Progress on the Inclusive Muon Neutrino Charged-current Cross Section Measurement in the NOvA Near Detector

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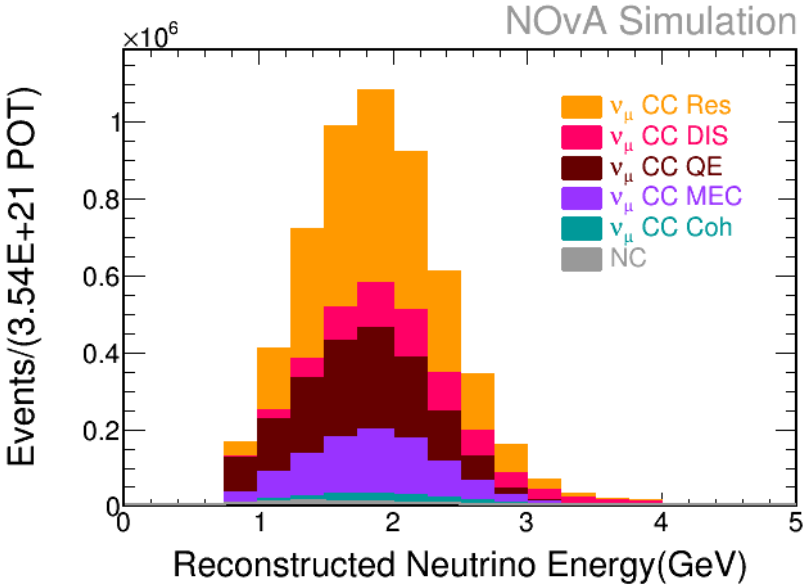
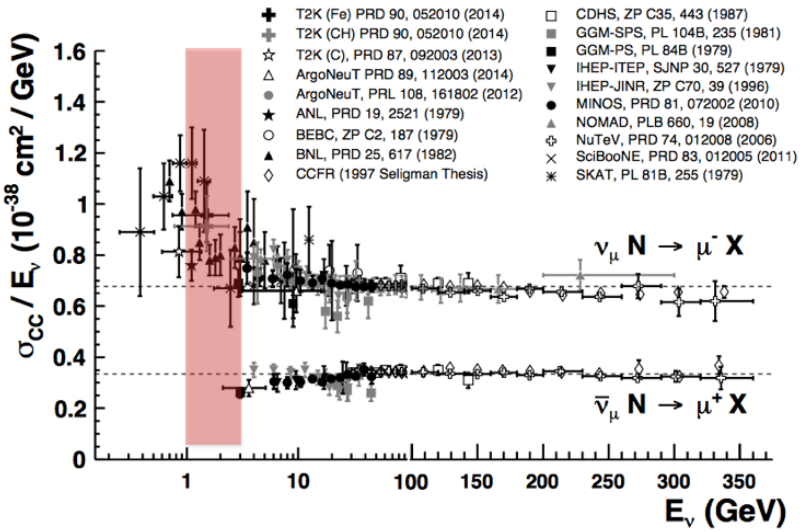
Motivation

- Long-baseline neutrino experiments are entering in the precision era, need to reduce systematic errors to the level of a few percent.
- Improving the precision of our oscillation measurement requires better knowledge of neutrino-nucleus cross section. NOvA has access to all interaction type with a narrow band beam(1-3GeV).





C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)

- The ν_μ CC inclusive process is a baseline measurement, one that can be used, to directly tune our simulation for the oscillation analysis and can be used for cross section ratio measurements with reduced systematic.

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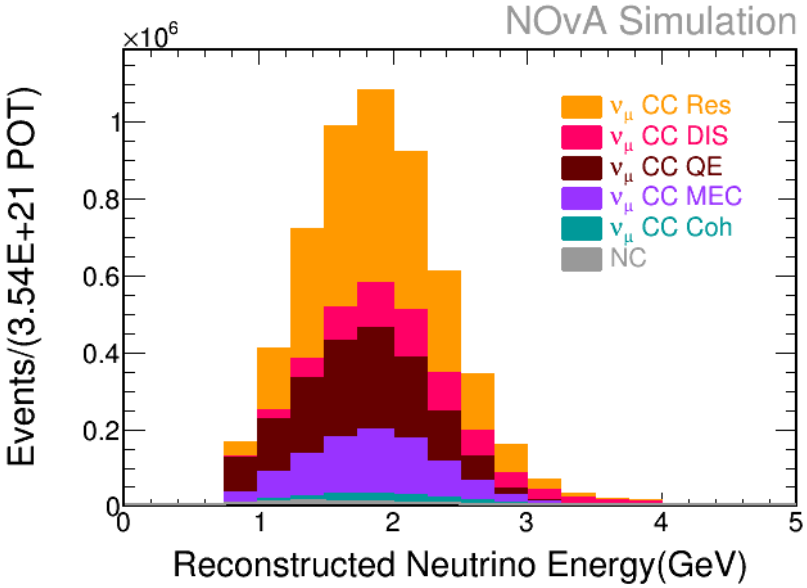

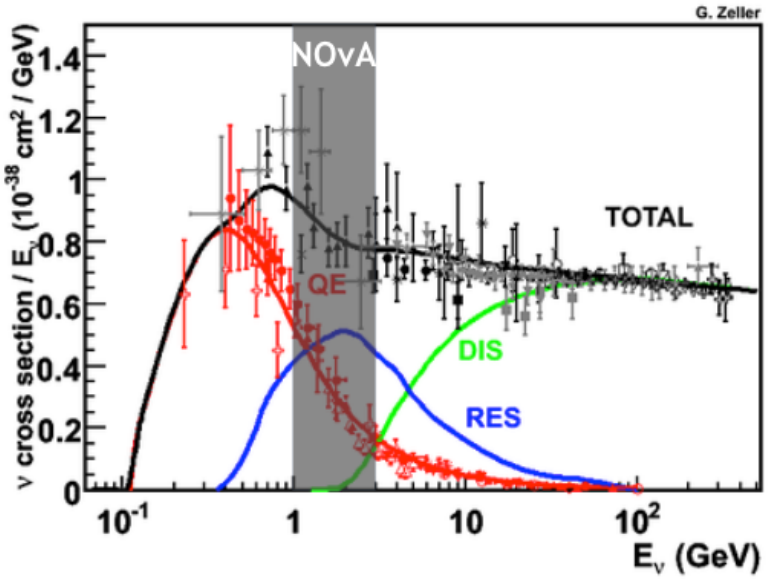

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NOvA: NuMI Off-axis ν_e Appearance

- NOvA can observe oscillations in two channels using a predominantly ν_μ beam (ν_e appearance and ν_μ disappearance).
- The Near Detector (ND), 1km from the source, Underground 100m from surface, 14.6 mrad off-axis w.r.t NuMI beam.

- Made up of PVC with liquid scintillator (mostly carbon), 3.9m X 3.9m X 12.67m, 193 ton, 192 planes, 20k channels.
- Low-Z, 1 plane $\sim 0.15X_0$, highly active tracking calorimeter, used to measure composition of the un-oscillated beam.

Muon Catcher:

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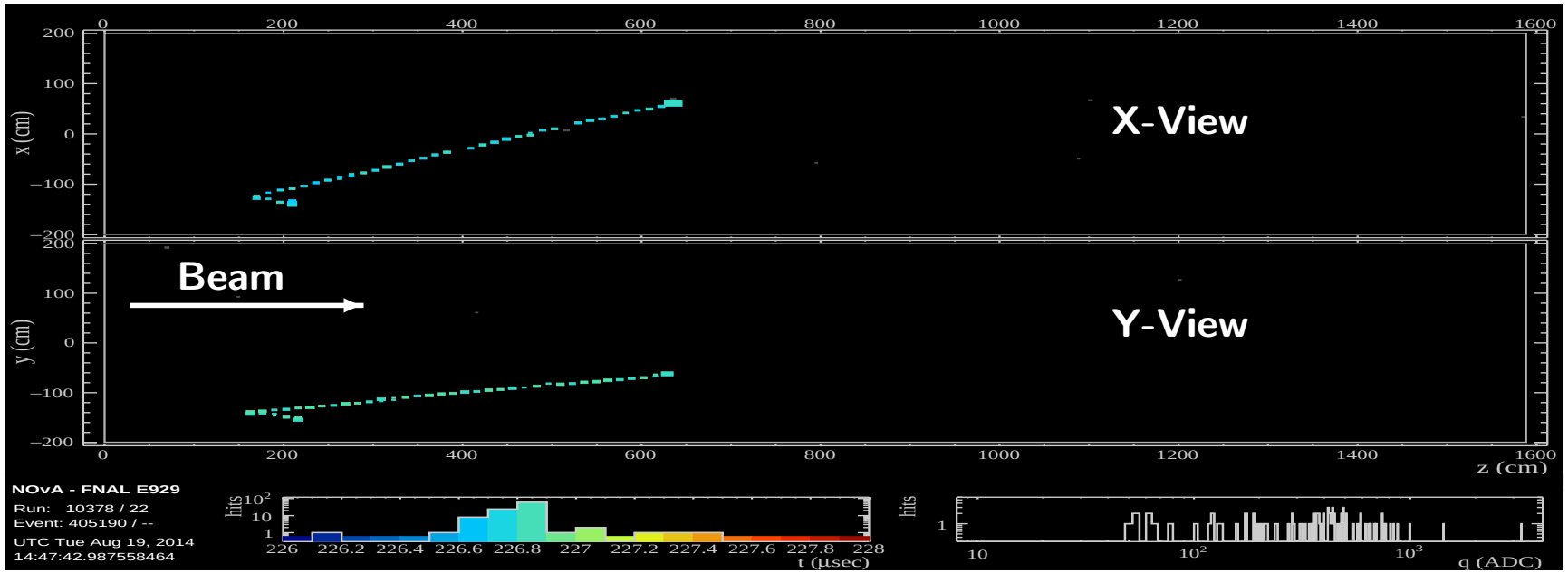

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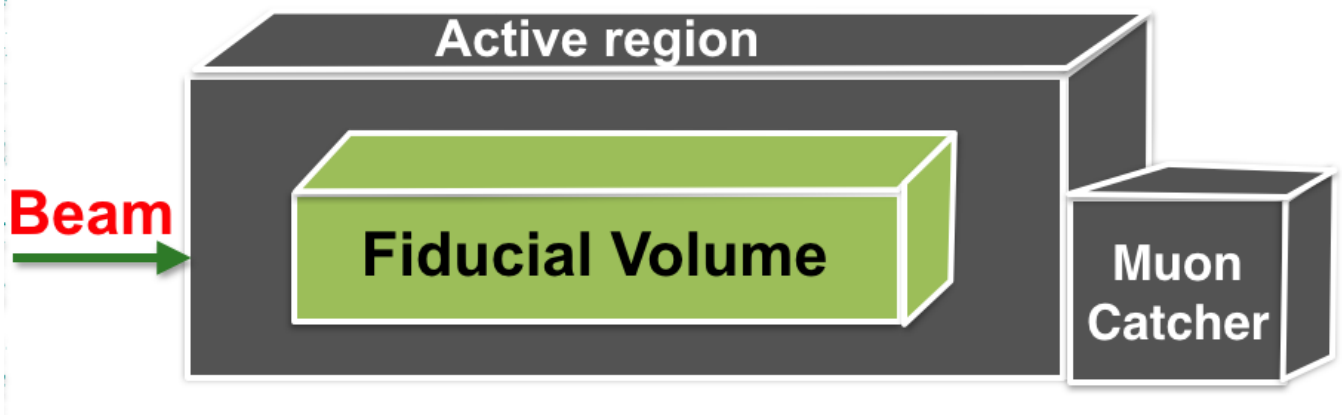
Cross section Measurement in the NOvA ND

- We will measure the inclusive cross section in bins of true neutrino energy and as well as flux-integrated double-differential with respect to the final-state muon's true kinetic energy and true angle.

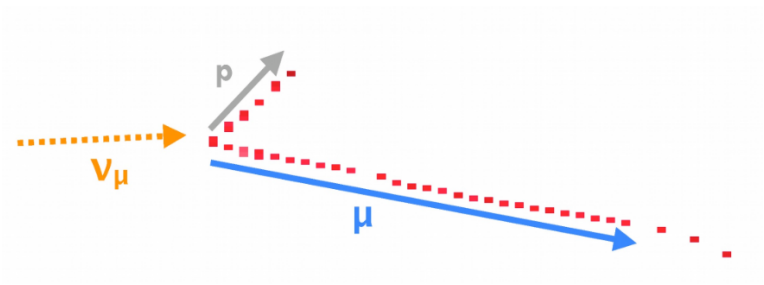
$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \frac{\sum_j U_{ij}(N^{\mathrm{sel}} - N^{\mathrm{bkg}})}{\epsilon N_{\mathrm{target}}\Phi} \tag{1}$$

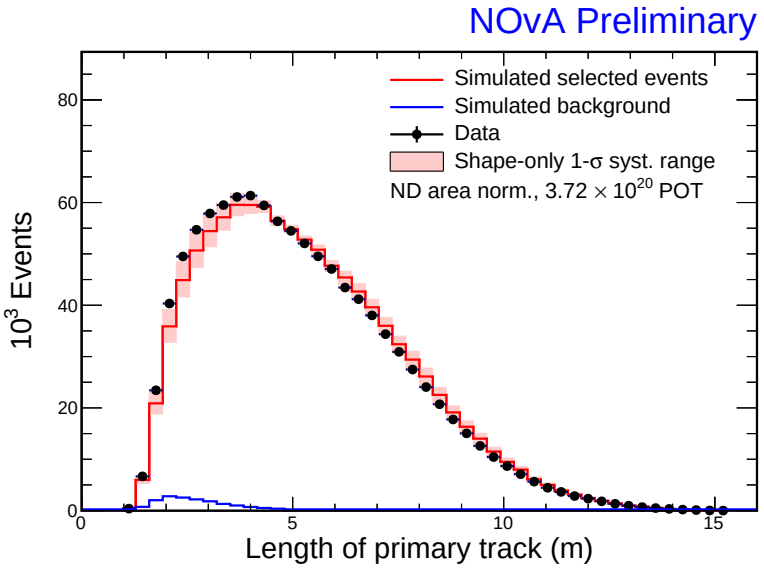
N^{sel} = Number of selected counts.
N^{bkg} = Number of estimated background counts.
U = Unfolding matrix that corrects the reconstructed quantities for detector resolution.
Φ = The neutrino flux.
ϵ = Signal selection efficiency.
N_{target} = The number of targets in the fiducial volume.

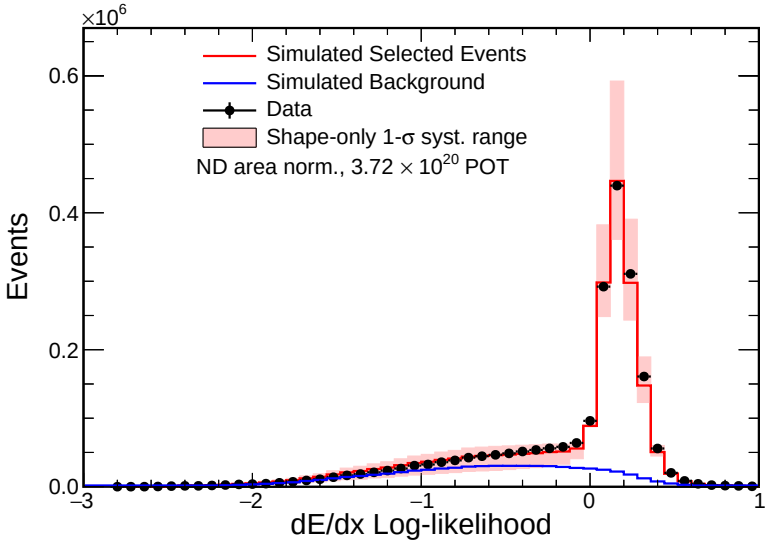


- We require that all track vertices start inside the fiducial volume.
- Cuts are designed to reject energy deposited by neutrino interactions in the surrounding rock.

Event Selection



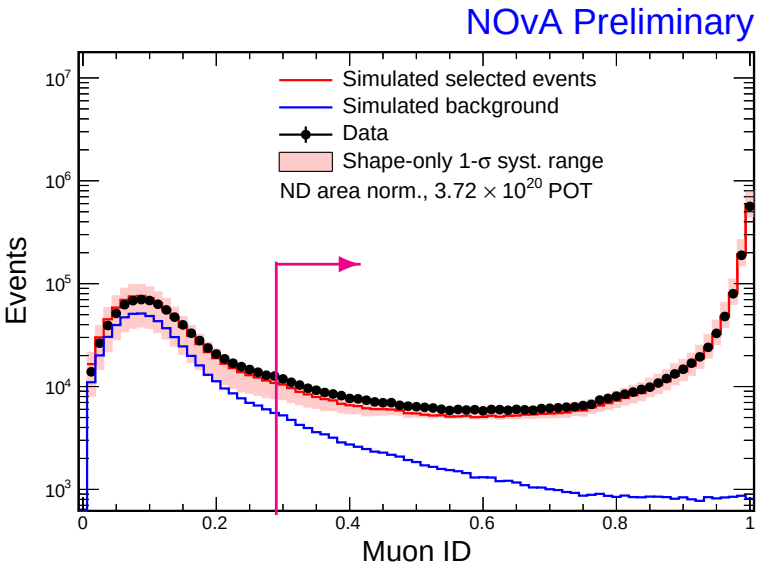


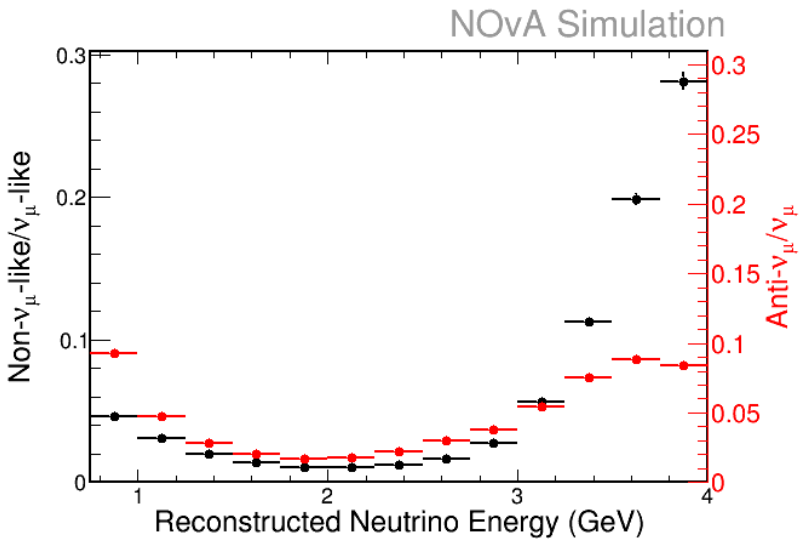


NOvA reconstructs muons as tracks and separates them from the hadronic background using a **k-nearest neighbors (kNN)** algorithm trained with four variables:

- track length
- longitudinal energy profile (dE/dx)
- scattering along the track and
- fraction of energy in the neutrino event associated with the track

Event Selection

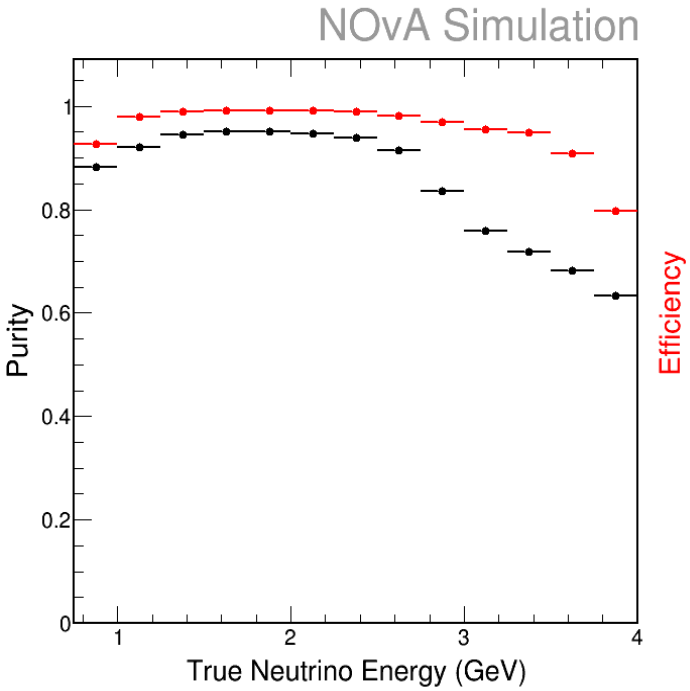


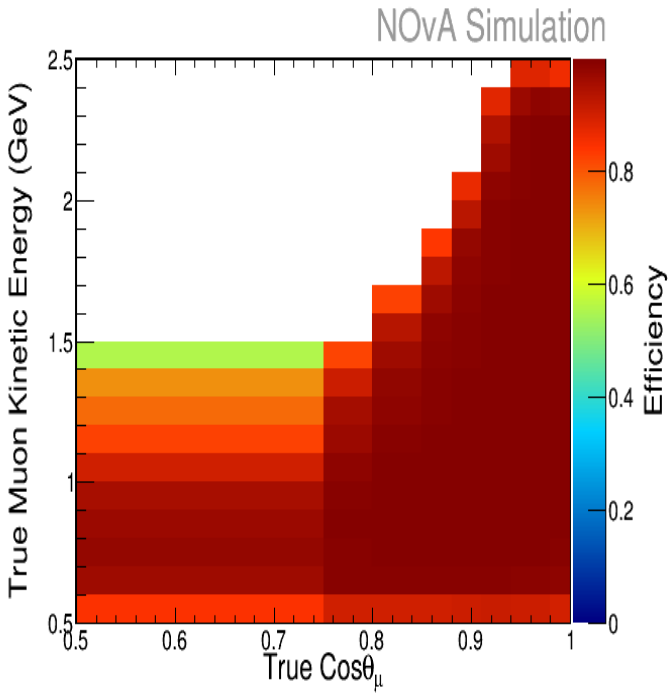


- Events with Muon ID > 0.29 (Optimized Muon ID w.r.t different interaction type by using F.O.M ($\frac{s}{\sqrt{(s+b)}}$)) are retained as candidate of ν_μ CC events.
- Backgrounds are Neutral Current(NC), ν_e, $\bar{\nu}_e$, $\bar{\nu}_\mu$ and non-fiducial.
- In the lower energy $\bar{\nu}_\mu$ CC is dominated, however NC is dominated in the higher energy region.

Efficiency and Purity for Contained Events

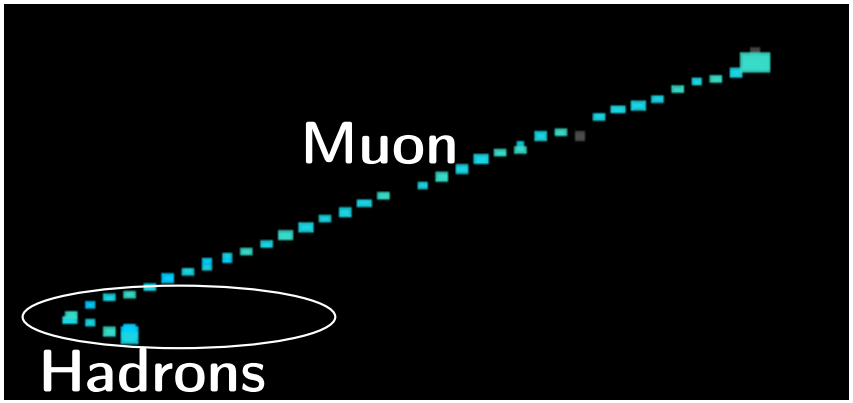
$$\text{Efficiency} = \frac{\#\text{ of selected true } \nu_\mu \text{ CC events}}{\#\text{ of true } \nu_\mu \text{ CC events}} \qquad \text{Purity} = \frac{\#\text{ of selected true } \nu_\mu \text{ CC events}}{\#\text{ of selected events}}$$





- Efficiency is ∼100% and Purity is ∼95% in the peak region.
- Our signal sample is very pure.

- NOvA is a tracking calorimeter, it offers detailed reconstruction of the hadronic part of ν_μ CC interactions. we reconstruct energy deposited in each cells.



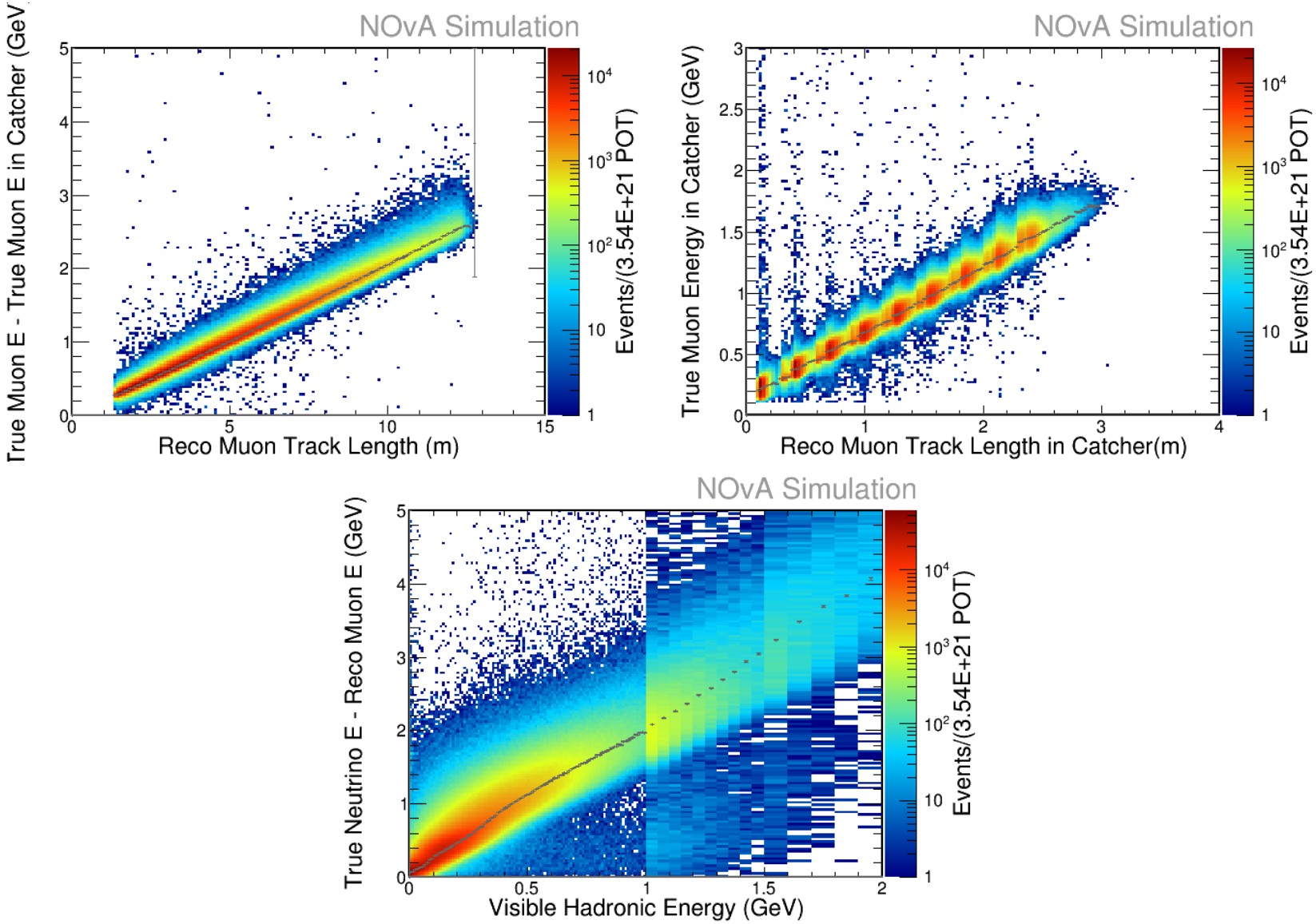
E_μ= Energy determined from the track length of muon.

E_{had} = Energy deposited in the cell(non-muonic).

Reconstructed Neutrino energy is sum of E_μ and E_{had}.

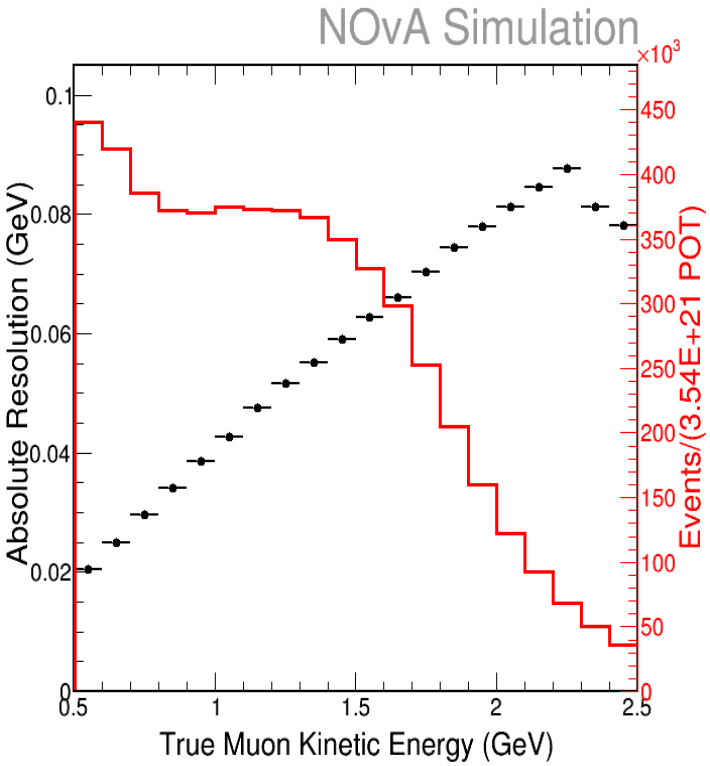
$$E_\nu = E_\mu + E_{had}$$

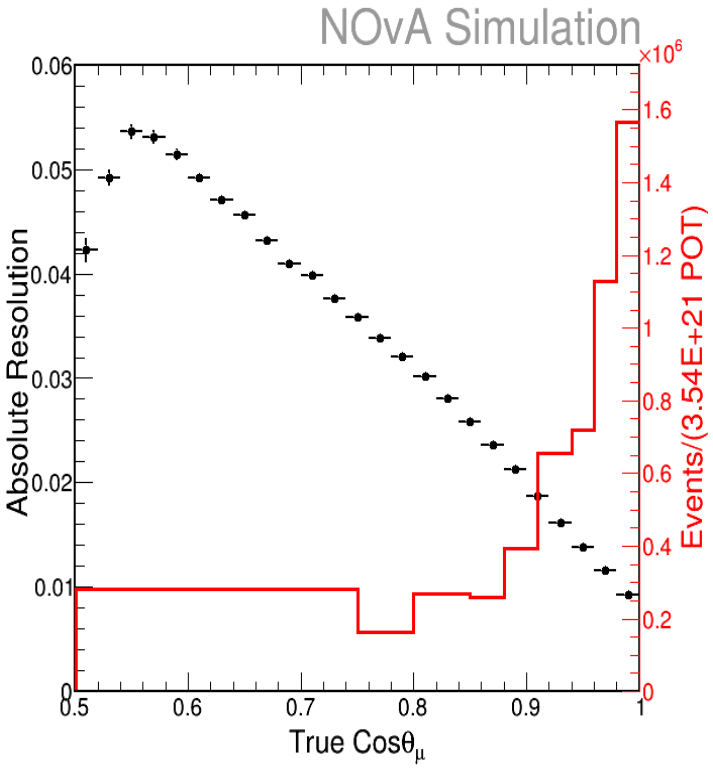
Energy Determination for Muon and Hadrons



- Muon starts at active region and stops at muon catcher region(top left), Muon starts and stops at muon catcher region(top right), and hadronic energy(bottom).

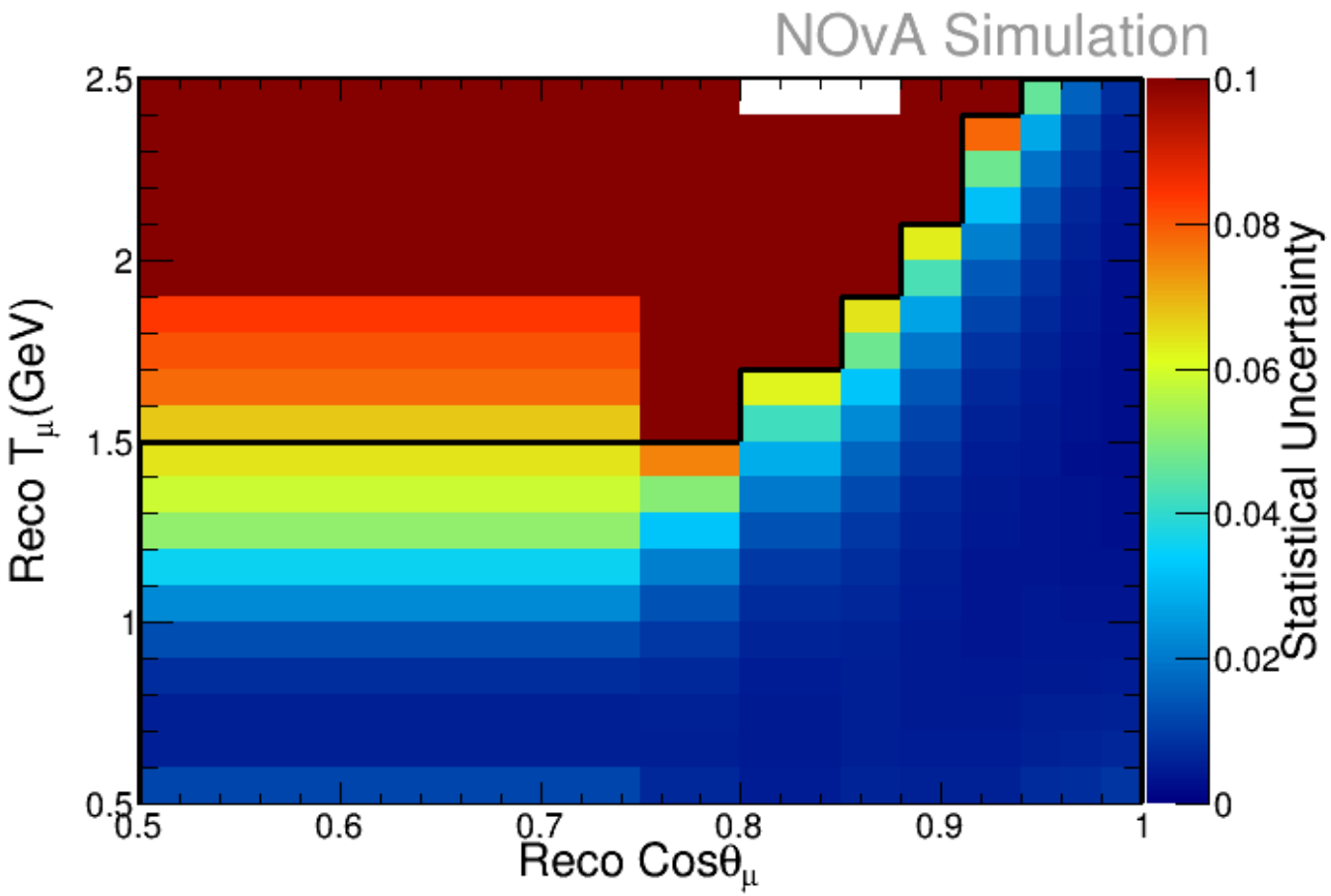
Resolution





- The predicted resolutions in both muon kinetic energy and angle for this sample are very good (averaged over the sample is 50 MeV and 0.04 respectively).

Statistical Uncertainty



- Measuring double differential cross-section.
- Statistics are $< 1\%$ for most of the bins.
- Measurable variable has very good resolution.
- Binning are determined based on the resolution.

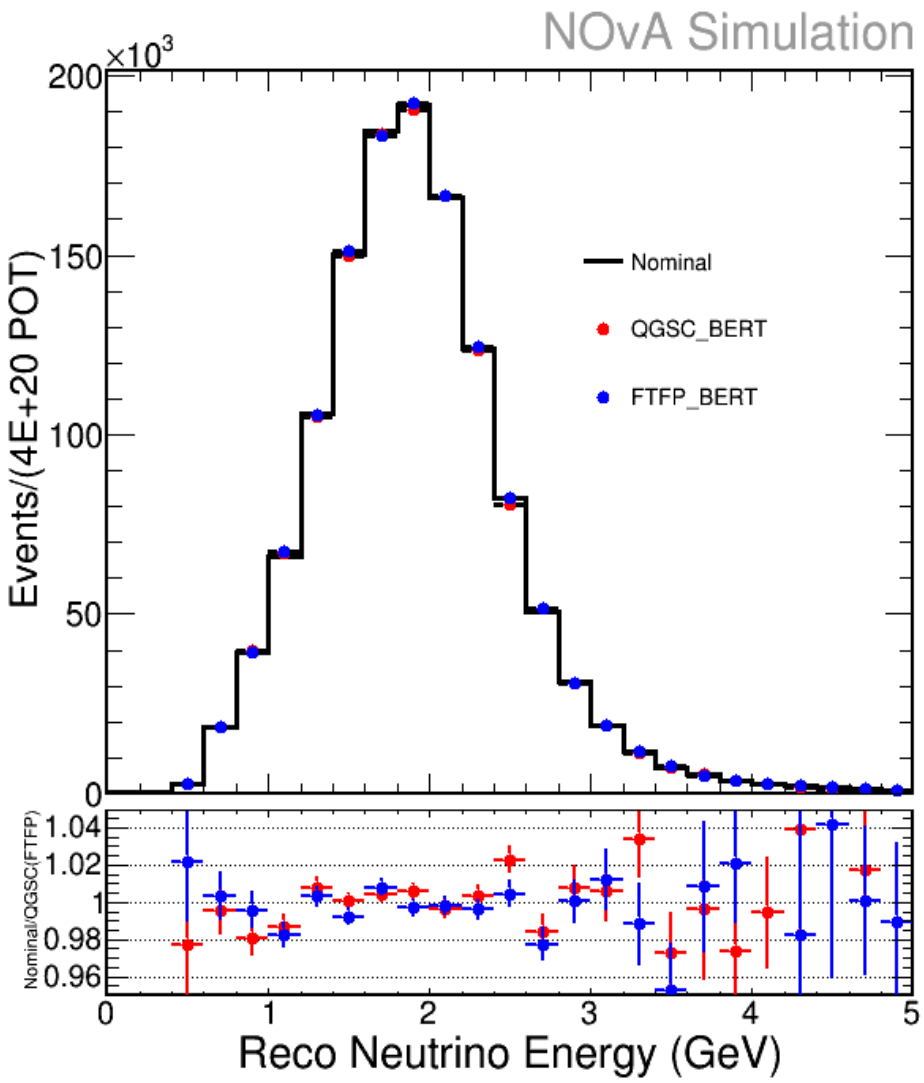
Sources of Systematic Uncertainties

- The uncertainty can be accessed by comparison of modified MC with our nominal MC.
- We are determining detector response($\sim$ 1-2%) by using different GEANT Physics lists.

- Flux : $\sim$ 8-10%
- Detector response : $\sim$ 1-2%

We are finalizing studying on:

- Neutrino interaction
- Backgrounds
- Calibration



Summary

- NOvA has an excellent sensitivity to measure the cross section in addition to neutrino oscillation study.
- Very good resolution and enriched muon neutrino events will allow us to measure double differential cross section.
- This study shows high efficiency and purity for ν_μ CC event selection.
- Most of the uncertainties are nearing completion.
- We are rich in statistics, systematic dominated by $\sim 10\%$, very relevant to future neutrino program.

Stay tuned for exciting results!!

Thank You!!

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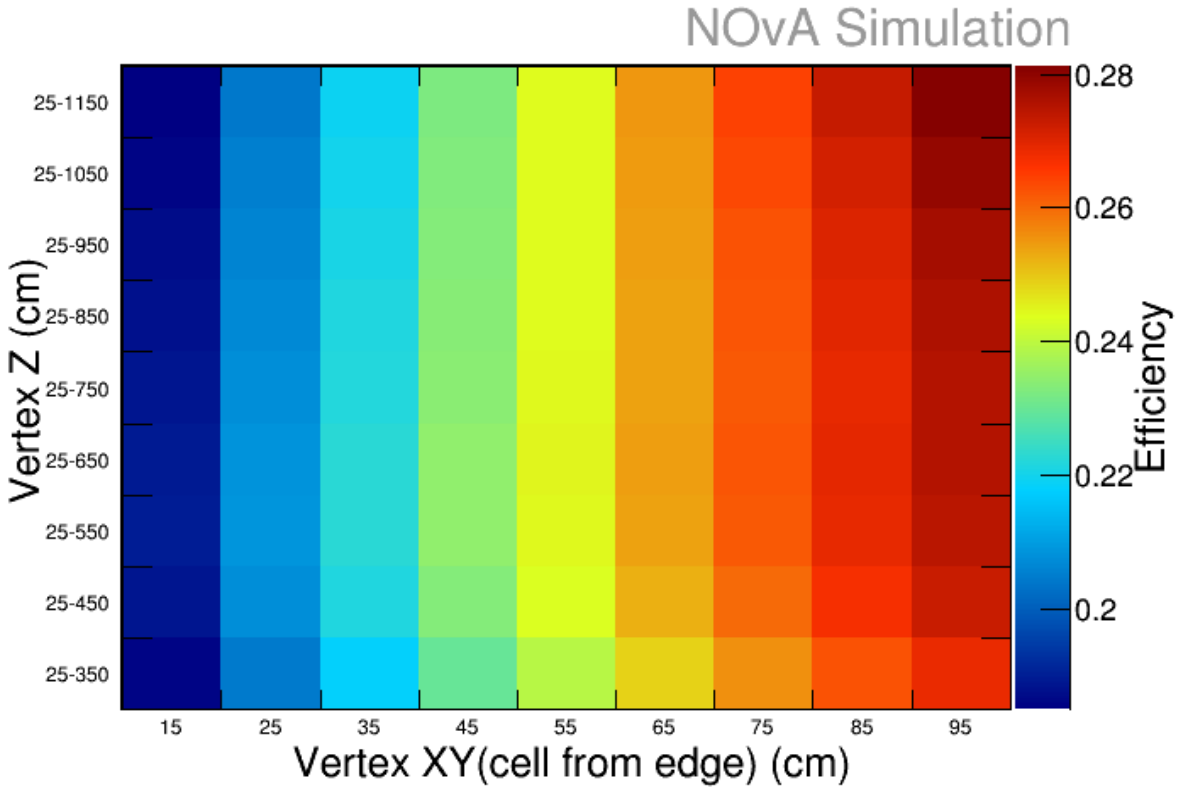
Efficiency (Vertex Z , Vertex XY)

- Efficiency $= \frac{\text{Total number of selected true } \nu_\mu \text{ CC events}}{\text{Total number of true } \nu_\mu \text{ CC events}}$
- Figure info : Efficiency calculated for different fiducial region. For this study I have fixed lower vertex Z position at 25 cm and upper vertex Z increasing 100cm starting from 350cm, on the other hand reducing 10 cm on vertex XY (cell from edge)



Plot: Efficiency as a function of different fiducial region by changing vertex Z and vertex XY value