Probing non-perturbative QED and new physics at the LUXE experiment

Raquel Quishpe on behalf of the LUXE collaboration

KIT – Karlsruhe Institute of Technology

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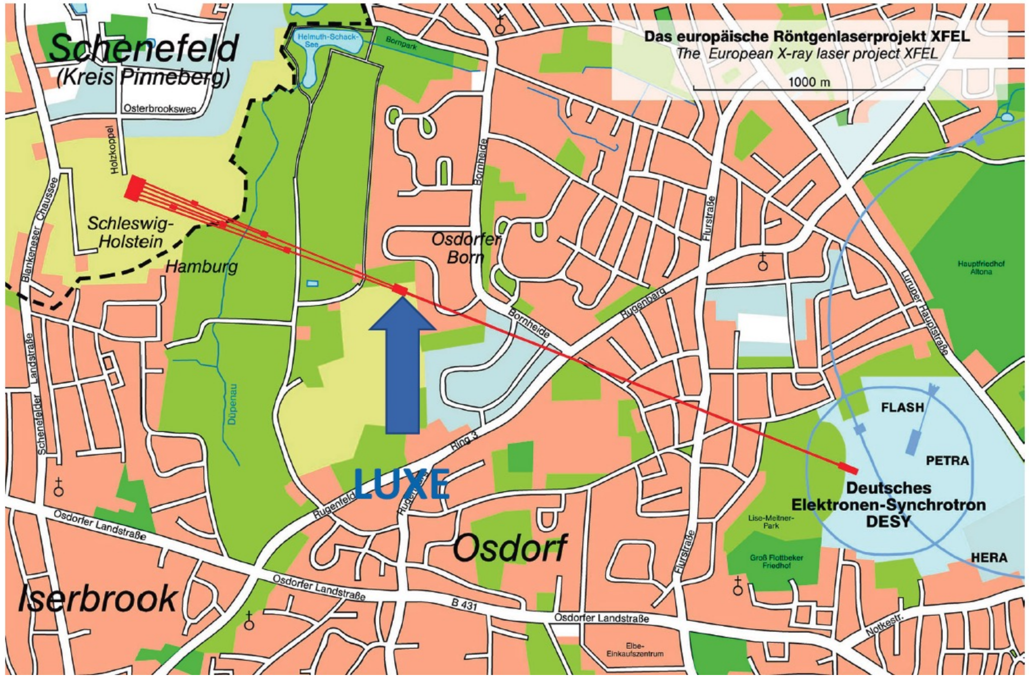
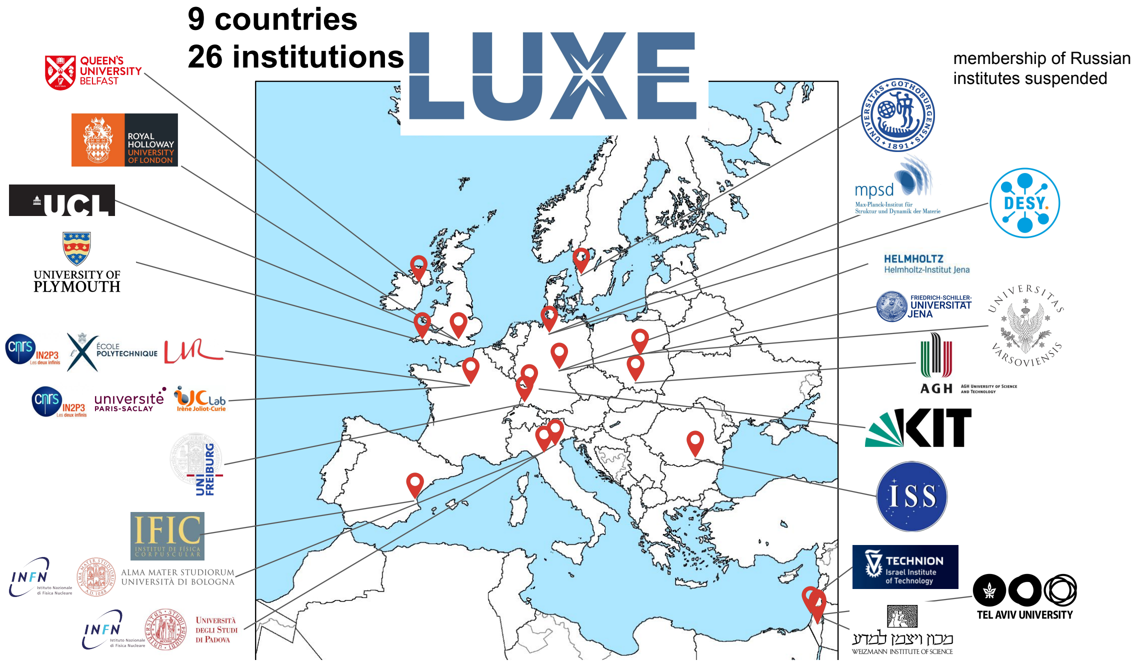
Karlsruher Institut für Technologie

Institut für Experimentelle Teilchenphysik

Laser Und XFEL Experiment

- Based at DESY and European XFEL (Eu.XFEL) in Hamburg and Schenefeld, Germany
- LUXE will collide Eu.XFEL electrons and bremsstrahlung photons with a high-intensity laser

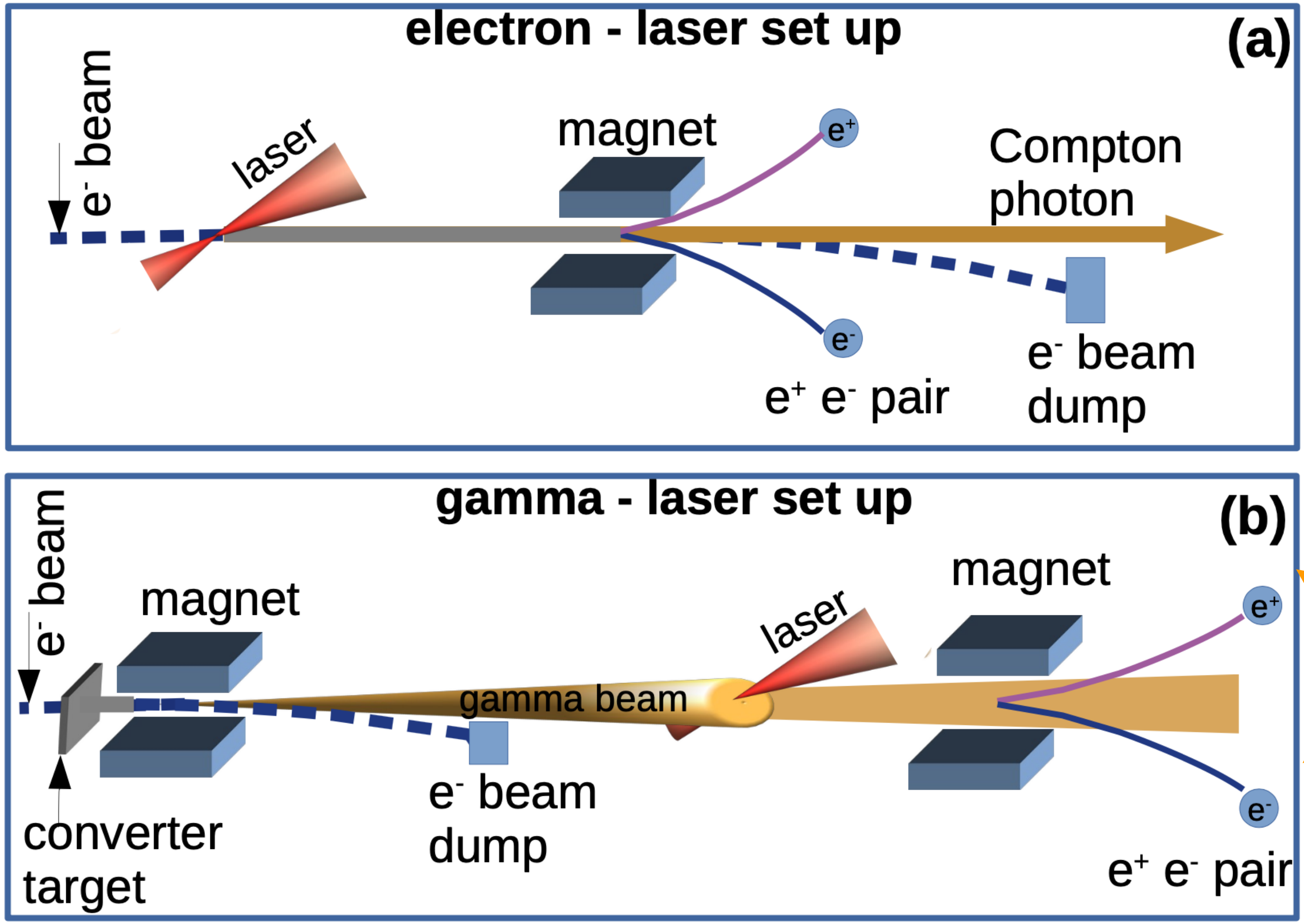




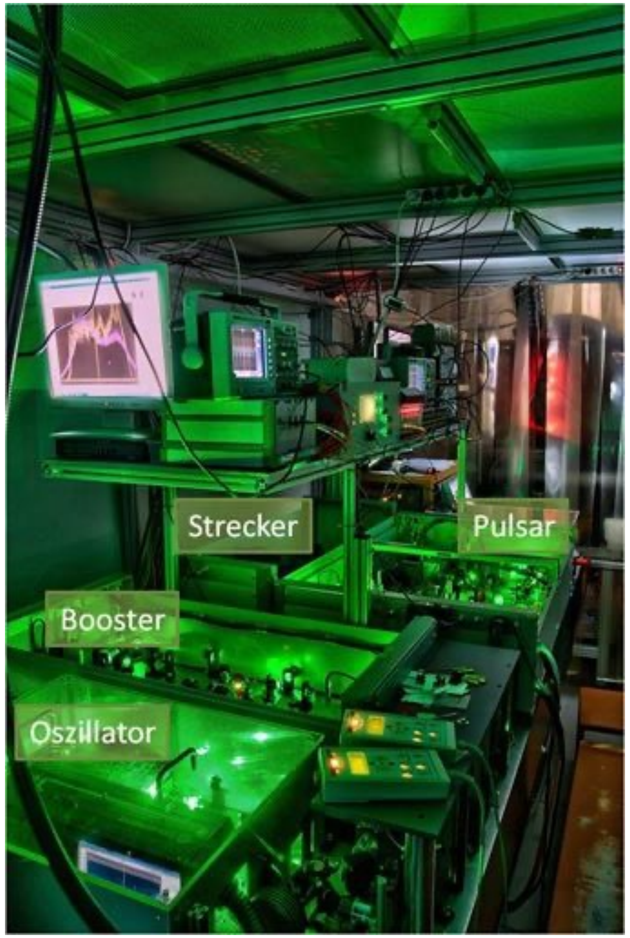
- CDR done in 2021, TDR done in 2023, reached CD-1
- *Physics goals*:

  study strong-field QED and **ALPs searches**

LUXE experimental setups

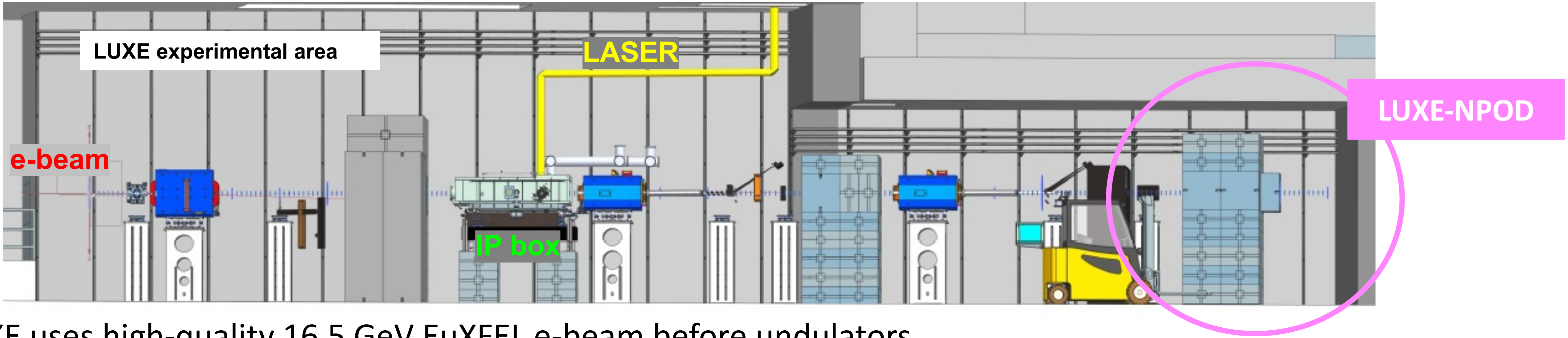


LUXE laser parameters



- active medium: Ti:Sa
- wavelength (energy): 800 nm (1.55 eV)
- crossing angle: 17.2°
- pulse length: 30 fs
- spot size: ≥ 3 µm
- power:
  - phase-0: 40 TW (JETI40, Jena or new)
  - phase-1: upgrade to 350 TW

LUXE experimental area



- LUXE uses high-quality 16.5 GeV EuXFEL e-beam before undulators
  - #electrons/bunch: $1.5 \cdot 10^9$
  - Repetition rate: 10 Hz
- Continuous data-taking with variable laser spot size (unique in LUXE)
- Location at the annex for future second EuXFEL fan(~2030‘s+)
  - LUXE can be built and operated before that
- Extract 1 bunch (out of 2700 bunches) per XFEL train for LUXE
  - No impact on photon science program

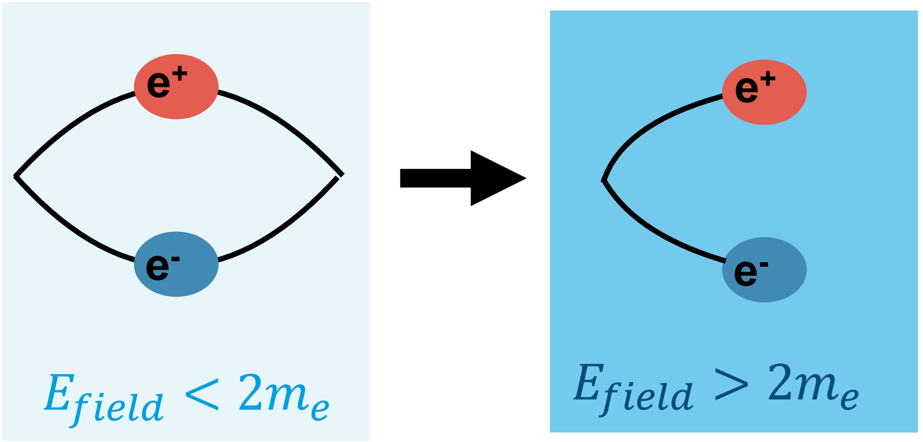
LUXE experimental area today

Strong-field QED (SFQED)

- QED is one of the most precisely tested theories in physics in the perturbative regime
- LUXE will probe QED in non-perturbative strong-field regime
- QED is predicted to become non-perturbative above the critical electric field, Schwinger limit

$$\mathcal{E}_{cr} = \frac{m_e^2 c^3}{e\hbar} \approx 1.32 \cdot 10^{18}\ \mathrm{V/m}$$

- Creation of e^+e^- pair from vacuum in constant field

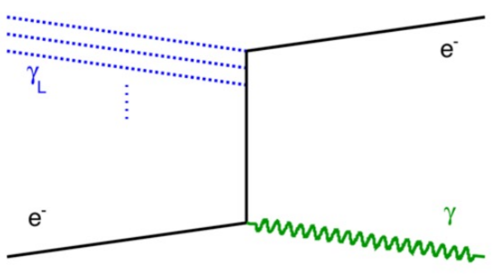


SFQED observables

Non-linear Compton scattering

- In strong fields, electrons obtain larger effective mass $m_* = m_e\sqrt{1+\xi^2}$
- Compton edge shifts as a function of the laser intensity parameter ξ

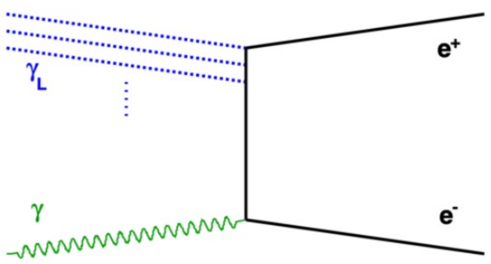
$$e^- + n\gamma_L \rightarrow e^- + \gamma_C$$



Breit-Wheeler pair production

- Positron emission probability depends on the ξ (ξ<<1 perturbative, ξ>>1 non-perturbative)
- *First experiment to measure Breit-Wheeler pair production with real photons*

$$\gamma_C + n\gamma_L \rightarrow e^+ + e^-$$



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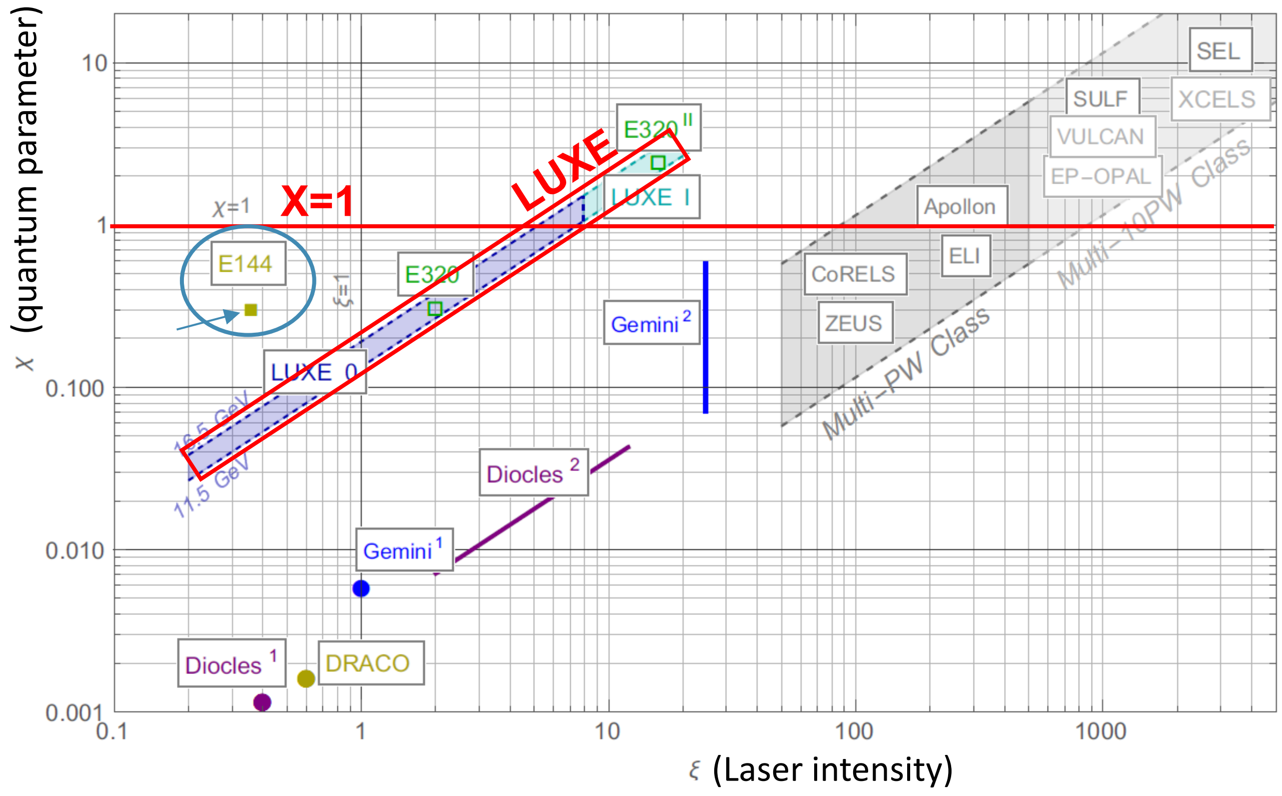
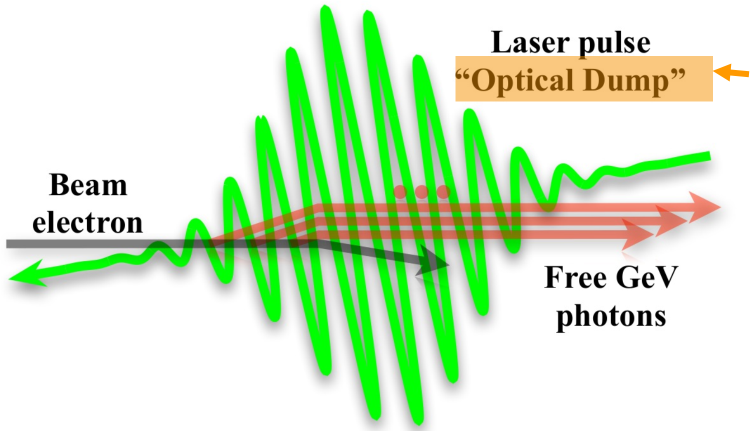


- LUXE will precisely map parameter space (ξ,χ) in transition region

LUXE-NPOD project

- **NPOD**: **N**ew **P**hysics searches with an **O**ptical **D**ump
- Collide a beam of 16.5 GeV electrons with the laser
- The laser behaves as a thick medium, leading to the production of a large flux of hard photons O(GeV)
- Photons see the laser as a transparent medium and can reach the physical dump
- Lower background from gamma photons



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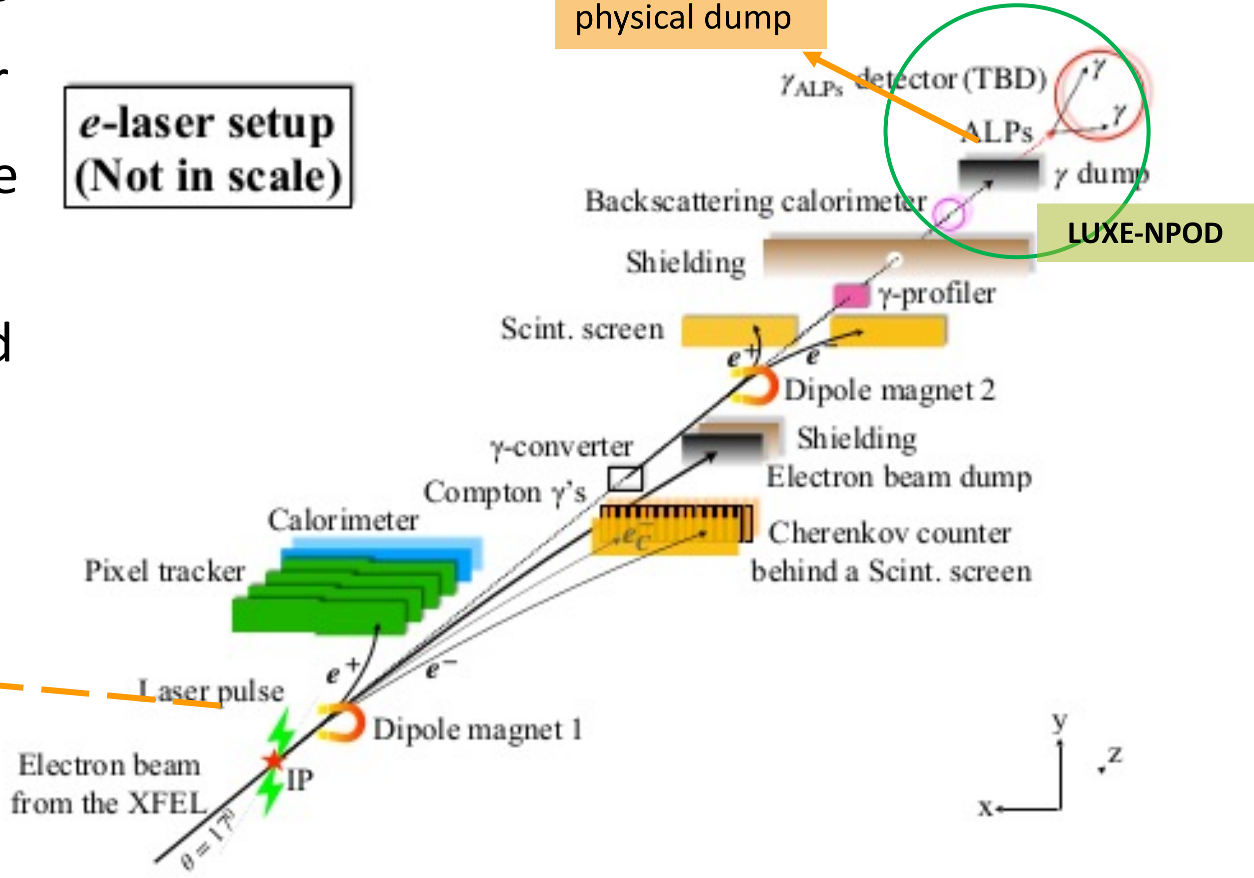


Laser repetition rate 1Hz
→ 10^7 bunch-crossings (BX) per year

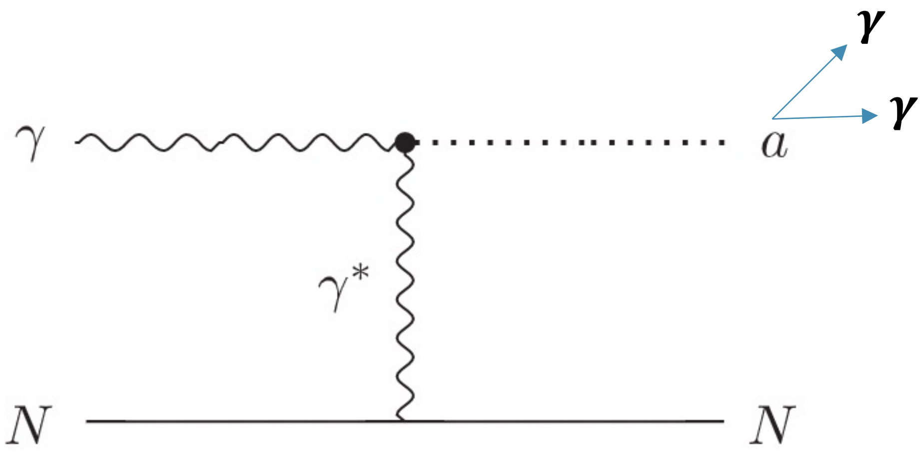
New Physics (NP) production mechanisms

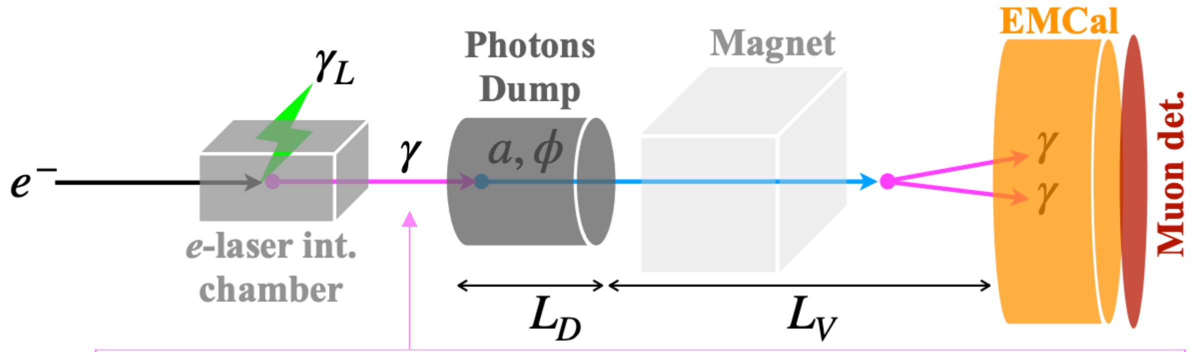
Main focus

- *Secondary NP production*:
  - Axion-like particles (ALPs) and scalar ($X = a, \phi$) production through Primakoff mechanism with a displaced decay to 2 hard photons

$$\mathcal{L}_{a,\phi} = \frac{a}{4\Lambda_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\phi}{4\Lambda_\phi} F_{\mu\nu}F^{\mu\nu}$$

  - ALP mass up to $\mathcal{O}(1)\mathrm{GeV}$

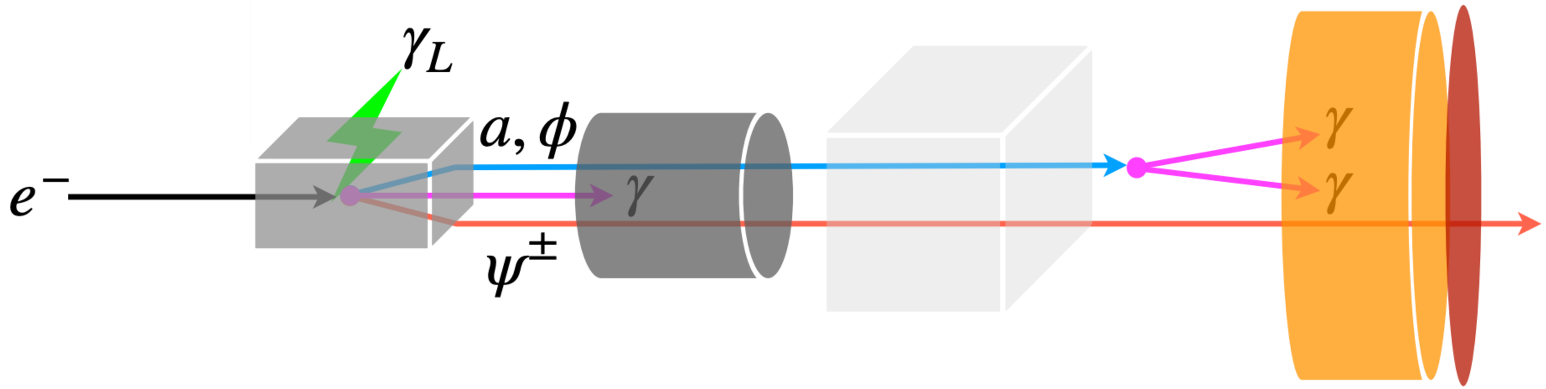




Photons produced in the e-laser collisions are freely propagating to collide with the nuclei of the material of the dump

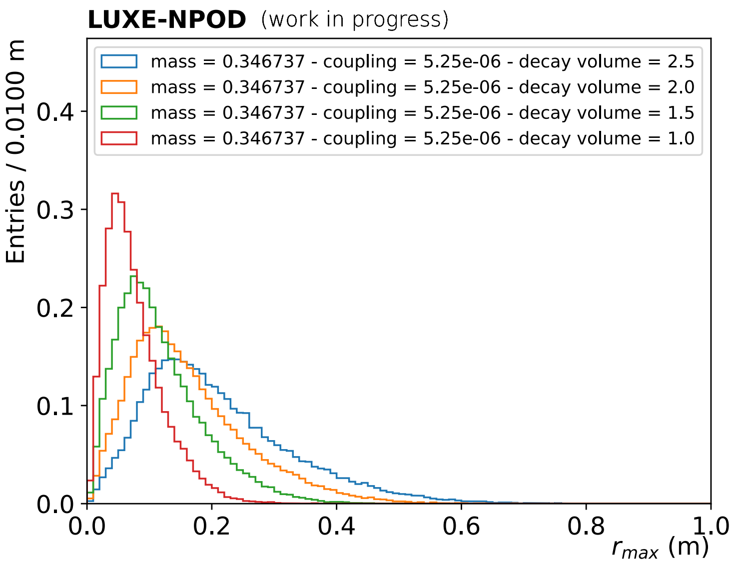
NP production mechanisms

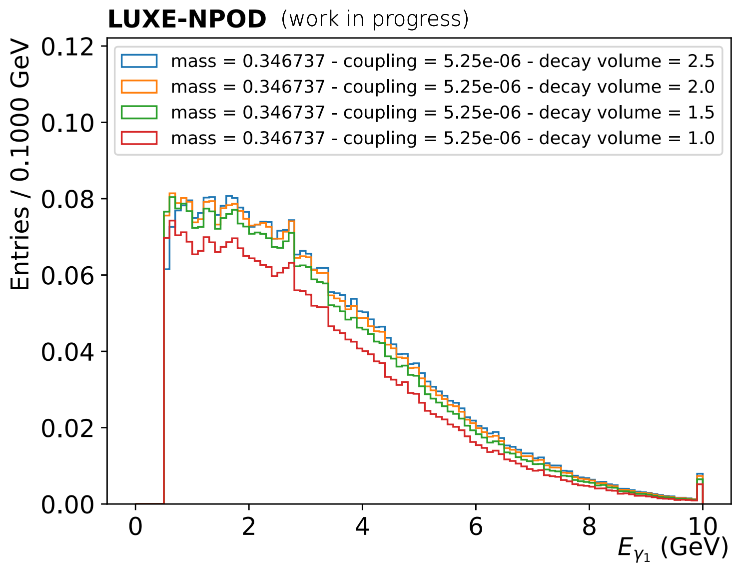
- *Primary NP production*:
  - NP is directly produced at the e-laser interaction region
    - X has couplings to electrons only : $e_V^- \rightarrow e_V^- + X$
    - X has couplings to photons only: $e_V^- \rightarrow e_V^- + \gamma^* \rightarrow e_V^- + \gamma + X$
  - mCP pairs direct production: $\gamma(\gamma^*) \rightarrow \psi^+ + \psi^-$
  - New particle mass limited to $m_{X,\psi} \lesssim \mathcal{O}(100)$ keV

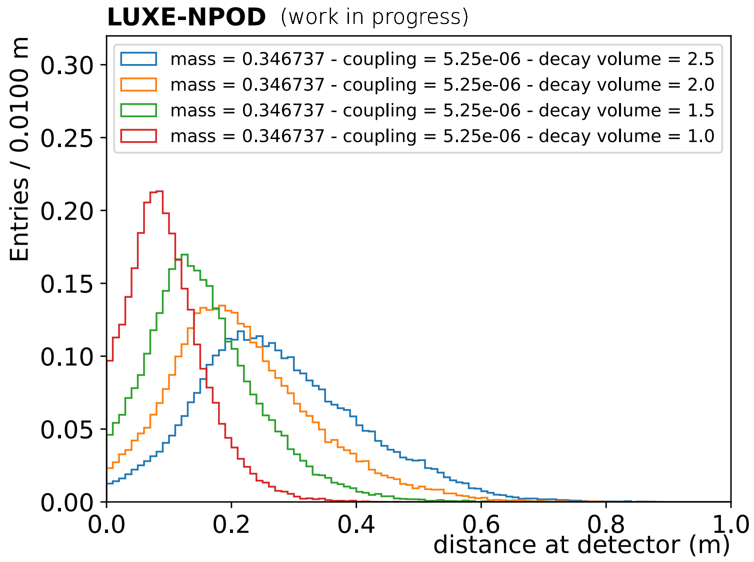


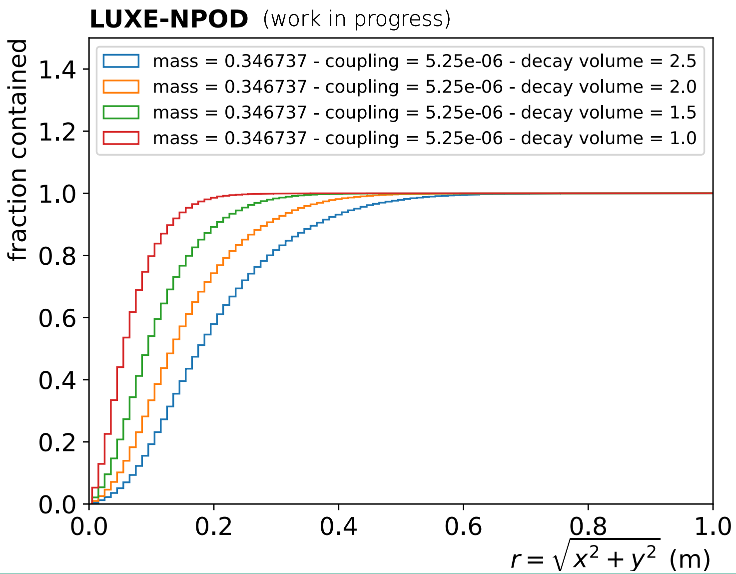
Signal efficiency

- ALPs production within the first mm of the dump
- Boosted $c\tau_{a/\phi}$ randomly drawn from $\exp(-L/L_{a/\phi})$ distribution
- ALP decay inside the decay volume
- $E_\gamma > 0.5$ GeV
- No photon separation requirement yet
- Shorter decay volumes require smaller detector surface

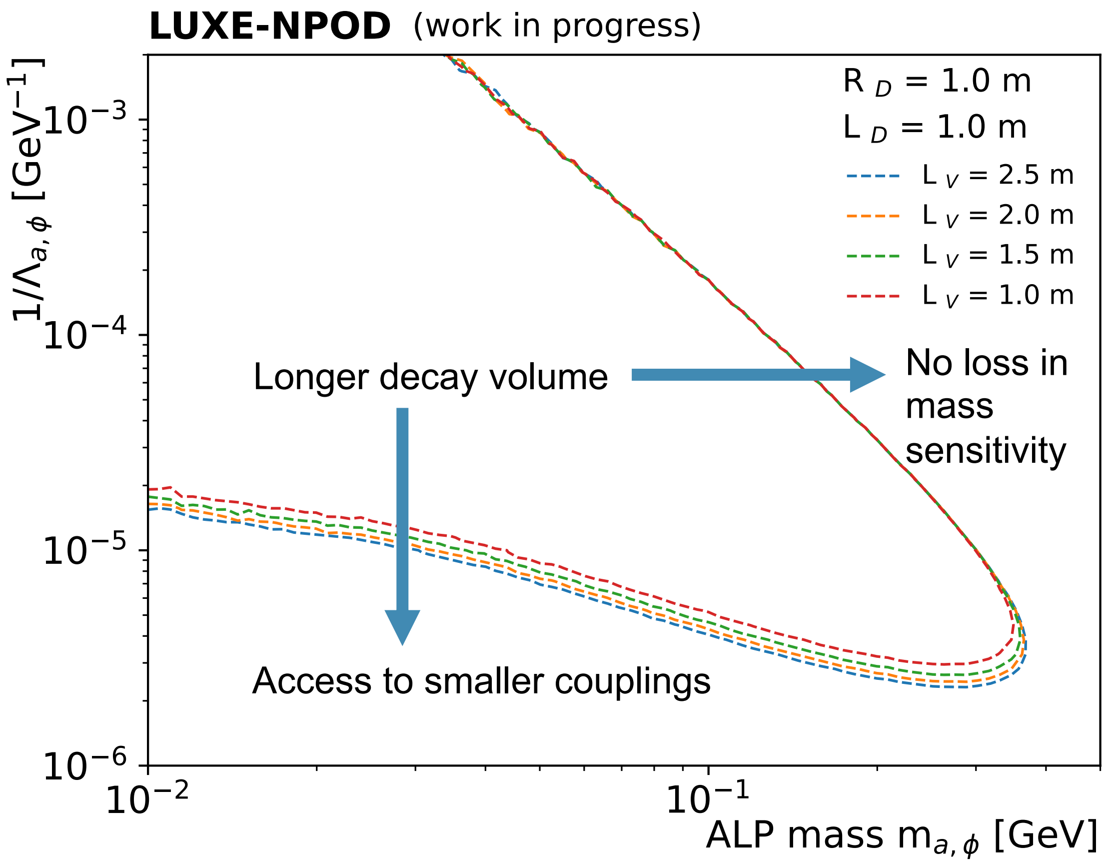




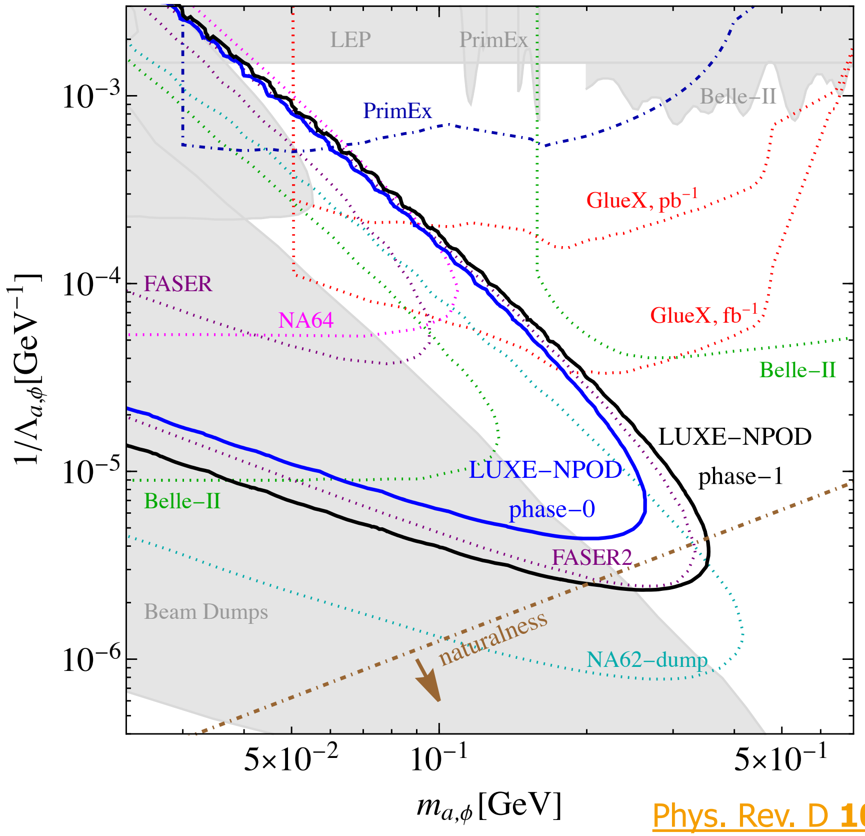




Expected results in phase-1



- Ongoing signal efficiency simulation studies
- LUXE phase-1 competitive with FASER2 or NA62-dump



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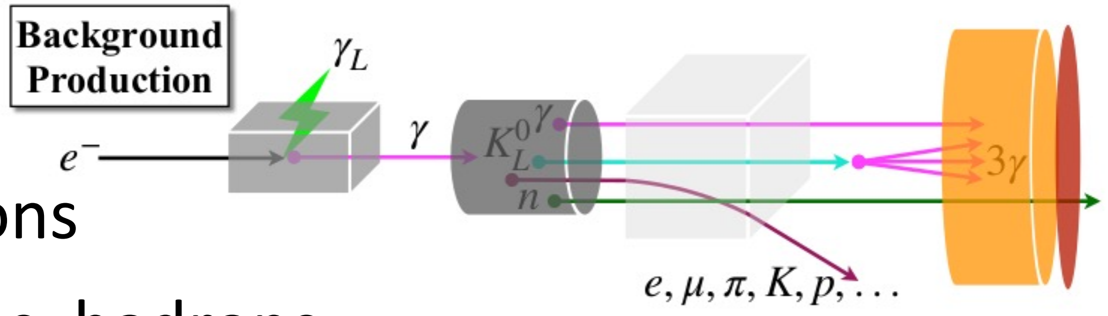
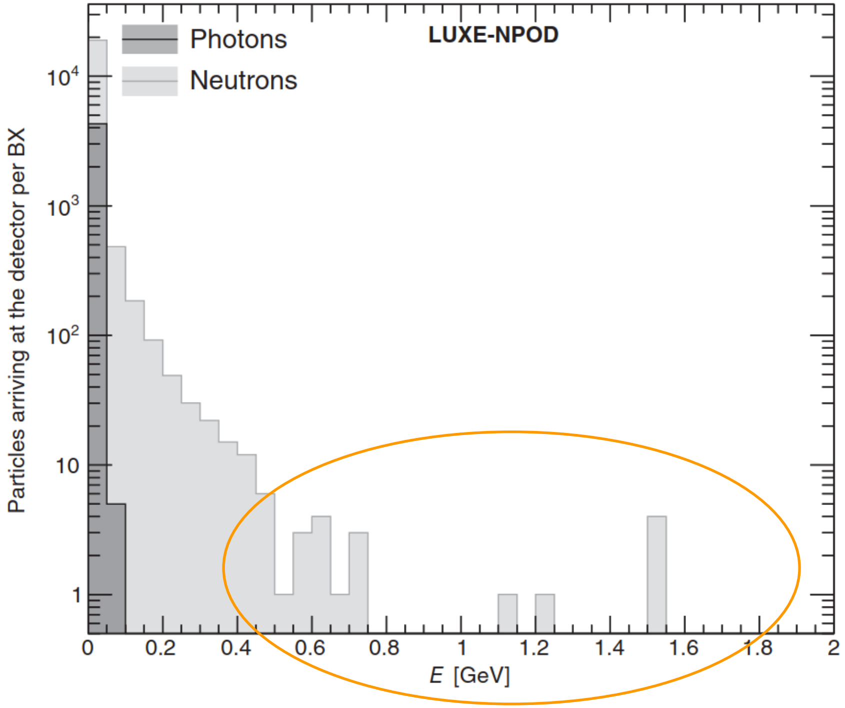
LUXE-NPOD background



- Types of background:
  - Fake photons: misidentified neutrons
  - Charged particles: electrons, muons, hadrons
  - Real photons: from EM/hadronic interactions at the end of the dump or from meson decays in the volume
- Background mostly neutrons and photons
- Softer background effects in phase-0 compared to phase-1
- The expected results are obtained assuming zero background

LUXE-NPOD background estimation

- Background estimated using GEANT4 simulations for phase-1
- First studies done with a *simplified detector* configuration (Tungsten beam dump, L_D =1 m, L_v = 2.5 m, R_v = 1 m)
- Photons seem too soft to be a source of background
- Neutrons statistics in E > 0.5 GeV is extremely low
- Simulated 10^{10} photons (~2BXs), need many more for proper estimate
  - Computationally challenging
  - Ongoing GEANT4 simulation studies for different dump-detector geometry to reduce background



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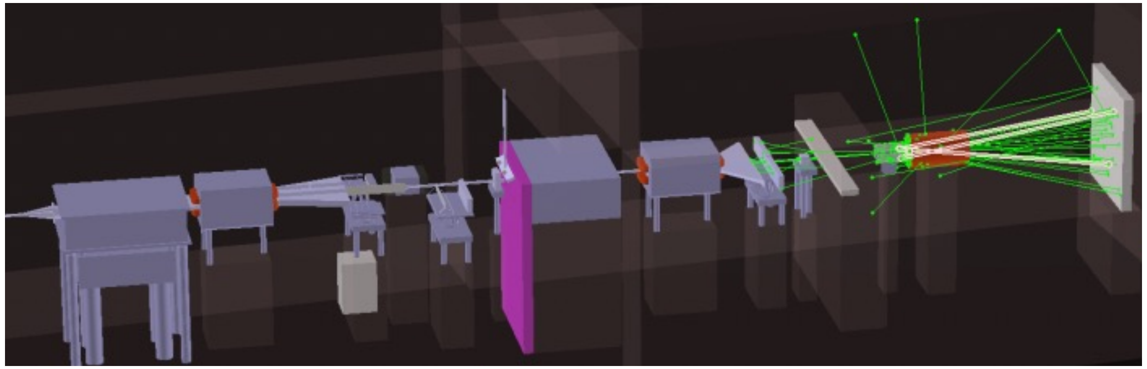
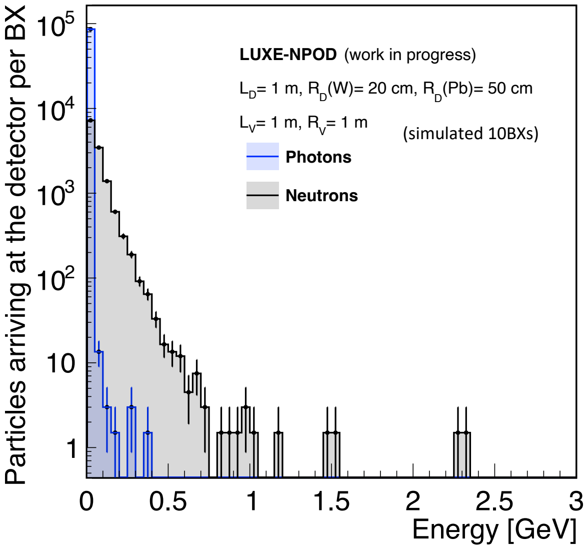
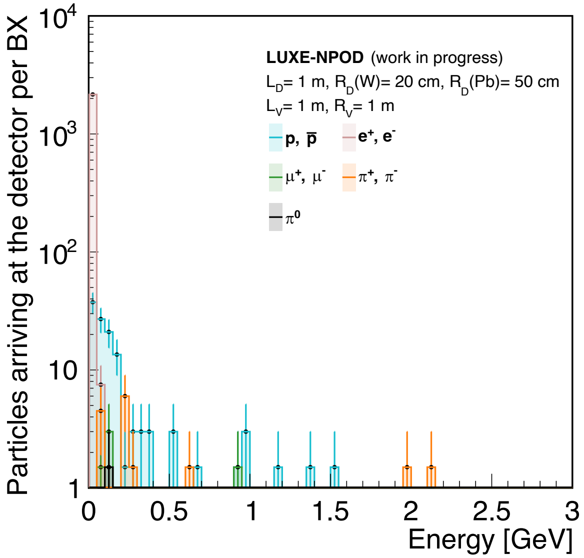
LUXE-NPOD background estimation

- Ongoing new GEANT4 simulations including full LUXE setup
- Presence of low-energy particles due to backscattering and particles escaping through the sides of the dump
  - not spotted by the previous simplified experimental model
- New dump-detector design under study
  - W dump + magnet wrap + concrete wrap
  - **W dump + Pb wrap + concrete wrap**
    - ⭐ *Good price-performance compromise*
- Low energy background from charged particles, can be handled with a magnet







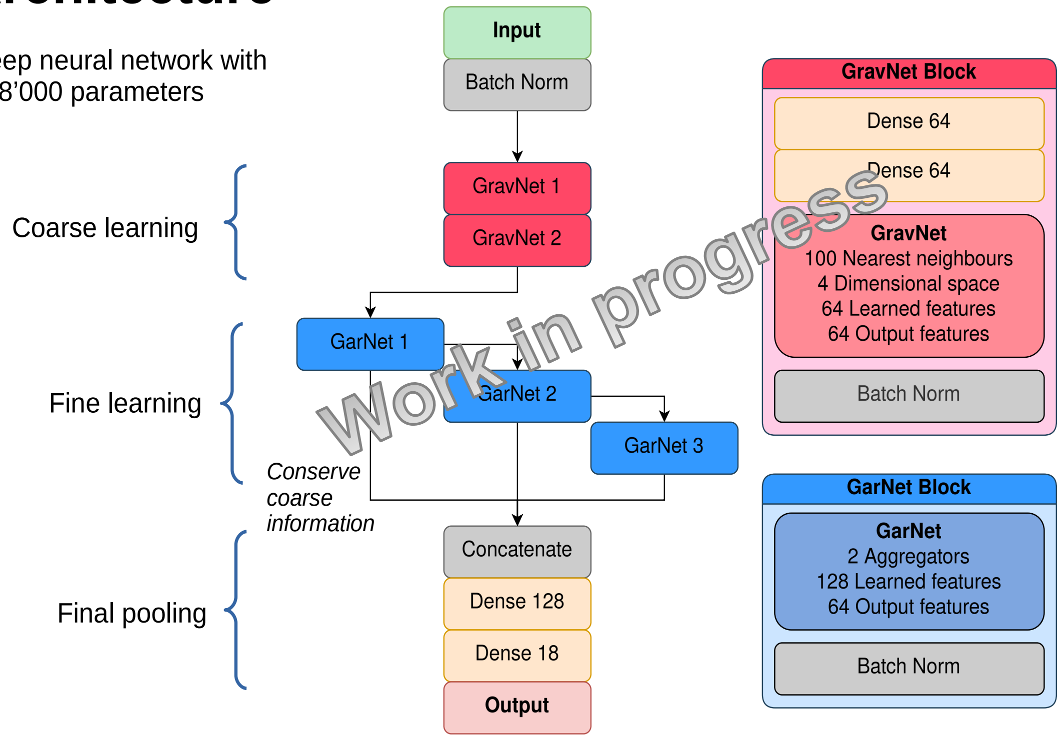
BSM detector requirements

- Signal efficiency
  - Photons shower separation (~1 cm)
- ALP invariant mass reconstruction
  - Good energy and vertex resolution
- Background suppresion (photons and neutrons)
  - Vertex resolution (non-resonant photons)
  - Shower shape determination (neutrons)
  - Good time resolution (< 1 ns) (neutrons)
- Ideal candidate: **CALICE SiW ECAL** D. Breton *et al* 2020 *JINST* **15** C05074

Reconstruction

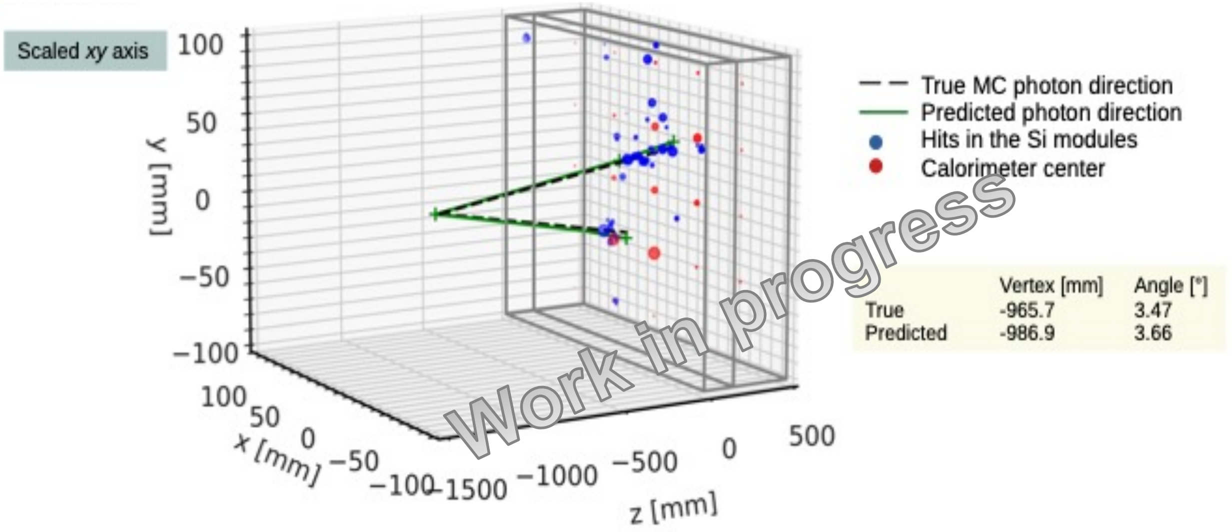
Architecture

Deep neural network with 408’000 parameters



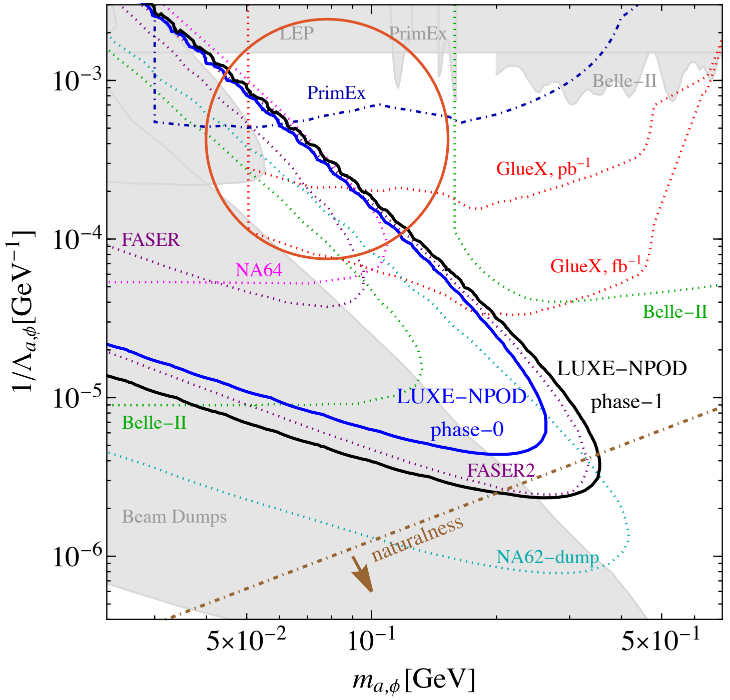
Credit: Kylian Schmidt (kylian.schmidt@student.kit.edu)

- General-purpose Geant4 simulation framework being implemented at KIT to deal with different detector layouts
- Use a neural network to reconstruct the two photons momenta and vertex
- Graph Layers: GravNet & GarNet arxiv:1902.07987
- Retraining on a new geometry is much easier than with a classic algorithm



Summary

- LUXE will explore QED in uncharted regime
- LUXE-NPOD acts as a background-free optical dump allowing the production of light ALPs with large couplings



- LUXE-NPOD phase-1 competitive with FASER2 or NA62-dump
- Exciting windows of opportunities and challenges ahead

LUXE webpage

LUXE CDR

LUXE TDR

LUXE-NPOD

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Thanks!