Muon Energy Reconstruction at NOvA

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Sources of muons in NOvA

Munus from Neutrino Interactions. NOvA has enough sensitivity to make sin^2 2θ: precision measurements through the ν_e disappearance analysis:

\[ P(ν_e → ν_μ) \approx 1 - sin^2 2θ \sin^2 (L/2E/L) \]

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

Figure 1. Muon energy loss in NOvA fibres as a function of distance traveled. From the NOvA Technical Design Report.

Muon from Cosmic Ray Interactions. NOvA expects a few neutrino interactions per day and a cosmic muon rate of ~120 Hz in the far detector. In the 10 μs time window around neutrino beam spills, the rate of cosmic muons to interactions is ~200 Hz.

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

Muon behaviour in the NOvA 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 as 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.

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_e interactions in the far detector with energies up to 2 GeV from the oscillation peak.

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

Because the best handles on μ energies depend on their containment, NOvA will use composite approaches as a means of energy reconstruction for uncontained events.

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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 profile are done in three sections to best describe the correlation.

This reconstruction method is used for contained events.

Multiple Scattering Method

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

\[ \theta_s = \frac{2.5}{E} \left( \sqrt{1 + 0.357 E_μ} - 1 \right) \]

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.

Conclusions

Muon energy reconstruction at NOvA 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 NOvA’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 NOvA.

Deposited Energy Method

As the muon travels through the detector it deposits all its energy. Adding the deposited energy in 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.

References


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*Figures:*

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

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 NOvA Technical Design Report.

Figure 3: The scatterplot of the Reco Energy vs True Energy for contained events. From the NOvA Technical Design Report.

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

Figure 5: On the left: the energy resolution for the method BM3. On the right: the energy reconstruction using this method in the muons' true energy for known muons from neutrino interactions. From the Neutrino Mass Energy Correlation: From the Neutrino Mass Energy Correlation. From the NOvA Technical Design Report.


Figure 7: Correlation between scattering angle at two points in the track and muon true energy.

Figure 8: On the left: the muon resolution for this method BM1. On the right: the energy reconstruction using this method in the muons' true energy for known muons from neutrino interactions. From the Neutrino Mass Energy Correlation: From the Neutrino Mass Energy Correlation. From the NOvA Technical Design Report.