

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

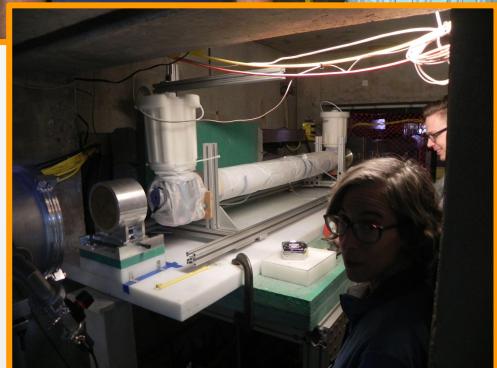


Defense Nuclear Nonproliferation
Research & Development Program

Introduction



DICER
detector
hall



ARTIE-I
target

Department and University:

Academic Advisor:

NSSC Research Focus Area(s):

Planned Graduation Date:

UC Davis, Physics Dept.

Michael Mulhearn/Robert Svoboda

Data Science, Modeling & Simulation

-

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):

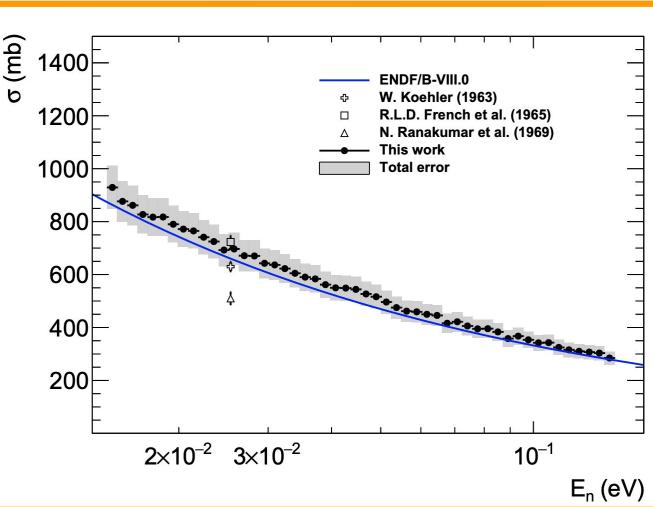
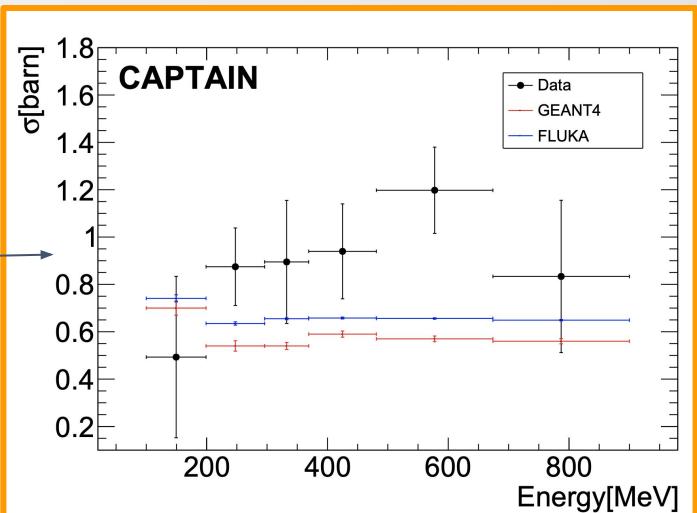
- **Neutron missing energy** from neutrino interactions causes huge shift in experimental fits.
- Neutrons are a **dominant background** in solar and supernova neutrino events.
- Uncertainties in **absolute energy reconstruction** in DUNE are the major contribution after the near detector.
- **Neutron 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**).

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

- **ACED¹ - (2018)** - capture cross section in the 0.015 eV - 0.15 eV range.
- **ARTIE-I² (2019)** - total cross section in the 20 keV - 70 keV range (resonance well).
- **mini-CAPTAIN³ (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).

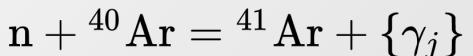
2 Measurement of the total neutron cross section on argon in the 20 to 70 keV energy range, S. Andriga et al., arxiv:2212.05448, (2023).

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

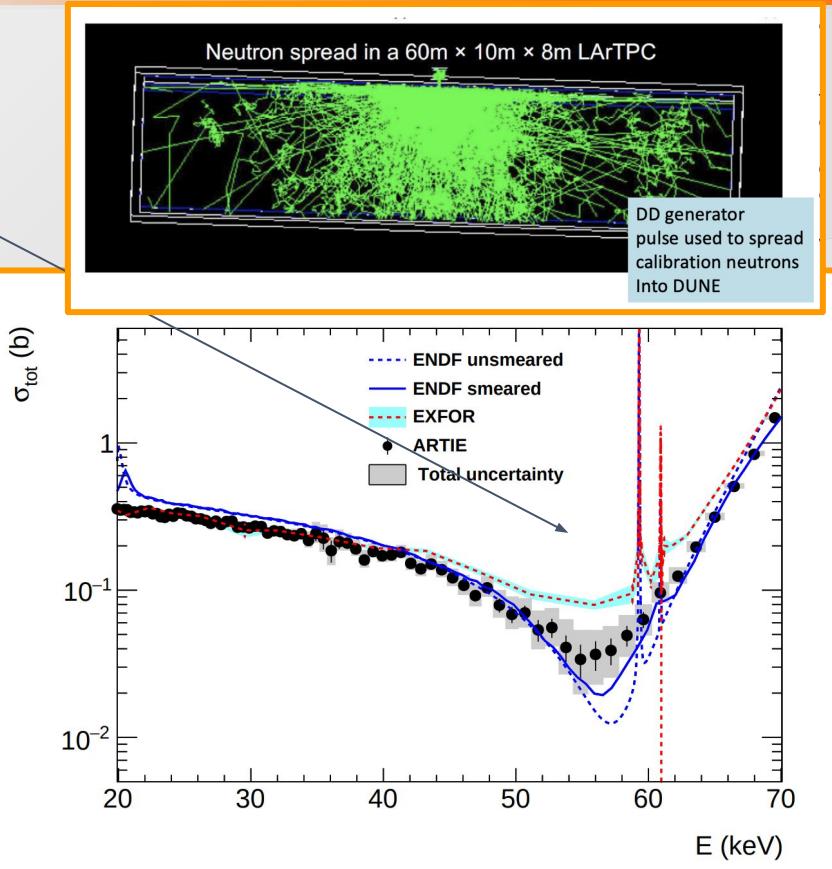
Benefits of low-energy neutrons for calibration:

- **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 ARTIE¹ 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.



$$\sum_j E(\gamma_j) \approx 6.1\text{MeV}$$

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>).



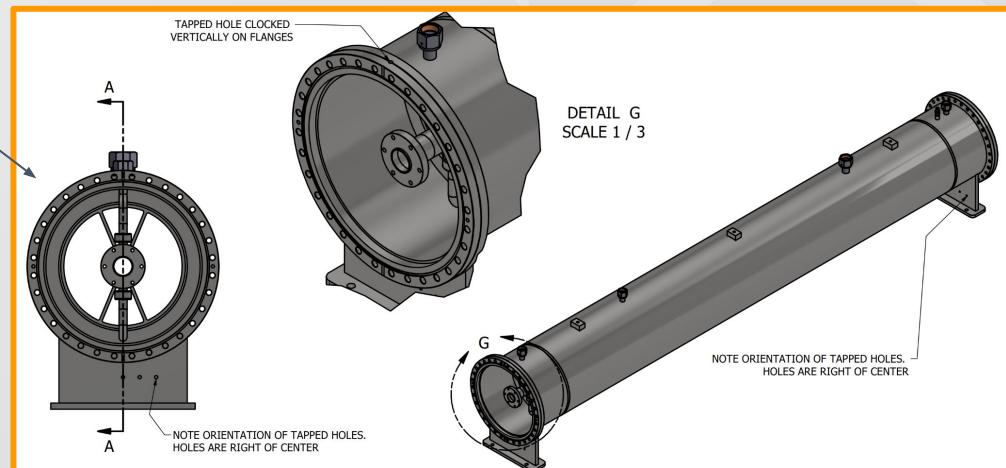
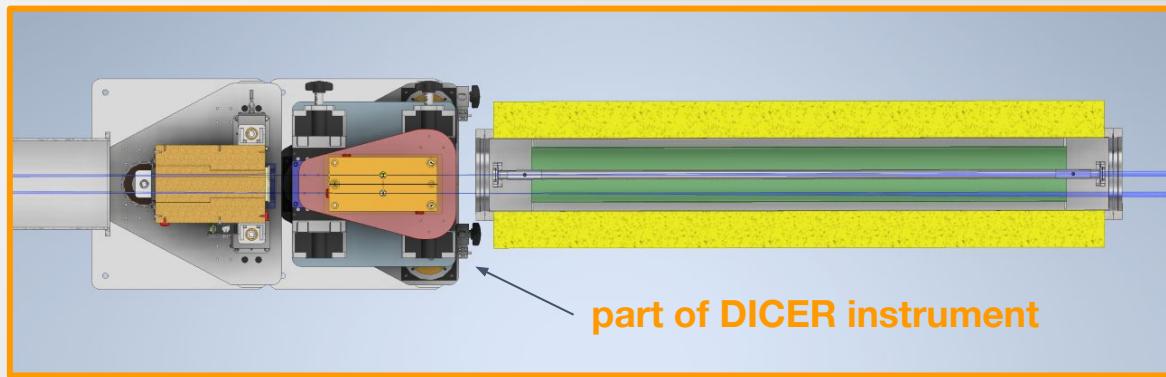
ARTIE-II (Argon Resonant Transport Interaction Exp.)



INNOVATE. COLLABORATE. DELIVER.

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.

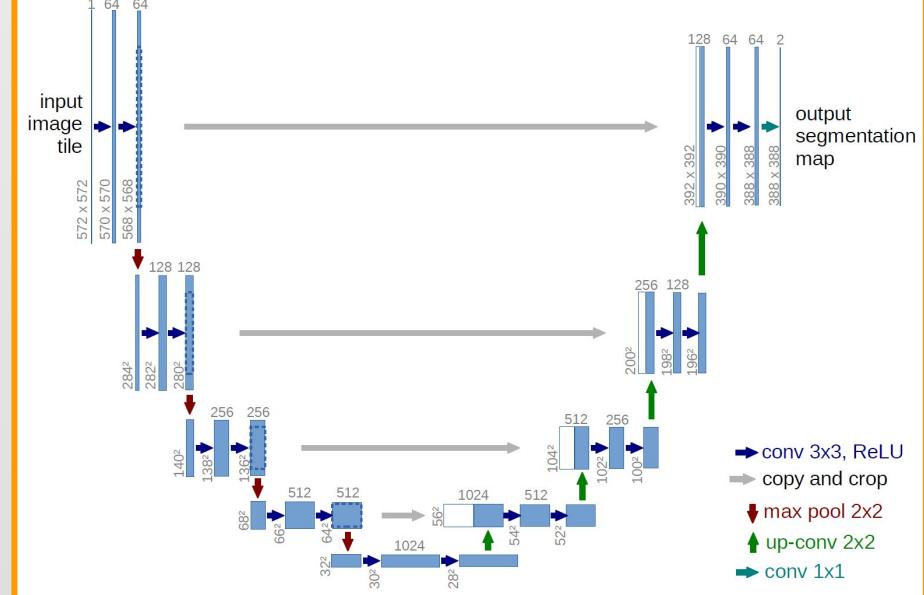
² BLIP: Blips and Low-energy Interaction PointNet, DUNE PNS Group (UC Davis), 2023, (<https://github.com/Neutron-Calibration-in-DUNE/Blip>).



Neutron Calibration in DUNE

Source code and documentation for the neutron calibration effort in the DUNE experiment.

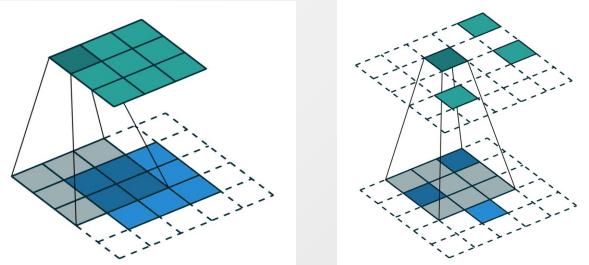
☞ <http://svoboda.ucdavis.edu/> ☎ ncarrara.physics@gmail.com



Preliminary BLIP Results

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

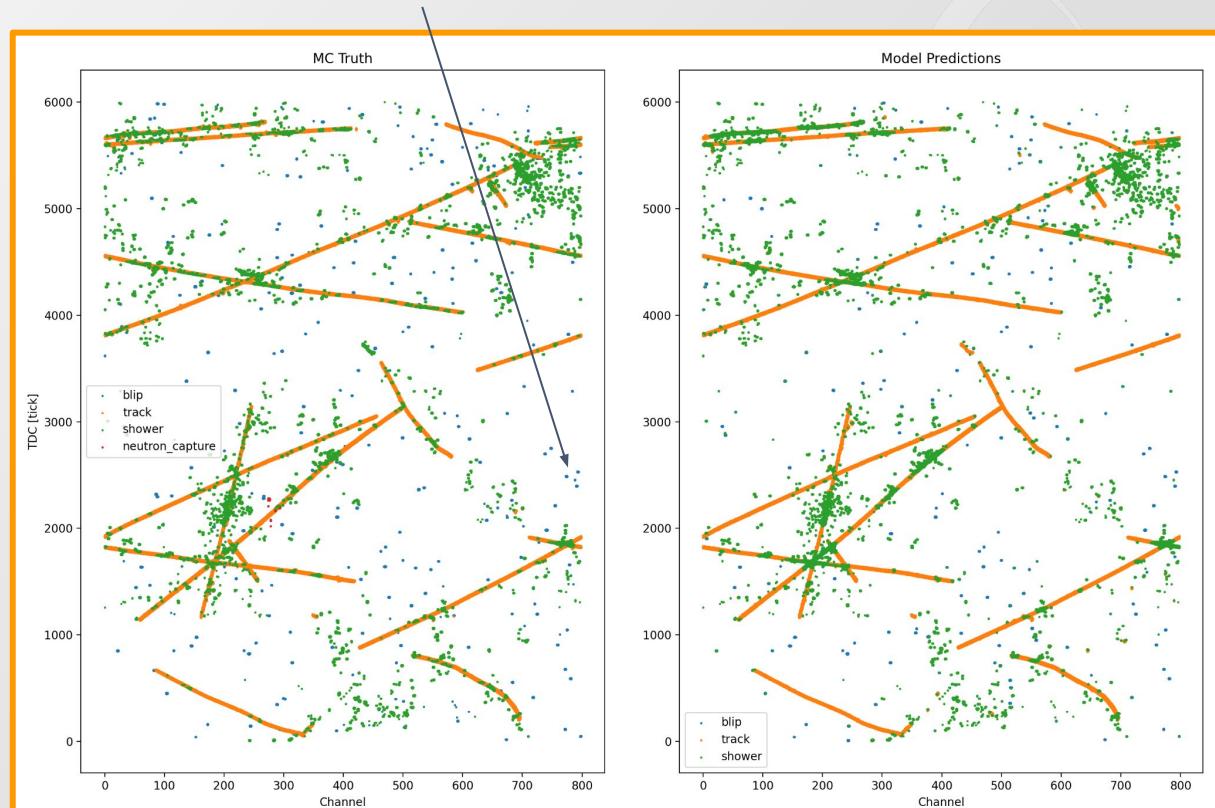
- A major challenge is sparseness (about 99% of voxelized event space is empty).
- Use a **SparseTensor³** representation



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

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This first module can be used to categorize blips



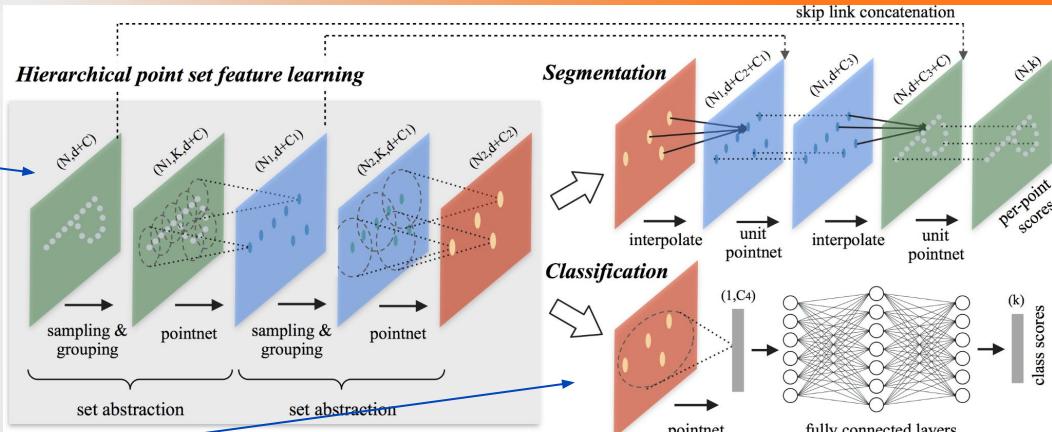
BLIP (Blips and Low-energy Interaction PointNet)



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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. PointNet⁴, EdgeConv⁶).



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>).

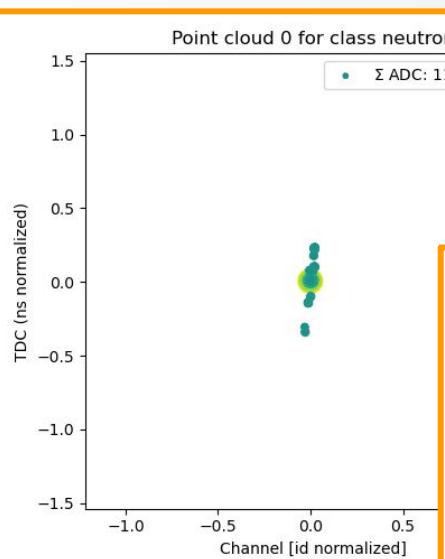
5 PointNet++: Deep Hierarchical Feature Learning on Point Sets in a Metric Space, C. Qi et. al., (<https://arxiv.org/abs/1706.02413>)

6 Dynamic Graph CNN for Learning on Point Clouds, Y. Wang et. al., 2018, (<https://arxiv.org/abs/1801.07829>)

Preliminary BLIP Results

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

Point cloud 0 for class neutron



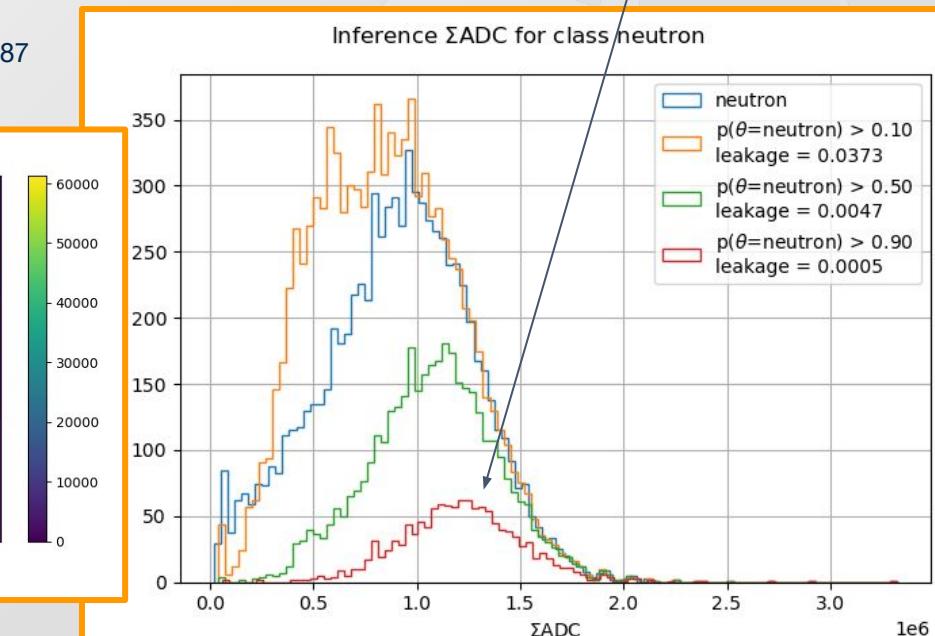
- Argon-39: 61,912 events (~53%)
- Capture Gammas: 46,793 events (~40%)
- Neutron Captures: 7,987 events (~7%)

Test Confusion Matrix

		Predicted label		
		ar39	gamma	neutron
True label	ar39	61303	609	0
	gamma	5036	41036	721
neutron	95	3787	4105	

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

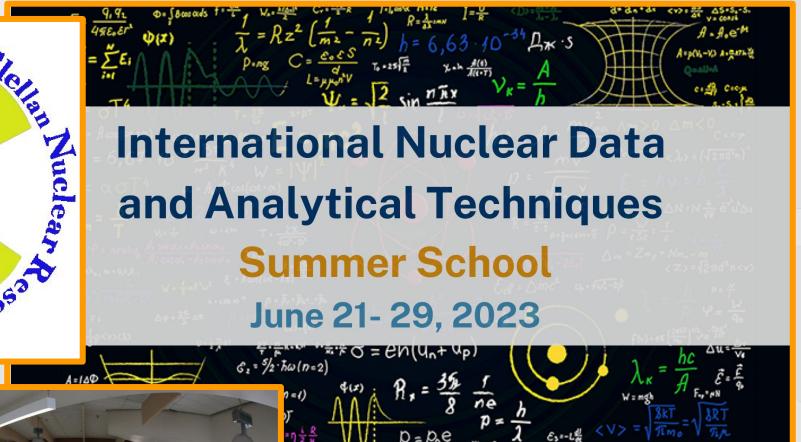
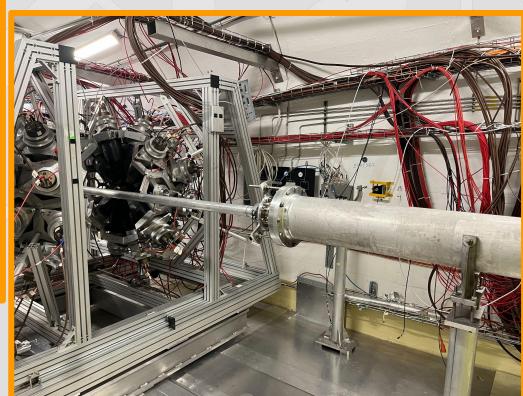
Inference Σ ADC for class neutron



The NSSC Experience

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.



International Nuclear Data and Analytical Techniques Summer School
June 21- 29, 2023

Acknowledgements

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

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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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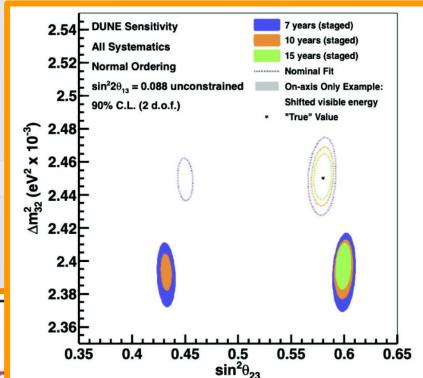
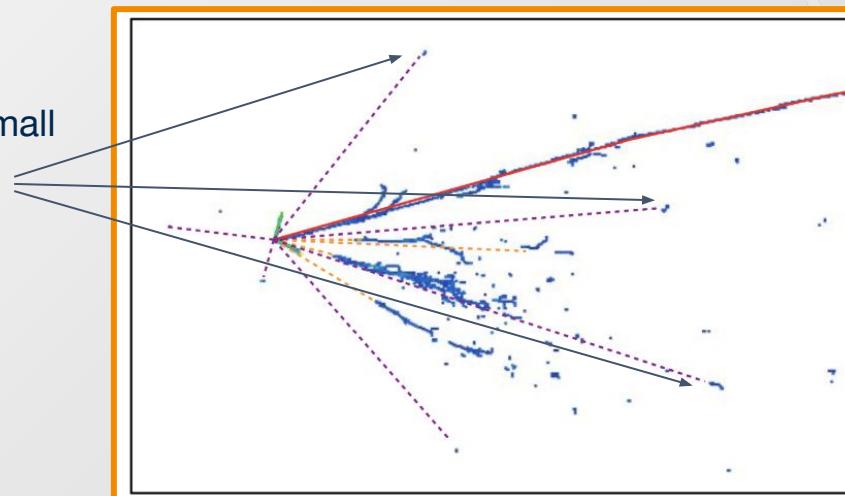


Missing neutron energy in neutrino interactions

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



DUNE simulation
3.1 GeV ν_μ CC

Neutron background and energy scale

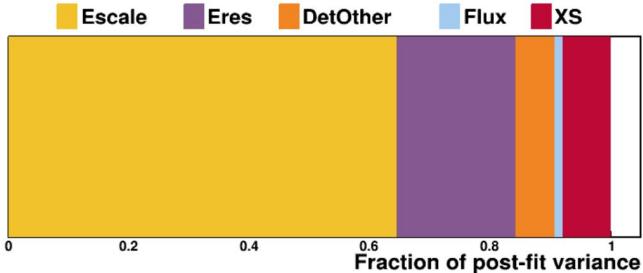
Uncertainties due to the **absolute energy calibration** are the major detector contributions that remain (after the input from the near detector).

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

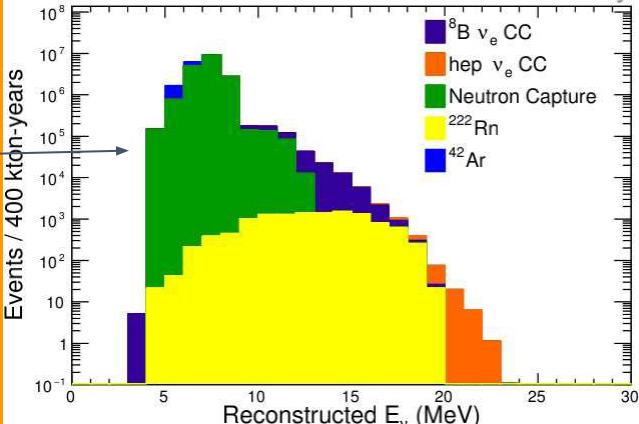
DUNE could have significant sensitivity to **solar neutrinos**:

- 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**!

Contributions to δ_{CP} systematic:



DUNE Preliminary



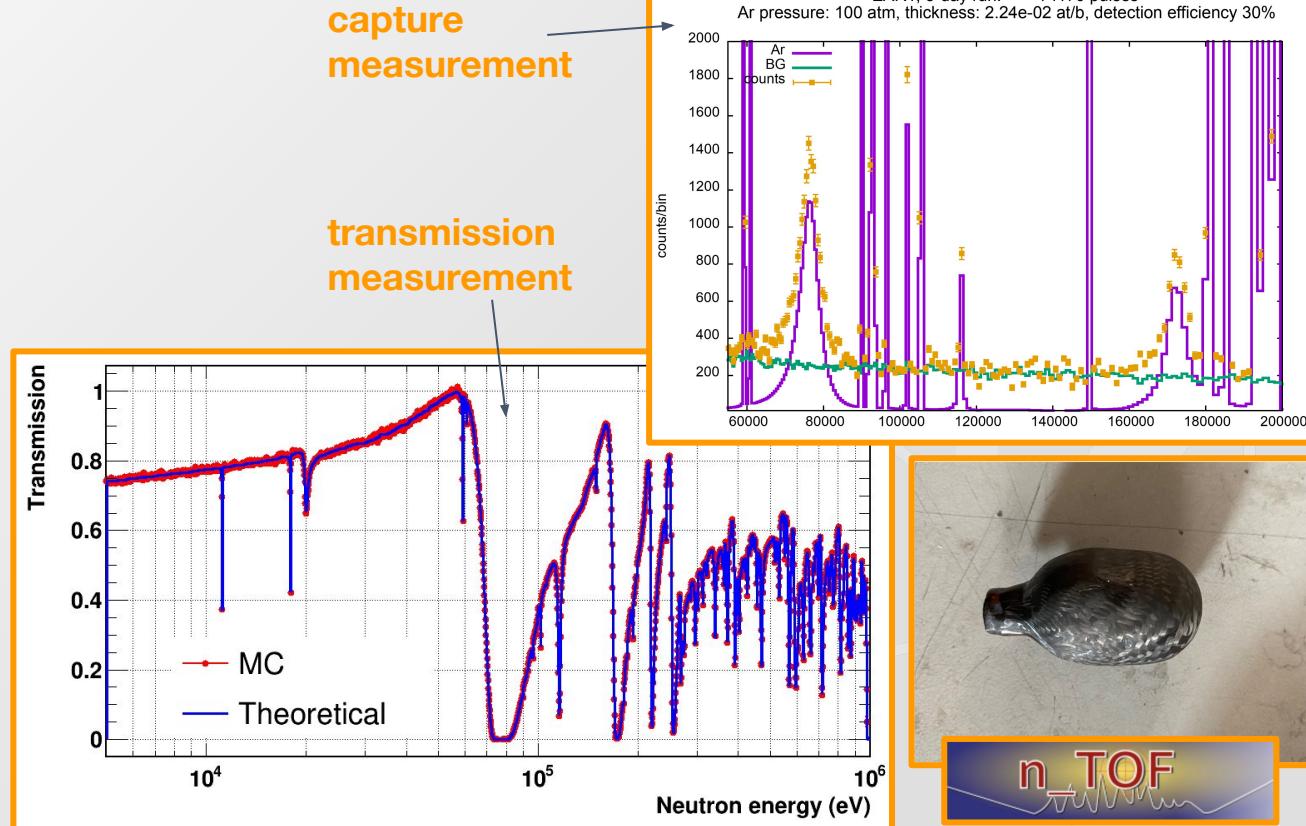
MArEX (Multiple Argon Experiments) Initiative



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

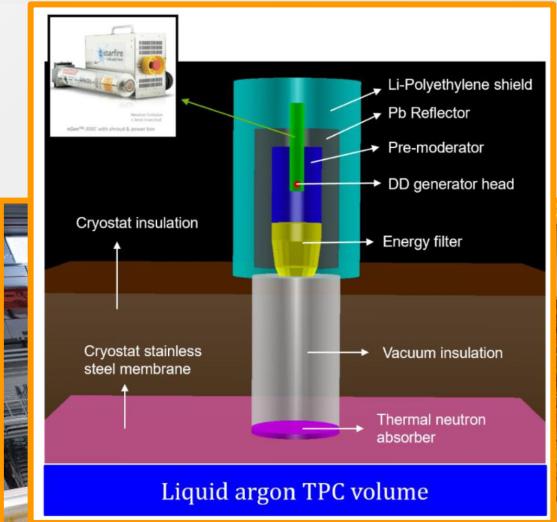
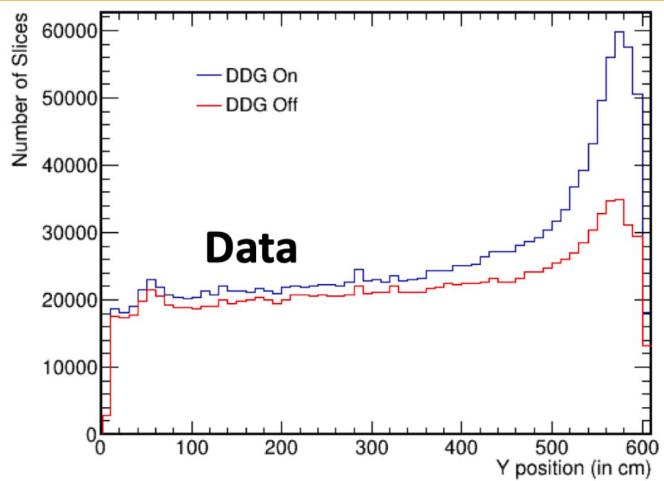
- **Carbon Fiber SCUBA** tanks (pressurized Ar gas up to 300 atm) (carbon cross-section is flat in ROI).
- 200 meter time of flight.
- Requested one month of running at both EAR1/EAR2 experimental areas.



Neutron Calibration in DUNE

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

