LUXE-NPOD
Calorimeter Options

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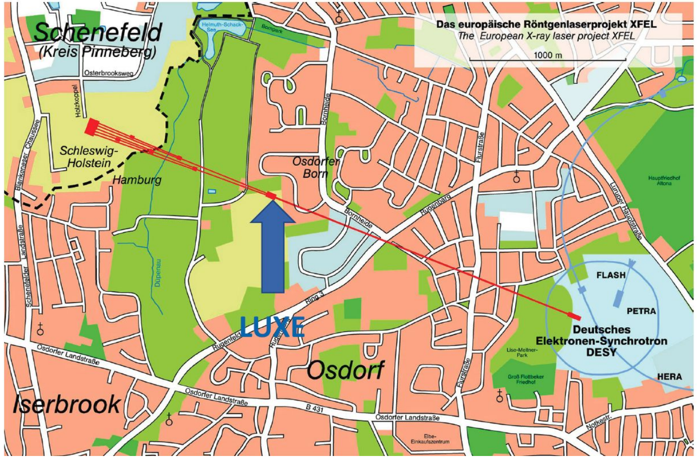
CALICE Collaboration Meeting 27-29 September 2023

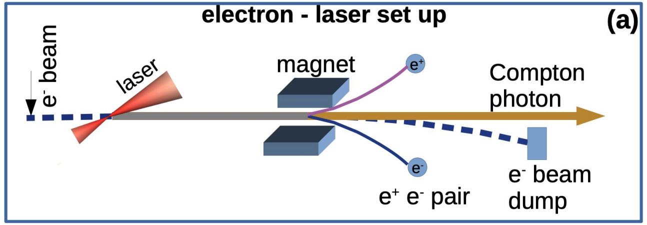
The LUXE Project at DESY

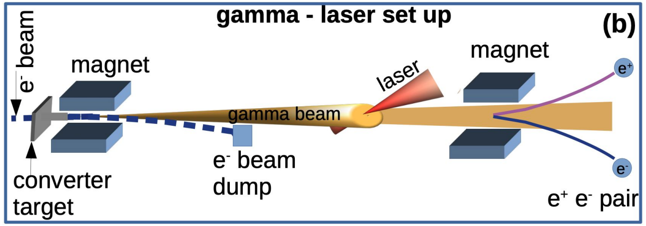
LUXE TDR: arXiv:2308.00515

LUXE: Laser Und XFEL Experiment

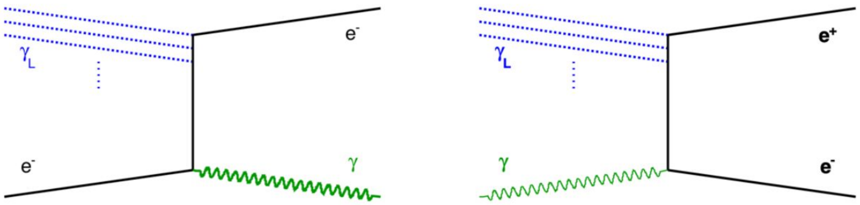
- XFEL provides a 16.5 GeV electron beam - and bremsstrahlung photons
- The electrons (or photons) and the laser photons “collide” producing high-intensity interactions
- Currently a project, first data foreseen in 2027







Overview of the LUXE Physics Program

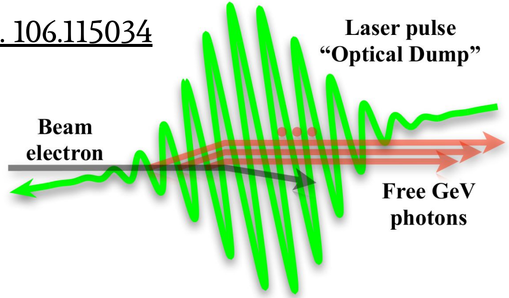


LUXE:

- Compare the predictions of full and perturbative QED in the Schwinger limit with the experimental results
- Measuring the e^+e^- flux produced by photon-laser or electron-laser interaction

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

Phys. Rev. D. 106.115034

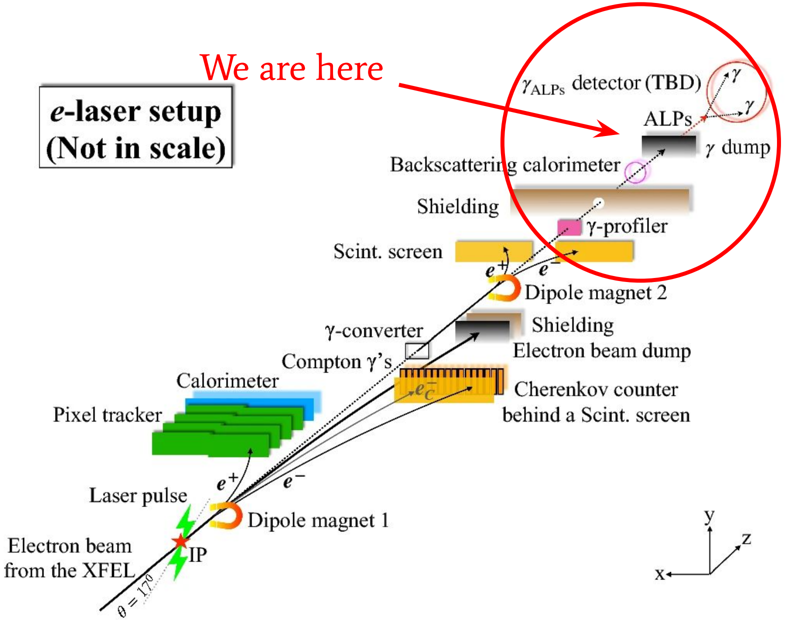


LUXE-NPOD:

- Collide a beam of 16.5 GeV electrons with the laser
- With the correct choice of the laser parameters:
  - The laser acts as a 'solid' dump for electrons, producing O(GeV) photons
  - These photons see the laser as a transparent medium and can reach the physical dump

Overview of the NPOD Project

NPOD: New Physics searches with an Optical Dump


We are here

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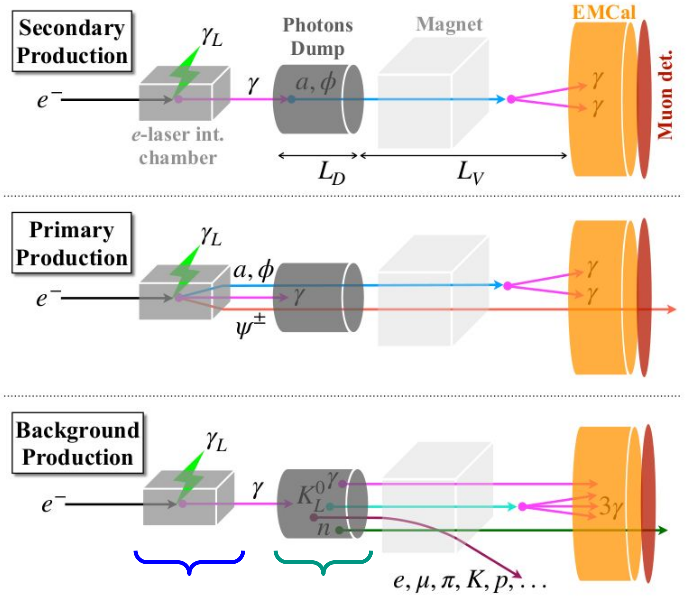


Photons from the optical dump can reach the physical dump and produce axion-like particles (ALPs). These, in turn, decay into pairs of photons.

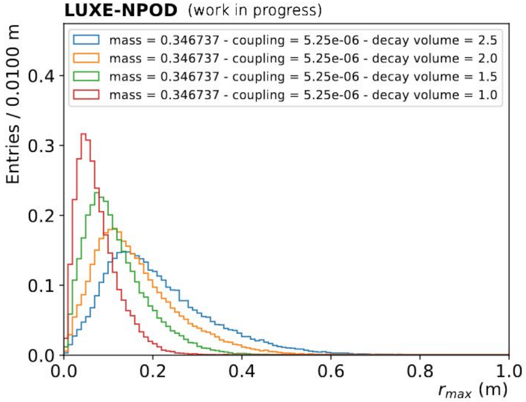
Our Criteria to Define the Calorimeter Requirements

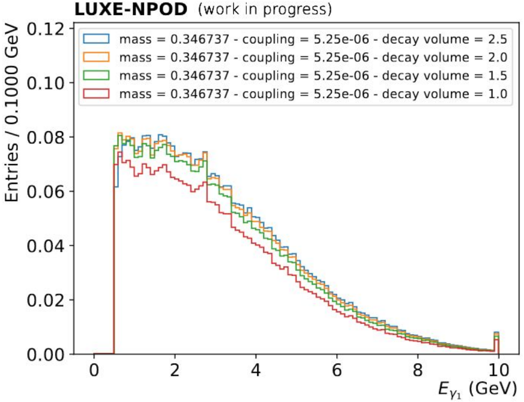
To guide us in the choice of the LUXE-NPOD detector, we consider:

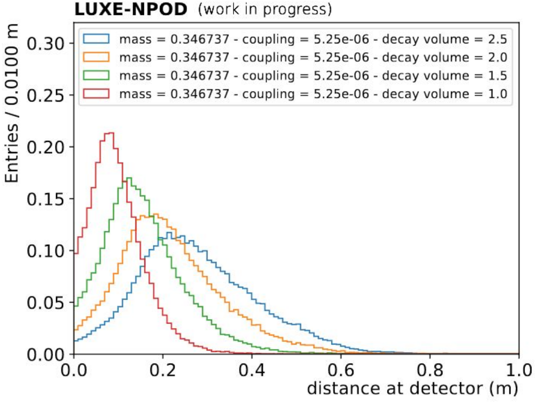
- Expected signal kinematical distributions
- Residual backgrounds reaching the detector
- Existing detectors or prototypes fulfilling the requirements of signal efficiency and background rejection
- Simulations to test the different options, in terms of detectors and reconstruction algorithms

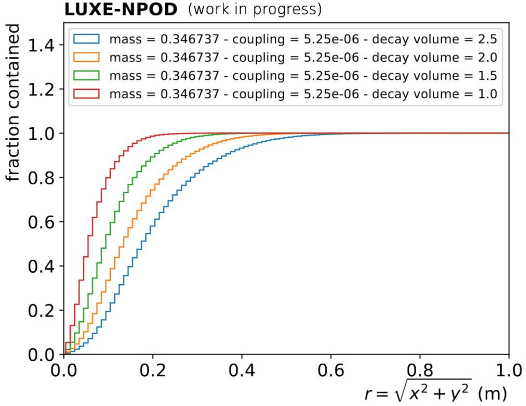
Signal Acceptance vs Decay Volume Length

- Photons produce ALPs in 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 photons separation requirements
- Shorter decay volumes require smaller detector surface
  - But also better photons shower separation



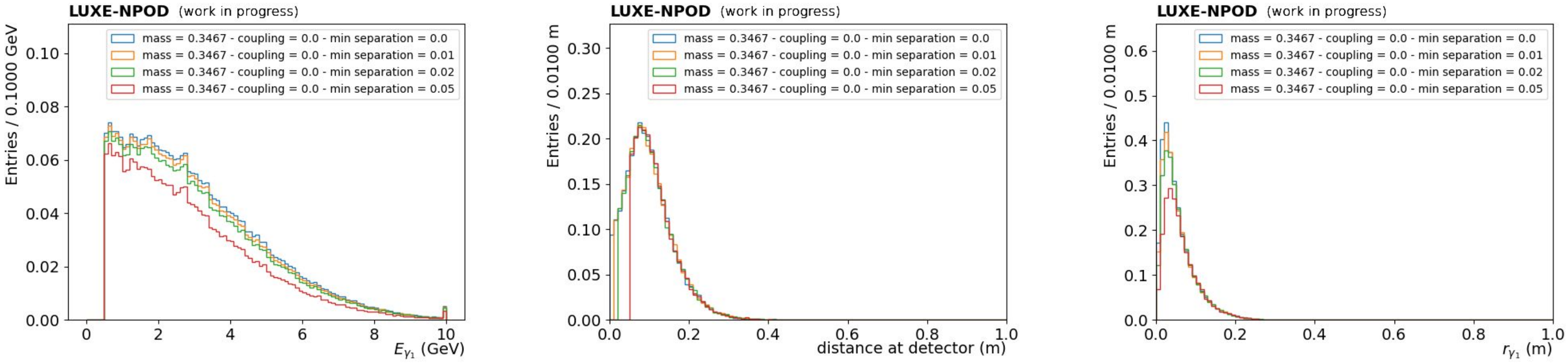






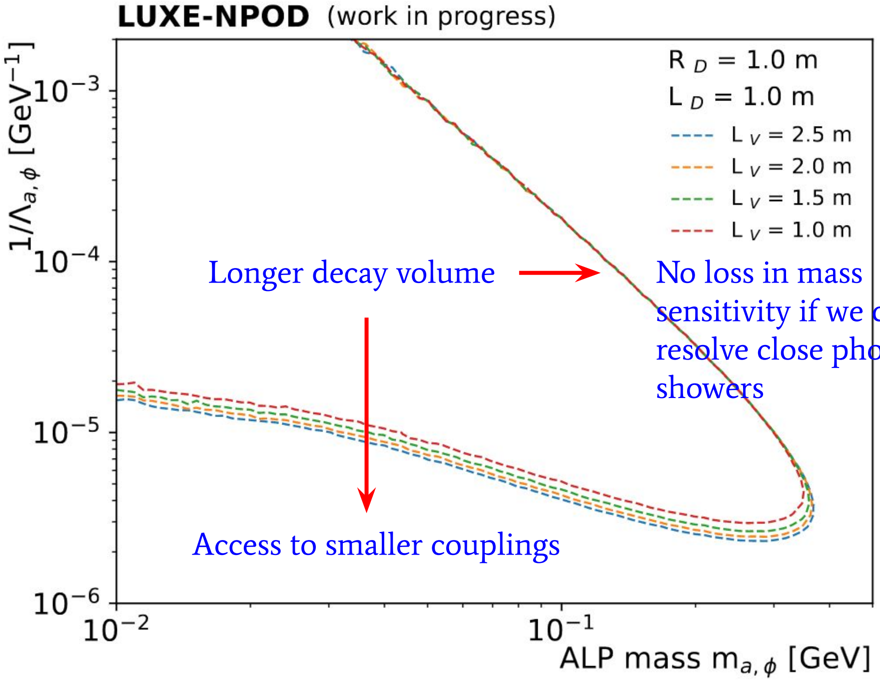
Signal Acceptance vs Minimum Photons Distance Resolution

- Photons produce ALPs in 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, testing different photons separation requirements
- We fix the decay volume to 1 m
  - Worst case scenario, photons distance wise



Expected Results vs Decay Volume Length

Limits assume zero background. No photons shower separation requirements.



Longer decay volume →

No loss in mass sensitivity if we can resolve close photons showers

Access to smaller couplings

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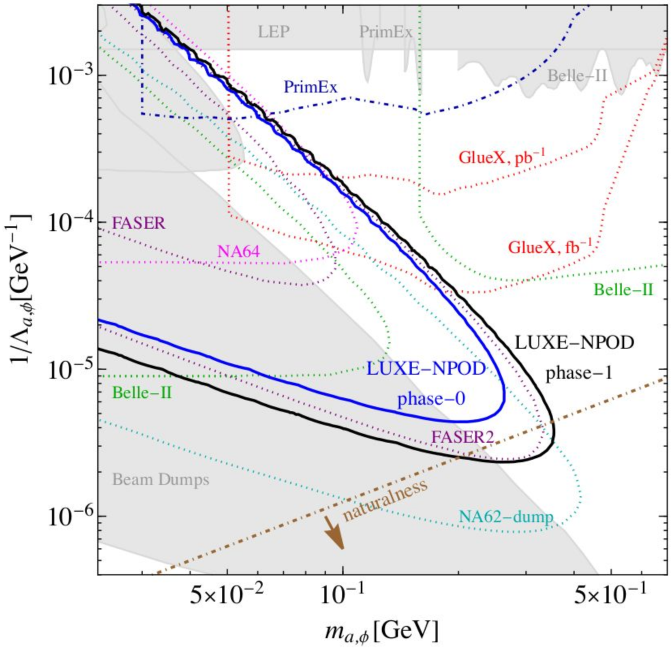
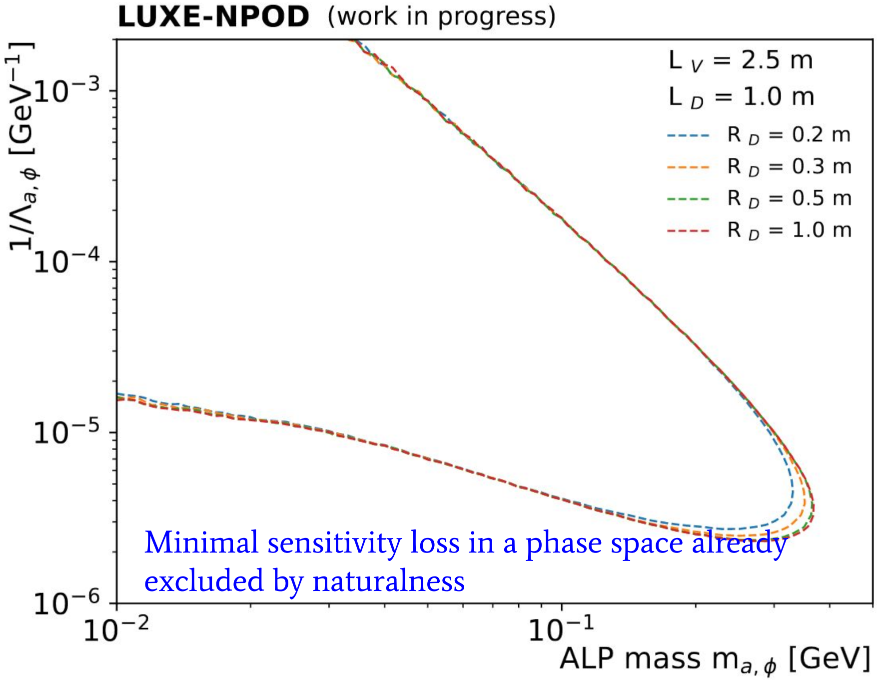


Expected Results vs Detector Transverse Size

We fix the decay volume to 2.5 m (worst case scenario)



Minimal sensitivity loss in a phase space already excluded by naturalness

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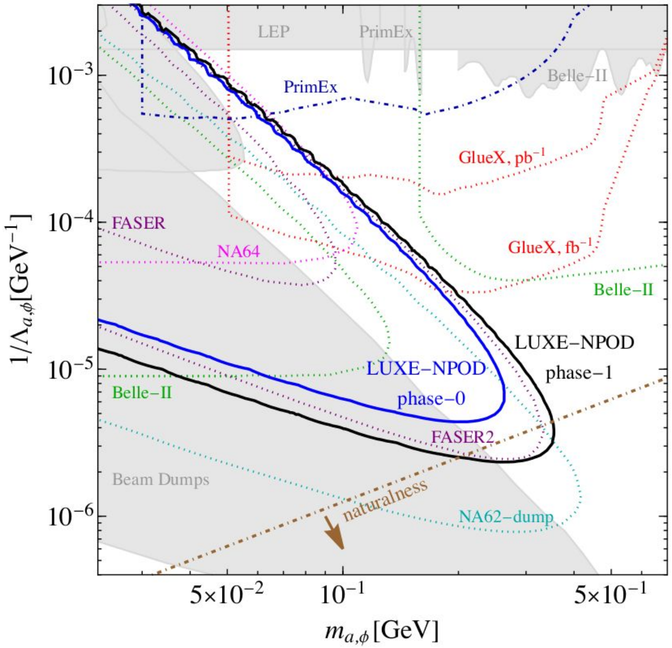
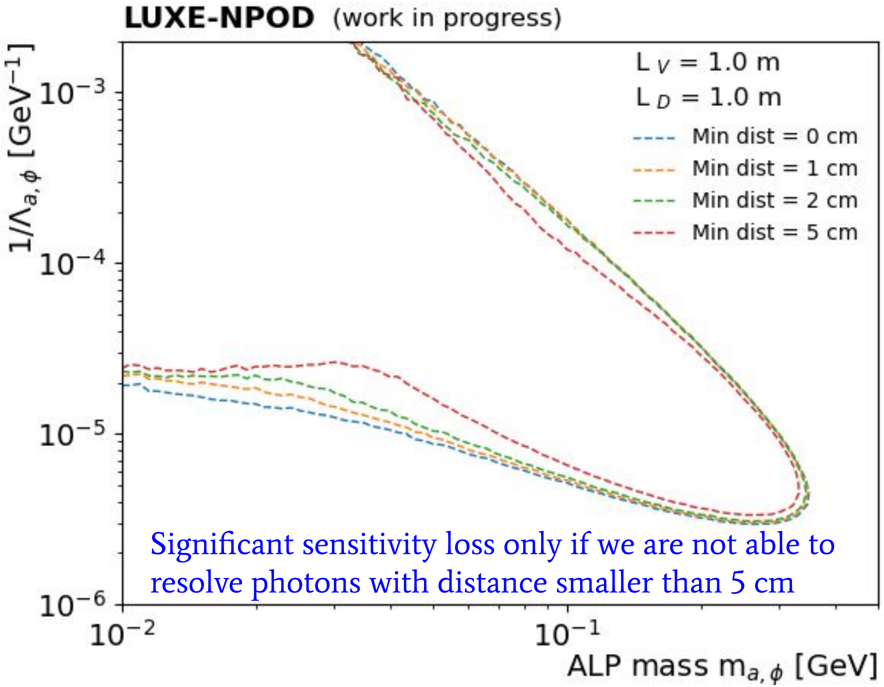


Expected Results vs Minimum Photons Distance Resolution

We fix the decay volume to 1 m (worst case scenario)



Significant sensitivity loss only if we are not able to resolve photons with distance smaller than 5 cm

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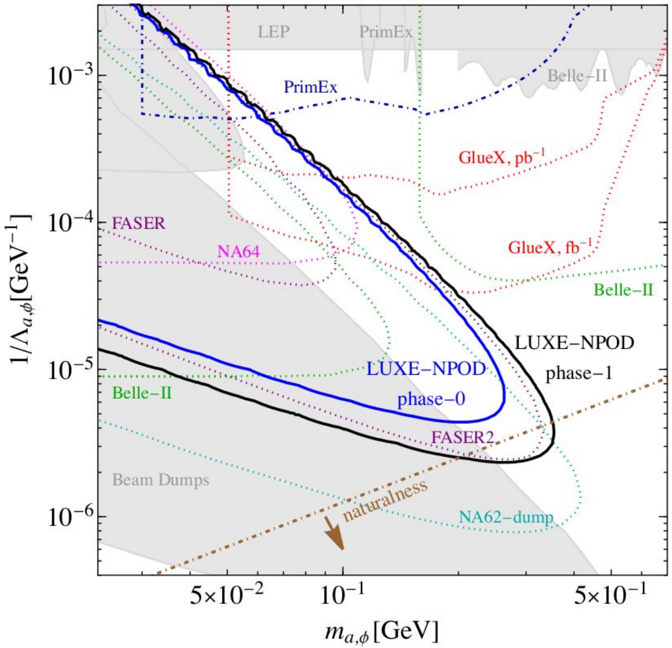
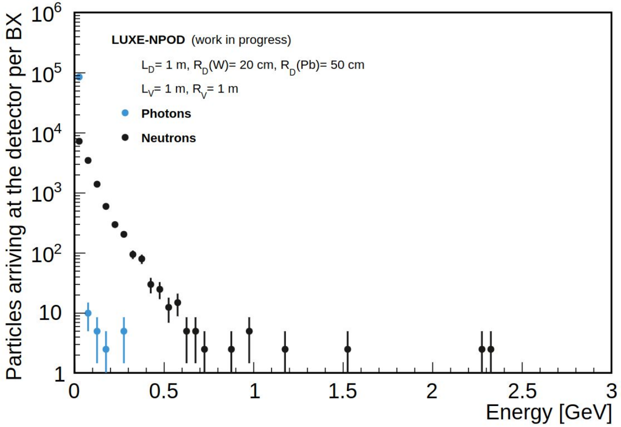
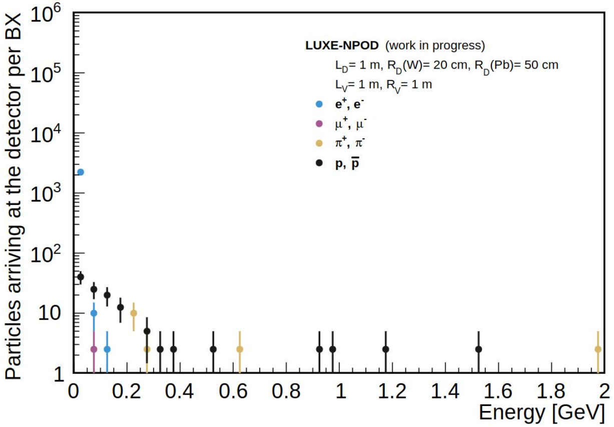


Expected Background Reaching the Detector

We expect some neutrons reaching the detector

- A detector able to distinguish neutrons from photons showers is needed to reject “fake” signals
- Here we consider a detector with radius R = 1 m
  - Number of background particles reaching the detector may be slightly overestimated



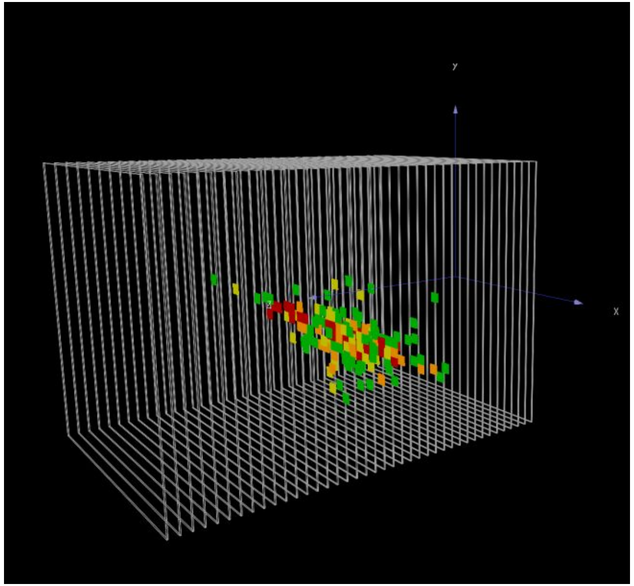


Summary of Detector Requirements

Detector physics goals:

- Signal efficiency
    - Photons shower separation (~ 2 cm)
- Suppression of residual backgrounds
    - Shower shape determination (neutrons)
    - Good time resolution (< 1ns) (neutrons)
- Precise reconstruction of ALP invariant mass
    - Good resolution of photons direction and energy (in the range of the few GeV)
    - Non-resonant photons rejections
- A small detector (r ≤ 30 cm) will also ensure a high signal acceptance

→ Ideal candidate: tracking calorimeter



10.1088/1742-6596/1162/1/012012

Fulfilling All the Requirements: ALICE FoCal

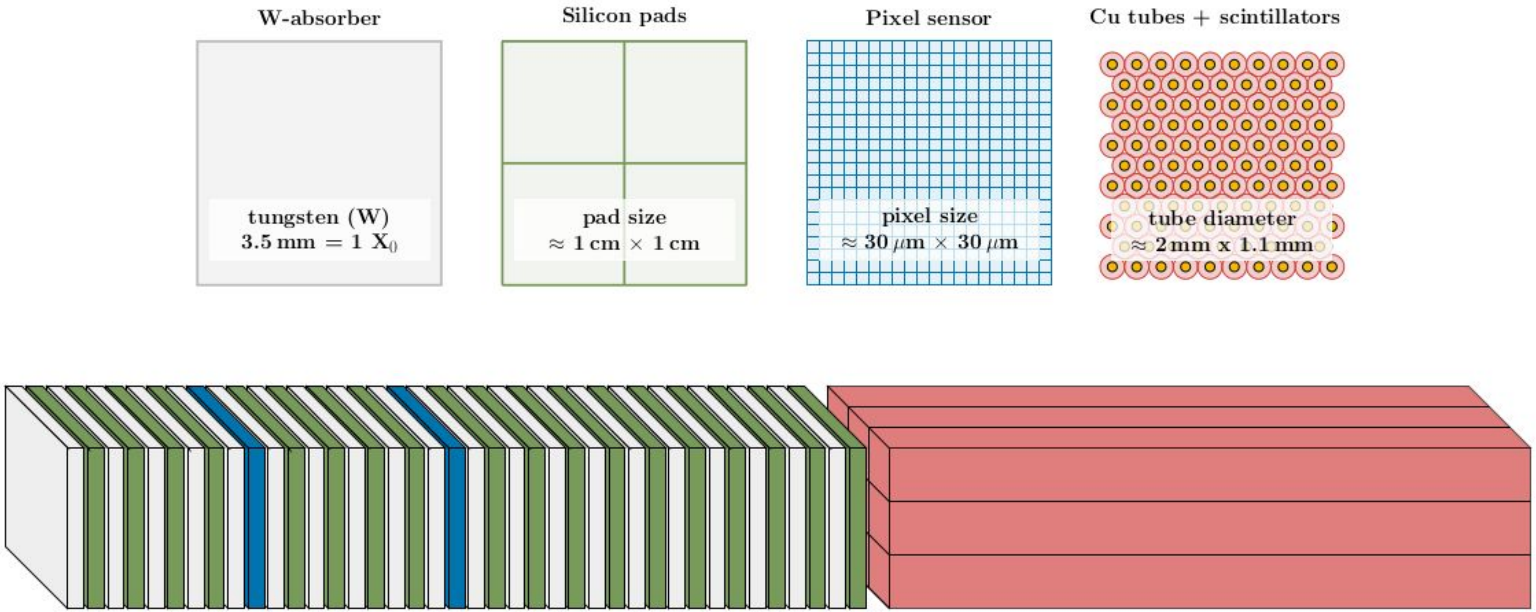
https://doi.org/10.22323/1.414.0317

High-resolution electromagnetic silicon-tungsten calorimeter using both low-granularity silicon pads and high-granularity silicon pixel layers:

- Proposal for ALICE forward calorimeter at HL-LHC
- 20 layers of W-plates, each with a thickness of one radiation length X_0 = 3.5 mm
- Main focus on discriminate single photons from pairs of photons from $\pi^0 \to \gamma\gamma$
    - Great shower resolution, also in case of close-by photons (closer than 5 mm)
    - Thanks to the small Molière radius of tungsten (r_M = 0.93 cm)
- ALPIDE monolithic active pixel sensor
- Transverse size is approximately 90 cm × 90 cm
    - *LHC-like* design: Minimum radial distance from the center is 4.5 cm

Fulfilling All the Requirements: ALICE FoCal

https://doi.org/10.22323/1.414.0317



FoCal-E

- 20 tungsten layers, with thickness of 3.5 mm = 1 X_0
- 18 layers of silicon pad sensors, pad size ≈ 1x1 cm^2
- 2 layers of silicon pixel sensors, pixel size ≈ 30 x 30 μm^2

FoCal-H

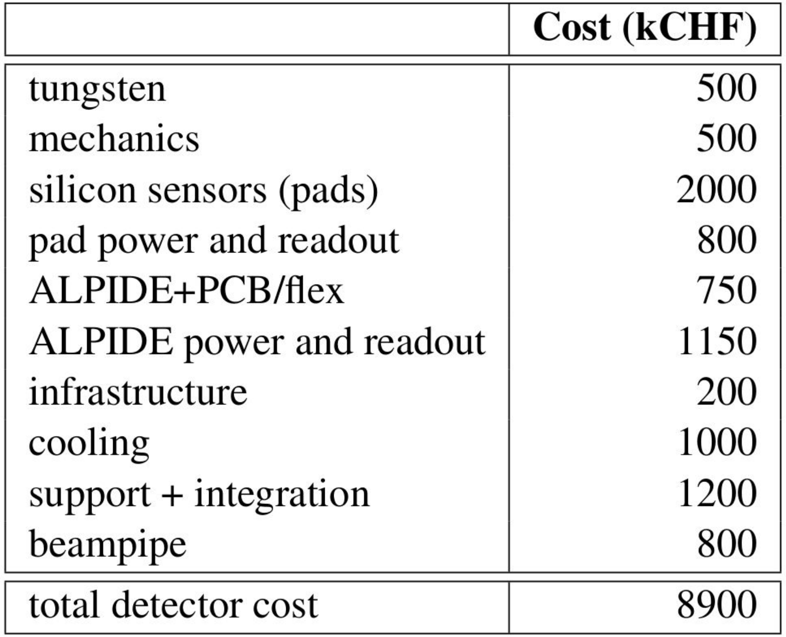
- length of 110 cm
- copper "strawtubes" with 2.0 mm diameter
- scintillating fibre with ≈ 1.1 mm diameter

Fulfilling All the Requirements: ALICE FoCal

https://doi.org/10.22323/1.414.0317

The ALICE Forward Electromagnetic Calorimeter seems to fulfill all our requirements, but:

- It is probably optimized for a different photons energy range
  - We have to check it
- The technology is expensive [LHCC-I-036]
  - The estimated total costs is about 9 MCHF
- Prototypes have been built
  - We can try to see if they are available and suit our needs
- We can also consider a smaller detector, based on the same design and technology



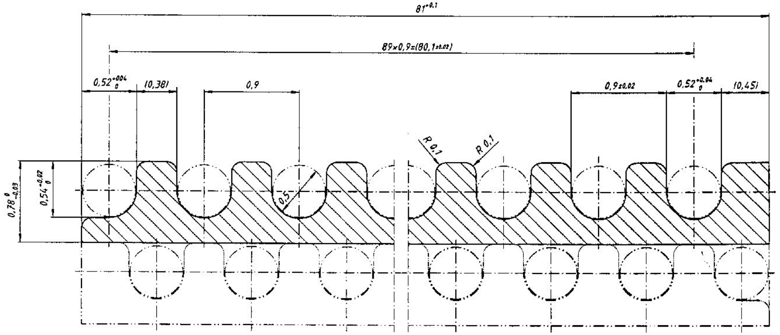
	Cost (kCHF)
tungsten	500
mechanics	500
silicon sensors (pads)	2000
pad power and readout	800
ALPIDE+PCB/flex	750
ALPIDE power and readout	1150
infrastructure	200
cooling	1000
support + integration	1200
beampipe	800
total detector cost	8900

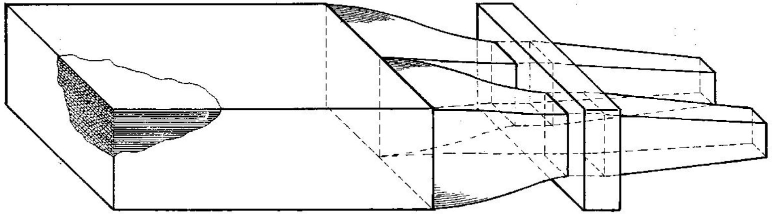
Existing Detector: H1 SpaCal

https://doi.org/10.1016/0168-9002(95)01443-8

High resolution lead/scintillating-fibre calorimeter

- Backward calorimeter used by the H1 experiment at HERA
- Tested on electrons in the energy range 2-60 GeV
- Energy resolution: $\sigma_E/E = 7.1\%/\sqrt{(E/GeV)} \oplus 1.0\%$
- Spatial resolution for impact point at the center of a cell $4.4\ \text{mm}/\sqrt{(E/GeV)} + 1.0\ \text{mm}$
- Time resolution better than 0.4 ns
- Design not optimal for shower-shape discrimination
  - Possibly not the ideal design for neutron rejection



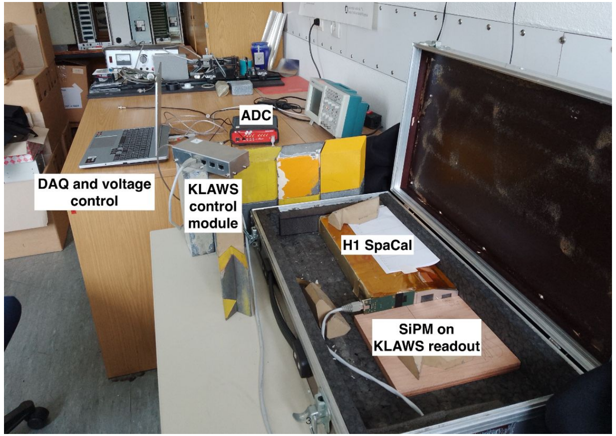


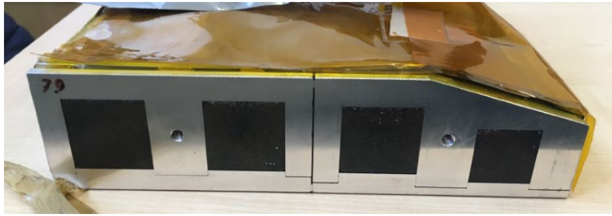
Existing Detector: H1 SpaCal

https://doi.org/10.1016/0168-9002(95)01443-8

One module of the H1 SpaCal is currently tested at KIT to assess the status of the fibres and verify the performances

- New SiPM installed
- Managed to read out a signal from a radioactive source
- The module currently inspected is a spare one, so never irradiated
    - Good to set a performance baseline
    - But we will need irradiated modules to asses the radiation damage



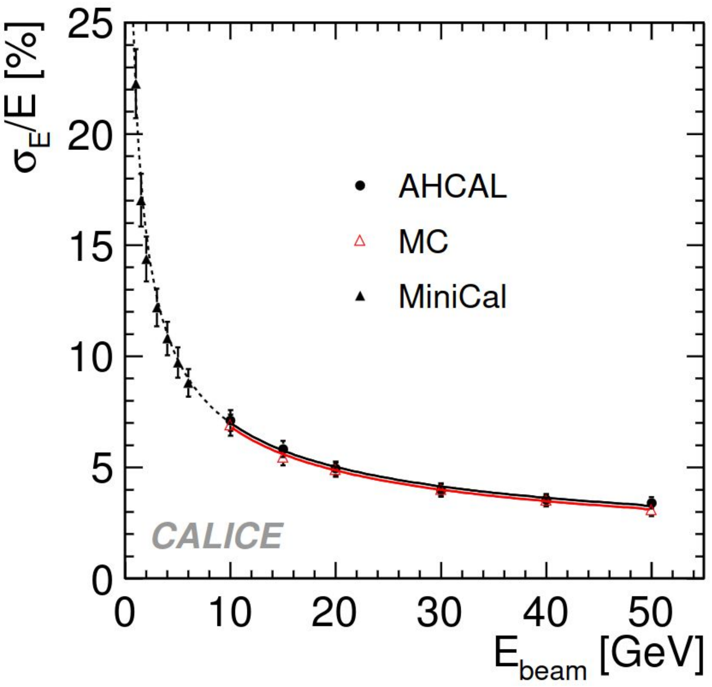


CALICE SiPM-on-tile calorimeter

https://doi.org/10.1088/1742-6596/1162/1/012012
https://doi.org/10.1103/RevModPhys.88.015003

Sampling hadron calorimeter of steel absorber plates and plastic scintillator tiles read out by silicon photomultipliers as active material

- Sampling structure: 1.24 radiation lengths X_0 per layer and effective Molière radius of 2.47 cm
- Active elements: 3 × 3 cm^2 plastic scintillator tiles
- Energy resolution: $\sigma_E/E = 21.9\%/\sqrt{(E/GeV)} \oplus 1.0\%$
    - Tested on positrons in the energy range 1-50 GeV
- Currently tested at Mainz, as a candidate for the SHADOWS experiment

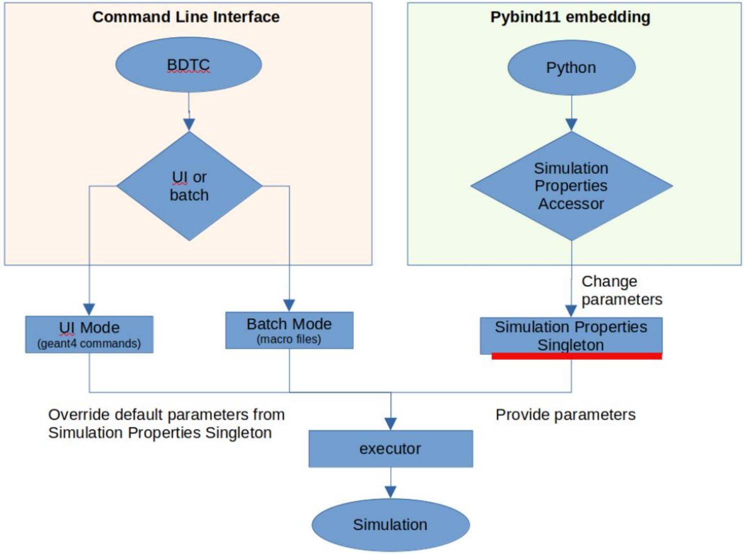


Status of the Simulation Code

At KIT, we are setting up a general-purpose Geant4 simulation framework to deal with different detector layouts

- User-friendly python interface to interact with the C++ backend
- Synergy with batch submission system
- Currently possible to configure sampling calorimeters
  - SpaCal layout implementation in progress
- Inputs can be particle gun or simulated signal events, provided in HEPMC format
  - Plan to include h5 as input format

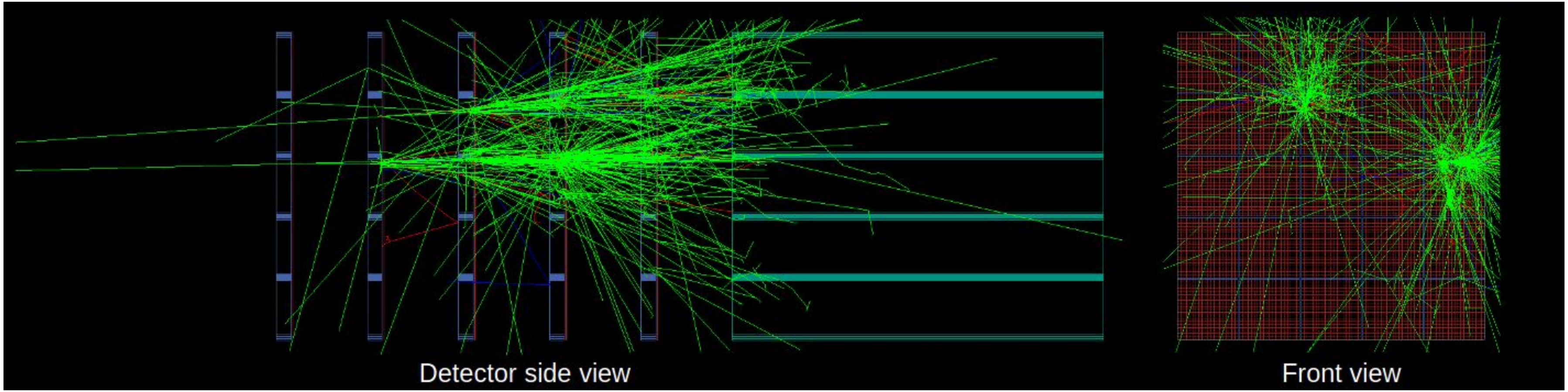
Program execution flowchart



Reconstruction Algorithm

Use a neural network to reconstruct the two photons momenta and the vertex

- Loss: mean squared error between predicted/actual track lines
- Currently testing existing NN architectures ([DeepJetCore](), [GravNet]())



Conclusions

The effort to choose the LUXE-NPOD detector is ramping up:

- Understand what we need in terms of signal efficiency and background rejection
- Considering existing technologies and available detectors or prototypes
- Moving forward with a simulation framework
    - Using input from signal samples
- Starting testing algorithms for events reconstruction
    - Get photons momenta and vertex
    - Reject neutrons

BACK-UP

Laser Properties

Process	Timescale
Compton scattering: $e^-_V \rightarrow e^-_V + \gamma$	$\tau_\gamma = 1/\Gamma_\gamma \sim \mathcal{O}(10)$ fs
Breit-Wheeler pair production: $\gamma \rightarrow e^+_V + e^-_V$	$\tau_{ee} = 1/\Gamma_{ee} \sim \mathcal{O}(10^4 - 10^6)$ fs
Laser pulse duration at LUXE	$t_L \sim \mathcal{O}(10 - 200)$ fs
Time scale of LUXE's 800 nm	$\sim 1/\omega_L \sim 0.4$ fs

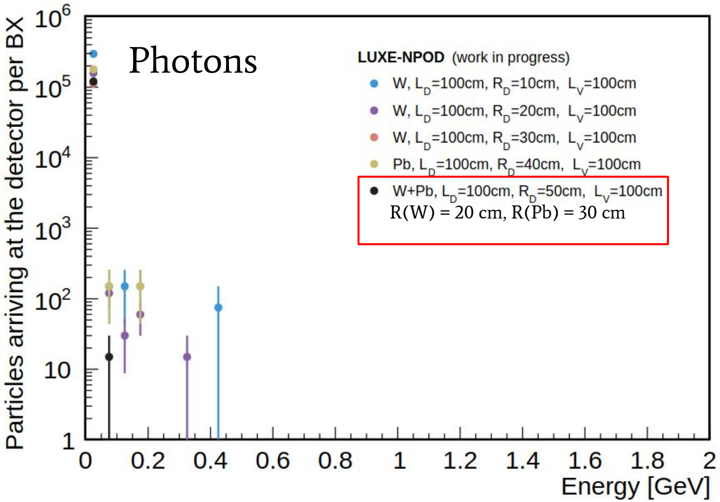
$$1/\omega_L << \tau_\gamma \lesssim t_L << \tau_{ee}$$

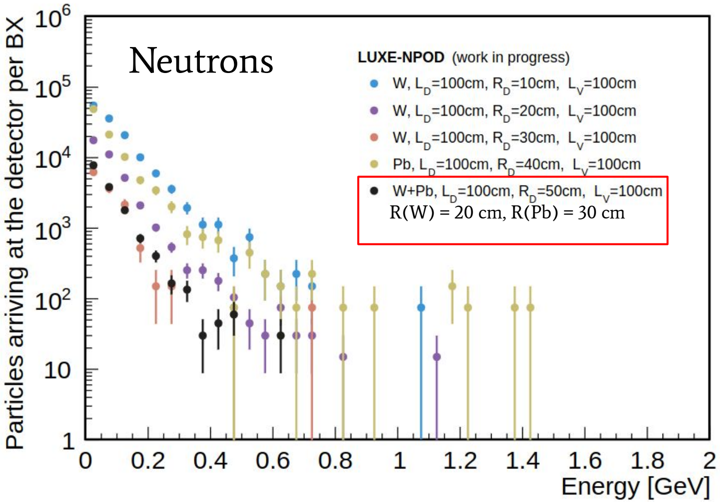
- Short τ_γ = plenty of time for electrons to produce photons → electrons see the laser as a thick target
- Long τ_{ee} = long timescale for a photon to produce electron pairs → photons see the laser as transparent

Expected Background Reaching the Detector

We expect some neutrons reaching the detector

- A detector able to distinguish neutrons from photons showers is needed to reject “fake” signals





Reconstruction Algorithm: Current Status

Current implementation does not properly reproduce the inputs:

- Mean values are ok, spread is underestimated. A few tests needed to fix this:
    - Change learning rate, node counts, and batch sizes
    - Include uncertainties in the loss function

$$d_i = \frac{\sum(\vec{p_i} - \vec{t})^2}{\sigma^2} + \ln(\sigma^2)$$

- Next steps:
    - Allow an arbitrary number of photons using object condensation
    - Classify into photons and neutrons, using shower shape information