Neutron Capture in Liquid Argon for Calibration: Key Results from the DUNE-VD Prototype at CERN

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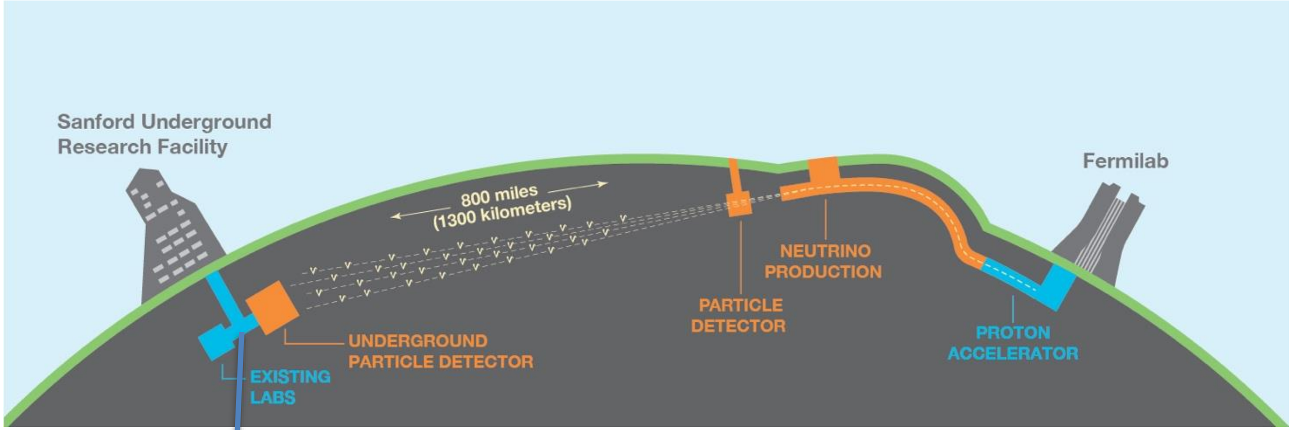
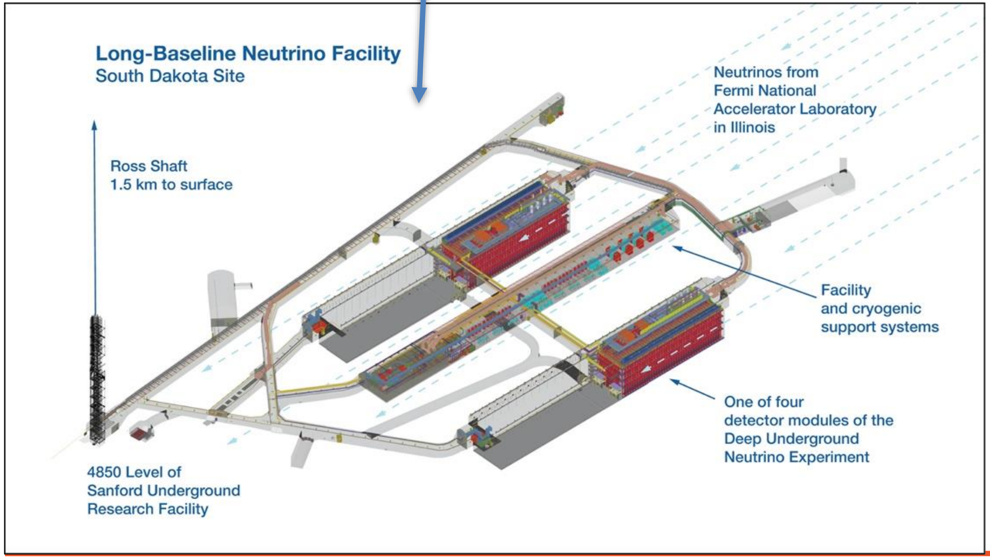
On behalf of the DUNE collaboration

CPAD 2024 (Nov 18-22, 2024) University of Tennessee, Knoxville

Deep Underground Neutrino Experiment (DUNE)



Physics goals: neutrino oscillations, CP violation, proton decay, supernova neutrinos.



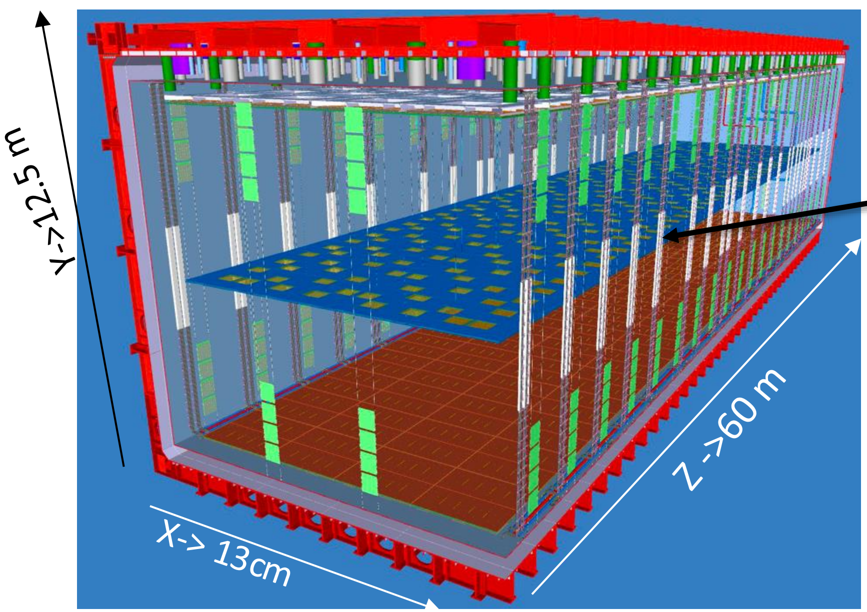
DUNE far detectors:

- (2 + 2) 17kt modules
- 1300 km away
- 1.5 km underground
- 1st module and 2nd module designs finalized
- 3rd and 4th modules to be built in Phase II, proposals and R&D ongoing

Planery talk by Sowjanya Gollapinni (Nov 21, 4:25 pm): DUNE Phase-II Detector R&D Status and Planning

DUNE VD LArTPC (Vertical drift)

- Photon Detection System (PDS) enable event time (t0) reconstruction and enhance energy reconstruction with improved coverage.
- PDS will be placed on the HV cathode surface (using the novel Power-over-Fiber technology described in arXiv:2405.16816 and signal-over-fiber technology), as well as behind the field cage. Additionally, the reflective CRP surface provides nearly 4π detector coverage.



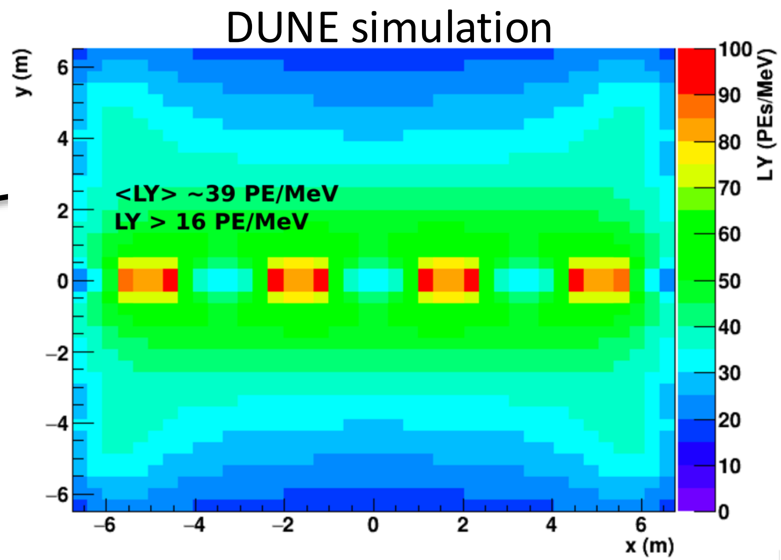


Fig: Simulated Map of the light yield (LY) in the central (x, y) transverse plane at z = 0 for the reference configuration. Fig from DUNE FD TDR (JINST 19 (2024))T08004

Light Yield = Number of Photo-Electrons per MeV of energy deposit

*Fig from: DUNE FD TDR (JINST 19 (2024))T08004

Neutron capture for calorimetry

- Neutron capture on Ar-40 produces a well defined 6.1 MeV gamma cascade

$$n \; + \; ^{40}Ar \; \rightarrow \; ^{41}Ar \; + \; 6.1 \; MeV$$

- **Most neutrons above 57 keV will fall into the cross-section dip where the scattering length is about 30 m**

- Gamma cascade is contained within ~1 m (compared to DUNE FD2 active volume 60x12x13 m^3)

Neutrons from pulsed neutron source

- ✓ Covers the bulk of the active volume
- ✓ has a well-characterized energy spectrum.
- ✓ Gamma cascade confined in a small region

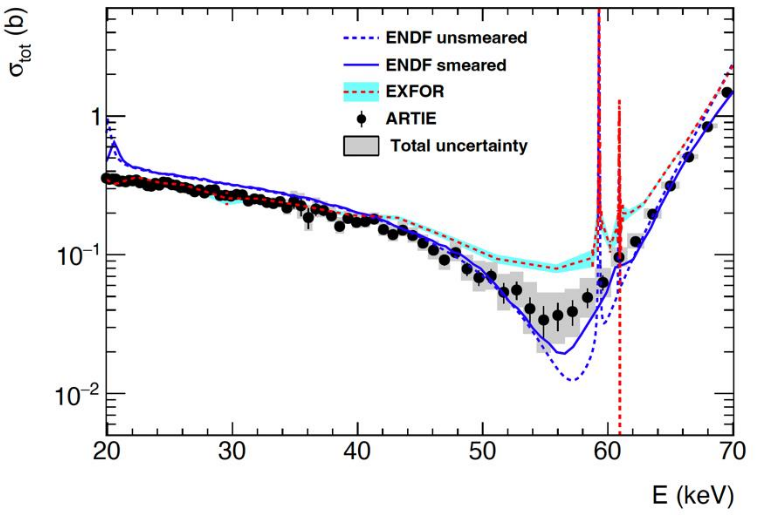
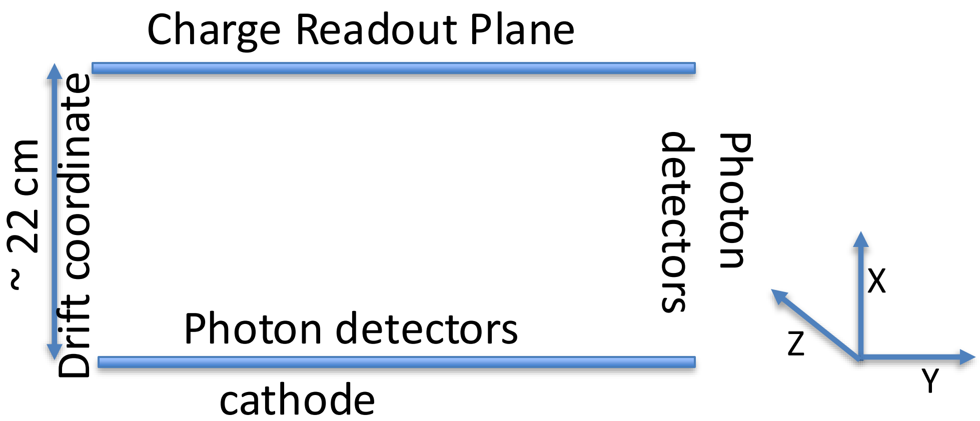


Fig: Neutron-argon total cross section as a function of energy.
https://arxiv.org/abs/2212.05448

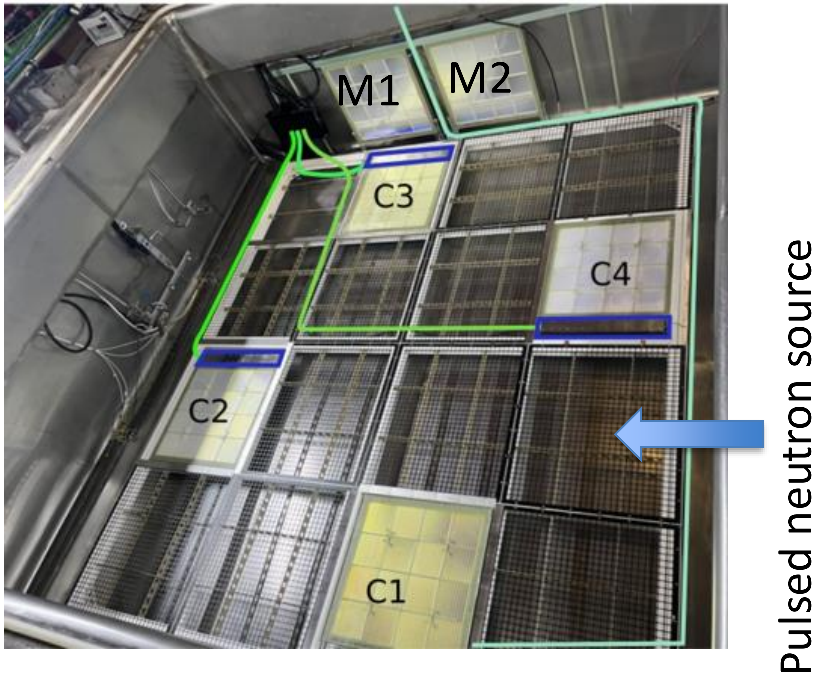
DUNE VD Coldbox setup

- Prototype using full scale charge readout planes (CRP) and X-ARAPUCA photon detectors to be used in DUNE FD2



Drift distance ~22cm; length ~3m and width ~3m

Top View, with CRP removed



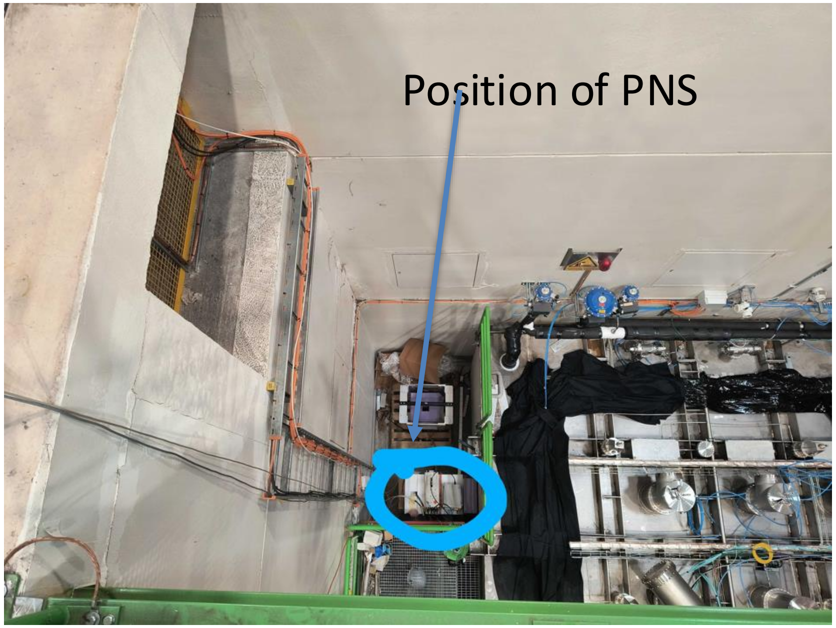
- 4 Photon detectors on the cathode (60 cm x 60 cm)
- 2 On the wall (60 cm x 60 cm)

Pulsed Neutron Source (PNS)

Commercial Thermo Fisher MP-320 Deuterium-Deuterium Generator (DDG), which produces monoenergetic 2.45 MeV neutrons with a flux of up to 10^6 neutrons/second.

$$^2H + {}^2H \rightarrow {}^3He + n + Q(2.5\,MeV)$$

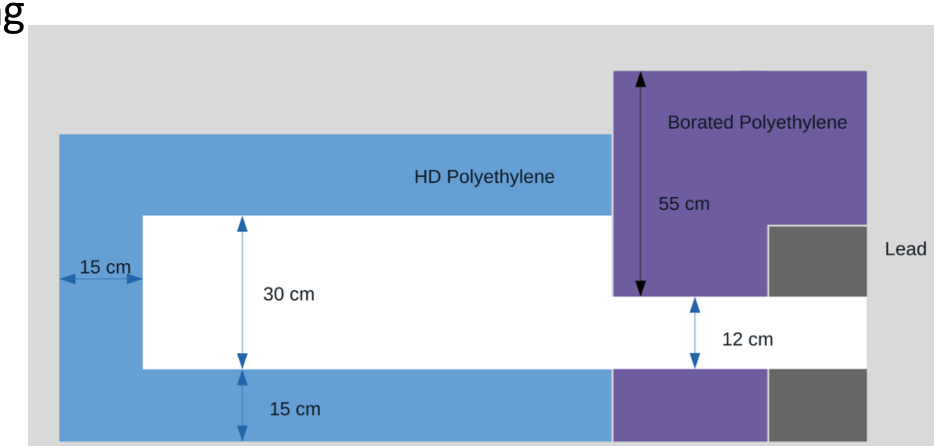
PNS installation



Polyethylene shielding enclosing PNS

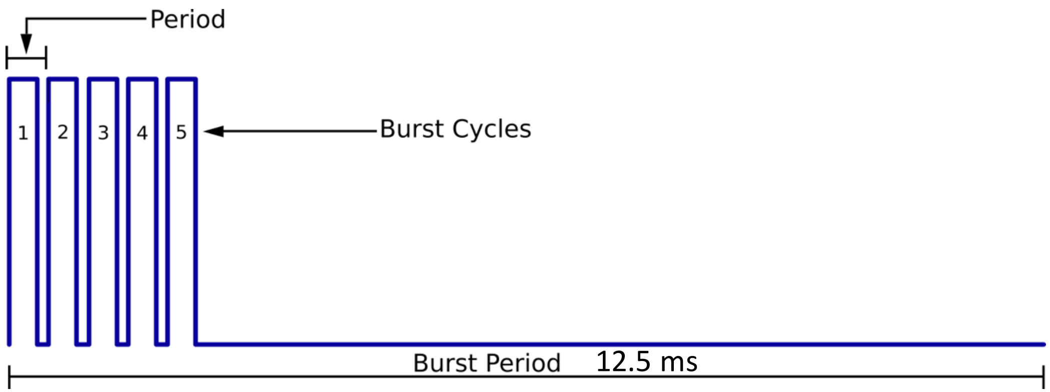
PNS before enclosing from back

Geometry used in FLUKA simulation



PNS data acquisition (simultaneous light and charge readout)

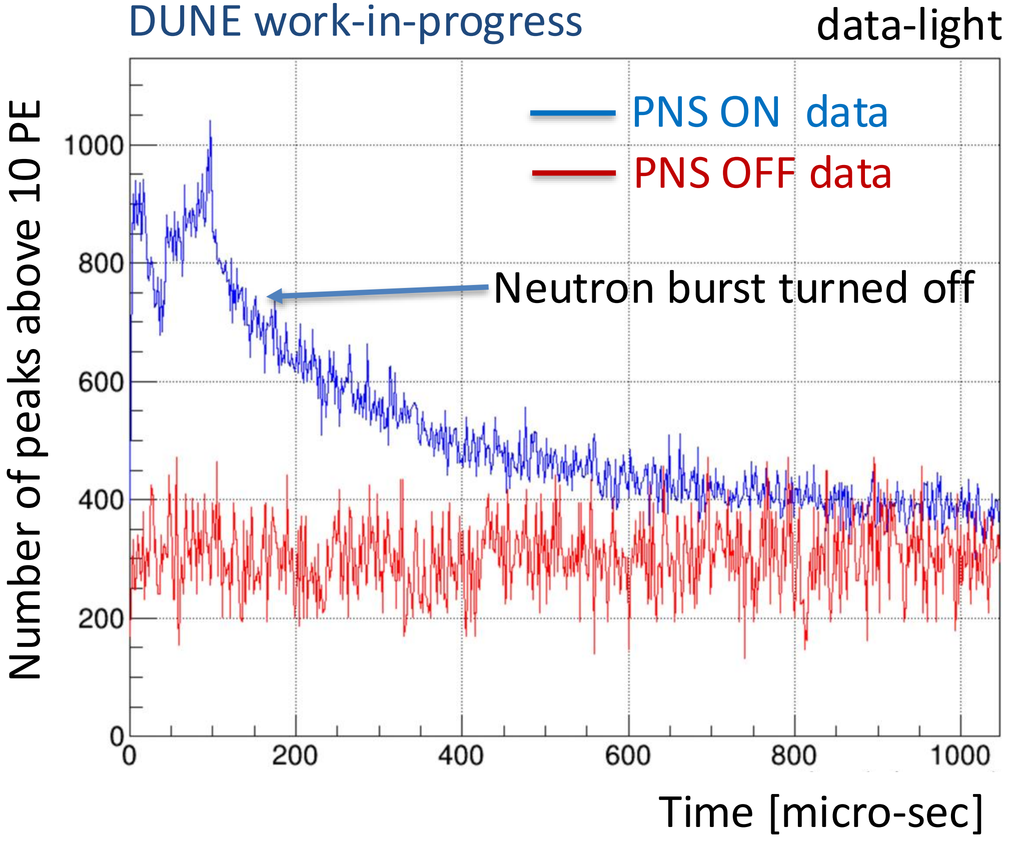
- Neutron beam produced in burst mode with a repetition frequency of 80 Hz
- A TTL pulse synchronous with the neutron beam is used for triggering the Data acquisition
- Charge and light data recorded simultaneously.
- Readout window of 1.2 ms after burst begins



Pulsed neutron source ON and OFF data

Photon detector signals on the detector closest to PNS (C4 PDS module)

The figure below shows the number of peaks above a threshold of 10 photoelectrons (PE) as a function of time since the neutron pulse was turned ON, compared to a cosmics-only run (PNS OFF).



Pulsed neutron source FLUKA simulation

A FLUKA simulation was performed with parameters identical to the data set, employing the DUNE VD Coldbox geometry.

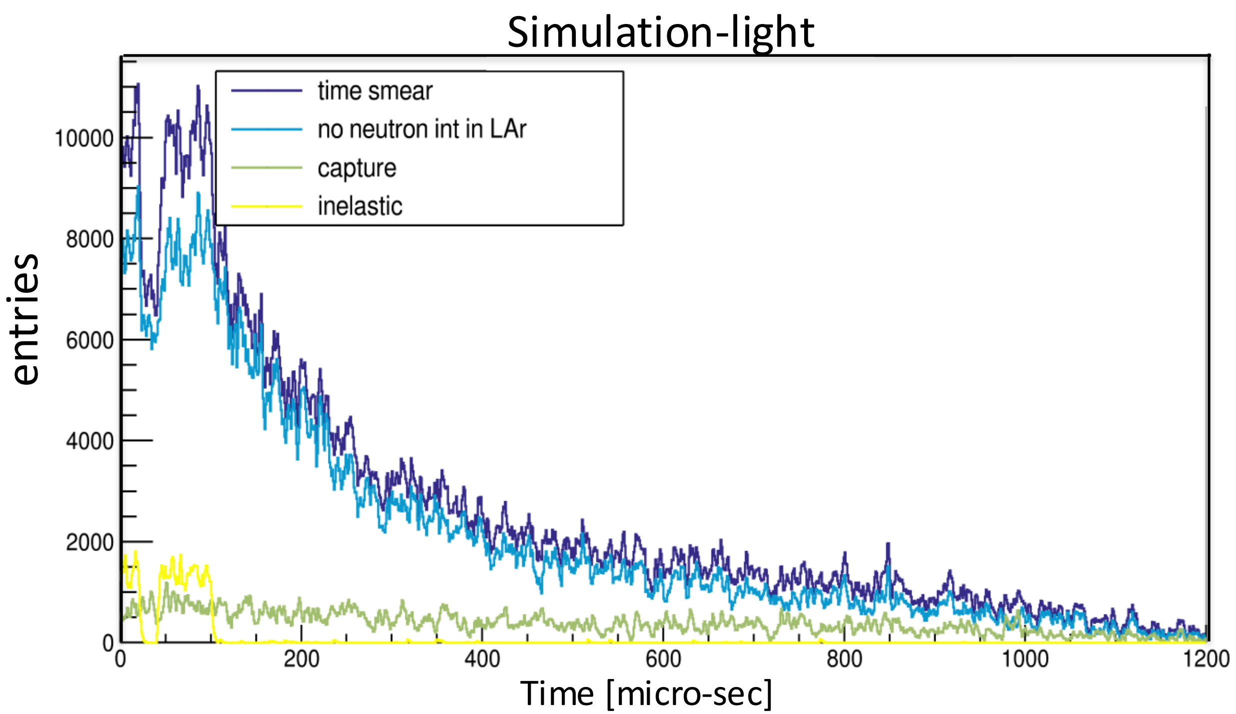
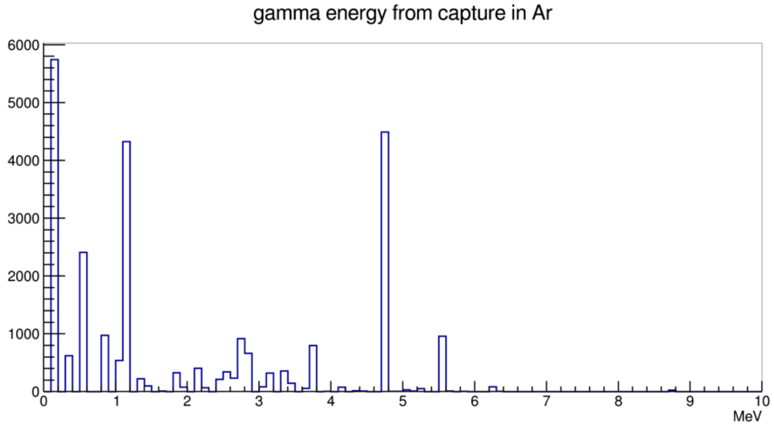
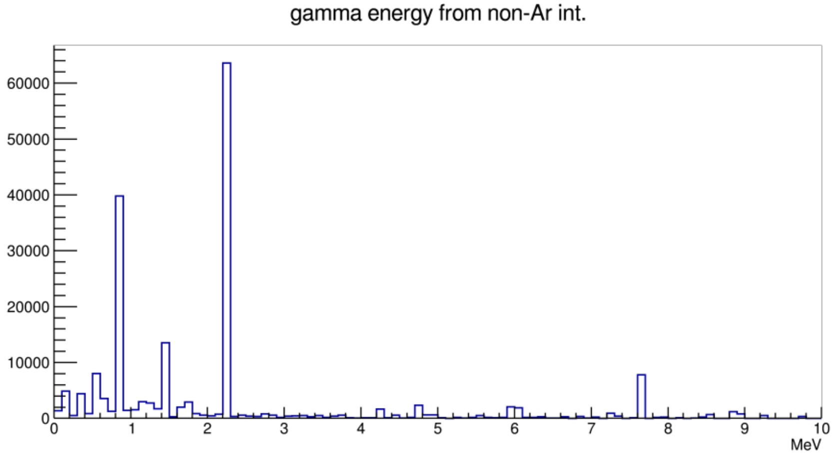


Fig: Optical photon time distribution (μs) by event type: total (dark blue), neutron capture (green), inelastic neutron interaction (yellow), no neutron interaction (light blue) for the photon detection system closest to the PNS source (C4 PDS module).

Neutron induced gamma simulation



spectrum of gamma rays from neutron captures in the active LAr region



Spectrum of gamma rays from neutron interactions in materials different from LAr

Selecting neutron capture candidates (work in progress)

Characteristics:

- Neutron capture appears as a cascade of gamma with energy summing to 6.1 MeV.
- Most energetic gamma deposit produces tracks <3.0 cm in length
- Gammas will appear as short clusters contained in ~1m

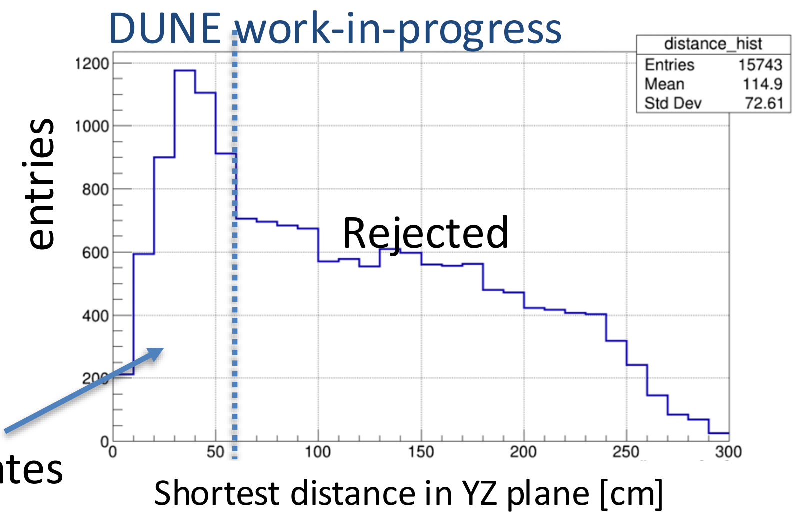
Major background are the cosmic muons and 39Ar:

→A fiducial volume cut is applied to remove cosmic backgrounds. Tracks starting or ending within 10 cm of Y and Z boundary and 1 cm from the top are removed.

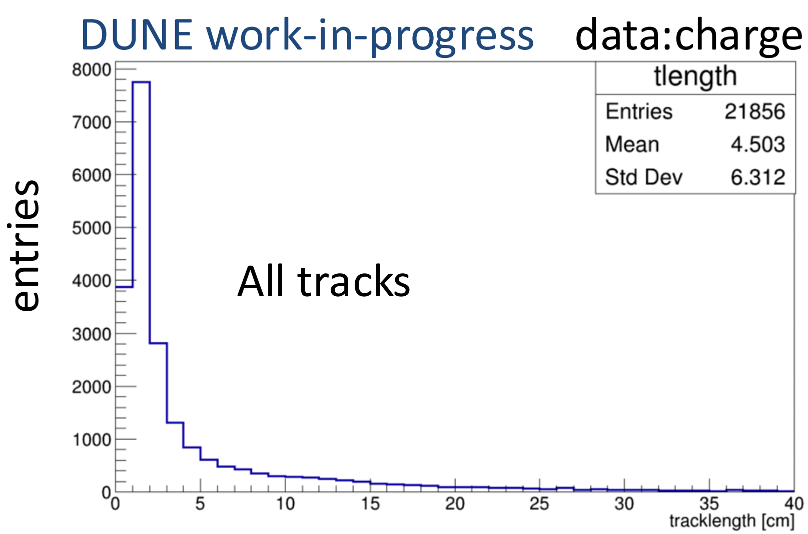
Light-charge matching

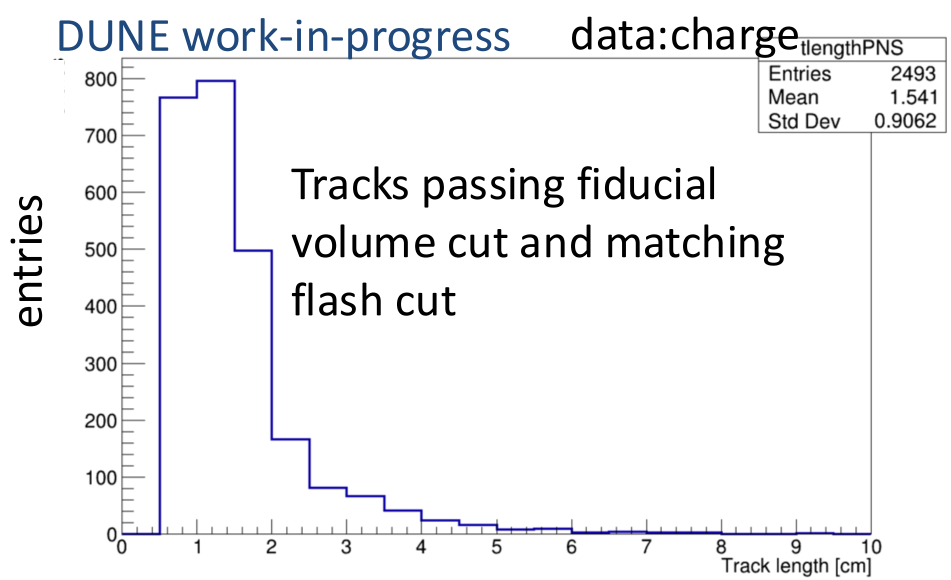
- After fiducial volume selection;
- Shortest distance between track and PDS Flash is estimated in the YZ plane.
- If shortest distance > 60 cm; track is rejected
- Time of matched PDS flash gives the t0 for the track.

Fig: Shortest distance between a track and any flash within 1 drift distance



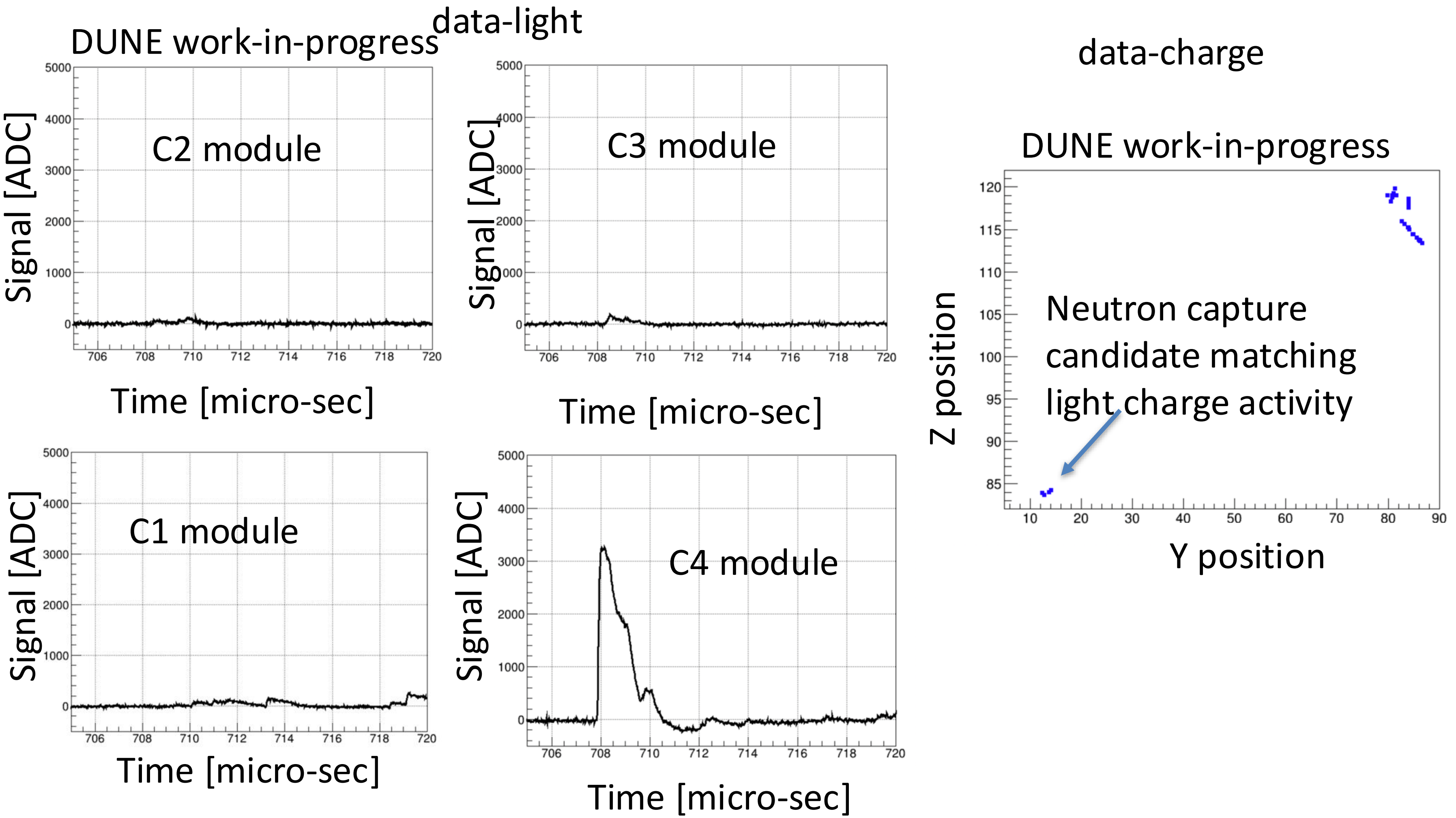
Light-charge matched candidates



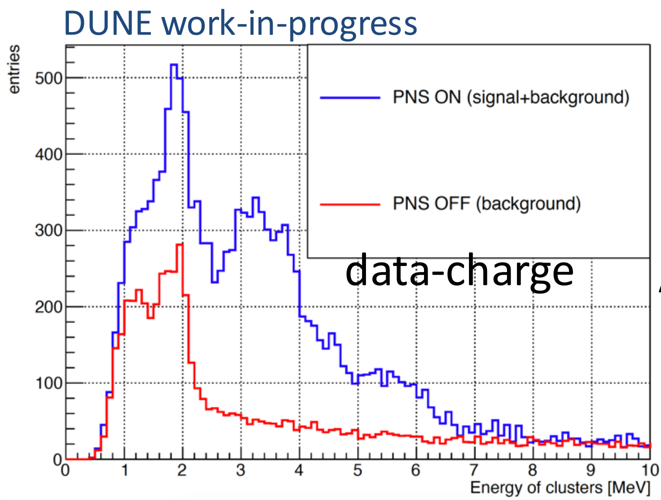


Fermilab DUNE

Event display for candidate neutron capture event

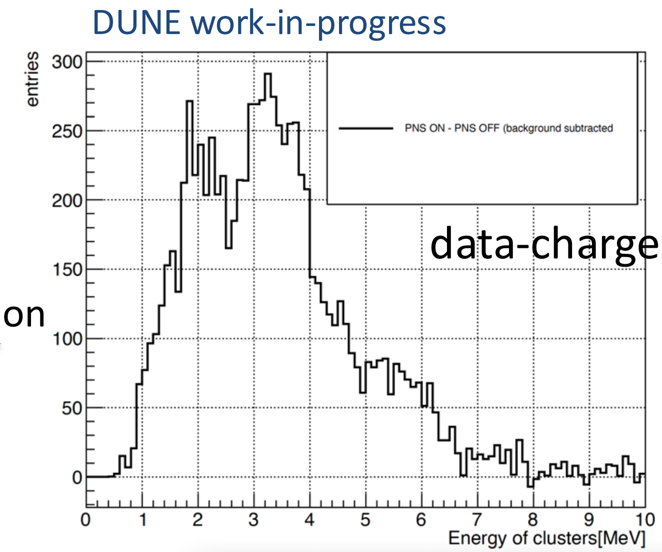


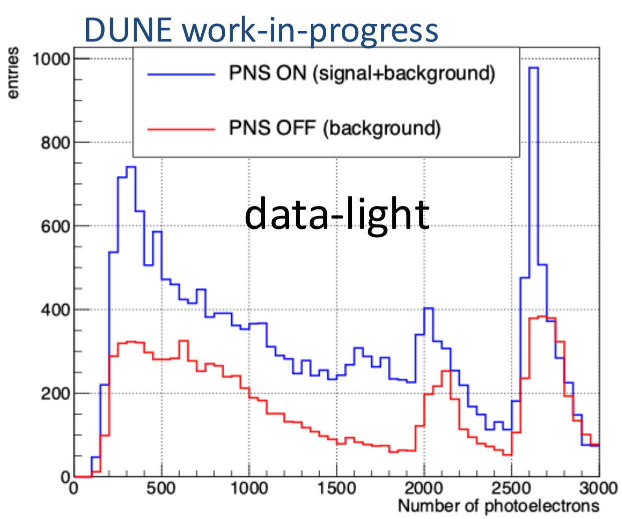
Charge and light distribution for the selected events



Summed charge for selected tracks

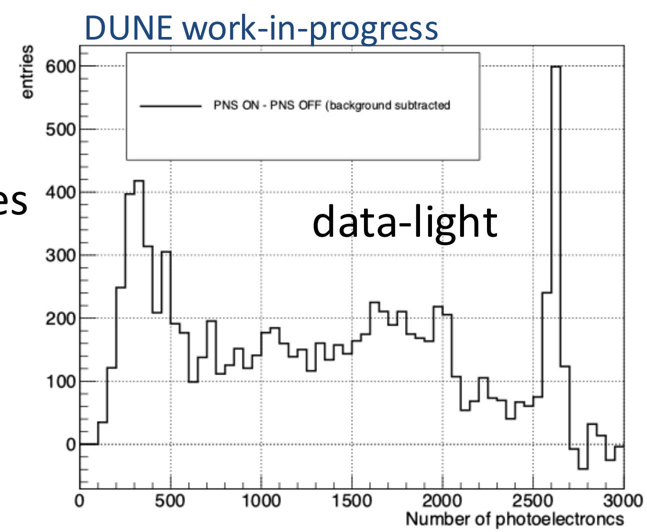
After background subtraction





# of Photo Electrons [PE] distribution for selected Neutron capture candidates

After background subtraction



Fermilab DUNE

Summary

Encouraging Results with DUNE VD Coldbox:

- The initial DDG neutron source run concluded successfully in April 2024, with data analysis ongoing.
- Performance observed in the DUNE VD Coldbox demonstrates strong potential for improved outcomes in larger LArTPCs like ProtoDUNE-VD and the DUNE Far Detector.

Looking Ahead

- Extensive data collection with larger prototypes at the CERN Neutrino Platform is planned for early 2025 to enhance calibration techniques.

BACKUP SLIDES

Motivation: DUNE low energy physics

- ❖ One of the major goals of DUNE: Detect neutrino flux from core-collapse supernovae within our galaxy during DUNE's lifetime.

- ❖ Dominant interaction of low energy neutrinos in LAr

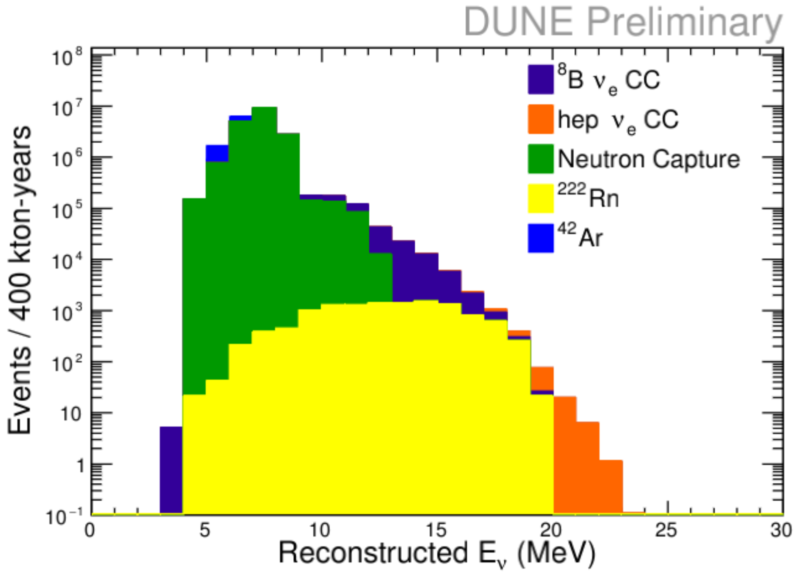
$$\nu_e + 40Ar \rightarrow e- + 40K^*$$

- ❖ Likely accompanied by de-excitation products (gamma rays and/or ejected nucleons).

(Eur. Phys. J. C (2021) 81:423)

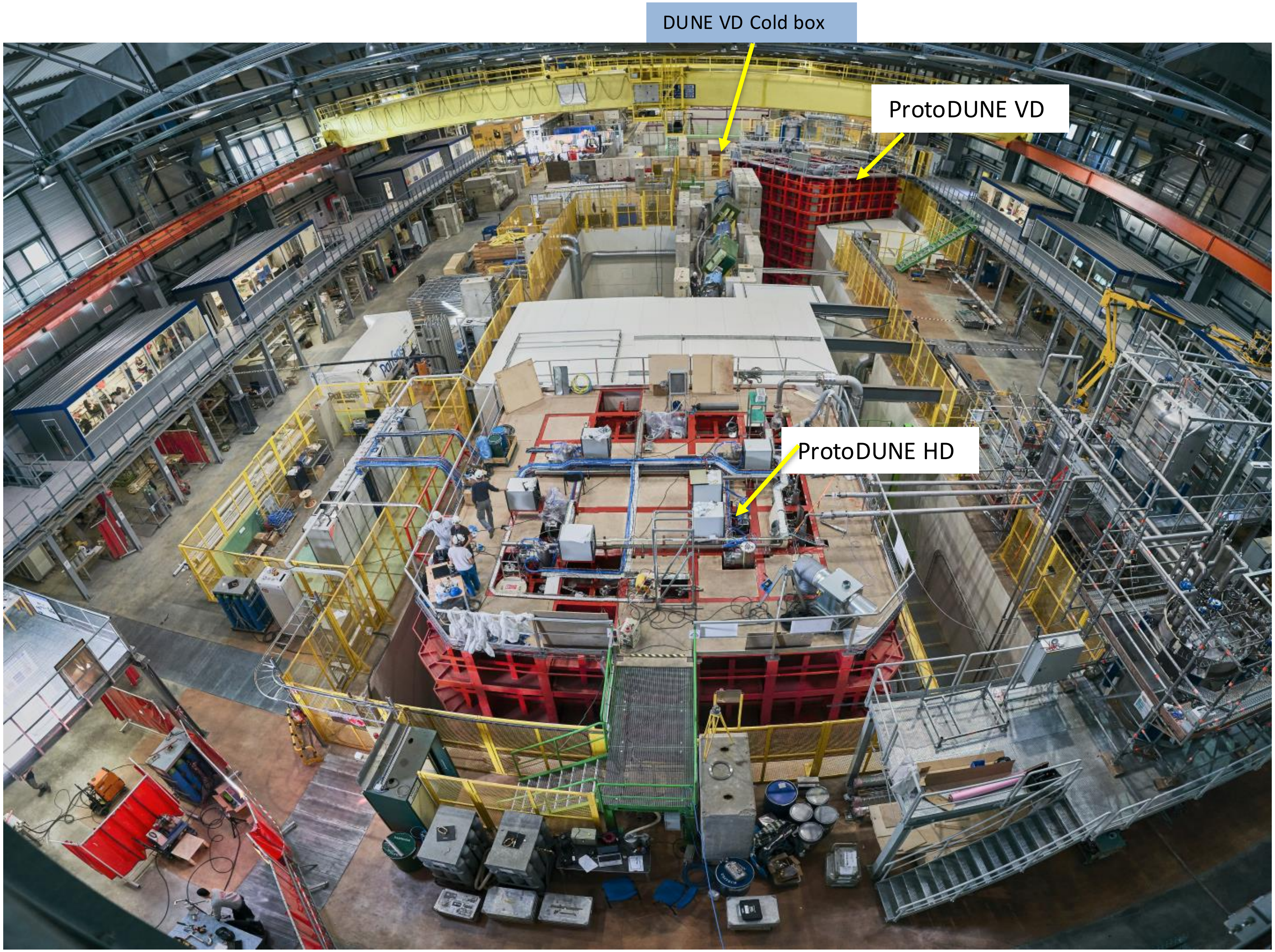
- ➢ Additionally, major background for the low energy solar neutrino spectrum comes from DUNE Far Detector cavern neutrons.

- ➢ Tagging neutron capture events is very important for DUNE low energy physics program.



Simulated solar neutrino spectrum with background for the DUNE Far Detector. Reference doi = {10.22323/1.414.0621}

PNS RUN AT THE CERN NEUTRINO PLATFORM



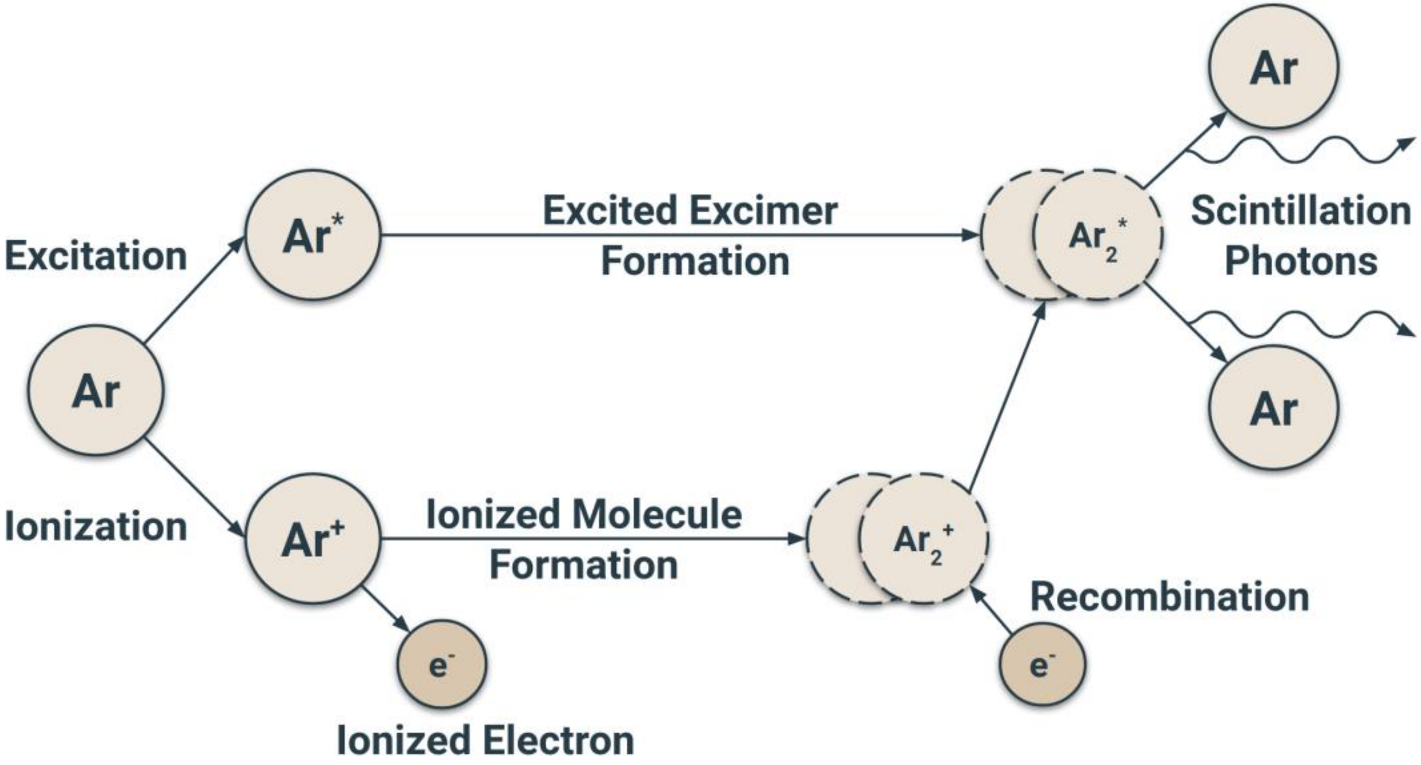
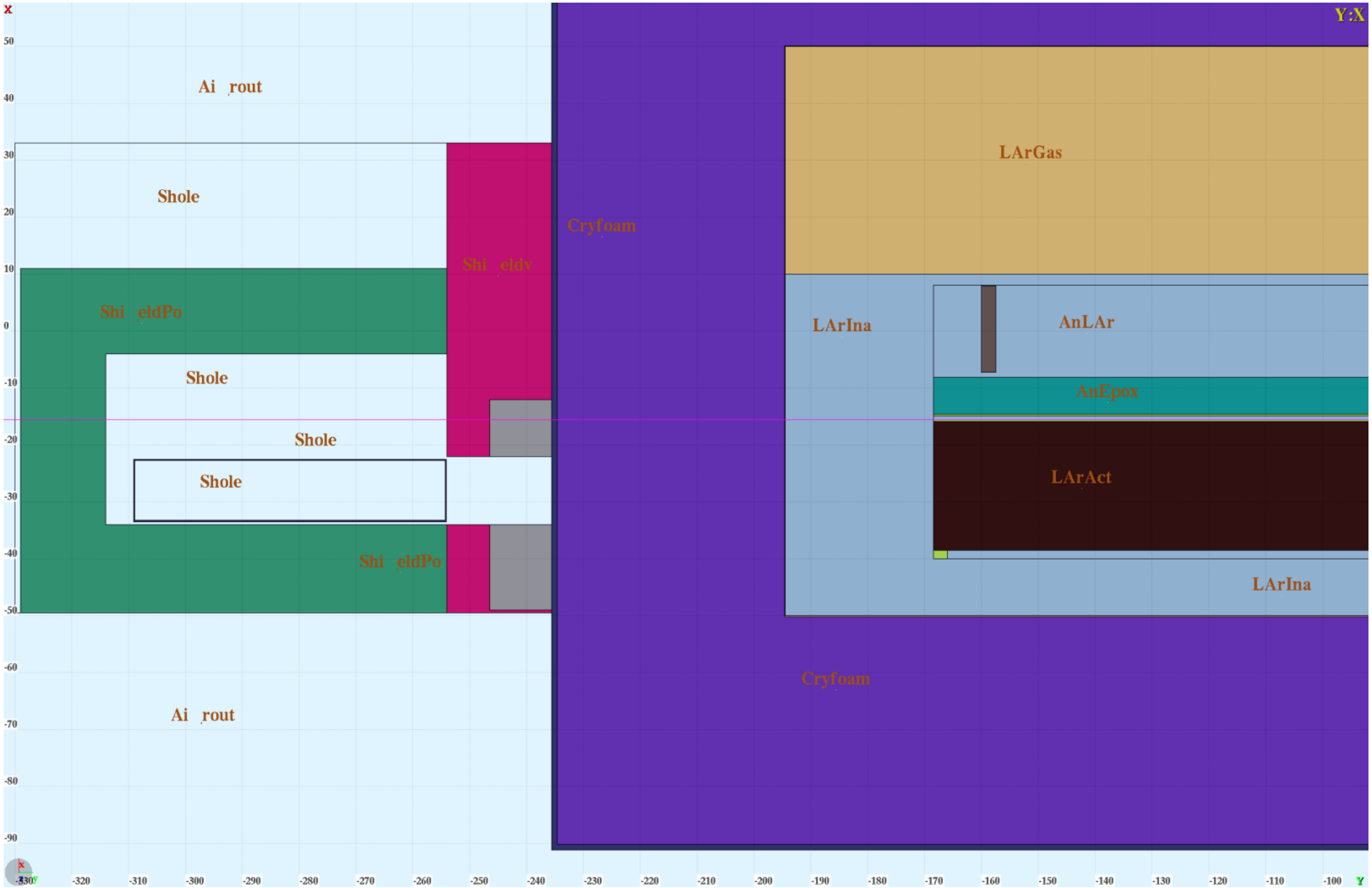


Fig: Mechanism of scintiallation light production in Ar.
Figure from arXiv:2002.03010



y-x cross section of the DUNE VD coldbox geometry

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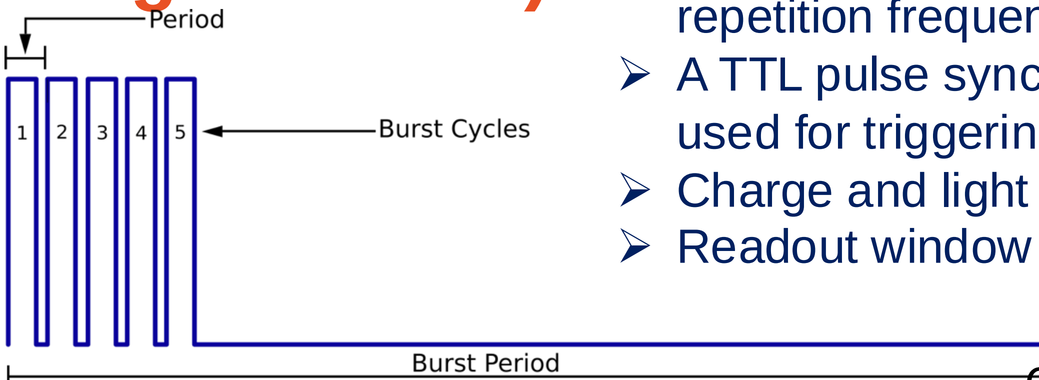
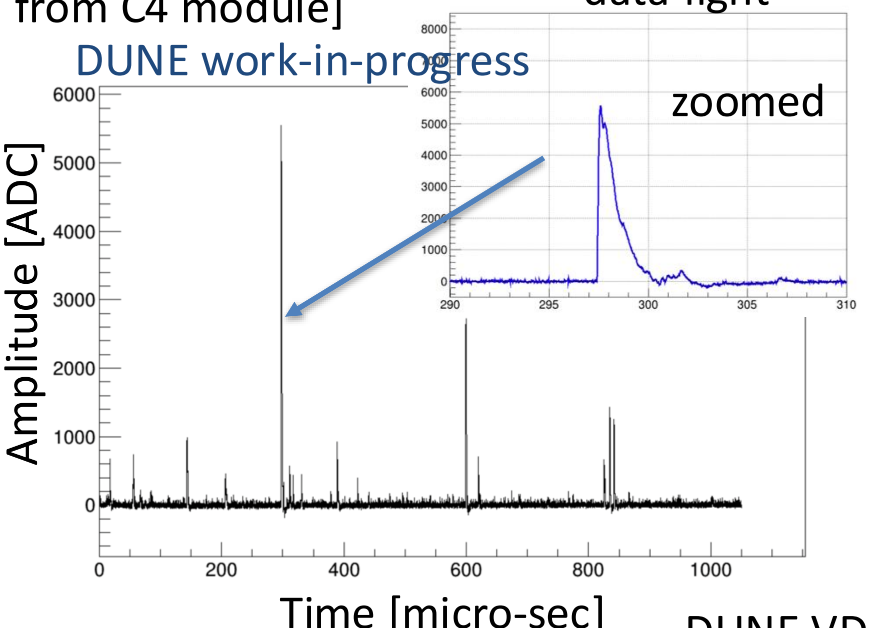
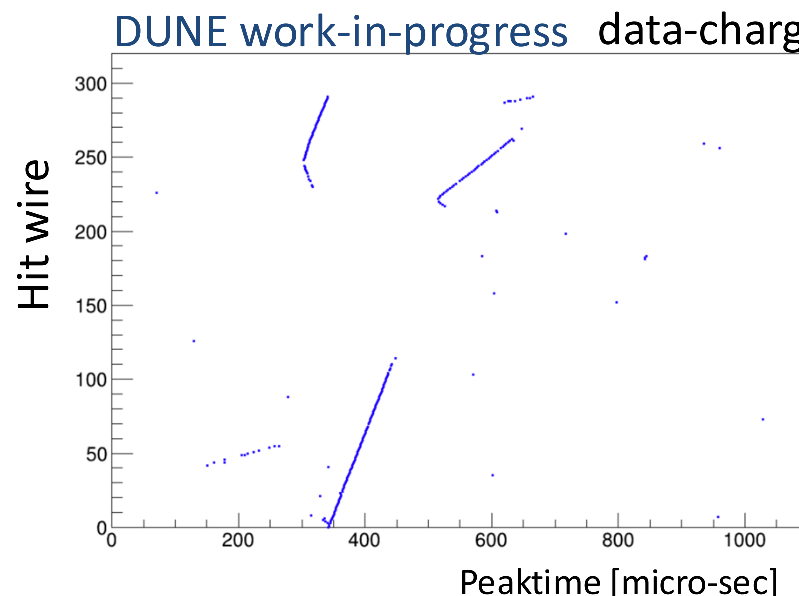


Light readout [showing one channel from C4 module]



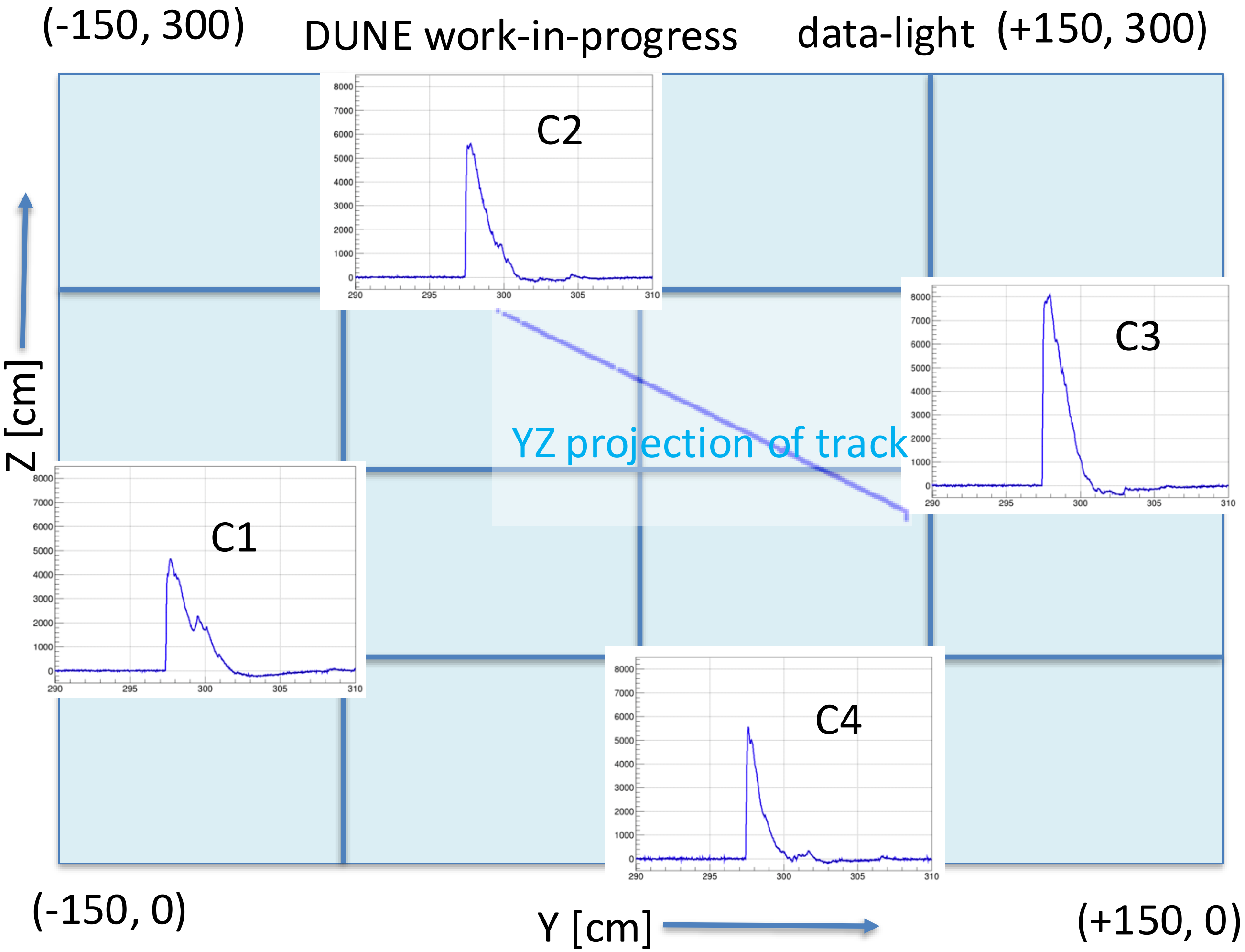
Charge readout [showing wire position vs time for collection plane]



DUNE VD coldbox data

Data analysis: PDS Flash reconstruction and TPC 3D Space-points

PDS reco Y = $\frac{\sum_{i=1}^{4} (PE_i \cdot PDS_i(Y_{\text{position}}))}{\sum_{i=1}^{4} PE_i}$ PDS reco Z = $\frac{\sum_{i=1}^{4} (PE_i \times PDS_i(Z_{\text{position}}))}{\sum_{i=1}^{4} PE_i}$



Coldbox view from top (schematic)

The grids on the left shows the cathode frame and the waveforms for the 4 X-ARAPUCA channels at corresponding location.