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Defense Nuclear Nonproliferation Research and Development

University Program Review (UPR) 2023 Meeting

Using Machine Learning To Identify Neutron Captures in Liquid Argon

NSSC – Nuclear Science and Security Consortium

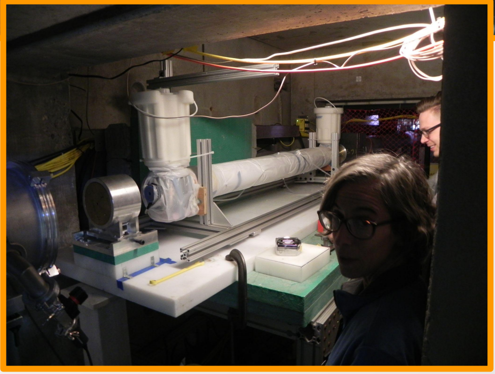
Review Date

Nicholas Carrara
UC Davis

Defense Nuclear Nonproliferation Research & Development Program

June 6 - 8, 2023

Introduction



DICER detector hall

ARTIE-I target

Department and University: **UC Davis, Physics Dept.**
Academic Advisor: **Michael Mulhearn/Robert Svoboda**
NSSC Research Focus Area(s): **Data Science, Modeling & Simulation**
Planned Graduation Date: **-**

Lab Mentor and Partner National Laboratory: Sowjanya Gollapinni, LANL

Mission Relevance of Research: DUNE/MArEX/ARTIE

Neutron interactions on Argon are the main focus of my research in 2023 (important for several reasons in neutrino experiments):

- ***Neutron missing energy*** from neutrino interactions causes huge shift in experimental fits.
- Neutrons are a ***dominant background*** in solar and supernova neutrino events.
- Uncertainties in ***absolute energy reconstruction*** in DUNE are the major contribution after the near detector.
- ***Neutron Calibration*** in DUNE using neutron captures as a standard candle.
- Using ***machine learning*** to identify neutrons in TPCs.

Several experimental efforts happening in 2023:

- Measuring the neutron ***total/capture cross-sections*** on argon at n_TOF (**MArEX** initiative).
- Measuring the neutron total cross-section in the ***anti-resonance well*** at LANL (**ARTIE**).

LANL + UC Davis

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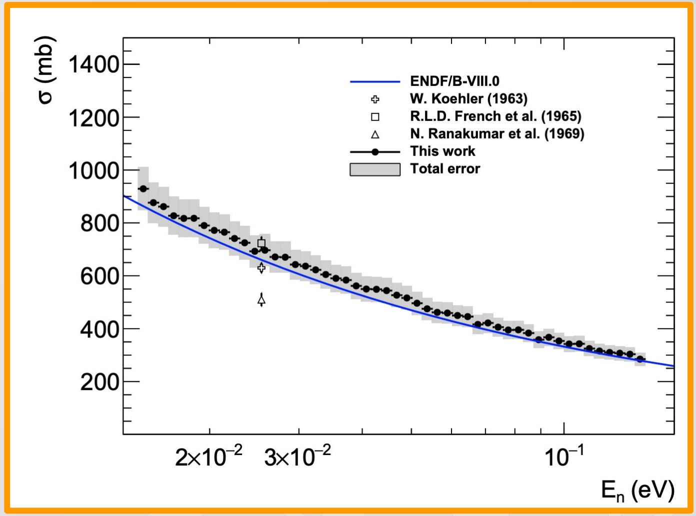
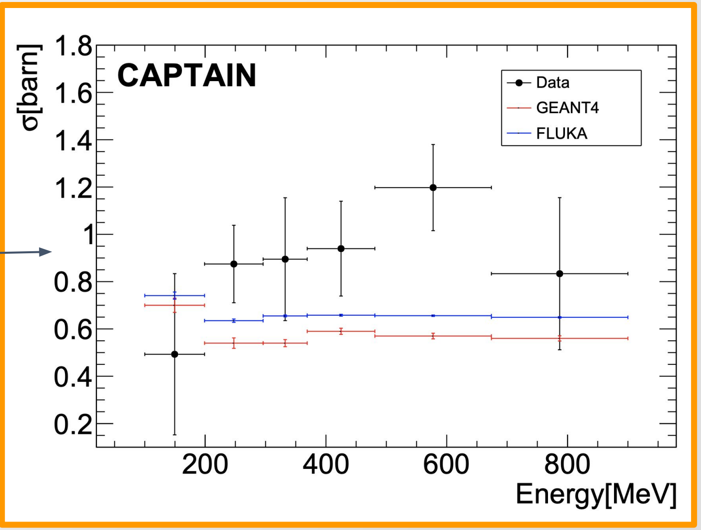
UC Davis and LANL has a growing collaborative history over several experiments.

- **ACED**[1] **- (2018) -** capture cross section in the 0.015 eV - 0.15 eV range.
- **ARTIE-I**[2] **(2019) -** total cross section in the 20 keV - 70 keV range (resonance well).
- **mini-CAPTAIN**[3] **(2019) -** cross section in the 100 MeV - 800 MeV range.
- **ARTIE-II (2023) -** 20 keV - 200 keV range.





1 *Measurement of the neutron capture cross section on argon, V. Fischer et al., Phys. Rev. D (2019).*

2 *Measurement of the total neutron cross section on argon in the 20 to 70 keV energy range, S. Andriga et al., arxiv:2212.05448, (2023).*

3 *First Measurement of the Total Neutron Cross Section on Argon Between 100 and 800 MeV, B. Bhandari et al., Phys. Rev. Lett. 123, (2019).*

Neutron Capture on Argon

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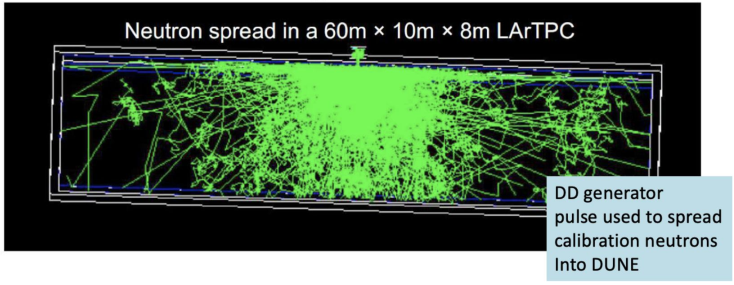
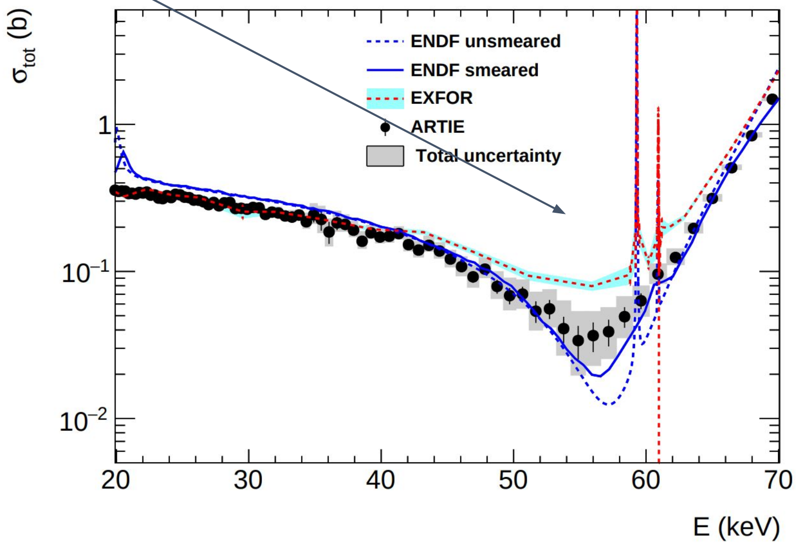
Benefits of low-energy neutrons for calibration:

- ***Scattering Length*** - Some percentage of neutrons above 57 keV will fall into the resonance well.
  - Average *fractional energy loss* is ~4.8%.
  - The *effective scattering length* is ~30 m.
  - The resonance well has been measured by the ARTIE[1] experiment at LANL, with a ***higher precision follow-up*** planned for this year.
- ***Standard Candle*** - Neutron captures on Ar-40 emit a 6.1 MeV gamma cascade.

$$n + {}^{40}\mathrm{Ar} = {}^{41}\mathrm{Ar} + \{\gamma_j\}$$
$$\sum_j E(\gamma_j) \approx 6.1\mathrm{MeV}$$



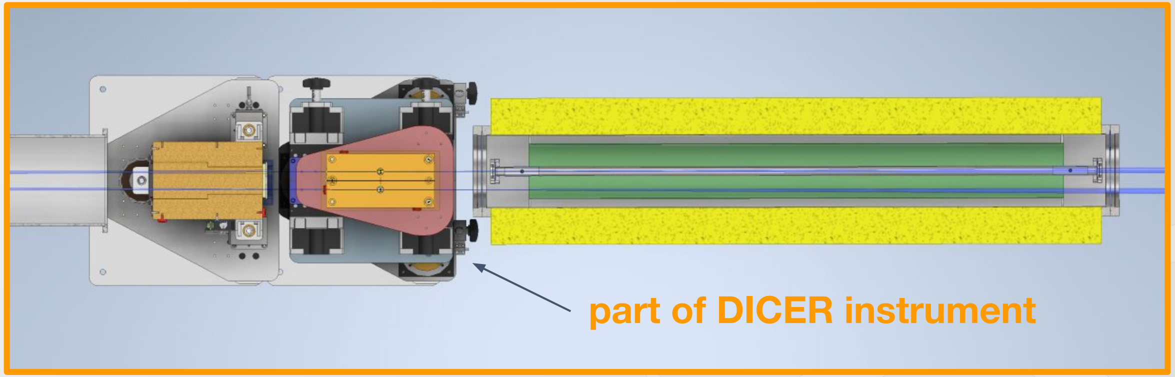


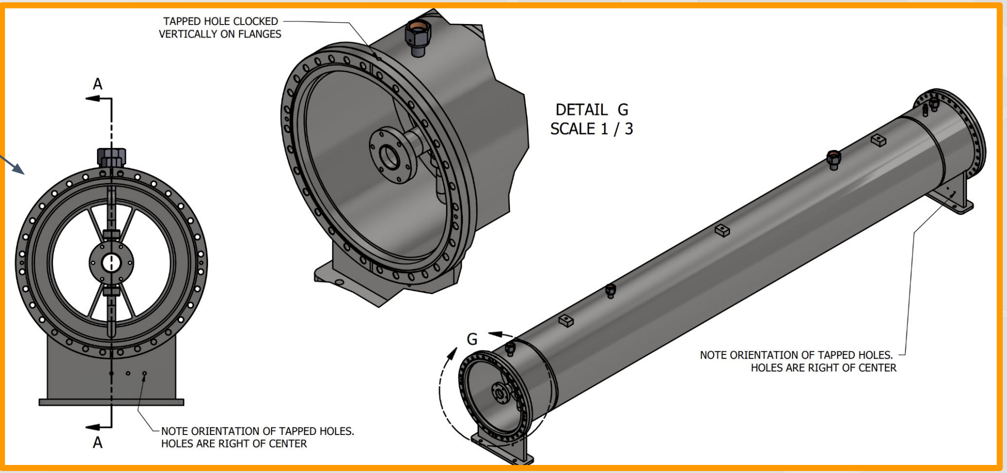
1 *Measurement of the total neutron cross section on argon in the 20 to 70 keV energy range,* The ARTIE Collaboration, In review at PRL, 2023, (https://arxiv.org/abs/2212.05448).

ARTIE-II (Argon Resonant Transport Interaction Exp.)

ARTIE-II will use the DICER instrument at LANSCE.

- Simultaneous **target-in/target-out** measurements.
- Annulus design by LANL engineers **reduces ARTIE-I heat load** by order of magnitude.
- 30 meter time of flight.
- 200 cm long target for sensitivity to **anti-resonance well.**
- Additional “short” target (15 cm) for measuring larger cross-sections/energies.





BLIP (Blips and Low-energy Interaction PointNet)

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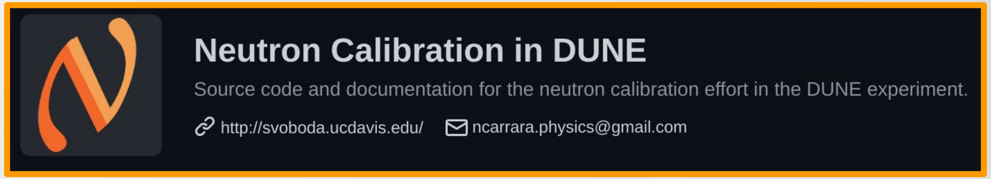
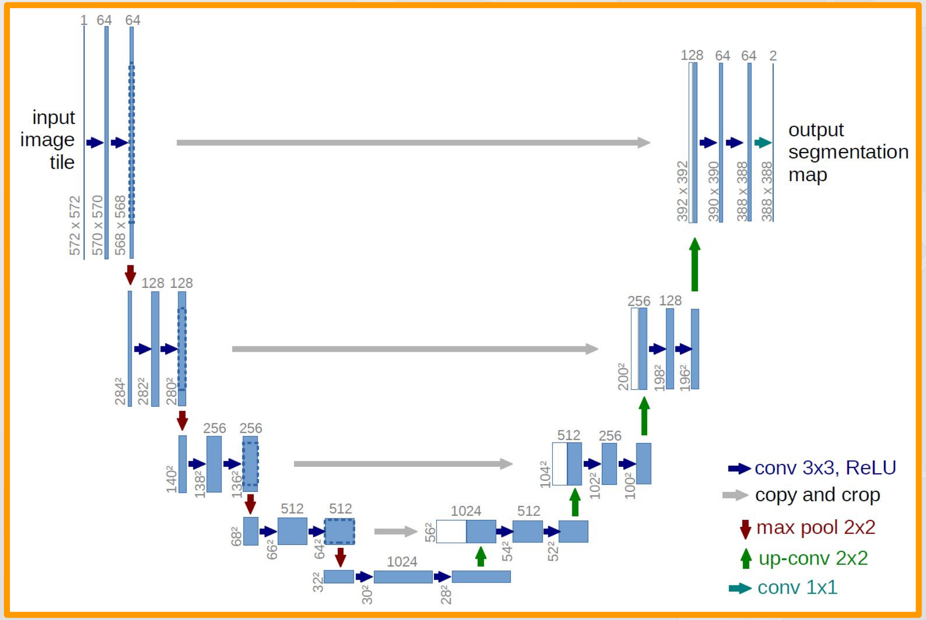
We introduce ***BLIP***[2], a collection of ML algorithms for classifying low energy interactions in LArTPCs.

- **Input variables** - 3D point clouds (*tdc, channel, adc*) from detector readout (normalized with respect to all events).
- **Labels** - Currently trains to classify individual point clouds, but will eventually work semantically on entire detector readout.

Benefits of this approach:

- Operates on ***detector readout only*** (no reconstruction needed!)
- Generates a model for each view rather than on reconstructed space points.





2 *BLIP: Blips and Low-energy Interaction PointNet,* DUNE PNS Group (UC Davis), 2023, (https://github.com/Neutron-Calibration-in-DUNE/Blip).

Preliminary BLIP Results

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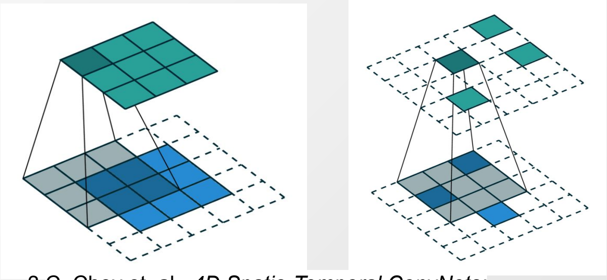
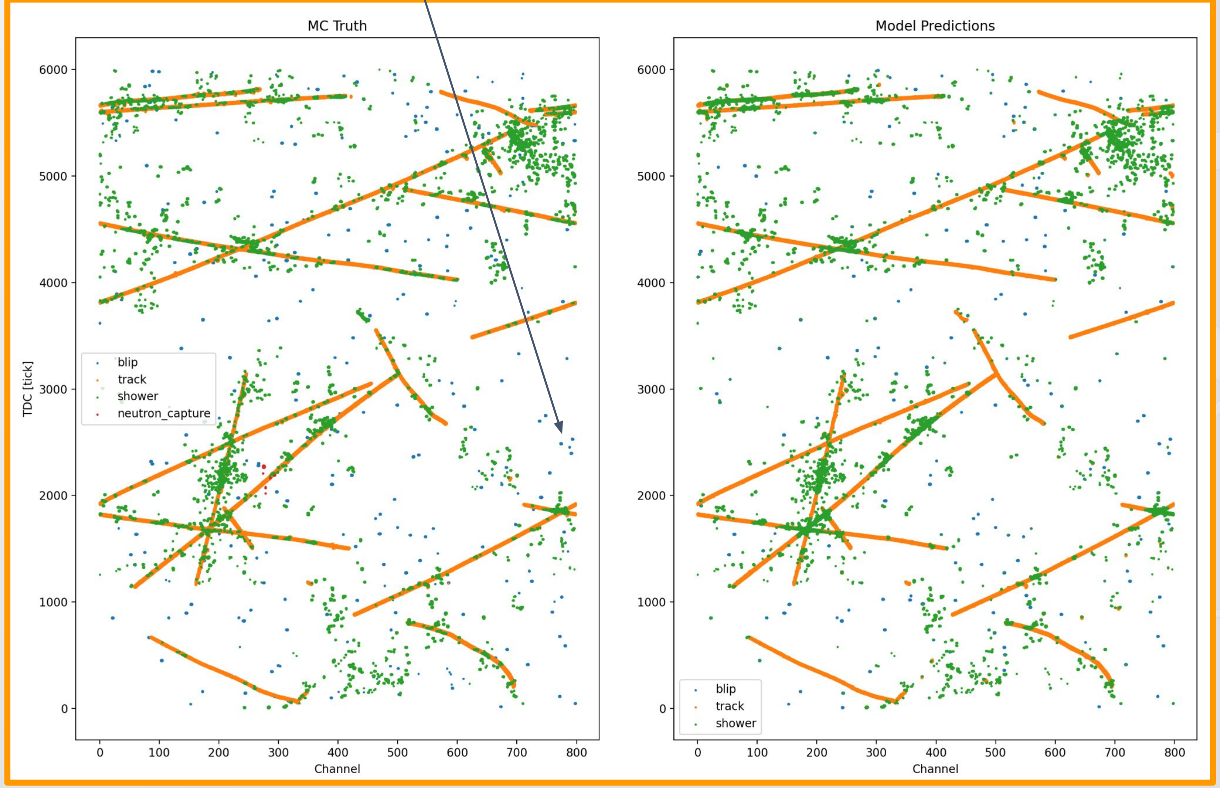
An initial stage of the algorithm conducts **semantic segmentation** on the detector output to classify shapes.

- A major challenge is sparseness (about 99% of voxelized event space is empty).
- Use a **SparseTensor**[3] representation



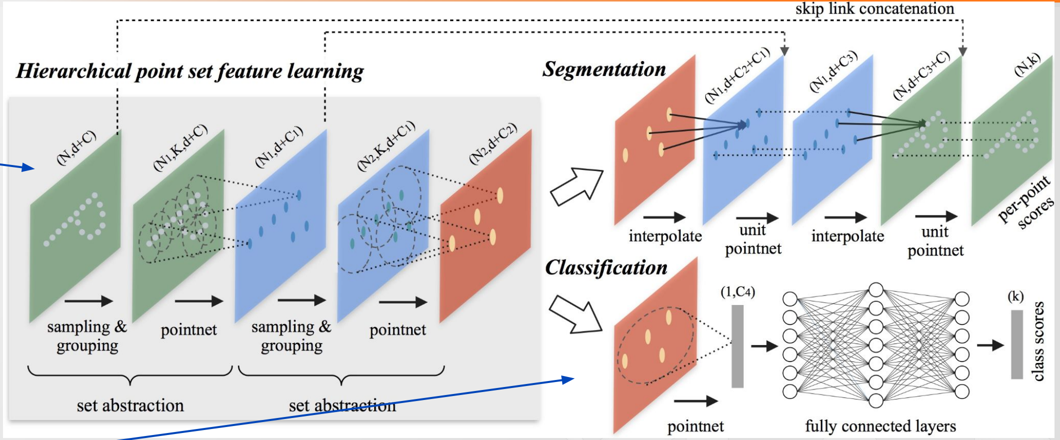
3 C. Choy et. al., *4D Spatio-Temporal ConvNets: Minkowski Convolutional Neural Networks*, arXiv:1904.08755, 2019.

This first module can be used to categorize blips



BLIP consists of at least two main models:

- **Semantic Clustering** - The first network will take in an entire detector readout for an event and learn to generate clusters (e.g. PointNet++[5]).
- **Cluster Segmentation/Classification** - The second network will learn to classify these clusters into different types (e.g. PointNet[4], EdgeConv[6]).



Models are built using the ***PyTorch Geometric*** API (https://pytorch-geometric.readthedocs.io/en/latest/)

4 *PointNet: Deep Learning on Point Sets for 3D Classification and Segmentation,* C. Qi et. al., CVPR 2017, (https://arxiv.org/abs/1612.00593).
5 *PointNet++: Deep Hierarchical Feature Learning on Point Sets in a Metric Space*, C. Qi et. al., (https://arxiv.org/abs/1706.02413)
6 *Dynamic Graph CNN for Learning on Point Clouds,* Y. Wang et. al., 2018, (https://arxiv.org/abs/1801.07829)

Preliminary BLIP Results

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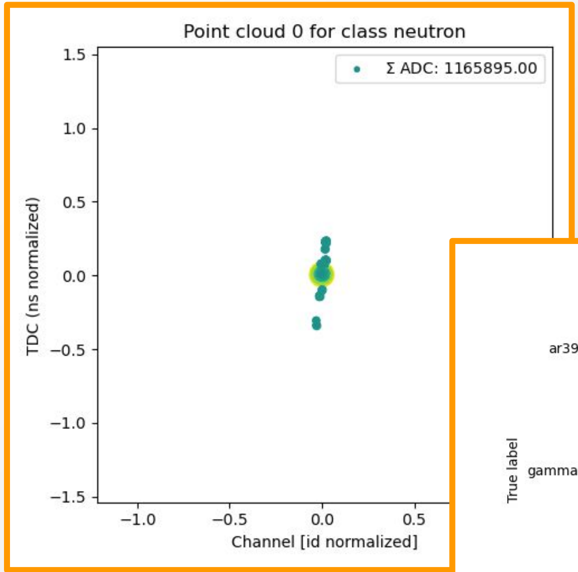
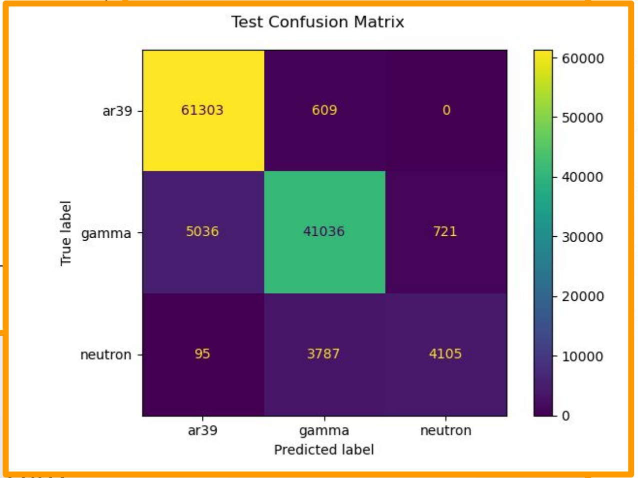
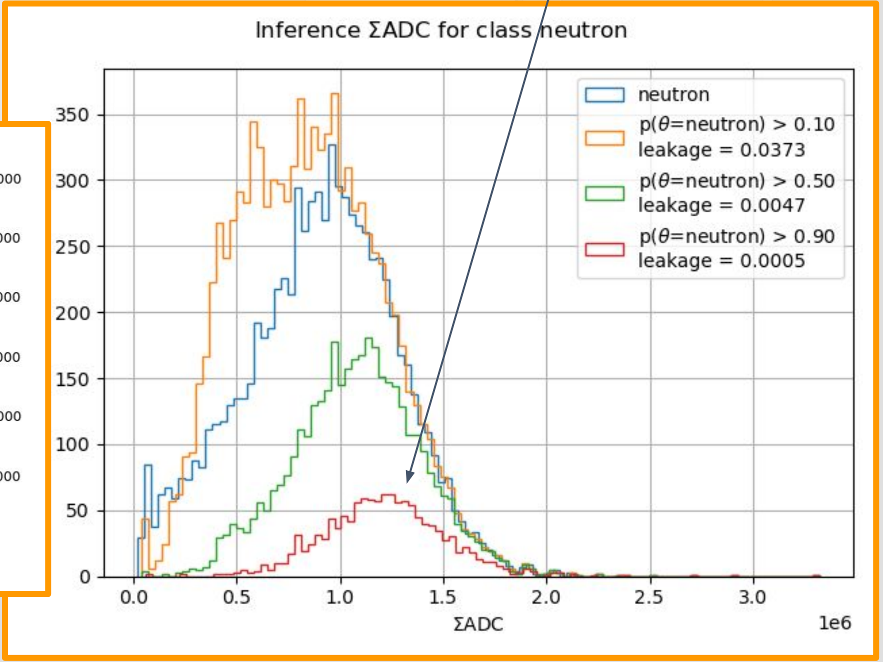
We trained a **BLIP** model on 116K point clouds with a 70/30 train/test split and the following classes:

- Argon-39: 61,912 events (~53%)
- Capture Gammas: 46,793 events (~40%)
- Neutron Captures: 7,987 events (~7%)

The resulting distribution of detector output ADC values can be used for calibrating energy!







The NSSC Experience

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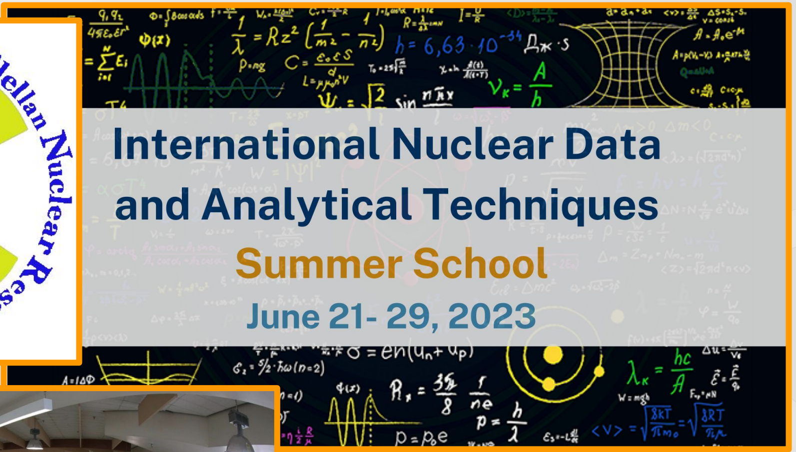
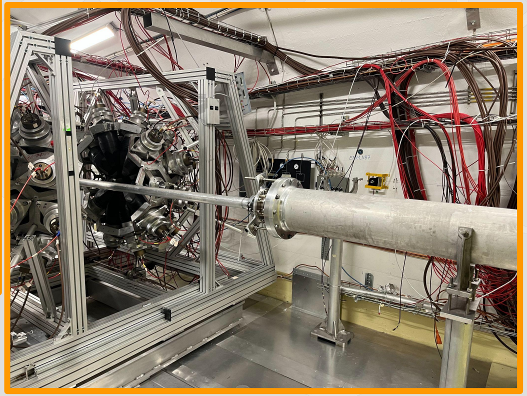
NSSC has provided me with several excellent opportunities:

- **Nuclear Data/Analytic Techniques (NAT)** Summer School hosted by UC Berkeley and **UC Davis**.
  - Organizer/Lecturer for nuclear activation/machine learning activity (2022-).
  - Hands-on reactor experience at McClellan Nuclear Research Center.
- **Two Neutron Experiments in 2023!**
  - **LANL/ARTIE** DICER Beam commissioning (2023).
  - **n_TOF/MArEX** Several year experimental effort at CERN.





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Acknowledgements

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UC Davis - Yashwanth Bezawada, Tyler Erjavec, Junying Huang, Michael Mulhearn, Emilija Pantic, Robert Svoboda

LANL (ARTIE/MArEX) - Jan Boissevain, Sowjanya Gollapinni, Paul Koehler, Eric Renner, David Rivera, Thanos Stomatopolous, John Ullmann

n_TOF (MArEX) - Michael Bacak, Alberto Mengoni, Nikolas Patronis

FNAL (DUNE) - Tom Junk, Kyle Knoepfel

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Backup Slides

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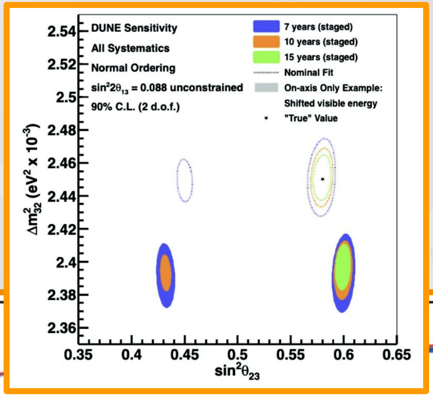
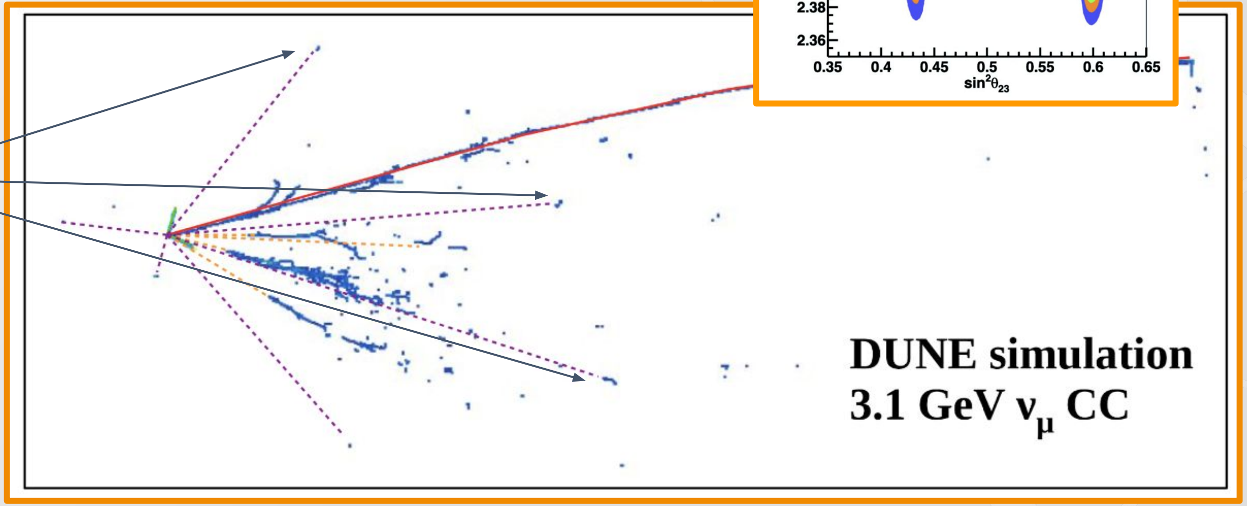
Missing neutron energy in neutrino interactions

It is necessary to be able to account for the neutron "missing energy" in order to make precision oscillation measurements (production and transport).

- Reconstructed neutrino energy is smeared by missing neutrons.
- Neutrons show up as small ***blips*** in LAr detectors.

fits with neutron energy missing





Neutron background and energy scale

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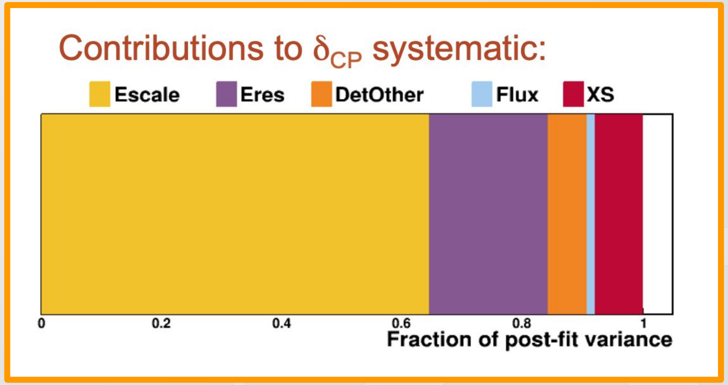
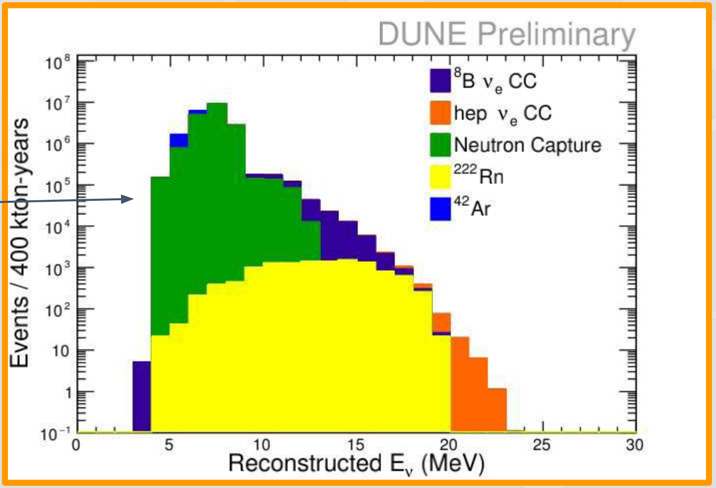
Uncertainties due to the **absolute energy calibration** are the major detector contributions that remain (after the input from the near detector).

- Assuming a 2% shift in **absolute energy scale.**



DUNE could have significant sensitivity to **solar neutrinos**:

- The rate of neutron background is expected to be a significant factor in triggering DUNE on a supernova neutrino burst!
- Depends on the ability to trigger on very small energy depositions and reject backgrounds due to neutrons!



MArEX (Multiple Argon Experiments) Initiative

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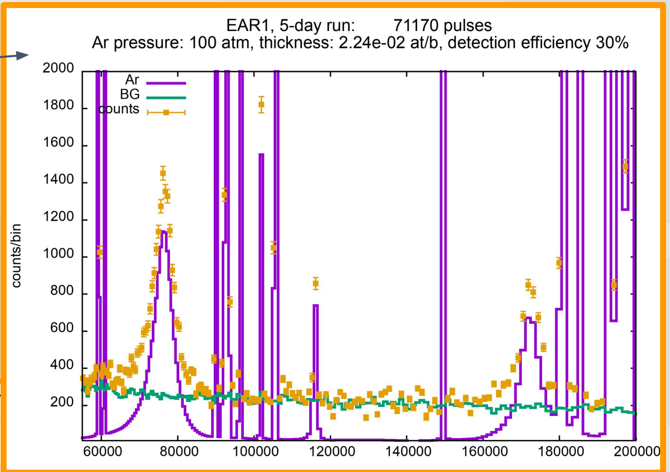
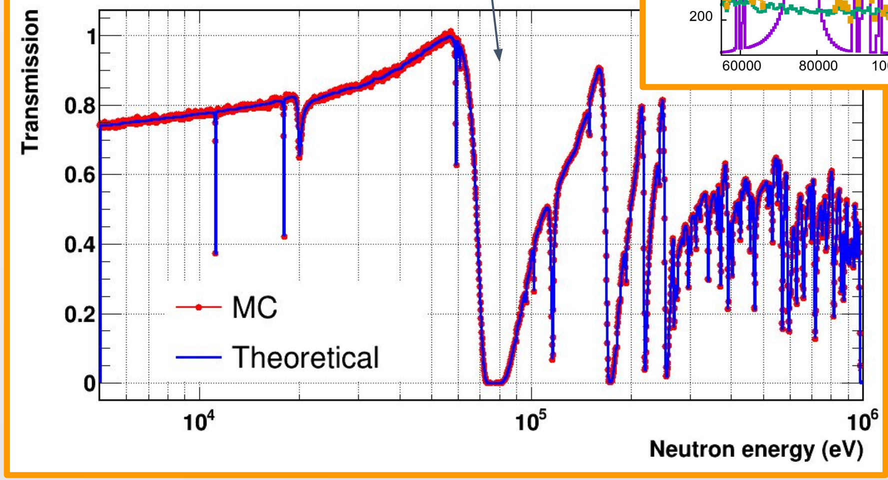
MArEX Initiative will conduct two feasibility measurements at n_TOF this year.

- **Carbon Fiber** SCUBA tanks (pressurized Ar gas up to 300 atm) (carbon cross-section is flat in ROI).
- 200 meter time of flight.
- Requested one month of running at both EAR1/EAR2 experimental areas.

capture measurement



transmission measurement



n_TOF

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Neutron Calibration in DUNE

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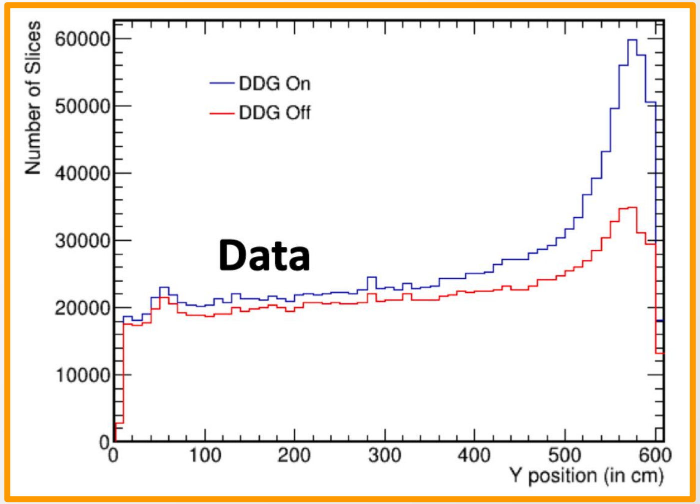
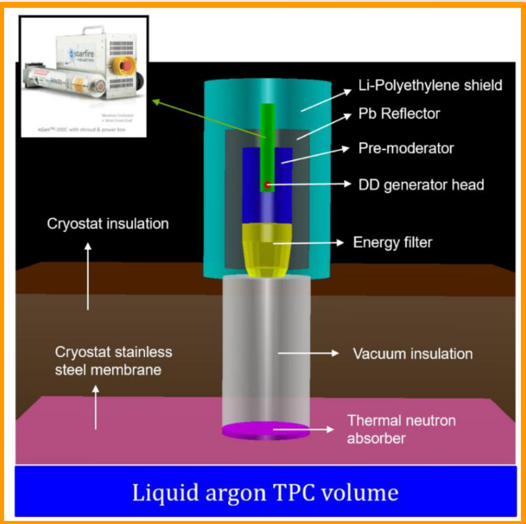
Pulsed Neutron Source (PNS)

- **External Deployment:** DD-generator (provided by LANL) sits outside the cryostat.
- **Scattering Length:** Confirmed in ProtoDUNE run I with DD-generator.





Schematic of DDG used in ProtoDUNE