Neutron capture event selection using light and charge matching in the second DUNE Far Detector (FD2) module prototype at CERN

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On behalf of the DUNE collaboration

LIDINE 2024- (Aug 26-28, 2024) Principia Institute, São Paulo (Brazil)

Outline:

- DUNE Far Detector module 2 detector (DUNE FD2)
- Photon detector system for calorimetry using neutron capture
- DUNE FD2 prototype coldbox at CERN
- Pulsed Neutron Source run
- Data analysis/Results

LArTPC working principle (HD design):

- Cathode at high voltage (few 100s of kV)
- Uniform electric field between cathode and anode (~500 V/cm).
- To make the Efield uniform field cage is installed covering the remaining TPC faces.
- A charged particle produces ionization electrons and scintillation light as it pass through the detector.
- Charge read by APA, and light detected by PDS

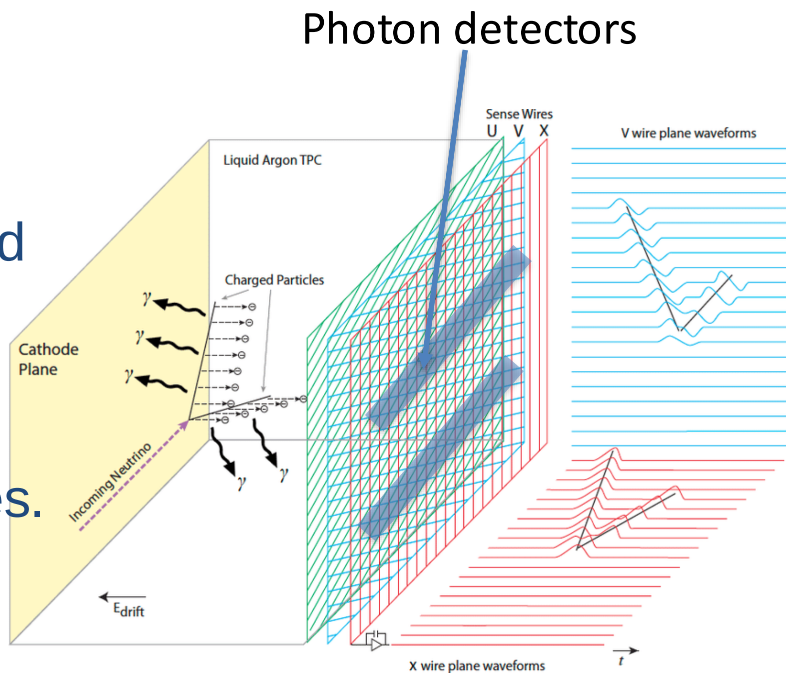
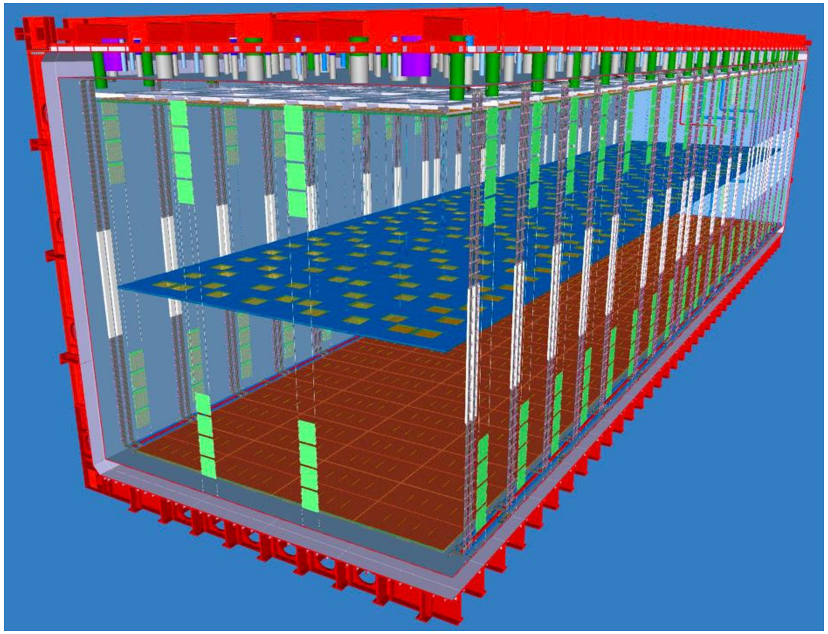


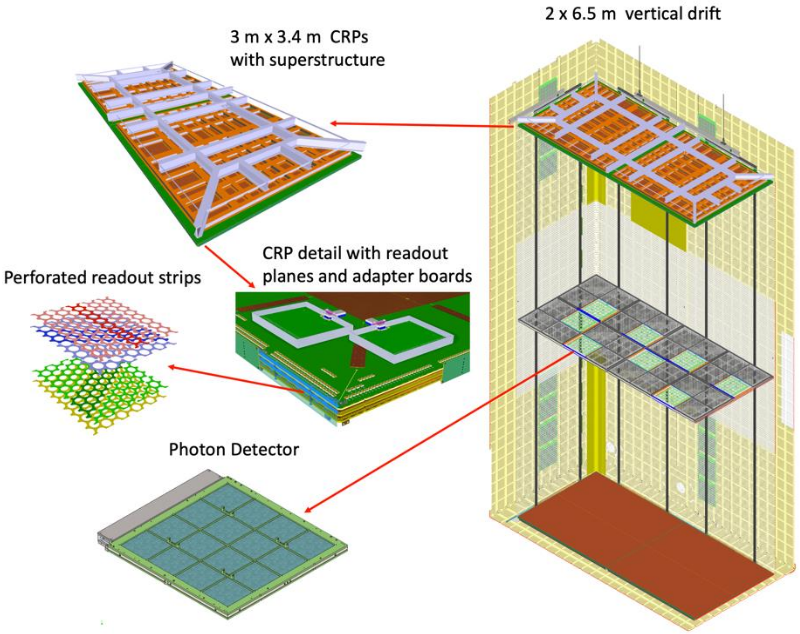
Fig: LArTPC working principle*

*JINST 13 (2018) 07, P07006.

DUNE FD2 LArTPC (Vertical drift):

- Charge readout plane (CRP) technology used
- CRPs have low transparency. Placing PDS behind CRP results in low light collection efficiency.
- Initial design field cage also had very low transparency.
- Placing the PDS on HV cathode surface (~300kV) allows higher light collection
- In the final design PDS placed behind field cage as well, and reflective CRP surface; makes the detector coverage of ~4π





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

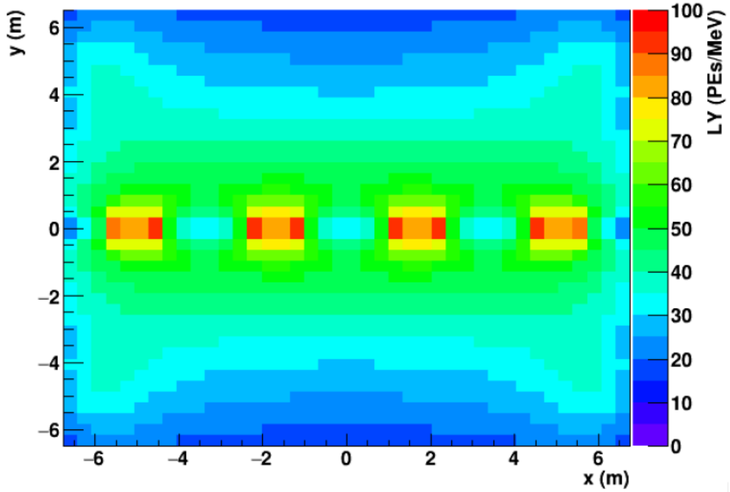


Fig: Map of the light yield (LY) in the central (x, y) transverse plane at z = 0 for the reference configuration. Fig from [DUNE FD TDR (JINST 19 (2024))T08004]

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

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Neutron capture for Calorimetry:

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

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

- Neutrons can travel ~30 m in liquid Argon before being captured

- Gamma cascade is contained within 1 m radius (compared to DUNE FD2 active volume60x12x13 m^3)

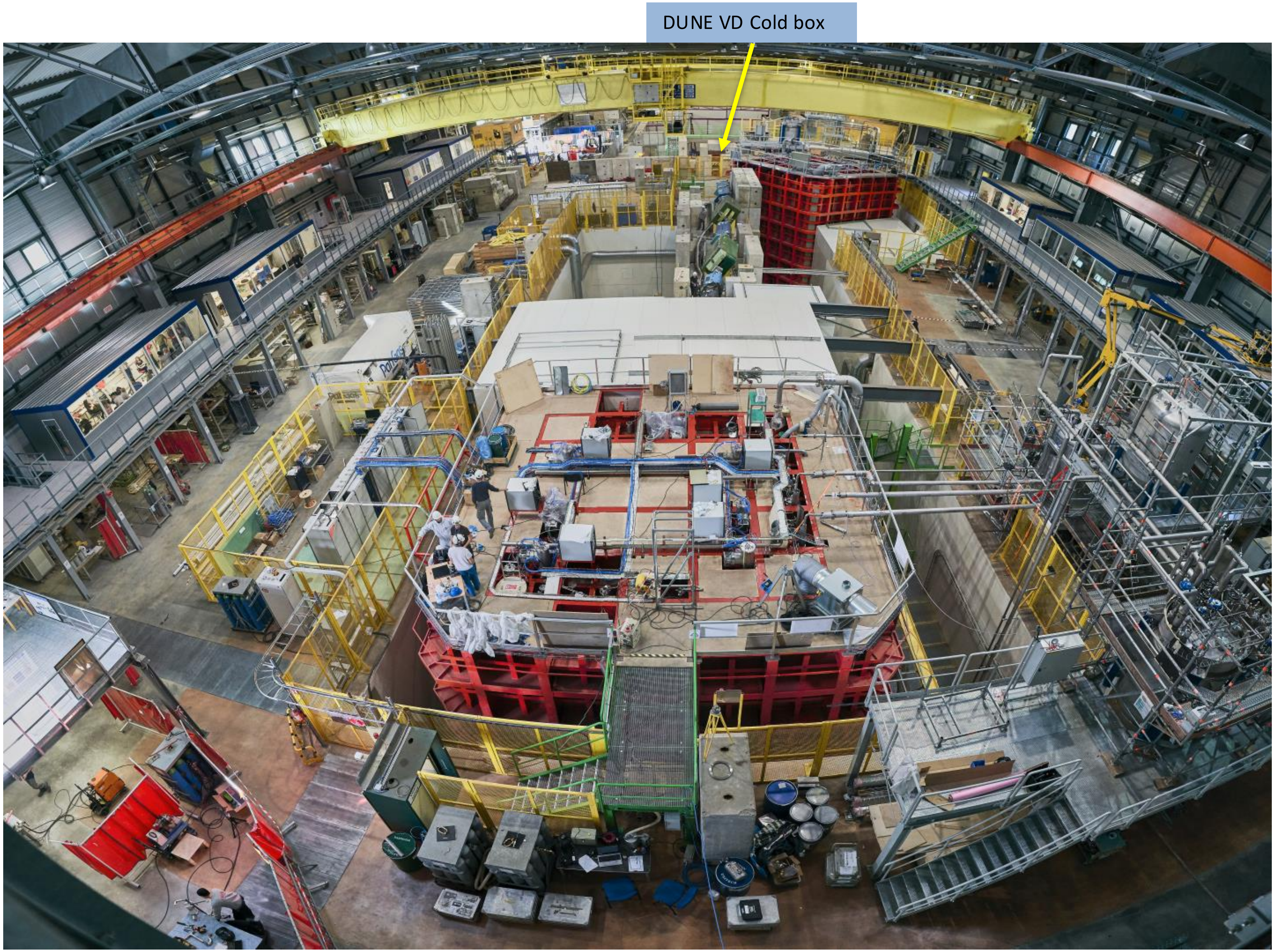
Neutrons from pulsed neutron source

- ✓ 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

Additionally: crucial to understand neutron capture signature for DUNE low energy physics:

- Cavern neutrons: major background for solar neutrino spectrum
- Efficiently tagging final state neutrons in supernova neutrino interaction will improve energy resolution

PNS RUN AT THE CERN NEUTRINO PLATFORM

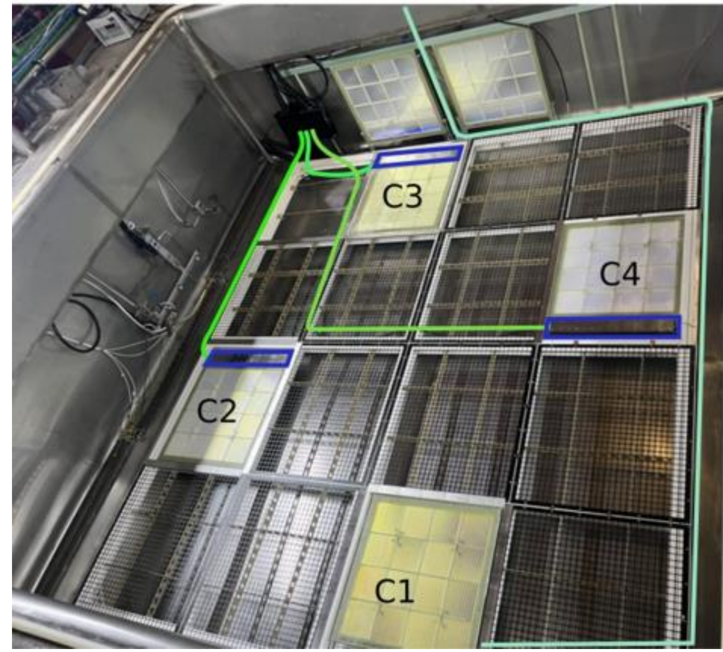


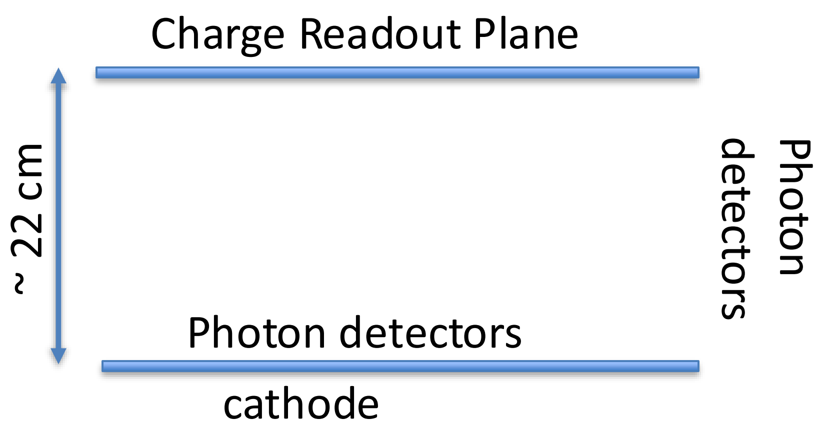
Pic credit (CERN)

DUNE FD2 Coldbox setup:

- Vertical Drift
- Prototype using full scale charge readout planes (CRP) and Photon detectors X-ARAPUCA [point to DUNE Photon detector talk] to be used in DUNE FD2

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)

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

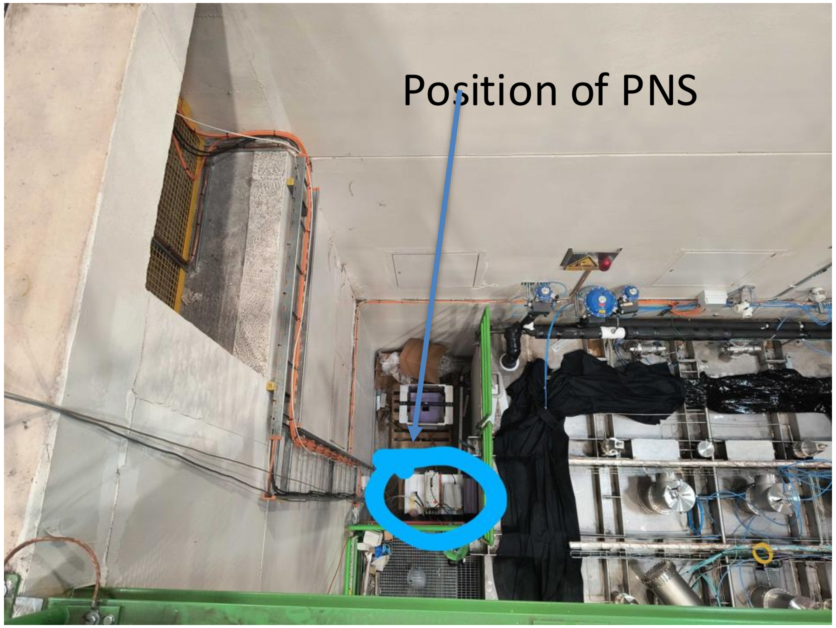
Pulsed Neutron Source (PNS)

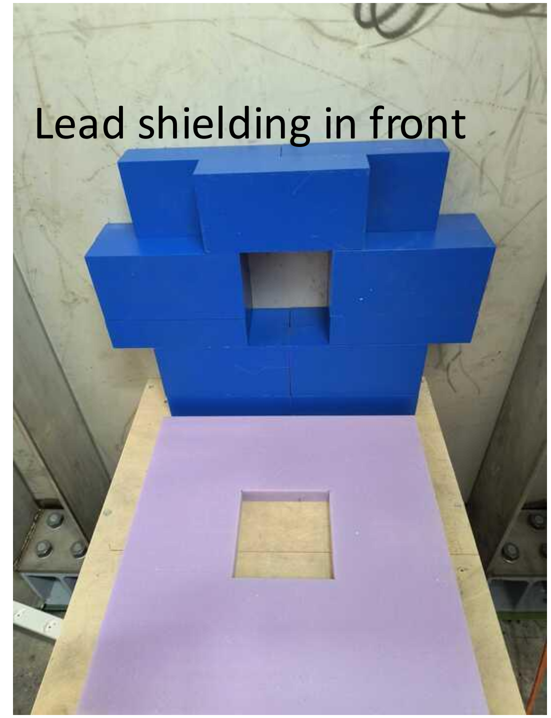
Commercial Thermo Fisher MP-320 Deuterium-Deuterium Generator (DDG), which produces monoenergetic 2.45 MeV neutrons with a flux of up to 10^6 neutrons/second.

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

- 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:

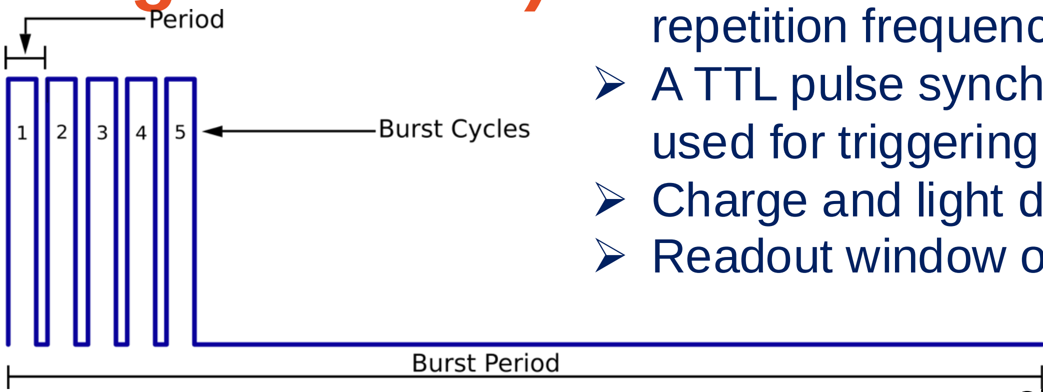




PNS before enclosing from back

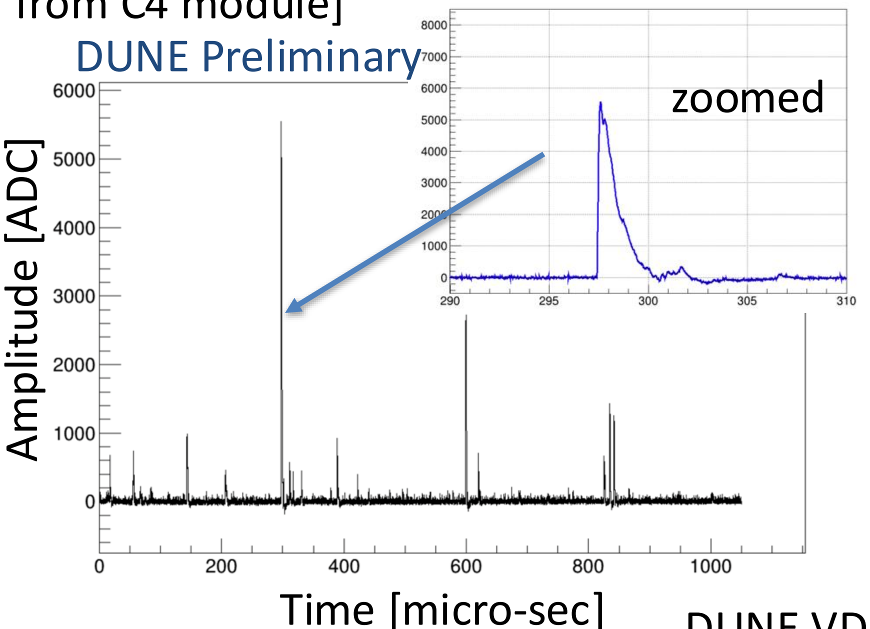
Polyethylene shielding enclosing PNS

PNS data acquisition (simultaneous light and charge readout):

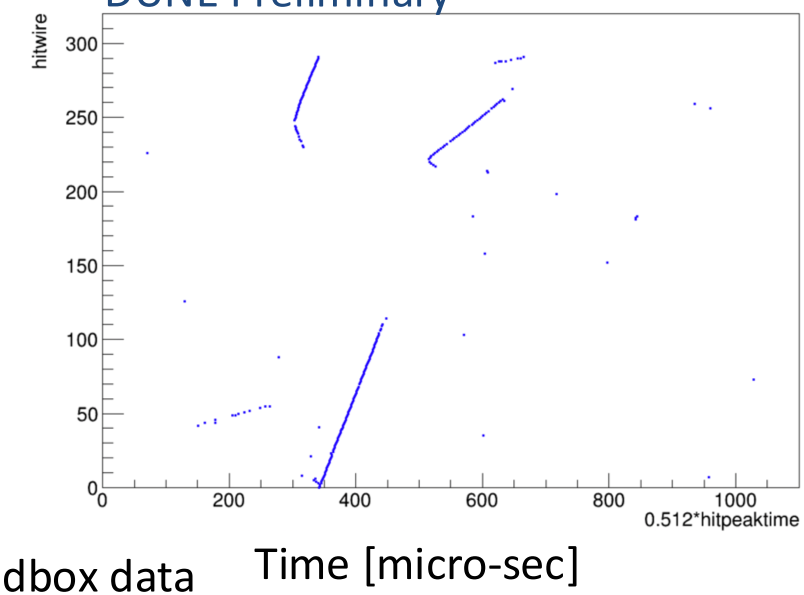


- Neutron beam produced in burst mode with a repetition frequency of 80 Hz
- A TTL pulse synchronous with the neutron beam is used for triggering the Data acquisition
- Charge and light data recorded simultaneously.
- Readout window of 1200 micro-sec after burst begins

Light readout [showing one channel from C4 module]



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

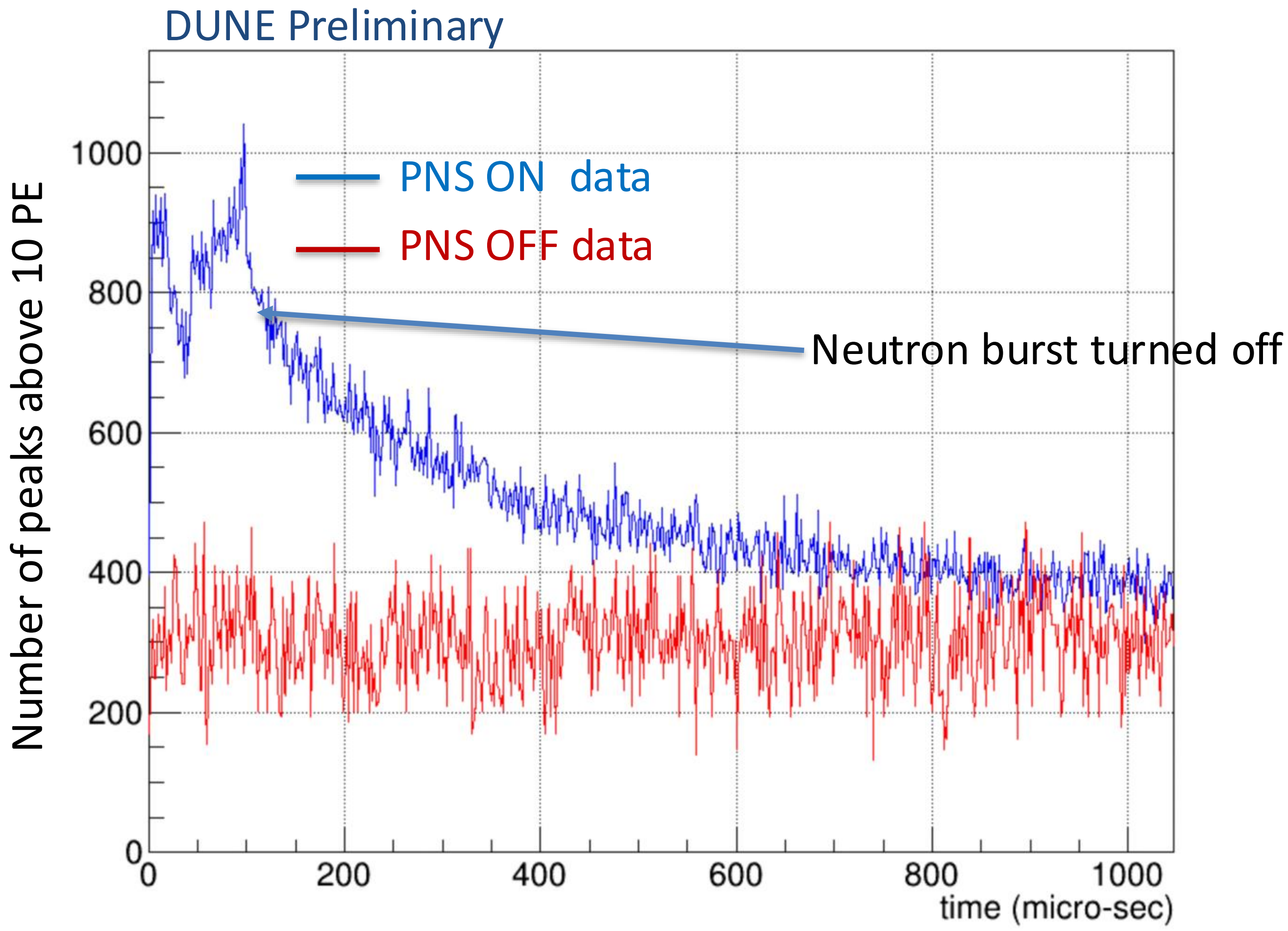


DUNE VD coldbox data

Pulsed neutron source ON and OFF data:

Photon detector signals, C4 module

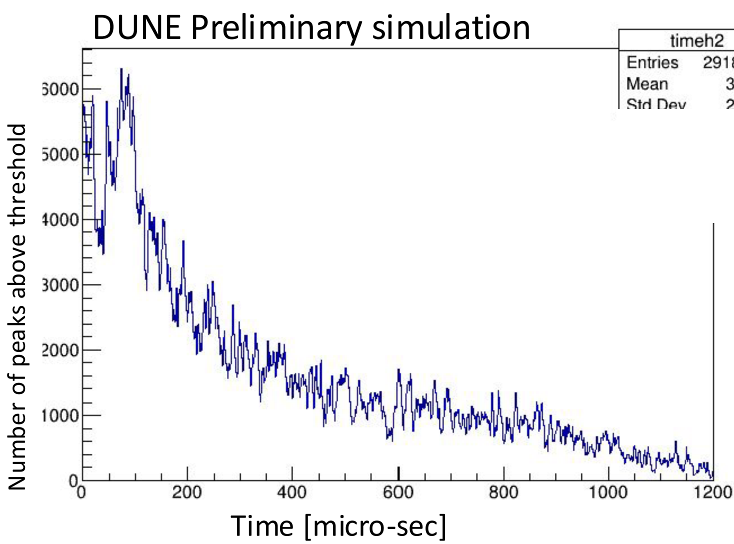
Number of peaks above a threshold of 10 PE as a function of time since the neutron pulse is turned ON compared with a cosmics only run (PNS OFF).



Pulsed neutron source FLUKA simulation:

Work by: A Heindel, P Sala

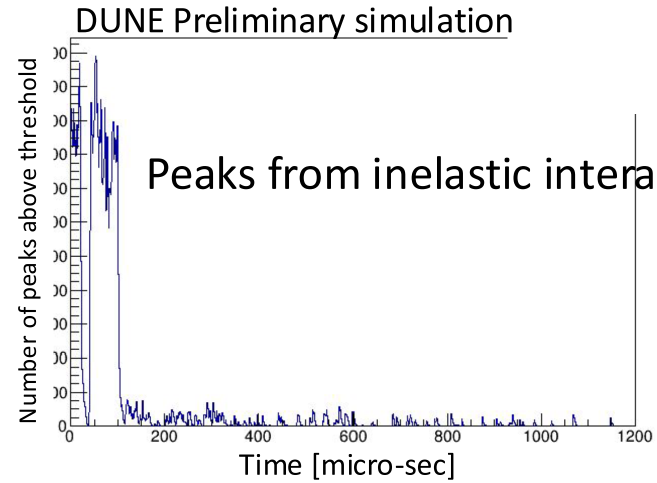
With the similar settings as data and using the Coldbox geometry FLUKA simulation was carried out:



All the peaks above threshold

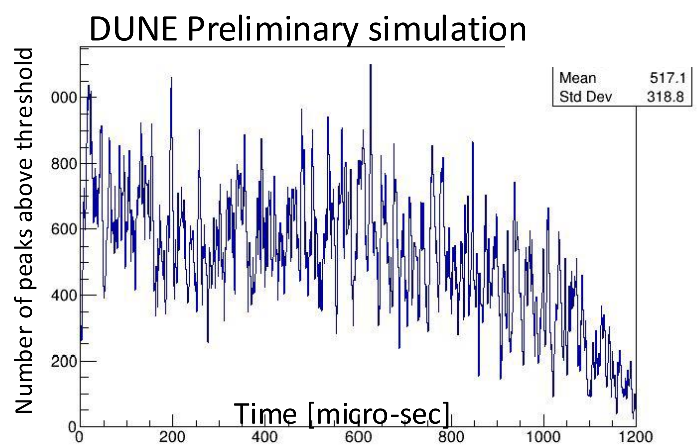
->Major processes the neutrons from the pulse undergo are inelastic interaction and neutron capture.

->Inelastic interaction happens when the beam is still ON



Peaks from inelastic interaction

Peaks from neutron capture



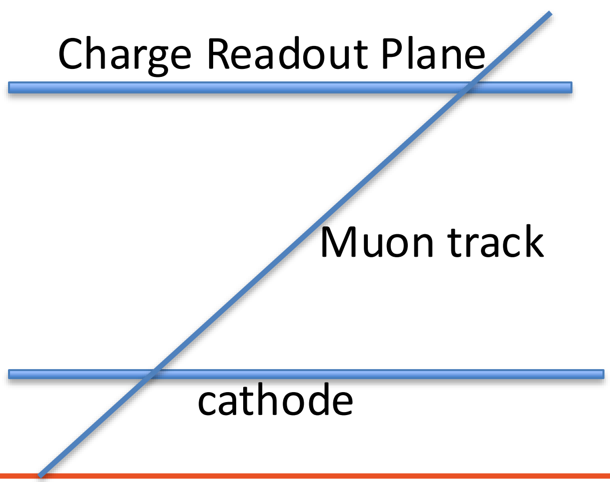
Light charge matching validation:

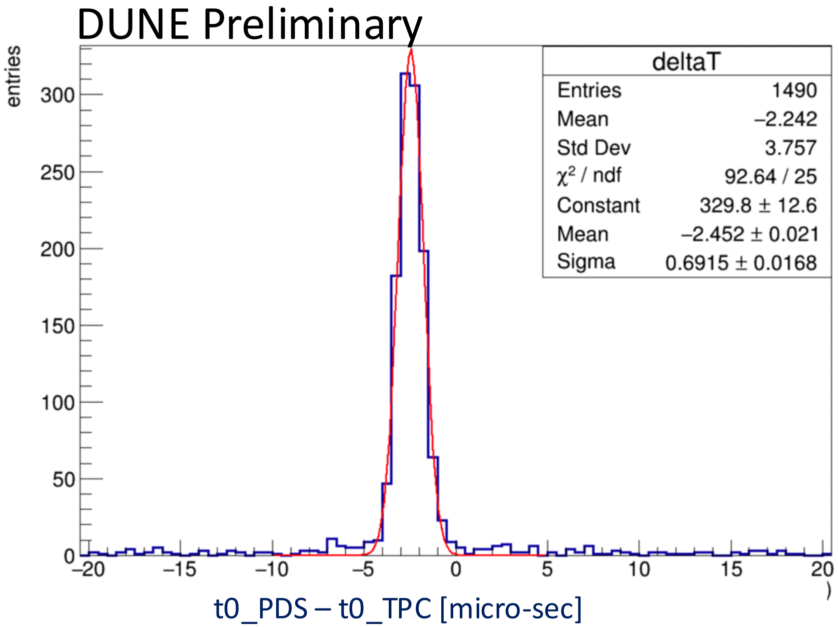
(Validation using cathode-anode crossing cosmic muons):

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:



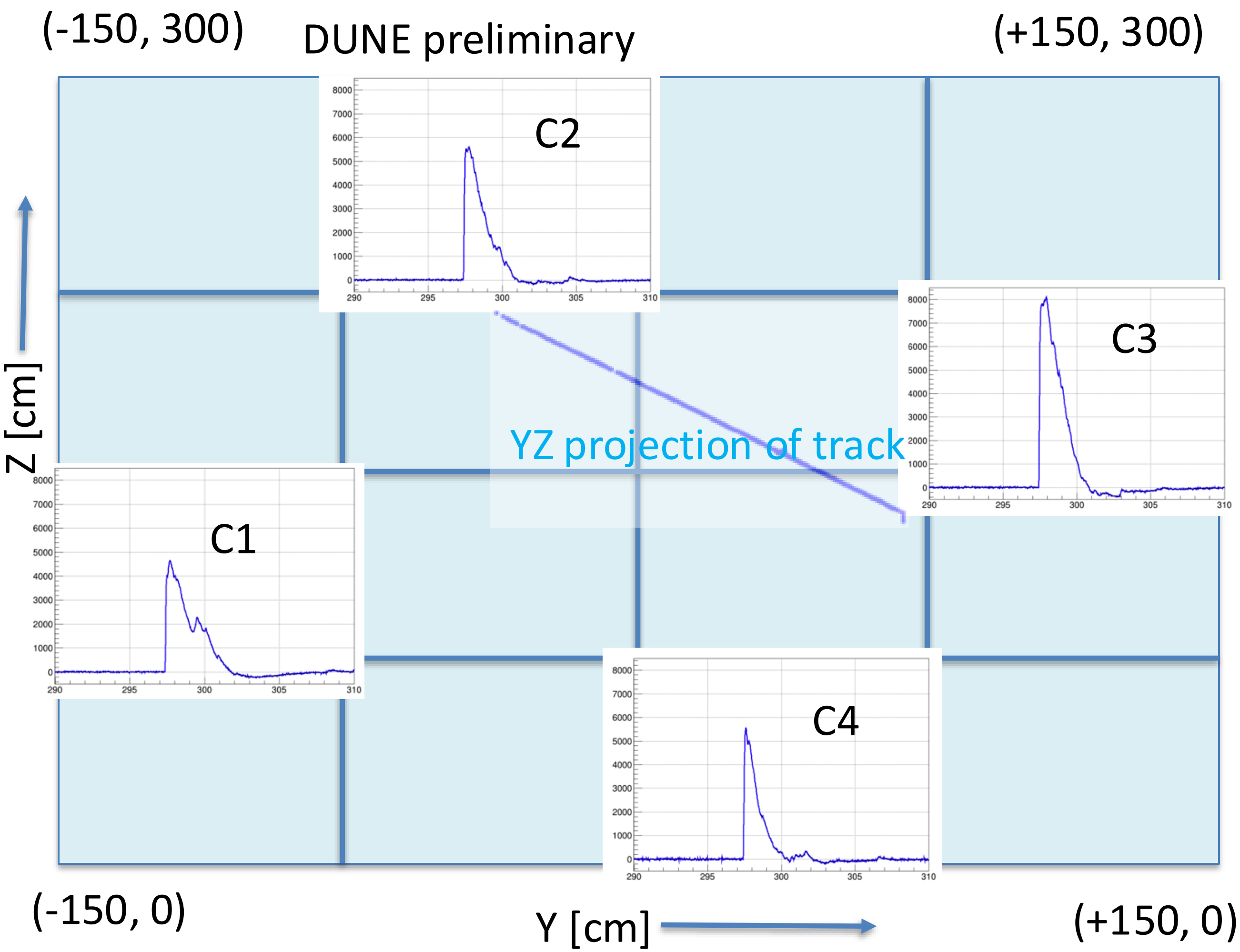


Data analysis:

PDS Flash reconstruction and TPC 3D Spacepoints

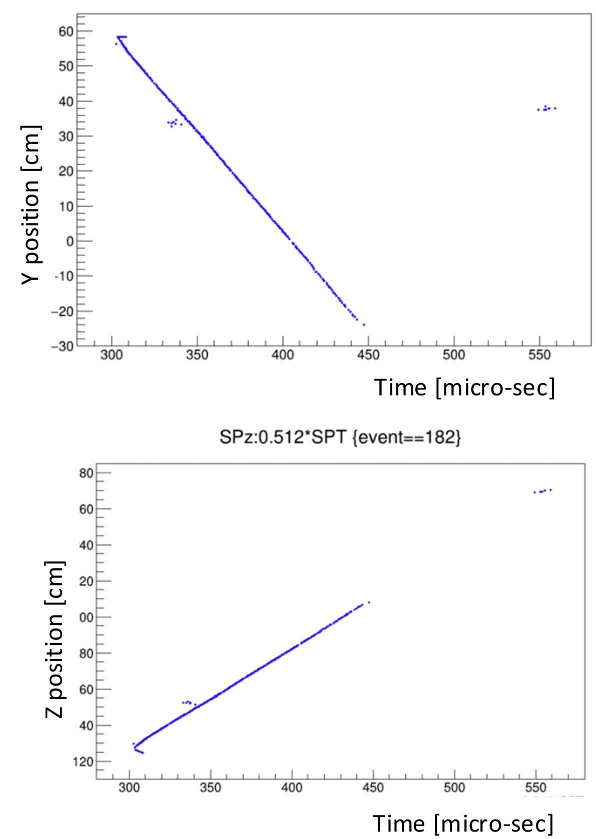
PDS reco Y = $\frac{\sum_{i=1}^{4}(PE_i \cdot PDS_i(Y_{\text{position}}))}{\sum_{i=1}^{4} PE_i}$

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



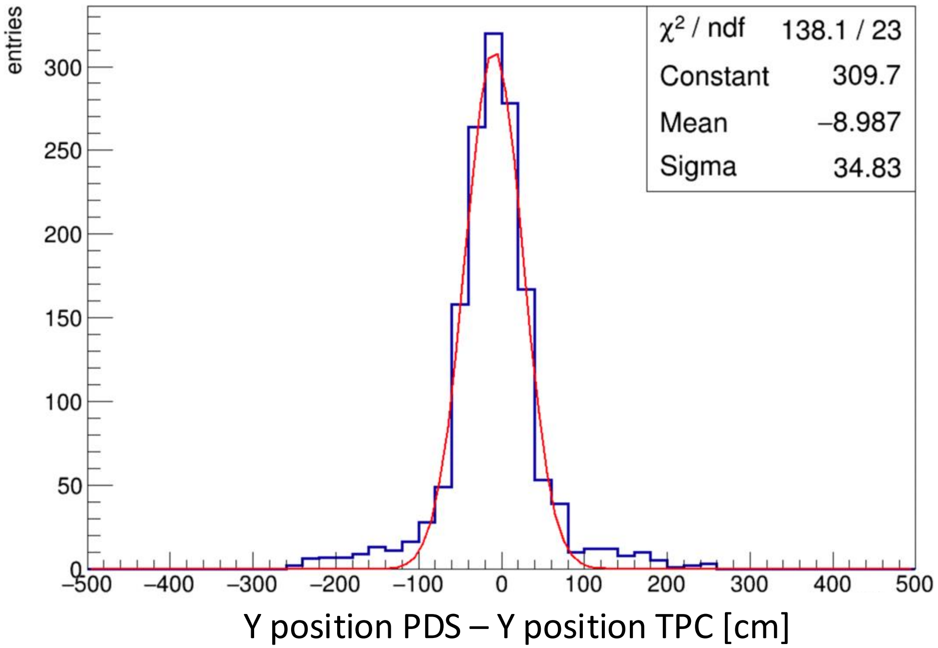
Coldbox view from top (schematic)

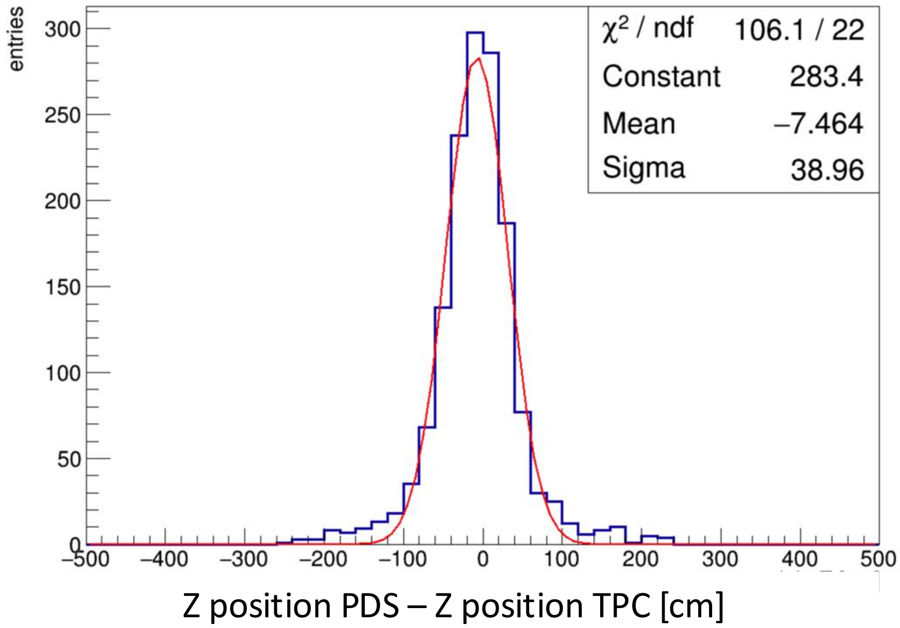
Reconstructed TPC space points



TPC, reco Y and Z are taken as the mid point of the track.

Y and Z position resolution:





Sigma t0=0.7 micro-sec; the main contribution is from the resolution of the charge readout, where each tick = 0.512 micro-sec

Sigma Y positon = 34.8 cm
Sigma Z position=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:

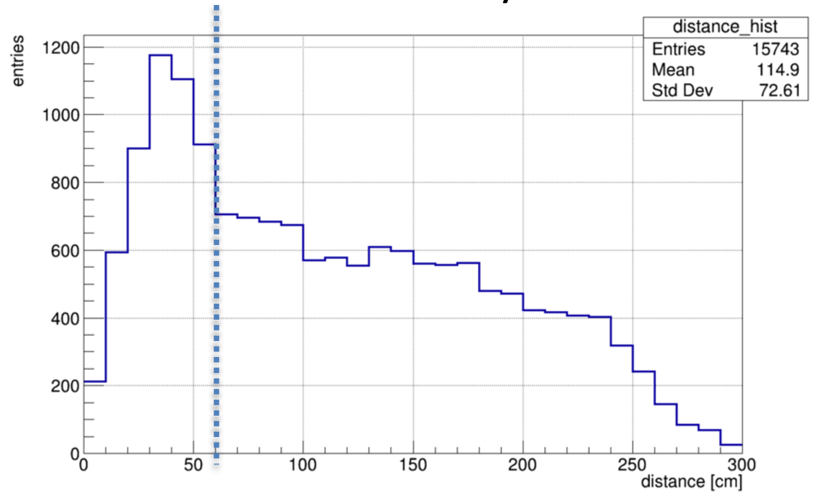
- Neutron capture appears as a cascade of gamma with energy summing up to 6.1 MeV.
- A single gamma deposit maximum energy of 4.7 MeV (<2.5 cm)
- Gammas will appear as short clusters contained in ~1m radius

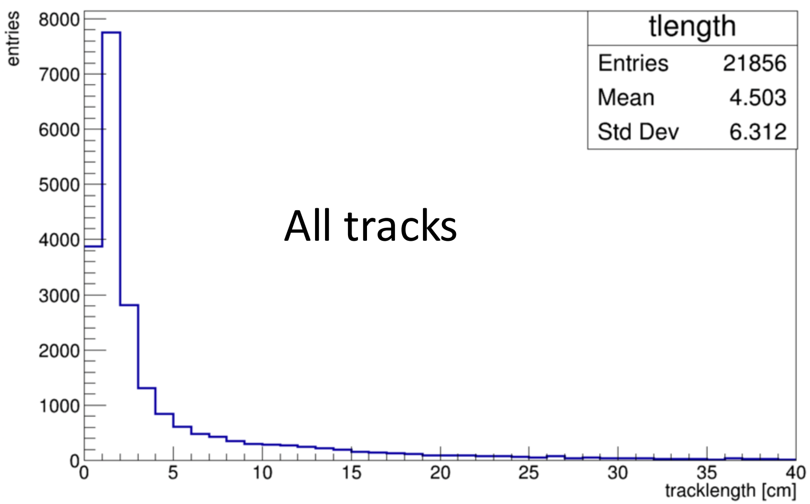
Major background are the cosmic muons and radioactive sources in Ar:

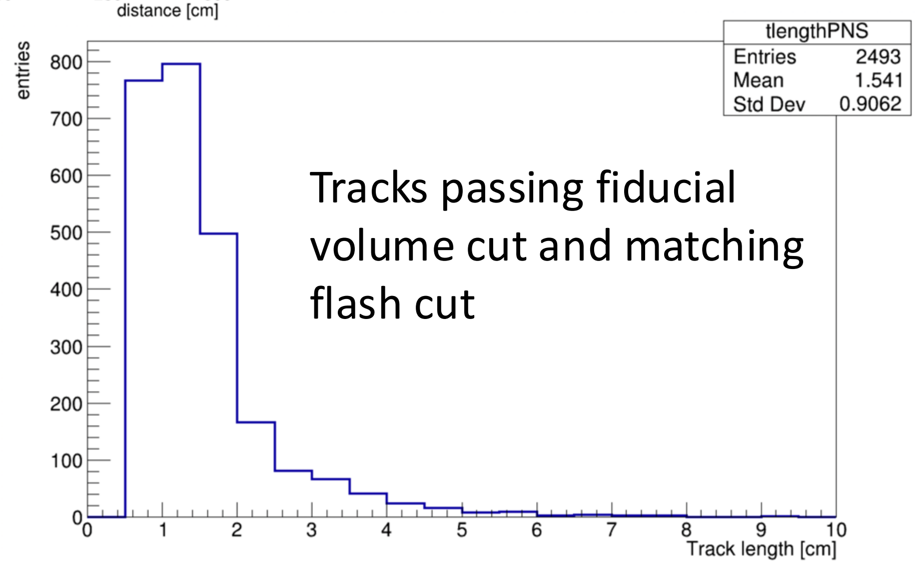
→For cosmic removal fiducial volume cut is used. Tracks starting or ending within 10 cm of Y and Z boundary and 1 cm from the top are removed.

Event Selection after fiducial volume cut:

After, fiducial volume selection; shortest distance between track and PDS Flash is estimated in the YZ plane. Matching PDS flash gives the t0 for the track; and track location can be used to get the precise YZ location of the activity.

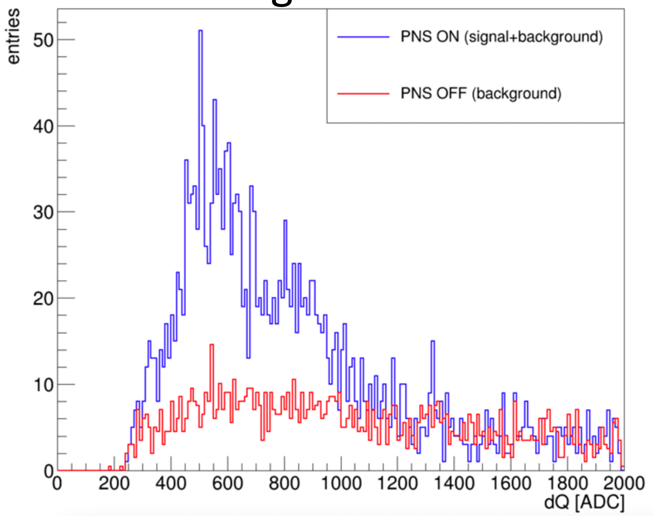




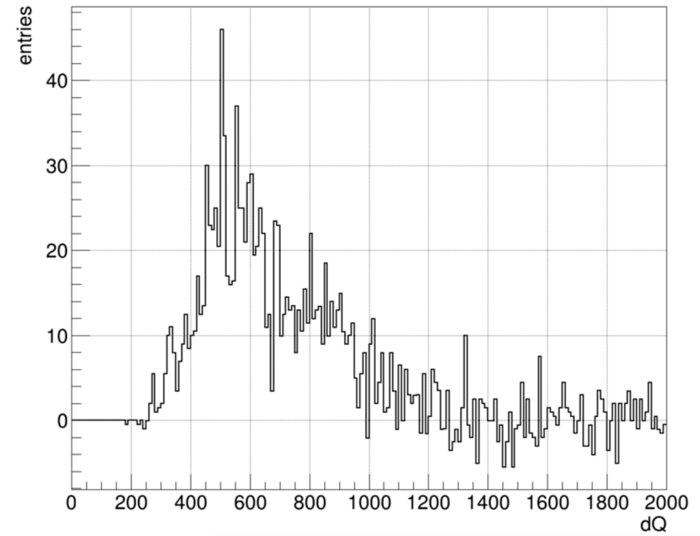


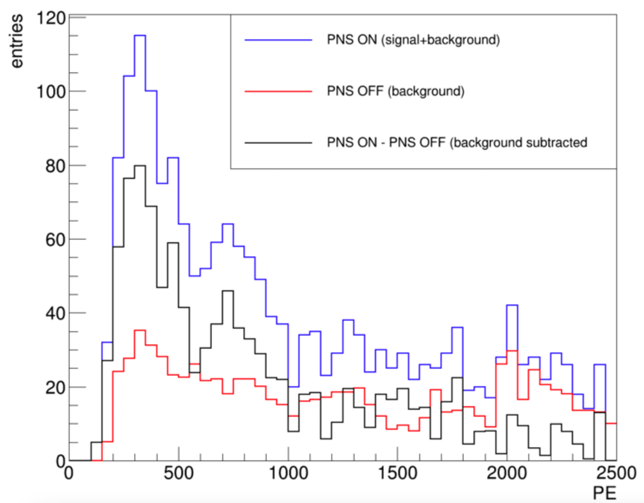
Charge and light distribution for the selected events:

Summed charge for selected tracks



Summed charge for selected tracks after background subtraction





PE distribution for selected Neutron capture candidates

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SUMMARY

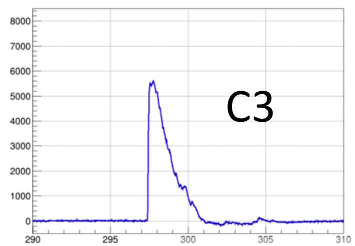
- LArTPCs are well suited for double calorimetry using charge and light information.
- Neutron capture a viable candidate to be used as a standard candle for energy scale calibration.
- First run with neutron source using DDG recently concluded, data analysis ongoing.
- More data collection in the bigger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

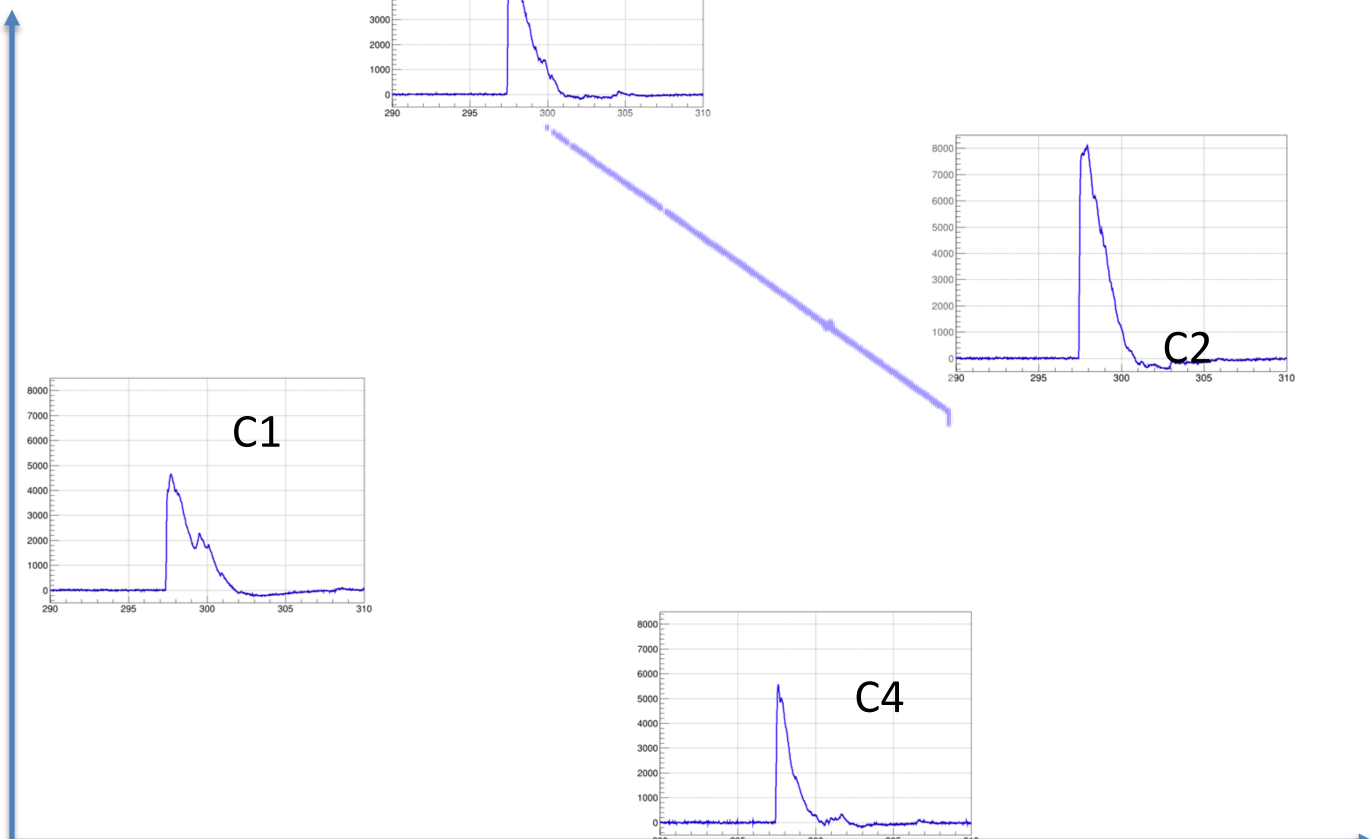
BACKUP SLIDES

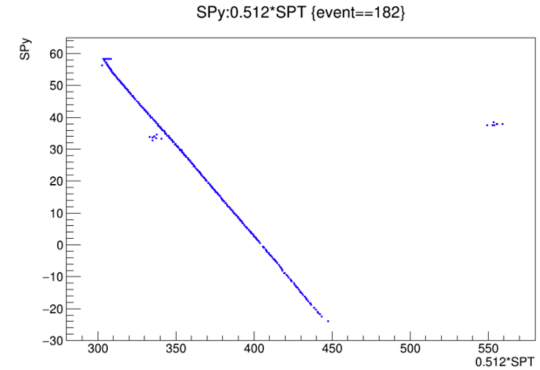
Data Collection and analysis:

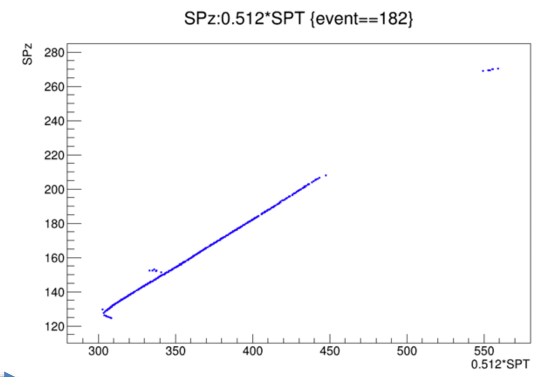
Reconstructed Yposition= Sum PE*detector center Y
Reconstructed Zposition= Sum PE*detector center Z

T0TPC=299.5 micro-sec
T0PDS=297.6 micro-sec
YTPC=17 YPDS=14
ZTPC168 ZPDS=169

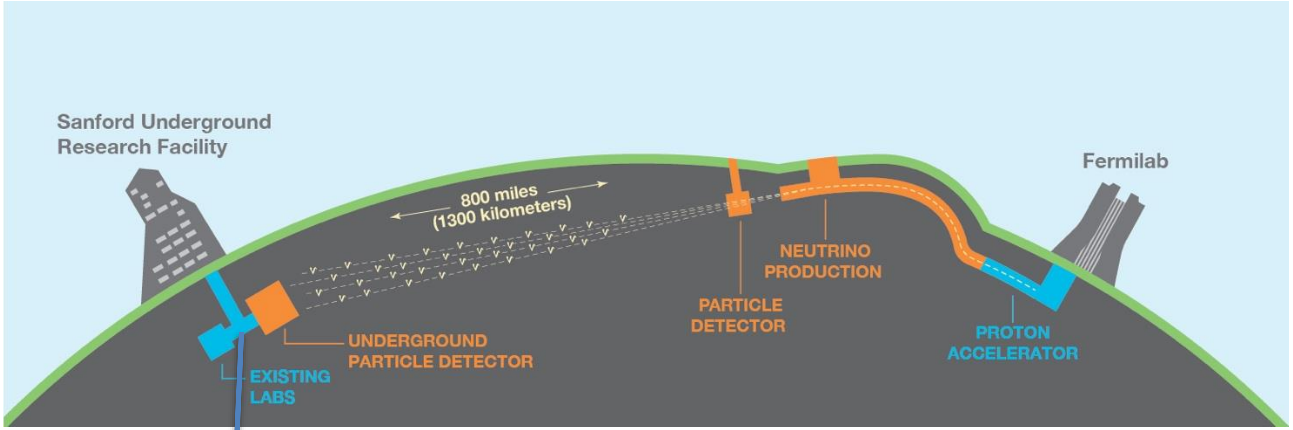




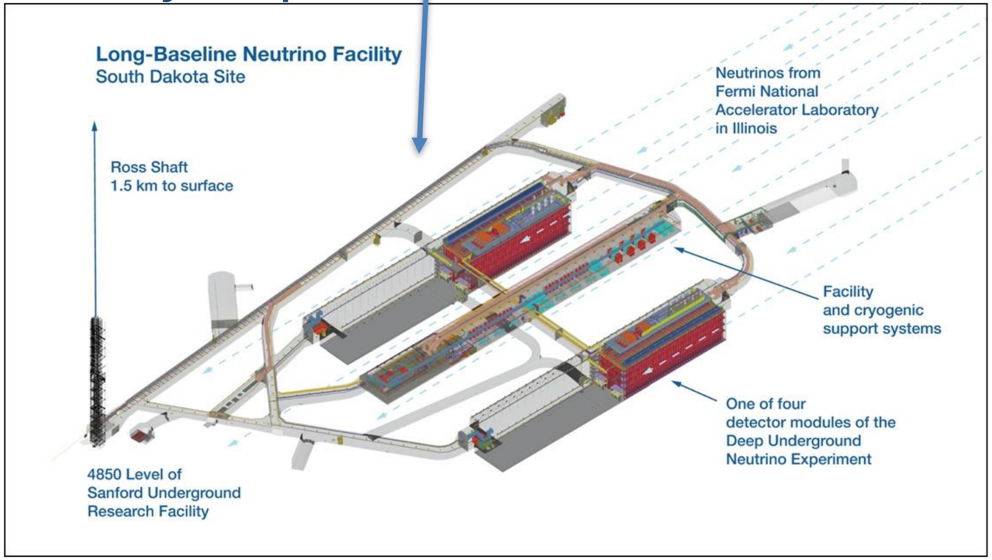




Deep Underground Neutrino Experiment



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



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

Light Charge matching

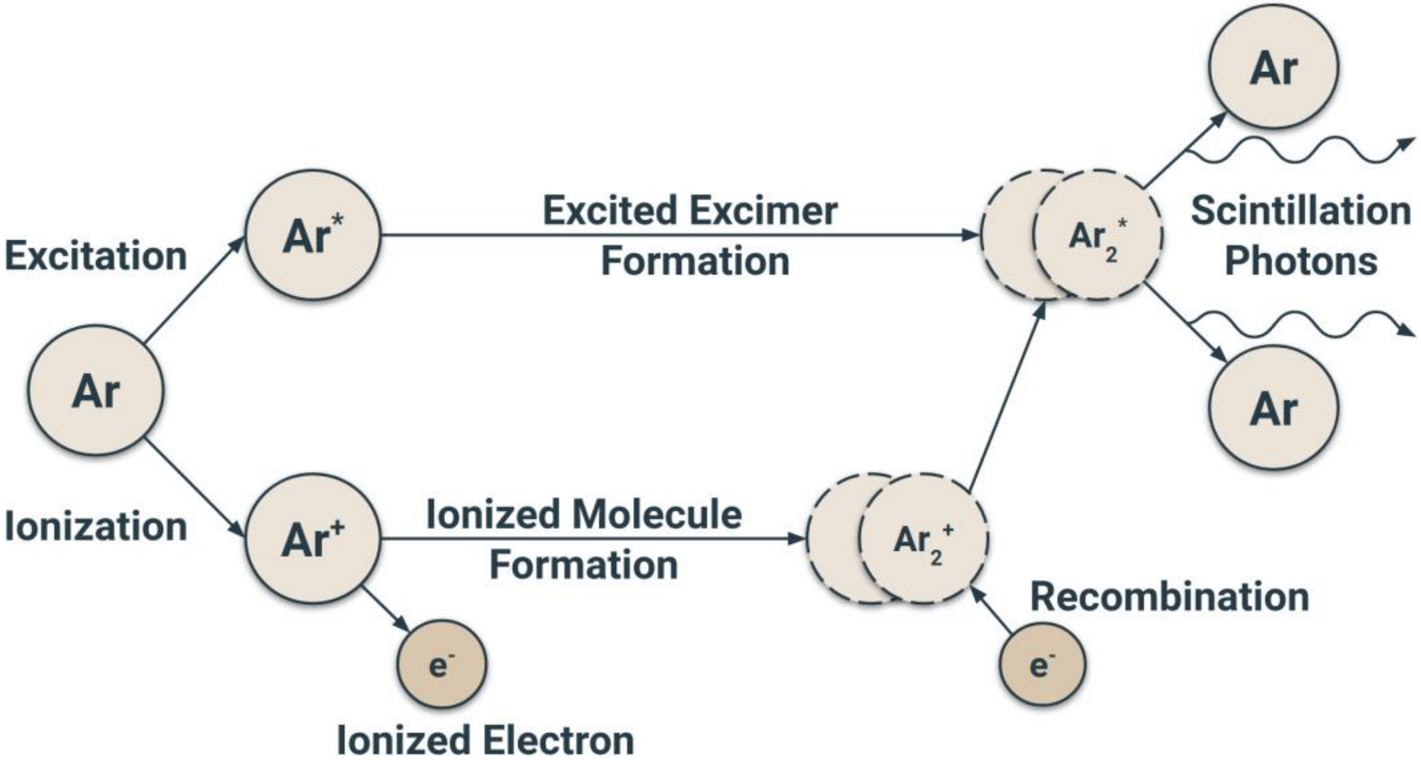


Fig: Mechanism of scintiallation light production in Ar.
Figure from arXiv:2002.03010

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