Neutrino Physics with Deep Learning on NOvA

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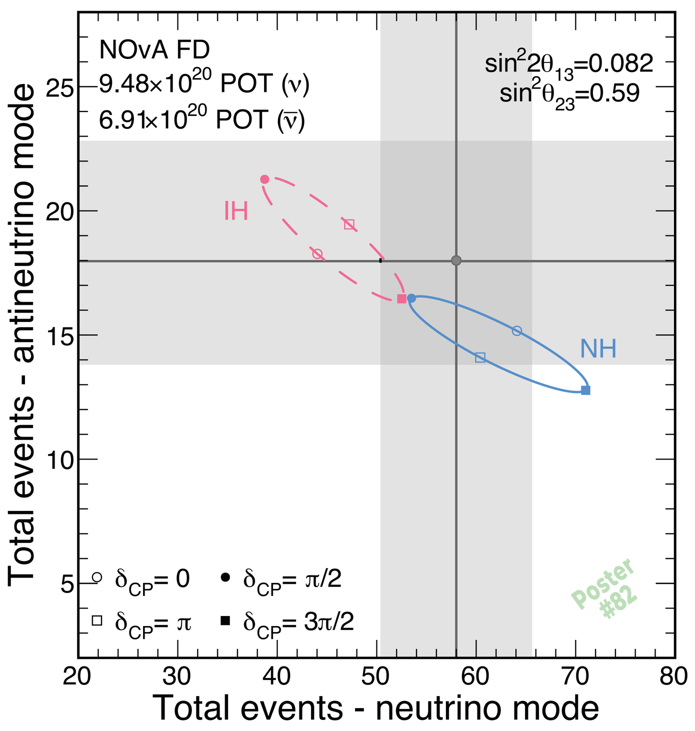
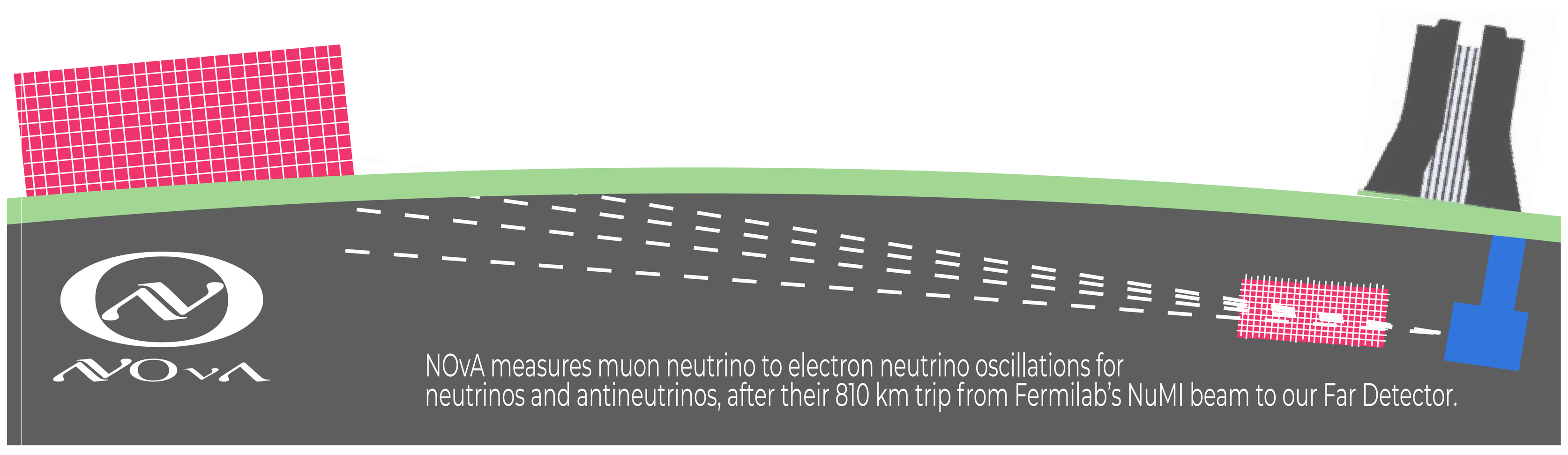
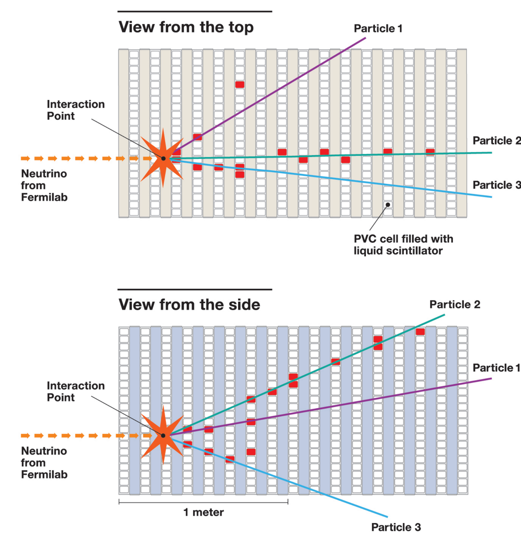
For the NOvA Collaboration

NOvA's Measurement

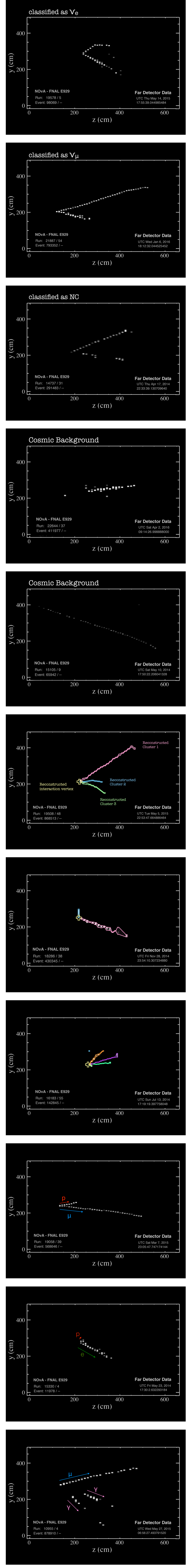






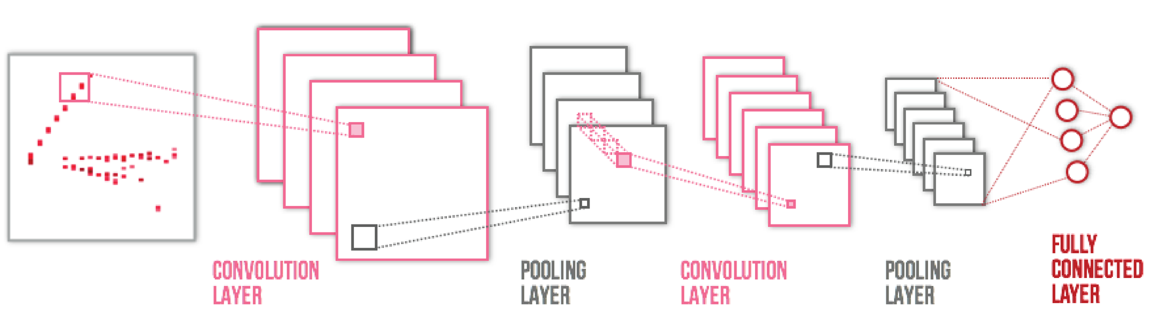
Measuring electron neutrino and electron anti-neutrino appearance probabilities gives sensitivity to CP violation and the mass hierarchy. Oscillation measurements rely on flavor identification and event reconstruction, for which we employ deep learning techniques.

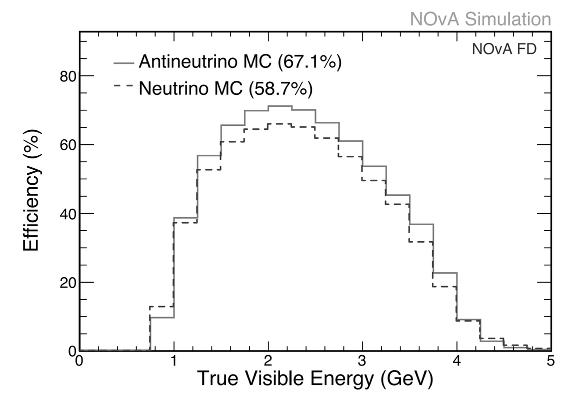
The NOvA detectors are sampling calorimeter optimized for electron identification. They use liquid scintillator in alternating vertical and horizontal PVC planes to allow for 3D reconstruction.



Event Classification

Our Convolutional Visual Netwokr (CVN) neutrino event classifier[1] **trains on the top and side views** of the event independently for all but the last layer of the network.





Efficiencies for the appearance analysis signal (analysis optimizations have been applied).

Improvements to CVNclassic event classifier used in 2018 analysis:

- Training labels from final state, not GENIE.
- Independent training for anti-neutrino events.
- Architecture and training sample optimization.

Anti-neutrino events are topologically different to neutrino events. Splitting the training helps to utilize those differences for classification.

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Improvement in efficiency from independent ν and ν̄ training

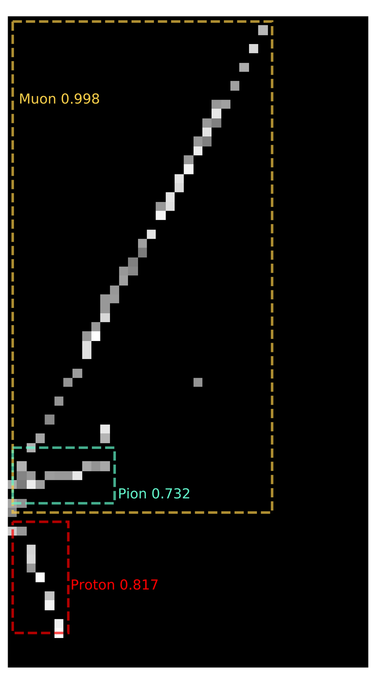
$\bar{\nu}$ Efficiency Improvement (ID>0.9)		
$\bar{\nu}_e$CC Signal	$\bar{\nu}_\mu$CC Signal	$\bar{\nu}$ NC Signal
13.8%	5.71%	9.75%

Table showing improvements in efficiency obtained for anti-neutrino test sample using anti-neutrino vs neutrino trained networks.

Single Particle Classification & Cluster Reconstruction

The newest deep learning development on NOvA is **simultaneous reconstruction and identification** using instance aware semantic segmentation.

One network: particle ID, clustering, & reconstruction



Our version of Mask R-CNN[2] is trained on **single view pixel by pixel MC truth, calibrated hits, and adjacency information**.

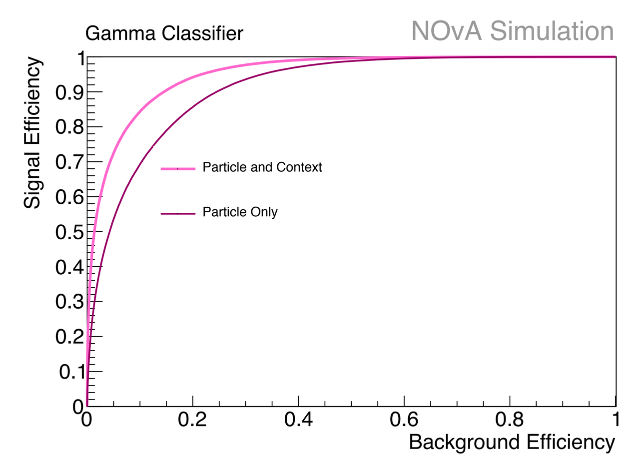
Bounding Boxes: The network defines regions of interest and from them builds bounding boxes aiming to contain all of one particle in one box.

Labels: A softmax function is used to classify the contents of each box.

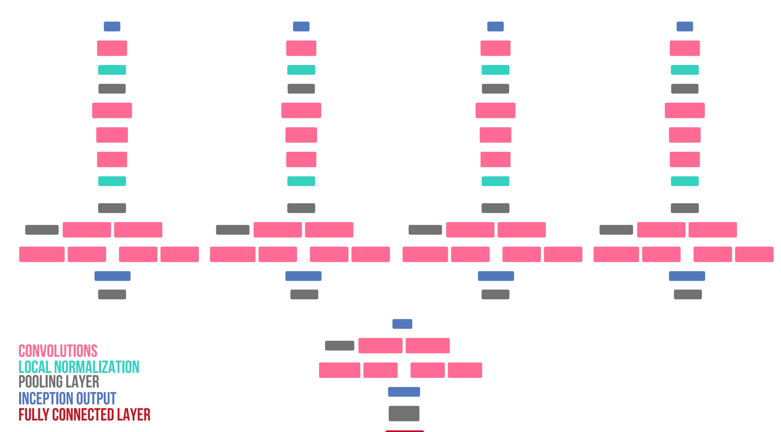
Clustering: Pixel by pixel clusters are defined to closely contain single particles.

Clustering is challenging for long tracks. Complimenting the inputs with adjacency information is a promising approach at improving clustering efficiency.

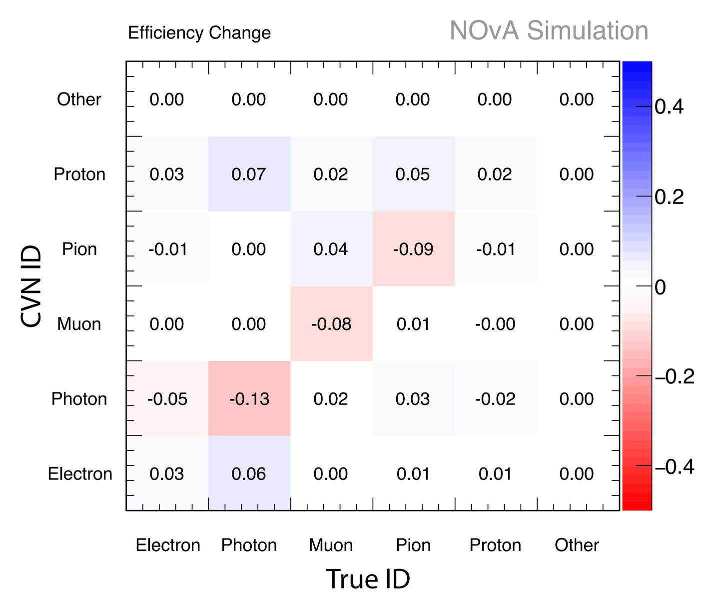
NOvA's single particle classifier[3] works on reconstructed clusters. The network is trained on the **two views of the cluster and the two views of the whole event.**



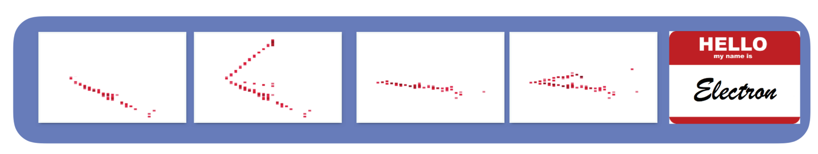
Selection efficiency for signal and background of gamma particles from the particle classifier.



Top: Diagram of the network architecture. Bottom: Input to the network.



Classification matrix for NOvA's single particle classifier. The diagonal elements show the change in efficiency for each training category when including the event in the training input.



The **views of the event let the network learn contextual information** about particles: relationship with the vertex or other particles.

Training with context event images yields an improvement in the efficiency of particle classification

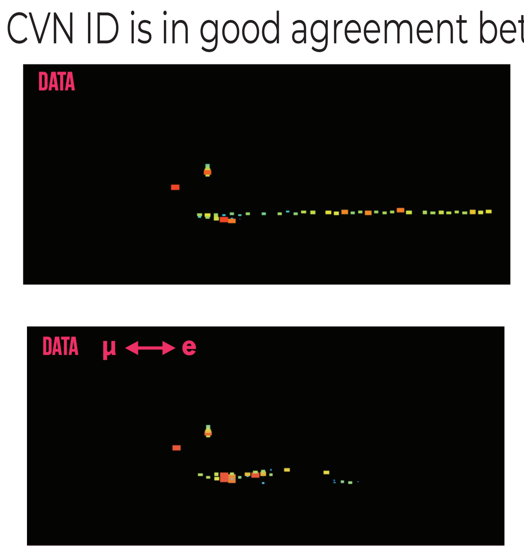
Single particle ID benefits from contextual information

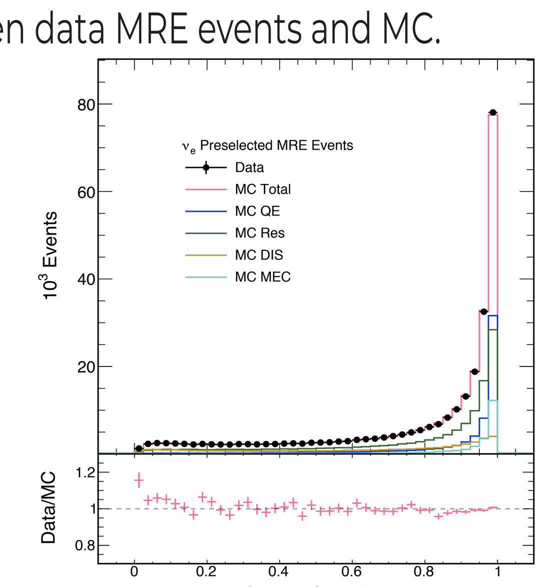
Physics & Data Cross-checks

Data-driven cross-checks use minimum bias cosmic ray data or well identified data in the near detector to check for indications of bias in the models.

In a Muon Removed Electron (MRE) event, a muon track from a selected muon neutrino interaction is replaced by a simulated electron of the same energy.

CVN ID is in good agreement between data MRE events and MC.





Left: Diagrams of MRE events before (top) and after (bottom) the substitution. Right: Electron neutrino ID scores for events after muon removal and replacing by an electron (CVN 2017).

Applications of Deep Learning on NOvA:

Event ID (CVN) :
Mmuon neutrino disappearance, electron neutrino appearance, and NC disappearance.

Particle classifier:
Single particle ID for energy reconstruction of electron neutrino events, neutral pion mass peak.

Applications in progress:
Final state selection with single particle ID for cross sections analyses, single particle ID for energy reconstruction of numu events & energy reconstruction CNNs

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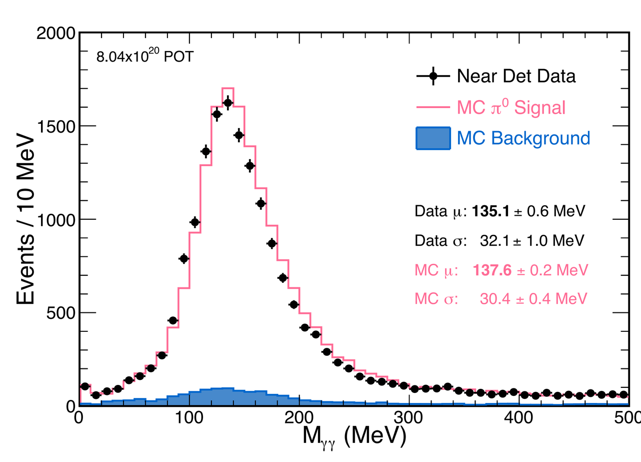
Example application: Reconstructing neutral pion events through photon identification using our single particle classifier.

On NOvA, photons from the decay of neutral pions are used as a calibration cross check. They are a useful gauge for understanding detector response to electromagnetic energy.



The reconstructed invariant mass of neutral pions in the NOvA near detector.

The two photons travel some distance before pair producing and initiating electromagnetic showers.

The two photons can be reconstructed and identified using the single particle classifier from the previous section.

THANK YOU FOR YOUR SUPPORT:

DOE Office of Science

ConTex Fellowships

Indiana University BigRed II Cluster

Fermilab Wilson Cluster

REFERENCES:

[1] NOvA CVN:

[2] Mask R-CNN:

[3] NOvA Single Particle Classifier:

NOvA webpage

Can you beat our neural networks?