Study of the energy response and position reconstruction with ^{22}Na source in DEAP-3600

Ludovico Luzzi (CIEMAT)
on behalf of DEAP-3600 Collaboration

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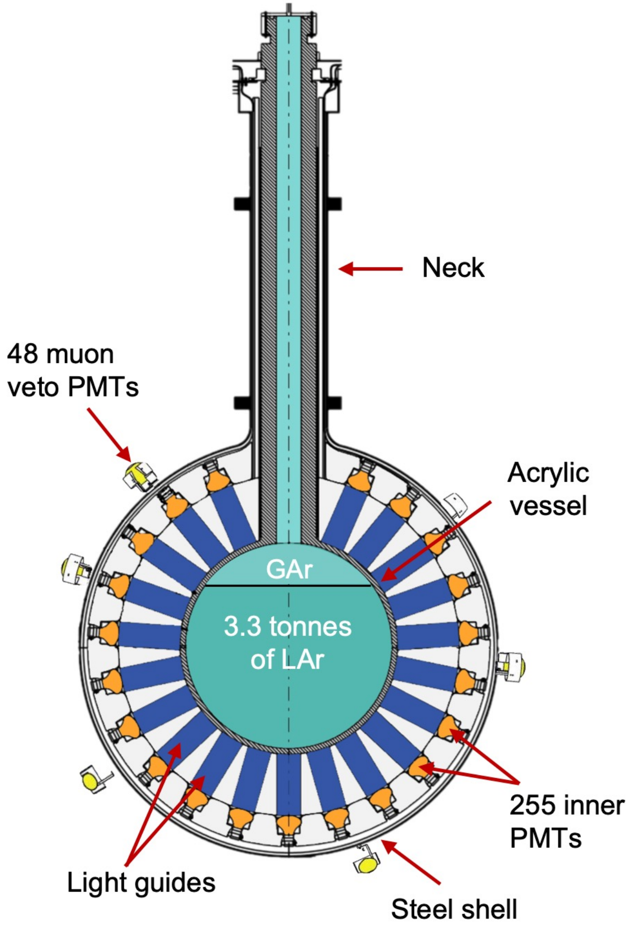
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CIEMAT física de partículas

The Detector

- Dark matter Experiment using Argon Pulse shape discrimination – 3600 (proposed mass of liquid argon in kg)
- Single-phase dark matter direct detection experiment at SNOLAB (6000 m.w.e.)
- 3300 kg of atmospheric argon in a high radio-purity acrylic vessel (AV)



- Argon scintillation produced light detected with 255 PMTs
- TPB wavelength shifter to convert VUV light into visible photons
- Extremely radiopure acrylic light guides transport visible photons to the PMTs
- Muon veto made of 48 outward looking PMTs in a 300 tonnes ultra-pure water tank

WIMP Search

10.1103/PhysRevD.100.022004

- First WIMP analysis (2019, 231-day exposure)

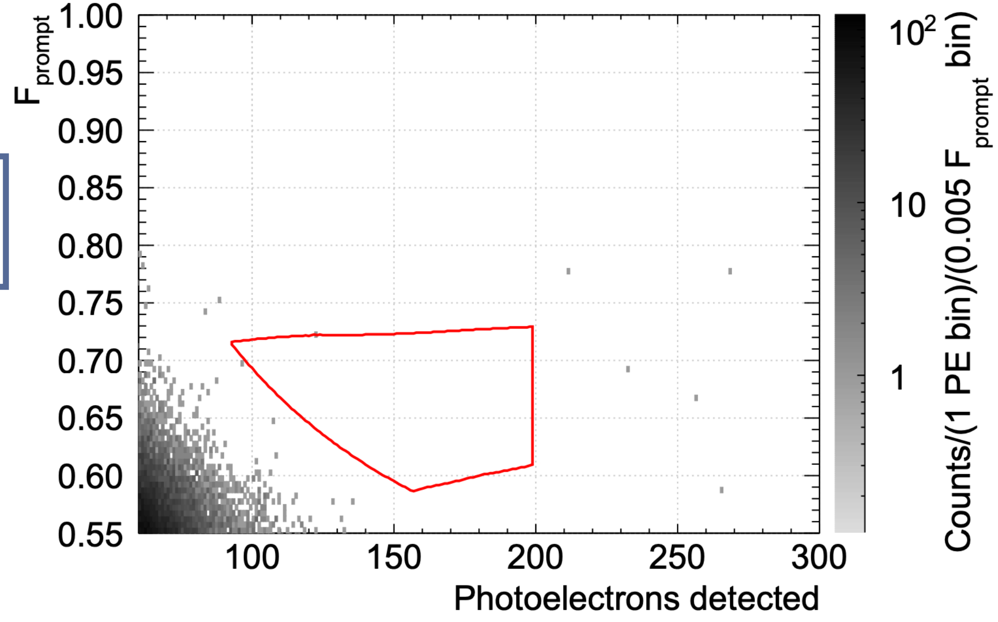
$$F_{prompt} = \frac{\sum_{t=-28ns}^{60\ ns} S(t)}{\sum_{t=-28ns}^{10\ \mu s} S(t)}$$

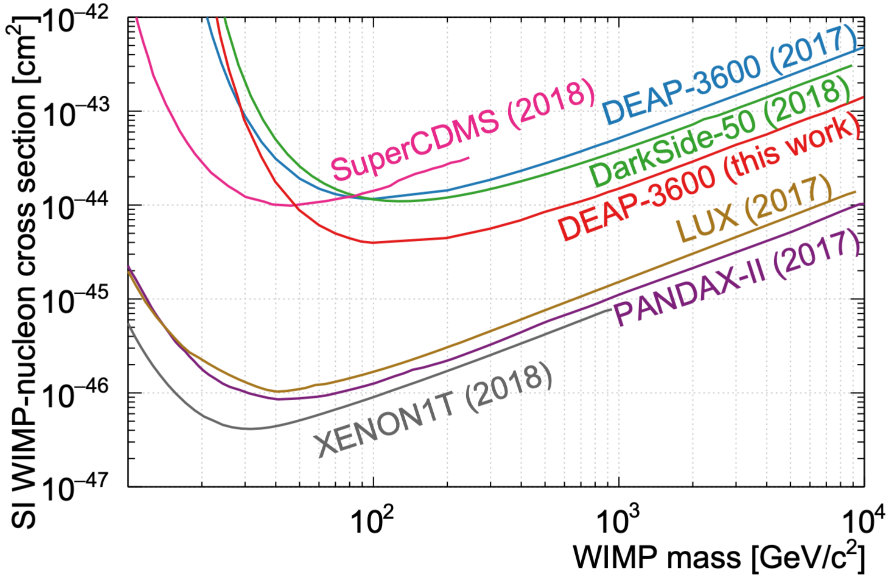
- Zero events in the ROI
  (Pulse Shape Discrimination + Fiducial Cuts)

- This analysis excludes spin-independent WIMP-nucleon cross section above
  3.9×10^{-45} cm^2 for WIMP mass of 100 GeV/c^2

DEAP-3600 sets the most stringent limit on WIMP-nucleon coupling with argon

- New WIMP search analysis ongoing with > 3 yrs data taking





Not only WIMPs…

- *Boosted decision trees approach to neck alpha events discrimination in DEAP-3600 experiment,* A. Grobov, 2020
- *Radiogenic neutron background predictions in DEAP-3600 and in situ measurements,* S. Westerdale, 2020
- *Electromagnetic backgrounds and potassium-42 activity in the DEAP-3600 dark matter detector,* R. Ajaj et al., 2020

Background studies

- *Pulse-shape discrimination against low-energy Ar-39 beta decays in liquid argon with 4.5 tonne-years of DEAP-3600 data,* P. Adhikari et al., 2021
- *The liquid-argon scintillation pulseshape in DEAP-3600,* P.Adhikari et al., 2020

PSD in LAr

- *Precision measurement of the specific activity of ^{39}Ar in atmospheric argon with the DEAP-3600 detector,* P. Adhikari et al., 2023

^{39}Ar activity

- *Study of the energy calibration of the DEAP-3600 detector using Na-22 source data and simulations,* L.Luzzi, 2024
  Recent results on a machine learning approach to event position reconstruction in the DEAP-3600 Dark Matter Search Experiment, A. Ilyasov, 2024
- *Energy response and position reconstruction in the DEAP-3600 dark matter experiment,* S.Langrock, 2020

Event reconstruction

- *First direct detection constraints on Planck-scale mass dark matter in DEAP-3600,* Michela Lai, 2022

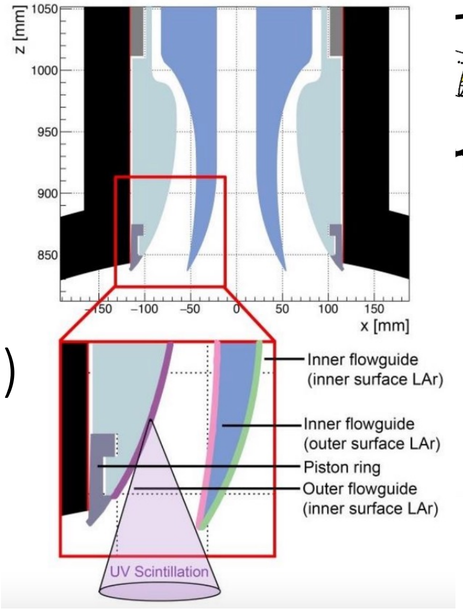
Planck-scale searches

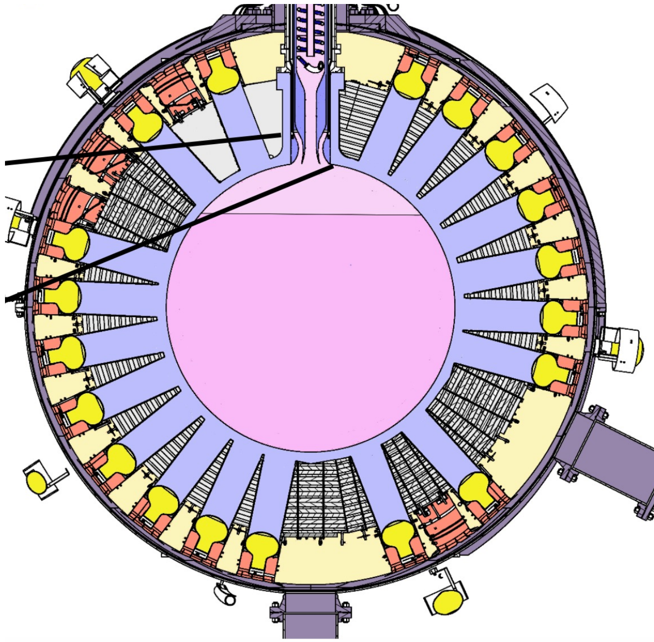
- *Relative Measurement and Extrapolation of the Scintillation Quenching Factor of α-Particles in Liquid Argon using DEAP-3600 Data,* P. Adhikari et al, 2024

Alpha quenching in LAr

α background from the neck

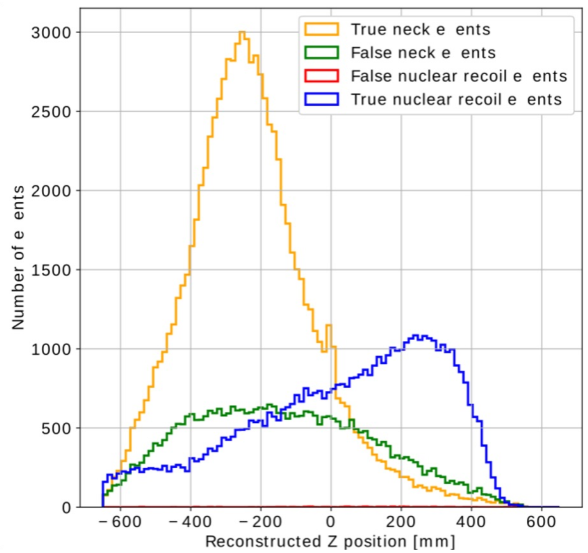
- Until 2018 α-decays in the neck were the most dominant background
  - they push an event in the southern hemisphere

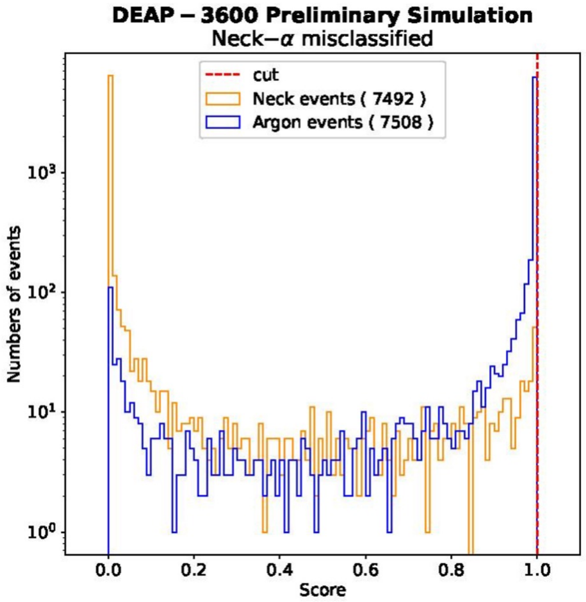




- Ciemat: with a multilayer neural network we are able to classify these events as background

- Today, based on simulation: background leakage of 0.1% with a signal acceptance of 90% (20% before AI)

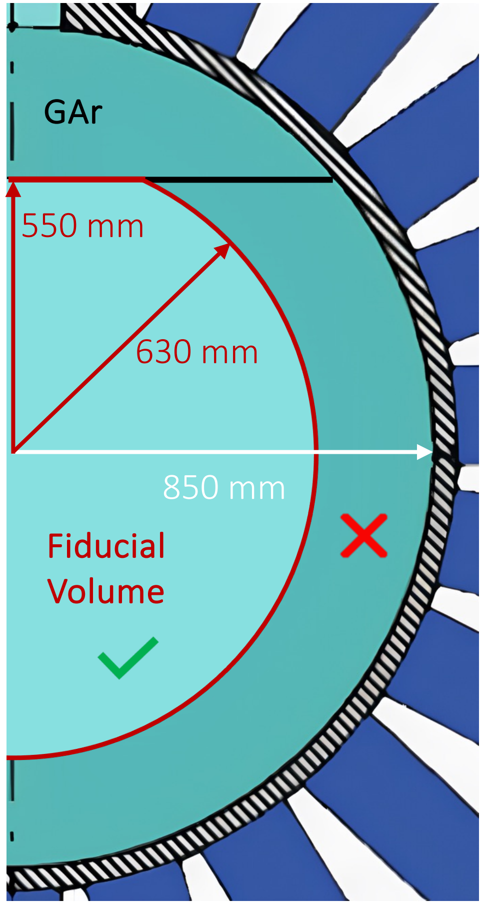




Neural Networks for Background Rejection in DEAP-3600 Detector
10.1007/978-3-030-61705-9_53

Position Reconstruction in DEAP-3600

- Events from the surface of the AV (α-decays) rejected via position reconstruction
  - a **fiducial volume** smaller than the total LAr content is defined
  - if an event interacts outside of it, it is excluded from the analysis



- The detailed study of the performance of position reconstruction is crucial
  - misreconstruction affects the confidence of tagging it as background or WIMPs
  - scintillation light only in DEAP-3600
  - useful in the context of the **GADMC** and directly related to DarkSide-20k

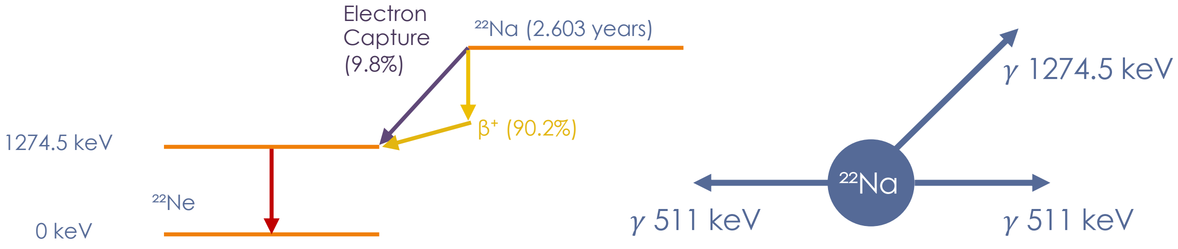
- Two position reconstruction algorithms:
  - Analysis of the charge patterns recorded by the PMTs (**hit pattern**)
  - Calculation of the arrival time of a photon at each PMT (**Time-Of-Flight**)

- The WIMP-search analysis relies primarily on the hit pattern algorithm for fiducialization

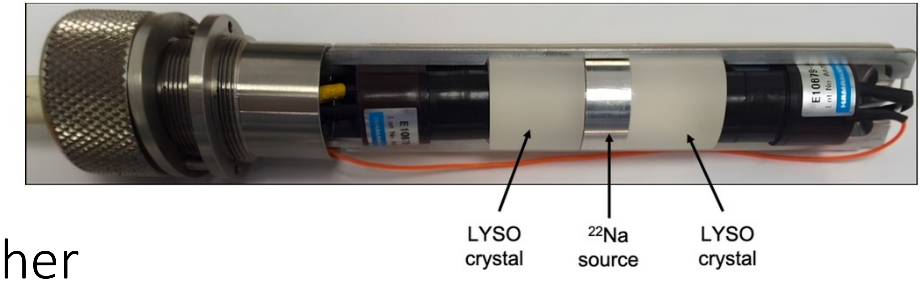
Goal: study the performance of the hit pattern algorithm and compare it with the TOF one

^{22}Na calibration source

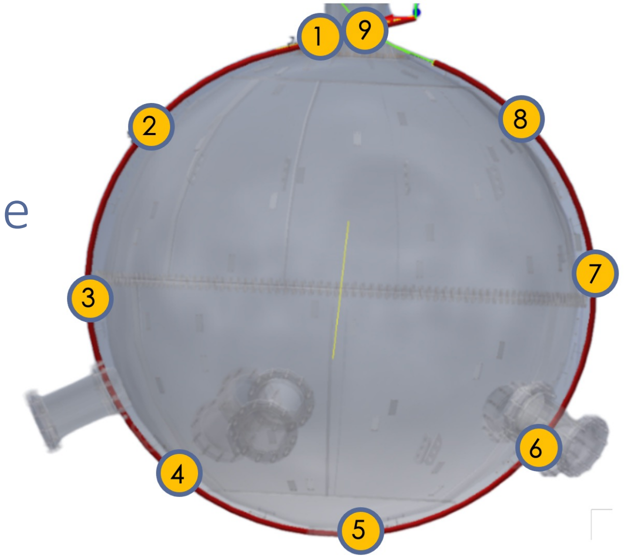
- Emission of three ”simultaneous” γ-rays
  - Excellent tagging scheme for ^{22}Na decays



- A cylindrical SS capsule contains the active element



- Two LYSO crystals with PMTs attached are placed on either side of the capsule to tag the γ-rays from ^{22}Na



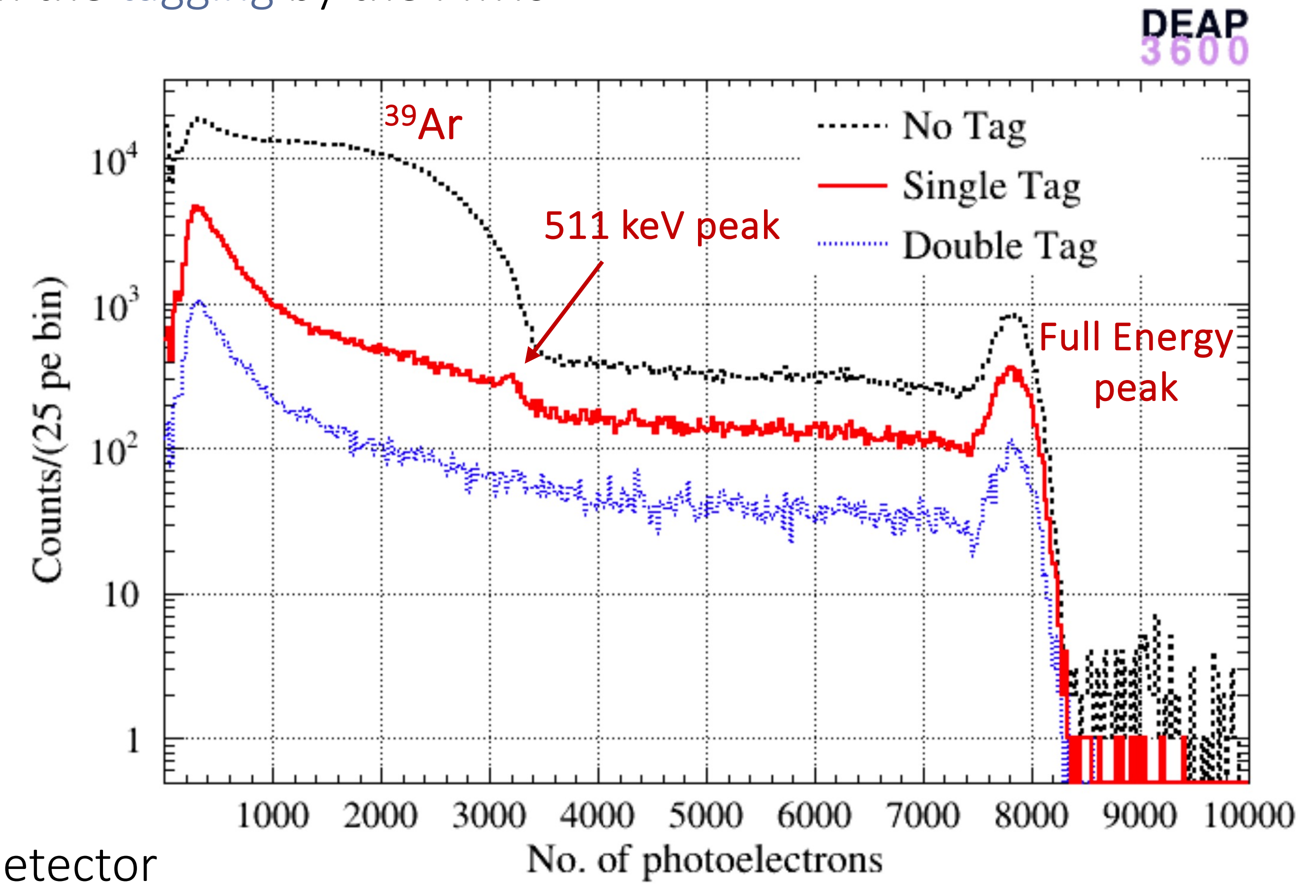
- The source is deployed around the outer steel shell in a calibration tube

- Along the cable, 9 positions of the source are marked

Tagging and energy response

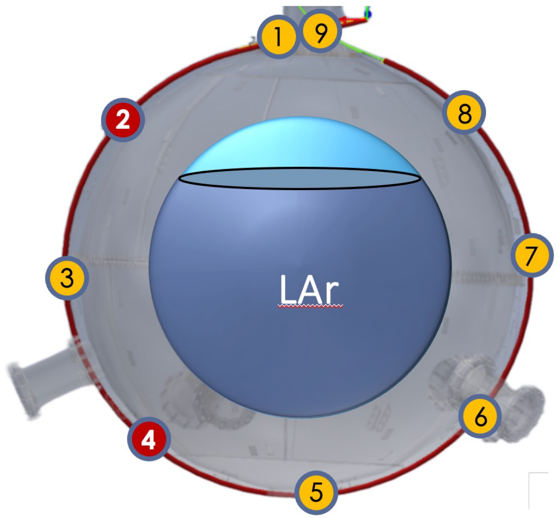
- The shape of the energy spectrum is dependent on the tagging by the PMTs

- Different tagging configurations:
  - Signal only in the detector (**black**)
    - ^{39}Ar beta decay on top of the ^{22}Na
  - Signal in the detector and just in one tagging PMT (**red**)
    - 511 keV peak
  - Signal in the detector and in both tagging PMTs (**blue**)
    - the most stringent tagging condition



- ^{22}Na source allows for energy calibration of the detector
  - Uniform energy response for all the positions
  - Average light yield of 6.16 ± 0.12 PE/keV

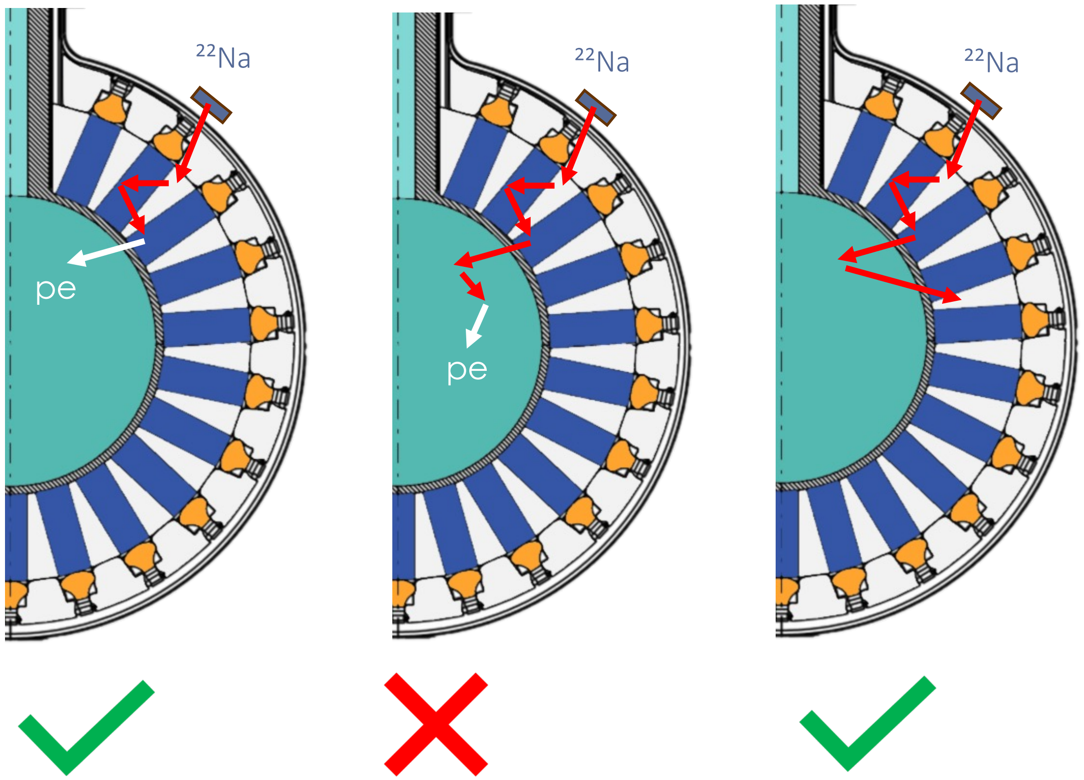
MC simulation of ^{22}Na source



- Positions 2 and 4 are simulated because opposite with respect to the LAr surface level

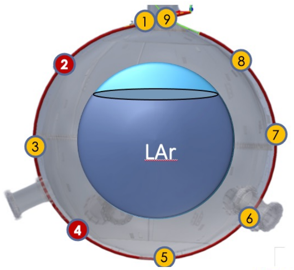
- To test the hit pattern algorithm, we select only single scattering events

We aim to reconstruct the positions of events for which the interaction position is defined

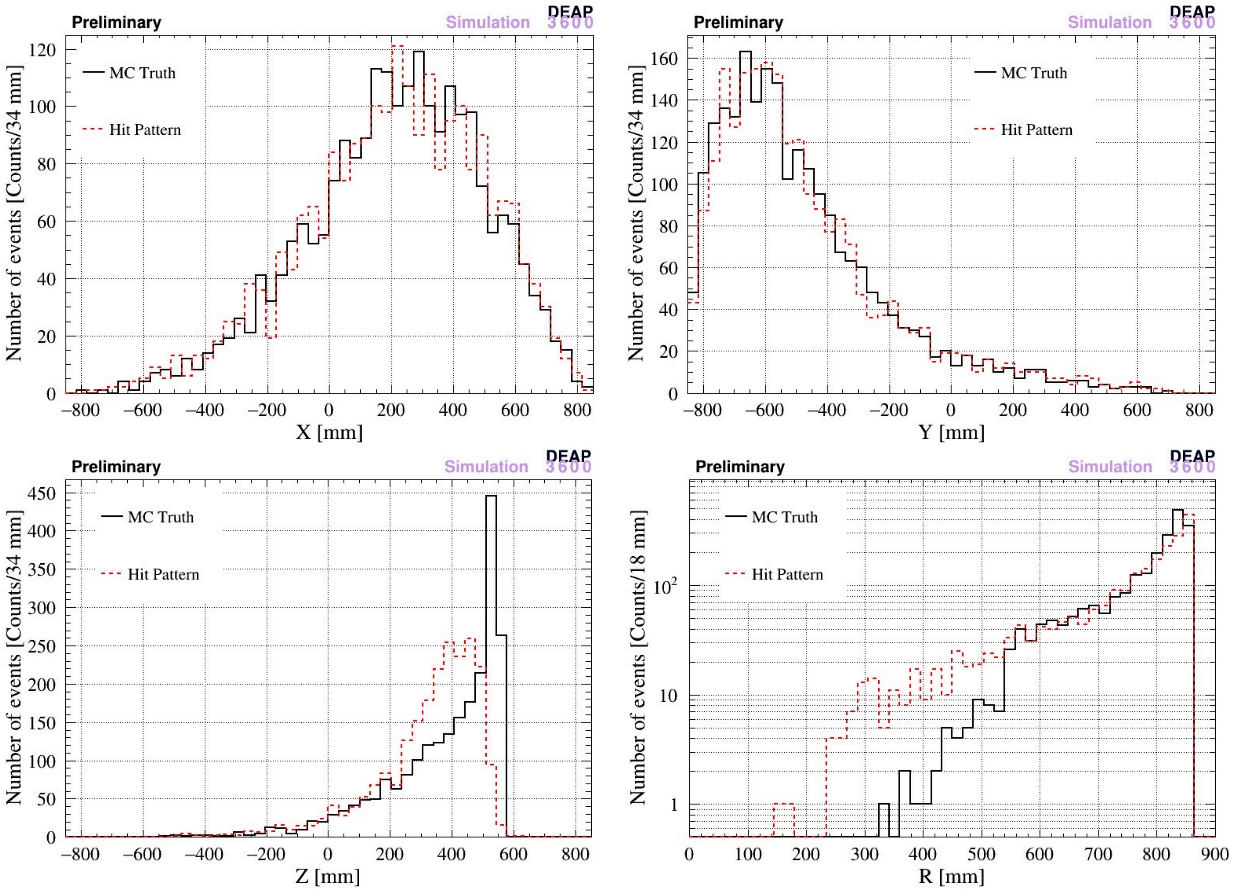


pe = photoelectric

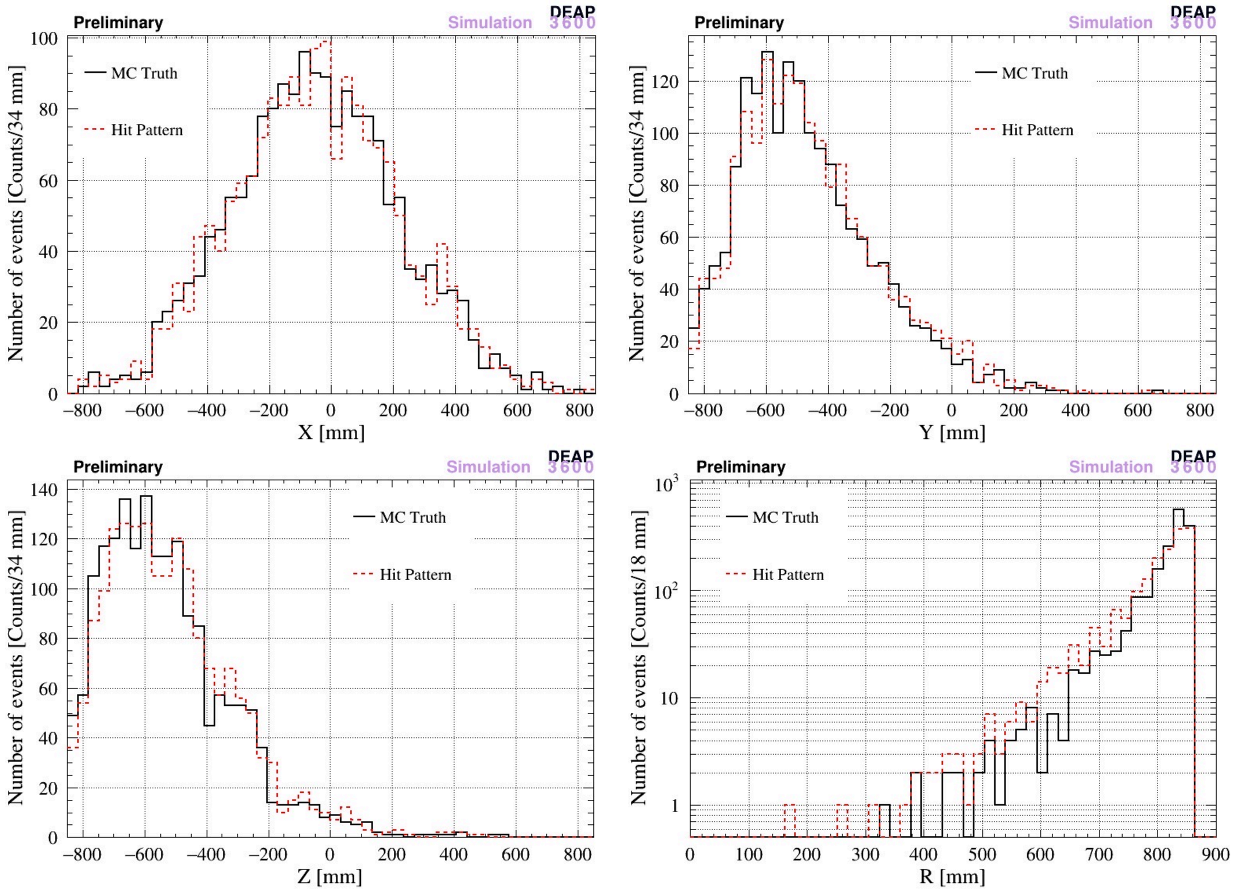
Single Scattering – Position Reconstruction



Position 2



Position 4



- Good reconstruction for almost all coordinates ✓
- For position 2 events tend to be reconstructed far from the liquid-gas interface, towards the centre of the detector
- *Residual = MC true - Reconstructed Position* Resolution ≈2 cm for all coordinates

Multiple Scattering Events

Is it possible to make an energy cut to select only single scattering events from the entire spectrum in the data set?

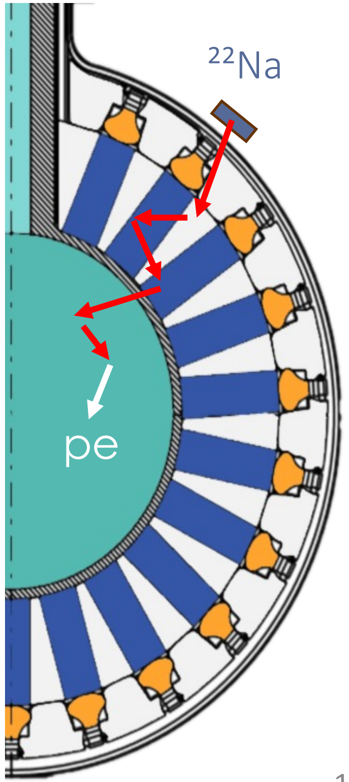
- In the range [30, 50] keV we maximize the number of single scattering events with respect to the total deposits: 86.7% for position 2 and 86.1% for position 4

We cannot apply an energy cut to select only single scattering events!

How does the algorithm perform when applied to events that deposit energy multiple times in the LAr?

- Good reconstruction!
- Same features of single scattering case
- Residuals with resolution <2 cm

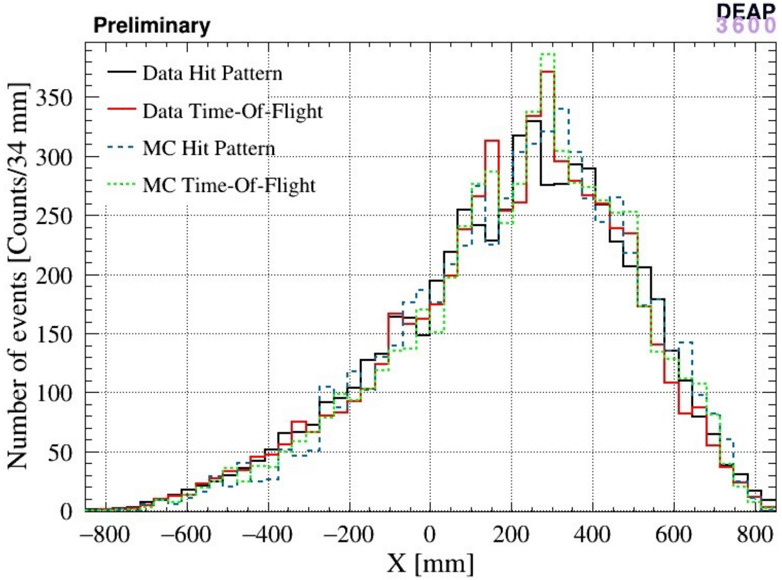
Hit pattern algorithm can be applied both to single and multiple scattering events

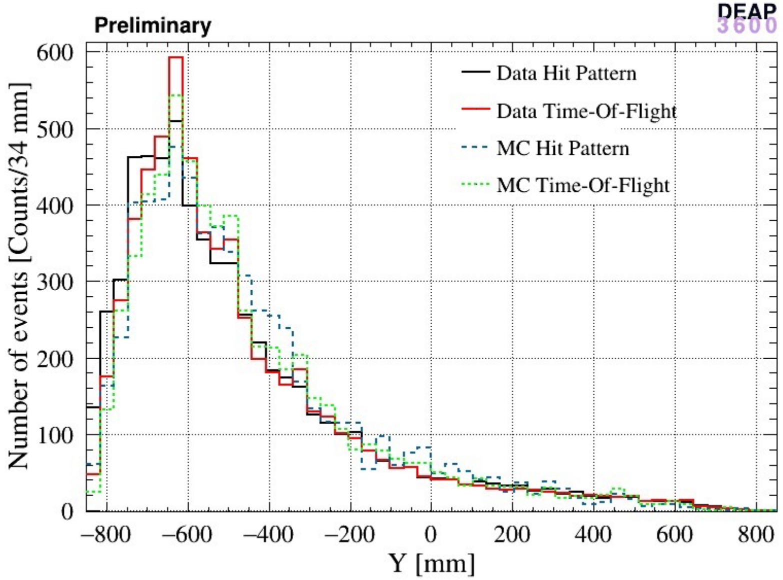


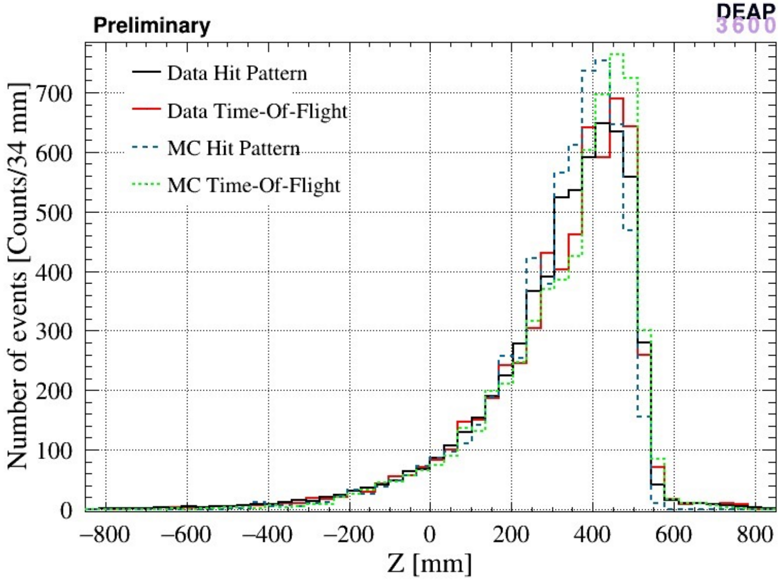
Hit pattern vs TOF – Data vs MC

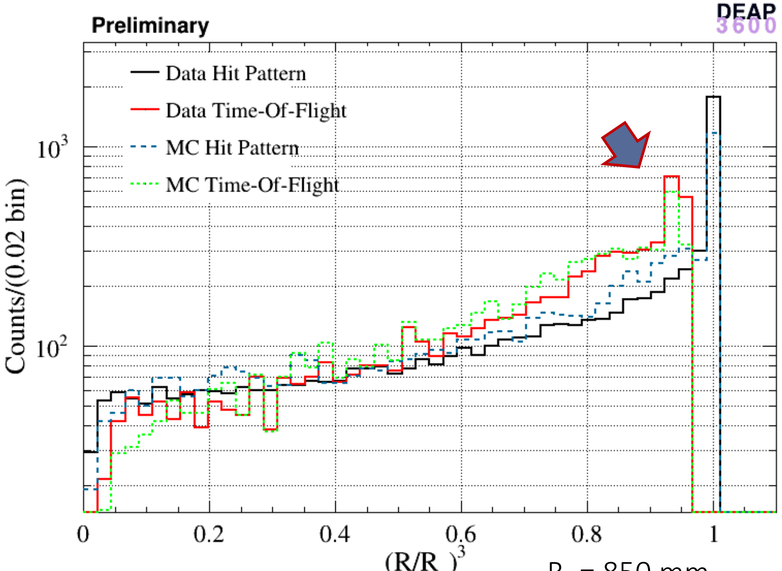
Position 2

- Both algorithms are now applied to MC and real data with ^{22}Na source
- Both single and multiple scattering events
- Both algorithms reconstruct in the same way data and MC
- The hit pattern algorithm performs better than the TOF algorithm when it comes to ^{22}Na source events
- Position 4 presents the same features









$R_0 = 850$ mm

Summary

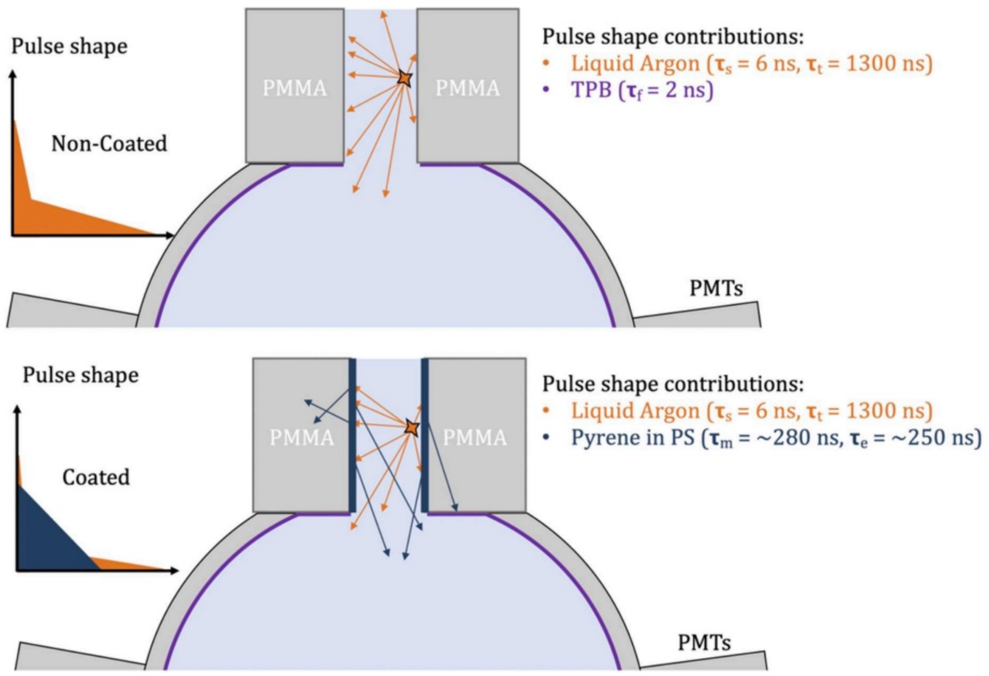
- DEAP-3600 sets the most stringent exclusion limit on WIMP-nucleon spin-independent cross sections with argon
- The detailed study of the energy calibration and position reconstruction in DEAP-3600 are fundamental for this experiment
- A ^{22}Na source in a custom made setup for tagging photons is ideal to study the energy calibration and position reconstruction
- The energy response is uniform in the detector, with average LY = 6.16 ± 0.12 PE/keV
- The position reconstruction based on hit pattern algorithm has resolution ≈2 cm on the MC data set for both single and multiple scattering events
- The hit pattern algorithm performs better than TOF one, for ^{22}Na source events
- There is agreement in reconstructing data and MC, for both algorithms

THANK YOU!

BACKUP

Detector Upgrades

JINST 16 P1209



Neck Alphas

- External cooling system to prevent gas argon condensation on the flowguides and consequent alphas scintillation
- Installed pyrene-coated flowguides to improve PSD against neck alphas

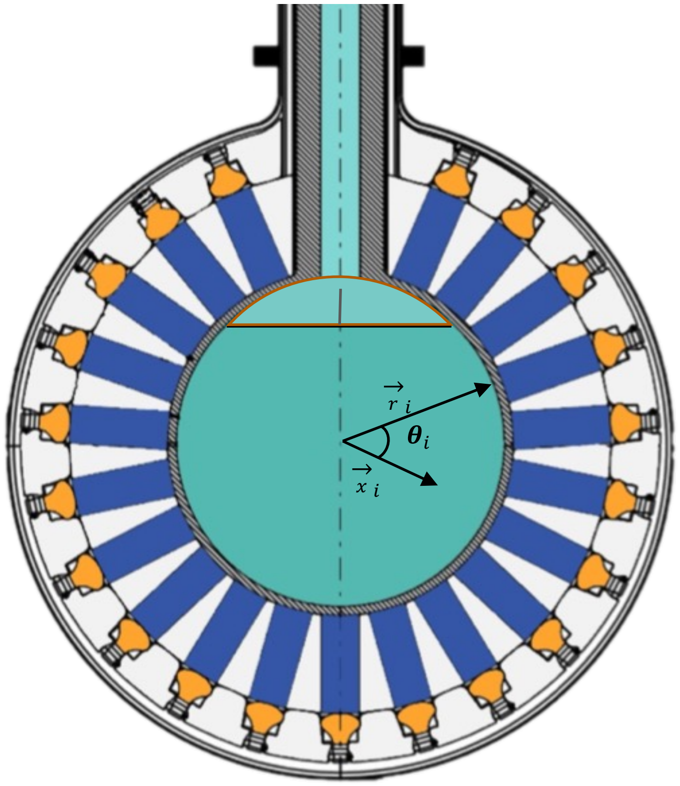
Dust Alphas

- Additional alpha-decays background consistent with metallic dust particulates ranging from 1 μm - 50 μm in diameter
- They could have entered the inner vessel during the purging with LN_2, after the resurfacing of the inner surface
- Reduction of dust background by extraction and filtration of LAr

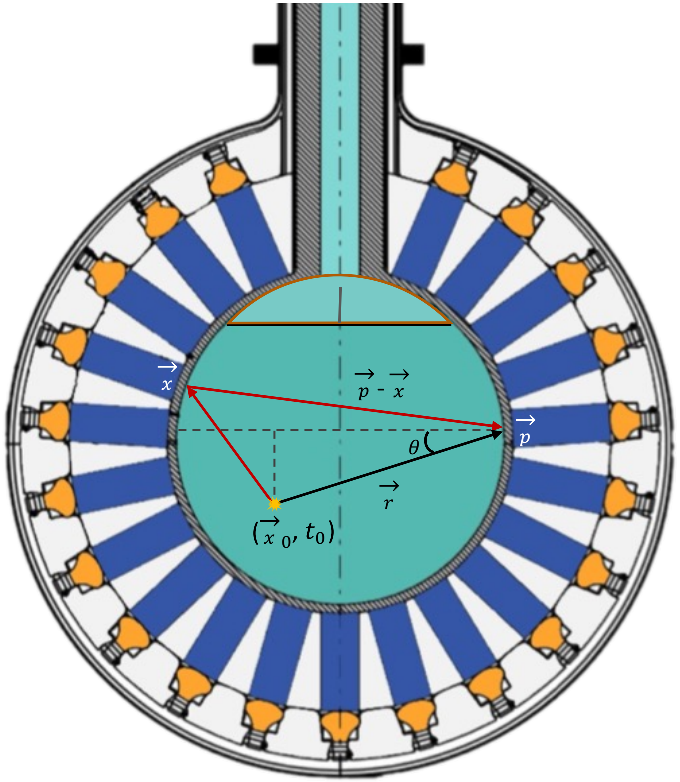
Position Reconstruction - Algorithms

- Two algorithms to reconstruct the position of an interaction in DEAP-3600:
  - Analysis of the charge patterns recorded by the PMTs
  - Calculation of the arrival time of a photon at each PMT

Hit pattern



Time-Of-Flight



Low-level and physics cuts

- Low level cuts are applied to reject bad events:
  - if (qPE <= 0) continue; // Skip events that have no charge information (primarily pre-scaled events)
  - if (subeventN > 1) continue; // pile-up cut, removes coincidence events
  - if (eventTime <= 2250) continue; // pre-trigger pile up cut, not typically identified by subeventN
  - if (eventTime >= 2700) continue; // post-trigger pile up cut, strongly correlated with subeventN
  - if (numEarlyPulses > 3) continue; // Cut on a significant amount of early light pulses in the first 1600 ns of the waveform
- Only double-tagging events are selected