Probing non-perturbative QED and new physics with a LUXE-type experiment at the ILC

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

LUXE

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Plan de Recuperación, Transformación y Resiliencia

GENERALITAT VALENCIANA Conselleria d'Innovació, Universitats, Ciència i Societat Digital

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AITANA MATTER AND TECHNOLOGY

LCWS2023 INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

1. Strong Field QED and the LUXE experiment
2. LUXE NPOD: new physics search with Optical Dump
3. LUXE at Higgs Factories
4. Summary & more

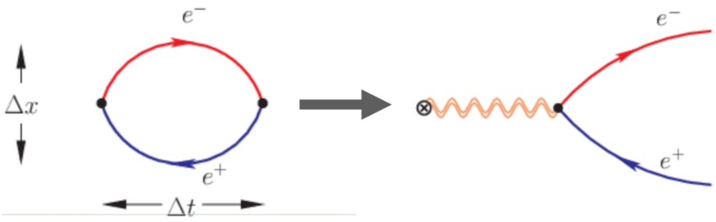
1

Strong Field QED and the LUXE experiment

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**

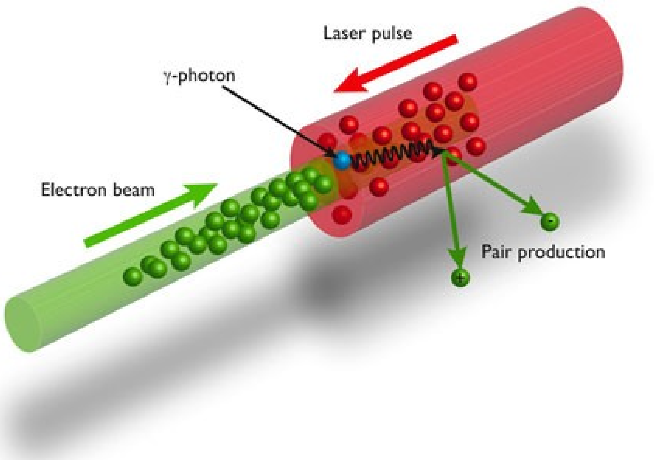
▶ **Such fields have not been probed** in laboratories although they are expected to exist:

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

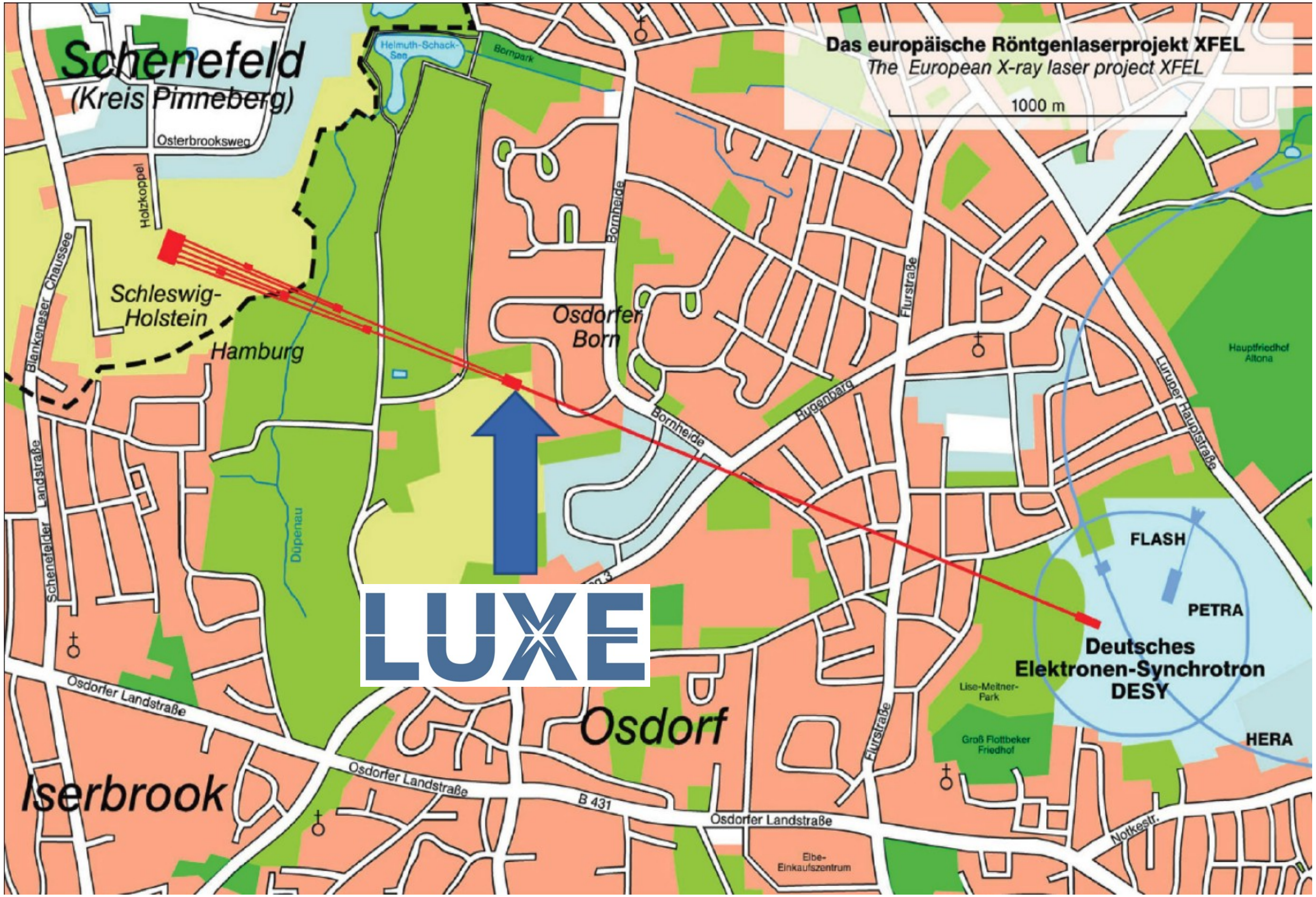
▶ **Can be reached** by colliding high intensity laser beams with a high-energy electron beam

- Laser field ~ 10^{14} V/m (current technology)
- Extra 10^4 has to be given by e- boost

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



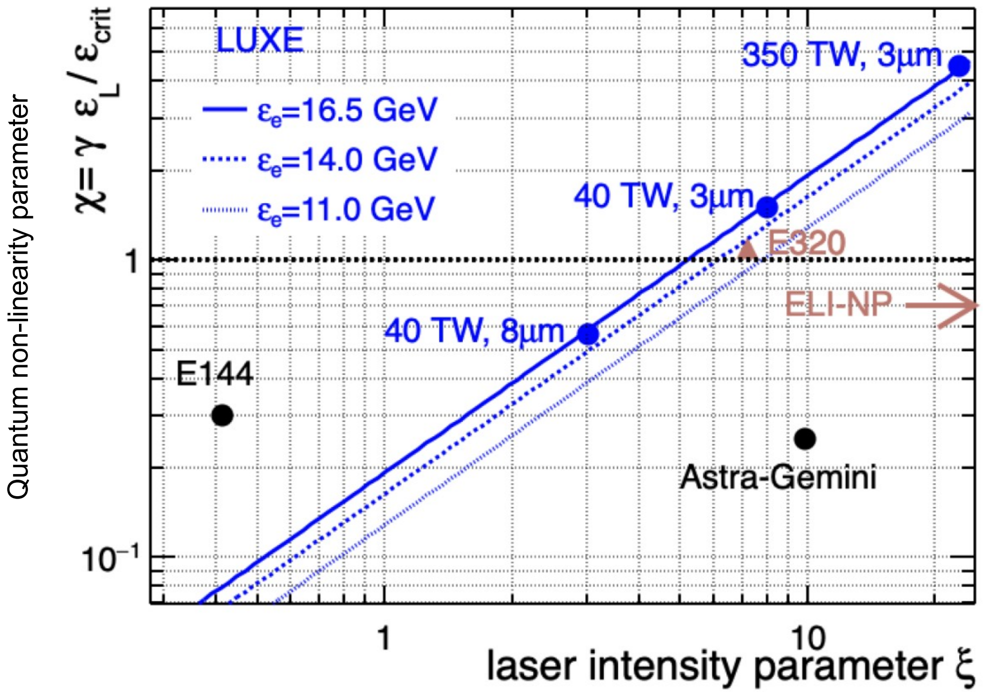
LUXE: Laser Und XFEL Experiment



LUXE: Laser Und XFEL Experiment

- Experiment based at **DESY-XFEL**
- **Strong EM field**:
  - 30-350TW **optical laser**
  - 16.5 GeV **e^- beam (from EU.XFEL)**
- Ambitious time-scale
  - **CDR** published,
  - TDR to appear during 2023
  - start data taking in **2026**

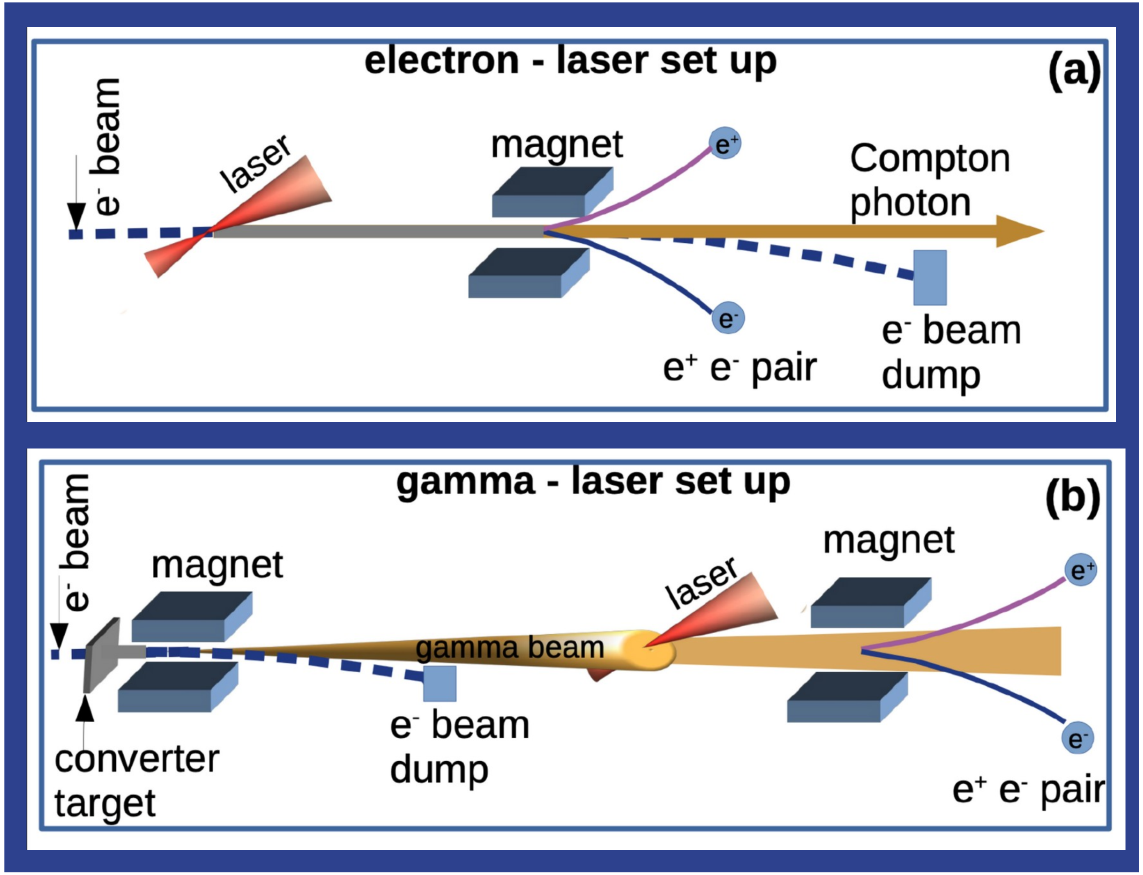
First experiment to try this E144 @ SLAC in 1990s.
Nowadays experiments : SLAC-E320 (US), Astra Gemini (UK), ELI-NP (RO)



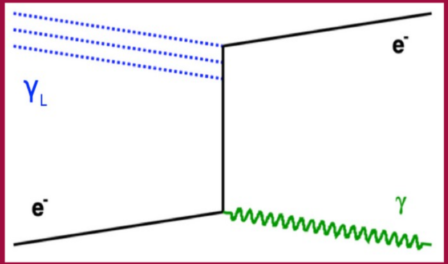
Field intensity parameter

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

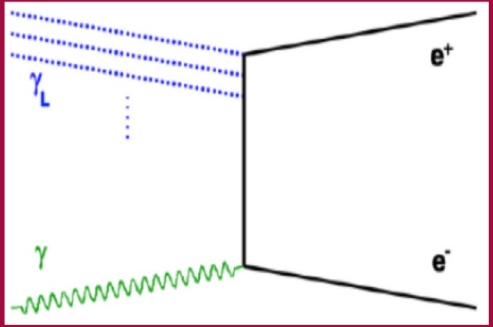
SFQED at LUXE



Physics processes



Non-linear Compton scattering



Non-linear Breit-Wheeler
(photons from gamma beam and from Compton production)

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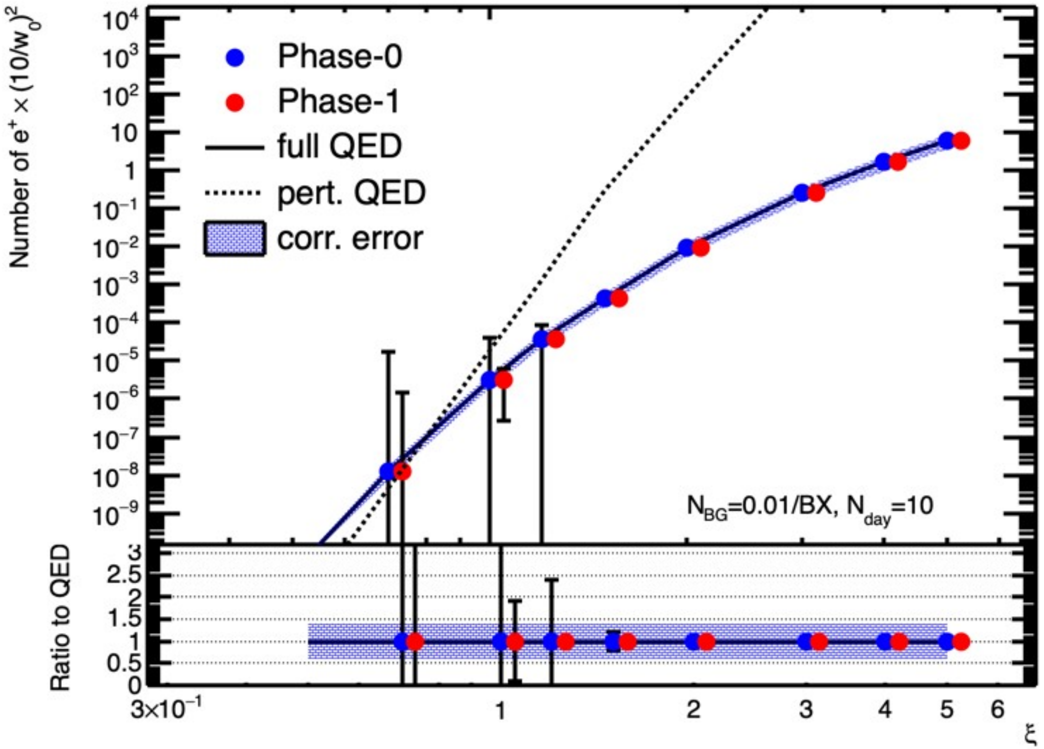
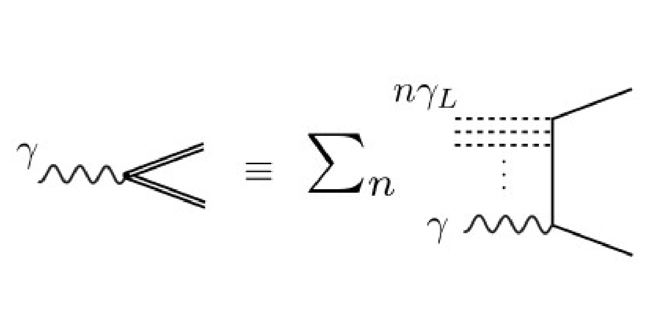
SFQED at LUXE: non-linear Breit-Wheeler





ξ> 1

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

Positron rate production between $10^{-5} - 10^{7}$ e^+/bunch

Non perturbative Breit-Wheeler has no classical equivalent

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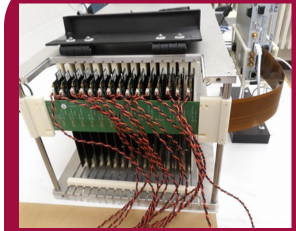
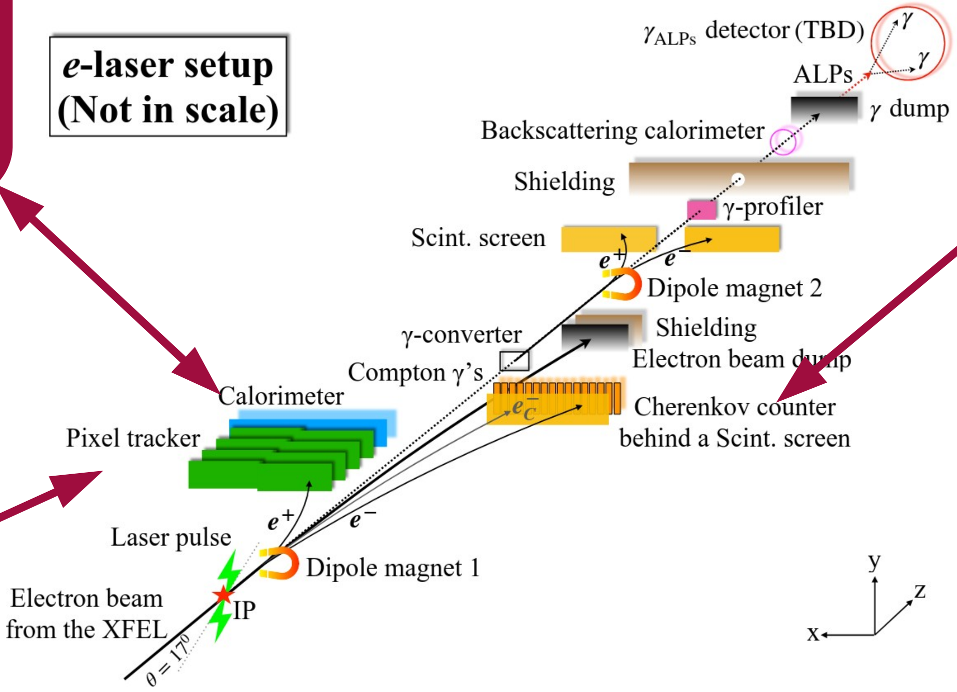
Detector challenges (few ILC-like cases)

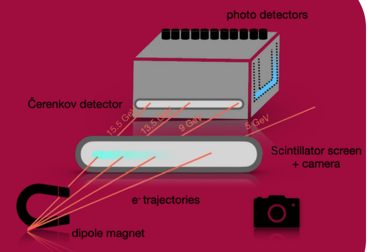


CALICE -type calorimeter

FCAL-type calorimeter

ALPIDE sensors (ALICE)





ILC polarimeter

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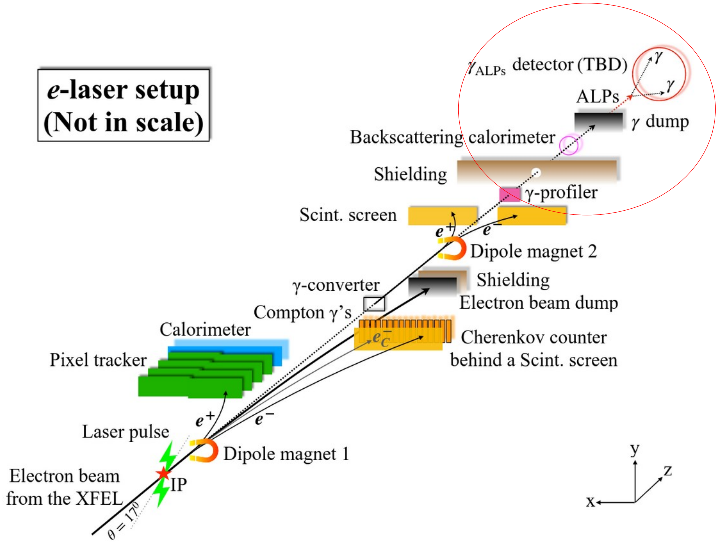
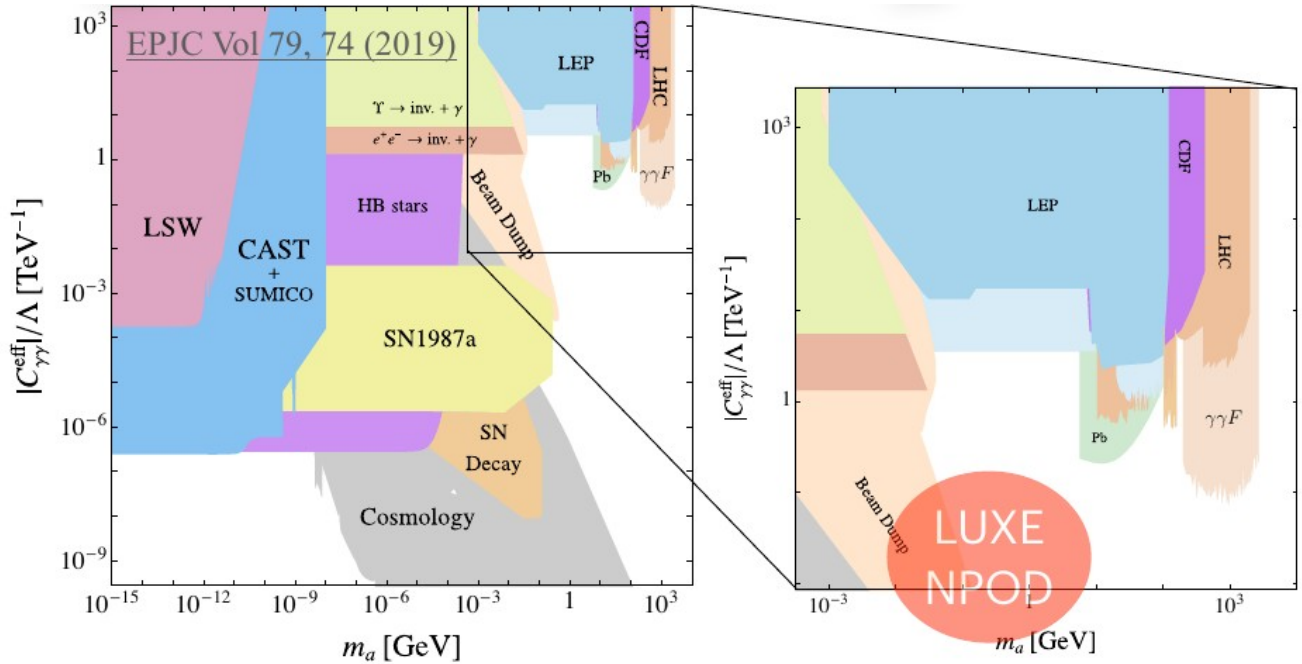
2 LUXE NPOD: new physics search with Optical Dump



Axions parameters landscape



LUXE-NPOD Can explore uncharted territory

- Axions appears in many BSM scenarios
- Solution to strong CP problem
  - (breaking Peccei–Quinn (PQ) symmetry) → Goldstone boson (non-zero mass)
- Natural candidate for Dark Matter

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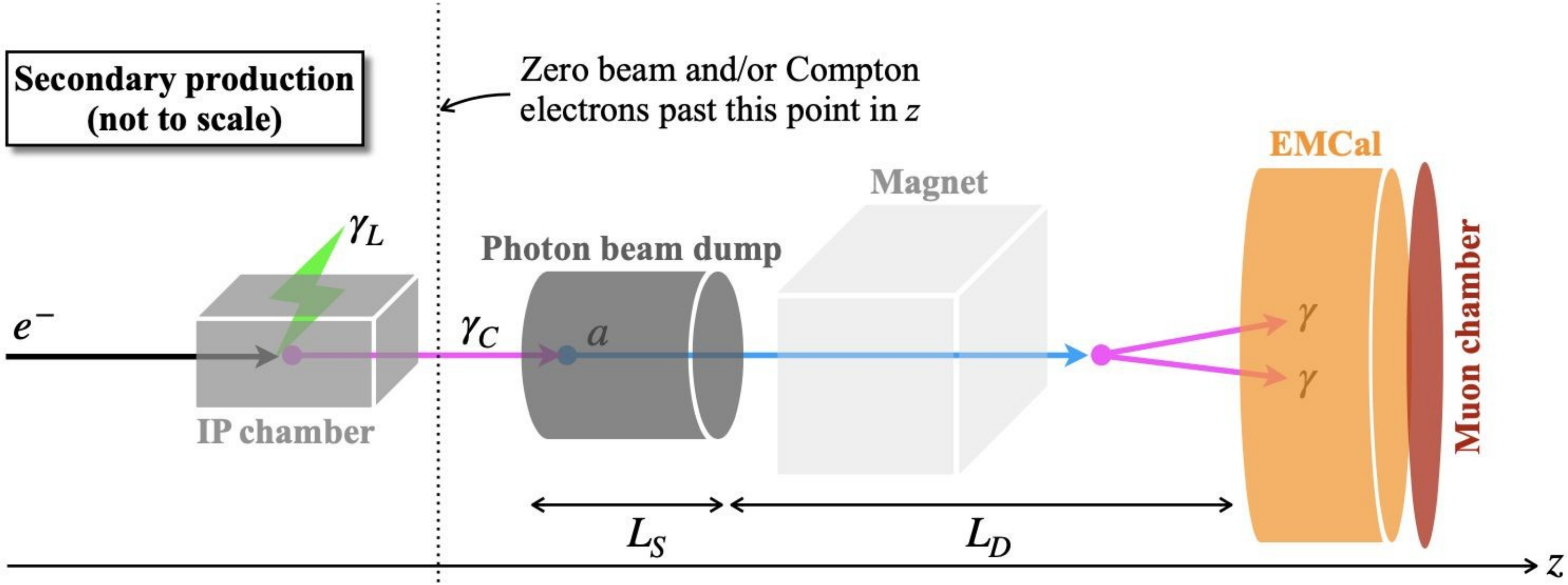
LUXE NPOD: new physics search with Optical Dump



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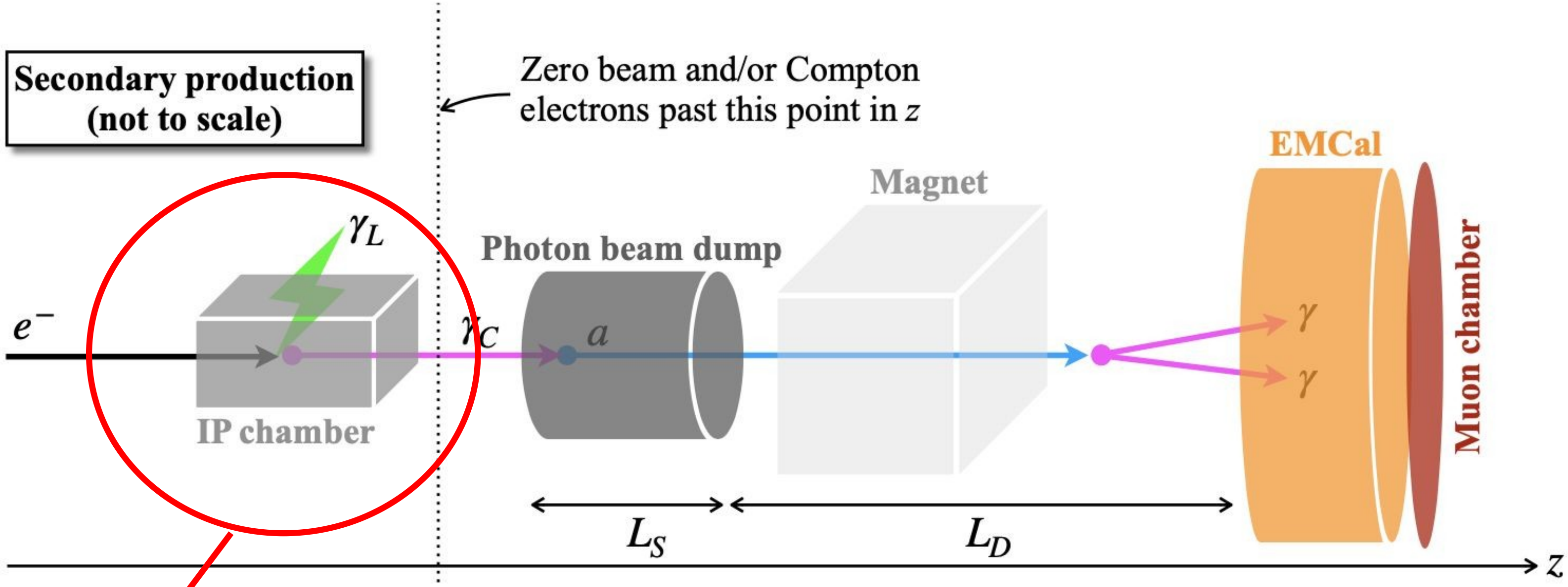

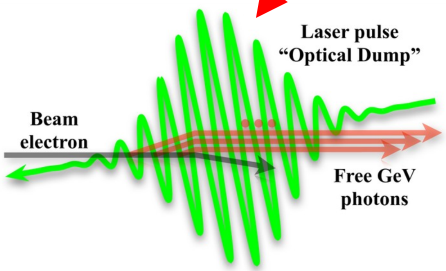

▶ The laser acts like a "solid dump" for electrons producing O(GeV) photons

- "laser medium" is transparent to photons
- → γ photons can reach physical dump
- Background free

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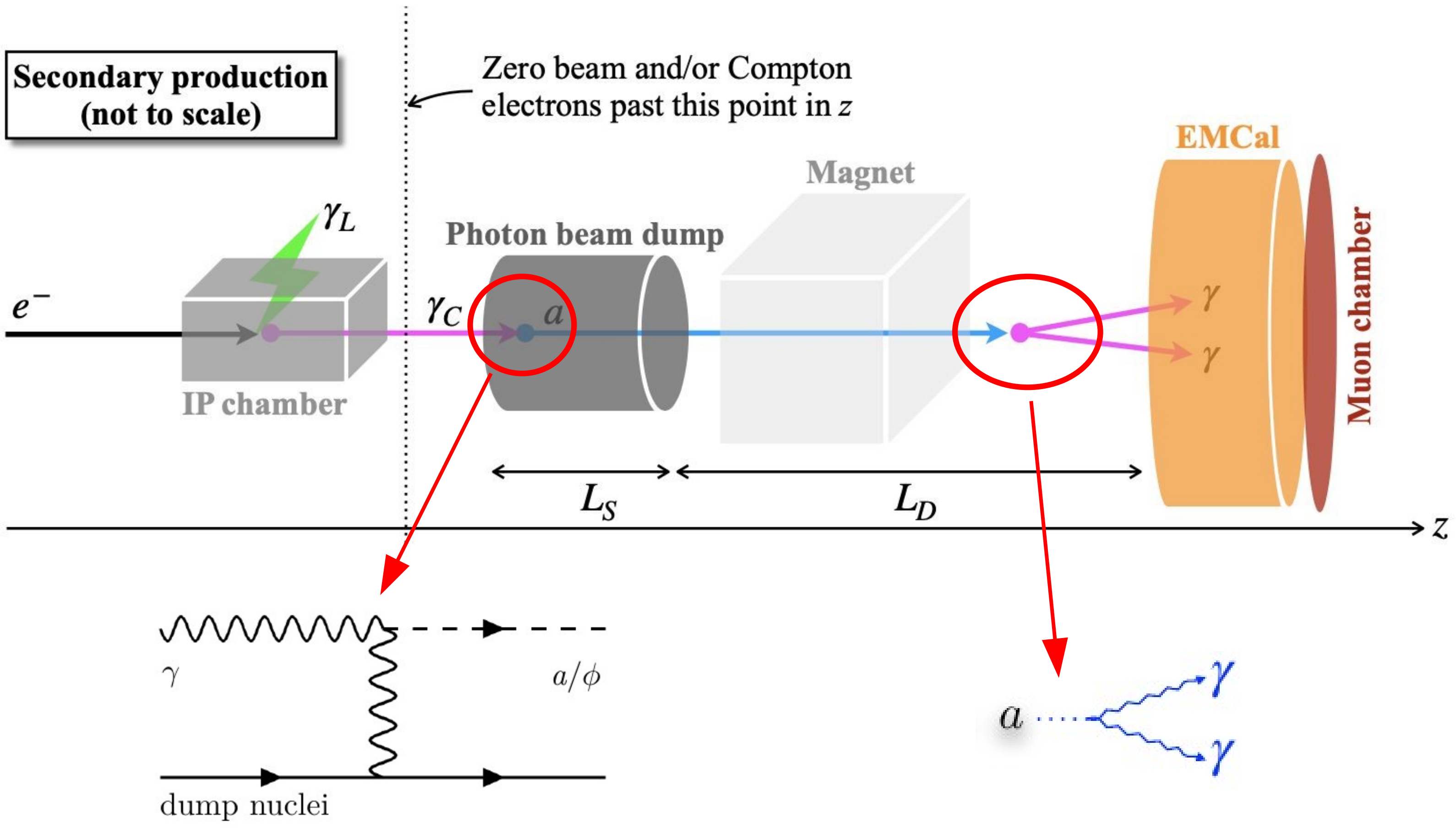
LUXE NPOD: new physics search with Optical Dump



Primakoff process (at nuclei in the dump)

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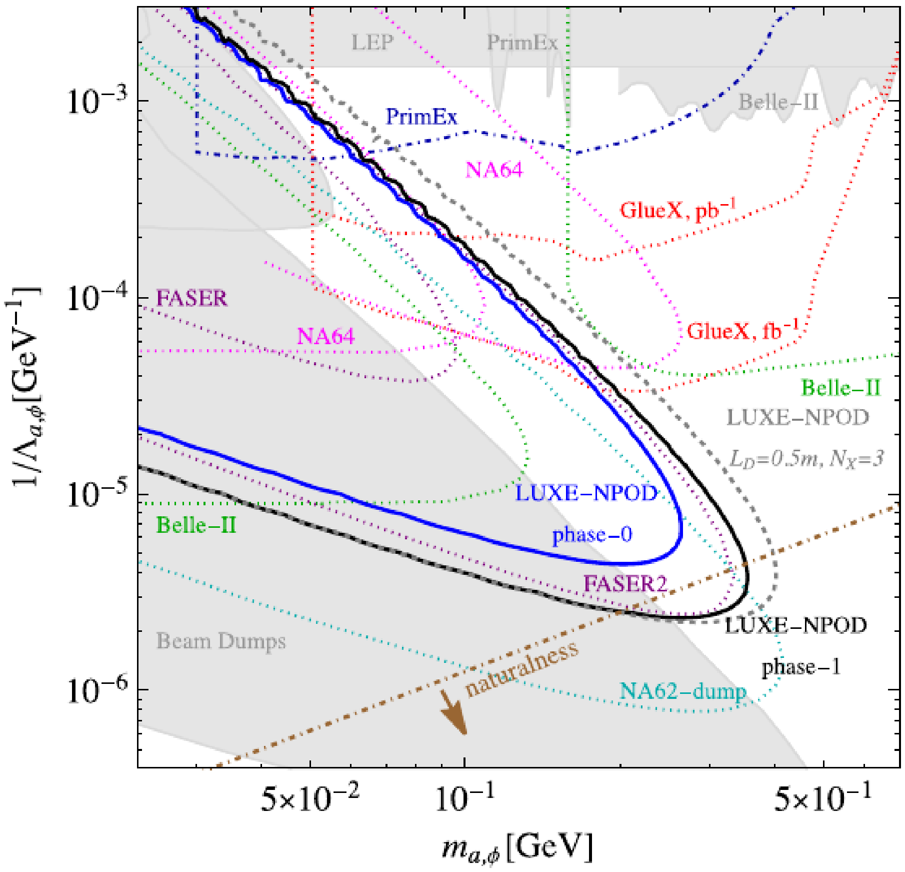
LUXE NPOD: new physics search with Optical Dump



- Absolute rates depends on:
  - Geometrical acceptance
  - Photons on target

$$\mathcal{L}_{eff} = N_{e-inBX} N_{BX} \frac{9\rho_N X_0}{7 A_N m_0}$$

- Projections for 1 year data taking (10^7 s)
  - expected background free
  - Optimization for different solid dump design
- 95%CL competitive with FASER2 (>2029) and NA62
- LUXE phase-1 can reach the naturalness bound

Current coverage

Proposed and future experiments

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3

LUXE at Higgs Factories

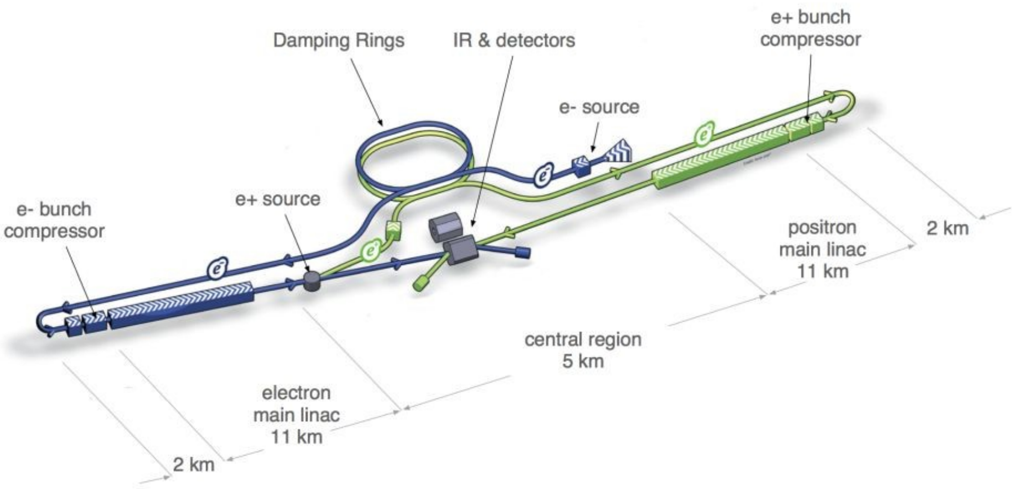
3

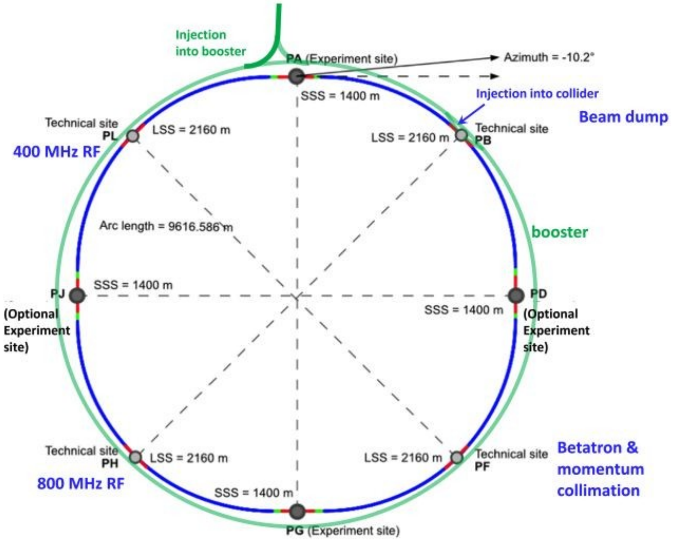
LUXE at Higg Factories

LU~~X~~E at ILC: LUIE ?

Prospects of a LUXE at Higgs factories

- Use ILC spent beams or FCC-ee beam dumps (its booster)
  - and an optical laser as in LUXE





Prospects of a LUXE at Higgs factories

Eu.XFEL	ILC 250	FCC-ee	FCC-ee booster
E_e = 16.5 GeV	E_e = 125 GeV	E_e = 120 GeV	E_e = 120 GeV
$N_e = 1.5 \times 10^9$	$N_e = 2 \times 10^{10}$	$N_e = 1.8 \times 10^{11}$	$N_e = 0.5 \times 10^{10}$
$N_{BX} = 10^7$	$N_{BX} = 6.6 \times 10^{10}$	$N_{BX} = 1.1 \times 10^5$	$N_{BX} = 3.3 \times 10^8$
Signal yield:	$\times$ 8.8 10^4	$\times$ 1.3	$\times$1.1 10^3

▶ Assumptions:

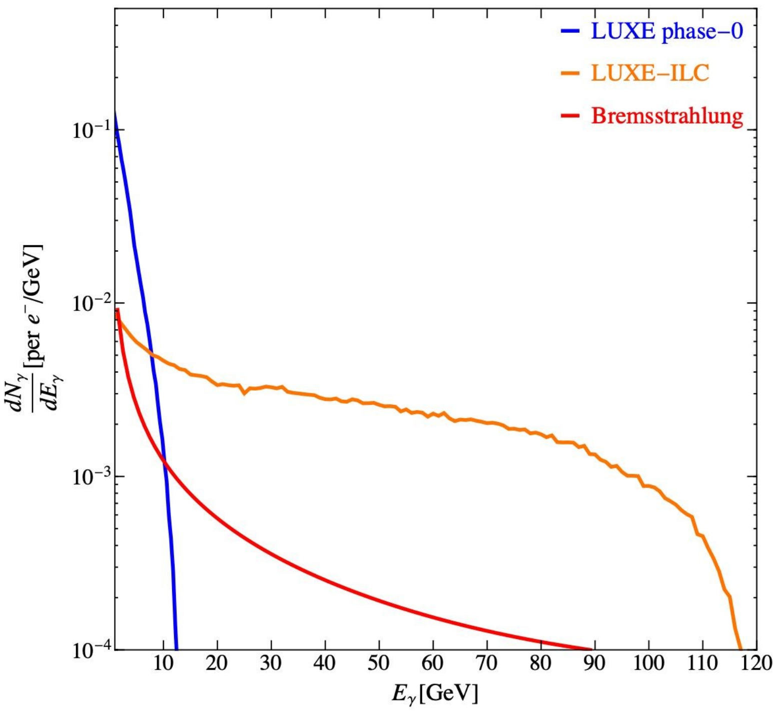
- 10^7 seconds of data-taking time per year
- Use ILC spent beams (broader energy spectrum is not problematic)
- Dump of FCC-ee beams 3 times per day
- Dedicated FCC-ee booster cycles for a beam dump every 10 seconds

* tables compiled by F. Meloni with input from J. List and F. Zimmermann

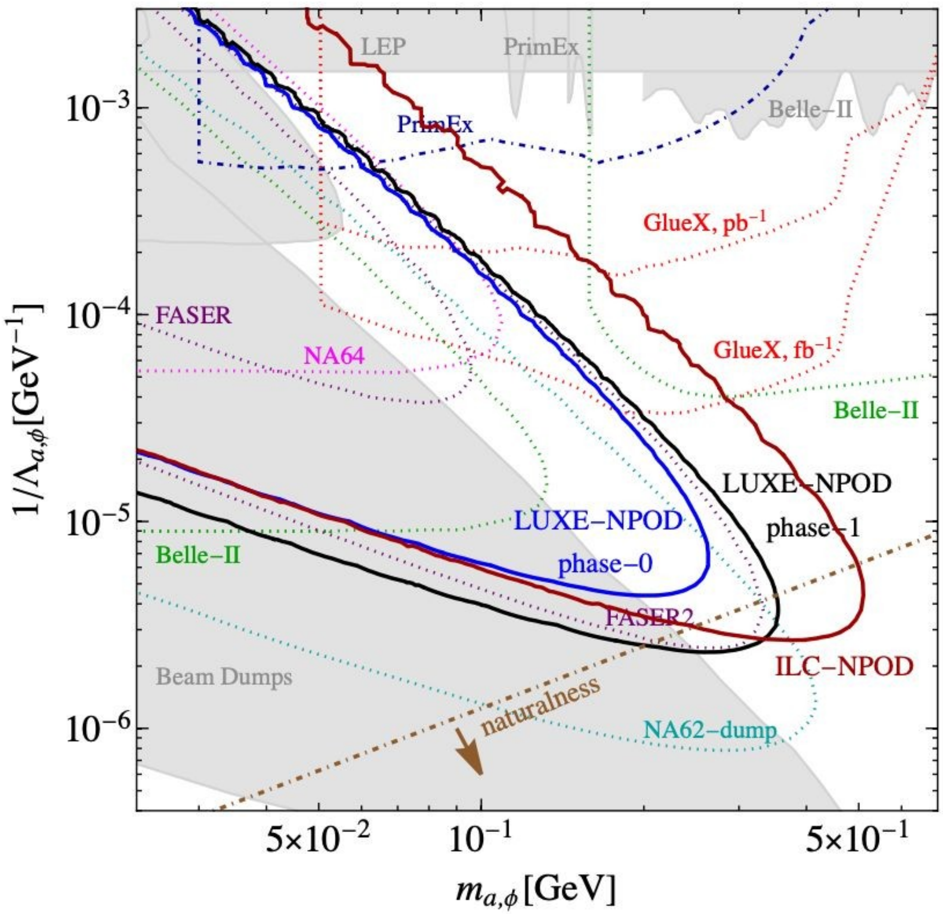
More info in J. List's talk

Prospects of a LUXE at ILC

- Harder photon spectrum
  - Average **E ɣ ~ 40 GeV**
  - **Lorentz boost** > 10 times EU.XFEL
- **ALPs** production
  - No large change in production cross-section
  - Significantly **larger ALP lorentz boost →** Access to larger masses!



ILC-NPOD: new physics search with Optical Dump



- ▶ background-free scenario
  - Double dump depth
- ▶ Keep all parameters as LUXE-phase-0, except for the beam energy
  - Only primakoff process (secondary production)
- ▶ **Sizeable gain in sensitivity**

Current coverage

Proposed and future experiments

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4 Summary & more

Summary

- **LUXE is a novel experiment for non-perturbative QED**
  - Data taking expected to **start in 2026**
- Designed to study **collisions** between **16.5 GeV electrons or photons** and **High Power optical Laser beam** (40 and 350 TW, phase-0/1)
- Direct searches of **BSM** physics thanks to the high intensity photon fluxe (of few GeV)
  - **LUXE NPOD** will study **uncharted** ALPs parameter space
- A dedicated experiment at a future **Higgs factory could offer major gains**
  - Higher **beam energy**
  - Much higher number of bunches

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LUXE

- 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

Interested? Join us !

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LUXE

membership of Russian institutes suspended

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back-up

SFQED at LUXE

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

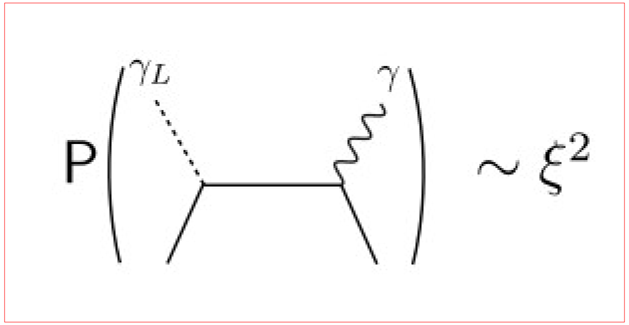
~ number of laser photons interacting with the electron beam at a given time

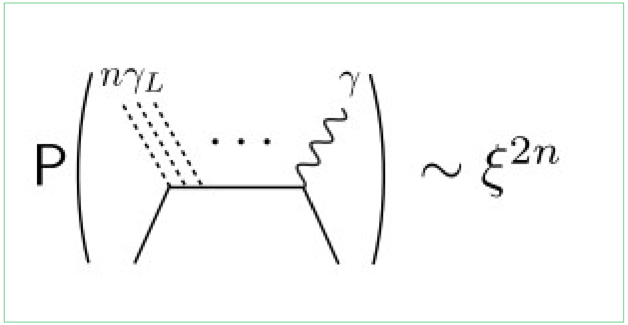
Laser photon density ~ ξ^2

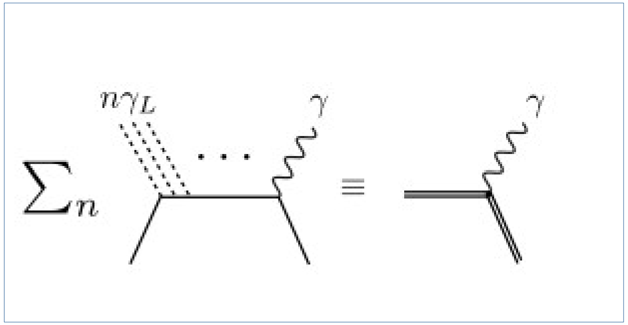
Theory Parameter		Definition	Range accessed in LUXE phase-0	phase-1
ξ	Classical non-linearity parameter	$\xi = \frac{m_e}{\omega_L}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$	≤ 6	≤ 19
η_i	Energy parameter	$\eta_i = \frac{\omega_L \varepsilon_i}{m_e^2}(1+\beta\cos\theta)$	$\eta_i \leq 0.2$	
χ_i	Quantum non-linearity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

How much the QED deviates from the classical limit

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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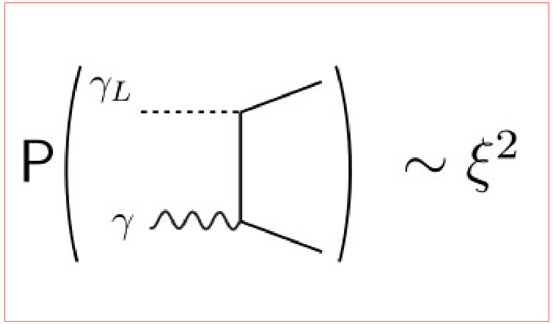
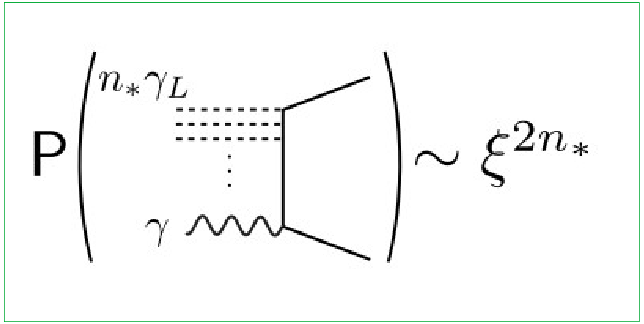
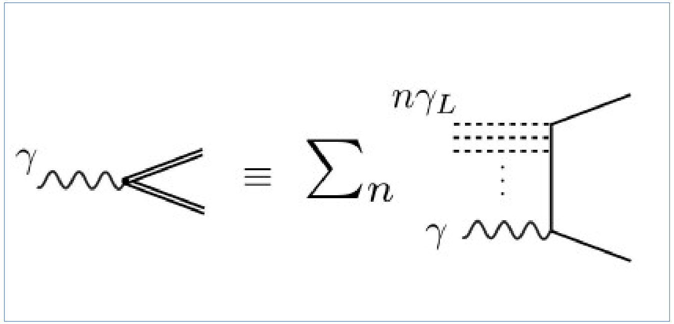
SFQED at LUXE: non-linear Breit-Wheeler







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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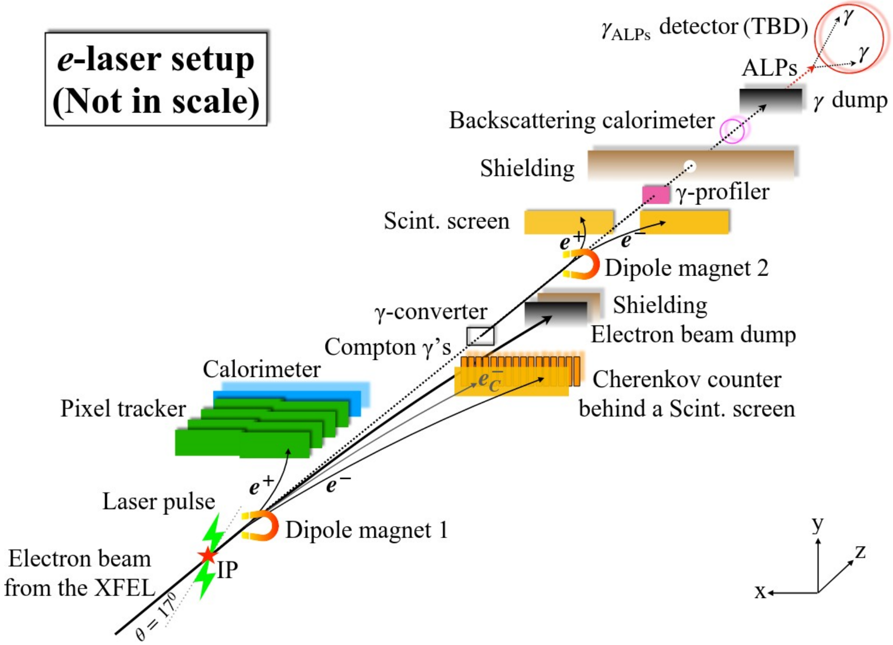
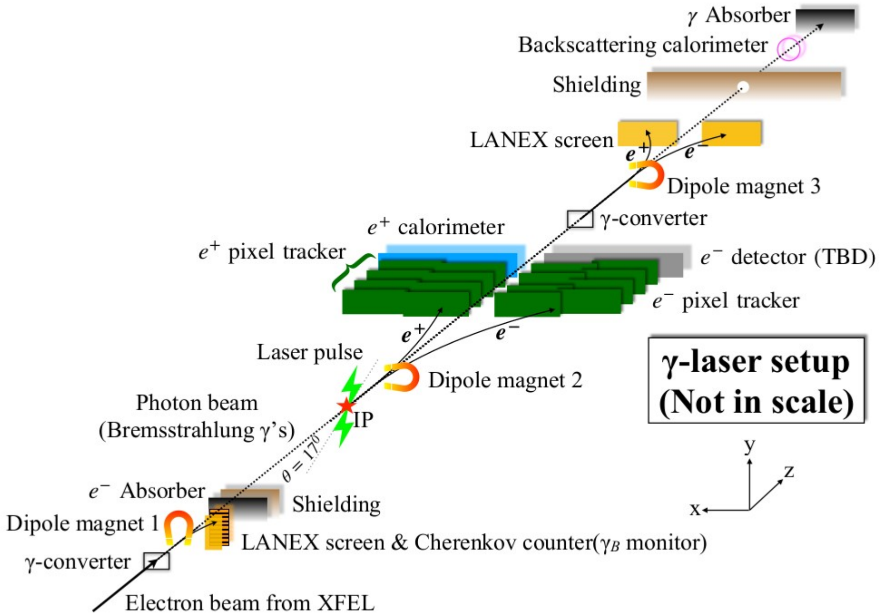
Detector challenges

- Vast range of multiplicities of signal and backgrounds per beam bunch depending on the mode of operation
  - Physics-driven detector technologies at each location





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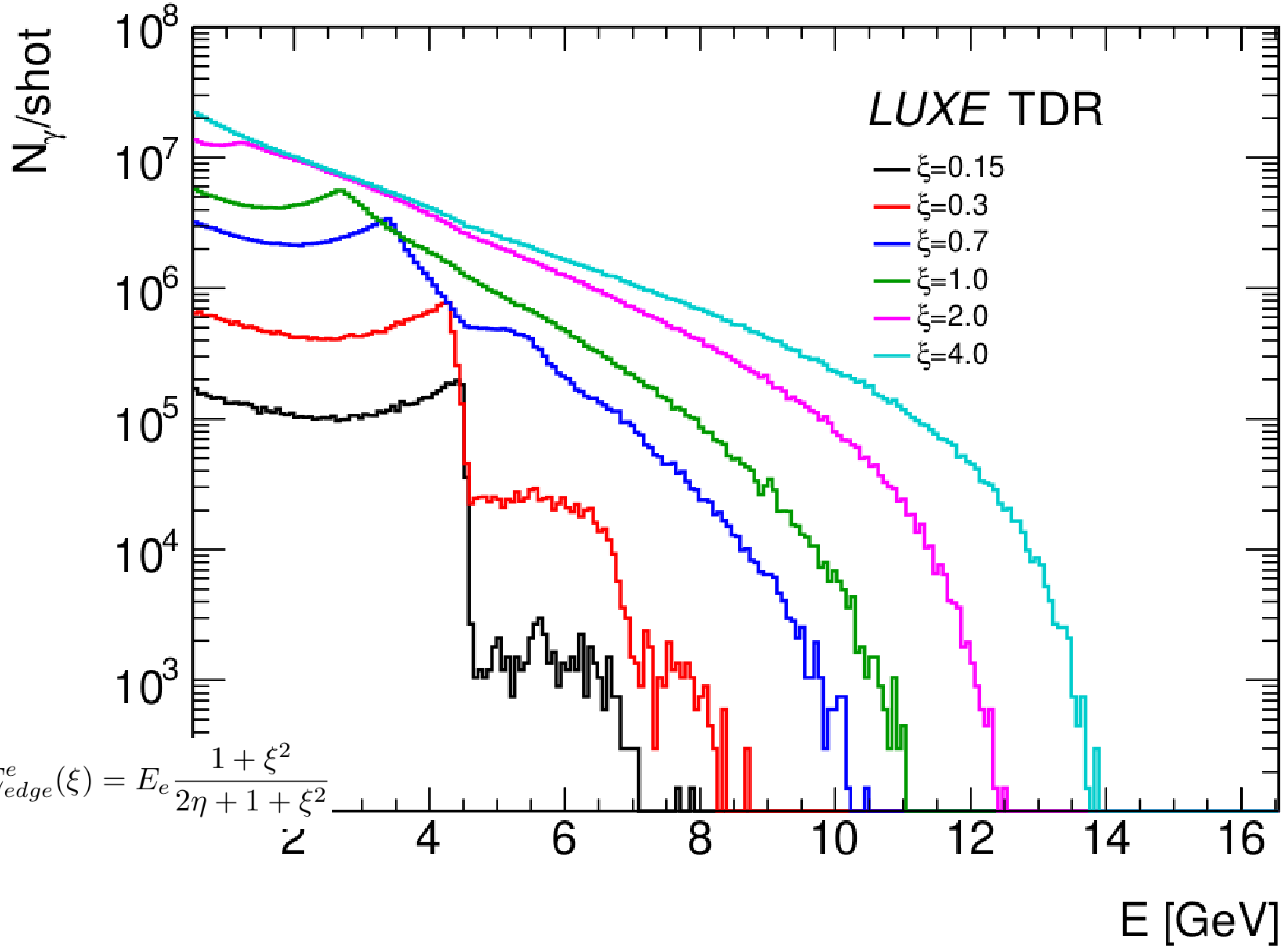
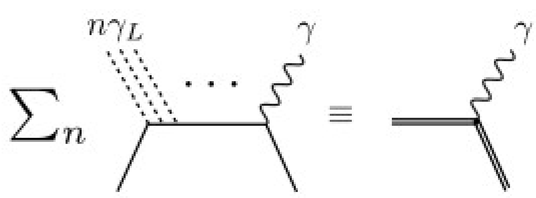
SFQED at LUXE: non-linear Compton Scattering



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



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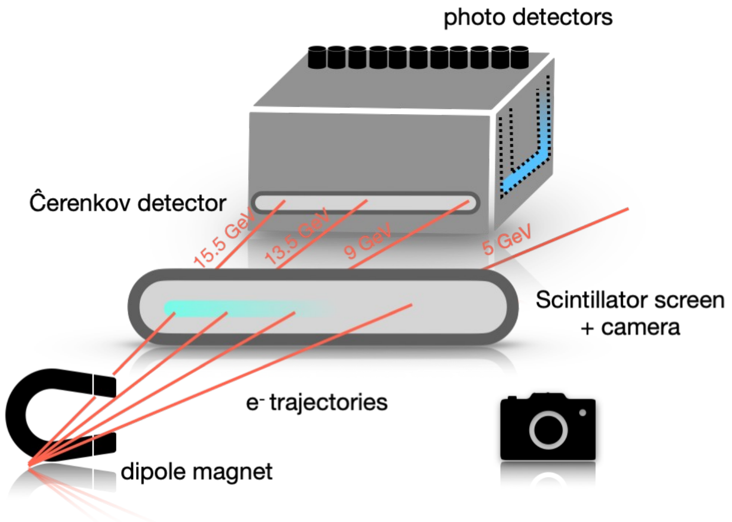
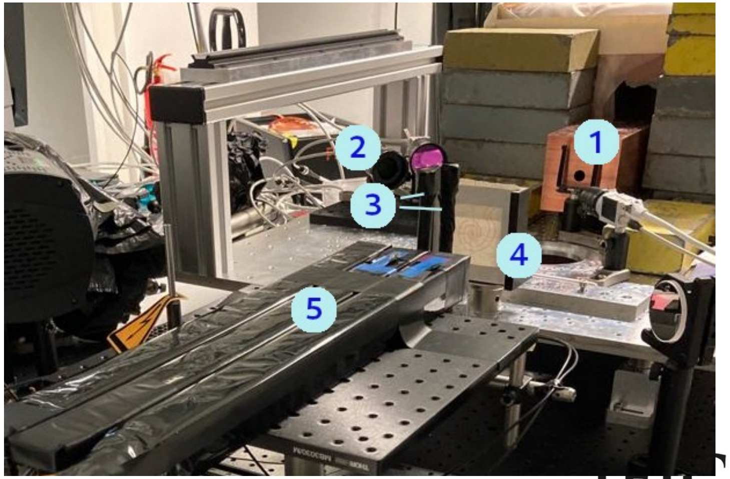
Electron side (electron-laser mode)

- 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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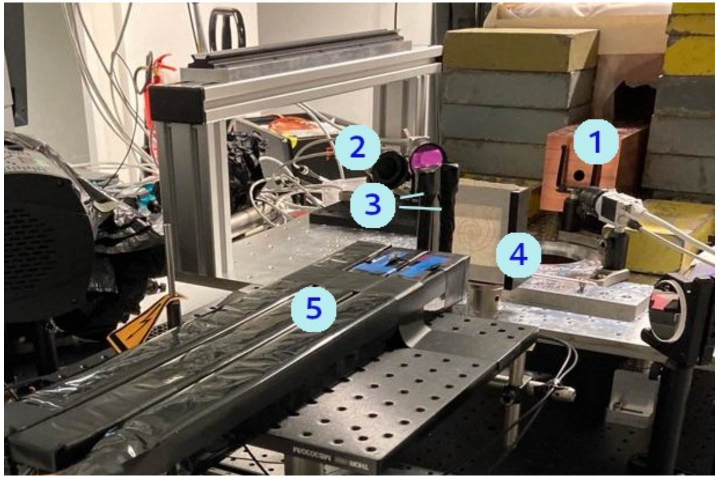

LUXE detectors test beam setup photo.
1 - collimator, 2 - cameras, 3 - Cherenkov detector
straws, 4 - scintillator screen, 5 - lead glass

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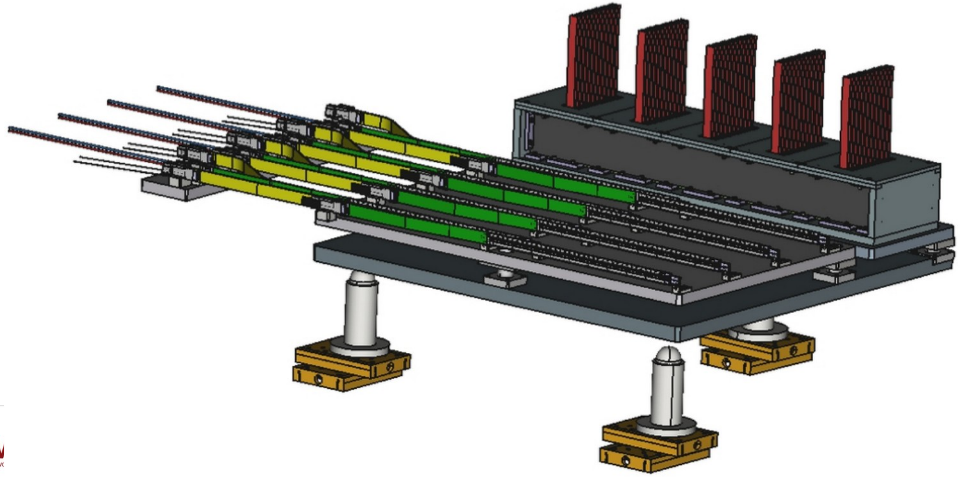
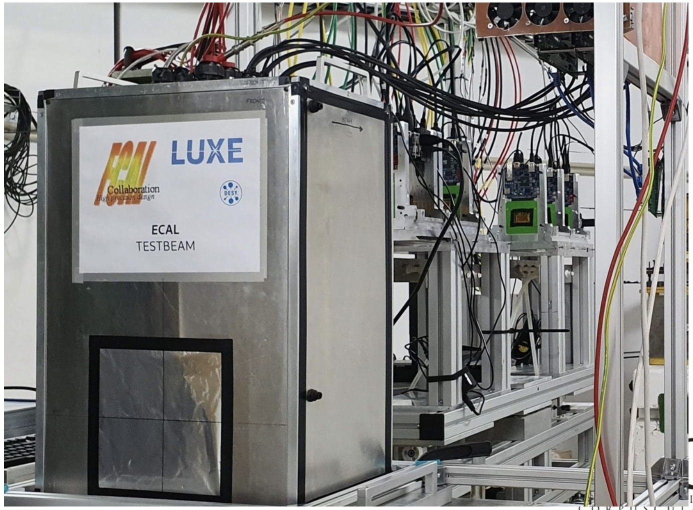
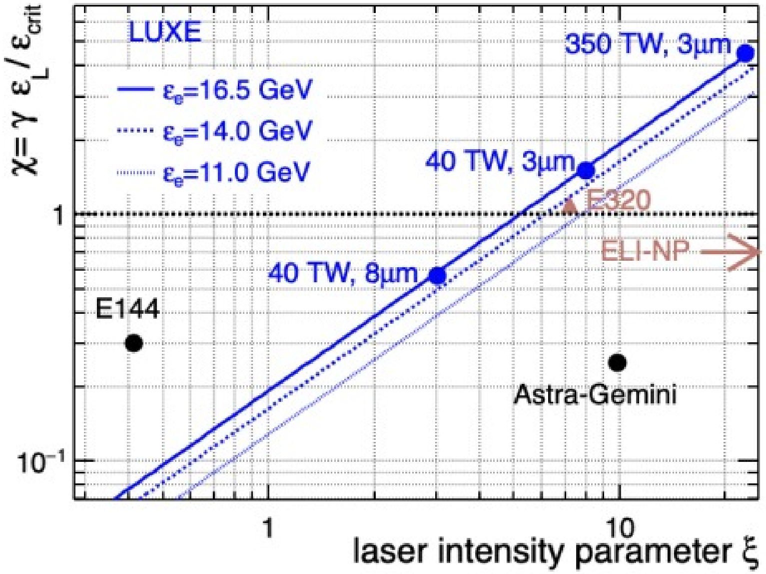
Positron side (electron-laser mode)

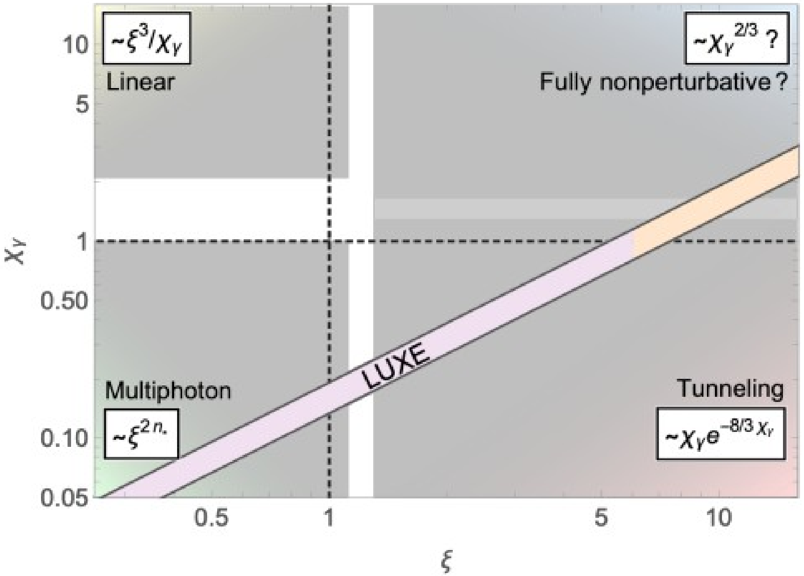
- Tracker based on ALPIDE sensors (developed by ALICE for phase 1 upgrade)
  - 5um spatial resolution
- Multilayer high granular calorimeters based on linear collider prototypes (FCAL and SiWECAL-CALICE)
  - $20X_0$, 5.5x5.5 mm^2 sensors (silicon and GaAs under study)
  - Ultra compact to ensure minimal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





LUXE in SFQED parameter space



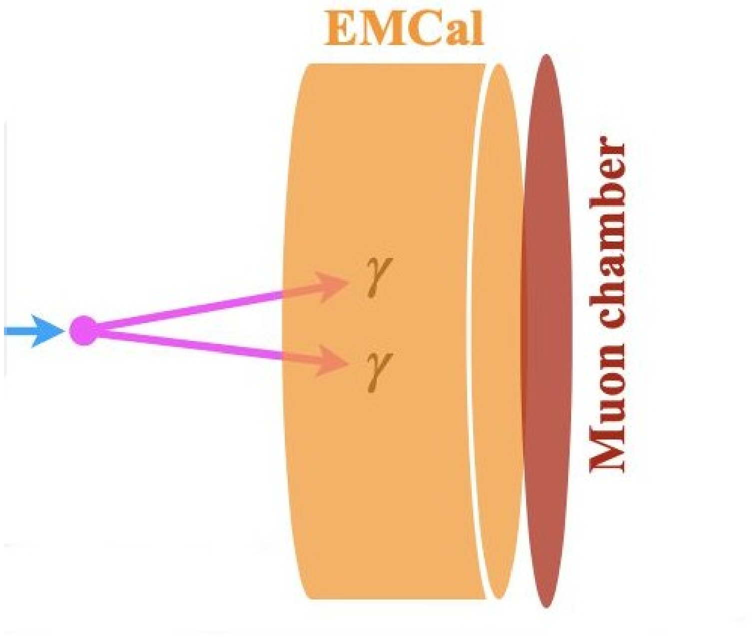


- E144: SLAC experiment in 1990's, using 46.6 GeV electron beam *[Bamber et al. (SLAC 144) '99]*
  → reached χ ≤ 0.25, ξ<0.4, observed $e^- + n\gamma_L \to e^- e^+ e^-$ process
  → observed start of the ξ^{2n} power law

- LUXE: - good chance to be first to enter ξ>1 and χ>1 regime!
  - directly study collisions between LASER and real GeV photons

LUXE NPOD: Detector requirements

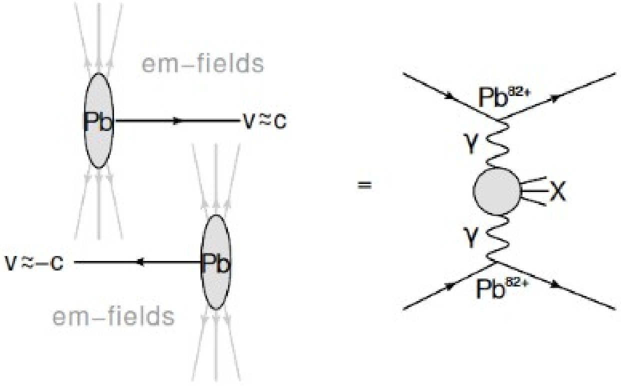
- Good energy and spatial resolution
  - Able to separate photon showers and reconstruct the originating vertex
  - Two photon system invariant mass reconstruction
- Background rejection:
  - Photon neutron discrimination
  - Timing <0.1 ns

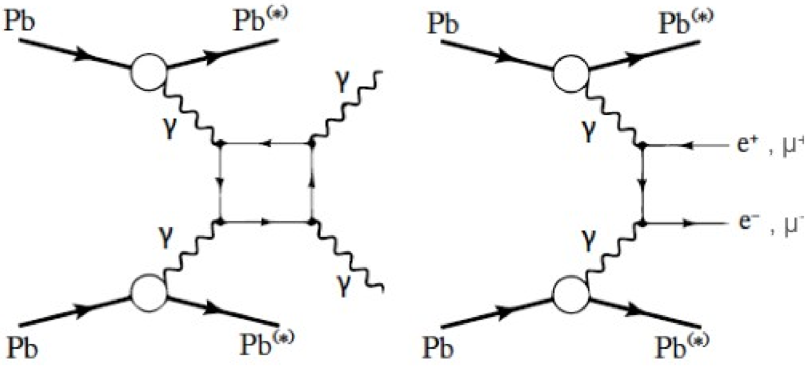


Detector proposal/design is in progress

LUXE and LHC light-by-light scattering

- LHC: photon-photon interaction in ultra-perophérial 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.
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Slide from R. Jacobs