Electron Neutrino Energy
Reconstruction in NOvA
Using CNN Particle IDs

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**NuMI Off-axis $\nu_e$ Appearance**

Studying oscillations over a 810km baseline with two functionally identical detectors and the world’s most powerful muon neutrino beam, NuMI.

Constraining energy improves background rejection.

ND: 330 ton, 1km from source. FD: 14 kton, 810km from source.
NOvA Physics Goals

Precise measurements:
$\Delta m_{32}^2$ and $\sin^2(2\theta_{23})$ for neutrinos and antineutrinos

Strong constraints on:

- $\theta_{23}$ octant
- $\delta_{cp}$
- mass hierarchy

A precise energy reconstruction is important for accurate determination of oscillation parameters in NOvA

$$P(\nu_\mu \rightarrow \nu_e) \approx \sqrt{P_{atm}} e^{-i(\Delta m_{32}^2 L/4E + \delta_{cp})} + \sqrt{P_{sol}}$$

$P_{atm} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$

Solar term contributes <1% at ~400 L/E
NOvA Physics Goals

Precise measurements:
\[ \Delta m_{32}^2 \text{ and } \sin^2(2\theta_{23}) \]
for neutrinos and antineutrinos

Strong constraints on:
- \( \theta_{23} \) octant
- \( \delta_{cp} \)
- mass hierarchy

A precise energy reconstruction is important for accurate determination of oscillation parameters in NOvA

See Jianming's Talk:
New Oscillation Results from NOvA
Layered planes of orthogonal views allow 3D reconstruction. Charged particles are detected though the scintillation light produced in each cell.
$\nu_e$ Signal Candidate

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**NOvA - FNAL E929**

Run: 18054 / 31
Event: 129 / PerCal
UTC Thu Nov 6, 2014 
09:38:4.952000000

$\nu_e [1.9_{\text{few}}] + ^{12}\text{C} \rightarrow e^- [1.4_{\text{few}}] + p [1.0_{\text{few}}] + X_{20000000101} \text{(QE)}$

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$x, y, z$ (cm) vs. $t$ (usec) vs. $q$ (ADC)
**Prong: Fuzzy K-Mean Algorithm**

Cluster hits into track-like structure — Prongs:

- In each of two detector views, compute distance between given hit and center of existing clusters;
- A hit is added to the cluster if the overall distance is minimized.
- 2D clusters are matched into 3D objects.

Cumulative energy profile as a function of path length along a prong for 3D match candidates.
CNNs take images as input and process through groups of layers to extract the abstract features from the inputs. Then the final layer compresses the result into a vector of scores as predicted values corresponding to the labels that the CNN has been asked for.
**Prong CNN: Particle ID Classification**

4 input pixel maps:
- 2 views of prongs
- 2 views of events

Output: a vector of predicted scores of each possible particle id for the 3D prong.
The diagonal shows the efficiency of the CNN predicting the label correctly and the rest are fractions of prongs being mislabeled.

The diagonal shows the purity of each predicted label and the rest are the backgrounds in each type of prediction.
Prong CNN Performance

Transfer high dimensional features to 2D preserving separation.

Distances represent how well Prong CNN can distinguish different particles.
Energy Reconstruction

**EM Shower Energy:**
Sum together energy of all EM-like prongs in the event.

**Hadronic Energy:**
Defined as the difference between the total hits energy and the EM Shower Energy.

\[ \text{EM}_\text{EM} = \text{electronID} + \text{photonID} \]
\[ \text{CNN}_\text{HAD} = \text{sum of the rest ID} \]
\[ \text{EM-like: CNN}_\text{EM} \geq \text{CNN}_\text{HAD} \]
**Energy Reconstruction**

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\[
\nu_e \text{ event}
\]

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Energy Reconstruction

Each bin filled by weighted average true energy.
Energy Reconstruction

A quadratic fit to weighted average true energy as a function of EM Shower energy and Hadronic energy is used for estimation.

\[ E_{\nu_e} = A \cdot E_{EM} + B \cdot E_{HAD} + C \cdot E_{EM}^2 + D \cdot E_{HAD}^2 \]
Energy Reconstruction

A flat resolution distribution along true energy between 1 and 4GeV.

Energy resolution is 11%.
Energy Reconstruction

Comparing to sum of total hits energy. Bias along true Energy is improved.

Energy resolution is 11%.
Summary of Energy Reconstruction

★ A precise energy reconstruction is important for many aspects of the NOvA analysis, for e.g. backgrounds rejection and determination of oscillation parameters.

★ We use a CNN-based classifier to sort prongs into EM-like or hadronic components and use them for energy reconstruction.

★ In the $\nu_e$ Appearance Analysis, energy resolution is 11% for signal events.

★ There are other works and publications using RNN and CNN to reconstruct energy which is different from this official method.
Thank you

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Backup
To identify neutrino event candidates we reject background events, by applying cosmic rejection, containment requirement and CVN-event classification.
Prong Convolutional Neural Network Identifier

Siamese towers similar to event CVN but 4 input pixel maps: 2 views of prongs and 2 views of events. 3M @ 8:2
Energy Reconstruction

A quadratic fit to weighted average true energy as a function of EM Shower energy and Hadronic energy is used for estimation.

\[ E_{\nu_e} = \frac{1}{1 + 0.057} \times (0.996E_{EM} + 0.869E_{HAD} + 0.025E_{EM}^2 + 0.054E_{HAD}^2) \]