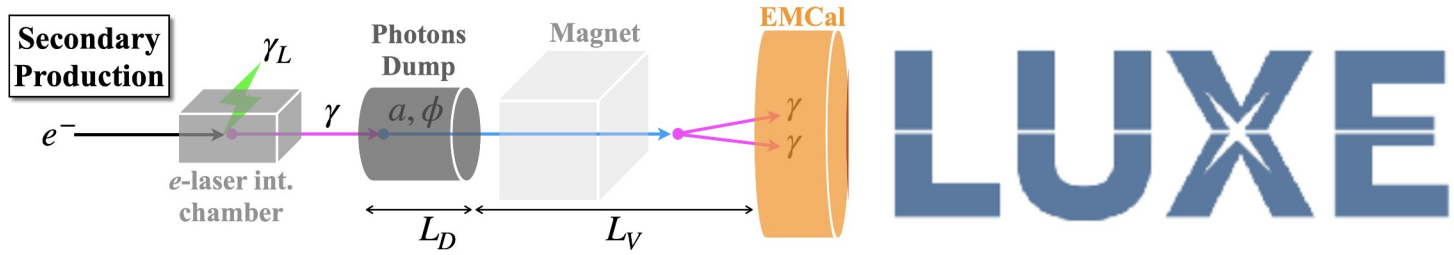
SiW-ECAL optimized for LUXE NPOD



LUXE

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DMLab Meeting, 17/10/25

CSIC
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Introduction

- Citable e-print available at https://arxiv.org/abs/2507.17716

Layout optimization for the LUXE-NPOD experiment

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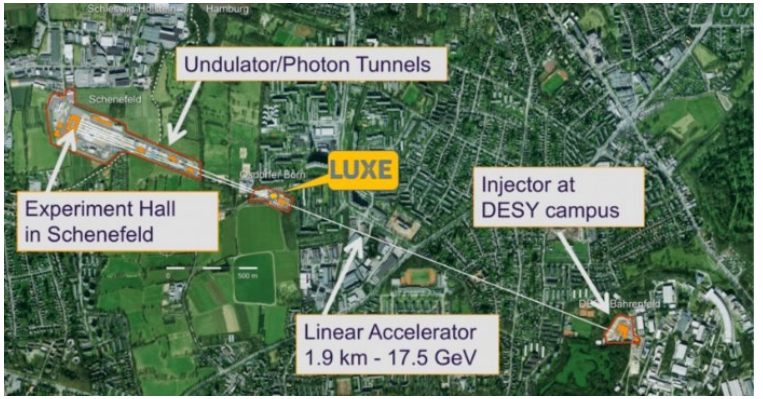
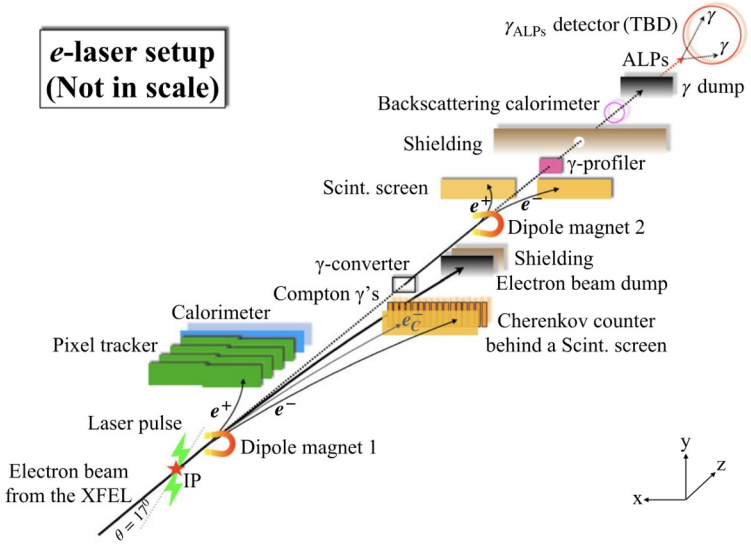
Abstract

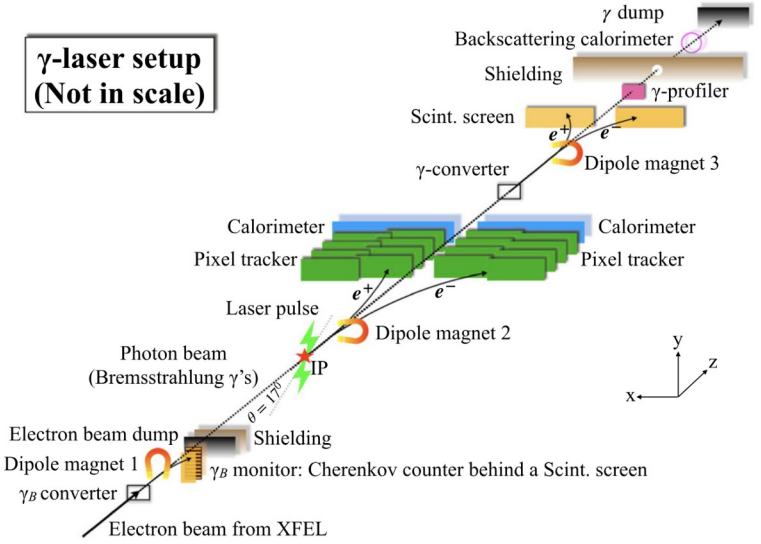
Beam dump experiments represent an effective way to probe new physics in a parameter space, where new particles have feeble couplings to the Standard Model sector and masses below the GeV scale. The LUXE experiment, designed primarily to study strong-field quantum electrodynamics, can be used also as a photon beam dump experiment with a unique reach for new spin-0 particles in the $10-350$ MeV mass and $10^{-6}-10^{-3}$ GeV^{-1} couplings to photons ranges. This is achieved via the "New Physics search with Optical Dump" (NPOD) concept. While prior estimations were obtained with a simplified model of the experimental setup, in this work we present a systematic study of the new physics reach in the full, realistic experimental apparatus, including an existing detector to be used in the LUXE NPOD context. We furthermore investigate updated scenarios of LUXE's experimental plan and confirm that our results are in agreement with the original estimations of a background-free operation.

LUXE: Laser und XFEL Experiment

- Study of strong field QED
  - Non-perturbative effects induced by strong electromagnetic field
  - High power laser (10, 40, 350 TW)
  - 16.5 GeV electron/photon beam
    - Extracted from XFEL
  - Detectors optimized for e-/e+/ɣ

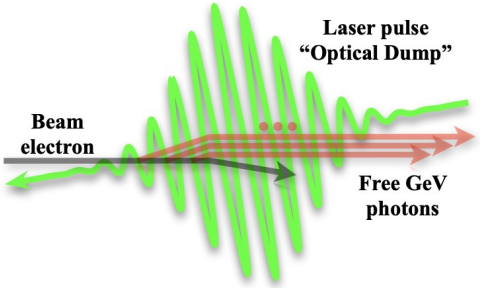






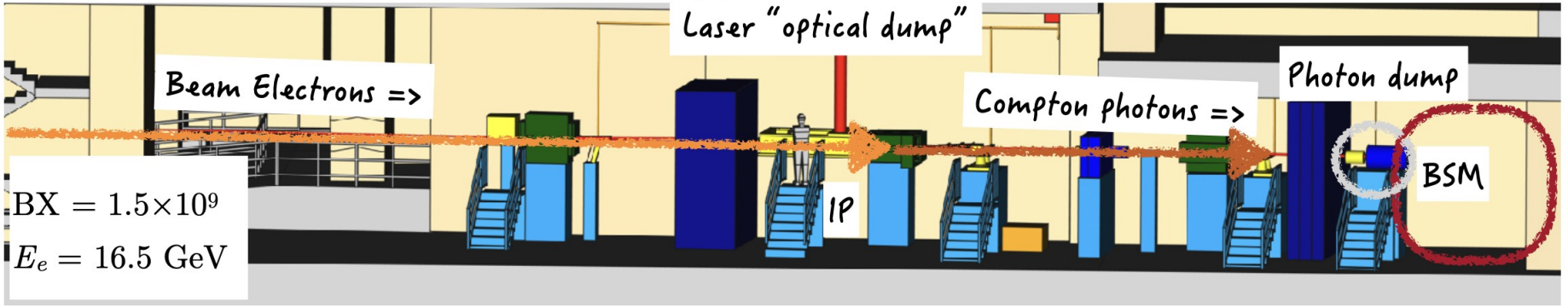
NPOD: New physics at optical dump

- An “optical dump” converts electrons from the beam into photons
  - via non-linear Compton scattering
- The photons move through the laser field until they reach a photon dump
  - Sensibility to a various of BSM signals when measuring after the photon dump



$I_L \approx 10^{18}\text{-}10^{21}$ W cm^{-2}

$\omega_L = 1.5$ eV



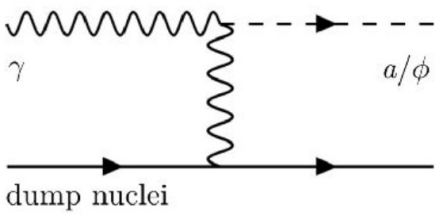
Axion-like particles beam-dump experiment

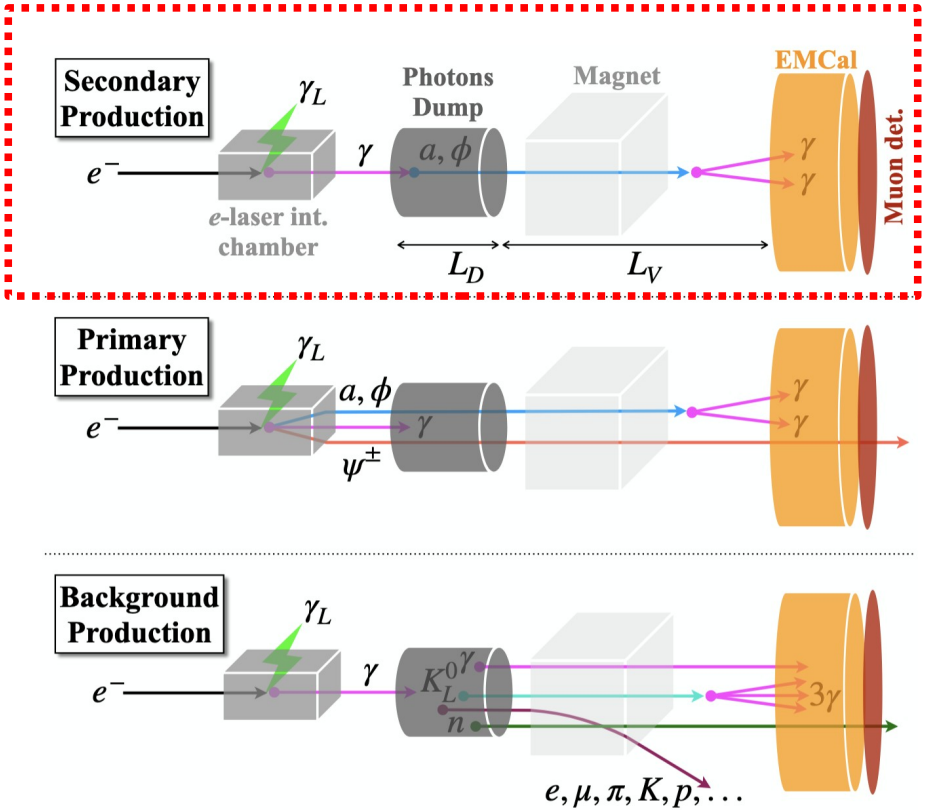
- BSM effective scalar or pseudo-scalar that can couple to two photons:

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

- Most background is exhausted in the dump
  - Charged particles deflected with a magnet

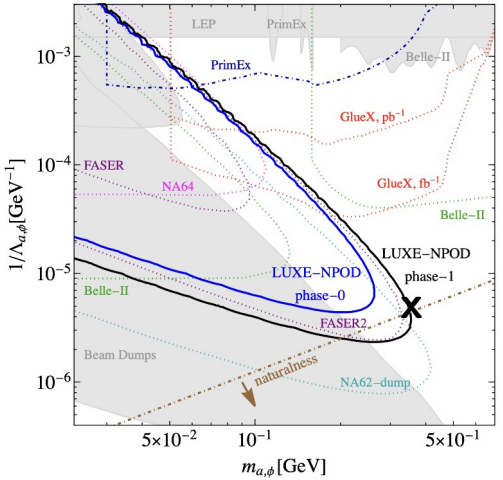
- The signal consist on ɣ pairs
  - Primary: ALP → ɣɣ
  - **Secondary**: ɣɣ → ALP → ɣɣ

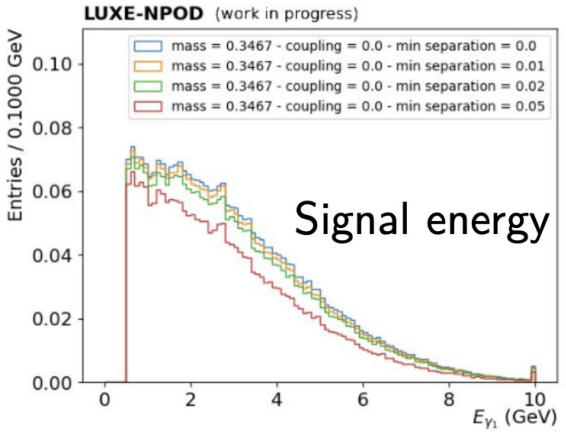


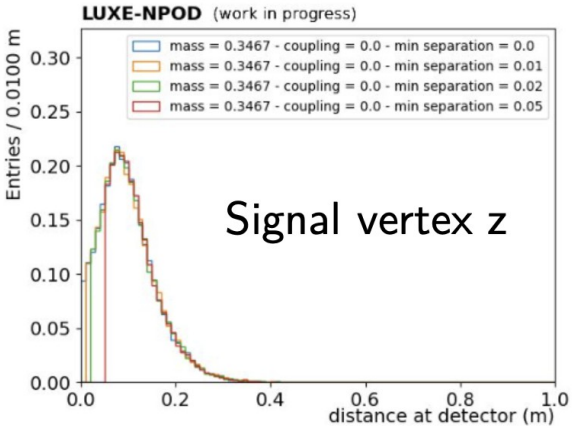


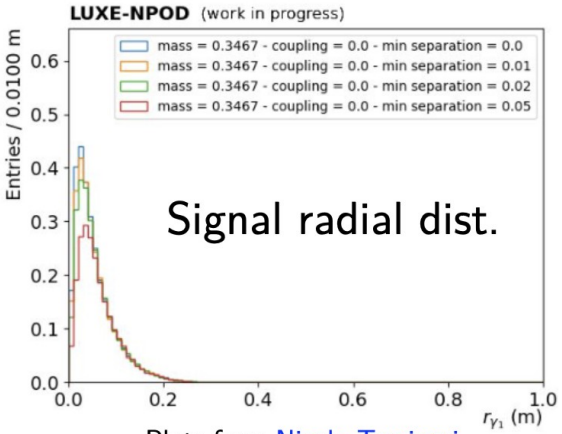
Requirements for ALP measurements

- Simulation with MadGraph
- We need to reconstruct:
  - Energies of the photons: $E_{\gamma 1}$, $E_{\gamma 2}$
  - Vertex reconstruction:
    - Opening angle (2θ)
    - Entry point resolution (Δ)





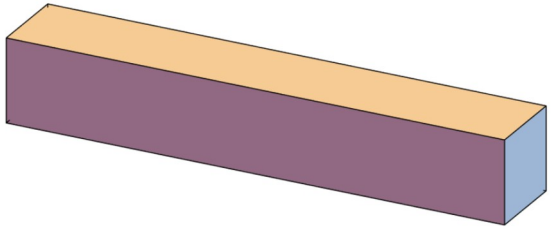


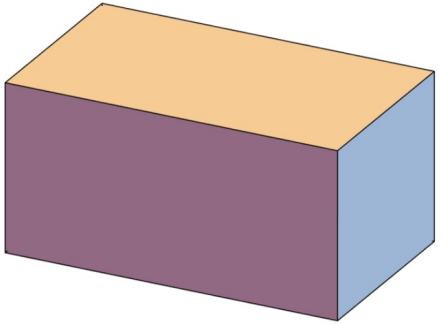


Plots from Nicolo Trevisani

LUXE ECAL-P & ECAL-E

- ECAL-P
  - (540 x 90) x 90 mm^3
  - (96 x 16) x 20 channels
- ECAL-E (only in LUXE ɣ-laser mode)
  - (360 x 180) x 225 mm^3
  - (64 x 32) x 15 channels
  - Based on the SiW-ECAL prototype
  - Homogeneus W & Si thickeness
    - 18 X_0 of W
    - 500 μm Si sensors
  -

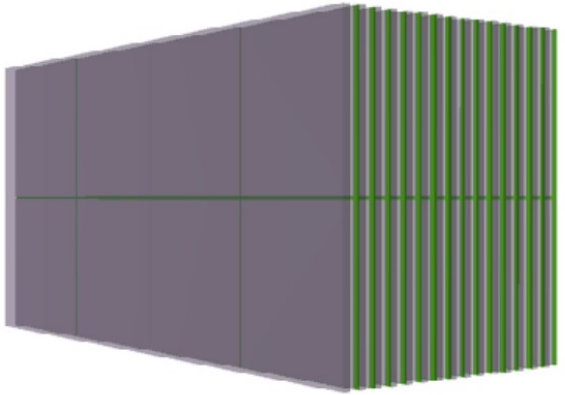




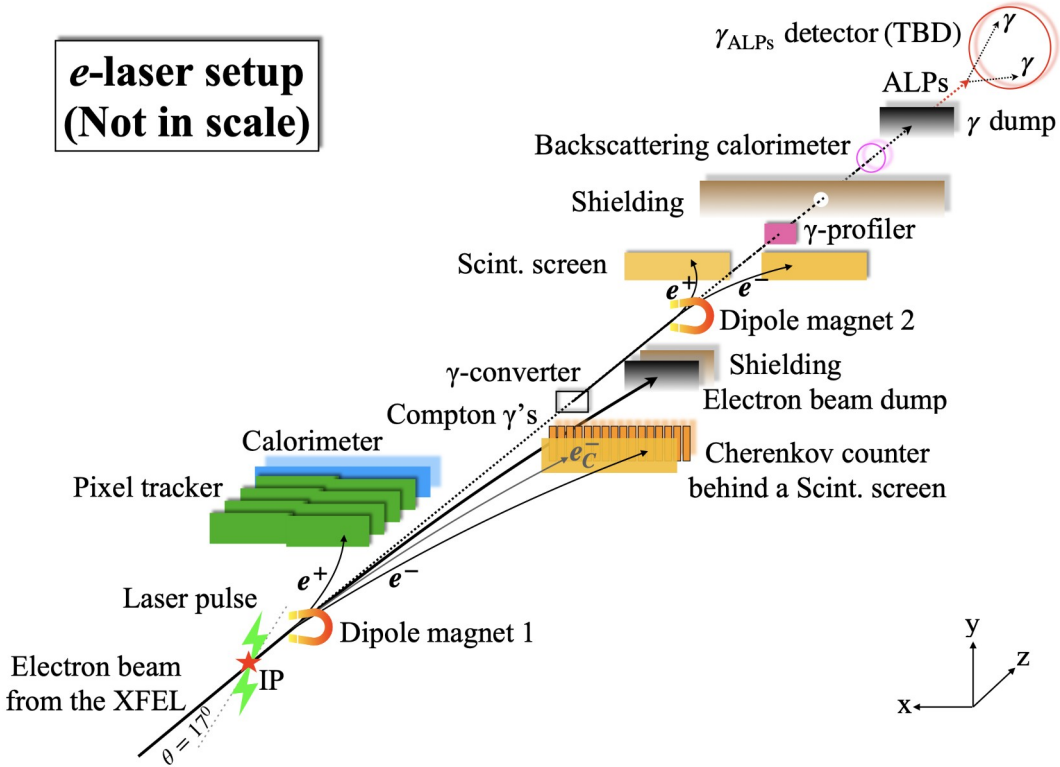
ECAL-P & ECAL-E envelopes

ECAL-E → NPOD ECAL

- ECAL-E is a natural candidate for the LUXE NPOD (NPOD ECAL)



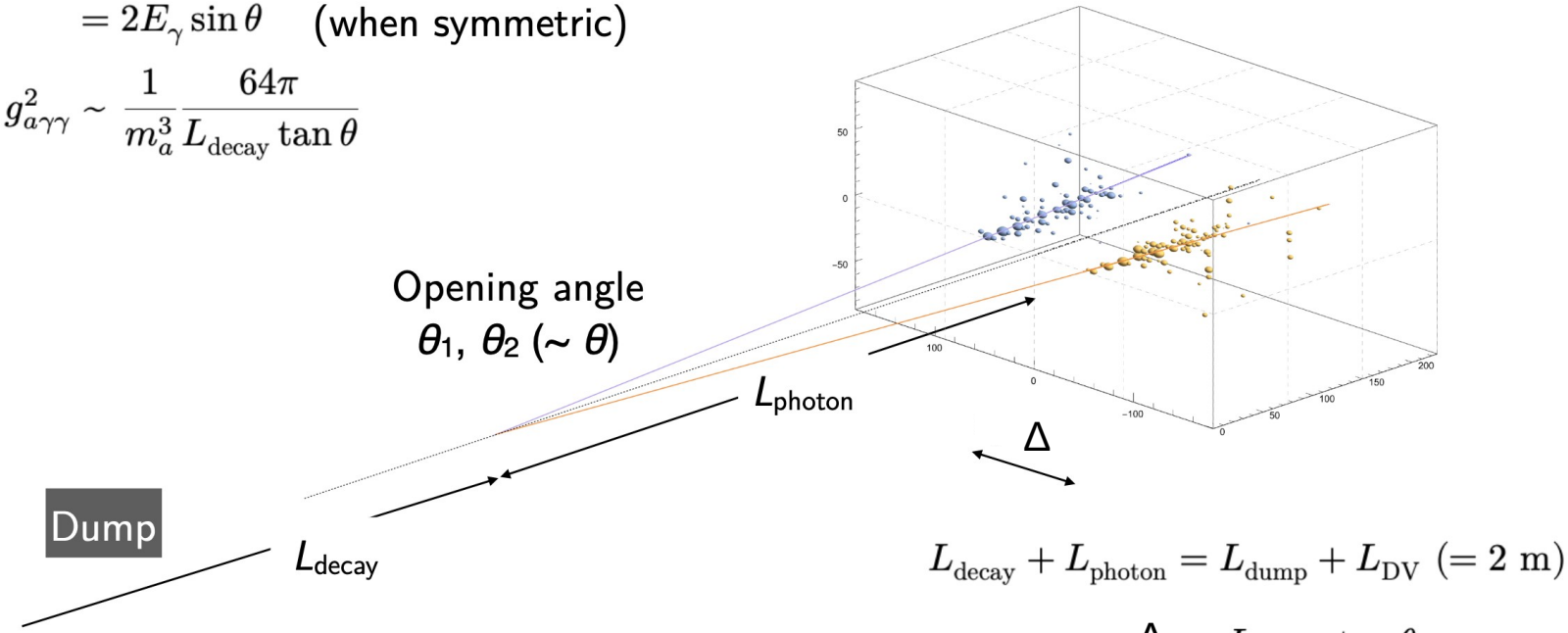
View of dd4hep ECAL-E/NPOD ECAL sim



ALP signal

- Analysis of the NPOD ECAL simulation
- First proof-of-concept: Axion decaying symmetrically into two photons

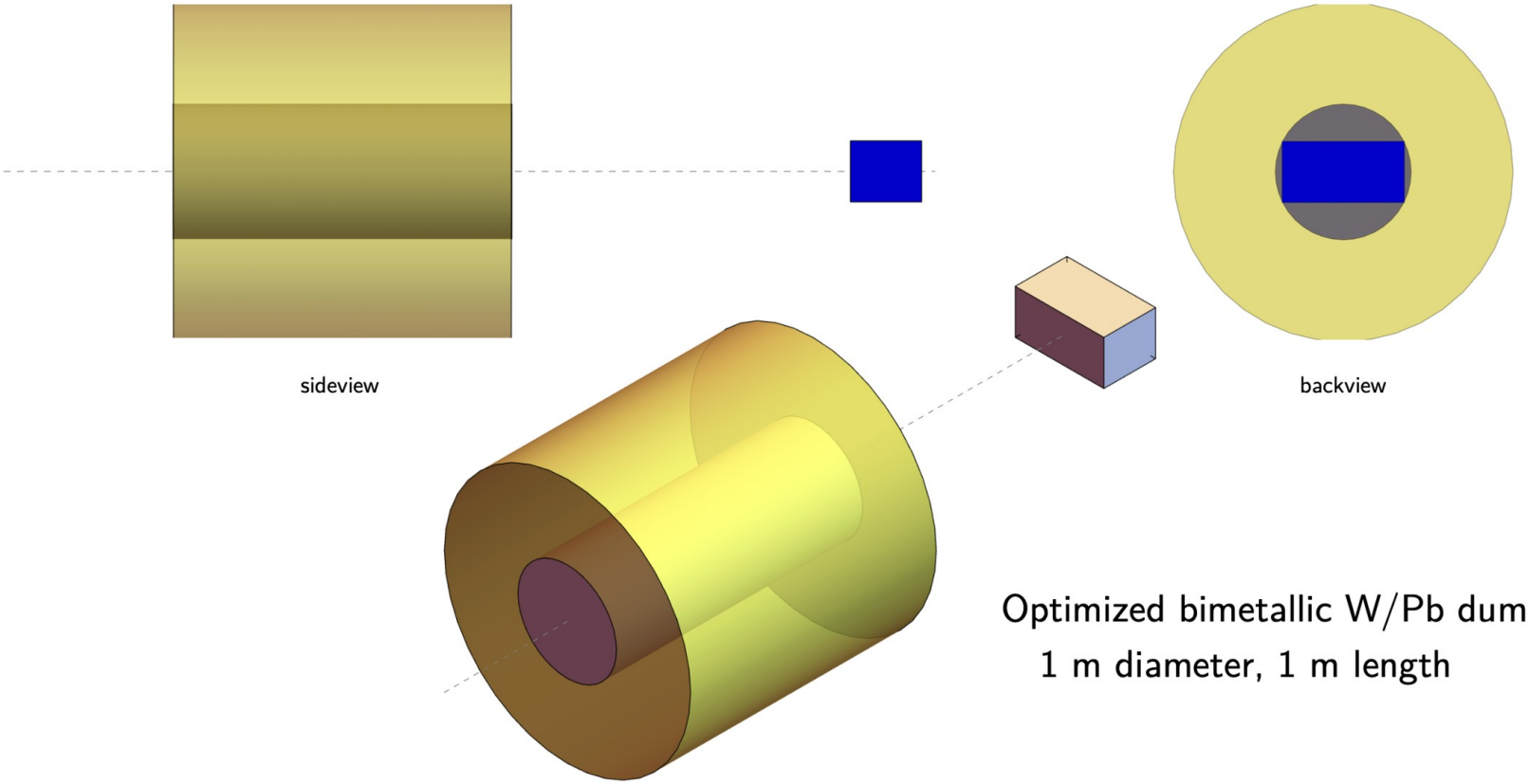
$$m_a = \sqrt{2E_{\gamma 1}E_{\gamma 2}[1-\cos(\theta_1+\theta_2)]}$$
$$= 2E_\gamma \sin\theta \quad \text{(when symmetric)}$$
$$g^2_{a\gamma\gamma} \sim \frac{1}{m_a^3}\frac{64\pi}{L_{\text{decay}}\tan\theta}$$



$$L_{\text{decay}} + L_{\text{photon}} = L_{\text{dump}} + L_{\text{DV}} \ (= 2\ \text{m})$$

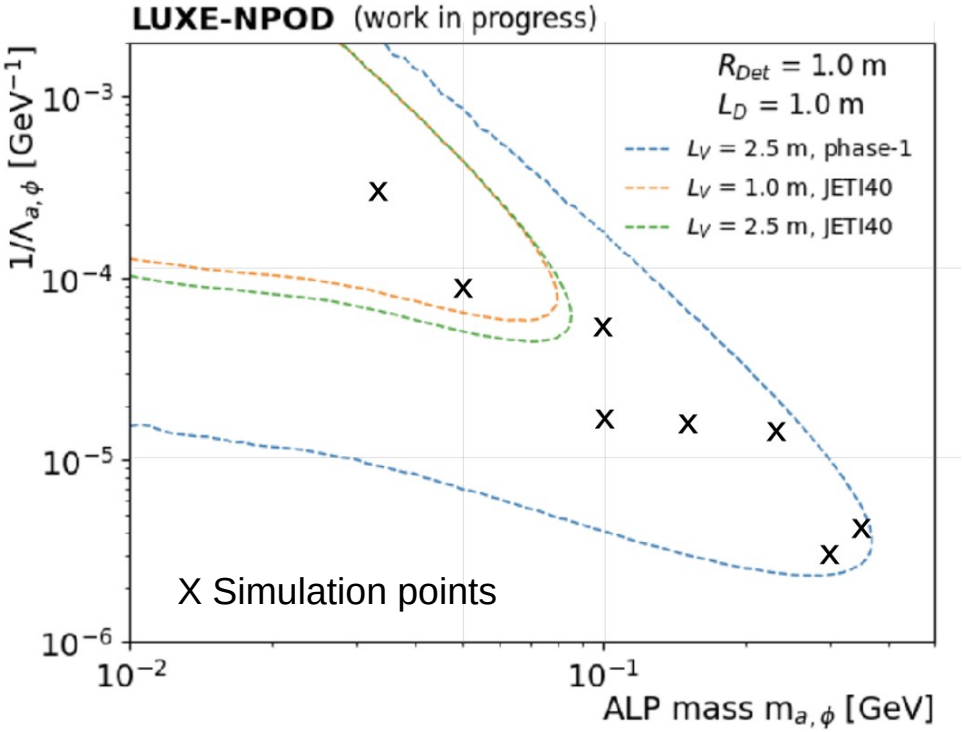
$$\Delta = L_{\text{photon}} \tan\theta$$

NPOD ECAL


sideview
backview
Optimized bimetallic W/Pb dump
1 m diameter, 1 m length

Simulation (DDSim)

- Using DD4Hep
- Simulation of photon pairs at 0.5, 1.5, 3.5 GeV
- Symmetrical from a fix point:
  - Δ=10, 20, … , 100 mm
  - L_{photon} = 0.35, 0.50, 0.75 m
- Simple digitization: Hit threshold at 0.5 MIP with 10% smearing
- Option to run with analogue or digital ECAL



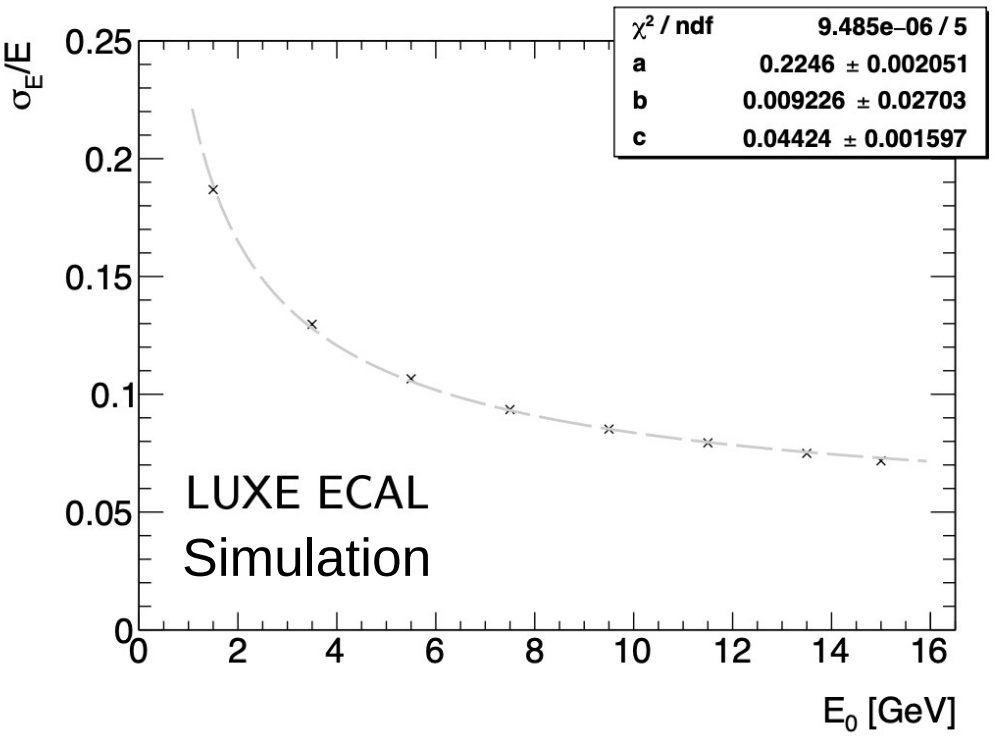
Energy resolution

- Scanned of different energies shows the expected logaritmic dependence

- Result of fit:

$$\frac{\sigma_E}{E} = \frac{(19.8 \pm 0.4)\%}{\sqrt{E_0/\ \mathrm{GeV}}} \oplus (4.9 \pm 0.3)\%,$$

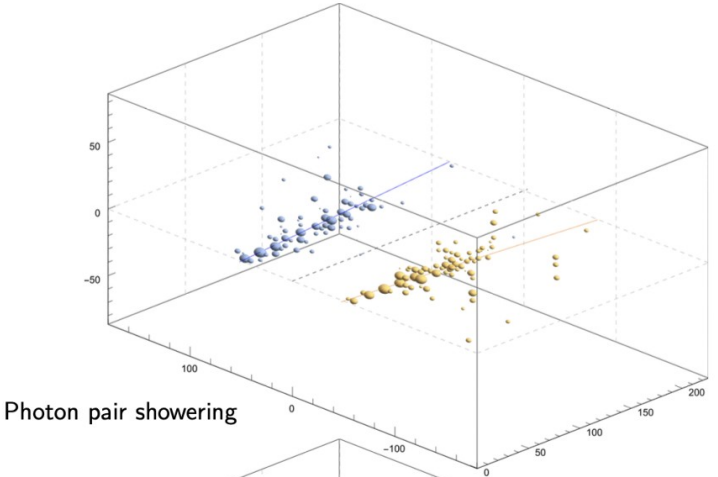
- Consistent with others SiW-ECAL results

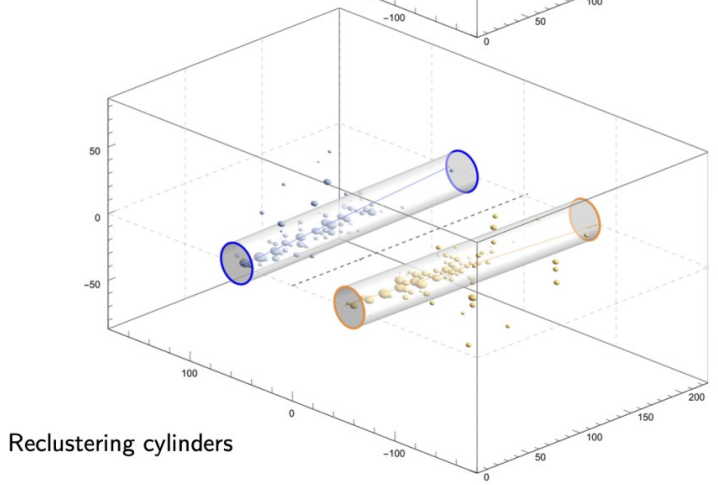


Clustering & tracking

- Reconstruction via Marlin processors
- Clustering: nearest-neighbor algorithm
- Tracking: Line fitting of the hit distribution
- Refining by another iteration:
  - Re-clustering: Collecting the hits withing an effective “Molière radius” of the cluster
  - Re-tracking: Line fitting of the reclustered hits

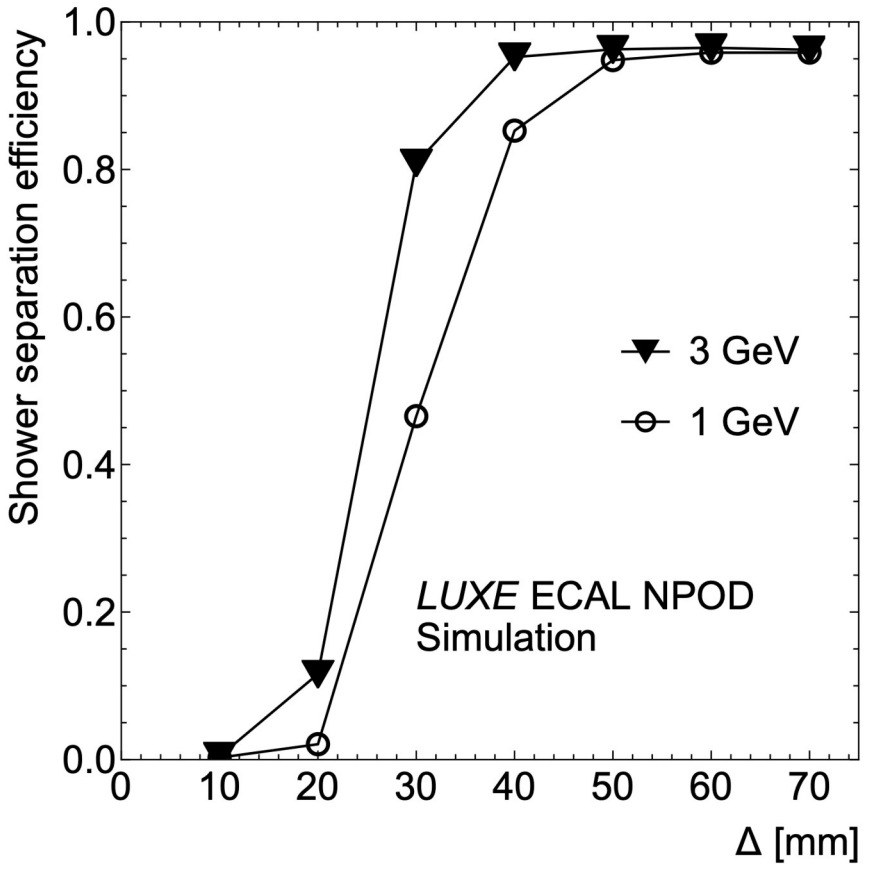
Repo (A. Irles): https://github.com/airqui/ECALe-lcio





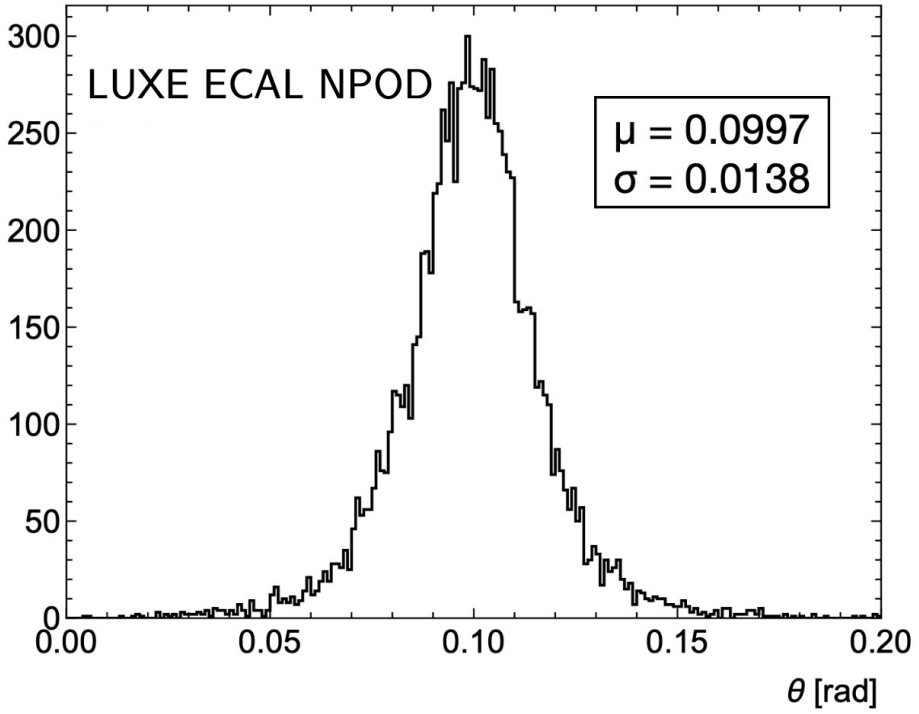
Power of separation

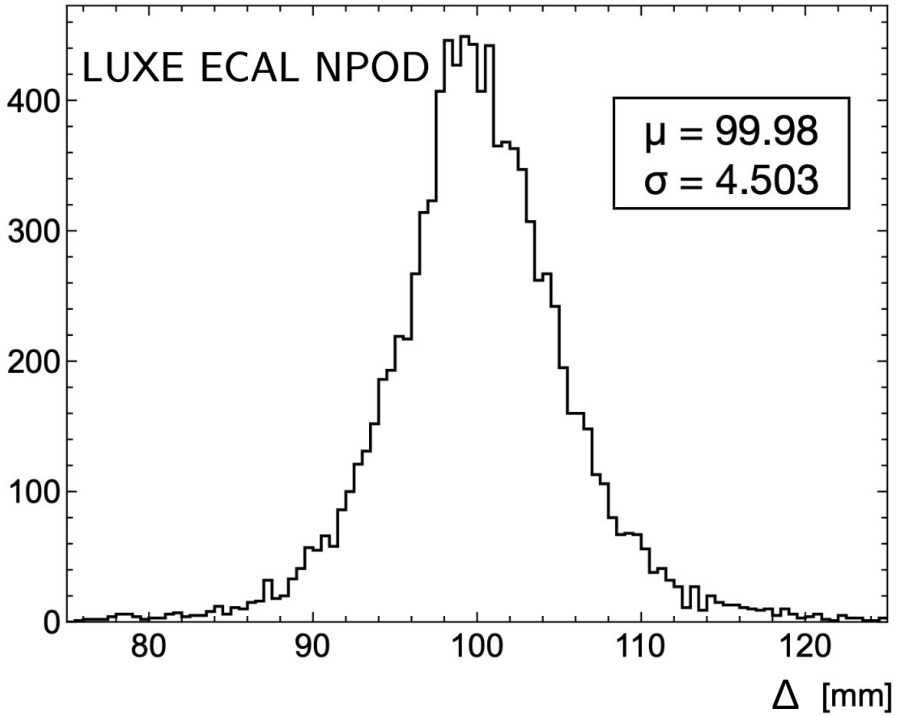
- First step of clustering
- Successful reconstruction:
  - $N_{clusters} > 1$
  - Two largest clusters with similar energy count ($½ < E_1/E_2 < 2$)
- If the separation is too small, showers overlap and the clustering fails
- Ratio = $N_{success}/N_{total}$
  - Convergence to 95% when Δ is big enough



Opening angle (θ) & Separation (Δ) - Example

- $E_{\gamma 1} = E_{\gamma 2} = 1.5$ GeV
- $\theta = 0.1$ rad
- $\Delta = 100$ mm



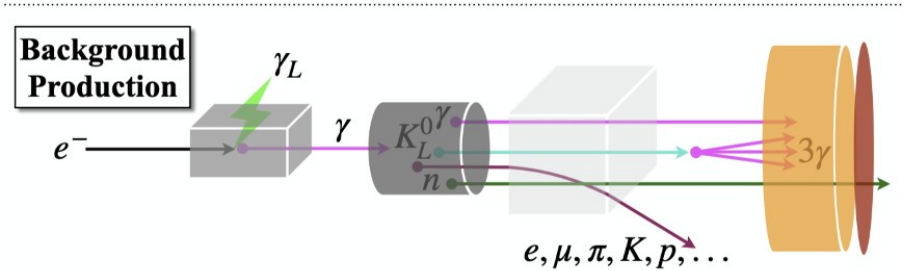


PID: Backgrounds

- A bimetallic W/Pb dump photon dump is optimized to minimize background for a one-year data taking
  - Fully eliminates ɣ background
  - Greatly alleviates n background

Setup, N_{BX}	Dump material	L_D [cm]	R_D [cm]	N_γ all	N_γ E_{kin}>0.5 GeV	N_n all	N_n E_{kin}>0.5 GeV
a, 0.5	W	30	10	9500	60	970000	26000
b, 0.5		50	10	2600	120	320000	5800
c, 0.5		100	10	3300	0	140000	1600
d, 0.5		100	20	840	0	39000	210
e, 0.5		100	30	300	0	14000	75
f, 0.5	Pb	100	40	900	0	84000	1900
g, 0.5	W+Pb	100	W: 20 Pb: 50	210	0	13000	30
g, 10				160	0	12000	68

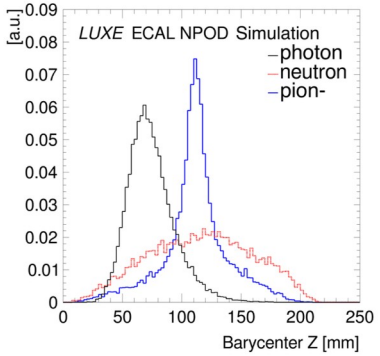
- However, some SM background could still reach the detector:
  - Neutral particles: n, ɣ
  - Charged hadrons: π, K, p, …
  - Charged leptons (e, μ) are trivially rejected

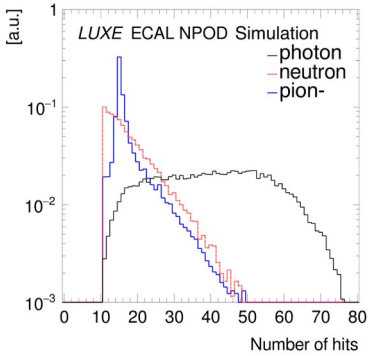


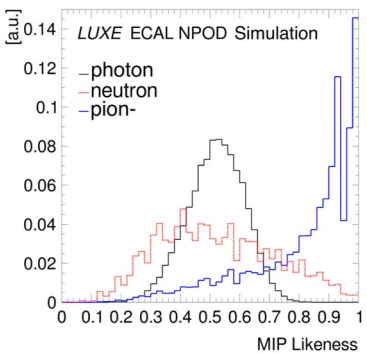
- We need our ECAL to properly separate ɣ from n and π (biggest sources of background)

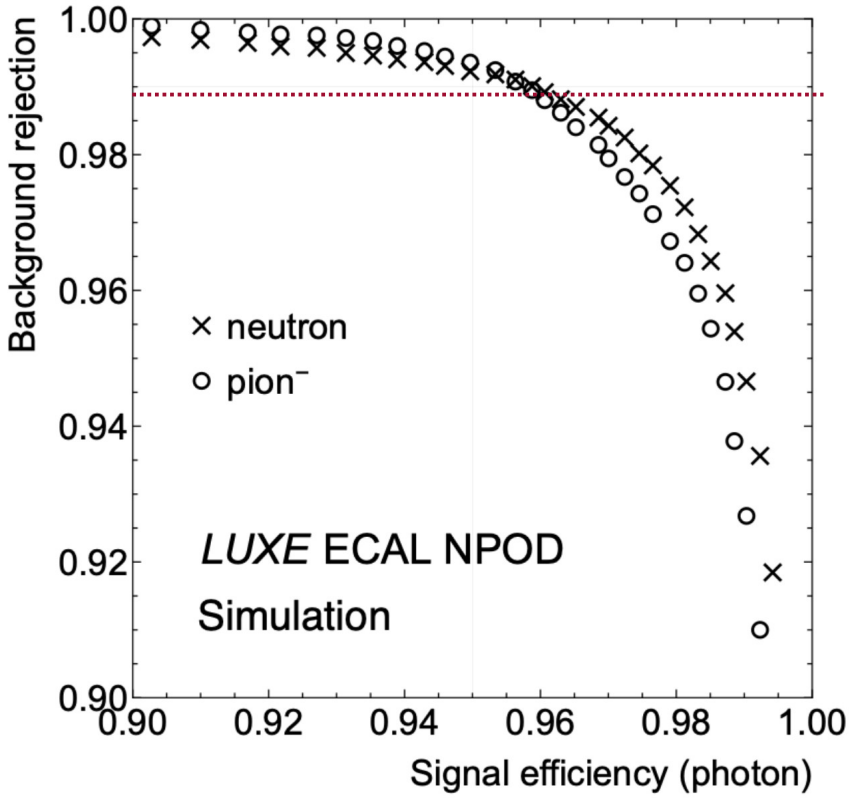
PID: Software and results

- DD4Hep simulation, MIP calibration, simple MIP threshold (E > 0.5 MIP) with 10% smearing
- Three-category BDT-based classifier (w.hyper-parameter optimization)
- The inputs are a set of shower characterization variables: Barycenter, eff. Molière radii, nhits, E, etc.



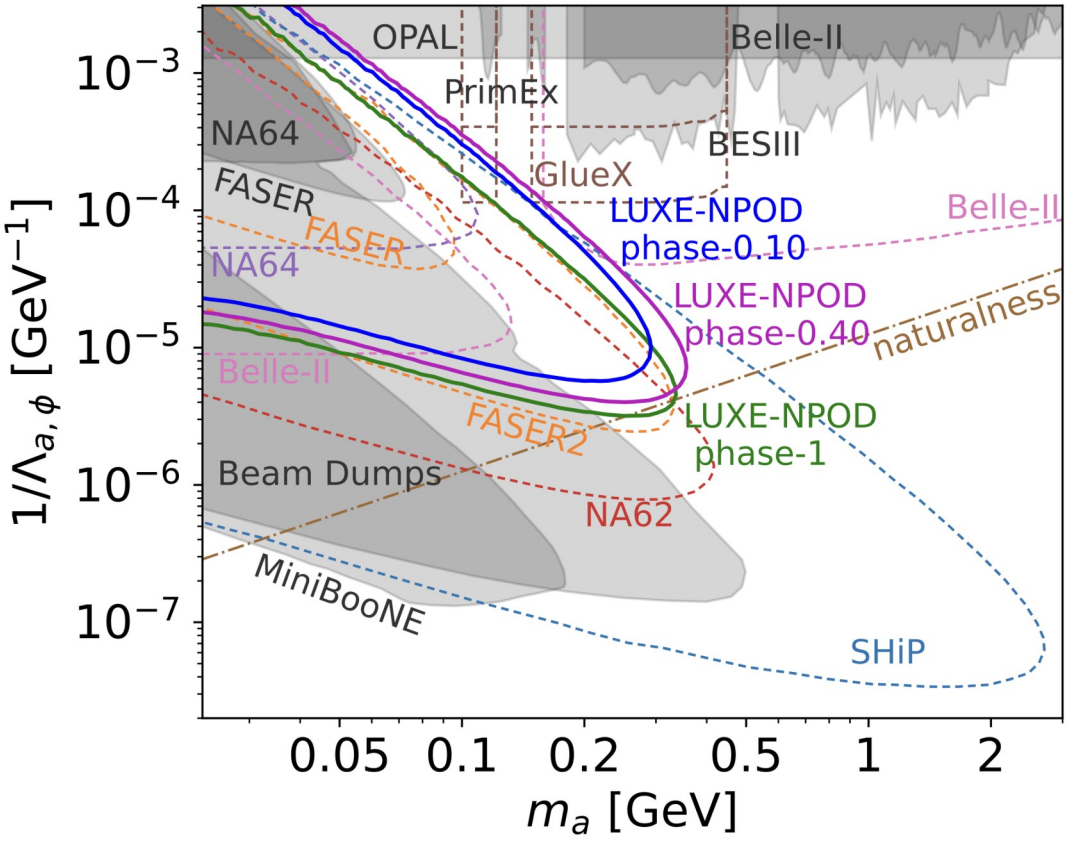






Repo (J. P. Márquez): https://github.com/marherje/Simplified_ECAL_PID

Axion parameter space discrimination



Conclusions/overview

- Correct reconstruction of:
  - Energy
  - Shower separation
  - opening angle

- Background reconstruction is successfully done by
  - Bimetallic W/Pb dump
  - BDTs classifier in the ECAL

- There’s still work TBD in the future:
  - More sophisticated tracking & clustering methods
  - More complex topologies (asymmetris signals)

Thanks for your attention

LUXE

IFIC

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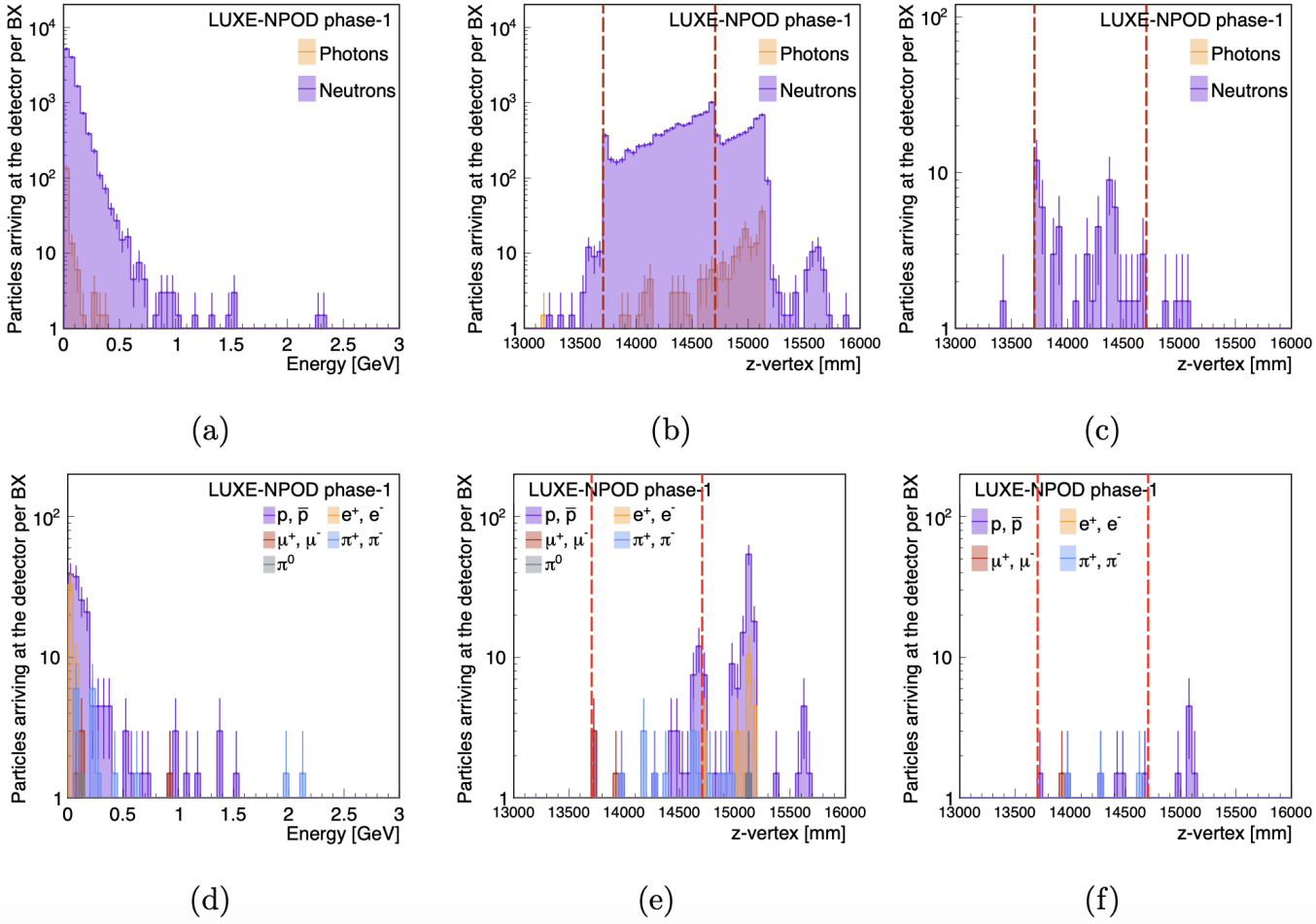
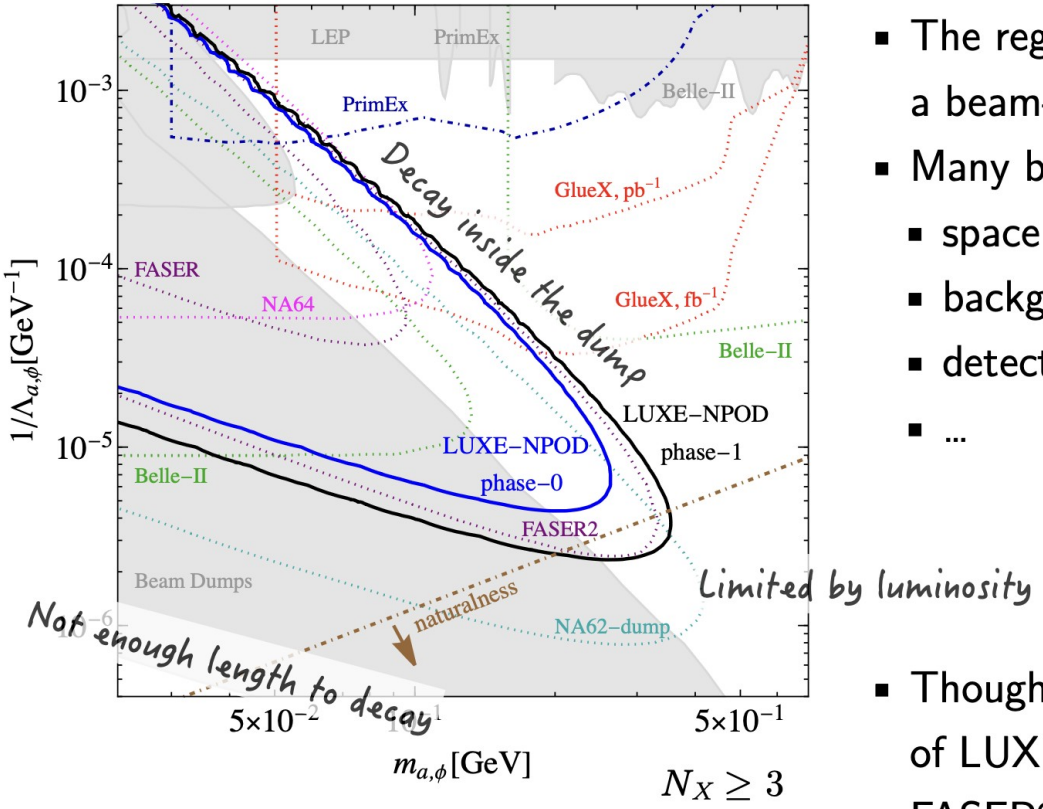
Laboratoire de Physique des 2 Infinis

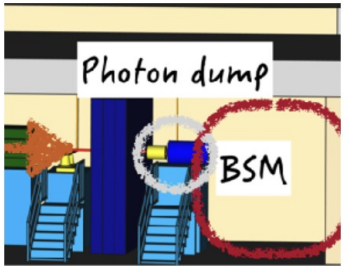
In-depth signal & background view



Space discrimination interpretation (S. Huang)



- The region has the typical shape of a beam-dump type experiment
- Many bargaining between:
  - space limit of the experiment
  - background suppression
  - detector size
  - ...



- Though with limits, the sensitivity of LUXE NPOD can compete with FASER2 and even NA62

PID run details

Results:

- A: Photons
- B: Neutrons
- C: Pions (-)

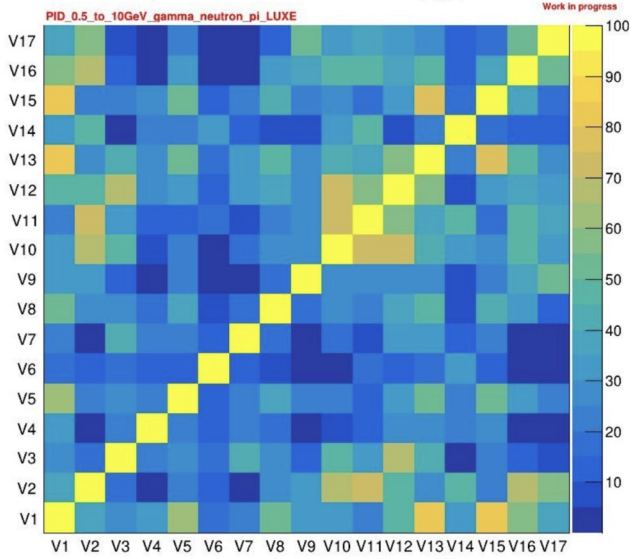
From a training in September 2024

Rank	Variable	Variable Importance
1	MIP_Likeness	1.085e-01
2	bar_z	1.071e-01
3	nhit	1.021e-01
4	hits_max_distance	9.364e-02
5	sume_layer_5	8.369e-02
6	mol	6.730e-02
7	sume_layer_1	6.327e-02
8	shower_sume_max	5.459e-02
9	radius90_layer_5	5.354e-02
10	shower_sume_end_10_layer	4.124e-02
11		

From a later training in November 2024

Rank	Variable	Variable Importance
1	MIP_Likeness	1.541e-01
2	hits_max_distance	1.313e-01
3	bar_z	1.224e-01
4	nhit	1.201e-01

|Variable correlation| (γ)



Variables:

V1: nhit
V2: bar_z
V3: mol
V4: MIP_Likeness
V5: hits_max_distance
V6: radius90_layer_1
V7: radius90_layer_5
V8: radius90_layer_10
V9: radius90_layer_14
V10: shower_sume_max_layer
V11: shower_sume_start_10_layer
V12: shower_sume_end_10_layer
V13: shower_sume_max
V14: sume_layer_1
V15: sume_layer_5
V16: sume_layer_10
V17: sume_layer_14

Curtesy of Melissa Almanza Soto