PROCEEDINGS OF SCIENCE

Cosmic Muon induced EM Showers in NOνA Detector

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The NuMI Off-Axis ν_e Appearance (NOνA) experiment is a ν_e appearance neutrino oscillation experiment at Fermilab. It identifies the ν_e signal from the electromagnetic (EM) showers induced by the electrons in the final state of neutrino interactions. Cosmic muon induced EM showers, dominated by bremsstrahlung, are abundant in NOvA far detector. We use the Cosmic Muon-Removal technique to get pure EM shower sample from bremsstrahlung muons in data. We also use Cosmic muon decay in flight EM showers which are highly pure EM showers.The large Cosmic-EM sample can be used, as data driven method, to characterize the EM shower signature and provides valuable checks of the simulation, reconstruction, particle identification algorithm, and calibration across the NOνA detector.

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1. Introduction

NOνA is a long baseling neutrino oscillation experiment based at Fermilab. Its main goal is to determine neutrino mass hierarchy and CP-violation in neutrino sector [1]. It has two detectors. Near detector is 0.3 kiloton situated 1 km downstream NuMI beamline and 330 feet underground at Fermilab. Far detector which is 14 kiloton and situted on surface at Ash River, is located 810 km downstream and 14.6 mrad off the Neutrinos at the Main Injector (NuMI) beamline [2]. Both the detectors are functionally identical and constructed of vertical and horizontal planes of PVC extruded cells of size 4×6 cm in dimension. The cells are filled with liquid scintillator.

NOνA can measure oscillation in $\nu_\mu \to \nu_\mu$ disappearance mode and $\nu_\mu \to \nu_e$ appearance mode. In appearance mode ν_e produces an electron induced EM shower through ν_e-CC interaction in far detector [3]. It is requisited to have proper modelling, reconstruction and particle identification (PID) for ν_e induced EM shower and we make use of cosmic induced EM shower to validate it. Callibration effects can also be controlled using cosmic EM shower.

NOνA far detector has a cosmic rate of $\sim$150 kHz. Cosmic muon induces EM showers (in sub-GeV range) through bremsstrahlung (51 Hz) or by decay in flight (DiF) electron (0.1 Hz) in the far detector. The EM shower region on cosmic muon track are identified and separated out. A muon removal algorithm is developed to removes the muon hits in the bremsstrahlung region, where as in case of DiF muon removal from shower region is not required. The EM shower sample genereated from cosmic muon can be used as data driven method to benchmark shower modelling, reconstution and PID at NOνA. An example of bremsstrahlung EM shower is shown in Fig 1. In the figure is shown the event display of the NOνA far detector. The top view is X-Z view and side view is Y-Z view and color coding represents the ADC value of hits registered. Left event display in shows an event of cosmic muon undergoing the process of bremsstrahlung. Right event display shows the same event with cosmic muon hits removed by using Muon-Removal algorithm. Next section descibes the shower extraction in more details.

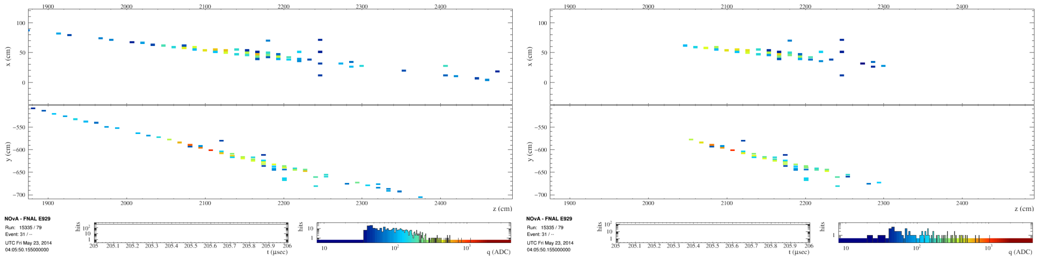

Figure 1: Bremsstrahlung shower from cosmic moun before (left) and after (right) muon removal.

2. Cosmic EM Shower Extraction

EM Shower extraction process begins by selecting a candidate muon track in a slice. A muon track should be long enough to get a chance to generate bremsstrahlung showers and therefore we require the number of planes that the muon track traverses to be greater than 30. The muon track is also required to be in the horizontal direction (as close to beam direction) by requirig cosθ >0.5, where θ is the angle of the muon track with respect to the beam axis (Z-axis). Thereafter the track candidate is scanned for shower region. A shower region is determined by energy deposition per plane (dE/dx) information downstream of the track. In the event of EM shower, energy deposition per unit plane increases in comparison to muon particle as muon is a minimum ionising particle (MIP). If on the track, five consecutive planes are found to have energy deposition more than 2*MIP, it is denoted as starting of shower. Given starting of shower, end of shower is found if five consecutive planes downstream are having energy deposition between 0.5*MIP and 1.5*MIP. After shower region is found, muon hits inside the shower region and outside of it are removed by a modified muon removal algorithm for charged current events [4]. The muon removal algorithm removes a mip of hit in the shower region in each plane and removes all the hits elewhere in the slice out of the shower region.

3. Cosmic EM Shower vs ν_e-CC Shower

Selected cosmic EM shower sample is put to the standard reconstruction chain present at NOνA for ν_e-CC shower. Reconstructed energy and angle are compared for both in Fig 2. Main difference between beam ν_e and cosmic EM sample arises as beam ν_e energy peaks at 2 GeV and its direction is along the NuMI beam line direction whereas cosmic EM shower is mostly coming from zenith as shown in Fig 2. We reweight the cosmic EM sample according to beam ν_e in energy and angle to resemble the samples as in Fig 3.

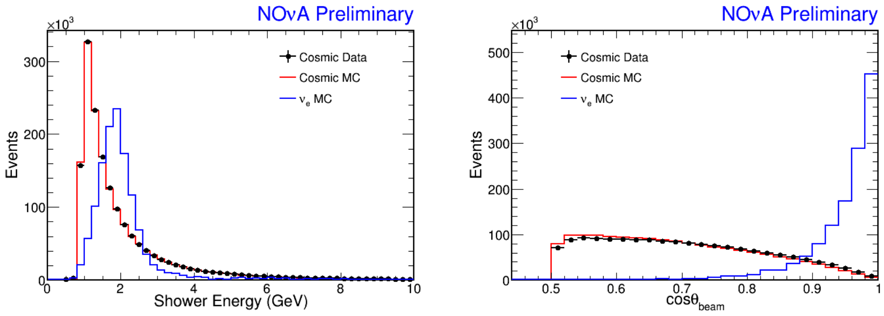

Figure 2: Cosmic EM shower and ν_e shower energy (left) and angle comparison (right).

4. PID Benchamarking and Selection Efficiencies

For first analysis [5] NOνA used the likelihood based ν_e identifier (LID). LID uses the dE/dx information of the charged particle to compute the likelioods that the candidate particle is an electron [6]. For second analysis, NOνA uses a Convolution Neural network [7] based PID which identifies neutrino interactions based on its topology. Most of the cosmic EM showers are selected as ν_e showers by both PIDs as shown in Fig 4. Selection efficiencies for LID (LID>0.7) as a function of positions in detecotor are shown in Fig 5. Vertex efficiency are pretty uniform across the detector and agreement between data and MC is well within 5%. The extent to which the efficiencies from data and MC do not agree motivates a systematic error on the predicted electron neutrino signal efficiency for the first electron neutrino appearance analysis.

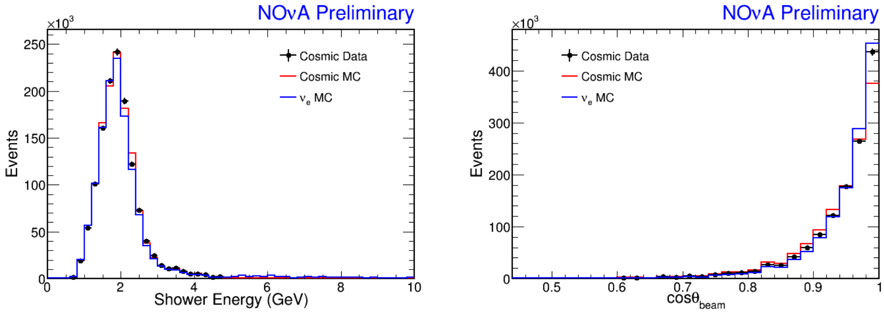

Figure 3: Cosmic EM shower vs ν_e shower after reweigting

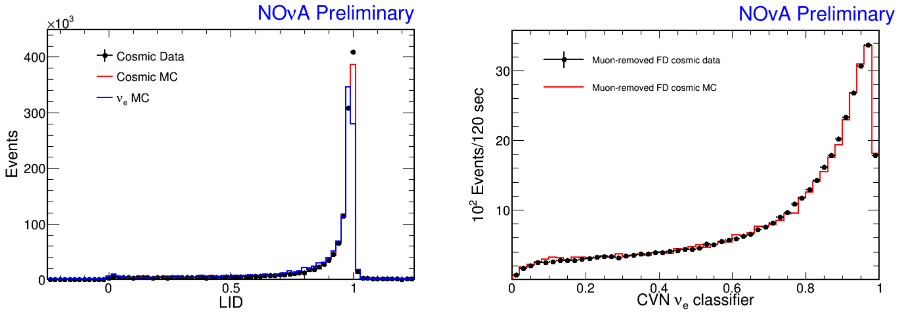

Figure 4: LID and CVN classifier result on cosmic EM sample

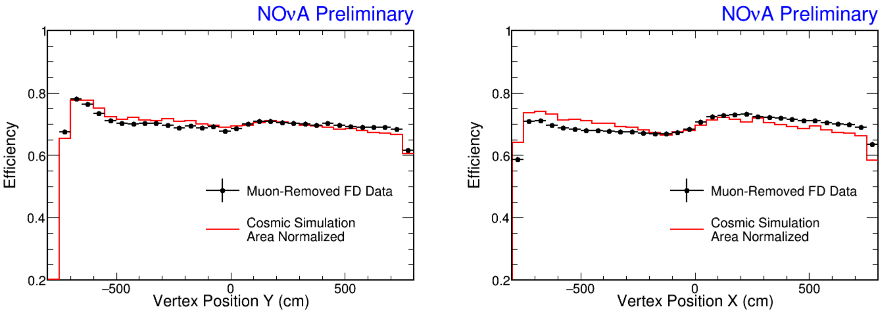

Figure 5: Vertex selection efficiency as a function of X and Y

5. Summary

We isolate cosmic muon EM showers from cosmic muon in data and MC in the NOνA far detector. A comparison using first analysis data and MC dataset shows consistent distributions, validating the EM shower modeling and reconstruction. PIDs are benchmarked by cosmic EM shower as data driven methods. The PID efficiencies as functions of vertex position have good data/MC agreement indicating the calibration effects as well controlled.

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