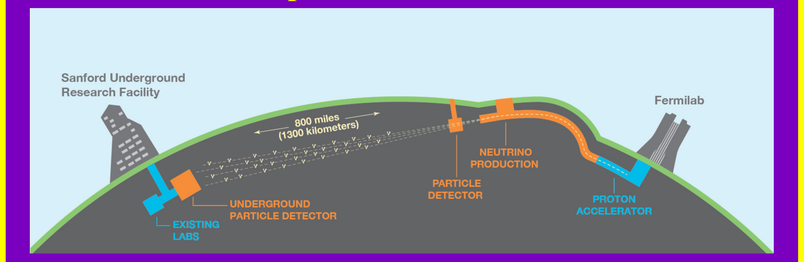
Deep Learning Based Event Reconstruction at DUNE

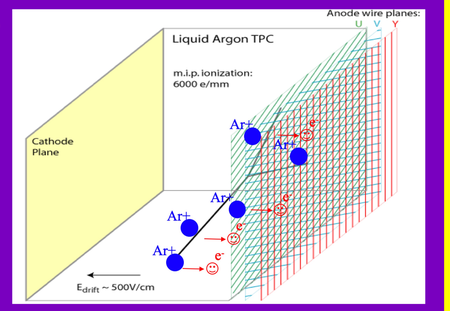
Jianming Bian
for the DUNE Collaboration
University of California, Irvine
bianjm@uci.edu

WIN2021, University of Minnesota

DUNE Neutrino Experiment

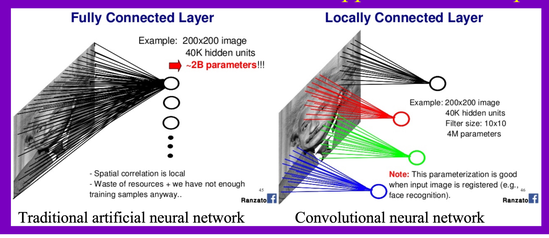


- DUNE is a next-generation international flagship neutrino experiment
- Far detectors based on liquid argon time projection chamber (LArTPC)
- The complex LArTPC offers excellent spatial resolution and particle identification, but neutrino event reconstruction is challenging



Convolutional Neural Network (CNN)

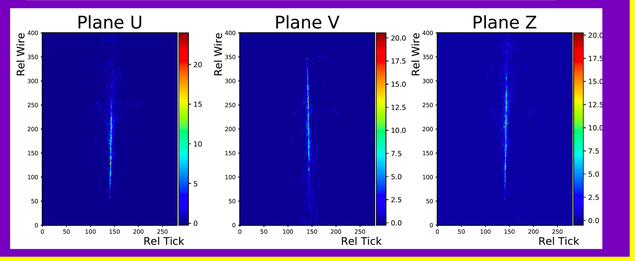
- LArTPC pixel maps for each event are either 3 x 2D images
- CNNs are neural networks specialized to taking images, using a set of translationally invariant filters
- Therefore, reconstructing DUNE events with CNNs is ideal application of deep learning techniques



- CNNs can be used for:

1. Regression: fitting for particle energy, event energy, or event vertex
2. Classification: Particle and event identification

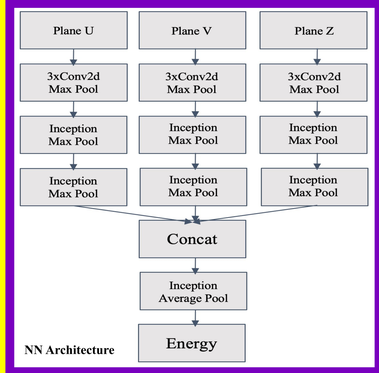
3 x 2-D images for a ν_e CC event in DUNE FD simulation: Wire ID vs Time Tick for U,V and Z wire planes



Regression Convolutional Neural Network for Energy Reconstruction

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

Loss function



- Provides appropriate surrogate to optimize energy resolution $E_{reco}-E_{true}/E_{true}$
- Linear output unit for energy
- Optimize energy resolution and reduce impacts from outliers.
- No regularization applied
- Use hyperparameter optimization software SHERPA
- Weighted events by energy to reduce energy dependent bias

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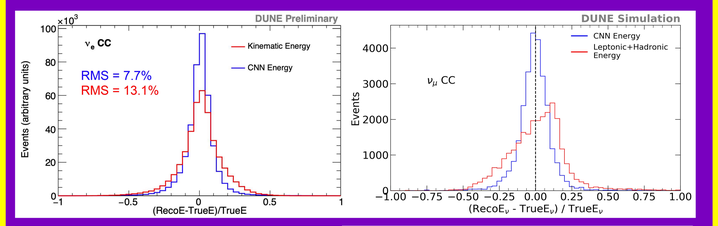
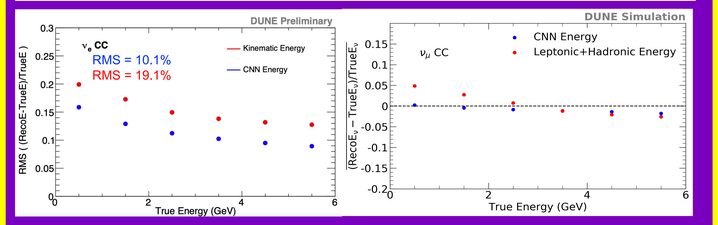
NuerIPS2020 workshop proceeding(2020), arXiv:2012.06181

ν_e CC and ν_μ CC Event Energy

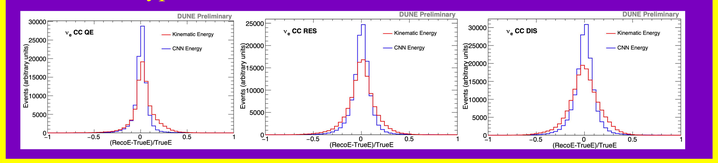
Regression CNNs outperform kinematic energy based energy reconstruction ($E(\nu) = E_{lep}^{cor} + E_{had}^{cor}$):

- Better resolutions in all energy regions
- Less energy dependent bias

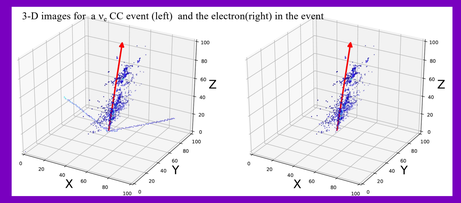




CNNs are also robust against neutrino interaction modes, because of high number of degrees of freedom to fit to different types of interaction

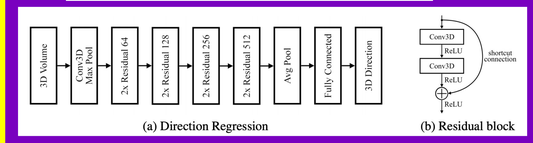


Particle Direction Reconstruction



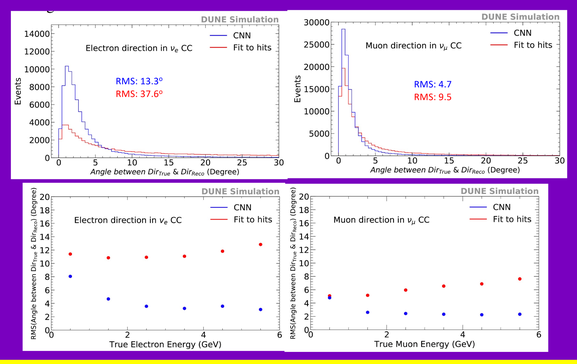
-Direction regression heavily dependent on 3-D geometry
-So we Designed a 3-D CNN to reconstruct particle directions.
-3-D image constructed from the 3x2D detector images

$$L_{\text{dir}} = \frac{1}{n}\sum_{i=1}^{n} \min\left(1 + \frac{\vec{d}^{\,i}_{\text{True}} \cdot \vec{d}^{\,i}_{\text{Reco}}}{\left|\vec{d}^{\,i}_{\text{True}}\right|\left|\vec{d}^{\,i}_{\text{Reco}}\right|}, 1 - \frac{\vec{d}^{\,i}_{\text{True}} \cdot \vec{d}^{\,i}_{\text{Reco}}}{\left|\vec{d}^{\,i}_{\text{True}}\right|\left|\vec{d}^{\,i}_{\text{Reco}}\right|}\right)$$



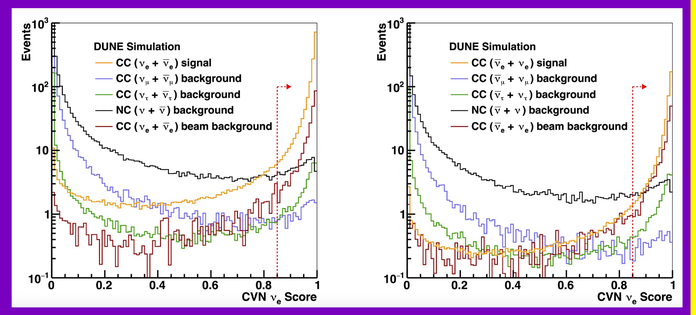
Model built on a series of residual blocks and a linear layer to output 3-D direction vectors. A cosine distance metric used for training

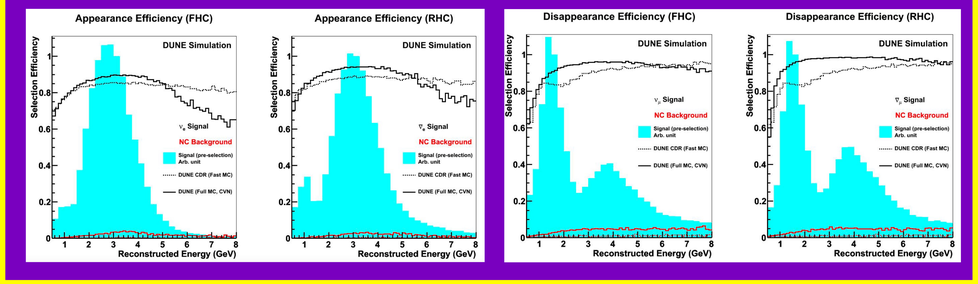
Regression CNNs beat traditional fit-to-hits method with better electron and muon resolutions in all energy regions



Classification CNN identifier in DUNE

- Classification Convolutional Neural Network has been implemented at DUNE for event identification (CVN)
- Identify ν_μCC, ν_eCC and NC events
- Performance is better than DUNE CDR assumptions
- Paper published: Phys.Rev.D 102 (2020) 9, 092003





Other Methods Being Developed

Sparse CNNs for Semantic Segmentation
- Takes advantage of sparseness of hits
- Shown promise for identifying individual pixels as part of tracks or showers

Graph Neural Networks (GNN)
- Breaks up hits into "graph" comprised as connected nodes with information such as geometry and energy composition
- Feeds these graphs to a NN which labels individual nodes
- Shown promise in ProtoDUNE