# Muon Removed Charged Current Events at NOνA

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## The NOνA Experiment

- NOνA is a long-baseline neutrino oscillation experiment.
- It consists of two detectors: Far Detector (FD) near International Falls, Minnesota and Near Detector (ND) at FNAL, Illinois
- The FD is designed to be 14kt and the ND, 0.3 kt.
- The ND will be used to measure the beam spectrum and composition before oscillation.
- We will use NuMI beam from FNAL, mainly $\nu_\mu$ in composition
- NOνA is located off-axis by 14mrad from the NuMI to maximize oscillation probability
- It will enable the study of $\nu_\mu \rightarrow \nu_e$ oscillation ( $\nu_e$ appearance) and also $\nu_\mu \rightarrow \nu_\mu$ oscillation ( $\nu_\mu$ disappearance)
- The detectors are composed of PVC modules that consist of tubular cells filled with liquid scintillator.
- Alternate modules are orthogonal in orientation to enable 3-D reconstruction.
- A loop of optical fiber runs through every cell
- Each fiber is read out by an Avalanche Photo-Diode (APD)

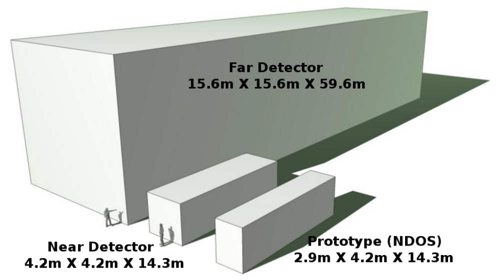
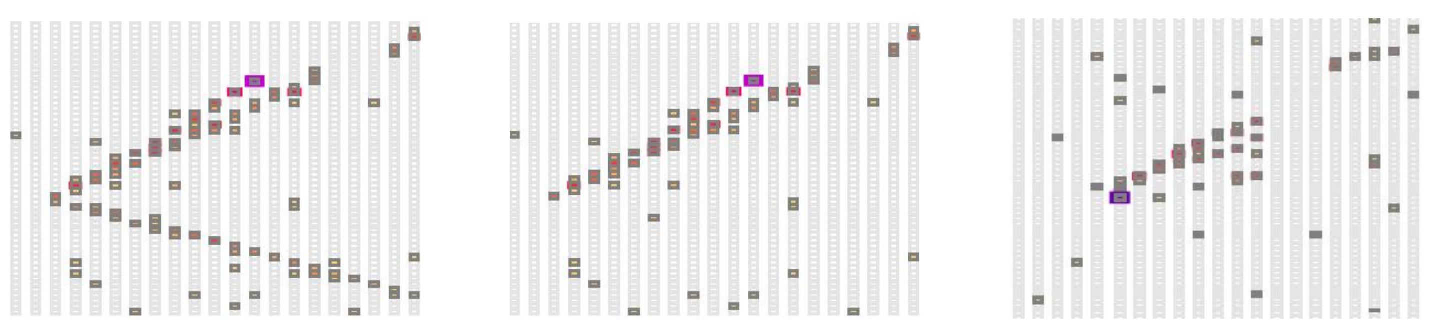




**Figure:** Top figure indicates the positions of the NOνA detectors while the bottom shows their relative sizes. NDOS was a prototype built to test detector systems.

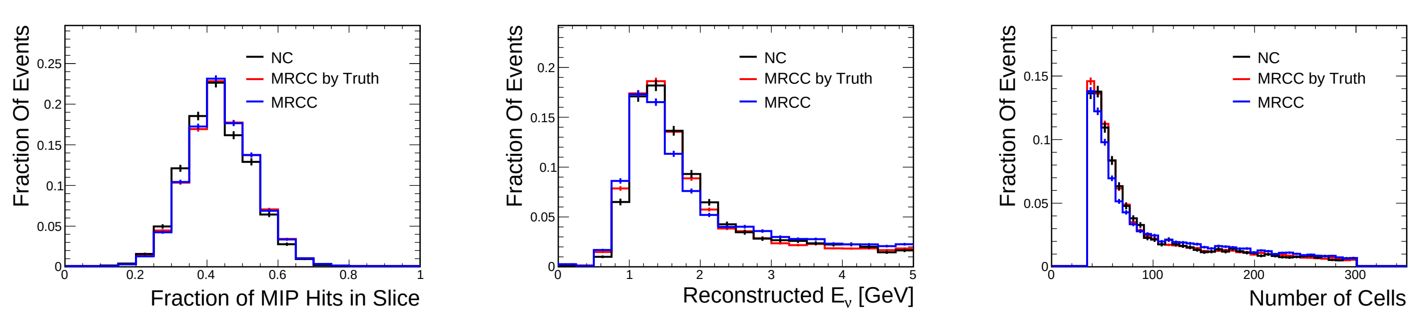
## Muon Removed Charged Current (MRCC) Events

- The main background to $\nu_e$ appearance search are neutral current (NC) events
- Showers in the hadronic recoil of NC events can appear like electromagnetic showers that mark an electron
- Muon Removed Charge Current events are $\nu_\mu$ CC events where the outgoing muon is removed. The leftover hadronic shower imitates the NC events



(a) $\nu_\mu$ CC (b) MRCC (c) NC

Figure: The top row shows the event display of a simulated $\nu_\mu$ CC interaction, its muon removed version and a simulated NC interaction. The figures at the bottom show the distributions of MRCC and NC events for various parameters that serve as inputs to the $\nu_e$ CC PID. Muon Removed by Truth refers to $\nu_\mu$ CC events where the muon energy has been removed by truth. These distributions indicate that MRCC events imitate NC events reasonably well.




## Using MRCC To Estimate NC Background

- MRCC is a data-driven way to estimate NC background using ND data
- We will produce MRCC samples for data and simulation, $MRCC_{Data}$ and $MRCC_{Sim}$
- NC background can be estimated in $i$th bin of energy as : $(NC_{Est})_i = \left(\frac{MRCC_{Data}}{MRCC_{Sim}}\right)_i (NC_{Sim})_i$

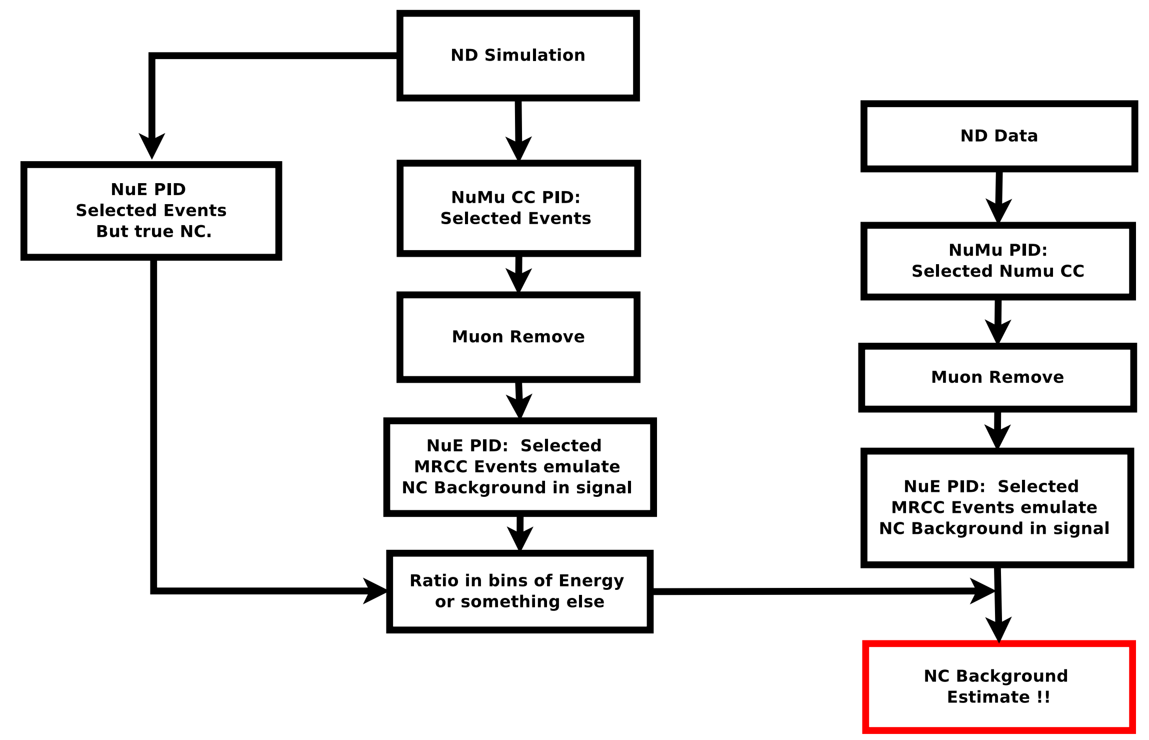



**Figure:** The figure shows the flow of MRCC analysis for prediction of NC background rate for $\nu_e$ appearance search.

## MRCC Event Construction

- Events that pass $\nu_\mu$ CC selection criteria are used in the MRCC analysis
- The track identified as muon is chosen for removal
- Close to the interaction vertex, where hadronic activity is significant, hadronic energy may overlap with muon track; this region is called the vertex region
- Assuming muon to be a minimum ionizing particle (MIP), we determine the fraction of energy, *muonWeight*, in a cell that comes from the muon
- *muonWeight* outside the vertex region is always assumed to be 1.
- For the hits on the muon track, the pulse height, measured in ADC counts is scaled down by muon weight, ie ADC after muon removal,

$$\text{ADC mrcc} = \text{ADC Original} - \text{muonWeight} \times \text{ADC Original}$$

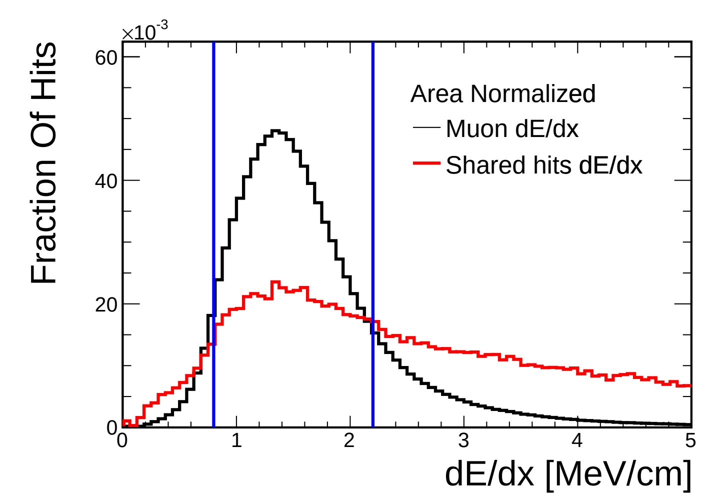



**Figure:** The figure shows the $dE/dx$ in MeV/cm for all the planes on the muon track. Planes are divided into two groups– in black are the planes that had energy only from the muon and in red are the planes that the muon shared with hadrons. The blue vertical bars indicate the allowed $dE/dx$ range for a muon hit. If a hit on the muon track is close to the vertex and has greater than the allowed $dE/dx$ , only energy deposition consistent with MIP is removed from the hit. This range correctly labels $\sim$ 75% of contaminated hits while wrongly labeling $\sim$ 25% of pure muon hits as having hadronic contribution.

## Determination Of Region Of Hadronic Contamination

- We use $dE/dx$ information to define the *vertex region*, the region on the muon track that has significant hadronic energy contribution
- We average the $dE/dx$ value over three consecutive planes in a given detector view on the muon track. If three consecutive average $dE/dx$ values fall below the MIP upper bound (2.2 MeV/cm), the vertex region is assumed to have ended
- Determination of vertex region is done independently in the two detector views

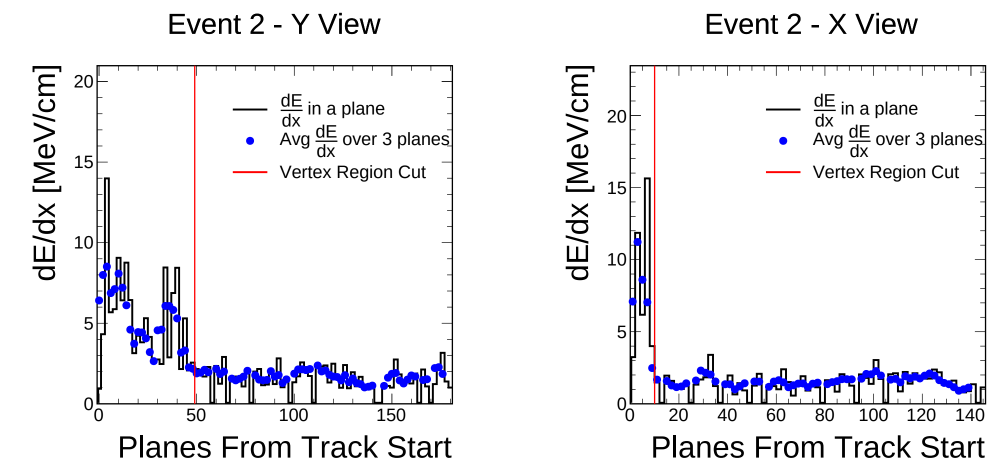



**Figure:** The $dE/dx$ profile of a muon in a typical simulated $\nu_\mu$ CC event for the x and y detector views. The blue markers are the averages of $dE/dx$ values over three consecutive planes. The vertical red bar indicates where the end of the vertex region was found to be using the above procedure.

## Performance of Muon Removal

- If muon removal procedure works perfectly, all of the muon energy and none of the hadronic energy in the event would be removed
- We use the following variables to assess the performance of muon removal:
  - Fraction of muon energy remaining in event after removal: $\frac{\sum_{\mu Hits}\left(E_\mu - E_{tot} \times \frac{\text{ADC removed}}{\text{ADC Original}}\right)}{\text{Total } E_\mu}$
  - Fraction of hadronic energy removed from event: $\frac{\sum_{hadHits}\left(E_{had} - E_{tot} \times \frac{\text{ADC mrcc}}{\text{ADC Original}}\right)}{\text{Total } E_{had}}$

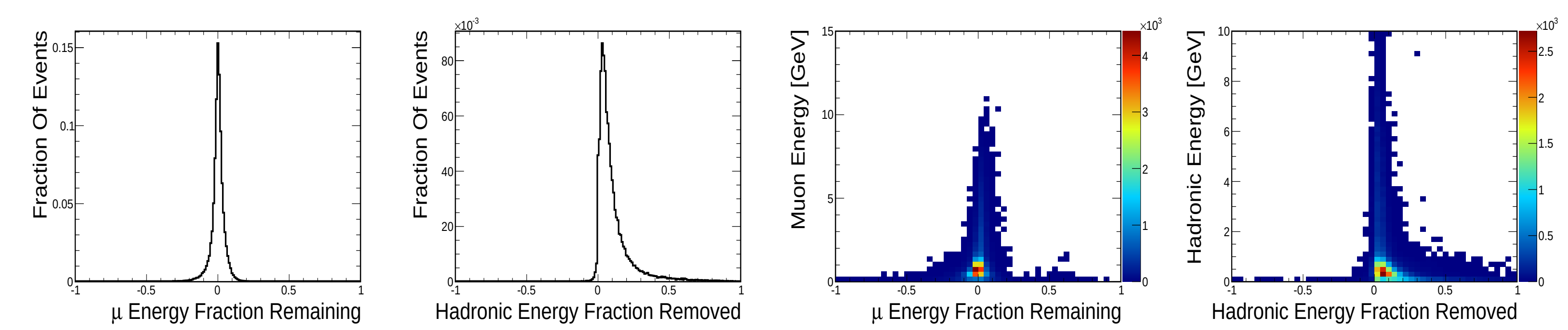



**Figure:** The strong peaks of the two plots on the left indicate that muon removal is working well. The two plots on the right show that most of the tail arises at low energies where contributions from muon and hadron become difficult to separate.

## Summary

The MRCC method is a data driven way of predicting NC background to the $\nu_e$ analysis. It is performing well and is ready to be exercised on the NuMI data.



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