Efficiency and Purity Studies for Charged Pion Semi-Inclusive Muon Neutrino Charged Current Cross-Section in NOvA

Jyoti Tripathi

Panjab University, India

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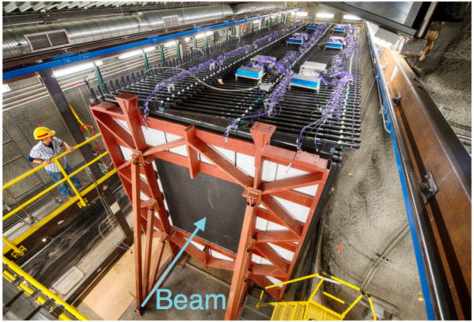
- NOvA is a long baseline experiment designed to study the neutrino oscillations.
    - The NuMI (Neutrinos at the Main Injector) is the neutrino source to the near and far detector.
    - The near and far detectors, are highly active liquid scintillators, placed 810 km apart.

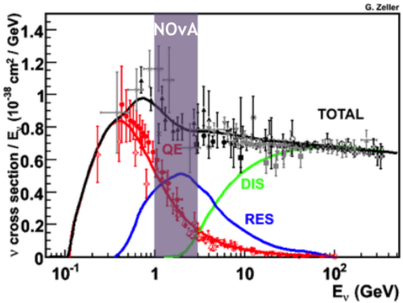
- The detectors are placed 14 mrad west of the NuMI beamline center
- The neutrino beam observed by the detectors is sharply peaked at around 2 GeV
- NOvA is sensitive to different neutrino-nucleus interactions that could help
    - Constrain the cross section systematics.
    - Understanding the neutrino-nucleus interactions.



NOvA Near Detector

- The NOvA Near Detector
  - 1 km from neutrino production target, having intense rate of neutrino interactions.
  - Provides a great oppurtunity to study neutrino-nucleus interactions.

- NOvA with a narrow band beam peaked at 2 GeV, sits in the middle of the energy regime of the T2K, MicroBooNE and MINERvA.
- It can help understand the transition from the Δ dominated to the DIS pion production.



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys., 2012

- Pion Production in ν_μ CC intercations.

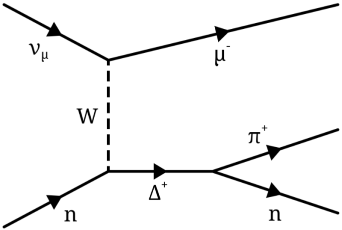
  $\nu_\mu + N \rightarrow \mu^{\mp} + \pi^{\pm} + X$

  - Source of systematic uncertainty in neutrino oscillation parameter measurement.
  - A single charged pion could make the event mimic the CCQE topology.
    Reinteraction $\longrightarrow \pi^+$ absorbed in nucleus $\longrightarrow$ QE like.
  - Important for correct estimation of the incoming neutrino energy.

- Single Charged Pion cross section measurements on carbon has been reported by the MiniBooNE (doi:10.1063/1.3274185) and K2K SciBar detector (arXiv:0805.0186), calculated using the ratio of $CC1\pi^+$ to CCQE.

- MINERvA has also reported $CC1\pi^{\pm}$ cross section measurements (arXiv:1406.6415) as a function of charged pion angle and kinetic energy.

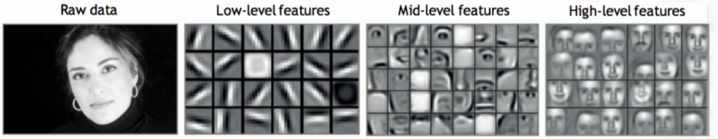
- A ν_μ CC interaction having a muon and a well reconstructed single charged pion in the final state.
  - 250 MeV $<$ True Kinetic Energy $<$ 900 MeV.
  - The interaction vertex should be contained in the fiducial volume.
- Using the Near Detector MC simulated data for studying the $CC1\pi^+$ events



Resonant Production: $CC1\pi^+$

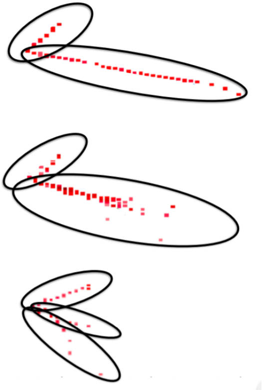
- Pre-Selections
  - Quality, containment and fiducial applied prior to the main selection algorithm.
  - Removes the background events unrelated to the NuMI beam as well as trims the beam related background.

- Traditional particle identification (PID) methods require some previous reconstruction.
- The features (e.g. track length, energy deposition) are based on monte carlo simulation or real data.
- PIDs developed using Convolutional Neural Network (CNNs) extract features associated with an interaction, rather than selecting on a set of features a priori.



- The network learns based on the input given and look at many features apart from those based in our physics assumptions.

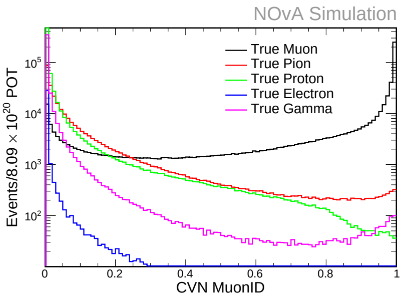
- NOvA uses CVN (convolutional visual network) trained on topological features of invidual particle tracks (prongs) seen in the detector.
- Use event images (event + particle track) to train CVNs to identify neutrino interactions.
- Trained using the caffe framework (http://caffe.berkeleyvision.org/)

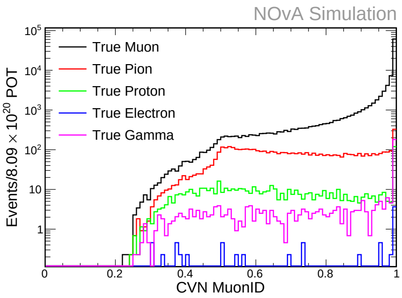


- It assigns 5 different score to each prong in the event under a specific particle hypothesis. The sum of the scores for each prong is normalized to 1

  Scores $\Longrightarrow$ PionID, MuonID, ProtonID, ElectronID, PhotonID.

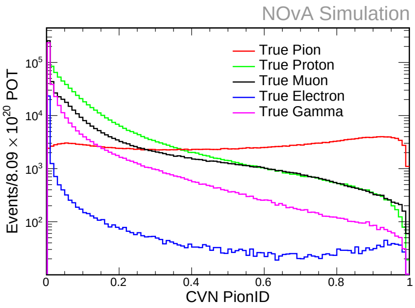
- Performance of the Muon CVNID
  - For all the true particle prongs.
  - For all those true particle prongs that are most likely to be the muons as per the Muon CVNID.

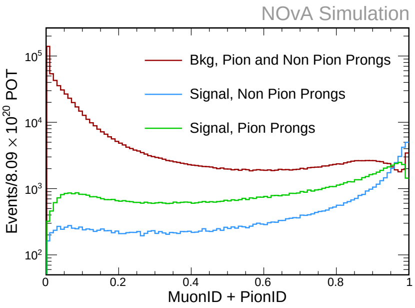




- Among all the prongs identified as the muon, the one with the highest muon score in the event is selected as the best muon.

- The second non muon prong is considered as the potential pion candidate.



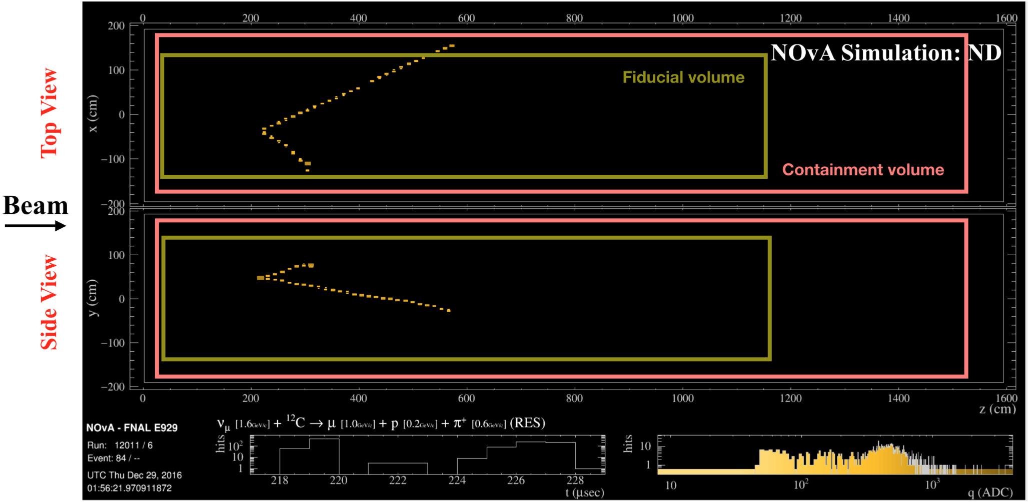


- Pion selection is based on the optimized sum of the pion and the muon score since the pions and the muons look alike a lot.

- Final event selection
  - The best muon prong is selected as the muon .
  - The second non muon prong having the sum of the muon and the pion score > 0.8 is selected as the pion.

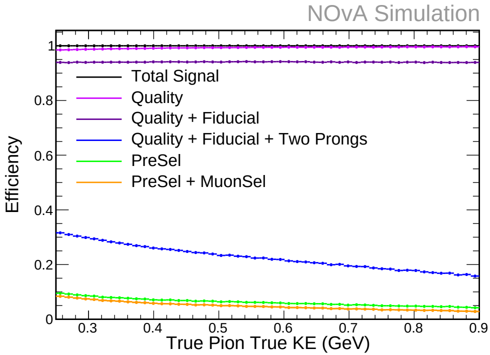
Selection	Selected	Efficiency (%)	Purity (%)	Background			
				CC Resonance (%)	CC DIS (%)	NC (%)	Coherent (%)
Total	7.16e+07	100	2.7	19.6	64	9.5	0.58
Preselections	5.27e+05	6.9	27.25	36	16.4	16.9	1.5
Muon Selection	3.56e+05	5.6	32.48	48.4	14.1	2.1	1.27
Pion Selection	43,927	1.5	70.3	15.7	10.78	1.2	1.9

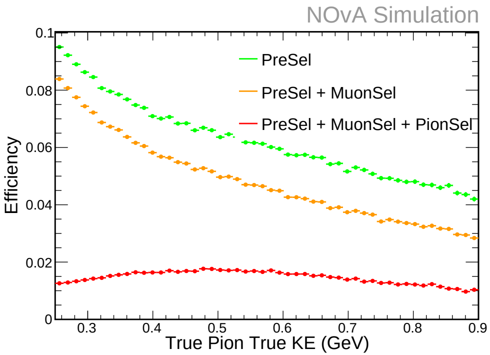
- The selected signal has 72.78% events from resonance, 7.5% from coherent and 19.6% from DIS repectively.



Simulation of a NOvA Near Detector Event

- Efficiency $= \frac{\text{Number of Selected Signal Events}}{\text{Total number of Signal Events}}$

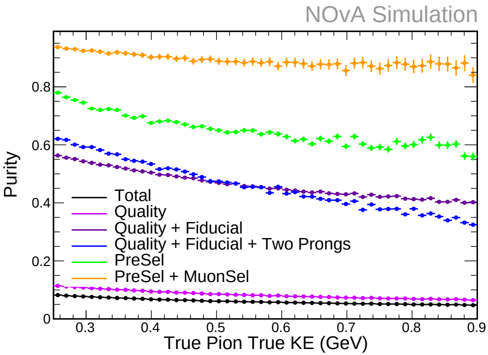


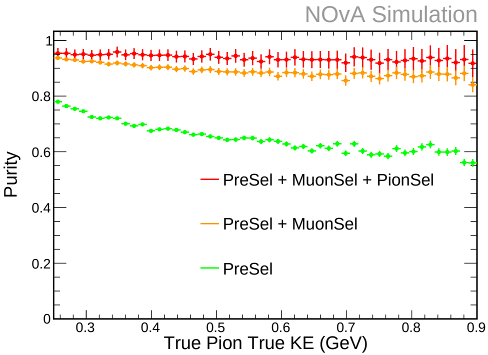


- The selection efficiency of CC1π^+ sample is 21% and 1.5% with respect to the preselection and the total respectively.

Purity of Selected Events

- $\text{Purity} = \dfrac{\text{Number of Selected Signal Events}}{\text{Total Number of Selected Events}}$





- Applying all the selection cuts, the purity of the selected sample is 93%.

- $CC1\pi^{\pm}$ measurement has a potential to look at the interactions with low W (invariant hadronic mass) leading to the improved model of these processes.
- We are planning to have a differential cross section measurement w.r.t to pion kinematics.
- PID for the pion selection has been tuned on MC simulated data. A reconstructed energy cut on the second non muon prong will help reduce the contamination from other particles.
- The total systematics are in the range of 5-15%, investigations are in progress.