CHARGED PARTICLE TRACK RECONSTRUCTION IN THE NOνA EXPERIMENT

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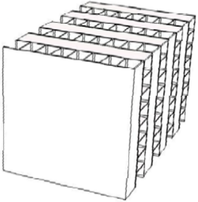
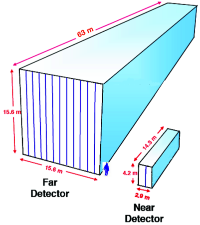
NOνA DETECTORS

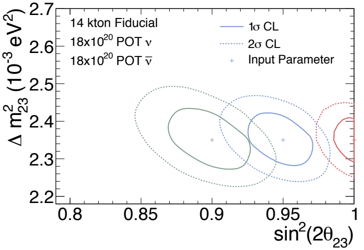
- “Fully active” tracking liquid scintillator calorimeter
  - Cellular structure gives 2 independent orthogonal detector views
  - Designed to resolve ν_e event topologies around 2 GeV beam energy peak
  - Also sensitive to ν_μ topologies with 2 GeV muons having a mean path length of 10 m



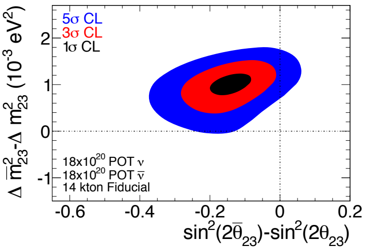
- Expected Data Rates
  - Near Detector (220 tons):
    - Cosmic Rate: $\sim$ 50 Hz (105 m overburden)
    - Neutrino Rate: 10μs spill every 1.33 s with 30 neutrino events/spill
  - Far Detector (15 ktons):
    - Cosmic Rate: $\sim$ 200 kHz (3 m eqiuvalant overburden)
    - Neutrino Rate: $\sim$ 3-4 events/day
  - Near Detector On the Surface (NDOS) ($\sim$ 200 tons):
    - Cosmic Rate: $\sim$ 3 kHz (no overburden)
    - Neutrino Rate: $\sim$ 16 events/day (NuMI beam) + $\sim$ 3 events/day (Booster beam)



- Primary goal is ν_e charged current shower reconstruction
  - Gives sensitivity to θ_{13}, mass hierarchy, and CP violation
- Reconstruction of muon tracks in ν_μ charged current interactions allows for other analyses
  - Precision θ_{23}, Δm^2_{23} measurements. Is θ_{23} maximal?
  - Resolution of neutrino - antineutrino disappearence parameters
    - ★ If MINOS central values are correct, NOνA will establish difference at 3 σ in 2 years and 5 σ in 6 years
  - ν_μ cross section measurements
- Reconstruction of cosmic muon tracks allows for background characterization



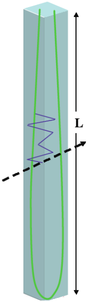
1 and 2 σ measurement contours of $\sin^2(2\theta_{23})$ after full 6 year run

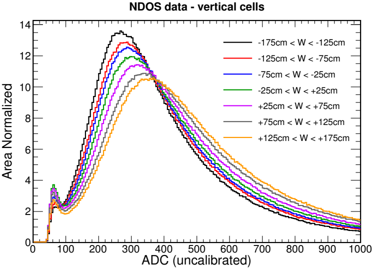


Muon neutrino - antineutrino disappearance parameters assuming MINOS central values after full 6 year run, 3 neutrino + 3 antineutrino

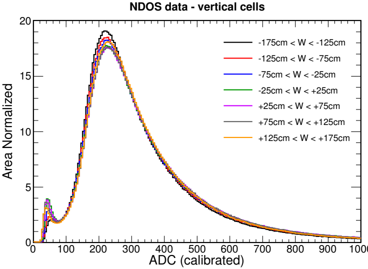
Detector Calibration

- Reconstruction of cosmic ray tracks provides calibration
- Detector Calibration
  - Cell to cell differences
  - Wavelength shifting fiber attenuation correction
  - Absolute energy calibration
    - ★ Michel electrons
    - ★ $\frac{dE}{dx}$ of stopped muons





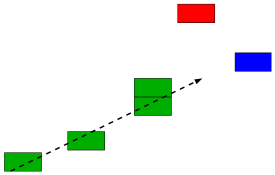
Path-length corrected response to cosmic muons for different distances from the fiber end for an example cell



Cosmic muon response after attenuation corrections for different distances from the fiber end for an example cell

Track Reconstruction Method

- Group hits associated in time into clusters (typically $\sim$ 900 ns long) from full trigger window (500 μs for NDOS)
- Reconstruct tracks on each time grouped hit cluster seperately
  1. Form track seeds by assuming adjacent hits in each orthogonal detector view are part of the same track
  2. Use a Kalman filter to propagate track seeds plane by plane through the view and group hits together that are consistent with straight tracks.
     - ★ Reject any hits that are inconsistent with the projected track



  3. Match tracks independently reconstructed in each view giving 3 dimensional tracks
- Configurable track reconstruction cuts:
  - Track must contain at least 4 hits in each orthogonal view
  - Track must cross at least 3 detector plane

Kalman Filters for Track Reconstruction

- Why Kalman Filter Reconstruction?
  - Track pattern recognition and fitting are both done in one step
  - Straight track reconstruction can be extended to encompass multiple scattering within the existing Kalman filter framework

- Kalman Filter Details

- The Kalman filter is a general tool for estimating the true value of a noisy linear dynamic system
- The filter provides a weighted average based on measurements of the system
- Kalman filters describe systems in terms of its true state ($\mathbf{x}_i$) and measurements of its state ($\mathbf{z}_i$) at discrete steps, i.
- The filter addresses the problem of determining the best estimate of $\mathbf{x_i}$ given the measurements $\mathbf{z_0}...\mathbf{z_i}$ by minimizing the error in the estimate.

- States evolve from step $i-1$ to i through:

$$\mathbf{x}_i = A\mathbf{x}_{i-1} + \mathbf{w}_{i-1} \quad (1)$$

$$\mathbf{z}_i = H\mathbf{x}_i + \mathbf{v}_i \quad (2)$$

where A describes the propagation matrix, H relates the system state to its measurement, and **w** and **v** describe the process and measurement uncertainty respectively.

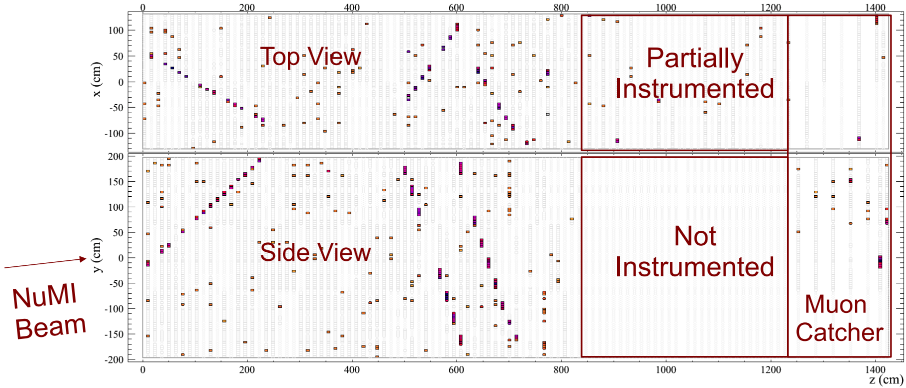
- Kalman filters provide a prediction equation, Eq. 1, and correction equation:

$$\mathbf{x}_i = \mathbf{x}_i^- + K_i(\mathbf{z}_i - H\mathbf{x}_i^-) \quad (3)$$

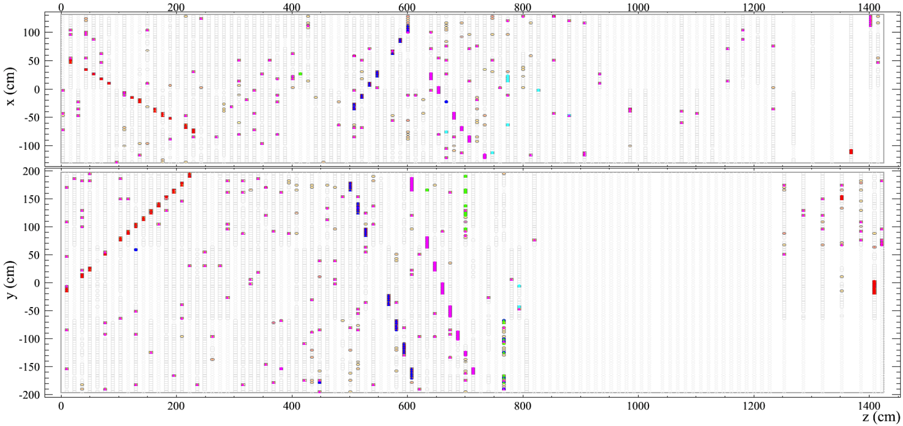
where $\mathbf{x}_i^-$ is the predicted state and K_i is the calculated filter minimizing the error in the estimate

- States can be reconstructed by predicting signals using Eq. 1 and then correcting the estimate by including measurements using Eq. 3

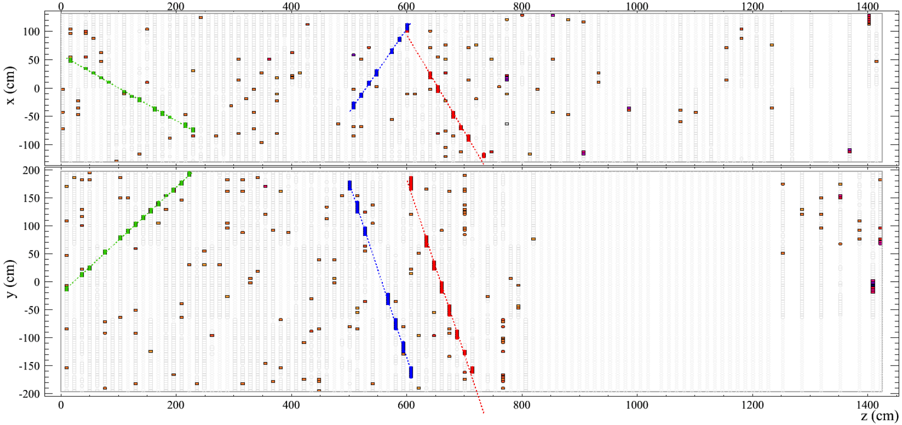
Raw Cosmic NDOS Data Event



Time Clustered Cosmic NDOS Data Event

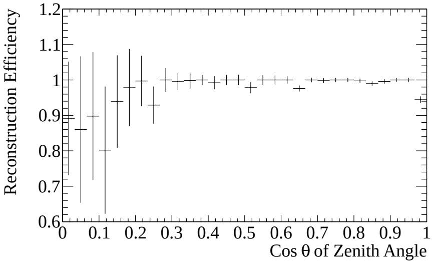


Track Reconstructed Cosmic NDOS Data Event



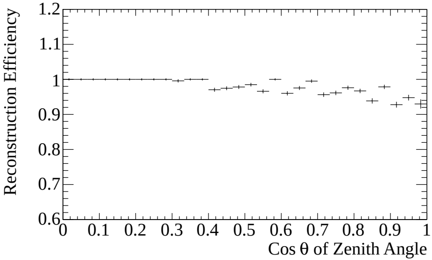
Preliminary Track Reconstruction Efficiency

- Cosmic Ray Muon Monte Carlo



Track reconstruction efficiency for Monte Carlo cosmic muons in NDOS as a function of track angle.

- 2 GeV Muon Monte Carlo

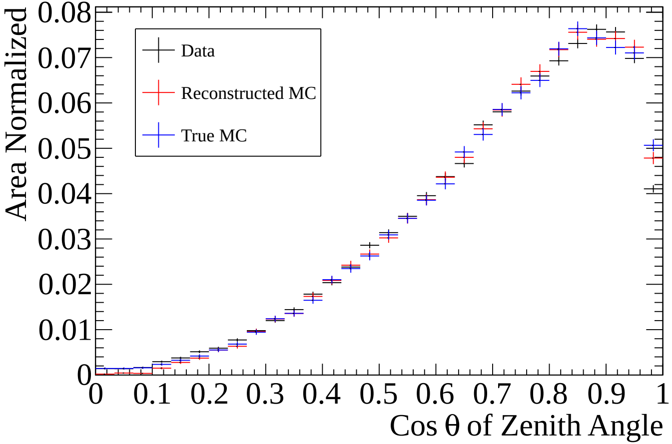


Track reconstruction efficiency for 2 GeV muons as a function of angle. Muon starting positions are uniformly distributed in the NDOS fiducial volume.

Reconstruction efficiency is calculated for simulated tracks that pass the requirements of having at least 4 hits in each detector view and pass through at least 3 separate planes

Cosmic Muon Angular Distribution

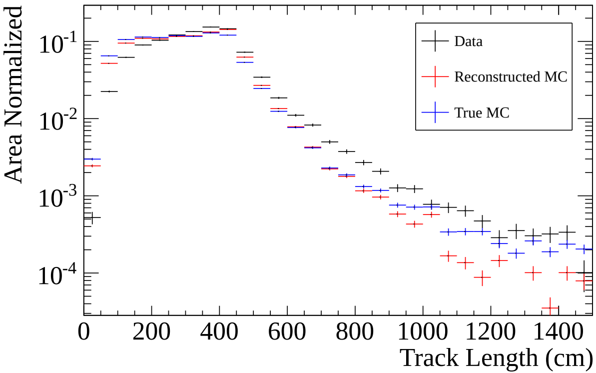
- Drop-off after $\cos\theta \sim 0.94$ due to requirement that the track pass through 3 separate planes



Angular distribution of reconstructed cosmic ray data from NDOS, reconstructed NDOS cosmic Monte Carlo, and true angle of reconstructed NDOS cosmic Monte Carlo. All tracks have greater than 4 hits in each view and pass through a minimum of 3 planes

Cosmic Muon Track Length

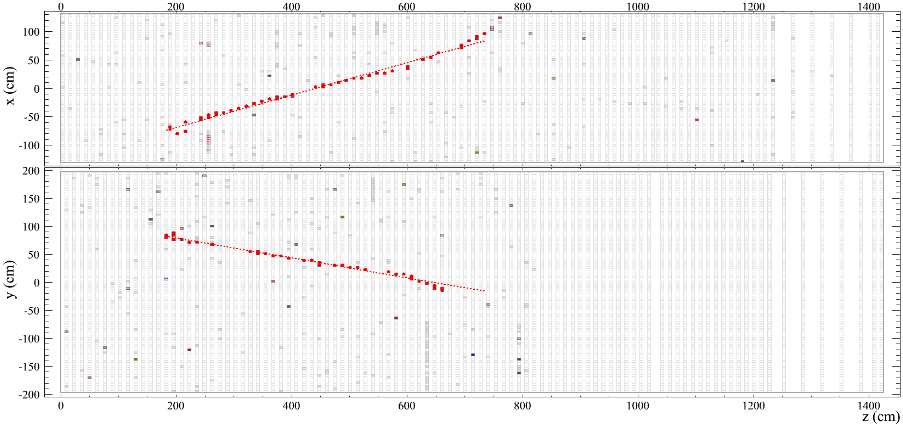
- Tracks are reconstructed up to the maximum total straight path length through NDOS with a peak near the vertical height of NDOS (400 cm)
- Monte Carlo assumes a fully instrumented, perfectly aligned detector giving better resolution to detector geometry than data



Track length of reconstructed cosmic ray data from NDOS, reconstructed NDOS cosmic Monte Carlo, and true length of reconstructed NDOS cosmic Monte Carlo. All tracks have greater than 4 hits in each view and pass through a minimum of 3 planes

ν_μ Candidate NDOS Data Event Reconstruction

- Reconstruction of cosmic background suppressed for clarity



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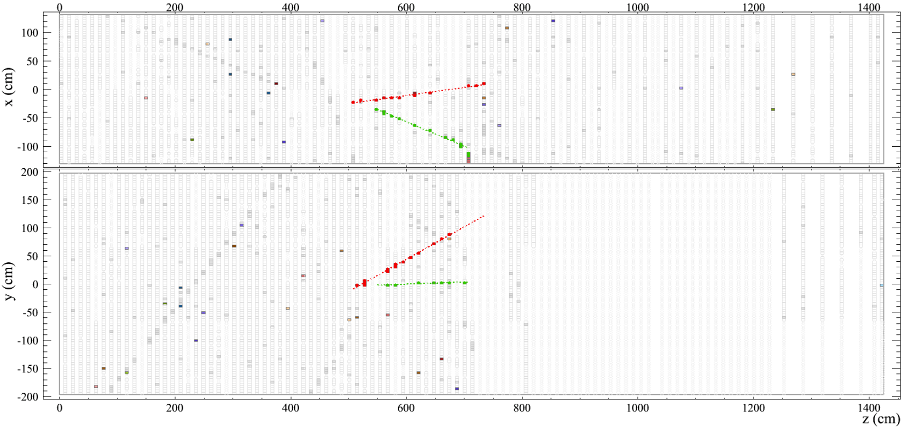

Summary and Outlook

- Accurate charged particle tracking is an integral part of detector calibration and data analysis goals
- We have developed a track reconstruction routine suited for muons based on Kalman filters
- The reconstruction method has been successfully applied to the data from NDOS prototype detector to reconstruct cosmic muons and candidate neutrino interaction events
- We are continuing to develop track reconstruction including the ability to reconstruct tracks with large multiple scattering effects