Probing light new physics with the LUXE experiment

RAQUEL QUISHPE on behalf of the LUXE collaboration

KIT – Karlsruhe Institute of Technology

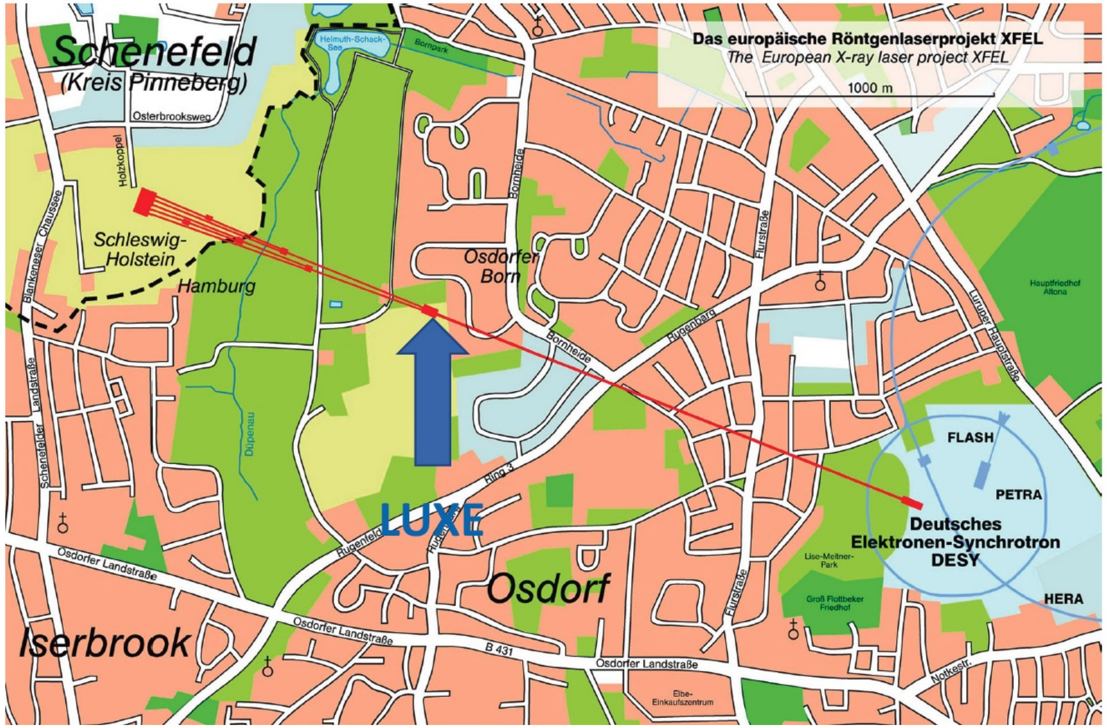
Light Dark World 2023

20.09.23 - Karlsruhe, Germany

Karlsruher Institut für Technologie

Institut für Experimentelle Teilchenphysik

Laser Und XFEL Experiment

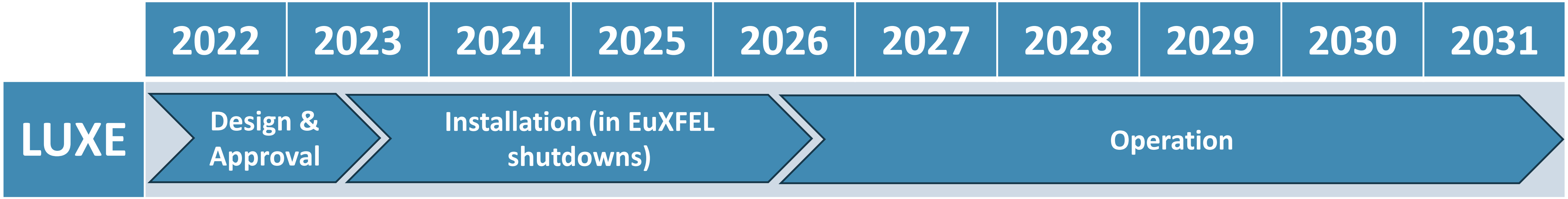


Based at DESY and European XFEL (Eu.XFEL) in Hamburg and Schenefeld, Germany

9 countries
26 institutes

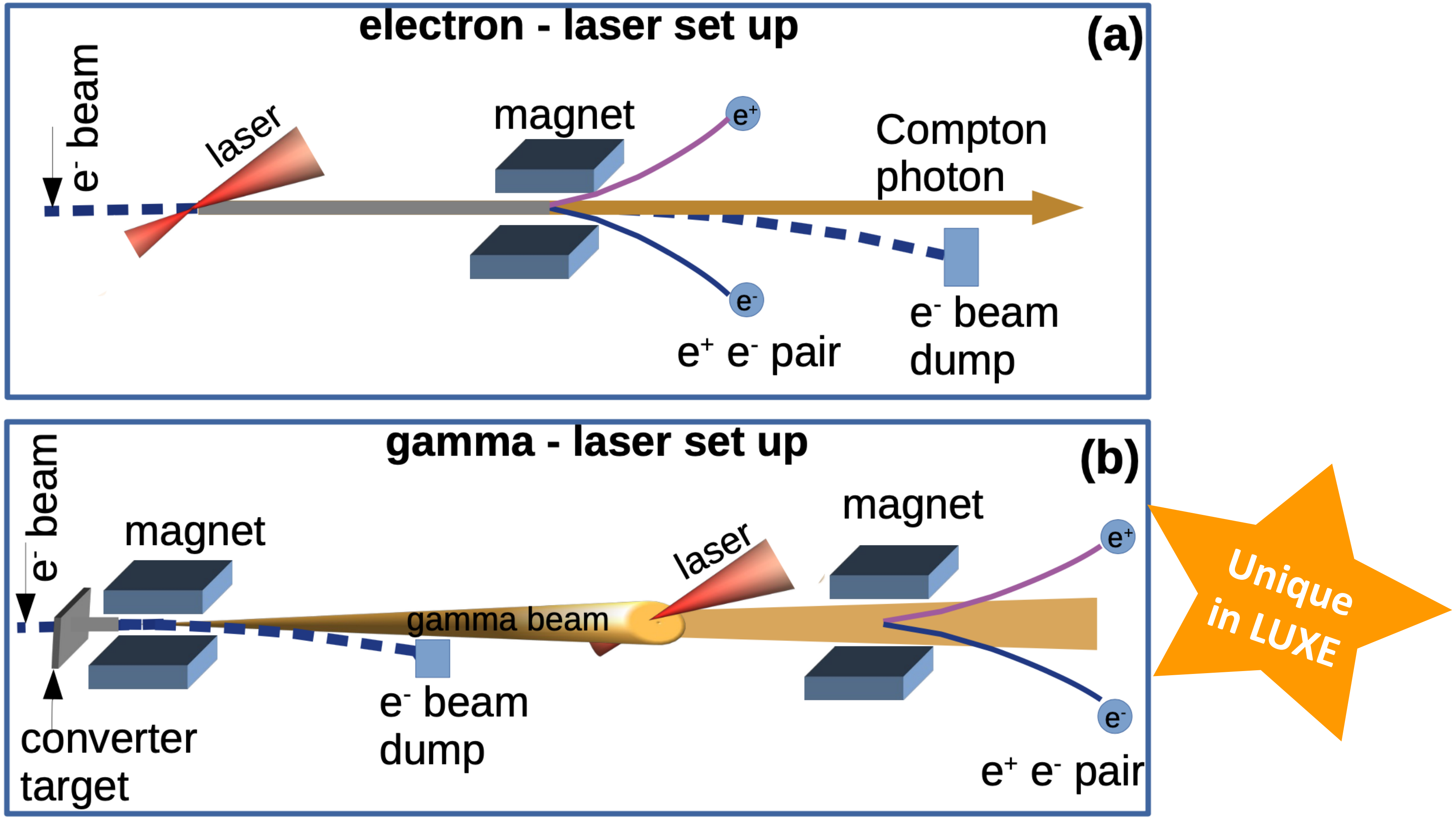
membership of Russian institutes suspended

Laser Und XFEL Experiment

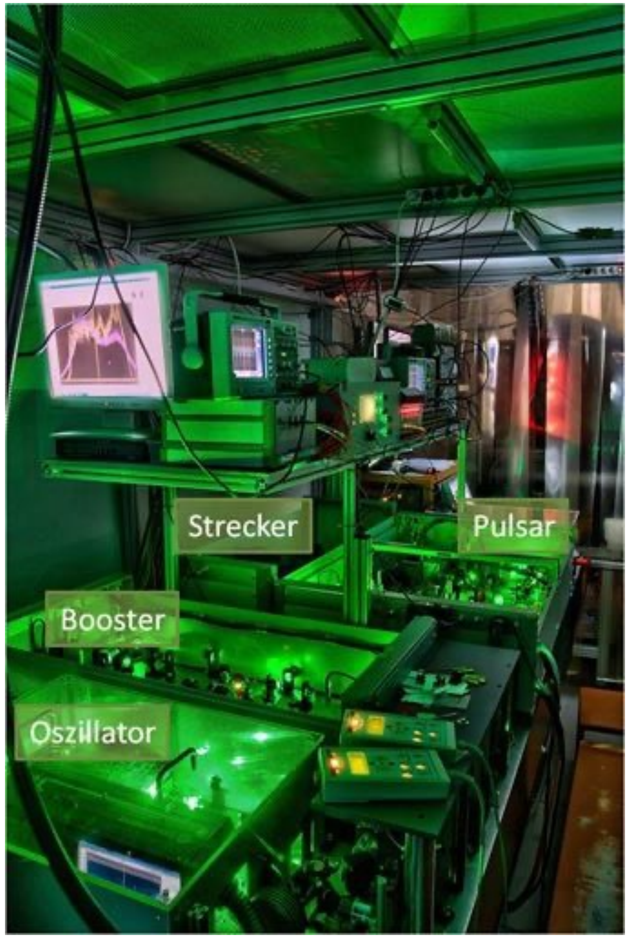


- LUXE will collide Eu.XFEL electrons and bremsstrahlung photons with a high-intensity laser
- CDR done in 2021, TDR done in 2023, reached CD-1
- First data foreseen in 2026
- *Physics goals*: study strong-field QED and ALPs searches

LUXE experimental setups

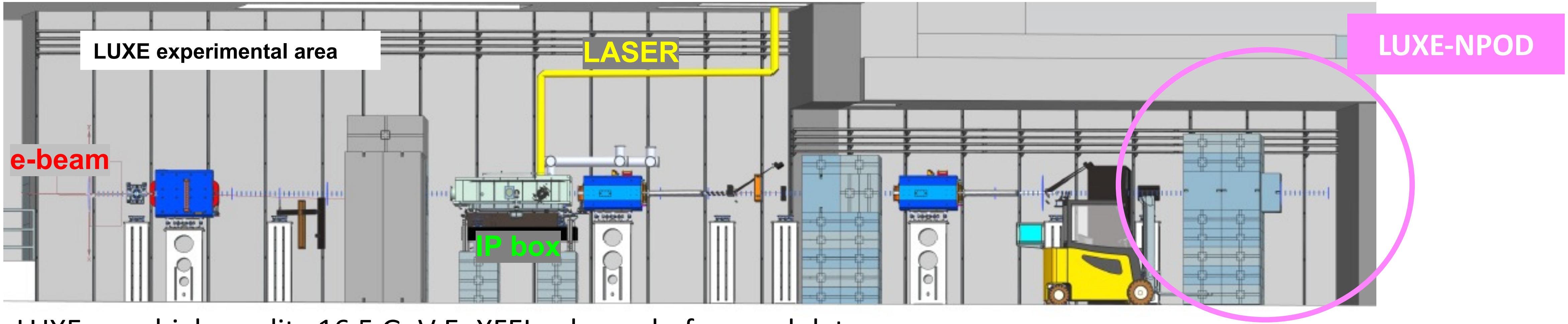


LUXE laser parameters



- 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



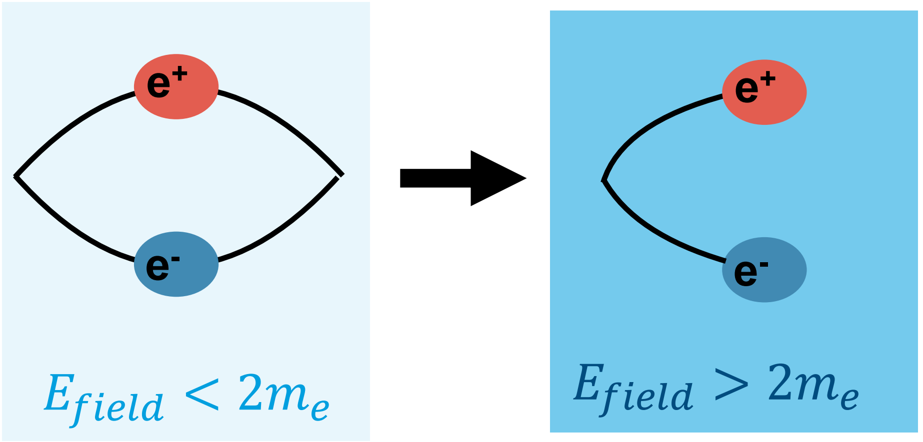
- LUXE uses high-quality 16.5 GeV EuXFEL e-beam before undulators
- #electrons/bunch: $1.5 \cdot 10^9$
- Repetition rate: 10 Hz
- Location at the annex for future second EuXFEL fan(~2030‘s+)
  - LUXE can be built and operated before that
- Extract 1 bunch (out of 2700 bunches) per XFEL train for LUXE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

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

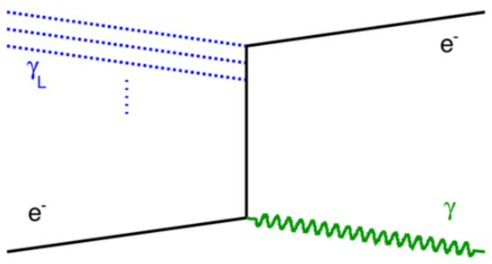


SFQED observables

Non-linear Compton scattering

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

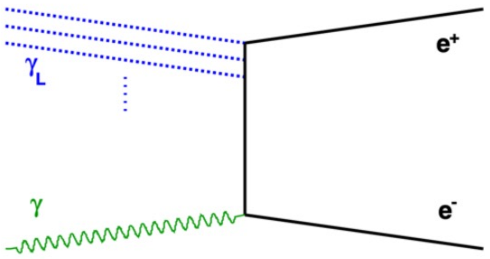
- In strong fields, electrons obtain larger effective mass $m_* = m_e\sqrt{1+\xi^2}$
- Compton edge shifts as a function of the laser intensity parameter ξ



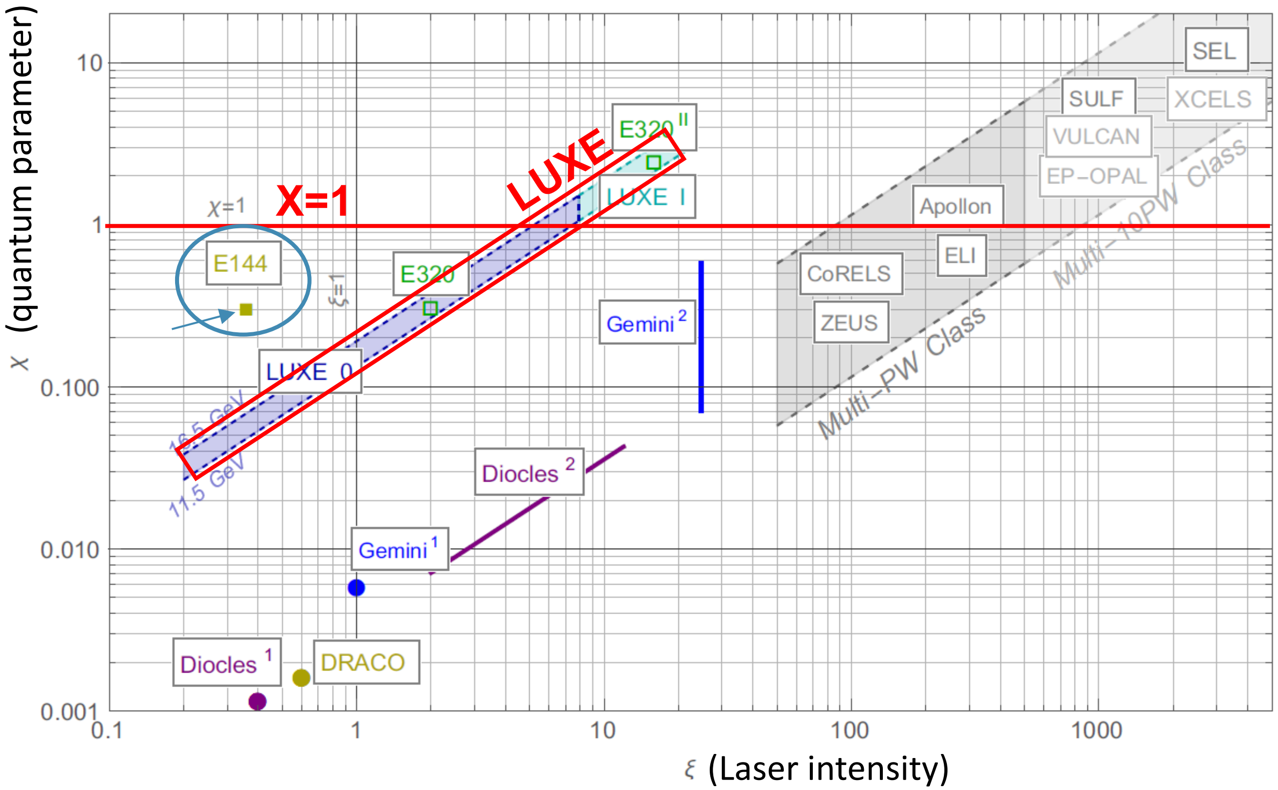
Breit-Wheeler pair production

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

- 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*



Eur. Phys. J. Spec. Top. **230**, 2445–2560 (2021)



- LUXE will precisely map parameter space (ξ, χ) in transition region
- Continuous data-taking with variable laser spot size (unique in LUXE)

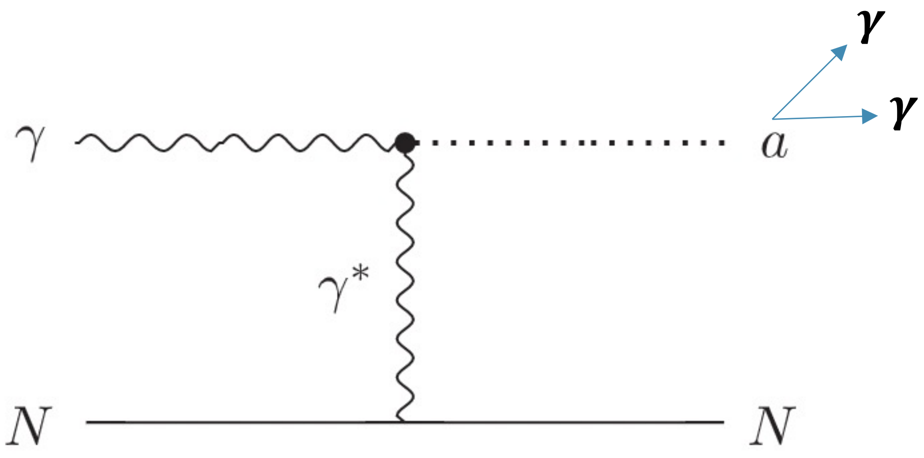
New Physics (NP) production mechanisms

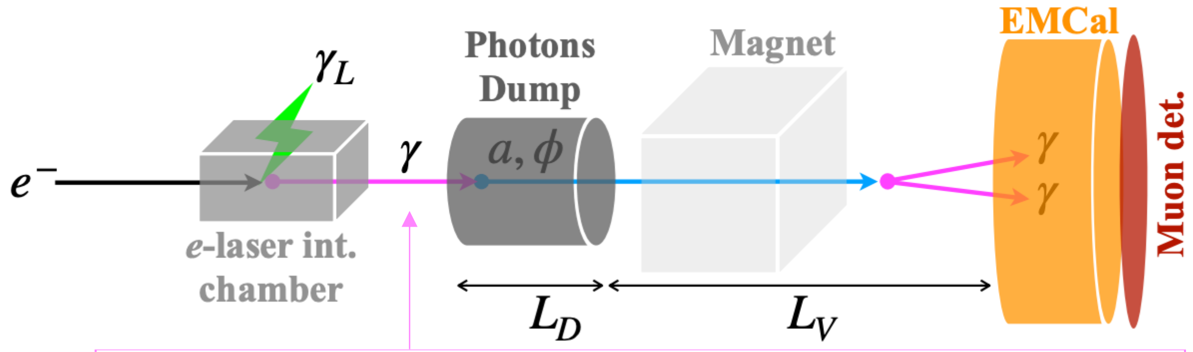
Main focus

- *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 $\mathcal{O}(1)\mathrm{GeV}$

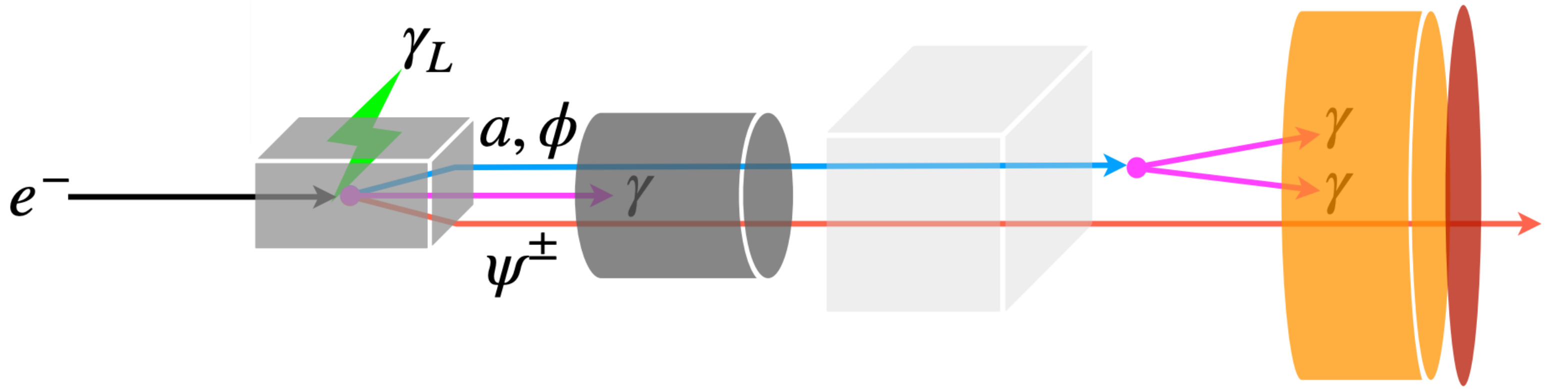




Photons produced in the e-laser collisions are freely propagating to collide with the nuclei of the material of the dump

NP production mechanisms

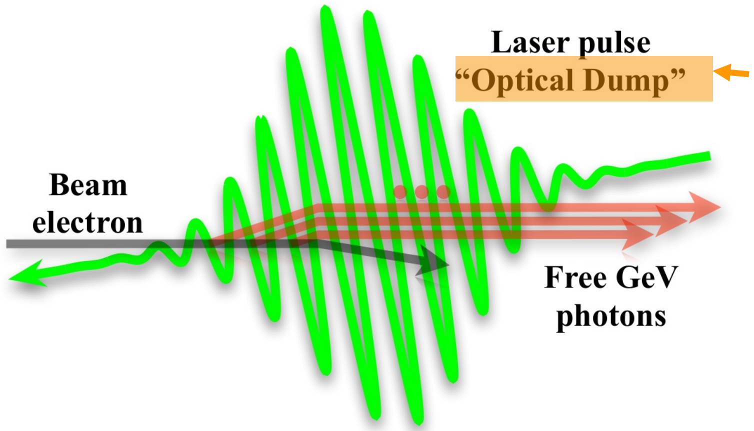
- *Primary NP production*:
  - NP is directly produced at the e-laser interaction region
    - X has couplings to electrons only : $e^-_V \rightarrow e^-_V + X$
    - X has couplings to photons only: $e^-_V \rightarrow e^-_V + \gamma^* \rightarrow e^-_V + \gamma + X$
  - mCP pairs direct production: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

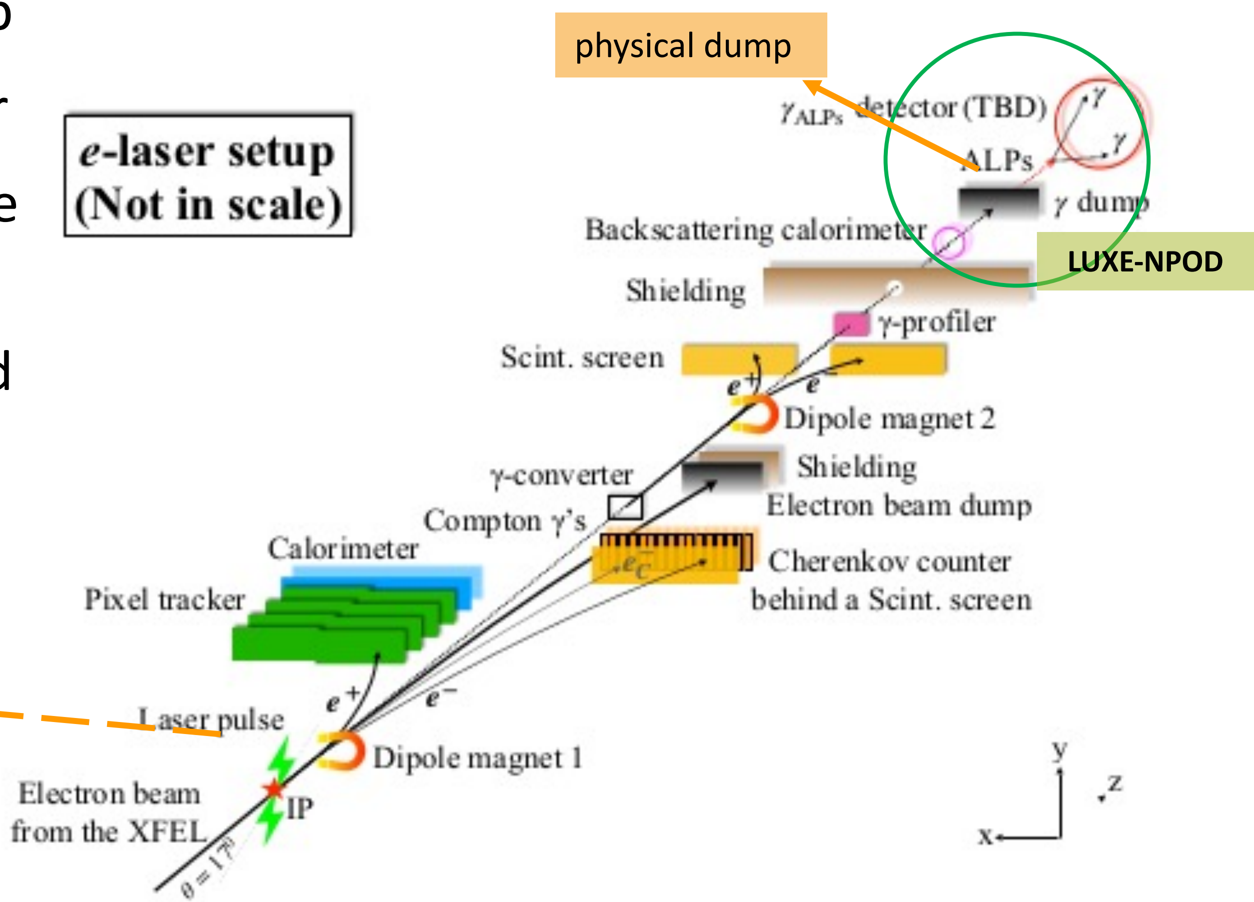


LUXE-NPOD project

Phys. Rev. D **106**, 115034

- **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

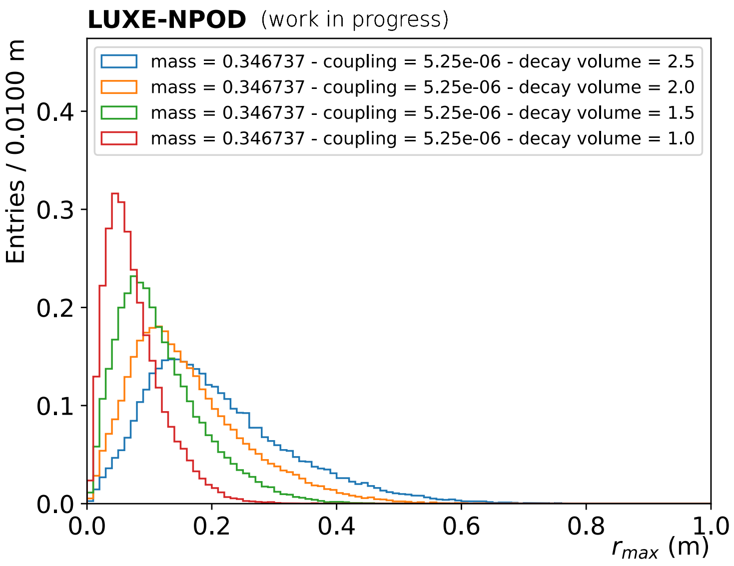


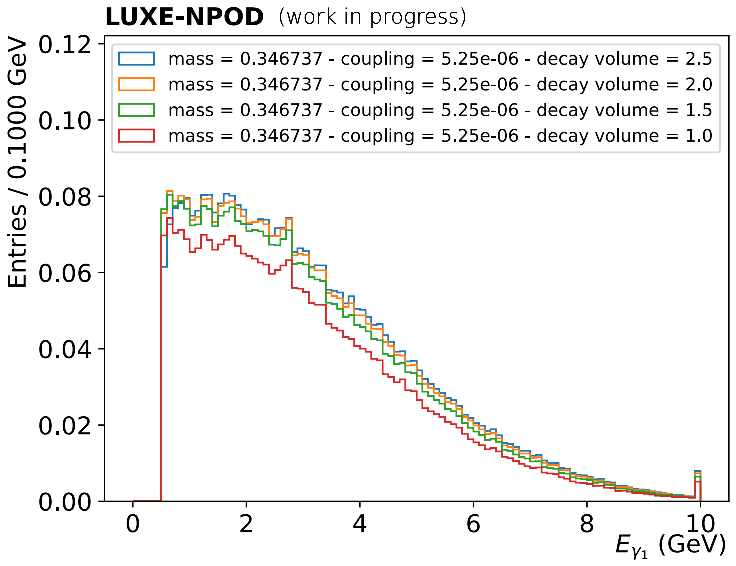


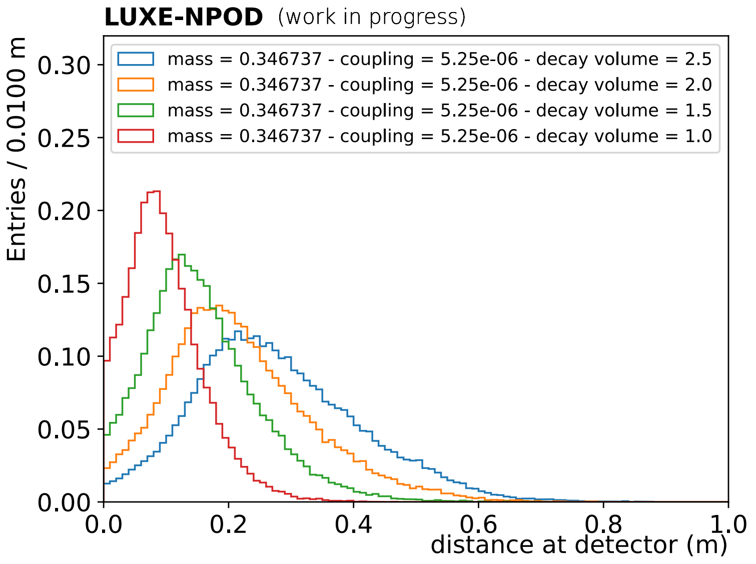
Laser repetition rate 1Hz
→ 10^7 bunch-crossings (BX) per year

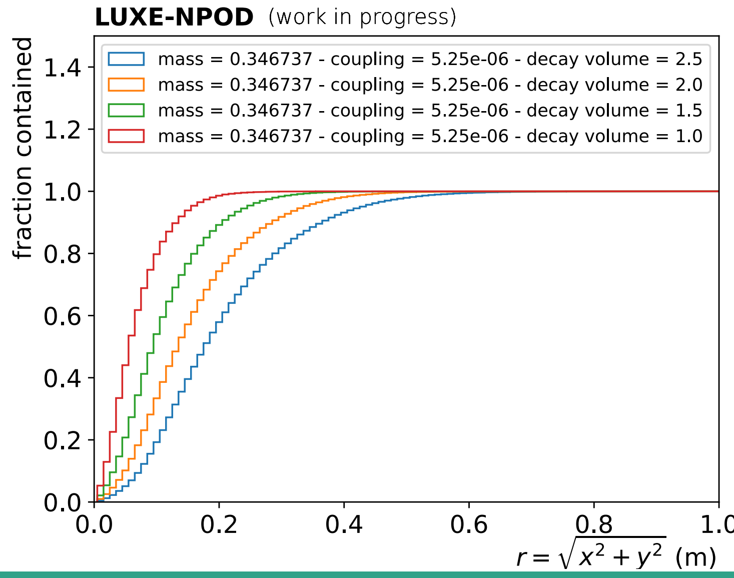
Signal efficiency

- 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

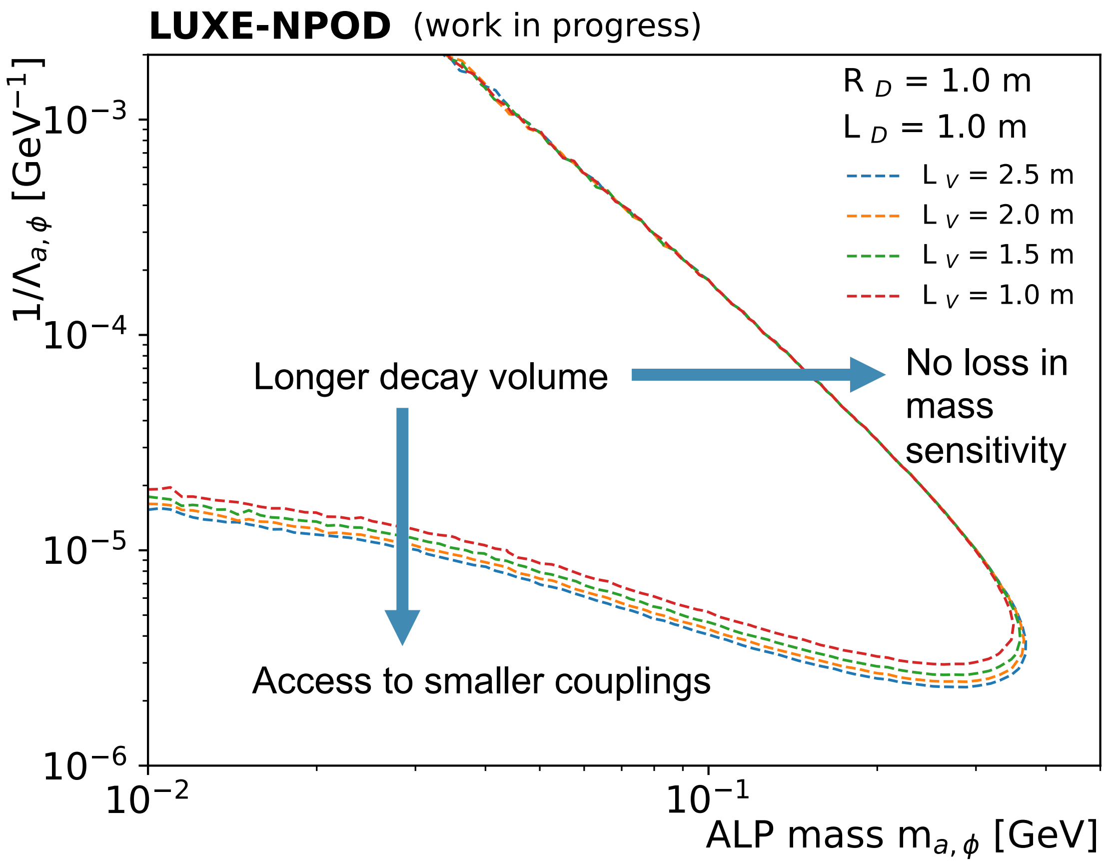




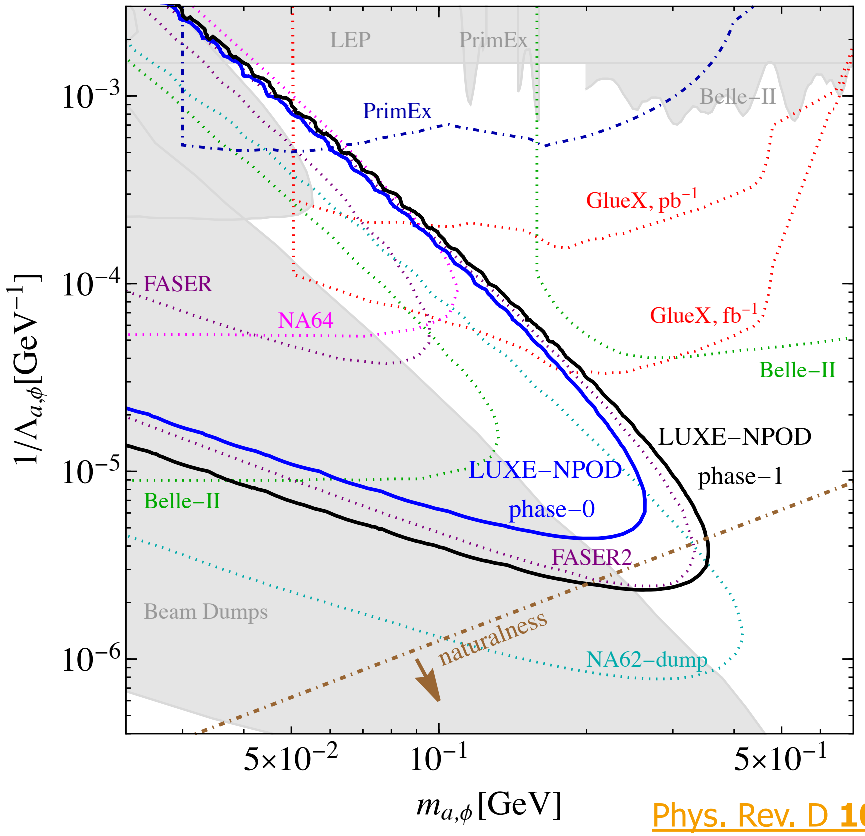




Expected results in phase-1



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



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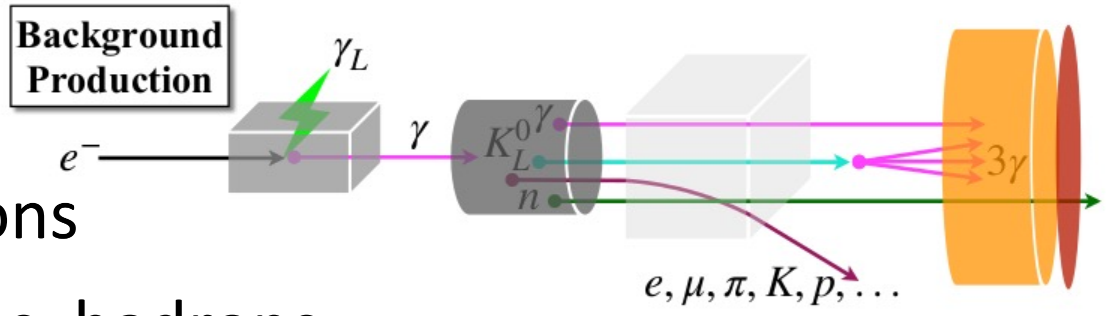
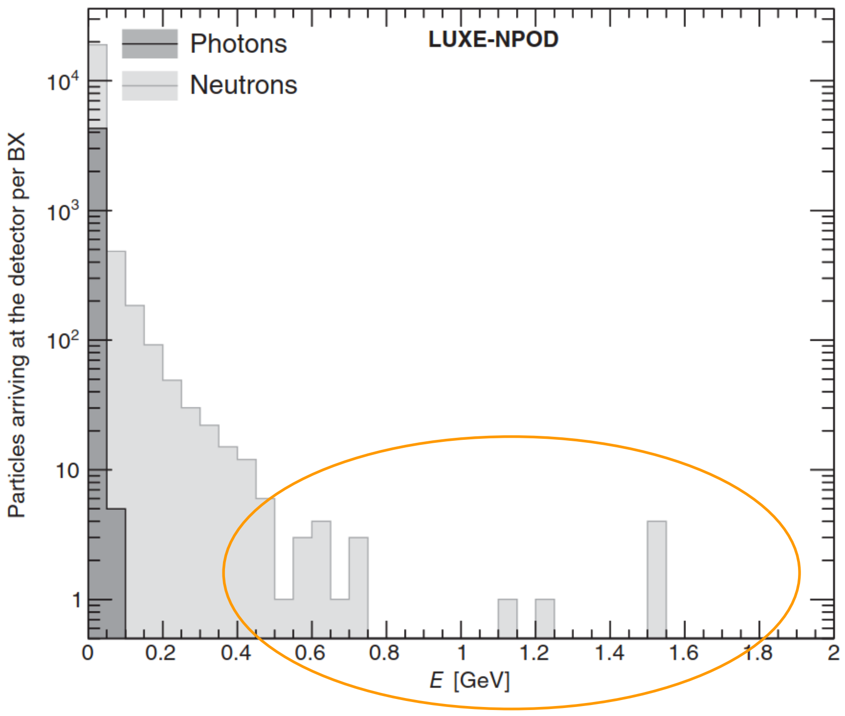
LUXE-NPOD background



- 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 *dummy 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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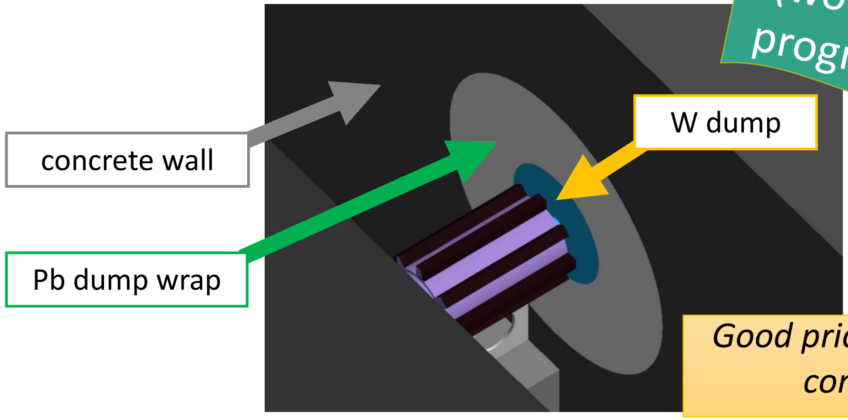
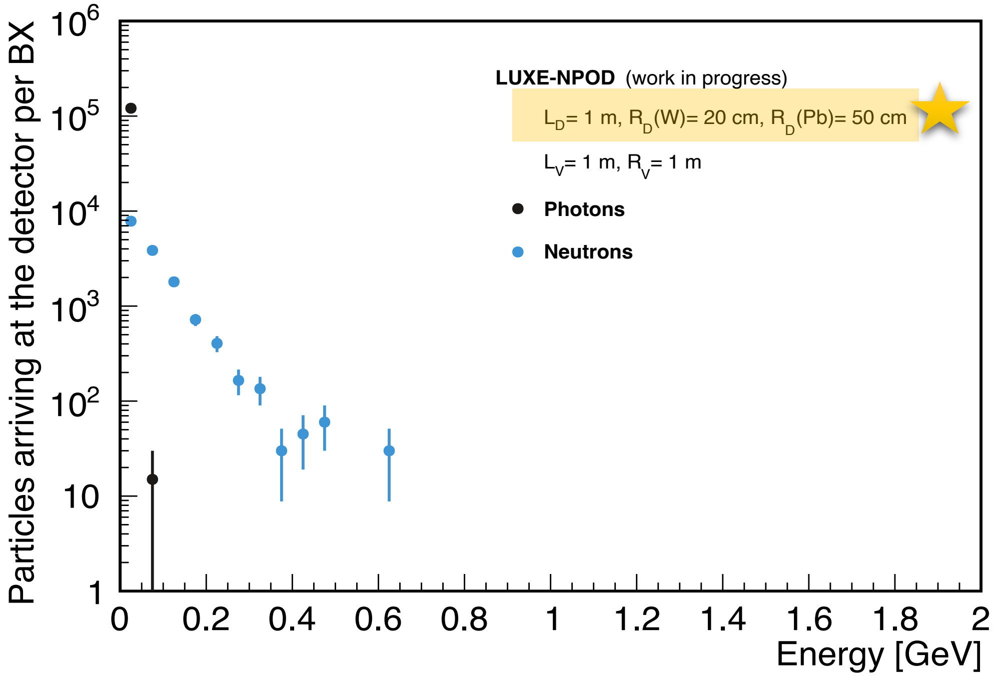
LUXE-NPOD background estimation

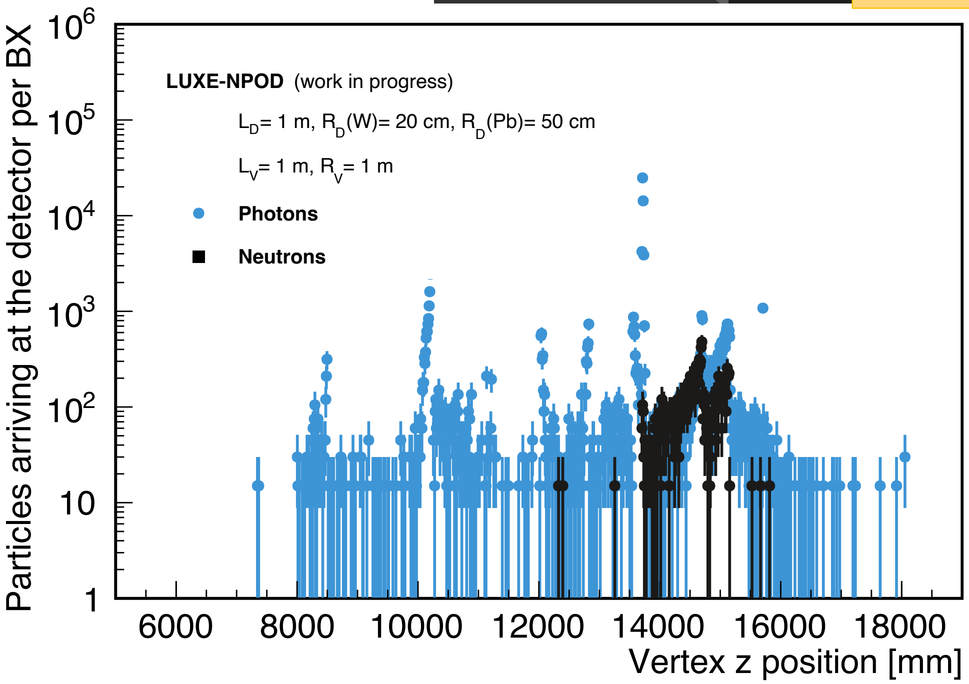
- Ongoing new GEANT4 simulations including full LUXE setup
- Presence of low-energy particles due to backscattering and particles escaping through the sides of the dump
  - not spotted by the previous simplified experimental model
- New dump-detector design under study

(work in progress)



Good price-performance compromise

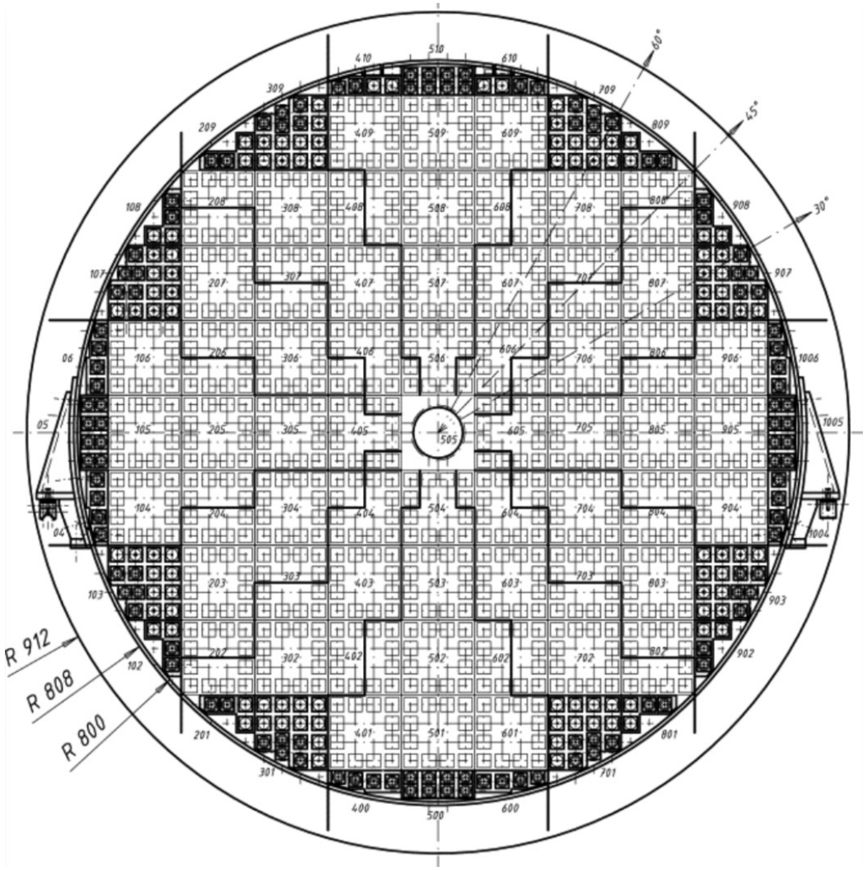




BSM detector requirements

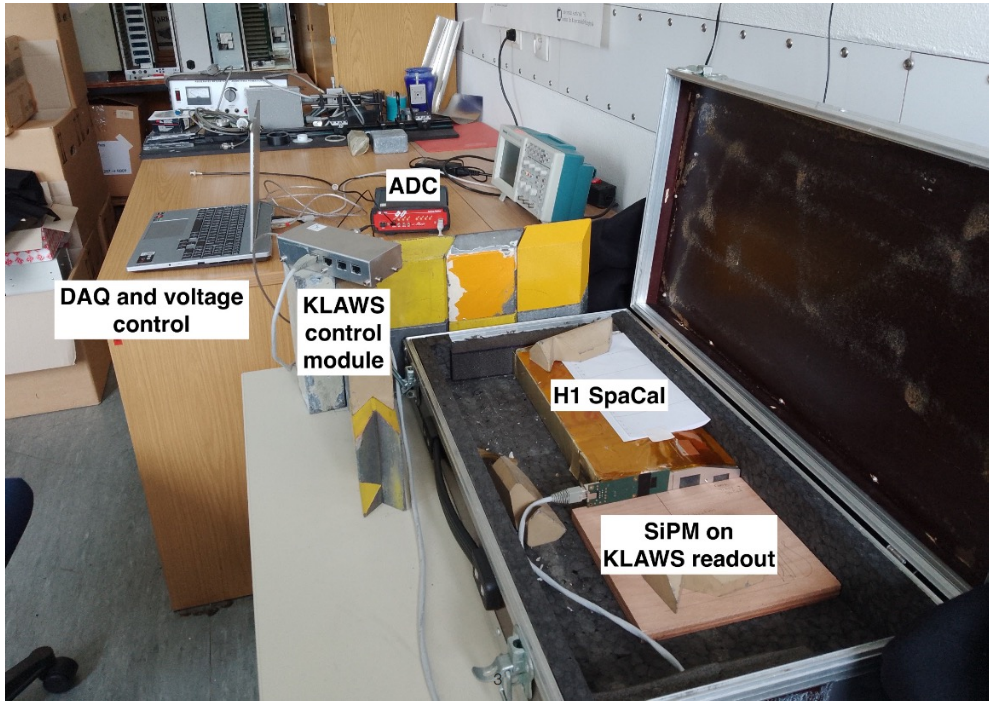
- Signal efficiency
  - Photons shower separation (~1 cm)
- ALP invariant mass reconstruction
  - Good energy and vertex resolution
- Background suppresion (photons and neutrons)
  - Vertex resolution (non-resonant photons)
  - Shower shape determination (neutrons)
  - Good time resolution (< 1 ns) (neutrons)
- Ideal candidate: tracking calorimeter

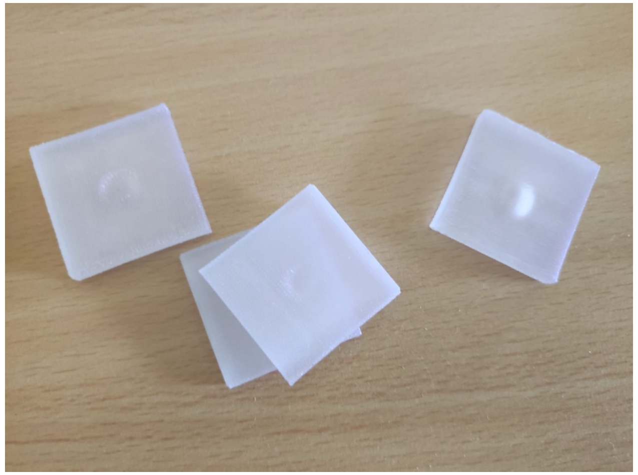
10.1016/j.cpc.2010.02.004

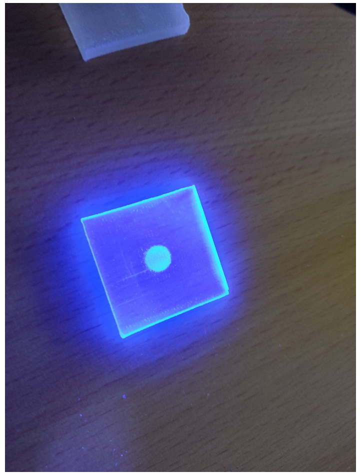


BSM detector proposal

- H1 lead/scintillating-fiber calorimeter:
  - One module currently tested at KIT
- Tile calorimeter:
  - e.g. Calice detector prototype
  - Currently studied at Mainz as a candidate for the SHADOWS calorimeter
- ALPIDE:
  - Silicon tracker
  - Same technology as the LUXE tracking detector or ALICE forward calorimeter

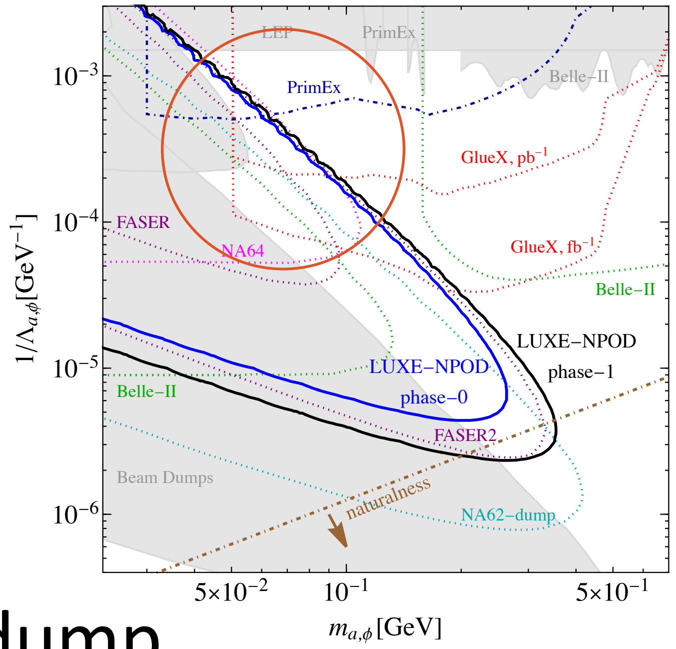






Summary

- LUXE will explore QED in uncharted regime
- LUXE-NPOD acts as an optical dump allowing the production of light ALPs with large couplings
- LUXE phase-1 competitive with FASER2 or NA62-dump
- Data taking foreseen for 2026
- Exciting windows of opportunities and challenges ahead



LUXE webpage

LUXE CDR

LUXE TDR

LUXE-NPOD

Thanks!

Backup

DESY: CRITICAL DECISION (CD) PROCESS

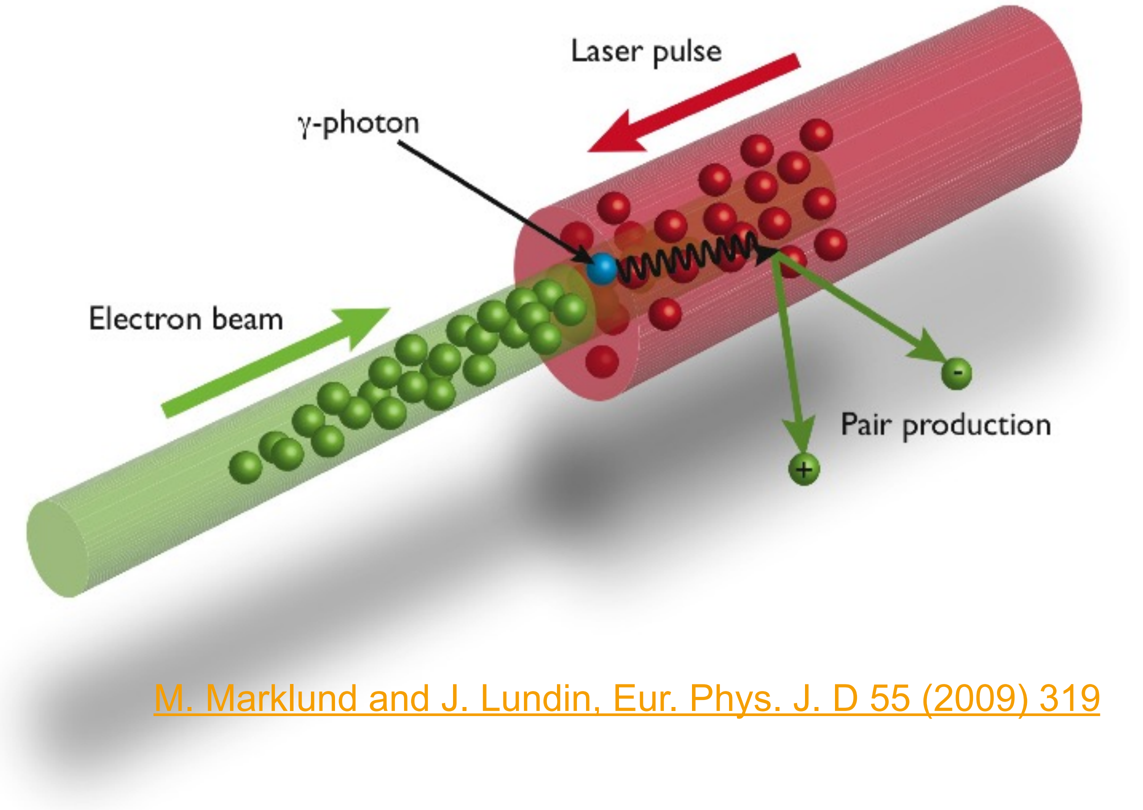
CD-Level	Voraussetzungen	Voraussetzungen werden festgestellt durch
CD 0: **Mission Need**	• The plan is presented in sufficient detail so that the scientific and strategic purpose as well as the resource requirements can be assessed • It is clear how it relates to the DESY strategy • In case there are constructions costs, they were estimated by BAU • No decision yet about the allocation of resources	Decision by Direktorate – after discussion in Klausur.
CD 1: **DESY-Roadmap**	• Project, time and resource planning available (specifically financial, personnel and space/rooms required) => resource loaded schedule • Risk assessment available • Future costs clear • Vetting of resource estimates by relevant DESY technical groups (BAU, MKK, MVS, safety, IT, ...) available • Project is generally recommended for inclusion in the overall resource planning (potentially to the disadvantage of other projects) • Possibly external evaluation	Decision by directorate after discussion in Klausur
CD 2: **Resource planning**	• Identification/Verification of Resources	Decision of directorate following proposal for financing by strategic controlling and financial controlling
CD 3: **Approaval of oversight committees**	• Endorsement by Stiftungsrat and Wissenschaftlicher Rat	Decision by SR/WR.
CD 4: **Project launch**	• Release of Direktorate	Strategic Controlling

SFQED in the laboratory

- Existing fields orders of magnitude too small compared to $\mathcal{E}_{cr}$
- But, non-linear quantum effects accessible in fields below $\mathcal{E}_{cr}$ with relativistic probe particles, i.e. fields O($\mathcal{E}_{cr}$) in particle rest frame
- Can be reached with Lorentz boosted electric field

$E^* = \gamma_e E(1 + cos\theta)$ with $\gamma_e \approx 10^4$

➡ *Use multi-GeV electrons and multi-TW laser*



M. Marklund and J. Lundin, Eur. Phys. J. D 55 (2009) 319

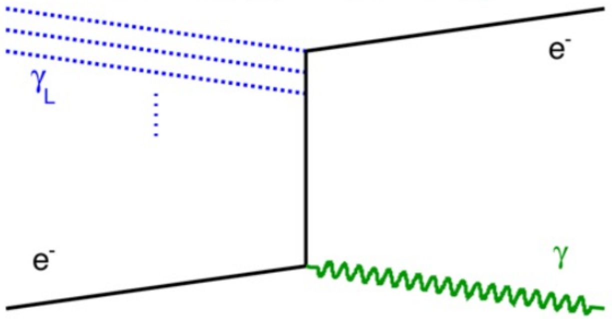
Non-linear Compton scattering

In strong fields, electrons obtain larger effective mass

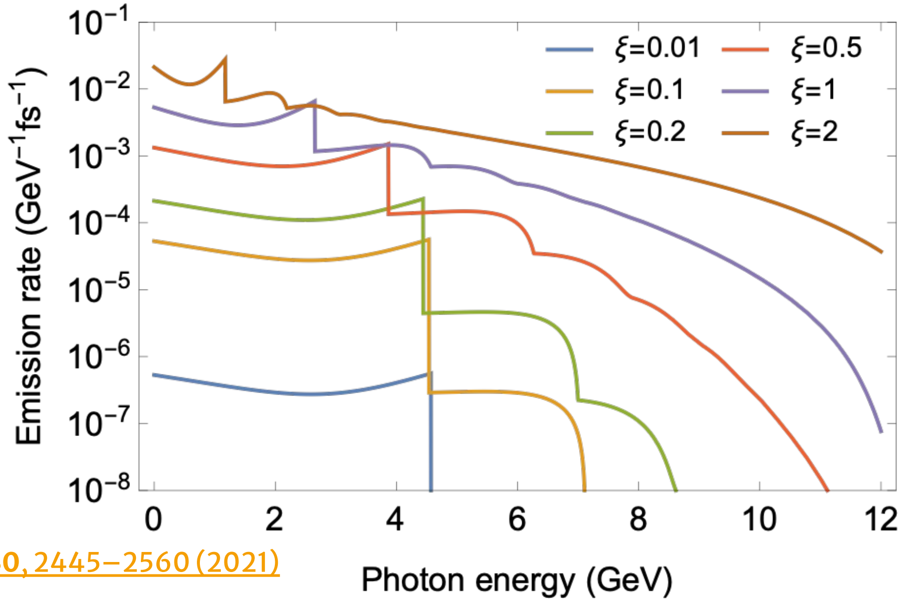
$m_* = m_e\sqrt{1+\xi^2}$

- Compton edge shifts as a function of the laser intensity parameter ξ
- Higher harmonics appear, i.e. interaction with *n* laser photons
- Non-linear Compton scattering has a classical limit, i.e. deviation between non-linear QED and non-linear classical Compton: quantum non-linearity parameter χ
- Parameters ξ and χ determined by laser intensity and electron beam energy

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



16.5 GeV electron, 800 nm laser, 17.2° crossing angle



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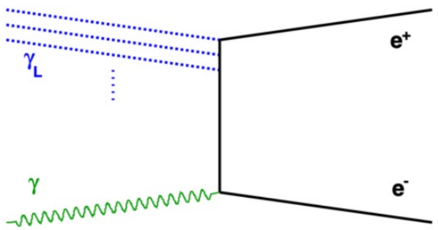
Breit-Wheeler pair production

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

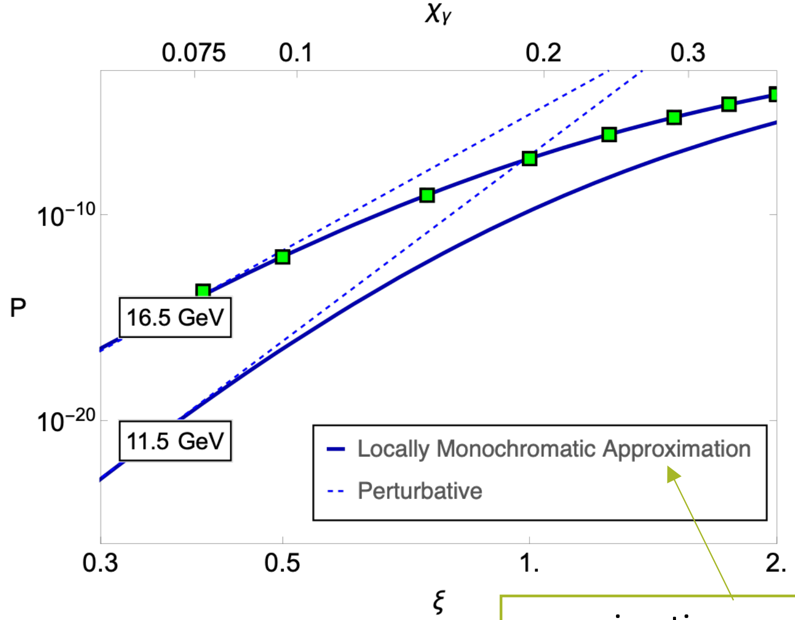


- Dependency of positron emission probability as a function of laser intensity

Perturbative regime: power law $\xi \ll 1$: $R_{e^+} \propto \xi^{2n} \propto I^n$

Non-perturbative regime $\xi \gg 1$: $R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$

- *First experiment to measure Breit-Wheeler pair production with real photons*

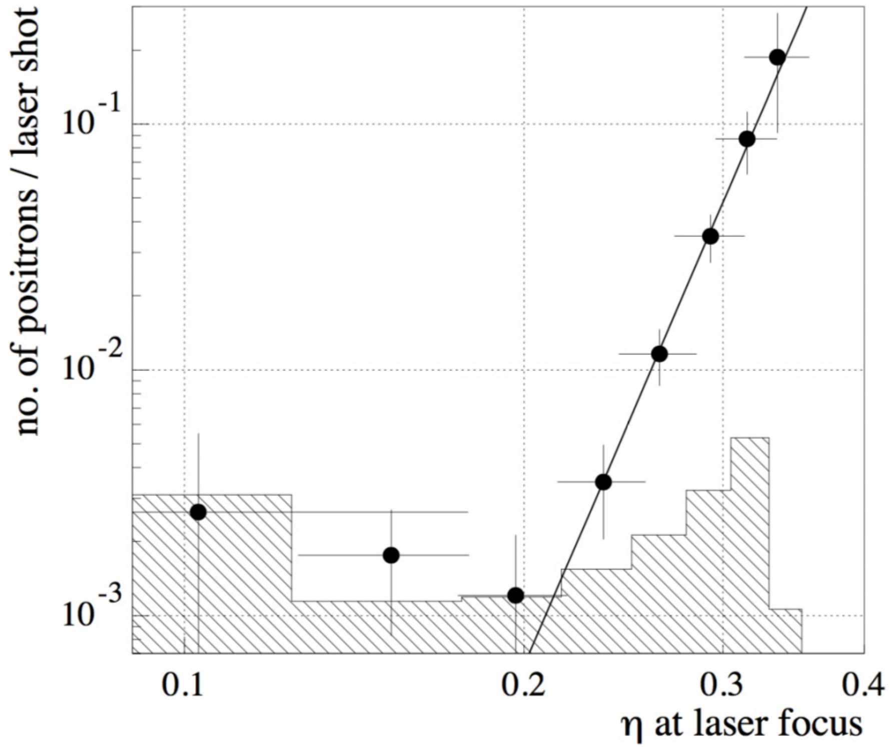


approximation used in simulations with realistic background field

Eur. Phys. J. Spec. Top. **230**, 2445–2560 (2021)

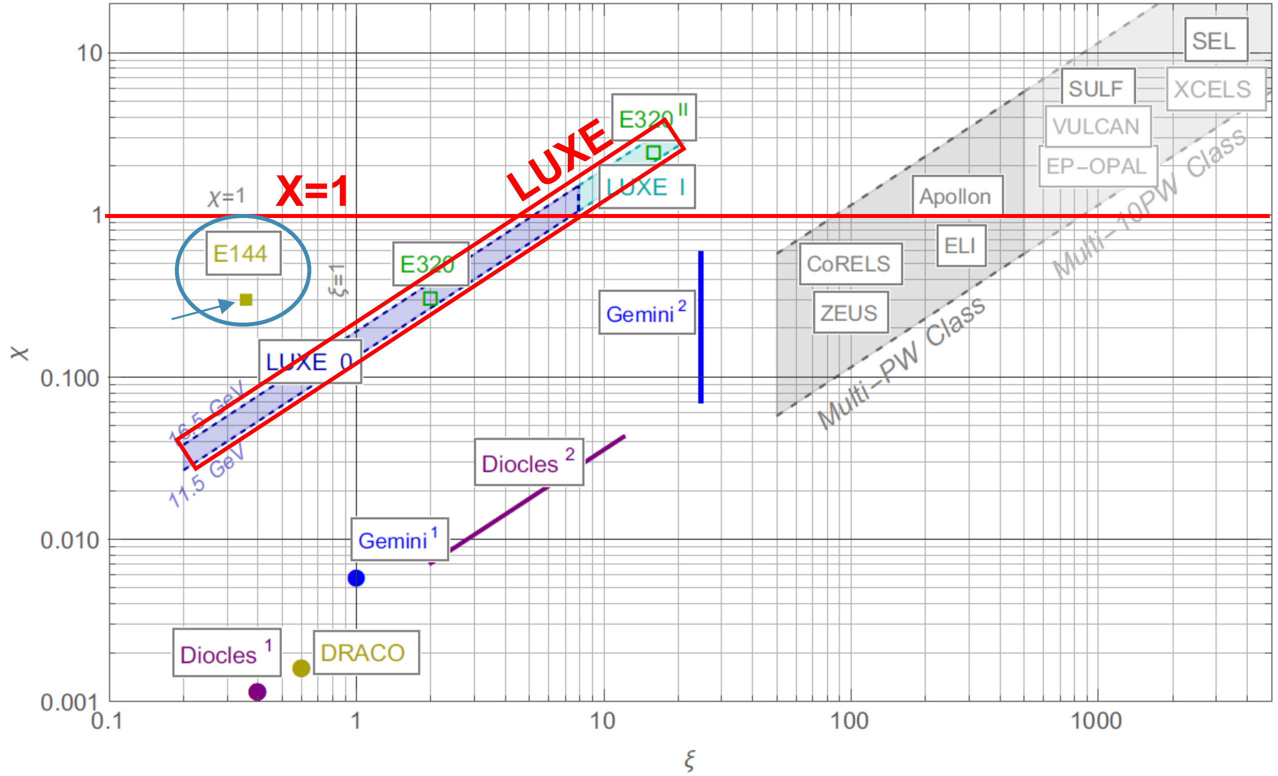
Previous experiment in SFQED

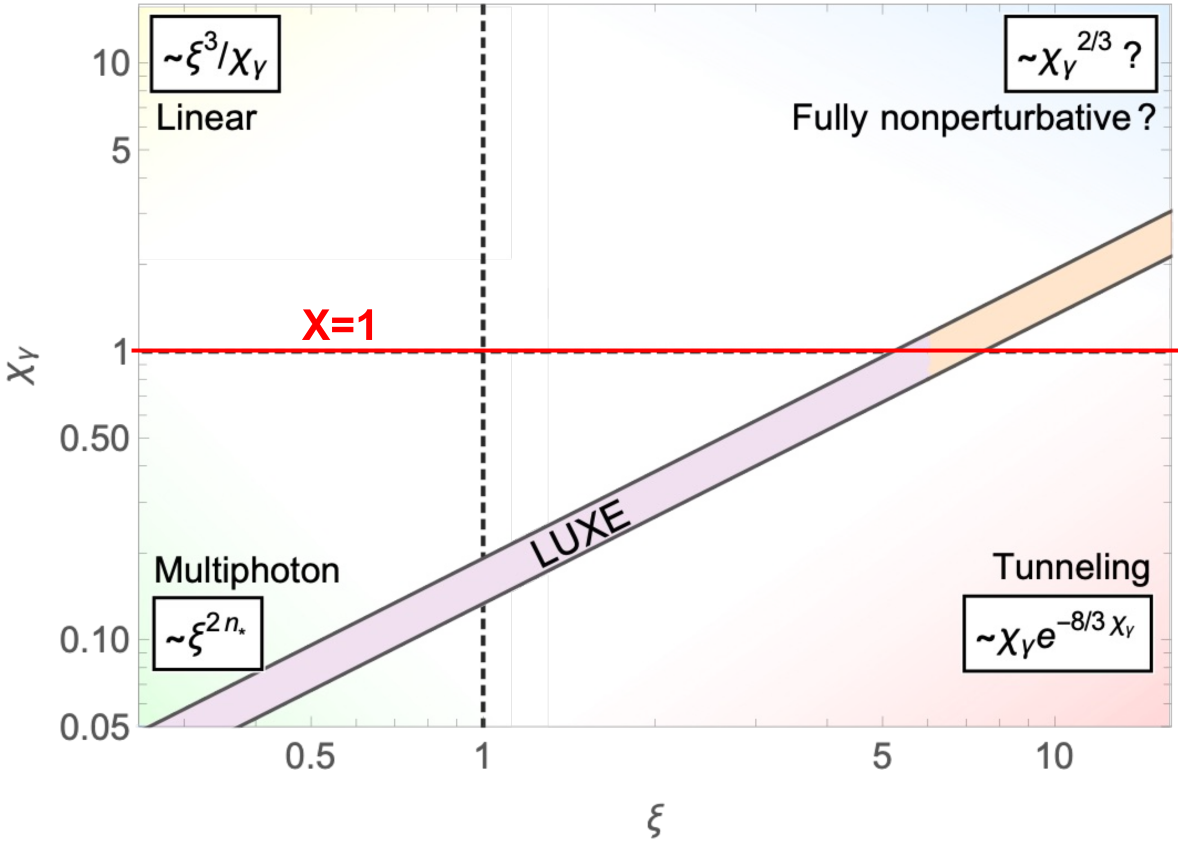
- Predecesor: E144 experiment at SLAC in the 90s
  - Used 1 TW laser and 46.6 GeV electron beam
  - Reached $\chi \sim 0.25,\ \xi \sim 0.4$
  - Observed process $e^- + n\gamma_L \rightarrow e^- + e^+ + e^-$
  - Observed start of ξ^{2n}power law, but not departure from it
- LUXE has a three orders of magnitude more powerful laser



E144 Coll., C. Bamber et al., Phys. Rev. D 60 (1999) 092004

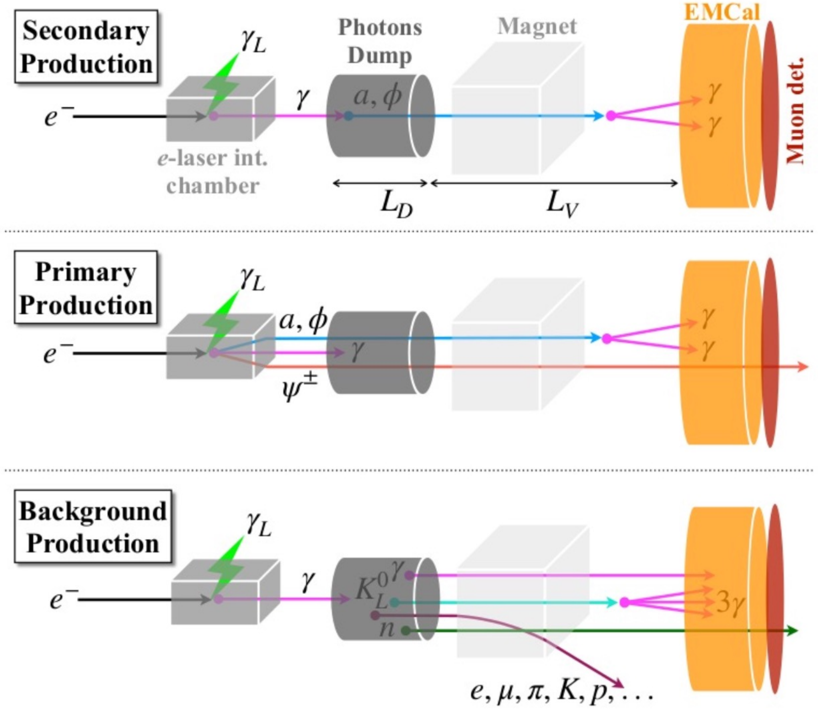
LUXE in SFQED parameter space





- LUXE will precisely map parameter space (ξ, χ) in transition region
- Continuous data-taking with variable laser spot size (unique in LUXE)

ALPs production photons spectra

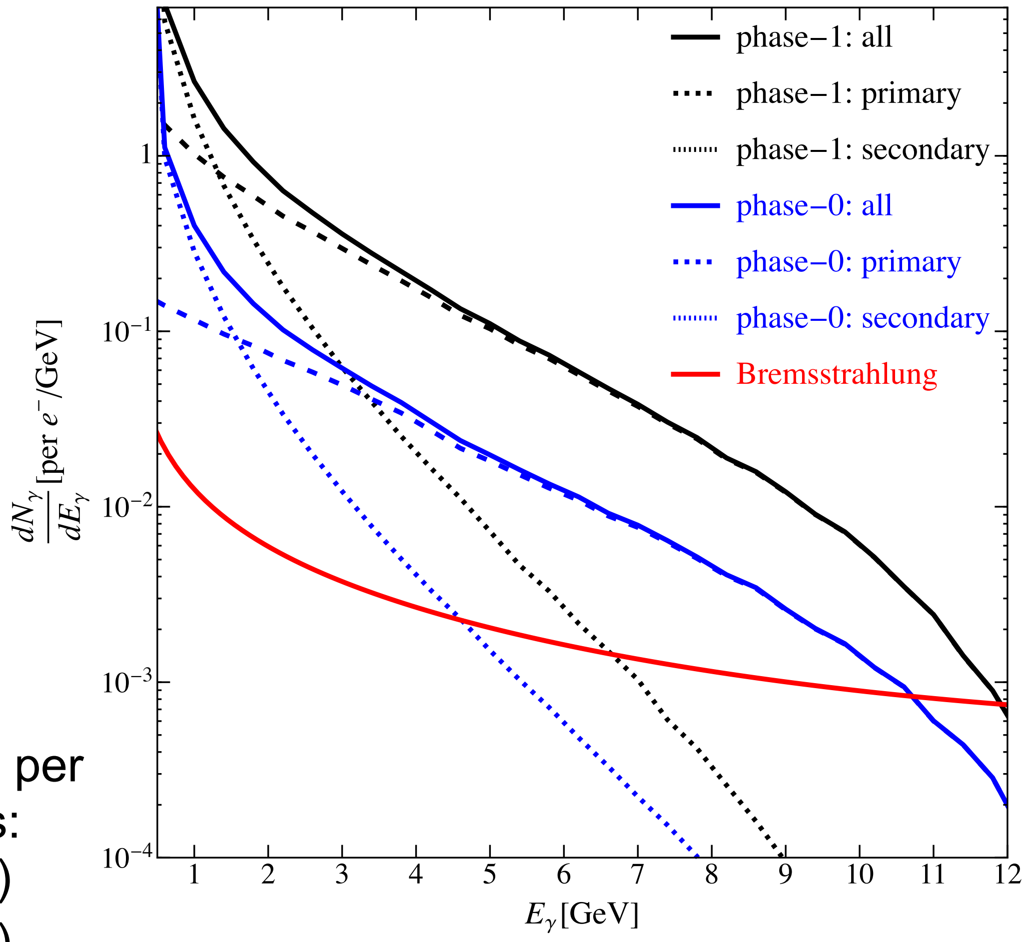


phase-0	phase-1
$\tau_{pulse} = 25fs$ $w_0 = 6.5\ \mu m$ $\xi = 2.4$	$\tau_{pulse} = 120fs$ $w_0 = 10\ \mu m$ $\xi = 3.4$

For phase-1, photons per incoming electrons:

~ 3.5 (E_γ > 0 GeV)

~ 1.7 (E_γ > 1 GeV)



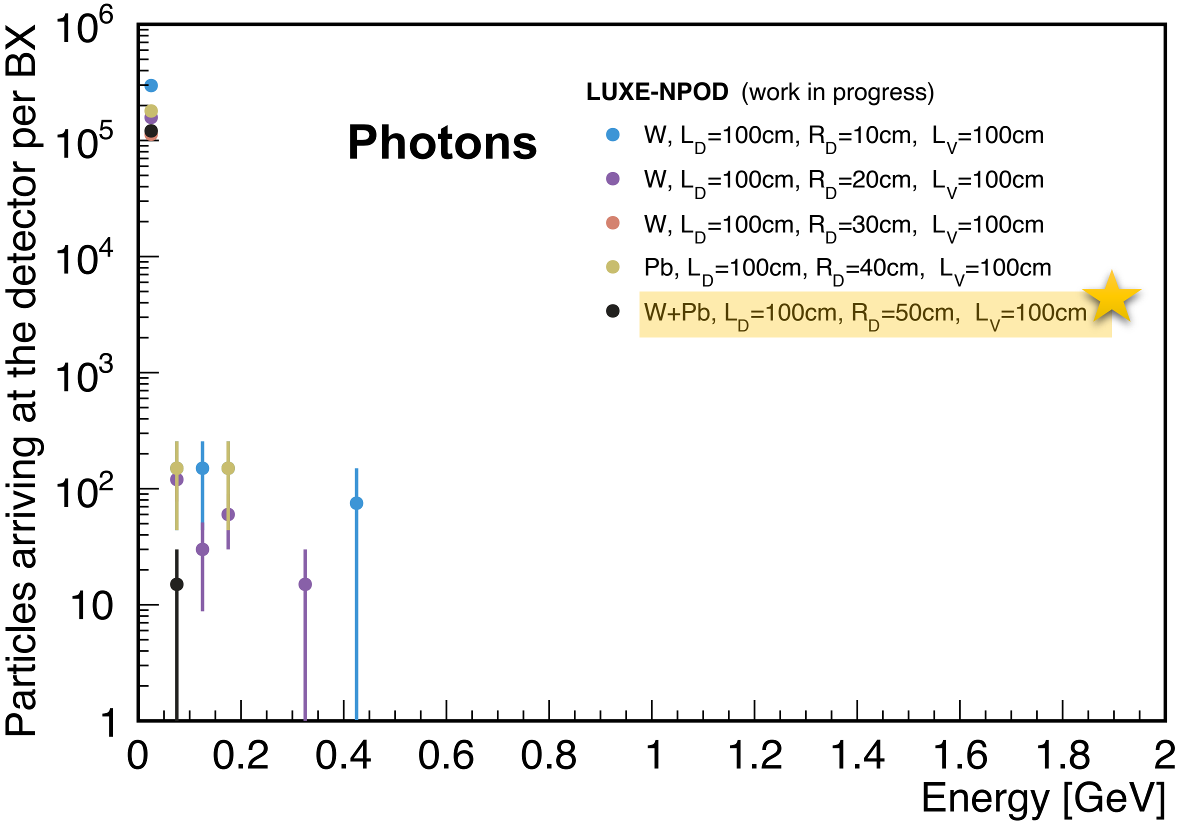
arXiv:2107.13554

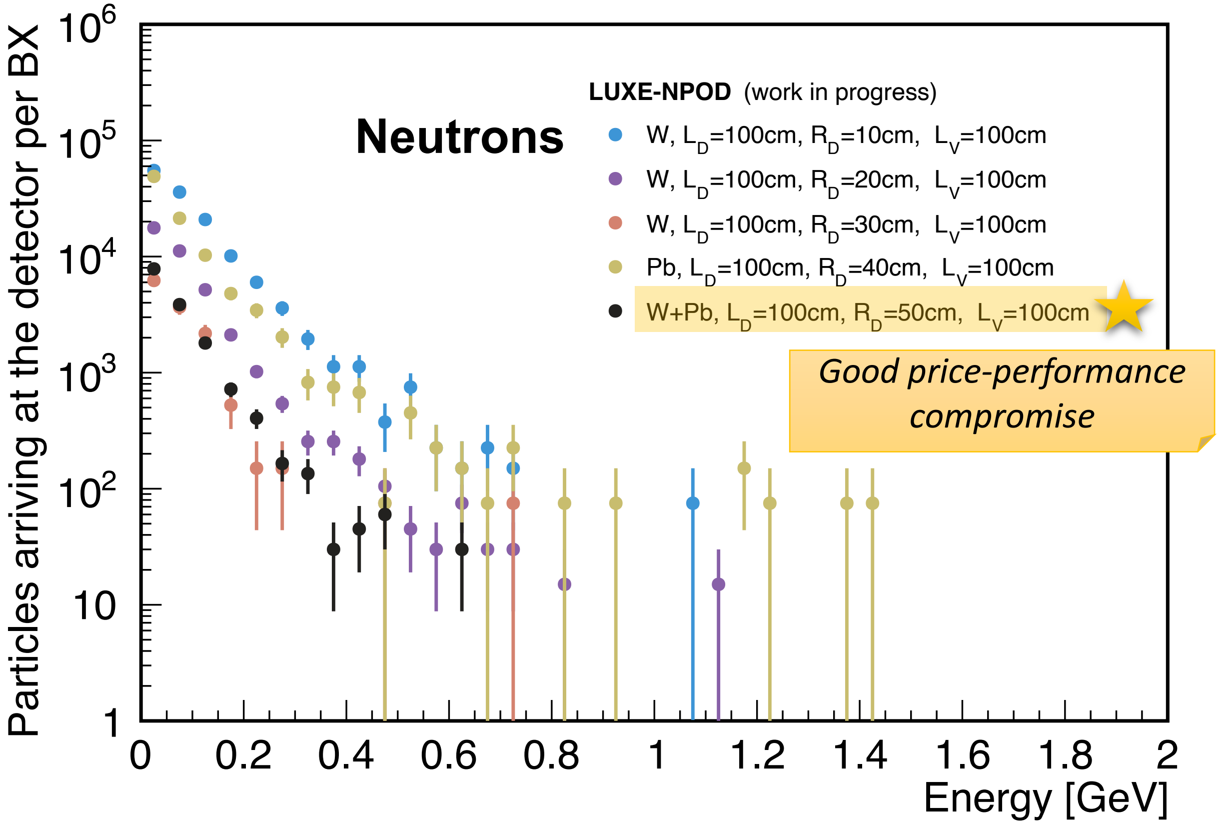
Photons separations at detector surface

m_X [MeV]	Λ_X [GeV^{-1}]	$<$ 20 mm [%]	$<$ 40 mm [%]	$<$ 50 mm [%]
50	10^{-4}	13	30	38
100	10^{-5}	8.4	17	22
150	6×10^{-6}	5.2	11	13
200	4×10^{-6}	3.8	7.6	9.7

LUXE-NPOD background estimation

- High number of neutrons with energy >0.5 GeV seen for dump made of only W or Pb
- Number of neutrons decrease for W(R = 20 cm) + Pb (R = 50cm) dump

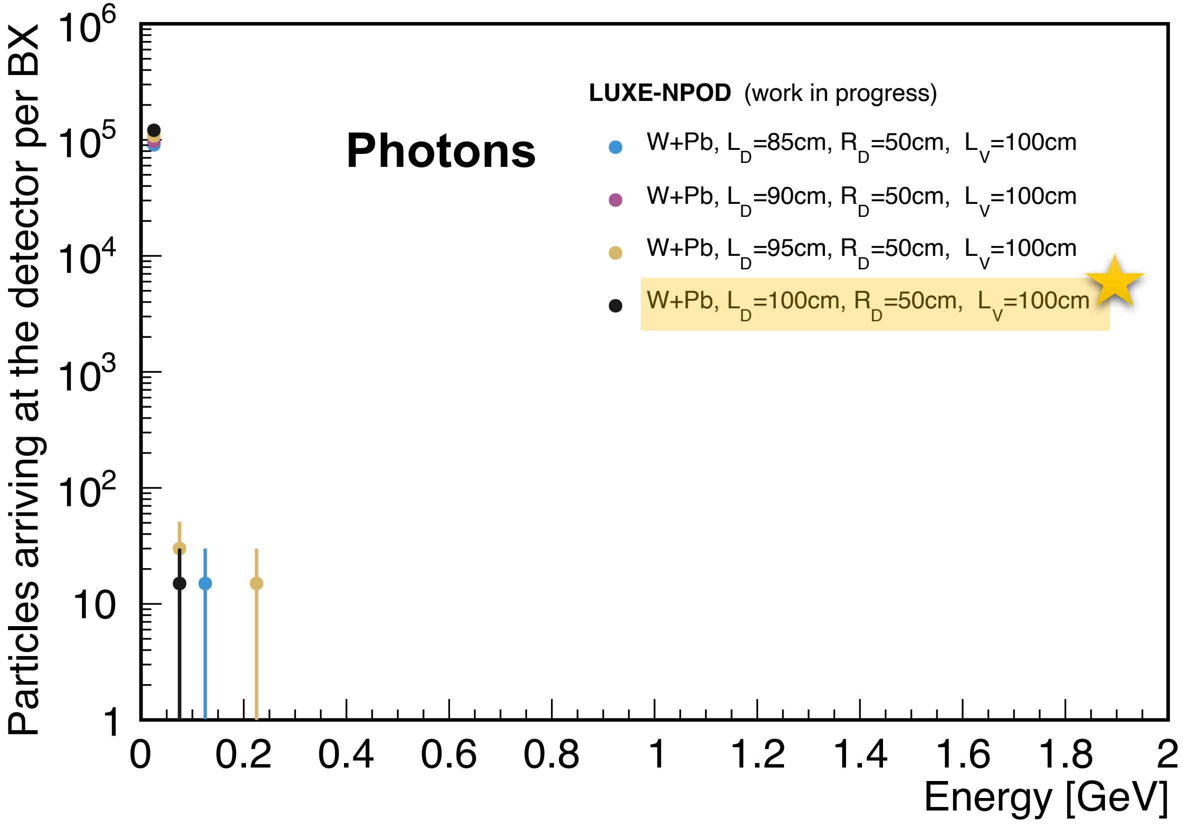


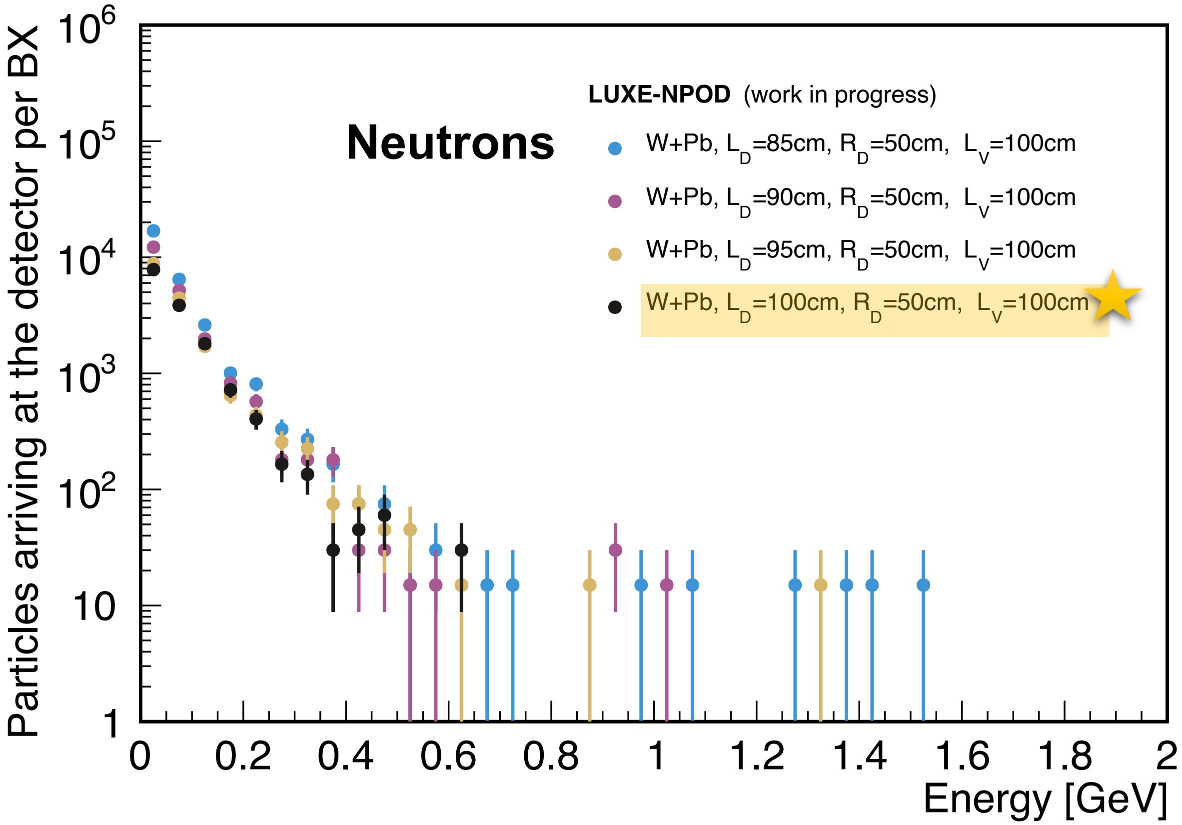


(1BX, R_V=1m)

LUXE-NPOD background estimation

- Shorter dump lengths would enhance the signal acceptance but also introduce more background

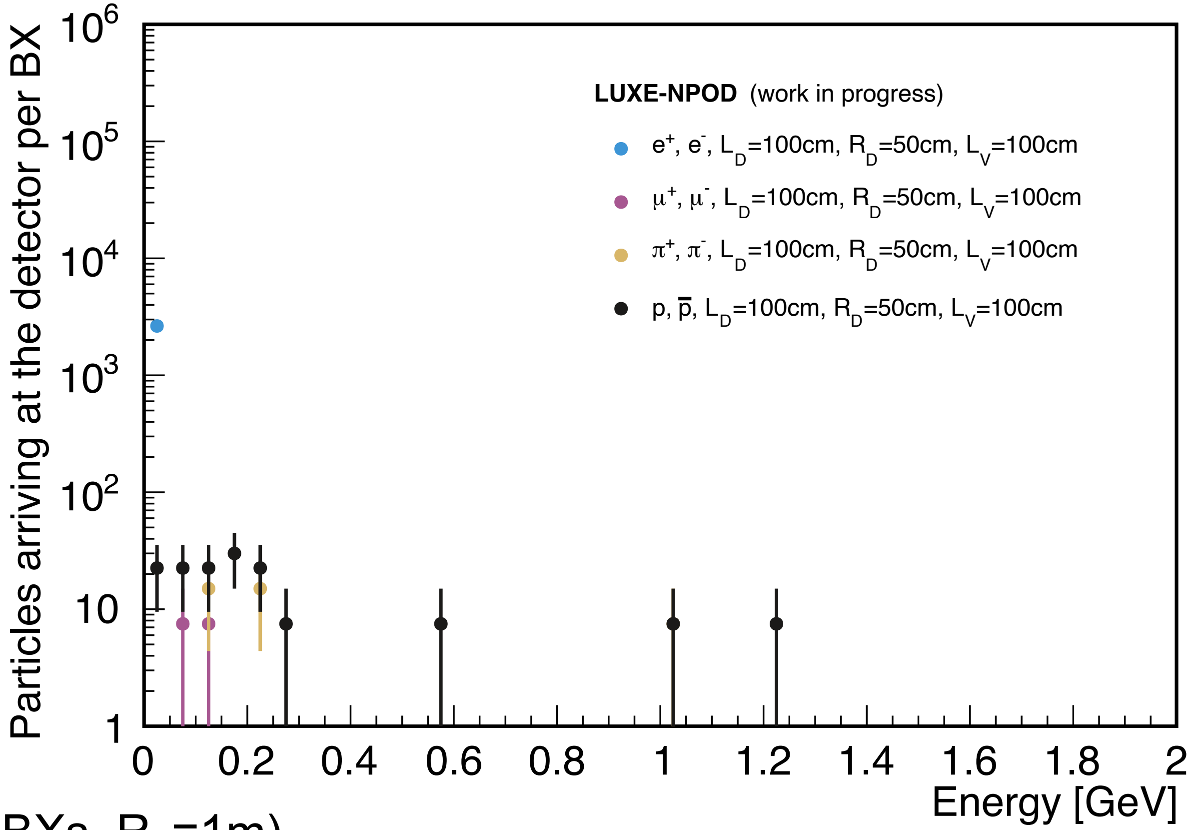


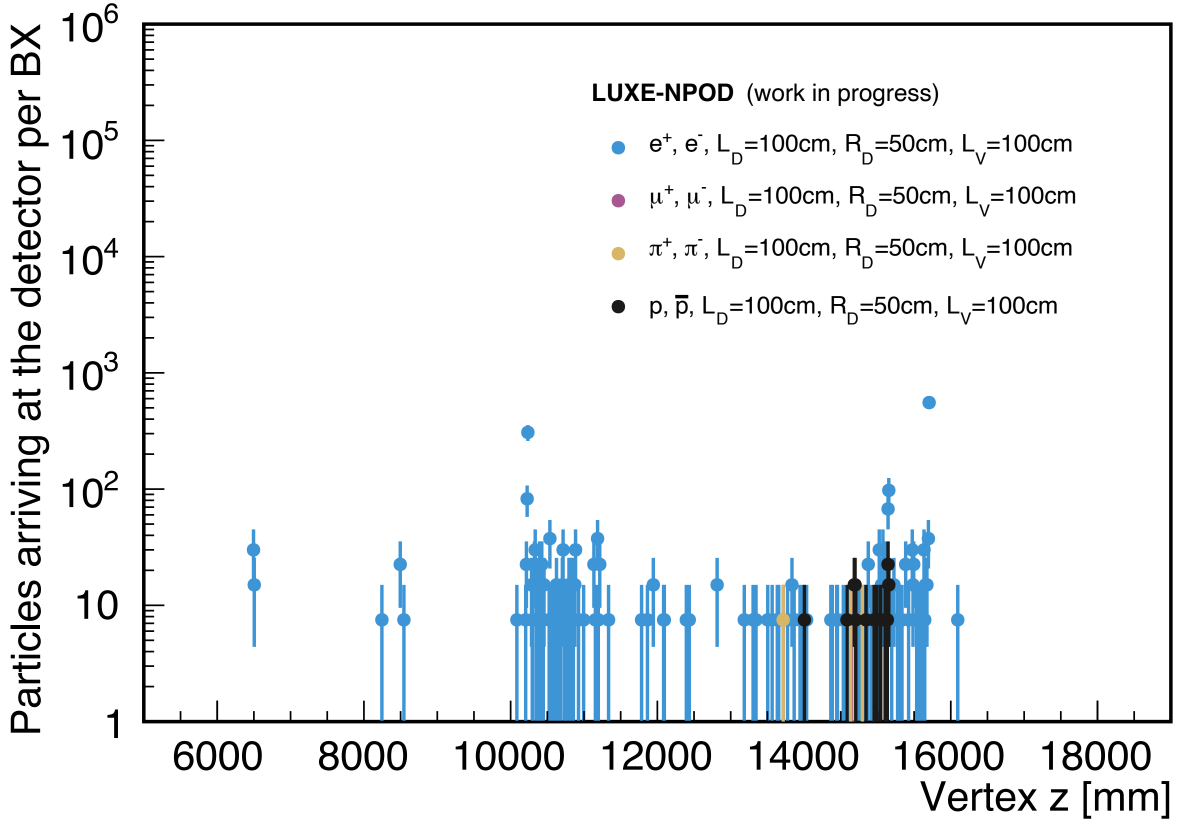


(1BX, R_W = 20 cm, R_{Pb}= 50 cm, R_V= 1 m)

LUXE-NPOD background estimation

- No significant background coming from charged particles above 0.5 GeV
- Background can be handled with a magnet





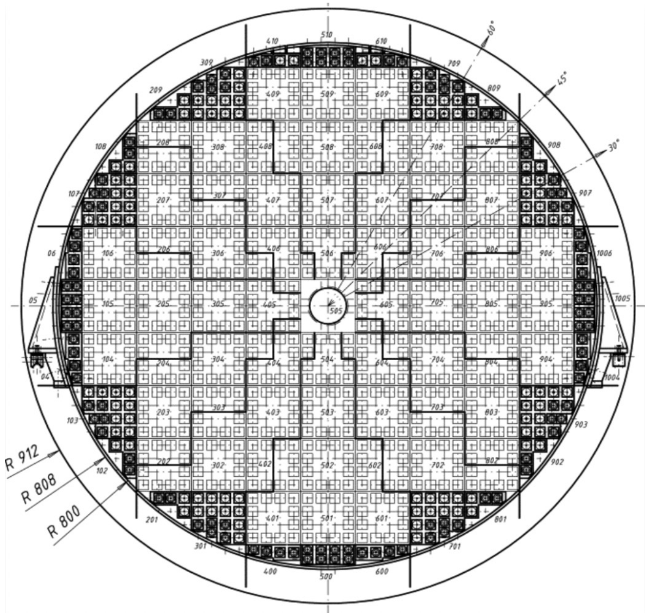
(2BXs, R_V=1m)

BSM detector proposal

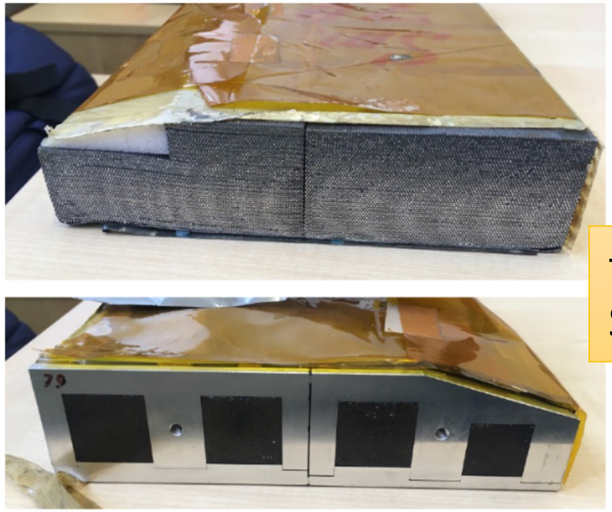
- Detector requirements:
  - Good energy and vertex resolution
  - ALPs invariant mass reconstruction
  - Background suppression (photons and neutrons)
    - Neutron rejection with calorimeter shower and time of arrival

- phase-0:
  - reuse existing calorimeter, e.g. spaghetti calorimeter (SpaCal) from H1
    - lead/fiber(2.3:1)
    - $4x4x25cm^3$ cells
    - energy resolution $7.5\%/\sqrt{E}+2\%$
    - time resolution < 1ns

- phase-1:
  - Preshower and vetoes
  - Tracking calorimeter, e.g. high granularity calorimeter (HGCal)



10.1016/j.cpc.2010.02.004



from SpaCal

Additional links

- SHADOWS Summary 2022: https://indico.cern.ch/event/1137723/contributions/4773516/attachments/2404601/4152201/shadows_SPSC_April2022_Lanfranchi.pdf

- ALPIDE detector at LUXE: https://indico.cern.ch/event/882870/contributions/3720001/attachments/1974963/3286730/The_LUXE_GG_Seminar.pdf