New approach to estimate electron neutrino energy for the NOvA 3 Flavor Analysis

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NOvA (NuMI Off-Axis ν_e Appearance)

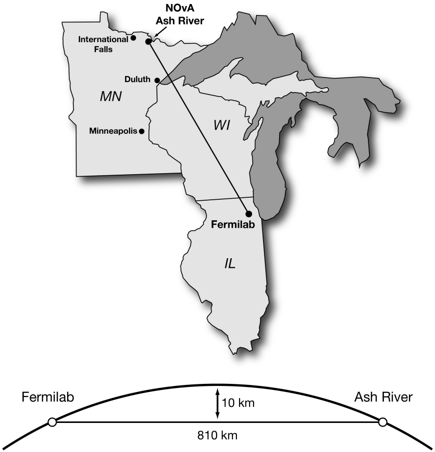
Long-baseline neutrino oscillation experiment, which goals are:

$\nu_\mu(\bar{\nu}_\mu)$ disappearance:

- measurement of Δm^2_{32}
- mixing angle θ_{23}

$\nu_e(\bar{\nu}_e)$ appearance:

- neutrino mass ordering
- CP violating phase
- mixing angle θ_{23}
- mixing angle θ_{13}



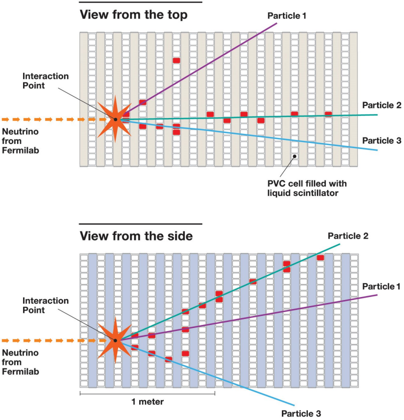
Neutrino beam from Fermilab (USA).

Near (1 km) and Far (810 km) detectors sit at 14.6 mrad off-axis.

NOvA Detectors

ND: 214 Planes, 290 ton **FD**: 896 Planes, 14 kton

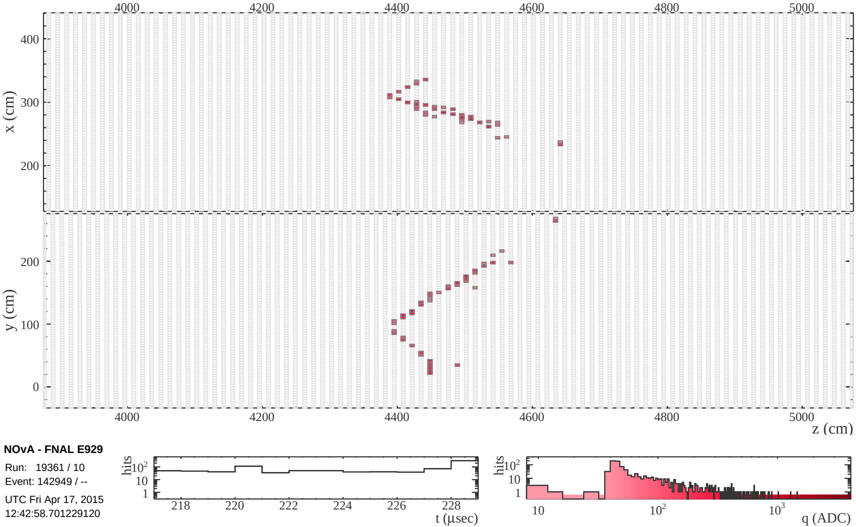
- Functionally identical tracker-calorimeters
- PVC cells filled with a liquid scintillator
- Cells are organized into *vertical* and *horizontal* planes to enable three-dimensional reconstruction
- Light is collected using a loop of wavelength-shifting optical fiber



Prong is a collection of hits that is associated with a *single particle* candidate.

Event Display

ν_e event with $E_{reco} = 2.17$ GeV and CVN score is 0.99.



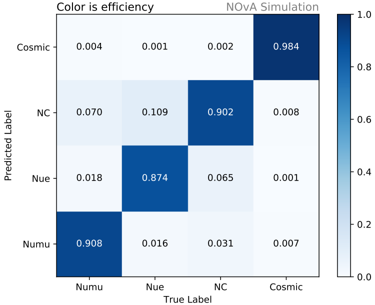
Event and particle classification

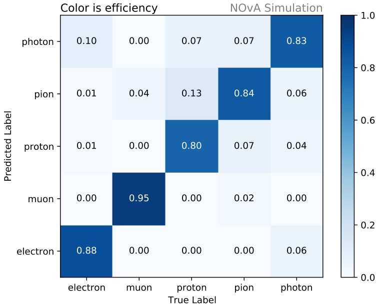
Event candidates that survive basic quality cuts pass into a deep-learning classifier CVN – the Convolutional Visual Network.

EventCVN:
- ν_μ CC
- ν_e CC
- NC
- cosmic

ProngCVN:
- electron
- muon
- proton
- pion
- photon

ProngCVN is used as part of the ν_e energy estimation.



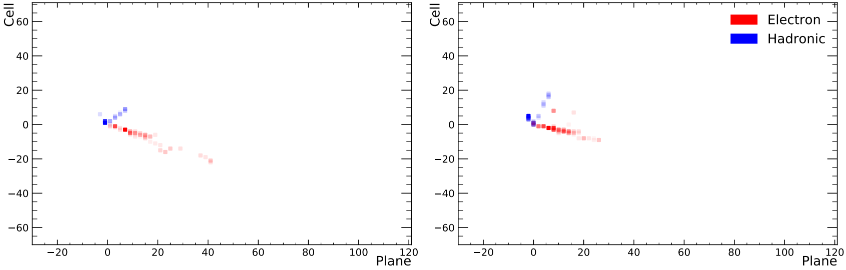


Electron neutrino evergy estimator

The response of the detectors is different for electromagnetic (EM) and hadronic (Had) depositions.

A quadratic fit function is used to compute neutrino energy:

$$E_{reco} = k \cdot (p_1 E_{EM} + p_2 E_{EM}^2 + p_3 E_{Had} + p_4 E_{Had}^2)$$



Two approaches to reconstruct EM energy

ProngCVN score for EM and Had components:

$$\mathcal{I}_{EM} = \mathcal{I}_e + \mathcal{I}_\gamma + \mathcal{I}_{\pi^0}$$

$$\mathcal{I}_{Had} = \mathcal{I}_p + \mathcal{I}_{\pi^\pm} + \mathcal{I}_n + \mathcal{I}_{\mu^-} + \mathcal{I}_{\text{other}}$$

3D prongs only

$\mathcal{I}_{EM} \geq \mathcal{I}_{Had}$

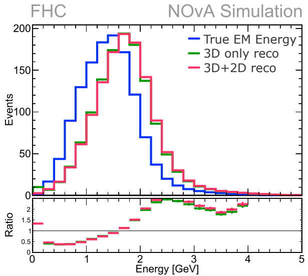
3D and unmatched 2D prongs

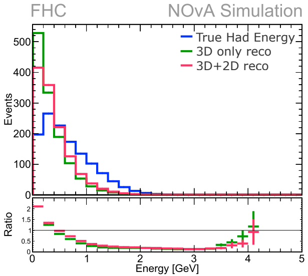
$\mathcal{I}_{EM}(3\text{D}) > 0.5$ and

$\mathcal{I}_{EM}(2\text{D}) > 0.7$

Energy deposited by all EM-like prongs $\rightarrow$ E_{EM}

Rest of the calorimetric energy $\rightarrow$ E_{Had}





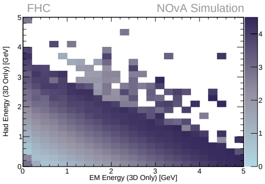
Algorithm for retraning the Energy estimator

For neutrino and antineutrino beam separately:

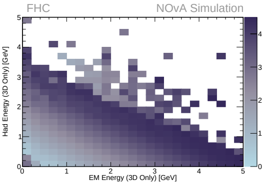
1. The Monte-Carlo files are evenly split into two parts for training and validating.
2. Events pass selection into *core* and *peripheral* samples.
3. χ^2-fit is performed on the reweighted Monte-Carlo sample, which has a flat distribution in true energy.

$$\chi^2 = \sum_{(x,y)} \left(\frac{\bar{E}_{true}(x,y) - E_{reco}(x,y,\mathbf{p})}{\sigma(x,y)} \right)^2$$

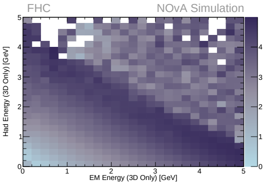
Core sample 3D only



Core sample 3D+2D



Peripheral sample



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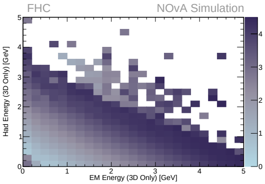

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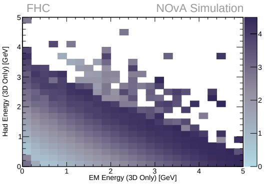
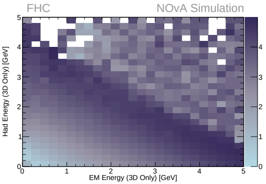


Peripheral sample



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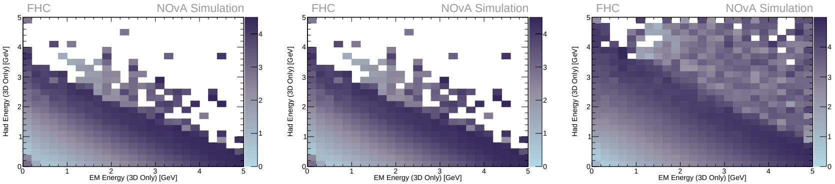
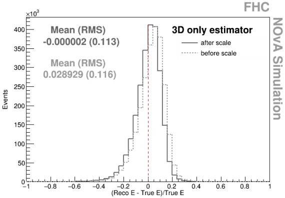
Core sample 3D only | Core sample 3D+2D | Peripheral sample

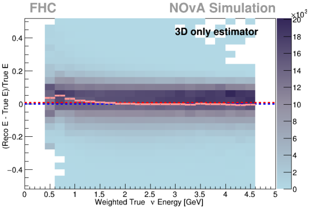


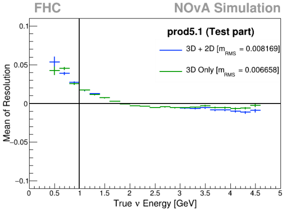
Algorithm for retraning the Energy estimator

For neutrino and antineutrino beam separately:

4. The fractional energy reconstruction error $\delta_E = (E_{reco} - E_{true})/E_{true}$ is scaled to make a distribution with a mean of zero.
5. The performance of the energy estimators are tested. Expected that the δ_E has symmetrical form. RMS value (the standard deviation of δ_E) is used as the *energy resolution* of the energy estimator.







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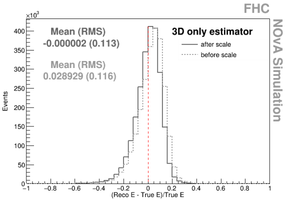
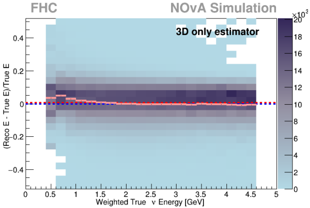
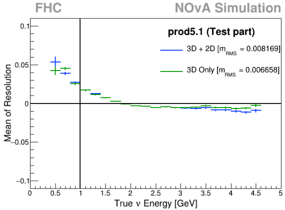




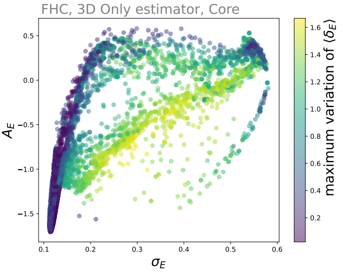


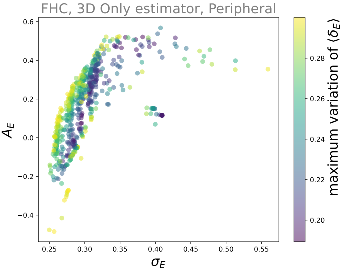
New strategy for fitting

Problem The fitting results (scaling factor k and parameters $\mathbf{p}$) can be very sensitive to the fitting range.

Solution Find the fitting range that gives the best results. The decision is made relying on a set of variables:

- mean of δ_E
- RMS of δ_E
- skewness of δ_E
- maximal variation of mean values of δ_E along the weighted true energy





Results

For the 2024 analysis, the best performance was obtained from:

Core an estimator with minimal RMS

Peripheral an estimator with minimal skewness

The retraining of ν_e energy estimator *increased* energy resolution for antineutrino beam and provide additional functions for peripheral events for the first time.

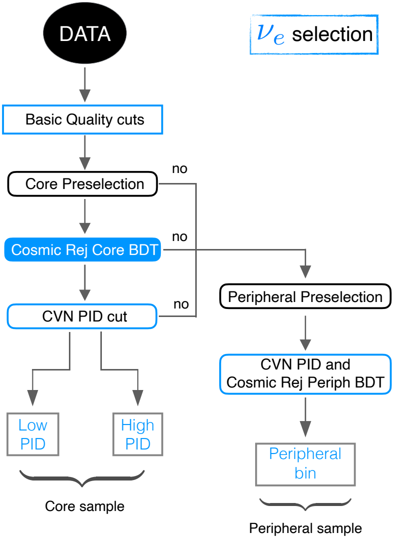
Energy resolution, %

Beam	Approach	Core	Peripheral
ν	3D only	10.8	24.1
$\bar{\nu}$	3D only	8.5	22.0
ν	3D + 2D	11.4	
$\bar{\nu}$	3D + 2D	9.0	

New NOvA 3Flavor analysis results will be presented at Neutrino 2024.

Backup

ν_e selection



Containment step eliminating a third of the potential signal events.

The events which fail containment criteria can pass selection to peripheral sample, where

- Events are not fully contained within fiducial volume.
- Energy range is increased.
- Special criteria for CVN PID score and Cosmic Rejection score.