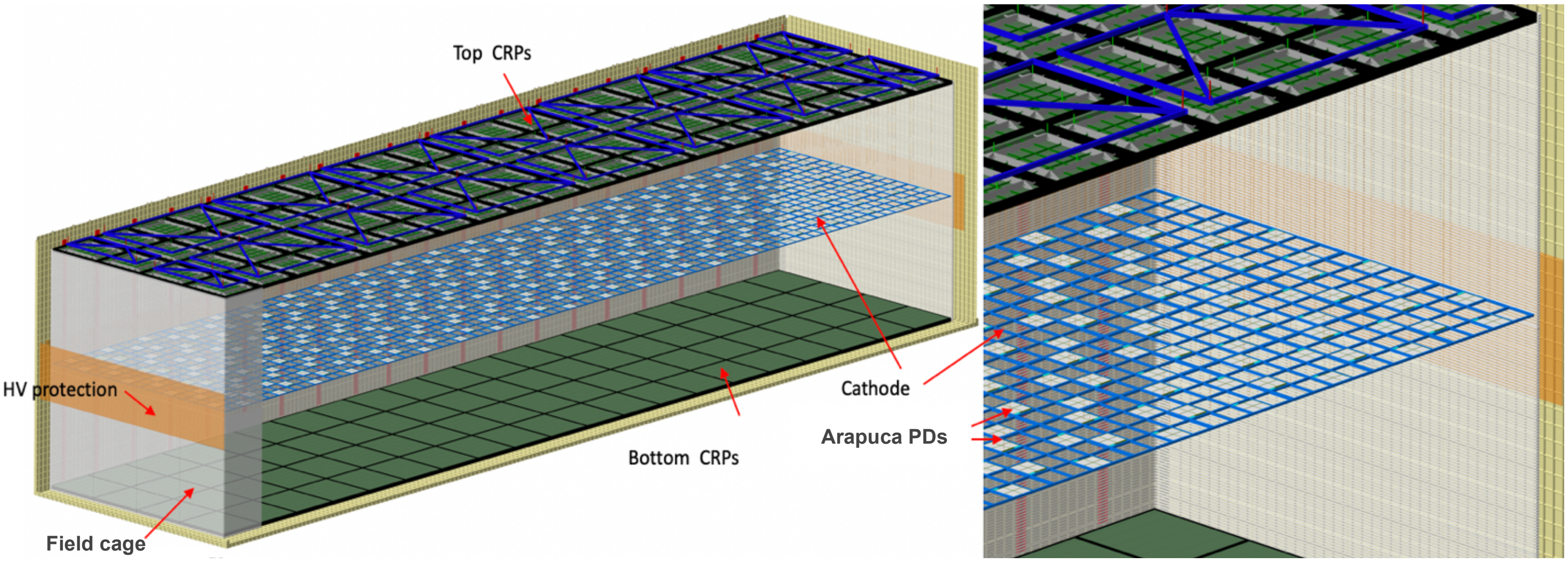
Vertical Drift Photon Detection System Simulation

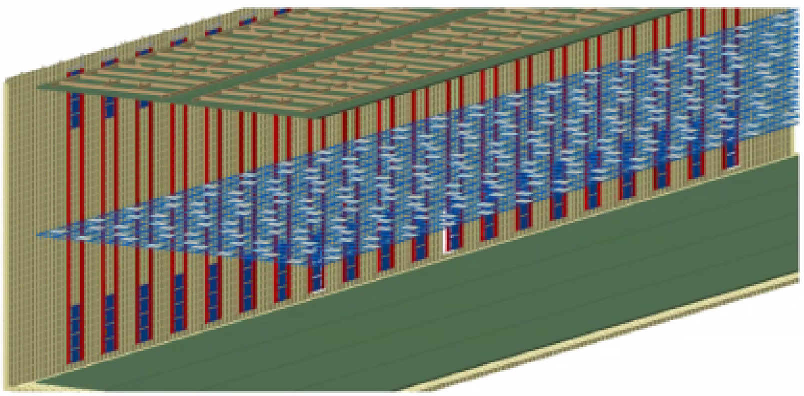


Laura Paulucci
(UFABC)

10 May 2021

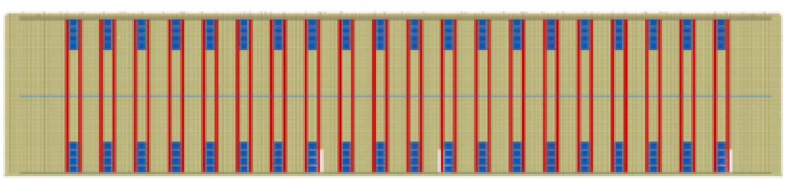
Vertical drift single phase PDS

Reference Design (Cathode & Membrane mounted PDS ⊕ Xe doping)

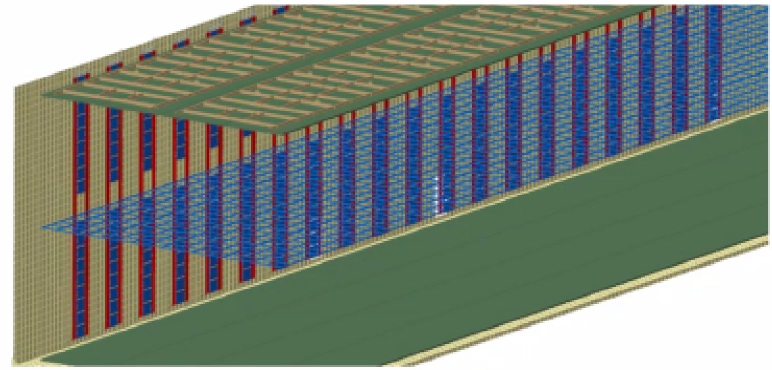


4 pi layout :

- Full trigger capabilities down to 10 MeV
- Energy, Position and T0
- xArapucas 60x60 on the cathode, 115 mq, analog readout
- xArapucas 60x60 on the cryo membrane, ~3m from Cathode

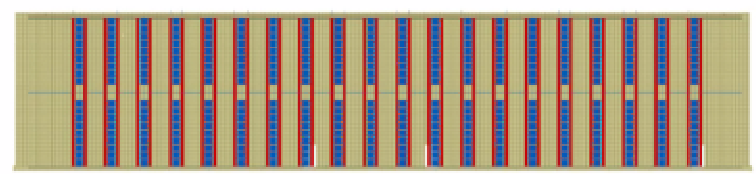


Backup Design (All-Membrane mounted PDS ⊕ Xe doping)



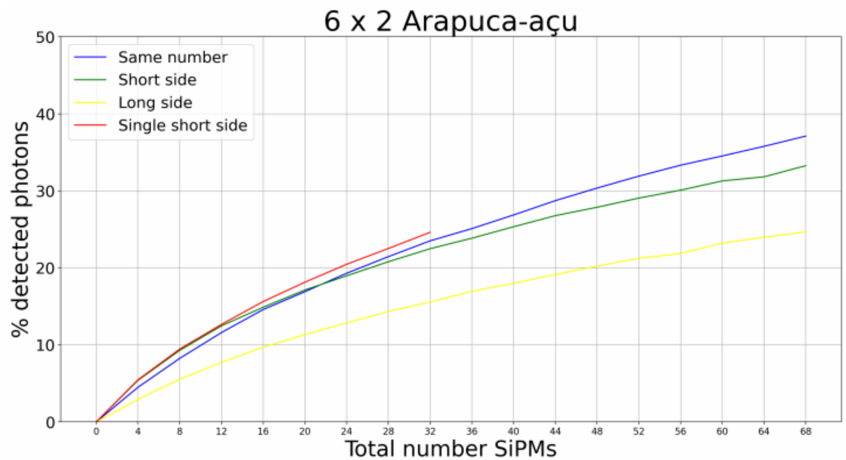
Minimal layout:

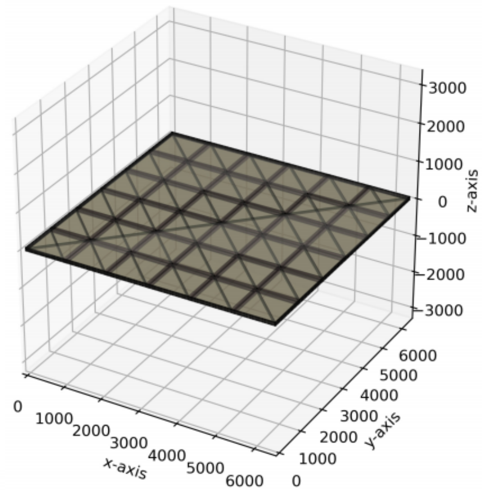
- Trigger via charge TPC readout down to 10 MeV
- T0, (Energy)
- xArapucas 60x60 on the cryo membrane, 20 columns, each column 18 xArapucas, SPHD readout



X-ARAPUCA Simulation

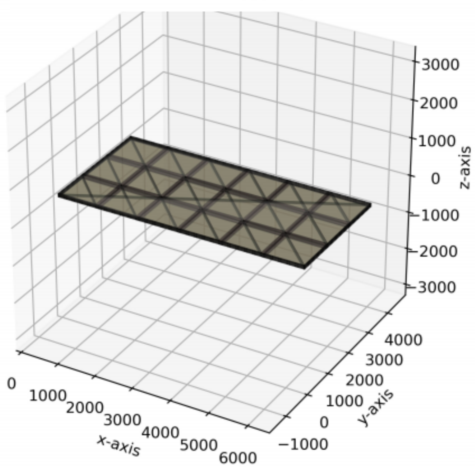
- Simulation of the photon detector →improve collection efficiency
- Dependence on number and position of SiPMs and other geometrical effects





Efficiency: 36,51%

Same SiPM density on sides



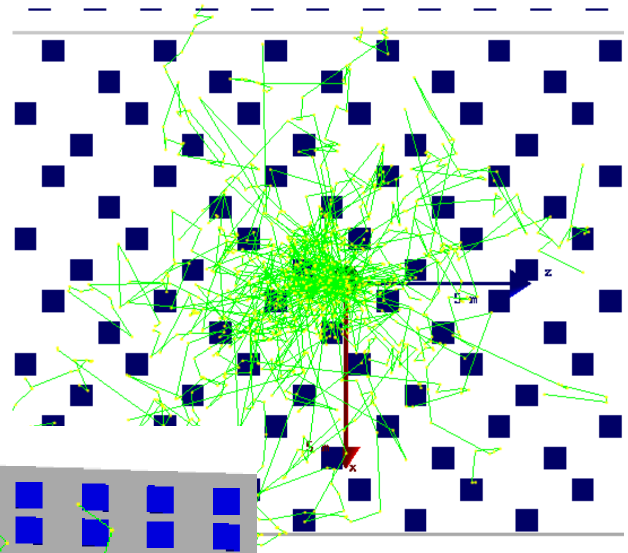
Efficiency: 40.5%

Reference Design Simulation

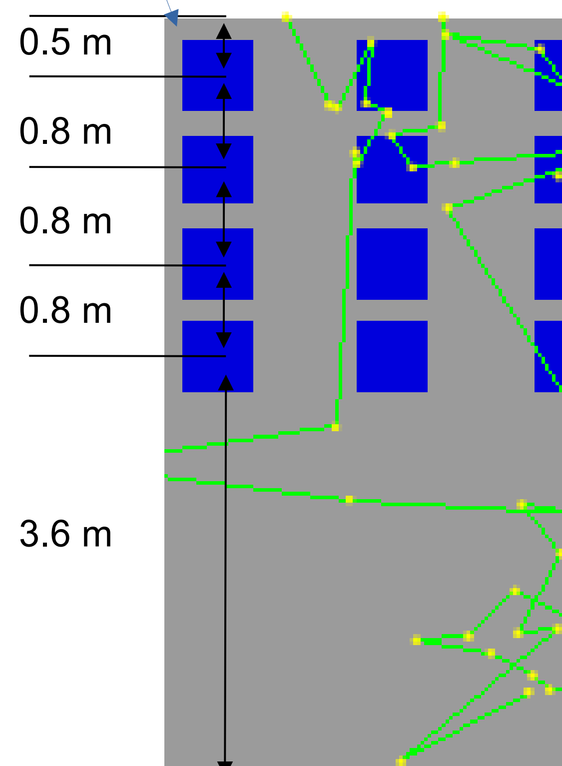
- Geant4
- Semi-transparent FC: T=70% and Cathode: T = 80%
- Anode R=20% (Xe)
- Abs length = 20 m
- λ_{Ar} = 99.9 cm, λ_{Xe} = 8.5 m

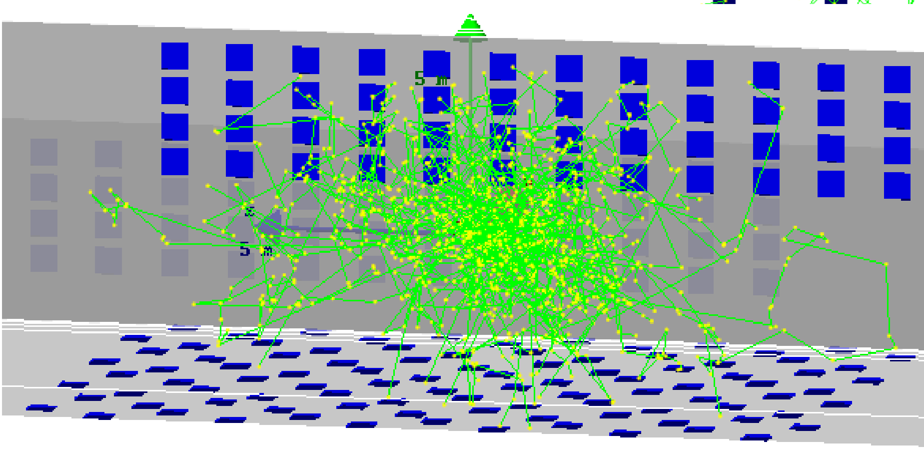
PDs 60 cm behind FC

Top view: Arapucas over cathode



Side view: Arapucas on membrane
20 columns per side





Top VD volume

Rayleigh Scattering in LAr

10 *M. Antonello et al. / Nuclear Instruments and Methods in Physics Research A ▮ (▮▮▮▮) ▮▮▮–▮▮▮*

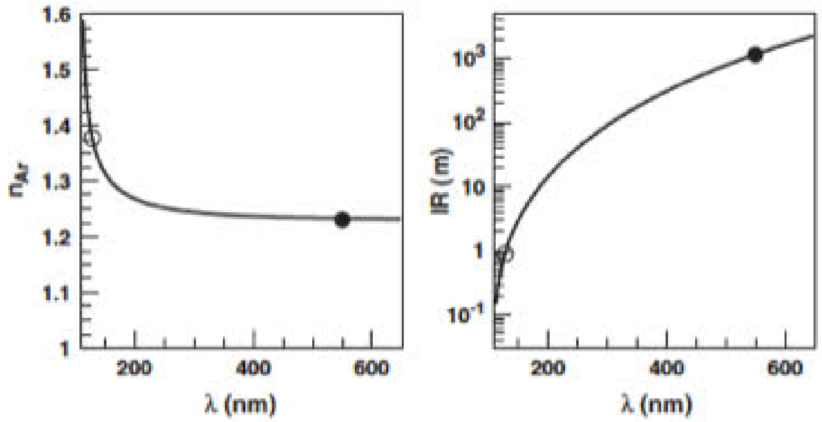
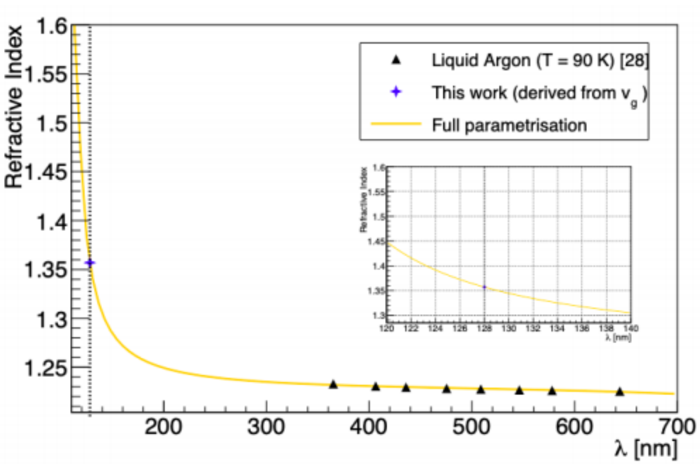


Fig. 8. [Left] Refractive index in LAr as a function of the photon wavelength [8]. Experimental measurements: $n_{Ar} = 1.22$ at 550 nm (full dot) and $n_{Ar} = 1.38$ at 128 nm (open dot). [Right] Rayleigh scattering length in LAr ($\ell_R(\lambda)$) as a function of the photon wavelength [9]. Full and open dots refer to 550 and 128 nm, respectively.

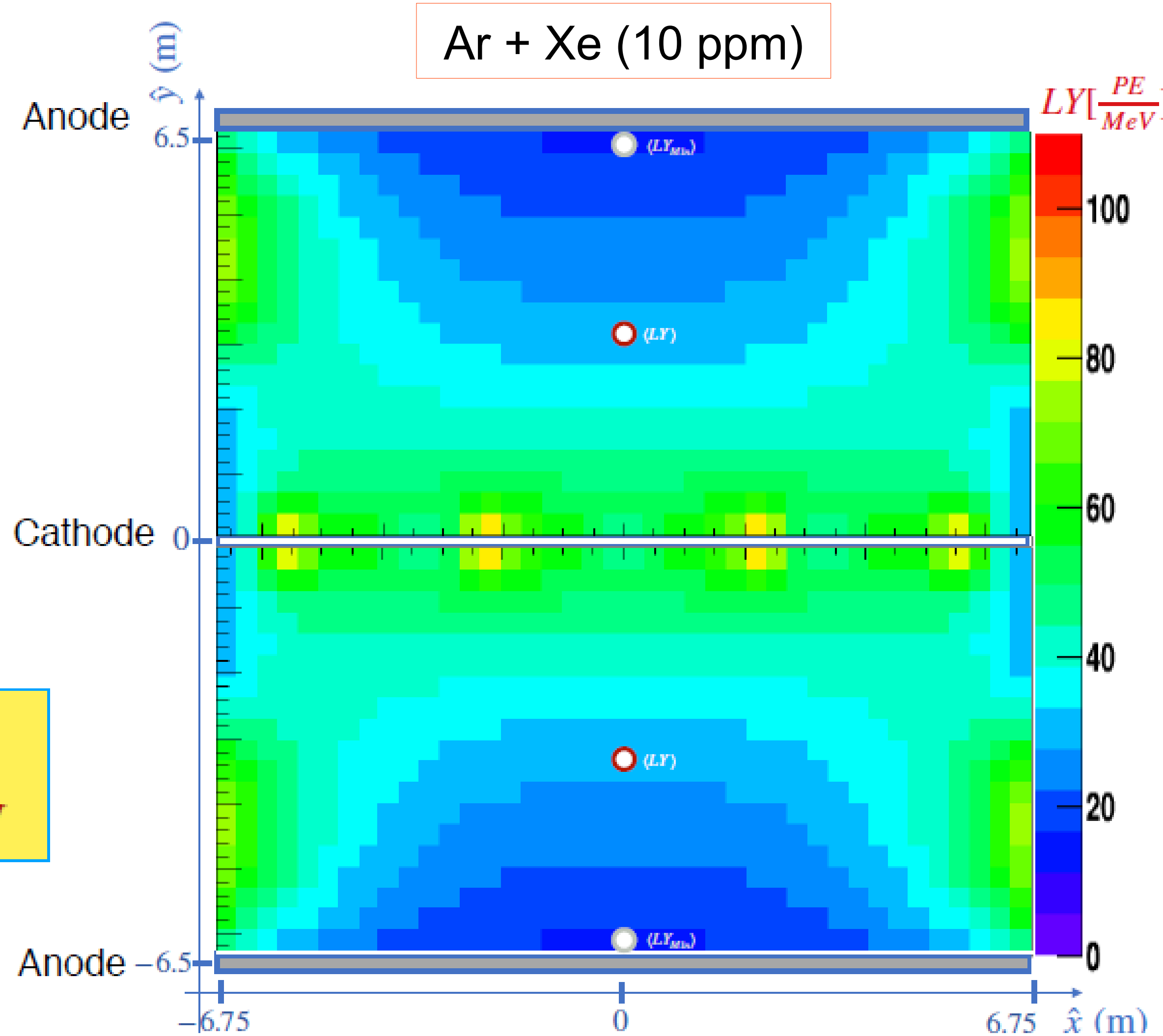
M. Antonello et. al., NIMA, Volume 516, Issues 2–3, 11 January 2004, Pages 348-363



Light Propagation in Liquid Argon, M.Babicz, S. Bordoni, A. Fava, U. Kose, M. Nessi, F. Pietropaolo, G.L. Raselli, F. Resnati, M.Rossella, P.Sala, F. Stocker, A. Zani, arXiv:2002.09346

PDS Reference Design: Light Yield Map

- 24000 photons per MeV of energy deposited
  - 70% for Xe
  - 30% for Ar
- 3% detection efficiency



○ $\langle LY \rangle = 38$ PE/MeV

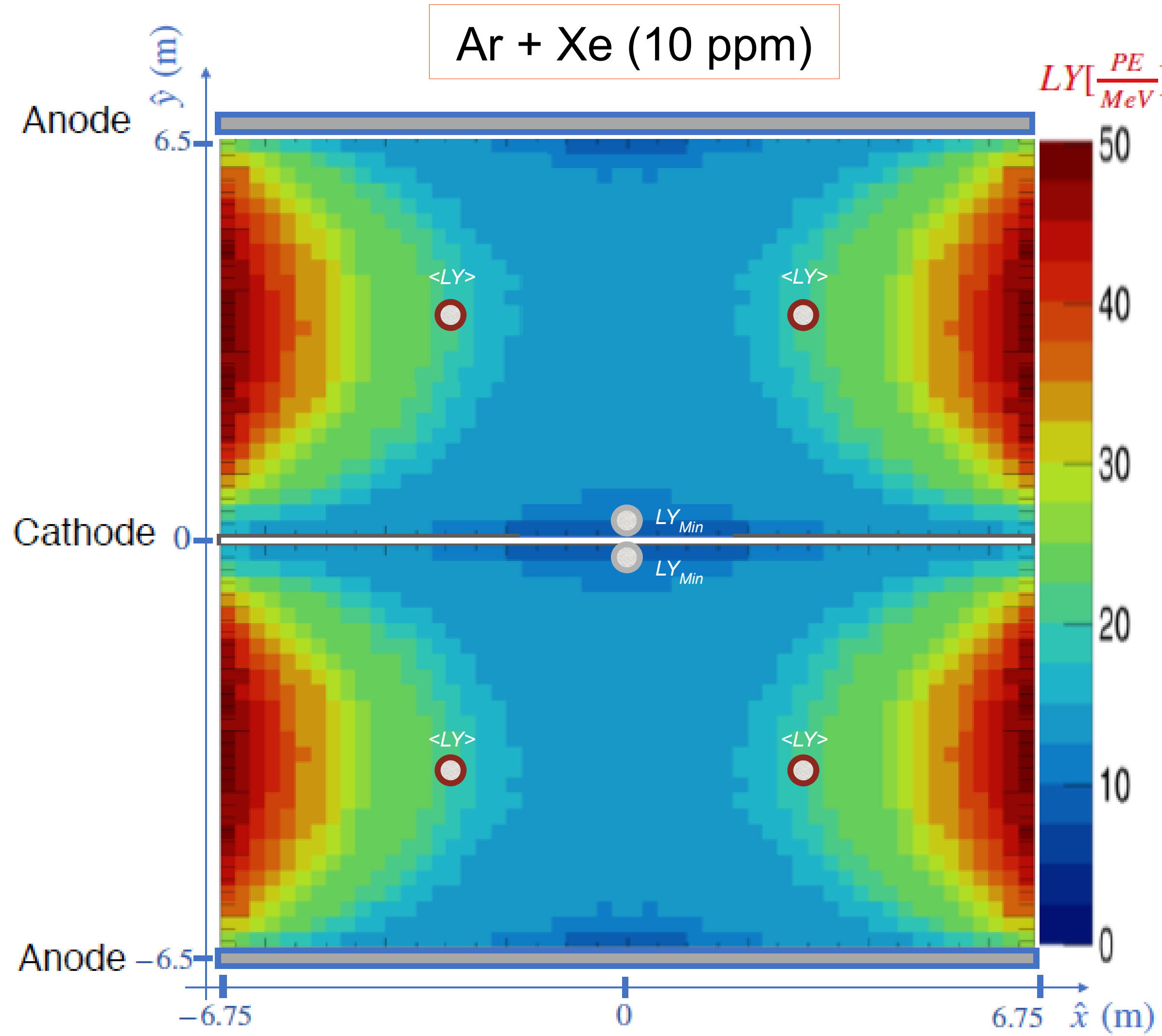
○ $LY_{Min} = 16$ PE/MeV

PDS Backup Design: Light Yield Map

- Fluka
- 24000 ph/MeV
  - 70% for Xe
  - 30% for Ar
- 3.5% detection efficiency
- λ_{Ar} = 90 cm, λ_{Xe} = 7 m
- FC structure

$\langle LY \rangle =$ 21.3 PE/MeV

$\langle LY_{Min} \rangle =$ 7.7 PE/MeV



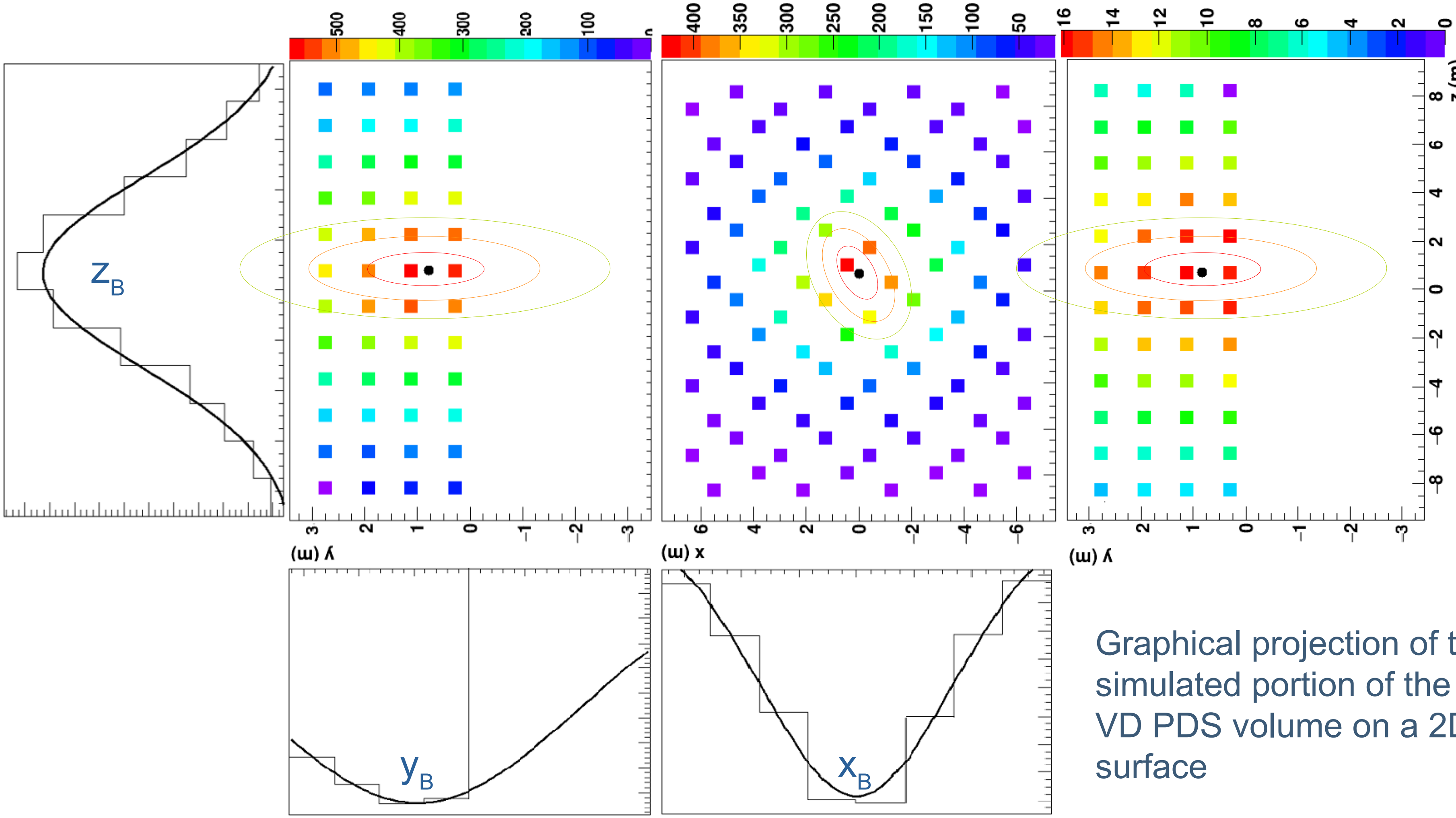
HD Single Phase PDS Requirements

Label	Description	Specification (Goal)	Rationale	Validation
SP-FD-3	Light yield	$>$ 20 PE/MeV (avg), $>$ 0.5 PE/MeV (min)	Gives PDS energy resolution comparable to that of the TPC for 5-7 MeV SN νs, and allows tagging of $> 99\,\%$ of nucleon decay backgrounds with light at all points in detector.	Supernova and nucleon decay events in the FD with full simulation and reconstruction.
SP-FD-4	Time resolution	$< 1\,\mu s$ ($< 100\,ns$)	Enables 1 mm position resolution for 10 MeV SNB candidate events for instantaneous rate $< 1\,m^{-3}ms^{-1}$.	
SP-FD-15	LAr nitrogen contamination	$< 25\,ppm$	Maintain 0.5 PE/MeV PDS sensitivity required for triggering proton decay near cathode.	In situ measurement
SP-PDS-2	Spatial localization in y-z plane	$< 2.5\,m$	Enables accurate matching of PD and TPC signals.	SNB neutrino and NDK simulation in the FD

- Current taken as guidelines

Position Resolution in the Reference Design

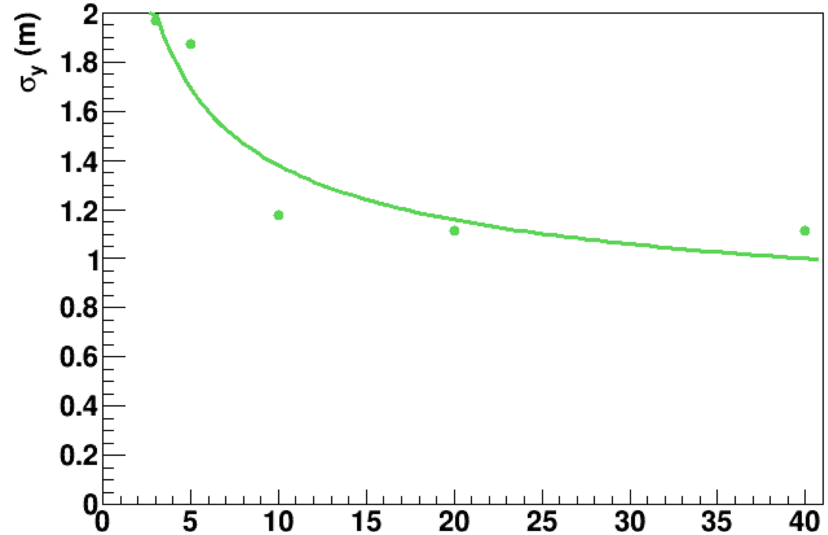
- From barycenter determination

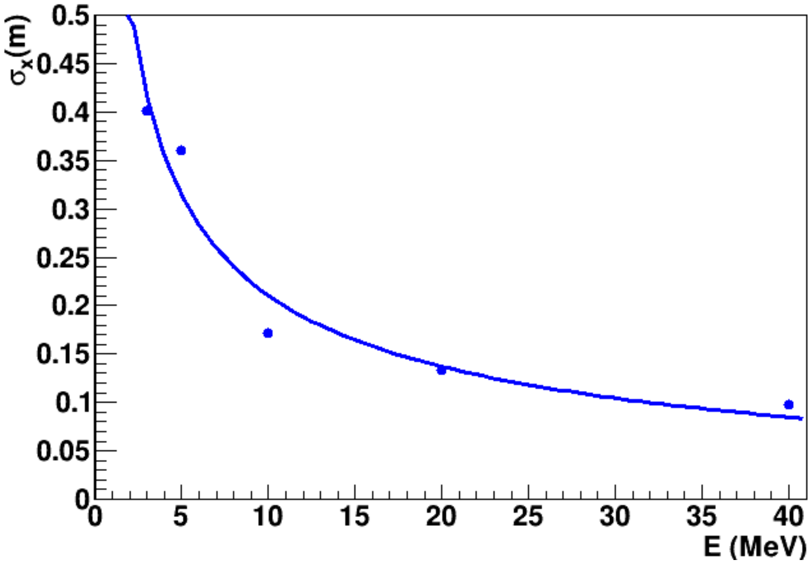


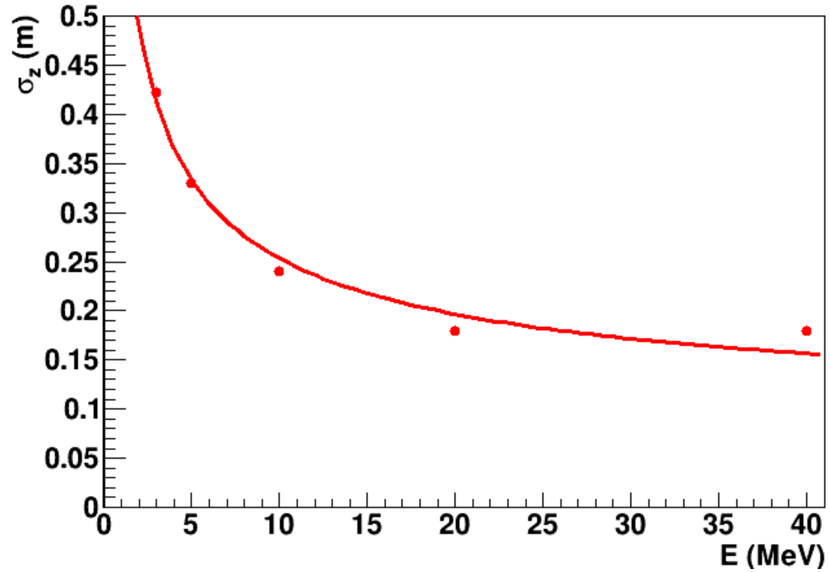
Graphical projection of the simulated portion of the VD PDS volume on a 2D surface

Position Resolution in the Reference Design

- Resolution propto 1/sqrt(E)
- Good position resolution in x and z
- In y: less PD tiles
- Expect improvements with timing information

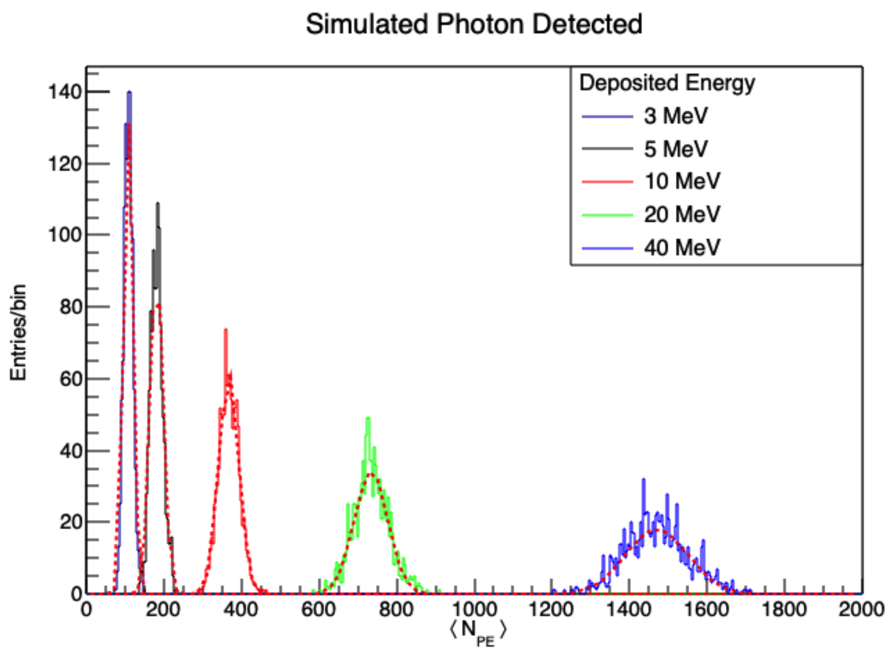


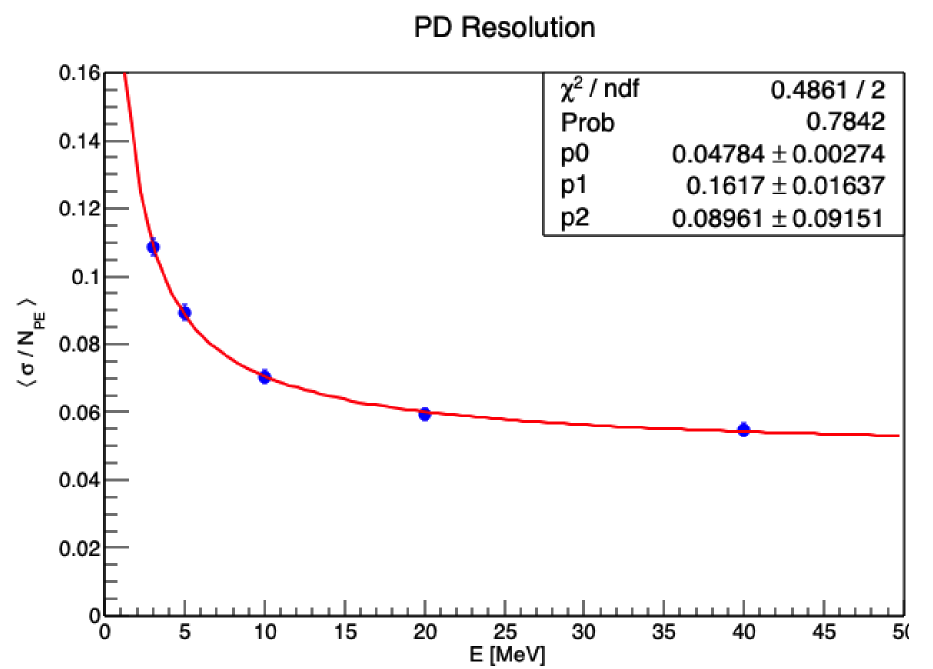




Energy Resolution in the Reference Design

- Point-like source at the center of top volume
  - Uncertainty on energy calibration (p0)
  - Statistical fluctuation (p1) on the number of detected PEs
  - Noise term (p2)



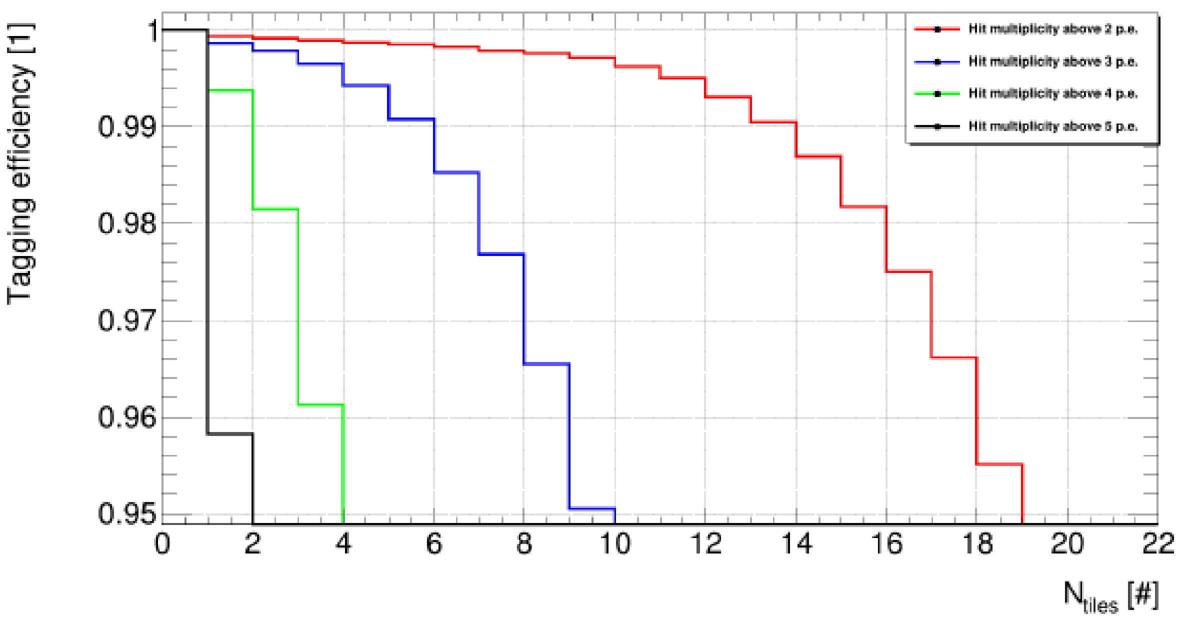


Trigger with the PDS: Backup Design

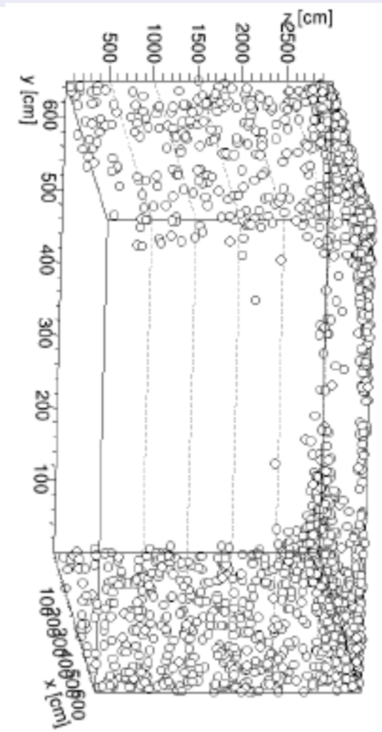
- 10 MeV events
  + ^{39}Ar background (10^7 Bq)

(N_{PE}, M_{Tile}) – Majority trigger condition

- Targeting overall 99 % tagging efficiency, two possible tagging combinations can be used
  - $(M_T, N_{pe}) = (13{,}2)$ - much more background robust, requires detectability of 2 p.e. signal with tiles
  - $(M_T, N_{pe}) = (5{,}3)$ - less background robust, easier to detect



For 5 MeV events, 90% tagging efficiency is achievable

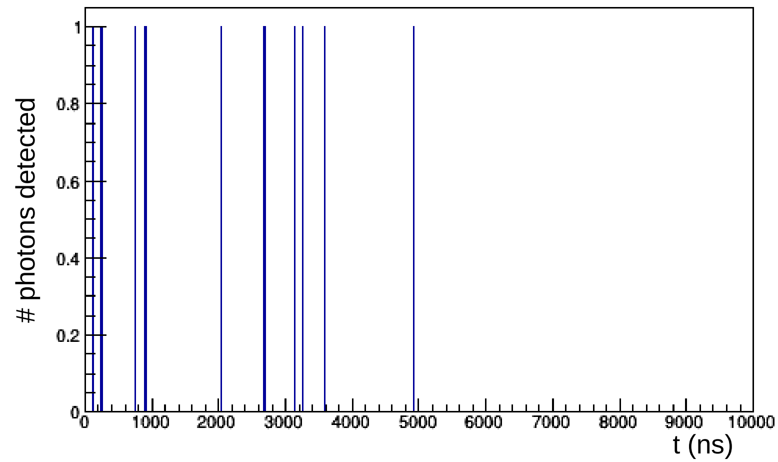


Position of untagged events

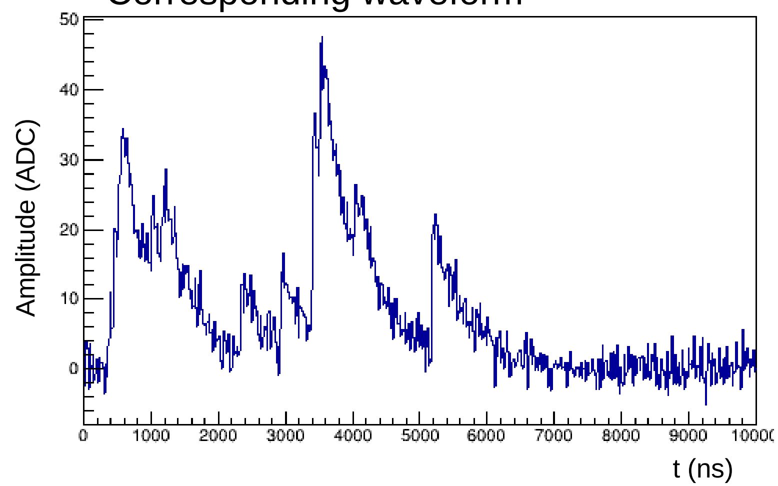
Time Information in the Reference Design

- Optical waveforms taking into account
  - Emission time (Ar and Xe)
  - Propagation time
  - X-ARAPUCA QE
  - X-ARAPUCA shifters
  - SiPM (single PE profile, crosstalk...)
- Detector performance studies
  - Timing resolution
  - Digitizer requirements (dynamic range, sampling frequency...)
  - Improving position resolution

Photon time of arrival for a given PD



Corresponding waveform



PDS Simulation Group

- Top priorities:
  - LArSoft simulation available
  - PDS Requirements
    - Comparison w/ Horiz. Drift (Light Yield, energy and timing resolutions and direct comparison for VD-Reference option and backup option)
    - Digitizer requirements (dynamic range, sampling freq., bandwidth)
  - PD trigger (and prompt background rejection) strategy
  - Goals for SNe and p-decay detection w/ PD

Summary:

- Current simulation efforts:
  - Tool for improving PDS performance
    - X-ARAPUCA
    - Anode reflection
    - PDs distribution...
  - Infrastructure for determination of VD PDS requirements
  - Infrastructure for physics studies
- Preliminary information on
  - Position and energy resolution
  - Trigger capabilities

BACKUP

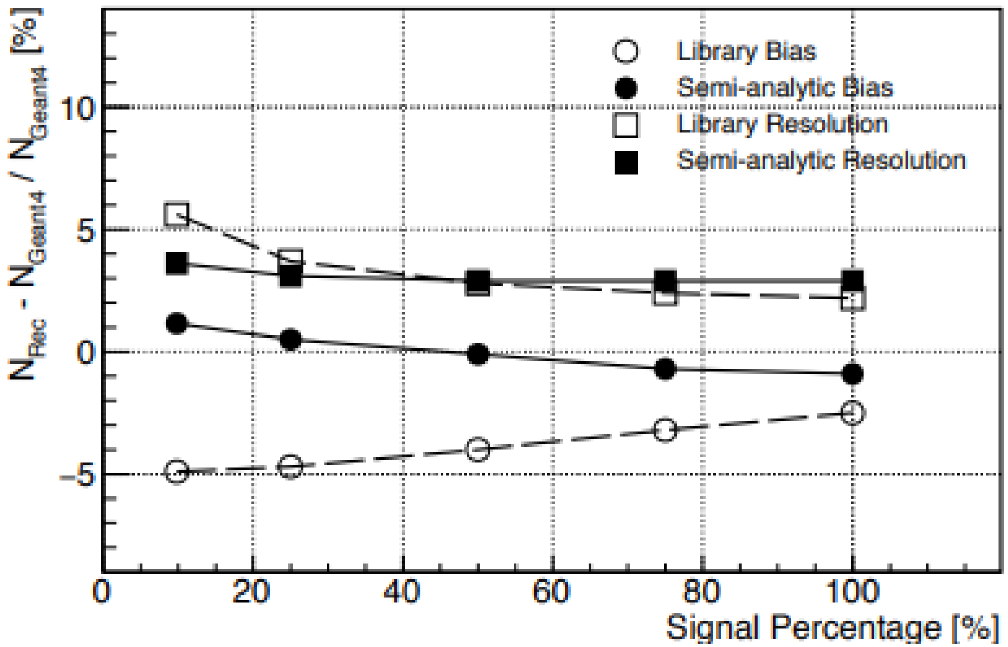
Some References for the X-Arapuca

- A. Machado, E. Segreto, D. Warner, A. Fauth, B. Gelli, R. Máximo et al.,The X-ARAPUCA: an improvement of the ARAPUCA device, J. Instrum. 13 (apr, 2018) C04026.
- L. Paulucci, F. Marinho, A. Machado and E. Segreto, A complete simulation of the X-ARAPUCA device for detection of scintillation photons, Journal of Instrumentation 15 (jan, 2020) C01047.
- C. Brizzolari, S. Brovelli, F. Bruni, P. Carniti, C. M. Cattadori, A. Falcone et al., Enhancement of the X-Arapuca photon detection device for the DUNE experiment, arXiv:2104.07548, 2021.

Comparison of fast light simulation models

- Semi-analytical model versus Optical Library in **SBND**

For the XARAPUCAS & Direct/VUV component

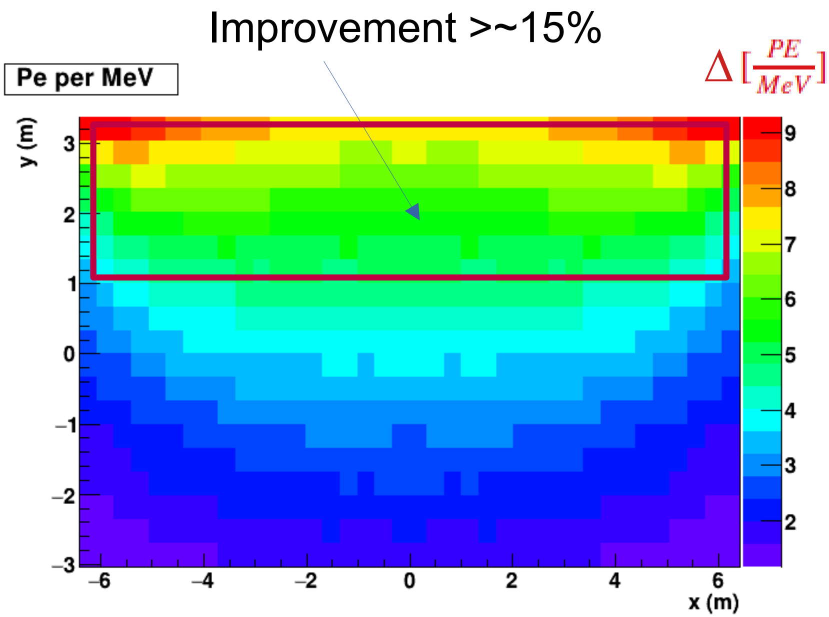


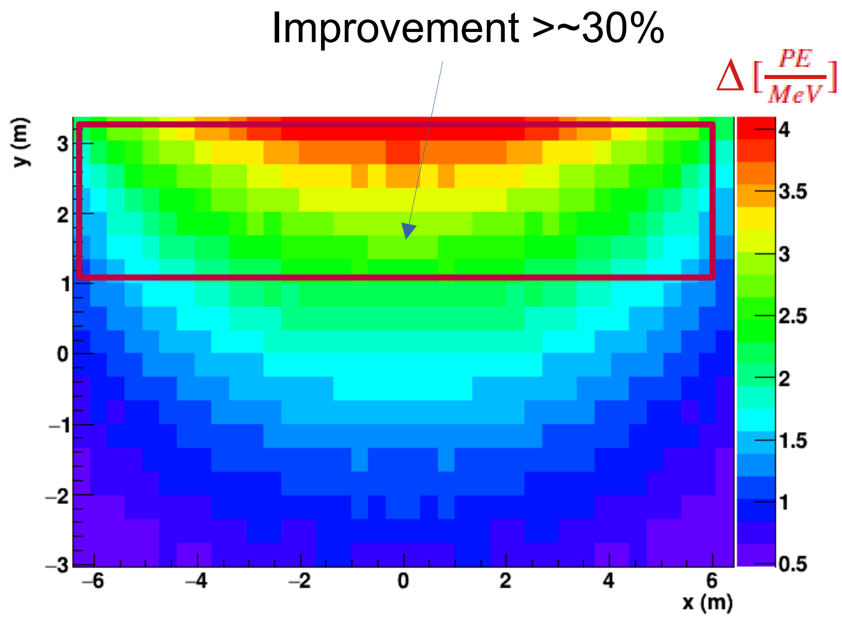
Optical library was created with ~1.6M scintillation points x 0.5M photons-each —> 7.9 x 10^{11} photons —> x10 more photons than in the Semi-Analytic model —> Size of OpLibrary **1.2 GB**

- In ProtoDUNE, slightly bigger voxels → problems with **memory** consumption during simulation
- To have an op. library for the DUNE FD volume is not viable

Anode Reflection

- Impact of improving the anode reflectivity from 25% to 50%: Impact on LY uniformity



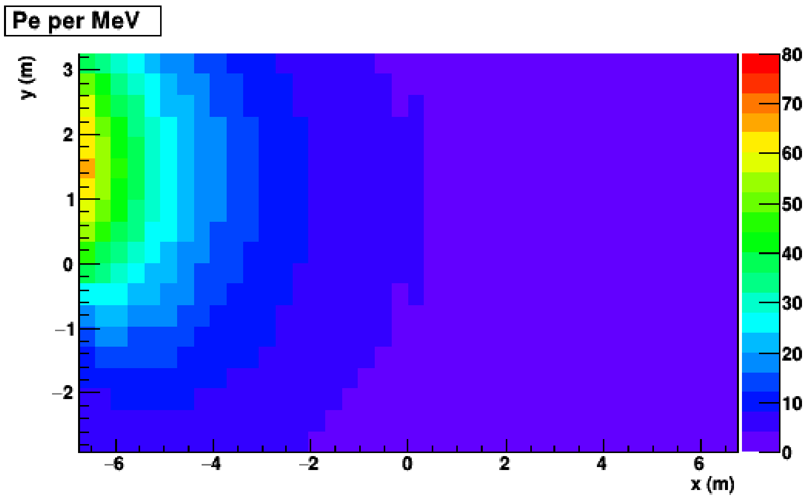


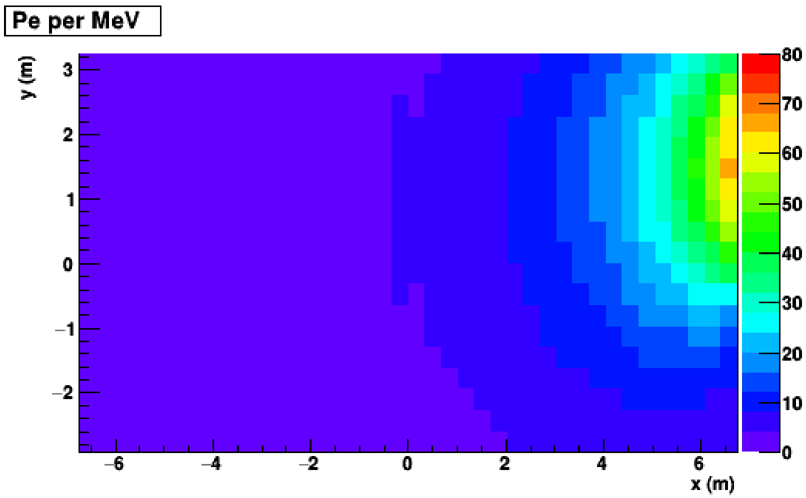
Former 4π design: Average LY up by ~6.6%

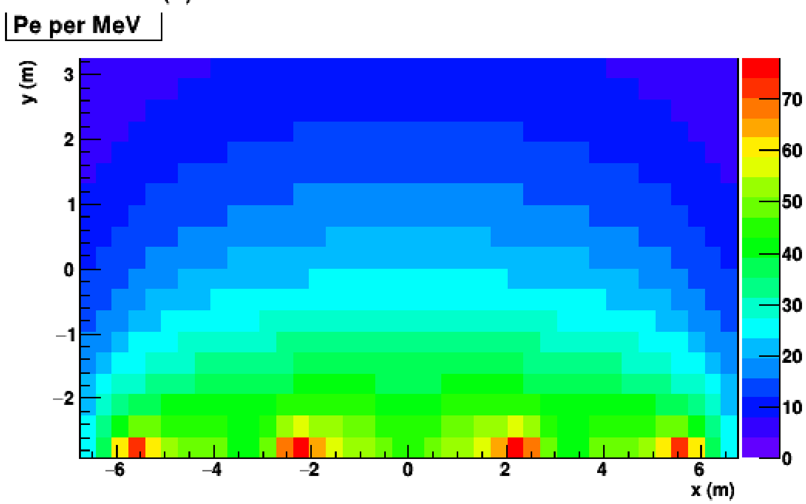
Cathode only: Average LY up by ~6%

Reference Design: Light Yield Maps

- LY map per detection plane

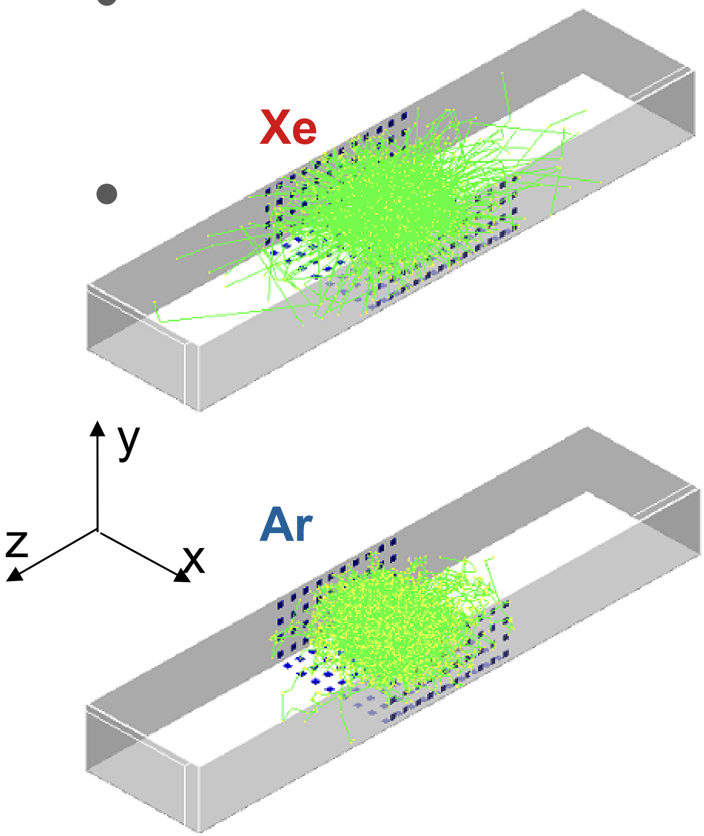


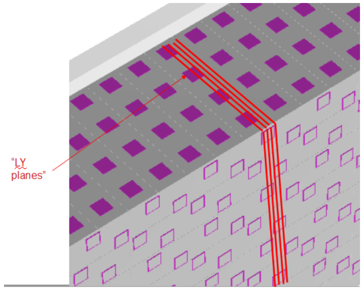


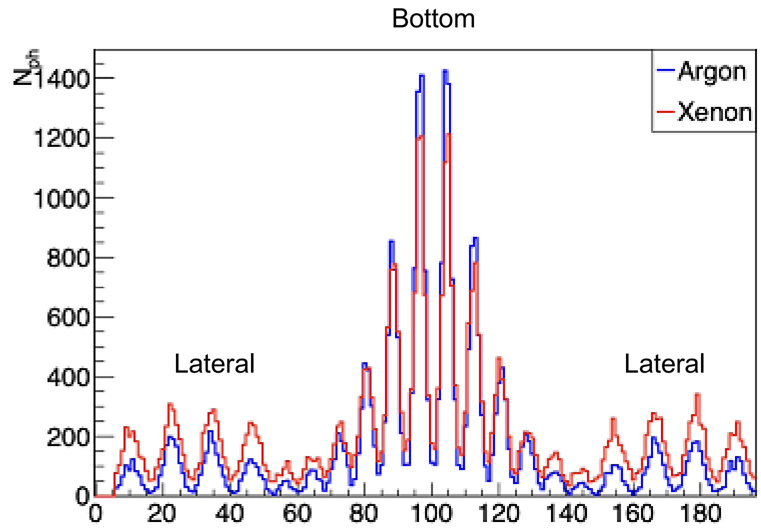


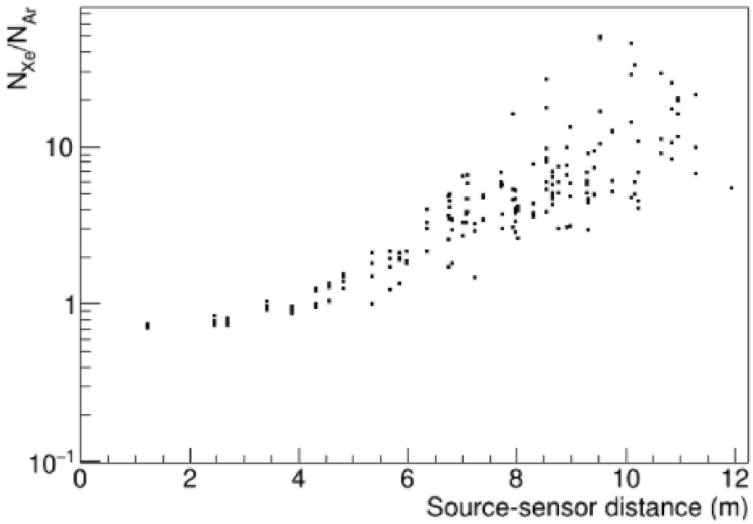
Reference Design Simulation

192 tiles in ~1/6 VDrift volume





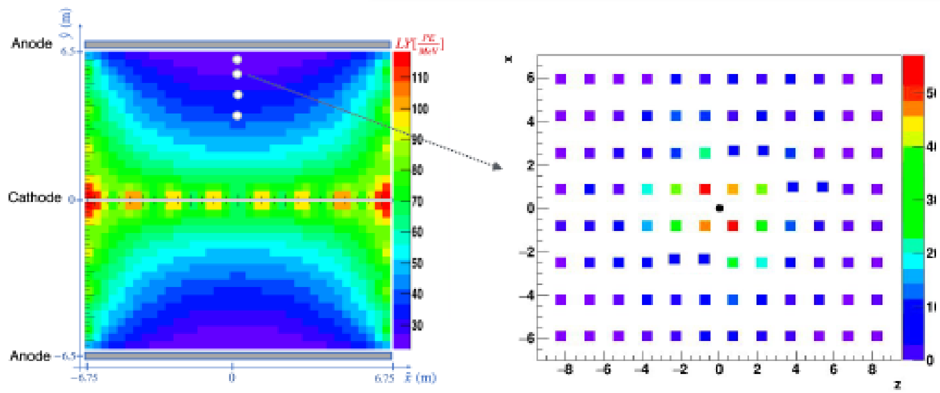


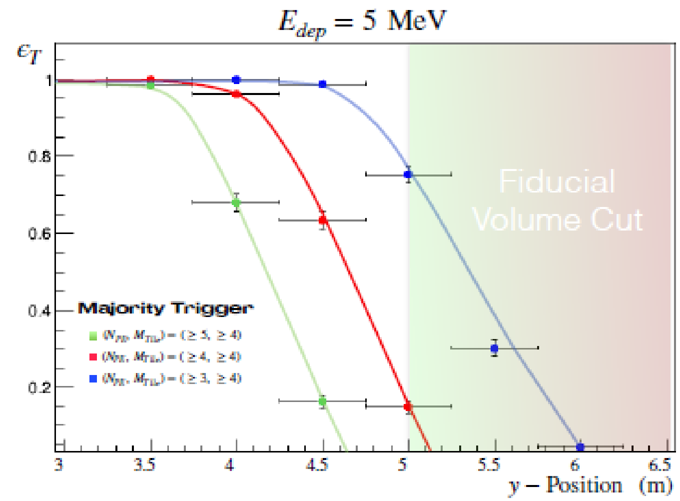


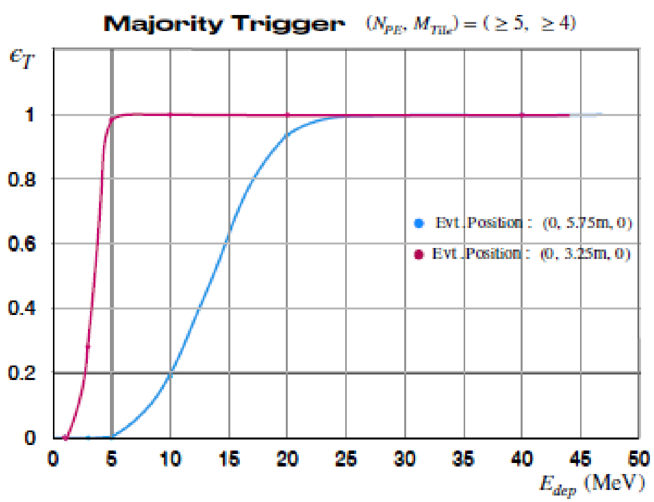
Trigger with the PDS: Early 4π design

- Events at lower LY region, no backgrounds

(N_{PE}, M_{Tile})– Majority Trigger condition

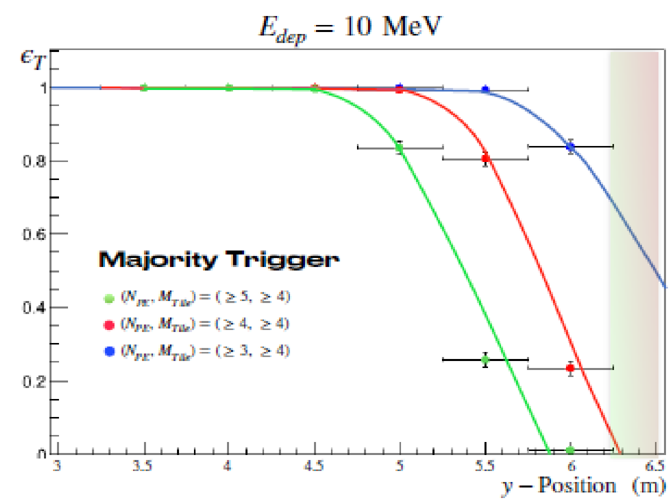






Relaxing (N,M)-Majority requirements enhance trigger efficiency, but also increase rate of false-positive triggers

Trigger Efficiency $\geq 99\,\%$ for interactions with $E_{dep} \geq 5$ MeV expected in 100 % of a 10 kT Fiducial Volume



Preliminary Dynamic Range Studies

- 6 GeV e- shower @ 0.5m from cathode
- Pure LAr, λabsorption = 50m