# Neutron capture event study using DUNE Far Detector prototype at CERN

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On behalf of the DUNE collaboration

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# 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

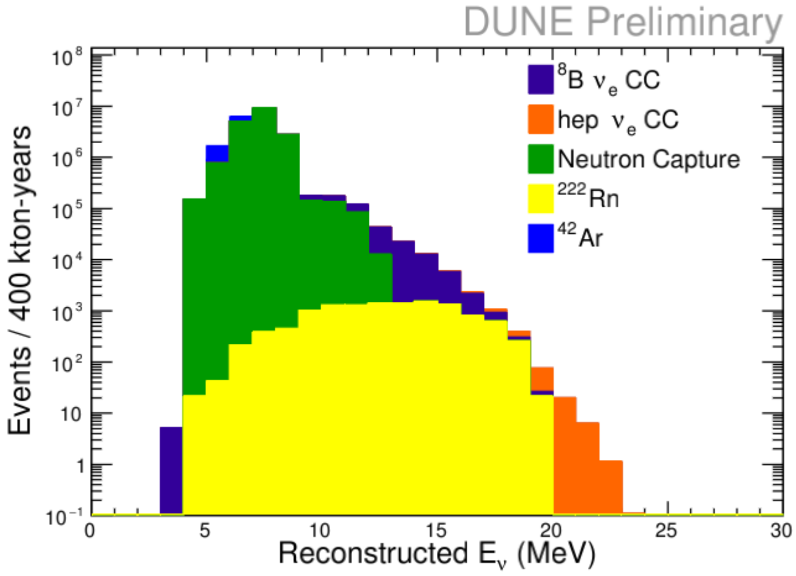
$$\nu_e + 40Ar \rightarrow e- + 40K^*$$

- 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.

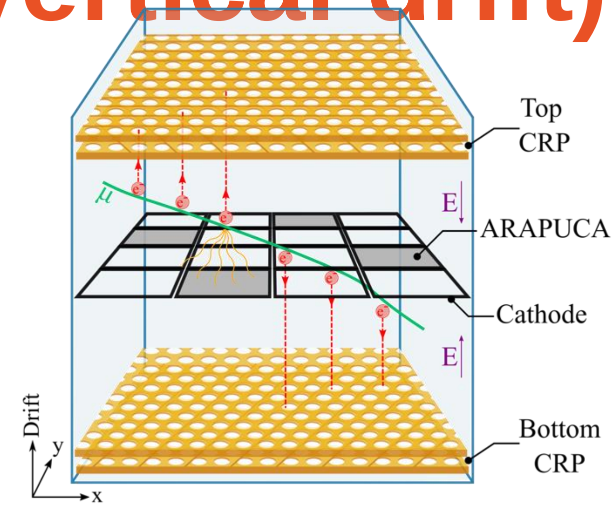
- Tagging neutron capture events is very important for DUNE low energy physics program.



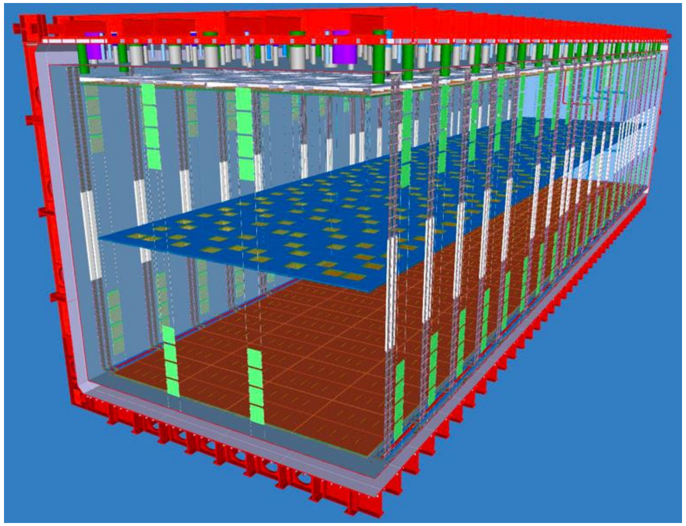

Simulated solar neutrino spectrum with background for the DUNE Far Detector. Reference doi = {10.22323/1.414.0621}

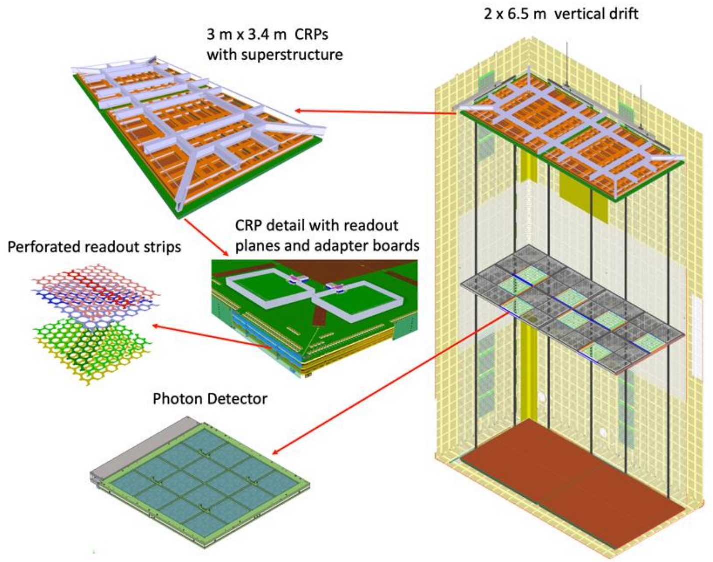
# DUNE FD2 LArTPC (Vertical drift):

- Charge readout plane (CRP) technology and X-ARAPUCA technology (photon detectors)
- PDS will be placed on the HV cathode surface (using the novel Power over fiber arXiv:2405.16816 and signal over fiber technology) and behind field cage as well, additionally reflective CRP surface; makes the detector coverage of ~4π




LArTPC working( Credit:Laura Zambelli)






*Active volume dimensions: 60 x 12 x 13 $m^3$

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

# PDS for calorimetry:

- For energy reconstruction using PDS, we will need a Light Yield (Number of photons detected per MeV of energy deposited) map as a function of 3D coordinate.

LArTPC calibration source:

- ➢ Cover the bulk of the active volume
- ➢ Should have a known energy spectrum
- ➢ Should be point like or at least confined in a small region

DUNE simulation

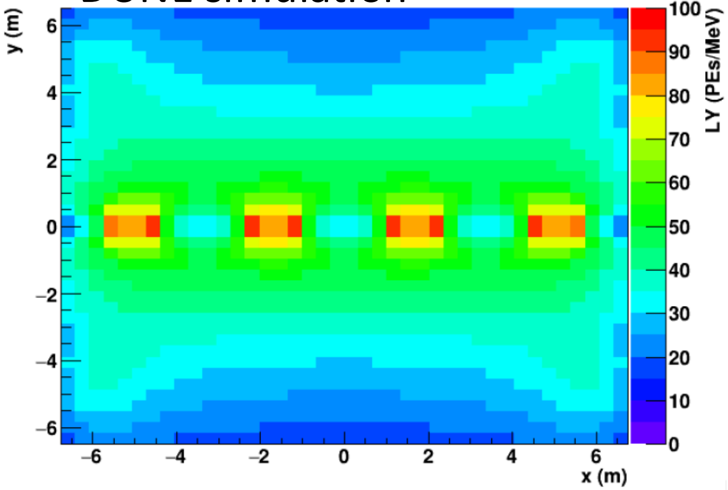



Fig: Map of the light yield (LY) in the central (x, y) transverse plane at z = 0 for the reference configuration. Fig from [DUNE FD TDR (JINST 19 (2024) )T08004]

#of photons detected → Light Yield Map (calibration) → Energy deposited

# 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 anti resonance 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
- ✓ Should have a known energy spectrum
- ✓ Should be point like or at least confined in a small region

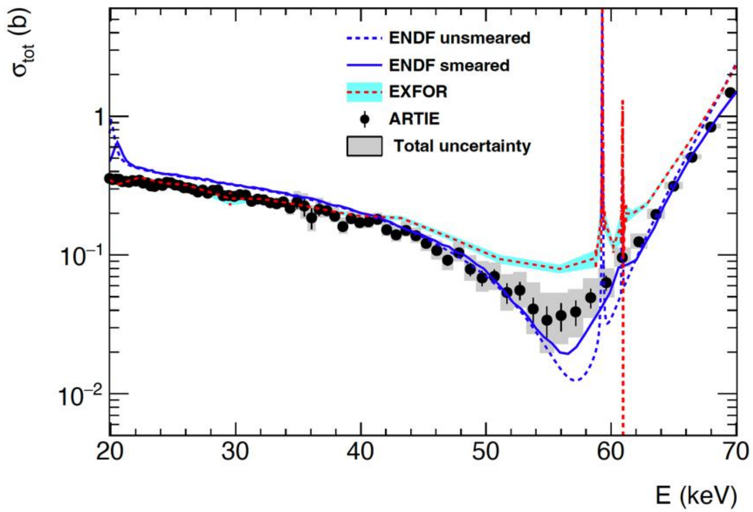
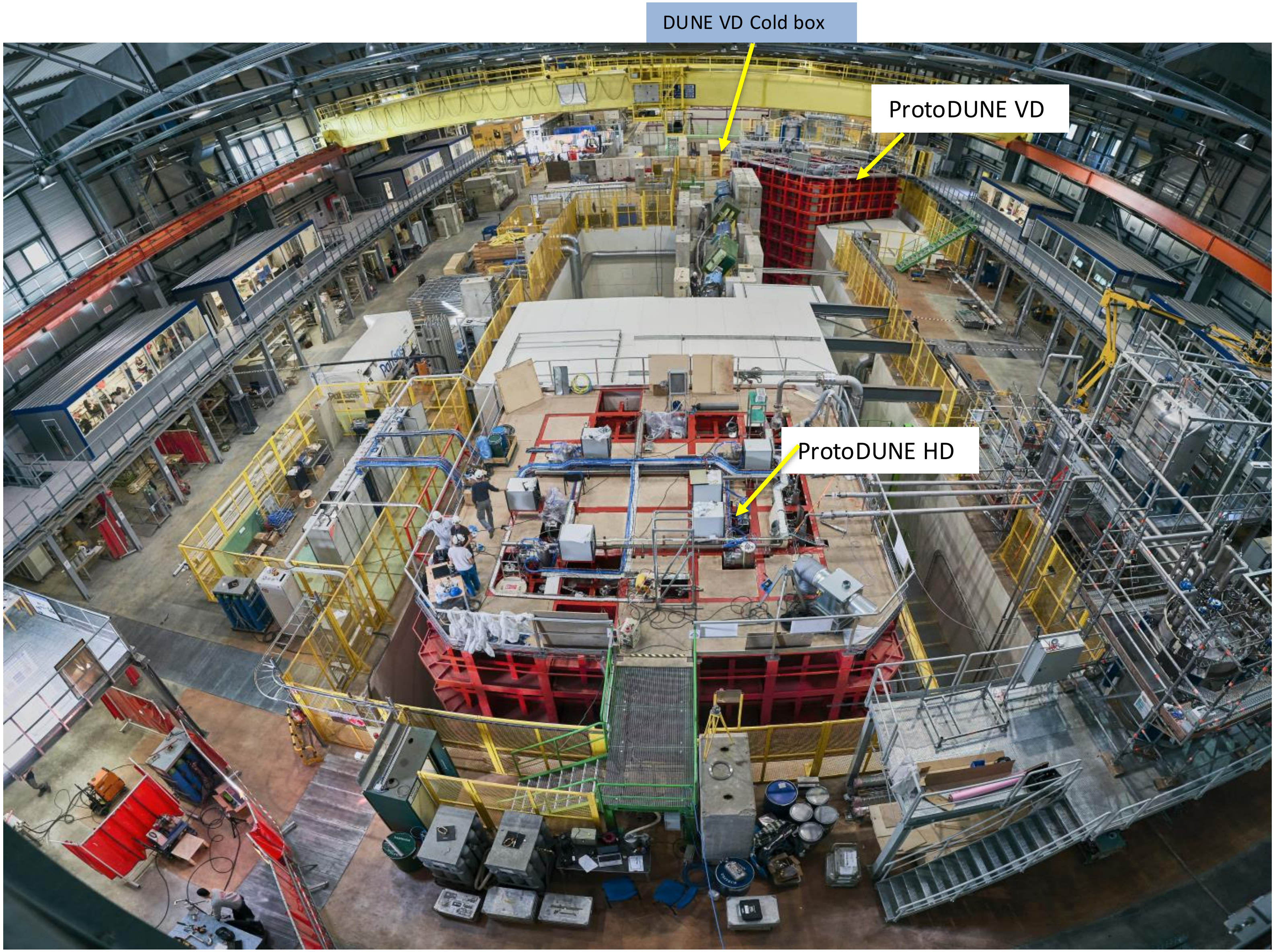



Fig: Neutron-argon total cross section as a function of energy.
https://arxiv.org/abs/2212.05448

# PNS RUN AT THE CERN NEUTRINO PLATFORM

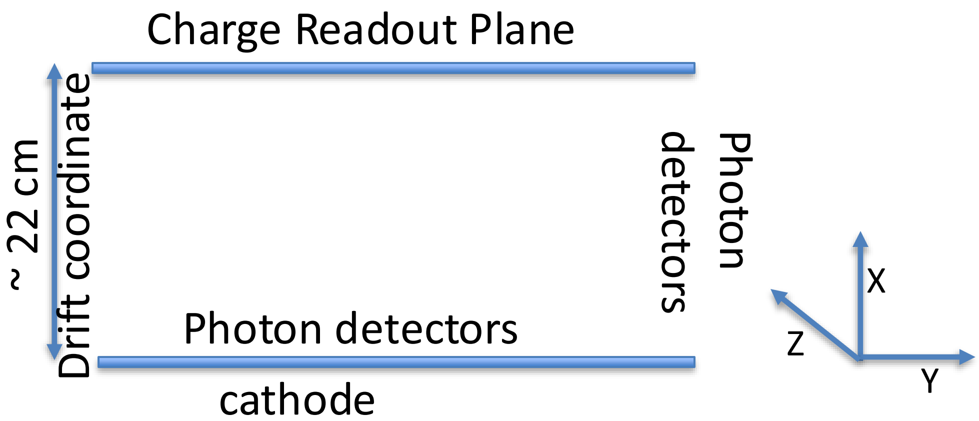




Pic credit (CERN)

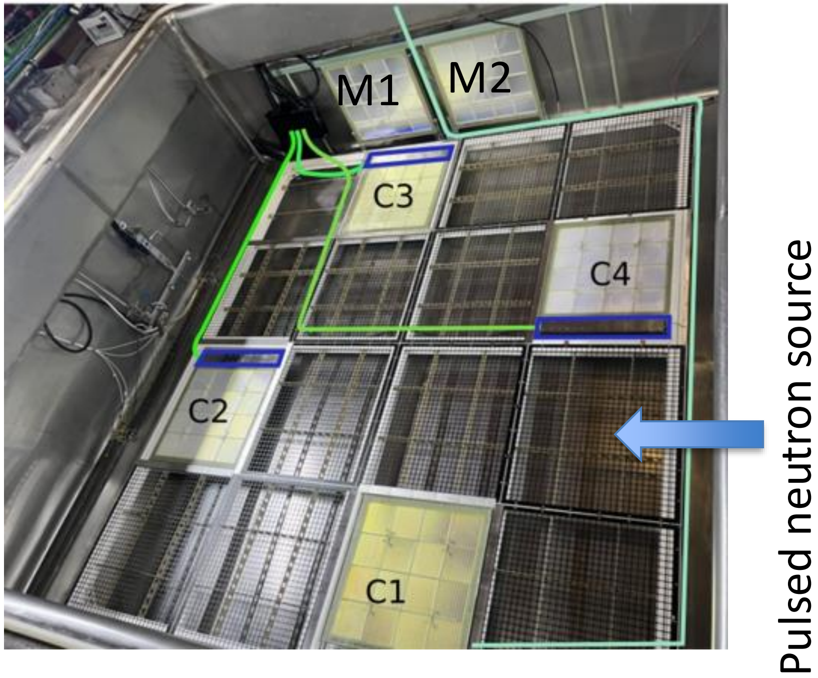
# DUNE VD Coldbox setup:

- Vertical Drift
- Prototype using full scale charge readout planes (CRP) and Photon detectors X-ARAPUCA 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)

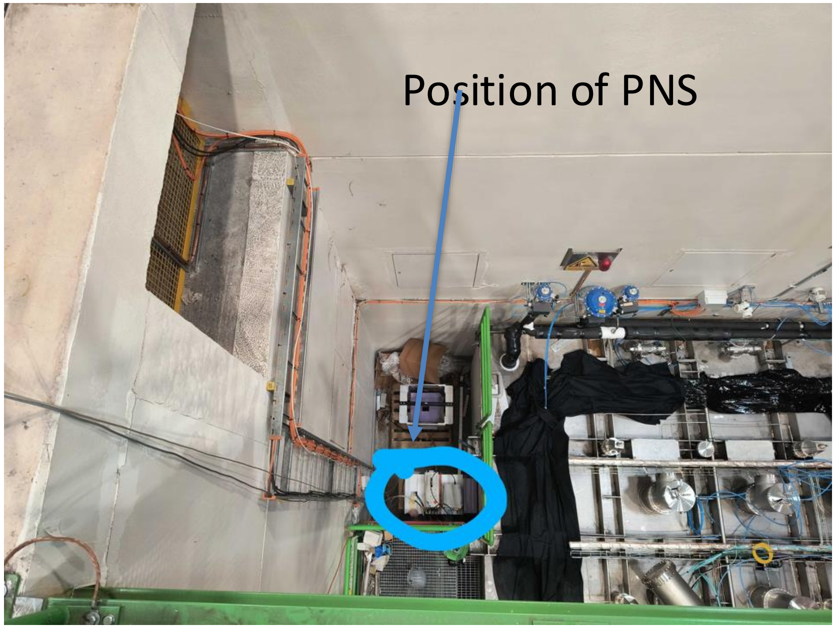
# Pulsed Neutron Source (PNS)

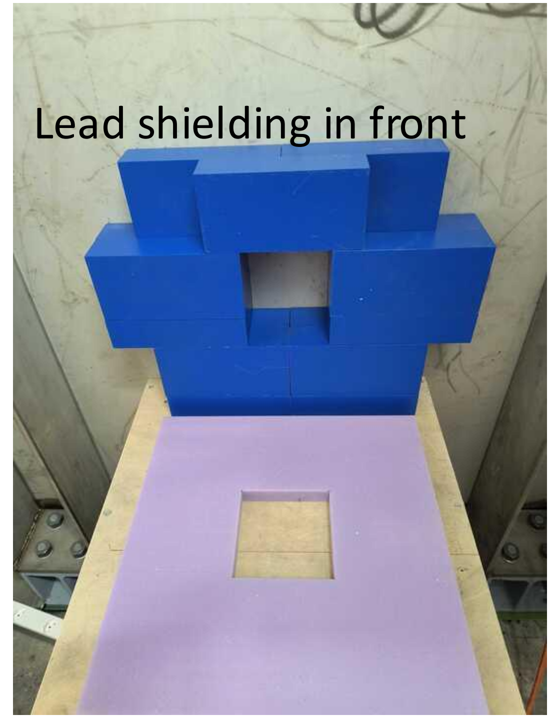

Commercial Thermo Fisher MP-320 Deuterium-Deuterium Generator (DDG), which produces monoenergetic 2.45 MeV neutrons with a flux of up to $10^6$ neutrons/second.

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

- Deployed outside the cryostat facing the active volume
- Adjustable neutron yield, pulse width and pulse rate
- Frequent calibration runs can be conducted installed at different location, due to the ease of deployment.

# PNS installation:



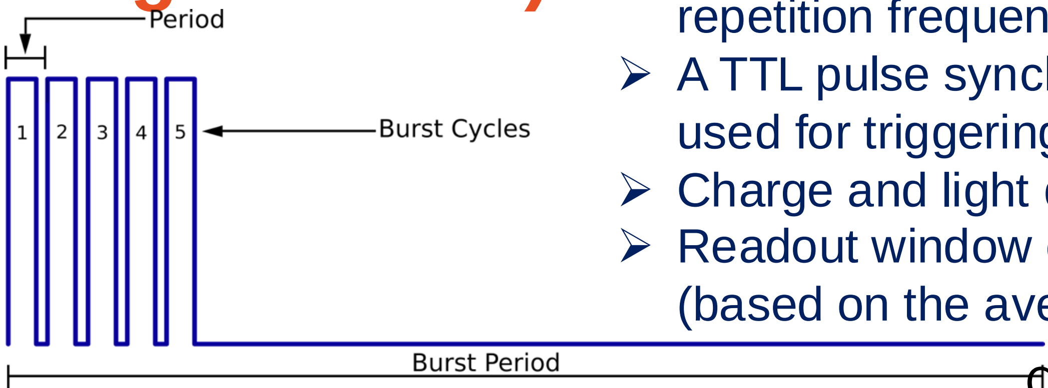




PNS before enclosing from back

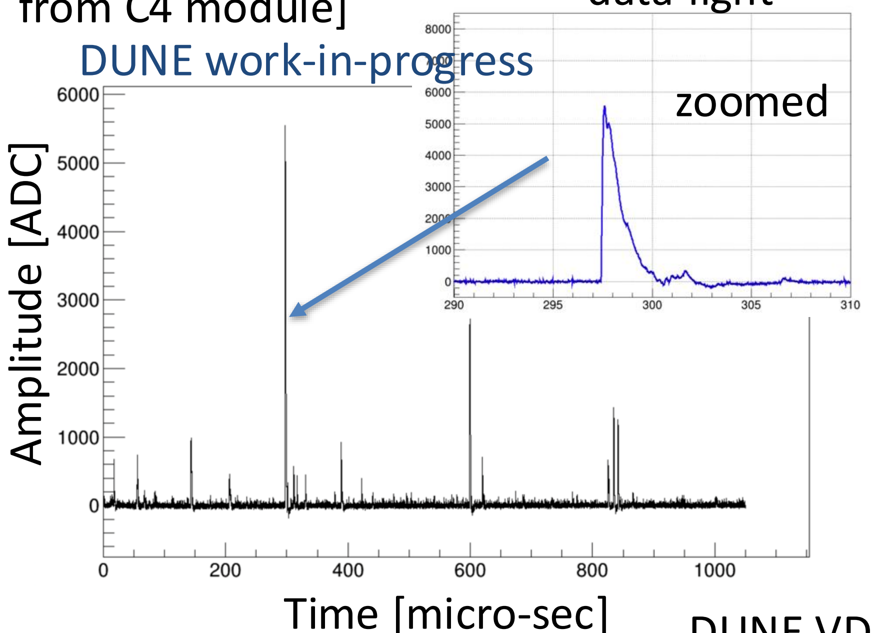
Polyethylene shielding enclosing PNS

# PNS data acquisition (simultaneous light and charge readout):

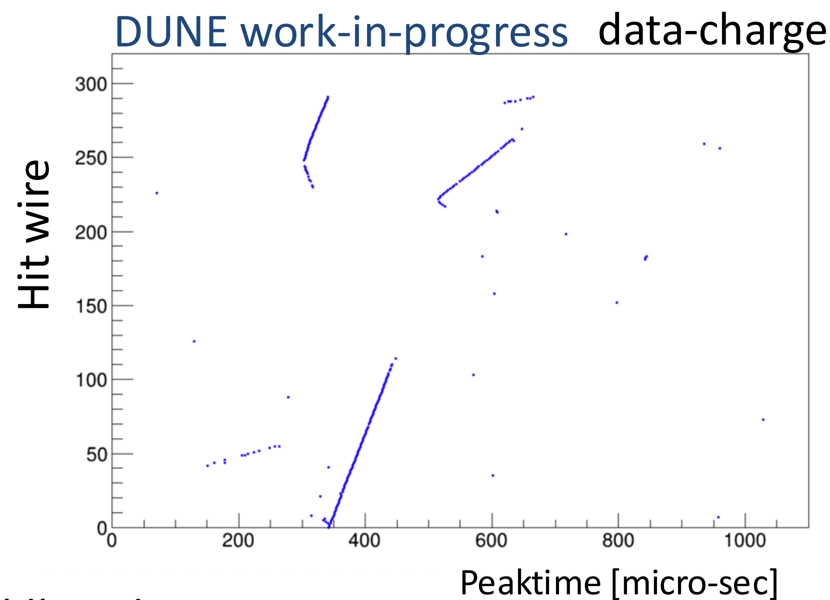
- Neutron beam produced in burst mode with a repetition frequency of 80 Hz
- A TTL pulse synchronous with the neutron beam is used for triggering the Data acquisition
- Charge and light data recorded simultaneously.
- Readout window of 1200 micro-sec after burst begins (based on the average capture time of 800 micro-sec)




Light readout [showing one channel from C4 module]




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

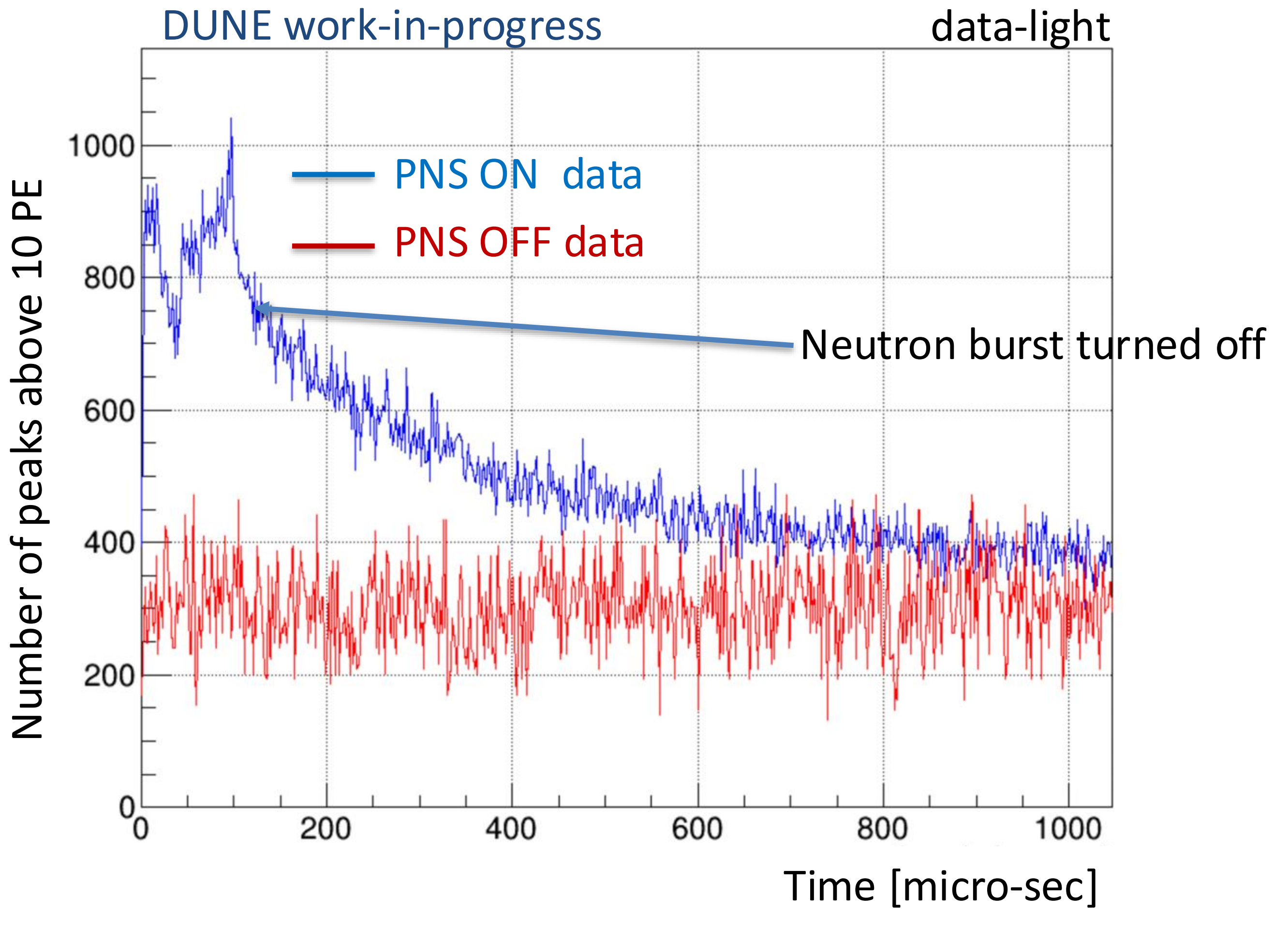



DUNE VD coldbox data

# Pulsed neutron source ON and OFF data:

Photon detector signals, C4 module

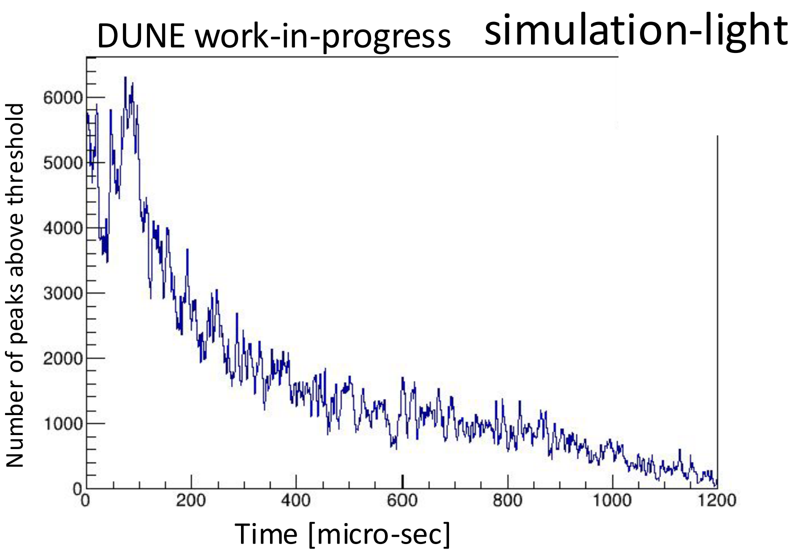
Number of peaks above a threshold of 10 Photo Electrons [PE] as a function of time since the neutron pulse is turned ON compared with a cosmics only run (PNS OFF).



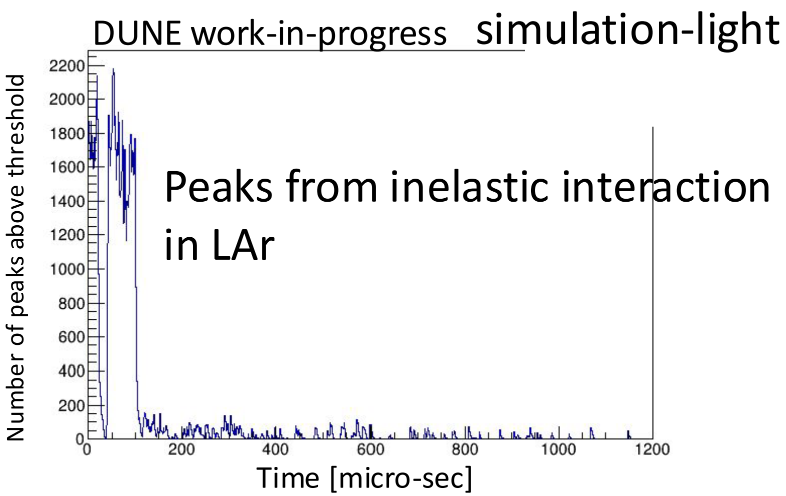
# Pulsed neutron source FLUKA simulation:

Work by: A Heindel, P Sala

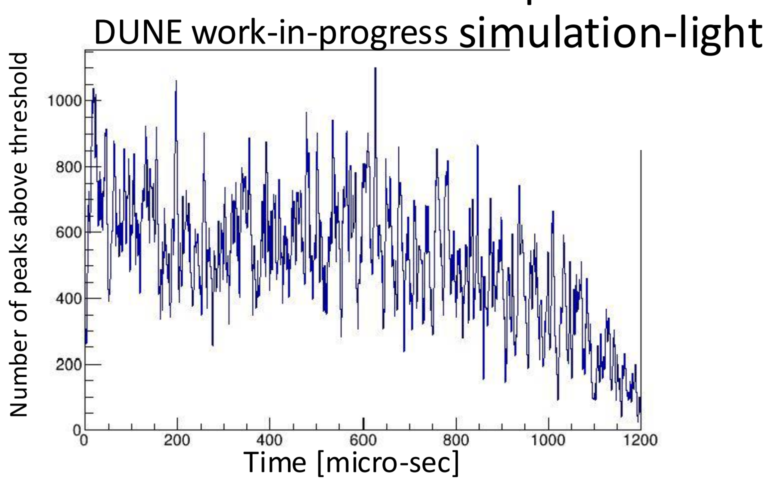
With the similar settings as data and using the DUNE VD Coldbox geometry FLUKA simulation was carried out:




All the peaks above threshold




Peaks from neutron capture in LAr




- Main processes the neutrons from the pulse undergo are inelastic interaction and neutron capture.
- Inelastic interaction happens when the beam is still ON

# Light charge matching validation:

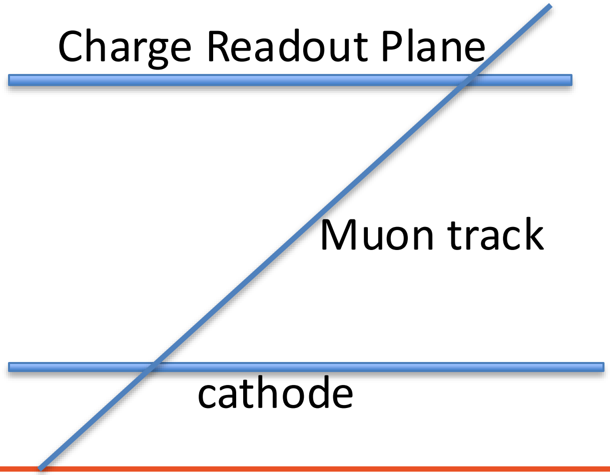
(Validation using cathode-anode crossing cosmic muons):

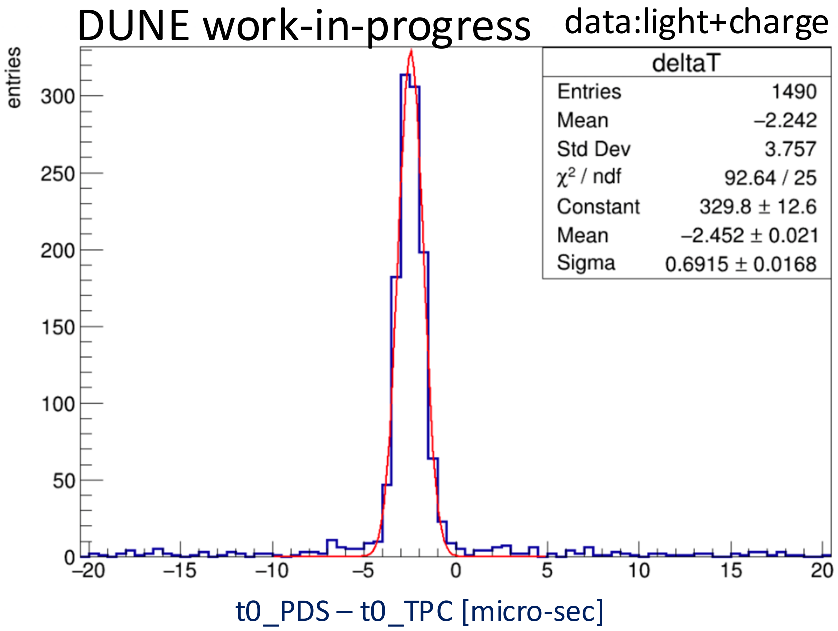
Jargon->PDS Flash: Signals hitting the photon detectors within 5 micro-sec window with one of the signal above 100 PE are combined.

For cathode-anode crossing tracks event time (t0) is equal to the time of arrival of first ionization electrons.

Comparing this time with the closest time for a Flash recorded by photon detection system:

Note: Sampling time of charge readout= 512 ns
Sampling time for light readout = 16 ns



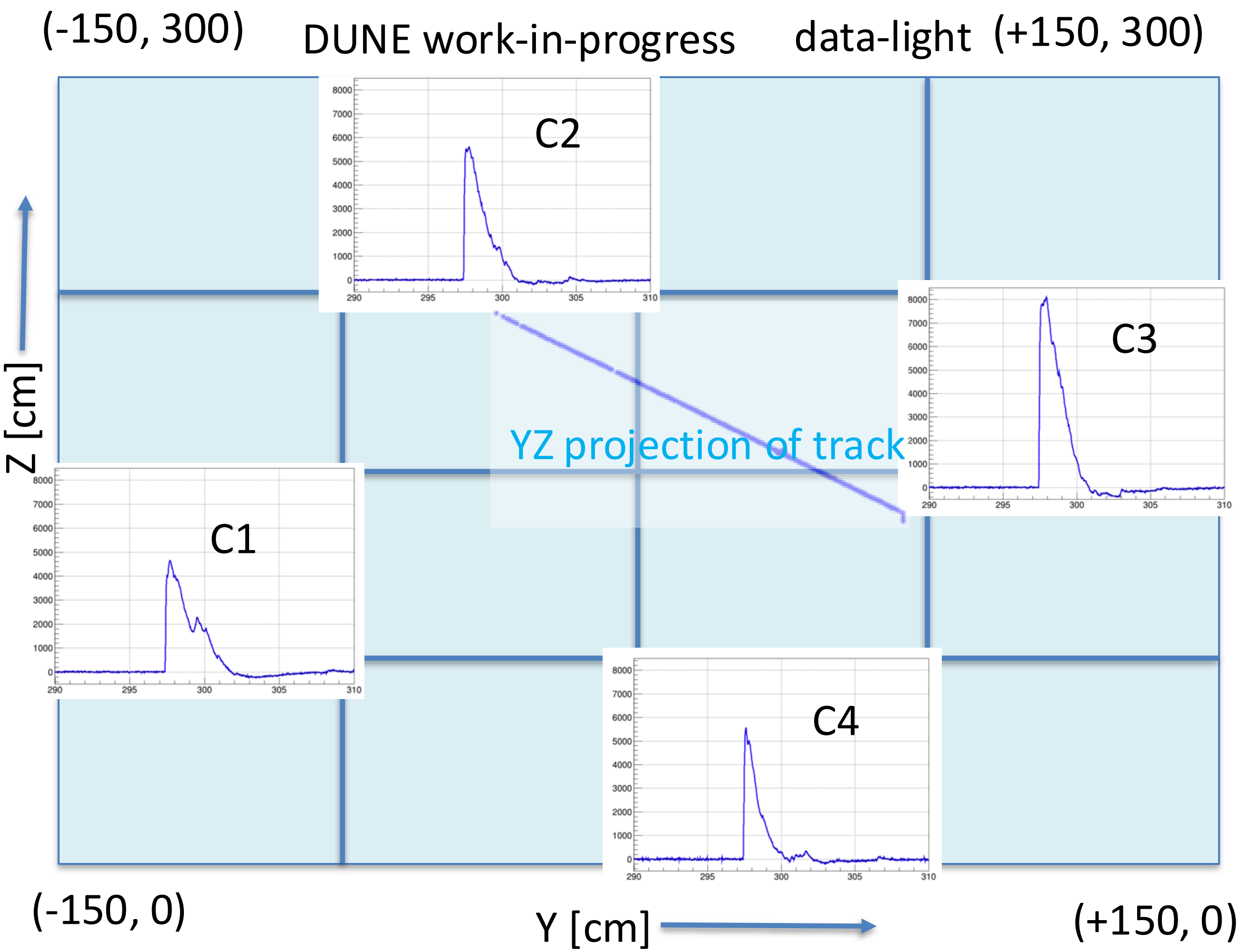



Fermilab DUNE

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

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

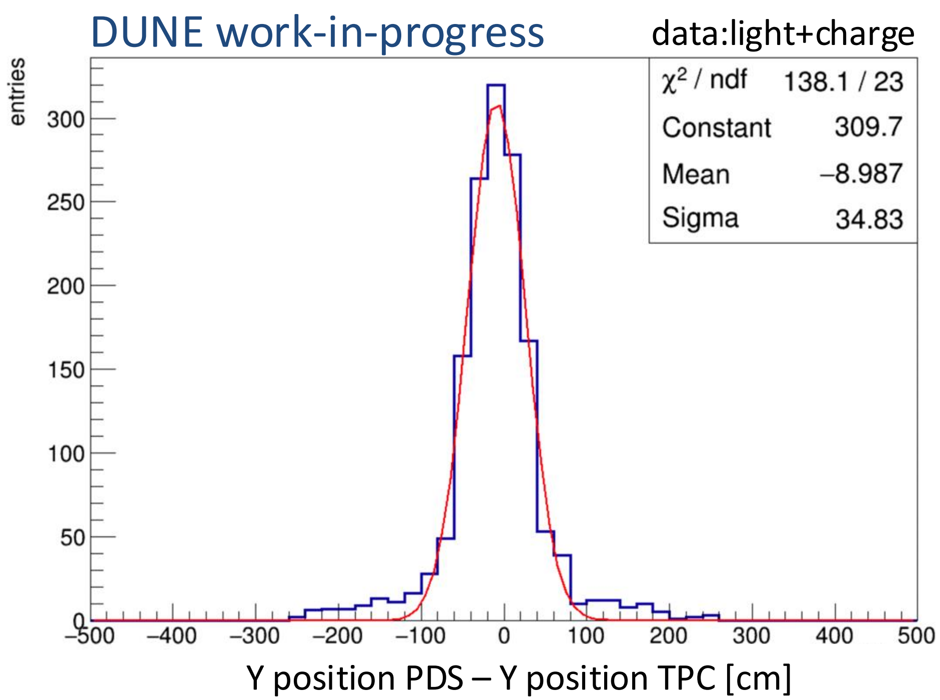
PDS reco Z = $\frac{\sum_{i=1}^{4}(PE_i \times PDS_i(Z_{\text{position}}))}{\sum_{i=1}^{4} PE_i}$

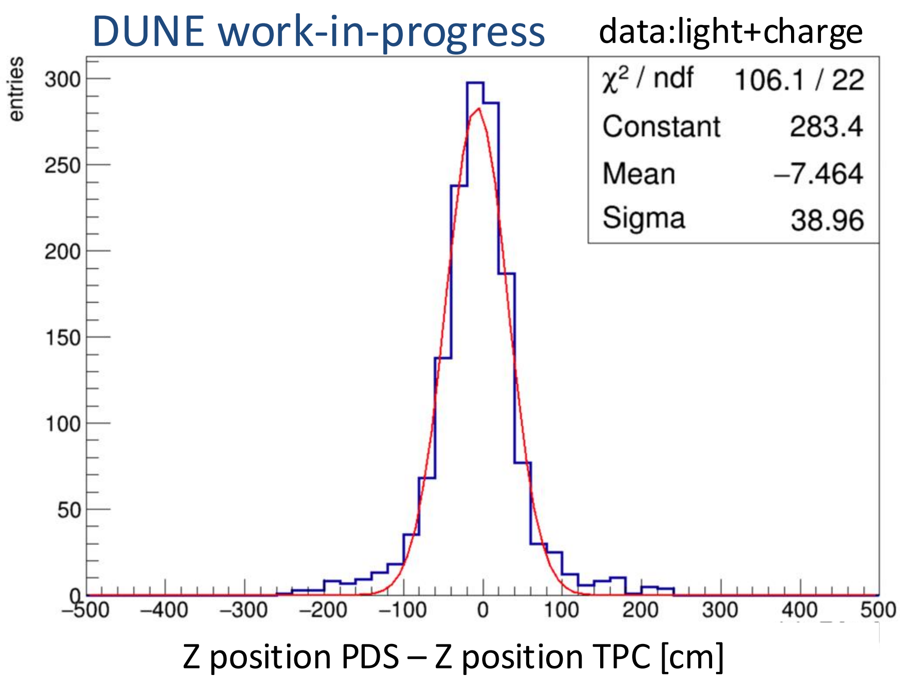



Coldbox view from top (schematic)

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

# Y and Z position resolution:




$\sigma_Y$ = 34.8 cm
$\sigma_Z$ =39 cm
} PDS tiles are 60 cm x 60 cm and CRP wire spacing ~0.5 cm

# Selecting neutron capture candidates (Work in progress):

Characteristics:

- ➢ Neutron capture appears as a cascade of gamma with energy summing up to 6.1 MeV.
- ➢ A  single gamma deposit maximum energy of 4.7 MeV (<2.5 cm)
- ➢ Gammas will appear as short clusters contained in ~1m

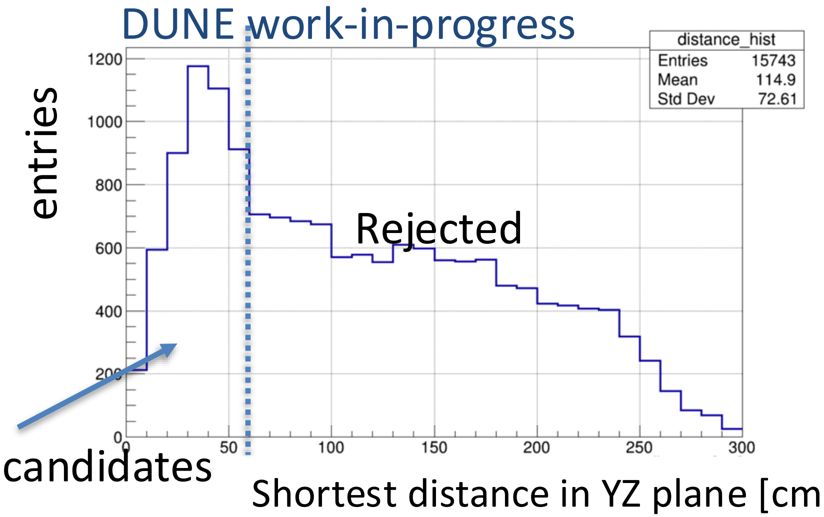
Major background are the cosmic muons and 39Ar:

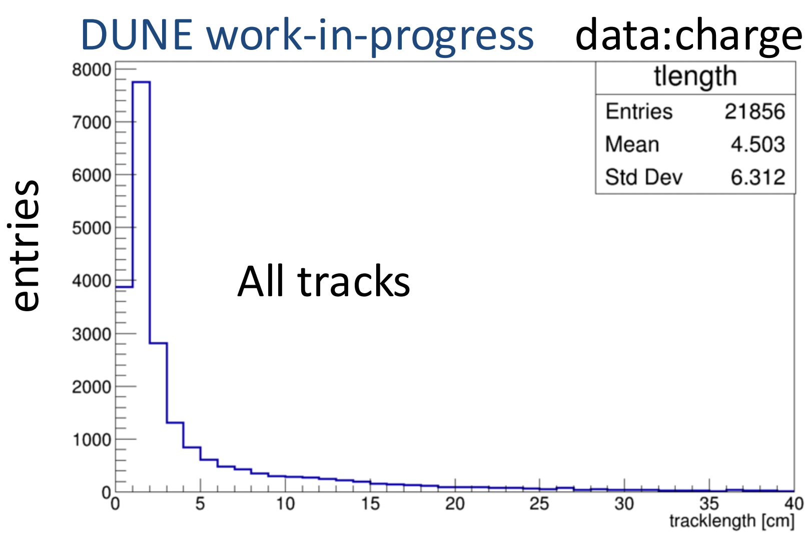
→For cosmic removal fiducial volume cut is used. Tracks starting or ending within 10 cm of Y and Z boundary and 1 cm from the top are removed.

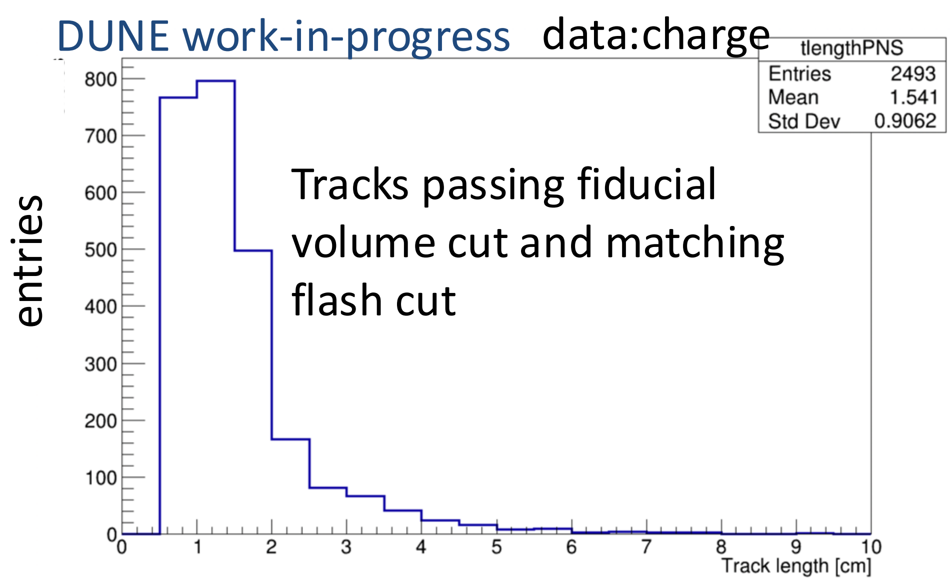
# Event Selection after fiducial volume cut:

- 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



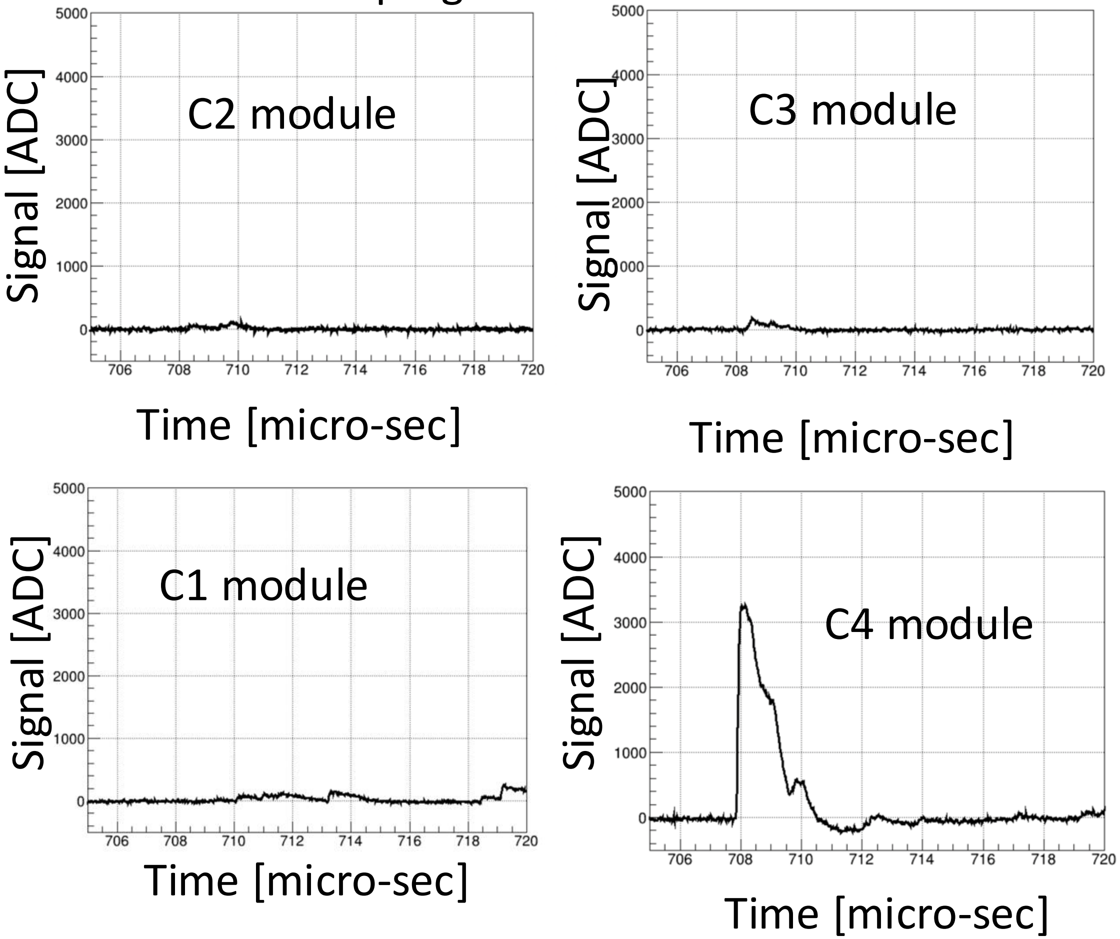



# Event display for candidate Neutron Capture event:

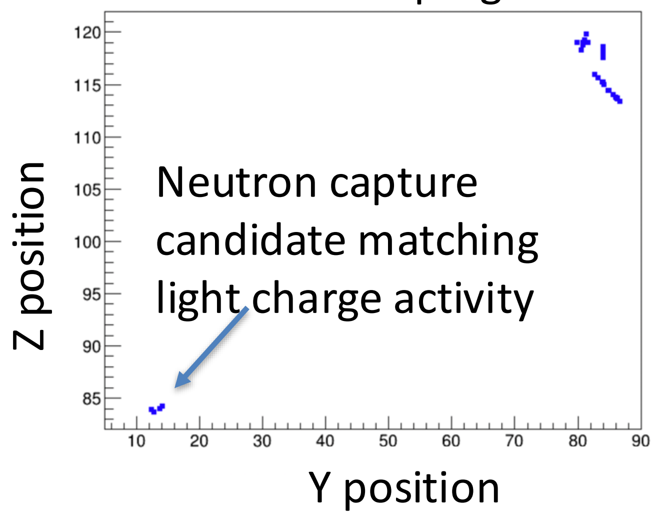
data-light

DUNE work-in-progress




data-charge

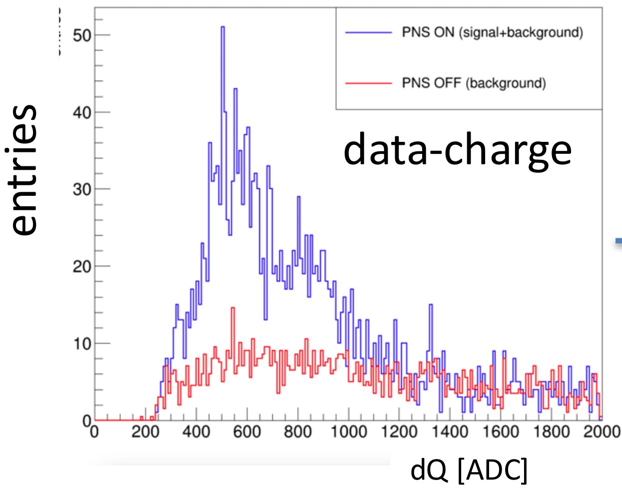
DUNE work-in-progress



# Charge and light distribution for the selected events:

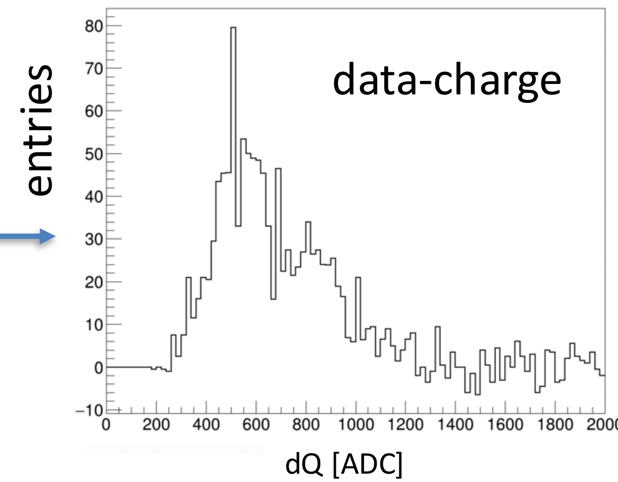
DUNE work-in-progress

Summed charge for selected tracks



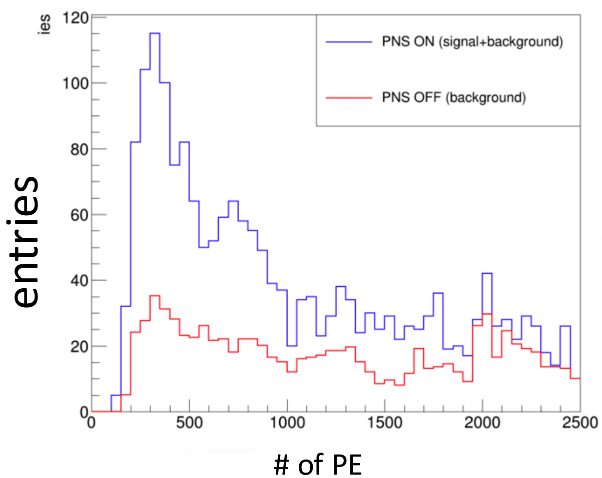

After background subtraction

DUNE work-in-progress




data-light

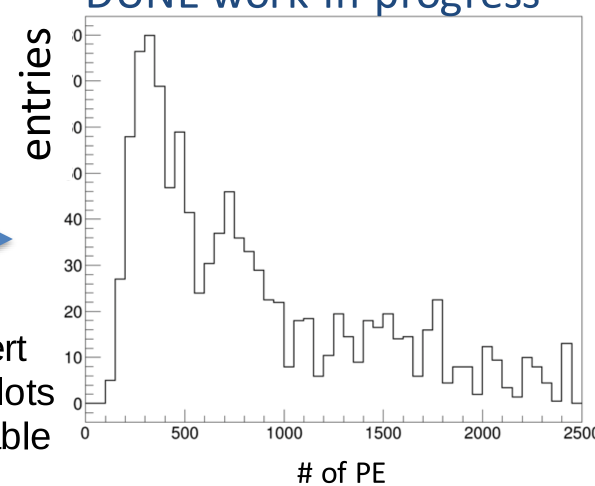
DUNE work-in-progress




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

After background subtraction

DUNE work-in-progress



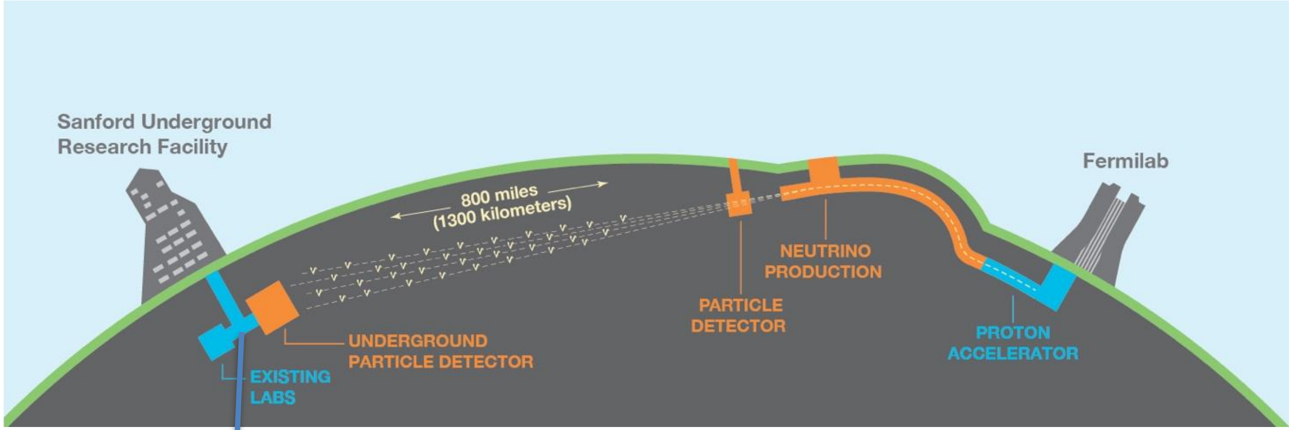

Note:
Calibration work in progress to convert charge/light into energy deposited. Plots are preliminary, using <10% of available statistics.

# SUMMARY

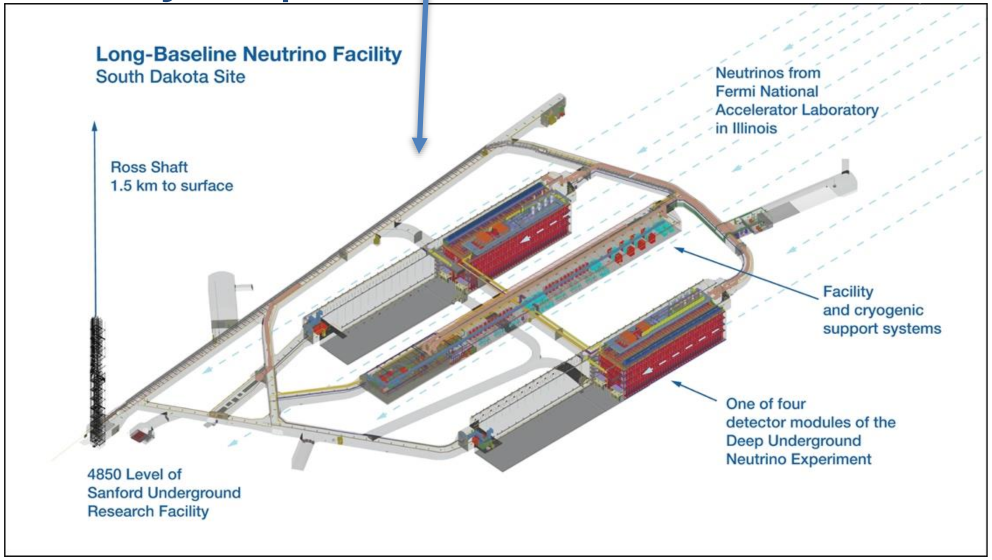
- LArTPCs are well suited for double calorimetry using charge and light information.
- Tagging neutrons efficiently can enhance the DUNE low energy physics program.
- Neutron capture is a viable candidate to be used as a standard candle for energy scale calibration.
- First run with neutron source using DDG recently concluded (April 2024), data analysis ongoing.
- More data collection in the bigger DUNE prototypes at the CERN neutrino platform planned for later this year.

# BACKUP SLIDES

# Deep Underground Neutrino Experiment




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




- (2 + 2) 17kt modules
- 1300 km away
- 1.5 km underground
- 1$^{st}$ module →Horizontal drift LArTPC
- 2$^{nd}$ module →Vertical drift LArTPC
- 3$^{rd}$ and 4$^{th}$ modules to be built in Phase II, proposals and R&D ongoing

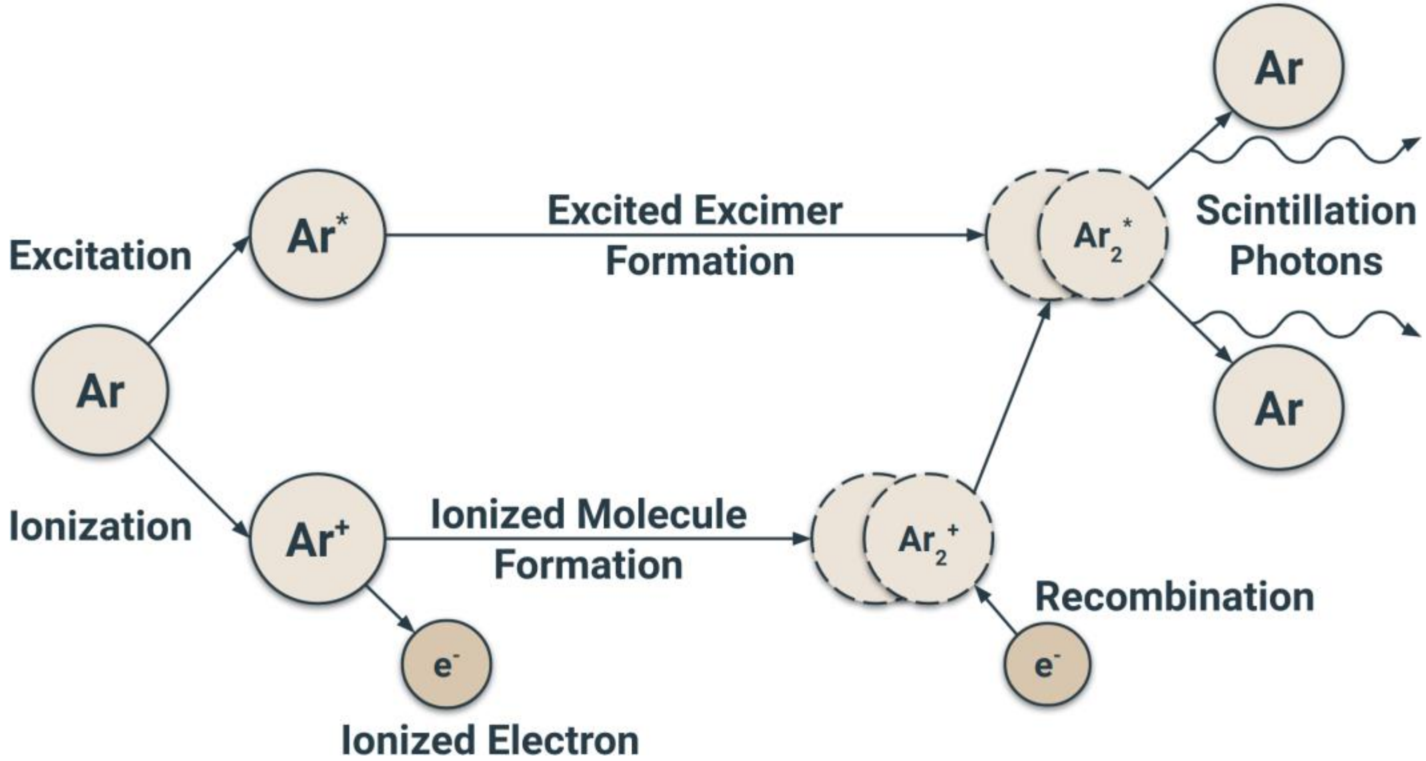



Fig: Mechanism of scintiallation light production in Ar.
Figure from arXiv:2002.03010