Study of QED in Strong Field Regime at LUXE Experiment

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Outline

LUXE – **L**aser **U**nd **X**FEL **E**xpriment

- Introduction
- Design of experimental setup at European XFEL
- Observables study in MC simulations
- Summary and plans

Strong Field QFT

- In a presence of strong electromagnetic field, the virtual charges, start to separate.
- In the Schwinger limit, an electric field ($\varepsilon_s = 1.3\times 10^{18}$V/m) does the work equivalent to separating two electron rest masses over a Compton wavelength

$$\frac{h}{mc} e\,\varepsilon \geqslant mc^2 \qquad \varepsilon_s = \frac{m^2 c^3}{h\,e}$$

- Vacuum state becomes unstable and the field is predicted to induce vacuum pair production.

Fields reach the Schwinger limit:

- in e+e- collisions;
- in heavy ion collisions;
- in an astrophysical setting near the surface of a magnetar.

High power laser facilities provide a possibility to study strong field QED in clean lab conditions.

LUXE is intended to use European XFEL e- beam and high power laser to probe strong field QED.

Laser-assisted pair production

$$\gamma + n\omega \to e^+e^-$$

One photon pair production (OPPP) at ultra high intensity - non-perturbative physics

The rate of laser-assisted (OPPP) rate:

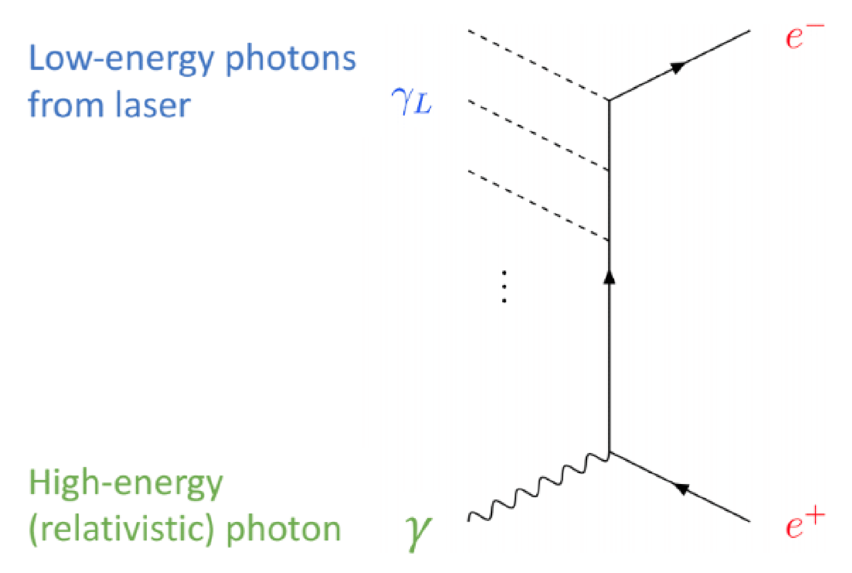
$$\Gamma_{\mathrm{OPPP}} = \frac{\alpha m_e^2}{4\,\omega_{\mathrm{i}}} F_\gamma(\xi, \chi_\gamma)$$

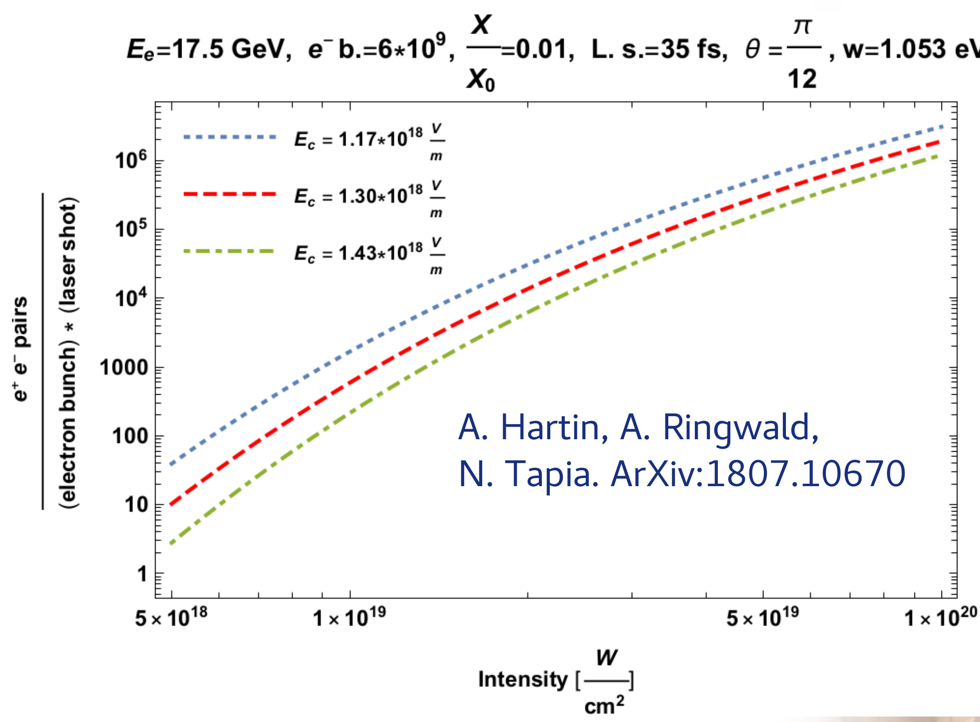
$$\xi \equiv \frac{e\,|\mathbf{E}|}{\omega m_e} = \frac{m_e}{\omega}\frac{|\mathbf{E}|}{\mathrm{E}_c}\,, \quad \chi_\gamma \equiv \frac{k\cdot k_i}{m_e^2}\,\xi = (1+\cos\theta)\,\frac{\omega_i}{m_e}\frac{|\mathbf{E}|}{\mathrm{E}_c}$$

Use bremsstrahlung photons produced by XFEL beam hitting tungsten target.

$$\Gamma_{\mathrm{BPPP}} = \frac{\alpha\, m_e^2}{4}\int_0^{E_e}\frac{\mathrm{d}\omega_i}{\omega_{\mathrm{i}}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}\omega_i} F_\gamma(\xi, \chi_\gamma(\omega_i))$$

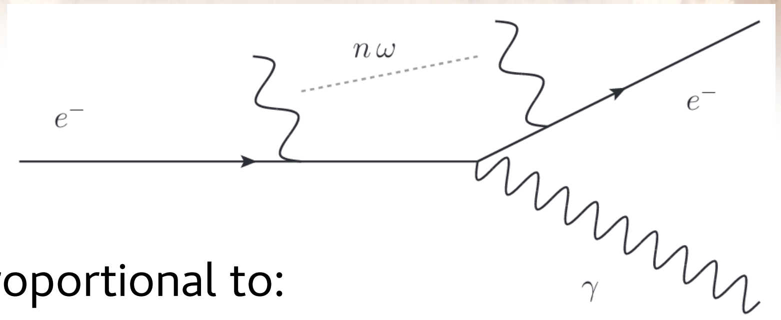
$$\Gamma_{\mathrm{BPPP}} \to \frac{\alpha\, m_e^2}{E_e}\frac{9}{128}\sqrt{\frac{3}{2}}\,\chi_e^2\, e^{-\frac{8}{3\chi_e}\left(1-\frac{1}{15\xi^2}\right)}\frac{X}{X_0}$$





High Intensity Compton Scattering

$$e^- + n\omega \to e^- + \gamma$$



The rate of High Intensity Compton Scattering (HICS) is proportional to:

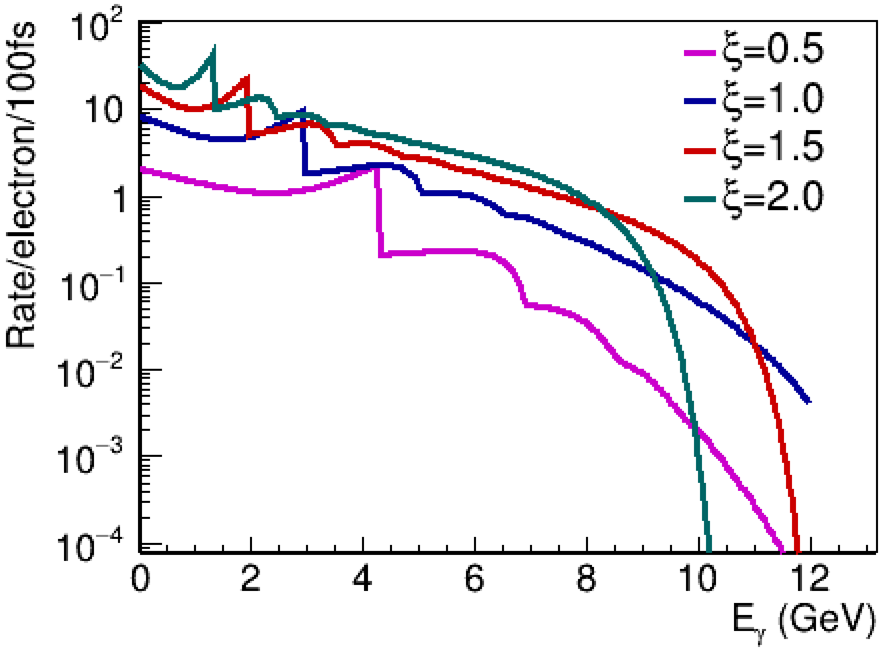
$$\sum_{n} \delta^{(4)}\left[p_i + k\frac{\xi^3}{2\chi_i} + nk - p_f - k\frac{\xi^3}{2\chi_f} - k_f\right]$$

Momentum conservation is a sum over external field photon contributions, *nk*

Even for *n=0* there is an irreducible contribution:

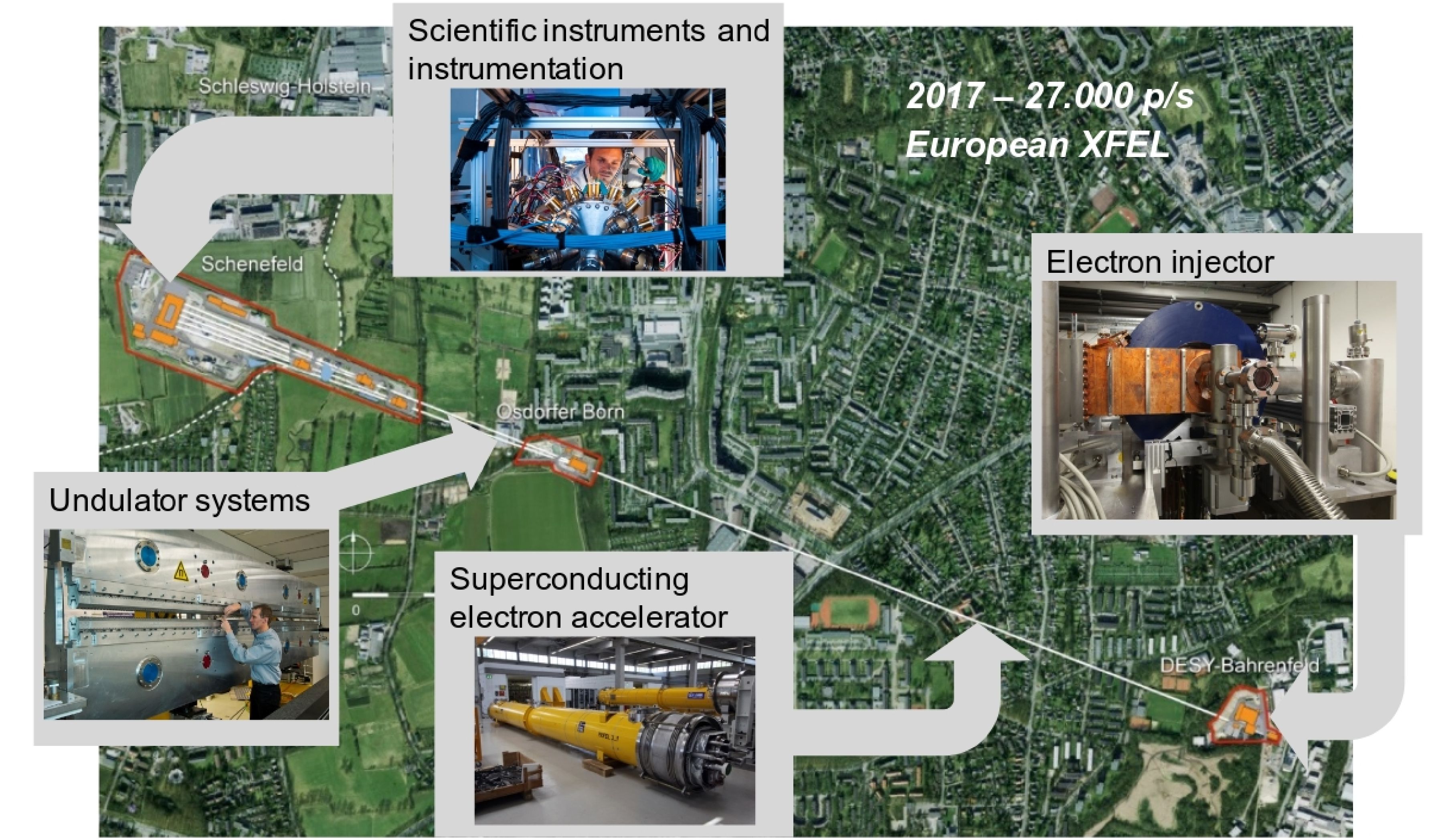
$$p_i + k\frac{\xi^3}{2\chi_i} \to p_i^2 = m^2(1+\xi^2)$$

- Strong field leads to increase in electron rest mass.
- Observation of Compton edge shift.



European XFEL

- The European XFEL is a research facility producing high-energy X-ray light for various studies;
- Under operation since 2017;
- Maximum electron beam energy so far: 17.58 GeV, (prediction based on accelerator module test facility is 19.3 GeV).



Electron and laser beam parameters

European XFEL electron beam:

- Electron beam parameters are defined by European XFEL LINAC;
- Energy 17.5 GeV (also possible 10 GeV and 14 GeV);
- Normalized emittance 1.4 mm mrad;
- Repetition rate 10 Hz.

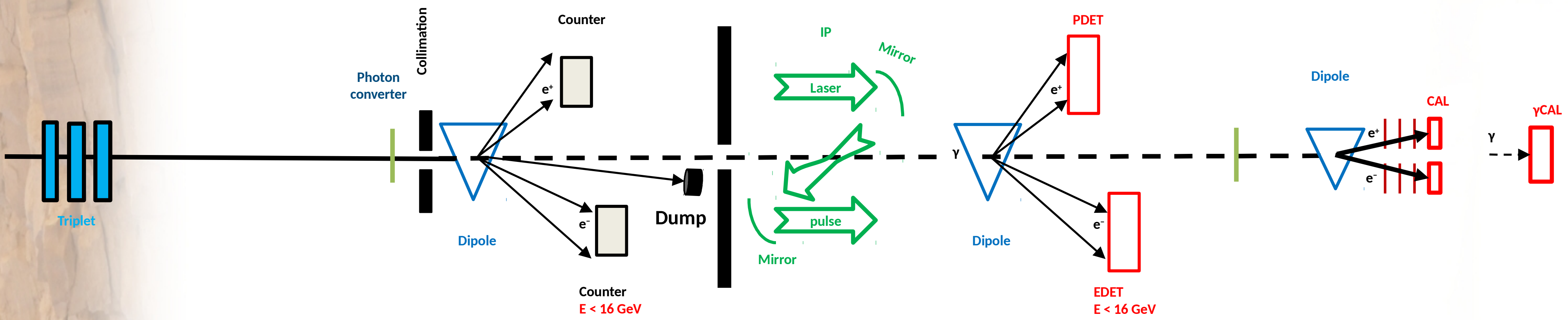
Laser:

- Laser wavelength = 800.00 nm (1.5498 eV);
- Circular polarized;
- Power:
  - Stage 0: 10^{19} W/cm^2, (0.35J, 100 μm^2, 35 fs, ξ = 1.5, χ = 0.3);
  - Stage 1: 2×10^{20} W/cm^2, (7.0J, 100 μm^2, 35 fs, ξ = 6.8, χ = 1.4);

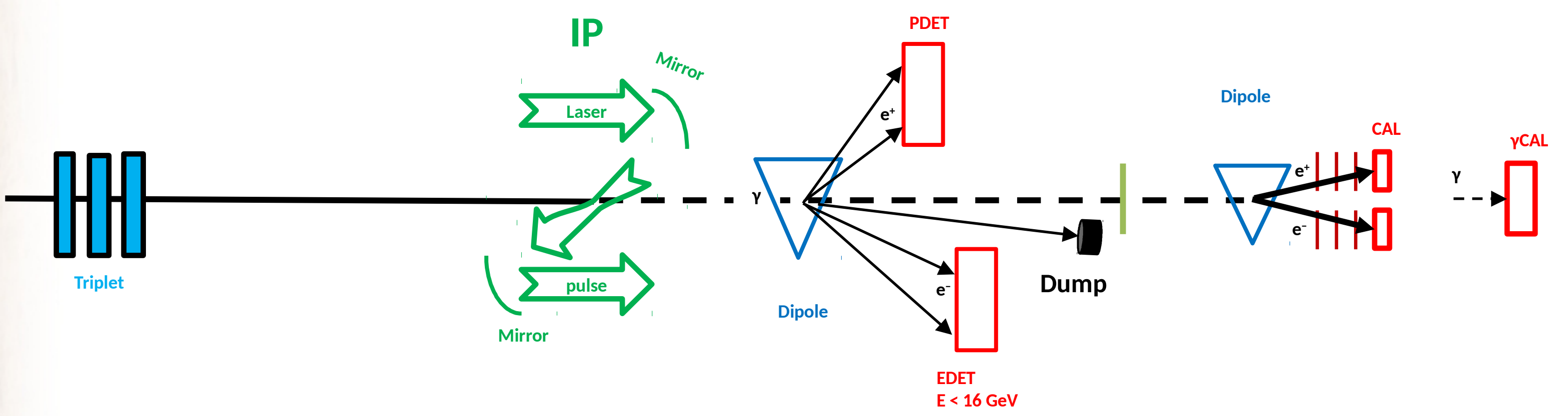
E_pulse, J	Crossing angle, rad	Laser σ_{xy}, μm	Laser σ_z, ps	N Electrons	Electron σ_x, μm	Electron σ_y, μm	Electron σ_z, ps
3.5	0.3	10	0.035	6.25E+09	5.0	5.0	0.08

LUXE Setup

Photon-Photon collisions at LUXE



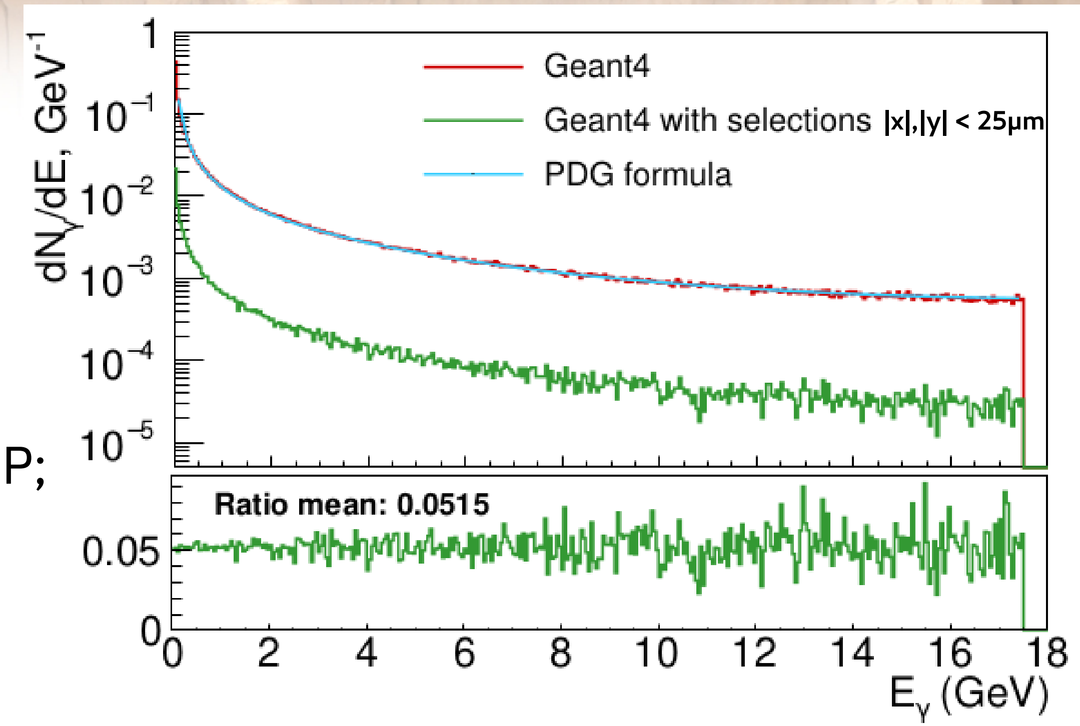
Electron-Photon collisions at LUXE



Bremsstrahlung Production in Simulation

Bremsstrahlung production (complete screening, thin target):

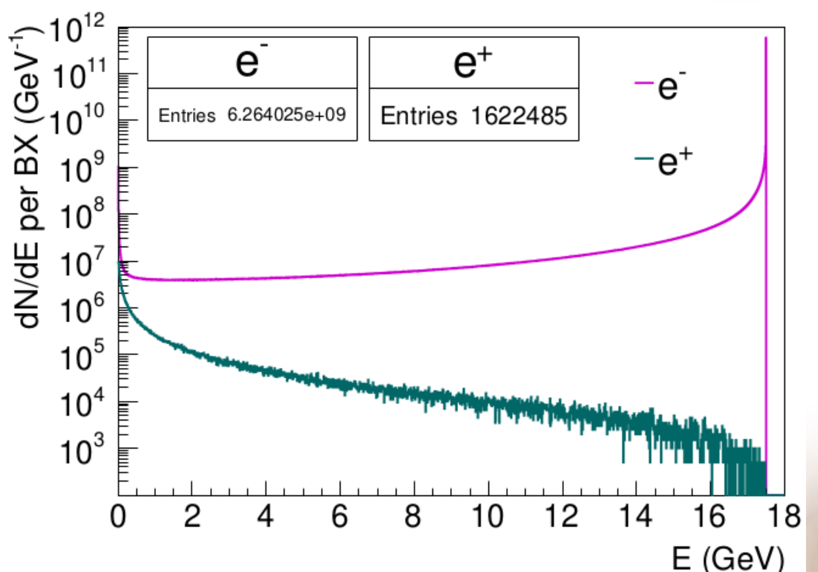
$$\omega_i \frac{dN_\gamma}{d\omega_i} \approx \left[\frac{4}{3} - \frac{4}{3}\left(\frac{\omega_i}{E_e}\right) + \left(\frac{\omega_i}{E_e}\right)^2\right] \frac{X}{X_0}$$



- Gaussian beam;
- Tungsten target 1%X0 (35μm), 2m from IP;
- Two histograms are compared:
  - |x| < 1mm and |y| < 1mm (read);
  - |x| < 25μm and |y| < 25μm (green).

- Electrons and positrons observed in forward area behind the target (θ<17°) for one BX.

N e-	6.26E+09
N e-, < 16 GeV	1.80E+08
N e+	1.62E+06



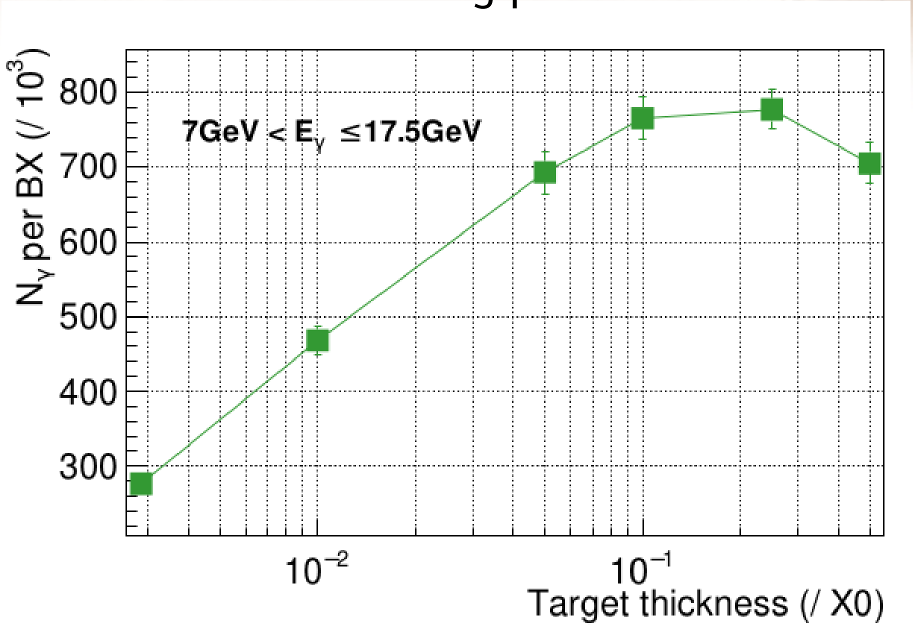
- Can be measured to monitor number of photons.

Target Thickness and Angular Distribution

- Gaussian beam;
- Tungsten target 5m from IP;
- Photons selection :
  - |x| < 25 μm and |y| < 25 μm;
  - E > 7 GeV.

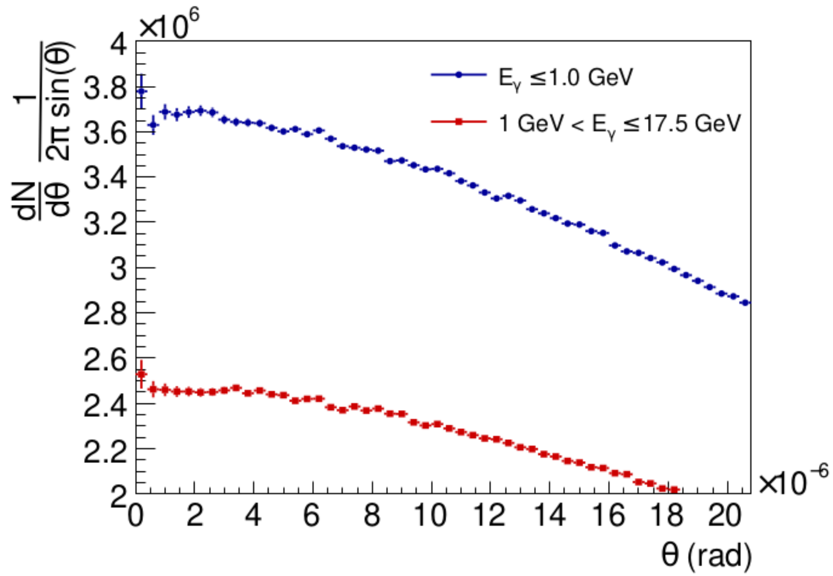
Nγ	4.91E+06
Nγ, E >7GeV	4.66E+05

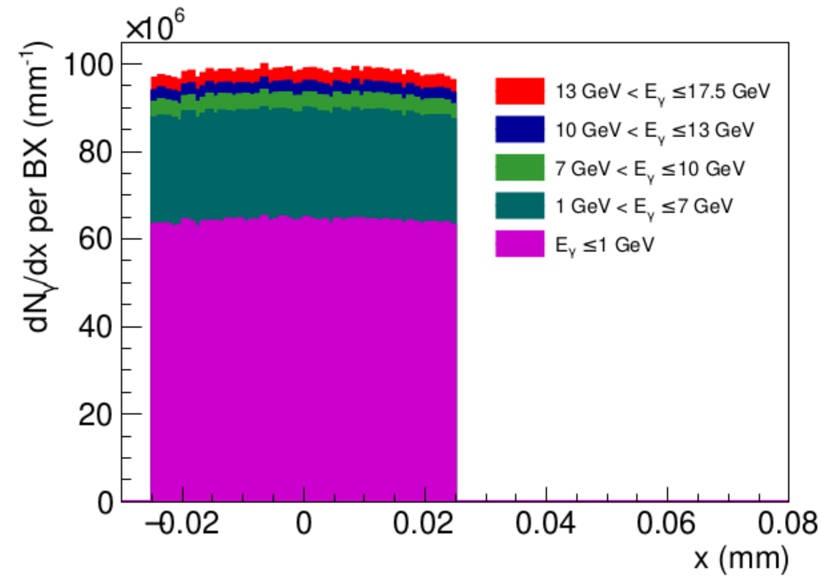
Number of bremsstrahlung photons in LUXE IP



For a distance *R* between target and IP:

$$N_\gamma(R) = \frac{R_0^2}{R^2} N_\gamma(R_0)$$

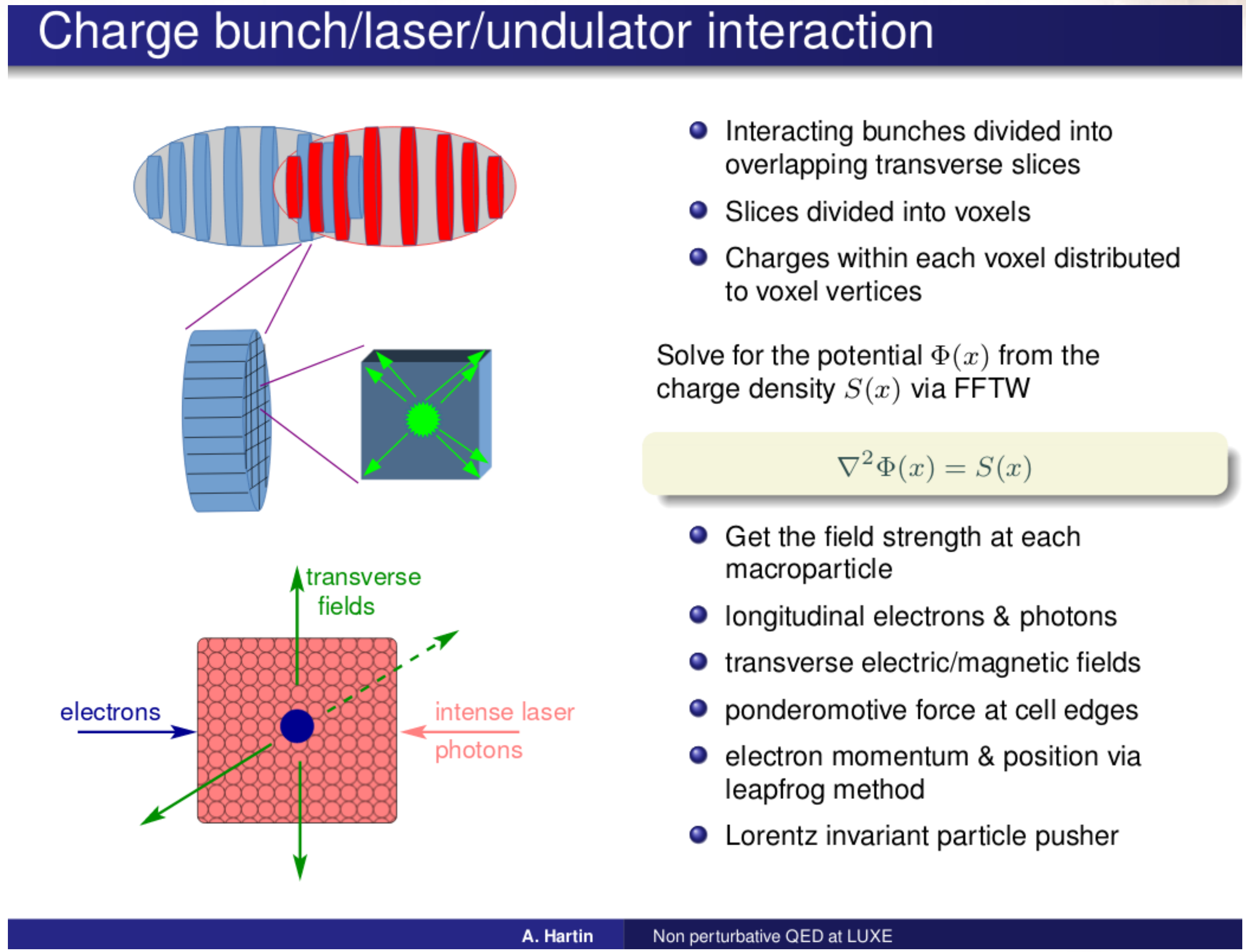




Angular and spacial distribution of bremsstrahlung photons at LUXE IP

MC Simulation

- Full SQED calculations in a pulse can be challenging, so approximations are attractive
- Locally constant field approx (LCFA) assumes ξ>>1. Not appropriate for LUXE.
- Laser pulse contains approximately 12 wavelengthes, it makes infinite plane wave (IPW) approximation suitable for LUXE and well understood Volkov solutions can be employed.
- The local intensity of the laser pulse along with the 4-momenta of initial states are used in a Monte-Carlo of the SQED transition rate.

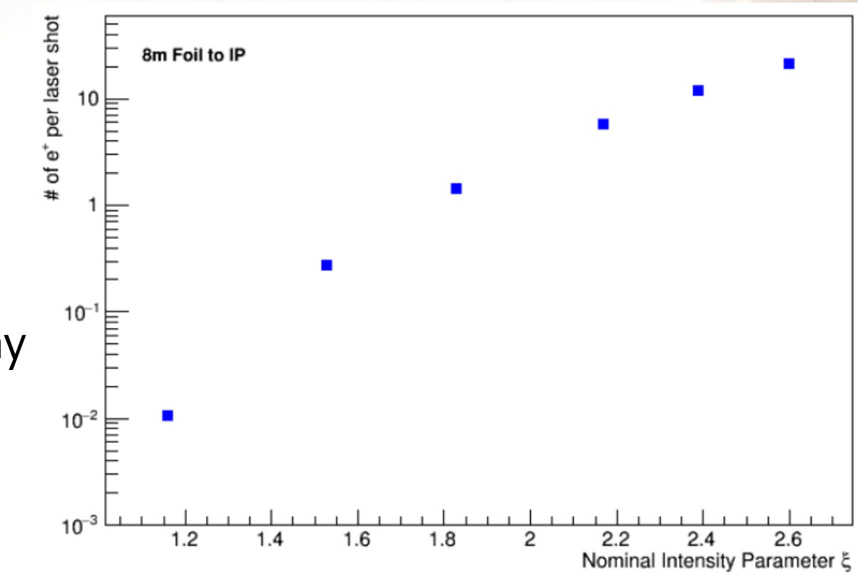


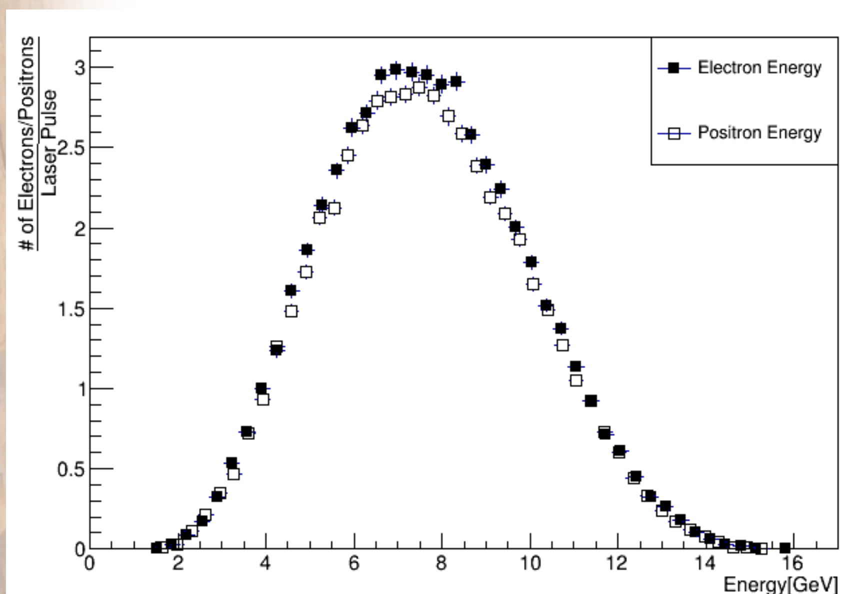
A. Hartin IJMPA 33, no. 13, 1830011 (2018), arXiv:1804.02934

One Photon Pair Production in MC

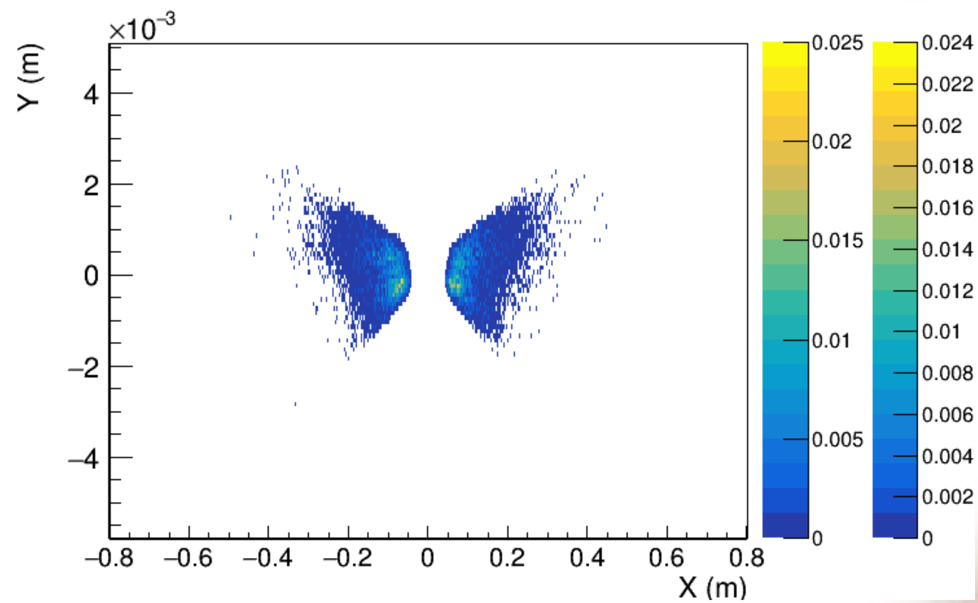
- The rate is up to ~100 e-e+ pairs per one bunch-laser interaction;
- The energy spectra peak at 7 GeV;
- Spectrometer:
  - 1.4T magnet of 1m length;
  - Pixel detector (100 x 100 μm^2 pixel) located 1m away from the magnet;
  - Detection efficiency ~99%.
- **Background and energy resolution to be studied !**

OPPP rate





OPPP e-, e+ spectra



Average occupancy of spectrometer detectors

Photon-Photon collisions at LUXE

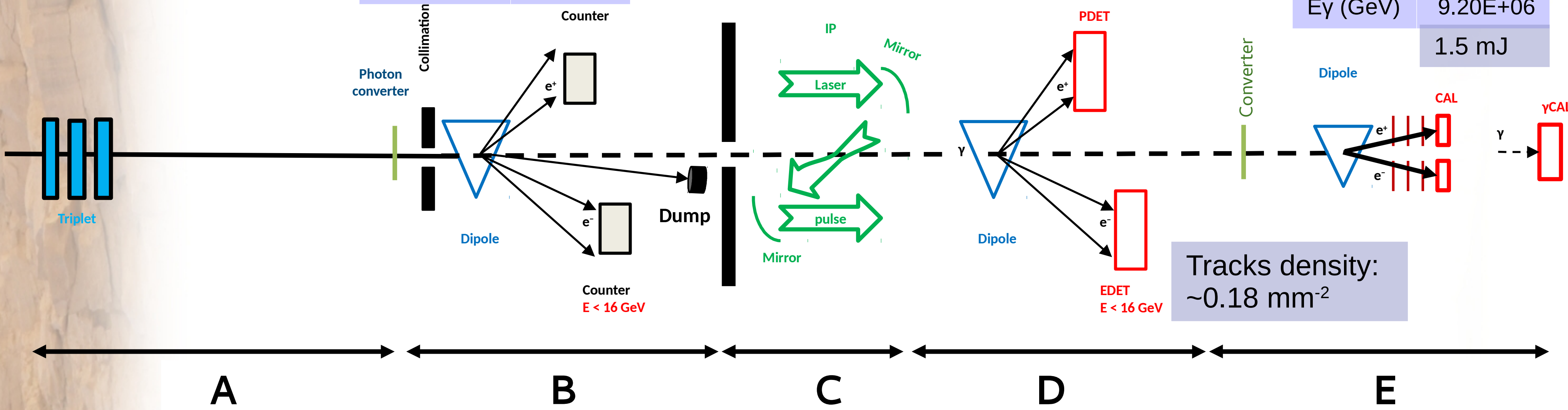
e-	6.25E+09

e-	6.26E+09
e-, < 16 GeV	1.80E+08
e+	1.62E+06
γ	5.60E+08

γ	4.91E+06
γ, E >7GeV	4.66E+05

	Stage 0	Stage 0.5
e-	1.32	24.5
e+	1.32	24.5

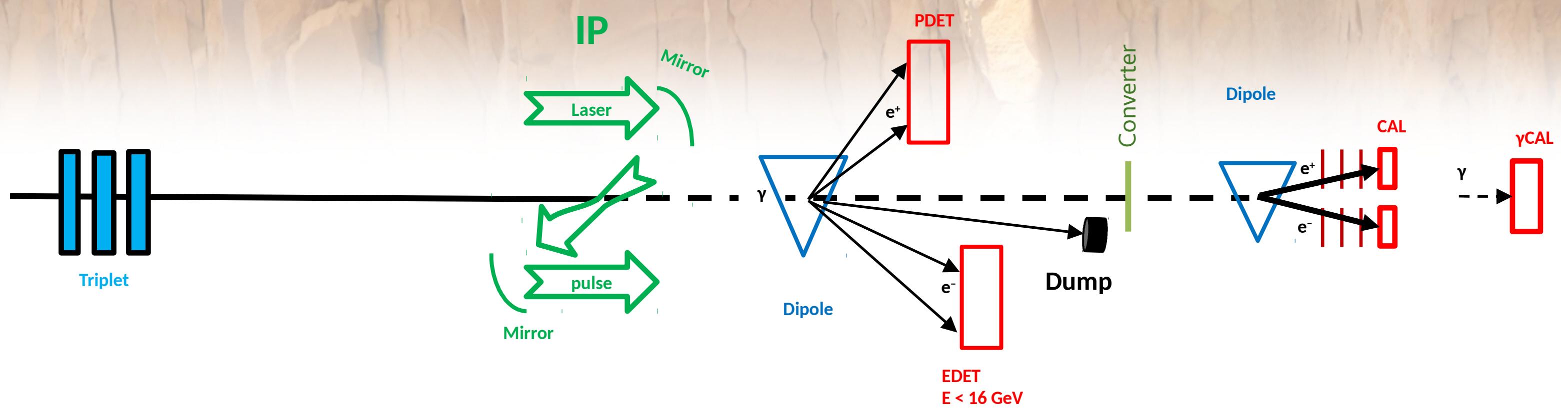
γ	4.80E+06
Eγ (GeV)	9.20E+06
	1.5 mJ



Tracks density:
~0.18 mm^{-2}

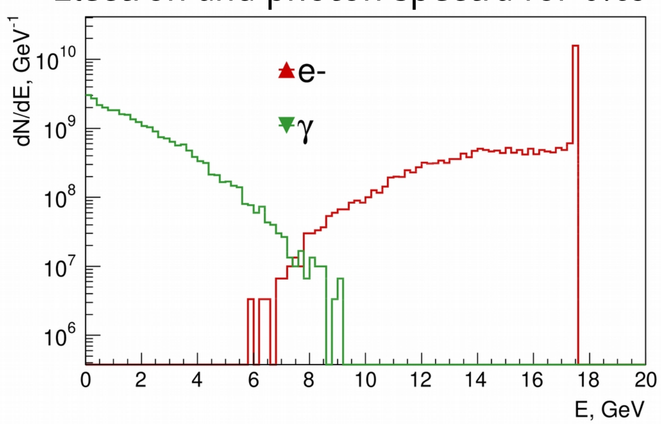
- Bremsstrahlung production monitor (section B): Cherenkov counters and calorimeters;
- OPPP measurements (section D): spectrometer (dipole + few layers of tracking detectors) and calorimeters;
- Forward detector (section E): low X0 target, spectrometer (dipole + few layers of tracking detectors), Cherenkov counters and calorimeters;
- γCAL: calorimeter capable of handling high photon flux.

Electron-Photon collisions at LUXE



MC simulation with 6×10^9 electrons per bunch;

Electron and photon spectra for 0.6J laser

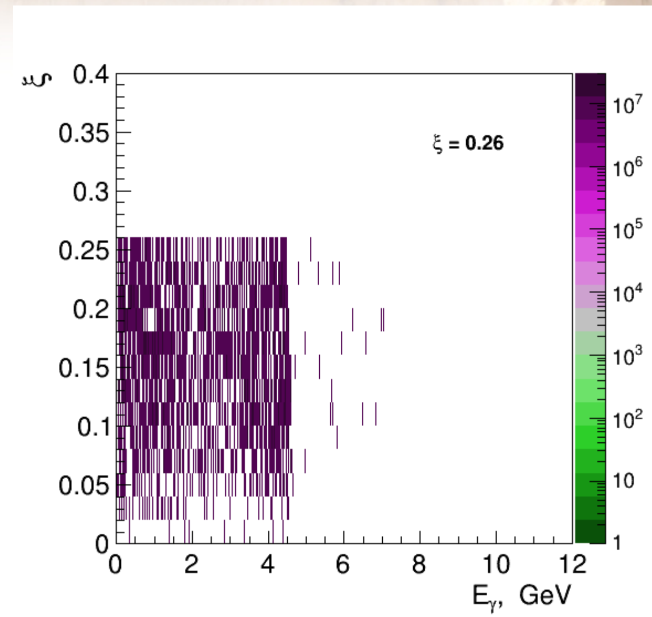


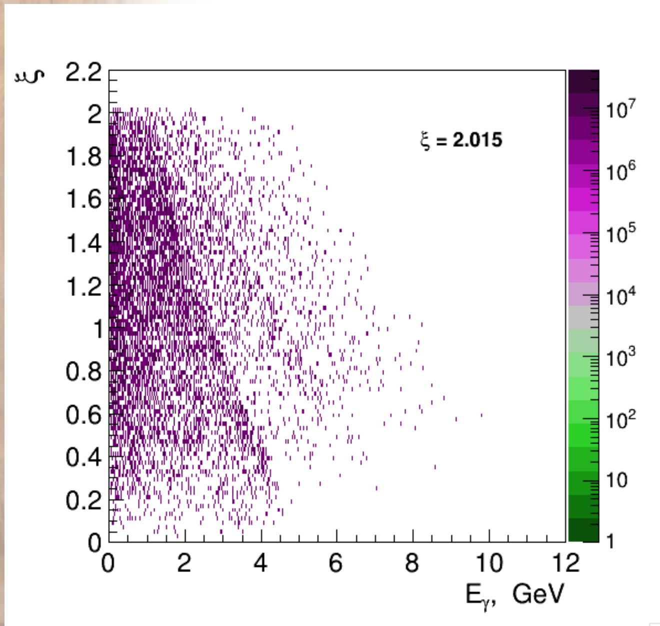
Laser Power, J	Number of e- E < 16.GeV	Number of γ
0.6	2.18E+09	5.74E+09
0.2	1.16E+09	2.31E+09
0.1	6.82E+08	1.24E+09
0.01	8.47E+07	1.35E+08

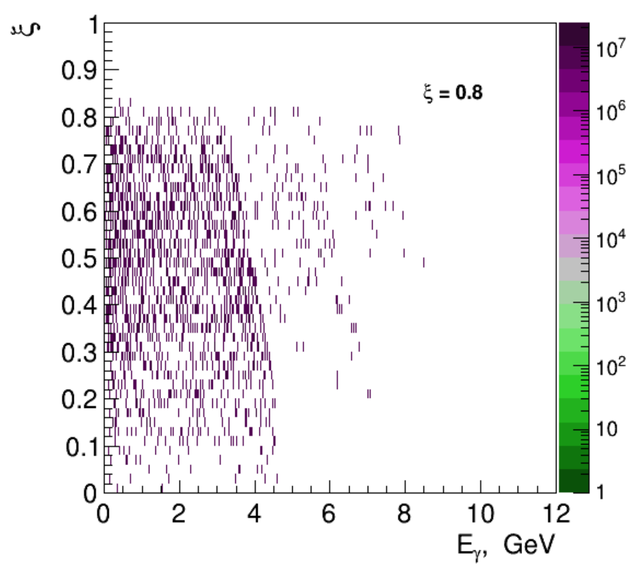
- Electron detection: dipole with Cherenkov counters;
- Trident positron detection (~0.1 per BX at 0.6J observed): spectrometer (dipole + few layers of tracking detectors) and calorimiter.
- Forward detector: low X0 target, spectrometer (dipole + few layers of tracking detectors), Cherenkov counters and calorimiters;
- γCAL: calorimeter capable of handling high photon flux.

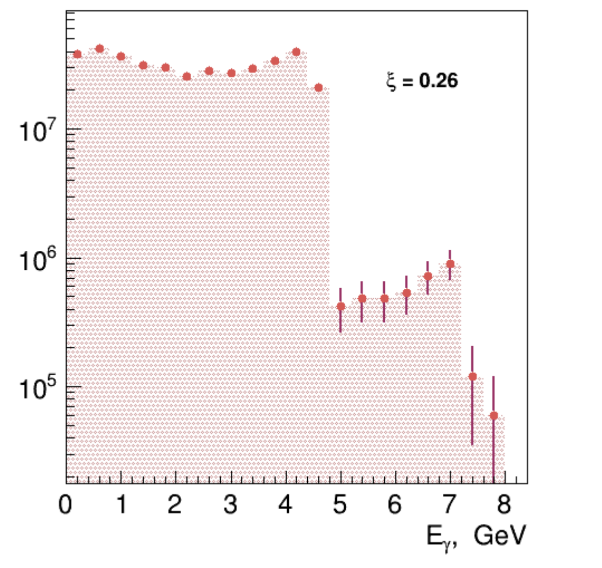
Observation of Kinematic Edges

- Kinematic edges are smeared because of the intensity distribution in the laser pulse;
- The effect is stronger for higher intensities;
- For low intensities the edges are well pronounced and measurable;
- For ξ=0.26 the edge is at 4.6 GeV while Compton edge would be at 5.3 GeV;
- 3D distributions of MC shows the spectra at instant intensity.





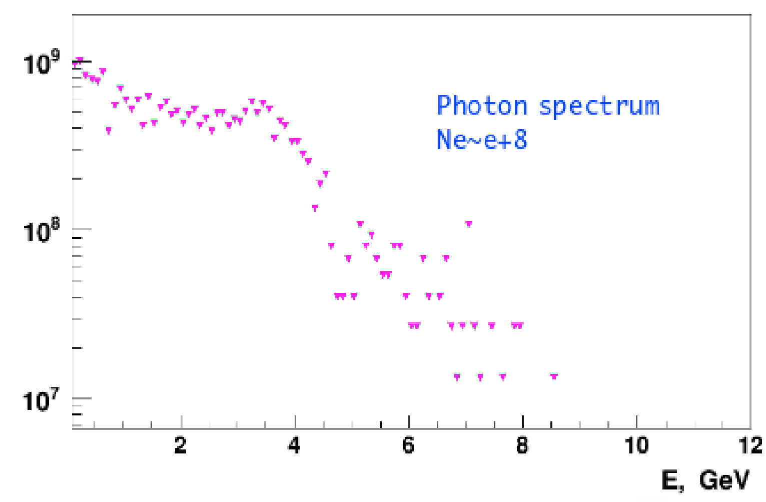


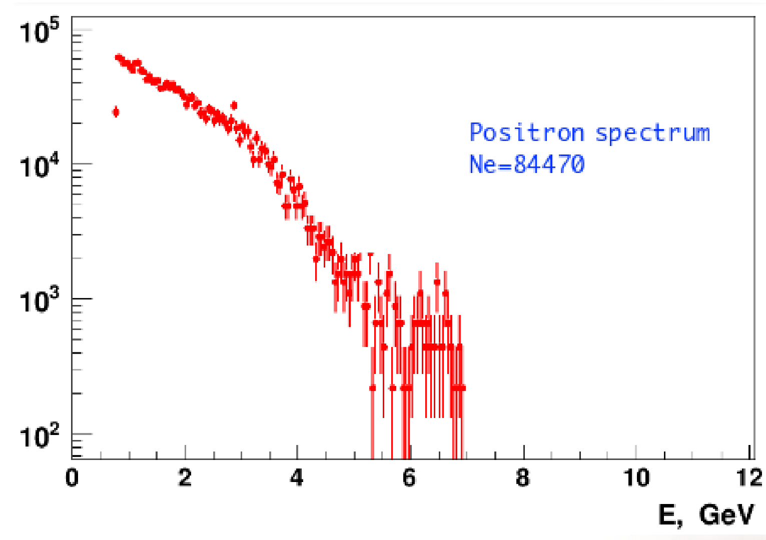


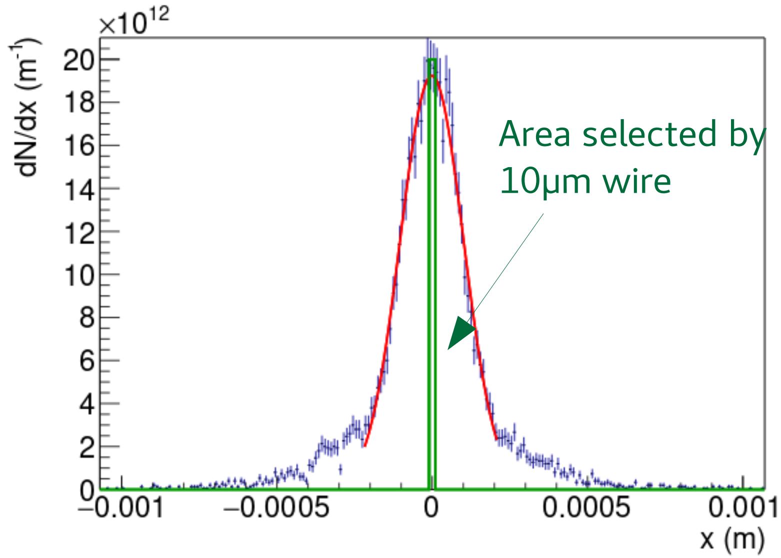
Active Wire Target for Forward Photon Detector

- Wire target of few microns thickness has~(10^{-3} – 10^{-4}) X0;
- Technology is available and was used in the past;
- It selects small (~10^{-3} – 10^{-4}) fraction of the photon flux because of its angular distribution;
- Produced number of pairs would be in the range (~10^{-2} – 10^{-3}) It is manageable number for the spectrometer with pixel detectors.
- Secondary electron emission (SSE) from the wire can be measured providing additional information about the photon flux.

Simulation with 10μm tungsten wire







Projected 1D photon distribution 10m from IP.

Summary

- LUXE at DESY proposes to extend scientific scope of European XFEL to probe fundamental physics in new regime of strong fields.
- Experimental study of laser assisted pair production and high intensity Compton scattering is feasible with European XFEL beam.
- Conceptual design study of LUXE experimental setup shows that the detector subsystems can be built using existing technologies for magnets, pixel tracking detectors, Cherenkov counters.
- Ongoing work on detailed background simulation and reconstruction algorithms development.
- Though the required lasers are available from the industry the technique and tools for their accurate power monitor need to be developed.