A new experiment to study Non-Perturbative QED in electron/photon-laser collisions

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speaking for the LUXE Collaboration [luxe.desy.de]

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Overview

LUXE: ***Laser und XFEL Experiment***

- A high power laser beam (40 or 350 TW)
- The EU-XFEL electron beam (16.5 GeV)

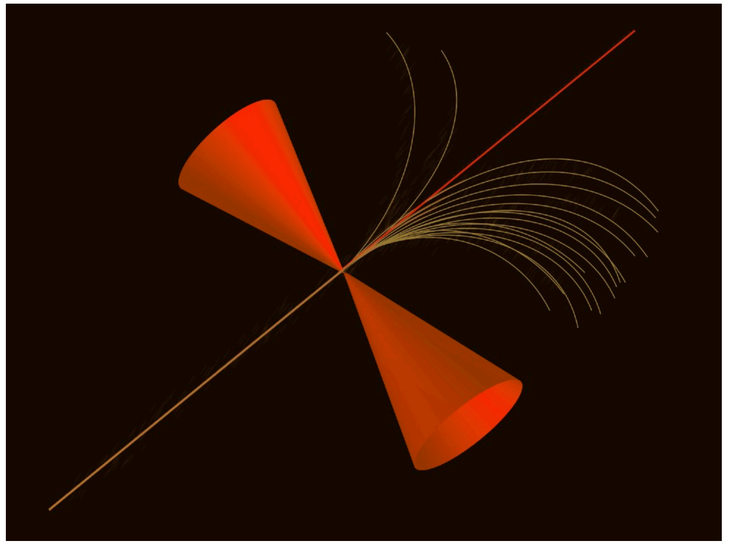
  ... or converted GeV gamma beam

Goal: precise measurement of non-perturbative QED

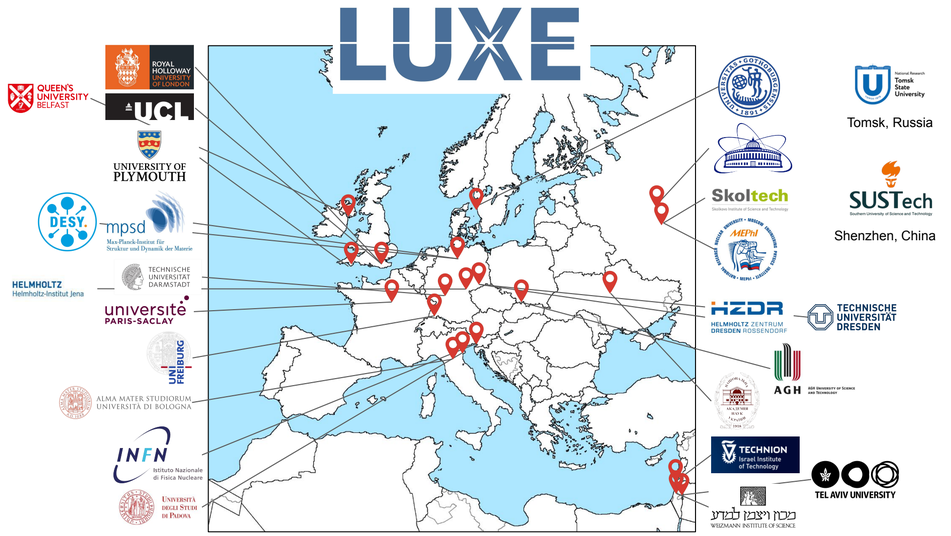
- **Physics above Schwinger limit**
  with an electric field in the centre-of-mass frame
- QED Theory's transition from linear to nonlinear
- BSM physics in the strong field interaction

An international collaboration

- 88 researchers from 29 institutes (till CDR)
- among high-energy particle physics and
  high-power laser physics communities



LUXE CDR (arXiv: 2102.02032, cover for EPJ ST)



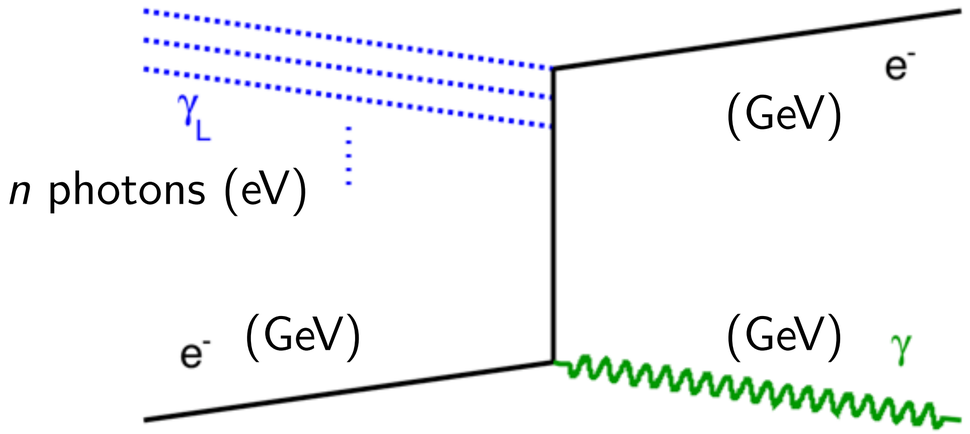
Introduction: Multi-photon process

Strong-field QED & Multi-photon process

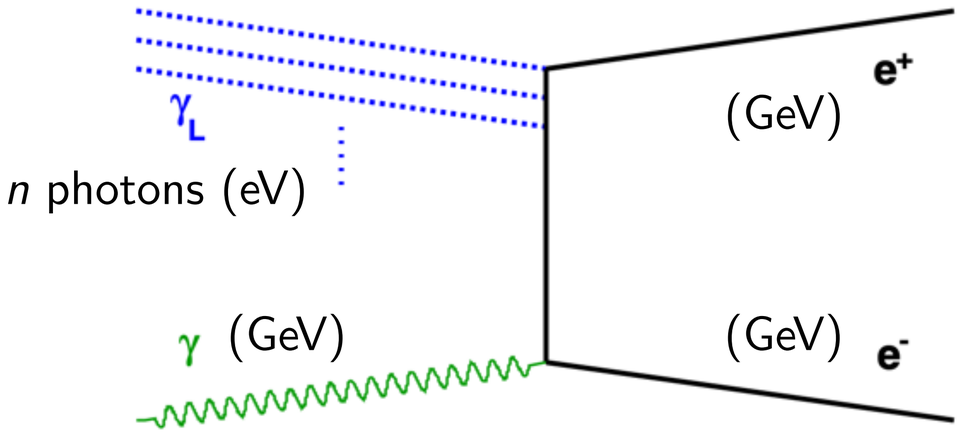
- Cross-section increased with the photon density that equivalent to light intensity $I \propto \xi^2$
- Photon number $n \gg 1$
- Effective field theory by Euler–Heisenberg at 1936
- An example: for inverse Compton scattering,
  production rate will increase, but cut-off energy will drop (the "Compton edge's shift").

$$\xi = (eE)/(m_e c\omega)$$

quoted as "intensity parameter"



Multi-photon Compton scattering



Multi-photon Breit–Wheeler process

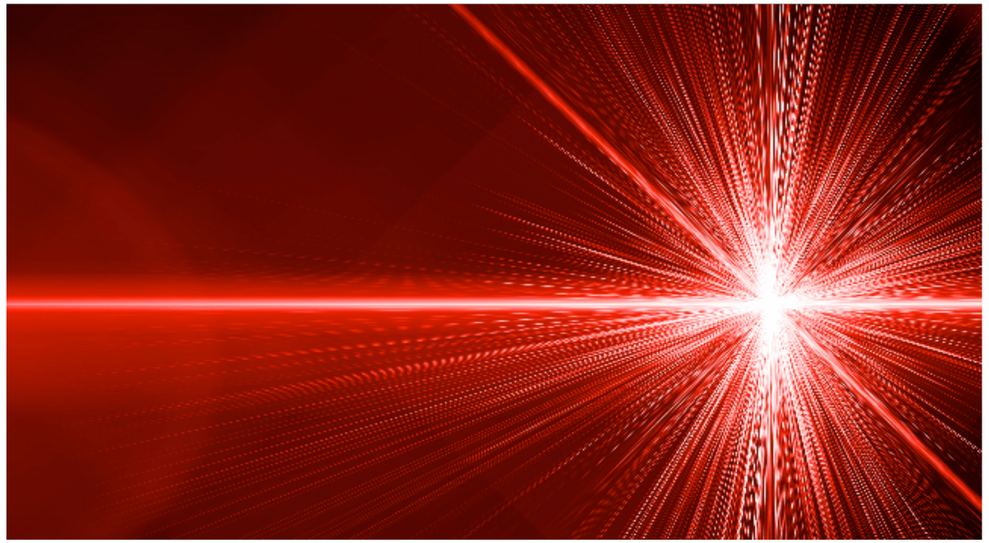
Introduction: Schwinger limit

Schwinger critical electric field E_{cr} (found by Sauter)

- pulling pairs out of vacuum
- corresponding to millions of photons confined in (electron's Compton wavelength)^3

Schwinger field $E_{\text{cr}} = \dfrac{m_e^2}{\alpha} = 1.32 \times 10^{16}\ \text{V} \cdot \text{cm}^{-1}$

$\xi = 3.29 \times 10^5$ for 800 nm laser in lab frame



Heating the vacuum to "boiling" with laser

How to reach the unreachable?

- Lorentz boost in a Lorentz-invariant EFT

$\chi =$ normalised boosted E field $\propto 2\gamma\xi$

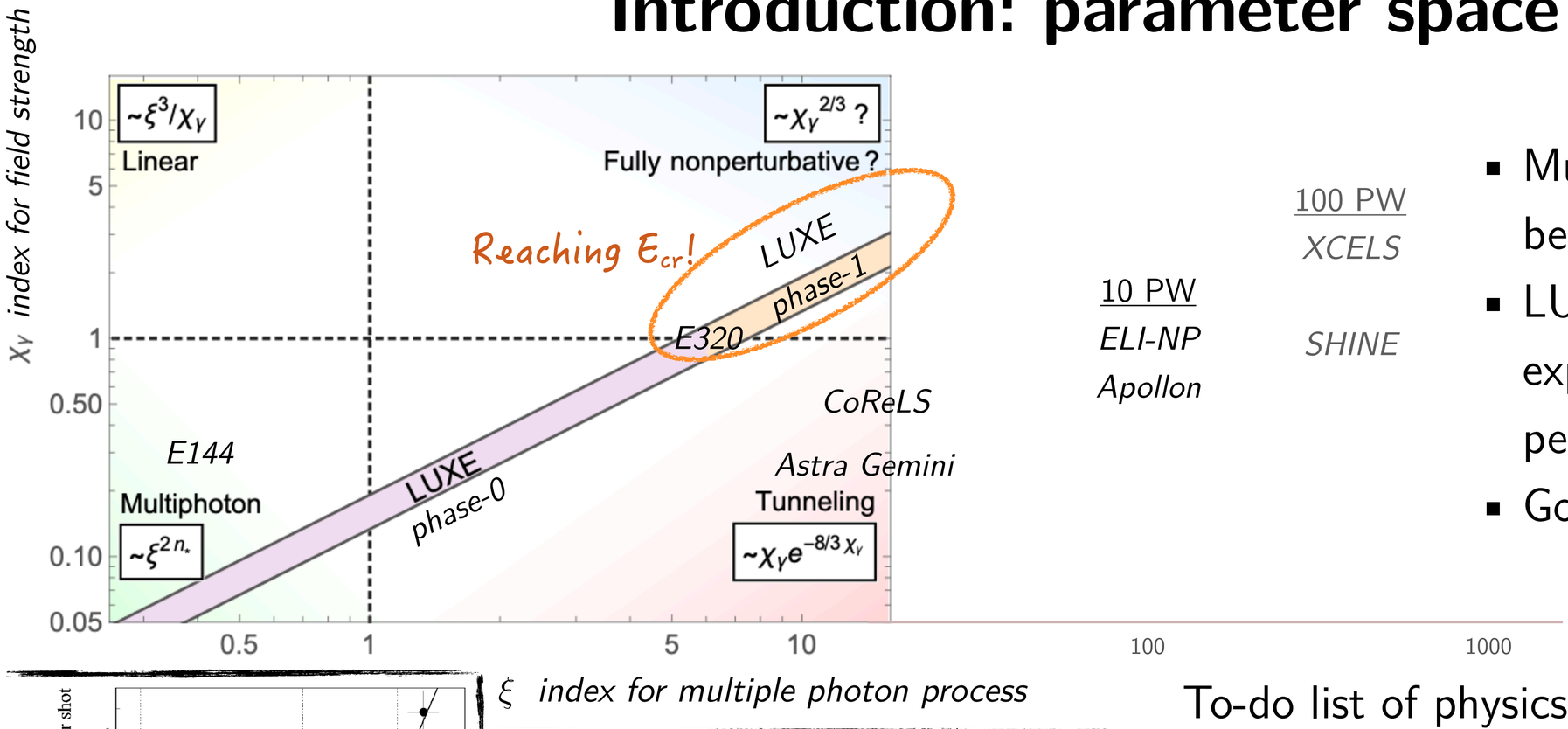
$\gamma = 3.3 \times 10^4$ for 16.5 GeV electron. Will reach E_{cr} with $\xi > 5$.

EFT Lagrangian $\mathcal{L}_{\text{EH}} = \dfrac{\alpha^2}{5760\pi^2 m_e^4}\left[4(F^{\alpha\beta}F_{\alpha\beta})^2 + 7(\tilde{F}^{\alpha\beta}F_{\alpha\beta})^2\right]$

the two invariants of electromagnetic field

- In lab frame, it's laser field interacting with electron beam's field

Introduction: parameter space

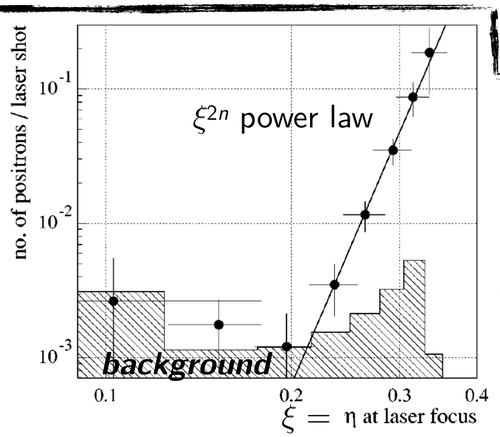


100 PW
XCELS

10 PW
ELI-NP
Apollon

SHINE

- Multiple facilities has been/are being built around the globe
- LUXE might be one of the first experiments to reach the non-perturbative regime
- Goal: Data taking in *2024*



PRD 60 092004 (1999)
E144 experiment: collision between 46.6 GeV electron and sub-TW laser beams
photon num. equivalent to $n \approx 5$

To-do list of physics above the critical field

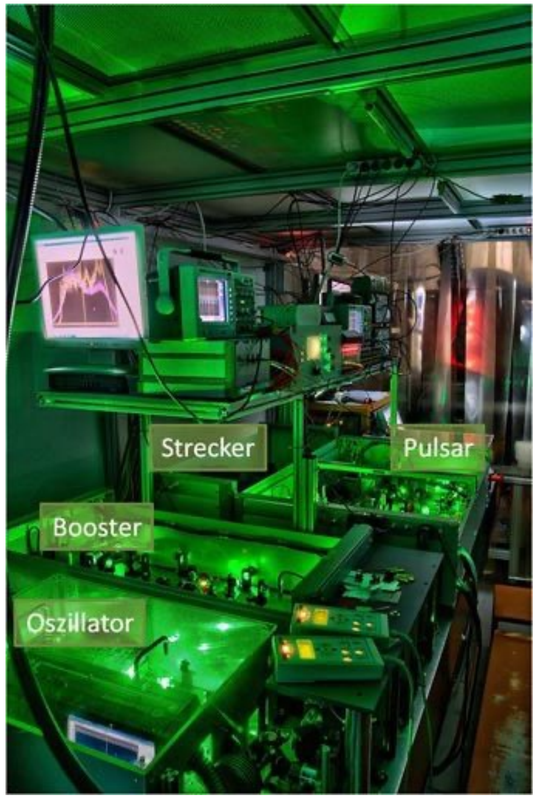
- Compton edge's shift
- Production rate's change in BW process
- Axion-like-particle's creation

Demand precise apparatus and measurement of photon & electron/positron spectra and rates

Experimental specs.: laser

- High power CPA Ti:Sapphire laser from HI Jena (JETI-40) and another commercial laser
- Laser repetition rate at 1 Hz
- High precision laser diagnose: less than 5% uncertainty on peak intensity & 1% shot-to-shot uncertainty
- Development & Installation in 2021-2024

	Phase 0		**Phase 1**
Power @ waist radius	40 TW @ 8 um	40 TW @ 3 um	350 TW @ 3 um
wavelength	800 nm red laser (1.55 eV)		
Duration	30 fs (10 cycles)		
Peak intensity	0.19×10^{20} W cm^{-2}	1.33×10^{20} W cm^{-2}	12×10^{20} W cm^{-2}
Peak ξ	3.0	7.9	23.6
Peak χ (16.5 GeV)	0.56	1.5	4.5
Collision angle	17.2° (angular coefficient = 0.978)		



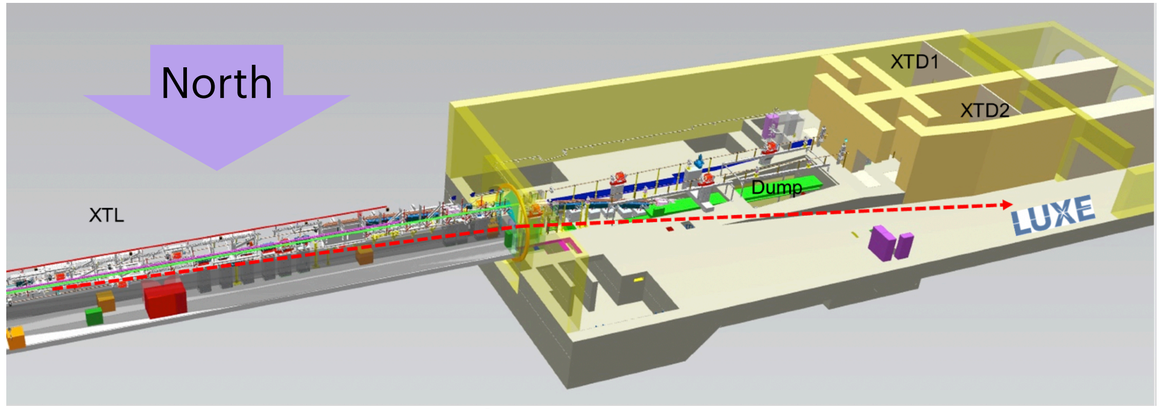
Experimental specs.: EU-XFEL

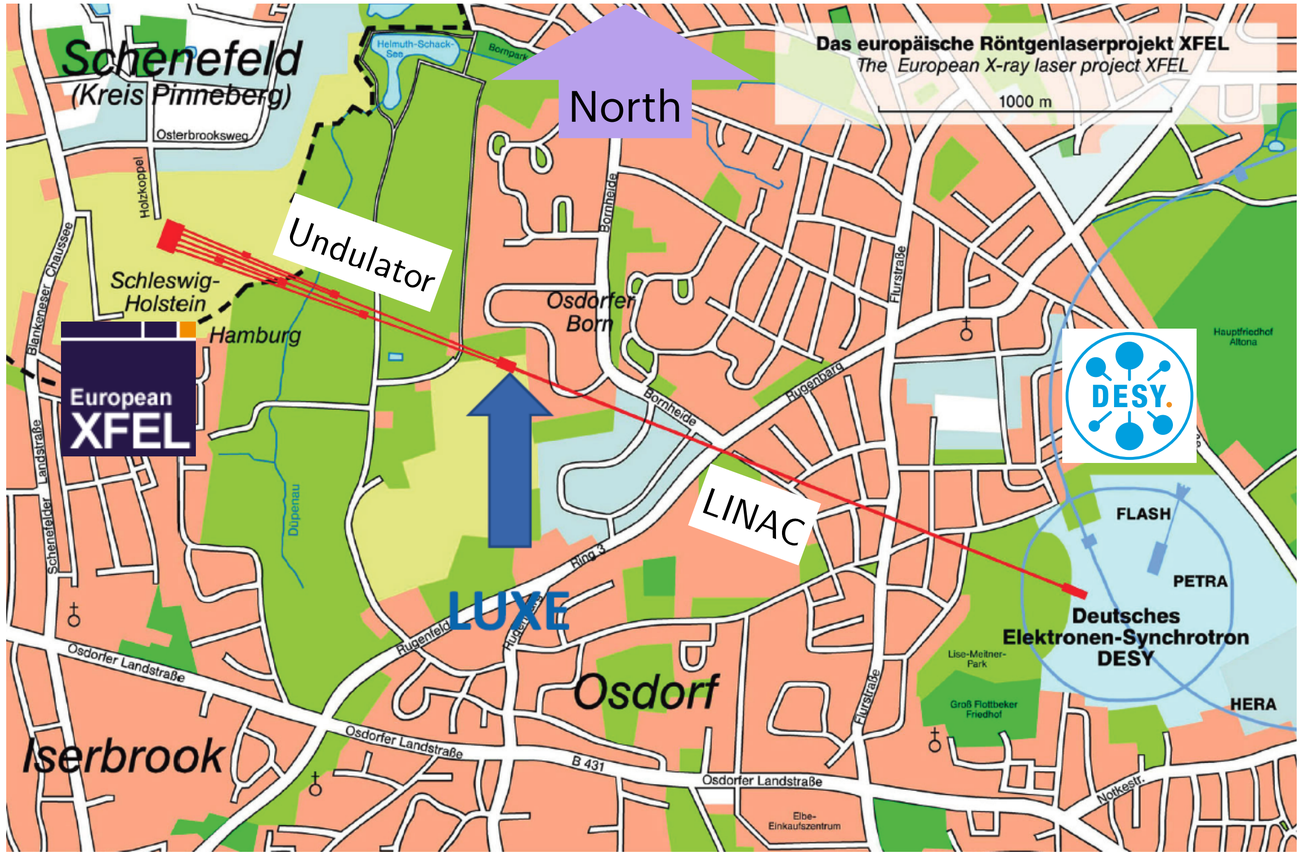
European X-ray Free-Electron Laser

- Electron beam injected at DESY campus
- Accelerated in a 1.9-km LINAC to a 17.5 GeV beam, and then turned into X-ray

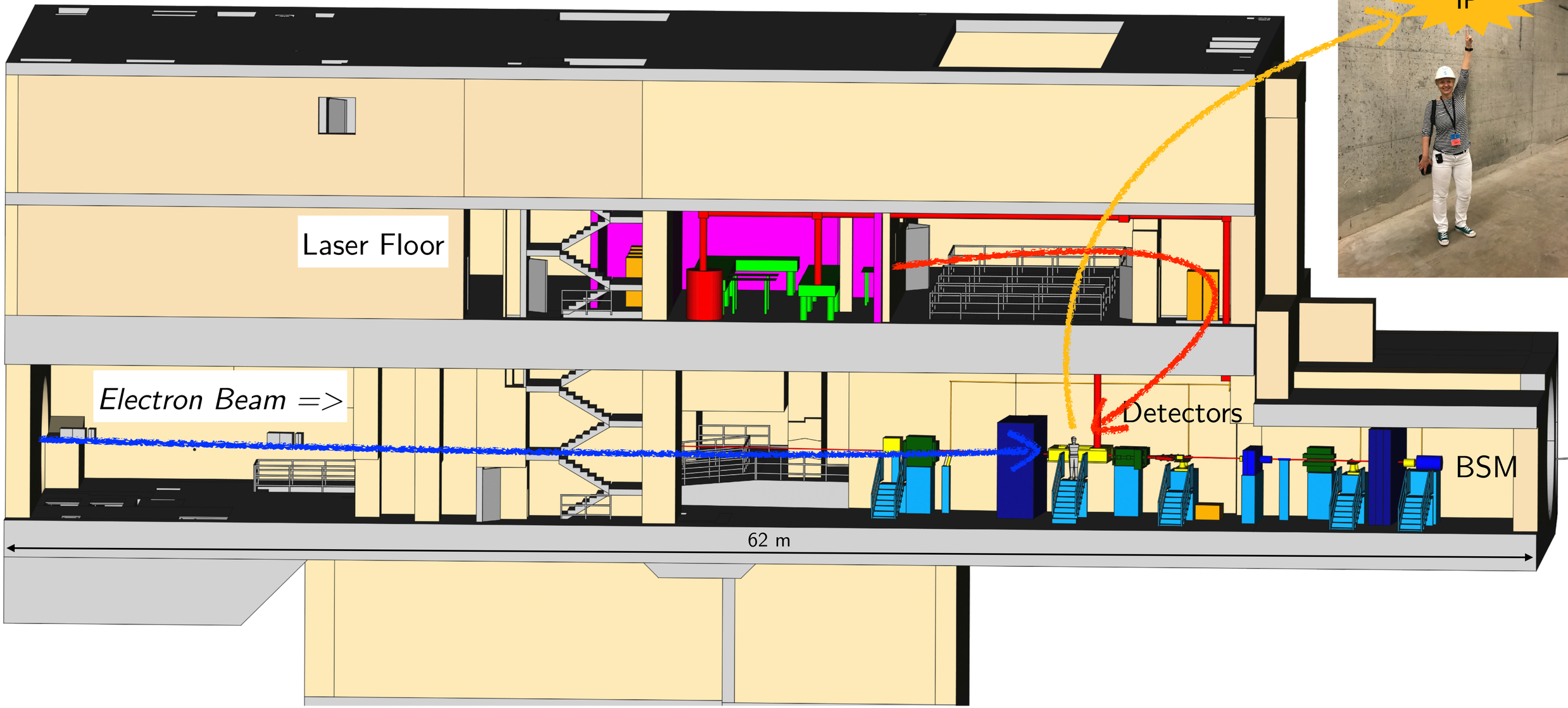
LUXE will use 1/2700 from one EU-XFEL "train"

- "Bunch": 16.5 GeV @ 10 Hz *laser running @ 1 Hz*
- 9 backgrounds + 1 signal data taking
- each bunch includes 1.5 x 10^9 electrons
- convertible into photons via Bremsstrahlung





Experimental specs.: LUXE setup



Simulations: SFQED processes

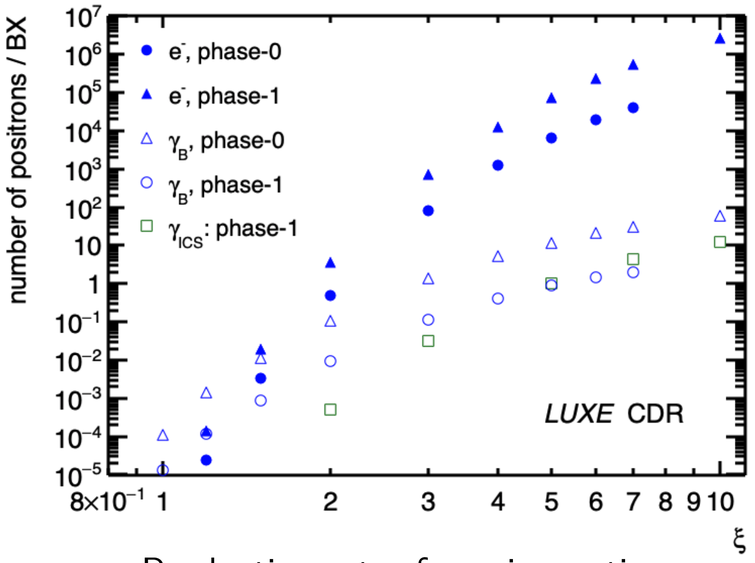
- Theory is based on plane-wave assumption
- In real world, focused laser has profile & envelope
- LUXE datasets are generated by PTARMIGAN

PTARMIGAN: a custom-built Monte Carlo code for SFQED

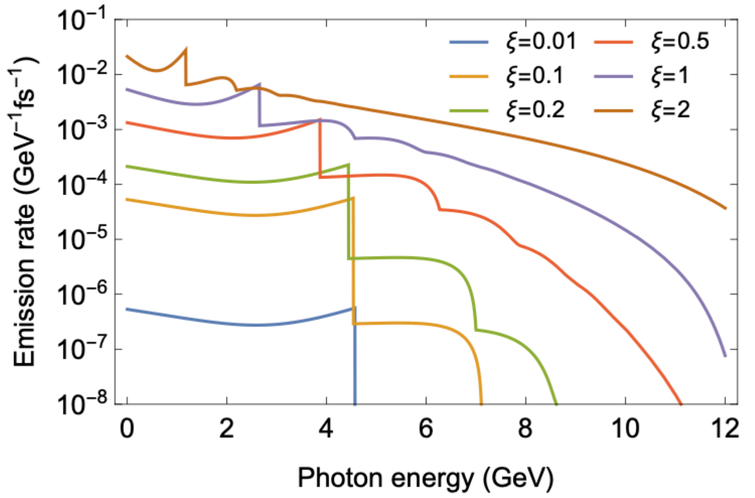
- Based on local approximation (LMA & LCFA)
- Benchmarked with direct plane-wave QED calculations
- Open source at Github

  https://github.com/tgblackburn/ptarmigan

- Simulations give a wide dynamic range for detectors
  - needs to cover more than 7 orders of magnitude



Production rates for pair creation



Compton photon spectrum

Analyses: Detectors & Geometry

Yan Benhammou's Talk earlier at 15.30

Detectors for electron & positron

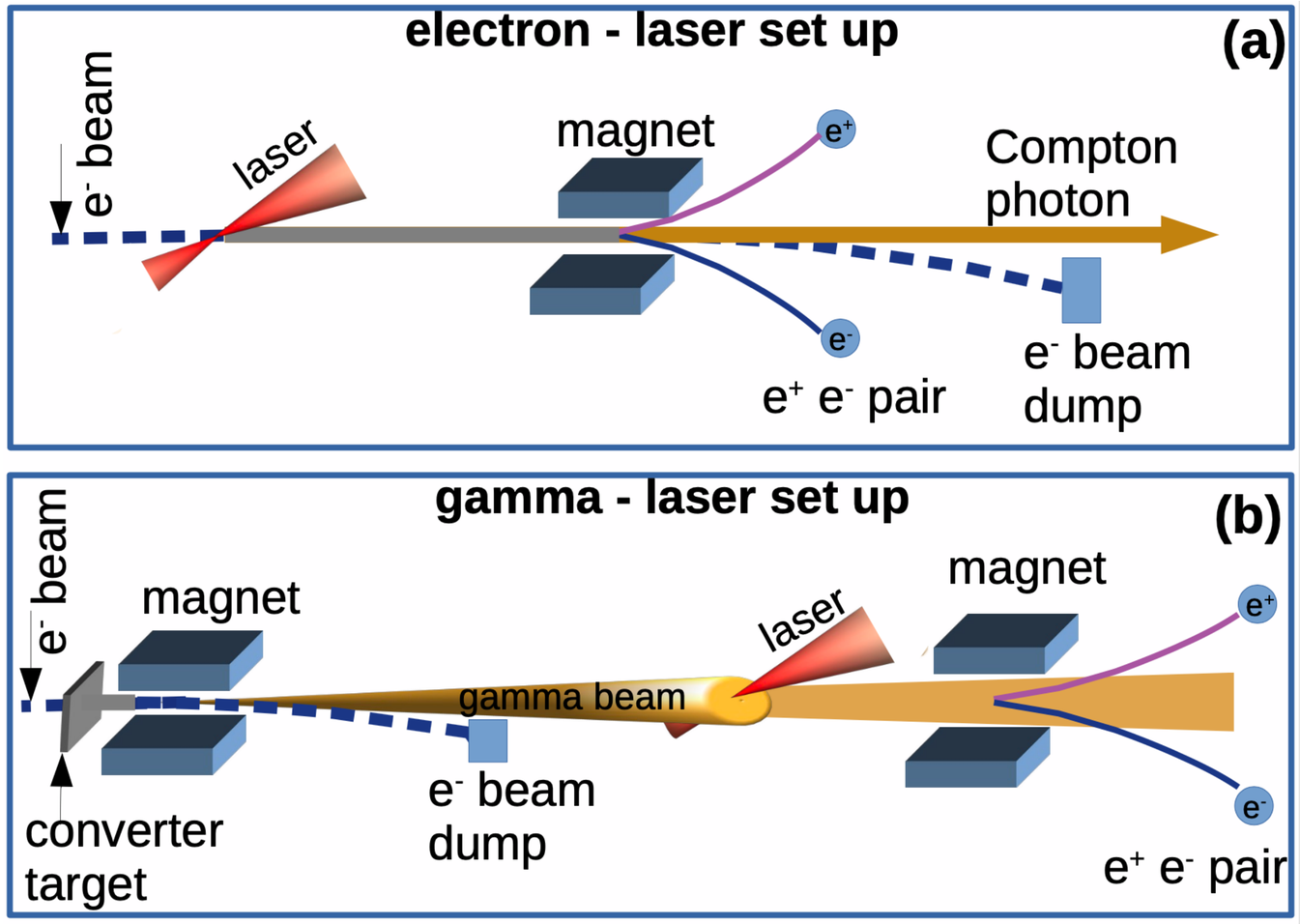
- Multiplicity: 1 to 10^7
  - Tracking detectors
  - Electromagnetic calorimeter
  - Cherenkov Detector
  - Scintillators

Detectors for photon

- Up to 10^9 Compton photons
  - Gamma spectrometer
  - Gamma profiler
  - Gamma flux monitor

Beam dumps & Background

- Shielding of detectors

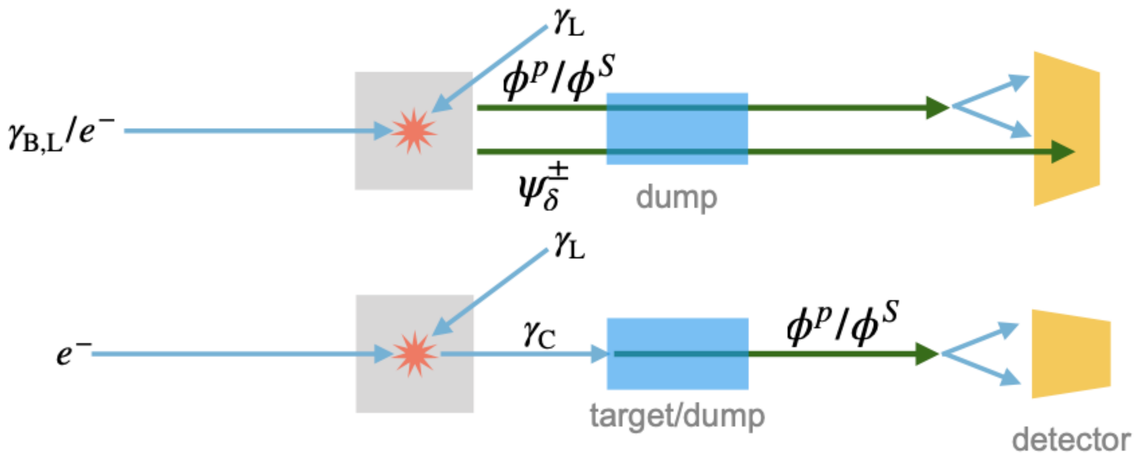


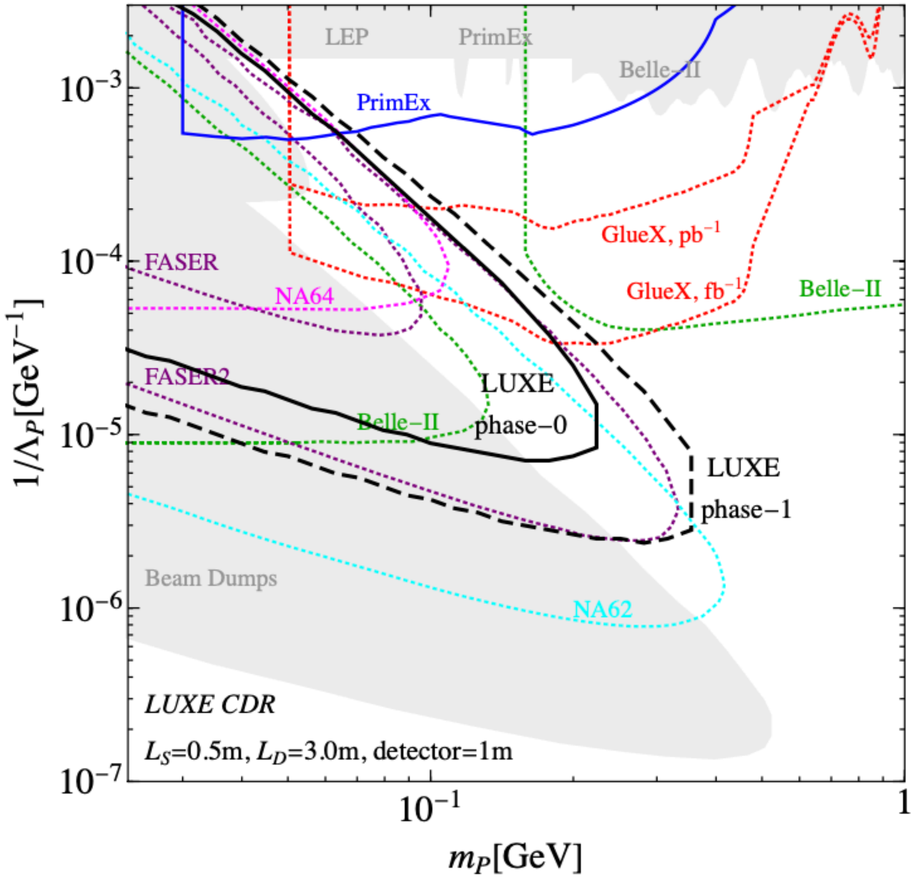
BSM physics

Arka Santra's Talk at 15.28 on 8 Sep.

Axion-like-particles at sub-GeV level

- Light-shining-through-wall method for ALP Primakoff process
- ALP could produce at
  - the IP, or
  - the beam dump
- A clean background behind beam dump for detector picking up abnormal photon

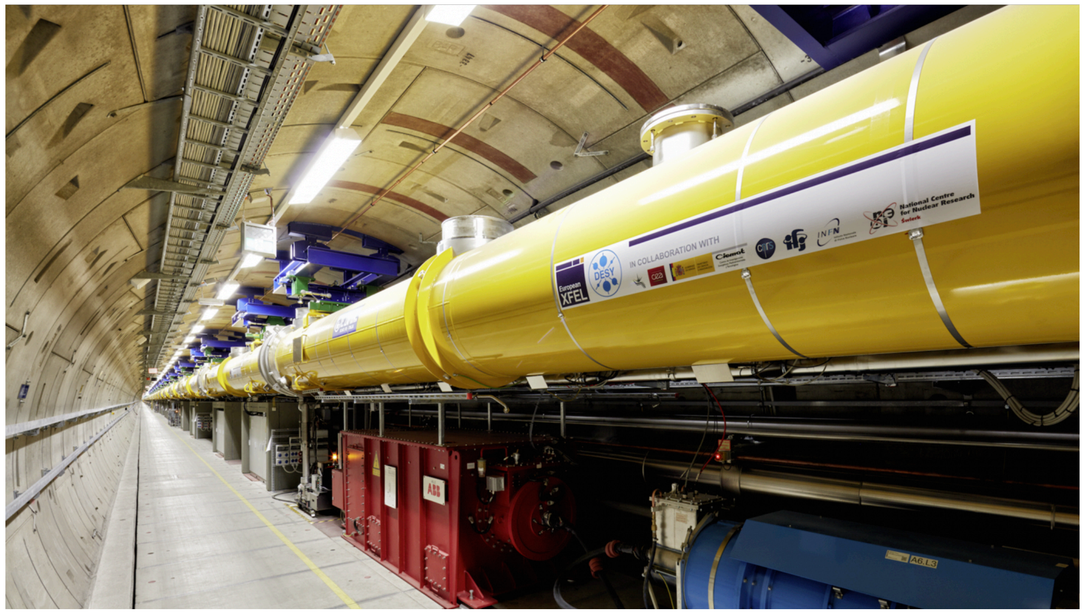




LUXE-NPOD, arXiv: 2107.13554

Schedule

- Passed milestones:
  - Letter of Intent released and approved in 2019 [arXiv: 1909.00860]
  - Conceptual Design Report released and approved in 2021 [arXiv: 2102.02032]
- Working towards Technical Design Report in 2022
  - Finalise all designs of laser, detectors, and beamline
- Detector's testing starts by the end of this year at DESY
- To be installed during the shutdown of EU-XFEL
- To start data taking
  - electron-laser mode at 2024
  - gamma-laser mode at 2025
- Upgrade to phase-1 laser at 2026



Summary

- LUXE is one of the first experiments to explore QED in an uncharted frontier, including
  - the transition of QED described by perturbative methods to the non-perturbative/non-linear ones,
  - the pair production by real photons out of vacuum, and
  - beyond-standard-model physics
- Cooperation between high-energy particle physics & high-power laser physics that requires
  - an extreme electron beam of 16.5 GeV,
  - highly stable TW to sub-PW laser device with high-precision diagnose system, and
  - the design and test of beamline and detectors adapting to a large dynamic range