High-flux Electron Detector to Study Non-linear Compton Scattering in the LUXE Experiment

Vienna Conference on Instrumentation 2025

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20th of February 2025

CLUSTER OF EXCELLENCE
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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

LUXE

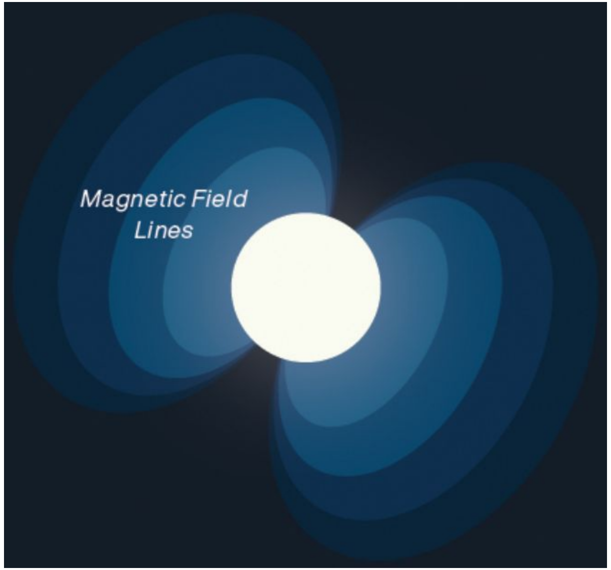
Laser Und XFEL Experiment

New experiment at DESY Hamburg & Eu.XFEL to probe strong-field QED – An uncharted regime

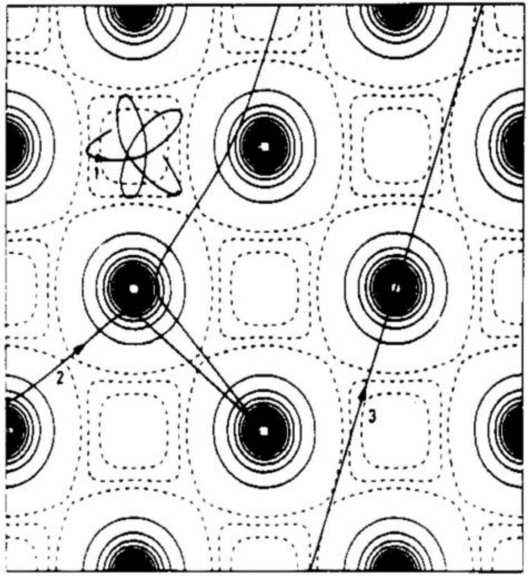
CDR 10.1140/epjs/s11734-021-00249-z TDR 10.1140/epjs/s11734-024-01164-9

Where Do We Obtain Strong Fields?

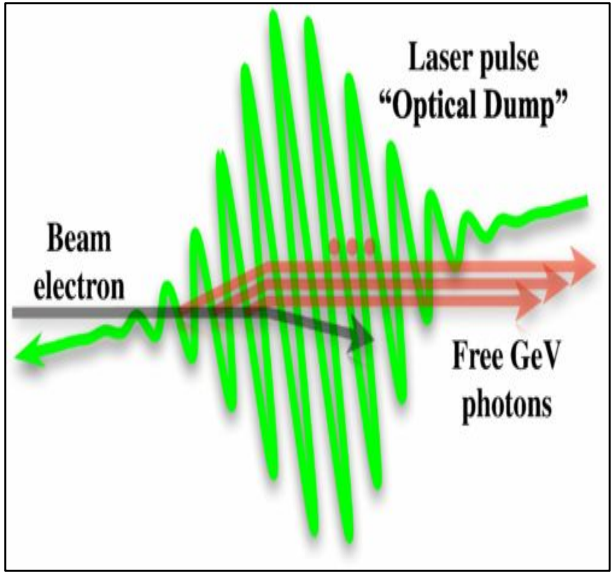
Astrophysics → Magnetars (Neutron stars with B > 10^{10} T)	Crystal lattice (NA63)	Beam-laser / photon-laser interactions



https://photojournal.jpl.nasa.gov/catalog/PIA23863



curtesy: Ulrik I Uggerhøj
(Aarhus University, Denmark)



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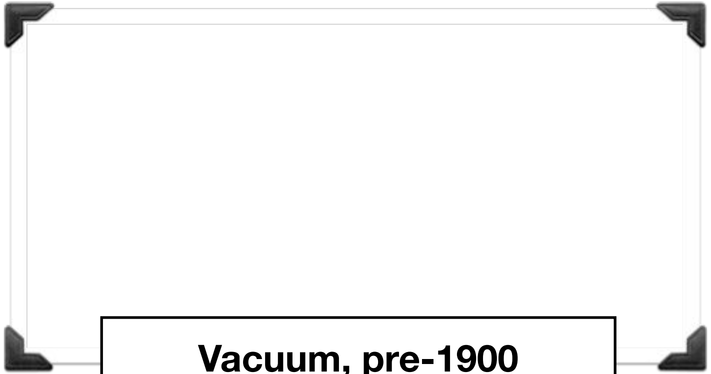
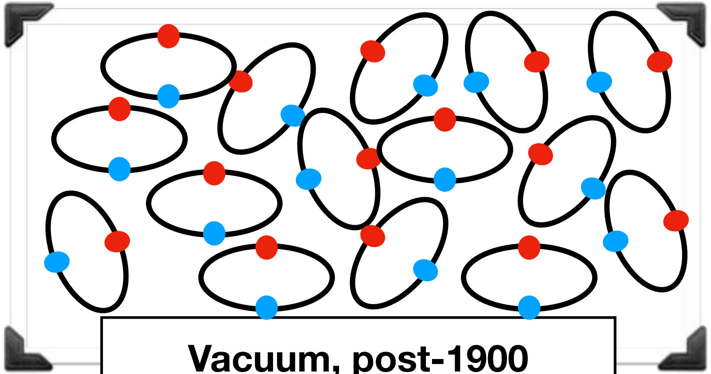
QED and the Vacuum

Emptiness

Virtual Particles



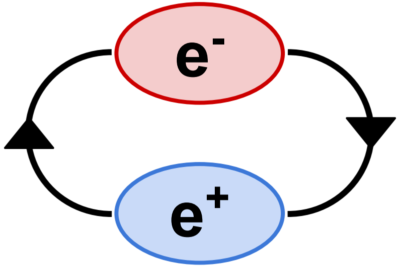
Vacuum, pre-1900



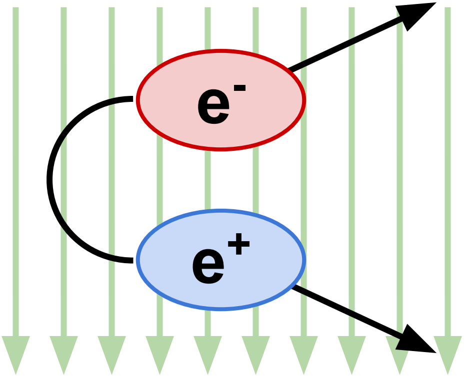
Vacuum, post-1900

The Quantum Electrodynamics is one of the most well-tested physics theories!

Strong-field QED



$W_{Field} > 2m_e$



$$\epsilon_{cr} = \frac{m_e^2 c^3}{e\hbar} = 1.32 \cdot 10^{18}\,\mathrm{V/m}$$

$$\epsilon_{rest\ fr.} = \gamma \cdot \epsilon_{lab\ fr.}$$

Strong-field QED Parameters

$\xi \equiv a_0$ is probe-background coupling

- Here: ξ ~ laser intensity
- $\xi > 1 \rightarrow$ non-perturbative regime

χ is background field to ε_{cr} ratio

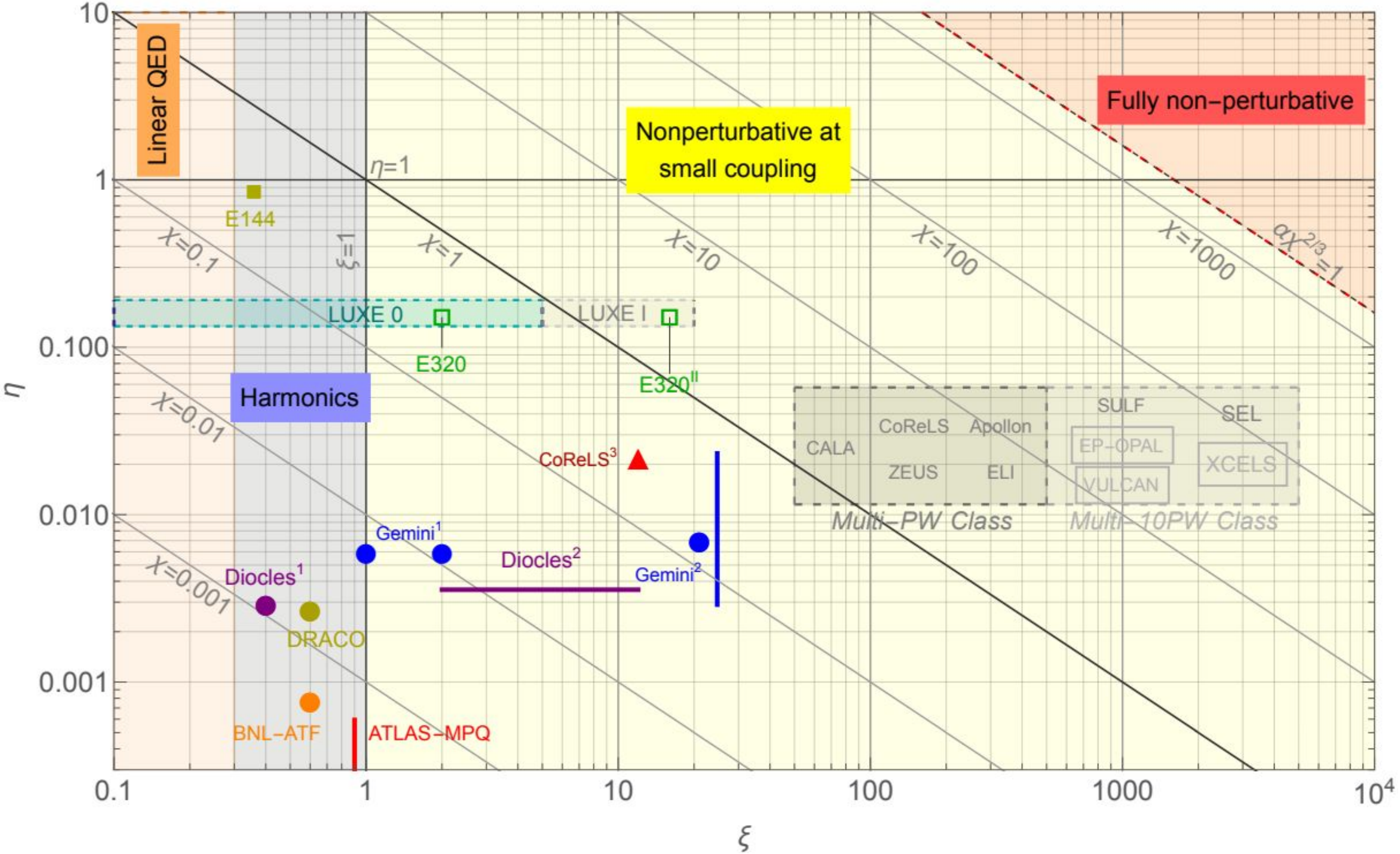
- Here: χ ~ laser energy transfer
- $\chi > 1 \rightarrow$ non-linear quantum effects

η is energy energy of collision

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

Strong-field QED Experiment Landscape

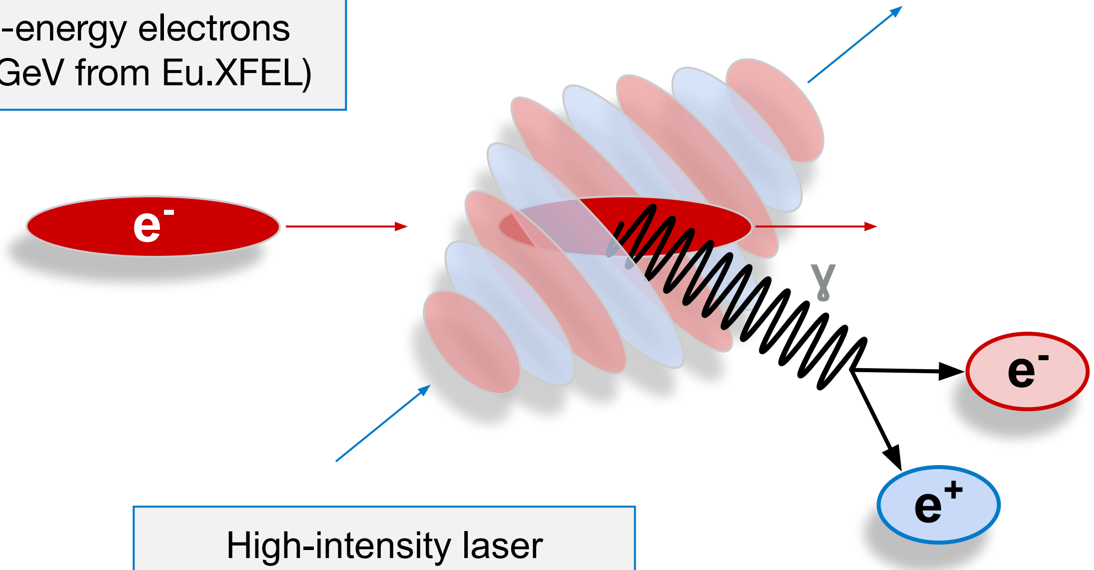
Non-linear Compton Scattering



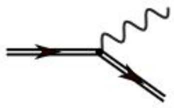
Beam Interactions at LUXE

Electron-Laser Collisions

High-energy electrons
(16.5 GeV from Eu.XFEL)



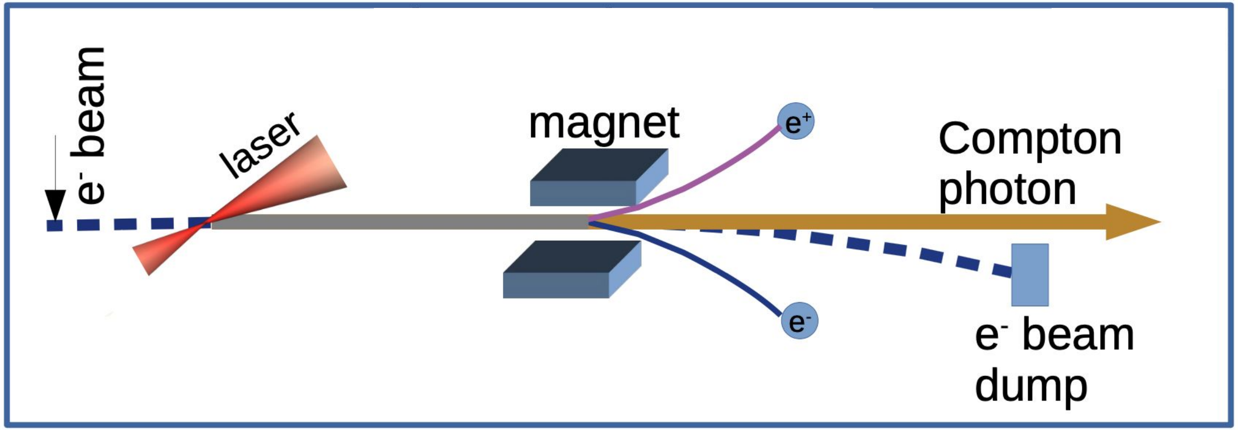
High-intensity laser
(Tera-Watt, 800 nm)



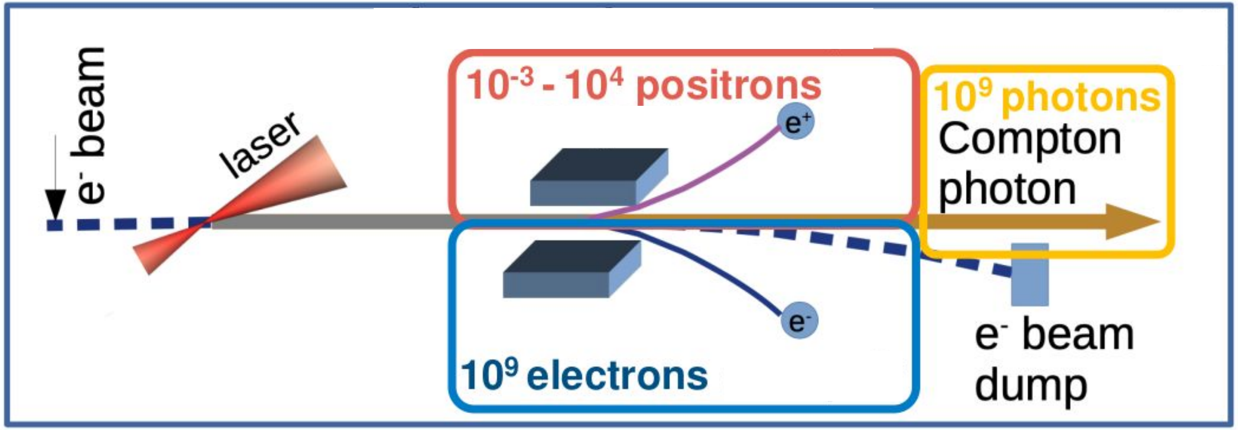
Nonlinear
Compton

Nonlinear
Breit-Wheeler

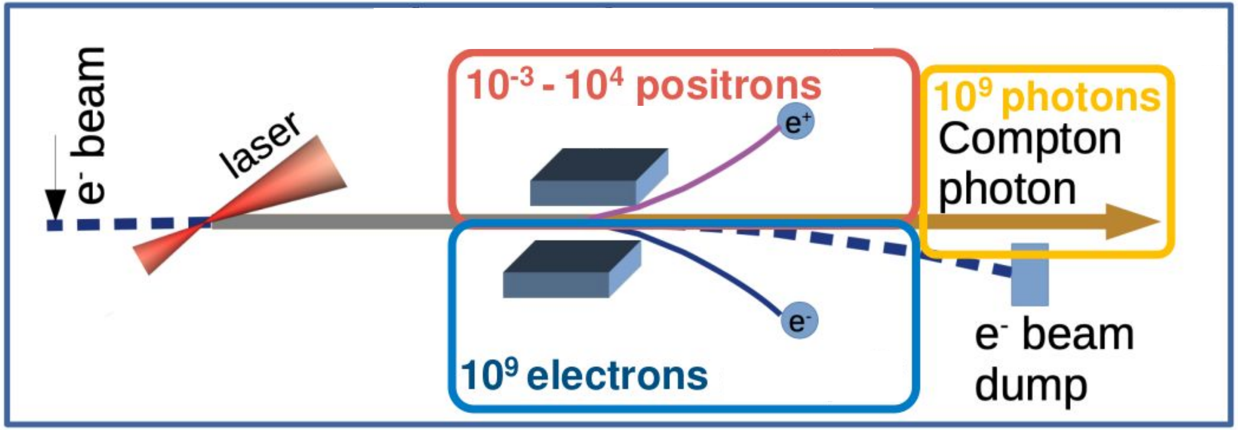
LUXE Experimental Setup



LUXE Experimental Setup



LUXE Experimental Setup



Goal ⇒ Flux and energy measurements of e^-, e^+, γ

- Testbed for a wide range of unique detection methods
- Two complementary detector technologies per type of particle
  → **cross-calibrations** and **low systematic uncertainties**

Electron Detection System

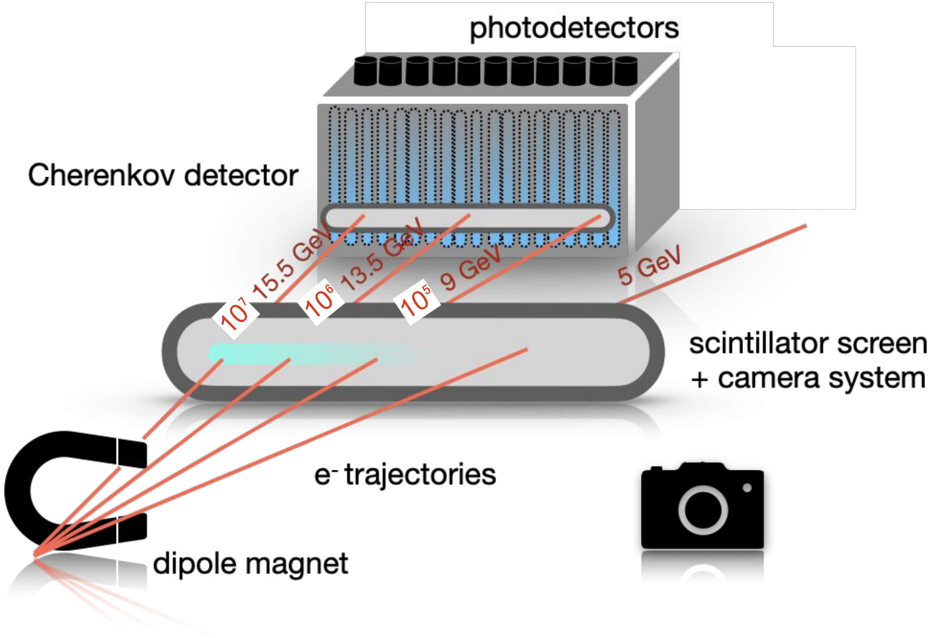
Basic Concept

Scintillating screen and camera

- < 500 μm position resolution
- 2% energy resolution

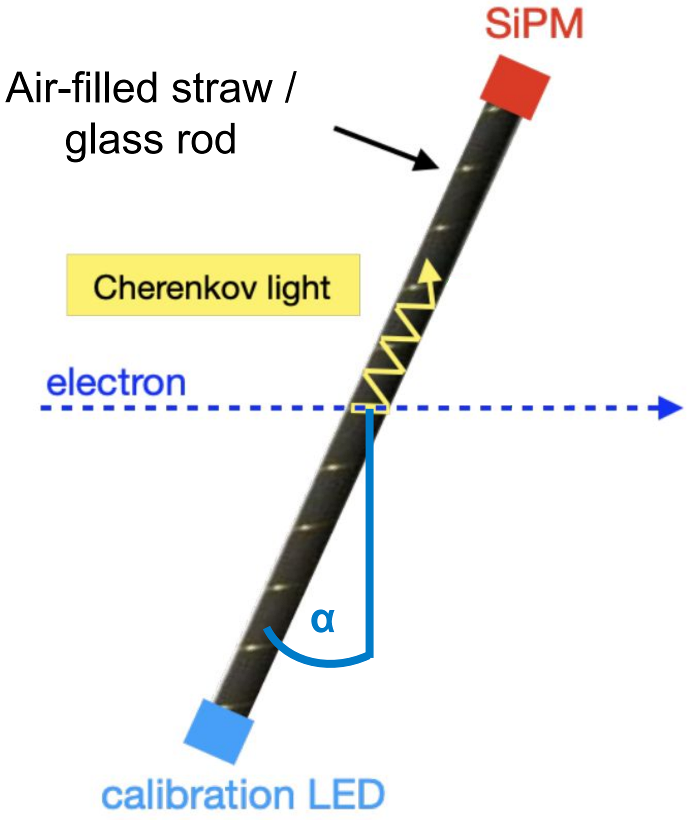
Cherenkov counter

- Segmented channels (‘straws’)
- Air-filled steel straws or glass rods
- < 2.1 mm spatial resolution



Electron Detection System

Straw Concept



Cherenkov volume

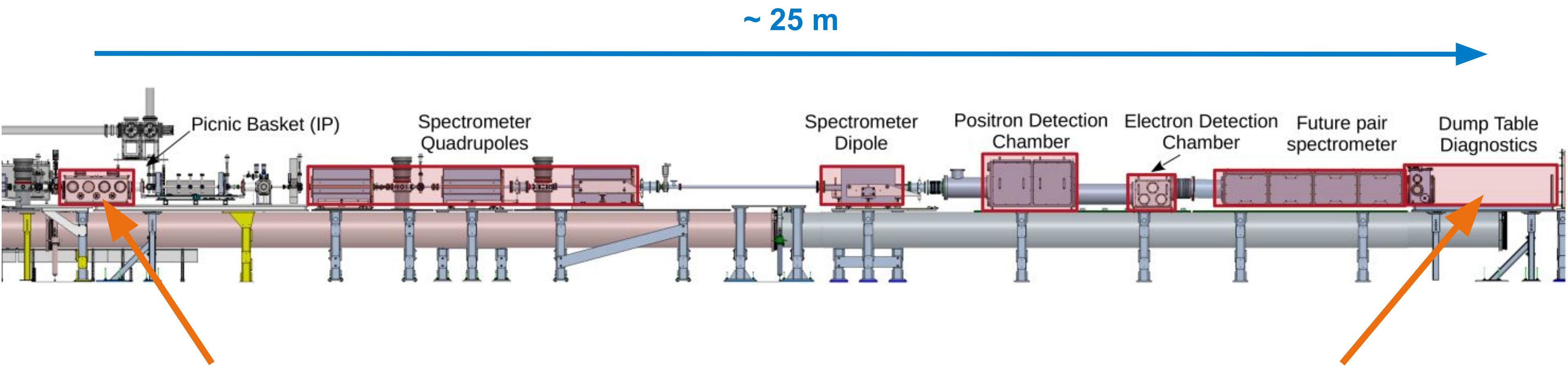
- Hollow tube filled with air
    - Low Cherenkov production rate
    - 21 MeV energy threshold
- Solid glass rod
    - Mainly SiO_2
    - Higher sensitivity to low e^- intensities

Silicon-Photomultipliers (SiPM)

- High dynamic range
- Low bias voltage
- Sensitive to charged particle hits

Strong-field QED Experiment at SLAC

The FACET-II E320 Experiment



Interaction point

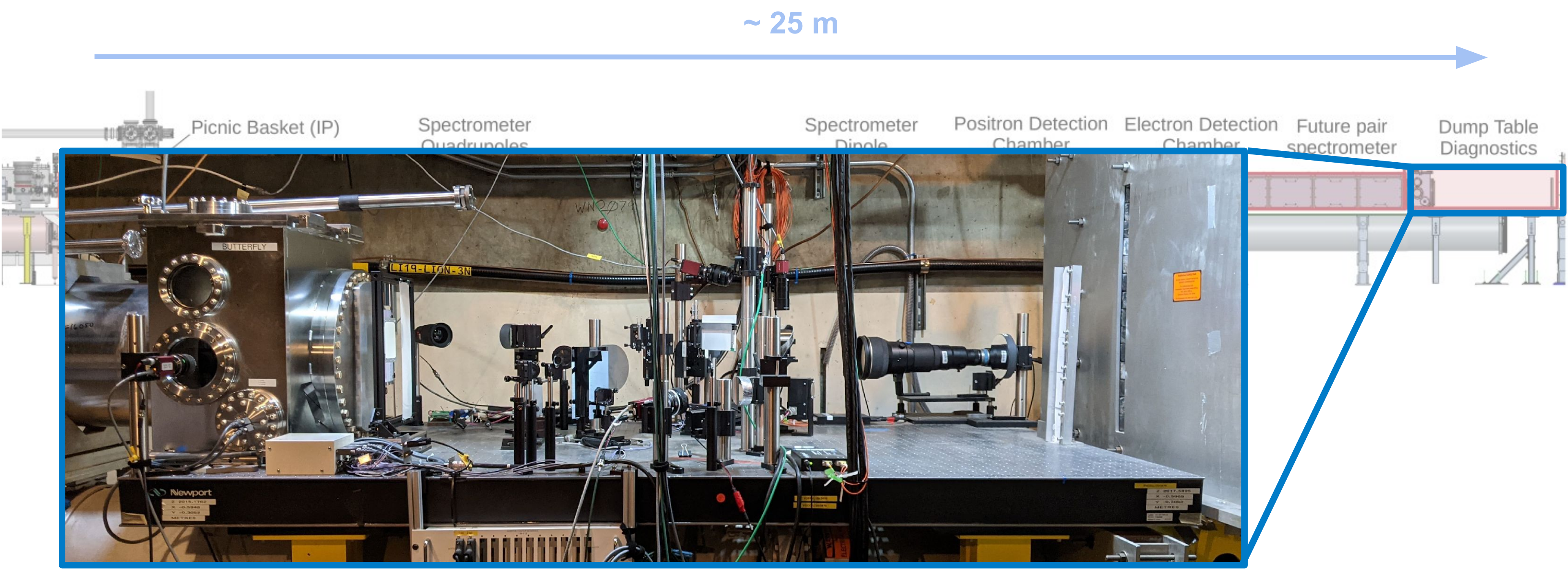
- 10 GeV electron beam with 1.6 nC
- 10 TW laser with ~0.3 J on target
- $\xi \sim 1 \ldots 5$

Dump table

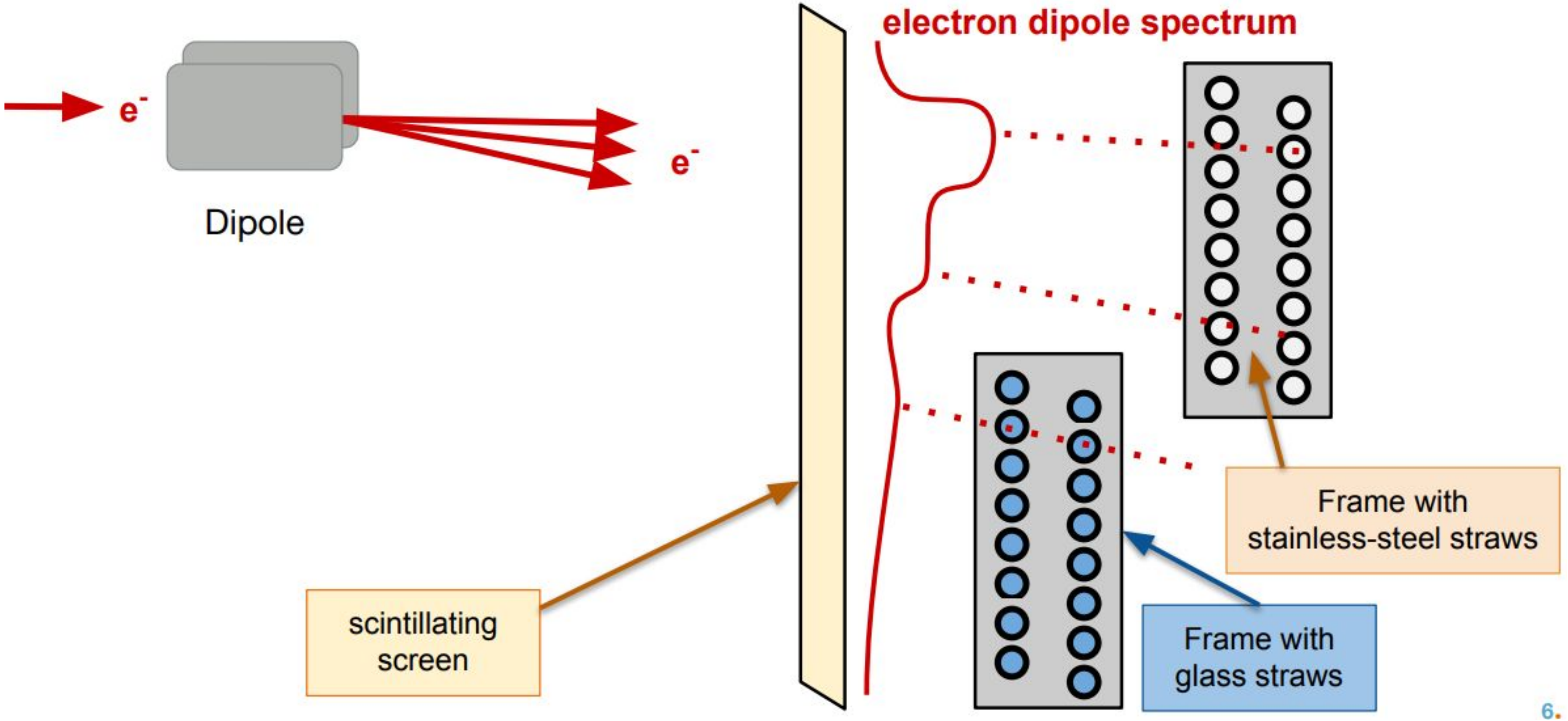
- In-air experimental area with scintillating screens & cameras

Strong-field QED Experiment at SLAC

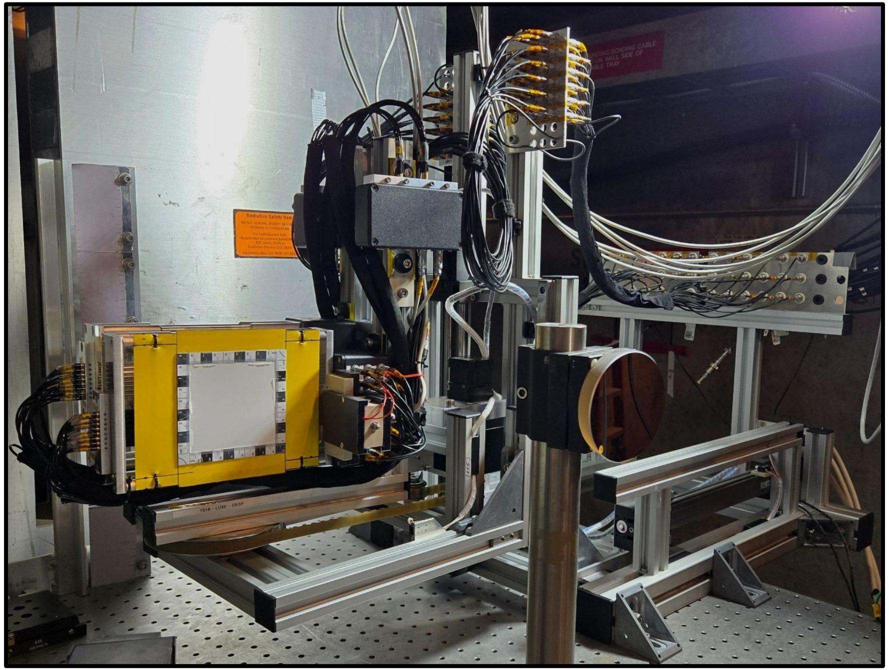
The FACET-II E320 Experiment



Electron Detection System at E320

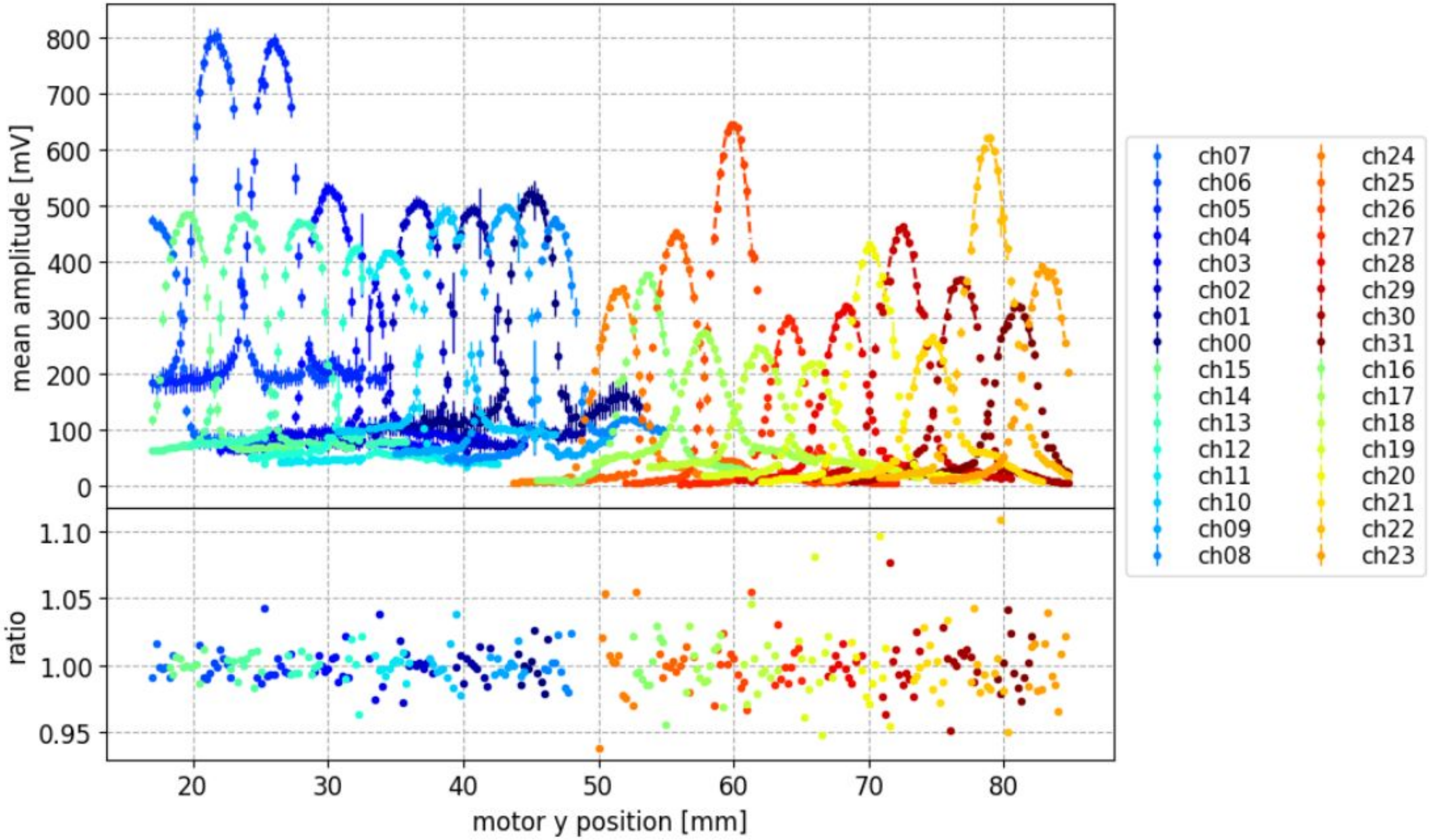


Electron Detection System at E320



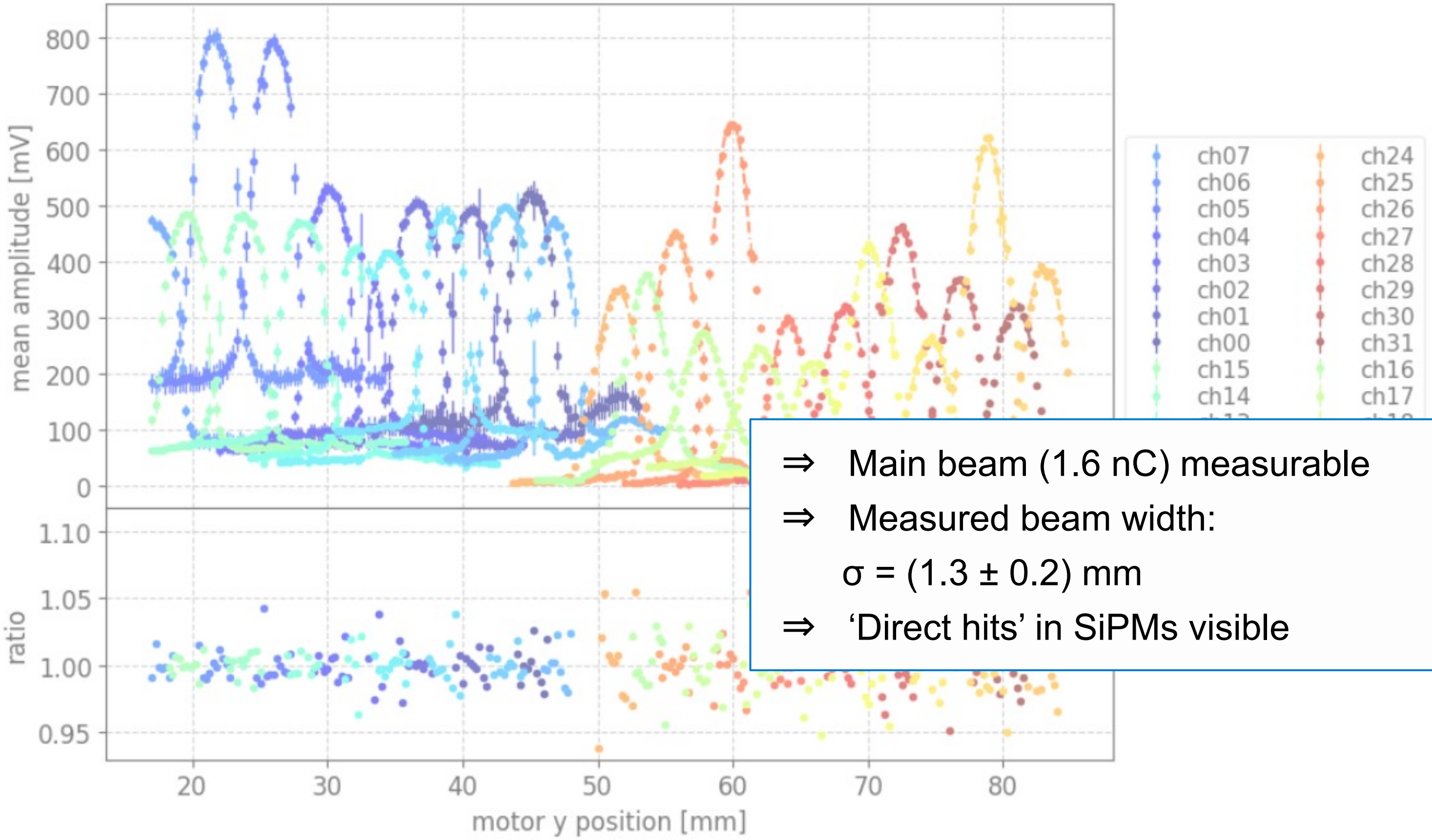
Electron Detection System at E320

Straw Detector – Pencil Beam Response



Electron Detection System at E320

Straw Detector – Pencil Beam Response



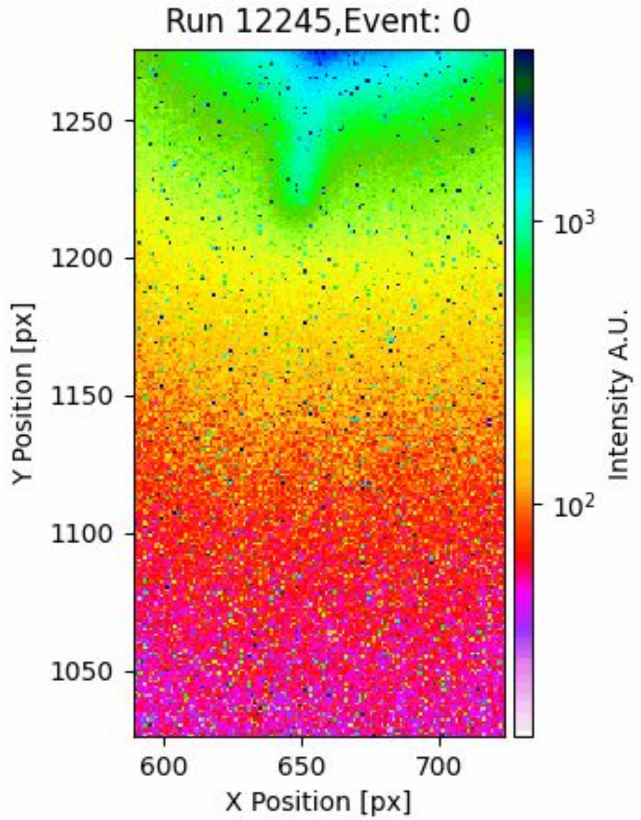
- ⇒ Main beam (1.6 nC) measurable
- ⇒ Measured beam width: $\sigma = (1.3 \pm 0.2)$ mm
- ⇒ 'Direct hits' in SiPMs visible

Electron Detection System at E320

Scintillating Screen – Energy Spectrum

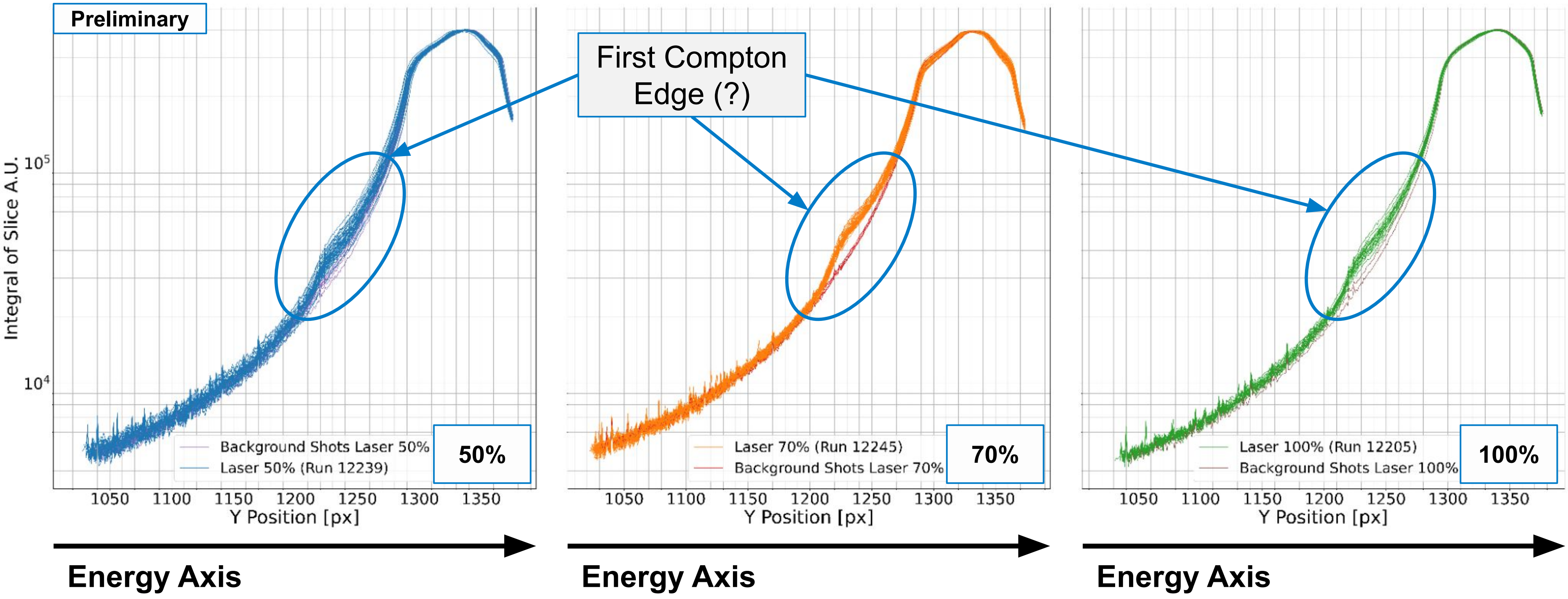
Analysis

1. Find main beam spot and get Compton spectrum region
2. Find background events
3. For each horizontal slice:
   - Filter noise and dead pixels
   - Subtract background from signal
   - Integrate slice



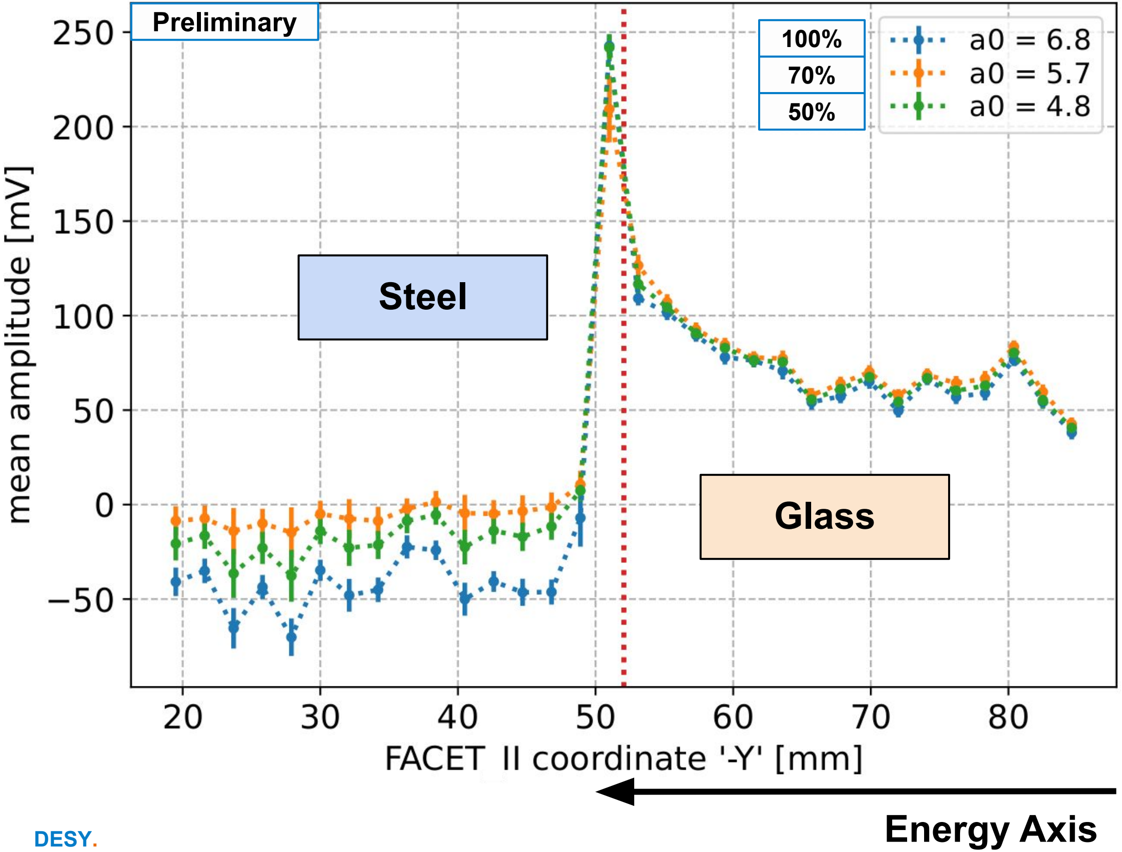
Electron Detection System at E320

Scintillating Screen – Energy Spectra for various laser intensities



Electron Detection System at E320

Straw Detector – Energy Spectra for various laser intensities

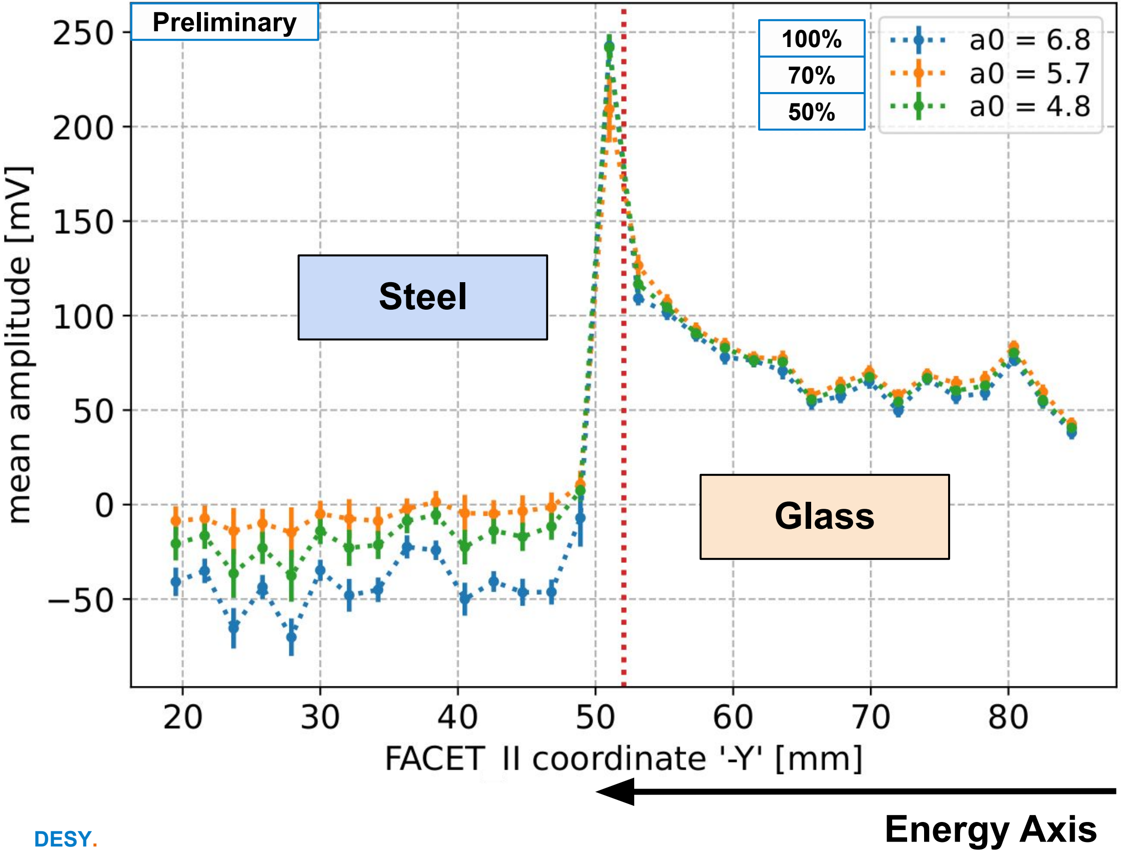


Mean Signal Amplitude

1. Measure waveform
2. Filter noise
3. Find Amplitude
4. Plot average and subtract background for every straw channel

Electron Detection System at E320

Straw Detector – Energy Spectra for various laser intensities



Mean Signal Amplitude

1. Measure waveform
2. Filter noise
3. Find Amplitude
4. Plot average and subtract background for every straw channel

Problems encountered

- Large noise/background issues
- Detector resolution not suitable
- No difference in laser intensities
- No Compton edge visible

Conclusion

LUXE will explore the uncharted regime of strong-field QED

Detector tests at FACET-II

- 1.6 nC signal measurable
- Screen shows Compton scattered electrons
- No Compton spectra with Straw Detector

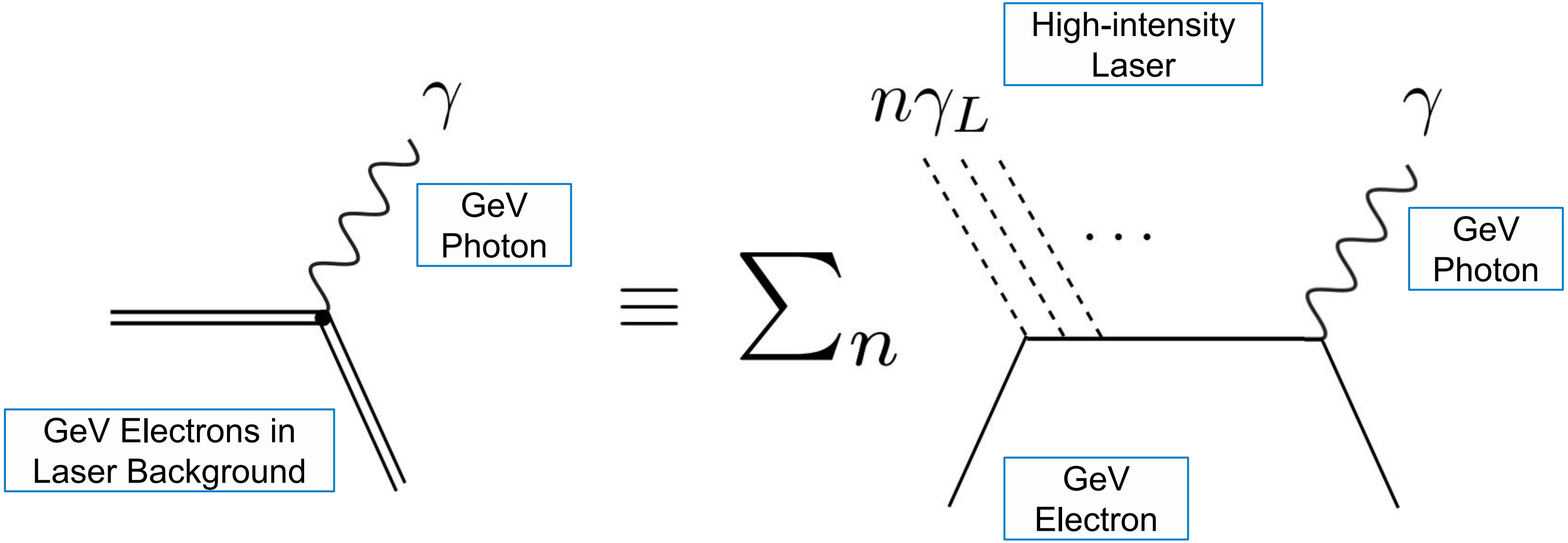
Next steps

- Further data analysis
- Background and noise studies for future upgrades

Backup

Strong-fields with Relativistic Probes

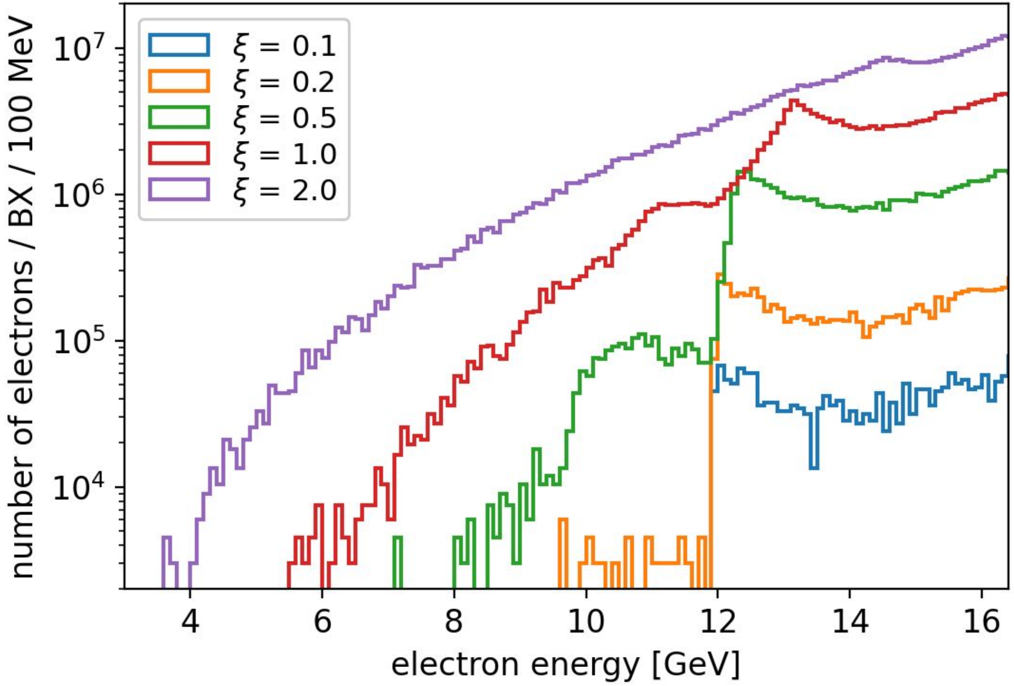
Non-linear Compton Scattering



$$e^{\pm} + n\gamma_L \rightarrow e^{\pm} + \gamma$$

Strong-fields with Relativistic Probes

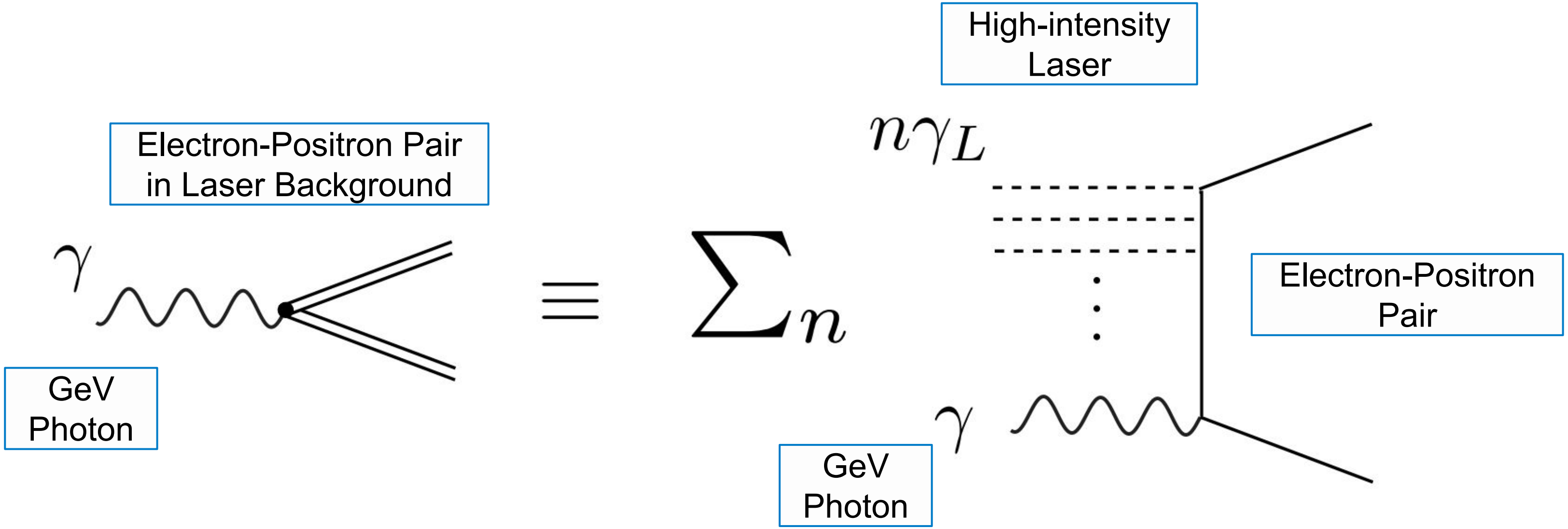
Non-linear Compton Scattering



- Electron obtains larger eff. mass
  → Compton edge shift with ξ
  → Higher harmonics appear
- One goal at LUXE:
  → Verify predictions

Strong-fields with Relativistic Probes

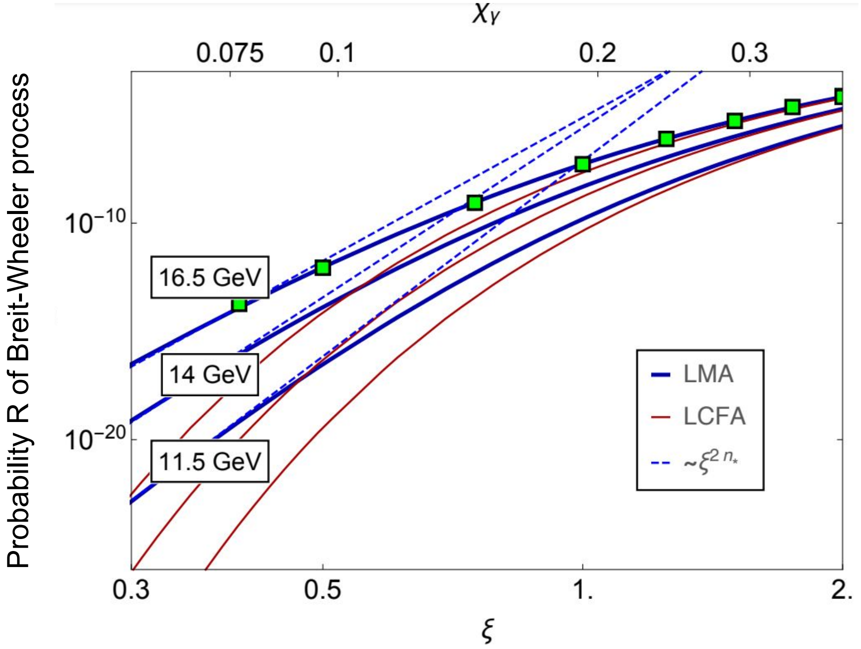
Breit-Wheeler Pair Production



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

Strong-fields with Relativistic Probes

Breit-Wheeler Pair Production



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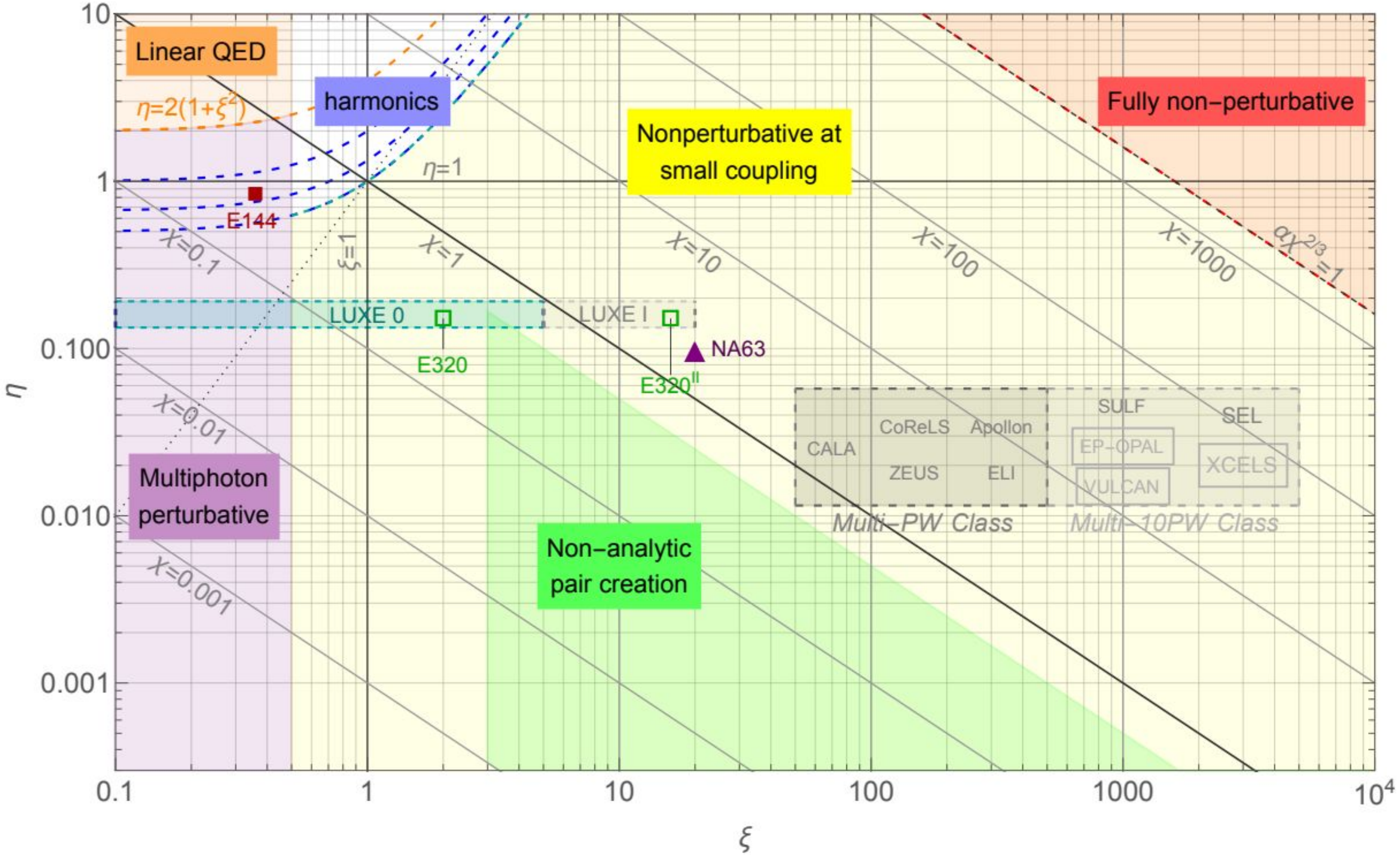
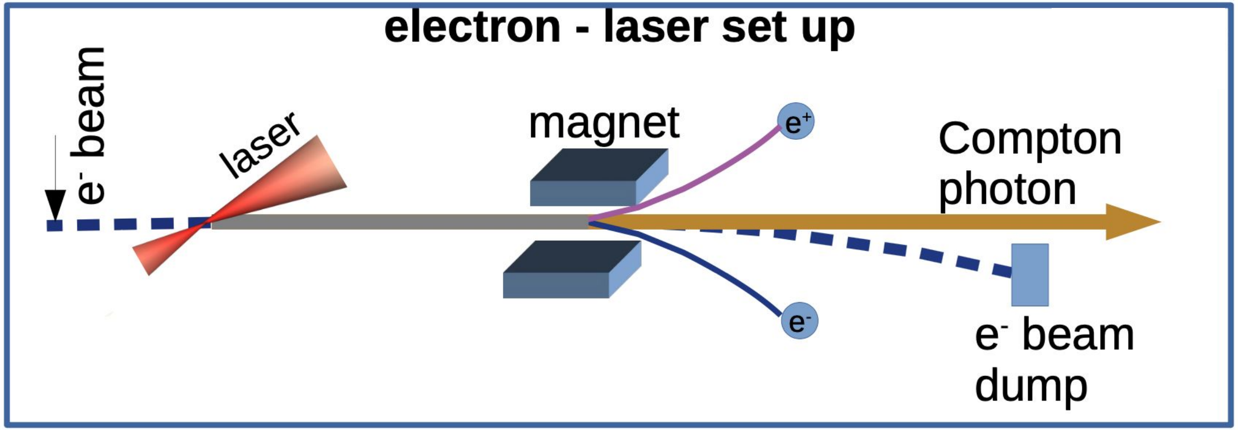
- $\xi << 1$
  → Perturbative Regime
- $\xi >> 1$
  → Exponential law
- One Goal at LUXE:
  → Breit-Wheeler pairs with real photons

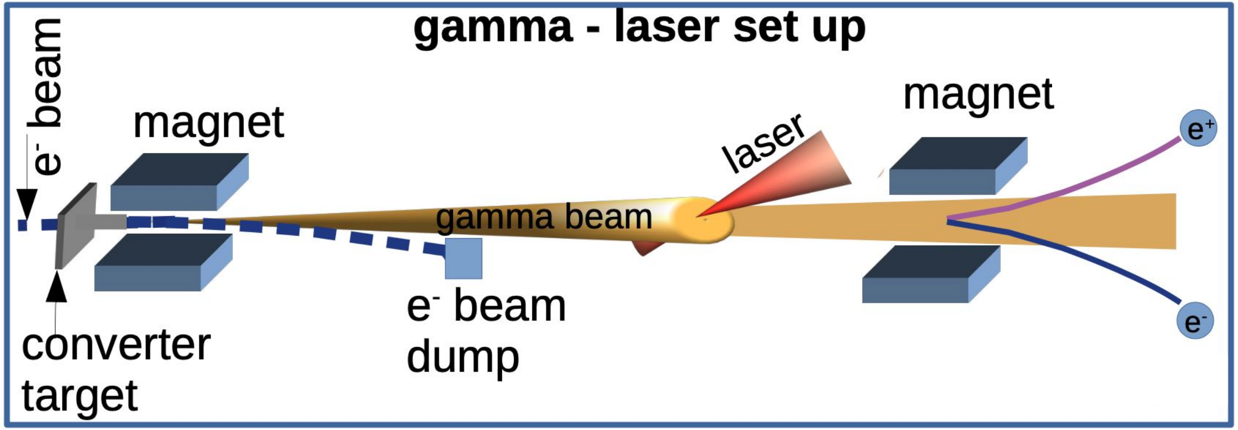
Strong-field QED Experiment Landscape

Non-linear Breit Wheeler Pair Production



LUXE Experimental Setups





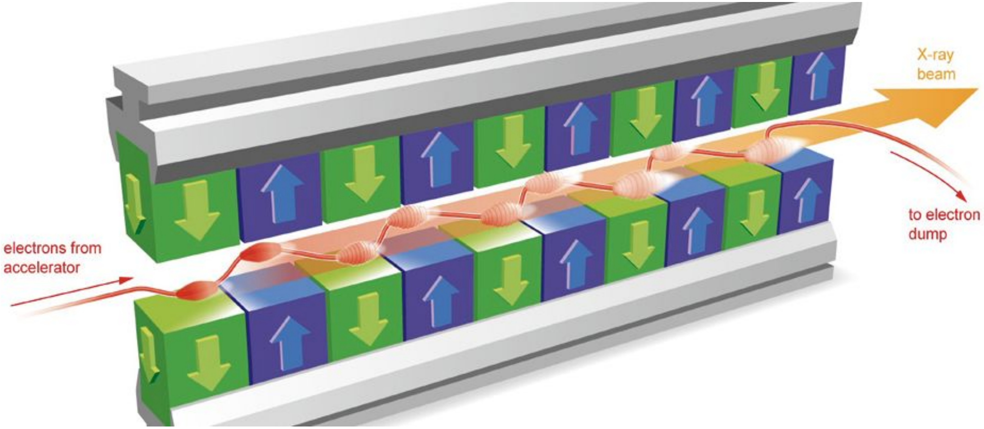
Unique
in LUXE!

The European XFEL

European X-Ray-Free-Electron-Laser

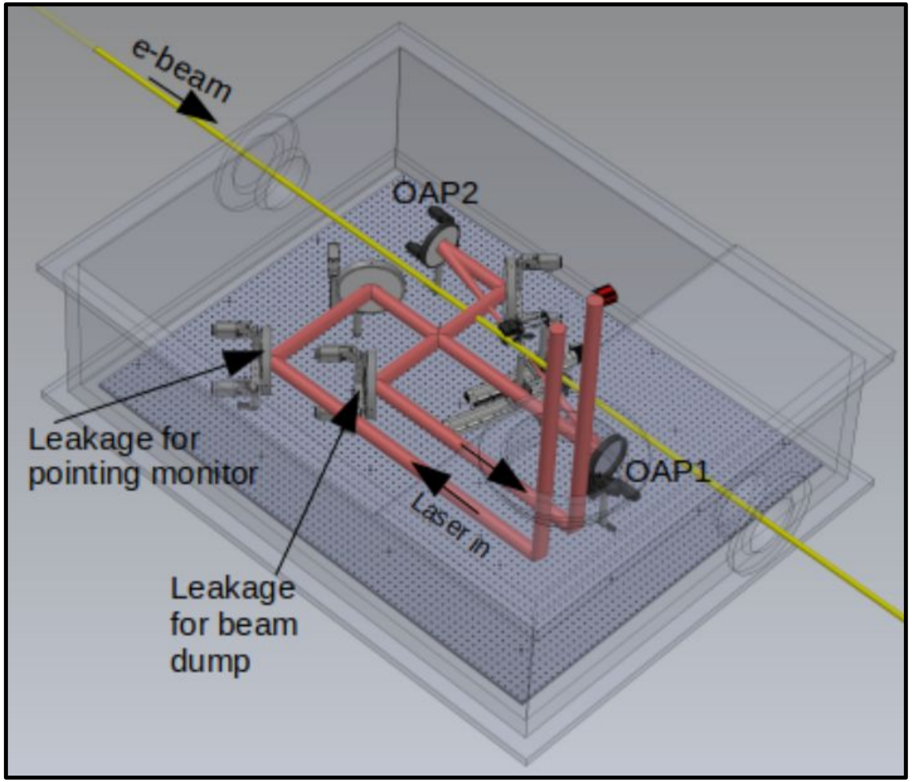
- In operation since 2017
- Linear electron accelerator
  - 1.9 km
  - 17.5 GeV max.
  - 2700 bunches at 10 Hz

- X-Ray photons for 6 instruments
  - Self-amplified spontaneous emission
  - 0.25 keV – 25 KeV



https://www.xfel.eu/

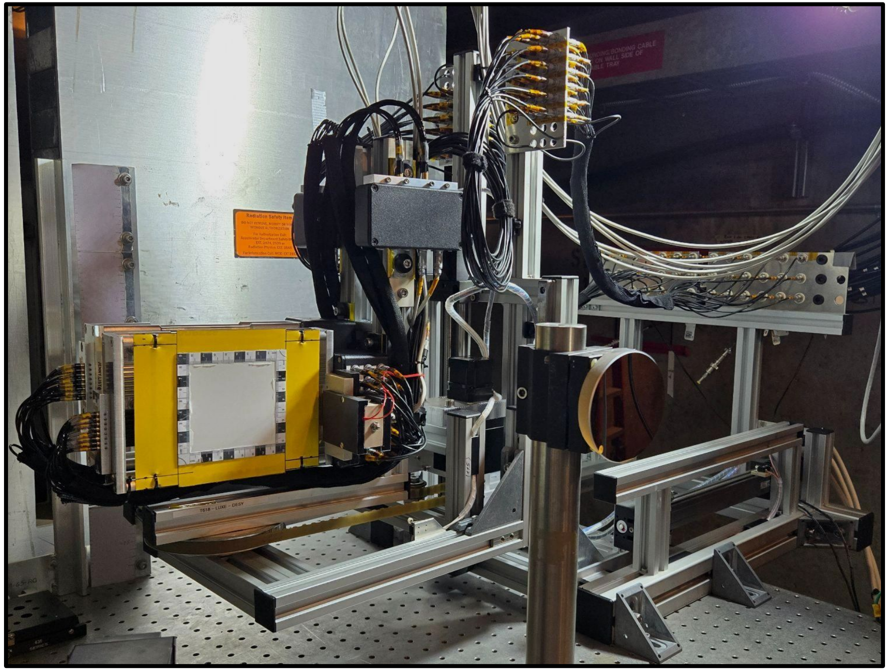
The Ti:Sa Laser at LUXE

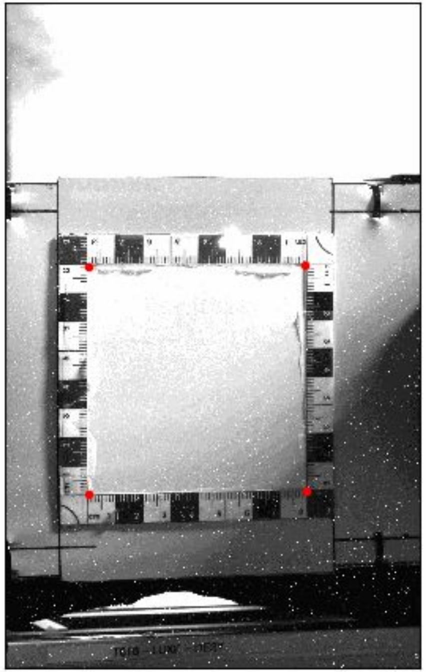


Ti:Sa laser parameters

- 800 nm wavelength
- 17.2° crossing angle at IP
- 40 (350) TW
- 13 – 120 * 10^{19} W/cm²
- ~ 3 µm spot size

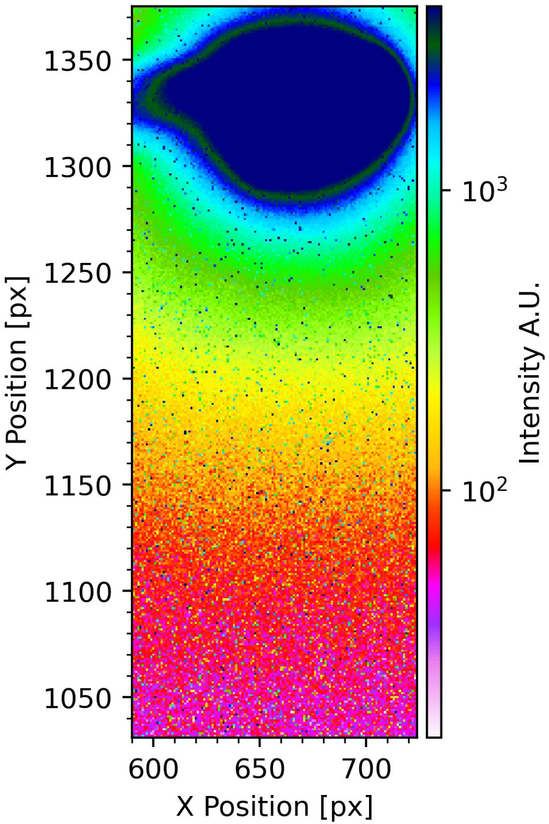
Electron Detection System at E320





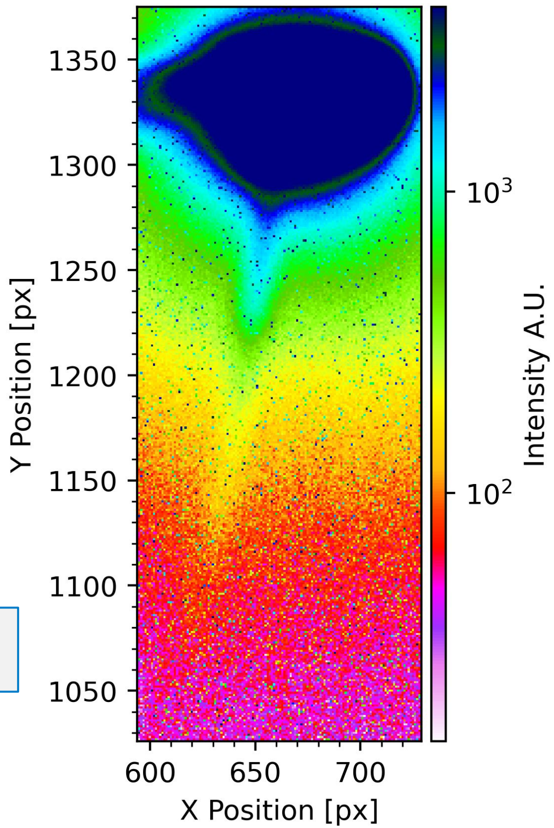
Electron Detection System at E320

Scintillating Screen

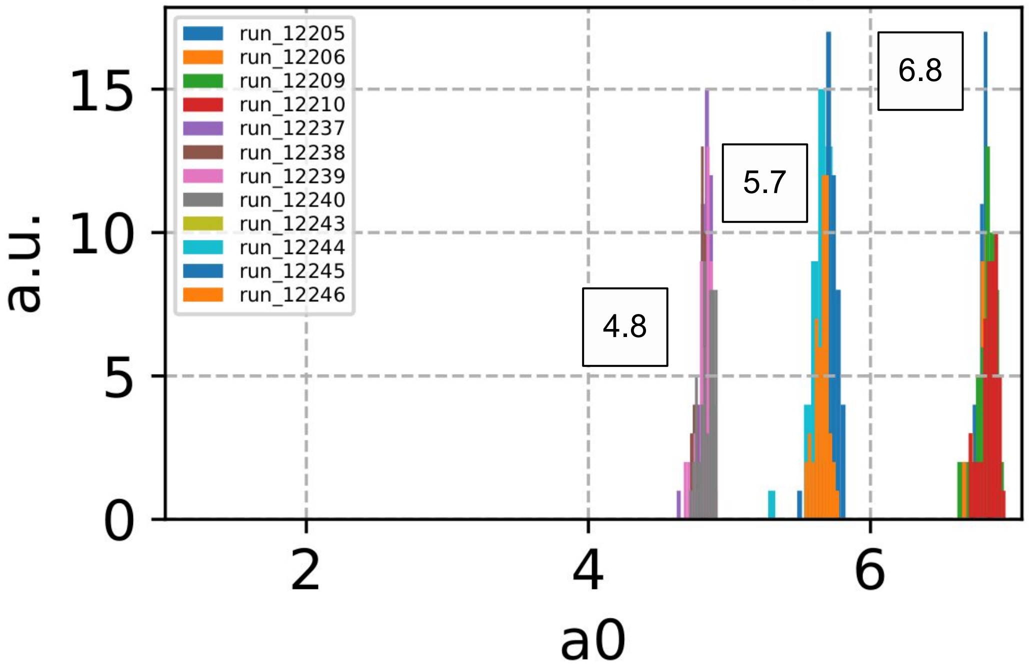


Background

Signal



Calculation Of a_0 Maximum



$$a_0 = 147.839 \cdot \sqrt{0.157\,E} \cdot \frac{\lambda}{w_0 \cdot \sqrt{\tau}}$$

$E \;\hat{=}\;$ Laser energy [J/0.157 (EPICS))]

$\lambda \;\hat{=}\;$ Laser wavelength [μm]

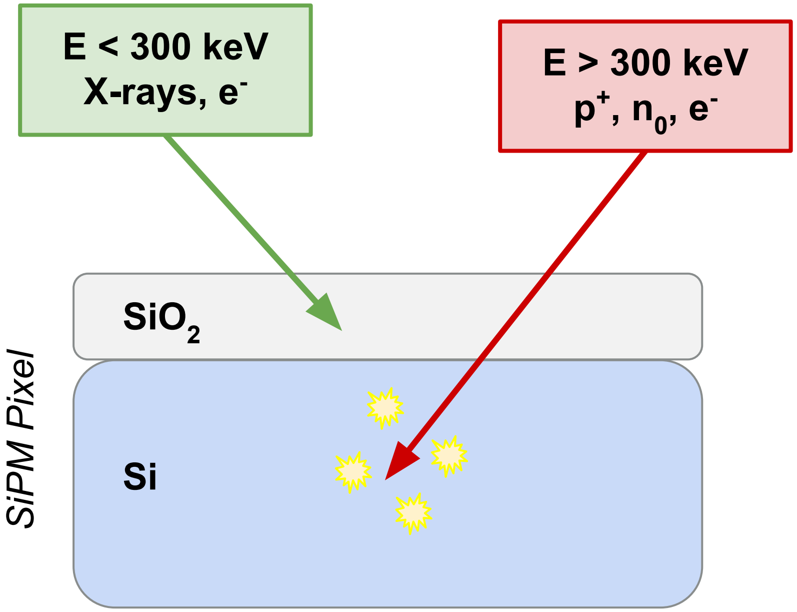
$w_0 \;\hat{=}\;$ Laser waist [μm]

$\tau \;\hat{=}\;$ Laser pulse length [fs (FWHM)]

Estimates

λ = 0.8 µm | w_0 = 2 µm | τ = 42 fs

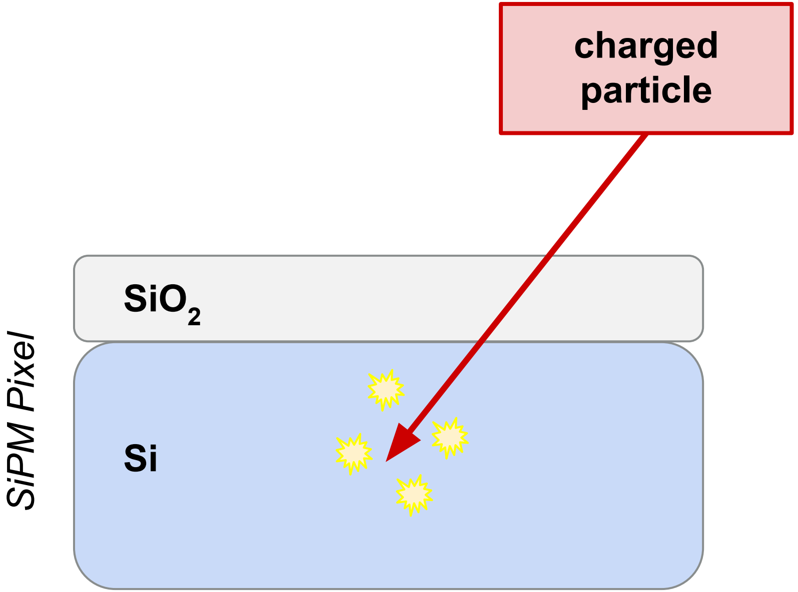
Radiation Effects in SiPMs



Courtesy: E. Garutti

- Surface damage: Charge accumulation in SiO_2
  → Increase in leakage current
- Bulk/Crystal damage: Lattice defects
  → Increase in leakage current
  → Increase in cross-talk

Direct Hits



What it is

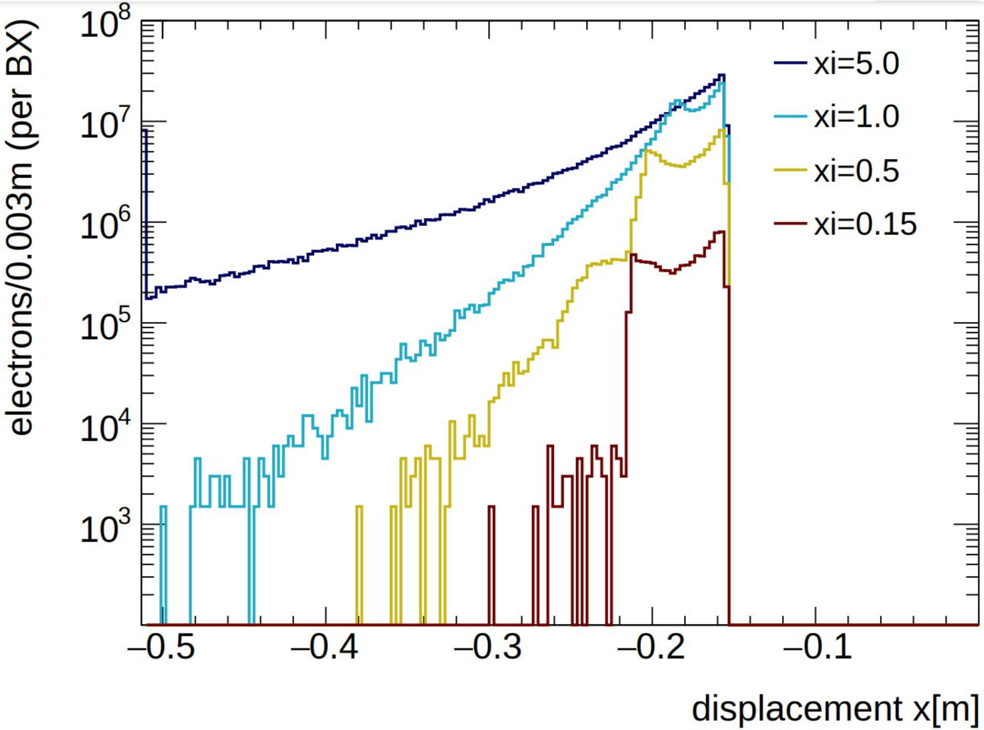
- Charged particles from beam halo, particle dump, beam jitter hit SiPM

How to prevent it

- Background measurements (blocking Cherenkov light)
- SiPMs far away from beam
- Shielding of electronics

Simulated Straw Detector Spectra

LUXE



E320