Neutron Physics in the DUNE 2x2 Demonstrator

Luis Mora-Lepin
On behalf of the DUNE collaboration
NuFact25
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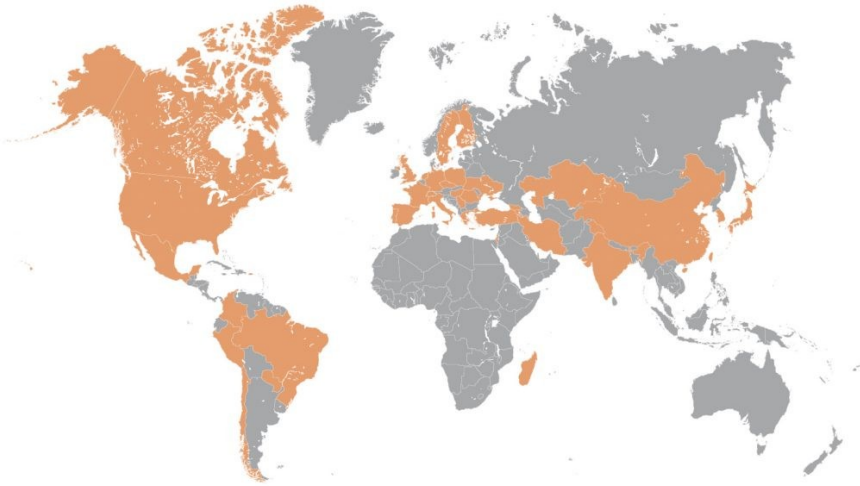
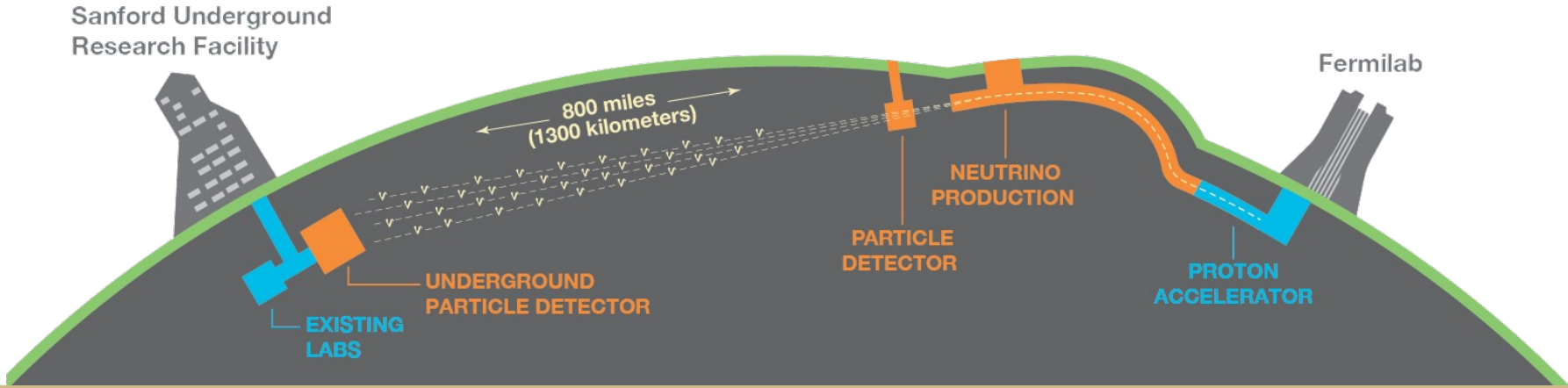
Email: lml24d@fsu.edu

The Deep Underground Neutrino Experiment

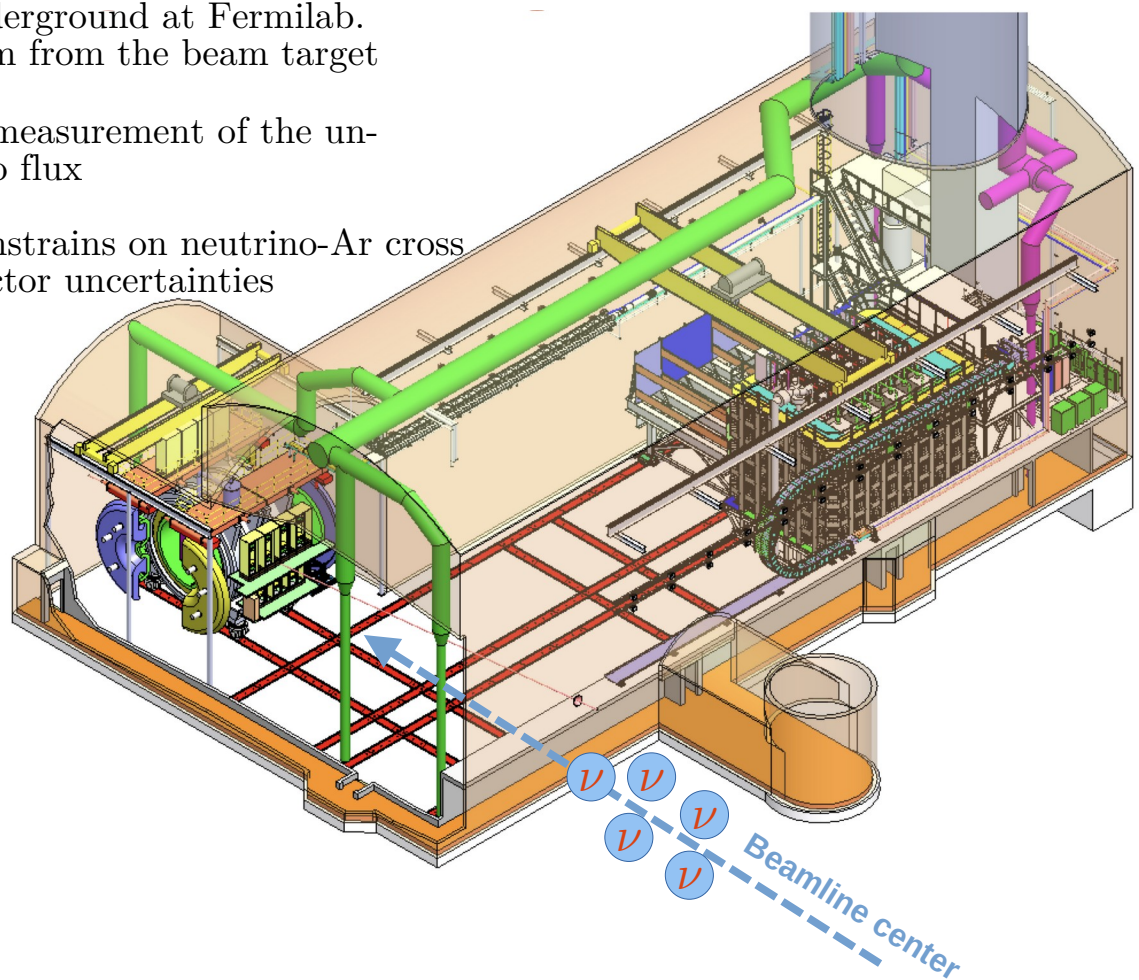
- International neutrino experiment on US territory
- More than 1400 collaborators from 35 countries
- Aims to perform a comprehensive study of neutrino oscillations (CP-phase, mass ordering, and others)
- Also, a suite of other physics studies such as atmospheric/solar neutrinos, neutrino cross sections and BSM searches





A closer look at the Near Detector

- Located 63 m underground at Fermilab. Baseline of ~400 m from the beam target
- It will perform a measurement of the un-oscillated neutrino flux
- It will provide constrains on neutrino-Ar cross sections and detector uncertainties



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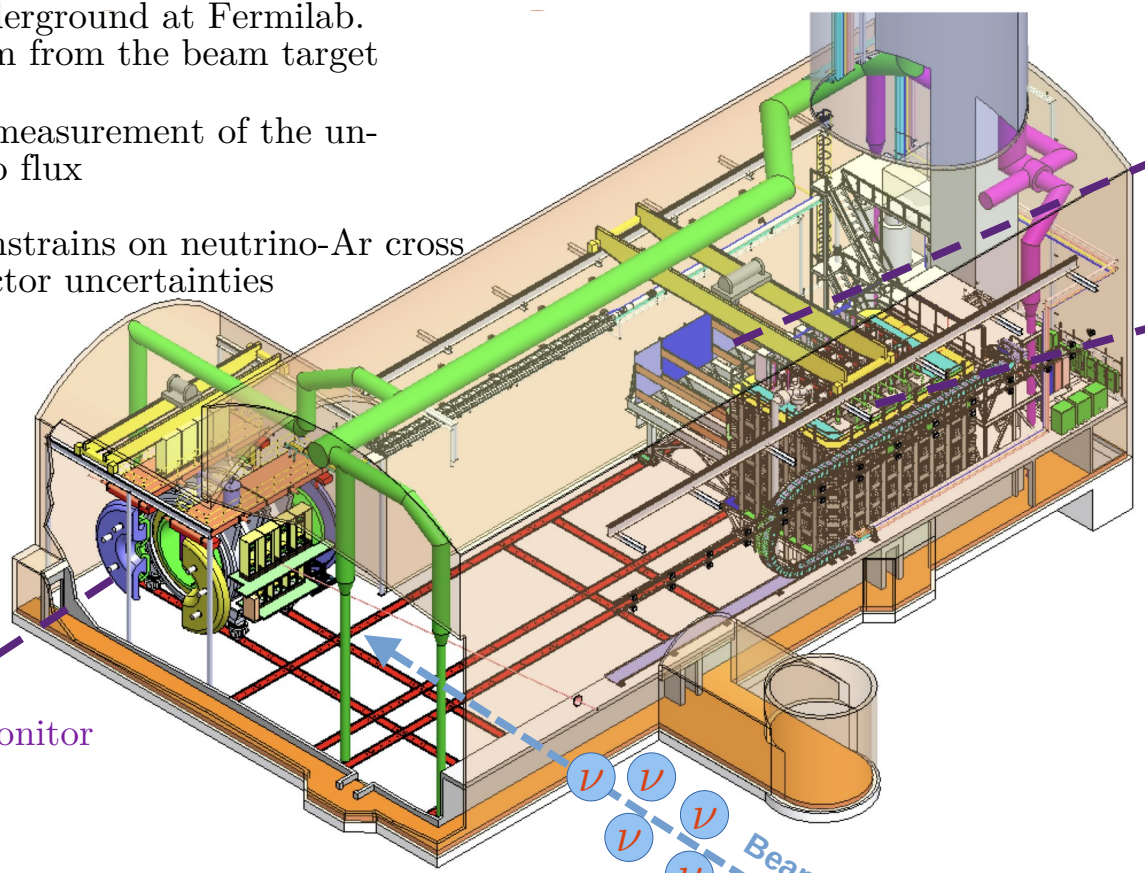

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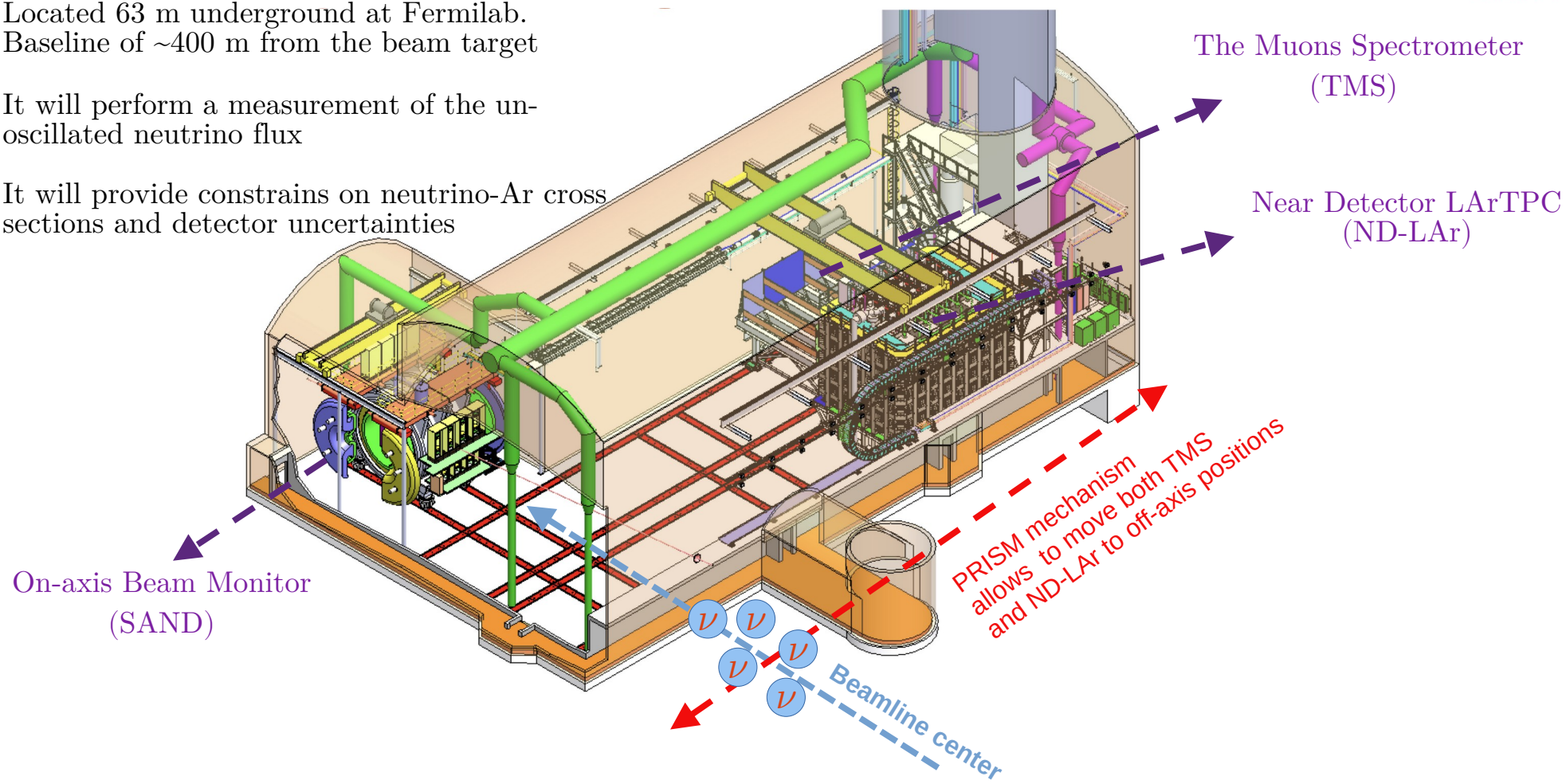

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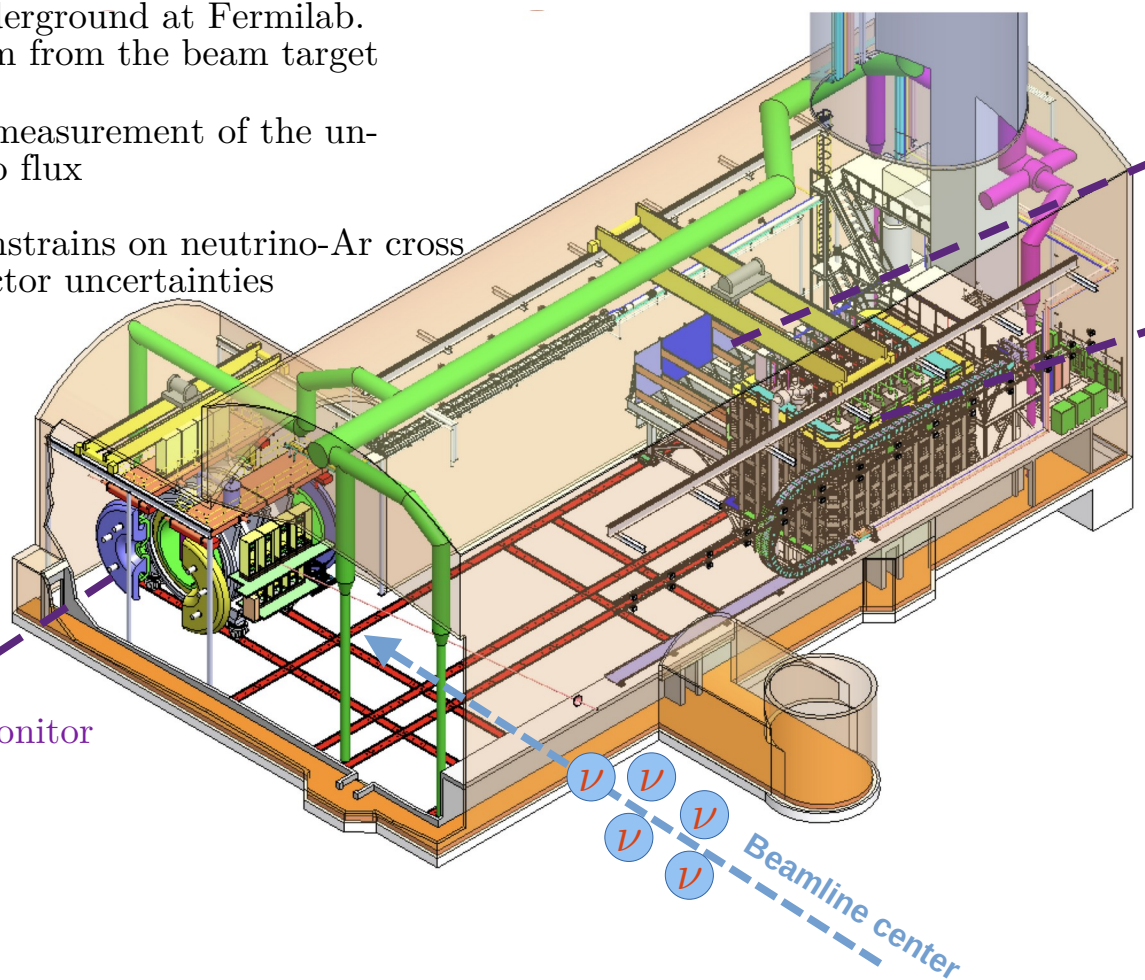
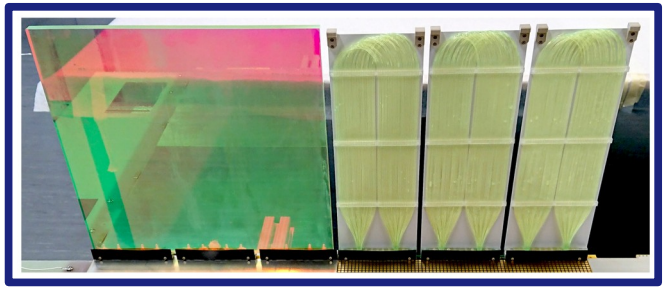


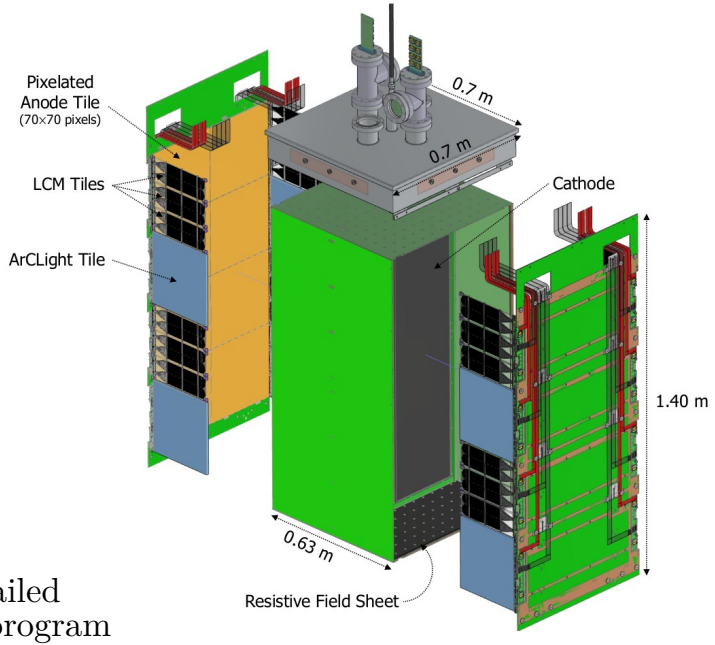
The ArgonCube Technology

- Novel design of segmented Liquid Argon Time Projection Chambers (LArTPCs)
- Each module has two optically isolated TPCs sharing common central cathode
- Native 3D charge reconstruction using the LArPix technology
- Use of light detectors inside the LAr volume with a fast timing resolution

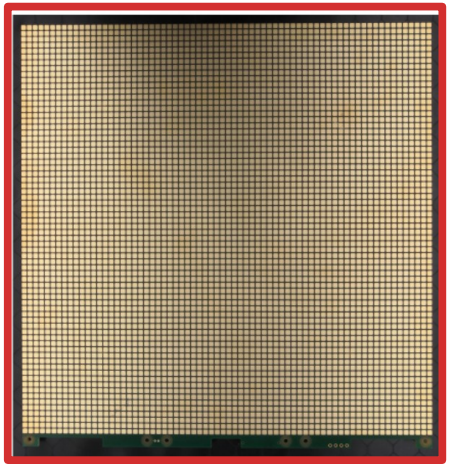
Light detectors



SiPM-based technology
O(1 ns) timing resolution



Pixel tile

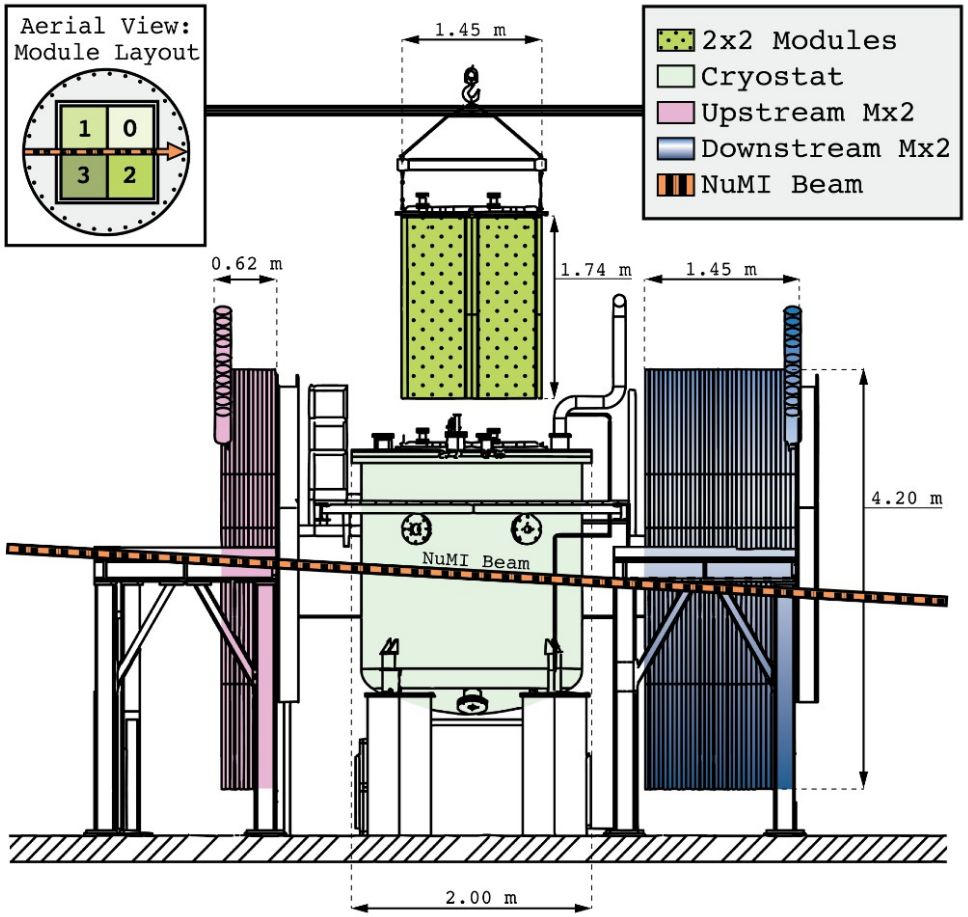


Each tile has 4900 pixels, with a pixel pitch of 4.4 mm

Ref: Instruments 2024, 8(3), 41
Also, see Richie Diurba's talk for a more detailed introduction to NDLAr and its prototyping program

The DUNE ND-LAr 2x2 Demonstrator

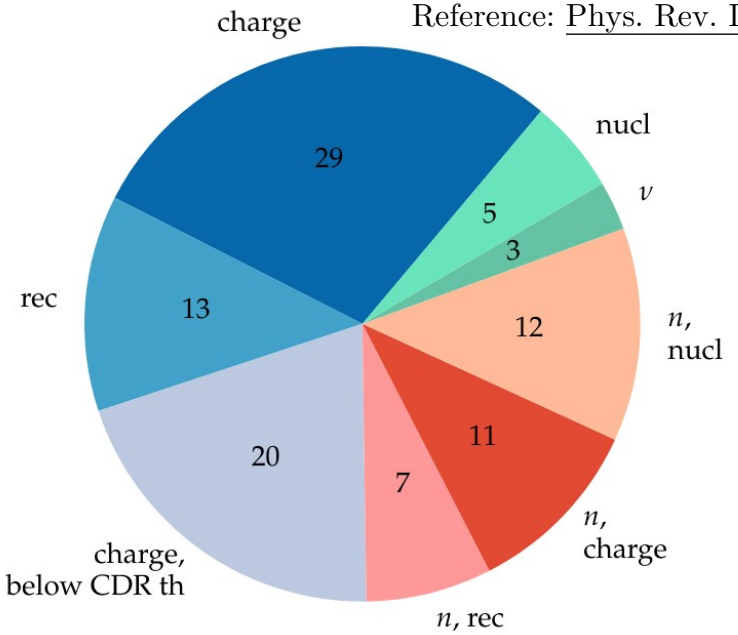
- Prototype of the future ND-LAr
- Each module is 14% of the volume of an ND-LAr module
- Located at Fermilab, 100 m underground
- Tracking planes (Mx2) are used to identify rock muons, and to reconstruct muons produced in the fiducial volume
- Studies neutrinos from the NuMI beamline
- Goals: To demonstrate the reconstruction of neutrino interactions in an environment similar to the one expected at ND-LAr. Perform neutrino-Ar cross section measurements, BSM searches, **neutron tagging** and more!
- First neutrino data taken in July 2024



The importance of neutrons

- Missing neutrons in neutrino energy reconstruction will result in a considerable bias since they carry a fraction of the neutrino energy
- Reconstructing neutrons is key to achieve DUNE goals, to improve neutrino generators and also to understand solar/supernova neutrino backgrounds

Reference: Phys. Rev. D 99, 036009

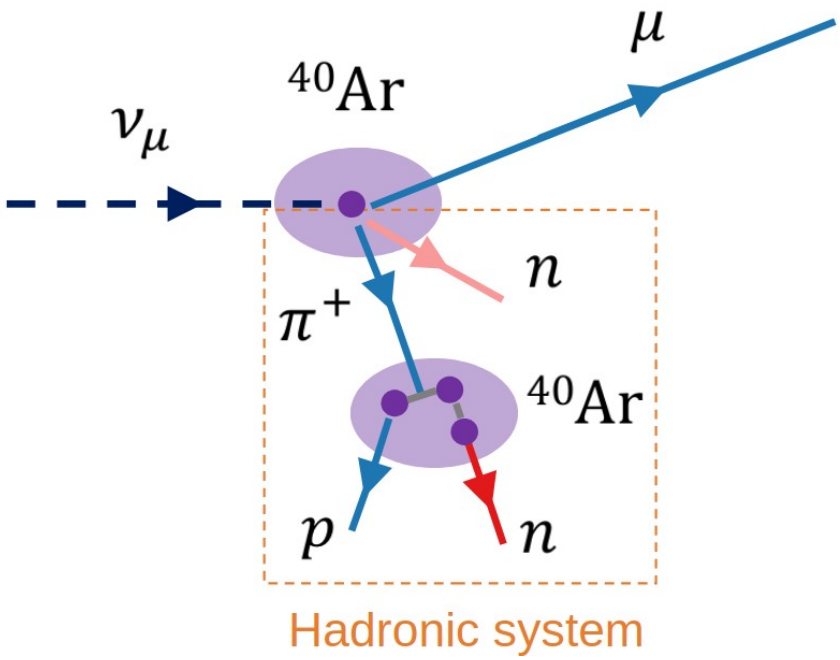


Hadronic energy budget taken from the average of 10,000 DUNE-like muon neutrino CC interactions. Shown are the fractions of the hadronic energy that go into ionization charge (charge) above and below the charge detection readout (CDR) thresholds, that are lost to recombination (rec), lost to nuclear breakup (nucl) and, finally, that escape as decay neutrinos (ν). The corresponding processes for neutrons are shown separately (n).

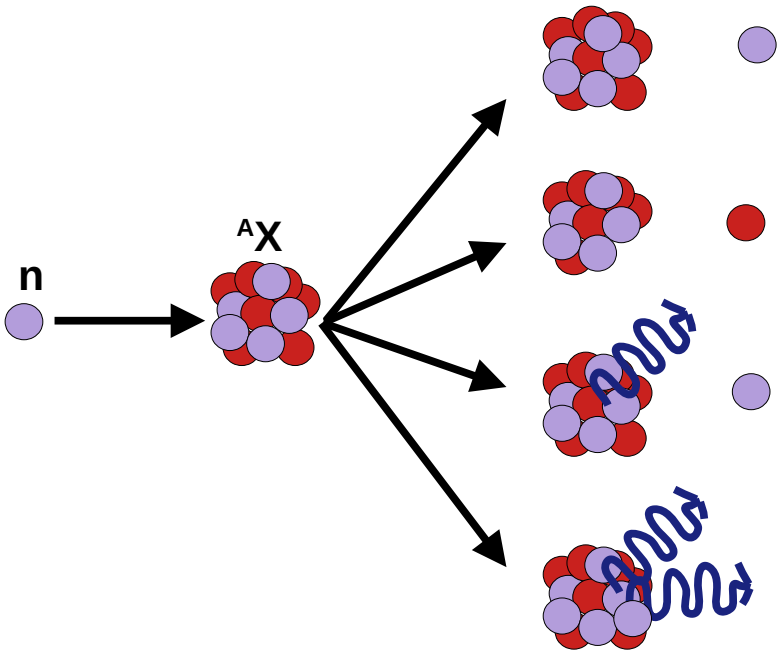
The importance of neutrons

- Missing neutrons in neutrino energy reconstruction will result in a considerable bias since they carry a fraction of the neutrino energy
- Reconstructing neutrons is key to achieve DUNE goals, to improve neutrino generators and also to understand solar/supernova neutrino backgrounds
- Neutrino interactions with argon are complex due to intranuclear interactions known as final-state interactions (FSI)
- In some cases FSI can produce several neutrons. We can only detect them if they interact with Ar
- Other great overviews of neutrons in LArTPCs:
  - Phys. Rev. D 102, 092010
  - arXiv:2203.00740

Reference: Phys. Rev. D 99, 036009



Neutron interactions in LAr



Elastic scattering
(n,n)

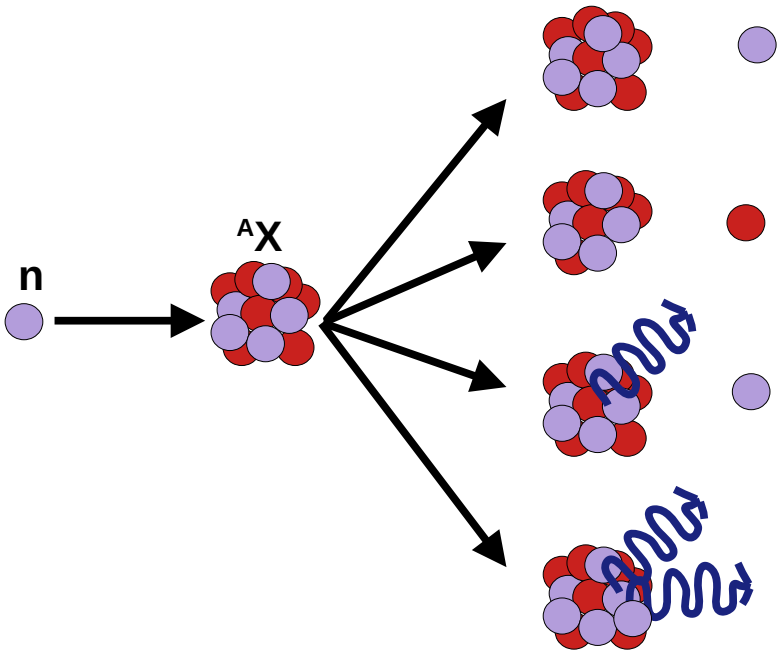
Transfer reactions
(n,p), (n,d), (n,α)

Inelastic scattering
(n, n'ɣ)

Capture
(n, ɣ)

By far, the most common interaction mechanism. Nevertheless, it does not produce any visible activity in the detector

Neutron interactions in LAr



Elastic scattering (n,n)

Transfer reactions (n,p), (n,d), (n,α)

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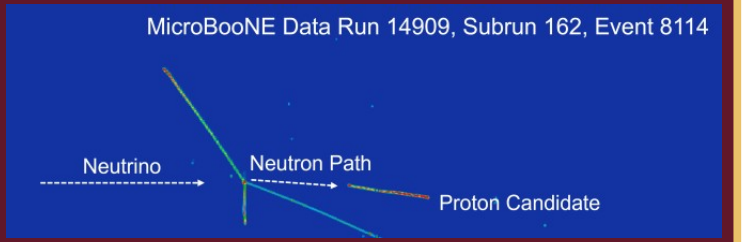
Capture (n, ɣ)

In these reactions the kinetic energy of the neutron is transferred to one or more nucleons, resulting in the emission of protons, deuterons or alpha particles. In the case of protons they will leave a short track that can be used to tag a neutron candidate. Studies of (n,p) signals have been performed in the past by

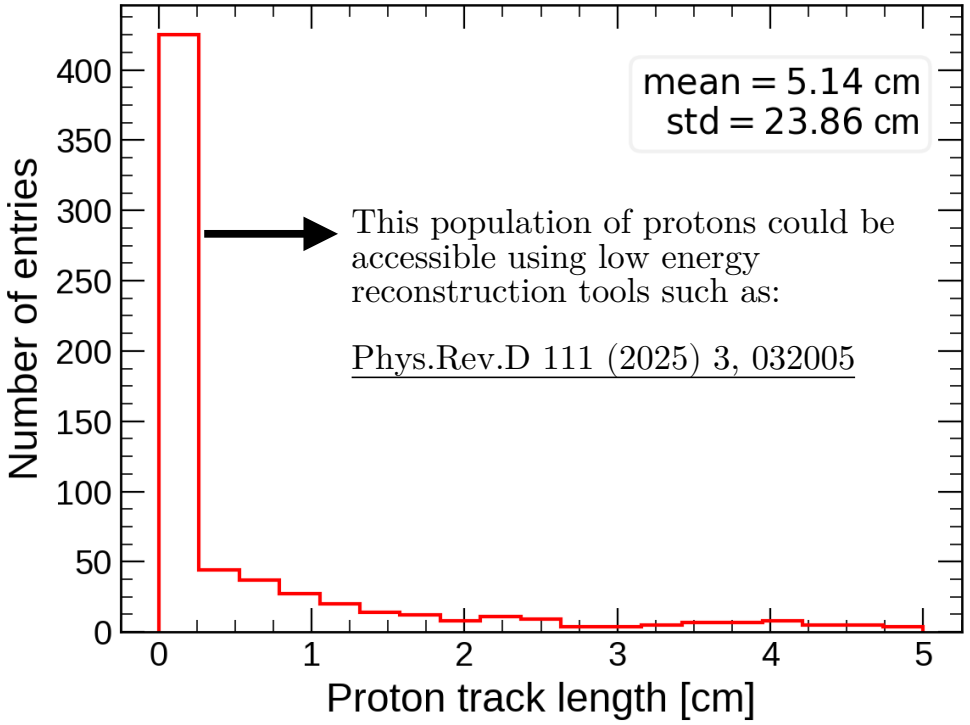
MINERvA: Phys. Rev. D 100,052002

MicroBooNE: Eur. Phys. J. C 84, 1052



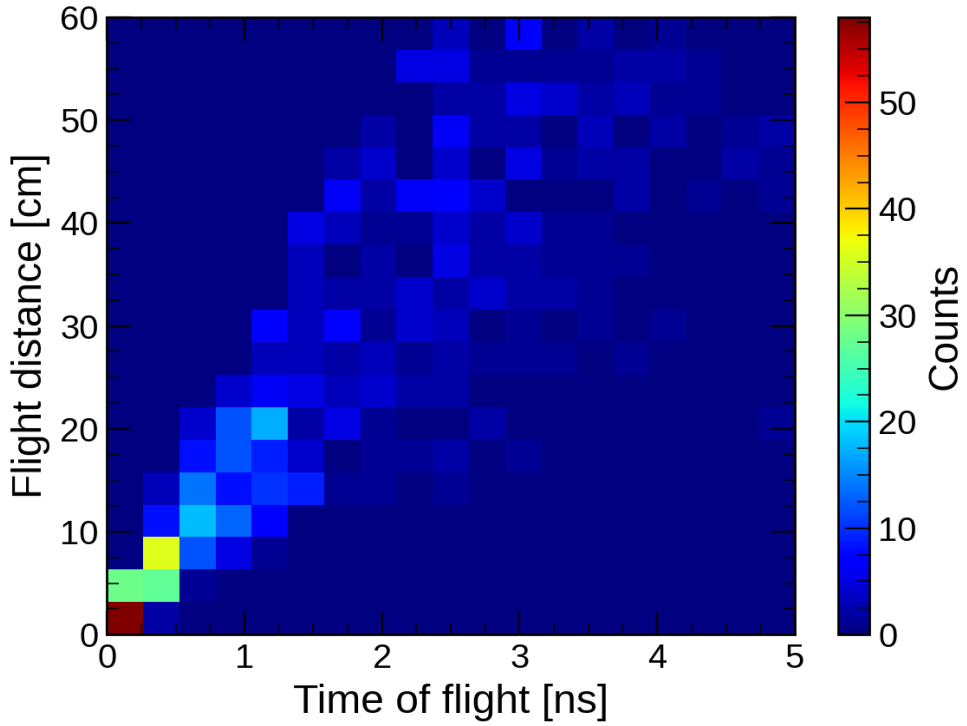
Characteristics of (n,p) events

Protons with a short track length are challenging to reconstruct with traditional neutrino reconstruction tools



DUNE ND-LAr 2x2 Work in progress, simulation

Most of the neutrino-induced (n,p) occur less than 2 ns after the neutrino interaction

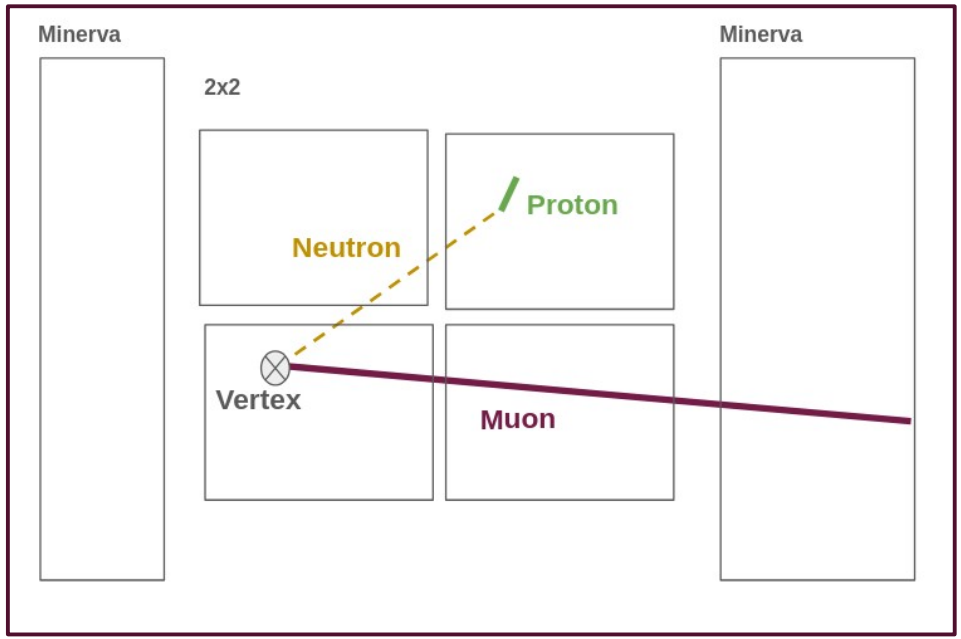


DUNE ND-LAr 2x2 Work in progress, simulation

Neutrino signal: $\bar{\nu}_\mu$CCQE

The signal definition has to be made according to what we would see in the detector

- Muon anti-neutrino CC interaction in the fiducial volume (5 cm)
- Muon energy > 1.0 GeV
- Muon $\cos(\theta_{\text{beam}}) > 0.9$
- At least one neutron produced at the neutrino vertex
- Protons from the neutrino vertex with a kinetic energy below ~ 40 MeV are ok (they are below the 2 cm length threshold)
- No other particles from the neutrino vertex



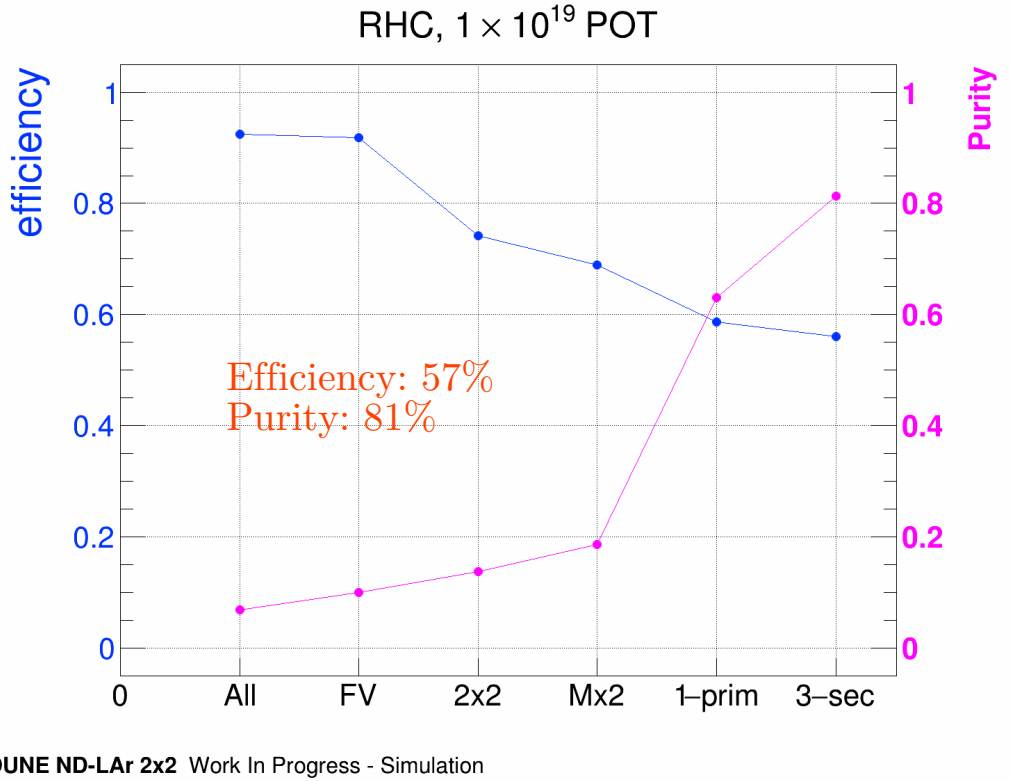
$\bar{\nu}_\mu$CCQE-like Reconstruction

For high-level reconstruction we use a framework called SPINE. This is a deep learning-based reconstruction package for LArTPCs. For now, it only relies on charge readout information

- Vertex candidate in the fiducial volume (FV). This is 5 cm away from any of the TPC walls
- Just one primary track exciting downstream (DS) the 2x2
- Reconstructed DS Mx2 track matching the direction of the track in the 2x2
- $1 <$ # Reco secondaries < 3

$$\text{eff} = \frac{\text{Number of reconstructed CCQE interactions}}{\text{Total number of CCQE interactions}}$$

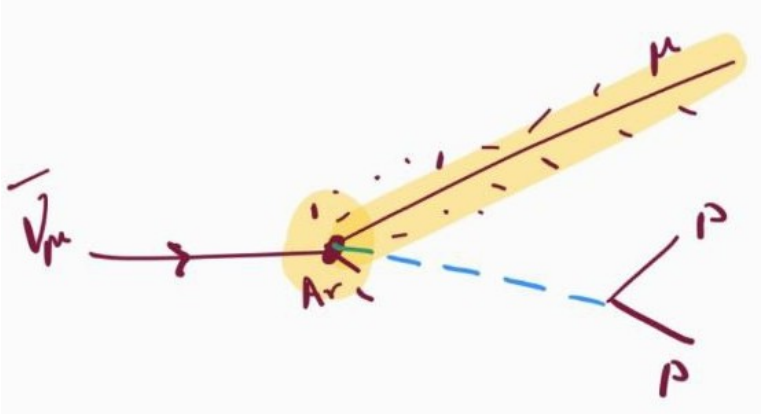
$$\text{Pur} = \frac{\text{Number of reco CCQE interactions}}{\text{Total number of reco interactions}}$$

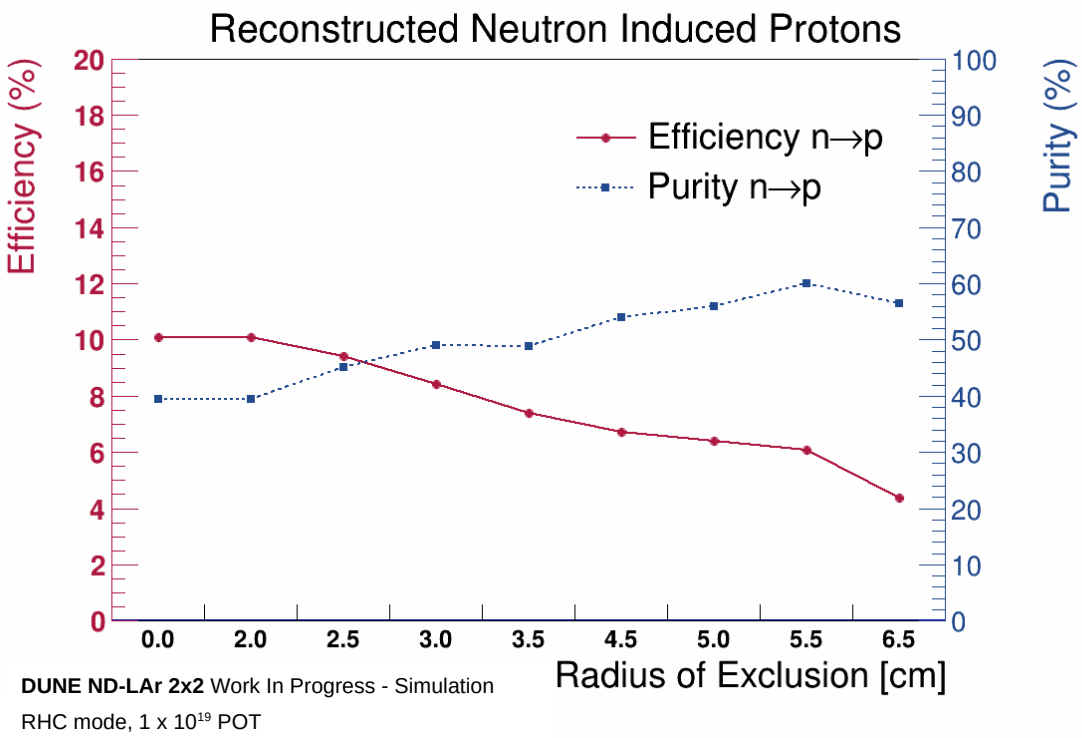


SPINE: https://github.com/DeepLearnPhysics/spine?tab=readme-ov-file

Neutron-Induced Proton Selection

- We use the previous CCQE-like sample
- Secondary proton track identified by SPINE
- Proton track contained in the 2x2
- Proton starting point more than 4.5 cm away from the neutrino vertex
- “Exclusion zone” of 2 cm around the reconstructed muon track to remove low energy activity





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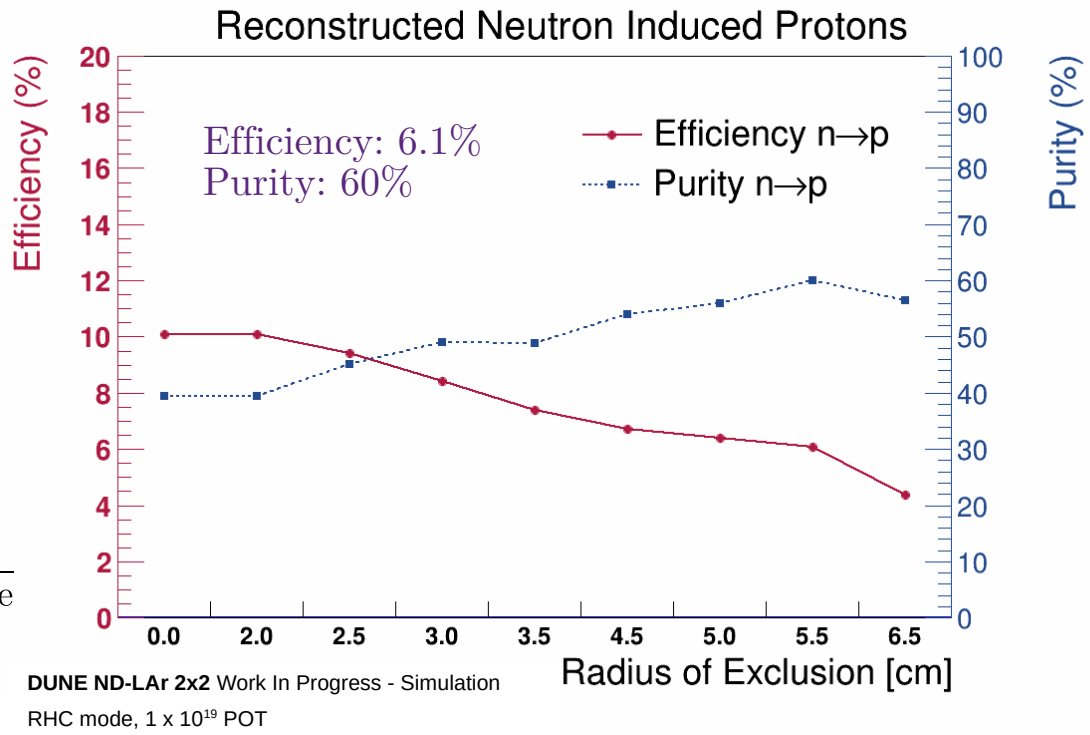
$$\text{eff} = \frac{\text{Number of reco neutron-induced protons}}{\text{Total number of neutron-induced protons in the sample}}$$

$$\text{Pur} = \frac{\text{Number of reco neutron-induced protons}}{\text{Number of reco secondary protons}}$$



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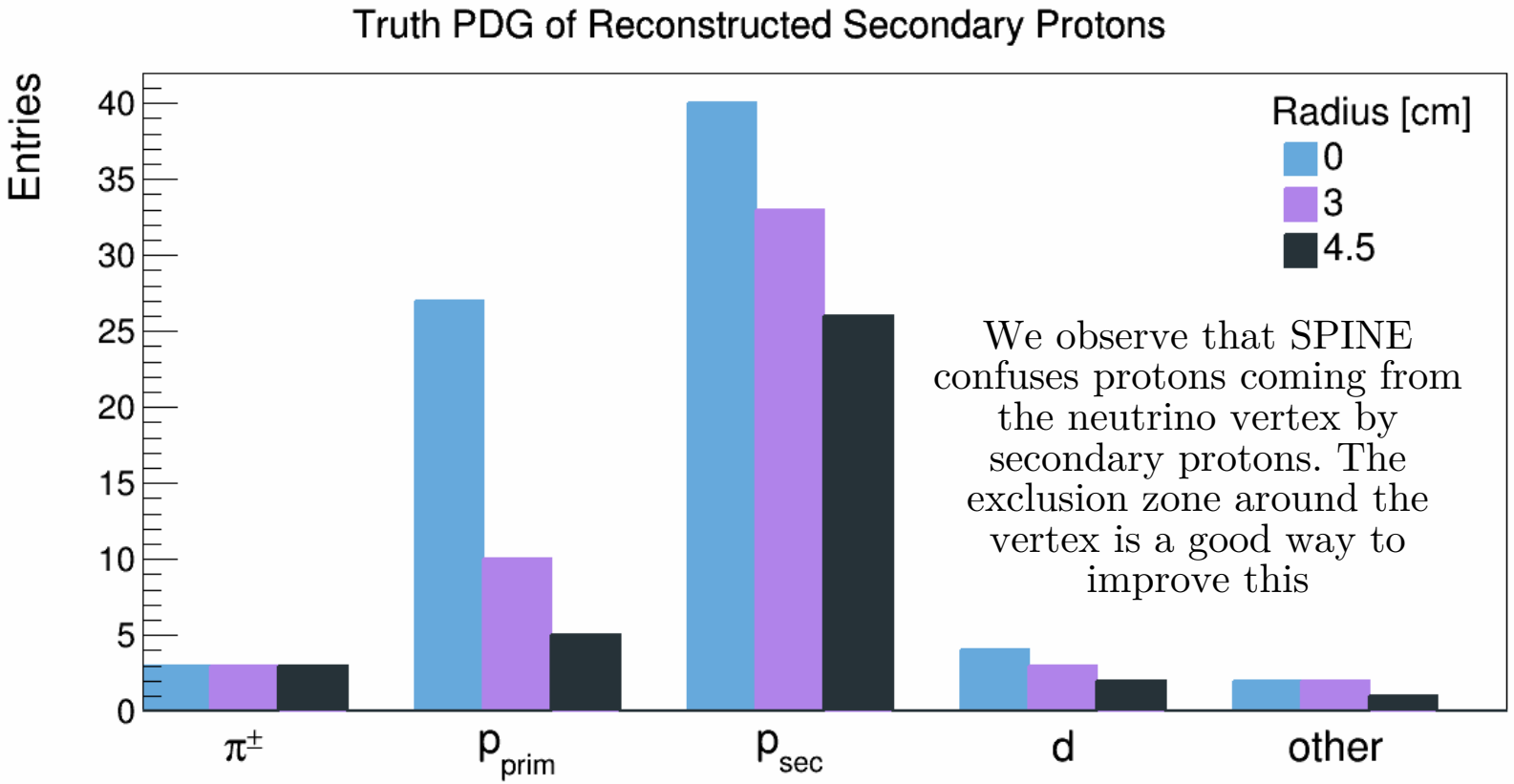
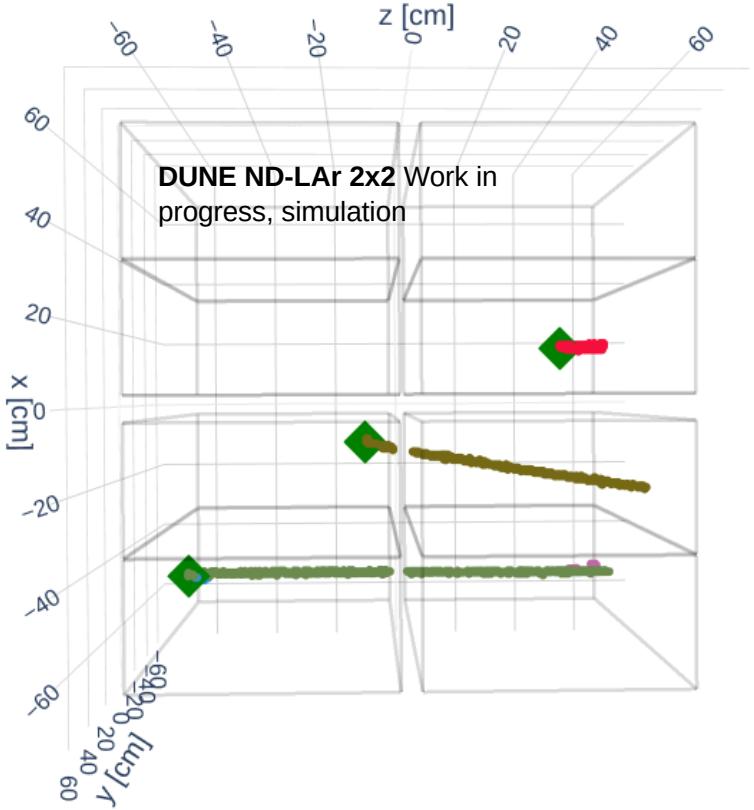


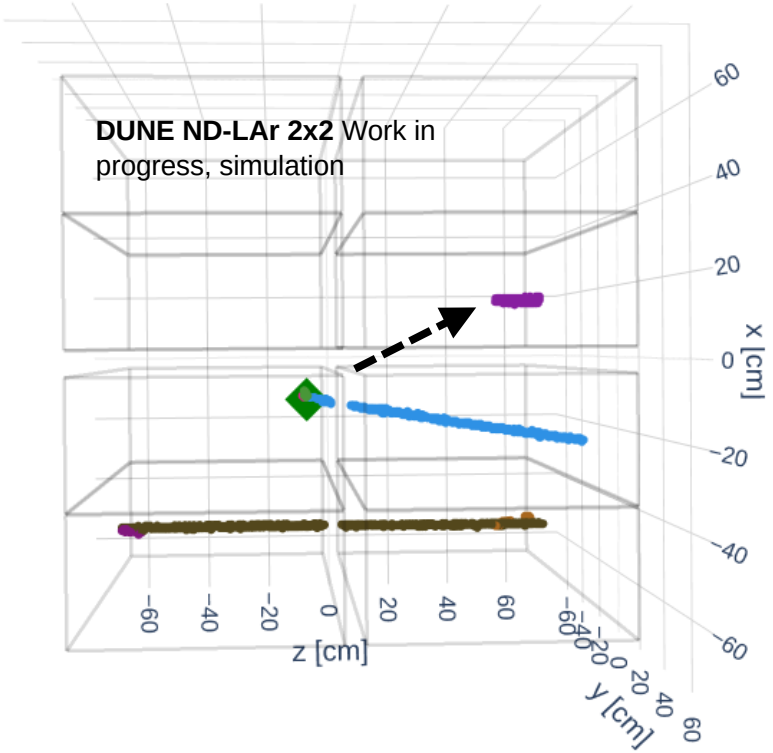
DUNE ND-LAr 2x2 Work In Progress - Simulation
RHC mode, 1 x 10^{19} POT

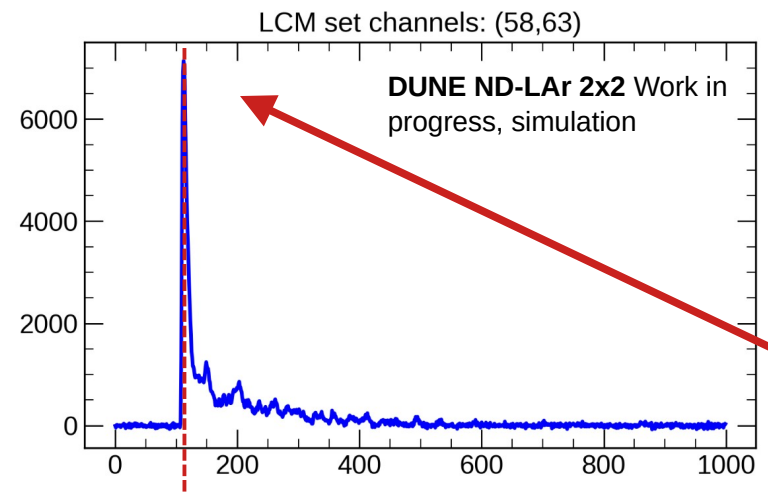
Badly Reconstructed (n,p)

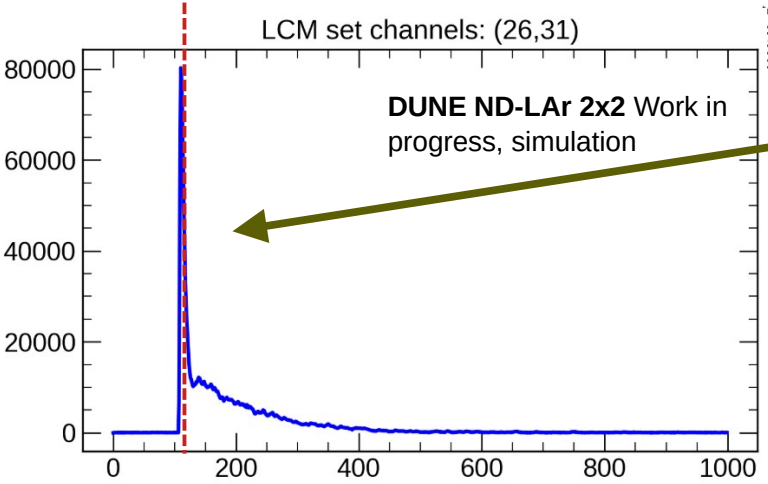
Reconstructed Interactions
SPINE thinks that the in FV muon track and the proton are different neutrino vertices!

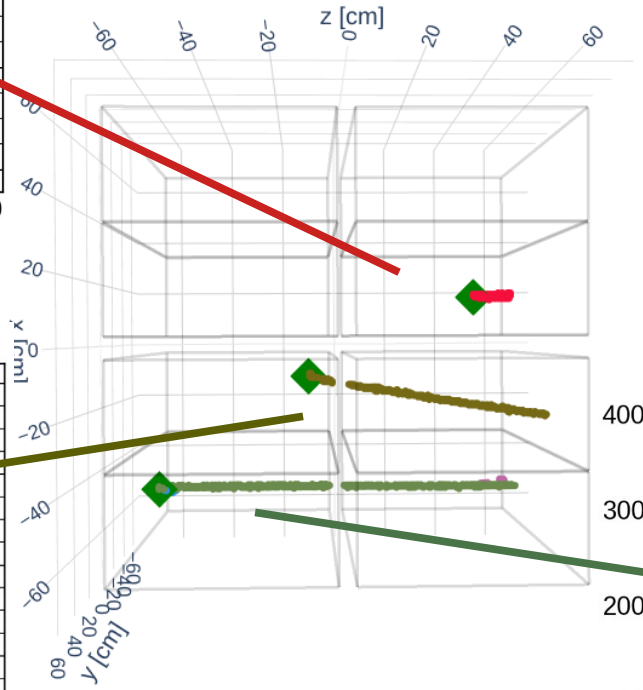


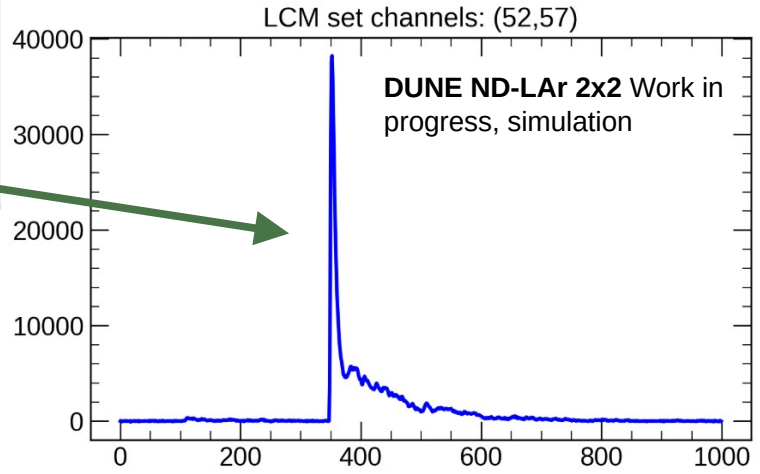
True Interactions
In FV muon track and proton track belong to the same neutrino interaction





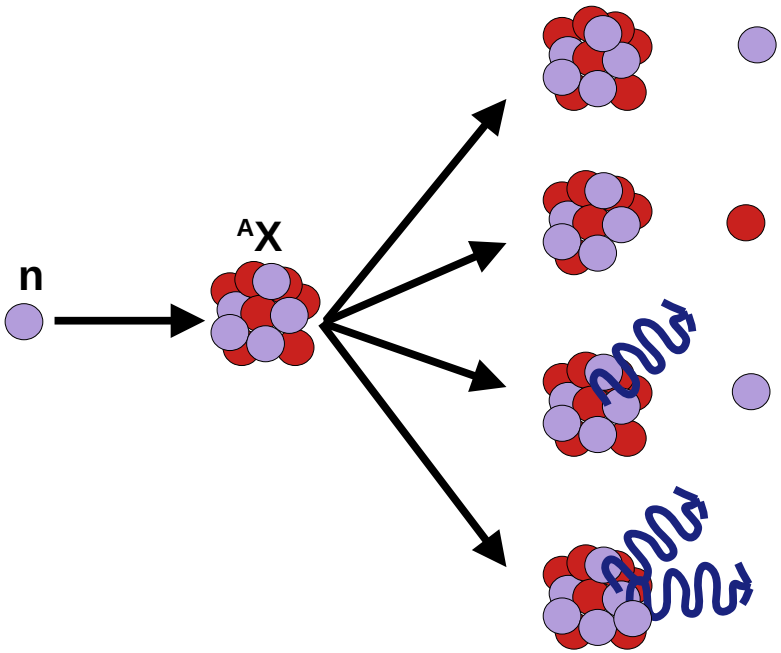






The 2x2 light detection system can complement SPINE reconstruction. Potential to improve the efficiency of this analysis using timing information.

Neutron interactions in LAr



Elastic scattering
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Transfer reactions
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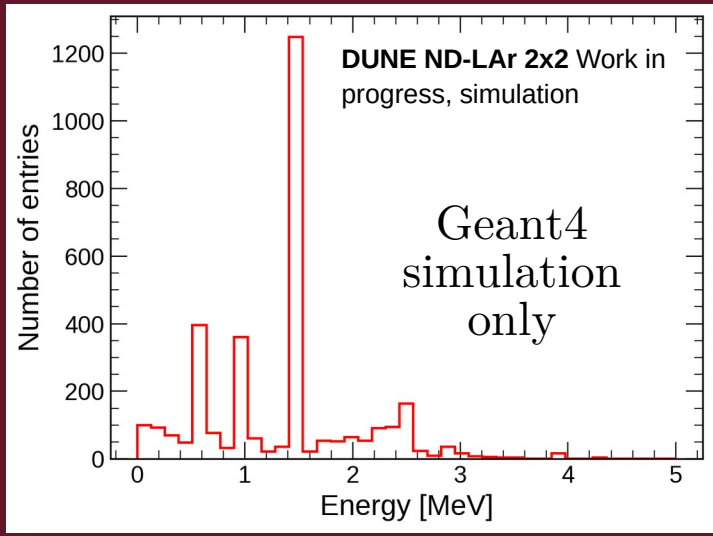
Inelastic scattering
(n, n'ɣ)

Capture
(n, ɣ)

In the 2x2, ~80% of neutrons will not produce a proton in the detector. In fact, most of the neutrons will undergo inelastic scattering. In this channel Ar is left in an excited state releasing a photon with a characteristic energy of ~1.46 MeV. This signal has been studied for the first time in a LArTPC by the ArgoNeuT collaboration

Ref: Phys. Rev. D 99, 012002 (2019)



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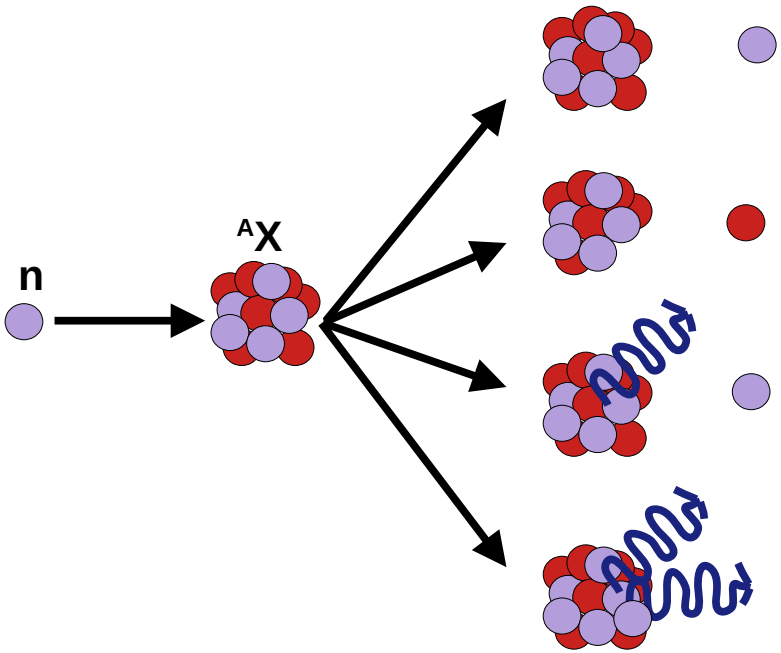

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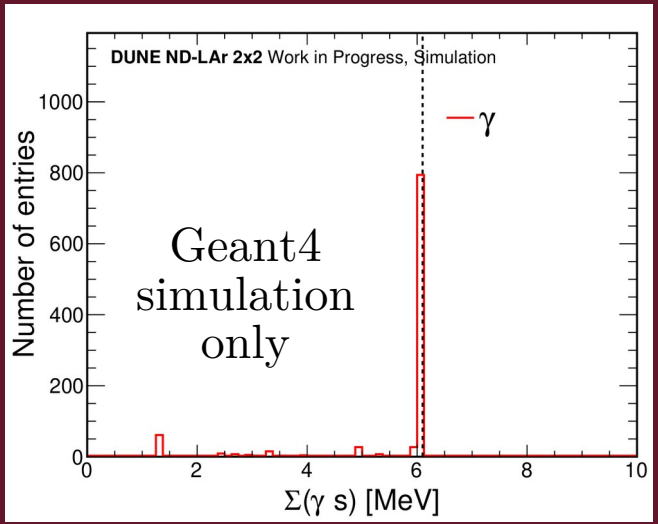
Capture (n, ɣ)

The neutron capture on an Ar nucleus produces a cascade of de-excitation photons. In most of the cases, the energy of all the released photons sum up to 6.1 MeV.

Neutron captures are being used at ProtoDUNE as a calibration source

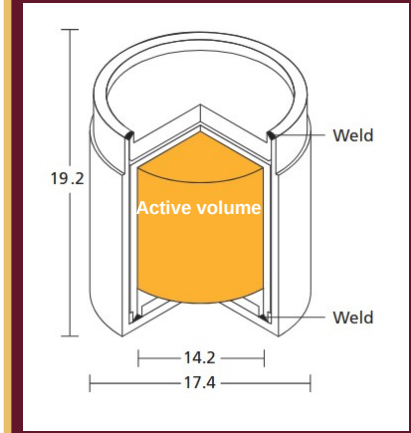


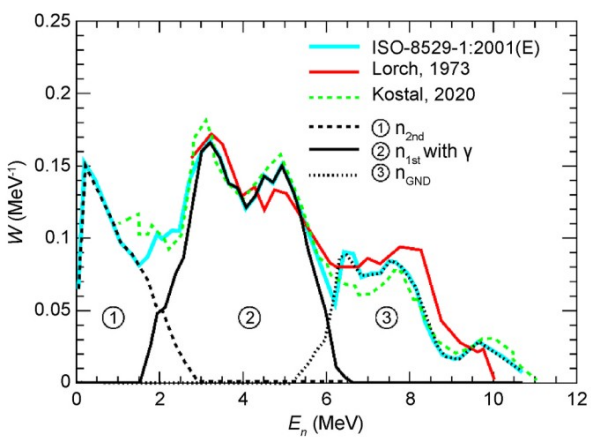
2x2 Neutron Source Run

The 2x2 is getting ready for non-beam run period during this fall. We will deploy two neutron sources to study low energy neutron activity on Ar. Reconstructed signals can be used to calibrate the low energy response of the detector.

Americium-Beryllium (AmBe)

This source emits neutrons in coincidence with a gamma of 4.4 MeV. The coincident signal can be used to identify when a neutron is emitted



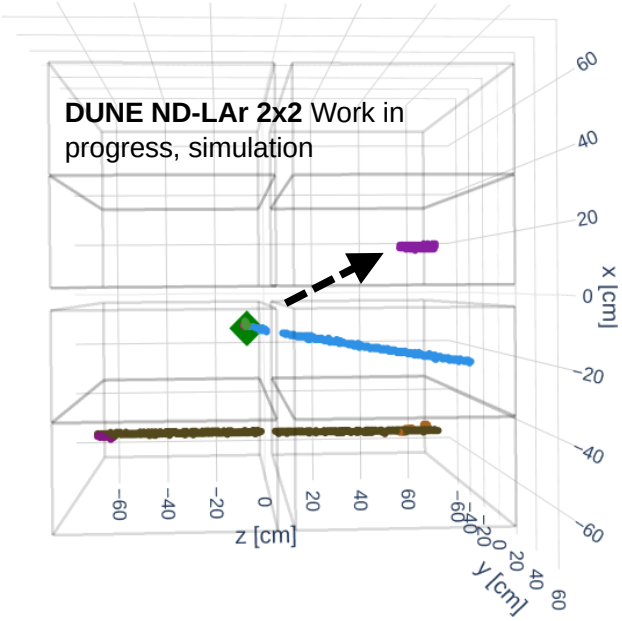


Deuterium-Tritium Generator (DTG)

This device produce “spills” of neutrons with a peak energy of 14 MeV, allowing to explore neutron capture and inelastic scattering. We will use the Thermo Fisher Scientific P385 generator.

Summary

- Identifying neutrons is important for an accurate neutrino energy reconstruction
- The 2x2 is exploring the use of distended proton tracks to tag neutrino-induced neutrons
- Charge-based track information yields good purity but low efficiency. We need to complement this analysis with light information and low energy reconstruction tools
- A dedicated neutron source run will take place during this year fall. It will allow us to study neutron capture on Ar and inelastic scattering
- This work paves the way for neutron studies that can be performed with the future DUNE NDLAr
- Thanks for listening!



More DUNE talks at NuFact25:
- Pierre Granger's plenary talk
- Grabriela Vitti's talk
- Jessie Micallef's talk
- Carmen Palomares' talk
- And more!