Probing for light new particle with the LUXE experiment

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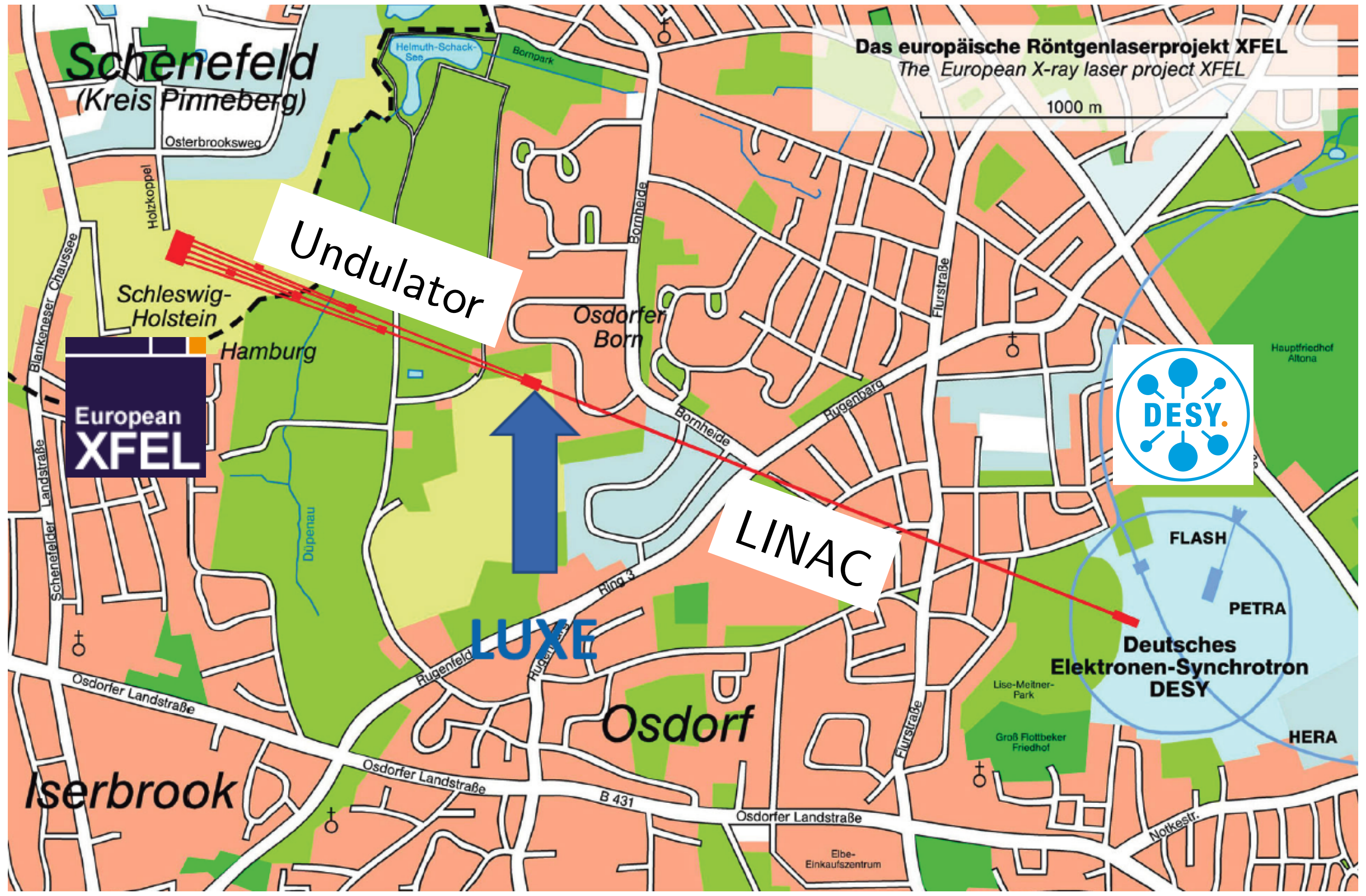
This research is supported by:

Laser und XFEL Experiment

LUXE is initially motivated by the strong-field QED

- Uncharted non-perturbativity in the presence of a strong electromagnetic field
- A high power laser (up to 350 TW)
- 16.5 GeV electron/photon beam (extracted from beamline at the European XFEL)
- Detection systems for e^-/e^+/gamma



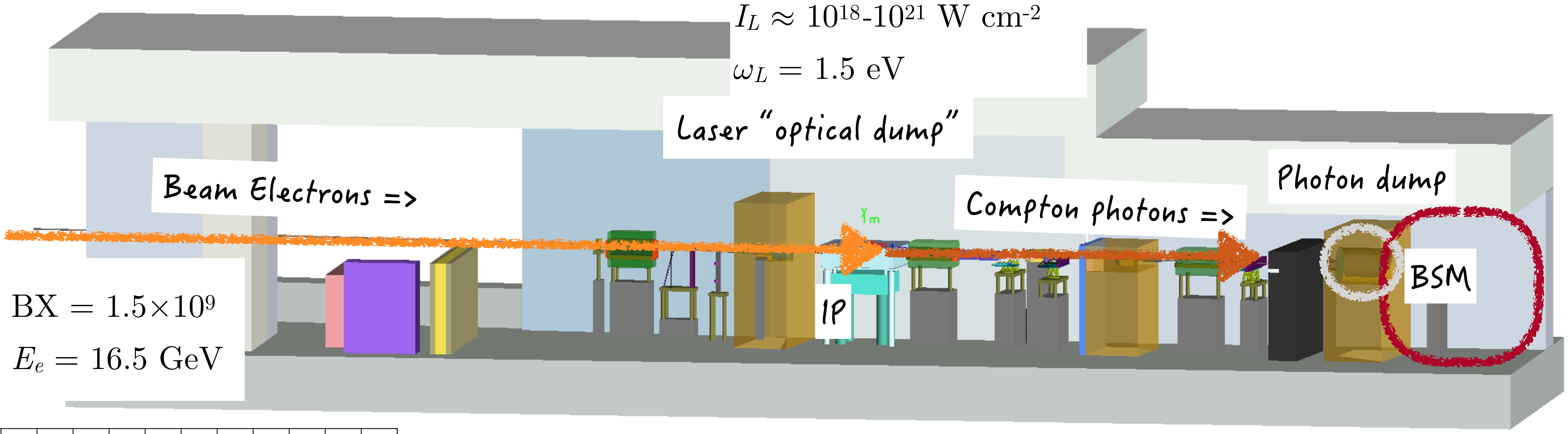
Two operation modes:

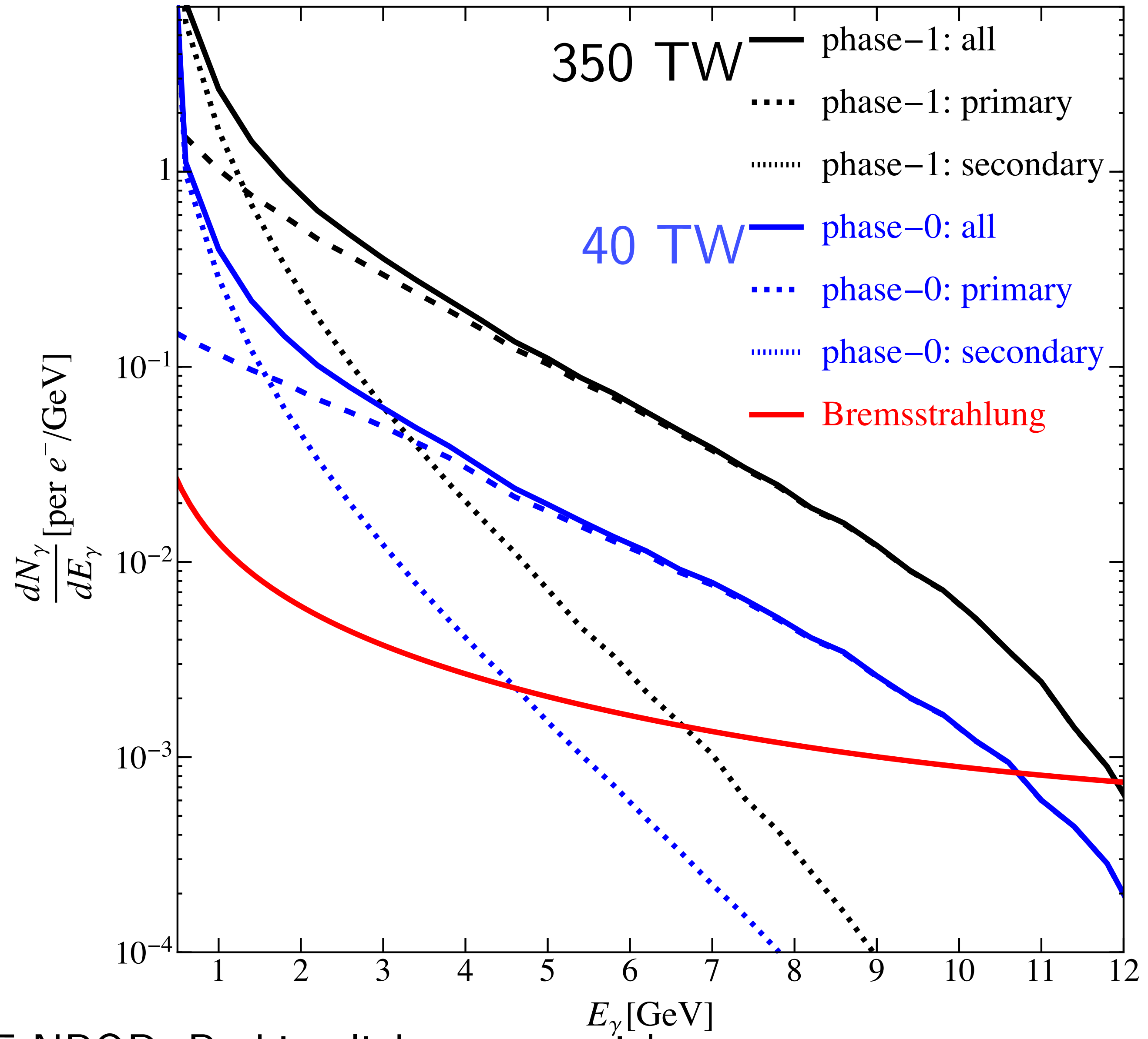
- electron-laser: **Compton scattering**; nonlinear BW pair production
- gamma-laser: light-by-light scattering; direct BW pair production

LUXE LoI: arXiv 1909.00860
LUXE CDR: EPJ ST 230 2445 (2021)
LUXE TDR: EPJ ST 233 1709 (2024)
LUXE Input ESPPU: arXiv 2504.00873

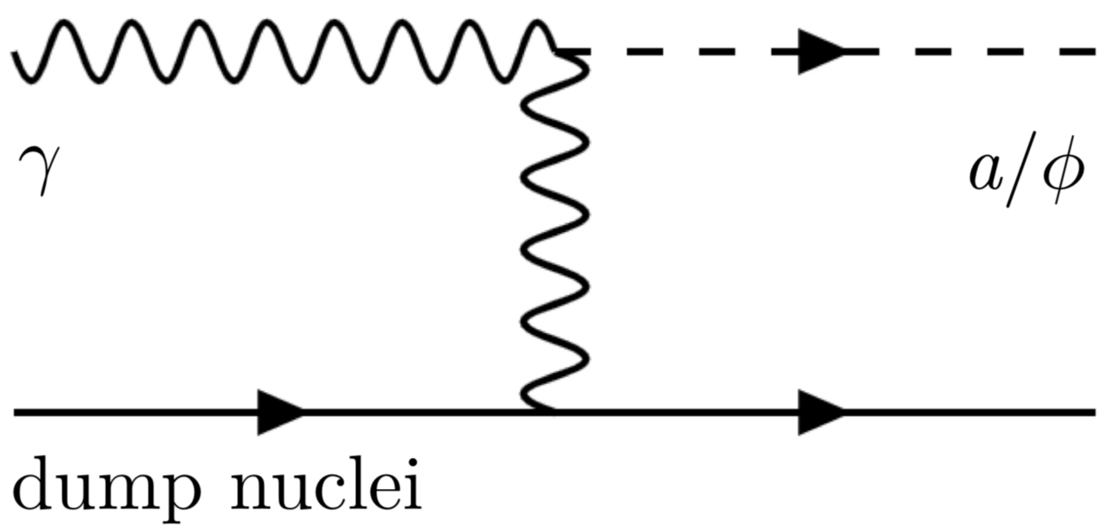
Other LUXE contributions at EPS HEP:
LUXE parallel talk (Tue) by Yan Benhammou
LUXE ECAL-P poster (Stand 18A-69) by Shan Huang

LUXE *New* ***p****hysics at* ***o****ptical* **d***ump*





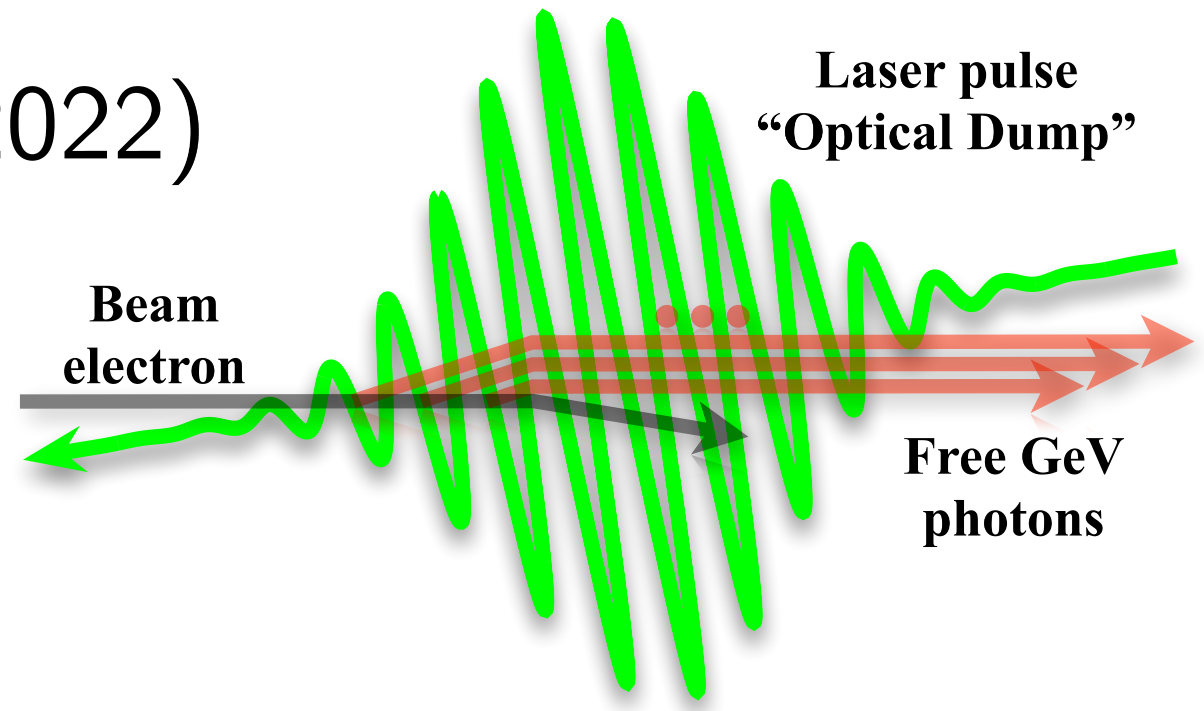
- Laser ("optical dump") converts electrons to photons via nonlinear Compton scattering
- The photons free stream through the laser field and go to a photon dump
- In average, one primary electron converts into **two to three** Compton photons (phase-1)



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

LUXE NPOD status

- We established the feasibility of LUXE NPOD in Phys Rev D **106** 115034 (2022)



For LUXE,

- A pilot 10-TW laser from Jena (phase-0.10) is being tested at DESY
- Part of the funds for beamline infrastructure secured
- Detector prototypes are being tested in simulations and in testbeam facilities

For NPOD,

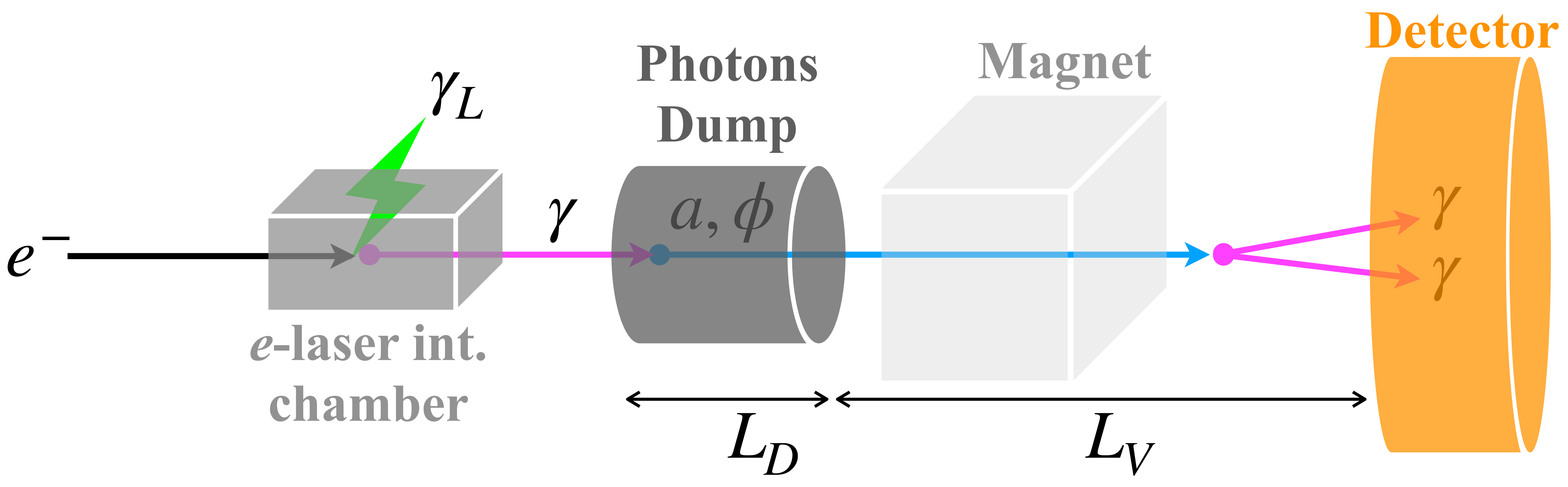
- More detailed simulative studies are carried out for sensitivity update and design optimization

Sensitivity simulation

- Compton scattering: Ptarmigan
  - Laser properties for LUXE phases of 10 TW, 40 TW, and **350 TW**
    phase-0 (10 TW, 40 TW) phase-1 (350 TW)
- ALP-photon interaction: MadGraph5 with a UFO model

Consider the effects on the sensitivity from

- Dump length
- Decay length
- Detector radius
- Detector resolution



Background simulation

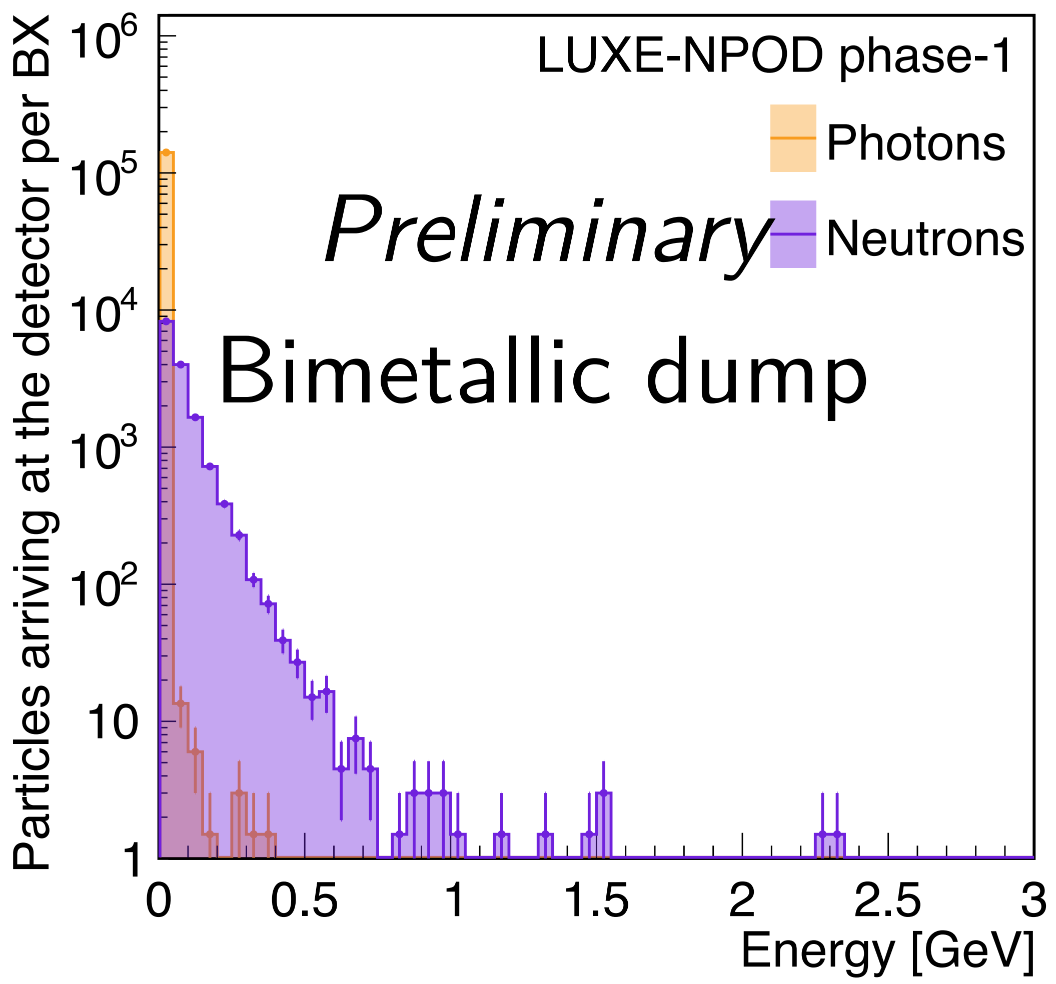
- We select above 0.5 GeV photons as signal candidate
- Detector radius is assumed to 1 m for benchmarking
  - Smaller detectors will reduce the background “acceptance”
- Neutrons are a concern because they easily mix with photon signals

- Geant4 v11 with `QGSP_BERT_HP`
  - Phase-0: no bkg above 0.5 GeV in 2 BXs
  - Phase-0 dump: W, $L_D = 25$ cm, $R_D = 10$ cm
  - Phase-1: photon flux is stronger and creates more background
  - Dump optimization:
    - Several options are tested, including a magnetised one
    - Eventually concluded with a bimetallic W+Pb design, which can suppress background leakage from the side, while being economic

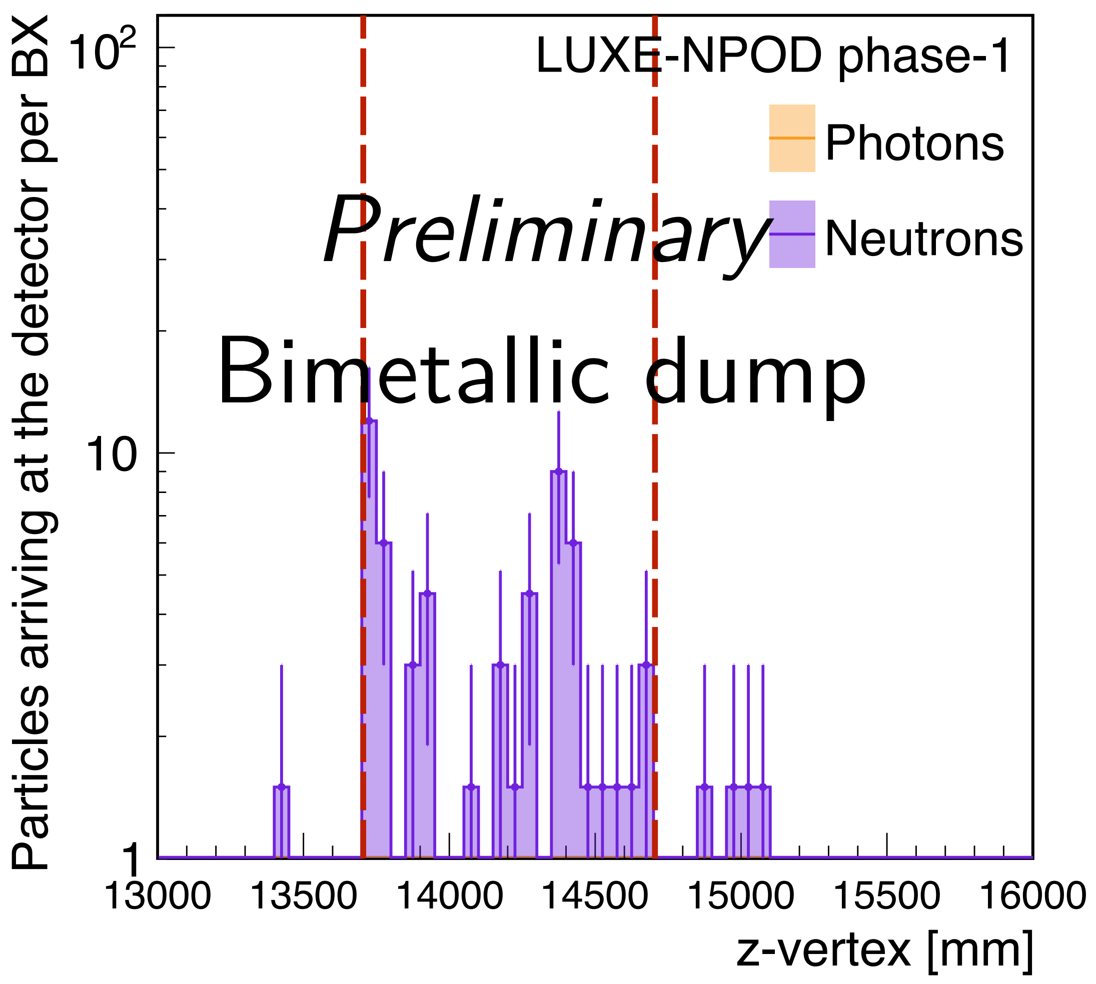
Dump optimization

We study the bimetallic dump with 10 BX background simulations

Dump of 1 m

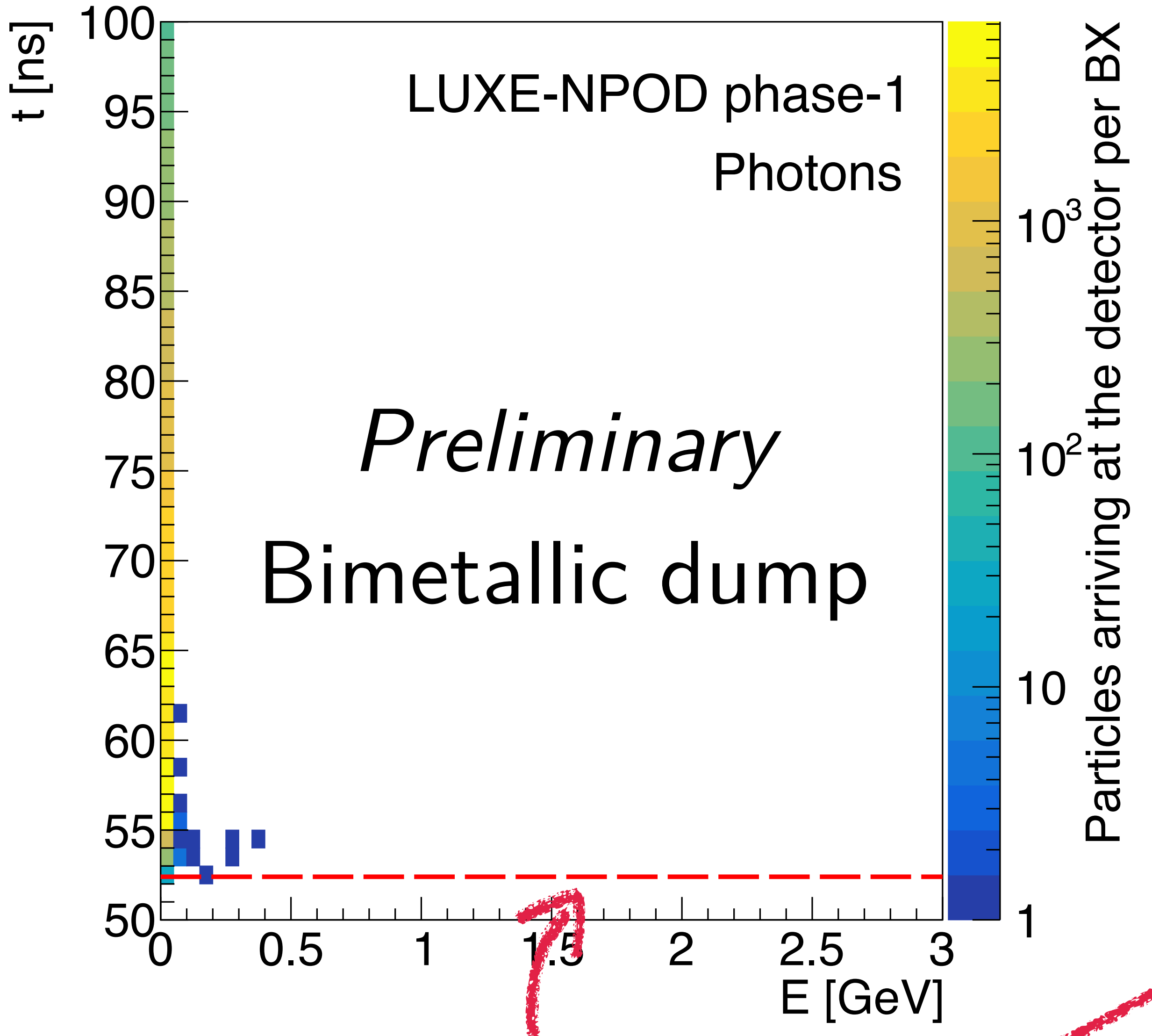


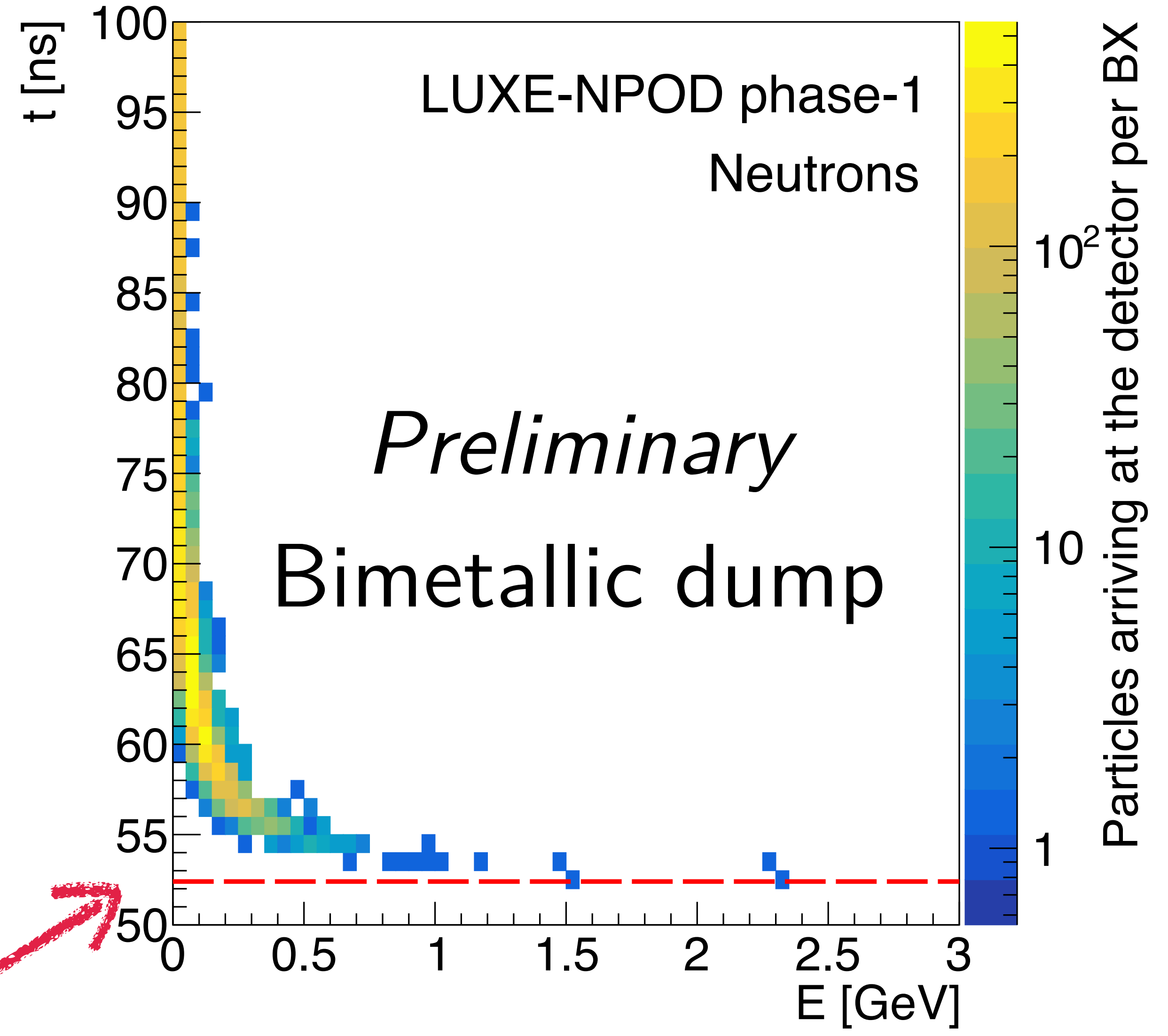
Background spectra



Vertex

($E > 0.5$ GeV)





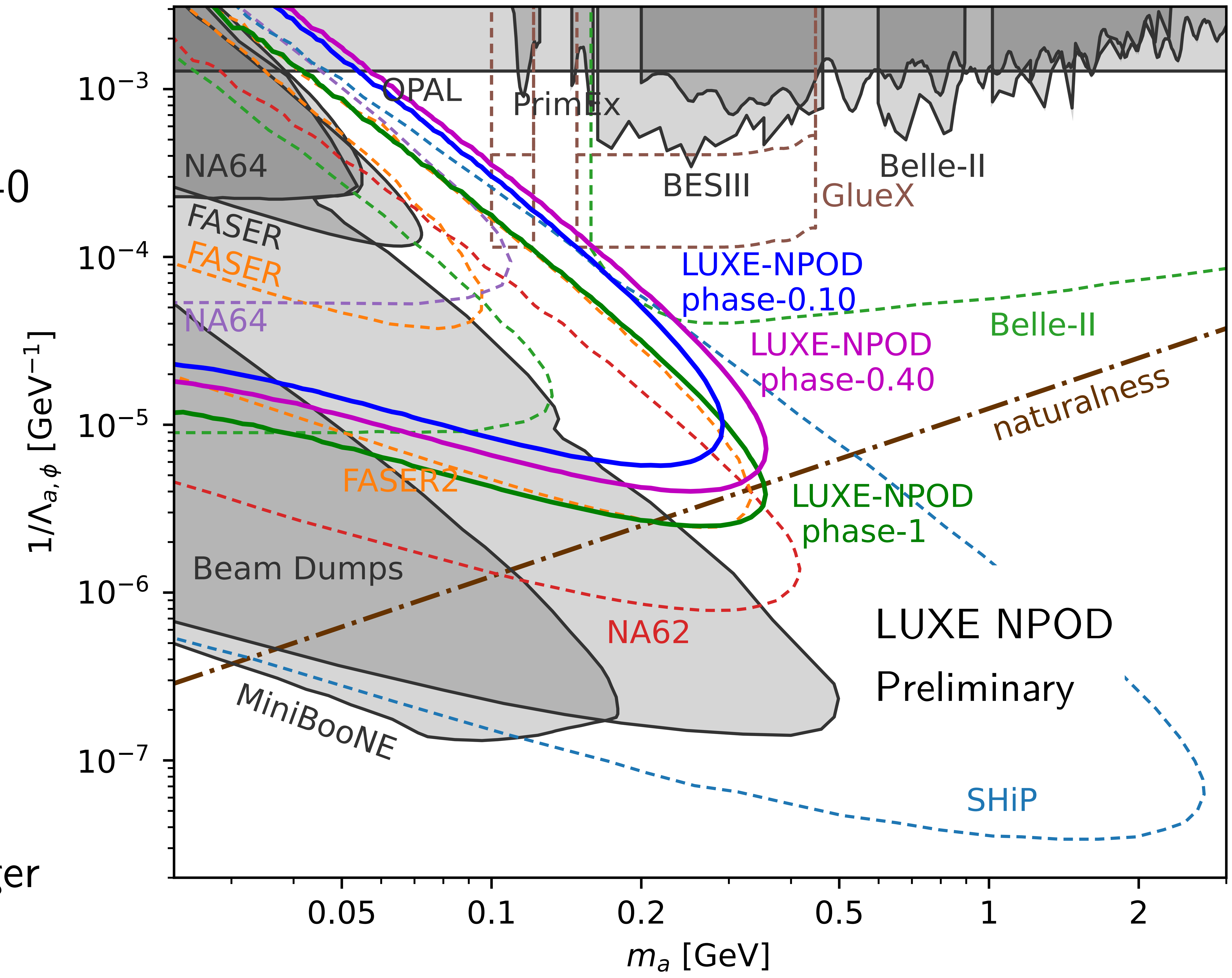
Timing

Signal arrives here

A detector with 0.5 to 1 ns timing resolution can reject most of the background

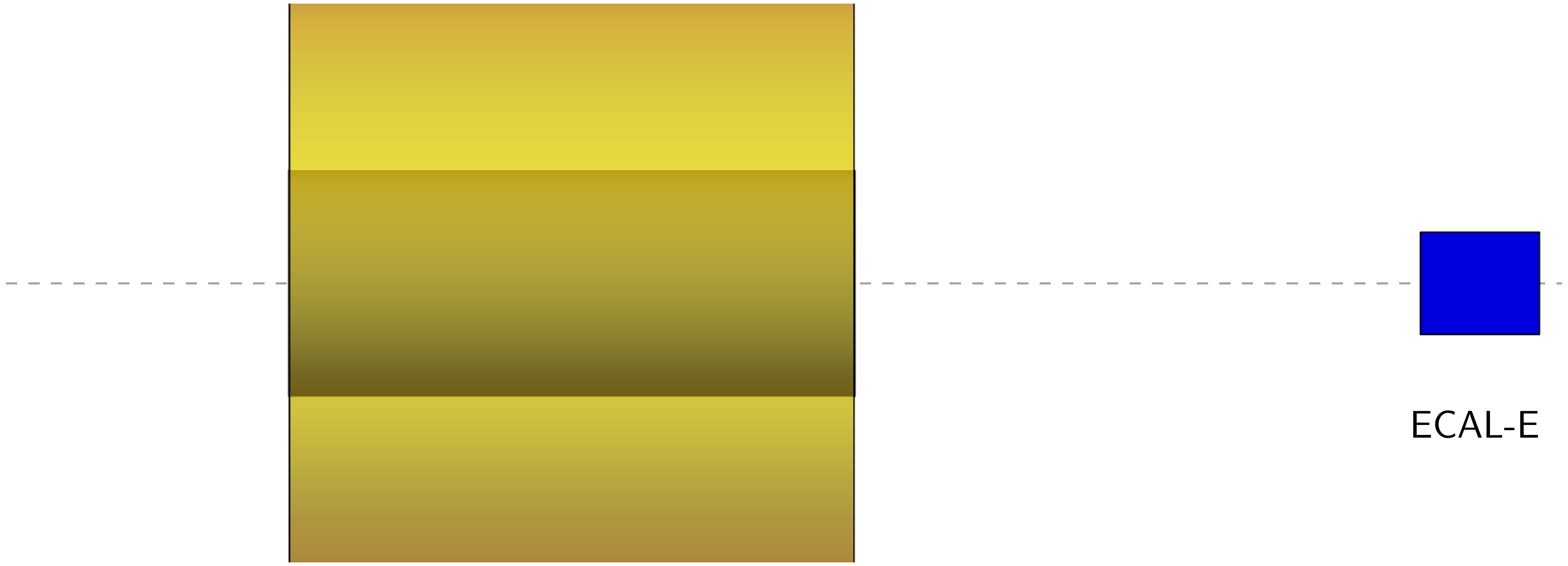
Sensitivity

- Assuming zero background
- For one-year (10^7 BX) data taking
- Easier background suppression in phase-0 allows a shorter dump, and benefits its sensitivities
- Dump length:
  - phase-0: 0.25 m
  - phase-1: 1.0 m
- Decay volume:
  - phase-0: 2.5 m
  - phase-1: 1.0 m
- Comparable to FASER2, NA62, and the SHiP experiment (who has a much longer data taking period)



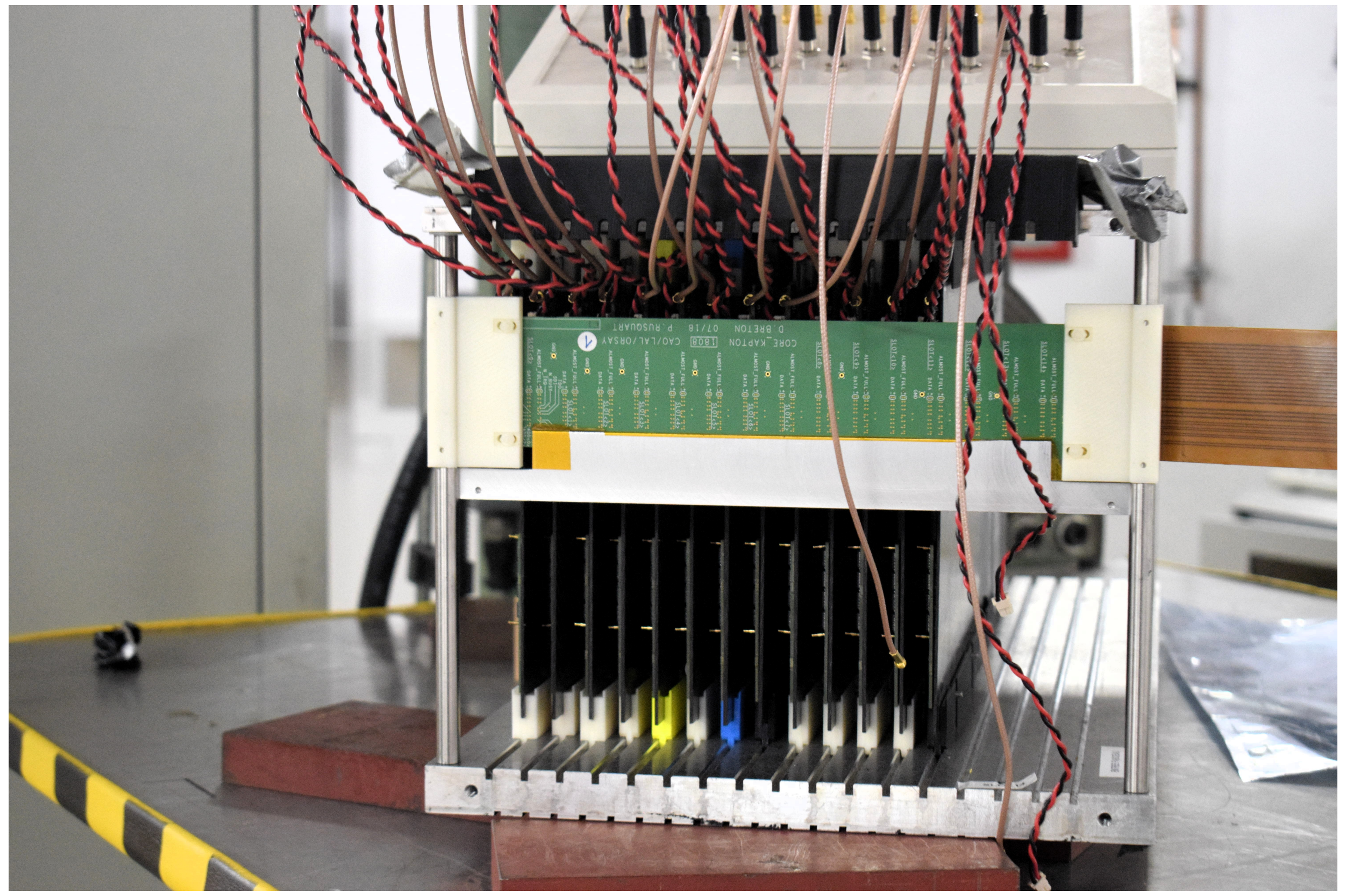
LUXE ECAL-E

- DRD6/CALICE SiW ECAL prototype
- Granularity of 5.5 mm
- Compactness: effec. Moliére radius ~10 mm
- Transverse size of 36 x 18 cm^2
- Longitudinal 22.5 cm with $18X_0$ tungsten
- Readout time resolution: 1 ns
- Energy resolution $\frac{\sigma_E}{E} = \frac{(19.8 \pm 0.4)\%}{\sqrt{E_0/\text{ GeV}}} \oplus (4.9 \pm 0.3)\%$



A natural candidate for NPOD detector in LUXE

- NPOD will run in LUXE e-laser mode
- ECAL-E will only be used in LUXE g-laser mode

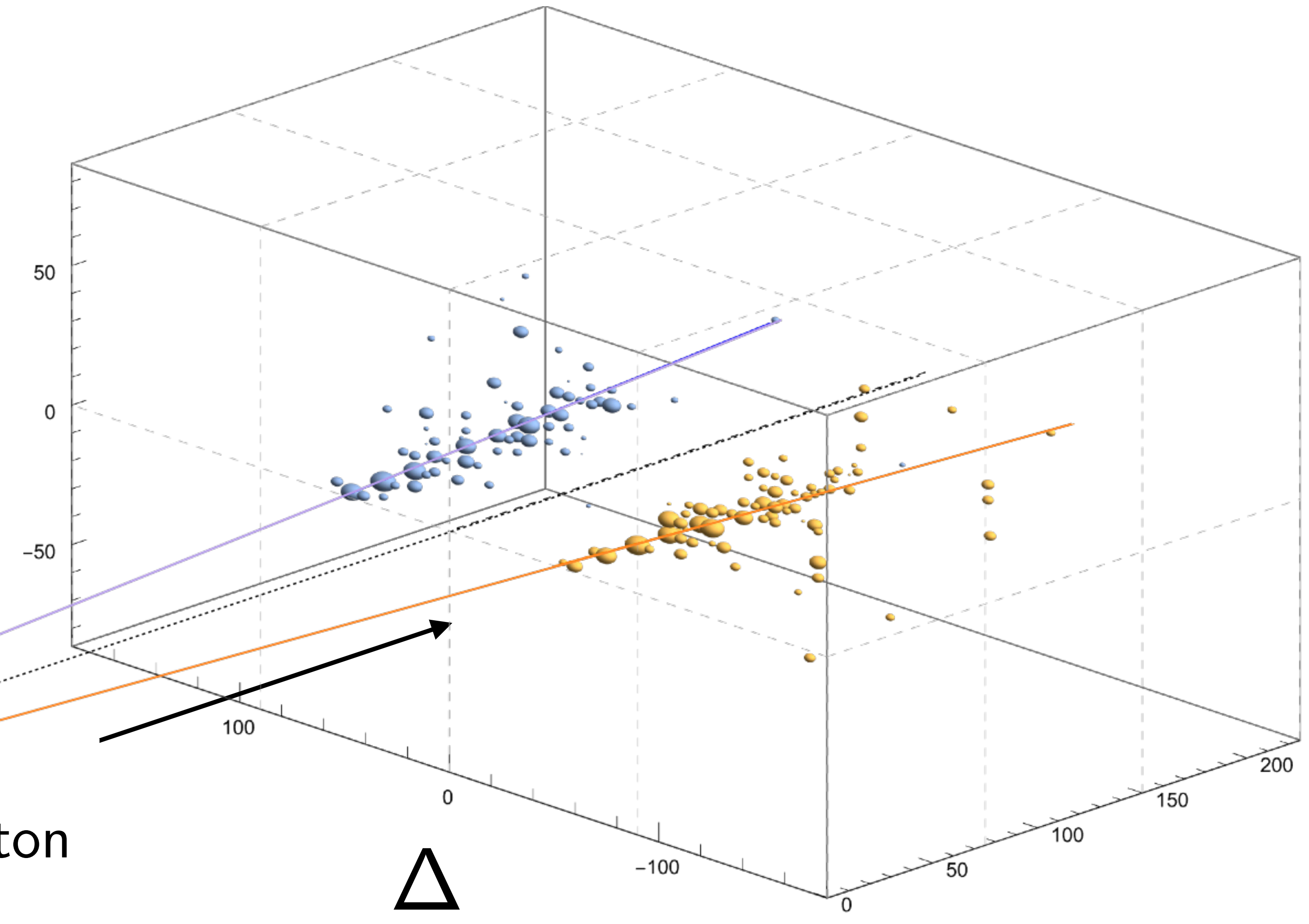


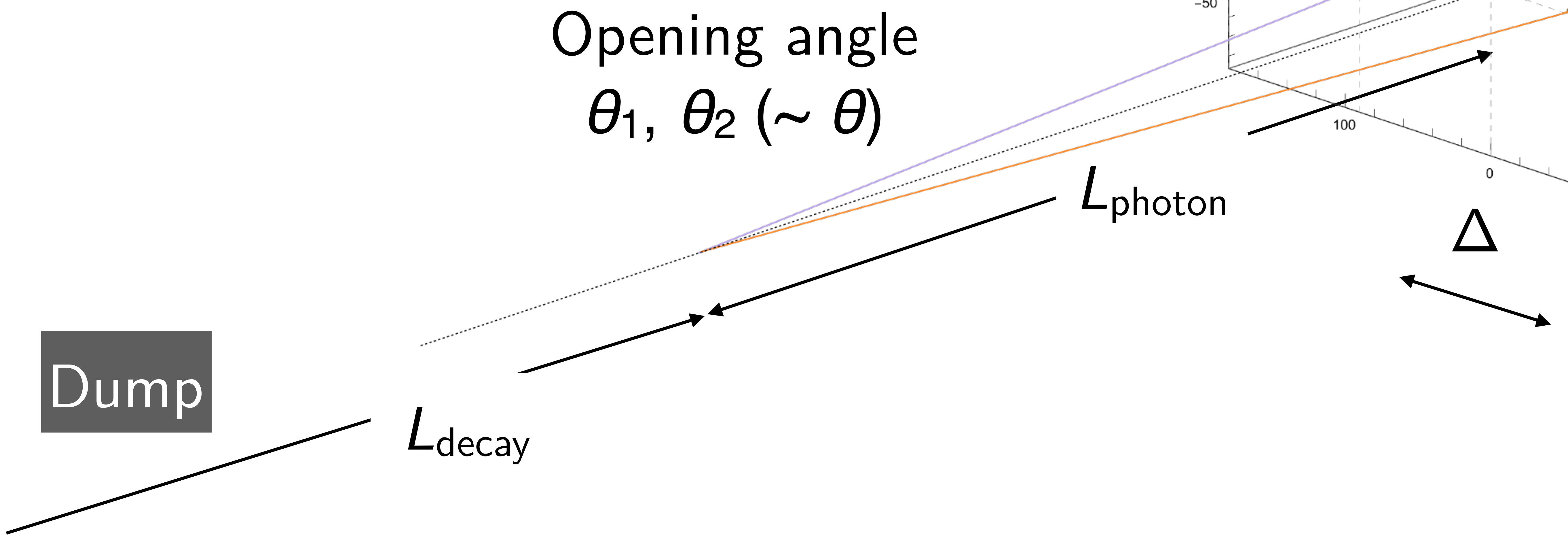
- Performance simulations with Geant4 v11 using DD4hep toolkit
- Analysis using Marlin framework

Repository: https://github.com/airqui/ECALe-lcio

To simplify the simulation and have a baseline understanding of the detector performance, we assume

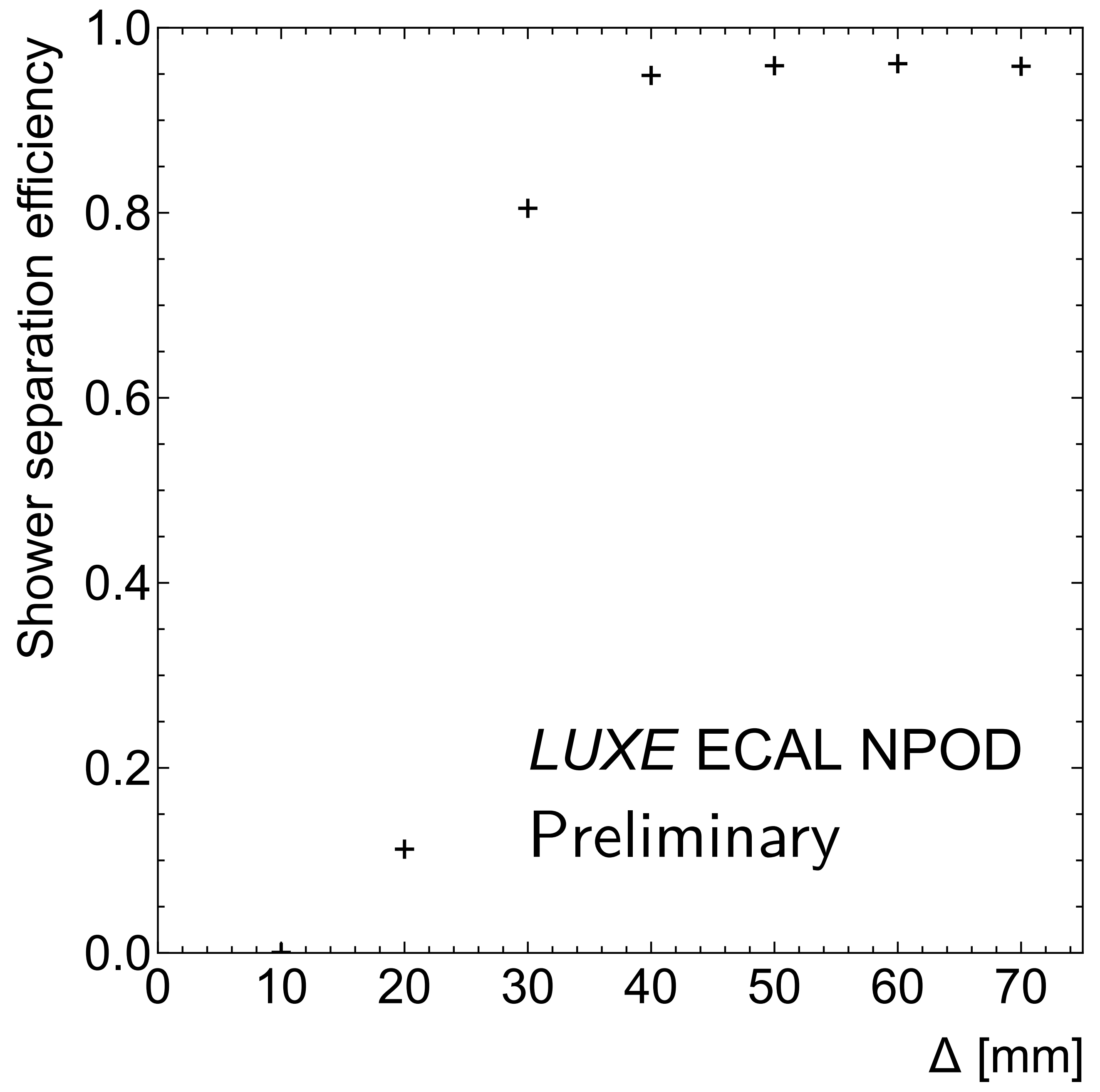
- zero background,
- the NP particle decays symmetrically, and
- the NP particle decays on the beam axis

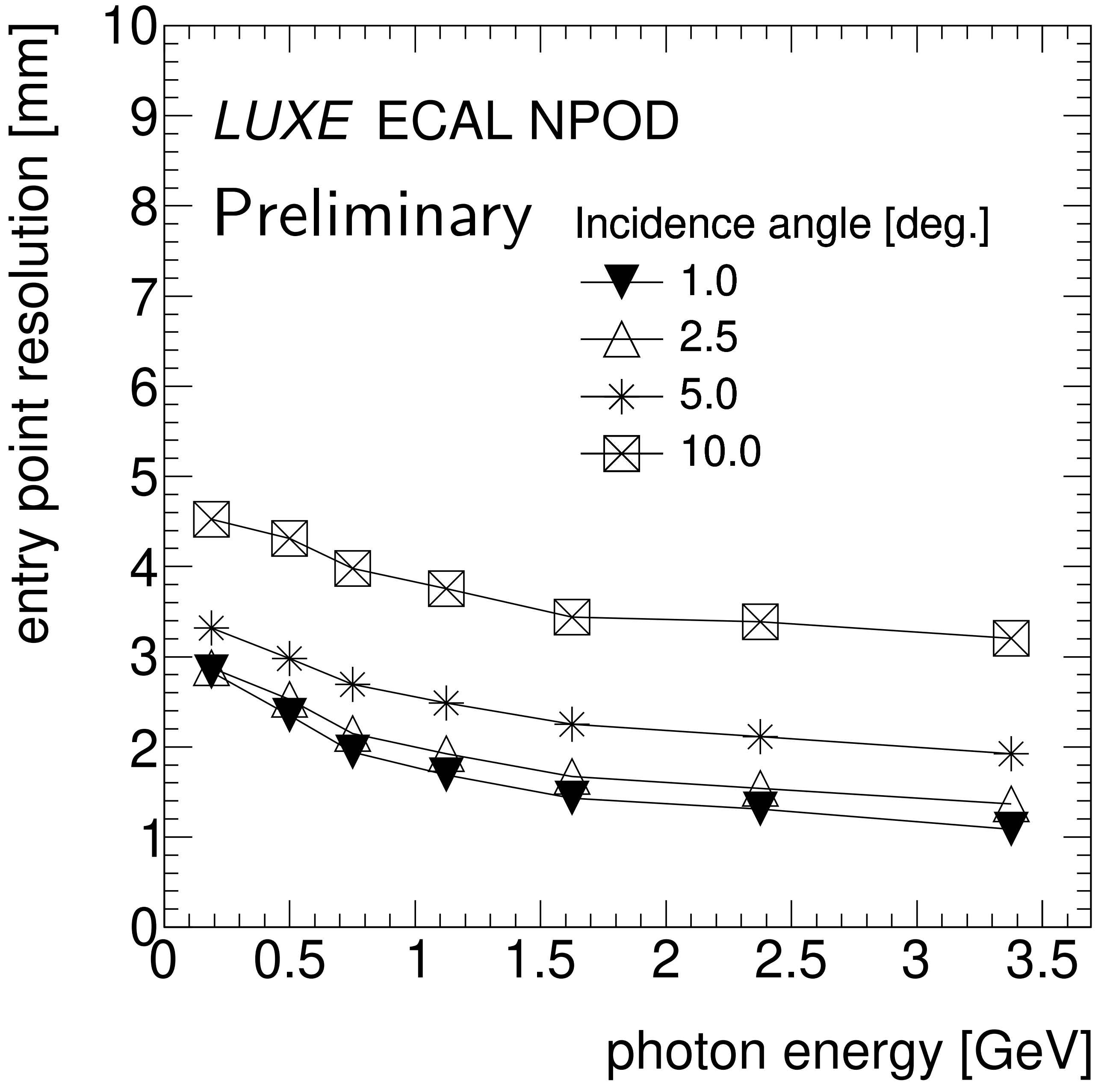


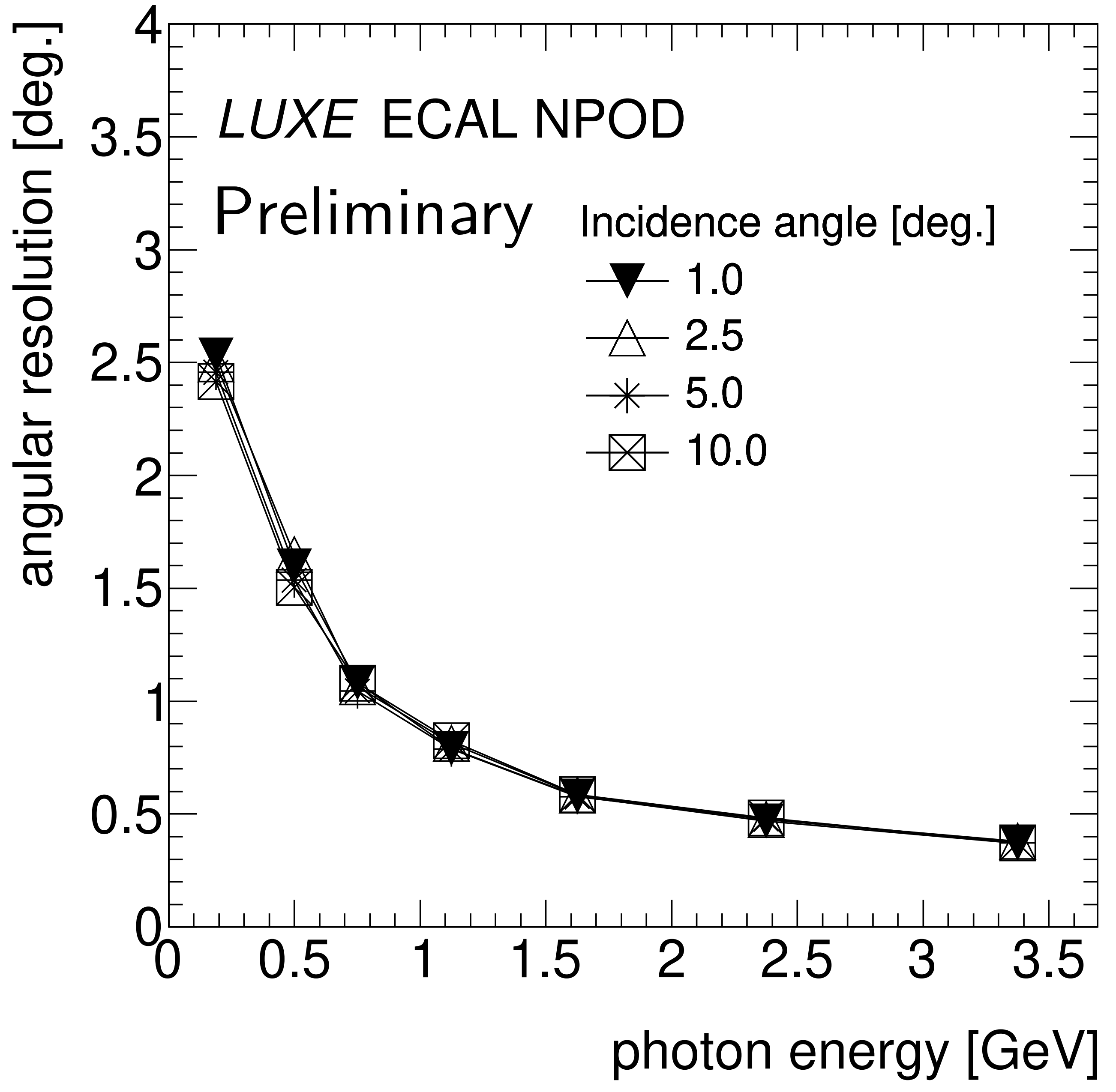


Signal reconstruction

- A simple nearest-neighbour clustering separates over 95% events when $\Delta > 40$ mm
- A proof-of-concept tracking of the clusters gives
  - entry point position resolution < 5 mm
  - angular resolution better than 1 degree for > 1 GeV photons

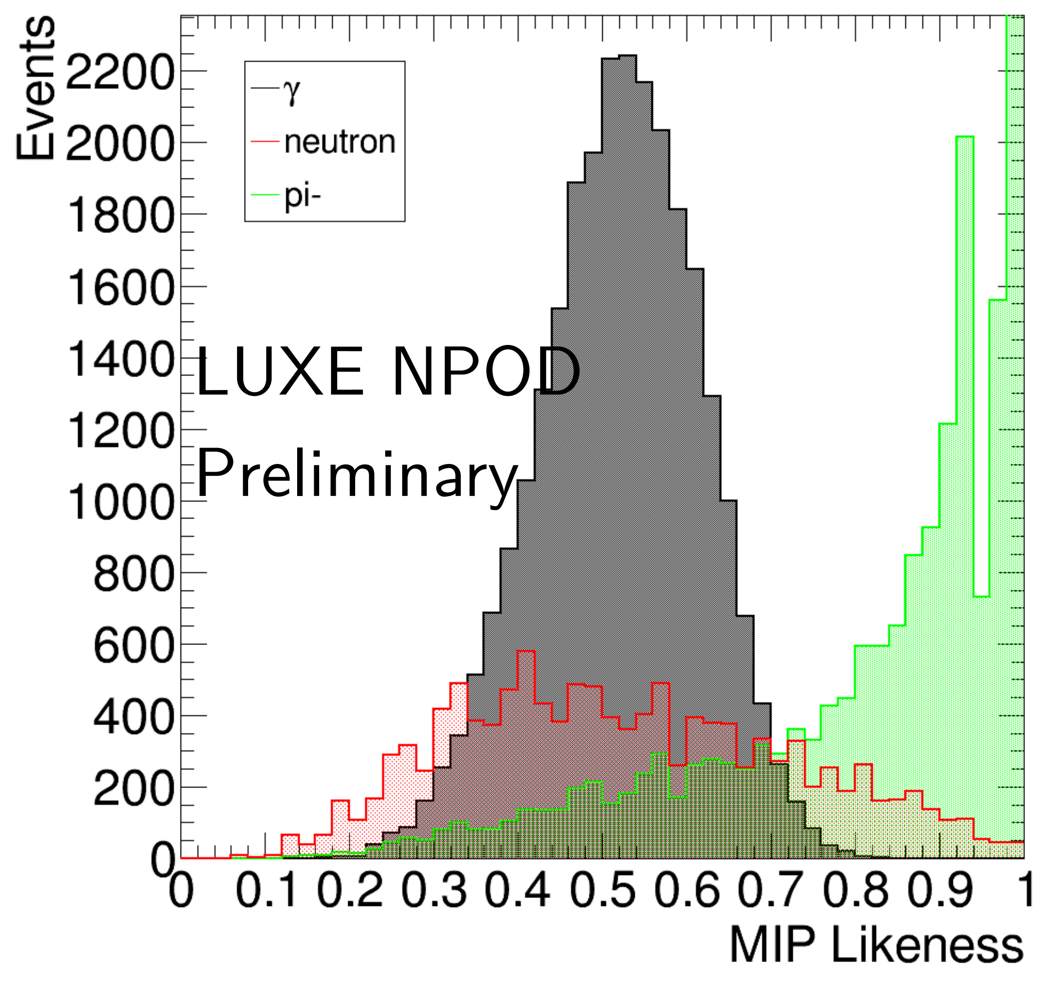


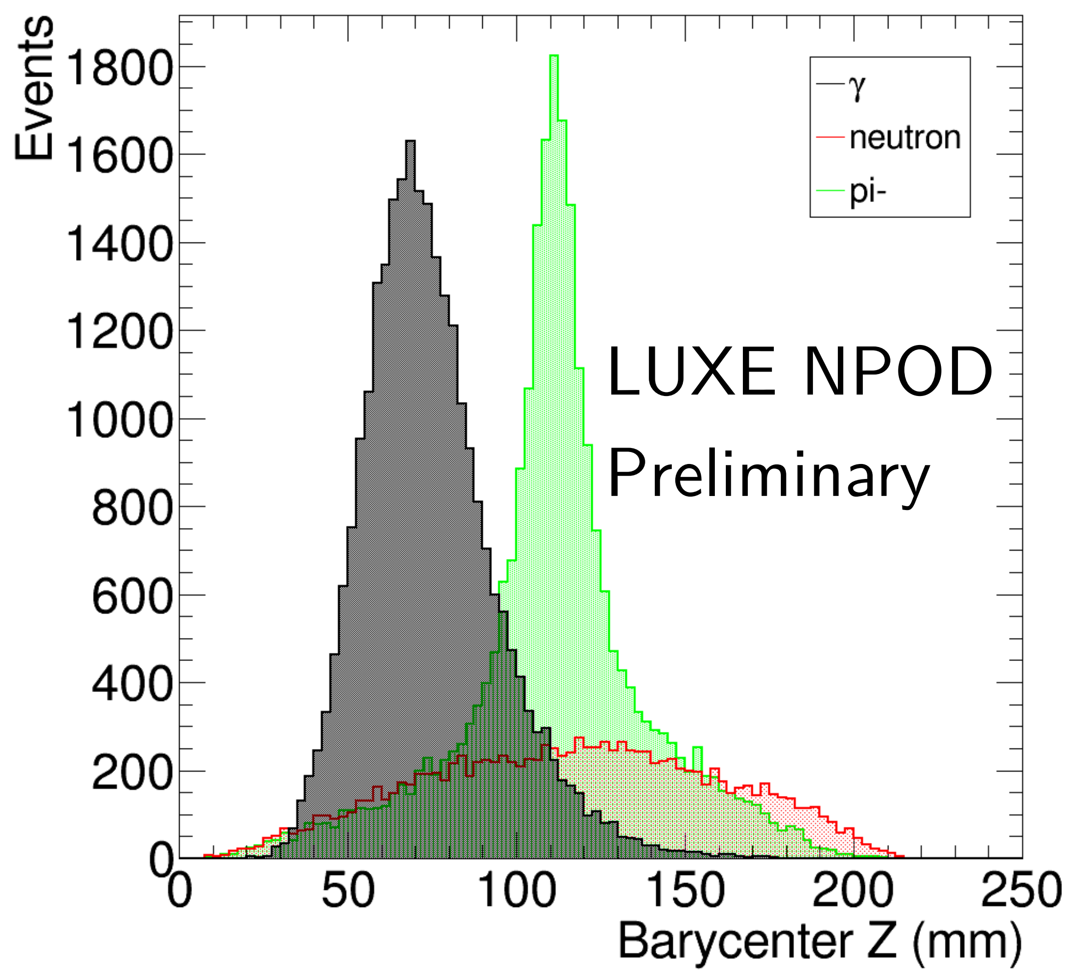


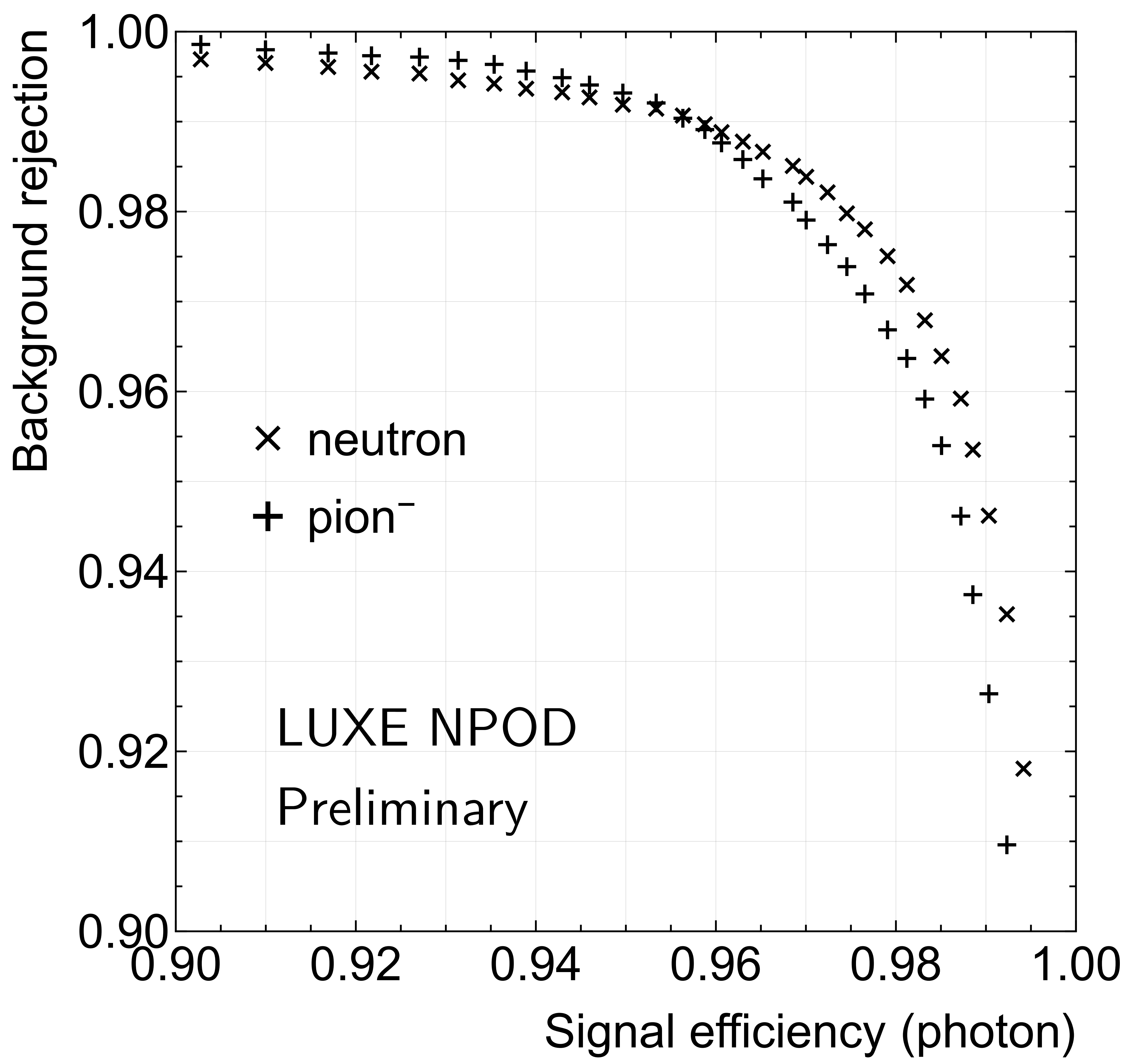


PID: further bkg rejection

- Particle identification using boosted decision tree (BDT), a widely-used machine learning tool
- We focus on background from neutron and pion
- BDT learns the signatures of incoming particles
- Successfully rejects nearly 99% background particles while maintaining over 95% of signal photons



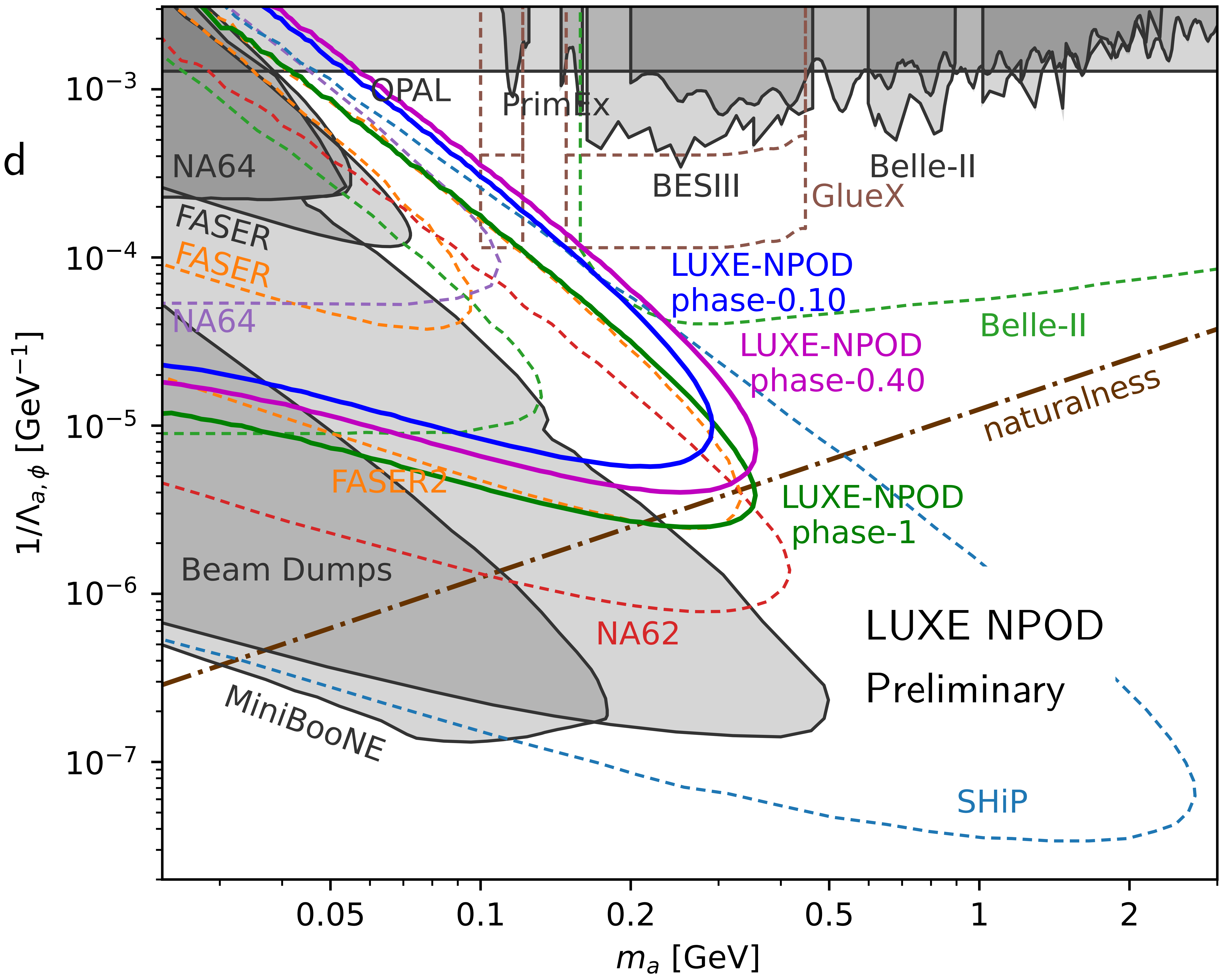




Repository: https://github.com/marherje/Simplified_ECAL_PID

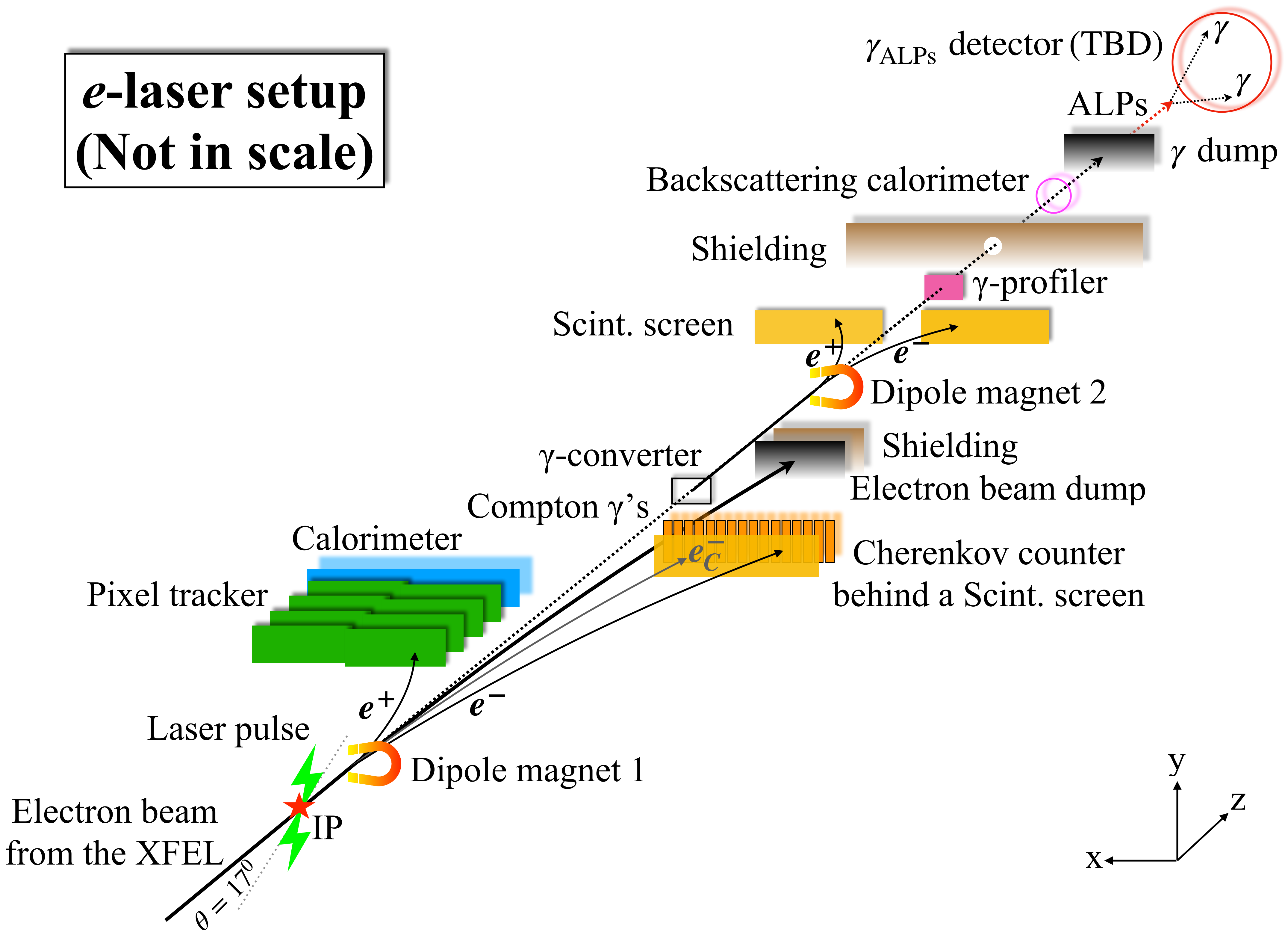
Summary

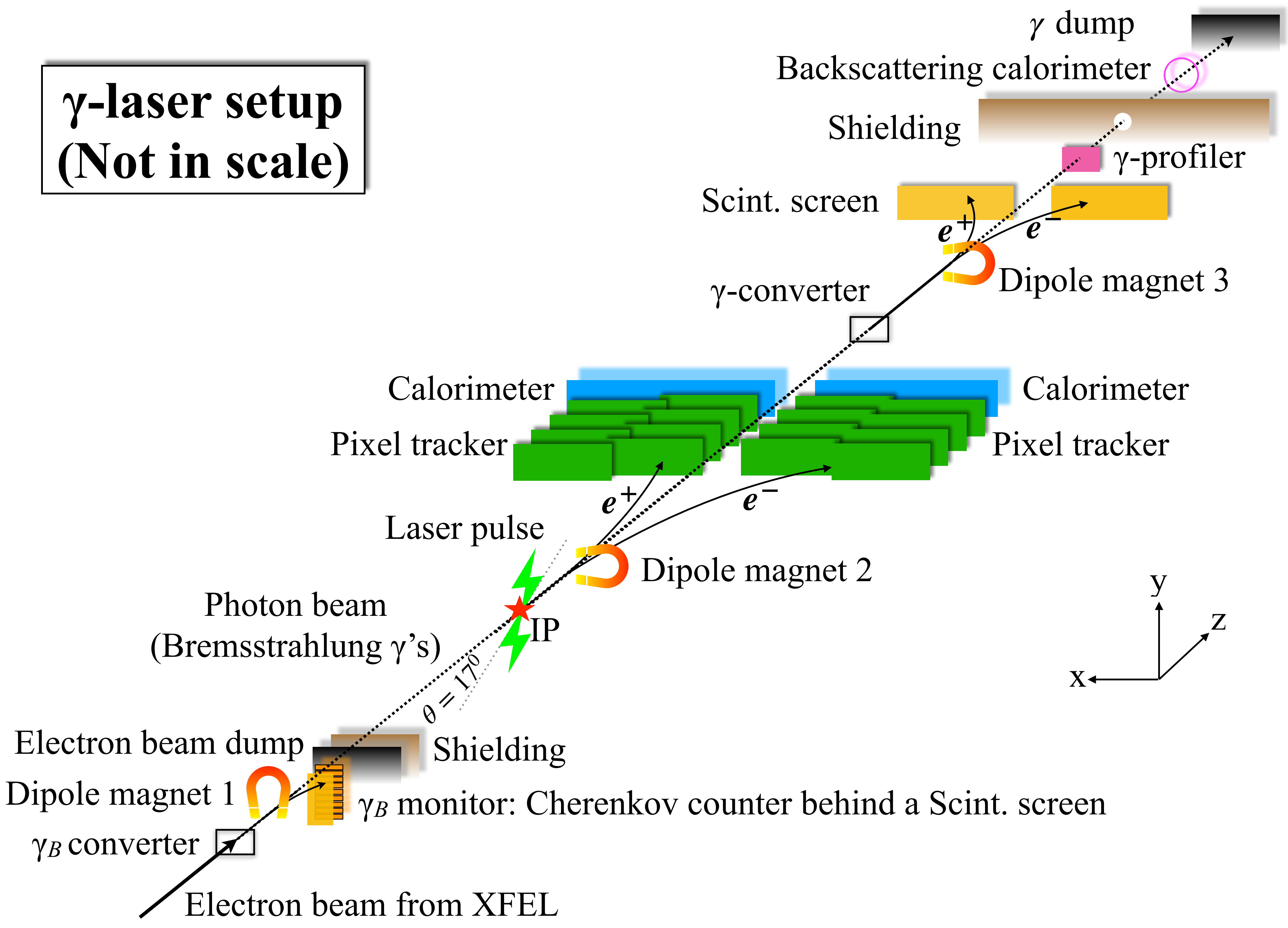
- LUXE NPOD is a beam-dump experiment probing ALPs with mass in 10 to 350 MeV, and coupling coefficient in 10^{-6} to 10^{-3} GeV^{-1}
- We validate our previous work with a more realistic experimental setup with a detector
- We further optimize the NPOD performance with much detailed dump design
- We test the updated scenarios with full-layout simulations
- LUXE secures a part of its funding and we are working towards the construction
- A paper is under preparation. Stay tuned for more updates!



Backup

LUXE detectors

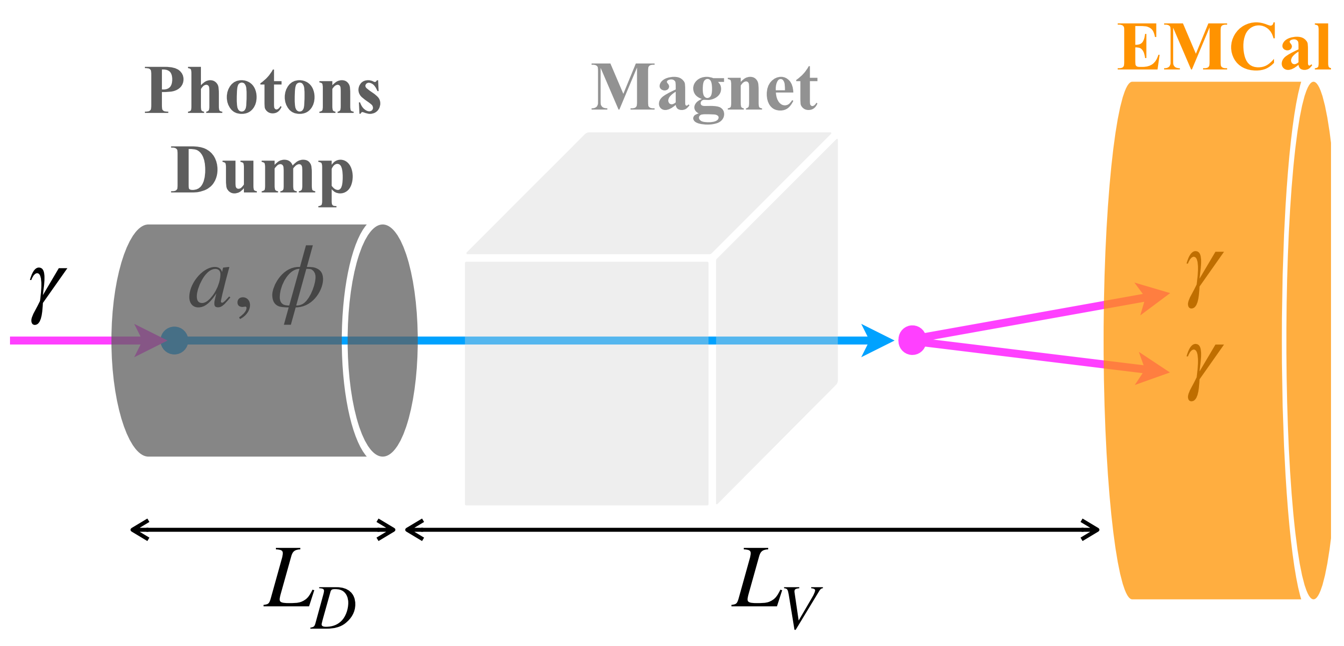


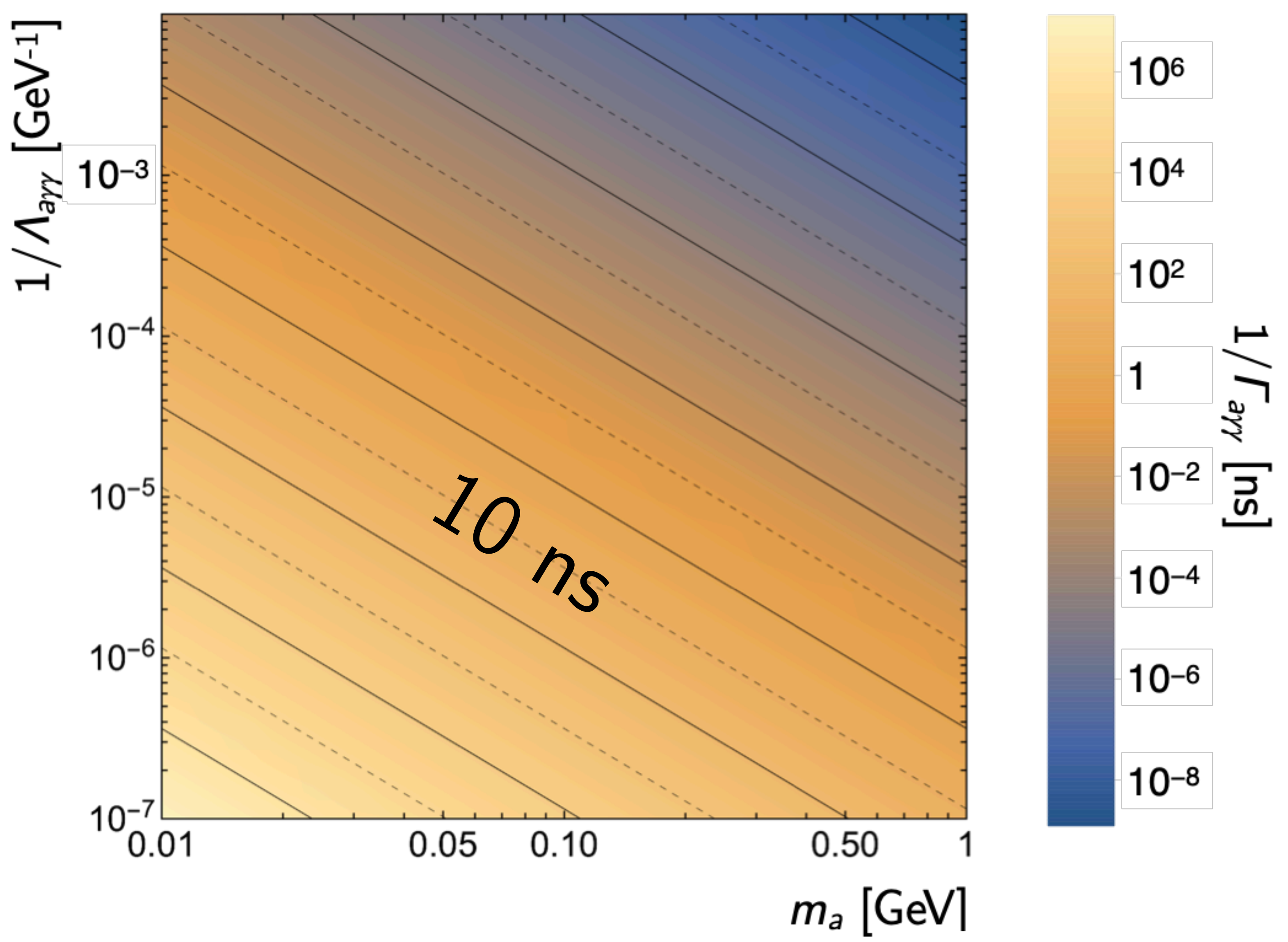


Luminosity cross-section Geometry

$$N_X \approx \mathcal{L}_{\rm eff} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_X(E_\gamma) \left(e^{-\frac{L_D}{L_X}} - e^{-\frac{L_V+L_D}{L_X}} \right) \mathcal{A}$$

Photon spectrum Detector acceptance





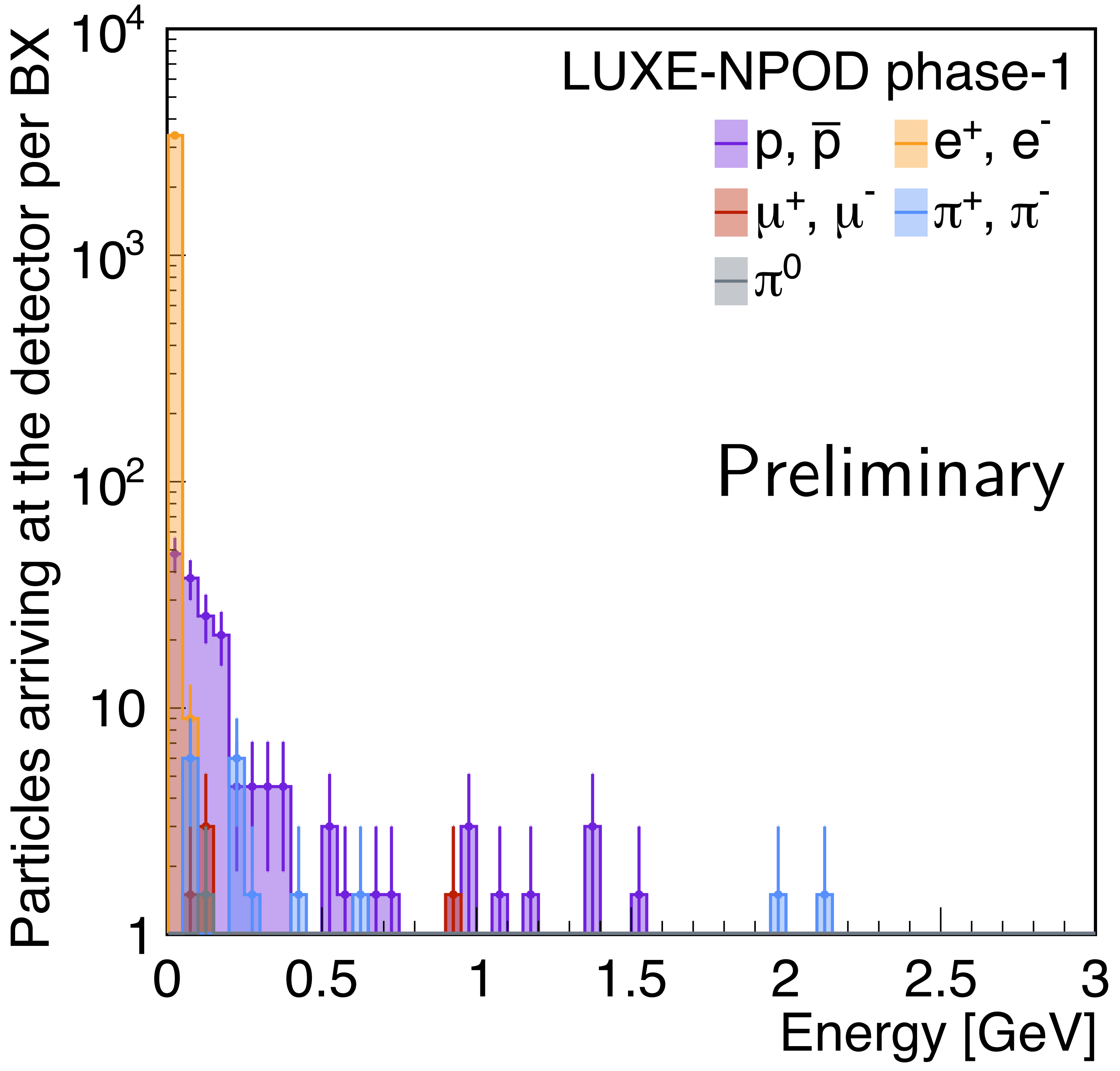
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\,\pi}$$

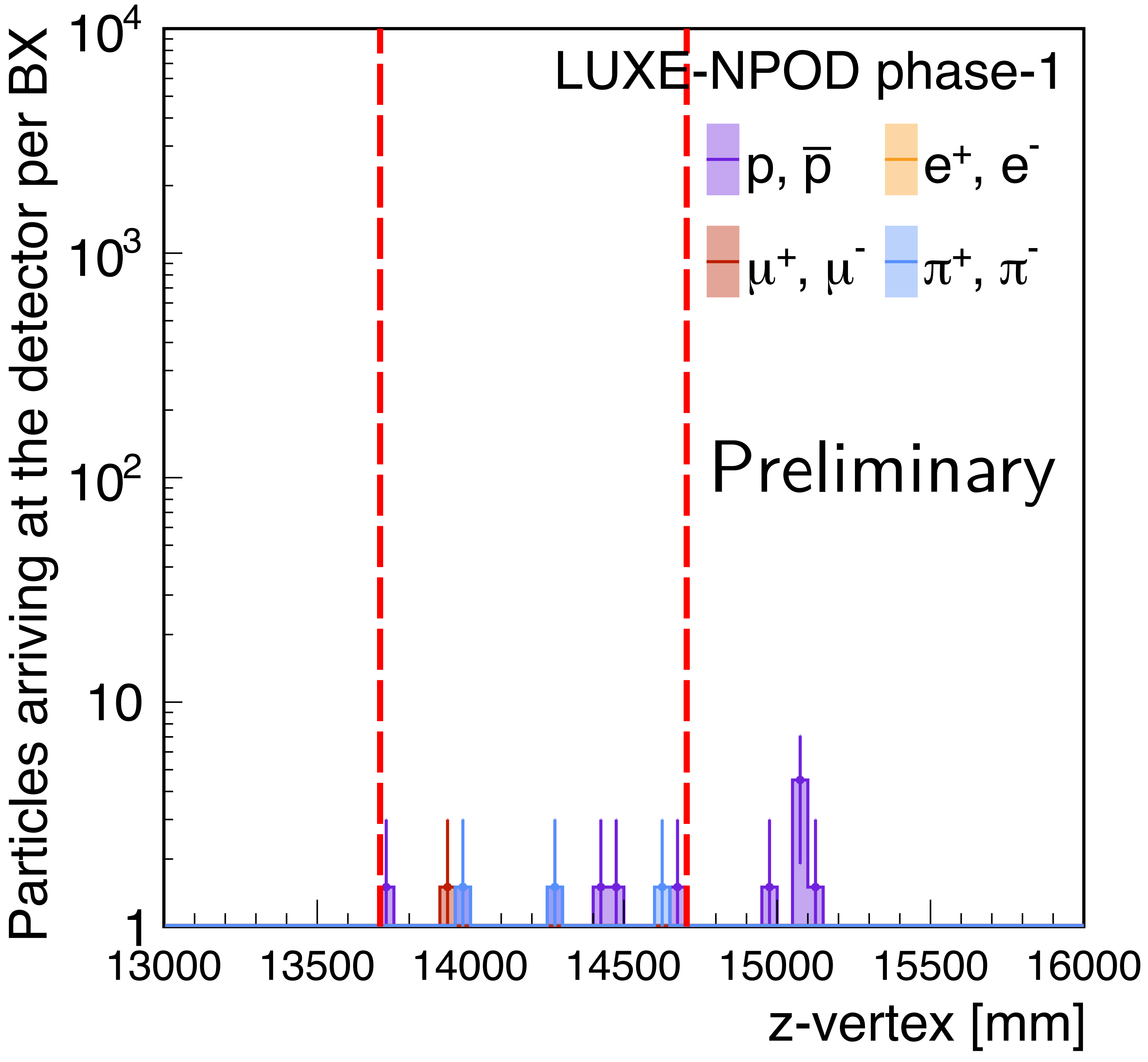
Dump optimization

- Phase-1 photon flux is stronger and creates more background
- Some background leaks out from the side of the dump
  - Bimetallic dump to suppress the leak while being “economic”

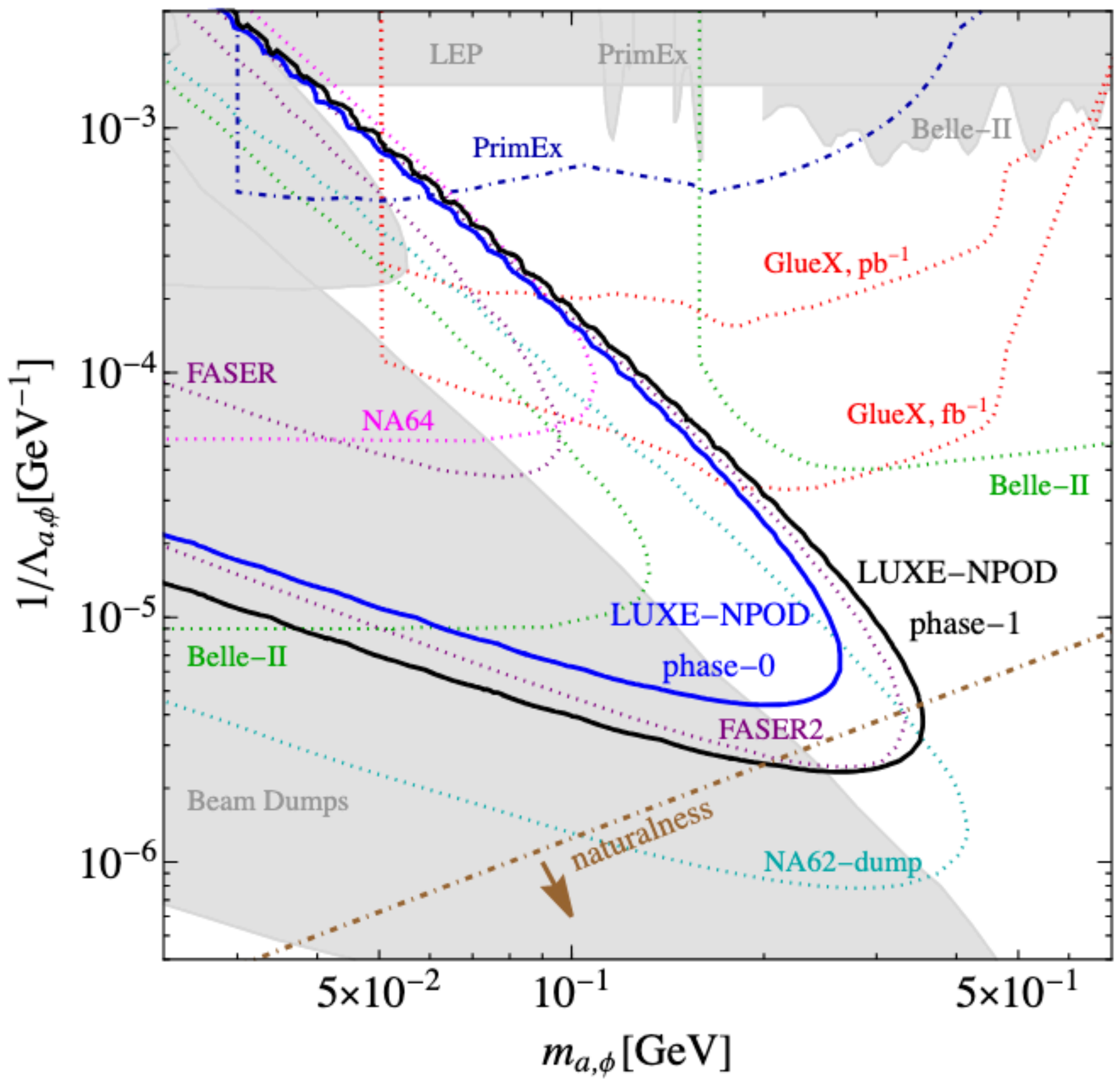
	Material	L_D [cm]	R_D [cm]	*N*. photon ($>$0.5 GeV)	*N*. neutron ($>$0.5 GeV)
Phase 1	**W**	30	10	0	2.48×10^4
		100	10	0	1.6×10^3
		100	30	0	2×10^2
	Pb	100	40	0	1.9×10^3

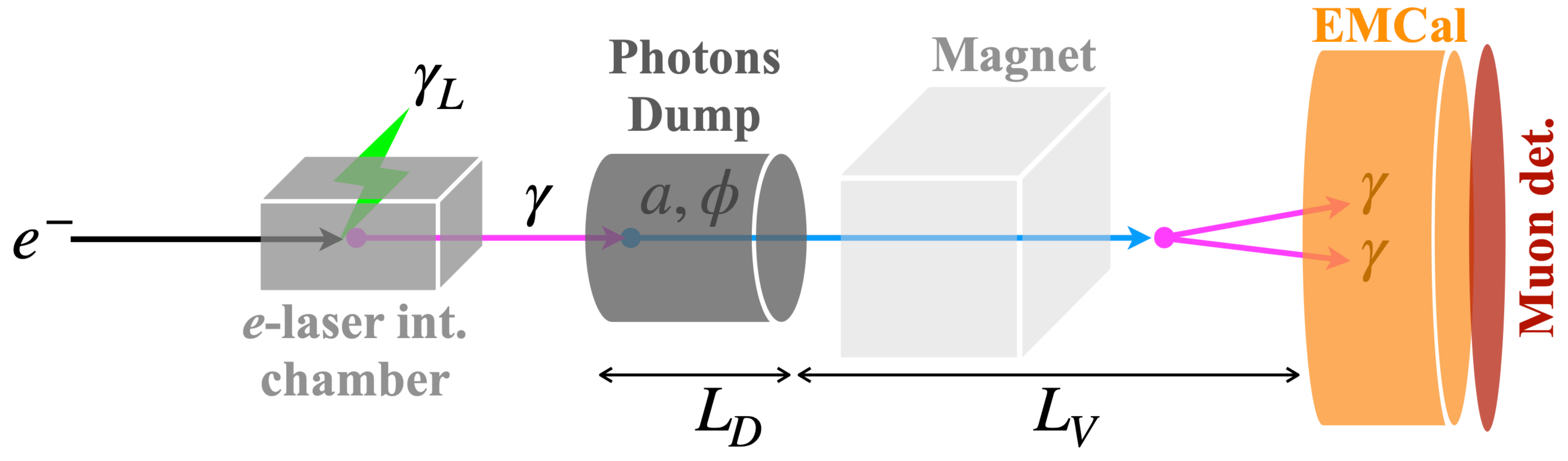
Charged-particle background





Previous sensitivity





LUXE NPOD: A beam-dump experiment

- Mass: 10 to 350 MeV
- Coupling to photon: 10^{-6} to 10^{-3} GeV^{-1}

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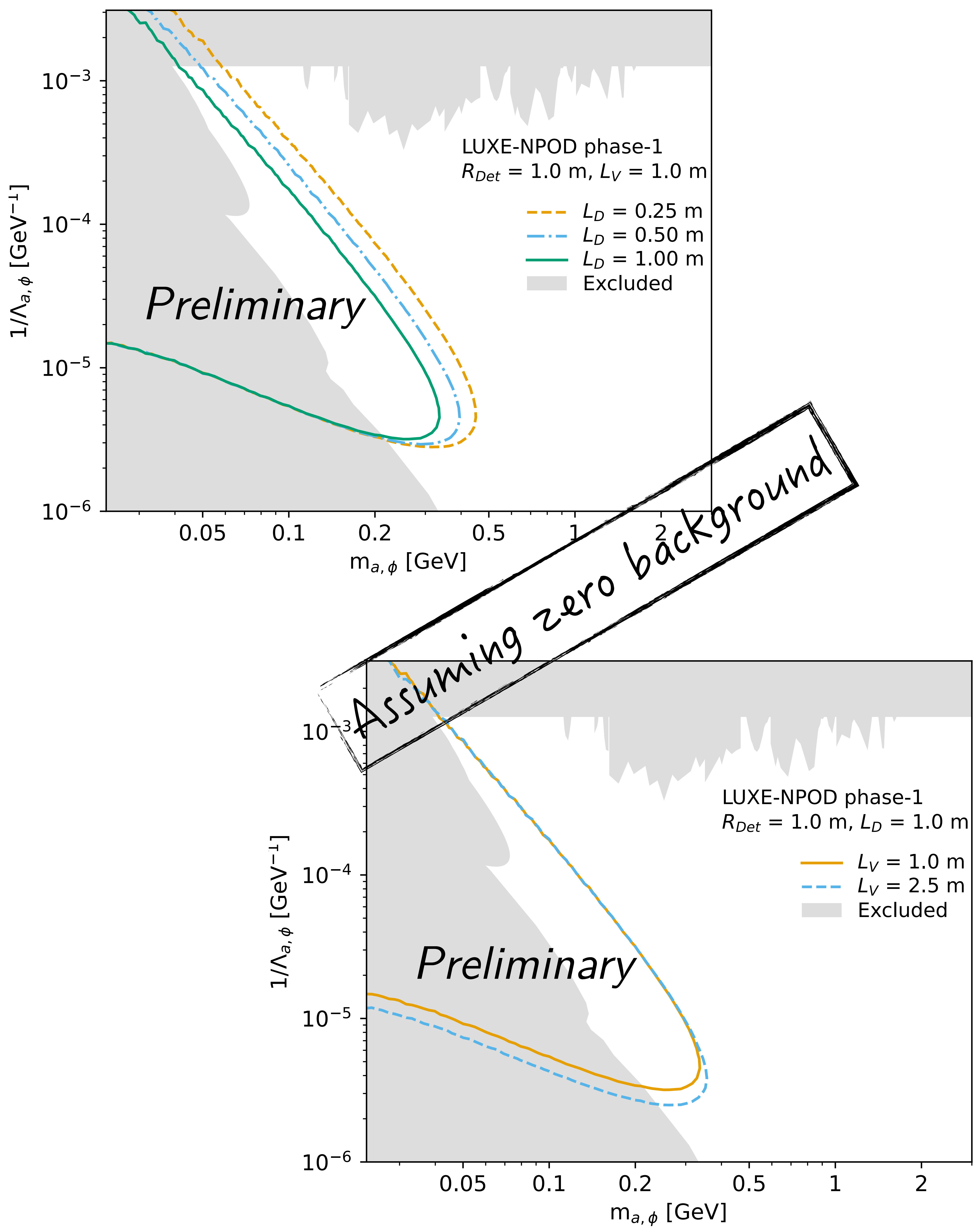
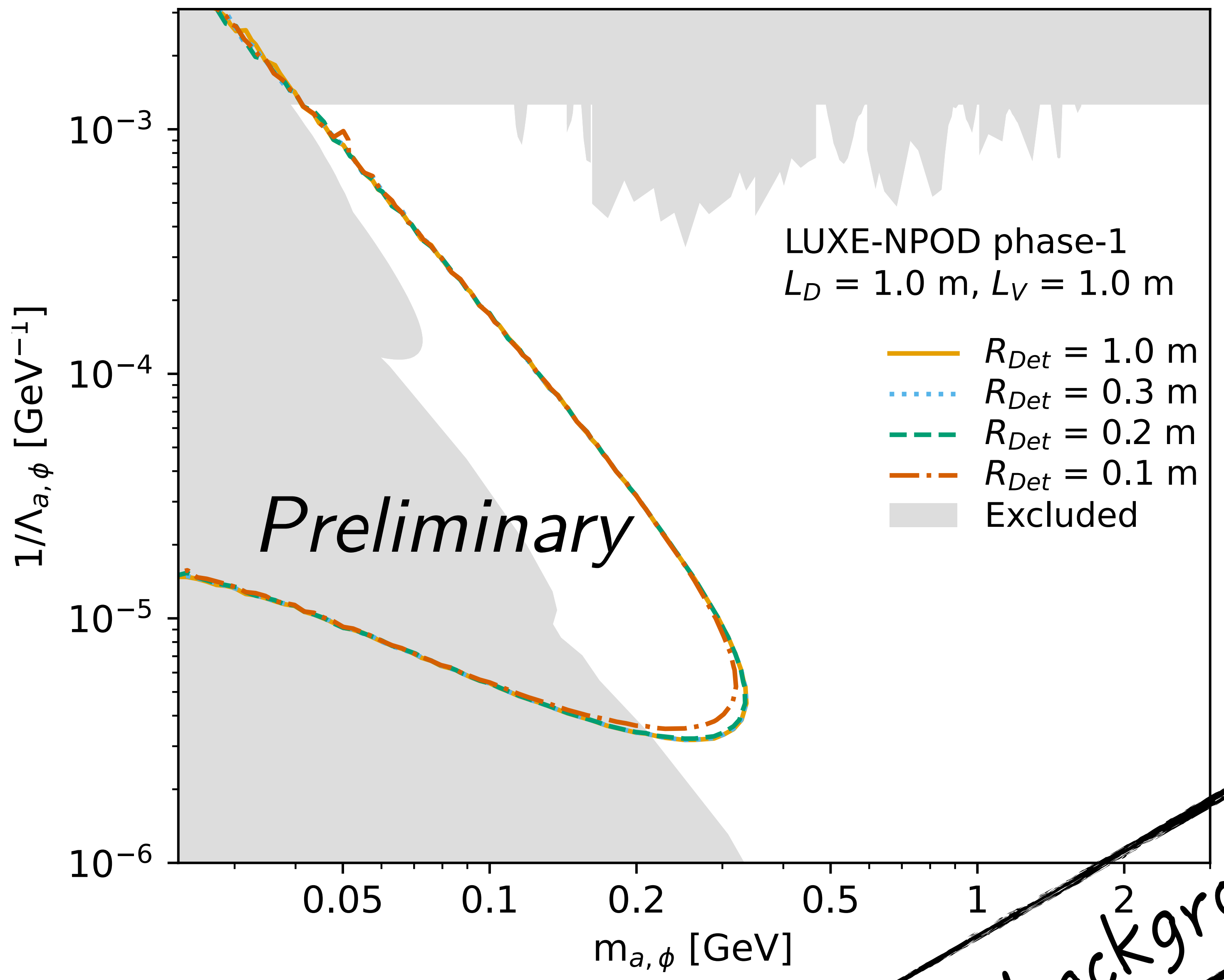
Sensitivity

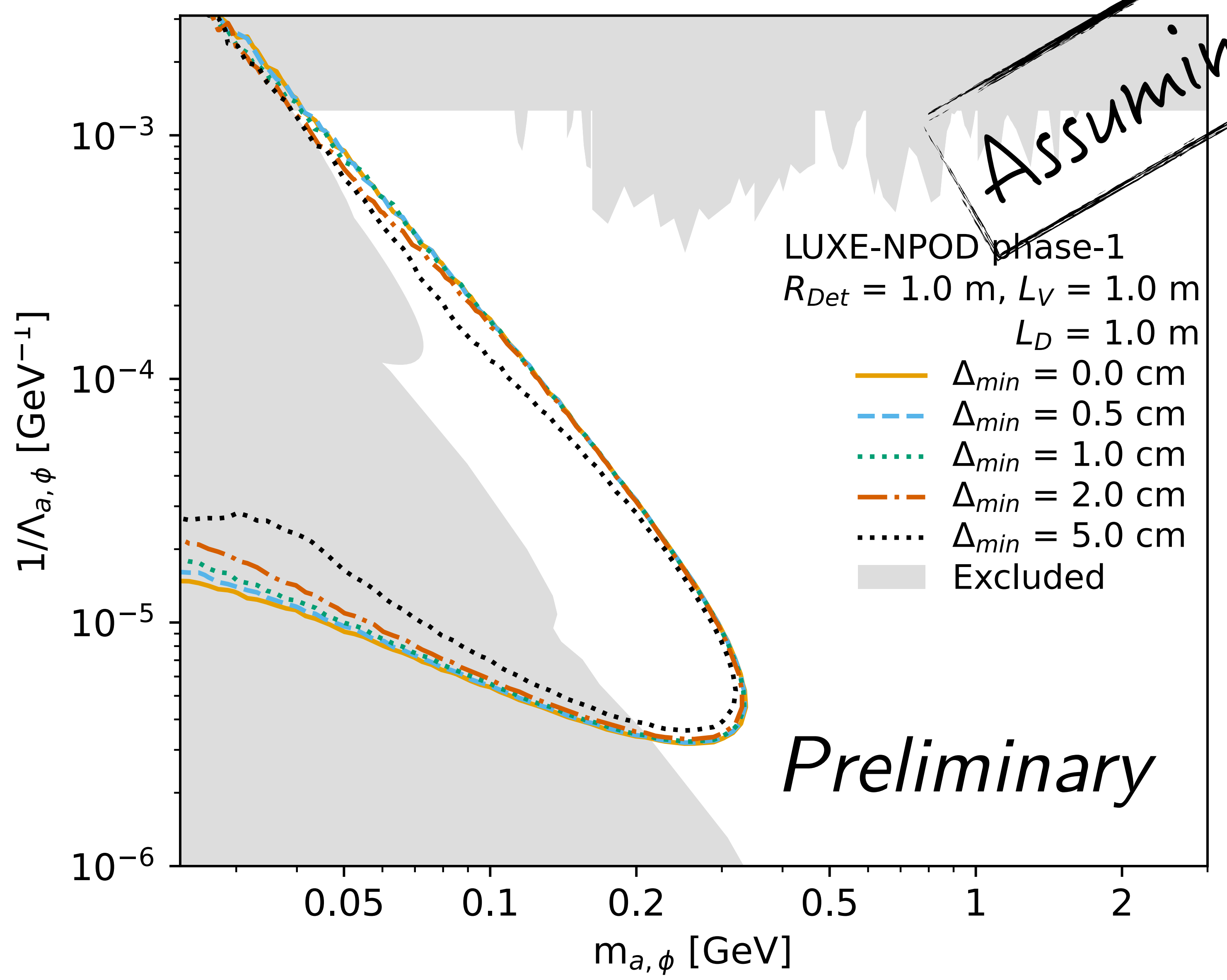
- Dump length:
  Shorter dump allows us to probe heavier NP particles at the cost of larger background
- Decay length:
  Longer decay length enables the probing of NP particles with weaker coupling



Sensitivity

- Dump length:
  Shorter dump allows us to probe heavier NP particles at the cost of larger background
- Decay length:
  Longer decay length enables the probing of NP particles with weaker coupling
- Detector size/acceptance:
  Limited influence: the signal pairs are close to the beam axis
- Detector separation power/resolution:
  Sensitivity influenced by the close-by photon pairs. NP particles created on the dump are boosted.



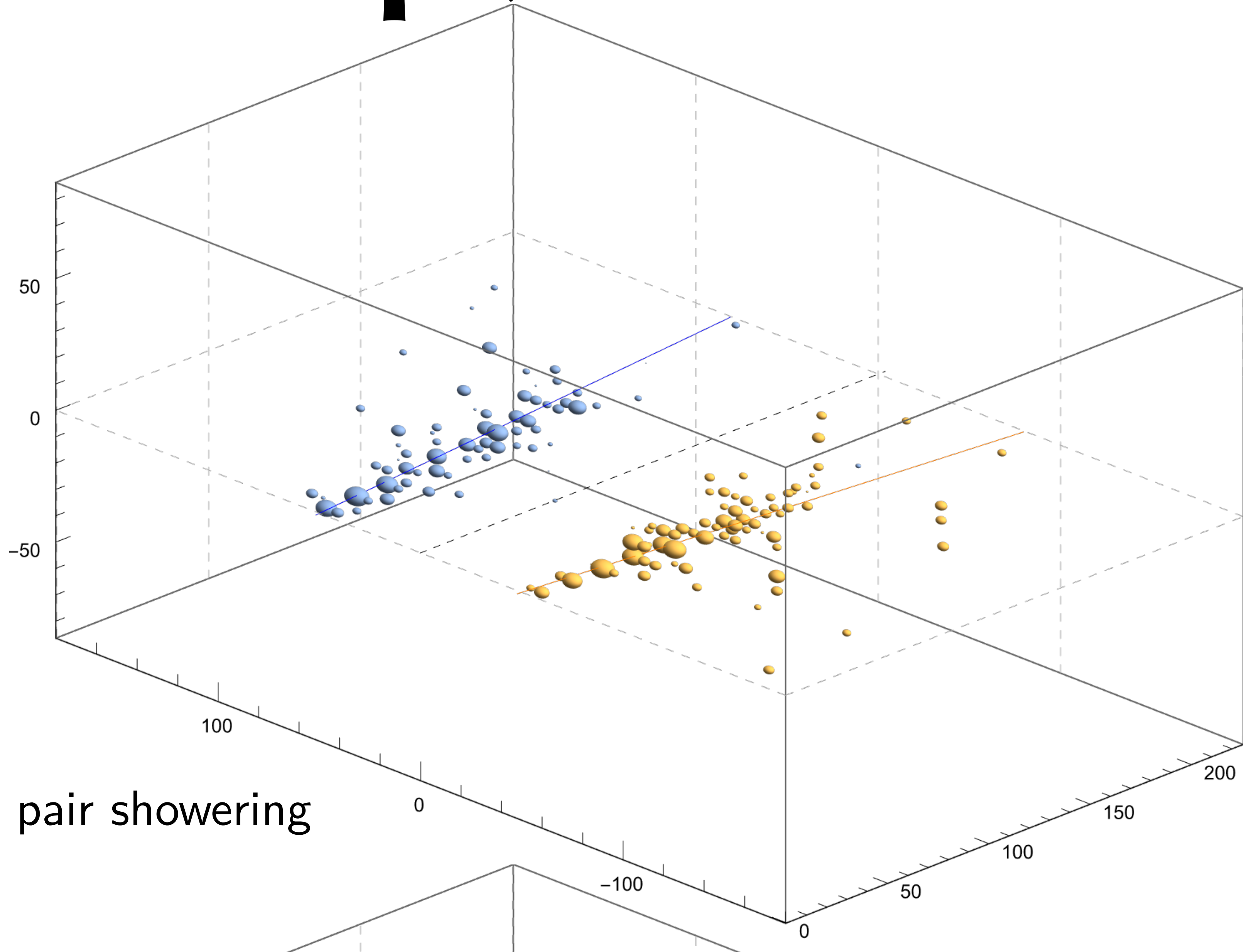


Assuming zero background

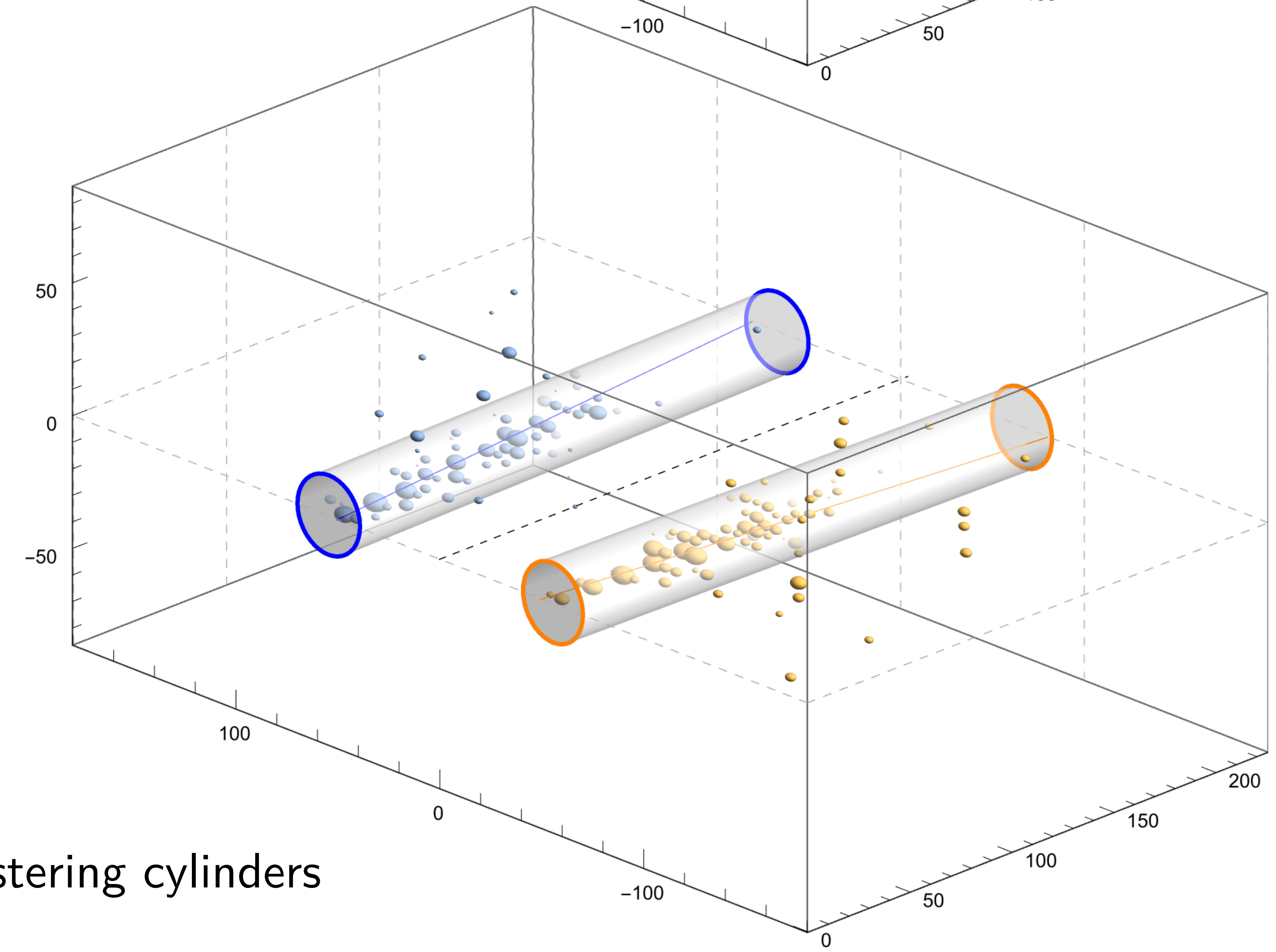
Analysis (proof-of-concept)

Proof-of-concept test

- Clustering: simple nearest-neighbour algorithm with optimized distance cut
  - Gives the pair separation efficiency
- First tracking: line fitting of the hit distribution, gives a preliminary tracks
- Reclustering: to collect the hits within a "Molière radius" of the cluster
  - The cylinder axis is the preliminary track
- Second tracking: line fitting with the updated cluster, gives the final tracks
- Vertex reconstruction using the tracks



Photon pair showering

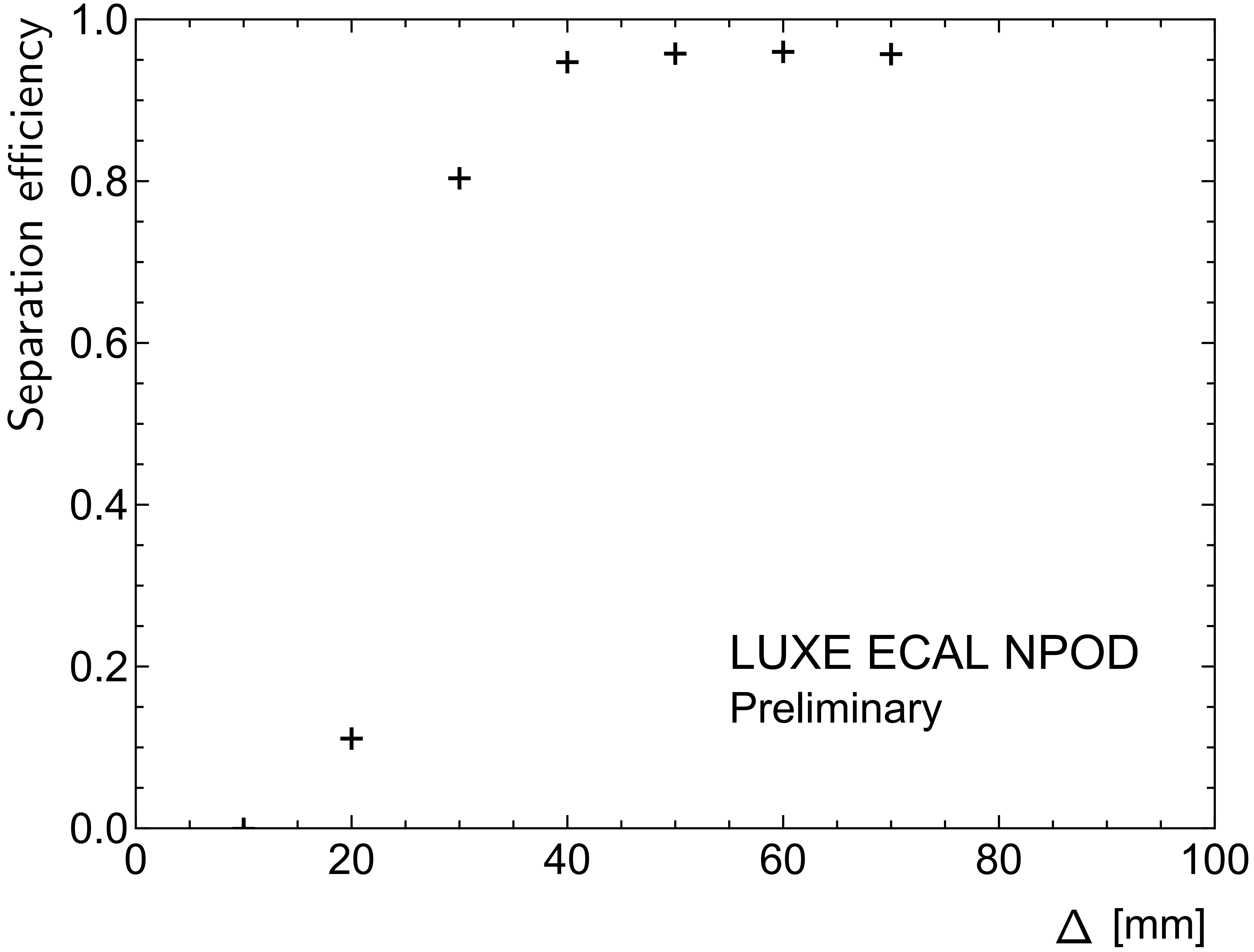


Reclustering cylinders

Power of separation

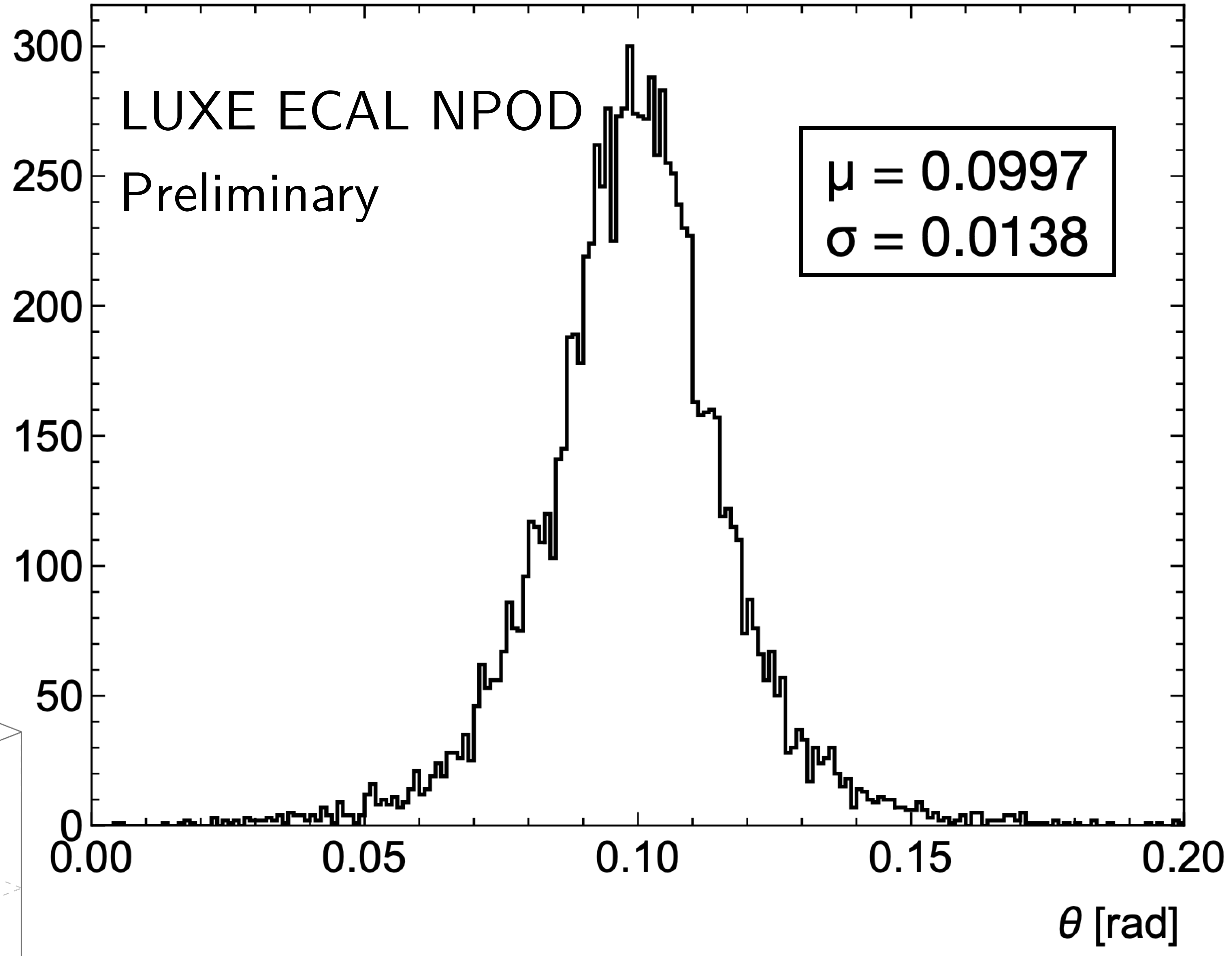
- We expect two major clusters for an event
- Separation efficiency is defined as
  N. successful events / N. all events
  - Success: obtaining at least two clusters
  - The two largest clusters has similar hit deposits ($1/2 < E_1/E_2 < 2$)

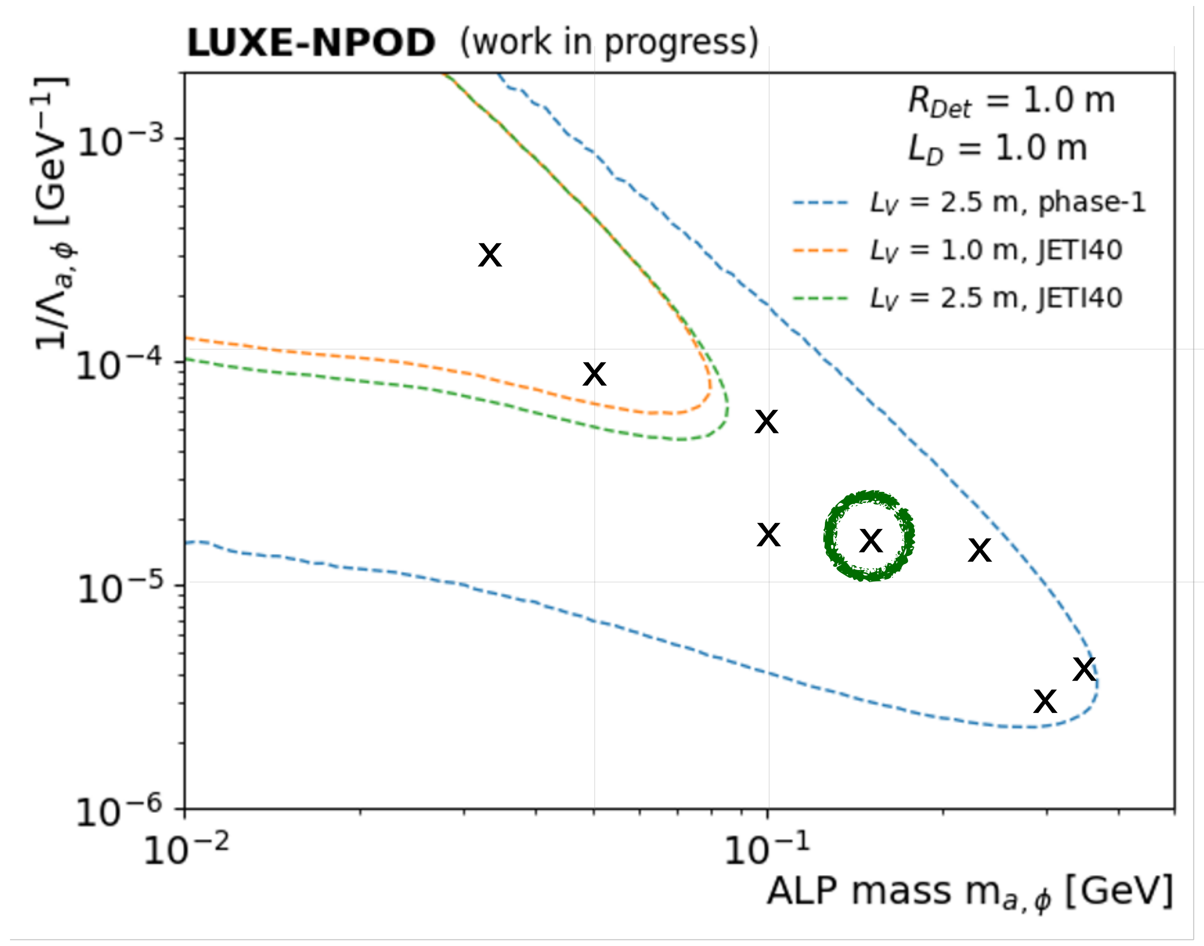
- When showers start to overlap with each other, NNClustering fails
- S. Effeciency $> 95\%$ when $\Delta > 40$ mm

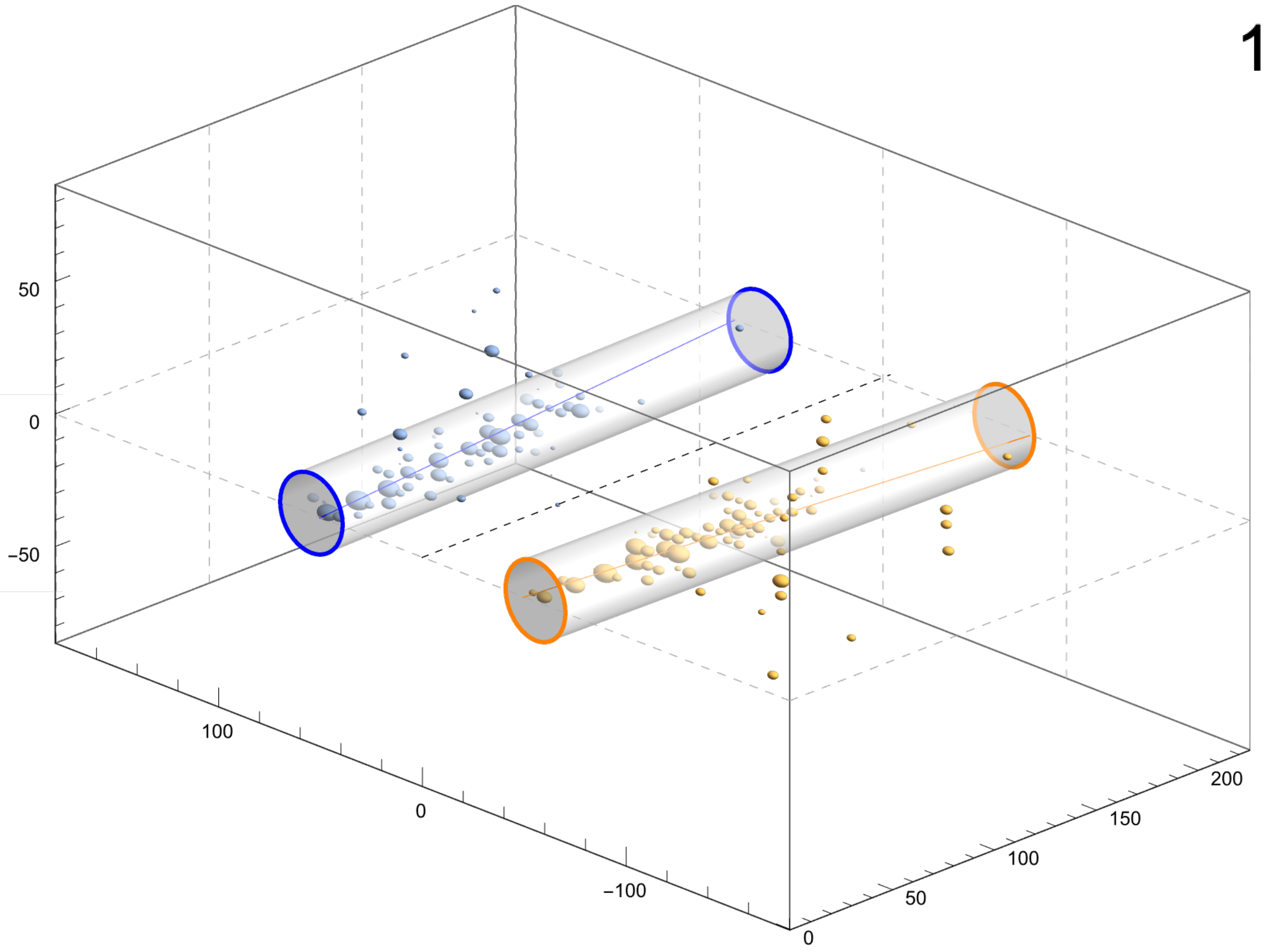


Opening angle

- A simple nearest-neighbour clustering
- S. Effeciency > 95% when $\Delta > 40$ mm
- Good resolution in tracking that enable us to infer the vertex position







Position

- A simple nearest-neighbour clustering
- S. Effeciency > 95% when $\Delta > 40$ mm
- Good resolution in tracking that enable us to infer the vertex position
- Can be improved with more sophisticated methods