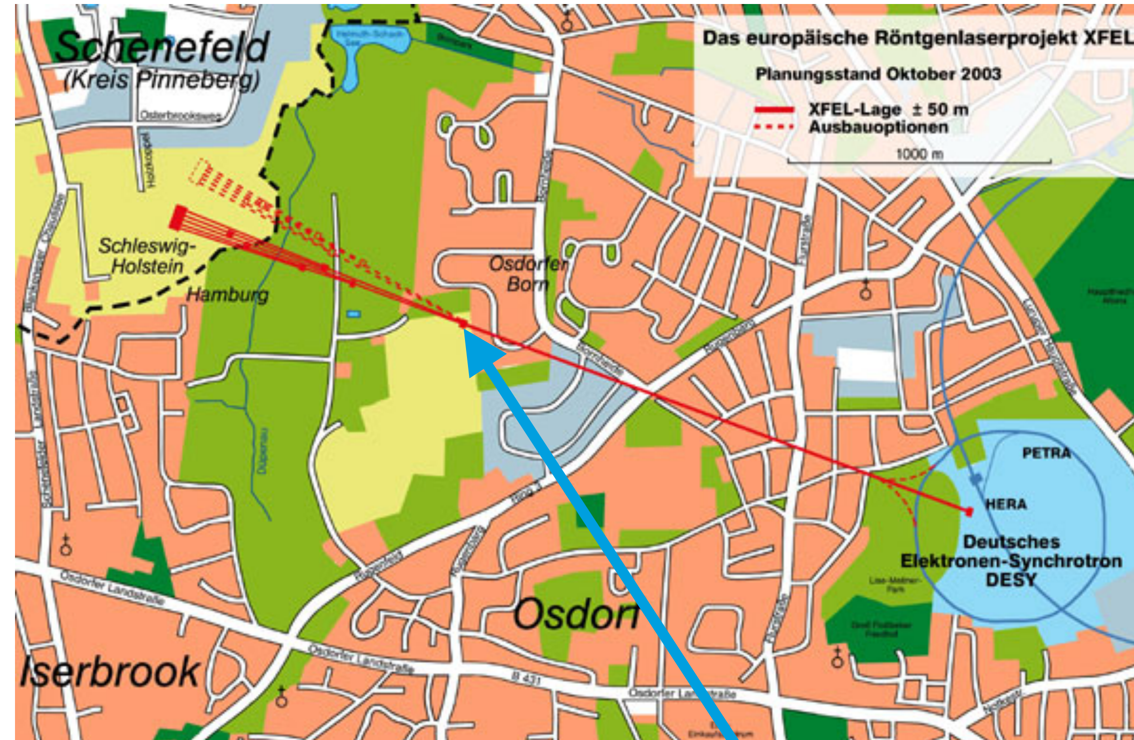
DIS 2021
Virtual @ Stony Brook University, NY

April 14th 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

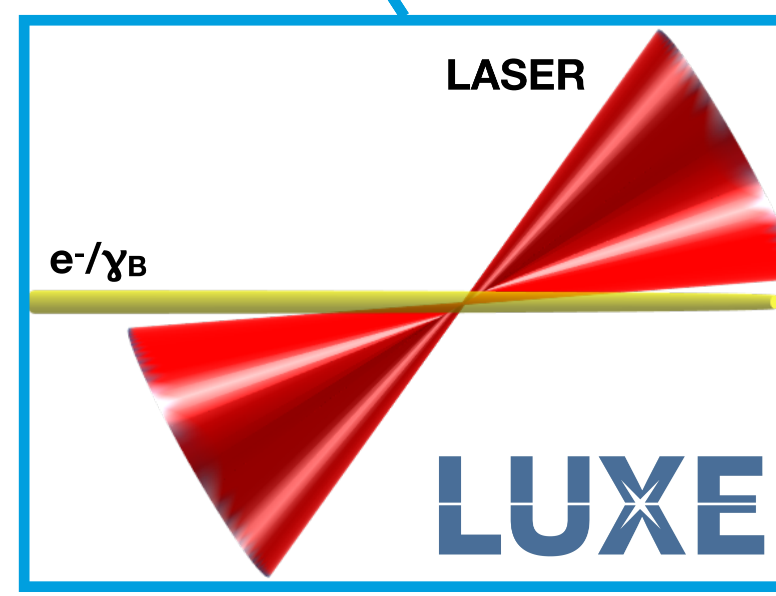
Overview



LUXE
LASER Und XFEL Experiment

What is the LUXE experiment?

- proposed new experiment at DESY and Eu.XFEL in Schenefeld & Hamburg, Germany
- collisions of XFEL electron beam and high-power LASER
- synergy between particle physics and LASER physics
- (growing) international collaboration
  → 88 members (26 institutes)



More documentation?

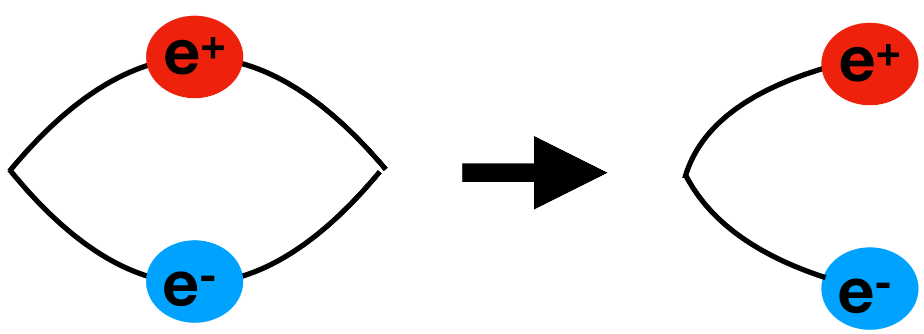
- LUXE CDR (newly released!): arXiv:2102.02032
- LUXE website: https://luxe.desy.de

Introduction: Strong-Field QED

Euler and Heisenberg
Z.Phys. 98 (1936) no.11-12, 714-732
(translation at arXiv:physics/0605038

Schwinger
Phys. Rev. 82 (1951), 664

- QED: most well-tested theory in physics
  → based on perturbative calculations
- LUXE will study QED in the strong-field regime
- strong external field: work by field over Compton wavelength > than rest mass of virtual particle
  → Schwinger-Limit



$E_{field} < 2m_e$

$E_{field} > 2m_e$

Field energy:

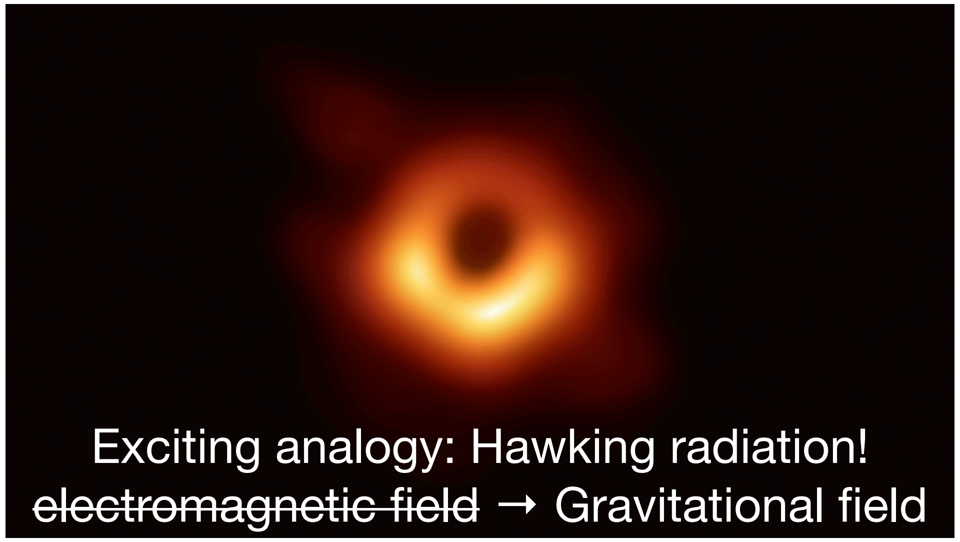
$$E_{field} = \frac{\mathscr{E}}{m_e}$$

Schwinger Limit:

$$\mathscr{E}_{cr} = \frac{m_e^2 c^3}{e\hbar}$$

e.g. for electrical field:

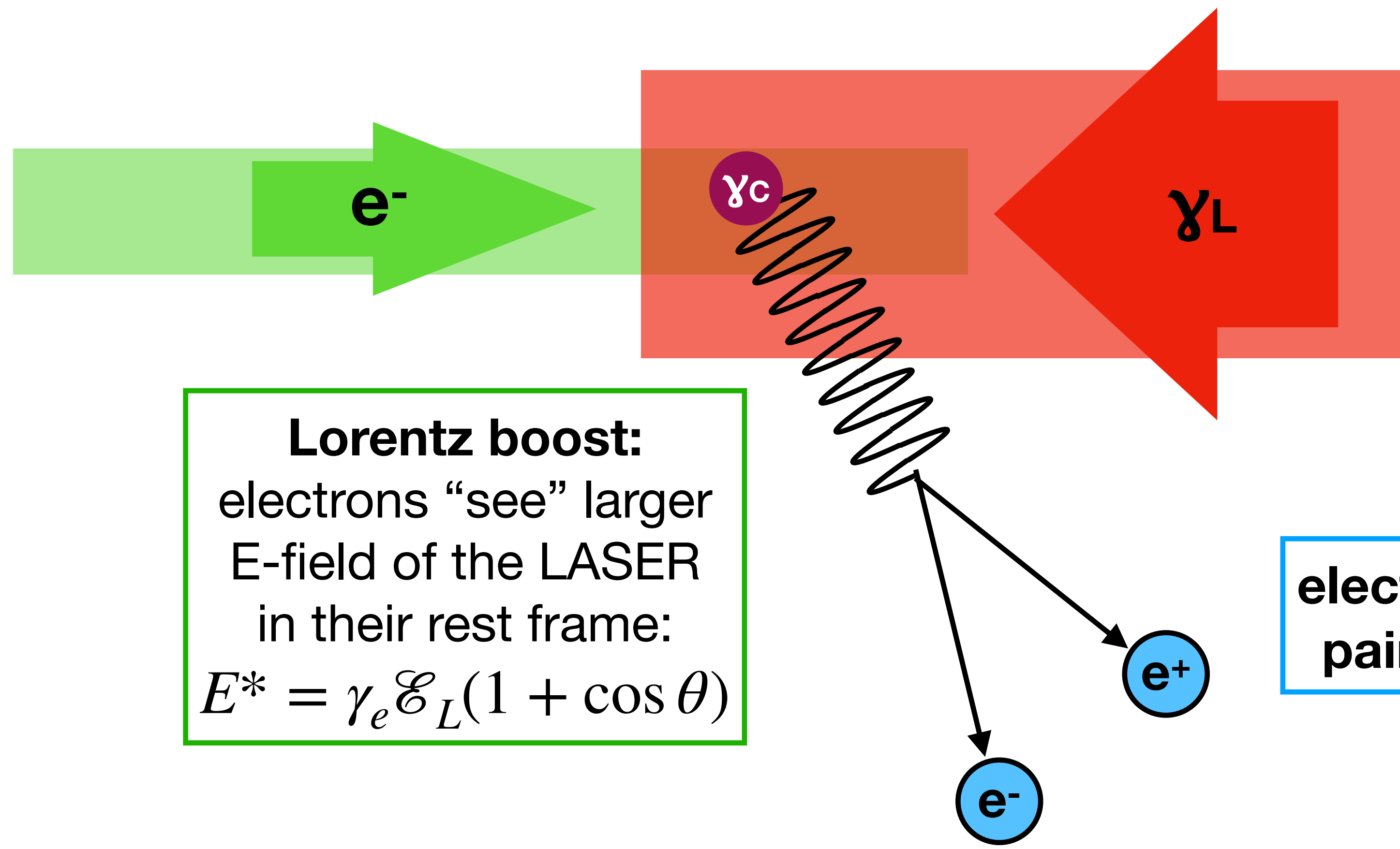
$\mathscr{E}_{cr} = 1.32 \cdot 10^{18}$V/m



QED becomes non-perturbative above Schwinger-Limit!

LUXE: Electron + LASER collisions

High-energy electrons
(16.5 GeV XFEL beam)

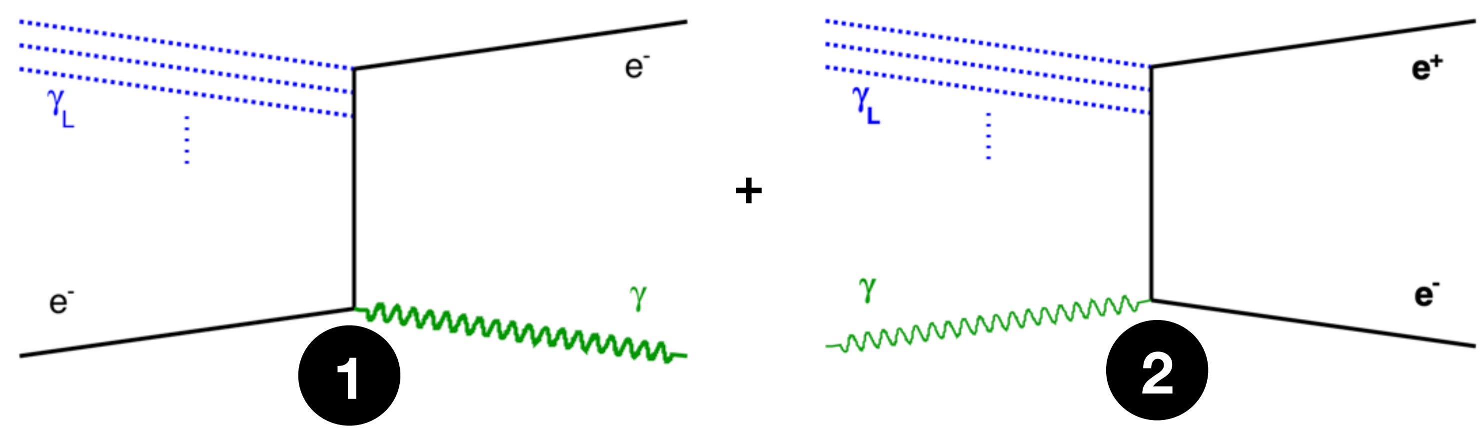


High-intensity LASER
(Tera-Watt, 800nm)
→ **large E-field**

note: in reality, LASER crossing angle θ=17.2°

Lorentz boost:
electrons "see" larger E-field of the LASER in their rest frame:
$E^* = \gamma_e \mathscr{E}_L (1 + \cos\theta)$

electron-positron pair production



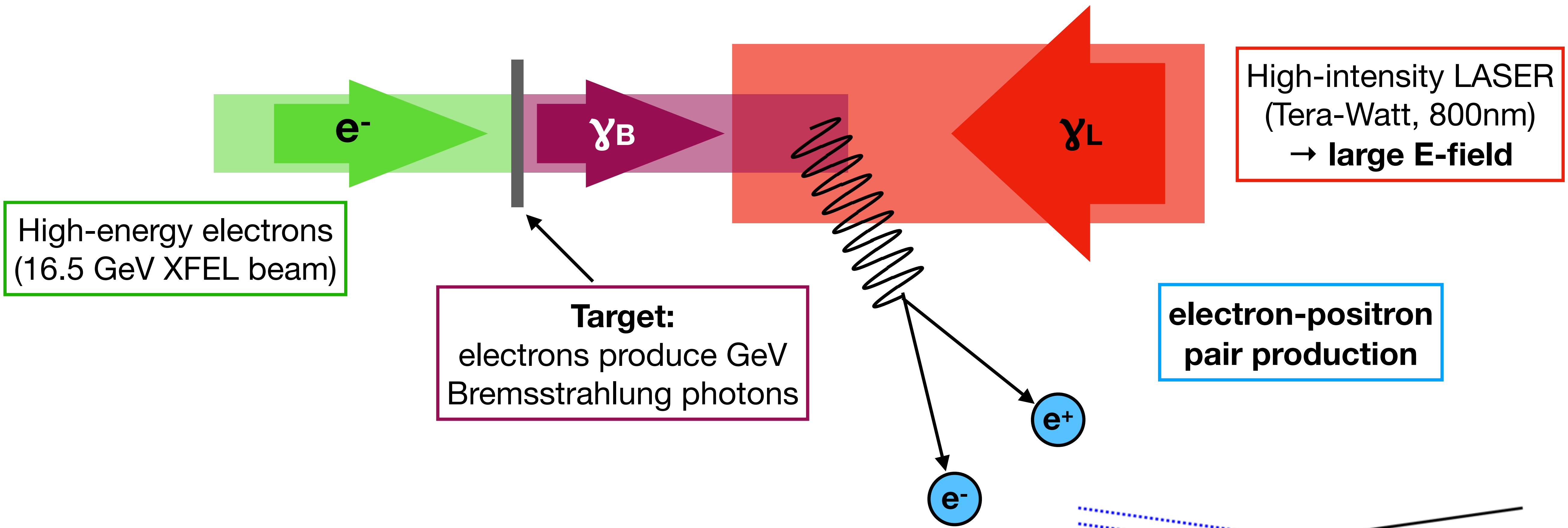
Physics processes:

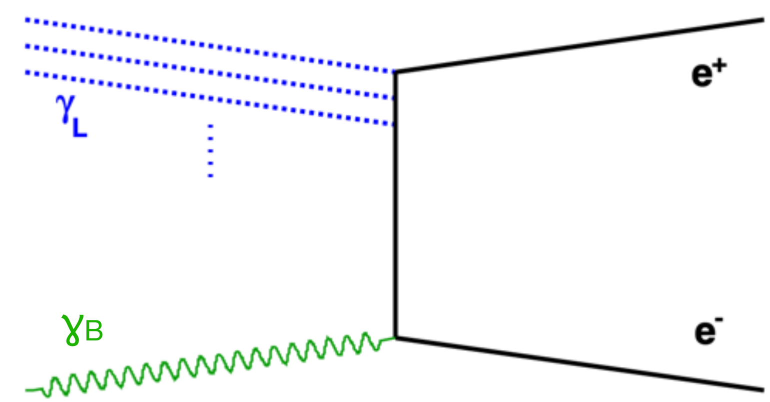
1 **Non-linear Compton Scattering:** $e^- + n\gamma_L \rightarrow e^- + \gamma_C$

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 : $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

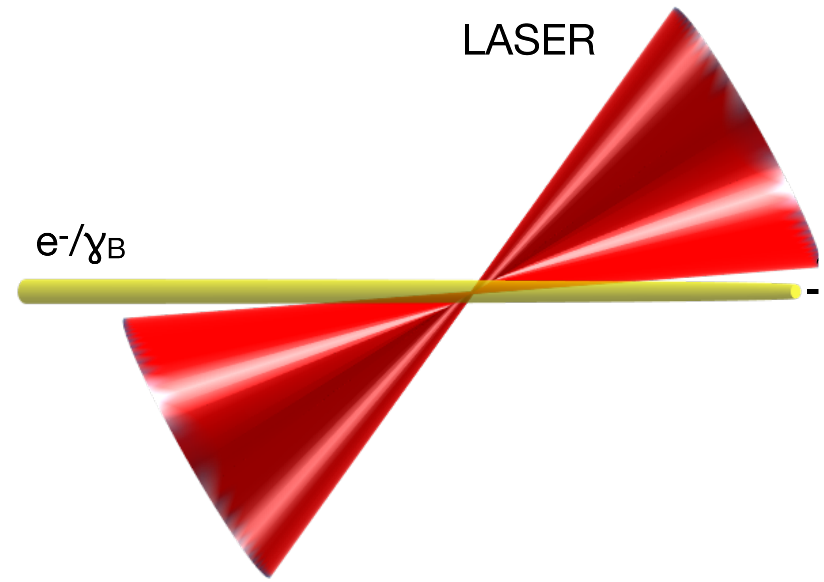
LUXE: first SF-QED experiment to probe directly photon-photon interaction

The 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/cm²]	13.3 / 120

Laser intensity:

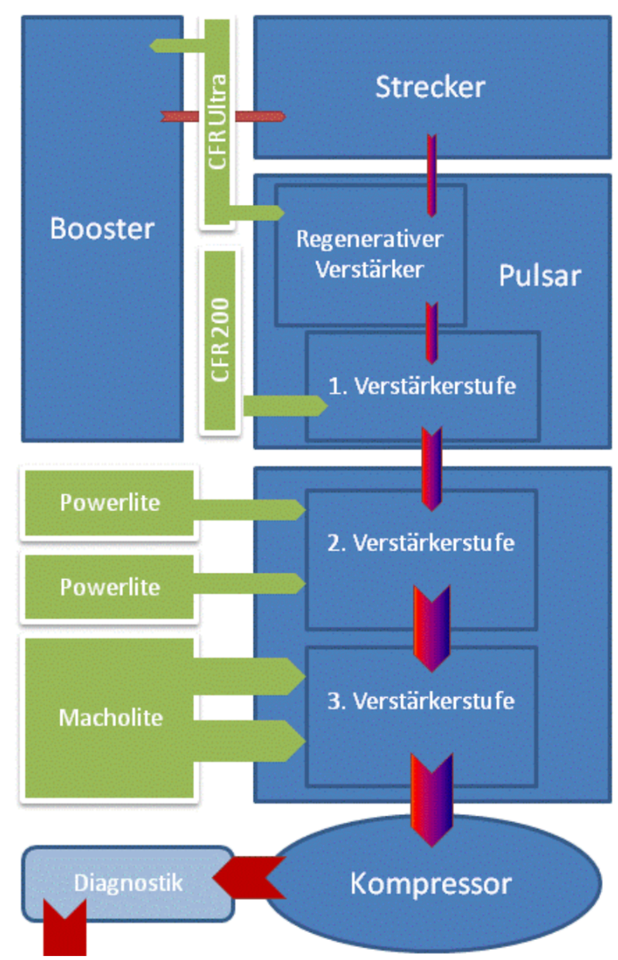
$$I = \frac{E_L}{\Delta t \pi d^2}$$



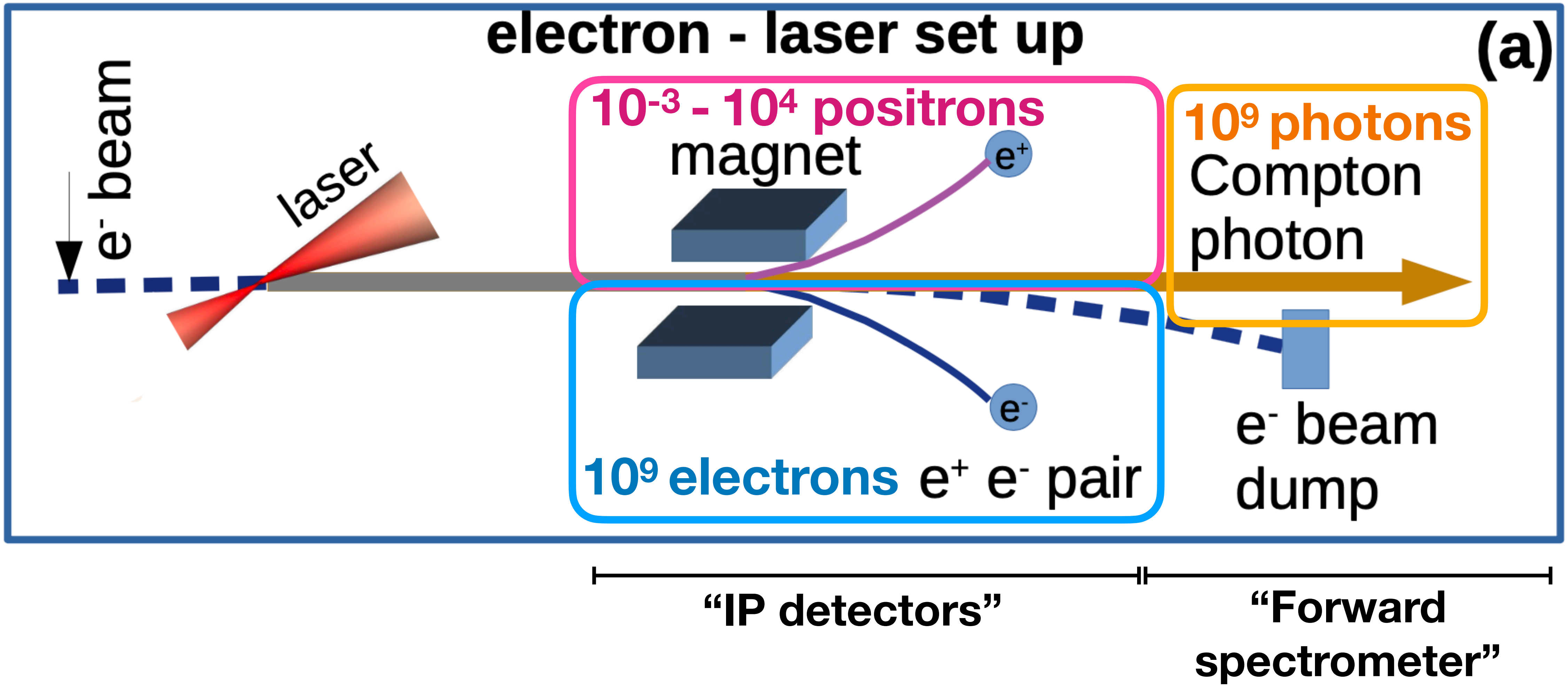
with

E_L: energy (J)
Δt: pulse length (s)
πd^2: focus area (m²)

- for LUXE Phase-0: existing JETI40 (Jena) LASER will be used
- thanks to electron boost, don't need to push the current limits in terms of intensity
- BUT: need exceptional shot-to-shot stability!

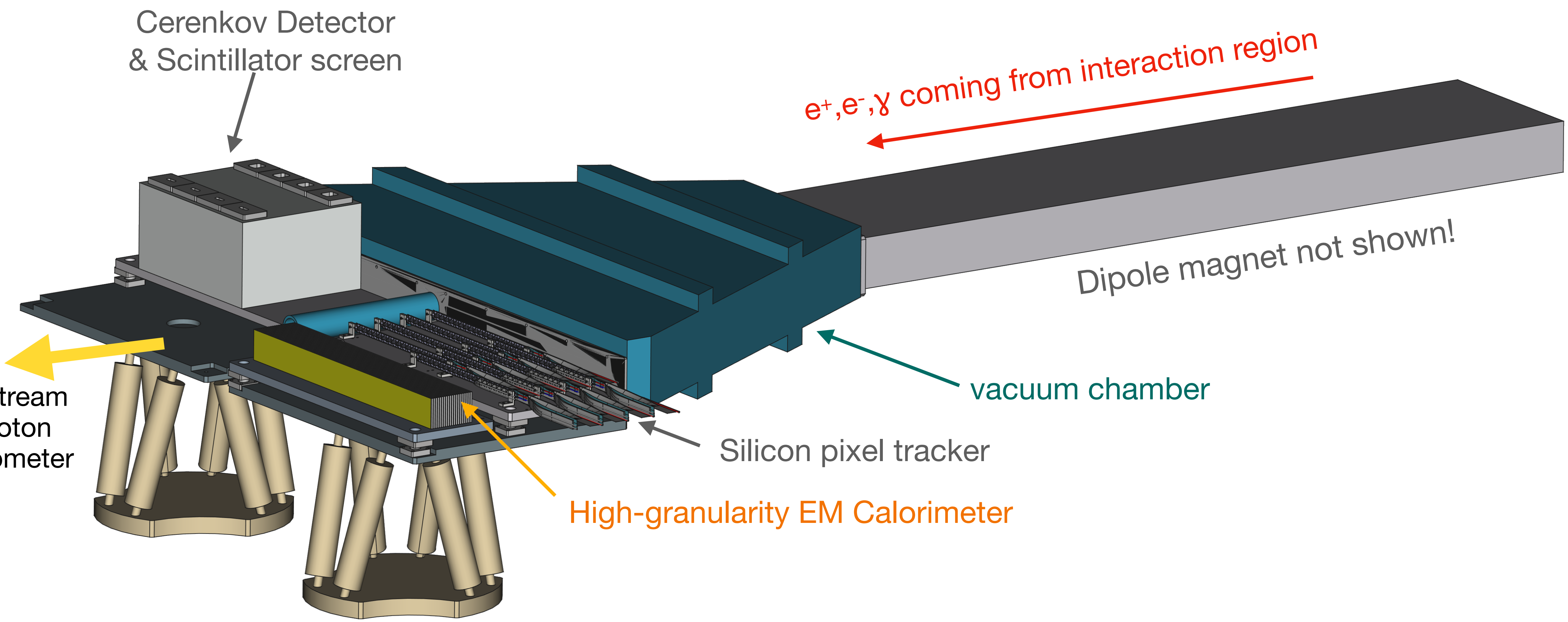


LUXE: Particle Detectors



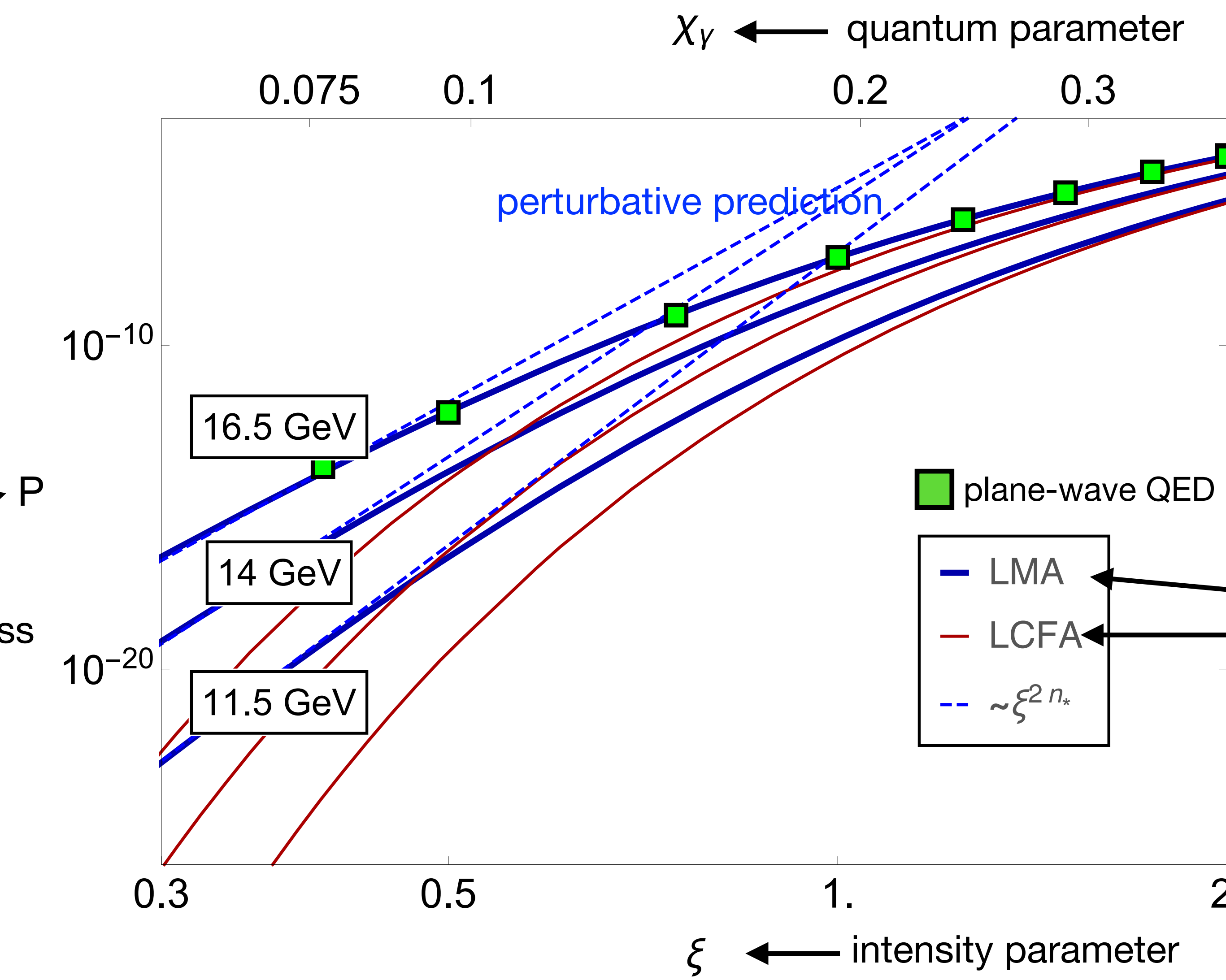
- Goal: Detection of electrons, positrons and photon fluxes and energy spectra
- Particle fluxes vary between ~0.01 e^+ and 10^9 (e^- and ɣ) per laser shot!
- Use technologies adapted to respective fluxes of signal and background

Electron & Positron Detectors



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

SFQED: Predictions & Expected results



probability
of Breit-Wheeler process

approximations used
in simulations

Quantum parameters:

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

Intensity parameter:

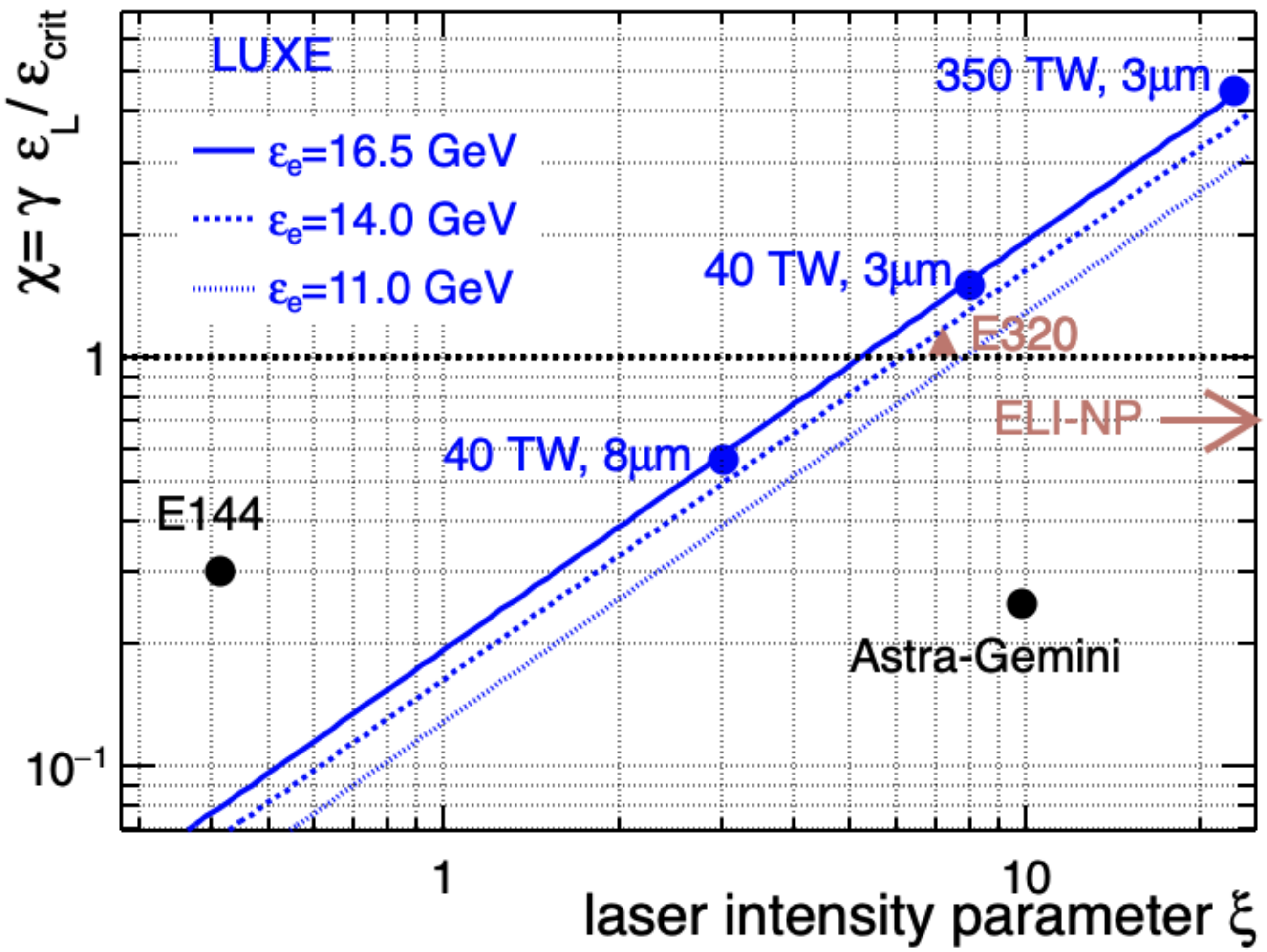
$$\xi = \sqrt{4\pi\alpha}\left(\frac{\mathcal{E}_L}{\omega_L m_e}\right) = \frac{m_e \mathcal{E}_L}{\omega_L \mathcal{E}_{cr}}$$

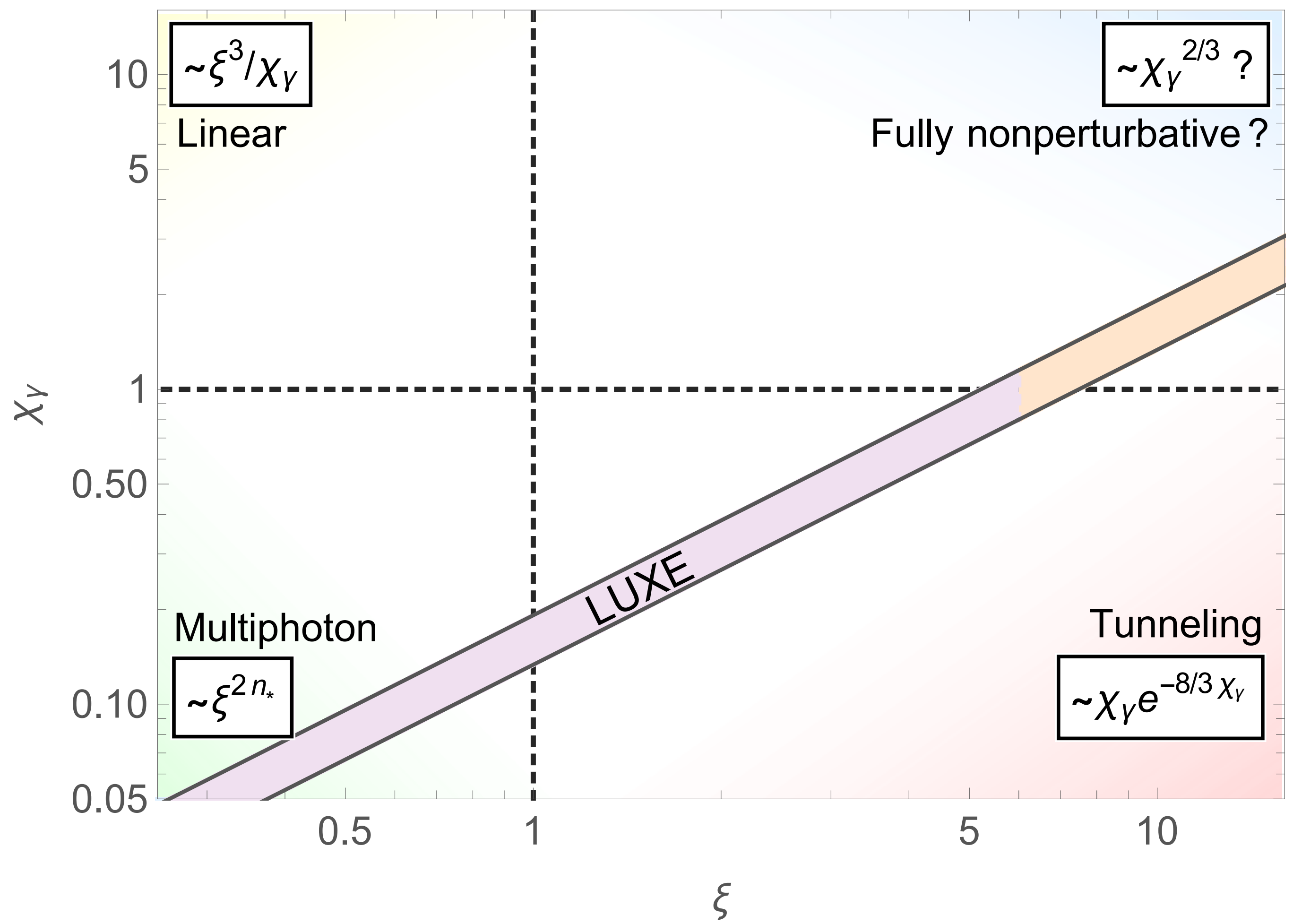
$\xi \ll 1$: $R_{e^+} \propto \xi^{2n} \propto I^n$ Perturbative regime, rate follows power law

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

LUXE: first to enter non-perturbative regime; aim to extract coefficient!

LUXE in Strong-Field QED Parameter Space



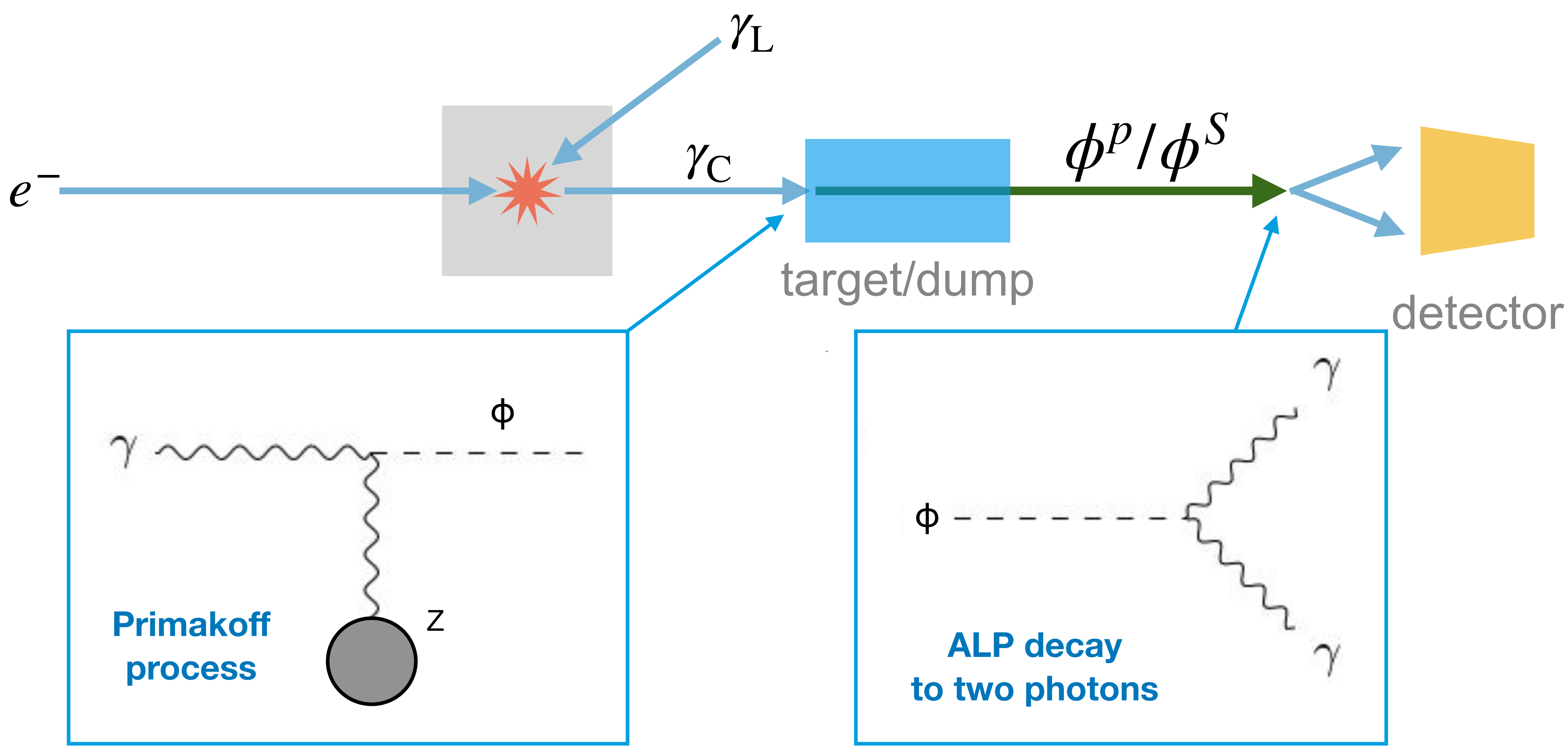


- E144: SLAC experiment in 1990's, using 46.6 GeV electron beam *[Bamber et al. (SLAC 144) '99]*
  → reached $\chi \leq 0.25$, $\xi<0.4$, observed $e^- + n\gamma_L \rightarrow e^-e^+e^-$ process
  → observed start of the ξ^{2n} power law

- LUXE: - good chance to be first to enter $\xi>1$ and $\chi>1$ regime!
  - directly study collisions between LASER and real GeV photons

Bonus: Searching for BSM Physics with LUXE

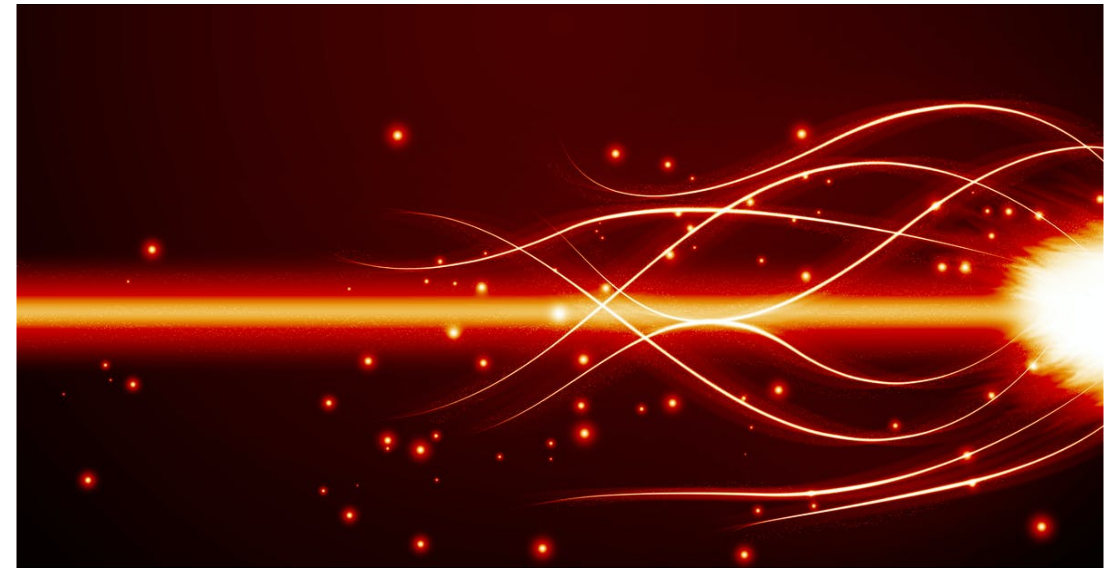
- **LUXE will produce a high-intensity photon beam**
  → produce ALPs or milli-charged particles (MCP) in photon beam-dump



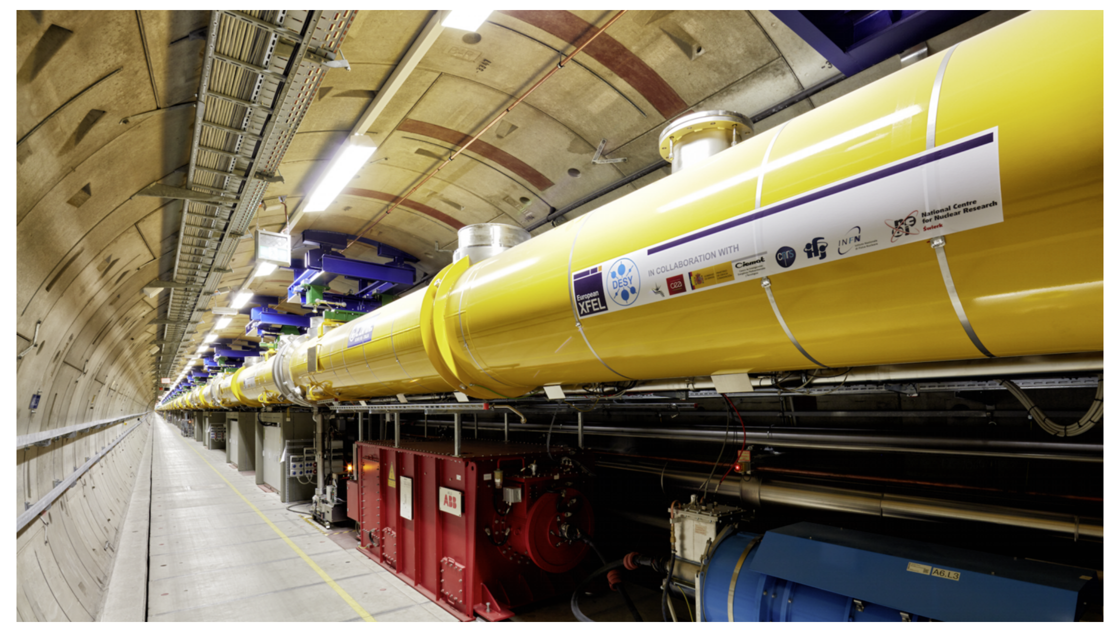
Sensitivity could be competitive with other experiments ongoing and in planning

Conclusion & Outlook

- **LUXE will explore QED in uncharted regime**
  - Observe transition from perturbative to non-perturbative regime of QED
  - Directly observe pair production from real photons
  - Parasitically: search for BSM physics



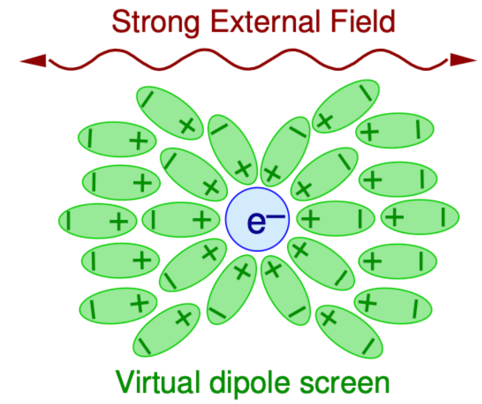
- **Goal: installation in 2024 during extended shutdown planned for European XFEL**
  - Conceptual design report released (arXiv:2102.02032)
  - Very diverse detector technologies used, optimized for LUXE physics goals
  - Reviews starting



Exciting times for LUXE ahead - stay tuned!
Got interested? Join us!

BACKUP

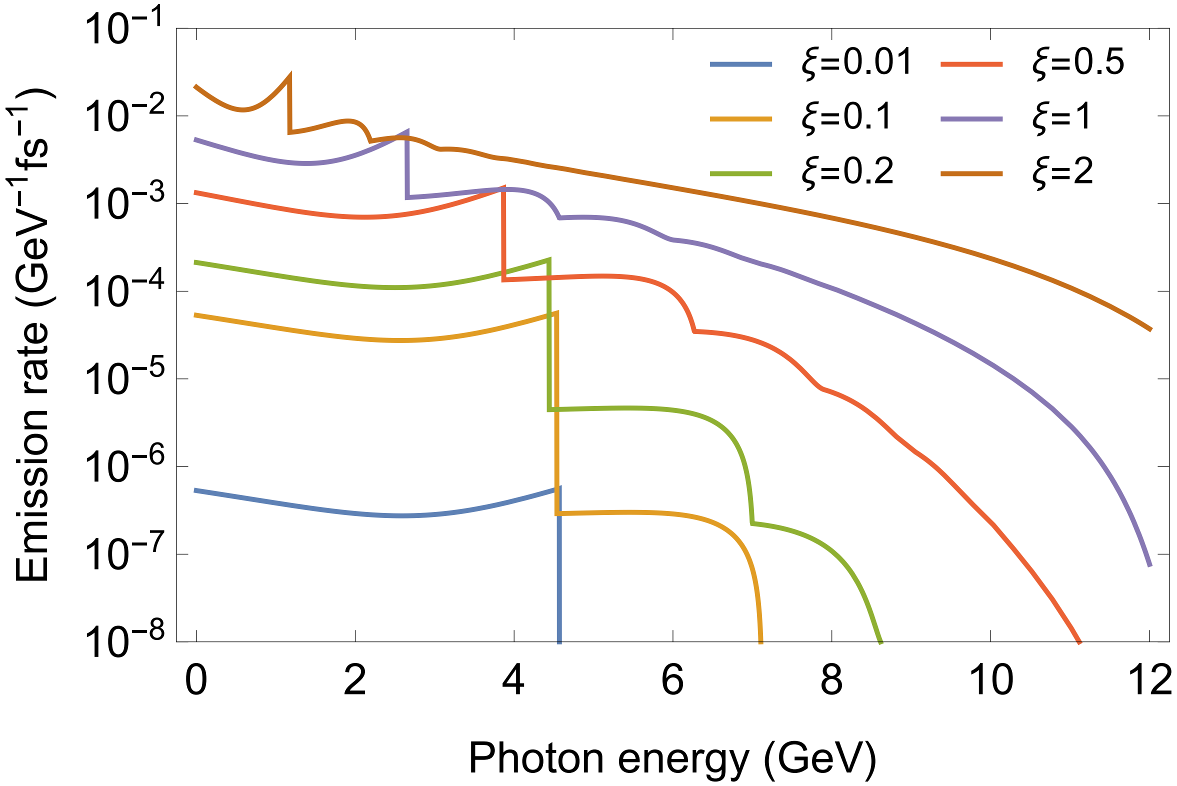
Compton Edge Shift

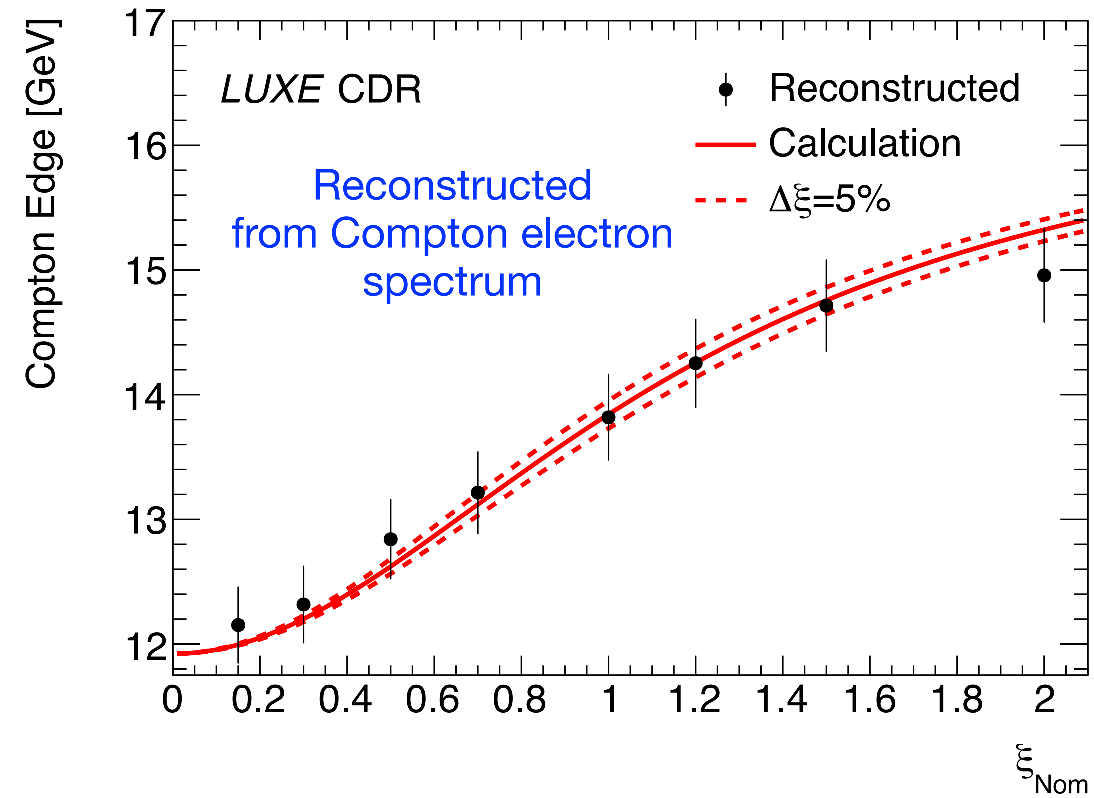


Compton Edge:

$$E_{\text{edge}} = E\left(1 - \frac{1}{1 + \frac{2E}{m_e c^2}}\right)$$

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 as function of ξ
- theoretical prediction: $E_{edge}(\xi) = E_e \frac{2n\eta}{2n\eta + 1 + \xi^2}$, with $\eta_{LUXE} = 0.192$
- reconstruct Compton edge in electron (Scintillator and Cerenkov detector) or photon spectrum (Photon spectrometer)

Introduction: Strong-Field QED

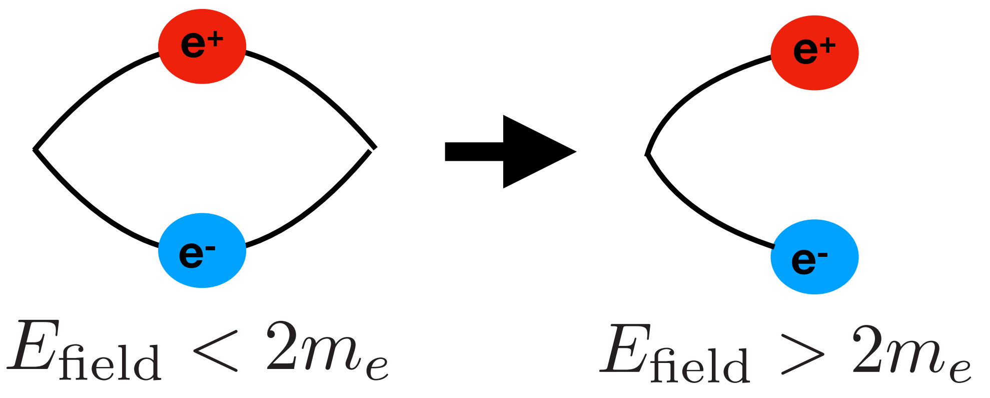
Schwinger Limit:

$$\mathscr{E}_{cr} = \frac{m_e^2 c^3}{e\hbar}$$

Consequences of non-perturbativity:

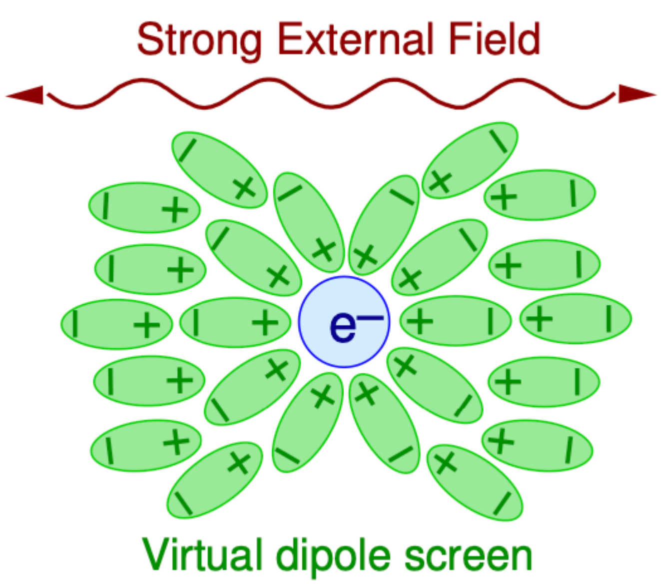
1) Field-Induced ("Breit-Wheeler") Pair Creation:

- physical particle-antiparticle pair production from vacuum



2) Modified Compton Spectrum:

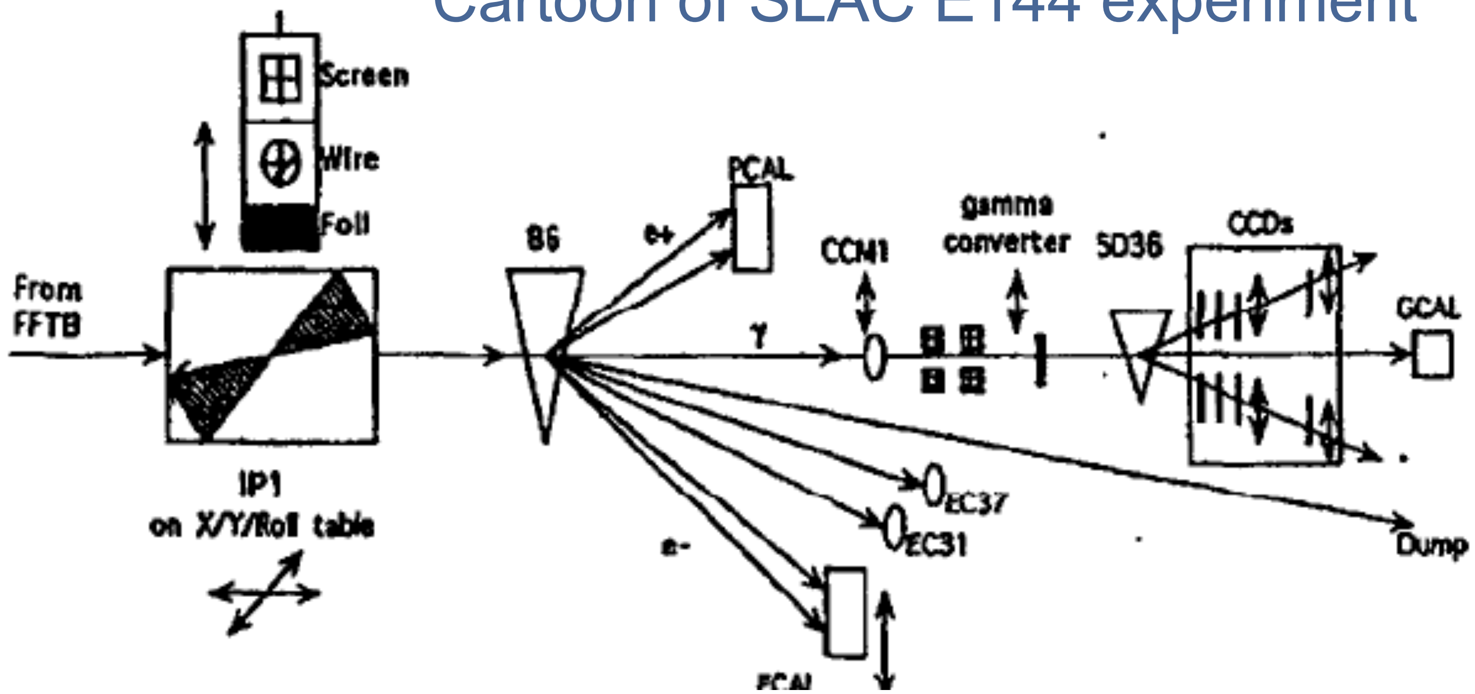
- electron obtains (significantly) larger effective rest mass → modified Compton spectrum

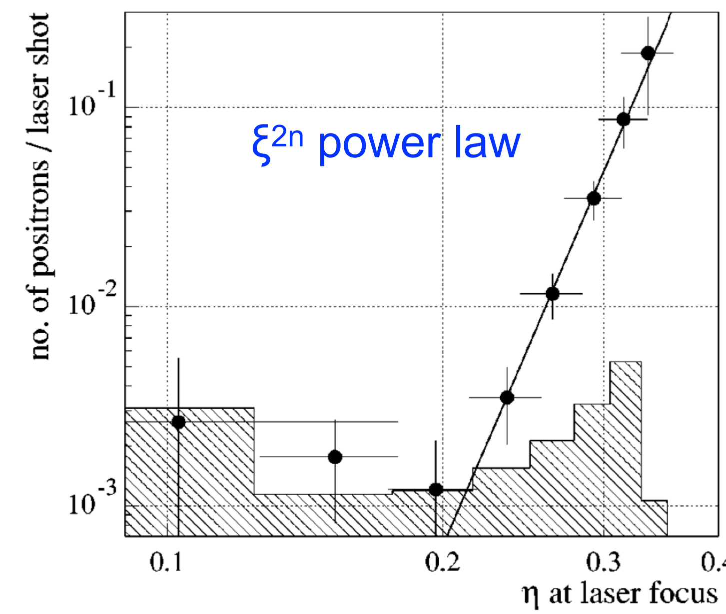


Schwinger-Regime has never been probed in clean lab conditions
LUXE will do so!

E144 experiment at SLAC

Cartoon of SLAC E144 experiment



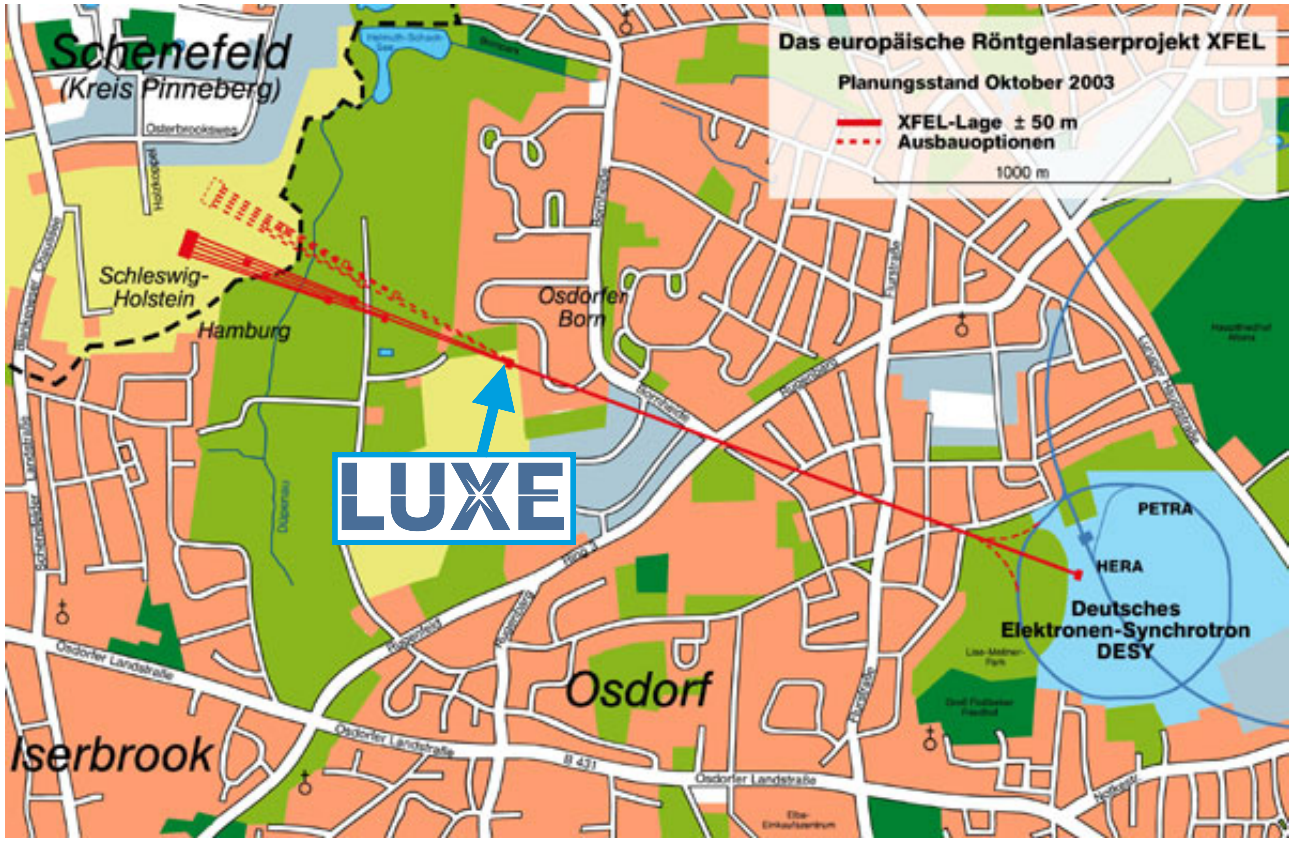


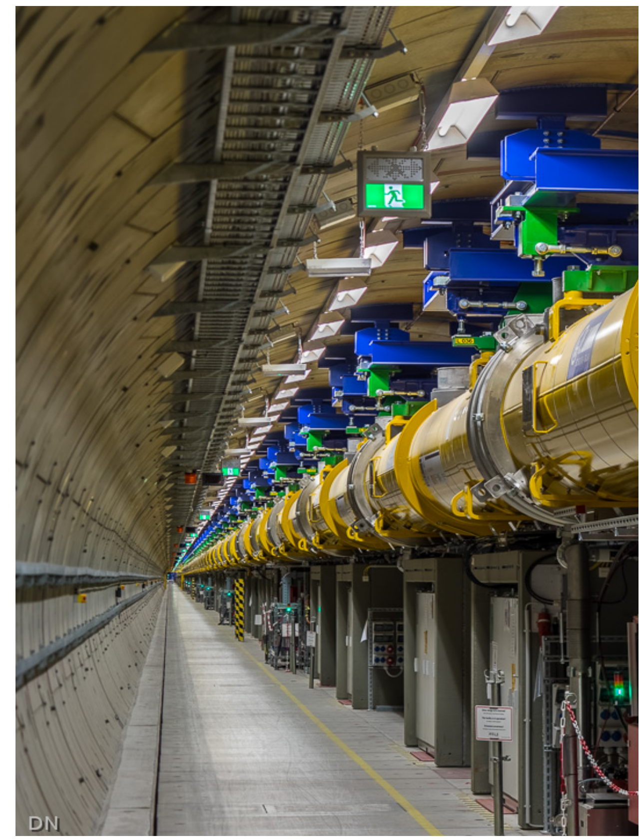
[Bamber et al. (SLAC 144) '99]

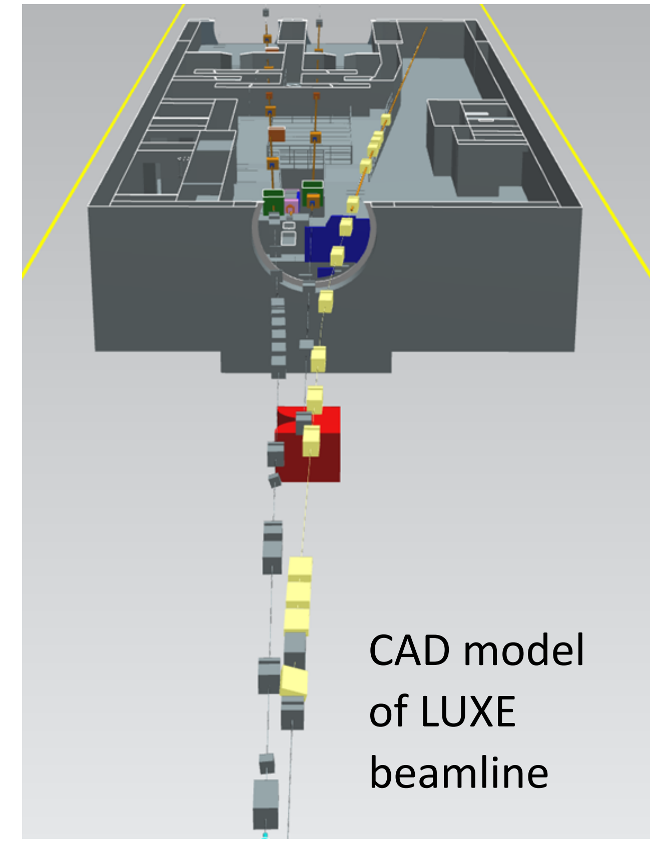
- E144: SLAC experiment in 1990's using 46.6 GeV electron beam (e+LASER only!)
- reached $\chi \leq 0.25$, $\xi<0.4$
- observed $e^- + n\gamma_L \rightarrow e^-e^+e^-$ process
- observed start of the ξ^{2n} power law, but not departure

LUXE will have 3 orders of magnitude more powerful LASER

LUXE: Experimental setup at DESY







- LUXE uses XFEL electron beam before undulators
- Building at Osdorfer Born: future additional fan for XFEL (construction starts in 2030's)
  → Unique possibility to build and operate LUXE before that!
- LUXE uses 1 bunch (out of 2700 bunches) per XFEL train
  → design goal: transparent to XFEL photon science!

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

LASER beamline & Interaction Chamber

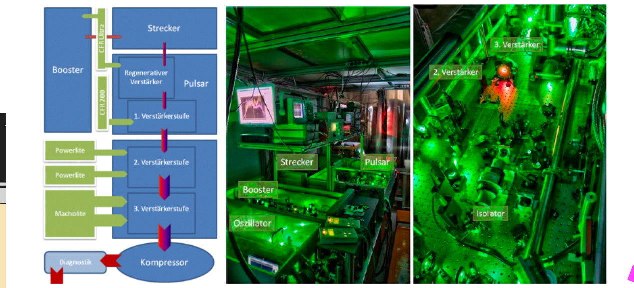
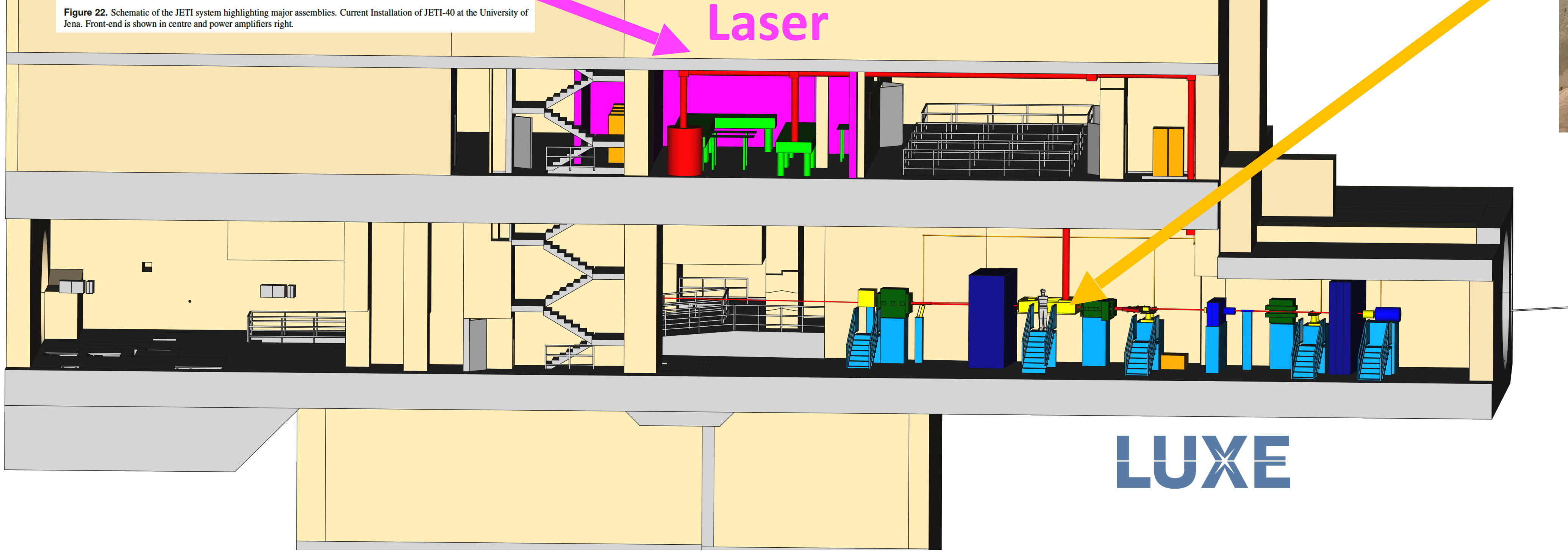
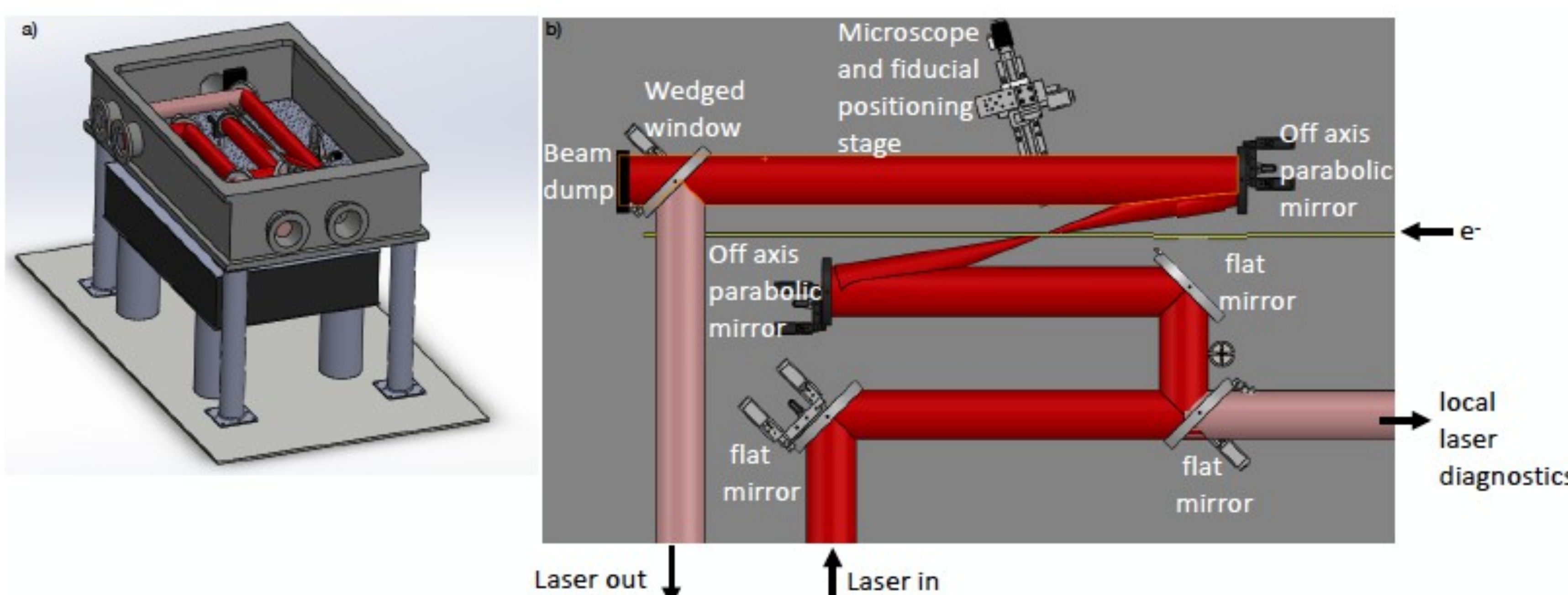
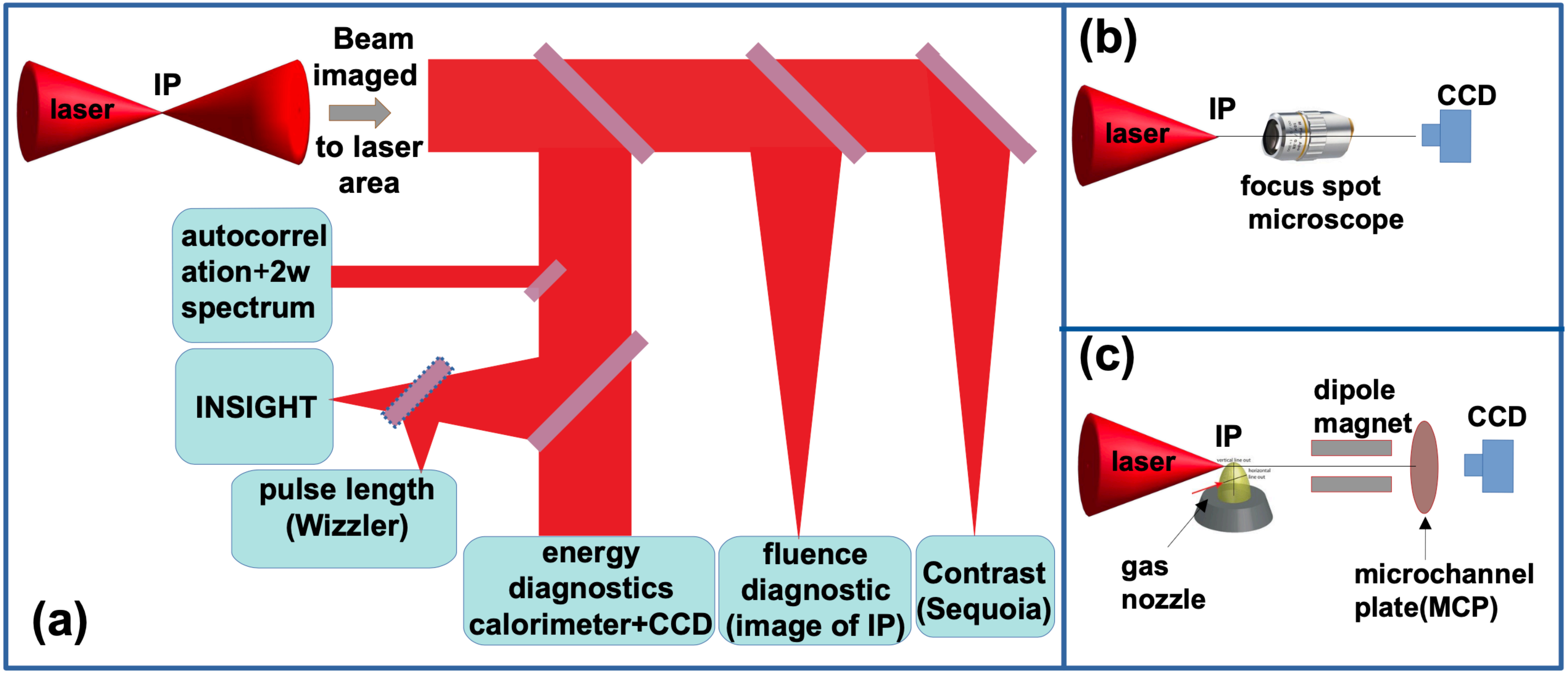


Figure 22. Schematic of the JETI system highlighting major assemblies. Current Installation of JETI-40 at the University of Jena. Front-end is shown in centre and power amplifiers right.



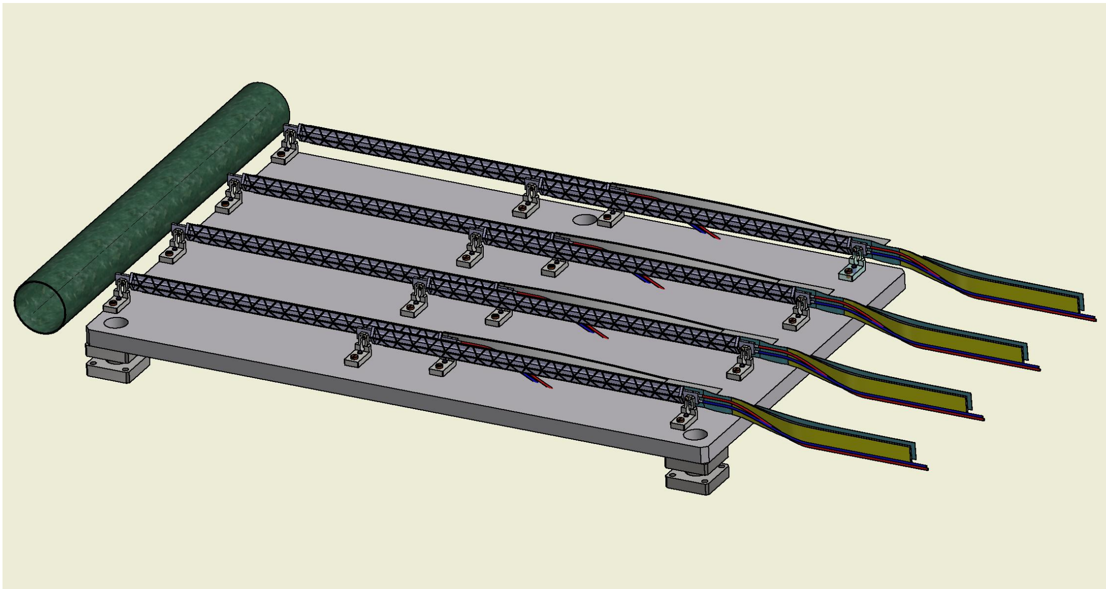


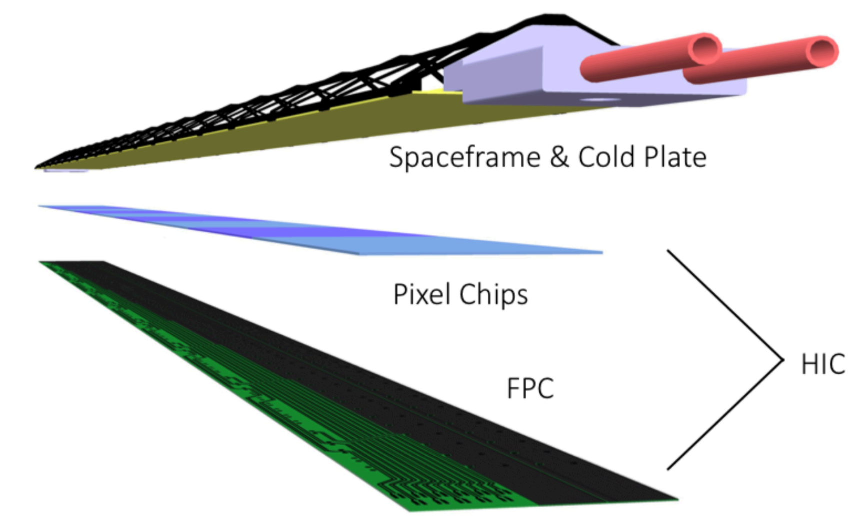
LASER Diagnostics

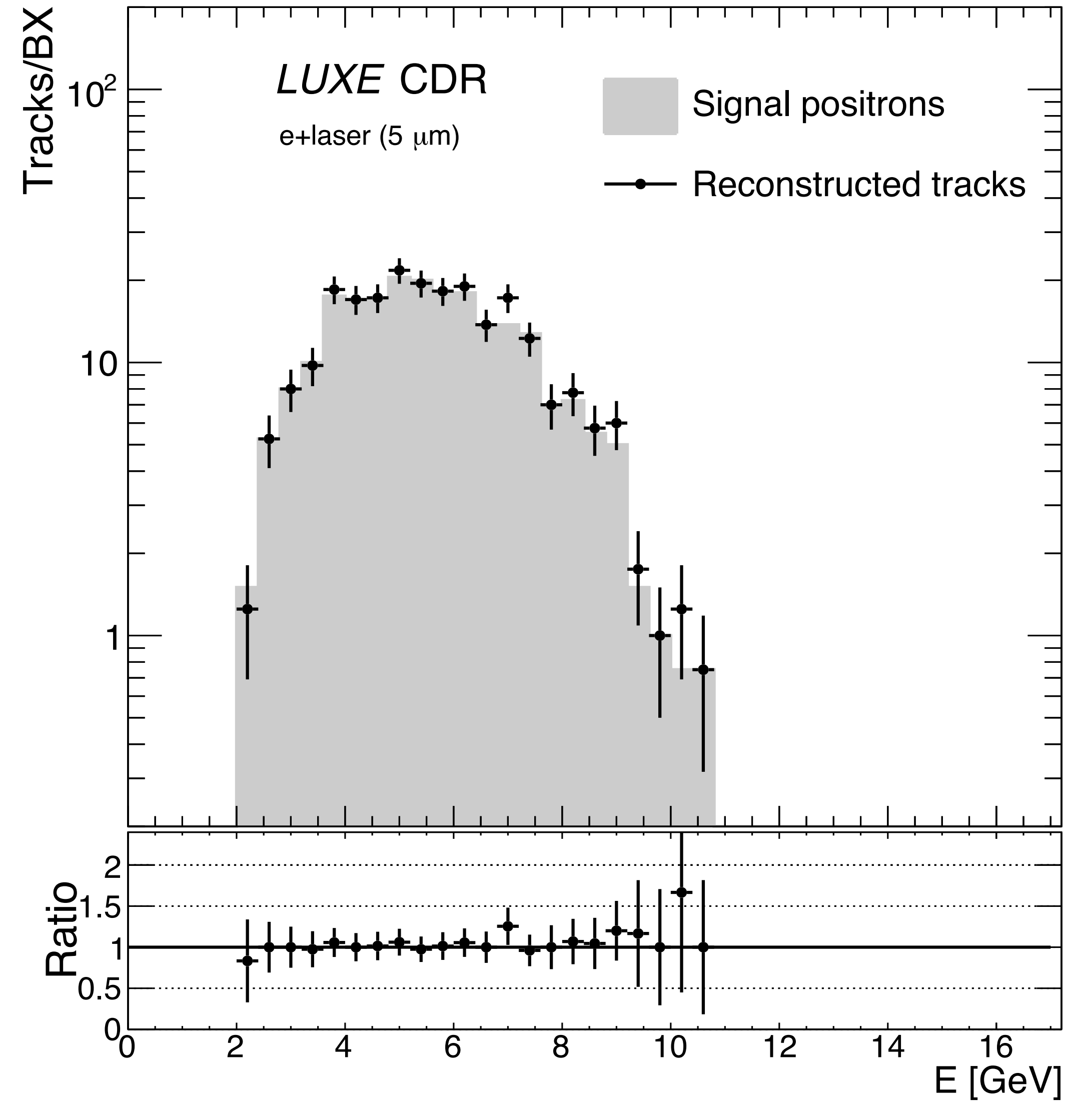


- LASER characterization quantities: energy, pulse length, spot size
- many (partially redundant) measurements planned
- LASER intensity uncertainty has a large impact on sensitivity
- goal: ≤ 5% uncertainty on LASER intensity, 1% shot-to-shot uncertainty

Silicon Pixel Tracker

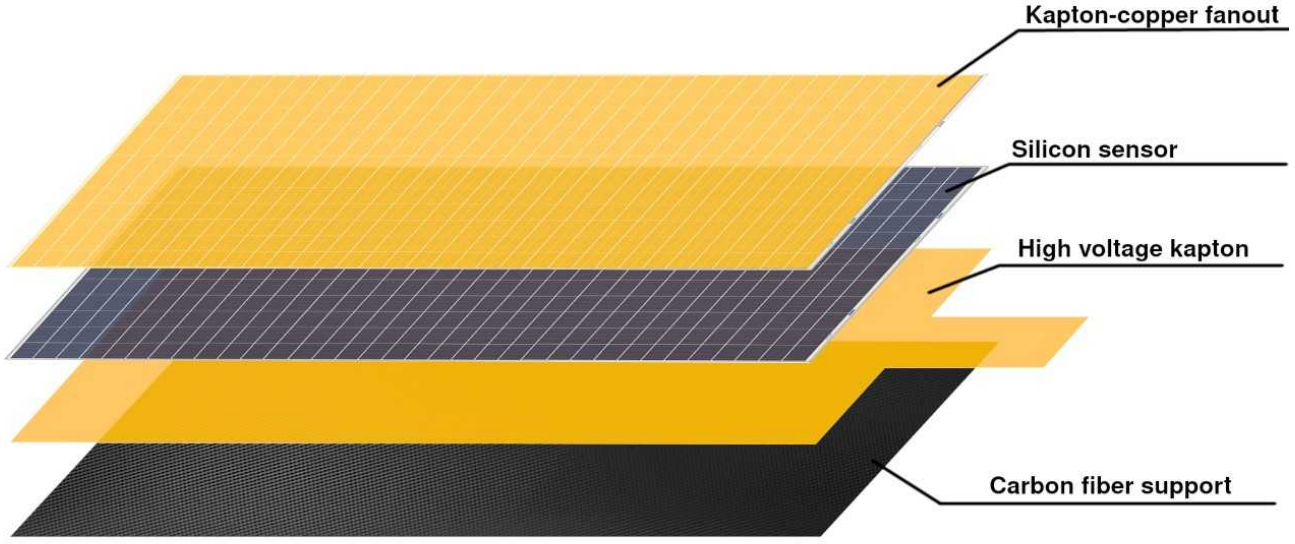


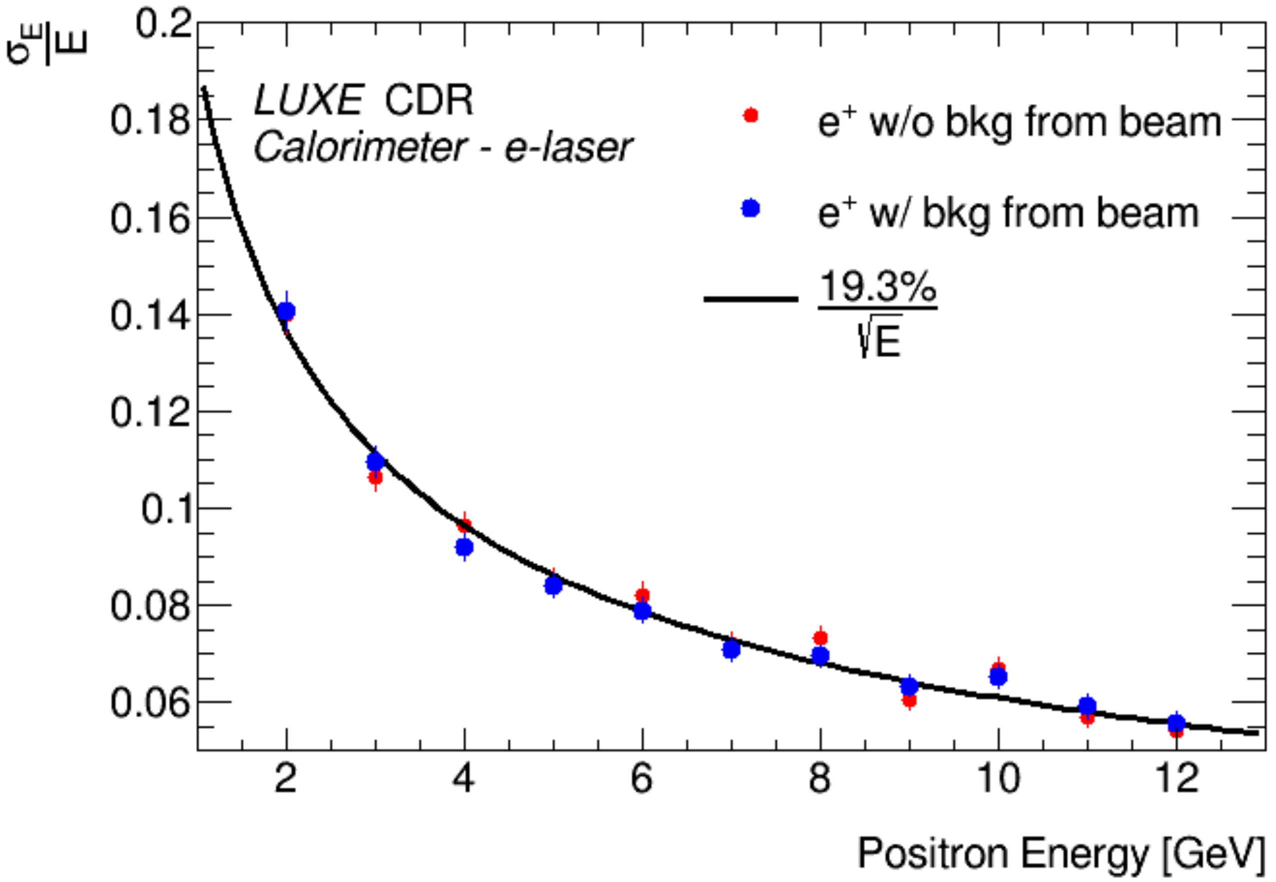




- four layers of ALPIDE silicon pixel sensors
  → developed for ALICE pixel tracker upgrade
- pitch size (27 x 29 μm), 5 μm resolution
- tracking: $\varepsilon > 98\%, \quad \frac{\delta p}{p} \approx 0.3\%$
- very small background (<0.1 event / bunch crossing)

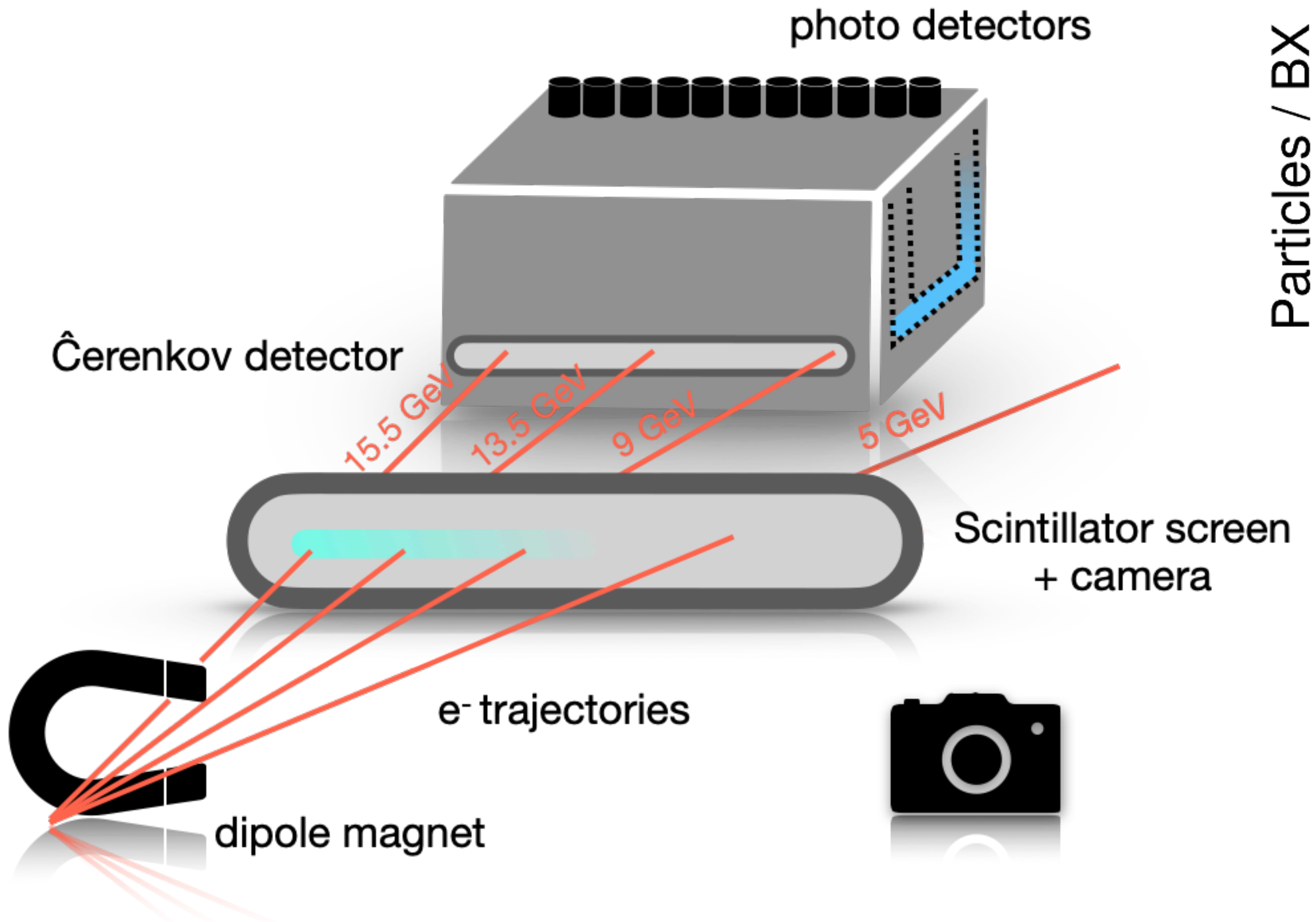
High-Granularity Calorimeter

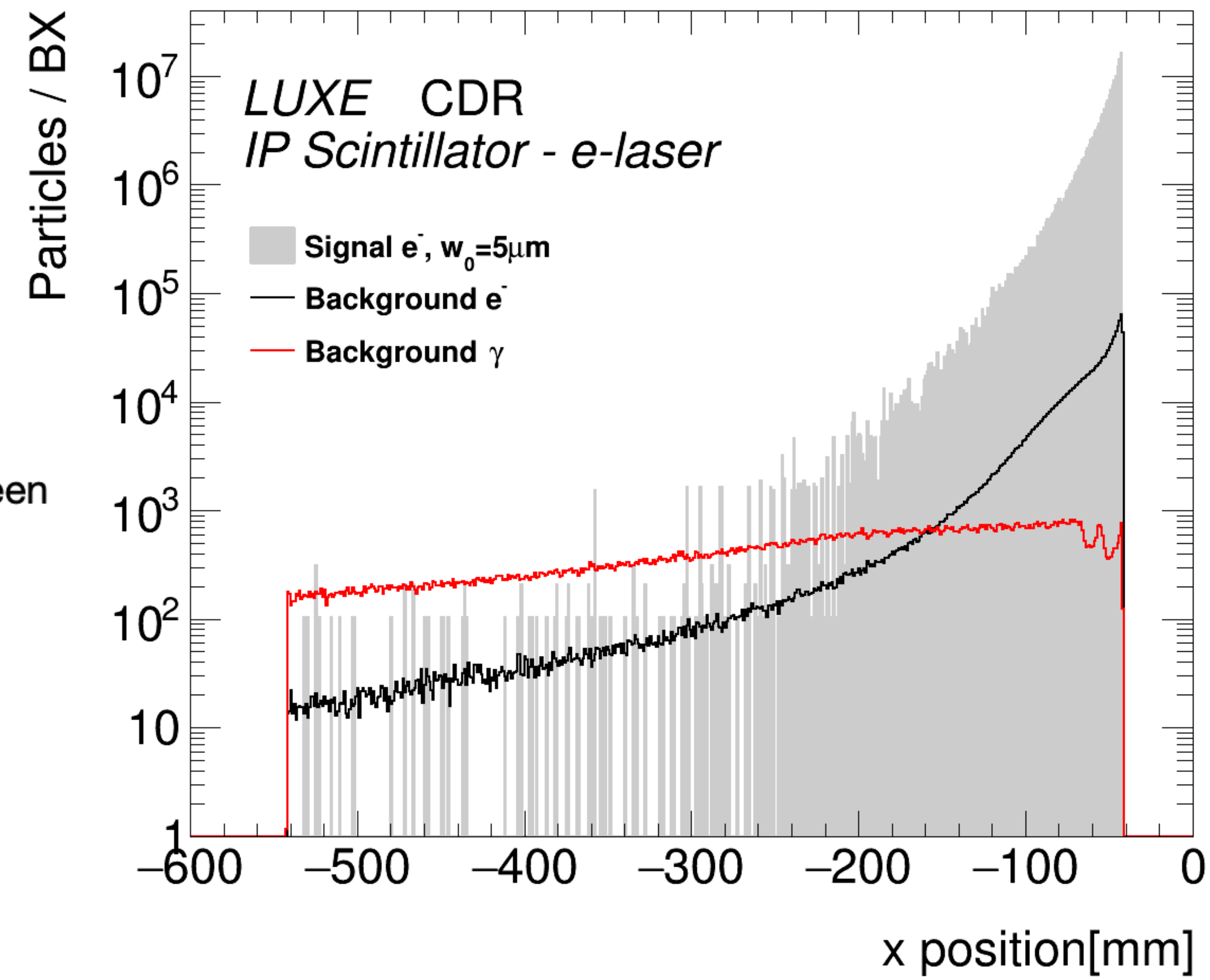




- high granularity: independent energy measurement from position and shower reconstruction
- 20-layer sampling calorimeter
- shower medium: 3.5mm Tungsten plates ($1X_0$)
- active medium: Silicon or GaAs sensors ($5x5cm^2$, 320μm thick)
- read out by FLAME ASIC (developed for FCAL)

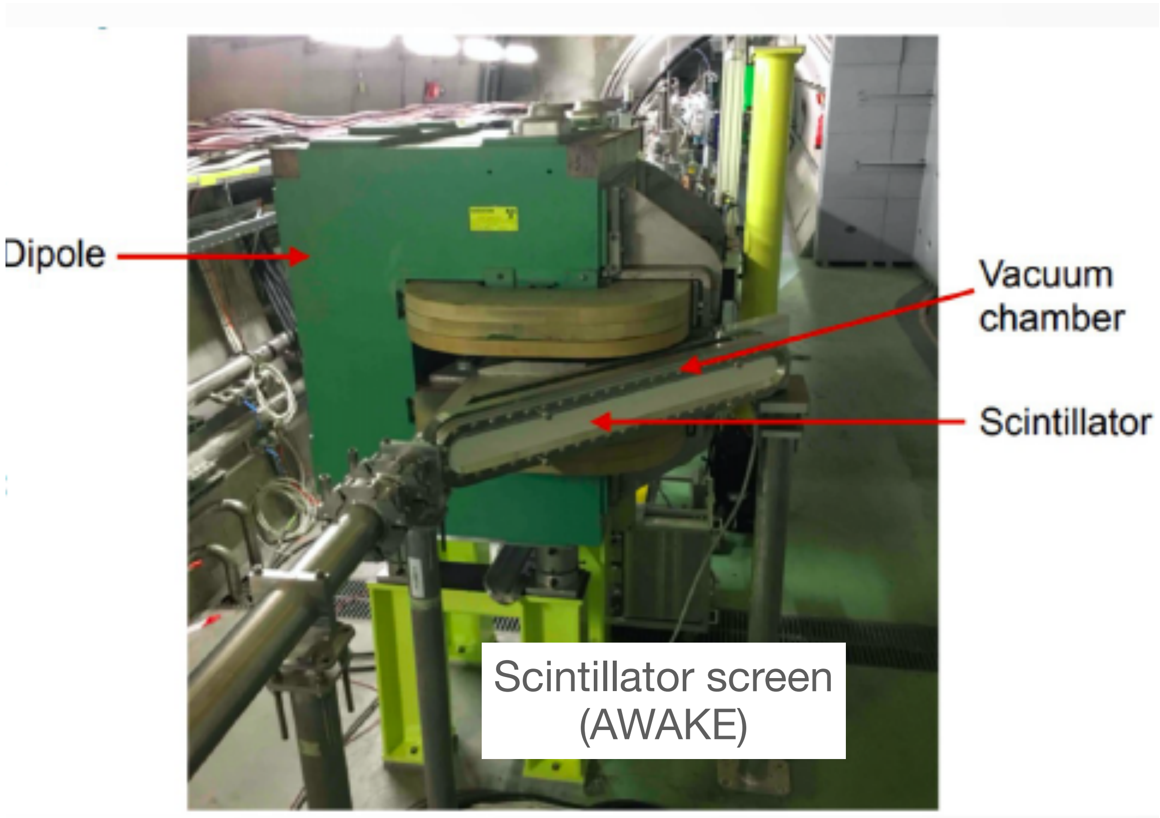
Electron side: Scintillator & Cerenkov

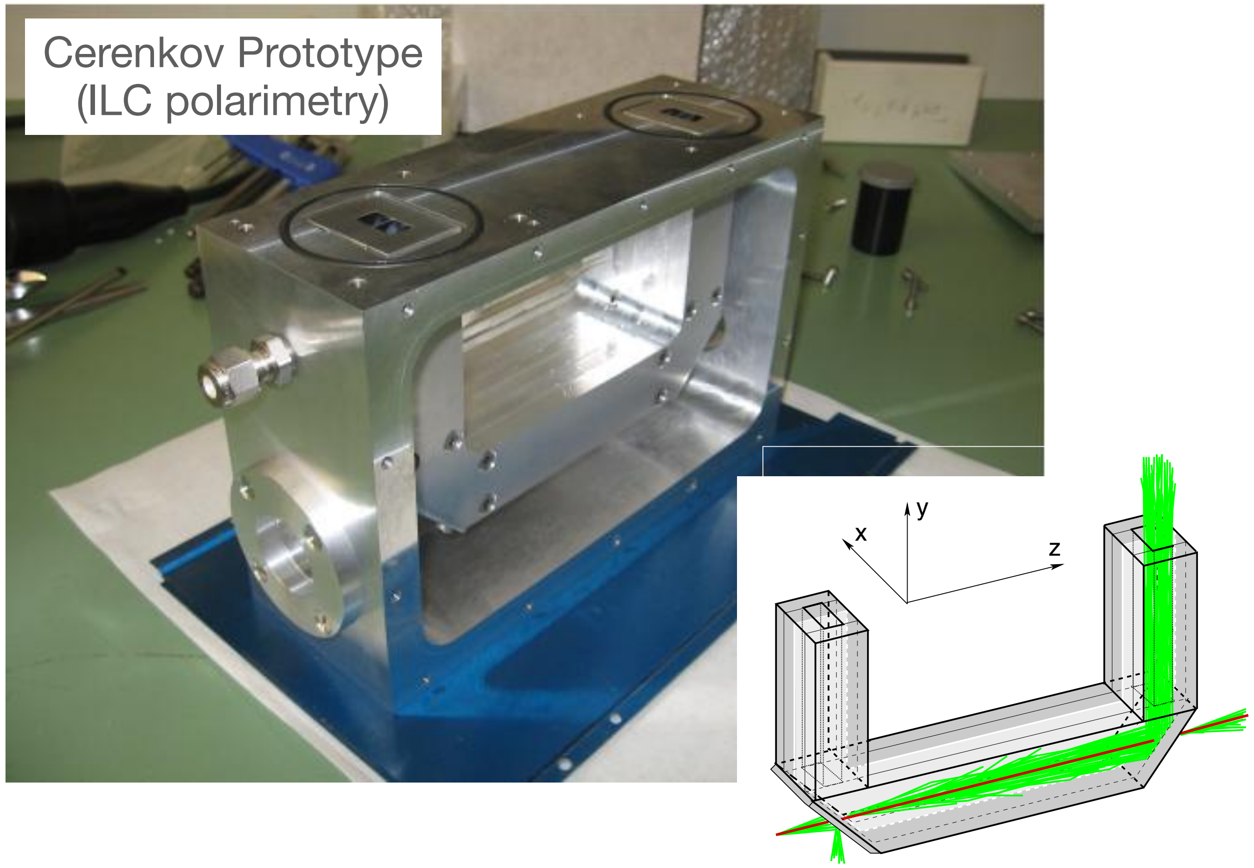


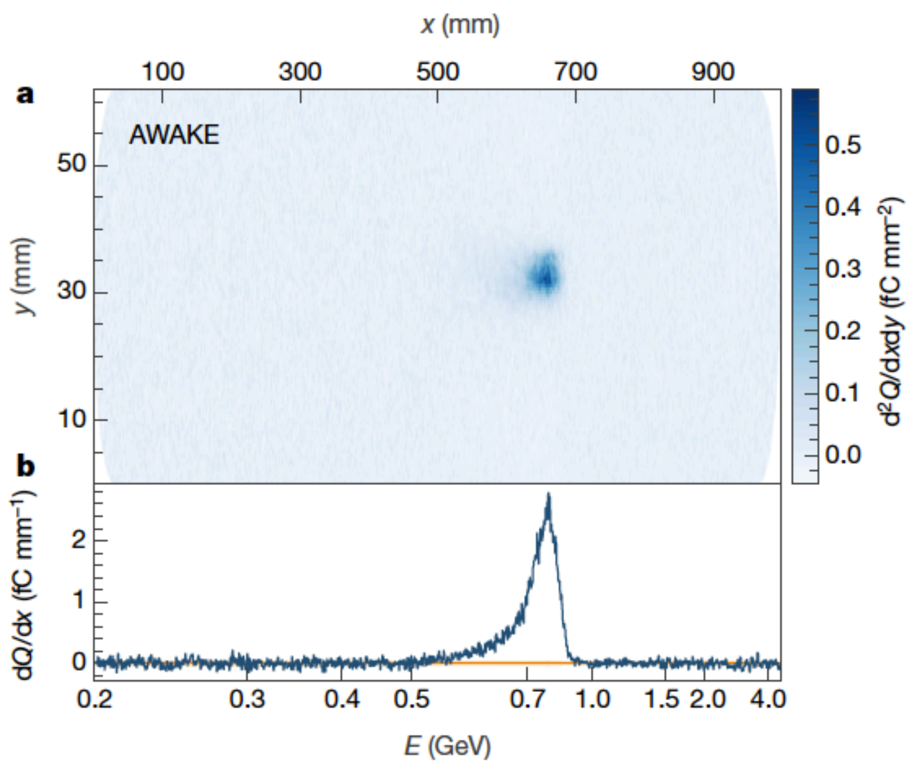


- challenge of electron side (in e+LASER): enormous electron rate from Compton scattering (Signal/Background ~100)
- goal: Measure non-linear Compton spectrum (more later)
  → N_e as function of the position after dipole magnet (→ Energy)
- combined system: Scintillator screen and segmented gaseous Cerenkov detector

Electron side: Scintillator & Cerenkov







AWAKE Coll., *Nature* **561,** 363–367 (2018)
https://www.nature.com/articles/s41586-018-0485-4

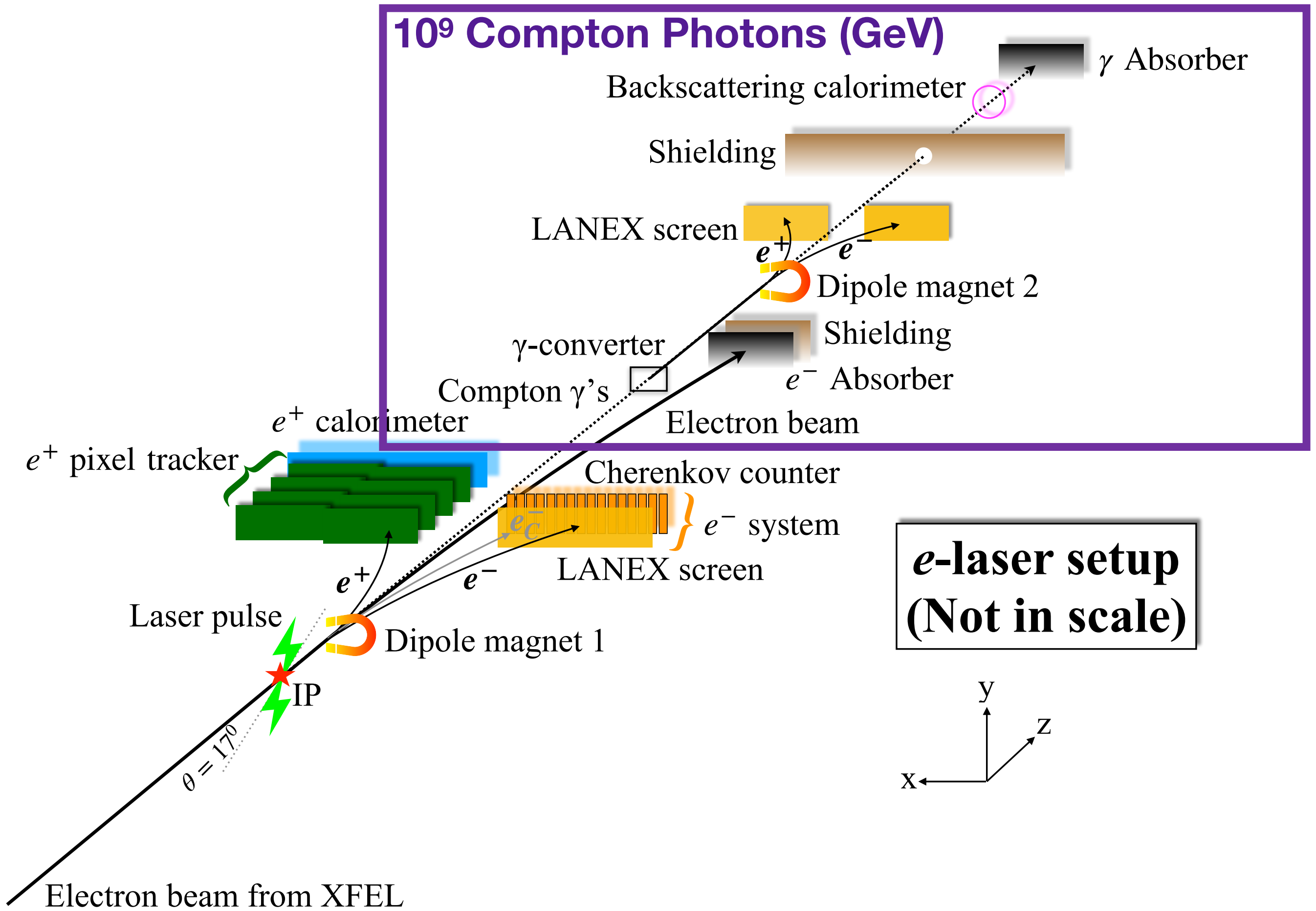
Scintillator screen (LANEX):

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

Cerenkov detector:

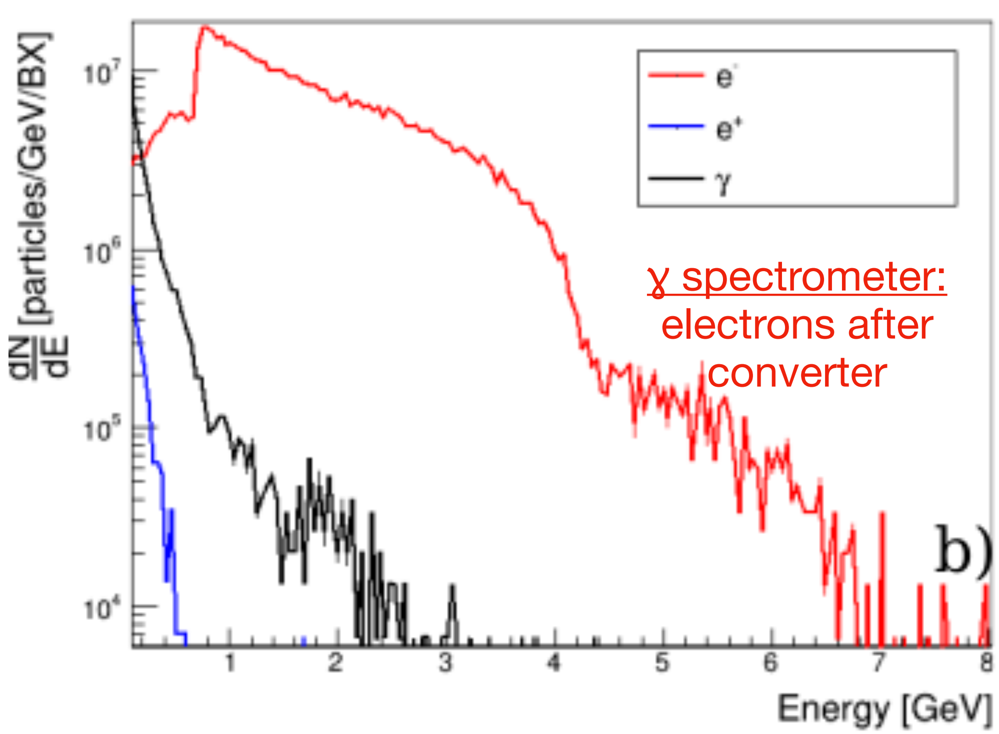
- finely segmented Argon-filled channels (1.5x1.5mm²)
- Ar gas: low refractive index helps to reduce light yield (Cerenkov threshold 20 MeV)

LUXE Detectors: Photon Spectrometers

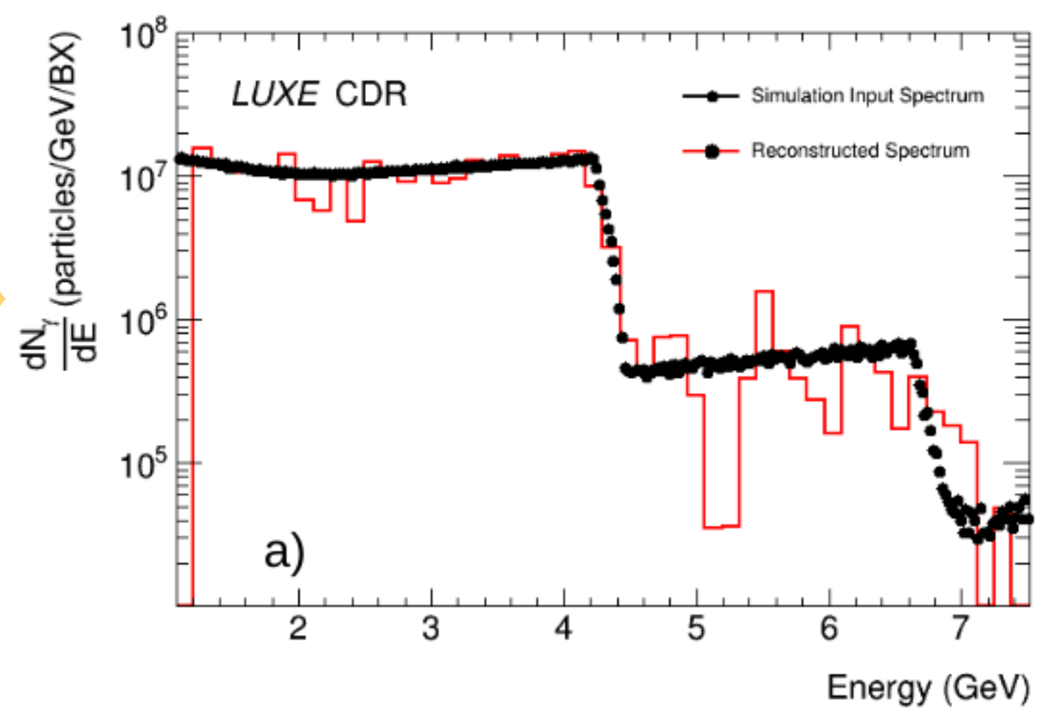


Three detector technologies:

- ɣ profiler (sapphire)
  → ɣ beam location
- spectrometer with scintillator screens behind converter
  → flux, energy spectrum ($\frac{\delta E}{E} < 2\,\%$)
- ɣ dump backscattering calorimeter
  → flux



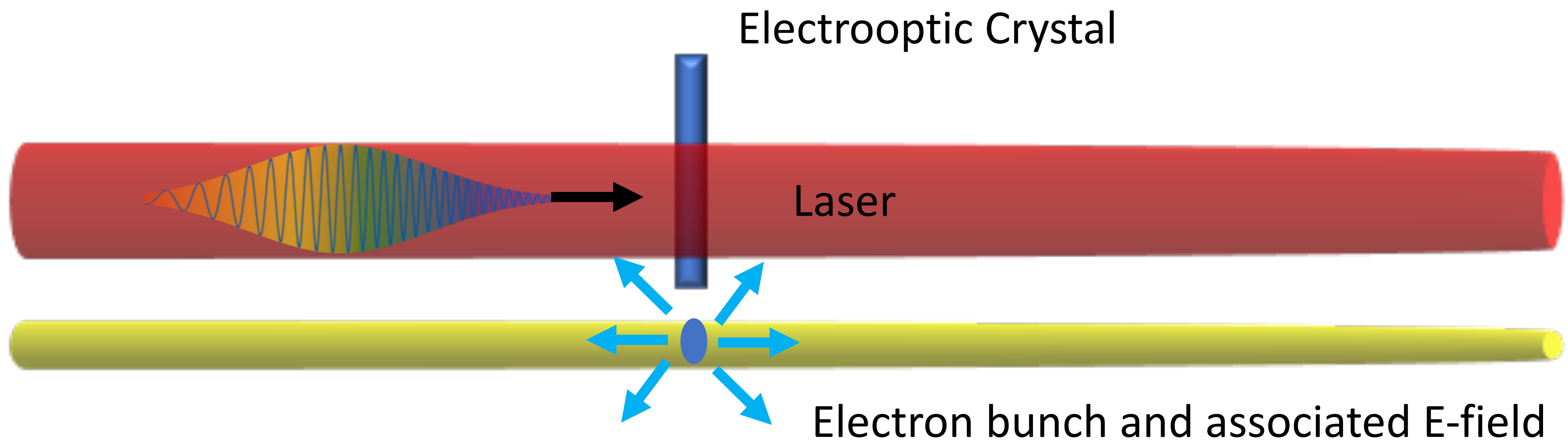
deconvolute



Alternative way to reconstruct Compton edges!

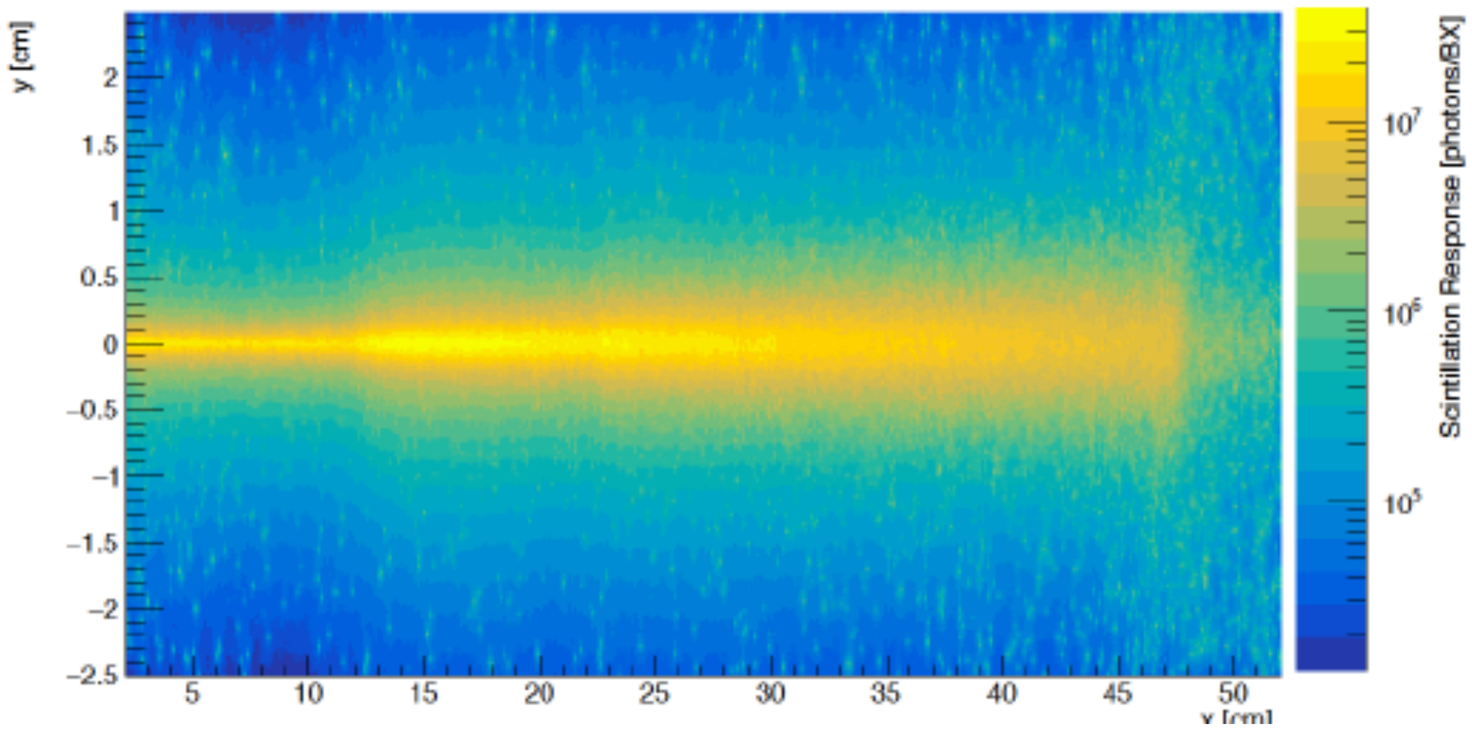
Synchronization

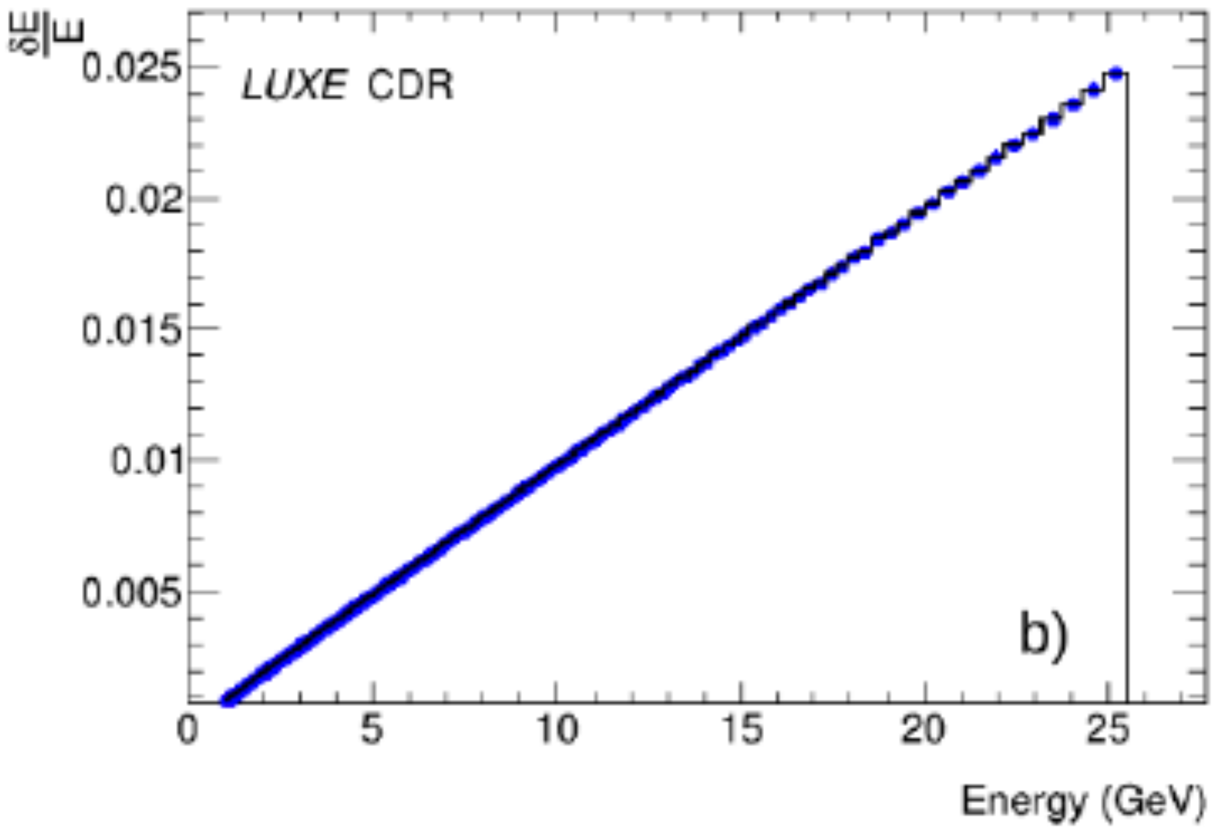
- critical: spatial and temporal overlap of electron beam and LASER
- temporal overlap requirement (30fs LASER pulse, >100fs electron bunch)
  → at least half the pulse width (50fs)
- XFEL developed world-leading syncronization system
  → sychronization of two RF signals to <13fs
- synchronise the XFEL.EU 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

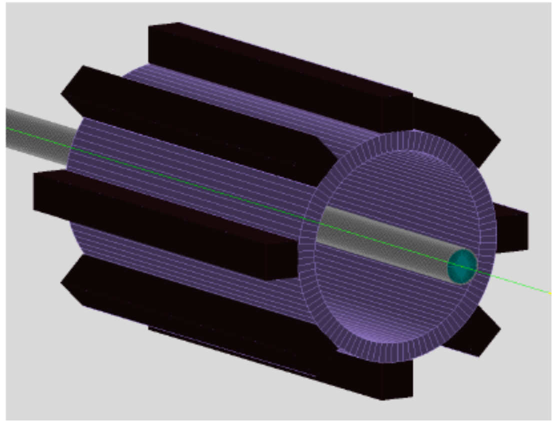
- **Up to 10^9 photons per bunch crossing with ~GeV energies**
- **Energy spectrum measurement**
  - Spectrometer with scintillators behind converter
  - Energy resolution <2%

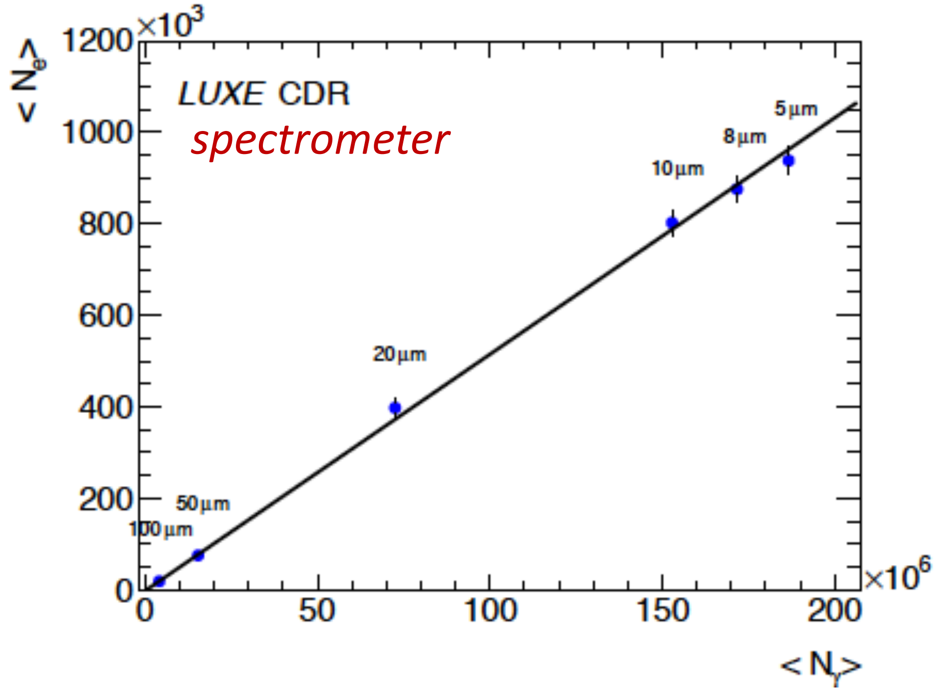


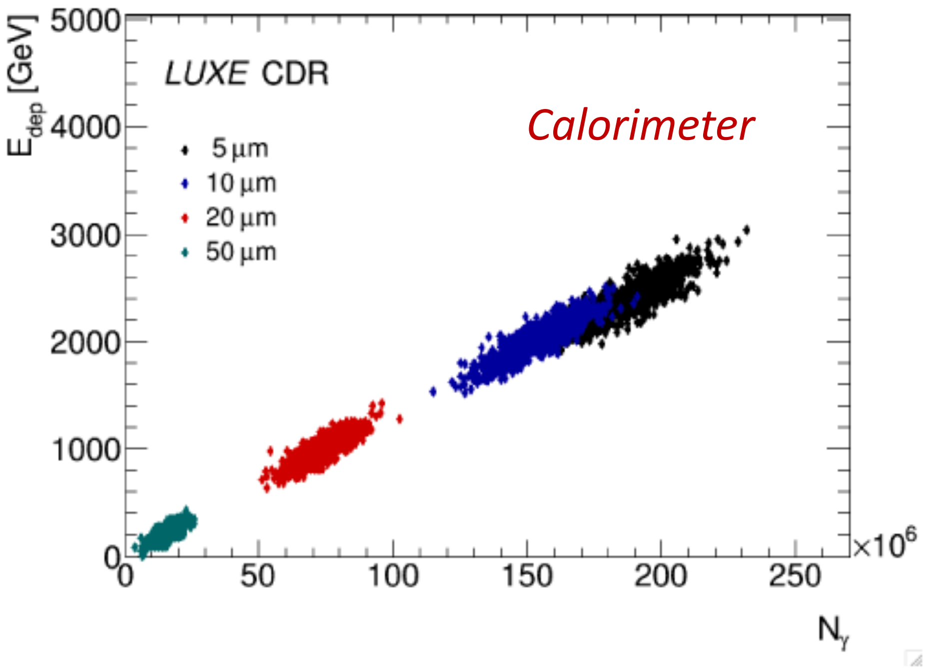


Backscattering Calorimeter

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

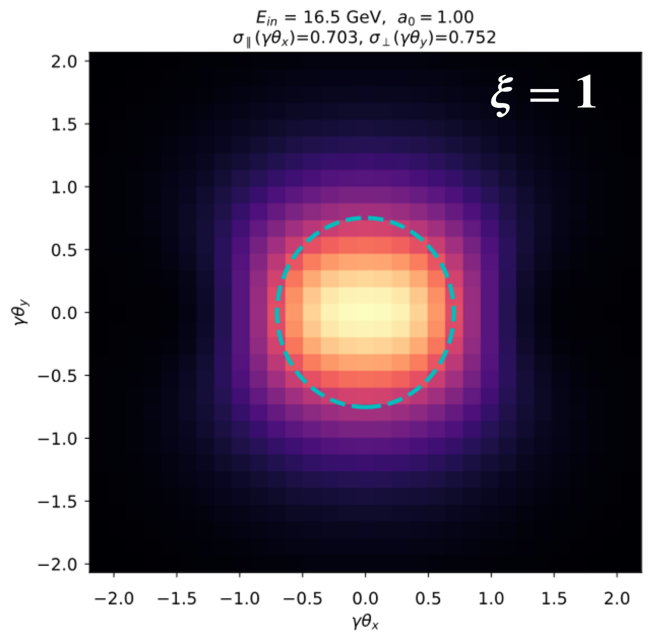


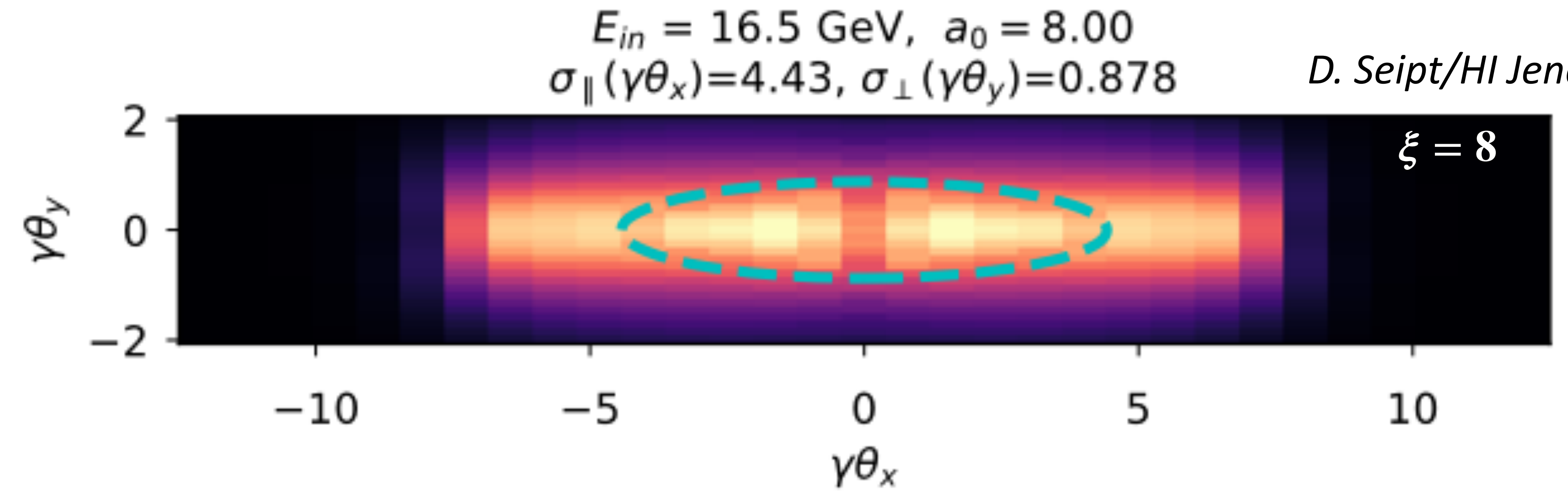




Gamma Profiler

- **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





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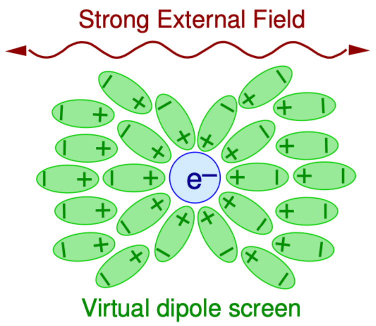
- **Measurement of 5 μm provides constraint: $\frac{\delta\xi}{\xi} < 1\%$ for ξ>2**

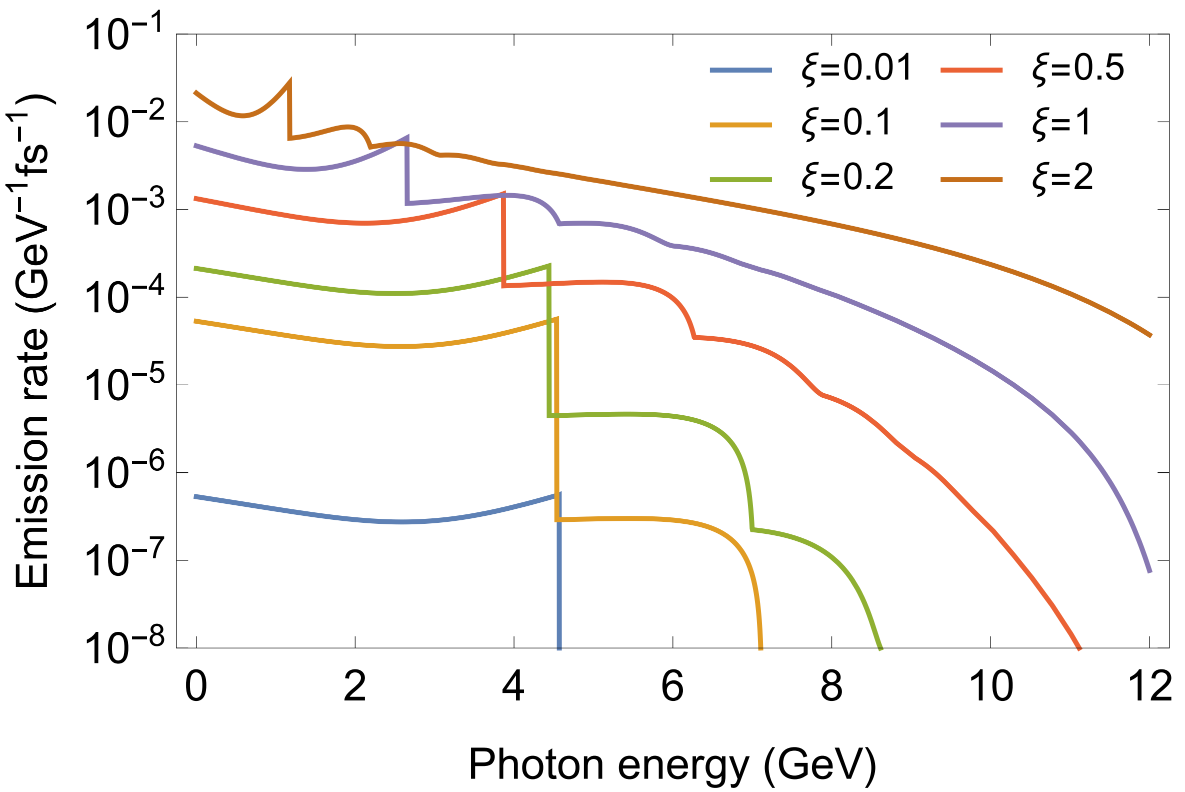
Compton Edge Measurement

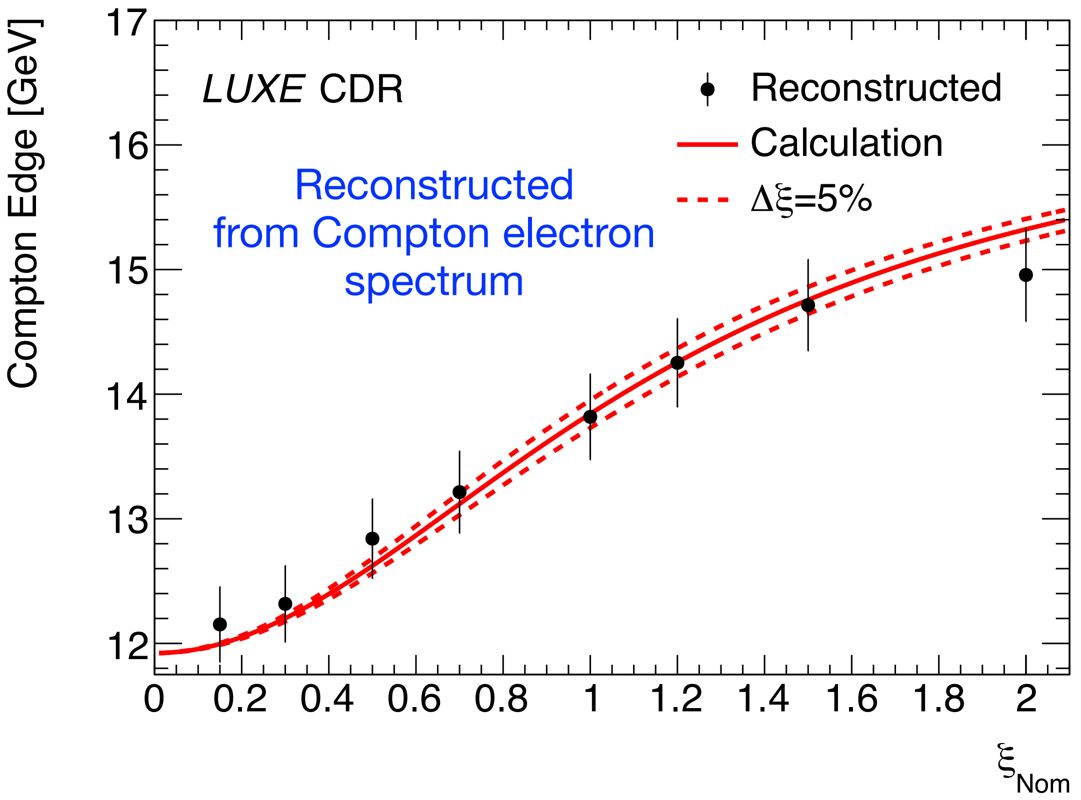


Compton Edge:

$$E_{\text{edge}} = E(1 - \frac{1}{1 + \frac{2E}{m_e c^2}})$$

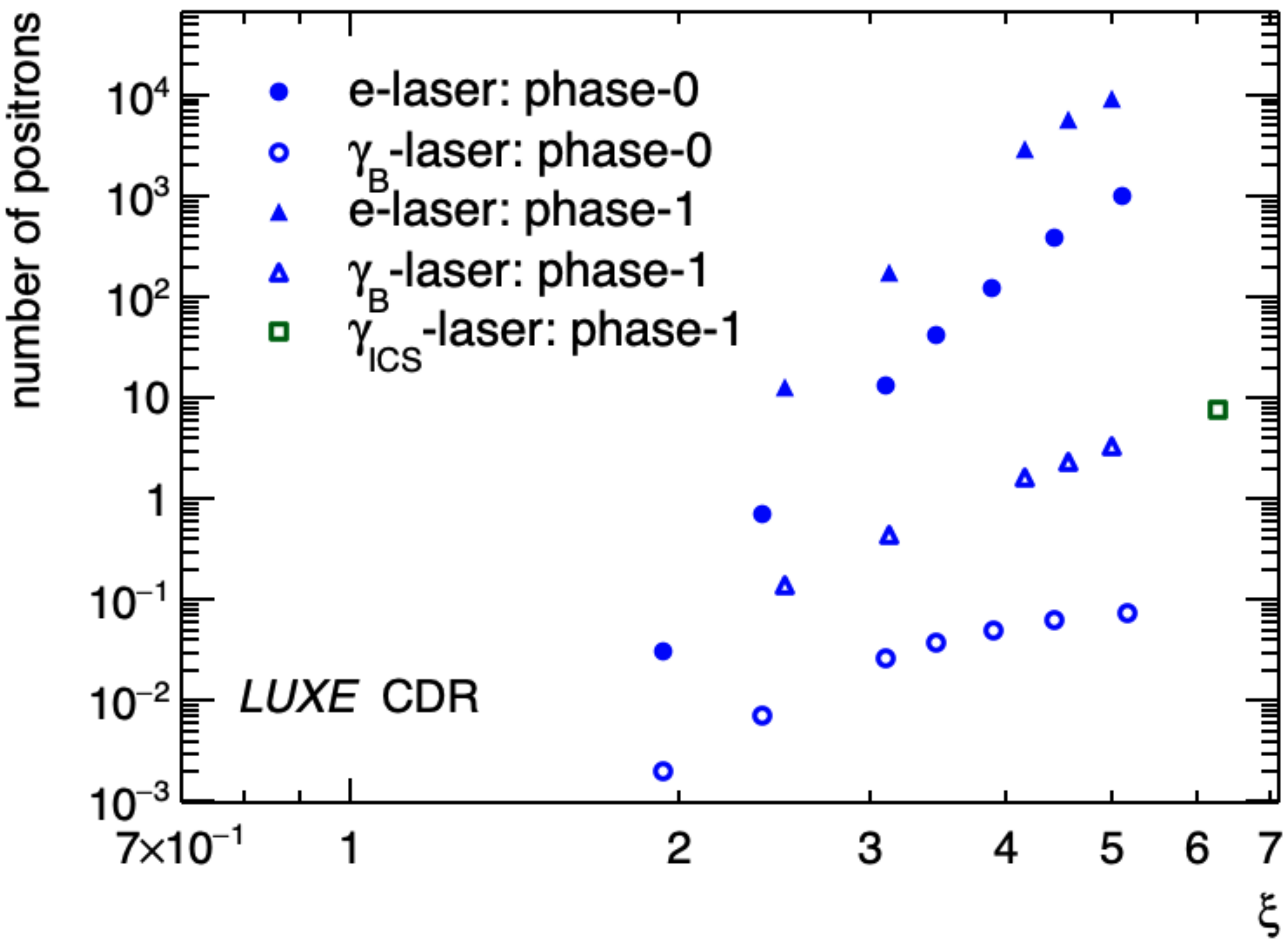
16.5 GeV electron, 800 nm laser, 17.2° crossing angle

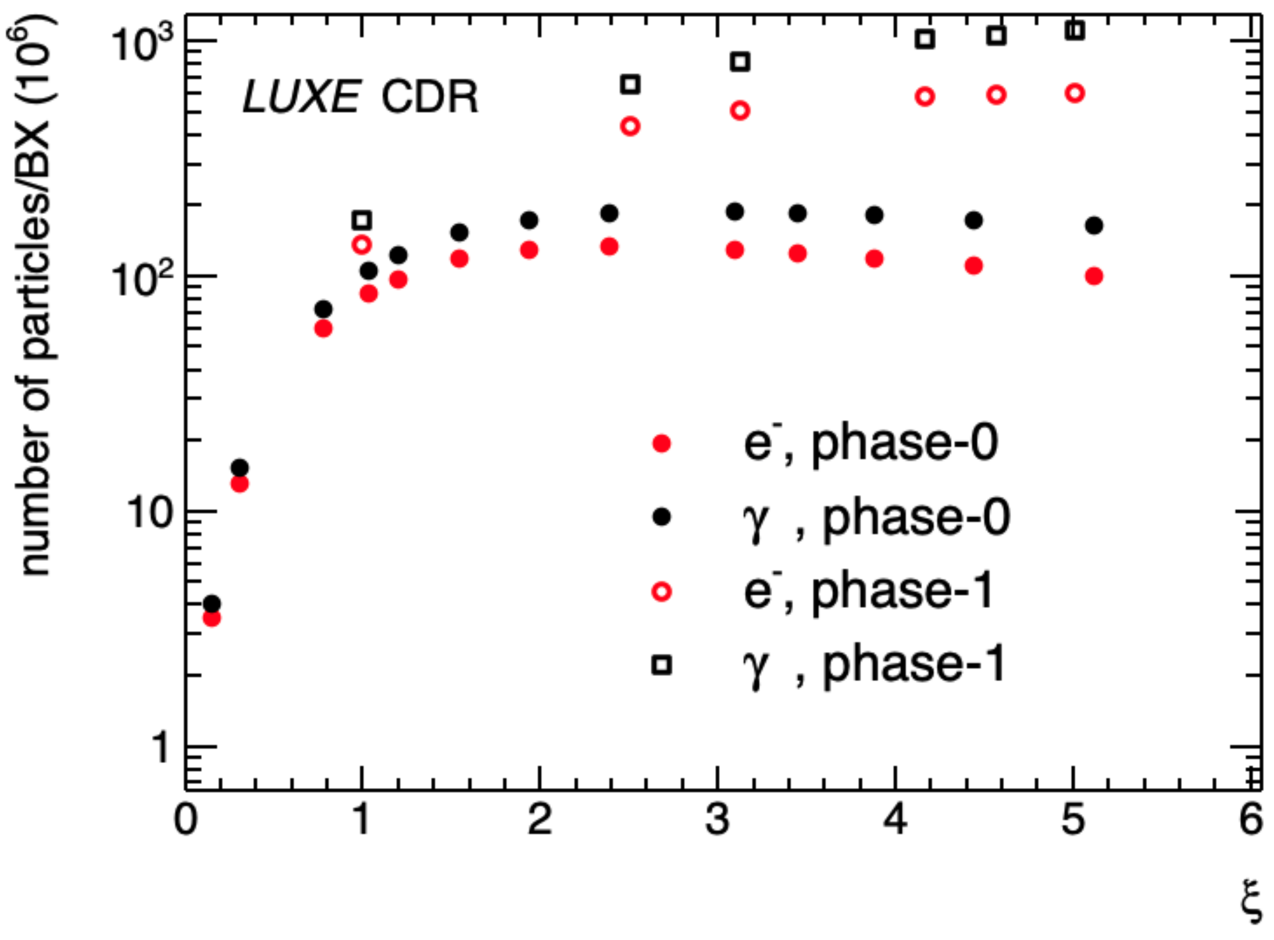




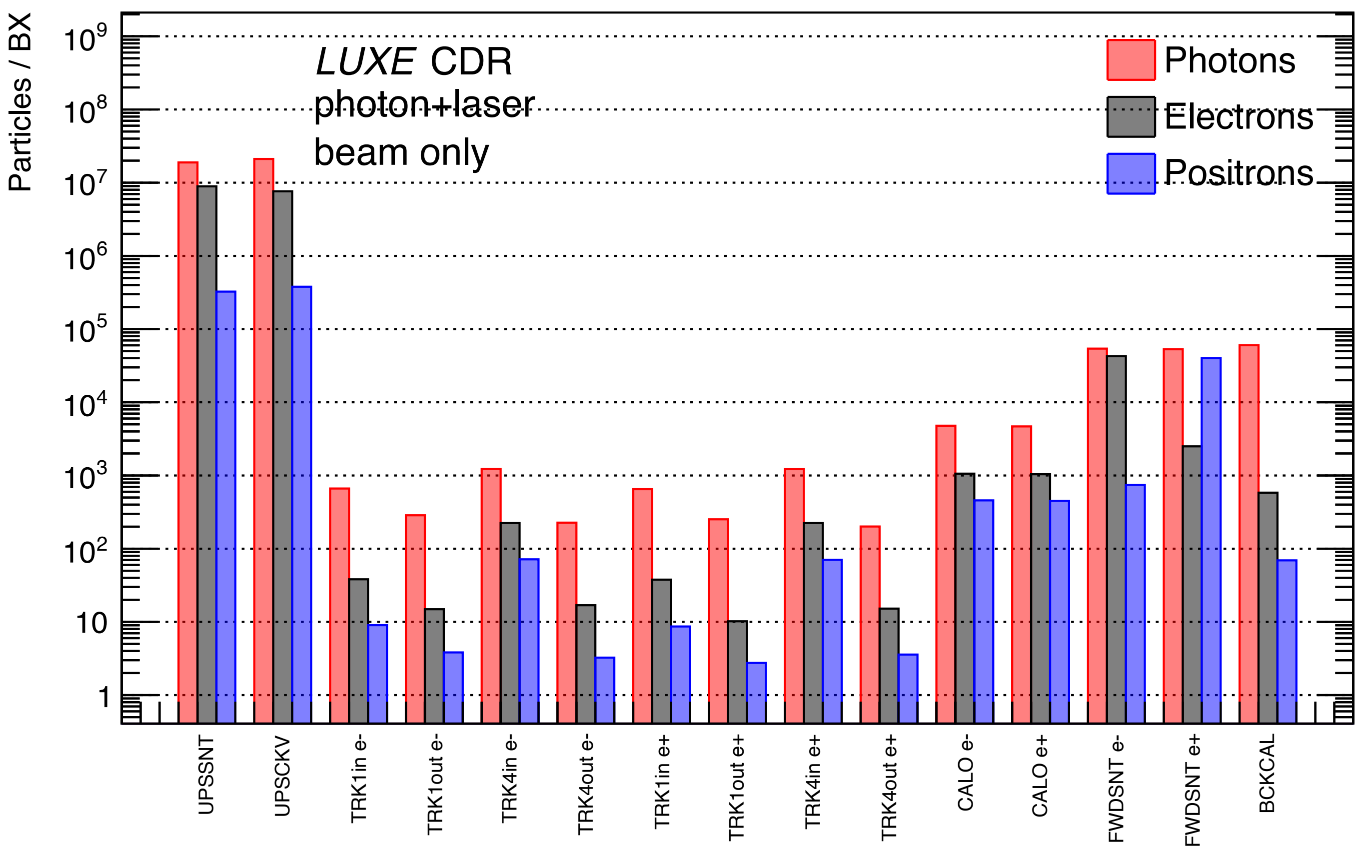
- reminder: in strong fields, electron obtains larger effective mass $m_* = m_e\sqrt{1+\xi^2}$
  → Compton edge shifts as function of ξ
- theoretical prediction: $E_{edge}(\xi) = E_e \frac{2n\eta}{2n\eta + 1 + \xi^2}$, with $\eta_{LUXE} = 0.192$
- reconstruct Compton edge in electron (Scintillator and Cerenkov detector) or photon spectrum (Photon spectrometer)

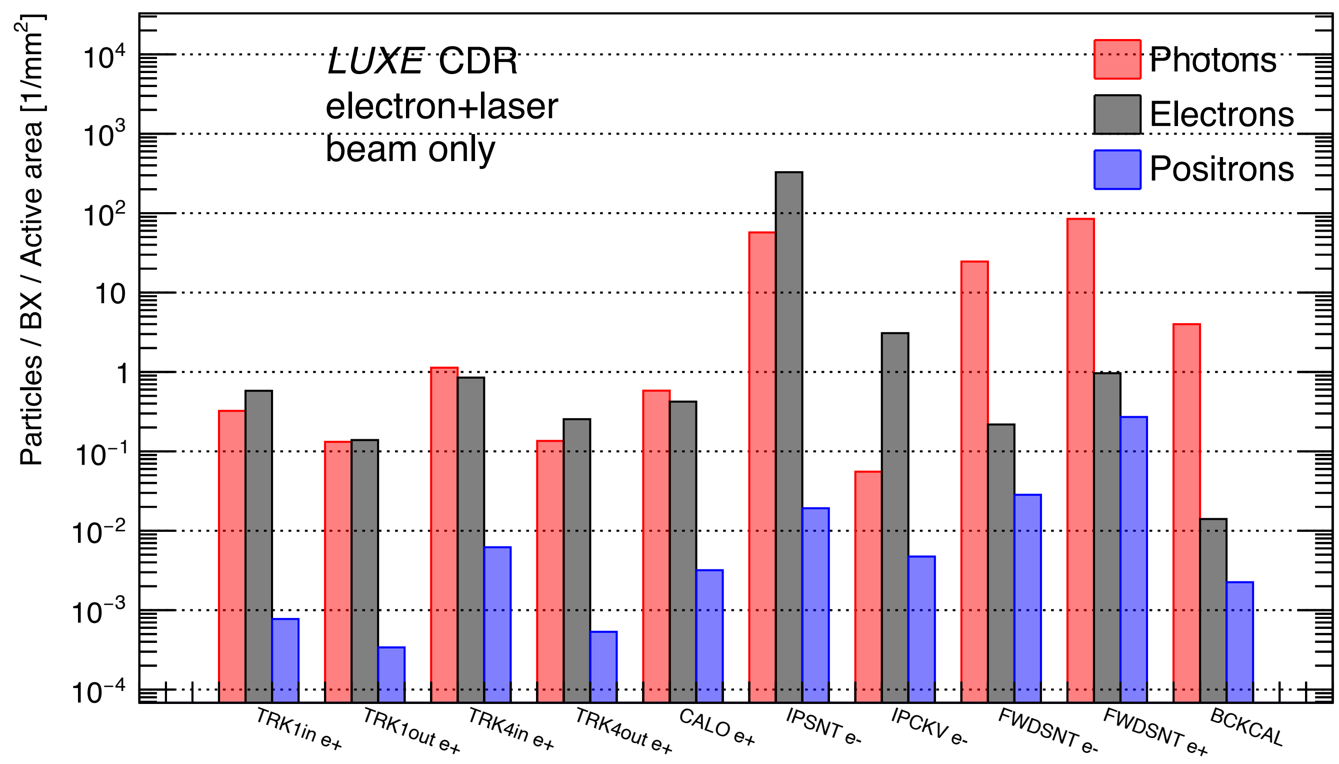
Particle rates



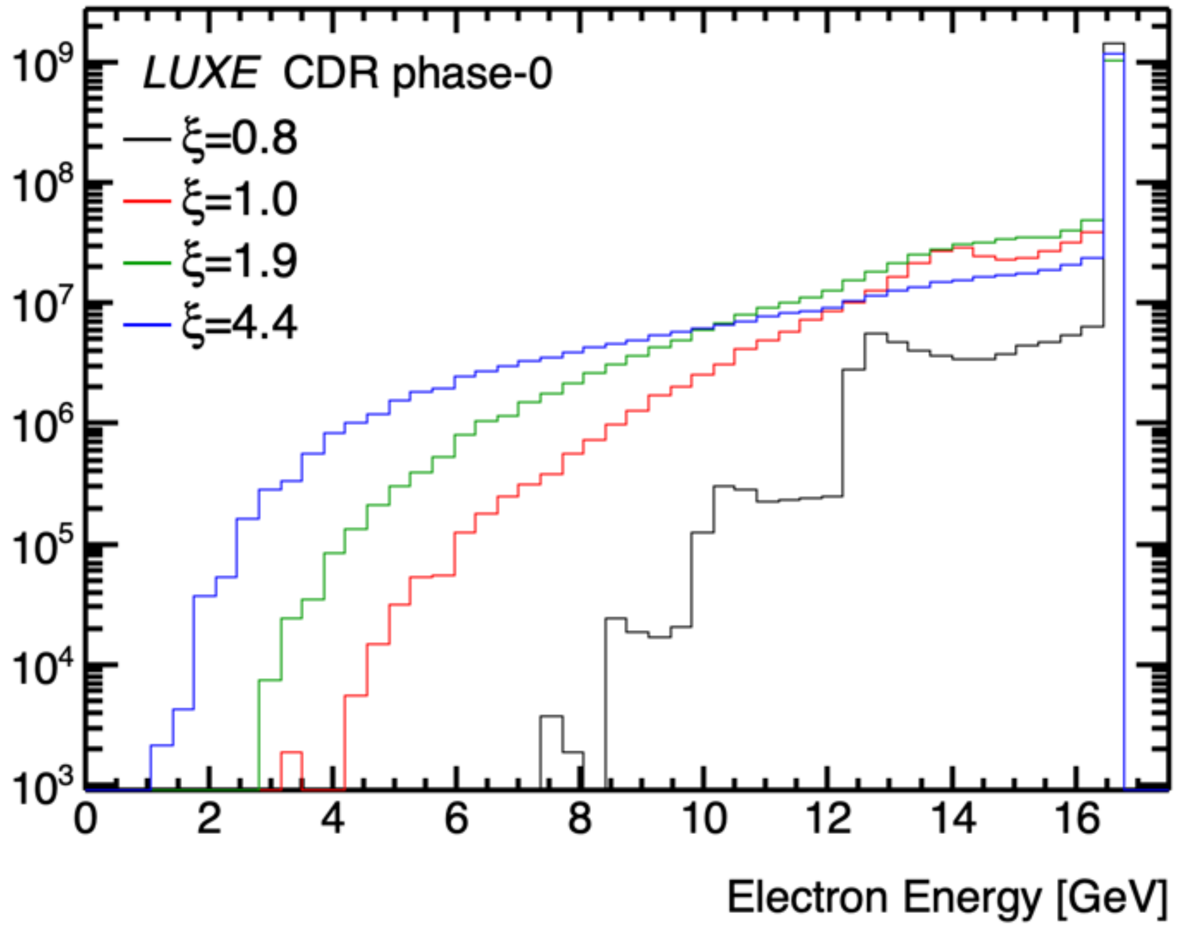


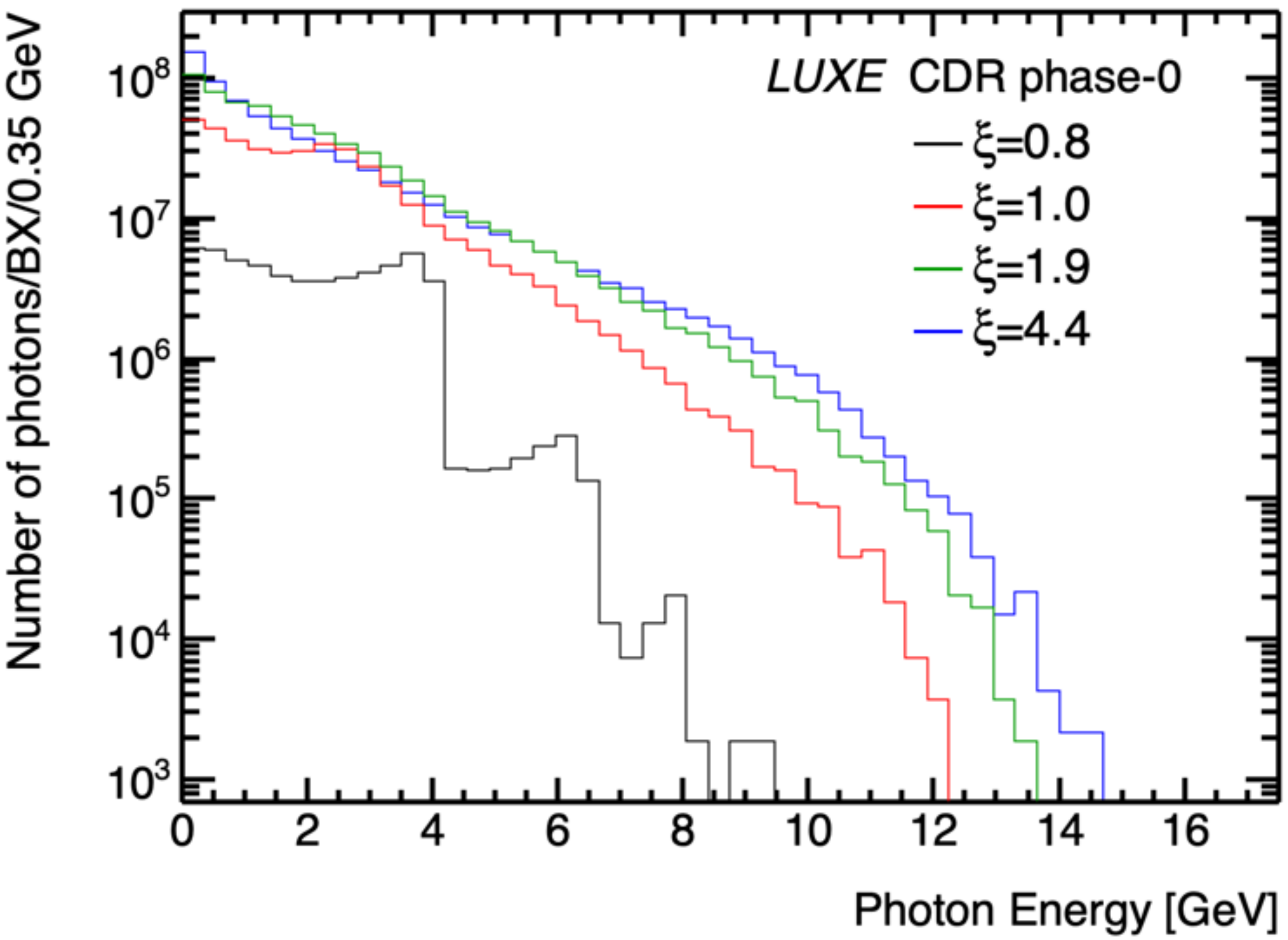
Beam Background rates



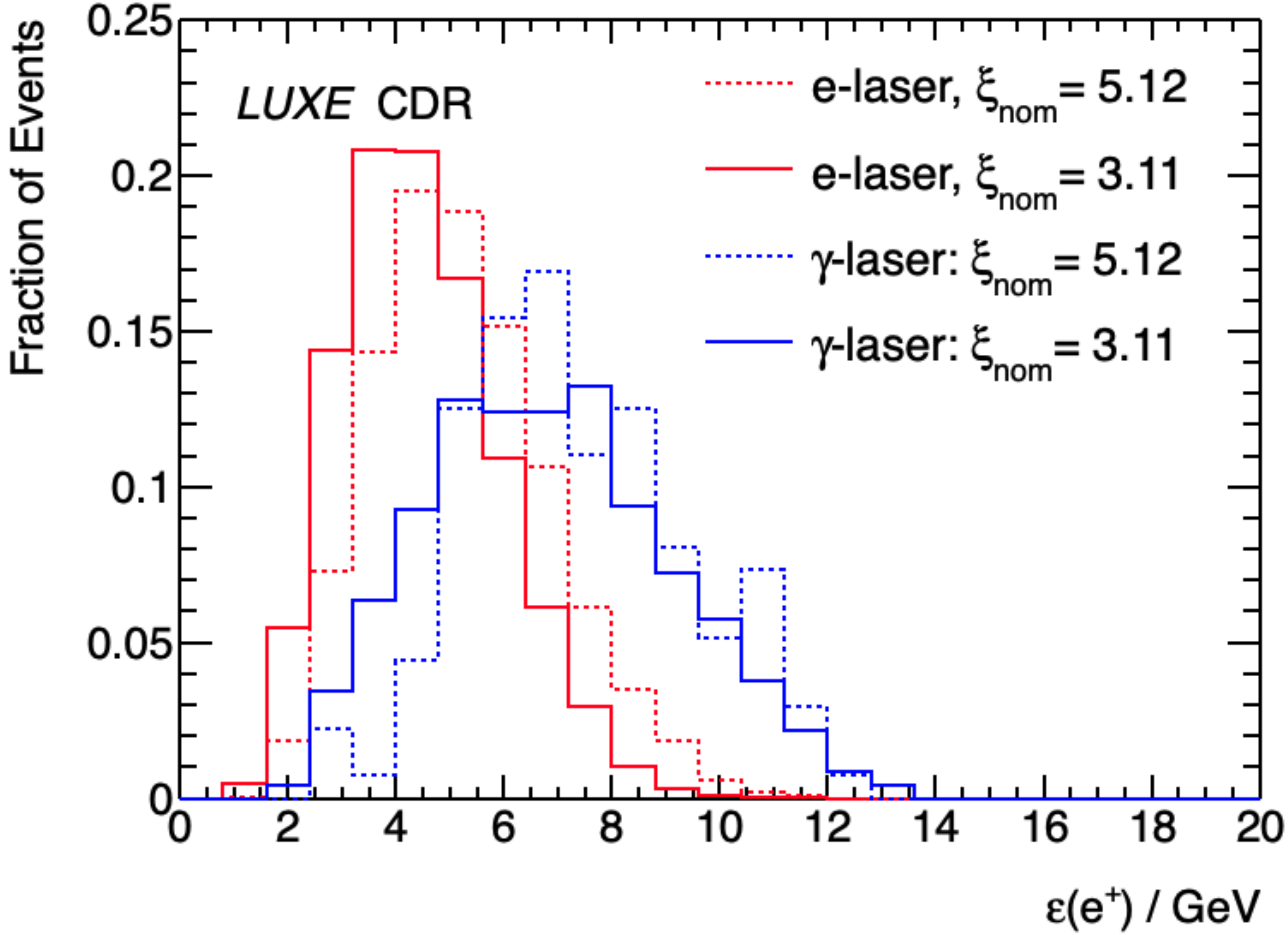


e+LASER Spectra

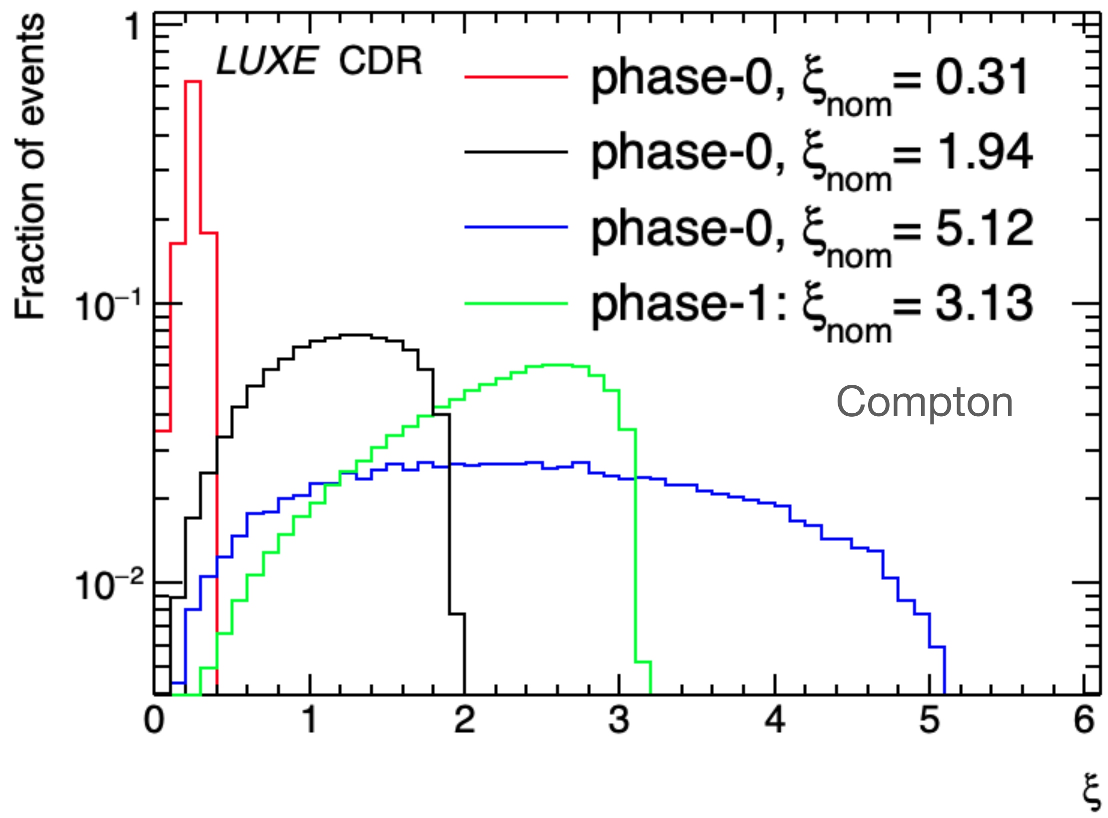


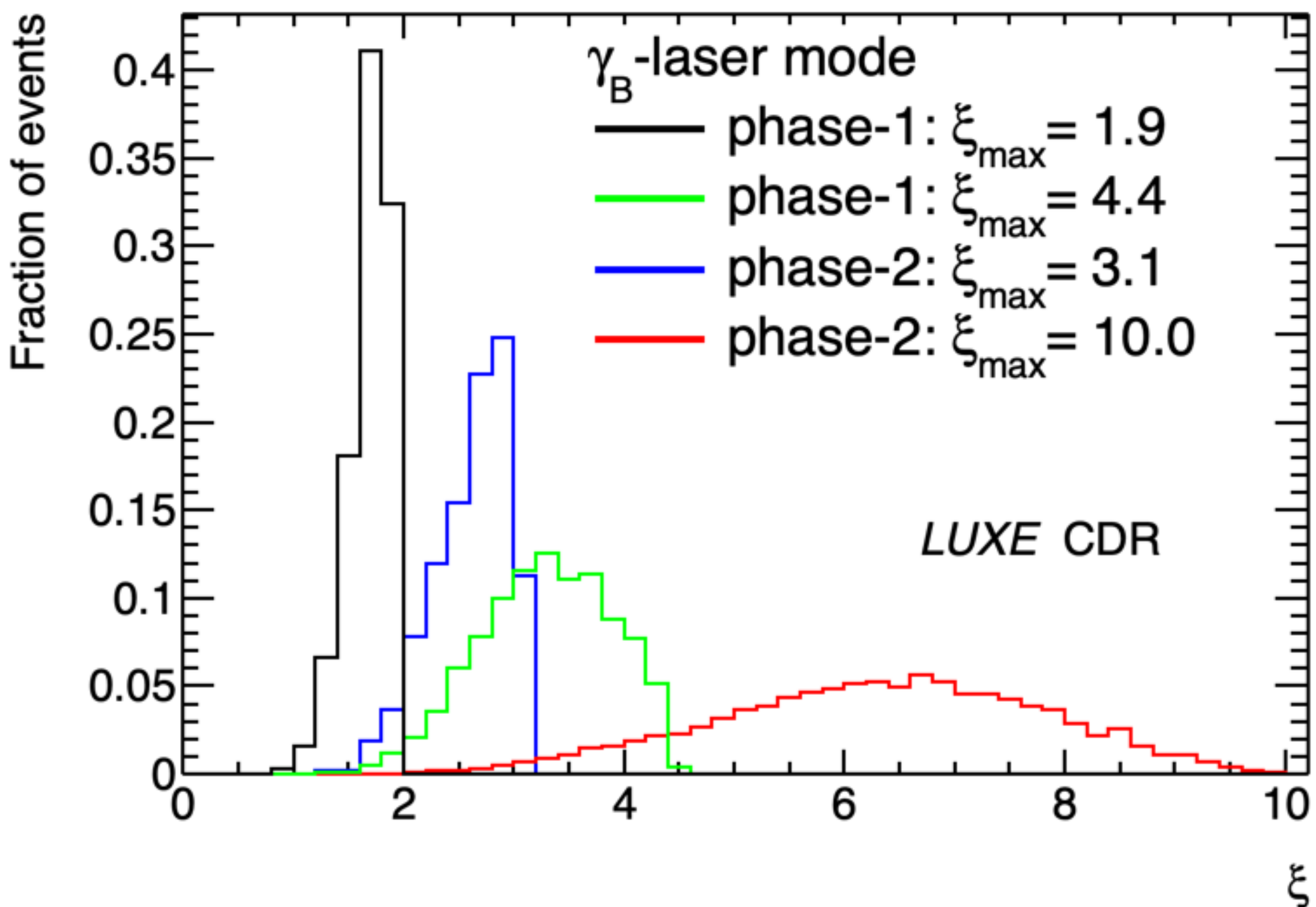


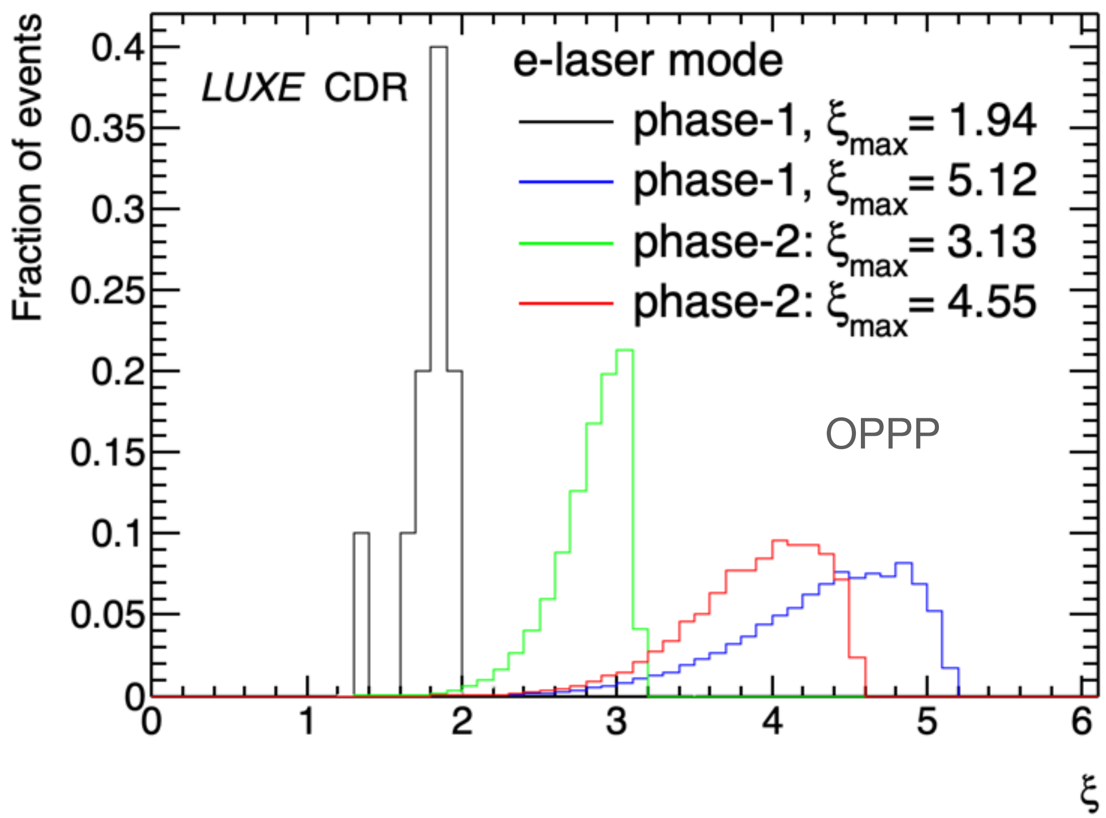
Positron Spectra



xi distributions

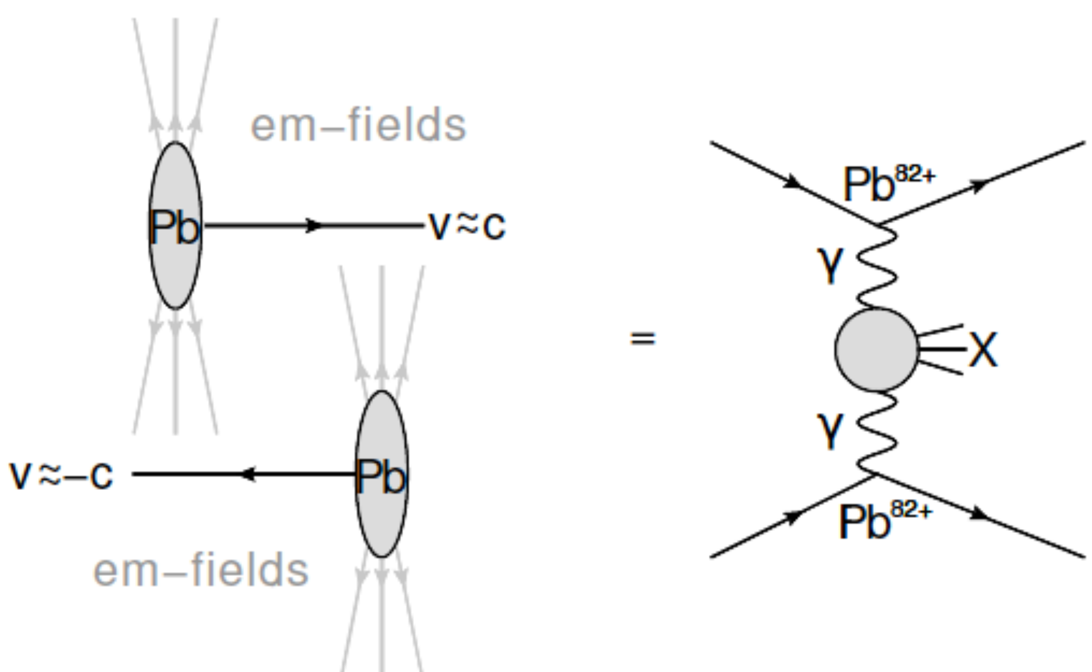


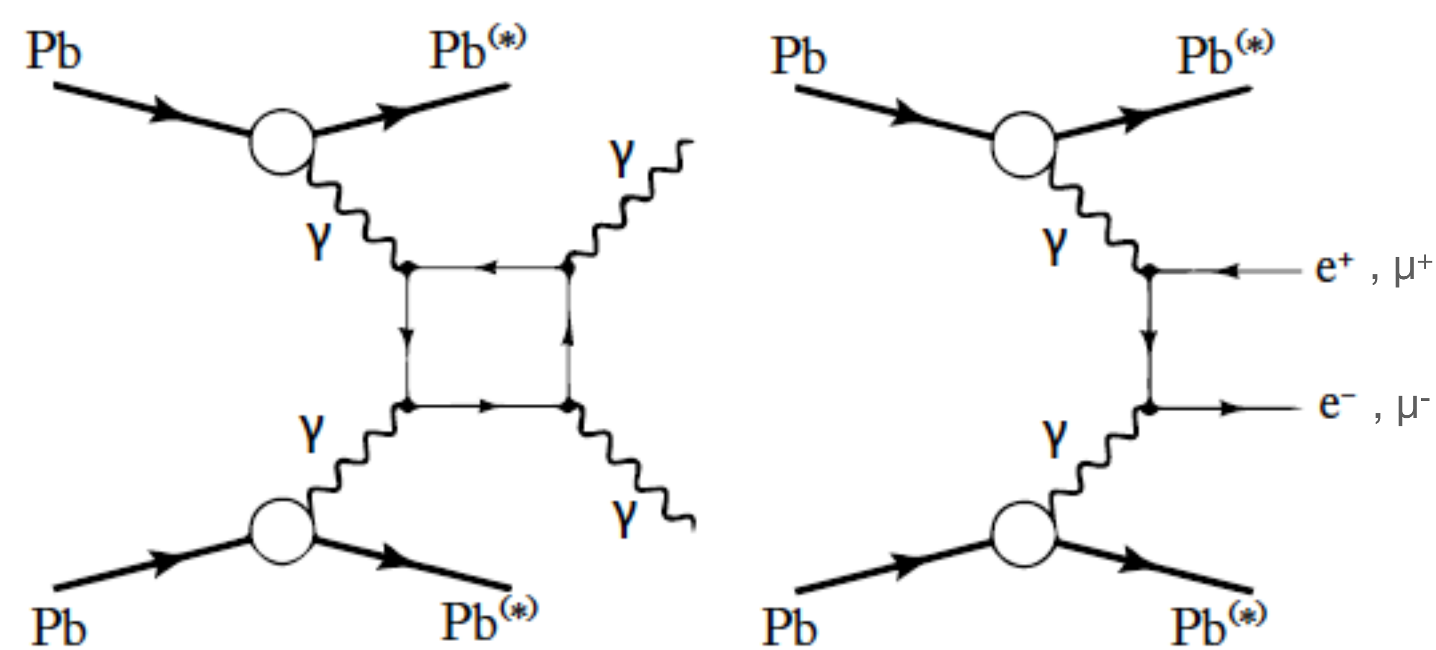




How does LUXE relate to LHC light-by-light scattering?

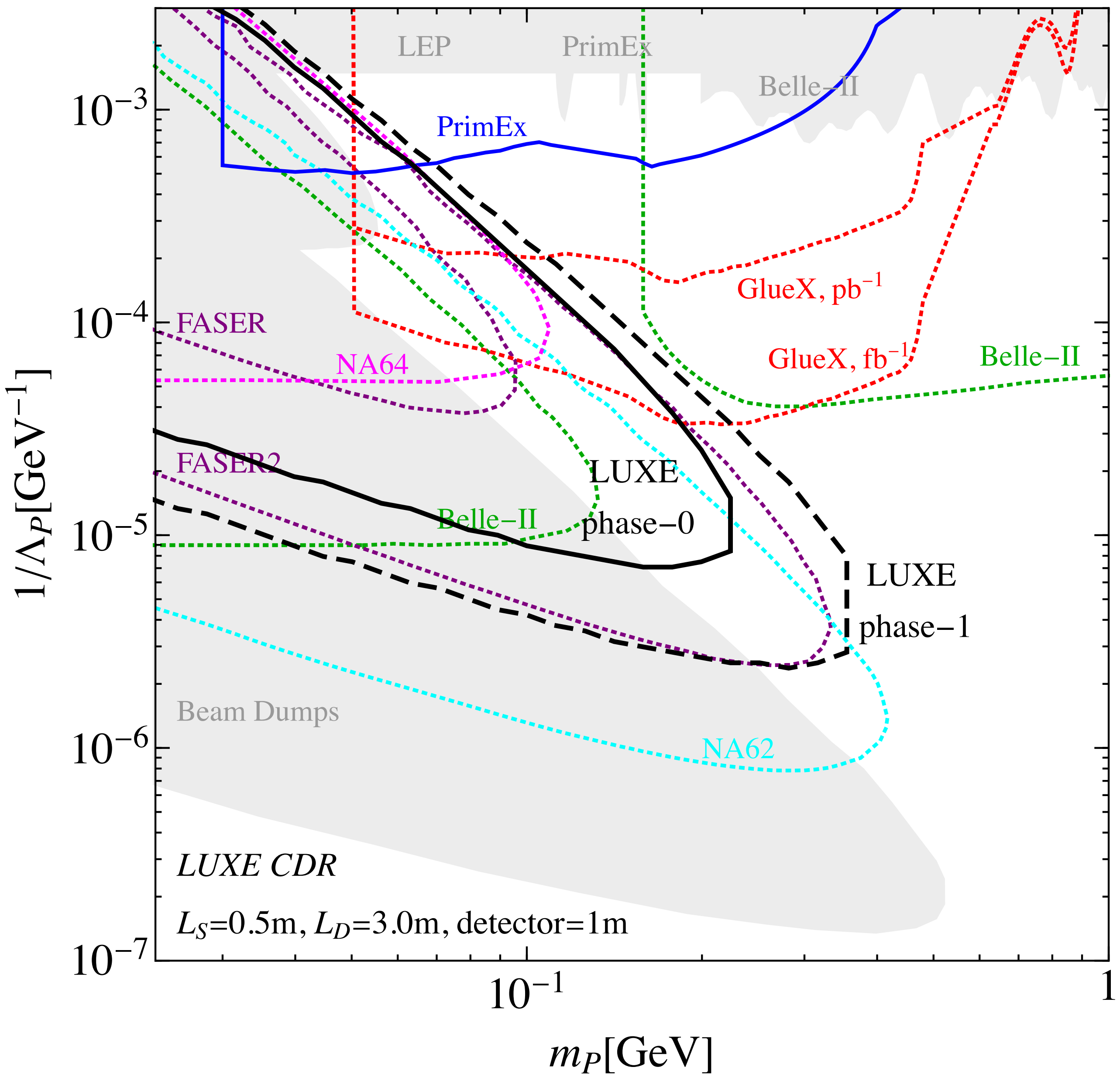
- LHC: photon-photon interaction in ultra-peripheral heavy-ion collisions (UPC) → e.g. $\gamma\gamma\to\gamma\gamma$, $\gamma\gamma\to\mu\mu$
- UPC: fields above the Schwinger limit can be reached in the lab
- main difference to LUXE: in UPC, EM field is extremely short-lived, cannot travel over macroscopic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

Bonus: Searching for BSM Physics with LUXE



- sensitivity estimated for 1 year data-taking assuming no background
  → still needs to be verified
- could be competitive with other experiments ongoing and in planning
  → similar to e.g. FASER-2