Expanding the Neutron Program for DUNE

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1. The Deep Underground Neutrino Experiment

DUNE is poised to answer some of the deepest questions about our universe through high-precision measurements of the properties of neutrinos (ν).

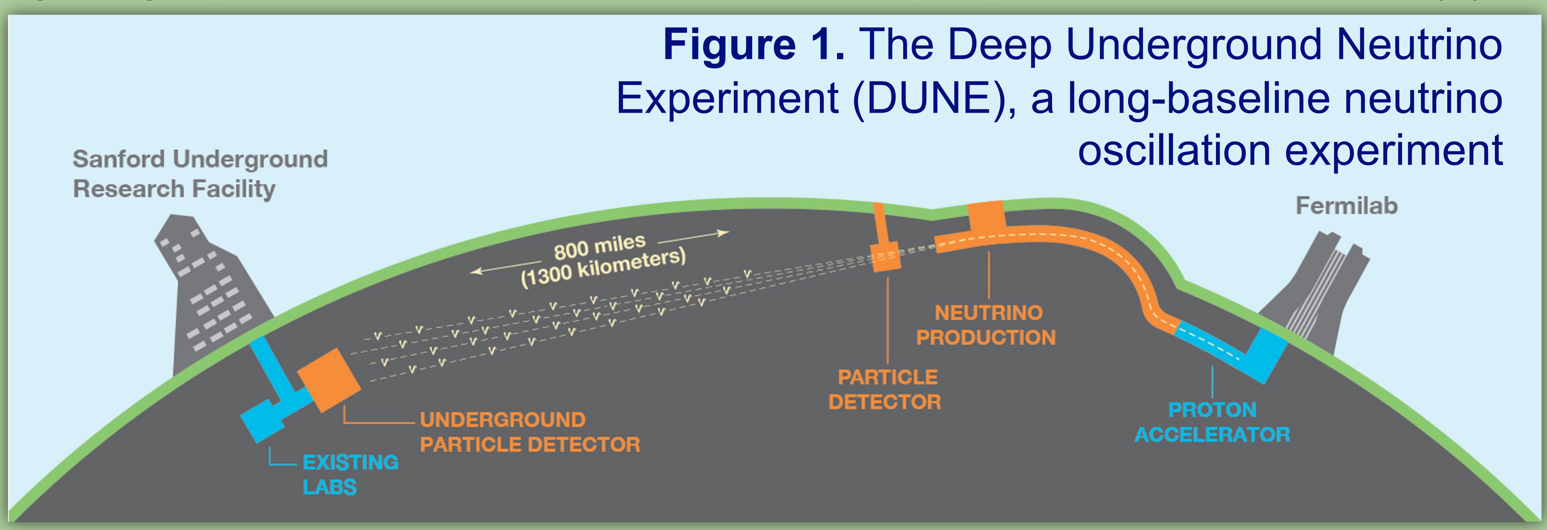


Figure 1. The Deep Underground Neutrino Experiment (DUNE), a long-baseline neutrino oscillation experiment

- Near Detector (ND) at Fermilab will sample ν beams near production point
- Far Detector (FD) 1.5 km underground in Lead, South Dakota will record ν interactions to search for Charge-Parity Violation (CPV) in the ν-sector, measure the ν mass hierarchy, and detect supernovae as well as solar νs.
- Two, 770-ton prototypes at CERN, ProtoDUNE Horizontal Drift (HD) and Vertical Drift (VD), are testbeds for full-scale DUNE technology.

2. DUNE Challenges And Requirements

At a nominal 70 kt of Liquid Argon (LAr), DUNE's far detector will be the largest LAr Time Projection Chamber (LArTPC)-based neutrino observatory.

Challenges:
- Wide-band energy $\nu/\bar{\nu}$ beams
  - (100 MeV – 10 GeV)
- *Unprecedented* requirements on energy and position resolution
- Neutrons transport energy away from the neutrino vertex and from subsequent interactions of primary component hadrons
  - Can interact far form the vertex or escape completely

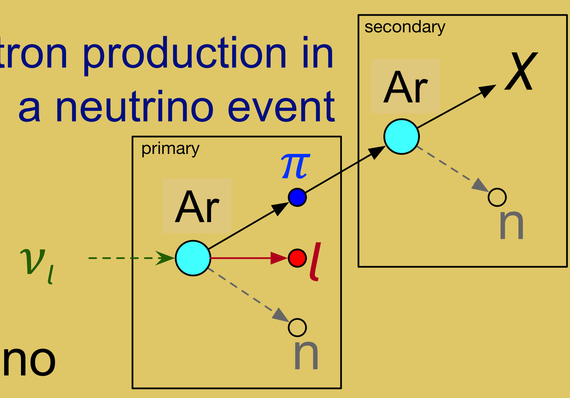


Figure 2. Neutron production in a neutrino event

physrevd.92.091301

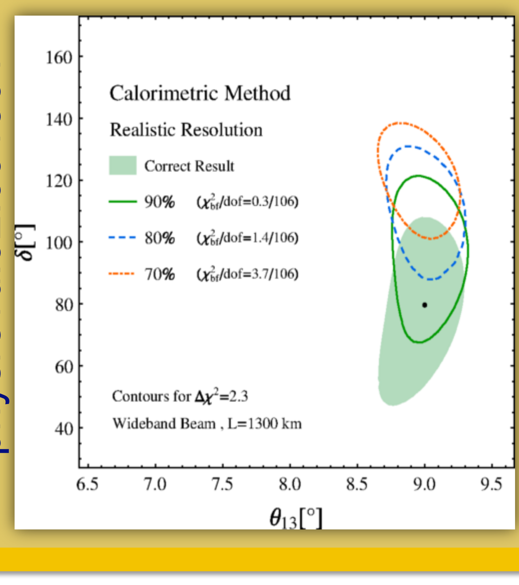


Figure 3. Effects of missing energy on the measurement of CPV and $\boldsymbol{\theta_{13}}$

$E'_{rec} = E_{rec} \times \left(p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}}\right)$

Particle	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

Figure 4. Energy uncertainty resolutions for DUNE by particle type.

arXiv:2002.03005 [hep:ex]

3. Neutron Production in ProtoDUNE

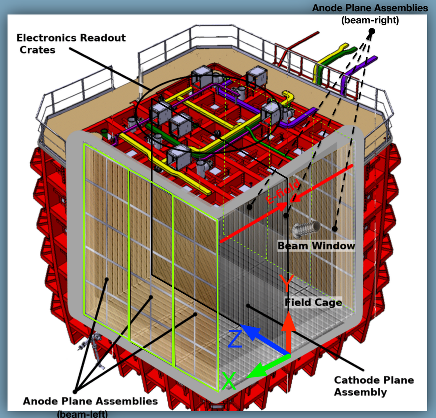


Figure 5. ProtoDUNE detector

Test-Beam: Charged particles with selected momentum between 0.3 and 7 GeV/c.
Selection: Disjoint protons produced by candidate neutrons in coincidence with the reconstructed beam particle candidates

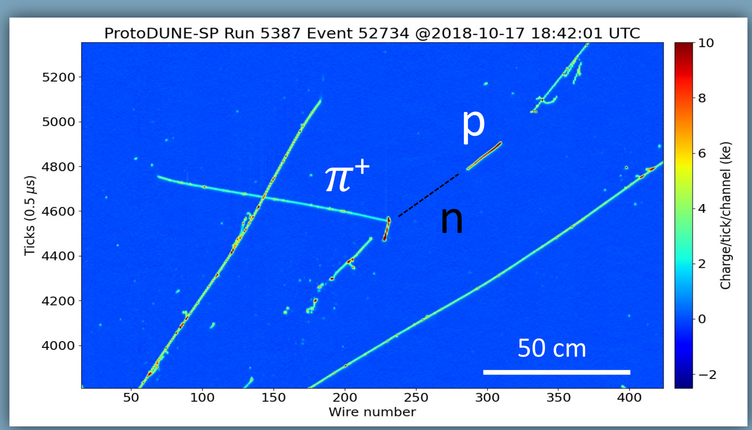


Figure 6. Neutron candidate event in run 5387.

Methodology: Generate probability distribution functions (p.d.f.s) for the radial displacement of the candidate protons and utilize a maximum likelihood method to fit to the data with variations of the nominal inelastic cross section in Geant4.

4. Cross Section Measurement in ProtoDUNE

1 GeV/c data analyzed for the cross section fit of the n-Ar inelastic cross section.

$\sigma(KE)' = C_{in-xs} \cdot \sigma_{nominal}(KE)$

$N_{candidates}(r) = n_{bkg} * bkg(r) + n_{sig} * sig(r)$

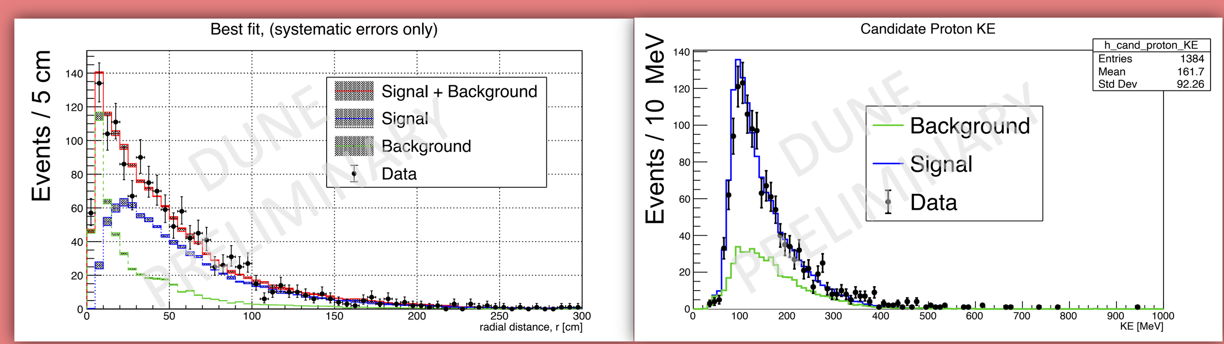
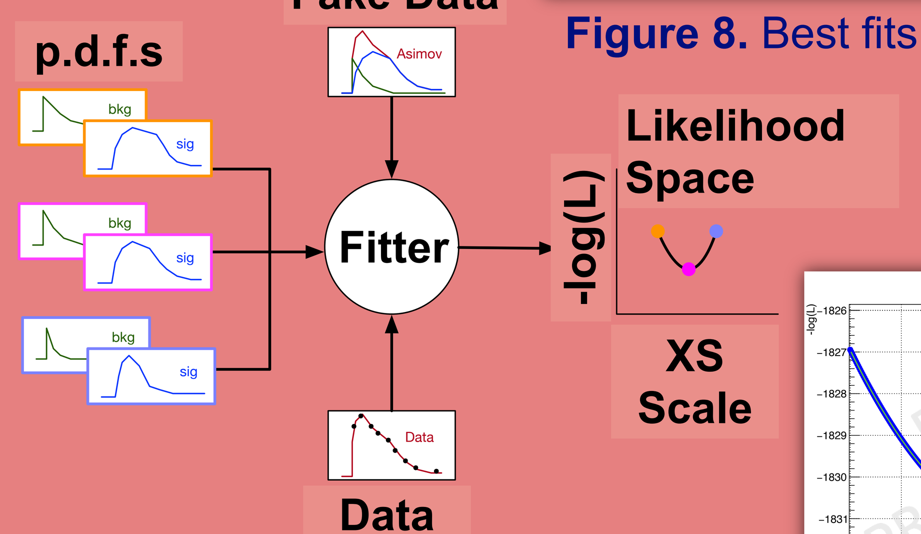
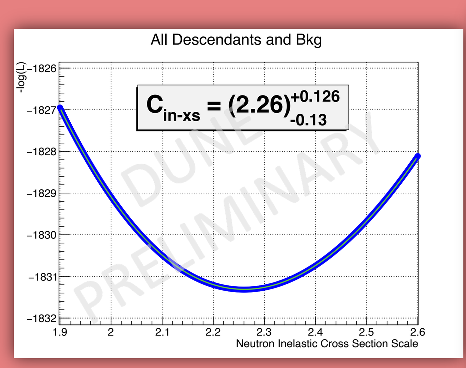


Figure 8. Best fits to the 1 GeV/c (data) candidate selection.



Statistical uncertainty, σ_θ

$\log(L \pm \sigma_\theta) = -\log(L_{max}) + \frac{1}{2}$



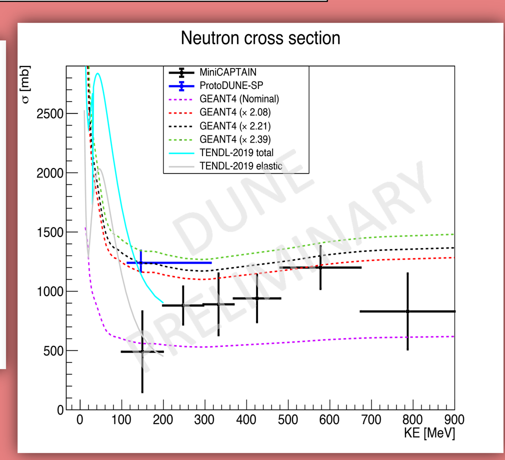


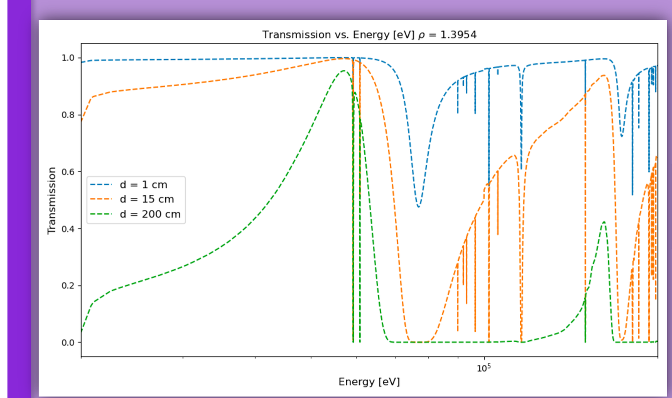
Figure 7. Variation of neutron inelastic cross section and fitting method.

- Best fit result from ProtoDUNE suggests higher than nominal neutron cross section in Argon
- Multiplicity studies and measurements at higher momenta ongoing

$\sigma_{inelastic} = 1.24^{+0.10}_{-0.05}\ barns$

5. Transmission Experiments

There are ongoing efforts to make direct measurements of the neutron-Argon total cross section using facilities at the Los Alamos Neutron Science CEnter (**LANSCE**) and at CERN's neutron Time-Of-Flight (**nTOF**) facility.



$\sigma(E) = -\frac{1}{n} ln[T(E)]$

$T(E) = \frac{Q_{out}}{Q_{in}} \frac{N_{in}(E) - B_{in}}{N_{out}(E) - N_{out}}$

Figure 9. Neutron transmission for a 1, 15, and 200 cm liquid Argon target

PhysRevC.108.L011601

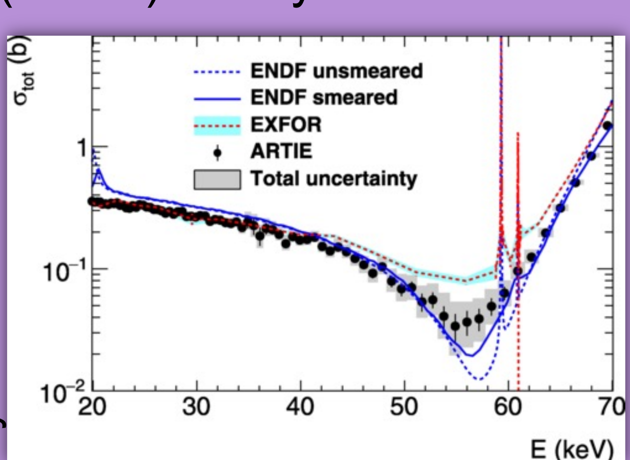
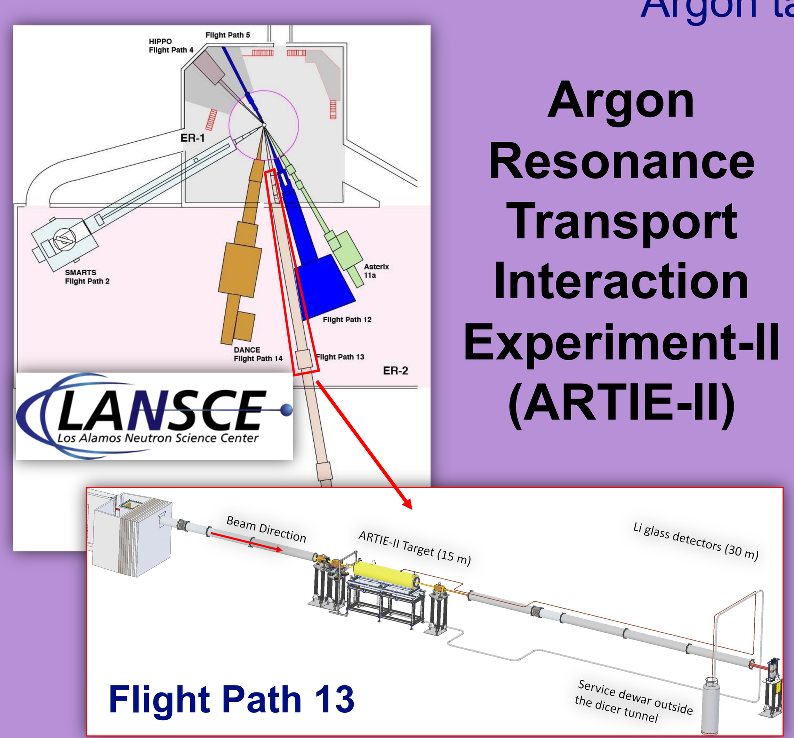


Figure 10. Results from the ARTIE-I 2019 Run



Argon Resonance Transport Interaction Experiment-II (ARTIE-II)

- 2-meter LAr target will be deployed at LANL to measure σ_{tot}
- "Binocular" setup allows for simultaneous measurement of target-in and target-out

Figure 11. ARTIE-II target to be used at the DICER facility at LANSCE.

Multiple Argon Experiments (MArEx)

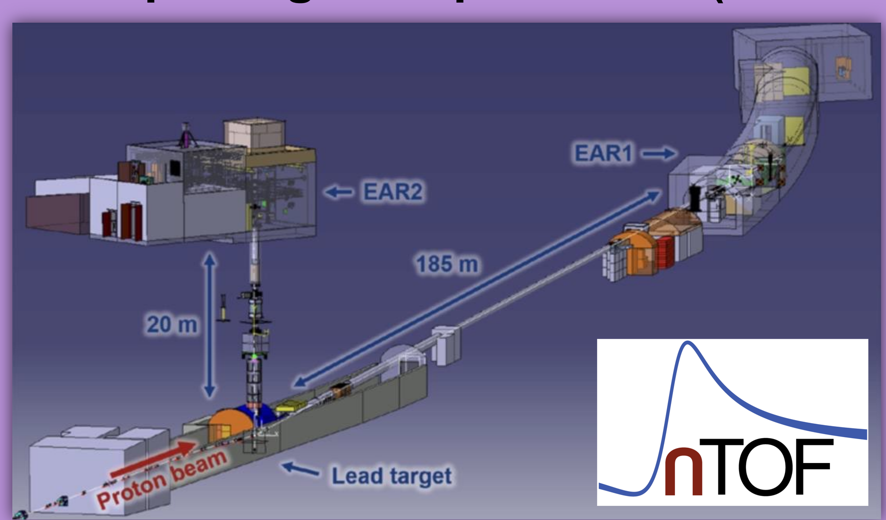


Figure 12. nTOF facility, located at CERN.

- Argon gas bottle at 200 bar, utilized to measure neutron cross sections

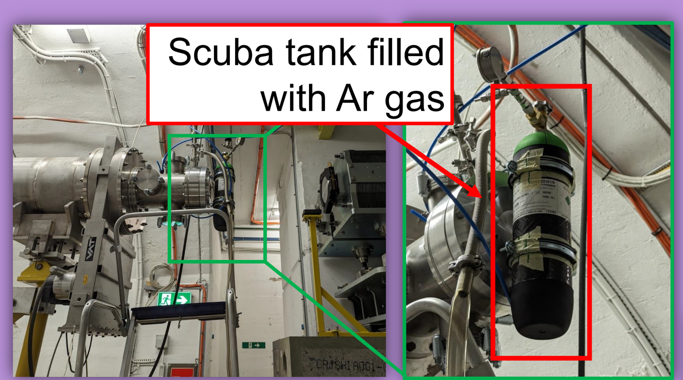
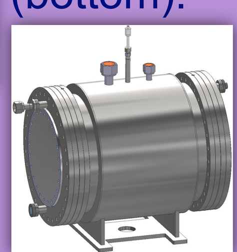


Figure 13. nTOF target station (left). New LAr target (bottom).

- 10 cm LAr target being fabricated at Los Alamos for deployment at nTOF in 2025



6. Prospects For DUNE

Neutron capture events will serve as a standard-candle, energy calibration source.

Pulsed Neutron Source (PNS):
- Neutrons can travel long distances and produce a 6.1 MeV γ-cascade upon capture on ^{40}Ar
- Deuterium-Deuterium Generator (DDG)
- PNS first deployed in ProtoDUNE Run 1
  - Improved design will be tested in Run 2

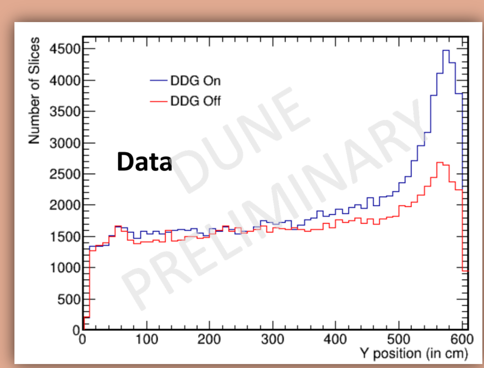


Figure 13. Hit rates in ProtoDUNE Run 1 with PNS on/off.

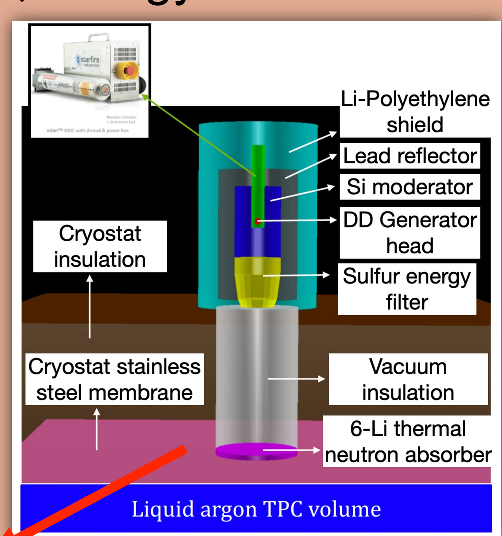


Figure 14. PNS system

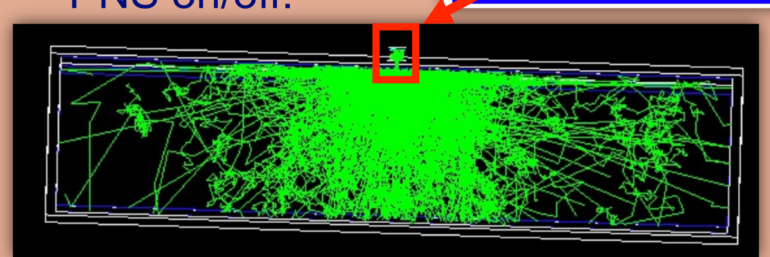


Figure 15. Simulated DUNE FD coverage for one module and a single PNS. Side view.

Collectively, these efforts will aid in understanding the neutron detector response over a wide range of energies and will be critical for improving DUNE's energy reconstruction.

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT nTOF Fermilab

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