LumiCal for LUXE

Oleksandr Borysov

FCAL Workshop
CERN, March 27, 2019

Outline

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

- Introduction
- Design of experimental setup at EU.XFEL
- Possible FCAL detectors application at LUXE

Strong field QFT

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

$$\frac{h}{mc} e \varepsilon \geqslant mc^2$$

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

Fields reach the Schwinger limit:

- in relativistic heavy ion collisions;
- in an astrophysical setting near the surface of a magnetar;
- in strong gravitational field near a black hole.

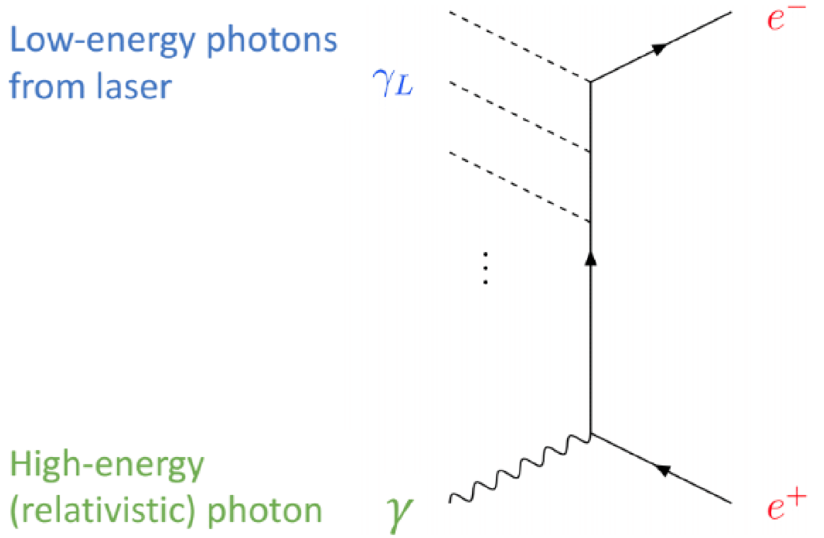
High power laser facilities provide a possibility to study strong field QED in clean lab conditions.

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

Laser-assisted pair production

$$\gamma + n\omega \rightarrow e^{+}e^{-}$$

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



The rate of laser-assisted (OPPP) rate:

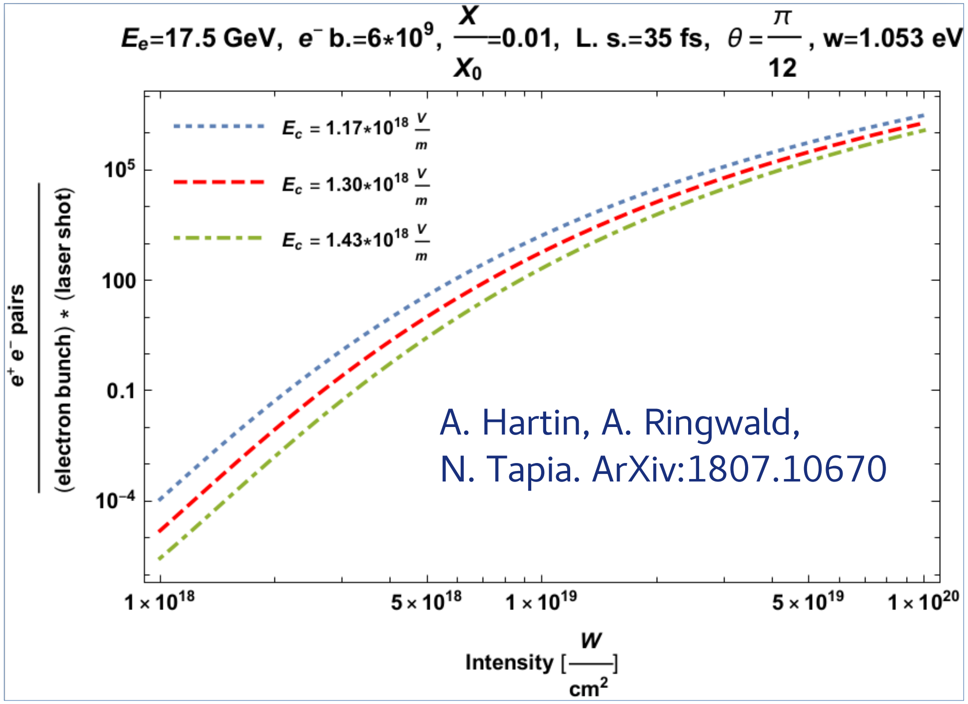
$$\Gamma_{\rm OPPP} = \frac{\alpha m_e^2}{4\,\omega_{\rm i}}\, F_\gamma(\xi, \chi_\gamma)$$

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

Use bremsstrahlung photons produced by XFEL beam hitting tungsten target.

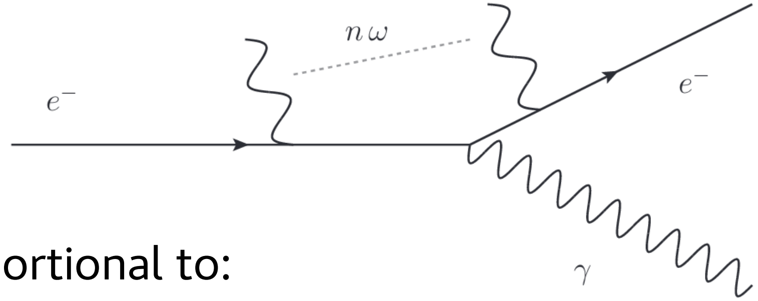
$$\Gamma_{\rm BPPP} = \frac{\alpha\, m_e^2}{4}\int_0^{E_e} \frac{\mathrm{d}\omega_i}{\omega_{\rm i}}\,\frac{\mathrm{d}N_\gamma}{\mathrm{d}\omega_i}\, F_\gamma(\xi, \chi_\gamma(\omega_i))$$

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



High Intensity Compton Scattering

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



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

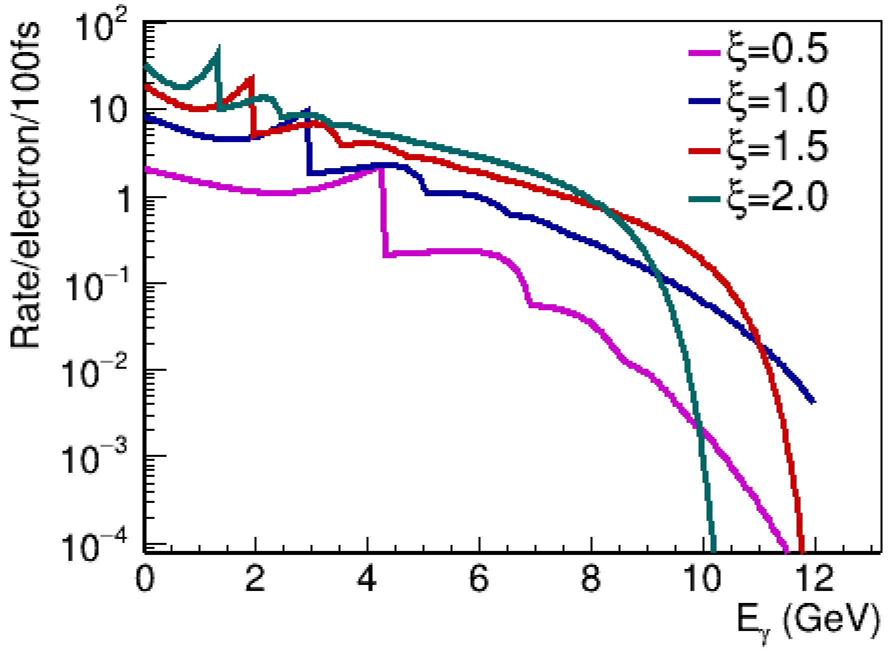
$$\sum_{\mathsf{n}} \delta^{(4)}\left[p_{\mathsf{i}} + k\frac{\xi^3}{2\chi_{\mathsf{i}}} + nk - p_{\mathsf{f}} - k\frac{\xi^3}{2\chi_{\mathsf{f}}} - k_{\mathsf{f}}\right]$$

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

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

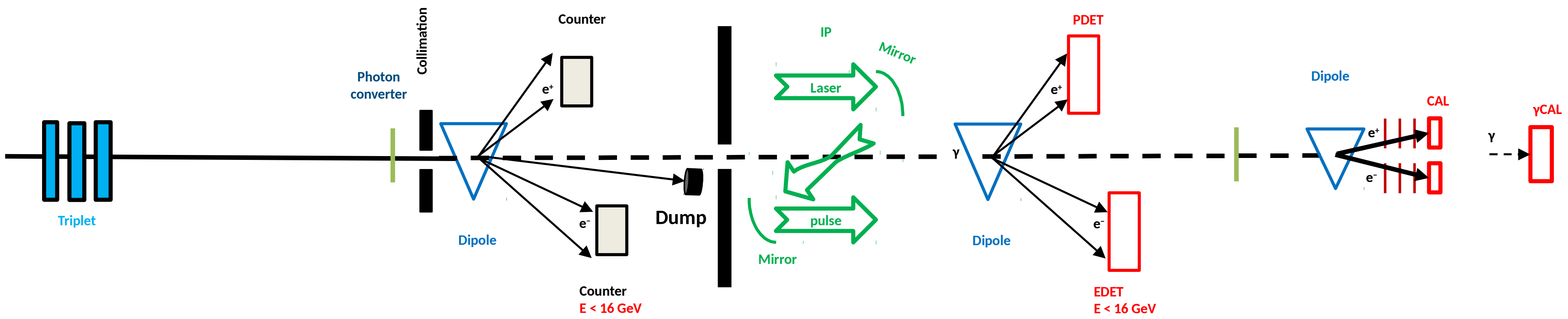
$$p_{\mathsf{i}} + k\frac{\xi^3}{2\chi_{\mathsf{i}}} \rightarrow p_{\mathsf{i}}^2 = m^2(1+\xi^2)$$

Observation of Compton edge shift

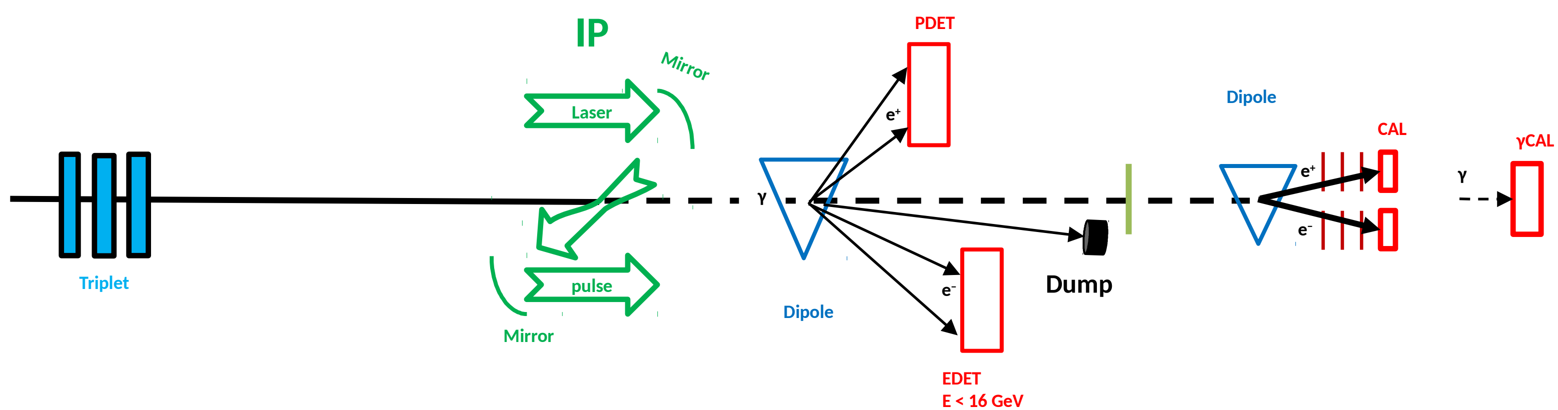


LUXE Setup

Photon-Photon collisions at LUXE



Electron-Photon collisions at LUXE



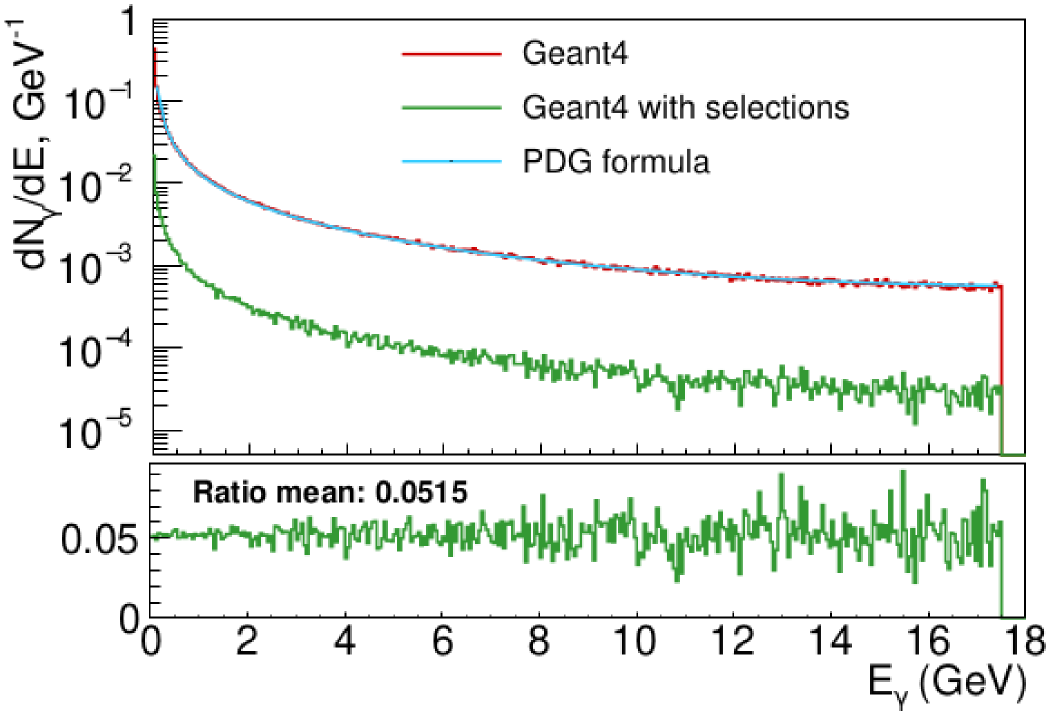
9 m 3 m 7 m

Bremsstrahlung production: Geant4 vs PDG formula

PDG recommended formula for thin targets for bremsstrahlung production:

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

It is used to calculate integral on slide 4 to get the pair production rate.



- The formula does not take into account angular distribution of bremsstrahlung photons
- Geant4 simulation:
  - account for laser beam transverse size
  - and thick targets to optimize the photon flux.

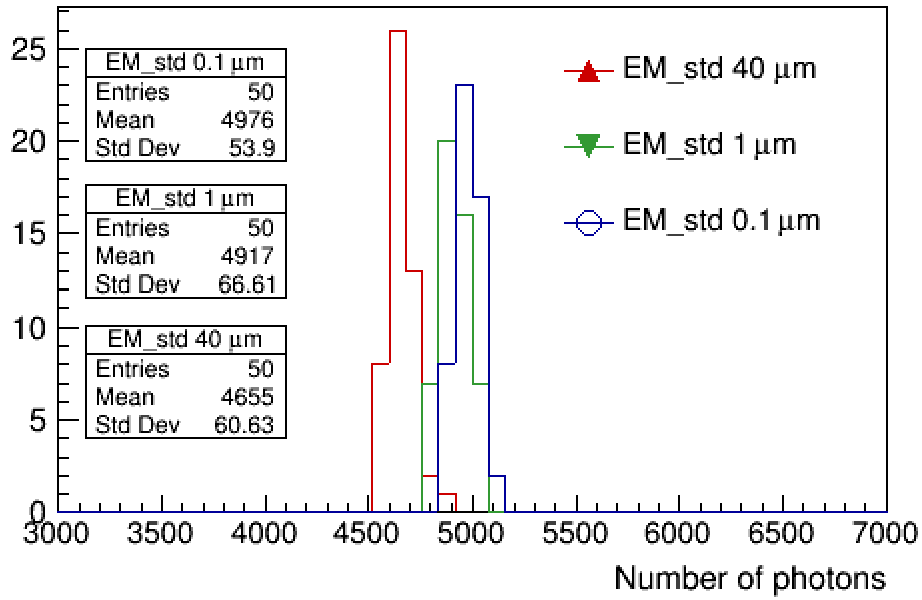
- Gaussian beam;
- Tungsten target 1%X0 (35um), 2m from IP;
- 10M electrons
- Two histograms are compared:
  - |x| < 1mm and |y| < 1mm;
  - |x| < 25um and |y| < 25um.

Geant4 simulation with different step, different physics lists, different beam

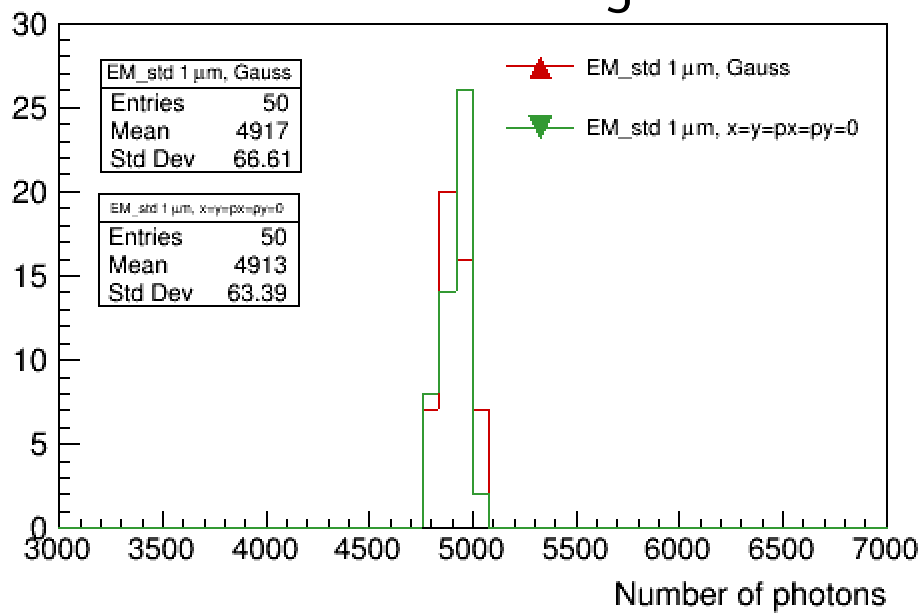
- Gaussian beam, focused on IP;
- Tungsten target 1%X0 (35um) thickness
- 5 m from IP;
- 6.25 M electrons (BX/1000);
- Production cut: 1 µm.

Number of photons inside
|x|<25um and
|y|<25um;

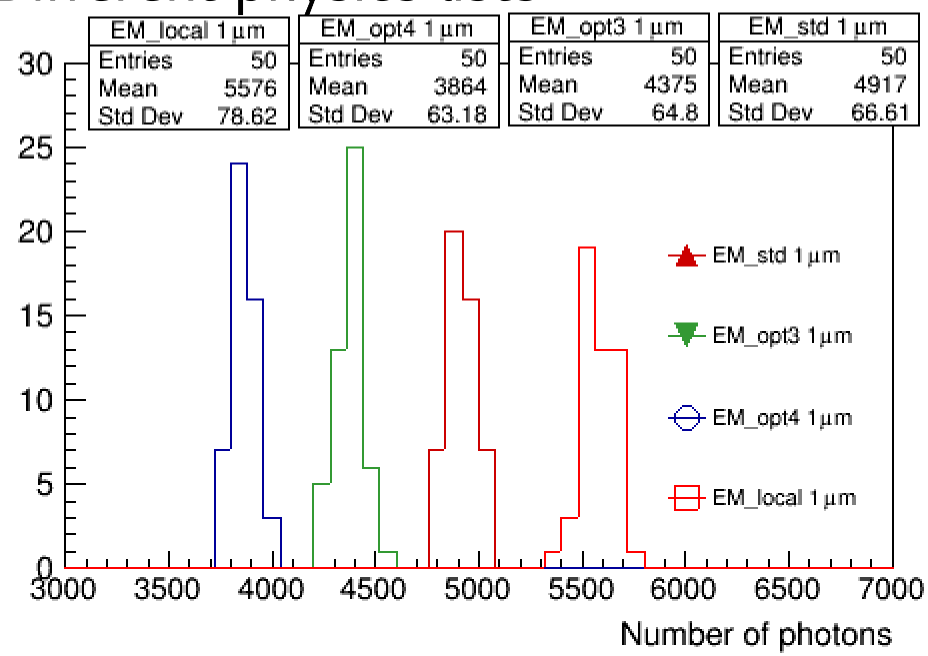
Different step



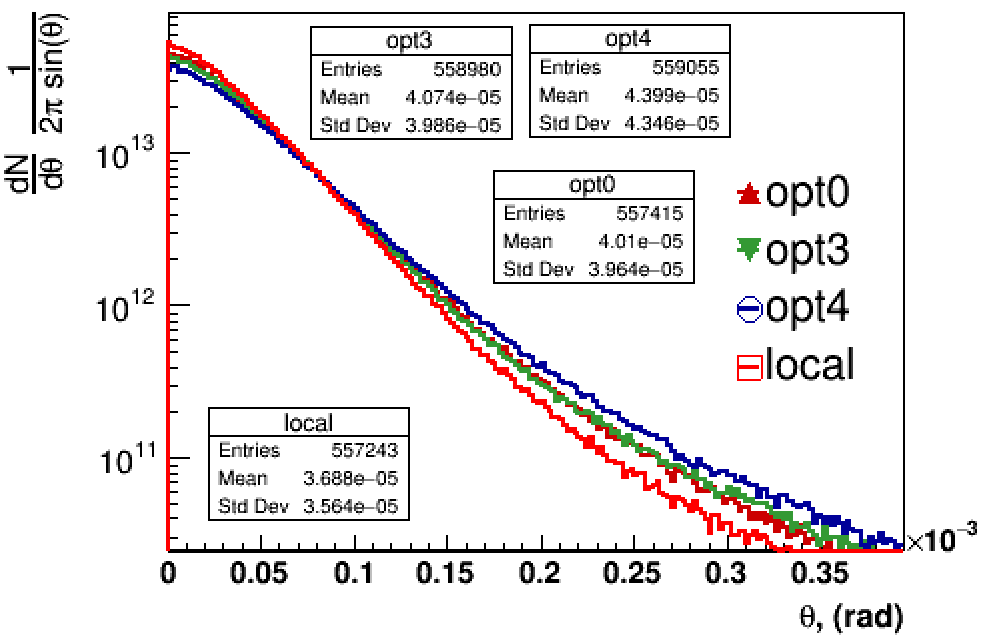
Different beam settings

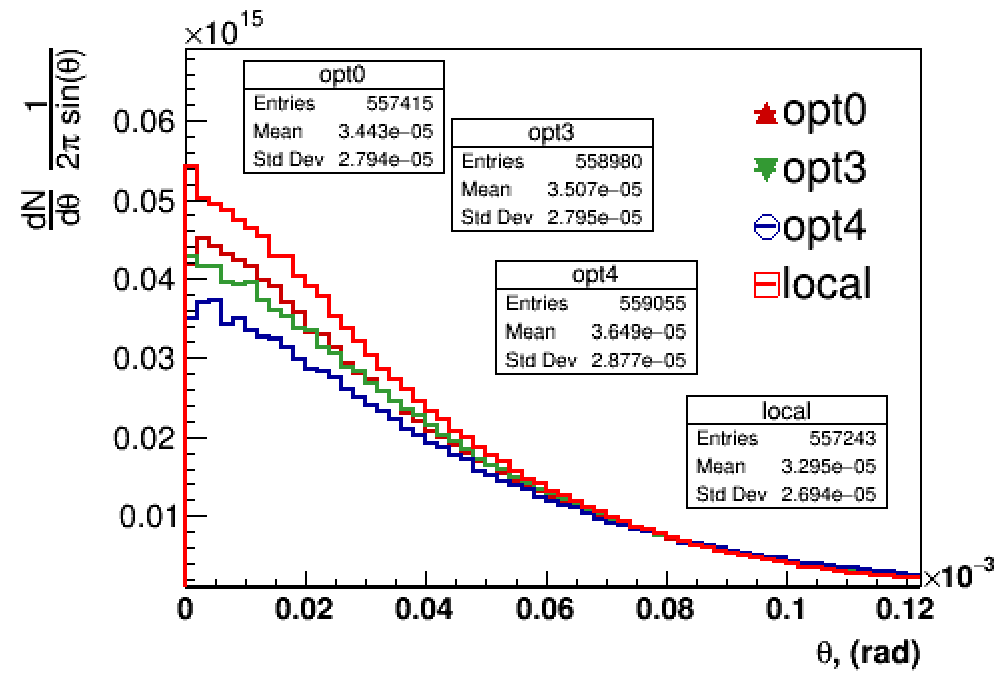


Different physics lists

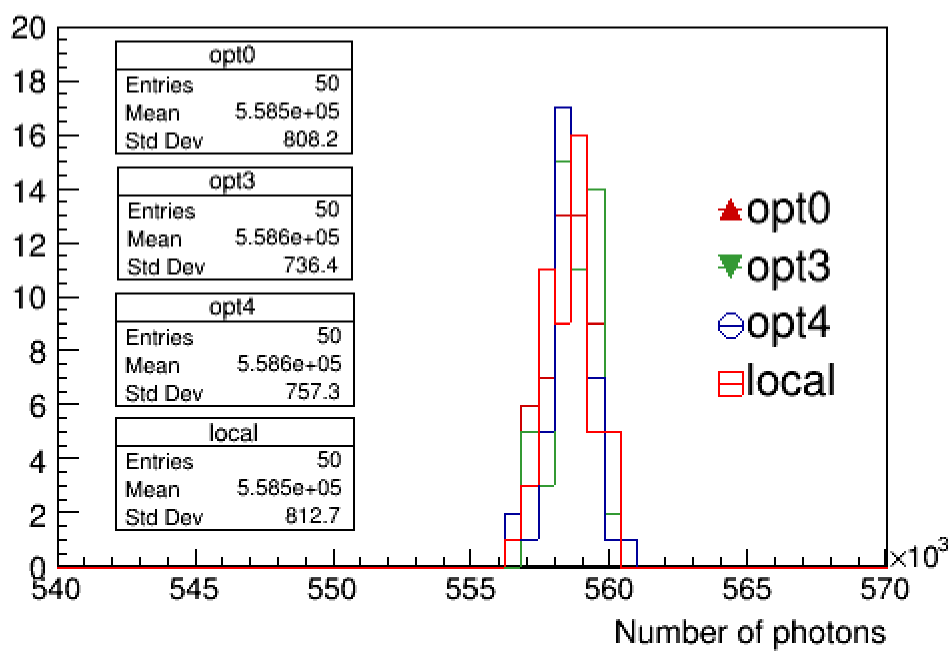


γ angular distribution for different physics lists





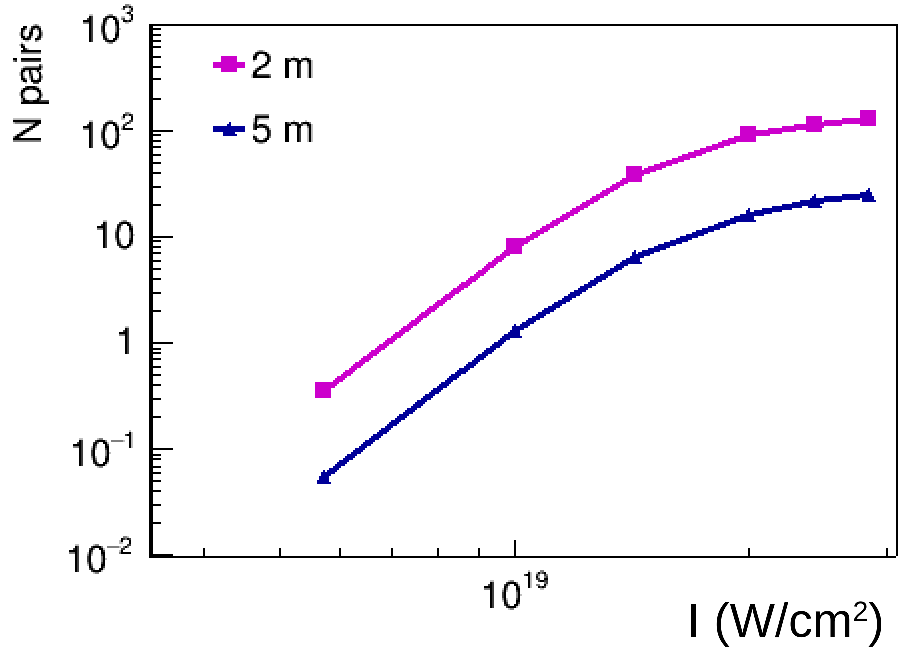
- Angular distribution is the widest for option_4 physics list.
- The difference in angular distribution explains the observed difference in the number of photons at IP.
- Total number of photons in forward region is identical for all physics lists.



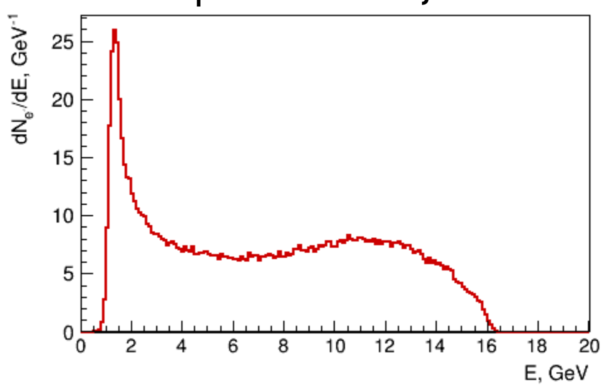
Number of photons inside
|x|<1.5 m and
|y|<1.5 m

One photon pair production in MC study

- Tungsten target 35 μm (1%X0) for bremsstrahlung production;
- Target is 5 m and 2 m upstream of IP;
- By changing a target thickness (to some extent) for a given distance between target and IP the photon flux and pairs production rate can be set at reasonable level.



e- spectrum at ξ=2.4



ξ	I (W/cm2)	N pairs 2m	N pairs 5m	N2/N5
1.16	5.71E+018	0.356	0.0557408	6.39
1.54	1E+019	7.89241	1.31872	5.98
1.84	1.429E+019	37.7175	6.52168	5.78
2.18	2E+019	89.0315	16.3754	5.44
2.4	2.429E+019	114.31	21.6355	5.28
2.6	2.857E+019	128.306	24.5345	5.23

Photon-Photon collisions at LUXE

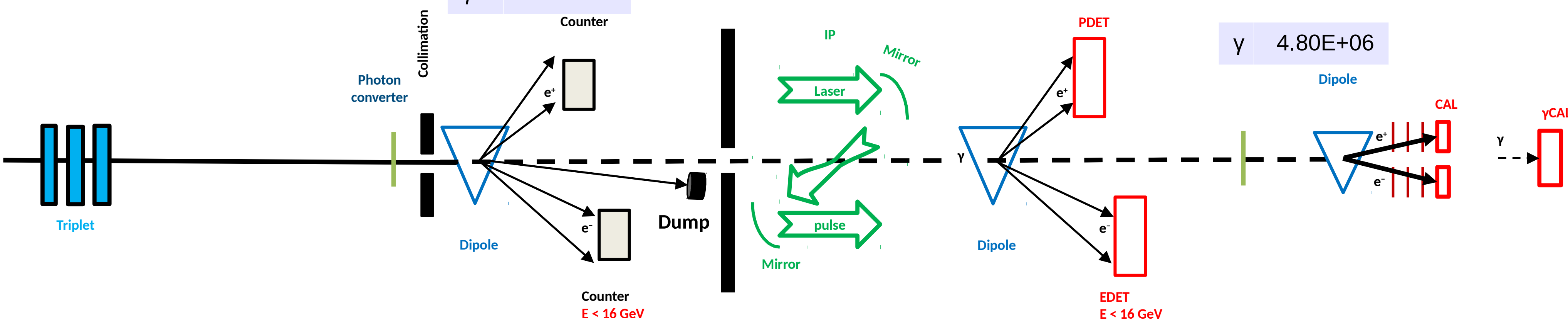
e-	6.25E+09

e-	6.26E+09
e+	1.62E+06
γ	5.60E+08

γ	4.91E+06
γ, E >7GeV	4.66E+05

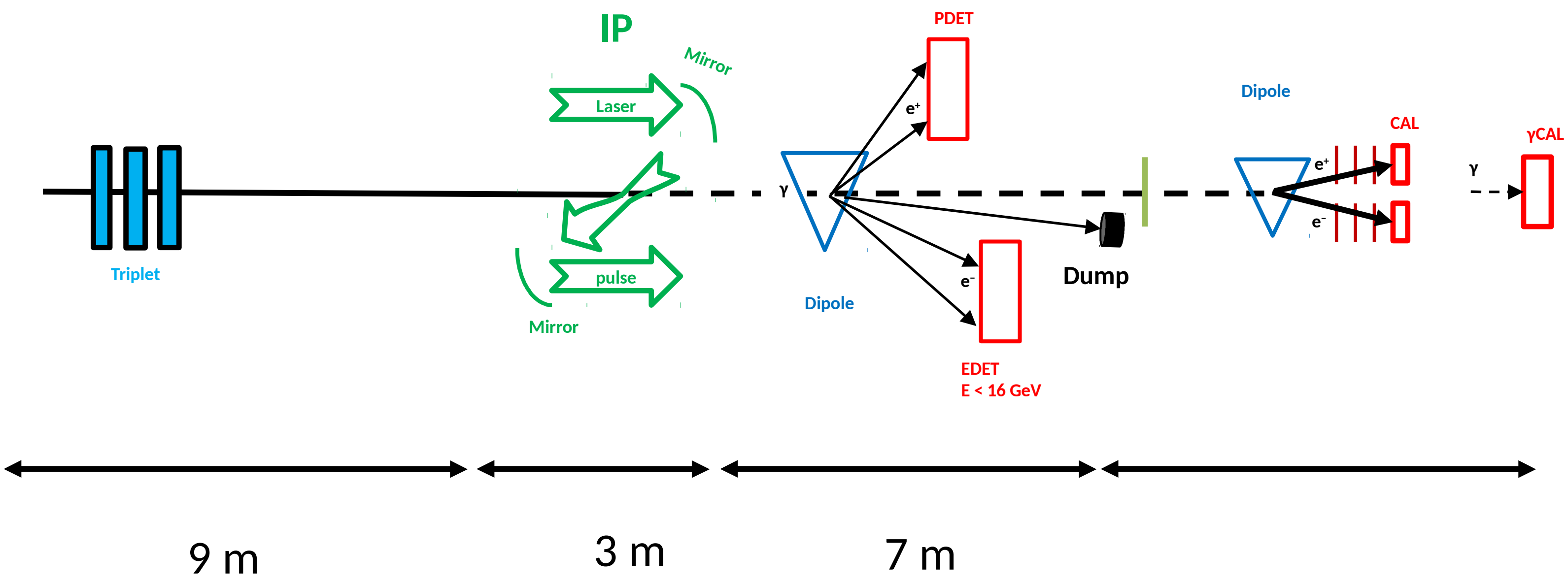
	Stage 0	Stage 0.5
e-	1.32	24.5
e+	1.32	24.5

γ	4.80E+06



Area	Desctiption	e-	e+	Gamma	Notes
A	Incident beam	6.25E+09			XFEL beam sigma_xy = 5μm, emittance: 1.4e-3
B	Target	6.26E+09	1.62E+06	5.60E+08	Tungsten 35 um, (1%X0), 5 m upstream of IP
C	Collimator	6.26E+09	1.62E+06	5.60E+08	After target: 35 um tungsten (1%X0); +/-10 cm
D	Dipole	6.26E+09	1.62E+06	5.60E+08	
E	IP			4.91E+06	Geometrical cut |x|<25um && |y|<25um is applied to match laser transverse size
	E > 7 GeV			4.66E+05	
	E > 12 GeV			1.92E+05	
F	Dipole				
	Stage 0	1.32	1.32	4.80E+06	Laser: 1.0e19 W/cm2, (0.35J, 100um2, 35 fs)
	Stage 0.5	24.5	24.5		Laser: 2.6e19 W/cm2, (1.0J, 100um2, 35 fs)
	Stage 1				Laser: 2.0E+20 xi=6.88
G	γ detector			4.80E+06	

Electron-Photon collisions at LUXE



Area	Desctiption	e-	e+	Gamma	Notes
A	Incident beam	6.00E+09			
B	HICS	6.00E+09		5.74E+09	6.0e-9 electrons were used as input in simulation

Possible LumiCal application at LUXE

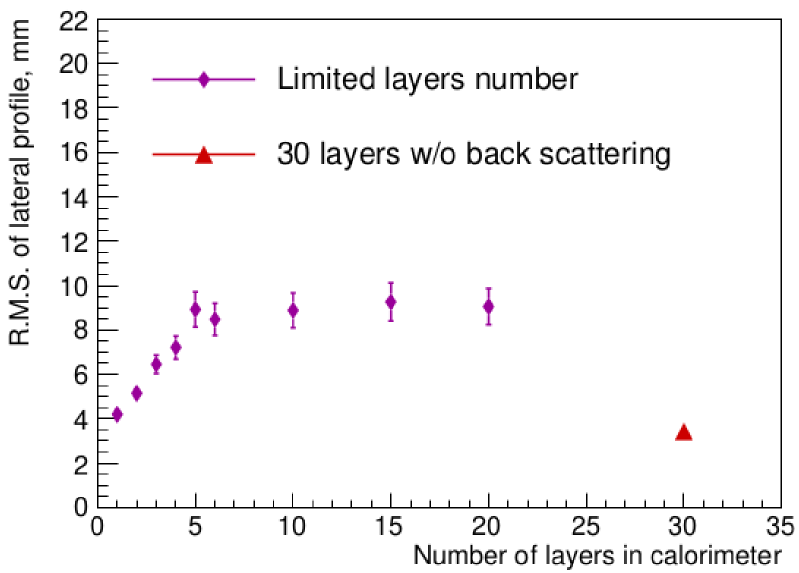
- One of the value that LUXE measures is the rate of pair production;
- For production study the accurate measurement of luminosity is essential;
- LumiCal could contribute to bremsstrahlung photons flux measurement in case of bremsstrahlung photon pair production (BPPP);
- Spectrometers designed for the pair registration can be accompanied by the calorimeters:
- It improves spectra measurements when the tracking through the magnet is not performed and the position of primary vertex might be uncertain;
- In this case small effective Moliere radius (good position resolution) good energy resolution are important

Challenges:

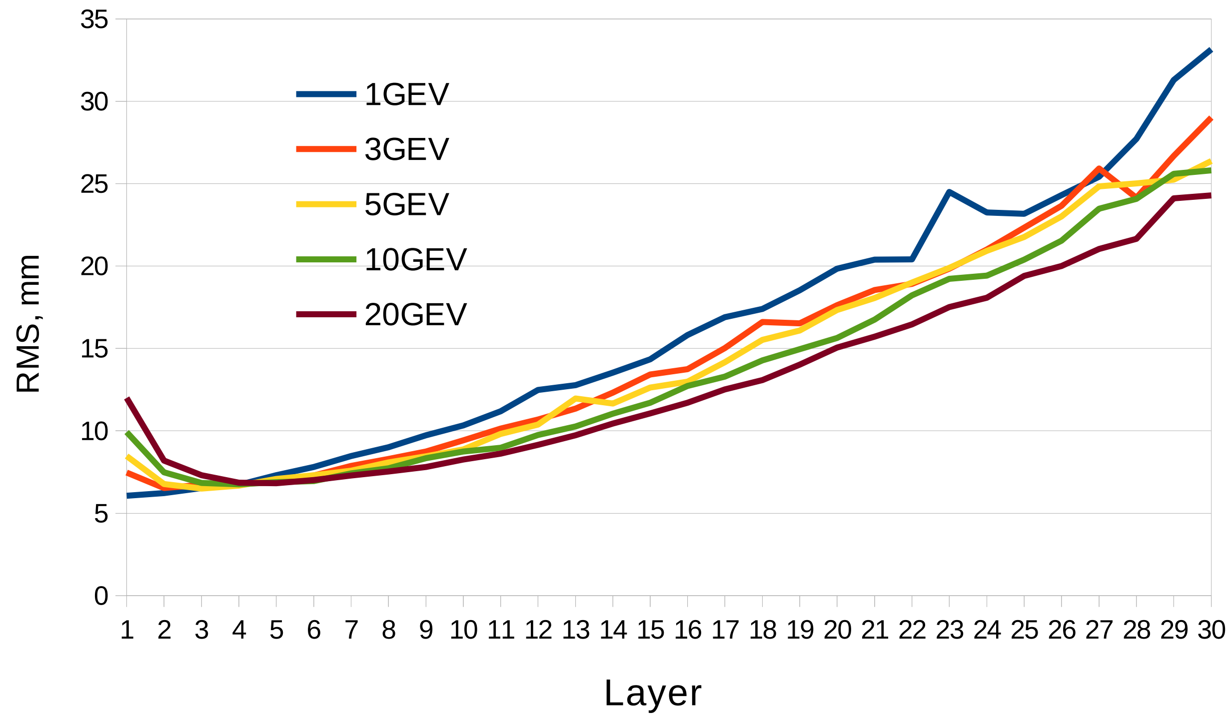
- High flux of bremsstrahlung photons:
- In case of BPPP ~5.0e6 of which ~5e5 with E > 7 GeV confined to about 1 mm^2.
- For HICS it is even higher, if used with XFEL nominal beam parameters, it is ~1e9;
  - Consider reducing bunch population, but there is a limit…
  - Defocusing e- beam, specific alignment…

Back scattering in calorimeter

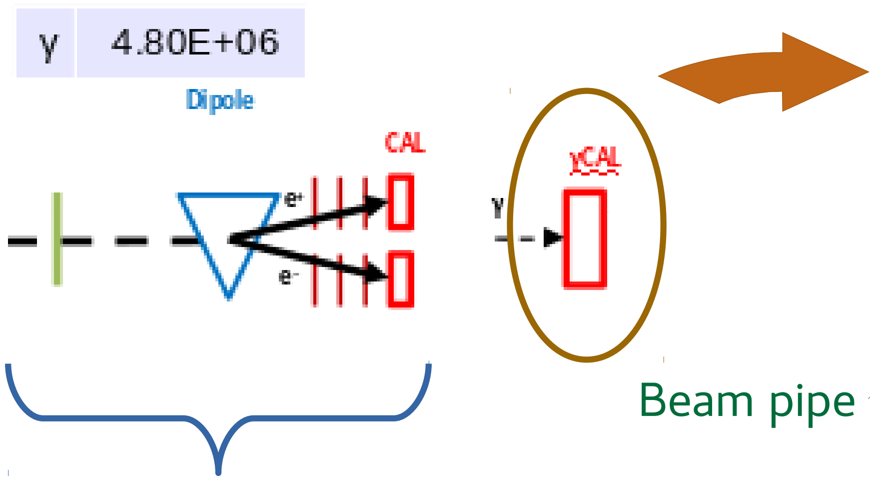
Effects observed in simulation for TB2016 with wide calorimeter of 30 layers with high granularity of the sensitive layers.



RMS of the lateral shower profile in different layers for different electron beam energy

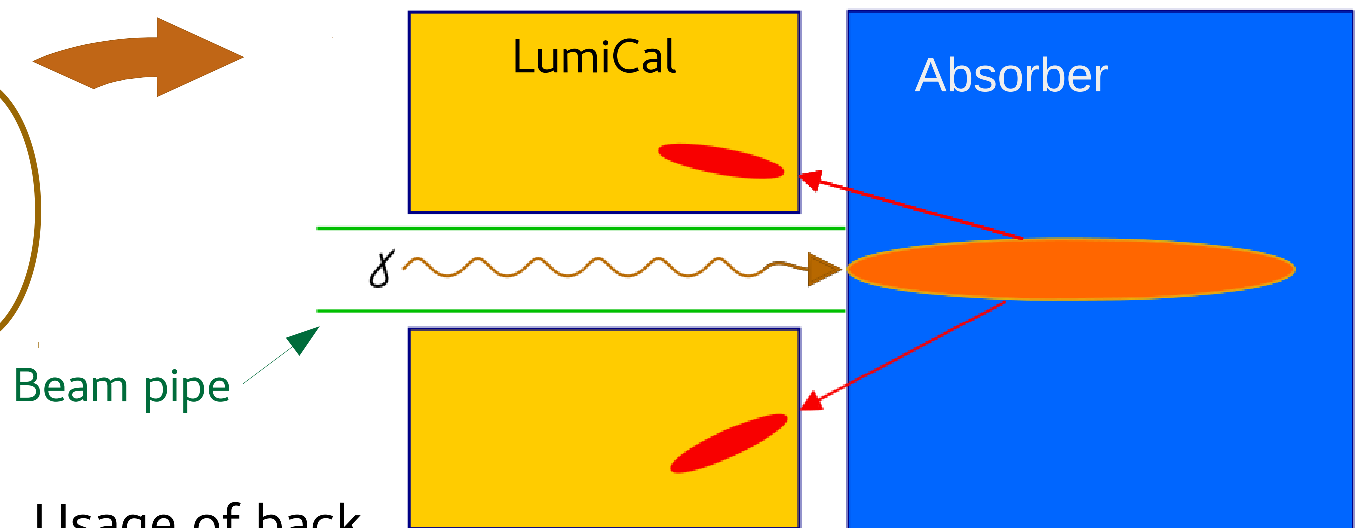


Possible techniques for gamma detector

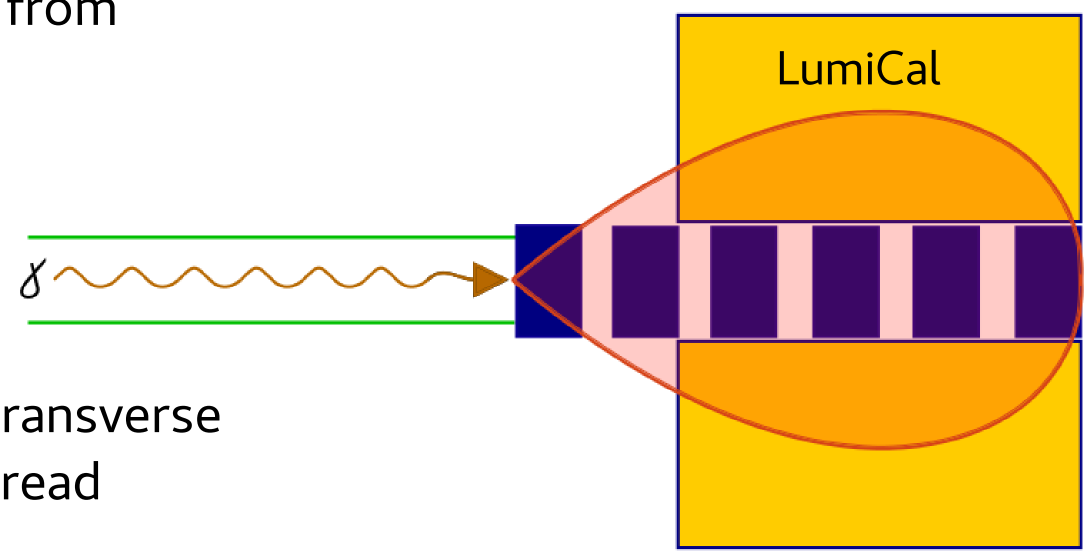


10 µm tungsten wire converter produce:

- ~5e5 e+e- for HICS;
- ~100 e+e- for bremsstrahlung (OPPP);
- By scanning x, φ probe E(θ)



Usage of back scattering from absorber



Usage of transverse shower spread

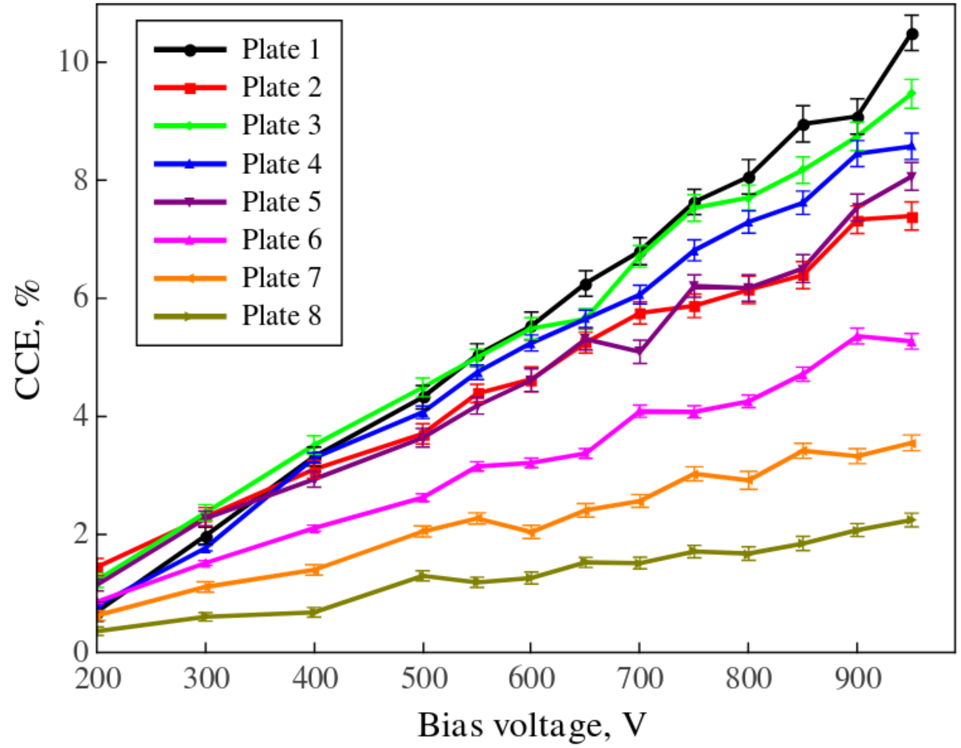
Sapphire sensor

arXiv:1504.04023

- For a CCE of about 10% of industrially produced sapphire,the signal expected for particles crossing a plate of 500µm thickness perpendicular to its surface is only about 1100 e;
- CCE depends on applied voltage and can be below 10%;
- Good radiation hardness.

For comparison: 300µm Si: ~25000 eh
with CCE ~100%

Thin sapphire sensors can be considered for usage in present design of LumiCal instead of silicon.



Summary

- LUXE at DESY proposes to extend scientific scope of EU.XFEL to probe fundamental physics in new regime of high intensity
- Lumical could provide complementary measurements of bremsstrahlung photons used for for e+e- pairs production study
- Calorimeters can also accompany spectrometers to improve spectra reconstruction of e+e- pairs
- High flux of bremstruhlung and HICS photons prevents direct application of electromagnetic sampling calorimeters like LimiCal.
- Several ideas can be studied in simulation to use LumiCal technology in LUXE:
  - Measure the back scattering produced by photons in passive absorber;
  - Measure energy deposition in far lateral periphery of the shower;
  - Sapphire sensors instead of silicon.

Back up

Electron and laser beam parameters

E_pulse, μJ	Crossing angle, rad	Laser σxy, μm	Laser σz, ps	N Electrons	Electron σx, mm	Electron σy, mm	Electron σz, ps
3.5*10^6	0.3	10	0.035	6.25E+09	0.005	0.005	0.08

- Laser wavelength = 800.00 nm (1.5498 eV);
- Circular polarized.