Detector Challenges of the strong-field QED experiment LUXE at the European XFEL

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57th Rencontres de Moriond,

La Thuile, 22nd March 2023

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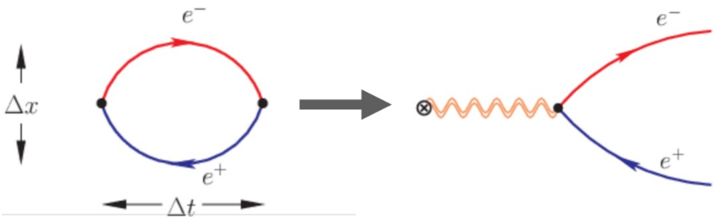
QED in strong fields: SFQED

▶ For large values of EM field **ε** → the **Schwinger critical** field is surpassed and **the vacuum becomes unstable** to pair production

- during the fluctuation, $E>2m_e$ is supplied



$$\mathcal{E}_{crit} = \frac{m_e^2 c^3}{\hbar e} = 1.32 \times 10^{18} V/m.$$

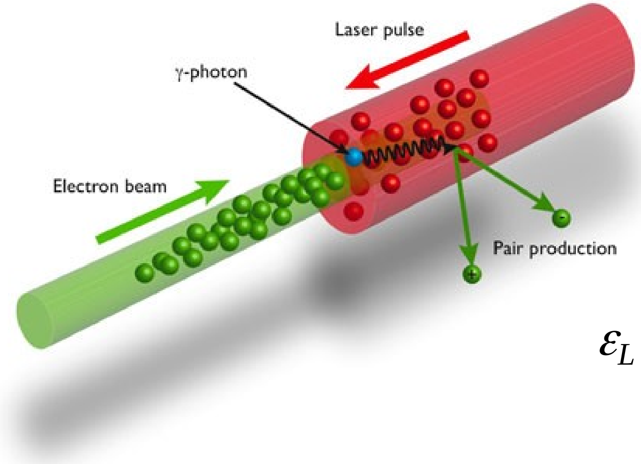
▶ **Perturbative QED breaks down** in the presence of **strong fields**

▶ **Such fields have not been reached experimentally** in laboratories although they are expected to exist:

- On surface of neutron stars
- In bunches of **future linear e+e− colliders**.

▶ **Can be reached** by colliding high intensity laser beams with a high-energy electron beam

- Lasers powerful enough don't exist yet
- A high energy e- beam is required: The EM field strength is boosted



$$\varepsilon_L = \gamma\, \varepsilon (1 + \cos\theta)$$

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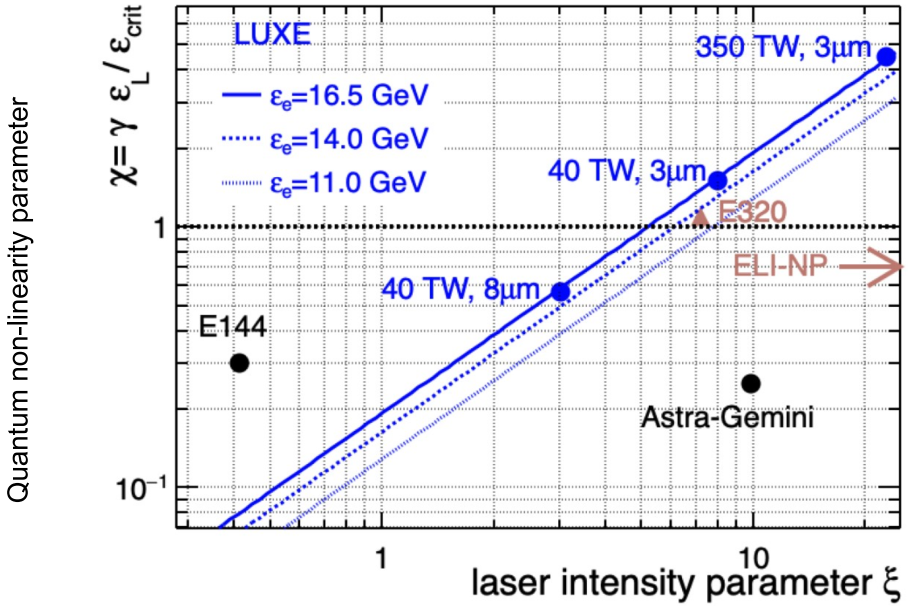
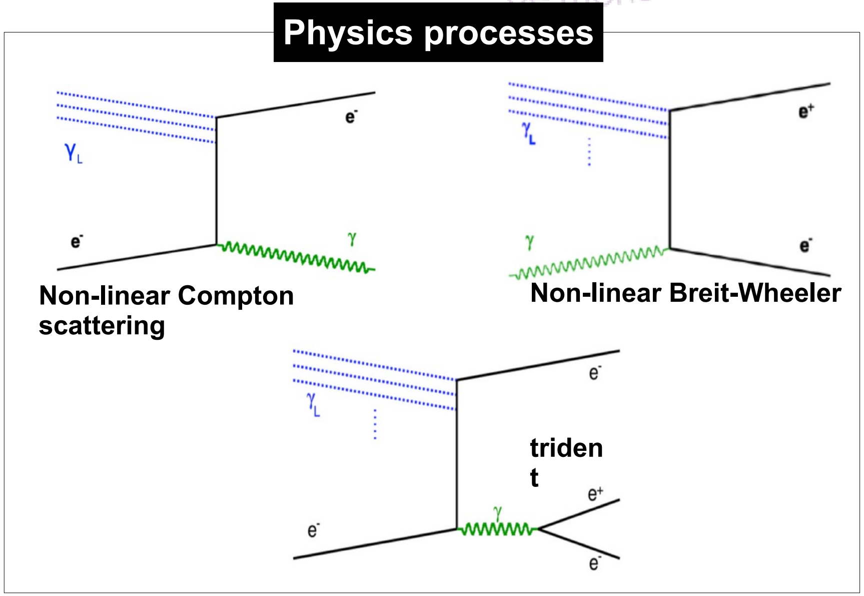
LUXE: Laser Und XFEL Experiment

- Experiment based at **DESY-XFEL**
- **Strong EM field**: 30-350TW **laser** & 16.5 GeV **e^- beam**
  - e^- / laser interaction mode and γ /laser interaction mode
- Ambitious time-scale (start data taking in **2026**)
  - **CDR** published, TDR to appear during 2023



Field intensity parameter

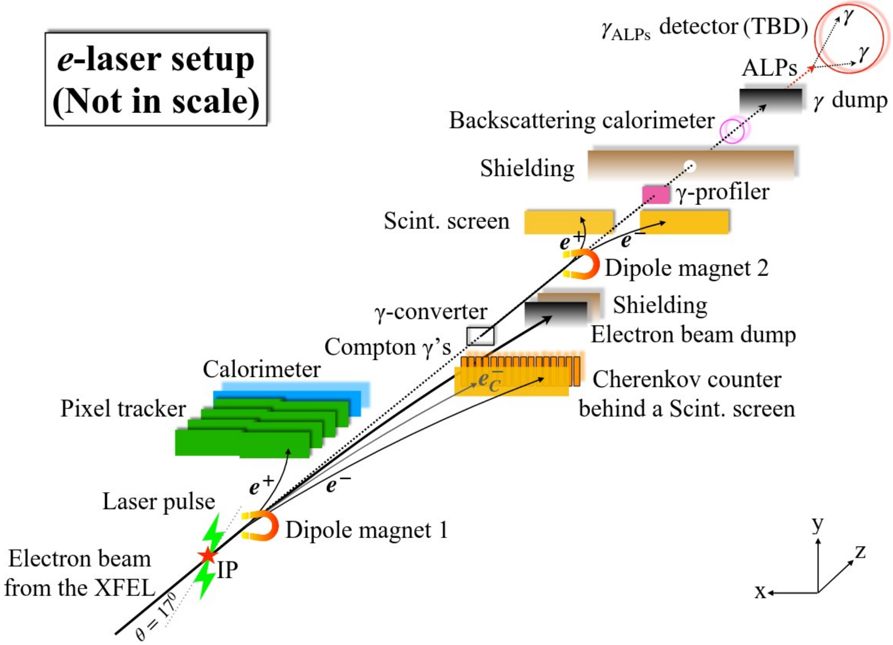
$$\xi = \sqrt{4\pi\alpha}\left(\frac{\varepsilon_L}{\omega_L m_e}\right) = \frac{m_e \varepsilon_L}{\omega_L \varepsilon_{cr}}$$

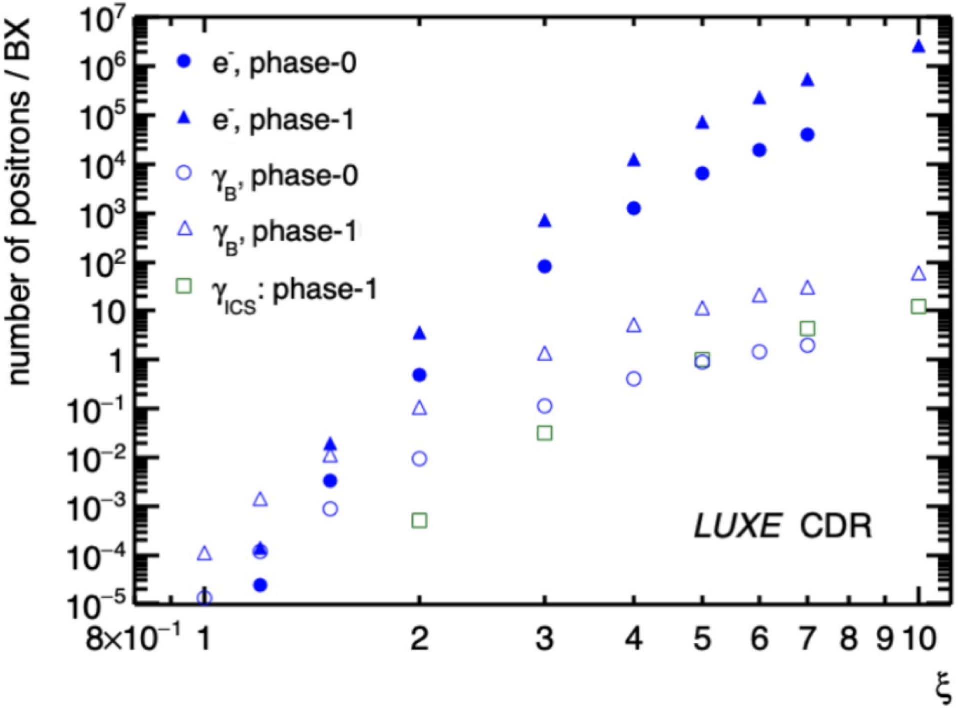


First experiment to try this E144 @ SLAC in 1990s.
Nowadays experiments : SLAC-E320 (US), Astra Gemini (UK), ELI-NP (RO)

Detector challenges

- Vast range of multplicities per beam bunch depending on the mode of operation
  - Physics-driven detector technologies at each location





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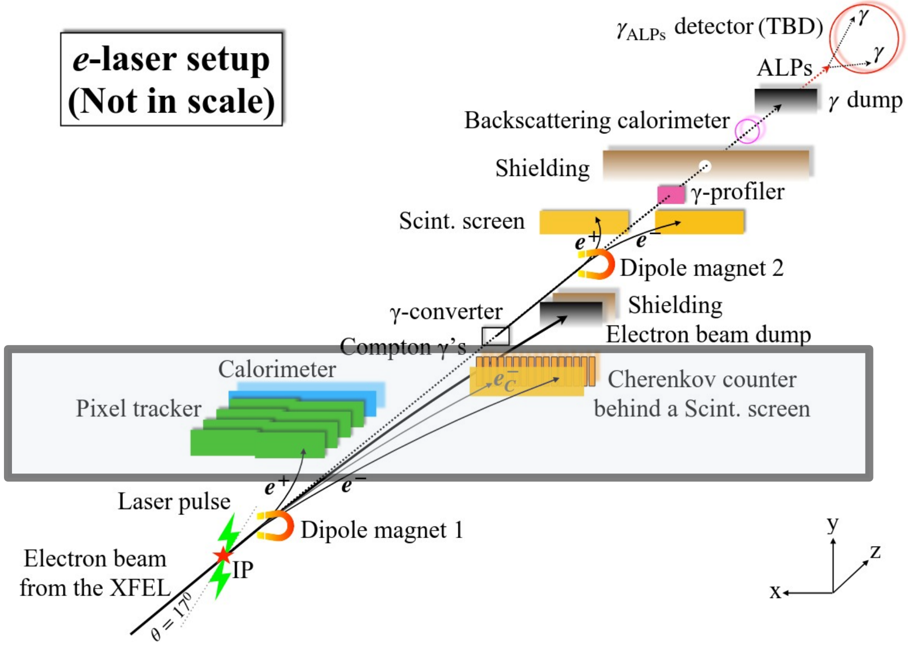

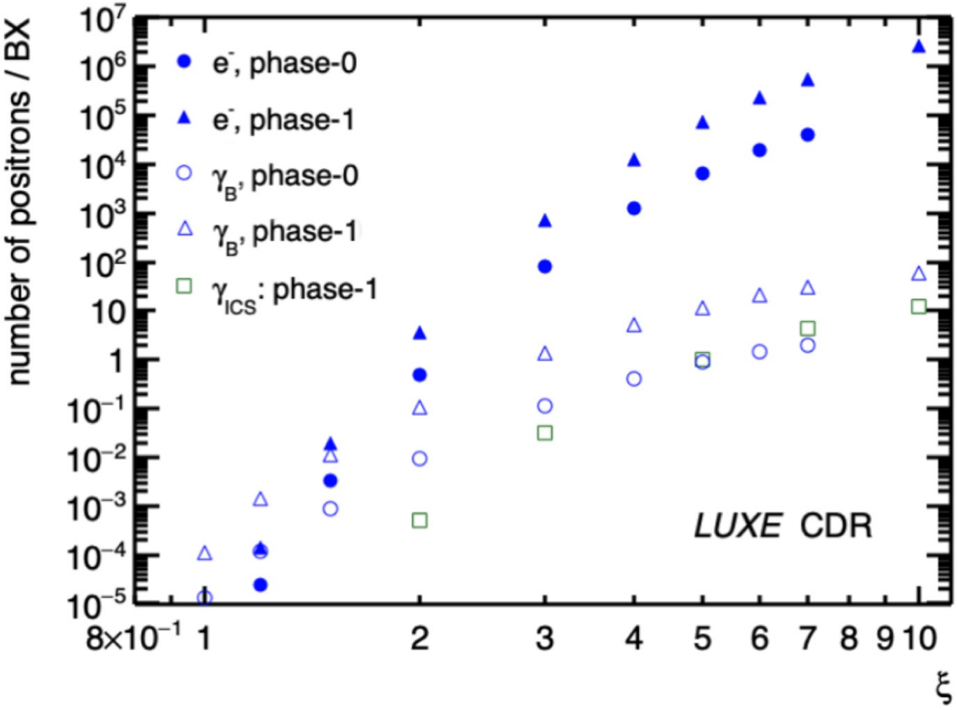

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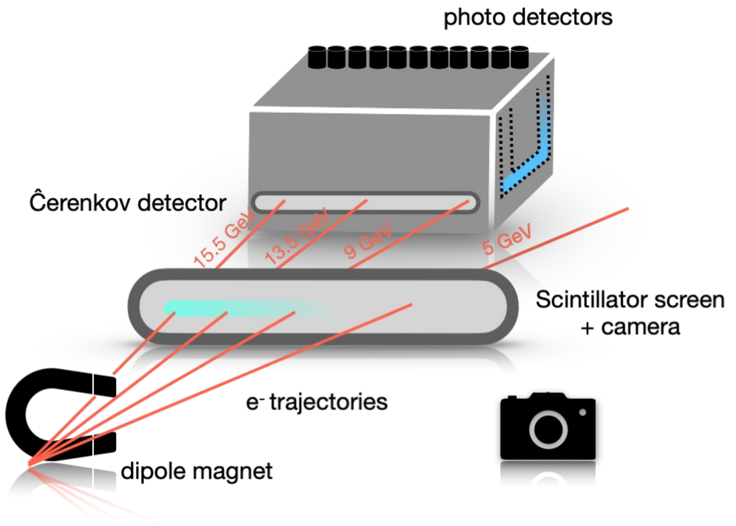
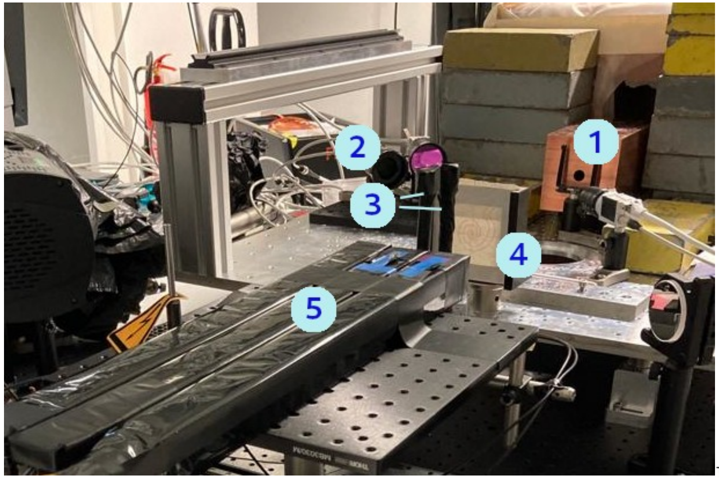
Electron side (electron-laser mode)

- Very large rates of electrons (10^9)
  - Measurement of the non linear Compton spectrum
- **Scintillator screen**
  - Used by the AWAKE collaboration at CERN
  - Camera takes pictures of the scintillation light. Resolution ~ 500 µm.
  - Signal/Background ~100 & Radiation hard (100 MGy)
- **Cherenkov gas detector**
  - Ar gas developed for ILC polarimeter
  - Low refractive index gas helps to reduce light yield (Cherenkov threshold 20 MeV)
  - Signal/background>1000





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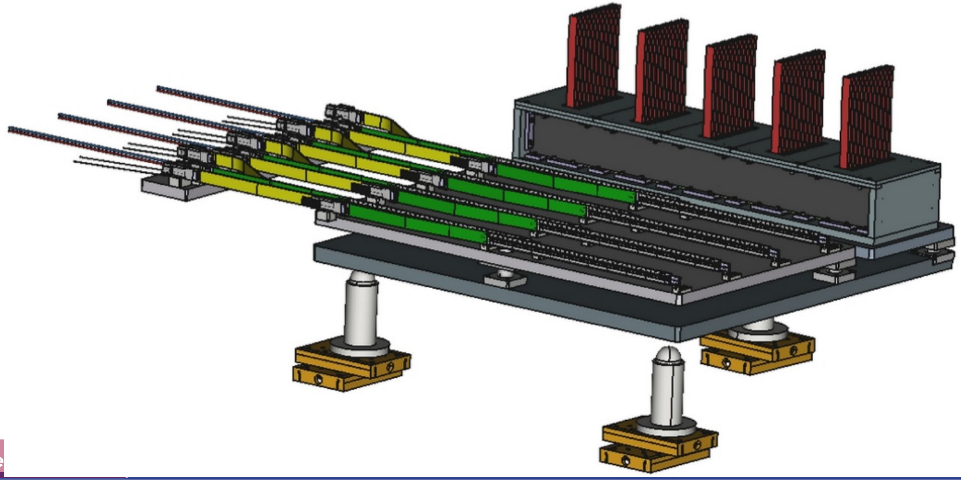
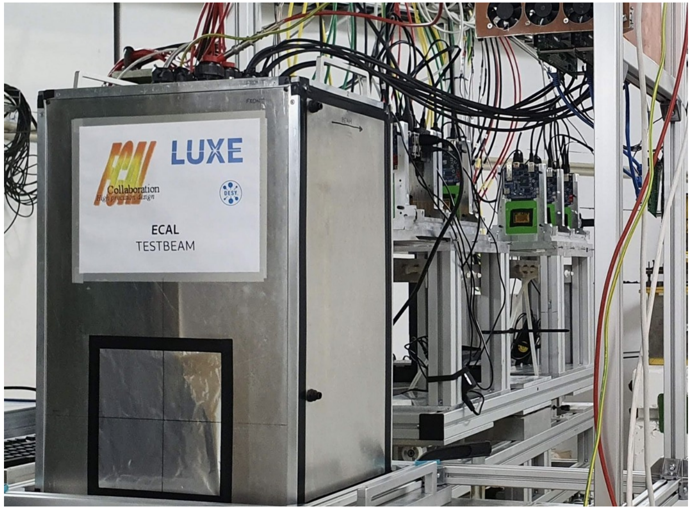
Positron side (electron-laser mode)

- Tracker based on ALPIDE sensors (developed by ALICE for phase 1 upgrade)
  - 5um spatial resolution
- Multilayer high granular calorimeters based on linear collider prototypes (FCAL and SiWECAL-CALICE)
  - $20X_0$, 5.5x5.5 mm^2 sensors (silicon and GaAs under study)
  - Ultra compact to ensure minimal Molière Radius of about R_M~3.5 mm
  - 1 mm between tungsten planes
- Dedicated algorithms for high multiplicity events





Thanks !

- Collaboration webpage: https://luxe.desy.de/
- LUXE CDR
- Collaboration talks and documents
- A LUXE review (A. Levy, DIS2022)
- **BSM direct searches (ALPs)** with an optical dump at LUXE. The LUXE-NPOD

Thanks to Ruth Jacobs, Yan Benhammou and many others for material and feedback

Interested? Join us !

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back-up

LUXE
membership of Russian institutes suspended
QUEEN'S UNIVERSITY BELFAST
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UCL
UNIVERSITY OF PLYMOUTH
IN2P3
ÉCOLE POLYTECHNIQUE
IN2P3
université PARIS-SACLAY
IJCLab Irène Joliot-Curie
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INFN
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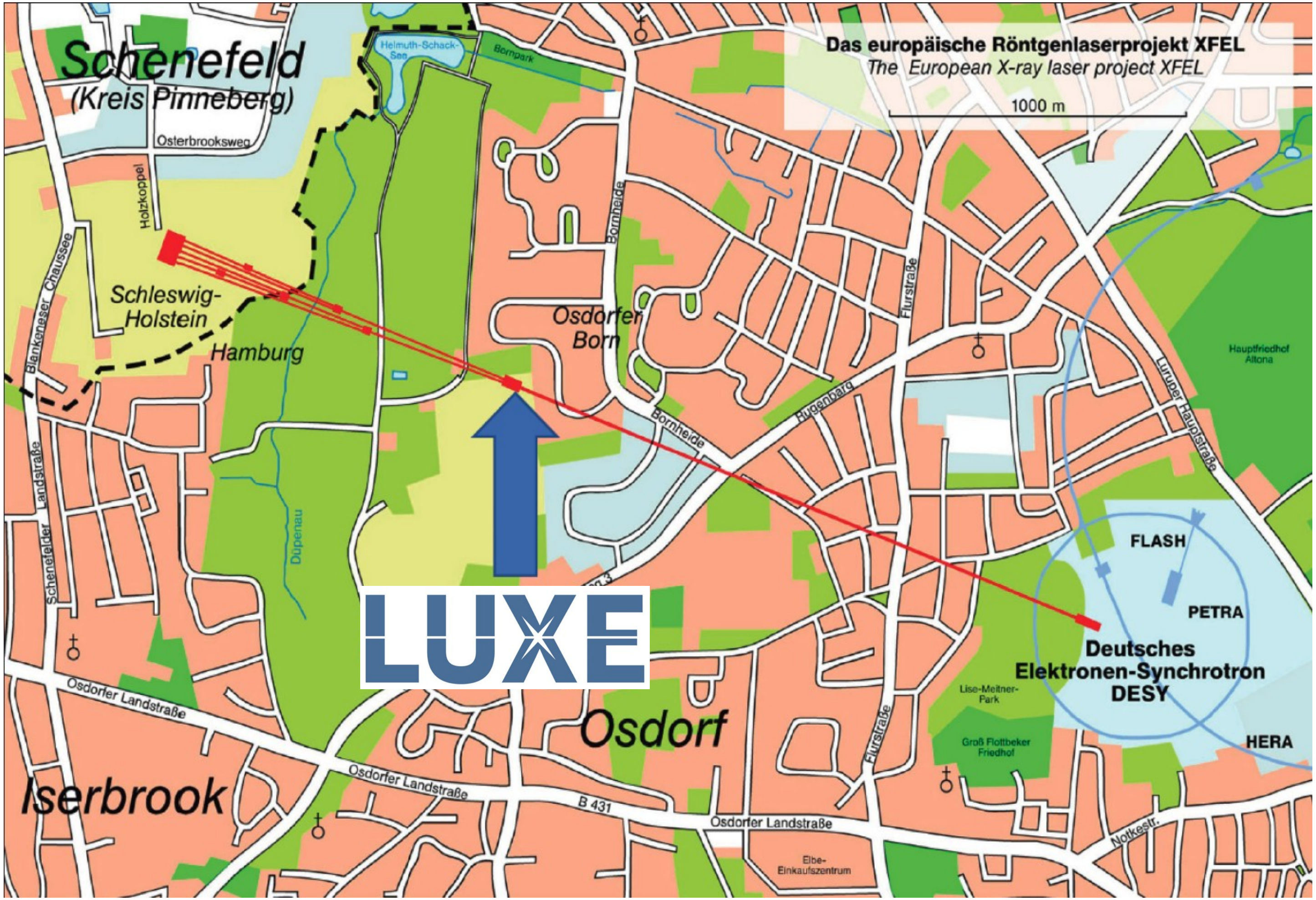
INFN
UNIVERSITÀ DEGLI STUDI DI PADOVA
UNIVERSITAS GOTHOBURGENSIS 1891
mpsd
Max-Planck-Institut für Struktur und Dynamik der Materie
DESY.
HELMHOLTZ
Helmholtz-Institut Jena
FRIEDRICH-SCHILLER-UNIVERSITÄT JENA
UNIVERSITAS VARSOVIENSIS
AGH
KIT
ISS
TECHNION Israel Institute of Technology
TEL AVIV UNIVERSITY
WEIZMANN INSTITUTE OF SCIENCE



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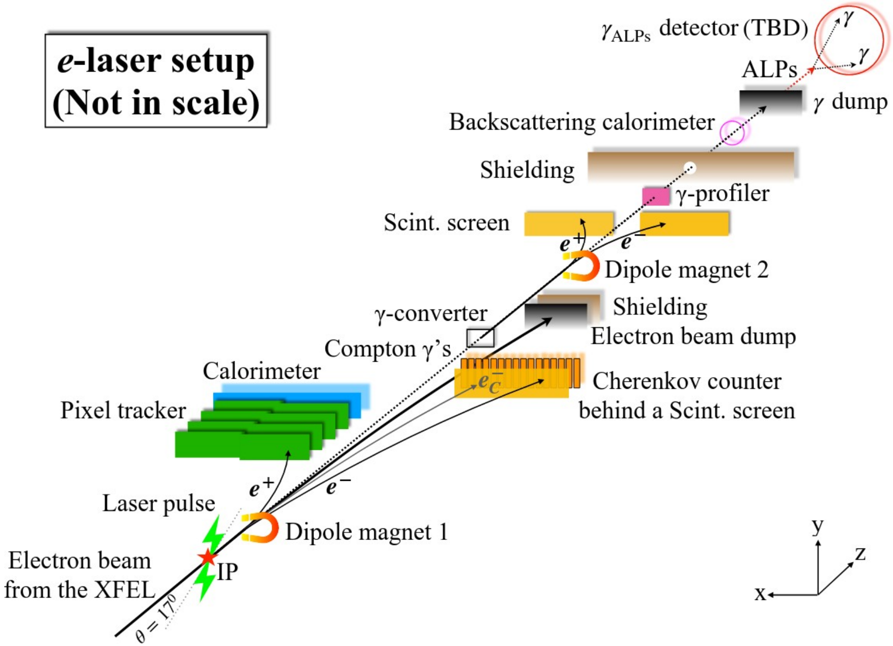
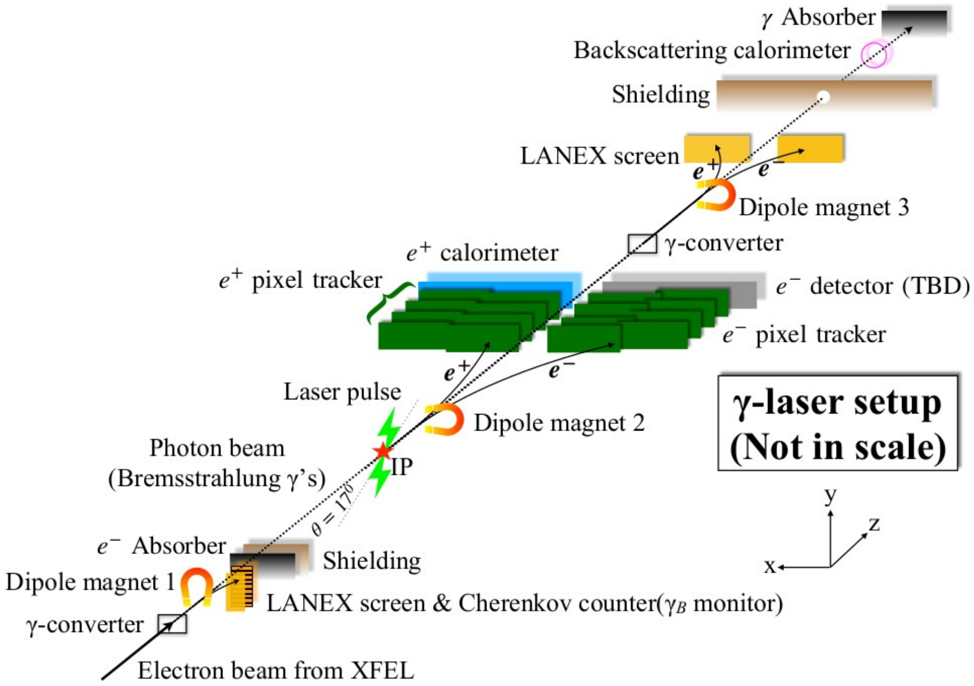
Operation modes





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SFQED at LUXE

Charge field coupling
→ work done by the EM field over electron Compton wavelenght in units of EM field

~ number of laser photons interacting with the electron beam at a given time

Laser photon density ~ ξ^2

	Theory Parameter	Definition	Range accessed in LUXE phase-0	phase-1
ξ	Classical non-linearity parameter	$\xi = \frac{m_e}{\omega_L}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$	$\lesssim 6$	$\lesssim 19$
η_i	Energy parameter	$\eta_i = \frac{\omega_L \varepsilon_i}{m_e^2}(1+\beta\cos\theta)$	$\eta_i \lesssim 0.2$	
χ_i	Quantum non-linearity parameter	$\chi_i = \frac{\varepsilon_i}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}(1+\beta\cos\theta)$	$\lesssim 1$	$\lesssim 3$

How much the QED deviates from the classical limit

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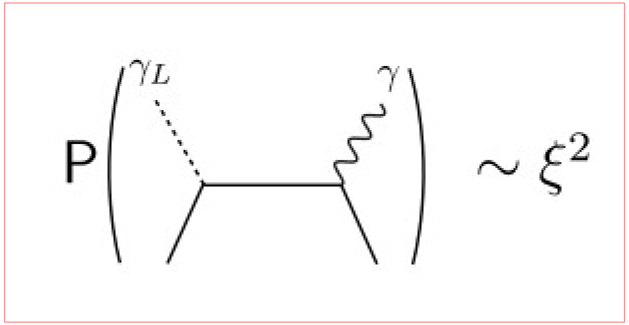
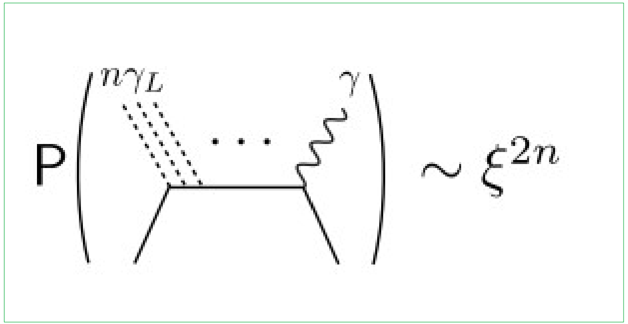
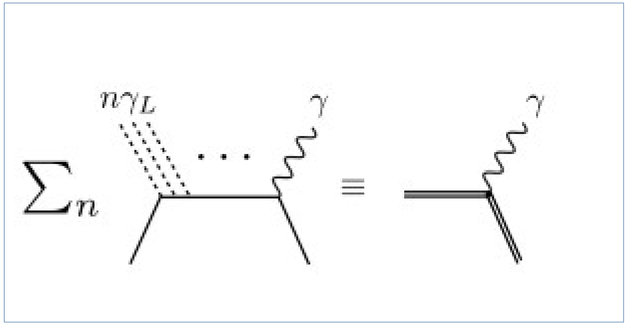
SFQED at LUXE: non-linear Compton Scattering







ξ< 1

The probability to produce one Compton photon is proportional to the density

Still the electron can collide with n laser photons (non-linear compton).
The process is still perturbative if **ξ< 1**

ξ> 1
There are no more leading order processes and we are require to resum all higher order contributions in **ξ**

The non-perturbative resulting expression can be expressed as an effective larger electron mass:

$$m_e(eff) = m_e\sqrt{1+\xi^2}$$

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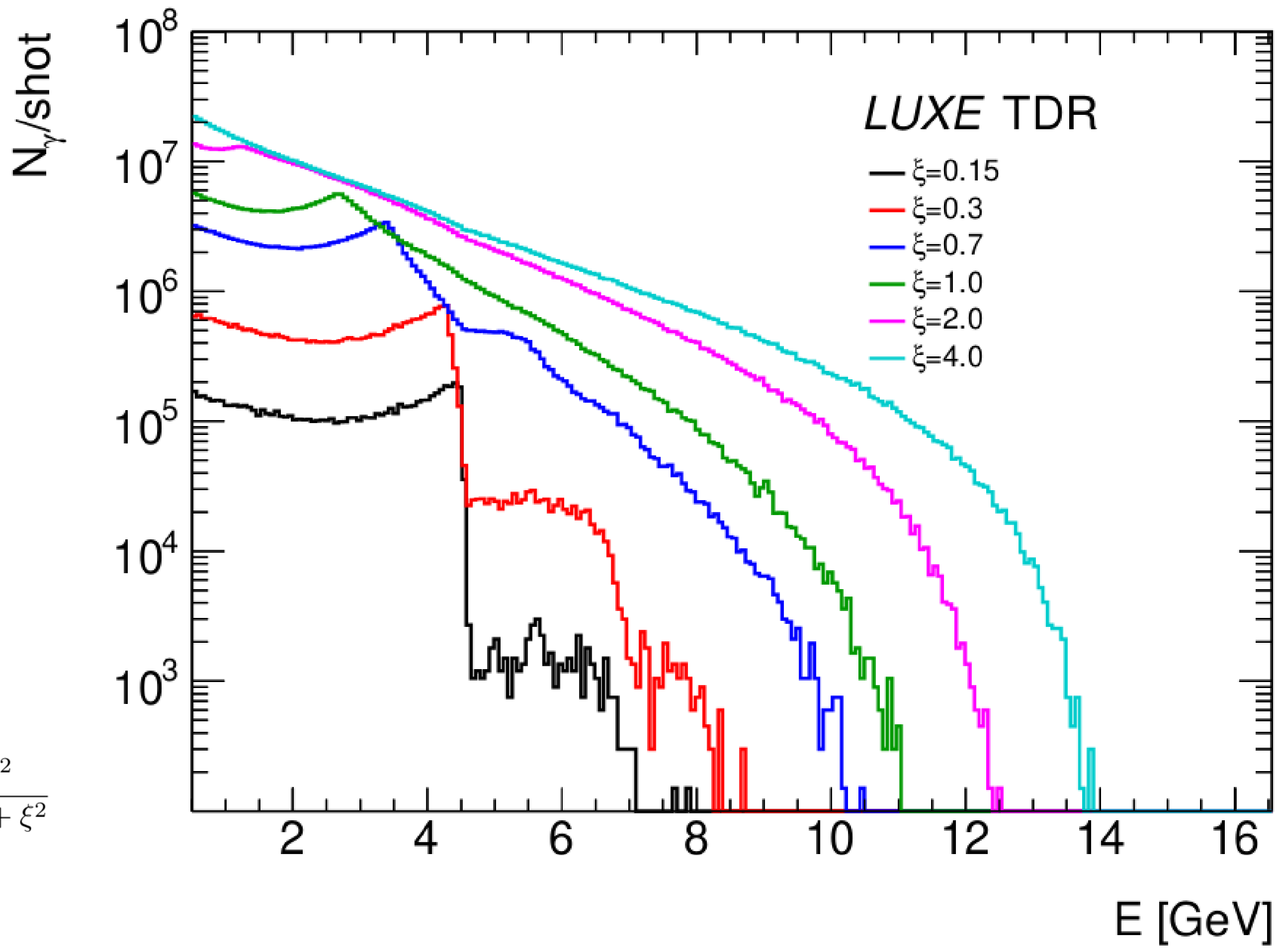
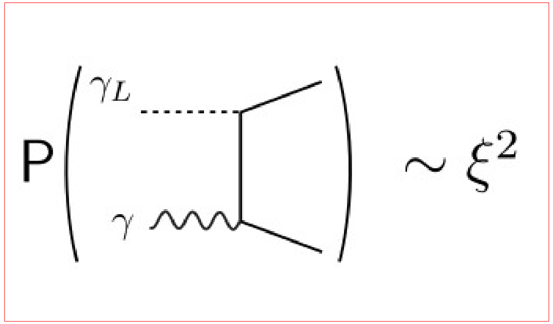
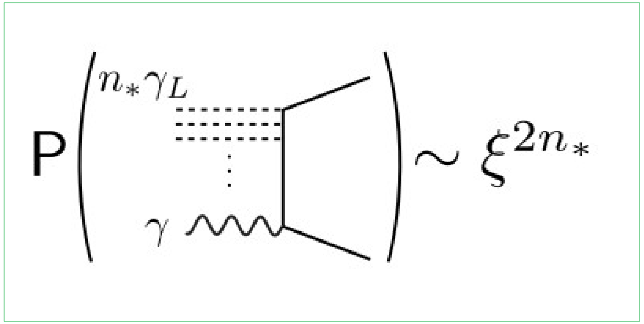
SFQED at LUXE: non-linear Compton Scattering

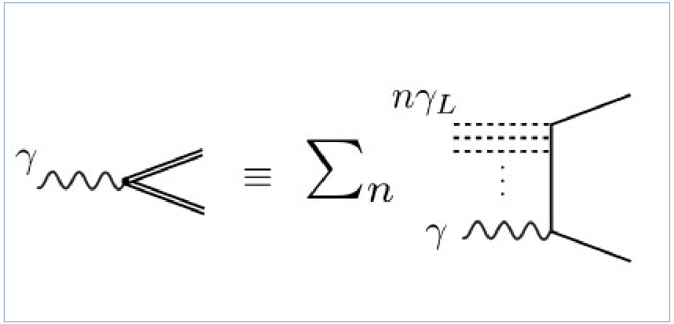


$$E^e_{edge}(\xi) = E_e \frac{1+\xi^2}{2\eta + 1 + \xi^2}$$

SFQED at LUXE: non-linear Breit-Wheeler







ξ< 1

One photon colliding with one laser photon (linear)

Still the photon can collide with n* laser photons (non-linear BW).
The process is still perturbative if **ξ< 1**

ξ> 1
Sum of all orders of ξ resulting in a non-linear non-perturbative BW process

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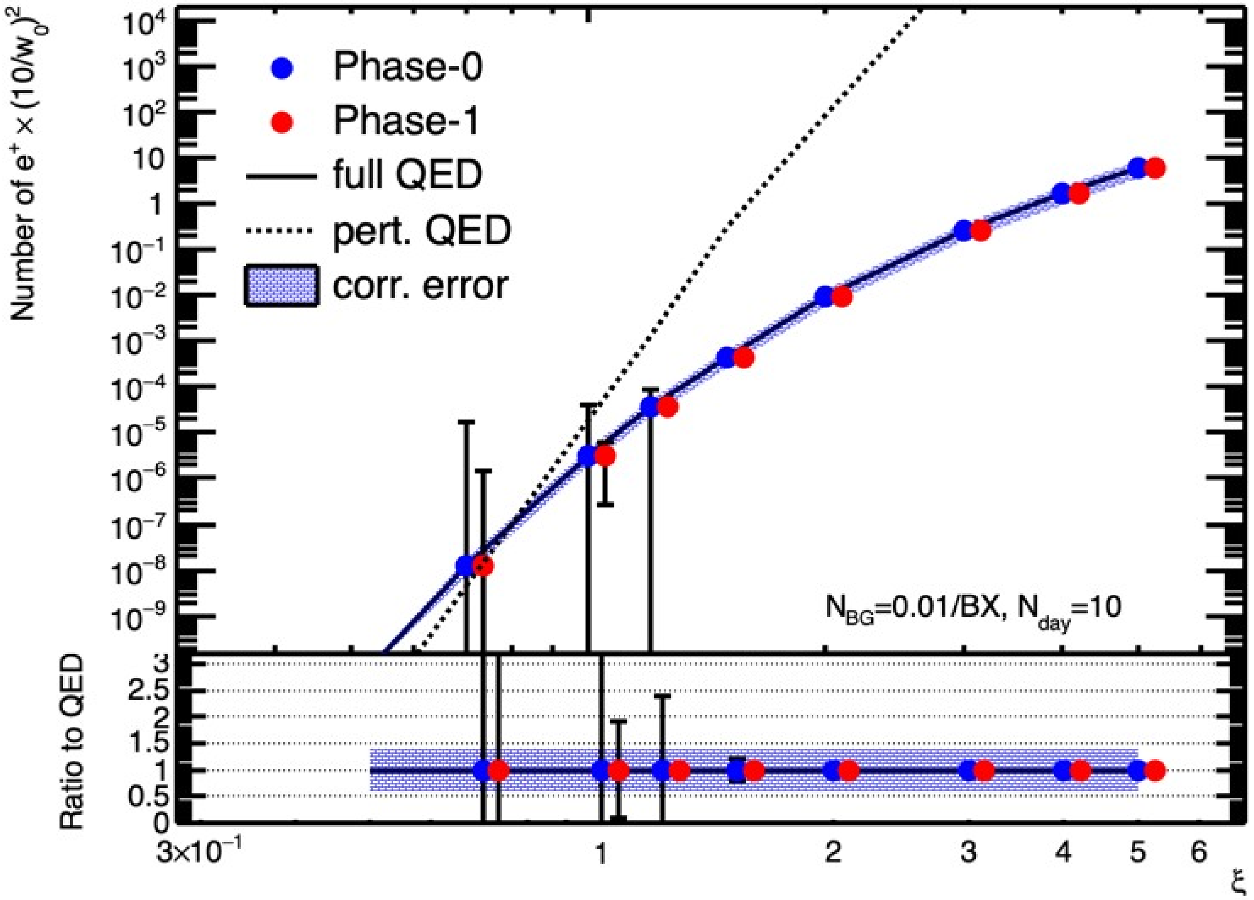
SFQED at LUXE: non-linear Breit-Wheeler



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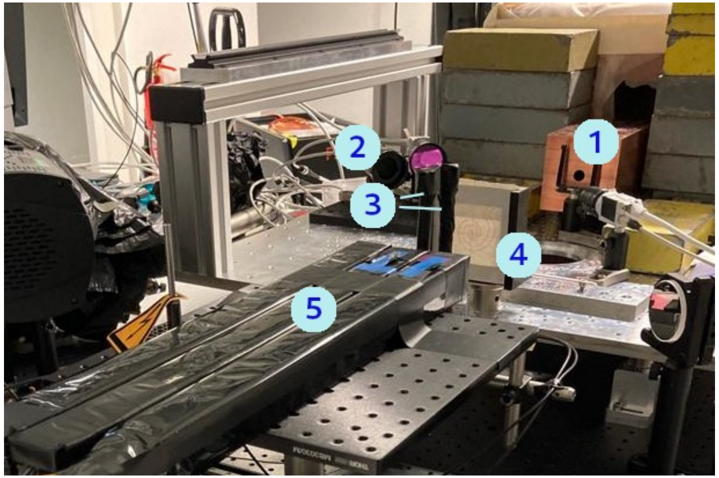
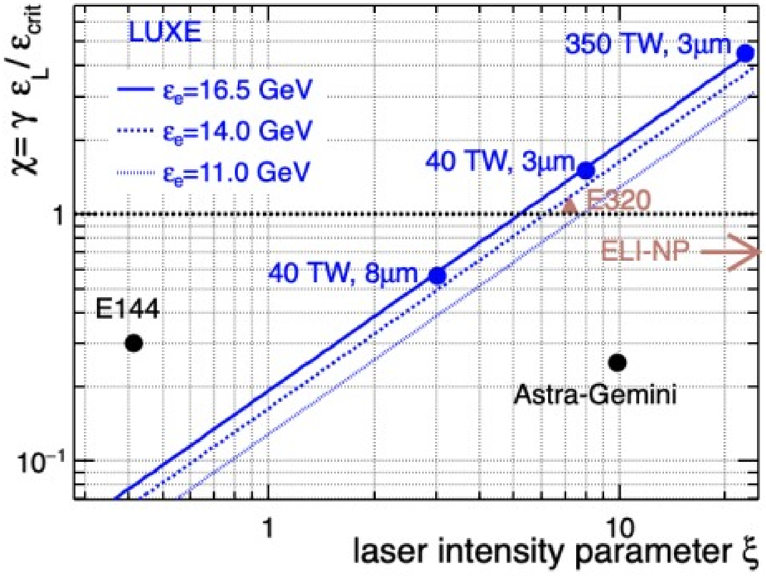
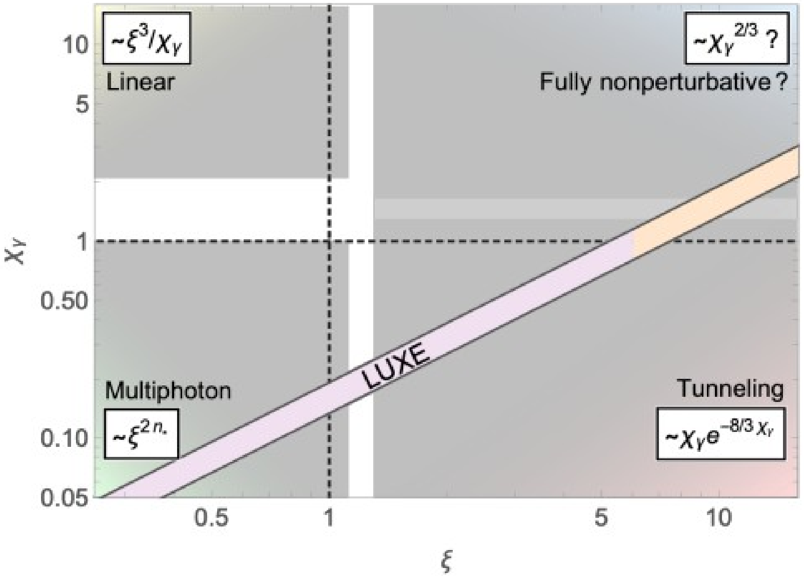


LUXE detectors test beam setup photo.
1 - collimator, 2 - cameras, 3 - Cherenkov detector straws, 4 - scintillator screen, 5 - lead glass

LUXE in SFQED parameter space





- E144: SLAC experiment in 1990's, using 46.6 GeV electron beam *[Bamber et al. (SLAC 144) '99]*
  → reached χ ≤ 0.25, ξ<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 ξ>1 and χ>1 regime!
  - directly study collisions between LASER and real GeV photons

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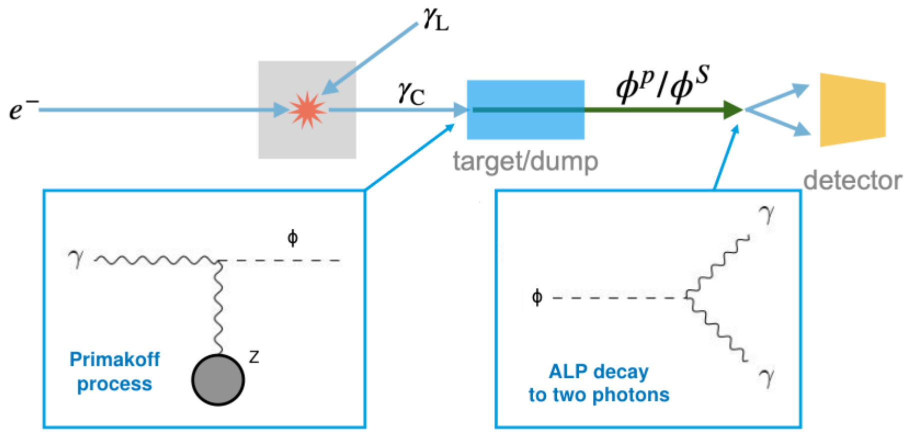
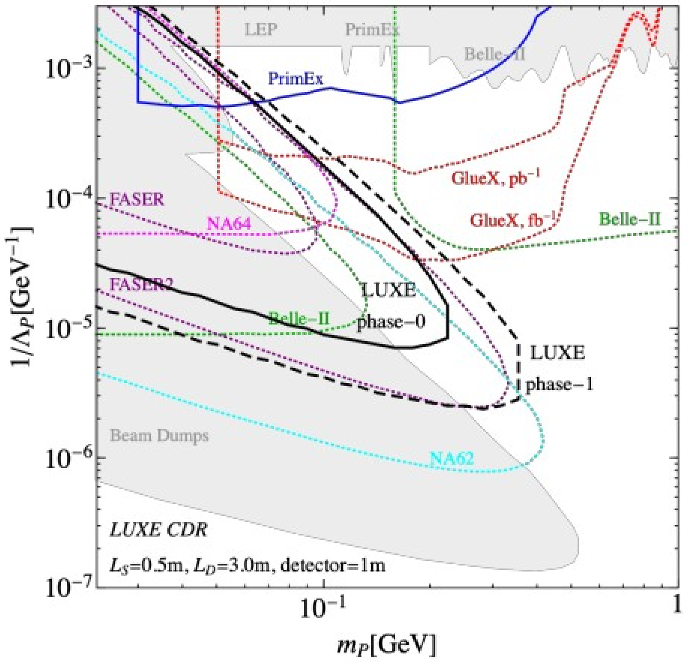
BSM direct searches with LUXE

▶ High intensyt photon beam produced → dumped in a wall



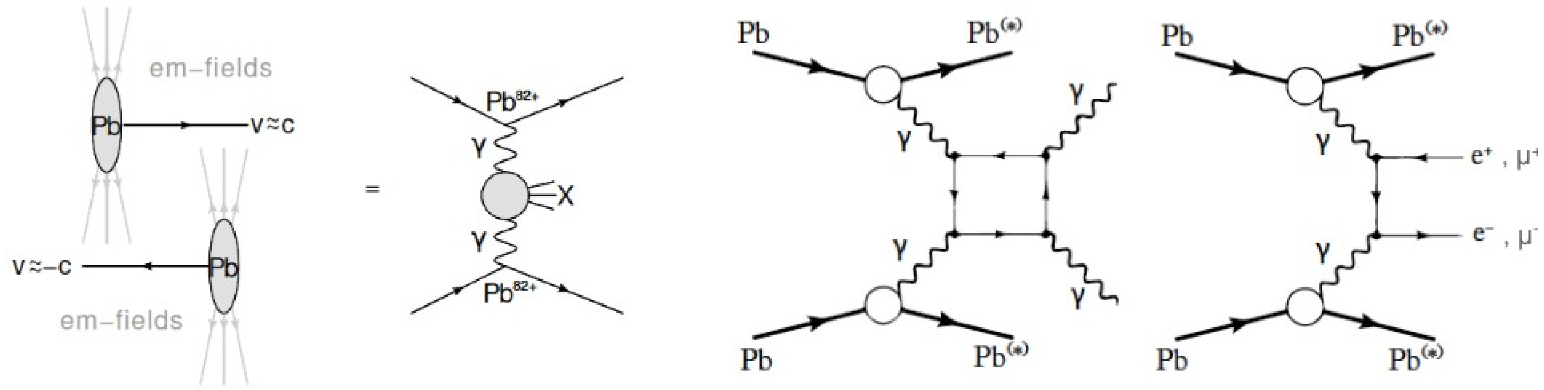


▶ Could be competitive with other experiments

- Estimations for 1 year of data taking with no background. WIP.

LUXE and LHC light-by-light scattering

- LHC: photon-photon interaction in ultra-perophierial heavy-ion collissions (UPC)
- UPD: fields above the Schwinger limit can be reached in the lab
  - Main difference to LUXE: in UPC, EM fiel is extremely short-lived (not travelling macroscopics 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!)

DESY. 13

Slide from R. Jacobs