Cosmic Muon Induced EM Showers in NO\(\nu\)A

Nitin Yadav, Hongue Duyang, Sanjib Mishra, Bipul Bhuyan, Peter Shanahan

Abstract Being a \(\nu_e\) appearance experiment, NO\(\nu\)A finds signal \(\nu_e\) events by detecting electrons in the final state of (\(\nu_e\)-CC) interaction. This requires correct modeling and reconstruction of electrons. The biggest background to \(\nu_e\)-CC signal events is from \(\nu_\mu\)-NC events where \(\pi^0\) from hadronic showers decay into energetic photons which can fake electron-induced electromagnetic (EM) showers. To reduce the background, the particle identification algorithm should be able to correctly identify an EM shower as either from an electrons or from a \(\pi^0\). Intrinsic beam \(\nu_e\) events and \(\nu_\mu\)-CC events where muon track is very short, also contribute to the background. Cosmic muons produce EM showers through interaction with detector media or via decay into electrons. These showers, once being isolated, can provide a test sample of pure EM showers. EM shower modelling and reconstruction efficiency in the NO\(\nu\)A detectors can be better understood and quantified using such a sample.

1 Introduction

In \(\nu_e\) appearance mode, the signal in the NO\(\nu\)A detector is an EM shower induced by \(\nu_e\)-CC interaction. It is important to use EM showers from data to test \(\nu_e\) identification algorithms and calibrations, especially in absence of test beam data. Cosmic ray muon induced EM showers provide such an abundant data sample. Cosmic ray muons induce EM showers by three different means: energetic muons undergoing bremsstrahlung radiation (Brem), muons decay in flight (DiF) and muons stopping in the detectors and decaying into Michel electrons. Bremsstrahlung and DiF, once

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isolated and extracted, provide abundant EM shower samples at few GeV energy region which overlaps with energy of beam $\nu_\mu$. Having identified the EM shower, a cosmic muon-removal (cosmic MR) algorithm is developed to remove the muon-hits from the shower region. Typically a muon deposits 1.5 MeV of energy per unit length (MIP) \cite{1} in the detector. In case of occurrence of the shower, energy deposition increases. Shower algorithm finds the shower by looking for increased energy deposition per plane (MIP plane) \footnote{Energy deposited in a single plane in the detector; more details are given in section 2} along the muon track. Shower samples are then reconstructed and the performance of the particle identification algorithms (PID) are studied. Data and MC comparison is performed with reconstructed shower variables. We introduce a $\nu_e$ reweighting technique to correct the differences between cosmic-induced and beam-induced EM showers; the reweighting makes the cosmic EM showers look more like "$\nu_e$-events" to benchmark the particle identification algorithm at NOvA.

Fig. 1 shows the various topologies of events at NOvA. $\nu_e$-CC exhibits itself as EM shower in the detector. Brem shower resembles $\nu_e$-CC shower topology as both are EM showers. The figure shows the $\nu_\mu$-CC (top), $\nu_e$-CC (middle) and neutral current (bottom) topologies; the NC is the main source of background to the $\nu_e$-CC signal \cite{2}.

Fig. 1 Event topology of $\nu_\mu$-CC (top), $\nu_e$-CC (middle) and $\nu_e$-NC (bottom) interactions in NOvA. The top and bottom topologies are for the background events and the middle is the topology for signal events, which is an EM shower.
2 Shower Finding and Extraction

Muon deposits a long minimum ionizing particle (MIP) track in the NOvA detector. In case of EM shower, the energy deposition in cells increases along the track as in figure 2. We have developed shower selection criteria based on energy deposition information and define a shower region. Cosmic MR algorithm determines the beginning of shower region if the MIP is found to be higher than the $2\times$MIP for five consecutive planes. End of shower region is determined if the MIP is found to be between $0.5\times$MIP and $1.5\times$MIP. Once the shower region is determined, the algorithm removes the muon hits on the track from outside and inside the shower region. Fig. 2 shows an example of DiF and Brem event.

![Fig. 2 Energy deposition distribution of cosmic induced EM shower in the NOvA detector in X-Z and Y-Z views. The left figures shows a DiF muon (blue) and the electron from decay (red). The right figures show a muon with a Brem shower. Shown from top to bottom, the reconstructed hit energy in XZ view, YZ view, energy deposition over planes, and number of cell hit with energy greater than 0.5 MeV.](image)

2.1 Muon Removal

A Muon-Remove program has been developed by NOvA as a tool to simulate $\nu_\mu$-NC background using $\nu_\mu$-CC data [3]. However, this program is designed to remove muons in beam $\nu_\mu$-CC events and cannot be applied directly to cosmic events. We developed a cosmic Muon-Removal technique (Cosmic MR). Cosmic MR algorithm
first looks at the cosmic ray muon track and determines if there is a shower on the track and delineates the shower region, as described above. Once the shower region is determined, the algorithm removes the muon hits from the track. In the case of DiF muon the task is relatively simple. With a shower region defined by the shower-finding algorithm, it just removes all hits outside that region and what left will be pure electron hits. In the case of bremsstrahlung showers one additional problem is that we have a muon track inside the EM shower region. Therefore the muon-removal algorithm should remove hits that belong to muon track with energy of a MIP in the shower region. As an example, muon hits along the track are removed from inside and outside the shower region by cosmic MR algorithm as shown in the Fig. 3. Left over hits are EM shower hits. Right(left) figure shows the muon track before(after) muon removal algorithm.

![Fig. 3](image-url) Example of cosmic Muon-Removal. The left plots show a muon with a bremsstrahlung shower. The right plots show the bremsstrahlung shower after Muon Remove. Hits outside of shower regions are all removed. In the shower region, a MIP is removed. From top to bottom plots are the 2D energy deposition in the XZ view of the detector; in the YZ view of the detector; sum of ADC on each plane; number of cell hit on each Plane. X axis is plane ID number.

### 2.2 Data and MC comparison

We found 0.3% of cosmic muon tracks produce bremsstrahlung shower with energy $> 0.5$ GeV. The rate for DiF is much (~50) lower. Reconstructed bremsstrahlung shower variables are plotted and compared between data and MC to check the simulations and the shower modeling at NO$
u$A. MC samples are generated using CRY...
generator with real detector conditions at NOvA. Data and MC comparison of shower variables are shown in the Fig. 4 and 5. Excellent agreement between data and MC is seen indicating that the EM simulation agrees with measurement within $\pm 5\%$ in NOvA.

Fig. 4 Data and MC comparison of the energy (left) and angular (right) distributions of the brems shower. We select showers such that $E_{\text{shower}} > 0.5$ GeV and muon track such that $\cos \theta > 0.5$

Fig. 5 Data and MC comparison of the shower-width (left) and shower-planes (right) distributions.

2.3 PID Efficiency

PID efficiency are calculated as functions of vertex position $x$ and $y$ to check calibration effects such as attenuation and alignment. The efficiency is defined as the number of showers passed PID cuts ($\text{LID} > 0.7$ and $\text{LEM} > 0.6$) divided by all show-

\footnote{Out of several shower variables only four are shown in the figures 4 and 5.}
ers selected. Fig. 6 and 7 show the PID\(^3\) efficiency across the x and y direction of the detector. Both data and MC efficiencies are flat across the detector and the difference is within 5%.

\[\text{Fig. 6 LID efficiency LID} > 0.7 \text{ as function of vertex position x, y. The overall efficiency is flat across the detector with data/MC difference within 5%}.\]

\[\text{Fig. 7 LEM efficiency LEM} > 0.6 \text{ as function of vertex position x, y. The overall efficiency is flat across the detector with data/MC difference within \sim 5\%}.\]

\section*{3 $\nu_e$ re-weight Method}

The energy and angle distributions of the cosmic-events are vastly different from those of $\nu_e$-induced electrons. The $\nu_e$ re-weight technique is developed to make the cosmic bremsstrahlung look more like $\nu_e$-CC event. The difference between cosmic induced EM showers and beam- $\nu_e$ energy mostly comes from shower energy and

\(^3\) For both PID: LID and LEM.
angle with respect to beam direction. A 2D matrix is constructed by taking the bin by bin ratio of bremsstrahlung shower sample energy and angle (cosθ) with that of corresponding νe shower sample. The 2D matrix is used to re-weight energy and angle (cosθ) of cosmic EM showers to beam νe events. Fig. 8 shows the energy and angle of bremsstrahlung shower before and after re-weighting. The re-weighted sample is further used verifying the PIDs at NOvA as described in the next subsection.

Fig. 8  Left and right figure shows bremsstrahlung shower energy and angular distribution in comparison with νe shower before and after re-weighting respectively

3.1 Benchmarking PID

The extracted νe-reweighted shower sample is used as data-driven methods to benchmark the PID at NOvA. NOvA has currently two main PID’s algorithms: LID (Longitudinal ID) and LEM (Library Enabling Matching). LID takes longitudinal and transverse dE/dx information of shower to make likelihoods which are fed into artificial neural network (ANN) whereas LEM [5] algorithm compares input events to a large Monte Carlo library events to find the most similar examples. LEM library events are generated using the usual NOvA Monte Carlo chain with realistic
beam flux and cross-sections. As in Fig. 9 and 10, after re-weighting most of the bremsstrahlung showers are identified as signal events by both PID algorithms.

![Fig. 9](image1.png)  
**Fig. 9** Left figure shows the LID input, and right figure shows the LEM output before re-weighting.

![Fig. 10](image2.png)  
**Fig. 10** Left figure shows the LID input, and right figure shows the LEM output after re-weighting.

### 4 Conclusion

We use cosmic Brem shower, with MR algorithm, to find and isolate EM showers from cosmic data and MC. Data and MC comparison, using bremsstrahlung sample, shows good agreement in energy, angle, and longitudinal and transverse topologies of the shower. The $\nu_e$-reweight method makes the EM showers look more like $\nu_e$ showers. The re-weighted sample of EM showers is used as data-driven method to benchmark various PIDs at NO$\nu$A experiment. Using the EM showers, we have found that overall simulations and PIDs are in good shape in NO$\nu$A.
References