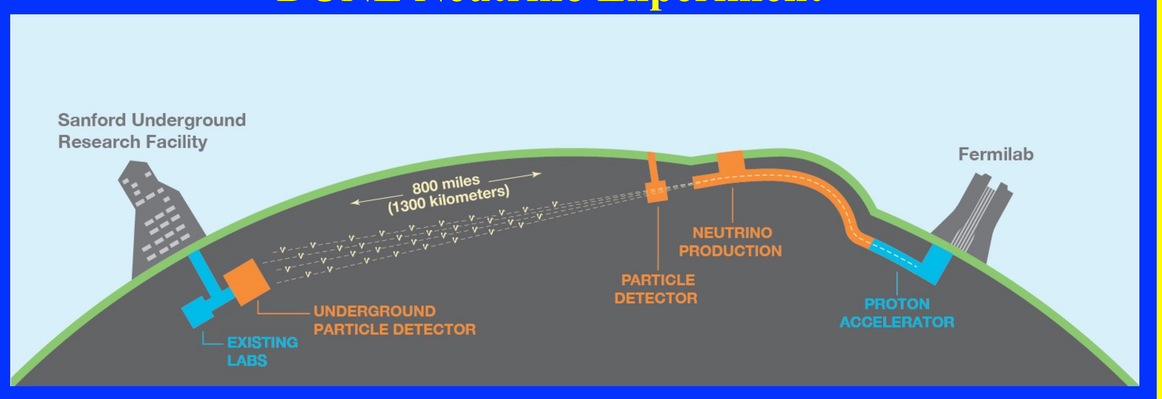
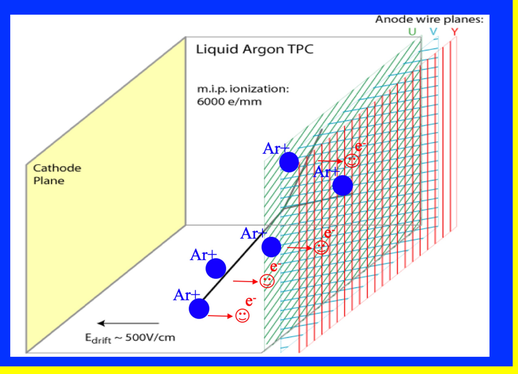
Deep Learning at DUNE

Jianming Bian
for the DUNE Collaboration
University of California, Irvine
bianjm@uci.edu

DUNE Neutrino Experiment

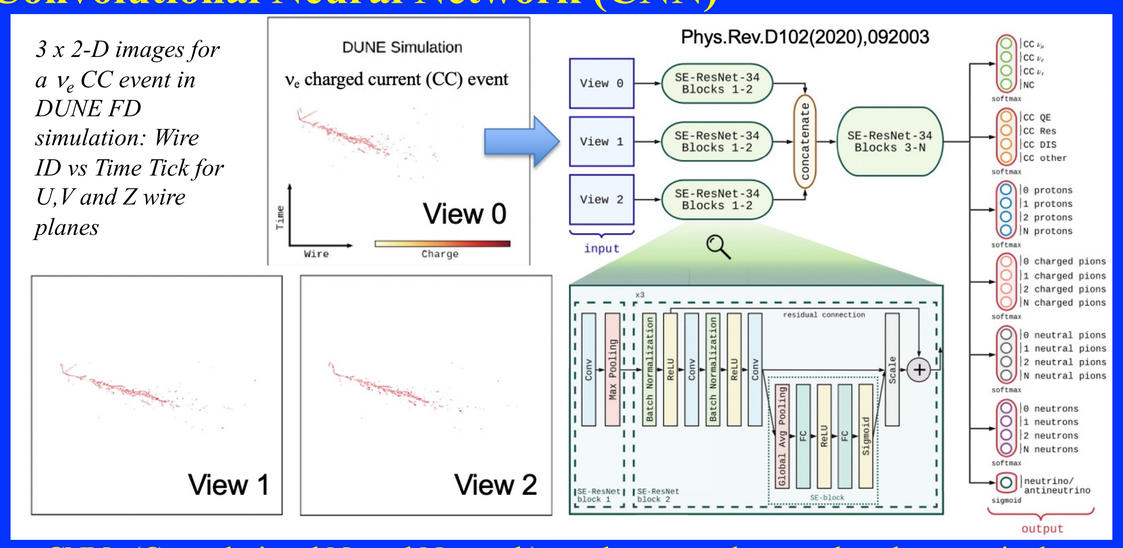


- DUNE is a next-generation international flagship neutrino experiment
- Far detectors based on liquid argon time projection chamber (LArTPC)
- DUNE's high-resolution LArTPC pixel map readout is ideal for image processing neural networks to reconstruct neutrino events
- Developing AI based Reconstruction Chain



Convolutional Neural Network (CNN)

3 x 2-D images for a ν_e CC event in DUNE FD simulation: Wire ID vs Time Tick for U,V and Z wire planes

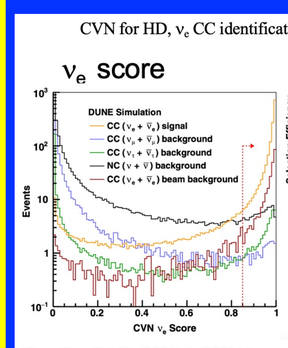


- CNNs (Convolutional Neural Network) are deep neural networks take raw pixel values input
- To reduce the number of parameters, CNNs apply convolutional filters to small regions of an image and then combine the features from these filters to produce the final decision
- Use the 3 x 2D readout images, one for each anode plane, as input to a ResNet CNN

Event Classification CNN identifiers for FD

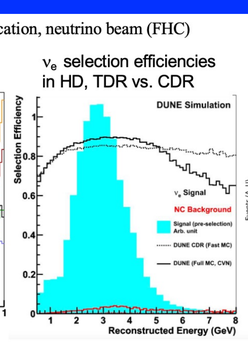
- CNN-based classifier ("CVN") to tag neutrino flavor, for both Horizontal-Drift FD (Phys. Rev. D 102, 092003, 2020) and Vertical-Drift FD (arXiv:2312.03130)
- Identify ν_μ charged current (CC), ν_e CC and neutral current (NC) events
- Basis for sensitivity projections

CVN for HD, ν_e CC identification, neutrino beam (FHC)



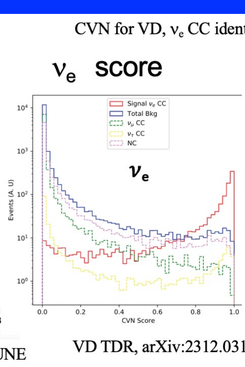
Phys.Rev.D 102 (2020) 9, 092003

ν_e selection efficiencies in HD, TDR vs. CDR



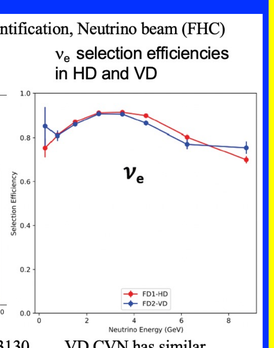
Performance is better than DUNE CDR assumptions

CVN for VD, ν_e CC identification, Neutrino beam (FHC)



VD TDR, arXiv:2312.03130

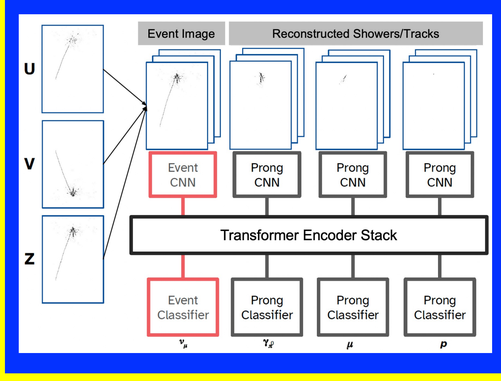
ν_e selection efficiencies in HD and VD



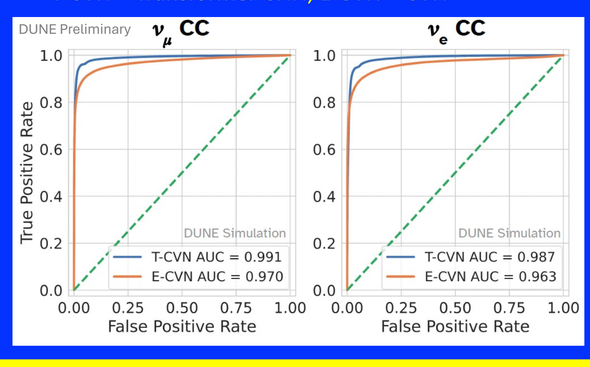
VD CVN has similar efficiency as HD

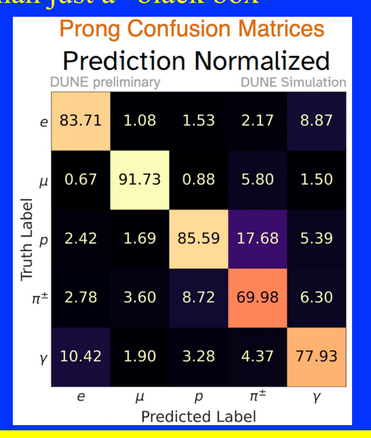
Transformer for Event and Particle Identification

- Transformer: attention based network, foundation of ChatGPT, ideal for training on variable-length collection of object such as prongs (shower/track reconstructed by Pandora)
- Uses both event and prong images as inputs, identifies neutrino flavor and each particle simultaneously.
- Attention mechanisms automatically focus training and evaluation on image regions important to the final decision, significantly reducing the computing burden and enhancing training performance
- Attention mechanisms also provides interpretability, making deep learning more than just a "black box"



T-CVN = Transformer CNN, E-CVN = CVN

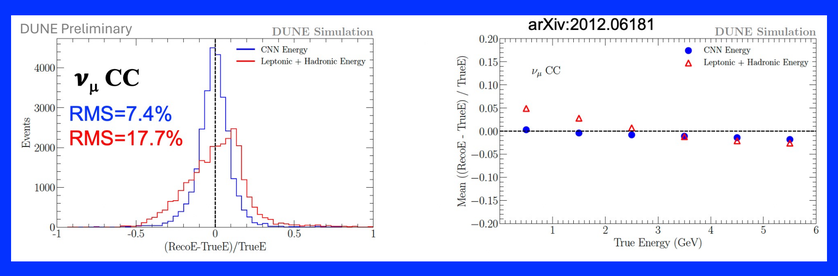


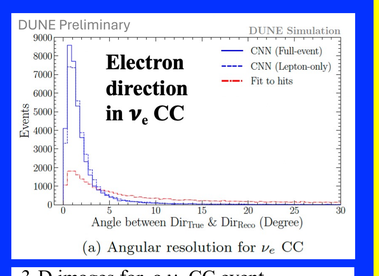


Deep-Learning Particle Energy and Direction Reconstruction

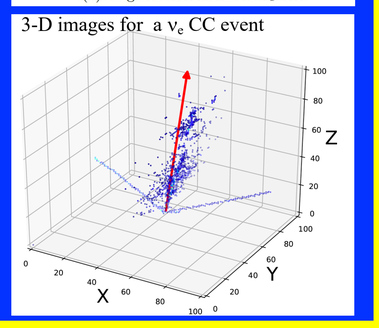
Energy:

- CNN with linear output regression for event energy, optimizing resolution $(E_{reco}-E_{true})/E_{true}$
- Weighted events by energy to reduce energy dependent bias in training
- Better resolutions than leption+hadronic energy method, less energy dependent bias with energy-reweighted training





(a) Angular resolution for ν_e CC

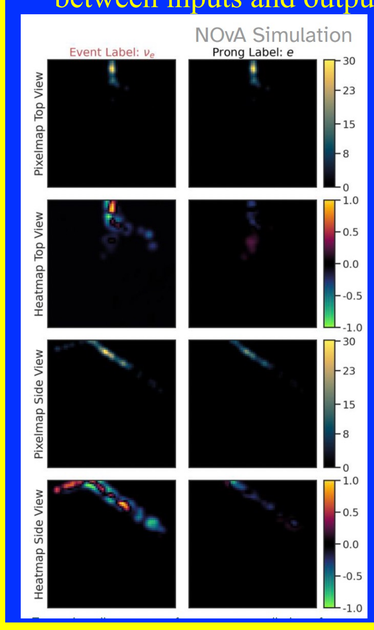


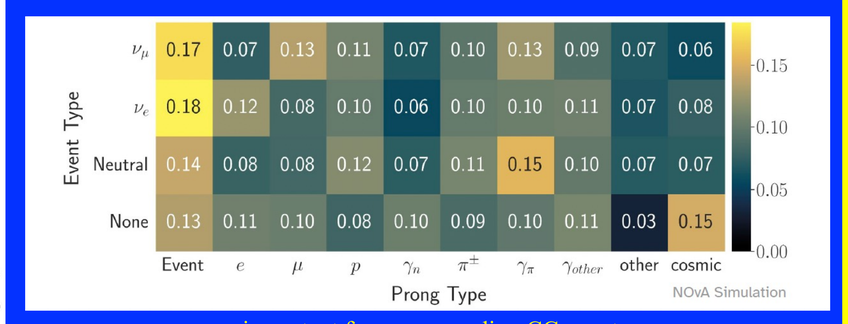
Direction:

- Direction regression heavily dependent on 3-D geometry, designed a 3-D CNN
- 3-D image constructed from the 3x2D detector images
- Optimizing angular resolution
- Regression CNNs beat traditional fit-to-hits method with better electron and muon angular resolutions in all energy regions

Interpretability of Transformer

- Attention scores indicate importance of different elements to the network output → diagnose neural network and explain decision
- Identify image regions that are important to the final decision; analyze correlations between inputs and outputs, as well as among outputs





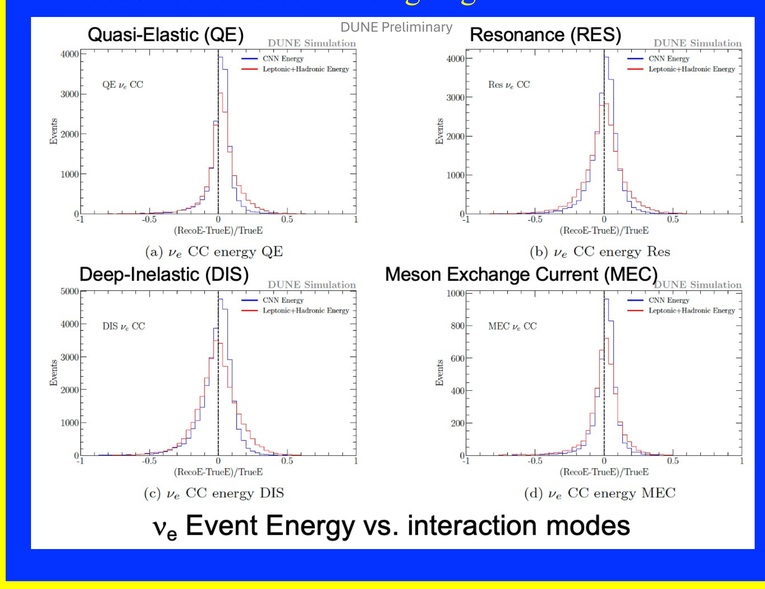
- e, μ important for corresponding CC events.
- p and π^0 important for NC.

Note: These interpretability studies come from NOvA (arxiv2303.06201), have not been conducted yet for DUNE simulation.

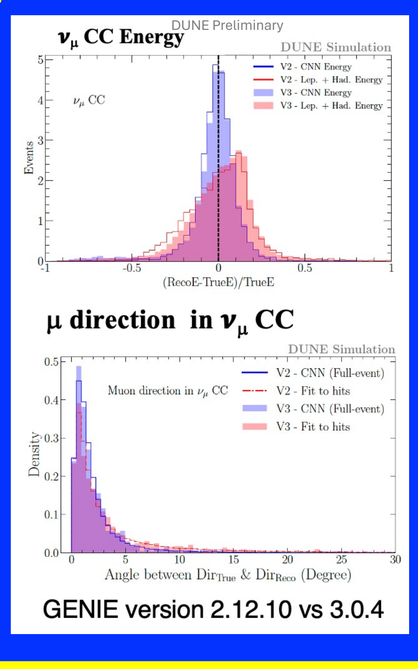
Red: more likely to predict the given flavor/particle type with more energy in that location.
Blue: less likely to predict if there is more activity (anti-correlation).

Neural Network Robustness Tests

- CNNs show robustness against neutrino interaction modes
- GENIE versions have small effects in CNNs
- Robustness studies still on going



ν_e Event Energy vs. interaction modes

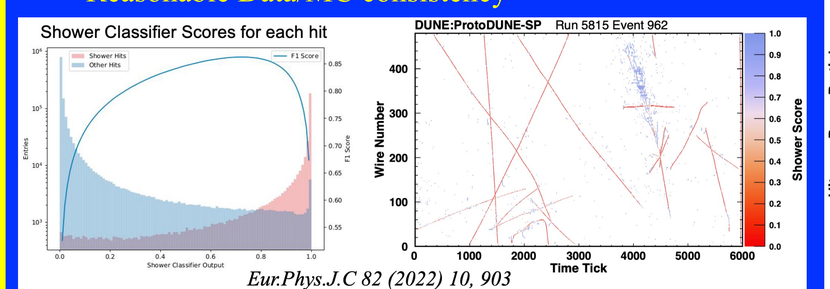


GENIE version 2.12.10 vs 3.0.4

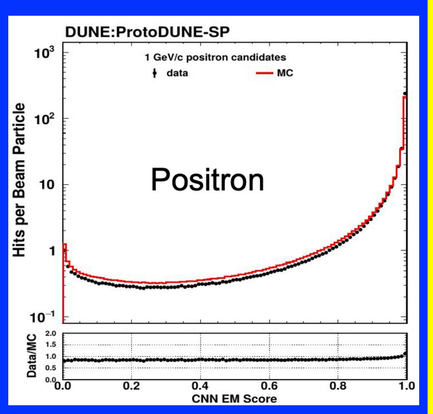
Deep-Learning Clustering Methods

CNN for Shower/Track Separation in ProtoDUNE

- ProtoDUNE-HD (SP in Phase I) and VD are two large DUNE prototype detectors at CERN
- ProtoDUNE-SP has collected test beam and cosmic ray data
- Use CNN to classify hits (pixels in LArTPC image) from Shower, Track and Michel electrons in ProtoDUNE-SP
- Hit classification used in clustering and PID
- Reasonable Data/MC consistency



Eur.Phys.J.C 82 (2022) 10, 903



Graph Neural Networks (GNN)

- Define input data as a graph represented by nodes and edges, convolutions on nodes and edges rather than the entire pixel to speed up training
- Successfully cluster LArTPC showers/tracks with GNN in ExtExa.TrkX project (a collaboration developing GNN reconstruction for HEP), implementing in DUNE