Session: Computational Physics and Algorithm / 12 mins

Neutrino Energy Reconstruction with Regression CNN at DUNE

Ilsoo Seong (University of California, Irvine)
For the DUNE Collaboration

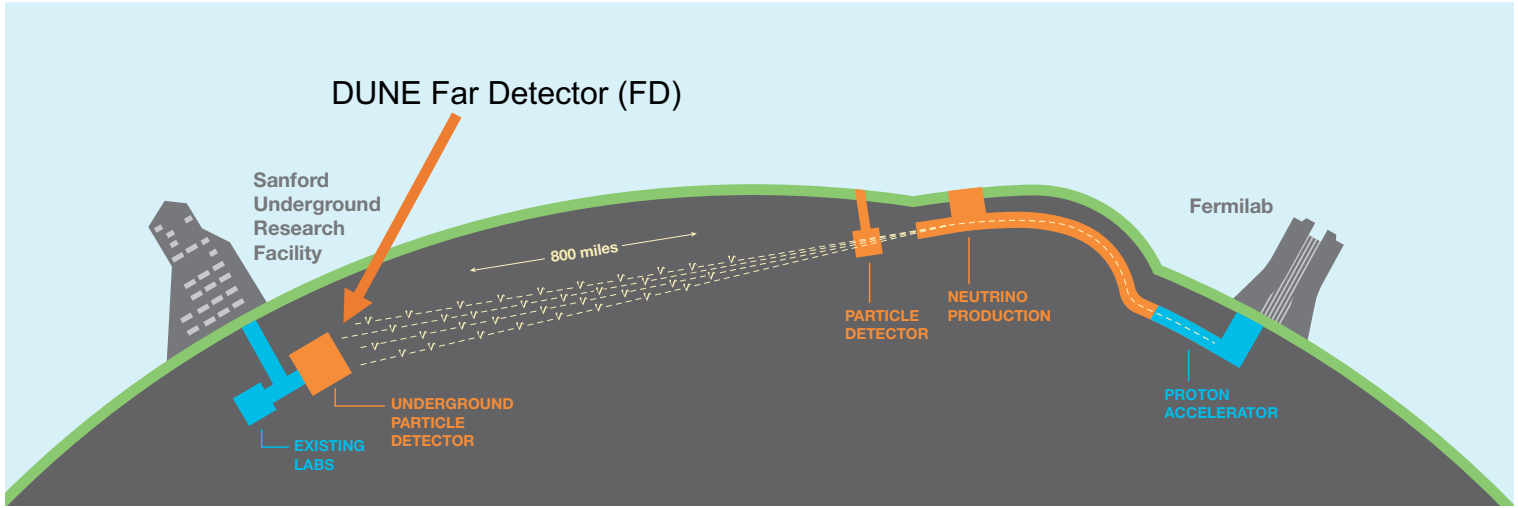
APS April Meeting 2019

UCI University of California, Irvine

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

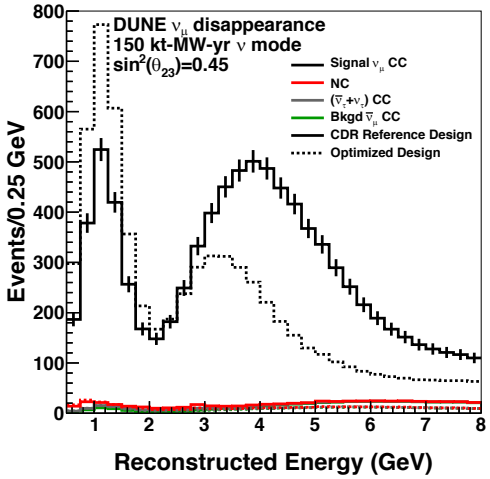
Introduction

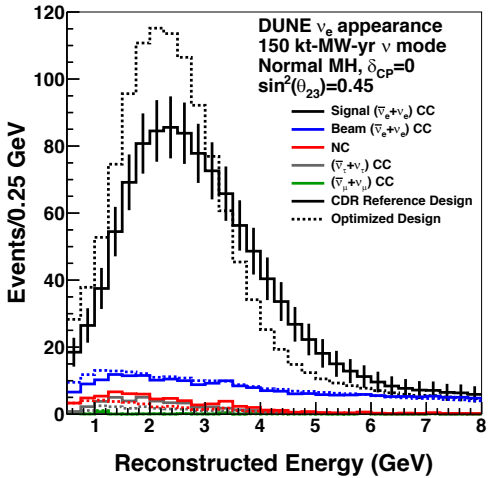
- DUNE is a long-baseline neutrino experiment
- DUNE Far Detector will be constructed 1300 km (800 miles) from Fermilab, which will supply 1.2 MW at 120 GeV neutrino beam
- Goals: to determine neutrino mass hierarchy and to measure the neutrino oscillation parameters including the CP-violation phase



Introduction

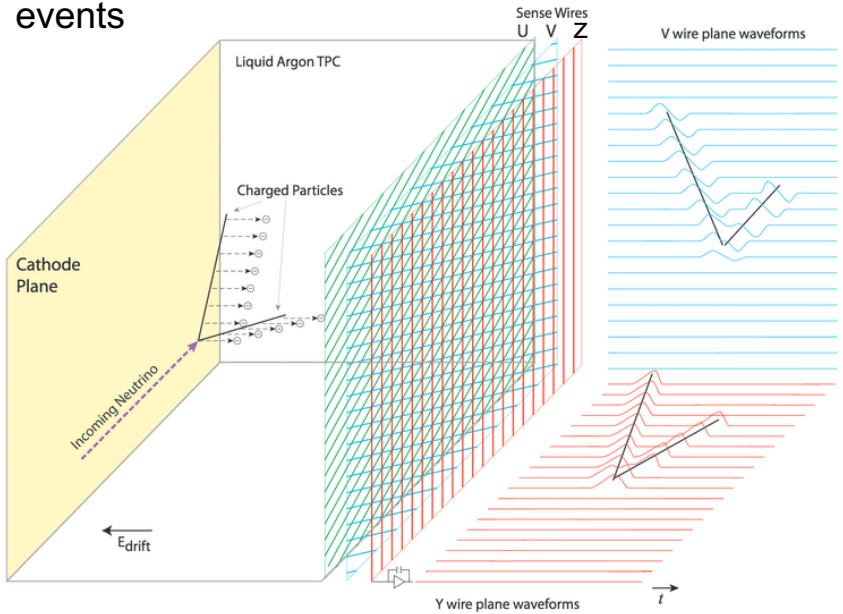
- Precise neutrino energy reconstruction is important for DUNE
  - because neutrino oscillations depend on true neutrino energy
- Two approaches:
  - Kinematic-based energy reconstruction: $E_\nu = E_{lep} + E_{had}$
  - Regression Convolutional Neutral Network (CNN) energy reconstruction



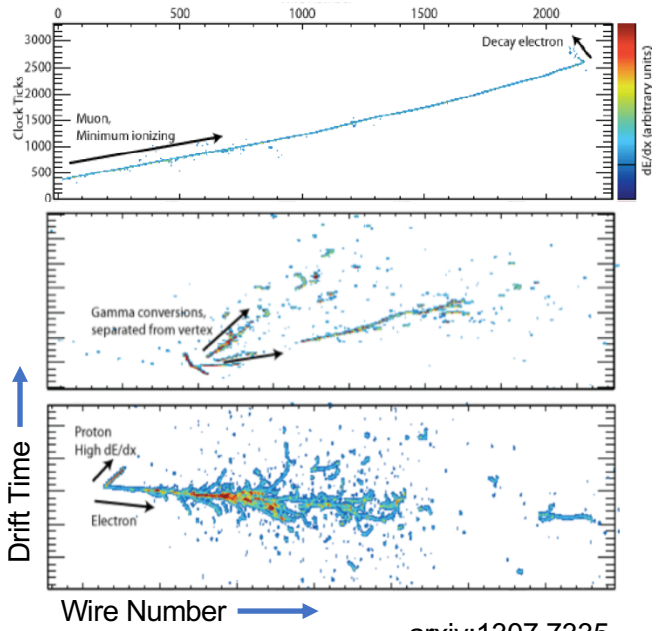


Introduction

- DUNE FD will use LAr Time Projection Chambers (TPC) technology with 40 kt fiducial mass
- Neutrino interactions in LAr produce charged particles that ionize Ar atoms
- Projection on wires + arrival time of the charge: produces **three high-resolution 2D images** of events



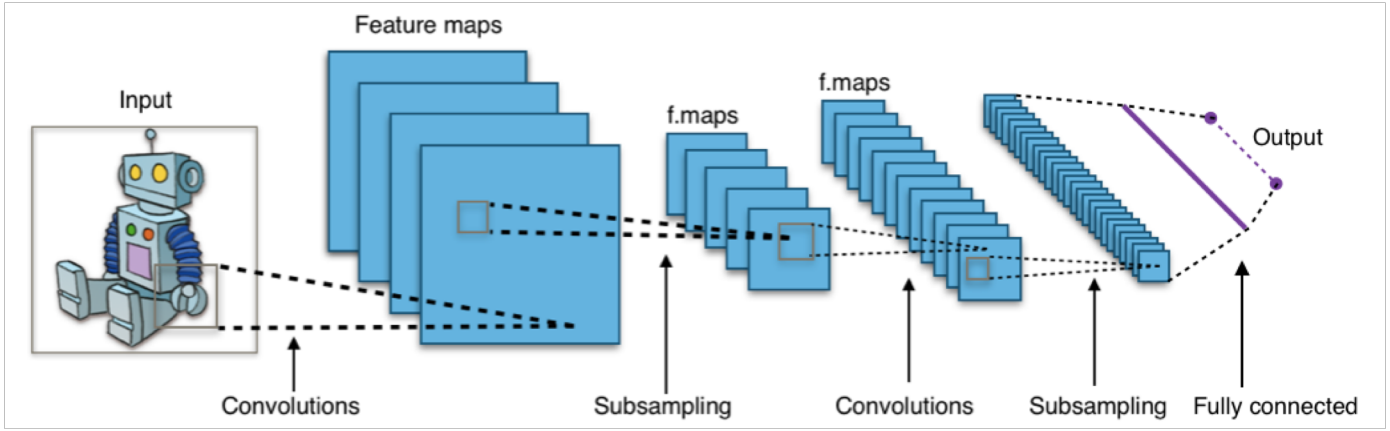
from MicroBooNE collaboration



arxiv:1307.7335

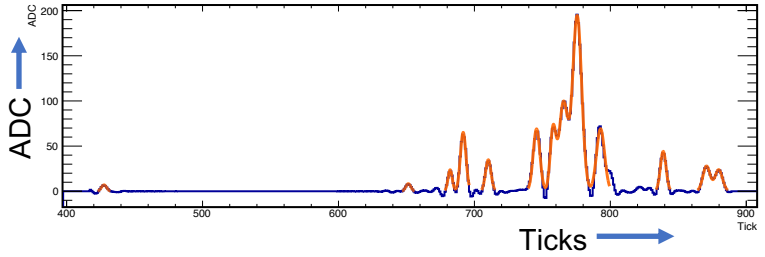
Regression Convolutional Neural Network

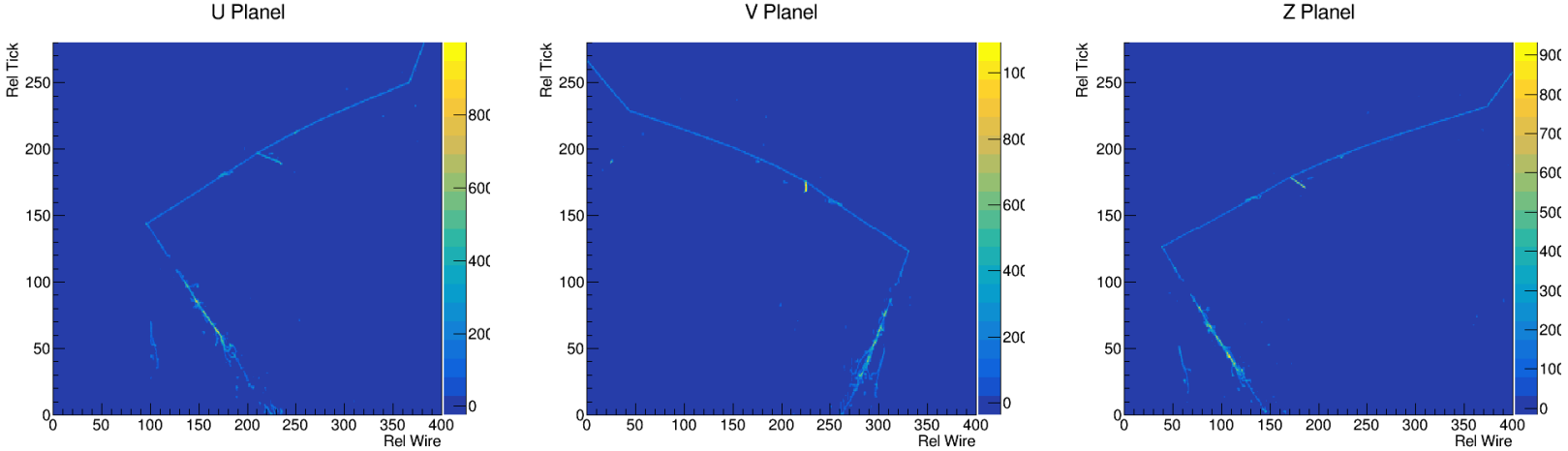
- Dead channels, detector response, invisible energy, or track/shower reconstruction quality can limit the kinematic-based energy reconstruction
- Convolution Neutral Networks (CNNs) have demonstrated success in classification problems such particle identification:
  CVN identification at NOvA and DUNE, image segmentation/prong identifier at MicroBooNE
- Regression CNNs can solve continuous variables, such as energy
- Developed Regression CNN models to reconstruct ν_e CC energy for DUNE



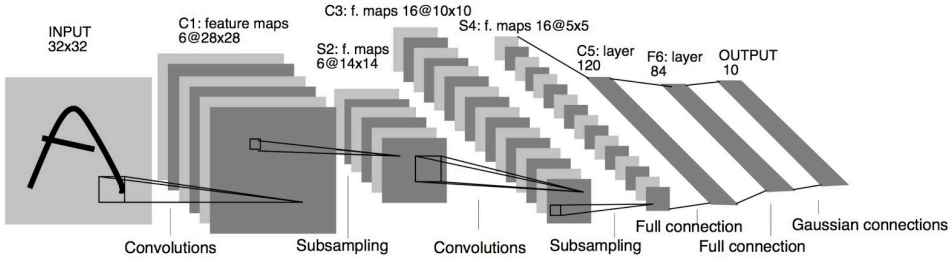
Input Images with Waveform

- Three pixel maps: 280x400 (real covered space: 1680 ticks x 400 wires): merged 6 TDC ticks
- Pixel map size has been chosen to contain 90% of hits on average
- Used processed signal as inputs:
  - ADC counts and TDC ticks
  - ADC counts corrected with electron lifetime





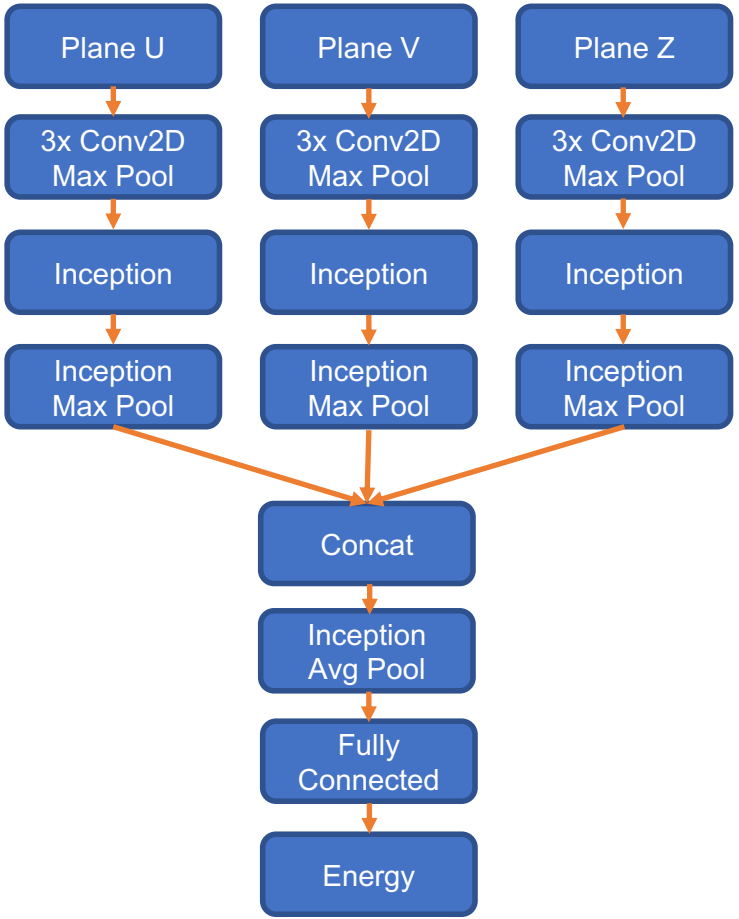
CNN Architecture



- Architecture based on NOvA CVN
- One linear output unit
- Loss

$$L(\mathbf{W}, \{\mathbf{x}_i, y_i\}_{i=1}^{n}) = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{f_{\mathbf{W}}(\mathbf{x}_i) - y_i}{y_i}\right|$$

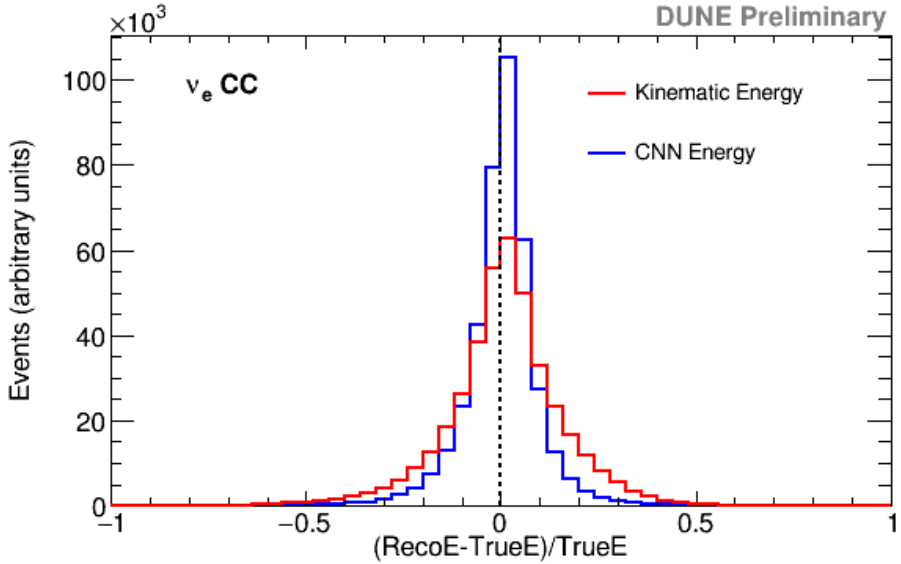
- Training examples: 745,529
- Validation examples: 186,389



Inception: https://arxiv.org/abs/1409.4842

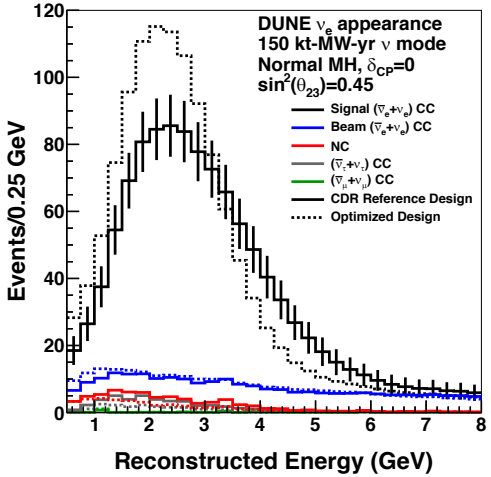
NueCC Energy Resolution

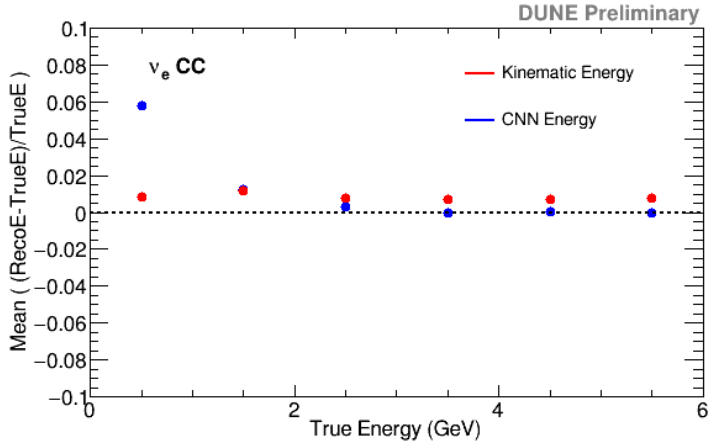
- Applied the trained model to the official Nue MC samples
- Fiducial volume is defined with the true vertex
- Fit with Gaussian within (-1,1)
- Sigma of Kinematic-based method: 13.1% and RegCNN: 7.2%

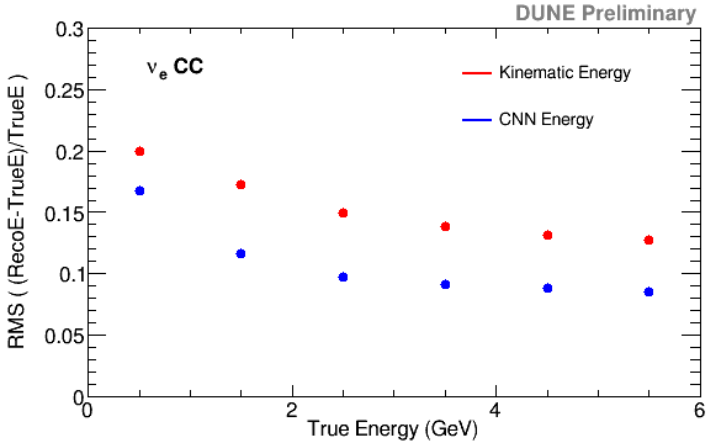


Energy Resolution Vs. True Energy

- Mean and RMS of energy resolution
- RegCNN has smaller RMS and over-estimates for low energies
- Bias is due of low statistics in low energy in the training samples
- To reduce the bias, flat energy spectrum is best option
- At this stage, re-weighted individual events to give the impression of flat energy spectrum samples





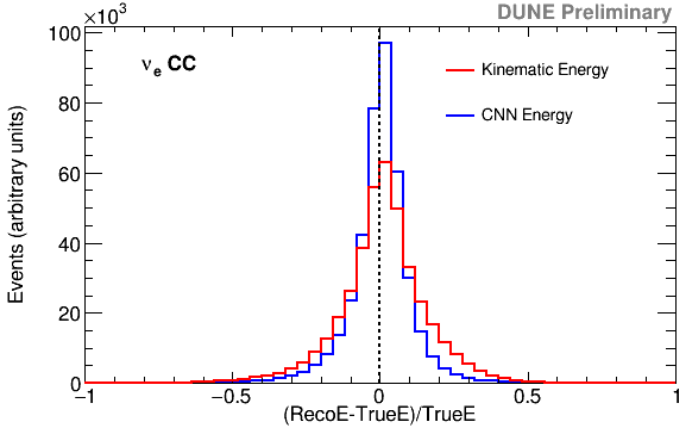


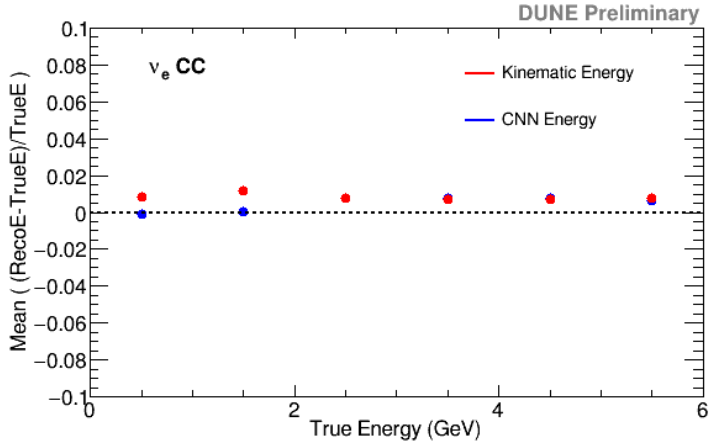
Weighted Training and Result

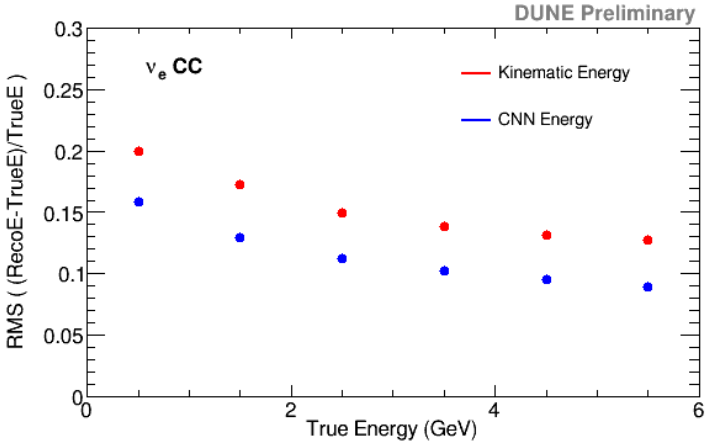
- Redefined the loss function

$$L(\mathbf{W}, \{(\mathbf{x}_i, y_i)\}_{i=1}^n) = \frac{1}{\sum_j^n \sqrt{\omega_j}} \sum_i^n \sqrt{\omega_i} L(\mathbf{W}, \mathbf{x}_i, y_i)$$

- Similar energy resolution: 7.2% → 7.3%
- Reduced bias in the low energy region

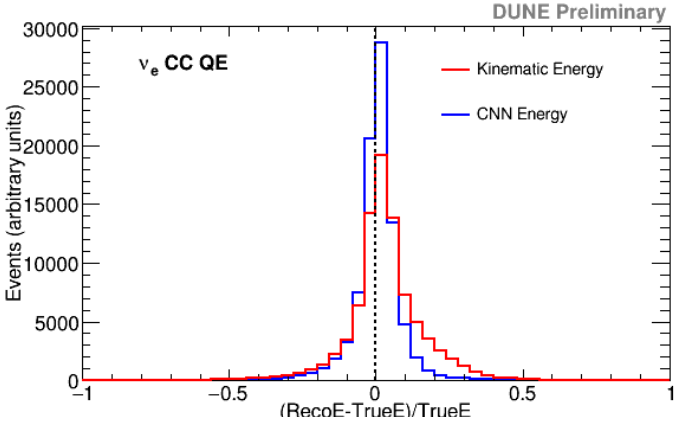


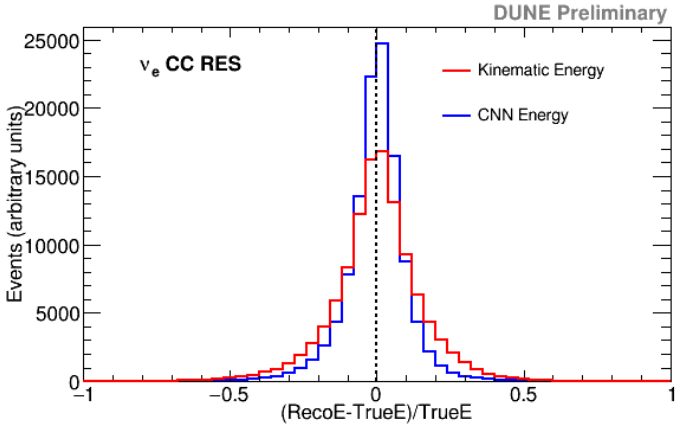


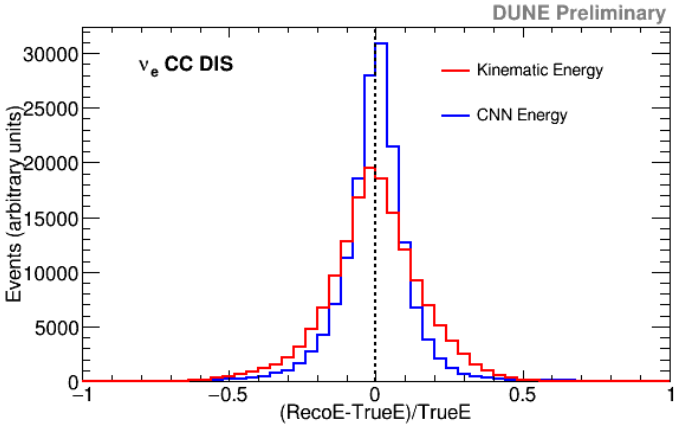


Energy Resolution with Different Interaction Modes

- RegCNN does not sensitive to interaction modes
- Fiducial volume is defined with the true vertex
- Fit with Gaussian within (-1,1)
- Resolutions:
  - RegCNN: 5.2% (QE), 8.3% (RES), 9.4% (DIS)
  - Kinematic-based: 9.5% (QE), 13.1% (RES), 15.2% (DIS)

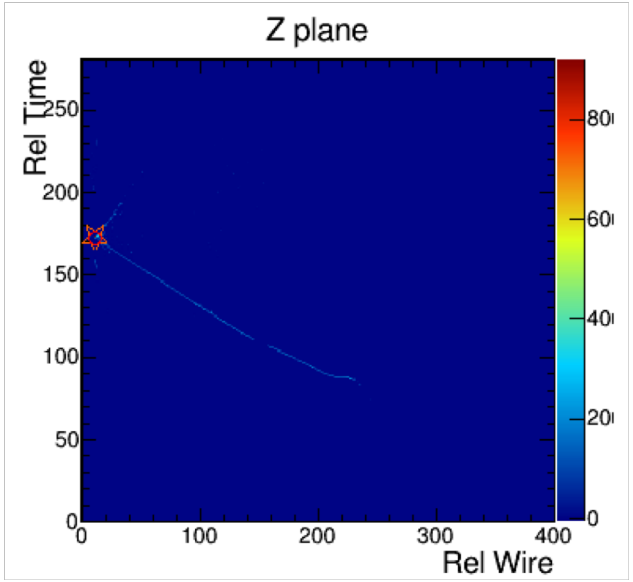






Numu Energy Reconstruction

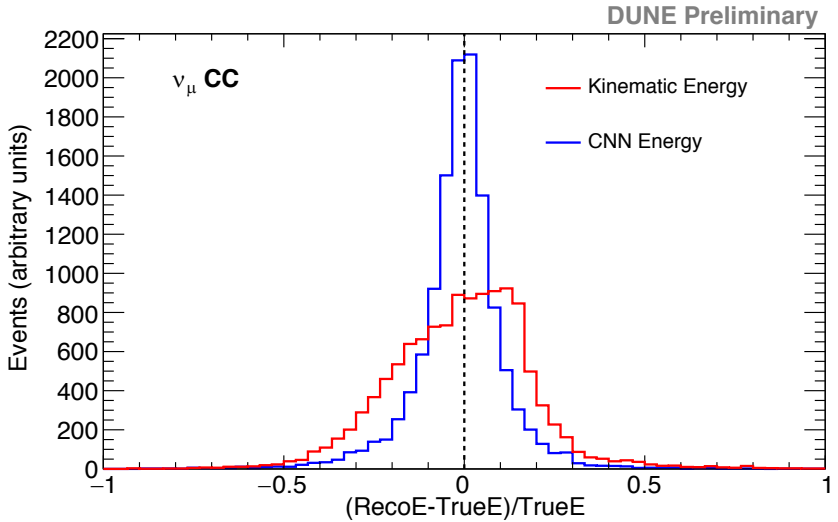
- For Numu events, long muons can exist the detector
- Kinematic-based method estimates the track momentum of exiting track from multi-Coulomb scattering (MCS)
- The kinematic-based method shows the energy resolution of 18% for events with contained tracks and 20% for events with existing tracks



- Working on developing RegCNN model for Numu CC energy reconstruction
- The pixel map size is the same (280x400), lower resolutions on Wires and TDCs to contain most hits
  - Merged 7 wires and 24 TDC ticks
- As a first step, performed the reconstruction for events with contained tracks

Numu CC Energy Resolution

- Selects events by requiring no hits at the detector ends: Trained with 240 k samples
- Fiducial volume is defined with the true vertex
- RMS of Kinematic-based method: 19.0 % and RegCNN: 12.5%
- Moving to study events with exiting muon track.



Summary

- Developed regression CNN models to reconstruct Nue CC and Numu CC events for DUNE
- Nue CC and Numu CC results show promising results and improved the energy resolution
- For Nue CC: 13.1% → 7.3 %, for Numu CC:19.0% → 12.5 % (for contained events)
- With weighted training, energy scale shows small dependence on true neutrino energy and interaction modes

Thank You