Muon Energy Reconstruction at NOνA

Fernanda Psihas, for the NOνA Collaboration

Sources of muons in NOνA

Muons from Neutrino Interactions. NOνA has enough sensitivity to make $\sin^2 2\theta_{23}$ precision measurements through the ν_μ disappearance analysis

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32}\ L/E)$$

Muon energy reconstruction plays a key role in measuring the surviving ν_μ energy spectrum, since muons are the main handle on ν_μ energies.

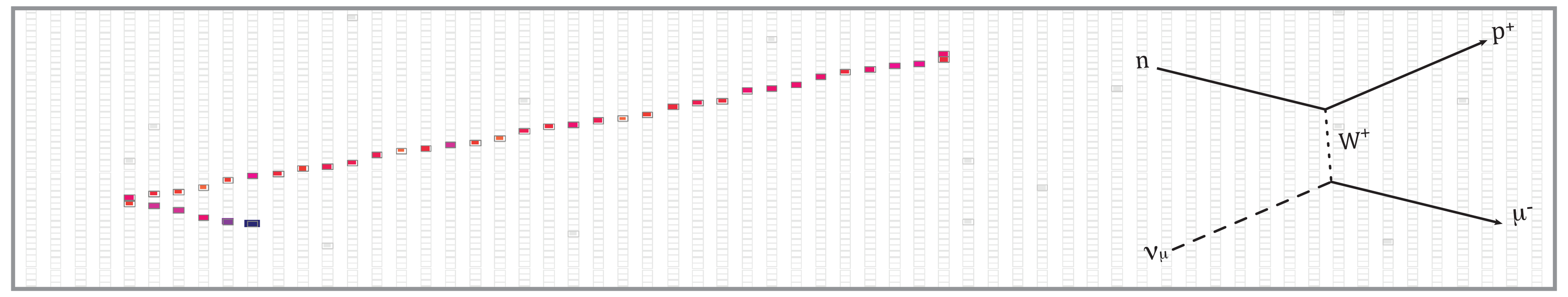

Figure 1: A muon neutrino charged current quasi elastic interaction in the NOvA event display, from montecarlo simulations and the diagram that represents it.

Muons from Cosmic Ray Interactions. NOνA expects a few neutrino interactions per day and a cosmic muon rate of ~120 kHz in the far detector. In the 10 μs time windows around neutrino beam spills, the rate of cosmic muons to ν interactions is 6200:1.

Cosmic muon rejection is crucial to neutrino event identification, but cosmic muon energy reconstruction is still important in non-oscillation analyses at NOνA.

Muon behaviour in the NOνA detectors

Understanding the behaviour of muons in our detectors allows us to make more accurate predictions and optimize energy reconstruction.

Two good handles on the μ energies are the reconstructed **distance traveled** by the μ inside the detector (track length) and the **energy deposited** by it as it moves through the detector.

Variables that, like these, depend on the particle's energy can be used to reconstruct it using these correlations.

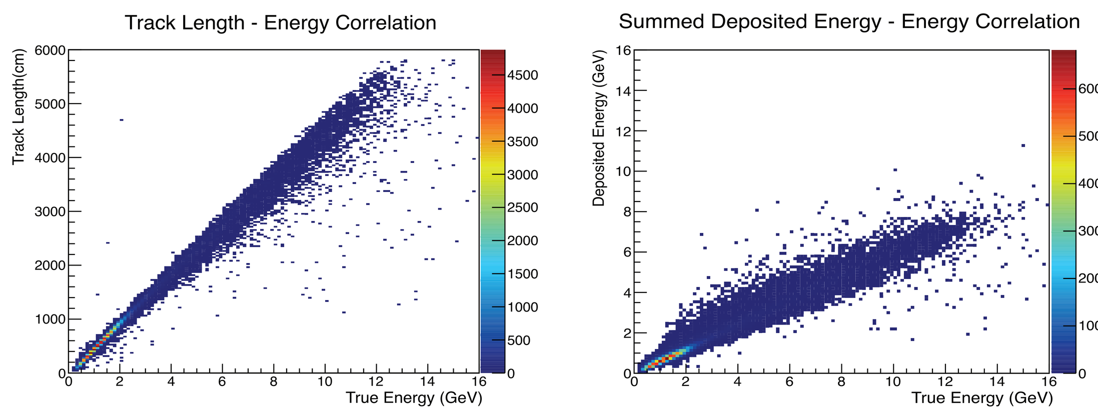

Figure 2: The correlation between the reconstructed track length and the muon's true energy, on the left, and the correlation between the summed deposited energy for each cell the muon traveled through and it's true energy, on the right. From the NuMI beam Monte Carlo for the NOvA far detector.

Motivation for Multiple Approaches

It is clear that the energy of muons can be well-reconstructed from their track lengths. However, some muons will escape the far detector before depositing all their energy. **Escaping muons** will make up **~28% of all the muons from ν_μ interactions** in the far detector with energies up to 2 GeV from the oscillation peak.

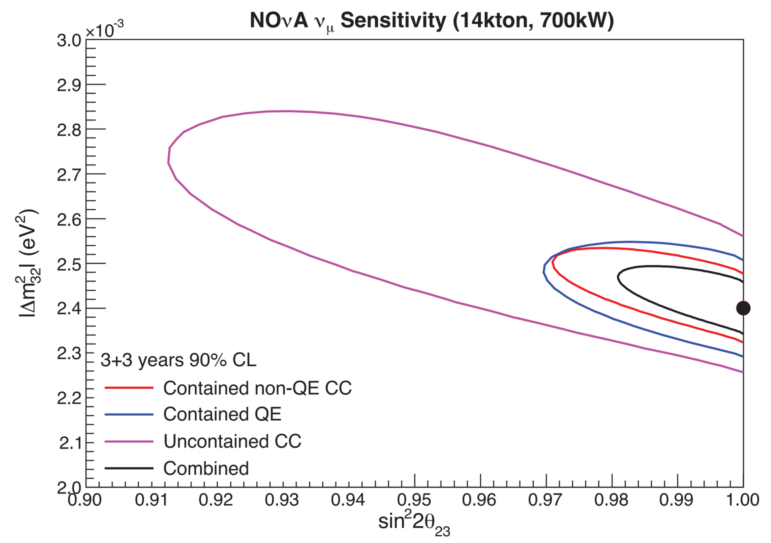

Figure 3: The expected $\sin^2 2\theta_{23}$ contours for $\sin^2 2\theta_{23}=1$. From NuMI beam Monte Carlo simulations for the NOvA detectors.

Reconstructing escaping events will **add statistics** to the long term ν_μ disappearance analysis. It will be of greater importance during building stages of the far detector during which the rate of escaping to contained muons will be even larger.

Because the best handles on μ energies depend on their containment, NOνA will use **composite approaches at μ energy reconstruction** for uncontained events.

Energy Reconstruction

Track Length Method

The simple and nearly linear correlation between the **distance traveled** by muons and their energy allows a simple approach at reconstructing energies.

Line fits to the correlation's profile are done in three sections to best describe the correlation.

This reconstruction method is used for **contained events**.

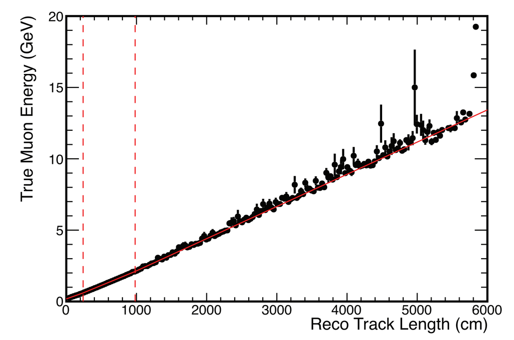

Figure 4: Linear fits to the true muon energy vs reconstructed track length correlation.

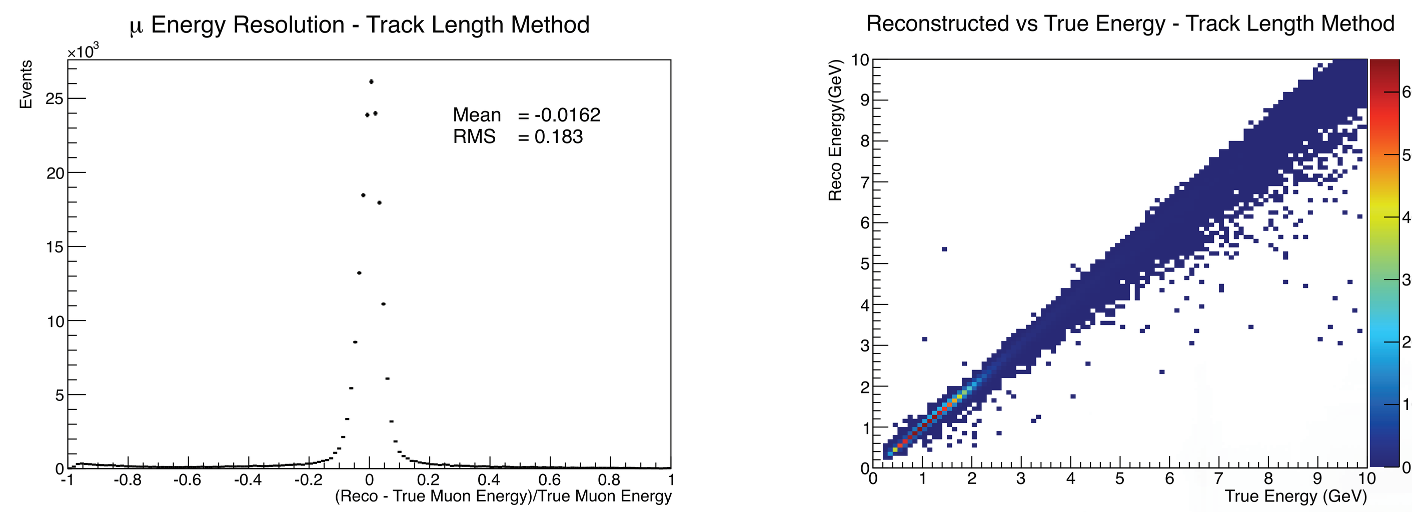

Figure 5: On the left: the muon resolution for this method (RMS). On the right: the energy reconstructed using this method vs the muon's true energy for known muons from ν_μ interactions. From the NuMI beam Monte Carlo for the NOvA far detector.

Deposited Energy Method

As the muon travels through the detector it deposits all its energy. **Adding the deposited energy** on each cell it crosses gives a handle on the particle's energy. A linear correlation is also assumed for this approach at reconstruction.

*Not all the deposited energy is accounted for with this method. The PVC modules will also absorb some of the muon's energy.

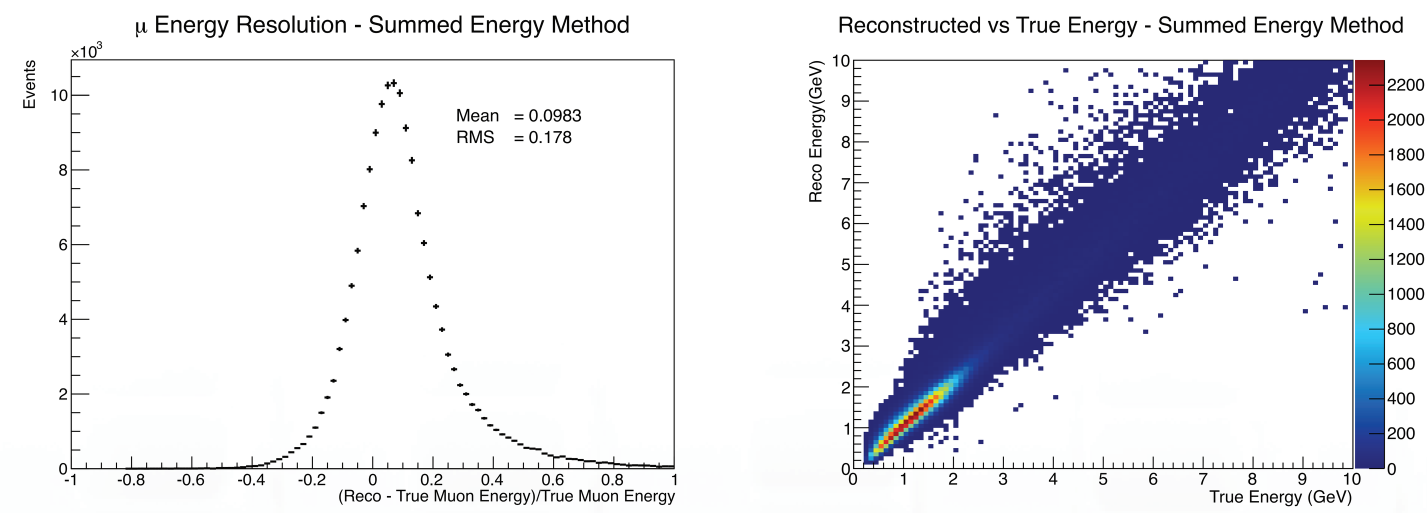

Figure 6: On the left: the muon resolution for this method (RMS). On the right: the energy reconstructed using this method vs the muon's true energy for known muons from ν_μ interactions. From the NuMI beam Monte Carlo for the NOvA far detector.

Multiple Scattering Method

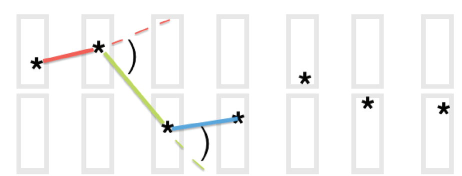

Diagram: Particle scattering in the detector

Muons undergo multiple scattering while traveling through the detector. These **small scattering angles** are related to the muon's momentum by[2]:

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \frac{x}{X_0}\right]$$

x - Distance traveled
X_0 - Radiation length
βc - Particle's velocity
p - Particle's momentum
θ_0 - Scattering angle standard deviation about zero

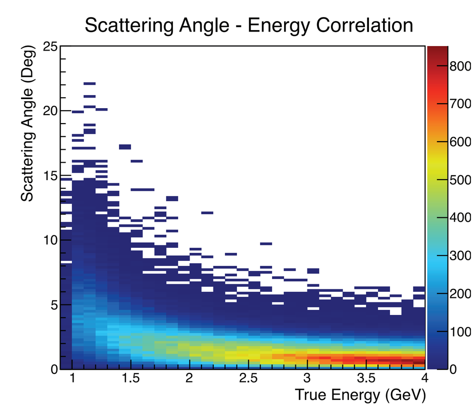

Figure 7: Correlation between scattering angle at two points in the track and muon true energy. Muons from the NuMI beam Monte Carlo for the NOvA far detector.

These angles can be measured along the muon track to be used as a handle on the muon's energy.

The scattering angle information is combined in neural networks and used to estimate the energy.

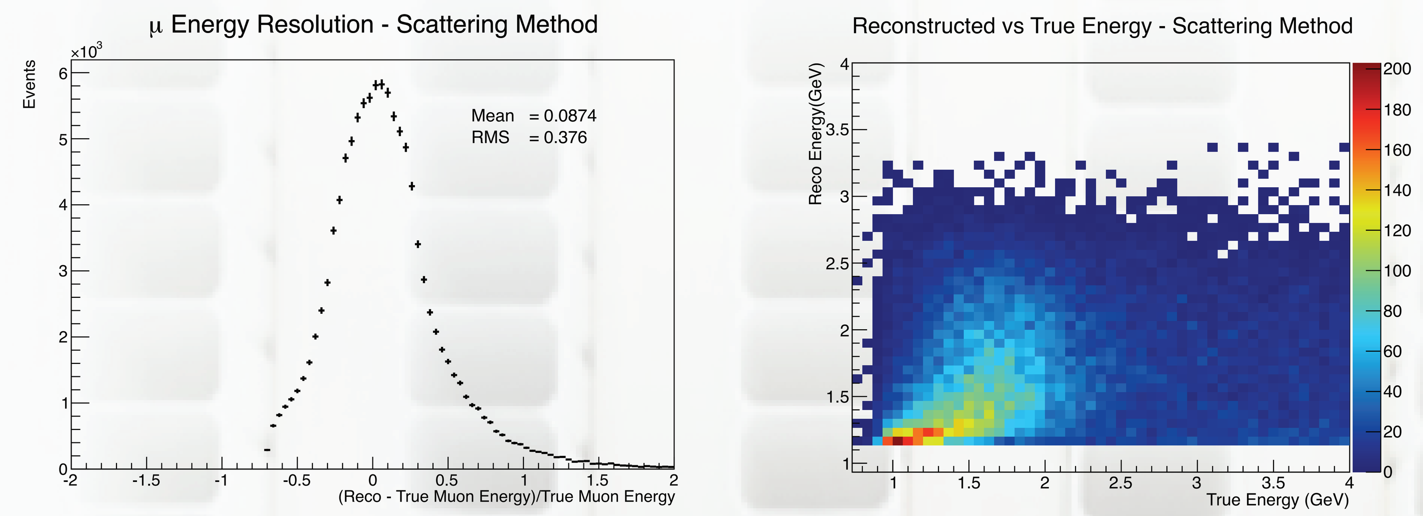

Figure 8: On the left: the muon resolution for this method (RMS). On the right: the energy reconstructed using this method vs the muon's true energy for known muons from ν_μ interactions. From the NuMI beam Monte Carlo for the NOvA far detector.

Conclusions

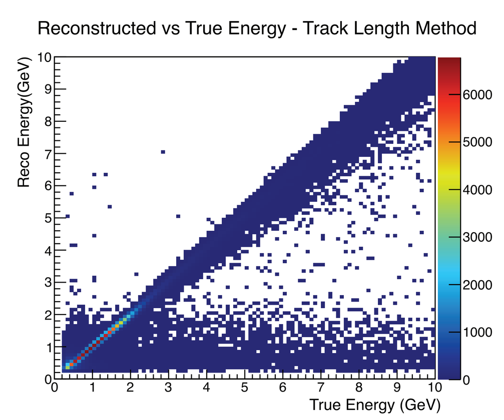

Figure 9: Analogous to figure 5 (right) for particles reconstructed and identified as muons from ν_μ interactions instead of known muons.

Muon energy reconstruction at NOνA is done using track length for contained events and is still being optimized for escaping muons.

Combined approaches will ultimately be used for escaping muons. Other parameters, like energy deposition per unit length (dE/dx), can also be used as handles on the energy.

The resolutions presented are calculated using known, well-reconstructed muons in the detector. Figure 9 shows reconstruction for all particles identified as muons by NOνA's particle identification algorithms. Ultimately, energy resolution is impacted by **track reconstruction**, **particle identification** and **energy reconstruction**, all of which are constantly being optimized by the analysis groups at NOνA.

References

[1] ***The NOvA Technical Design Report*** - NOvA Collaboration (Ayres, D.S. et al.) FERMILAB-DESIGN-2007-01

[2] ***Momentum measurement by the Multiple Coulomb Scattering method in the OPERA lead emulsion target*** - The OPERA Collaboration arXiv:1106.6211v1 [physics.ins-det]