Event and Energy Reconstruction in the NOνA Experiment

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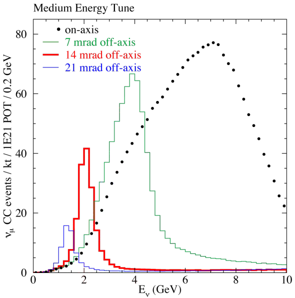
Overview

- Introduction to NOνA Experiment - See Xuebing Bu's talk
- Calibration
- Neutrino Event and Energy Reconstruction
  - ν_e Appearance Analysis
  - ν_μ Disappearance Analysis

The NuMI Off-Axis ν_e Appearance (NOνA) Experiment

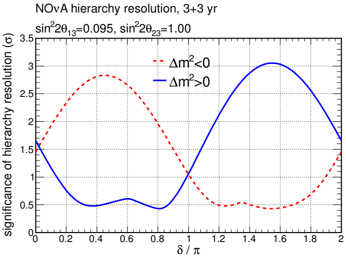
- NuMI[1] beam at Fermilab
  - Primarily ν_μ
- Long-Baseline Oscillation Experiment
  - Two functionally identical detectors
  - Detectors separated by 810 km baseline
  - 14 milliradians off-axis
  - Narrow band energy spectrum



[1] Neutrinos at Main Injector

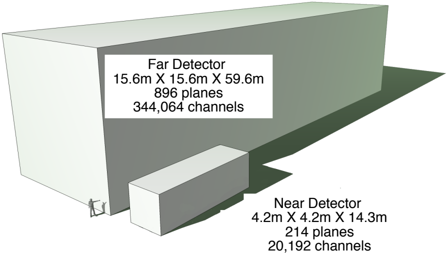
NOνA Physics

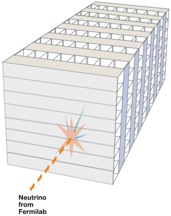
- Oscillation Channels
  - Appearance: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Disappearance: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- Physics Goals
  - Mass hierarchy
  - CP violation
  - θ_{23} maximal/octant
- See Xuebing Bu's talk for more details

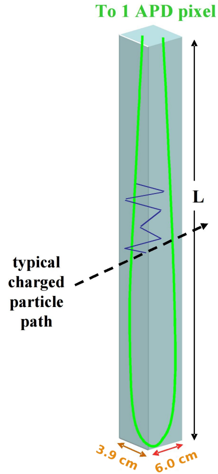


Detector Design

- The NOνA detectors are tracking calorimeters
- Cellular structure
- Each cell is a tube of reflective PVC filled with liquid scintillator
- An optical fiber loop transports scintillation light to a pixel of an avalanche photodiode (APD)
- Cells are arranged in planes with each plane orthogonally rotated from the previous

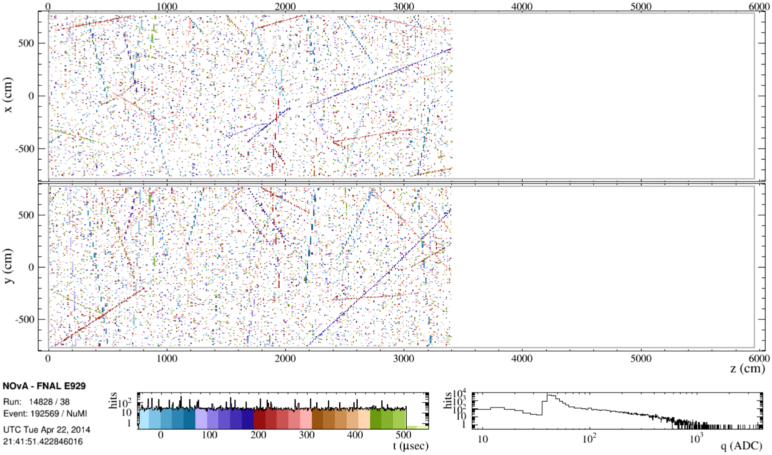






Far Detector Data

- Early far detector data from a 550 μs trigger window data



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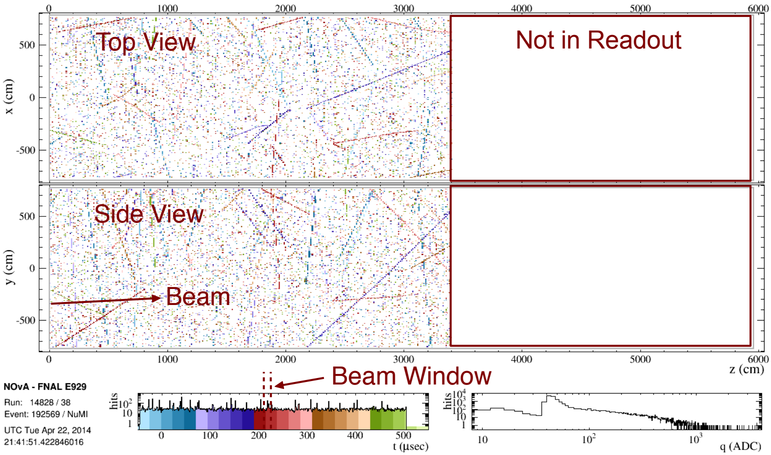

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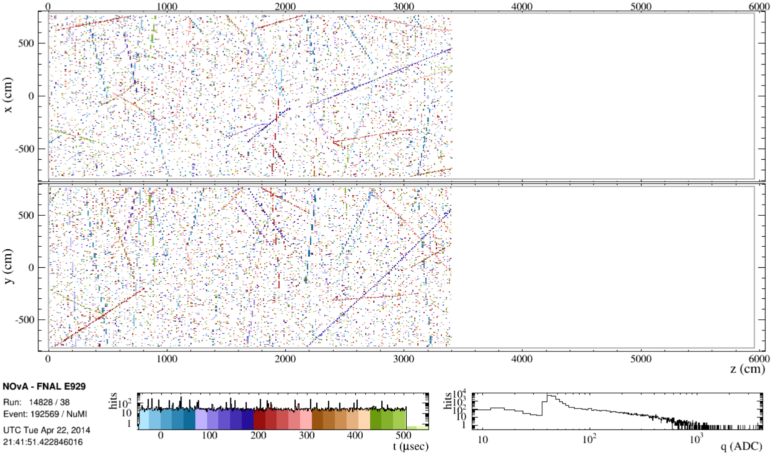
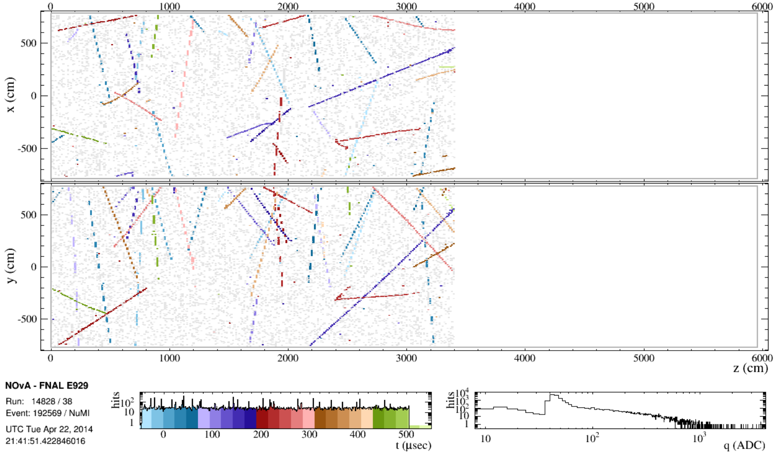


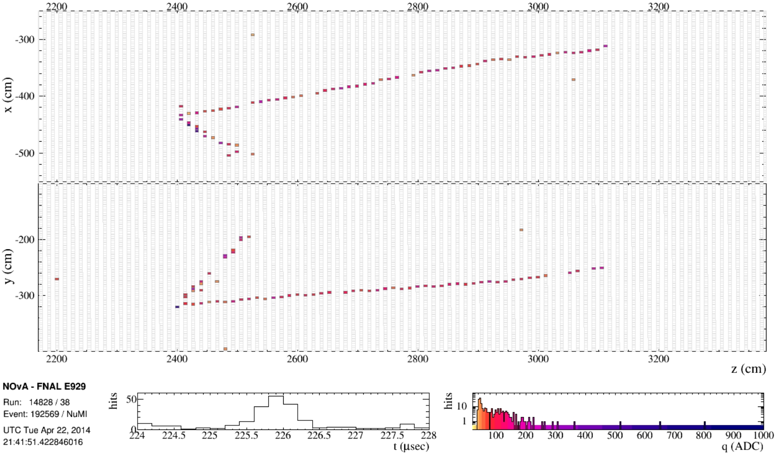
Space-time Clustering

- First step in reconstruction is to cluster hits by space-time coincidence

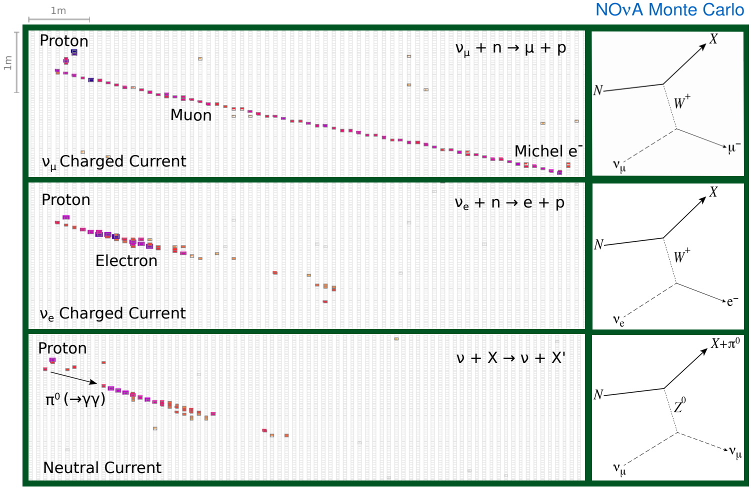


Space-time Clustering

- Single space-time cluster



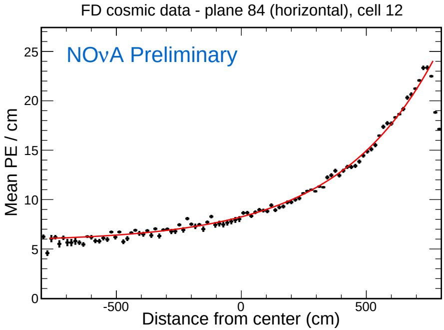
Neutrino Event Topology



- Minimum ionizing particles deposit ~10 MeV/cell
- Each plane samples ~0.18 radiation lengths

Cell Calibration

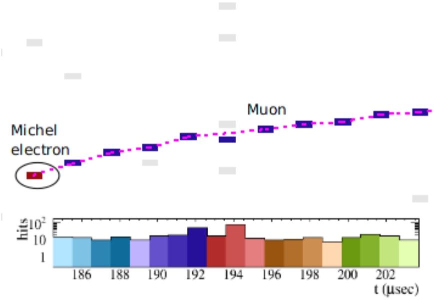
- Cosmic ray data is used to correct for the fiber attenuation in each cell
- An exponential fit to the number of photo-electrons (PE) per path length gives the cell response as function of depth in the cell



- Drift calibration applied to correct for temporal changes in the detector
  - Mean $\frac{dE}{dx}$ measured in APDs weekly and normalized to baseline response

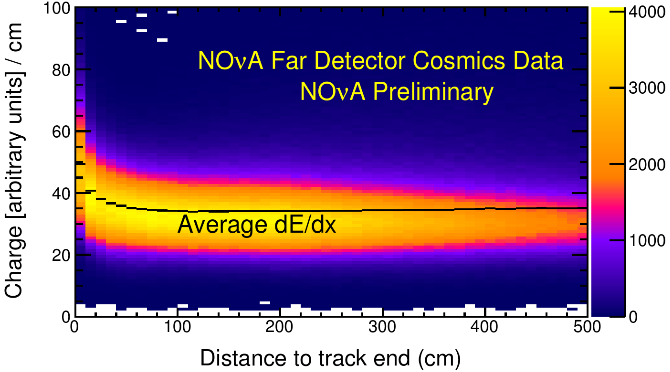
Absolute Energy Calibration

- Converts attenuation corrected signal into visible energy measurement
- Absolute energy scale determined from stopping muons
- Stopping muons tagged by Michel electron



Absolute Energy Calibration

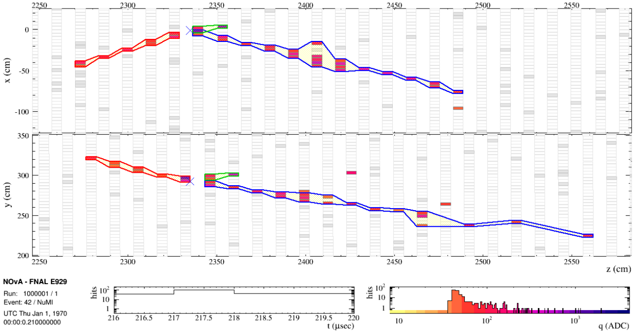
- $\frac{dE}{dx}$ measured between 100 and 200 cm from the track end
- Simulation is tuned to match the measured $\frac{dE}{dx}$ from data
- Absolute energy scale is obtained from tuned simulation



ν_e Appearance Analysis

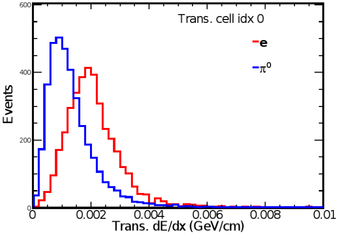
ν_e Event Reconstruction

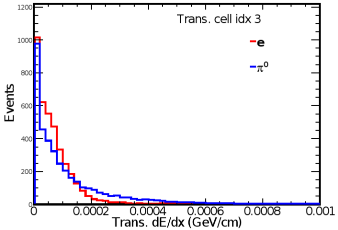
- Global event features reconstructed
  - Vertex determined using modified Hough transform lines
  - Prongs determined by angular clustering
- Two independent ν_e identification approaches developed
  - EID: Log-Likelihood based shower identification from prongs
  - LEM: Energy deposition comparison to a library of events



Electron Identification (EID)

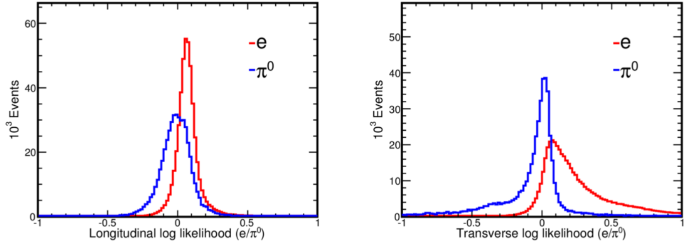
- EID uses shower energy profiles to identify particles
- $\frac{dE}{dx}$ is measured in each plane transverse and longitudinal to the shower
- The probability for the $\frac{dE}{dx}$ is determined from profiles generated from simulation for a particle hypothesis





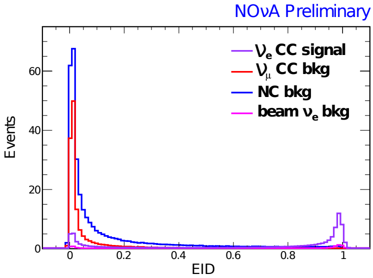
Electron Identification (EID)

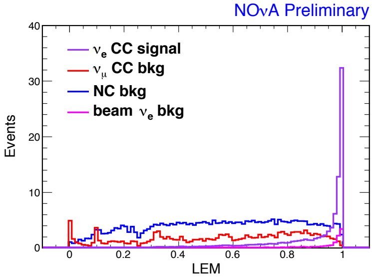
- The log-likelihood (LL) for a particle is computed from summing all the probabilities over all shower planes
- Particle discrimination determined from differences in LL, e.g. $LL(e) - LL(\pi^0)$



ν_e Event Identification

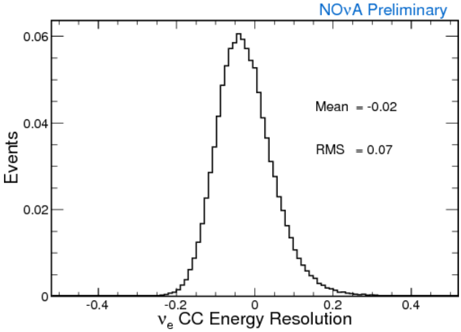
- A neural network (ANN) provides the final EID event identification
  - Differences of log-likelihoods
  - Other reconstructed variables, e.g. gap between shower start and vertex
- LEM uses the properties of the best matched library events to calculate a PID value
- Both identification methods show a similar performance in selecting ν_e events





ν_e Energy Reconstuction

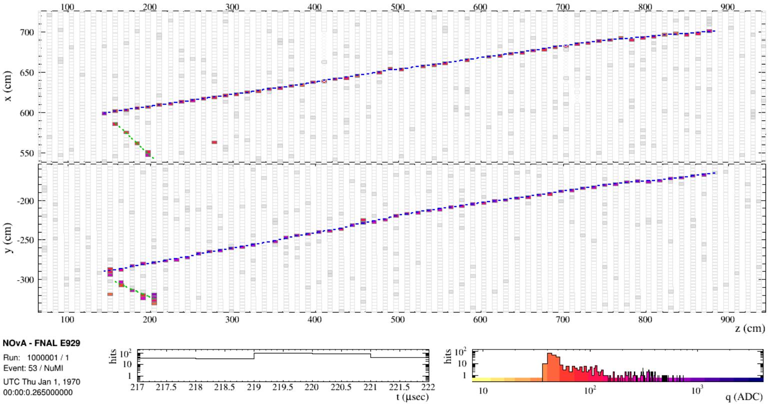
- Several methods have been developed to estimate the overall ν_e event energy
- One method uses a fit of the true energy to the visible calorimetric energy from simulation
  - The energy resolution for events with ANN $>$ 0.95 is $\sim$ 7%



ν_μ Disappearance Analysis

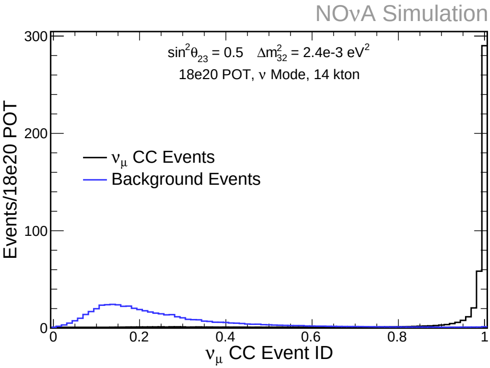
ν_μ Reconstruction

- A Kalman Filter based tracking algorithm reconstructs fine-grained trajectories

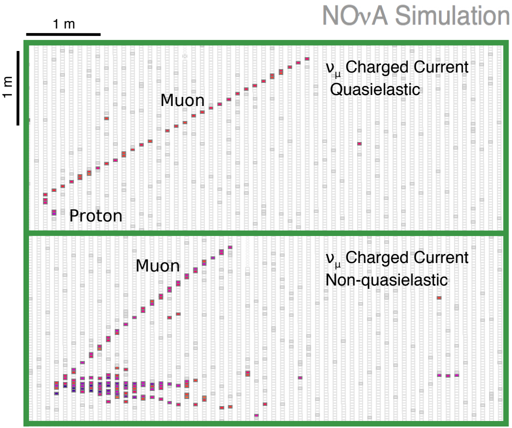


ν_μ Event Identification

- Muon identification formulated from reconstructed track variables
  - $\frac{dE}{dx}$ $LL(\mu) - LL(\pi^\pm)$
  - Scattering $LL(\mu) - LL(\pi^\pm)$ - Measures scatter on track
  - Track length
  - Amount of overlapping hadronic activity on the track
- Nearest neighbor (kNN) algorithm used to identify existence of a muon track



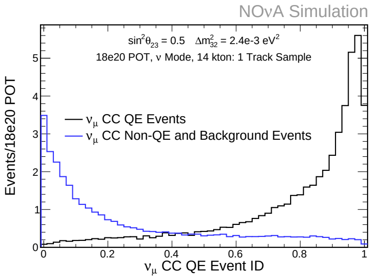
ν_μ Quasielastic Separation



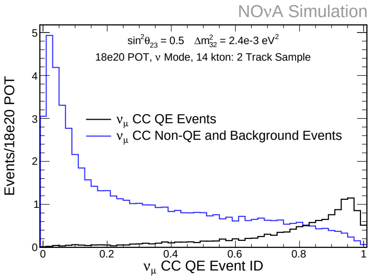
- Further step in event identification separates quasielastic (QE) and non-quasielastic (non-QE) events
  - QE events have better energy resolution
  - QE events have less NC background

- Select QE events with at most 2 reconstructed tracks
- Multivariate analysis based on event energy distribution
  - Relative difference of QE energy estimators
  - Off-track energy ratio
  - Ratio of average track $\frac{dE}{dx}$ (events with two reconstructed tracks only)

1 Track Sample



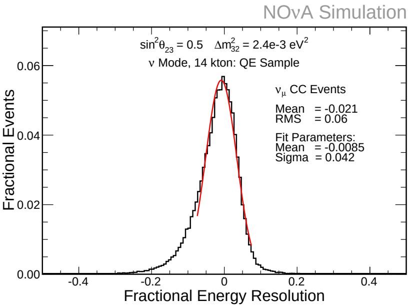
2 Track Sample



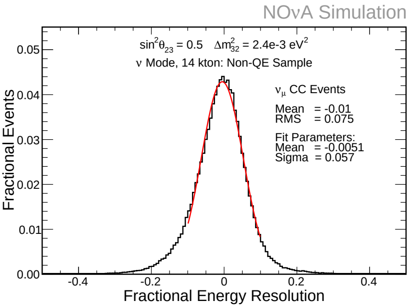
ν_μ Energy Reconstruction

- Interactions are split into muon and hadronic component
  - Muon energy determined from a fit of the track length
  - Hadronic energy determined from fit to visible hadronic calorimetric energy
- Sum of the muon and hadronic energies gives the neutrino energy
- Selected QE Sample: 4.5% energy resolution
- Selected Non-QE Sample: 6% energy resolution

QE Sample



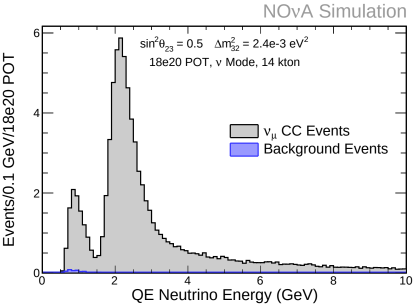
Non-QE Sample



Selected ν_μ Spectra

- Final energy spectrum of selected contained ν_μ samples

QE Sample



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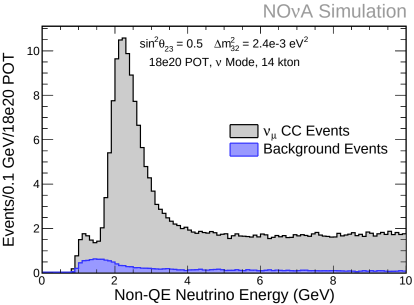


Conclusions

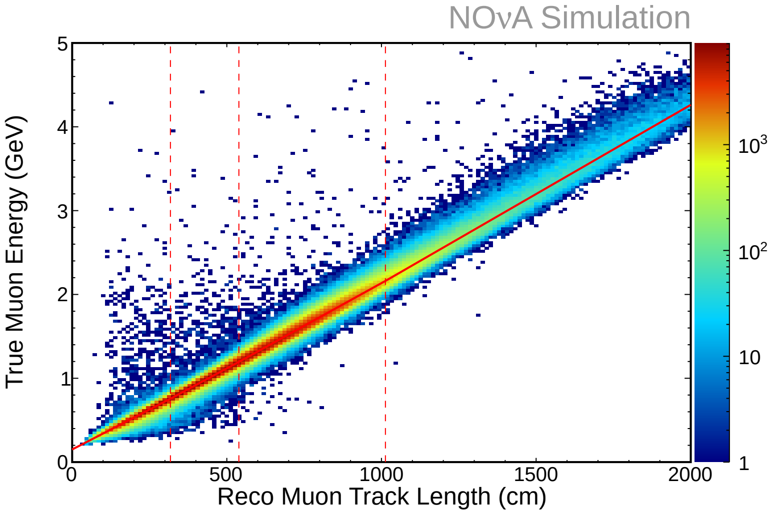
- NOνA has developed reconstruction methods to achieve the oscillation physics goals
- Neutrino reconstruction exploits unique tracking and calorimetric features of the detectors

- Refer to other NOνA talks for more details:
  - The NOνA Experiment, Xuebing Bu
  - Charged-Current Cross Section Measurements in the NOνA Experiment, Lisa Goodenough
- More information also available from NOνA posters:
  - Overview of the NOvA experiment, Jan Zirnstein
  - Event Selection for the NOνA ν_μ Disappearance Analysis, Nicholas Raddatz
  - Energy Estimation for the NOνA ν_μ Disappearance Analysis, Susan Lein

Backup

Muon Energy

- Fit of muon range to true energy



ν_μ Quasielastic Energy

- Relative difference between QE energy estimators for selected ν_μ CC events