Estimating Neutrino Energy for the NOvA 3-Flavor analysis

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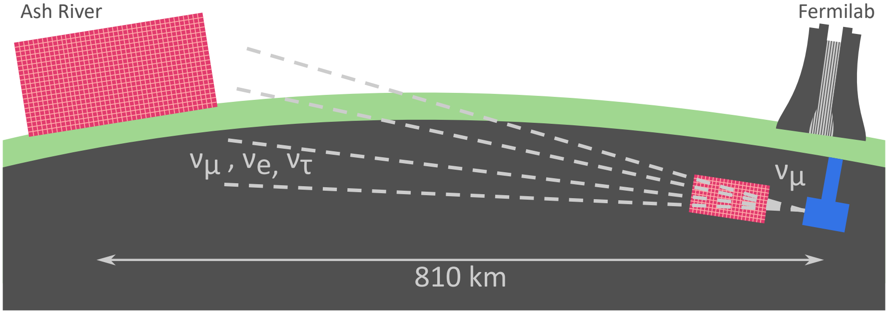
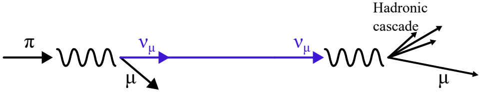
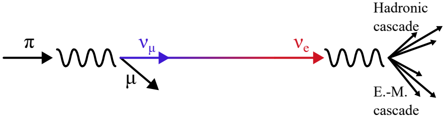
NuMI Off-axis ν_e Appearance Experiment (NOvA)



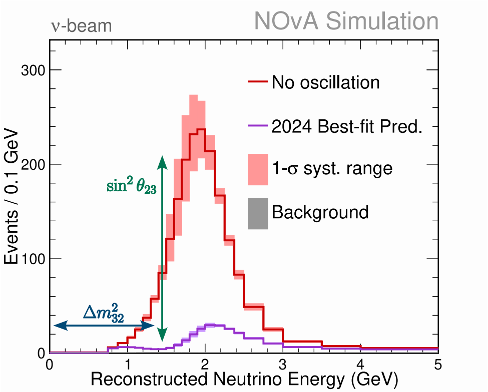
- NOvA is a long-baseline off-axis neutrino oscillation experiment at US.
- Neutrino source is Fermilab's Megawatt-capable NuMI beam.
- Two functionally identical, finely granulated detectors, filled with liquid scintillator.

3 Flavor Physics at NOvA





- NOvA's primary goal is measurement of oscillation parameters from both $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance.
- Accurate energy estimation is vital to make good measurements of oscillation parameters: $P\left(\nu_\alpha \to \nu_\beta\right) = P(E_\nu, \vec{\theta})$
- The estimation methods must be model independent and strong enough to handle different event topologies.



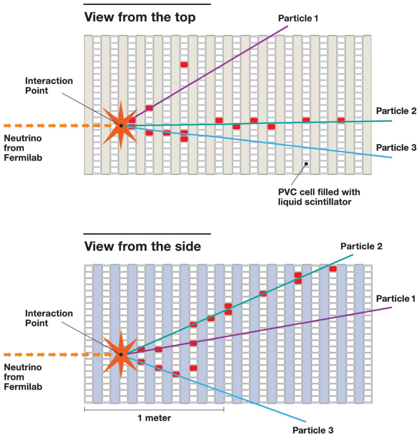
Event reconstruction

Reconstruction chain:

1. hits (cells, where a particle deposited energy)
2. slice (individual event interactions)
3. vertex
4. prongs (hit clusters with a start point and a direction)
5. tracks (actual path of the particle)
6. identification

Reconstructed physics variables:

- energy of a neutrino event
- position of the interaction point
- directions of outgoing particles



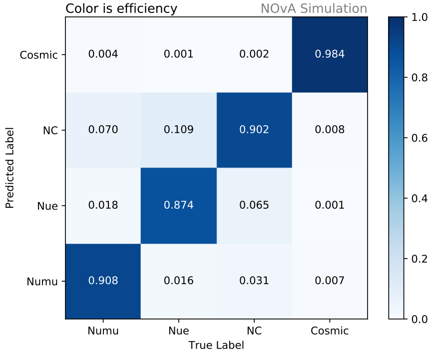
Near Detector: 214 Planes, 290 ton

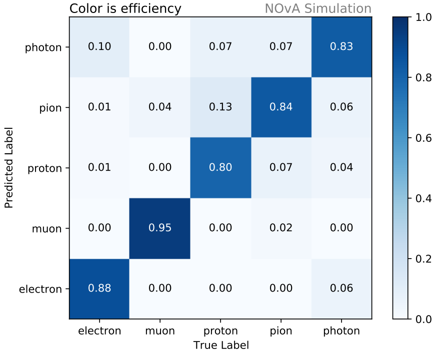
Far Detector: 896 Planes, 14 kton

Event and particle classification

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

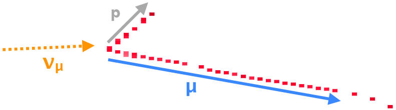
EventCVN: ν_μ CC, ν_e CC, NC, cosmic
ProngCVN: electron, muon, proton, pion, photon (used as part of the ν_e energy estimation)





ν_μ Energy estimator

Muon neutrino energy estimator

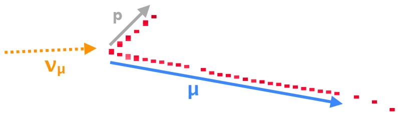


Spline-Based Method

Muon neutrino or antineutrino energy is estimated as a combination of muon and hadronic deposited energy:

$$E_{reco} = E_{\mu} + E_{Had}$$

Muon neutrino energy estimator



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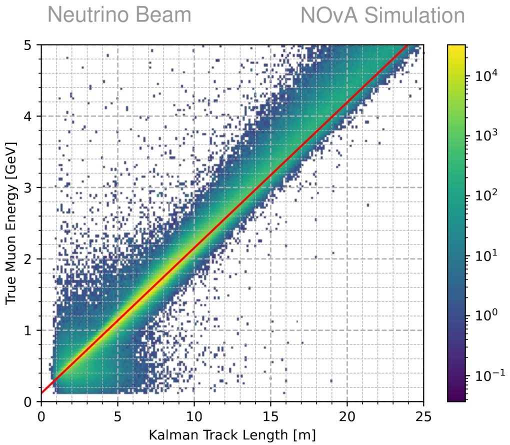
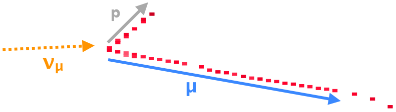


Muon energy is estimated from a fit to Kalman track length.

Muon neutrino energy estimator



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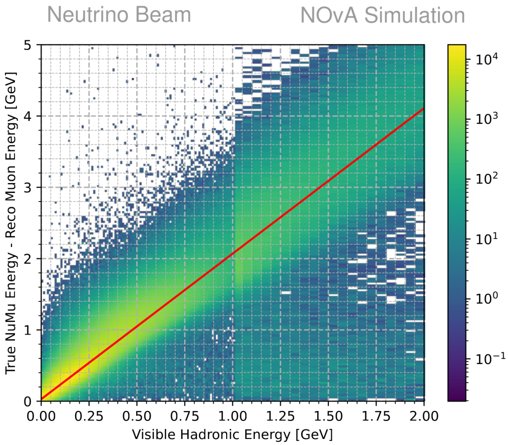
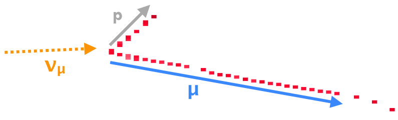
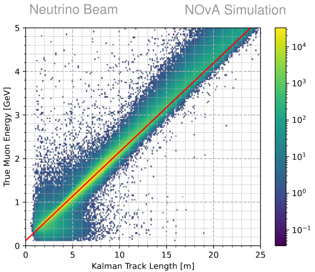
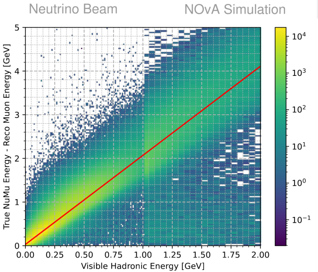


Hadronic energy is estimated from a fit to visible deposited hadronic energy.

Muon neutrino energy estimator







Spline-Based Method

Muon neutrino or antineutrino energy is estimated as a combination of muon and hadronic deposited energy:

$$E_{reco} = E_\mu + E_{Had}$$

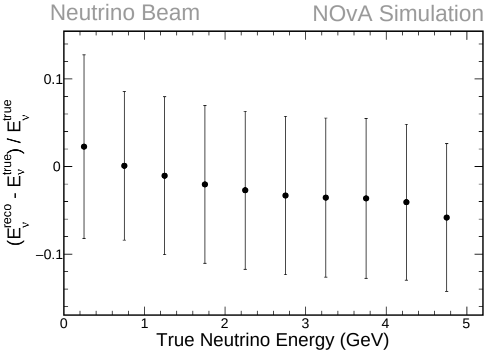
- Construct two-dimensional histograms of the reconstructed quantity vs the true quantity.
- For each bin of reconstructed energy a Gaussian fit is performed.
- The mean of the Gaussian in each slice is used to fit a piece-wise linear spline.

Muon neutrino energy resolution

ν_μ energy estimator performance of the Ana2024 energy estimator in terms of overall bias and resolution is taken as the mean and standard deviation of the fractional energy reconstruction error

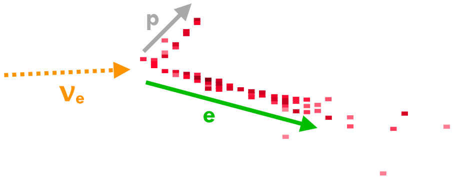
$$\delta_E = \frac{E_{reco} - E_{true}}{E_{true}}$$

Beam	Detector	Resolution
Neutrino	Far	9.30%
Antineutrino	Far	8.06%
Neutrino	Near	12.18%
Antineutrino	Near	9.98%



ν_e Energy estimator

Electron neutrino energy estimator

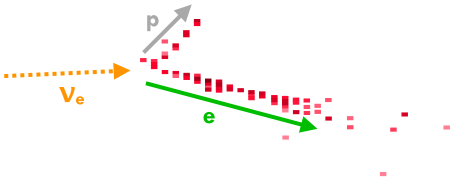


Calorimetric Method based on ProngCVN

Electron (anti)neutrino energy is estimated by a quadratic fit function, dependent on the electromagnetic (EM) and hadronic (Had) components, because EM and Had deposition have different detector response:

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

Electron neutrino energy estimator



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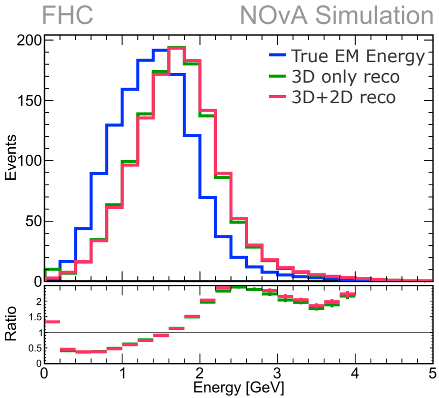
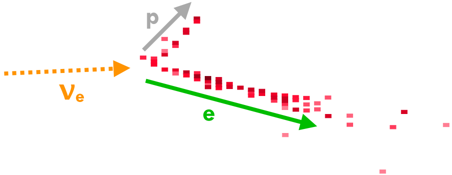


Energy deposited by all EM-like prongs.

Electron neutrino energy estimator



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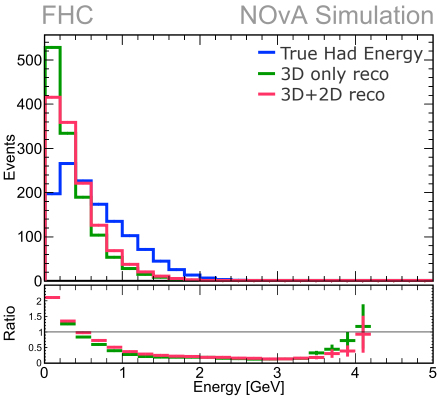


Rest of the calorimetric energy.

Estimator adjusting

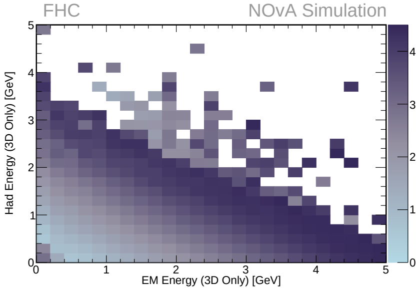
$$E_{reco} = k \cdot (p_1 E_{EM} + p_2 E_{EM}^2 + p_3 E_{Had} + p_4 E_{Had}^2)$$

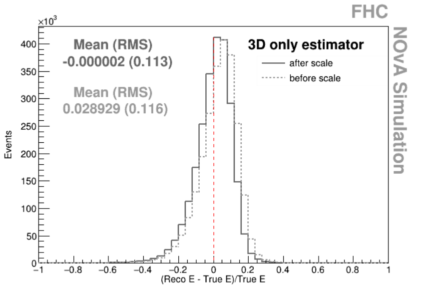
The parameters $p_{1,\ldots,4}$ are optimized to produce the best energy resolution $\sigma(\delta_E)$, where:

$$\delta_E = \frac{E_{reco} - E_{true}}{E_{true}}$$

To get the fitted parameters, a χ^2-fit is performed on the reweighted Monte Carlo sample, which has a flat distribution in true energy.

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



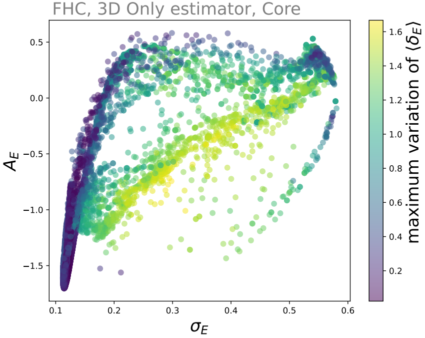


New strategy for fitting

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:

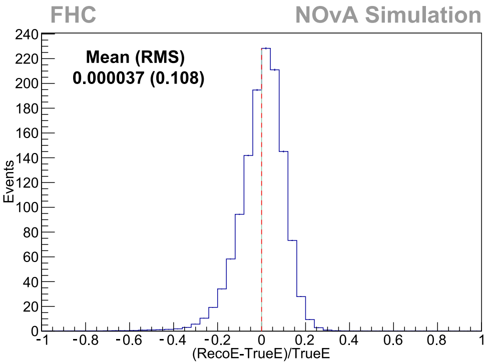
- mean of δ_E
- standard deviation of δ_E
- skewness of δ_E
- maximal variation of mean values of δ_E along the weighted true energy

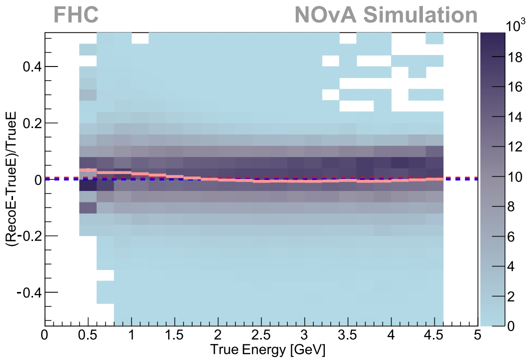


Electron neutrino energy resolution

The average energy resolution is

- 10.8% for the neutrino beam,
- 8.5% for the antineutrino beam.





Conclusion

- Each new analysis requires retraining energy estimators, as they are based on Monte Carlo simulations.
- Good adjusted energy estimators are important for making precise measurements of oscillation parameters.
- In the latest NOvA 3 flavor neutrino oscillation analysis,
  - calorimetric method based on ProngCVN was used for $\nu_e/\bar{\nu}_e$ events.
  - tracking spline-based method was used for $\nu_\mu/\bar{\nu}_\mu$ events.
- Both methods are well understood and provide good performance.
- For the future analysis, alternative neutrino energy estimating approaches based on machine learning algorithms are under construction.