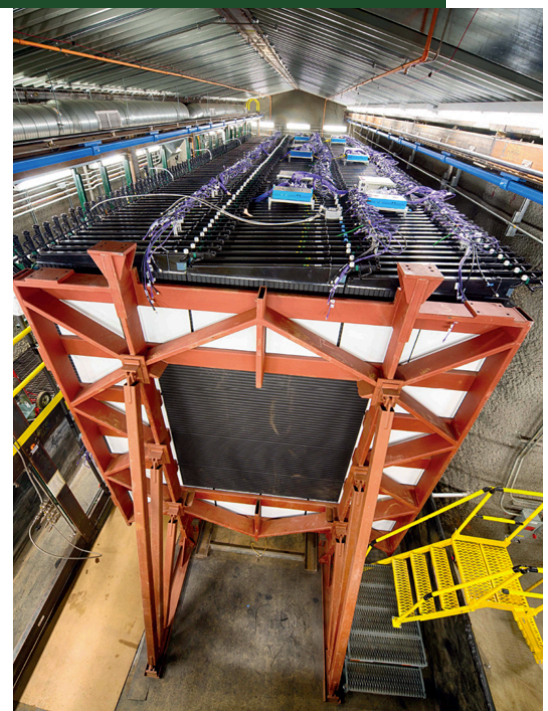
Neutrino Cross-Section Measurements in the NOvA Near Detector at Fermilab

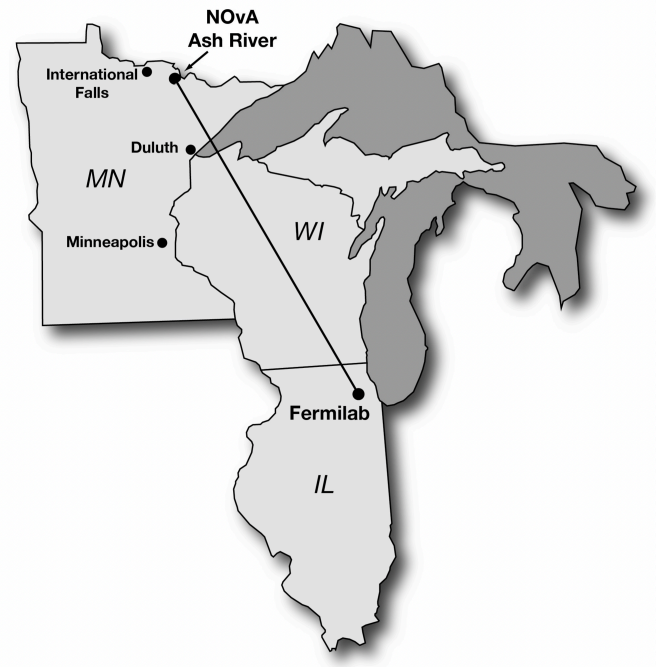
Shih-Kai Lin
on behalf of the NOvA Collaboration

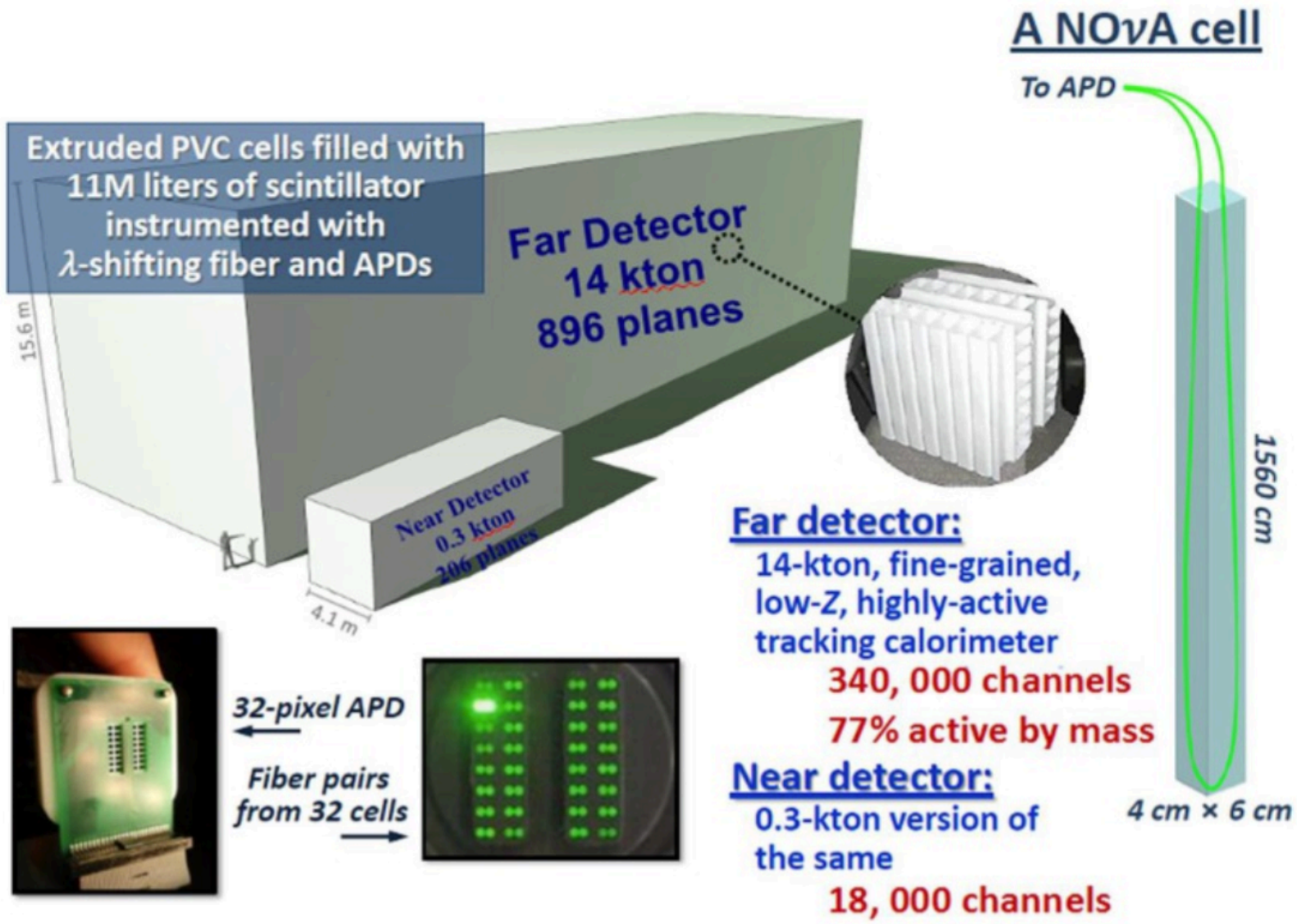
Colorado State University

SUSY 2019
Corpus Christi, TX
May 21, 2019



The NOvA Experiment & Detectors

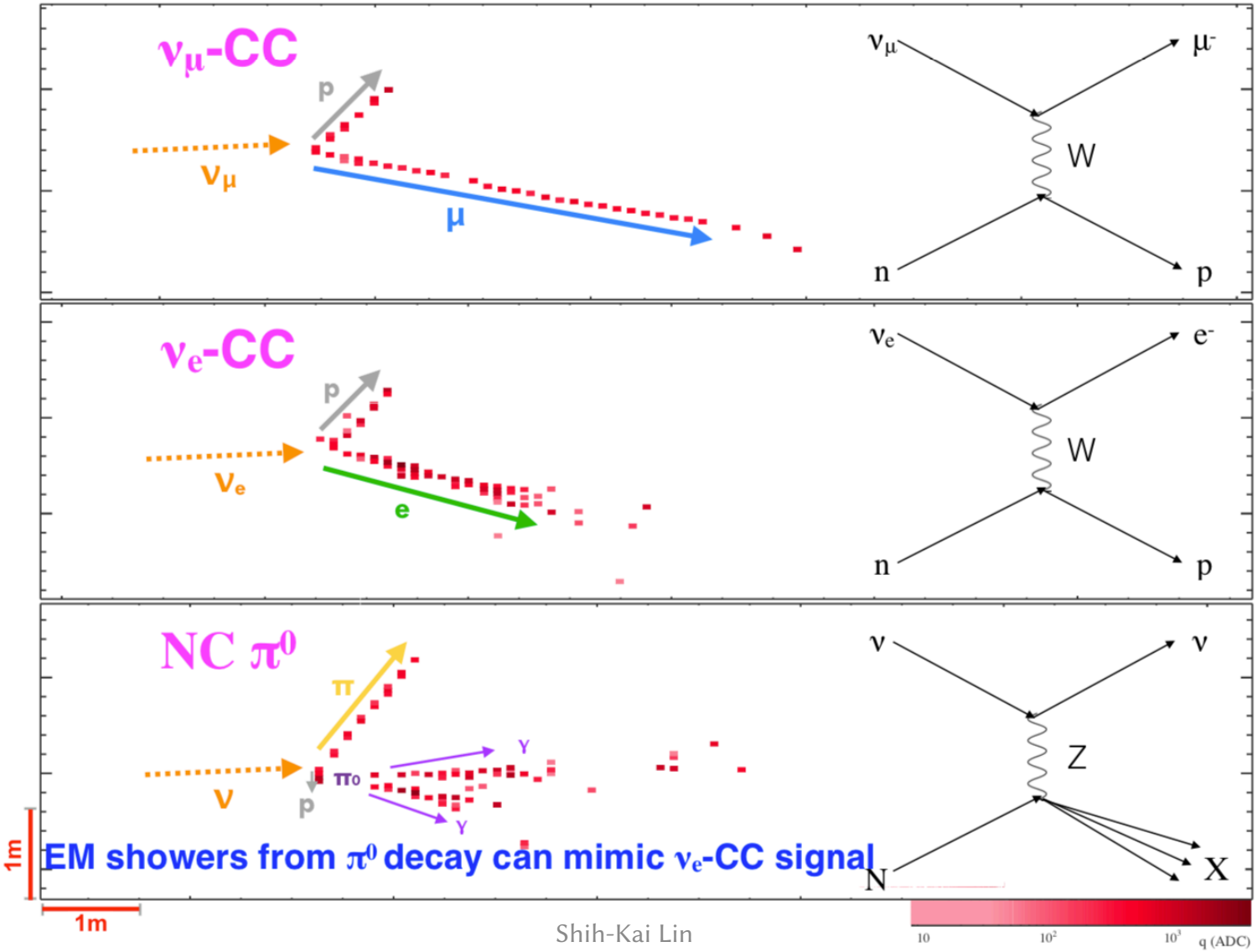




NuMI Off-Axis Electron Neutrino Appearance (NOvA)

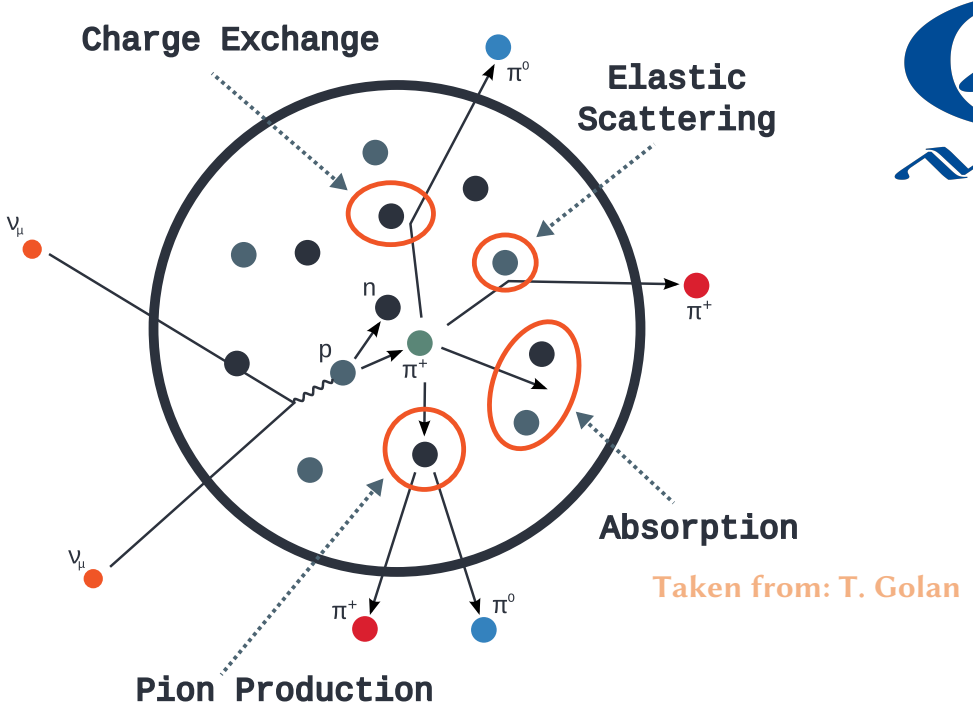
- A long baseline neutrino oscillation experiment
- For more details, refer to R. Gandrajula's talk on May 20.

Event Topology

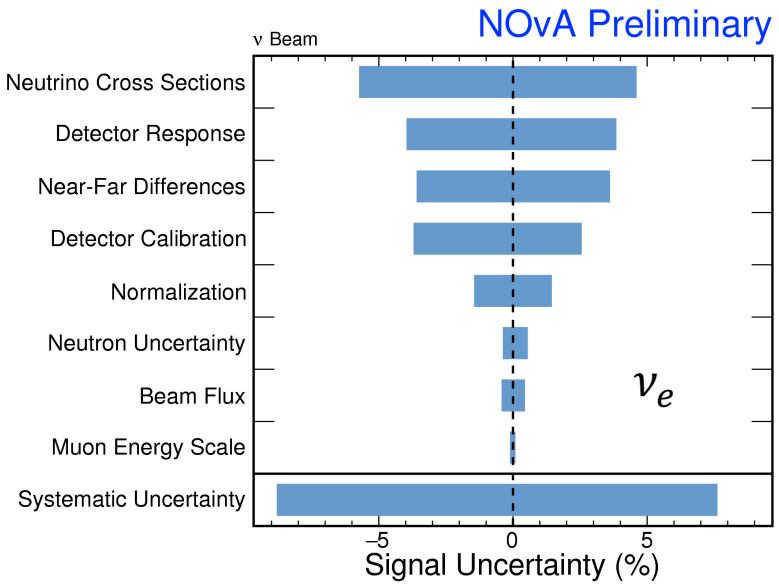


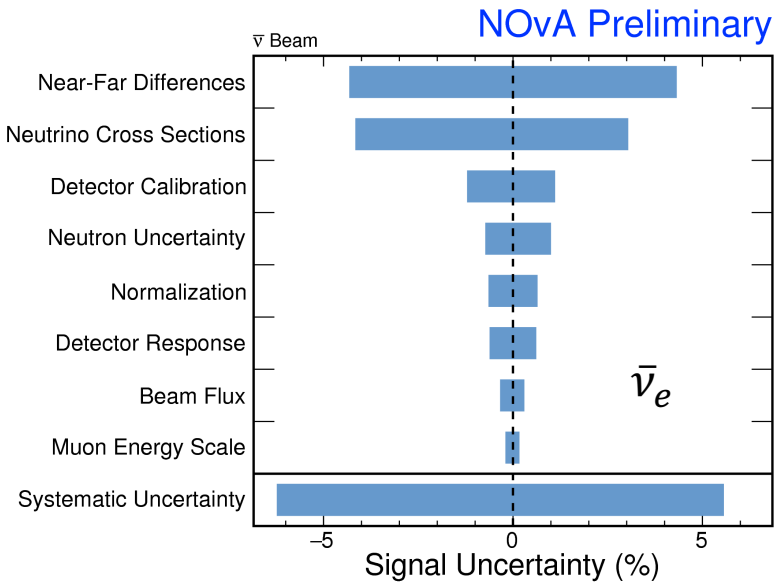
Motivation

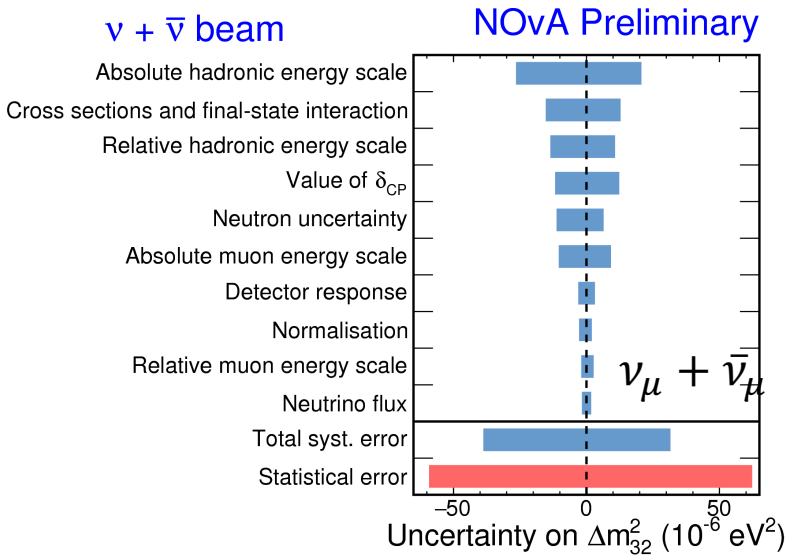
- Neutrino cross section is physics rich in its own right.
- Using nuclear target to increase event rate makes the physics more difficult
  - Intranuclear rescattering
- Cross section modeling is one of the leading systematic uncertainties for NOvA's measurements.



Taken from: T. Golan







NOvA Cross Section Analyses

FHC (ν_μ beam)	RHC ($\bar{\nu}_\mu$ beam)
ν_μ CC π^0 Semi-Inclusive	$\bar{\nu}_\mu$ CC π^0 Semi-Inclusive
ν_μ CC Inclusive	$\bar{\nu}_\mu$ CC Inclusive
ν_e CC Inclusive	$\bar{\nu}_e$ CC Inclusive
ν_μ CC $\pi^{+/-}$	
ν_μ CC 2p2h	$\bar{\nu}_\mu$ CC 2p2h
ν_μ CC 0π/QE	
NC coherent π^0	
NC π^0 Inclusive	NC π^0 Inclusive
ν-e Flux Constraint	

NOvA Cross Section Analyses

FHC (ν_μ beam)	RHC ($\bar{\nu}_\mu$ beam)
ν_μ CC π^0 Semi-Inclusive	$\bar{\nu}_\mu$ CC π^0 Semi-Inclusive
ν_μ CC Inclusive	$\bar{\nu}_\mu$ CC Inclusive
ν_e CC Inclusive	$\bar{\nu}_e$ CC Inclusive
ν_μ CC $\pi^{+/-}$	
ν_μ CC 2p2h	$\bar{\nu}_\mu$ CC 2p2h
ν_μ CC 0π/QE	
NC coherent π^0	
NC π^0 Inclusive	NC π^0 Inclusive
ν-e Flux Constraint	

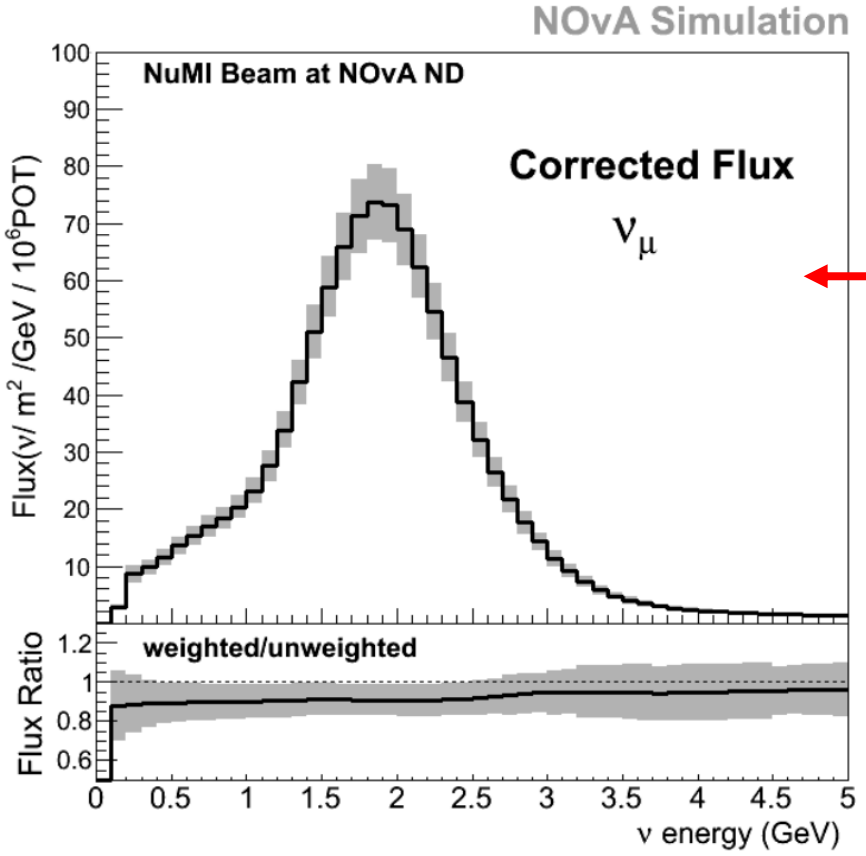
Internal review

Will focus on these two analyses.

Submitted to PRD

Topics Shared by Multiple Analyses

Topics Shared by Multiple Analyses
Systematic Uncertainties



Detector Uncertainties

- Considered calibration, light yield, Cerenkov light
- Using systematically-shifted MC to assess the impact

Flux

- Geant4 based simulation that carefully implements NuMI (Neutrinos at the Main Injector) geometry
- Correction for hadron production mismodeling from dedicated hadron production measurements.
- Uncertainties are incorporated with the multi-universe approach. Randomized physics parameters drawn according to central values and uncertainties.
- Used 100 universes.

Cross-Section Model

- NOvA uses GENIE as the neutrino generator
- GENIE has tens of tunable physics parameters (knobs, ex. m_A^{QE})
- Multi-universe approach as flux. Using O(100) to O(1000) universes.

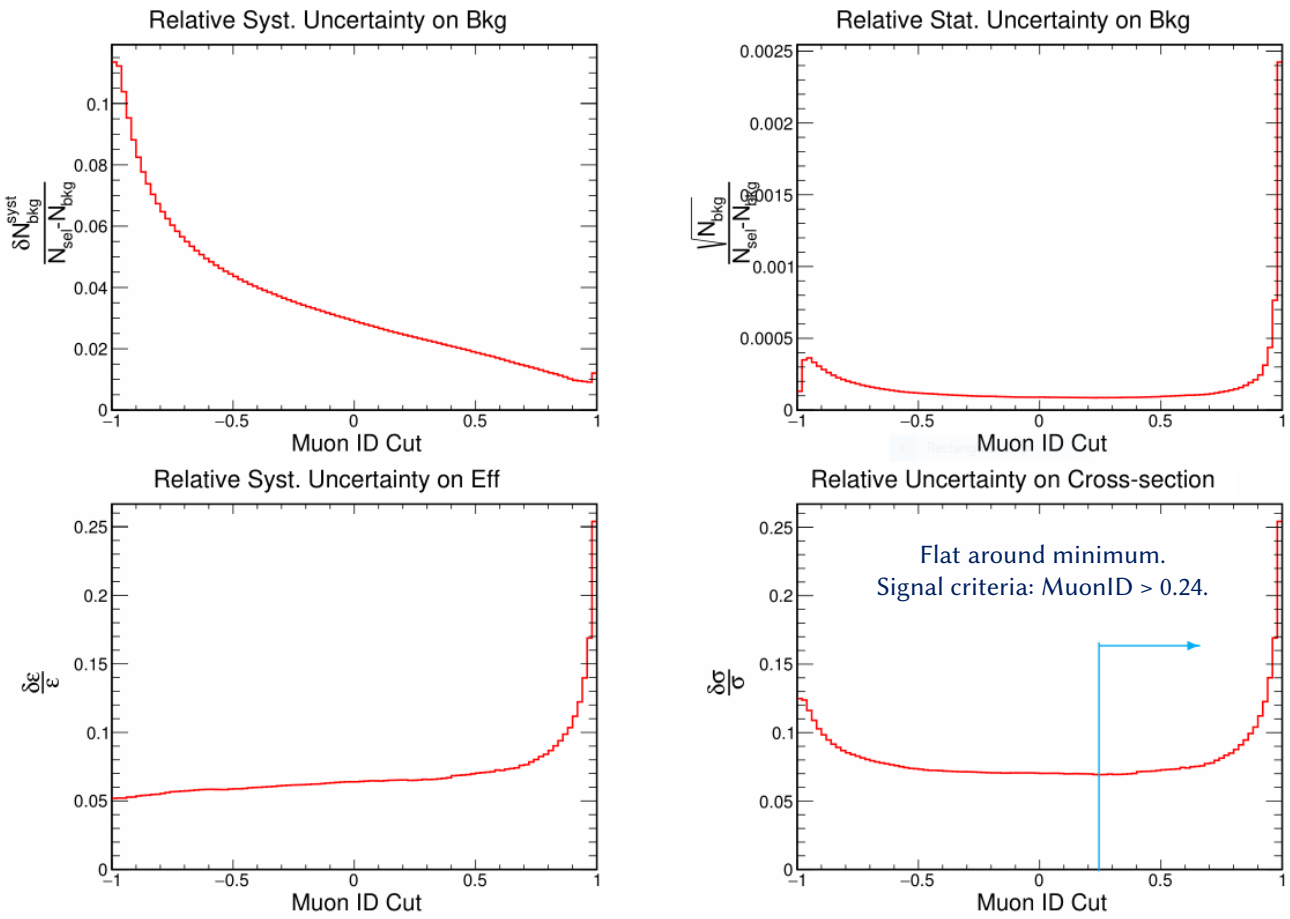
Topics Shared by Multiple Analyses
Cut Optimization

- Taking ν_μ CC inclusive analysis' muon ID as an example.
- A general strategy in many analyses is to determine selection criteria that minimize the systematic uncertainty of the total cross section:

different analyses can have slightly different formula

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\left(\delta N_{bkg}^{syst}\right)^2 + \left(\delta N_{bkg}^{stat}\right)^2}{\left(N_{sel} - N_{bkg}\right)^2} + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

- At low cut values, uncertainty is dominated by background. At high cut values, uncertainty is dominated by the efficiency.
- The same optimization method is used for fiducial and containment cuts as well.



ν_μ CC Inclusive

ν_μ CC Inclusive Measurement Goals

Our major delivery* is flux-averaged double-differential cross section as a function of the final-state muon's true kinetic energy and true angle:

$$\left(\frac{d\sigma}{d\cos\theta_\mu\, dT_\mu}\right)_i = \frac{\sum_j U_{ij}(N^{sel}(\cos\theta_\mu,\, T_\mu)_j - N^{bkg}(\cos\theta_\mu,\, T_\mu)_j)}{\epsilon(\cos\theta_\mu,\, T_\mu)_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i N_{target}\phi}$$

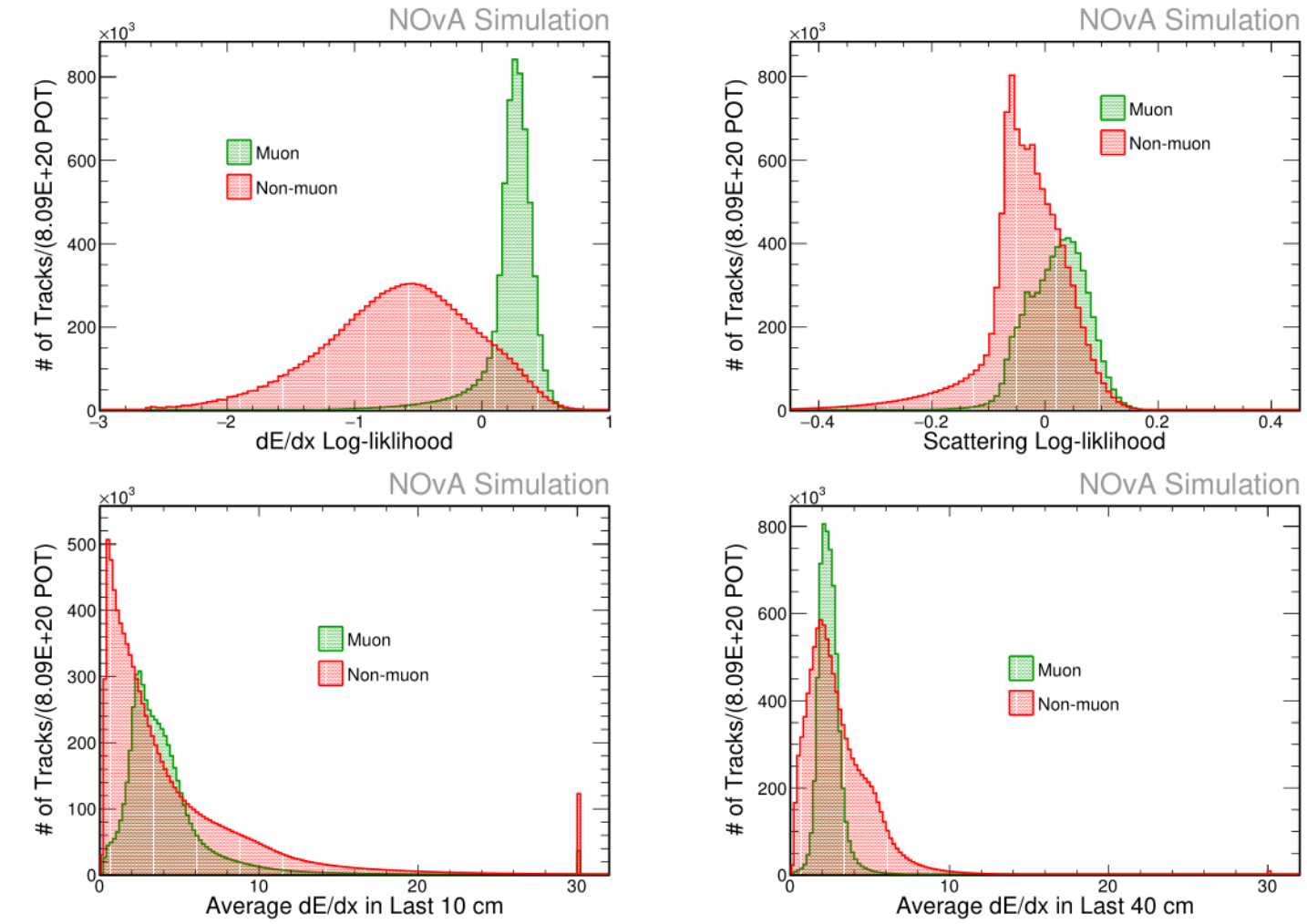
i:	bin index
U:	unfolding matrices
ϵ:	signal selection efficiency
N_{target}:	number of targets in the fiducial volume
ϕ:	neutrino flux

*We will also report the cross section as a function of the derived quantities E_ν and Q^2:

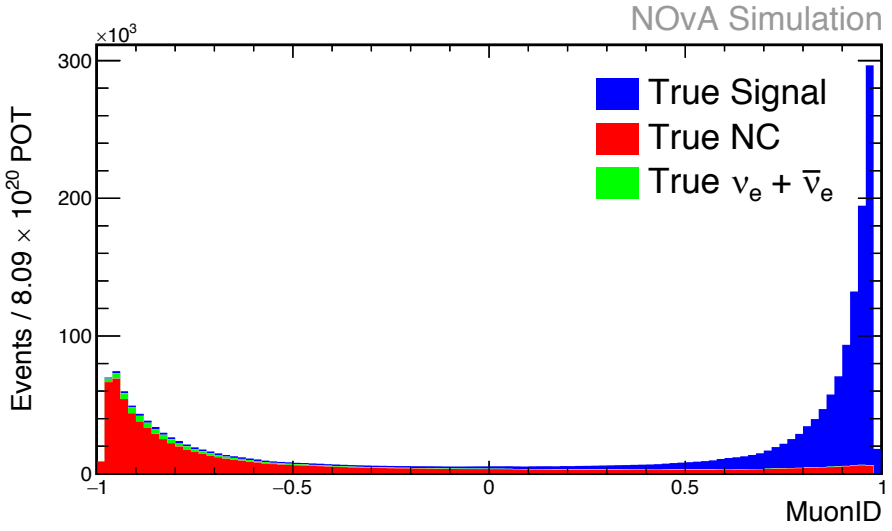
$$\sigma(E_i) = \frac{\sum_j U_{ij}(N^{sel}(E_j) - N^{bkg}(E_j))}{\epsilon(E_i)N_{target}\phi(E_i)}$$

ν_μ CC Inclusive Muon Identification

$$\frac{U(N^{sel} - N^{bkg})}{\epsilon \phi N_{target}}$$

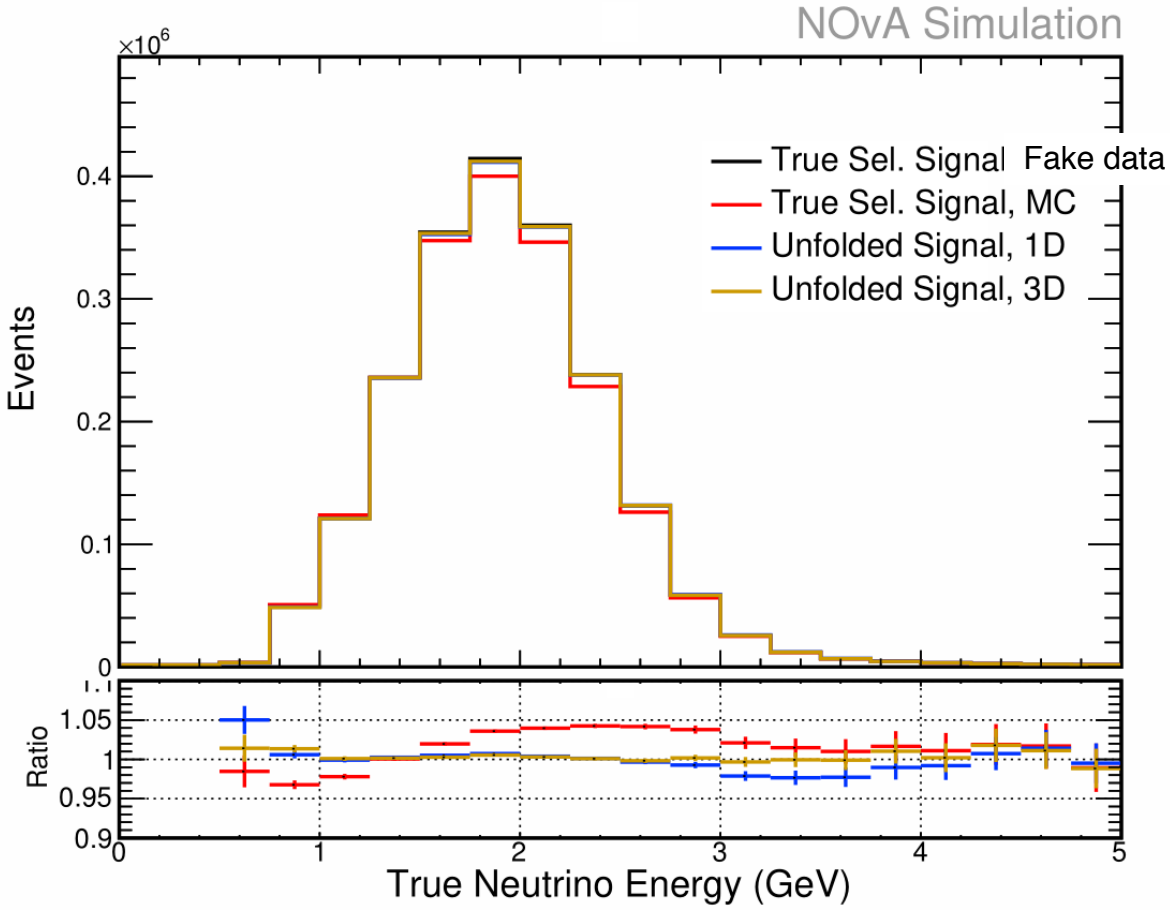


- Four variables are used for training a BDT
  - dE/dx log-likelihood
  - Scattering log-likelihood
  - dE/dx in the last 10 cm of the track
  - dE/dx in the last 40 cm of the track
- Referred to as MuonID
- N^{bkg} in this analysis is estimated by simulation.



ν_μ CC Inclusive Multidimensional Unfolding and Efficiency Correction

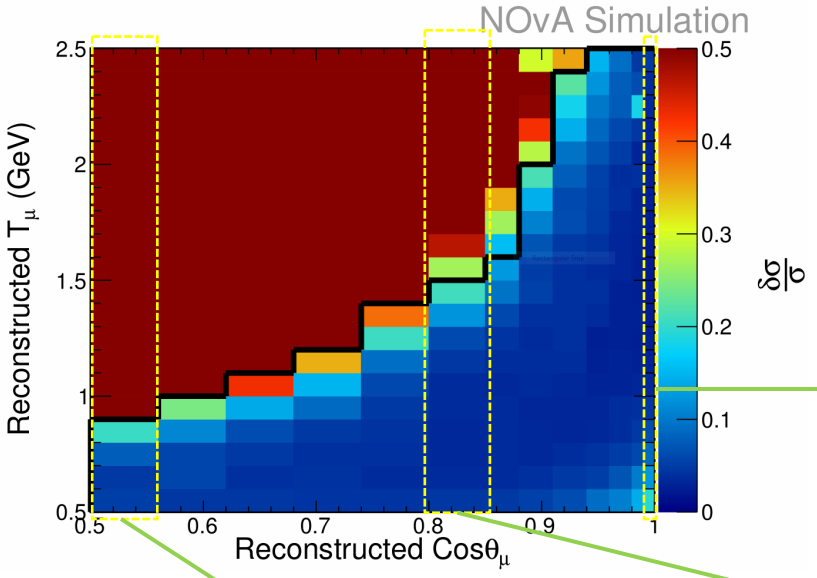
- We performed unfolding and efficiency correction in 3D space, $(cos\theta_\mu, T_\mu, E_\nu)$
  - Cross section depends not only on muon variables, but also hadronic variables (E_ν as a proxy)
  - Doing unfolding and efficiency corrections in lower dimensional spaces loses information
  - This testing shows 3D unfolding gives better results.
- Efficiency correction in 3D followed by unfolding.
- Projection to 1D or 2D space for results in the end.
- NOTE: we are in the process of switching from strongly model-dependent E_ν to less model-dependent observable E_{avail} as the 3rd axis.

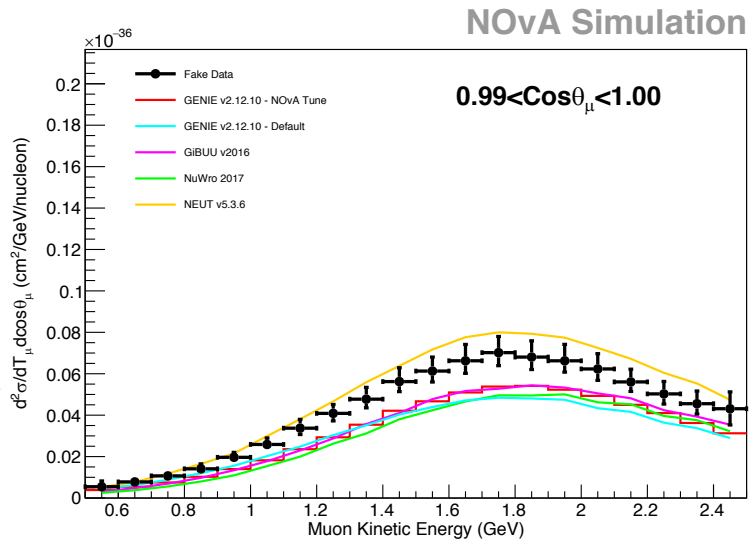


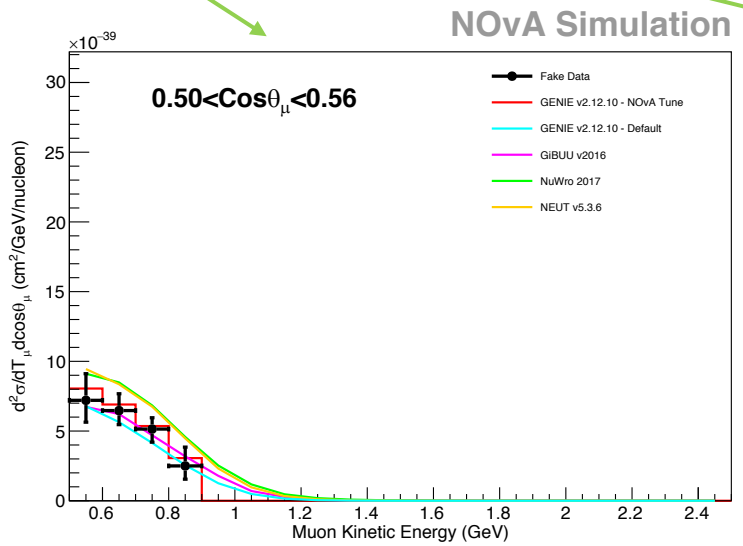
ν_μ CC Inclusive - Fake Data Results

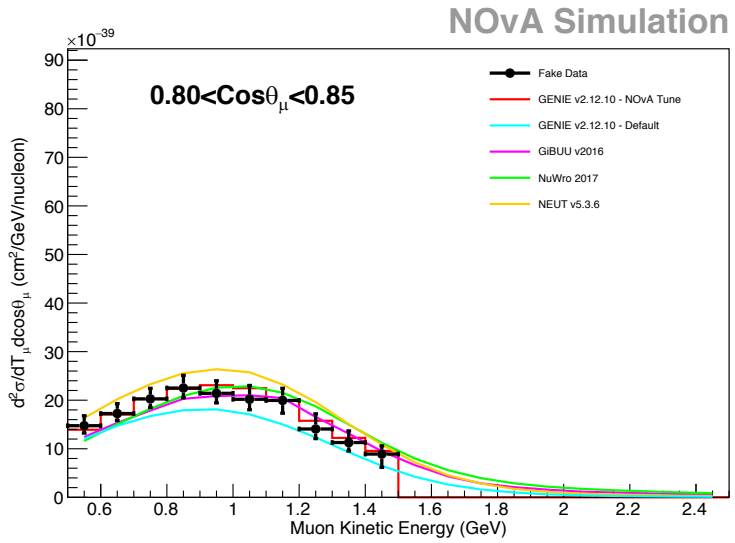
- Fake data are generated by data POT equivalent, statistically independent MC events.
  - With flux weights
  - Without interaction model weights
- Different neutrino generator predictions are overlaid.
  - GENIE v2.12.10 with NOvA tune*
  - Default GENIE v2.12.10
  - GiBUU v2016
  - NuWro 2017
  - NEUT v5.3.6

* c.f. Greg's NOvA APS talk.





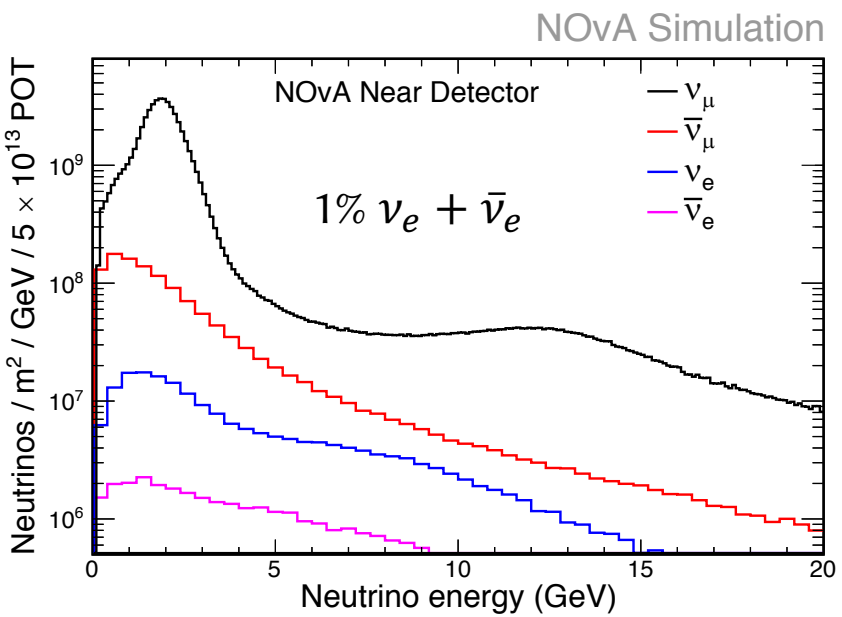


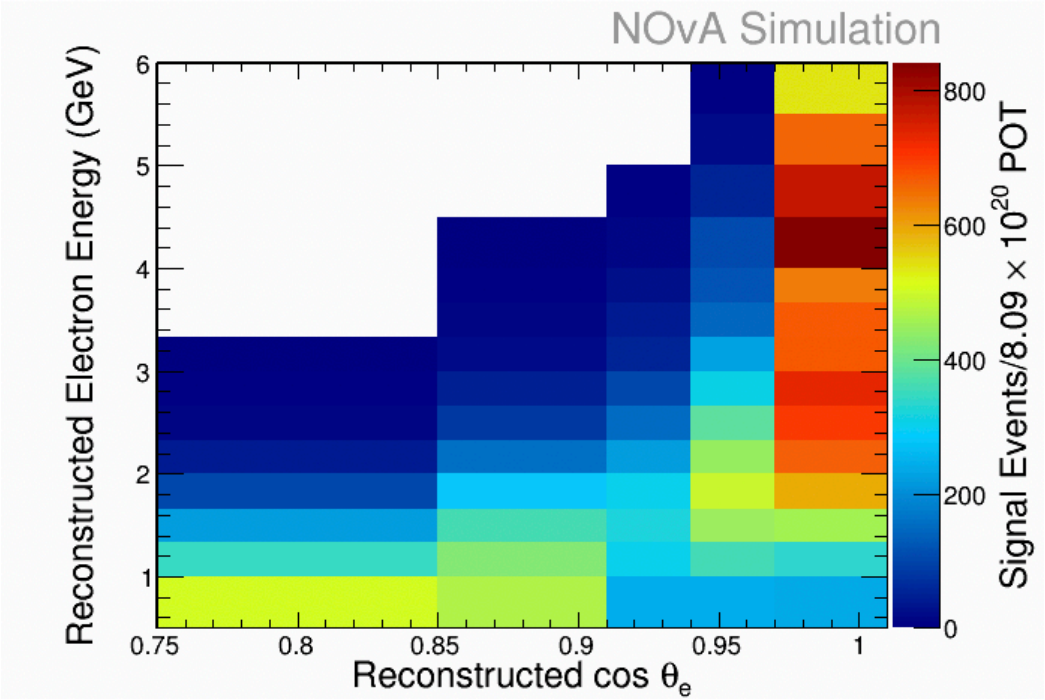


ν_e CC Inclusive

ν_e CC Inclusive Overview

- Signal of appearance measurement
- ν_e account for ~1% of the flux
- Goal
  - Double differential $d^2\sigma/dE_e dcos\theta_e$
  - $\sigma(E)$
  - Long term: ratio to ν_μ CC inclusive



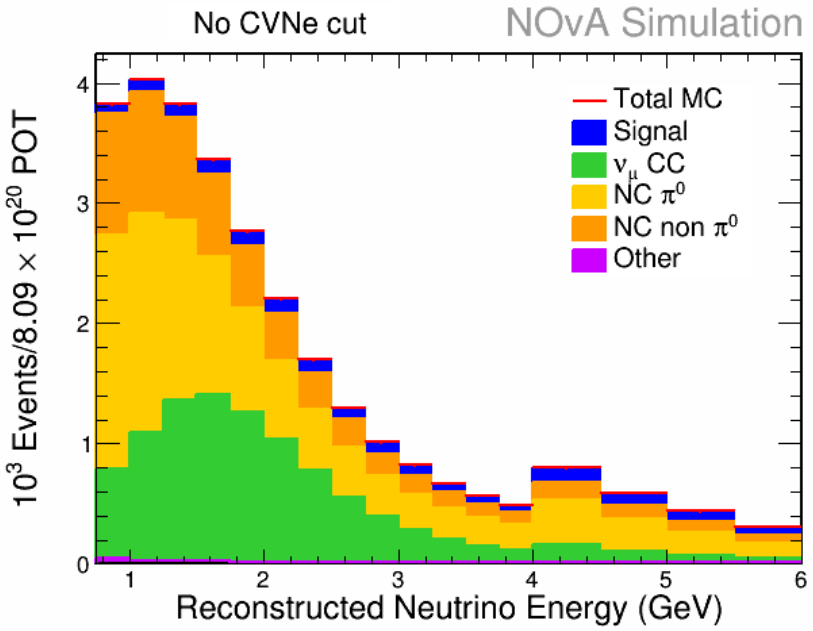


ν_e CC Inclusive Event Selection

cut flow table

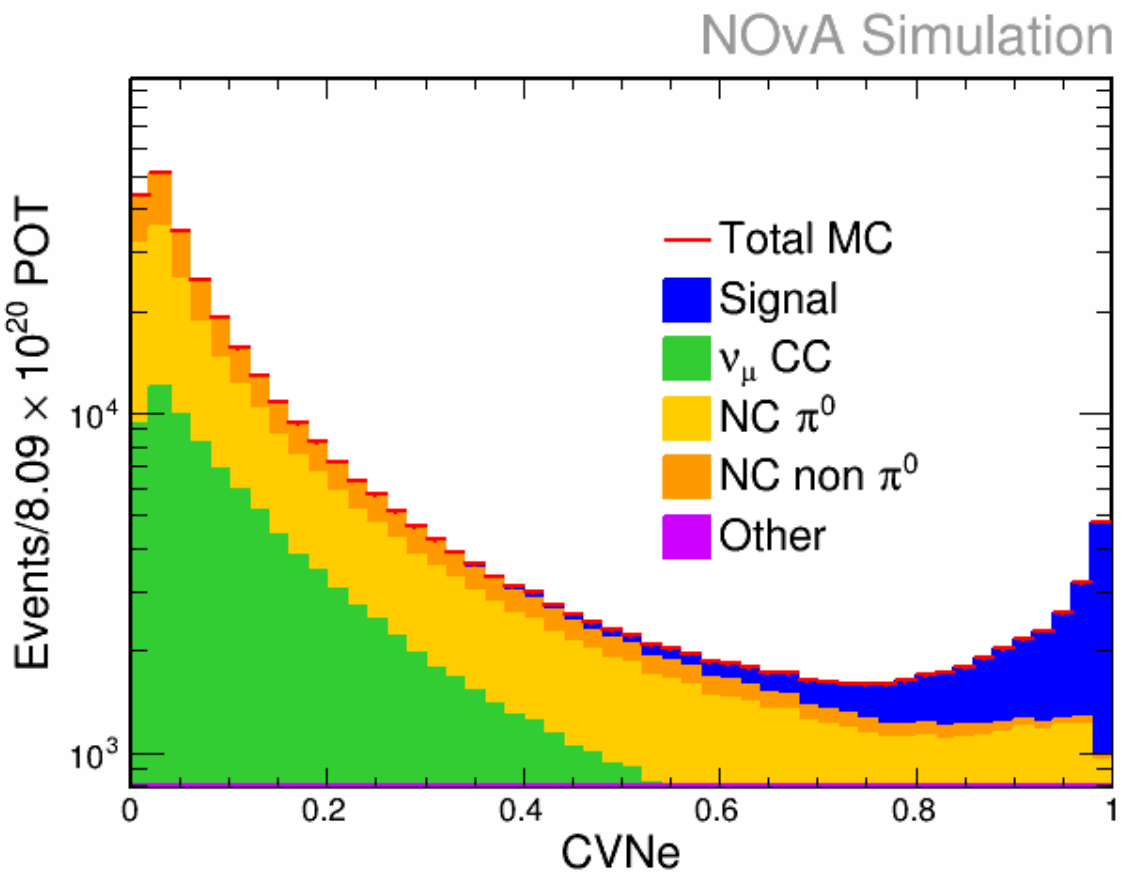
Cut	Signal	Background
Slicing	1,530,520 (100%)	134,201,000 (100%)
Data Quality Cuts	721,905 (47.2%)	85,528,000 (63.7%)
Fiducial	113,160 (15.7%)	6,403,530 (7.5%)
Containment	36,430 (32.2%)	1,278,050 (20.0%)
Front Planes	36,187 (99.3%)	1,269,240 (99.3%)
Number of Hits in Event	22,533 (62.3%)	1,158,890 (91.3%)
Muon ID	19,105 (84.8%)	322,951 (27.9%)

- Primary cuts are applied to remove background events
  - Mostly ν_μ CC
- After these, still left with enormous background events
- More powerful tools required



ν_e CC Inclusive Event Identification

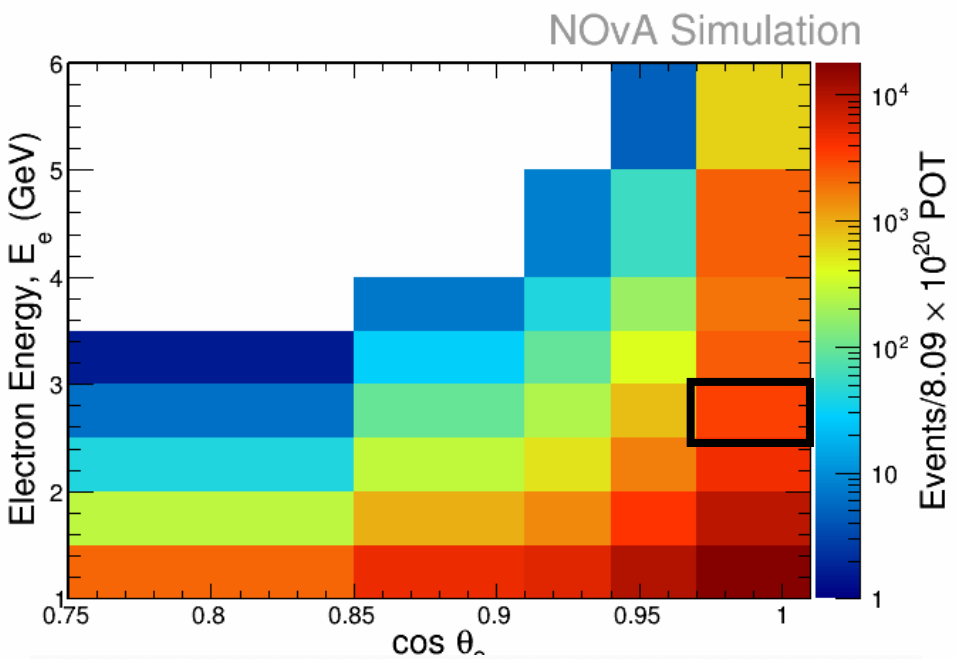
- Convolutional Neural Network based event identification method called CVN
- Identify events by their topological features
- Effort is put into removing event generator dependence
  - Trained on single particle events

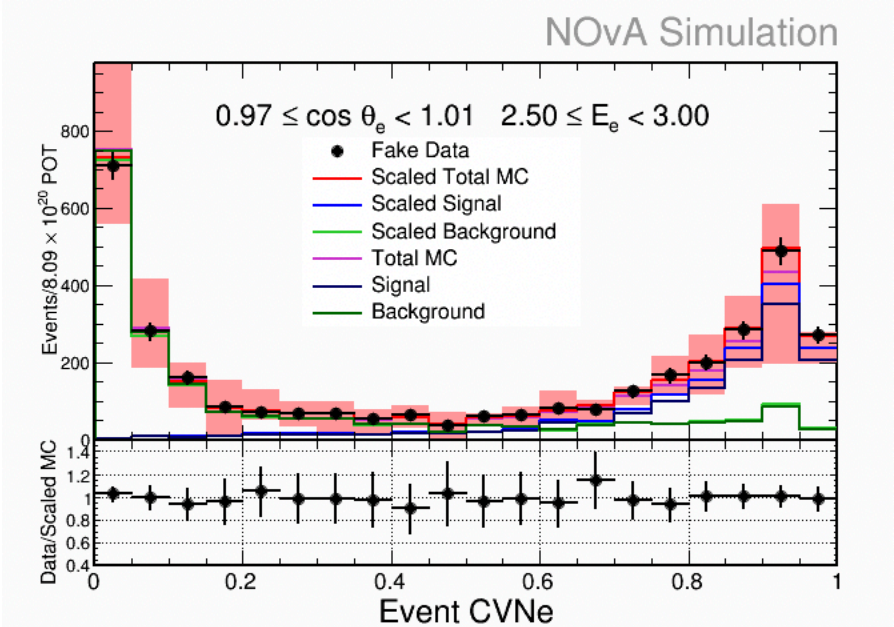


ν_e CC Inclusive Template Fitting

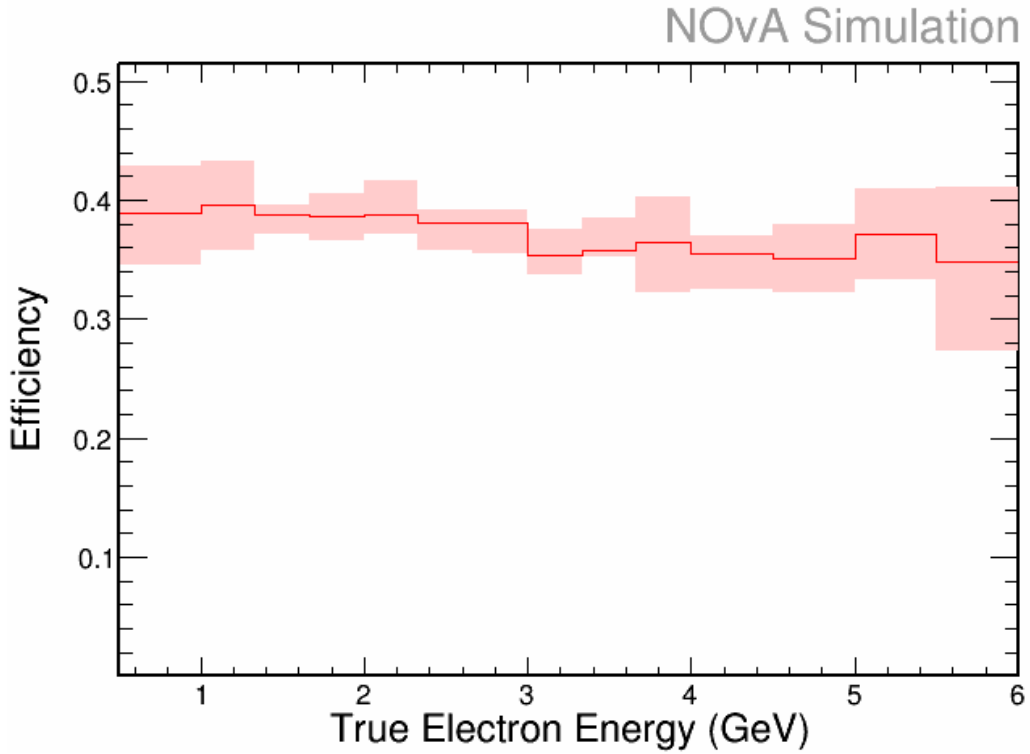
- To further estimate signal and background, template fit is performed
  - Same technique used in ν_μ CC π^0 as well
- Fit adjusts normalizations of signal, ν_μ CC, and NC templates to match data distribution, bin by bin
- Fit also takes into account various systematic uncertainties and the correlations between them
  - Systematic uncertainties are estimated by modified MC (for detector calibration) or by reweighting existing MC (cross-section model uncertainties)

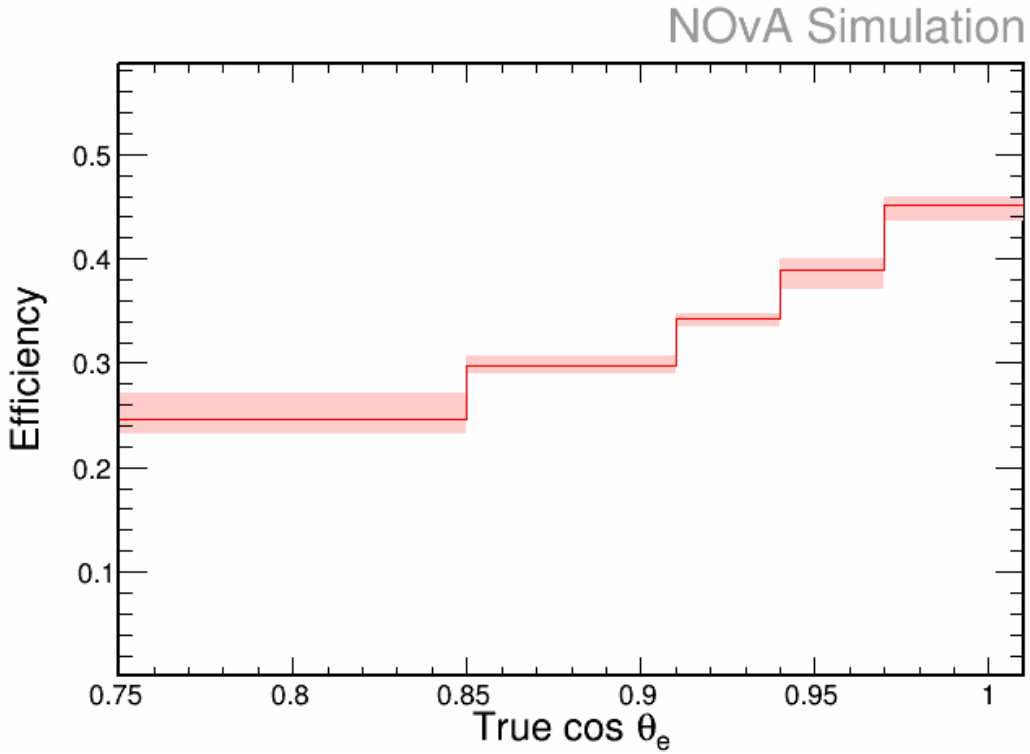
$$\chi^2 = (\mathrm{Data}_i - \mathrm{MC}_i)^T V_{ij}^{-1} (\mathrm{Data}_j - \mathrm{MC}_j)$$
$$V_{ij} = V^{\mathrm{stat}} + V^{\mathrm{syst}}$$





ν_e CC Inclusive Selection Efficiency





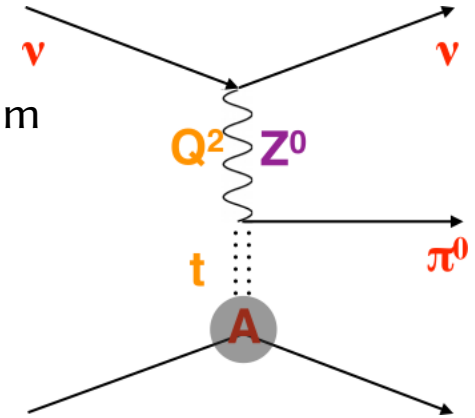
- Template fit leaves efficiency at a relative high level, ~40%
- Systematic uncertainties are estimated by modified MC (for detector calibration) or by reweighting existing MC (cross-section model uncertainties)
- Data driven methods are used and found data MC discrepancy within 2%.
- Preliminary results for this analysis are in place. Stay tuned.

NC Coherent π^0

NC Coherent π^0 Overview

1. Neutrino coherently scatters off target nucleus via neutral current exchange

2. Very small momentum transfer. No quantum number (charge, spin, isospin) exchange



4. Single forward-going pion in the final state. No other pions or nucleons.

3. Target nucleus stays in ground state; No vertex activity.

- π^0 production is one of the most important backgrounds to ν_e appearance oscillation analysis.
- Partially Conserved Axial Current (PCAC) models:
  relate coherent cross- section to pion-nucleus elastic scattering at Q^2=0 limit.
- Challenges: coherent cross-section is relatively small compared to other π^0 production modes
  - Small number of signals (large stat. uncertainty)
  - Large number of background (large syst. unvertainty)

NC Coherent π^0 - Results

6.7% statistical uncertainty with 3.7E20POT data

10.4% systematic uncertainty from background modeling, constrained by control sample data

Selected data

Normalized Background

$$\sigma = \frac{N_{Data,selected} - N_{Bkg,norm}}{\epsilon \times N_{Target} \times \phi}$$

Signal efficiency

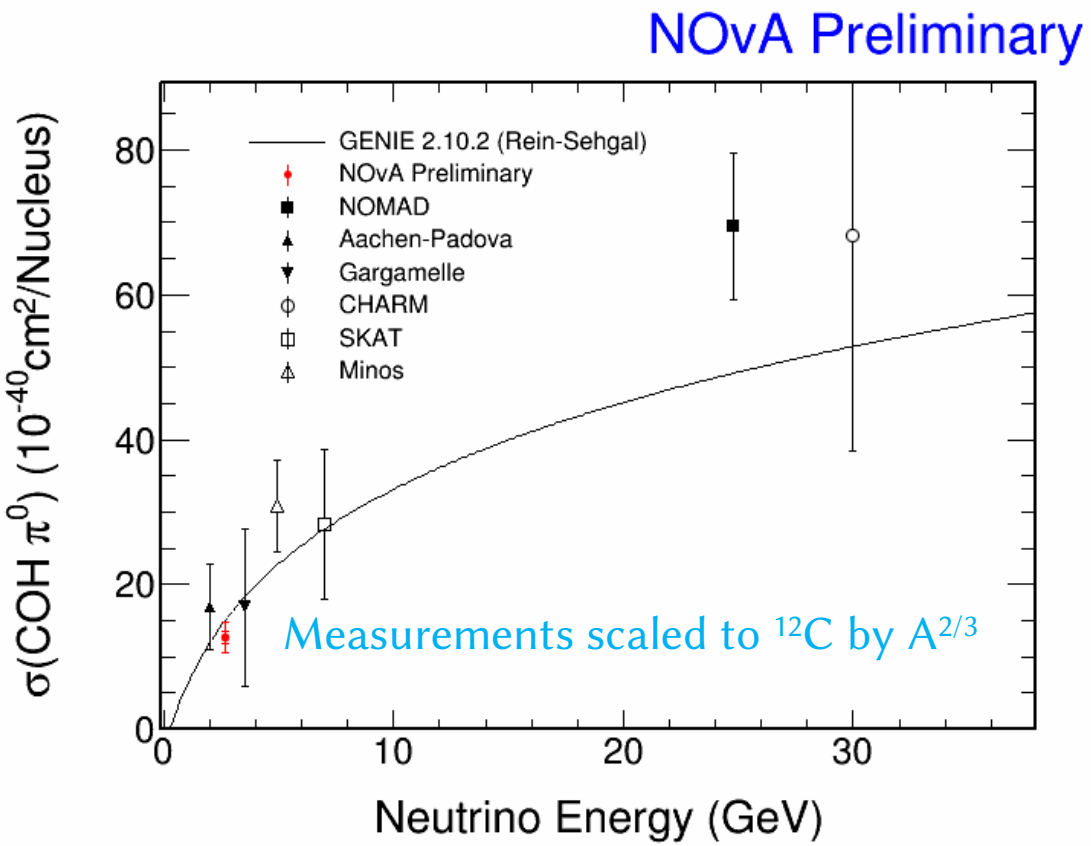
3.7% Uncertainty from signal modeling and 1% from EM shower modeling

Number of target nucleus

<1% uncertainty from detector simulation

Flux

9.4% uncertainty Constrained by external hadron production data

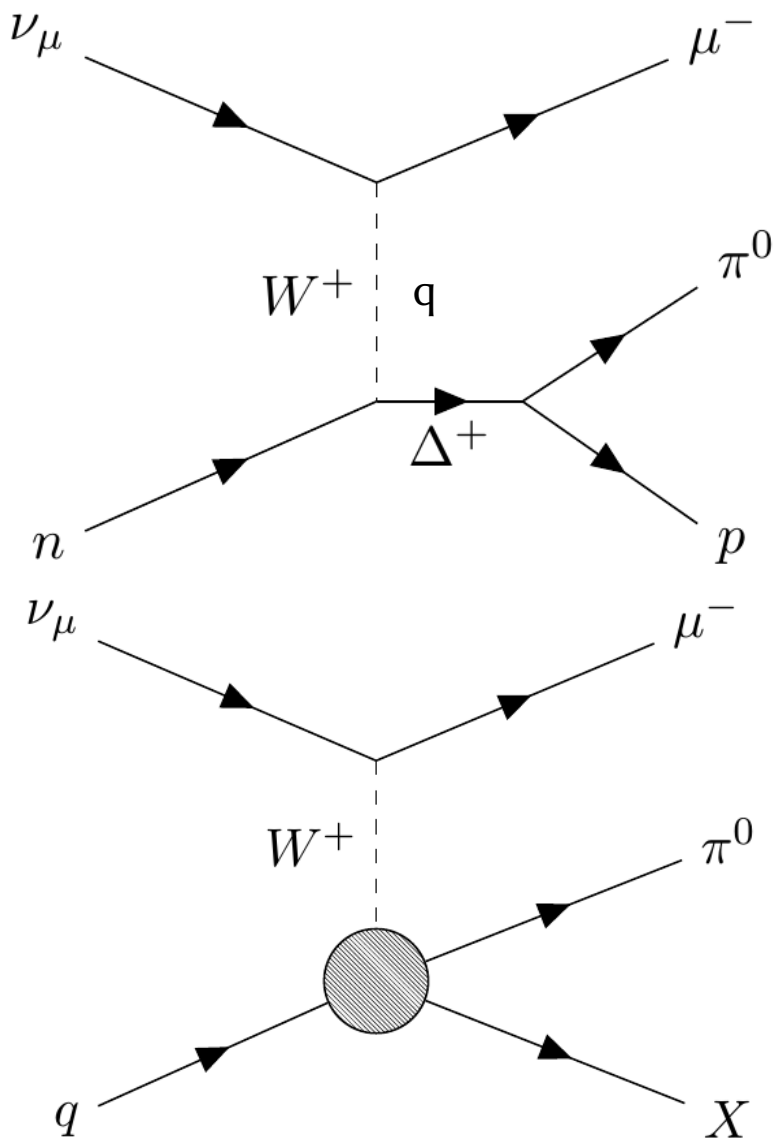


- Measured flux-averaged cross-section:
  σ = 14.0 ± 0.9(stat.) ± 2.1(syst.)×10^{-40} cm2/nucleus
- One of the best measurements in the few-GeV region.

ν_μ CC π^0 Semi-Inclusive

ν_μ CC π^0 Semi-Inclusive Overview

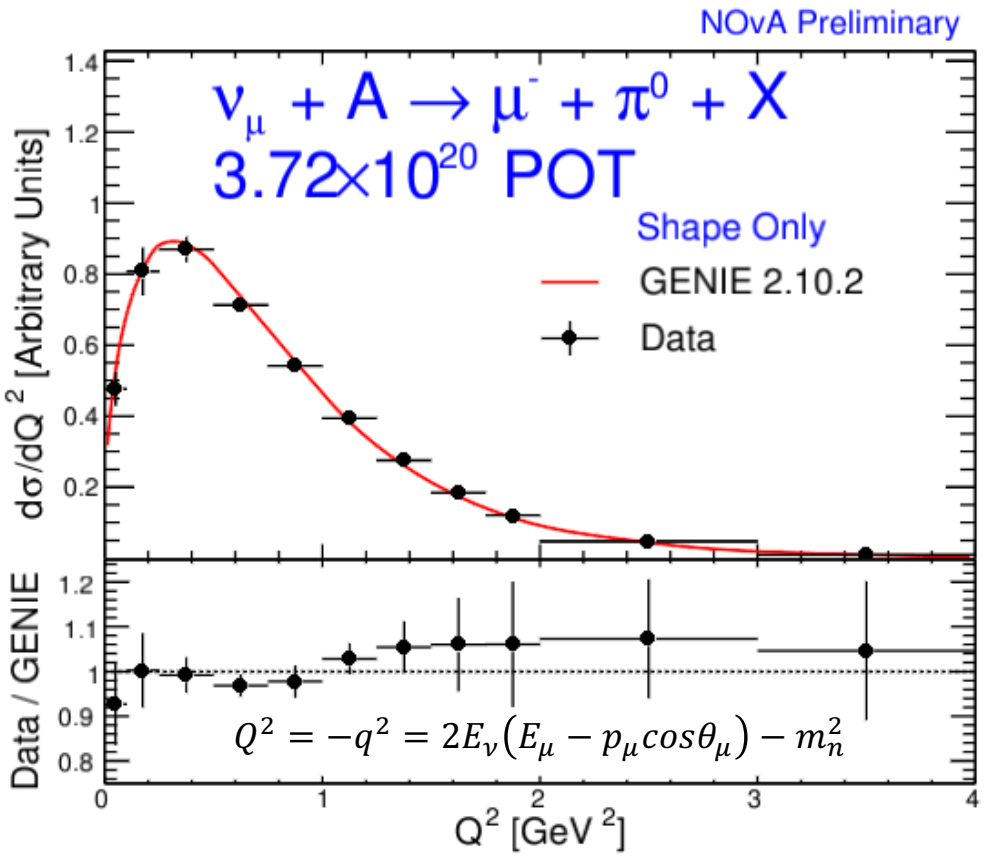
- Deliver flux-averaged cross sections differential in:
  - direct observables $p_\pi, cos\theta_\pi, p_\mu, cos\theta_\mu$
  - four-momentum transfer to hadronic system: $Q^2 = -q^2$
  - invariant mass of the hadronic system, useful for separating DIS and Res events: $W = \sqrt{(n+q)^2}$

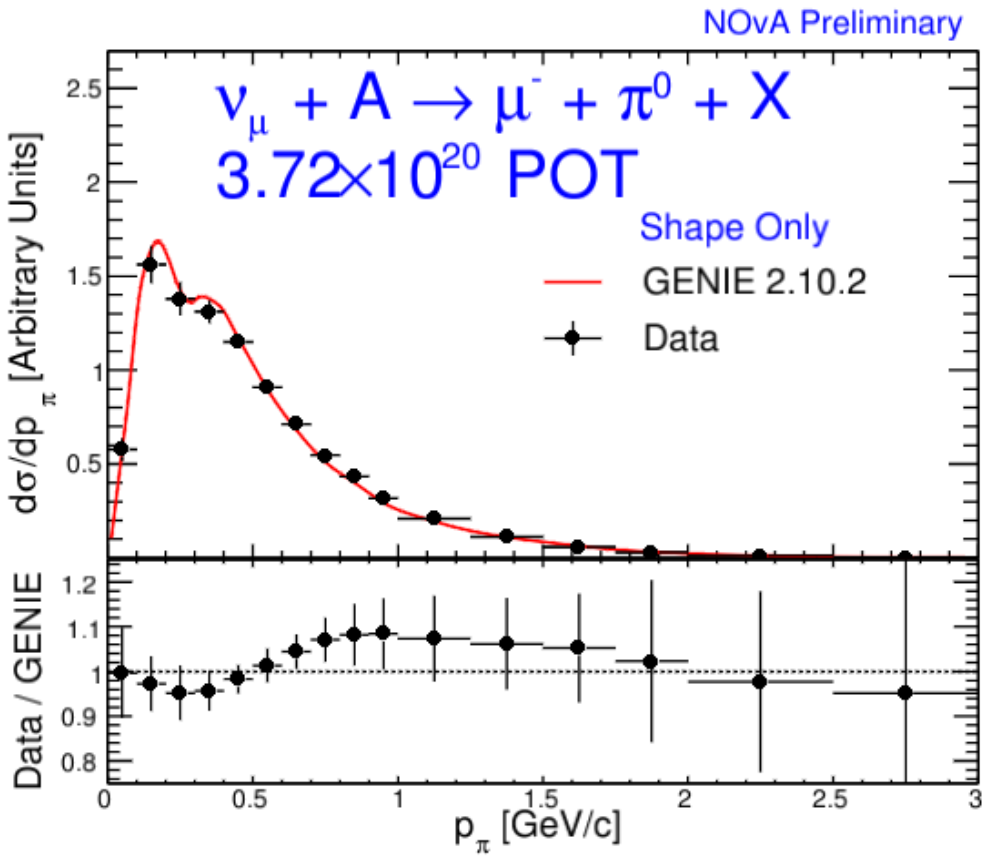


resonant interactions

DIS interactions

ν_μ CC π^0 Semi-Inclusive Results





- Systematic uncertainties are similar to other analyses
- In both cases, data suggests harder shape than the generator.
- Other variable results are also available but not shown.

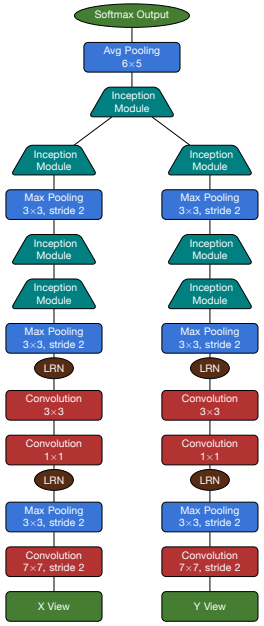
Summary and Outlook

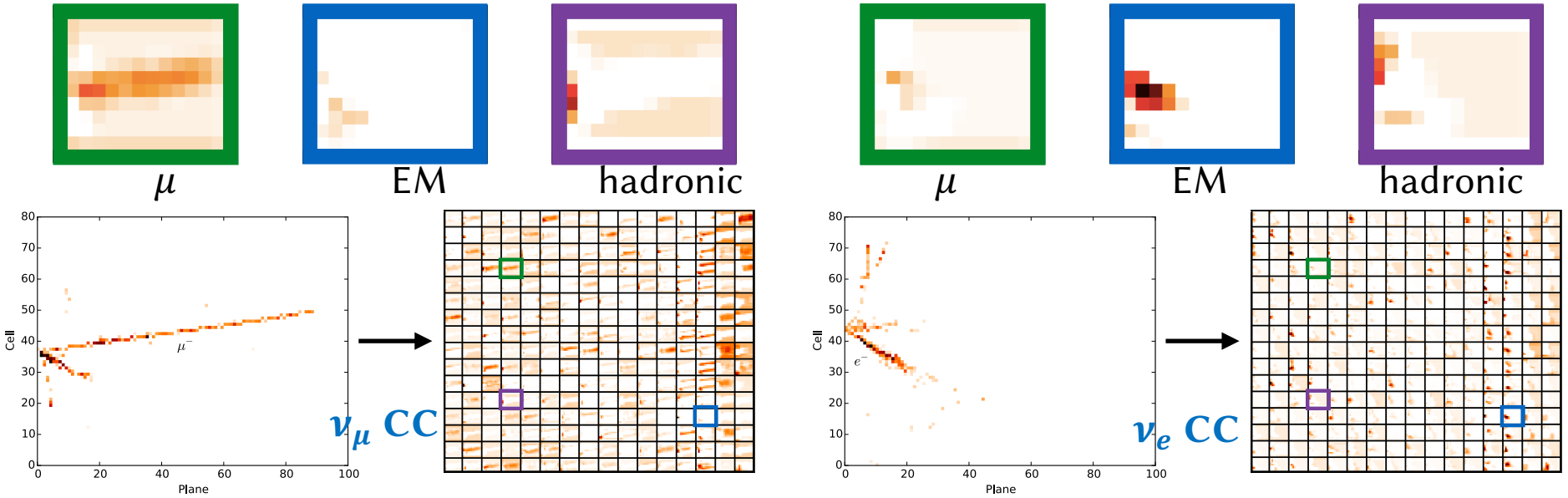
- The ideas and methods of four NOvA cross-section measurements were presented
  - ν_μ CC inclusive
  - ν_e CC inclusive
- NC coherent π^0 and ν_μ CC π^0 semi-inclusive has gone through the Fermilab JETP seminar, a milestone before publication
  - NC coherent π^0 has been submitted to PRD and is under review
  - ν_μ CC π^0 semi-inclusive is under collaboration review
- Many other measurements with reversed horn current beam are underway, and ratio measurements will follow.

Thanks!

Backup

Topics Shared by Multiple Analyses
Convolutional Visual Network (CVN)

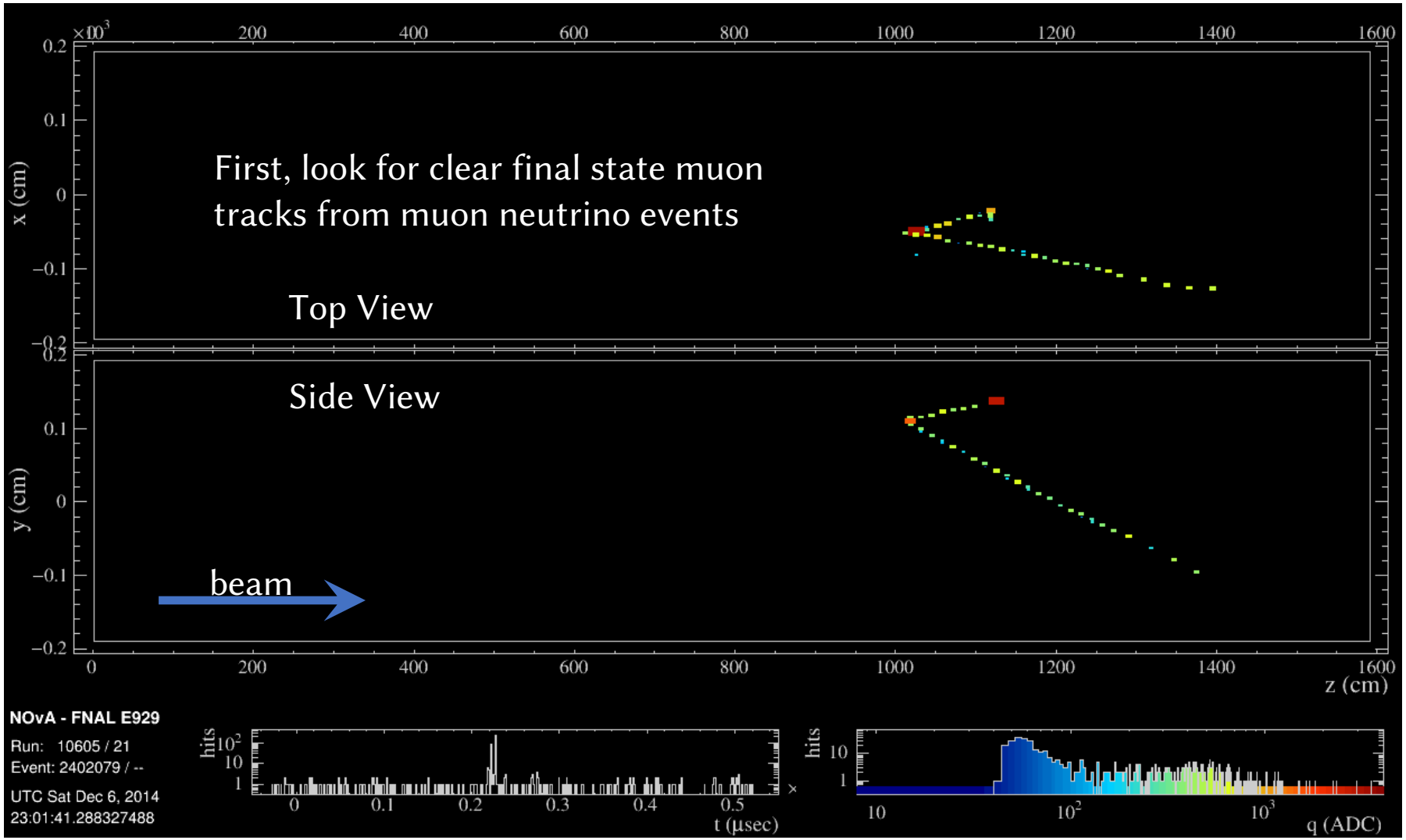




- Deep neural networks developed by computer scientists
- By stacking many hidden layers, such networks are able to extract more and more advanced features, and eventually outperform human in image recognition.
- NOvA adopted the technology and it turned out to perform well in identifying topological features of different types of neutrino events.

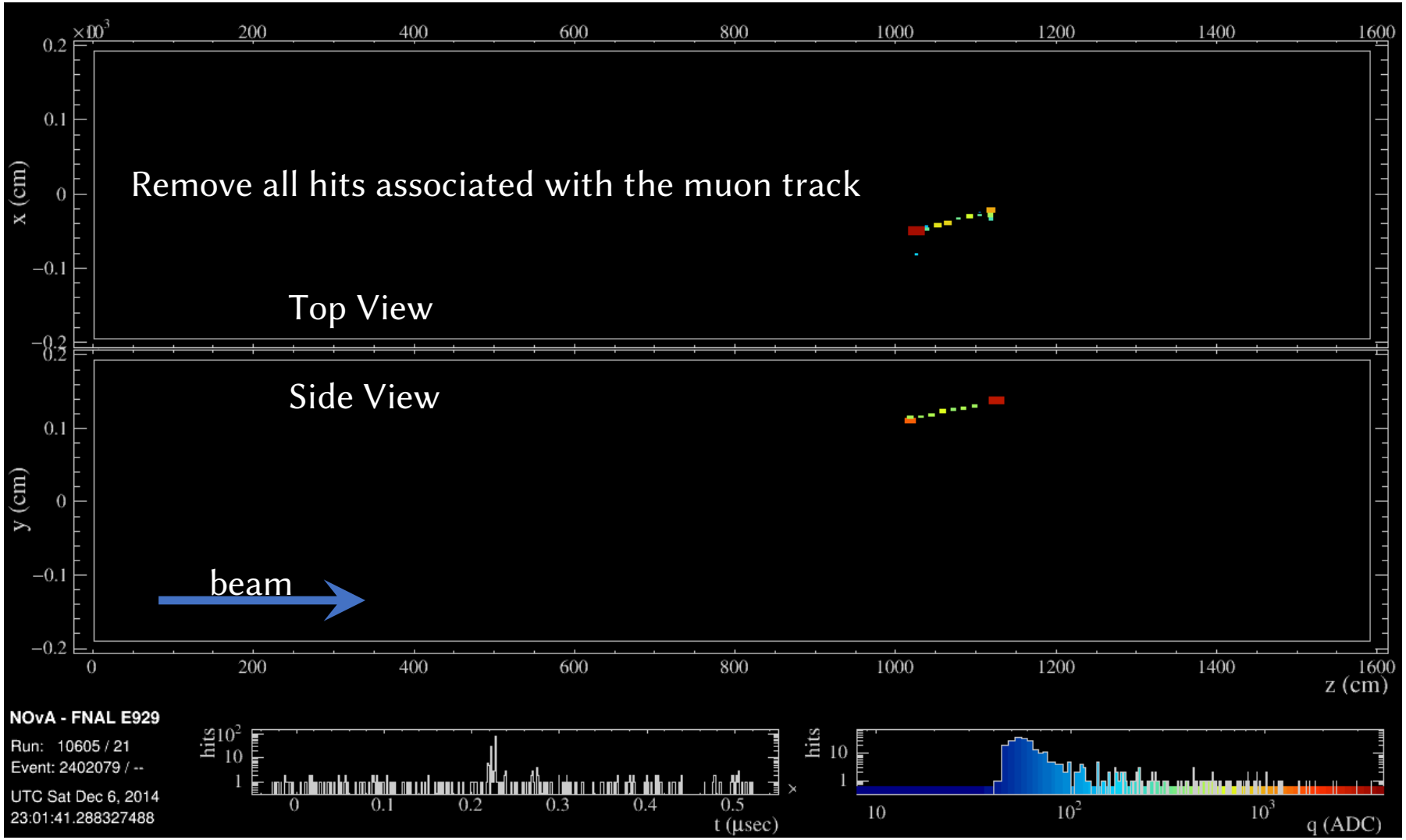
ν_e CC Inclusive

Data Driven Method for Checking Selection Efficiency



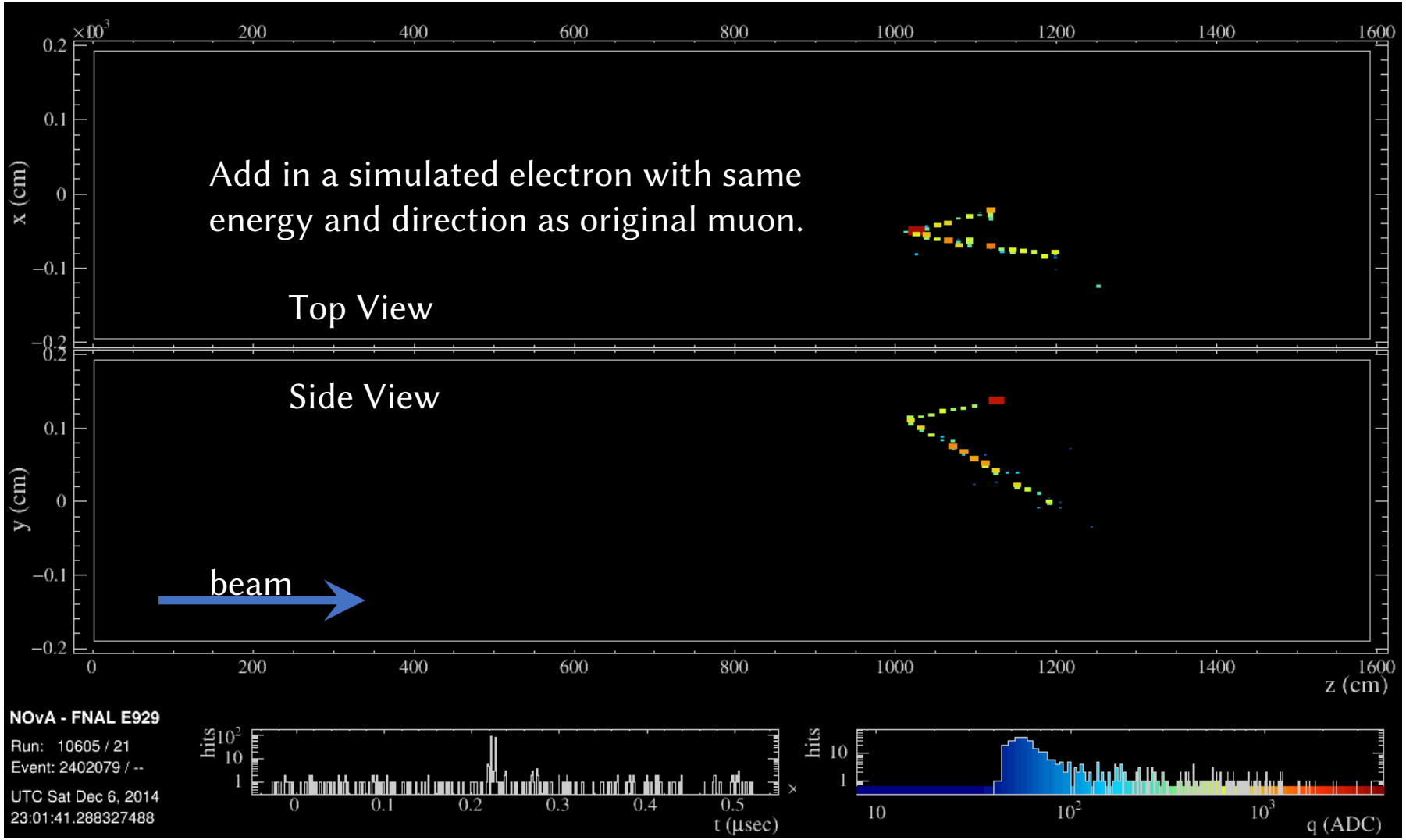
ν_e CC Inclusive

Data Driven Method for Checking Selection Efficiency



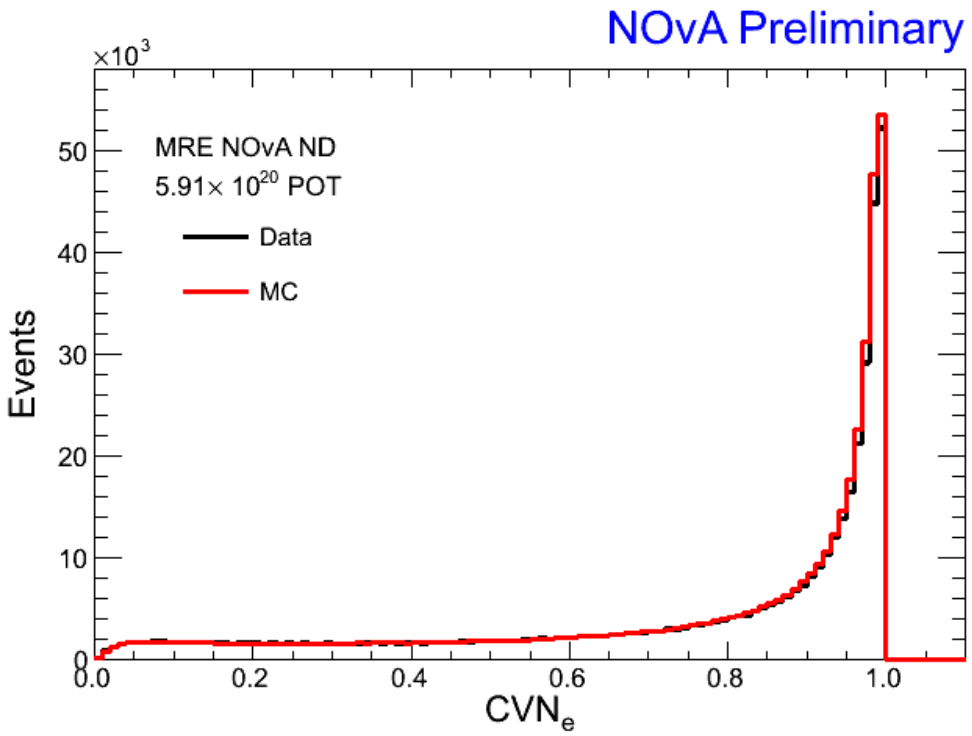
ν_e CC Inclusive

Data Driven Method for Checking Selection Efficiency



ν_e CC Inclusive
Data Driven Method for Checking Selection Efficiency

- This technique is called Muon Removal - Electron Added (MRE)
- Our selection is applied to each of these modified datasets and the differences in efficiency can be compared
  - Allows for the study of the hadronic response and effects it has on our selection
- Total selection efficiency difference between data and MC is ~2%.

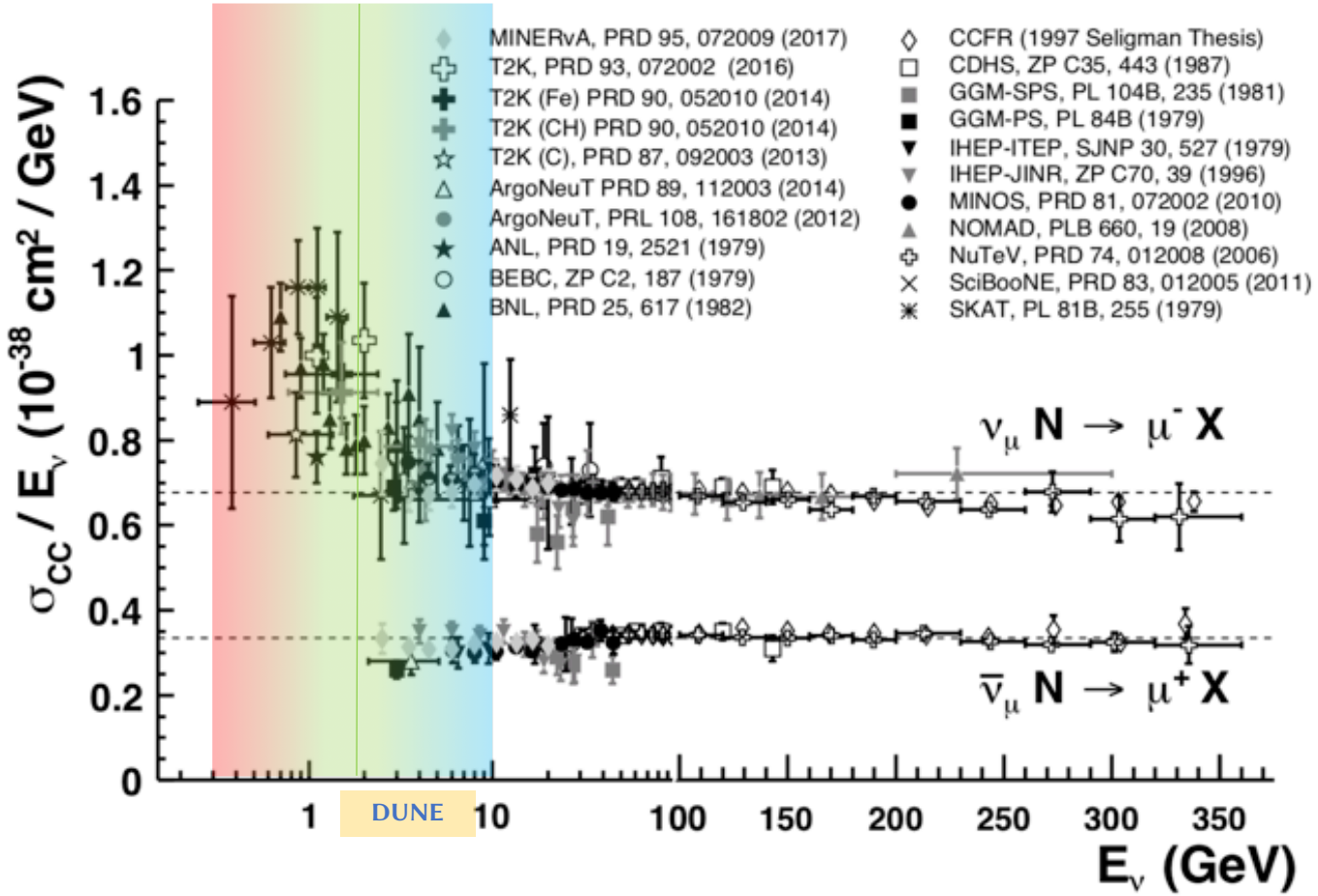


Motivation

- Accurate knowledge of neutrino-nucleon interaction cross section is required for energy measurement, crucial for oscillation analyses.
- Previous measurements in NOvA energy range has 10-20% uncertainties.

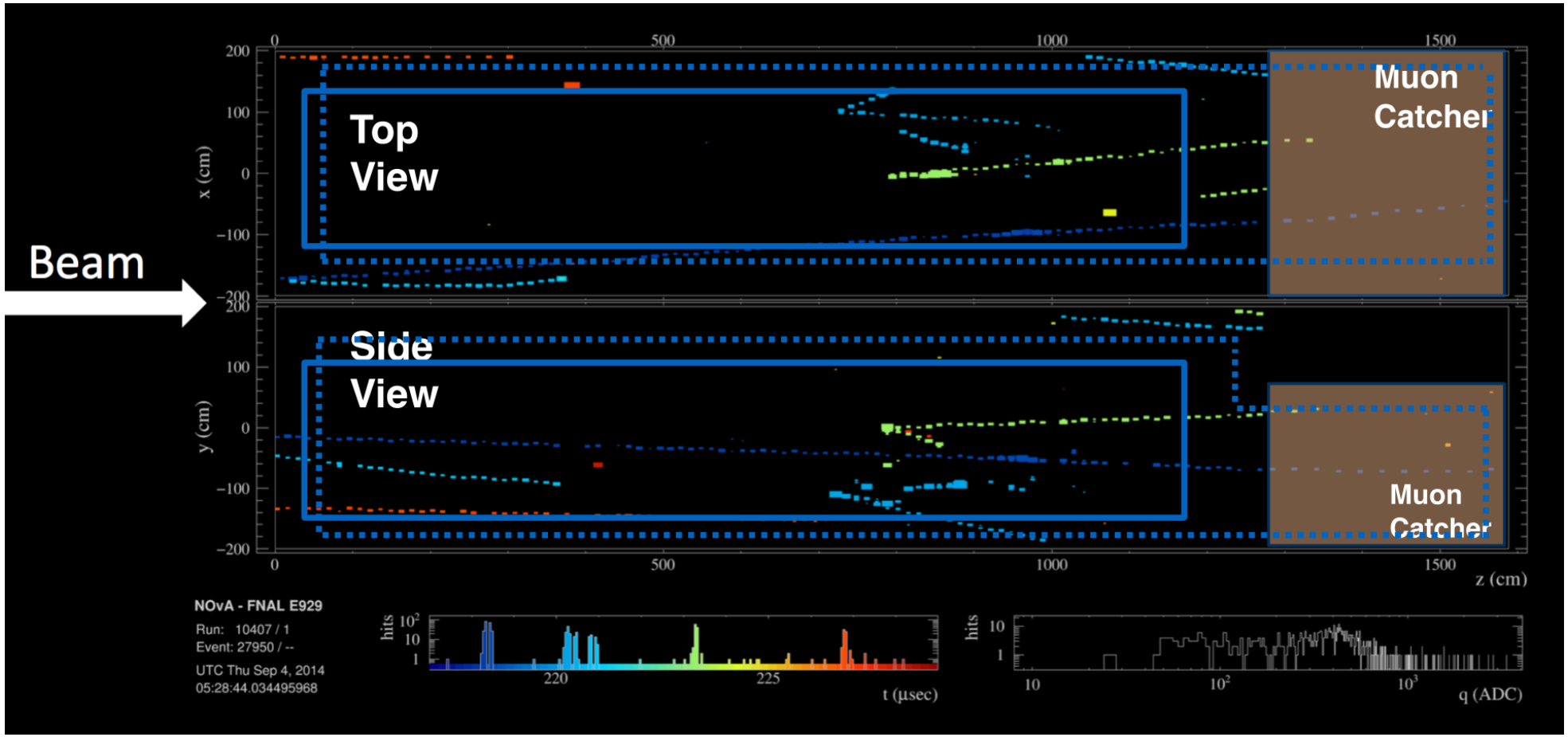
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

T2K+MicroBooNE+NOvA+MINERvA



Event Selection – Fiducial and Containment

$$\frac{U(N^{sel} - N^{bkg})}{\epsilon \phi N_{target}}$$



- Fiducial (solid)
  neutrino interaction vertices in fully active region to remove interactions in rock which enter the detector
- Muon containment (dashed)
  muon is contained in the detector to ensure good muon energy reconstruction

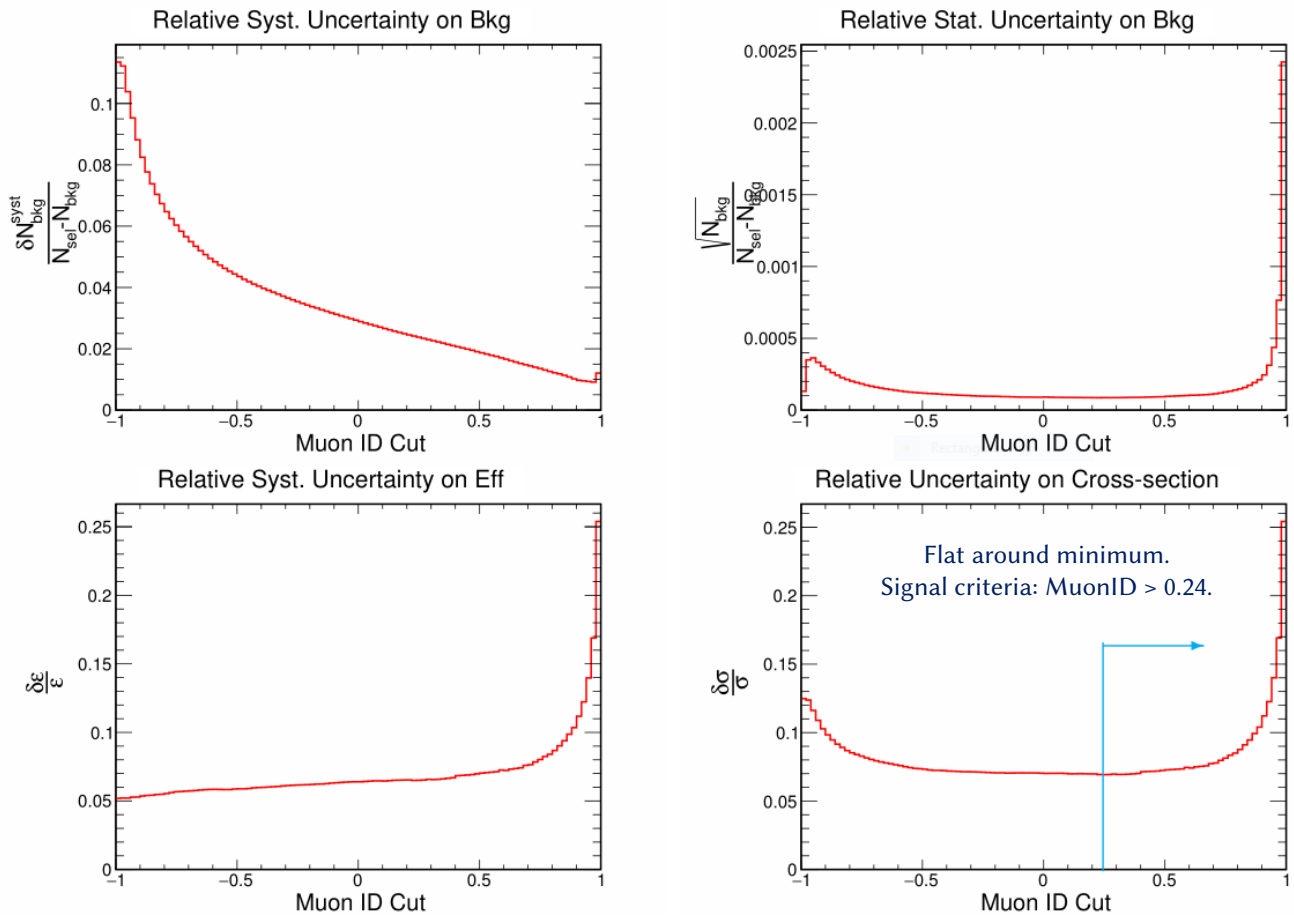
MuonID Cut Optimization

$$\frac{U(N^{sel} - N^{bkg})}{\epsilon \phi N_{target}}$$

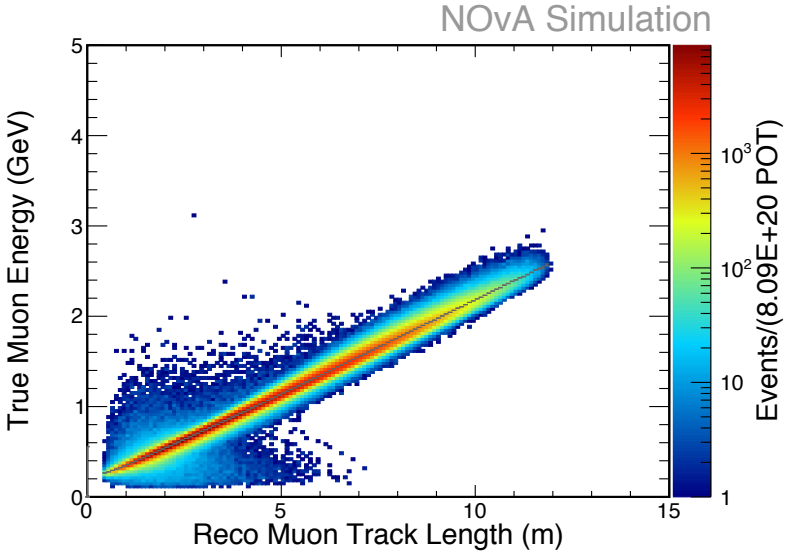
- A general strategy in this analysis is to determine selection criteria that minimize the systematic uncertainty of the total cross section:

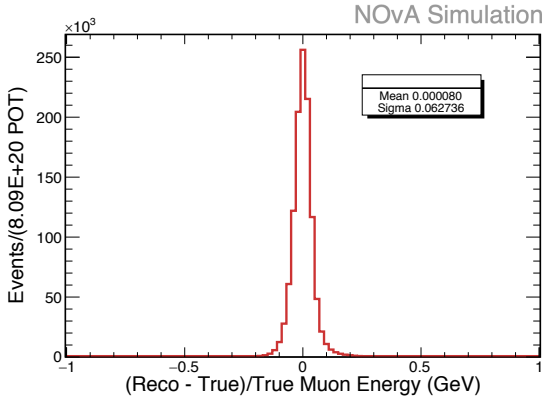
$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\left(\delta N_{bkg}^{syst}\right)^2 + \left(\delta N_{bkg}^{stat}\right)^2}{\left(N_{sel} - N_{bkg}\right)^2} + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

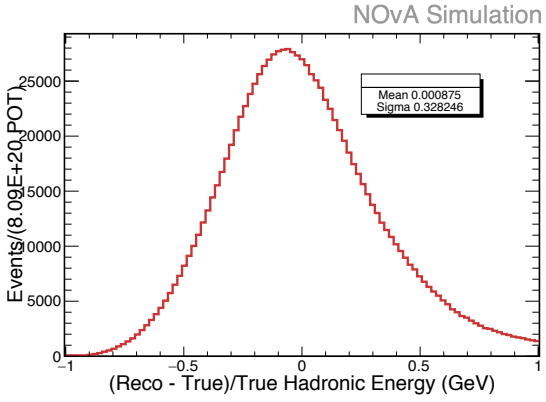
- At low cut values, uncertainty is dominated by background. At high cut values, uncertainty is dominated by the efficiency.
- The same optimization method is used for fiducial and containment cuts as well.

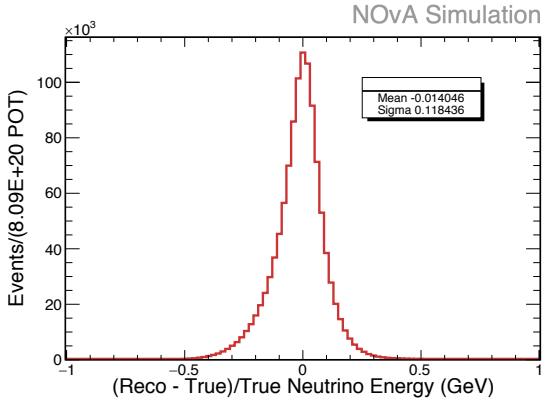


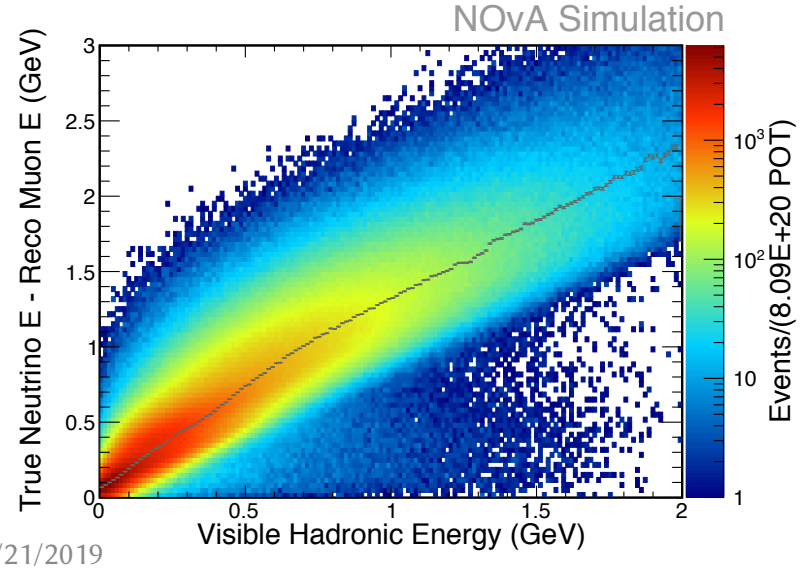
Energy Estimation









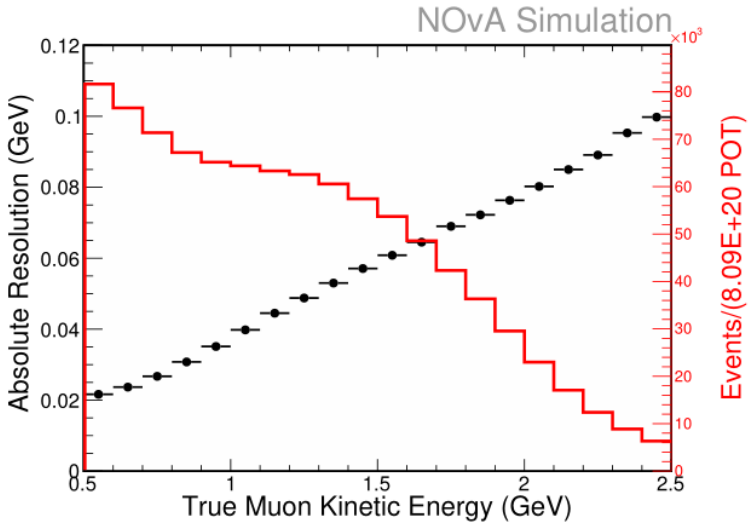


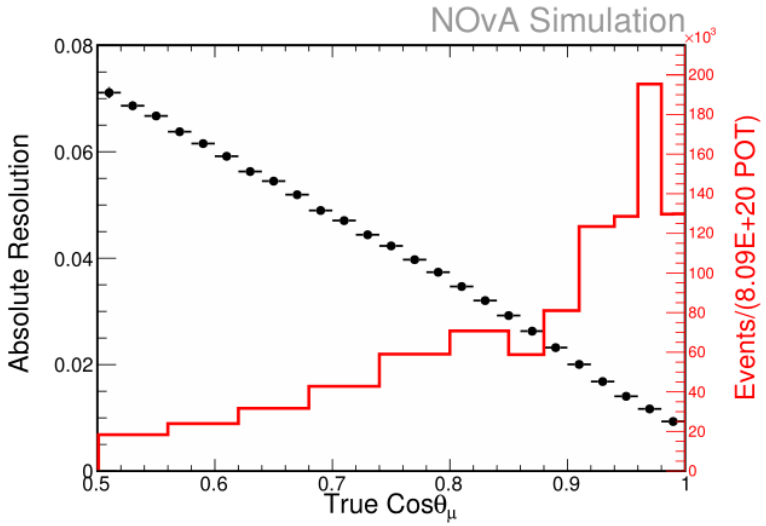
$$E_\nu = E_\mu + E_{had}$$

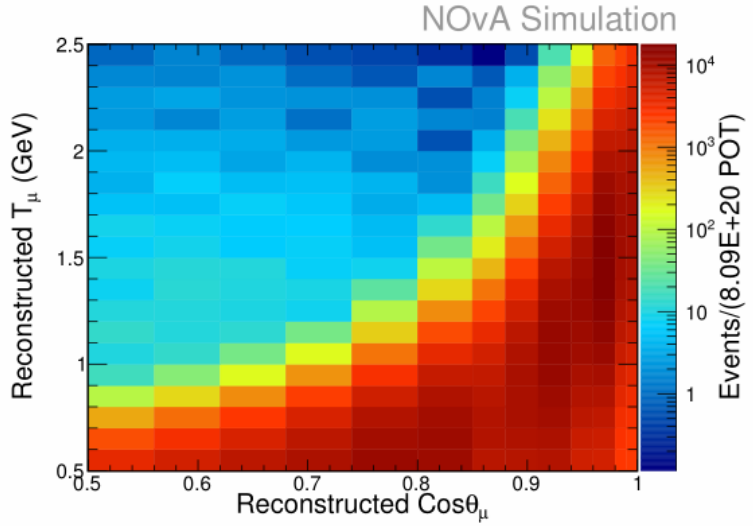
- Using muon track length and visible hadronic energy to estimate muon energy and hadronic energy, respectively.
- Profiles of the plots on the left are fit to polynomial functions.
- Resolution (from standard deviation):
  - Muon ~6%
  - Hadronic ~33%
  - Neutrino ~12%

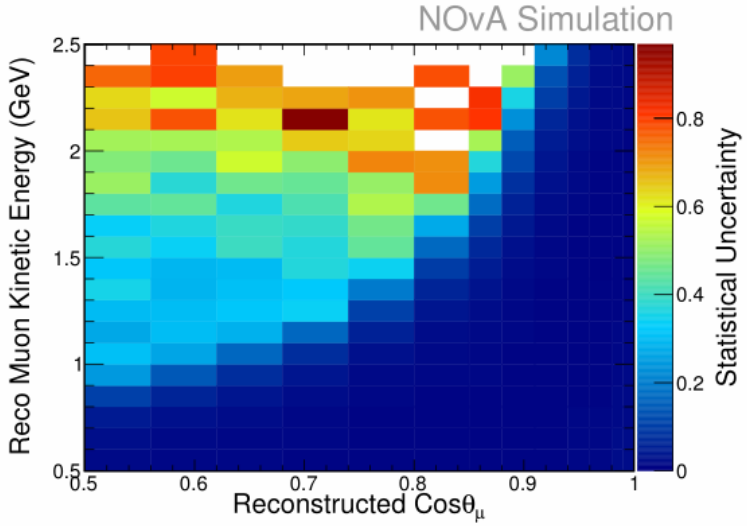
Binning in Muon Kinematic Space

- Binning is determined by resolution, statistics, and number of bins
- T_μ:
  20 even bins in [0.5, 2.5] GeV
- $cos\theta_\mu$:
  13 variable-sized bins
- Small statistical uncertainty in the bottom right region.

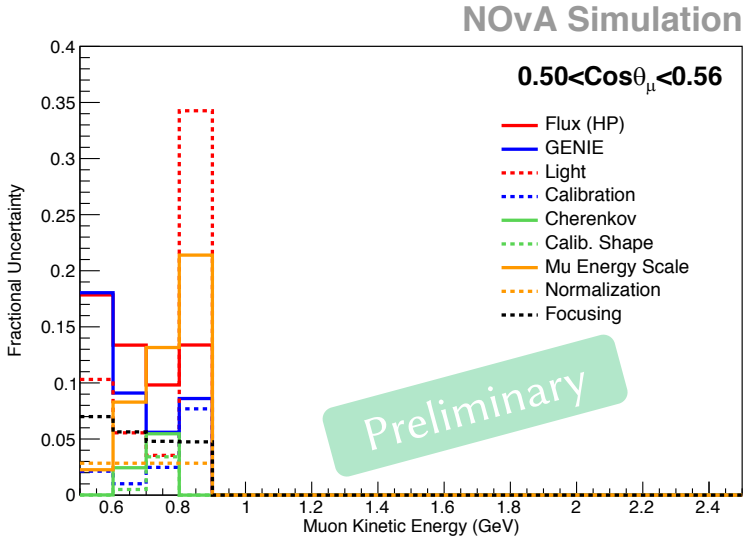


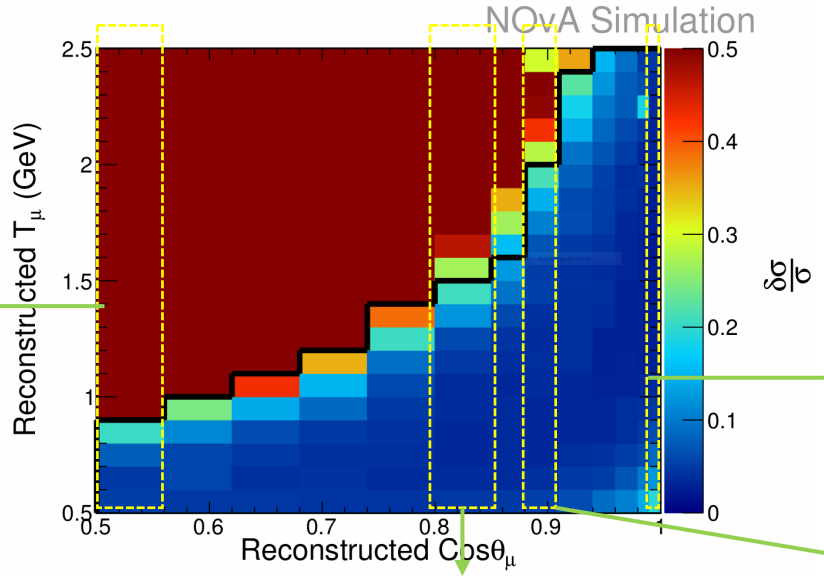


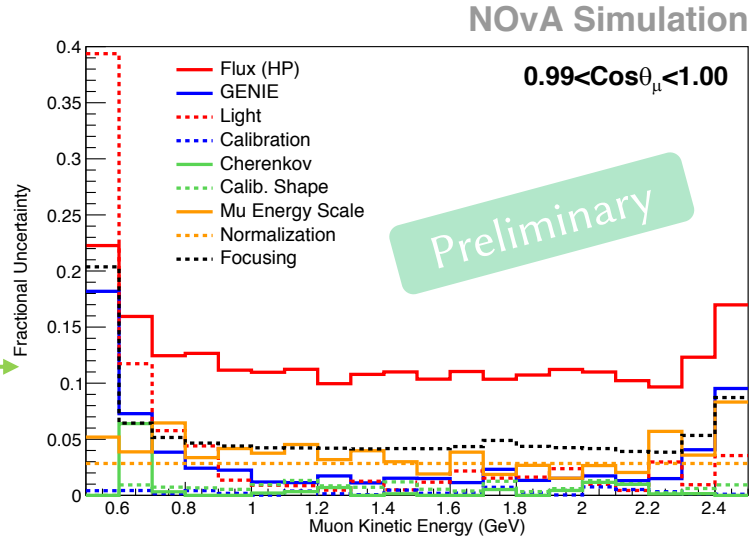




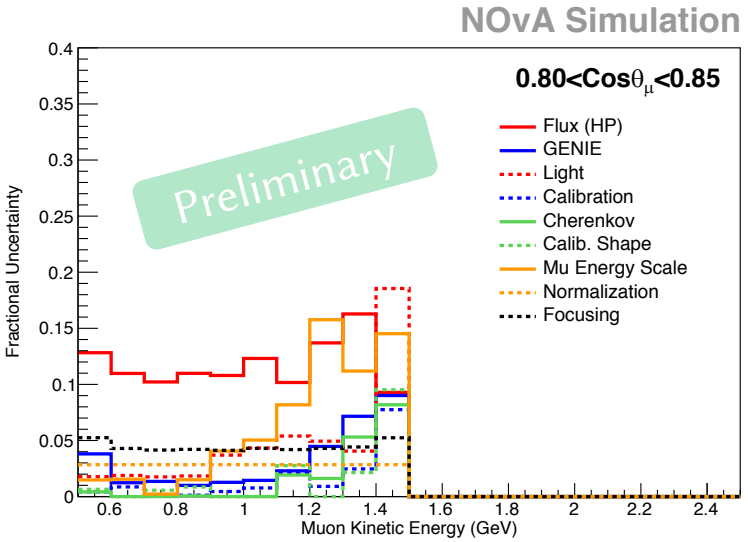
Uncertainties

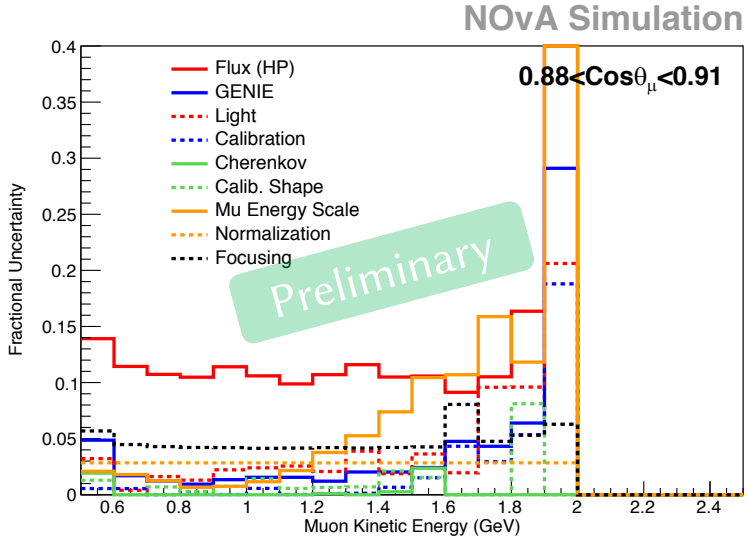




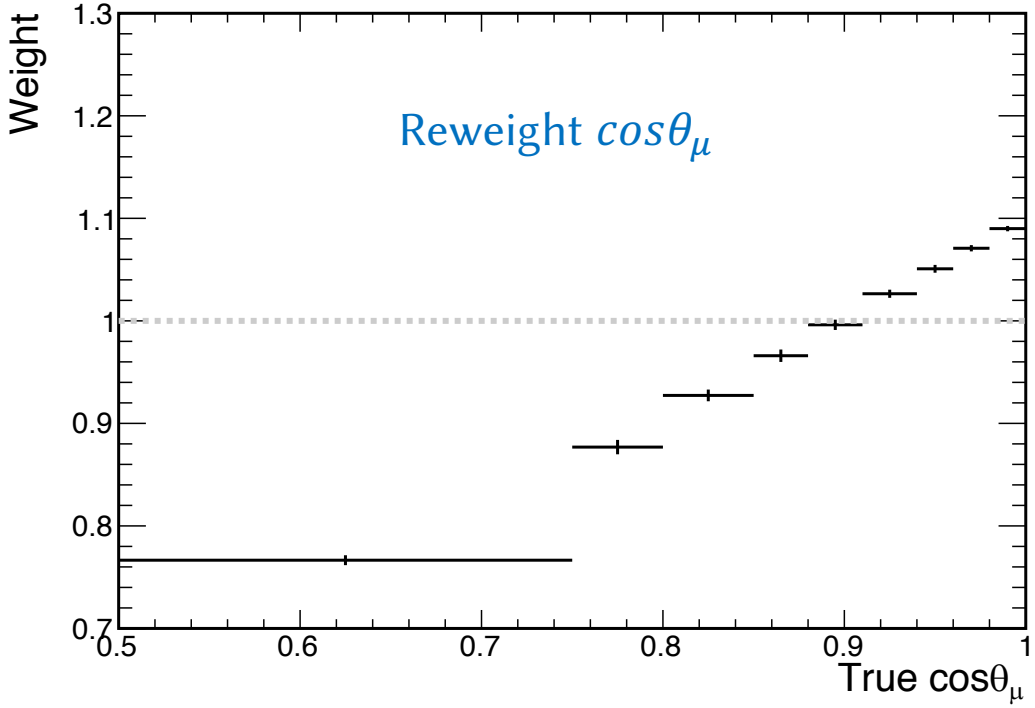


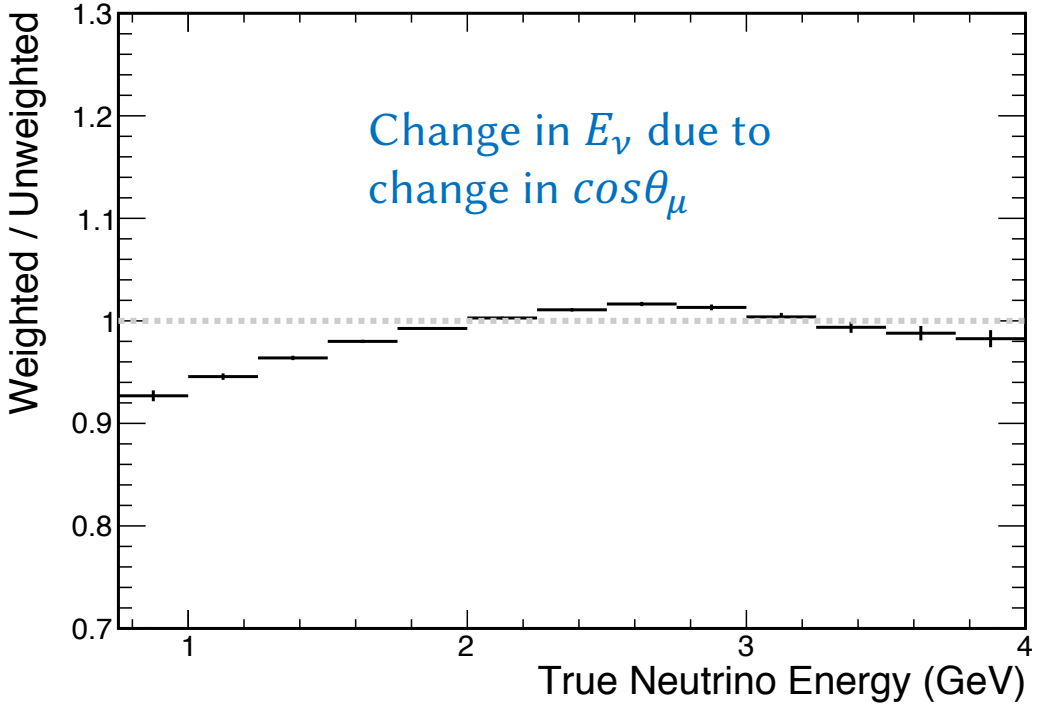
- Adopt multi-universe approach for GENIE as well.
- Still under heavy study and subject to change.
- Overall <20% for most of the bins.





Reweighted Spectrum for 3D Unfolding In-out Test

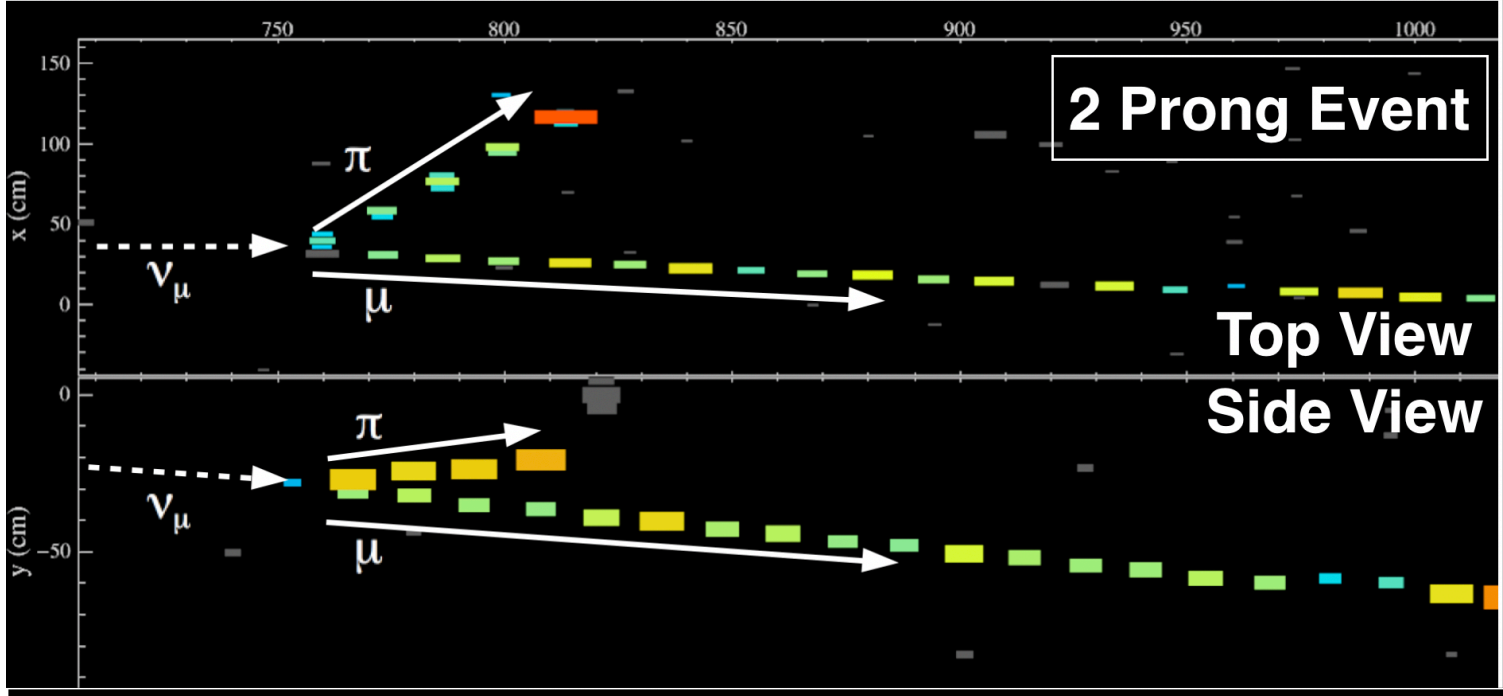


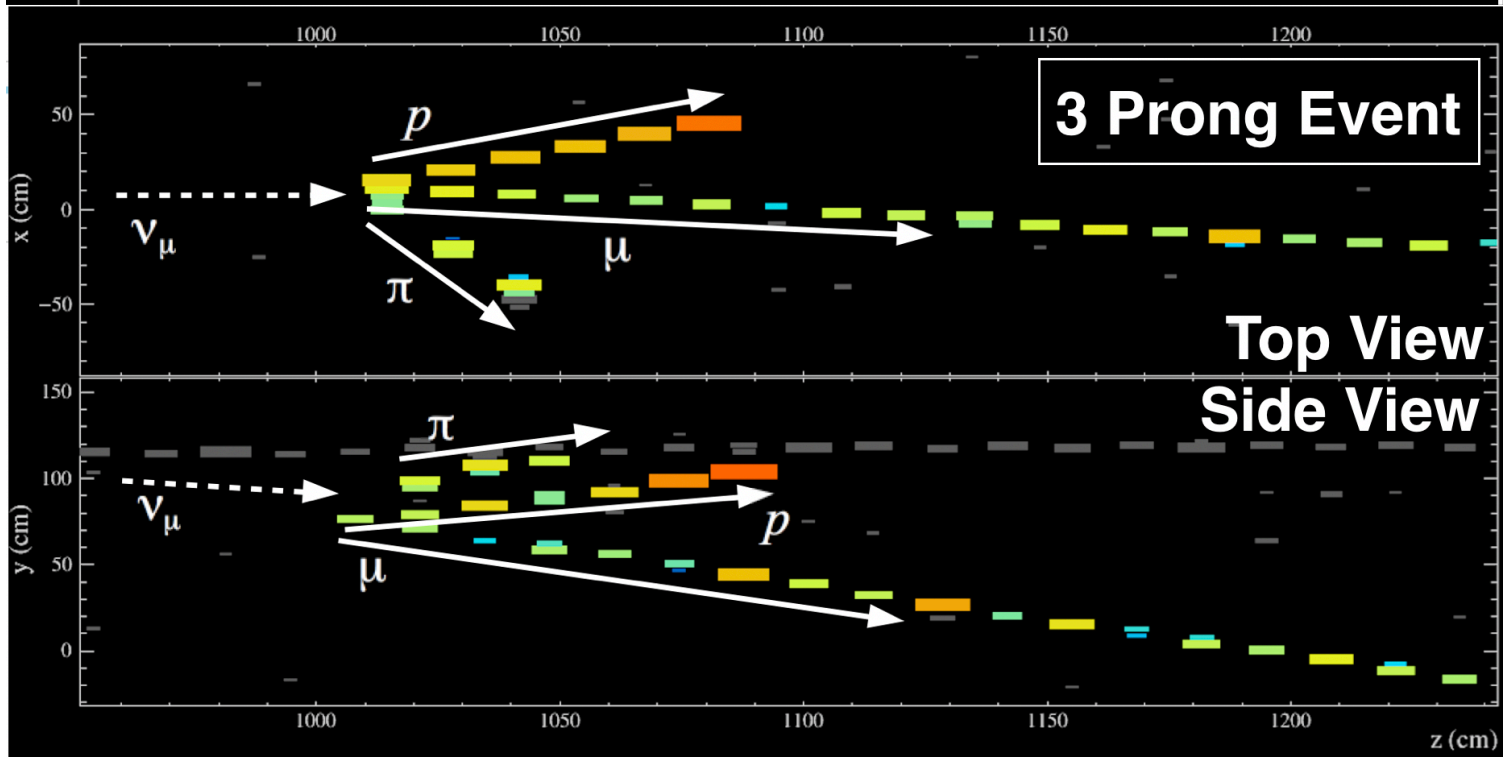


ν_μ CC $\pi^{+/-}$ & 0π

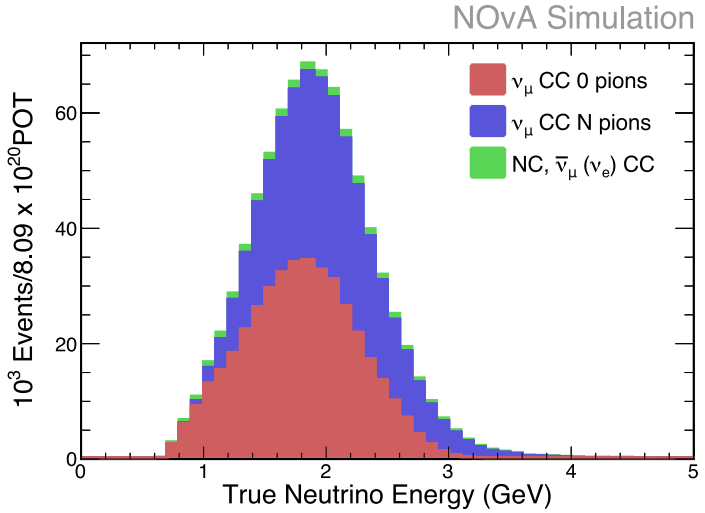
ν_μ CC $\pi^{+/-}$ & 0π

- Each analysis requires the ability to identify and distinguish between protons and pions.
- Makes use of single particle trained CVN to classify reconstructed objects

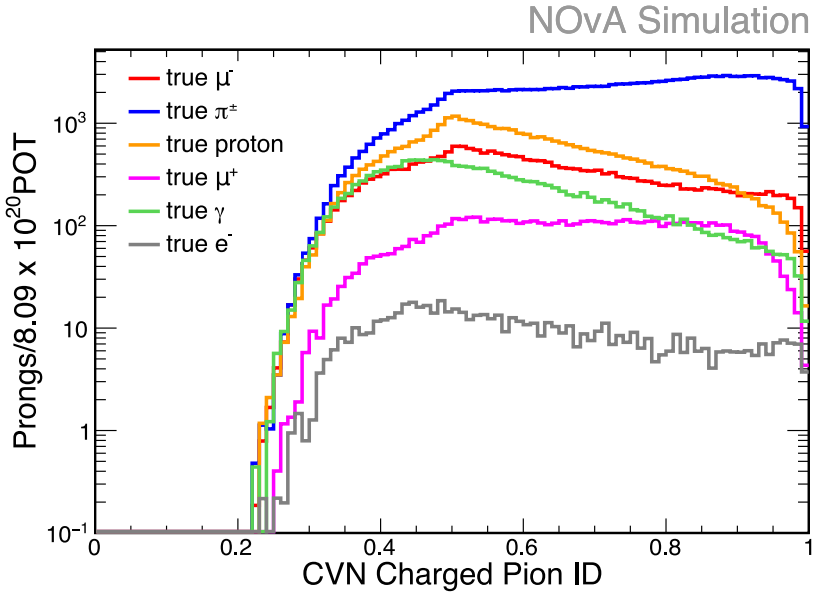


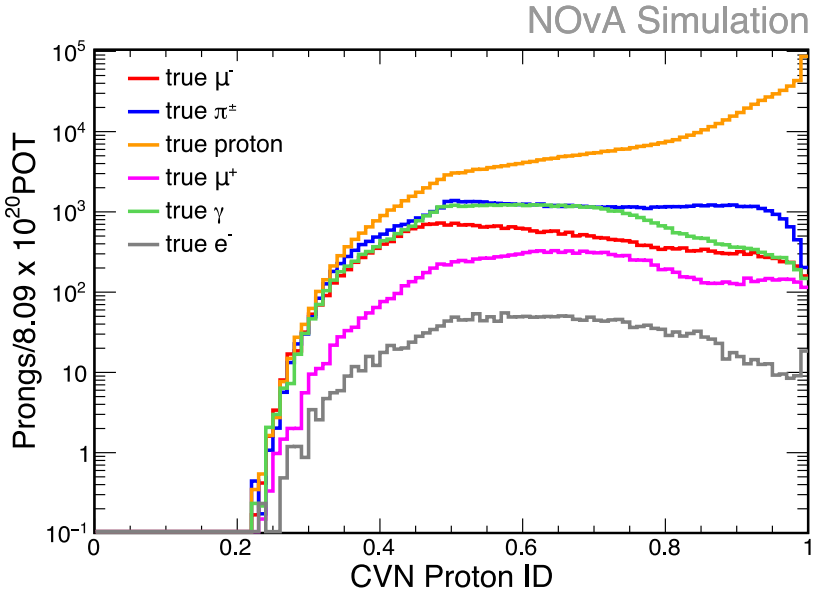


ν_μ CC $\pi^{+/-}$ & 0π



- Start with the ν_μ CC inclusive sample
- Identification of pions can be challenging
- Efficiency of proton selection is 92.8% at >0.5 and 98% at CVN Proton ID at 0.8





Coherent π^0 Analysis Strategy

NC π^0 sample

no muon track, two photon showers, no other particles

Control sample

dominated by non-coherent π^0s, for background normalization.

Bkg Norm

Signal sample

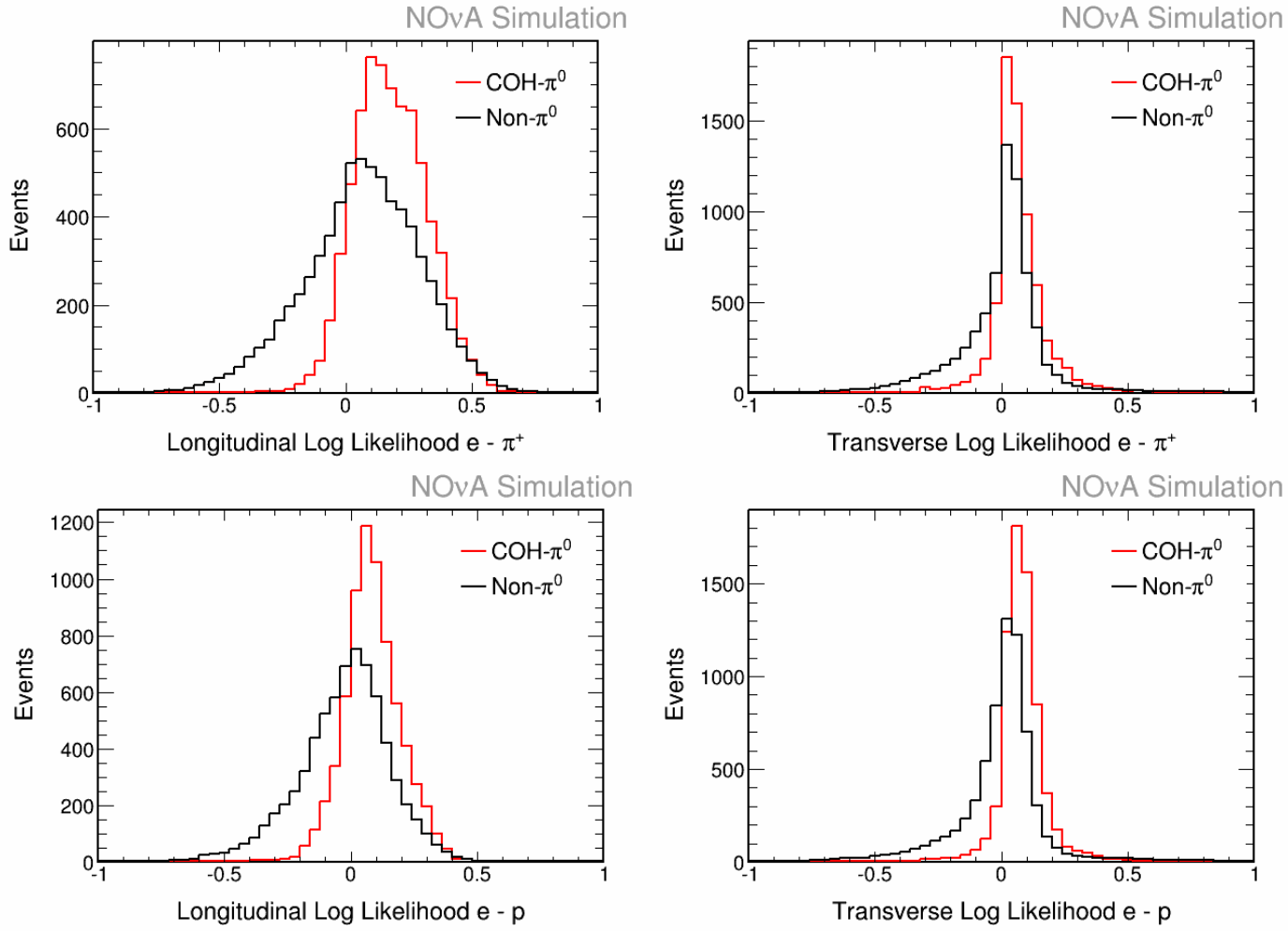
includes most of the coherent signal

Flux-averaged cross-section measurement

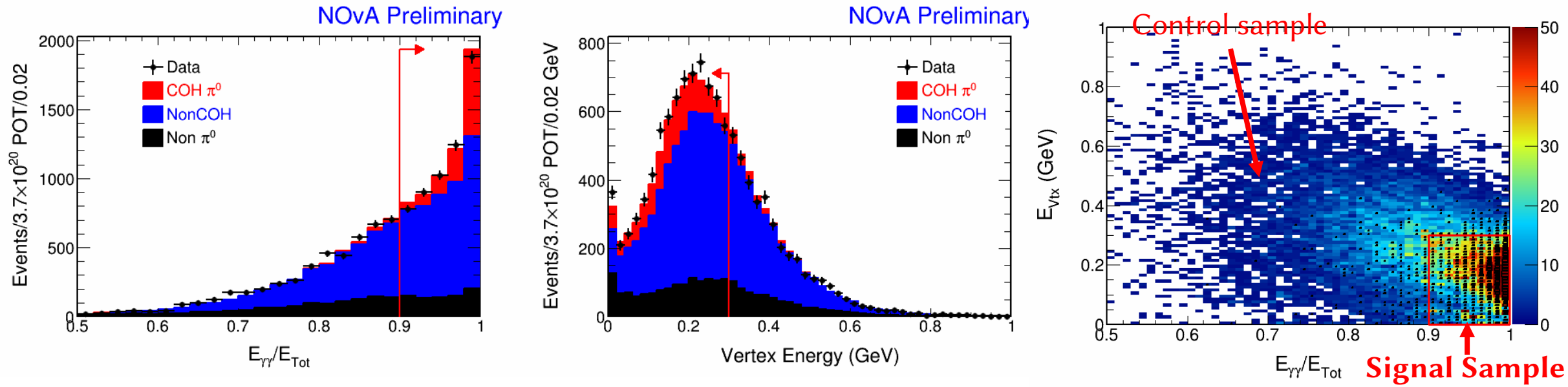
from data excess over background prediction in the coherent region in the pion kinematic phase space.

Coherent π^0 Photon Shower Identification

- Identify photons by likelihoods build upon shower longitudinal and transverse dE/dx information

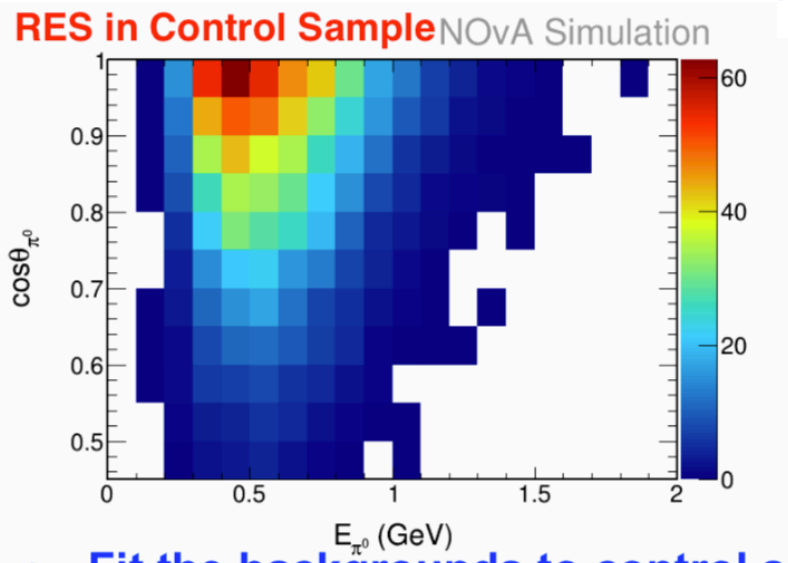


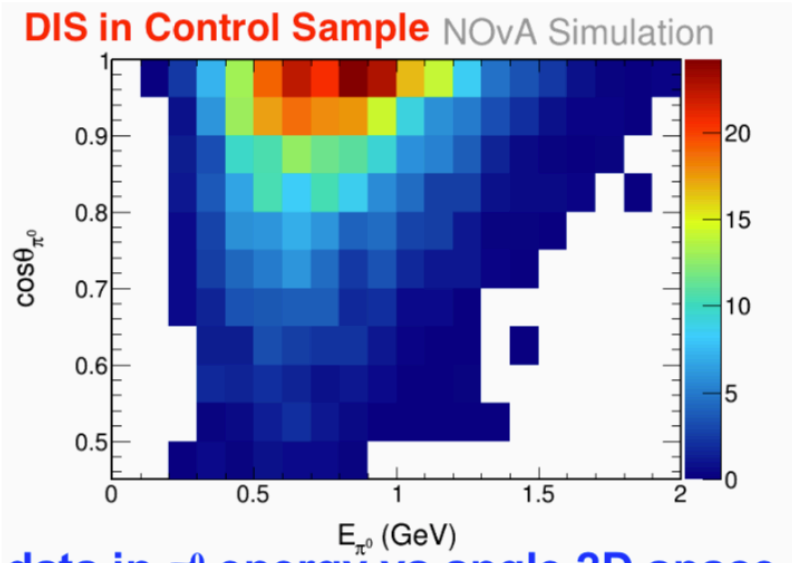
Coherent π^0 Signal and Control Samples



- Divide the NC π^0 into two sub-samples:
  - **Signal sample:** events with most of their energy in the 2 photon showers and low vertex energy: it has >90% of the signal.
  - **Control sample:** the events with extra energy other than the photons or in the vertex region, dominated by non-coherent π0 s (RES and DIS).

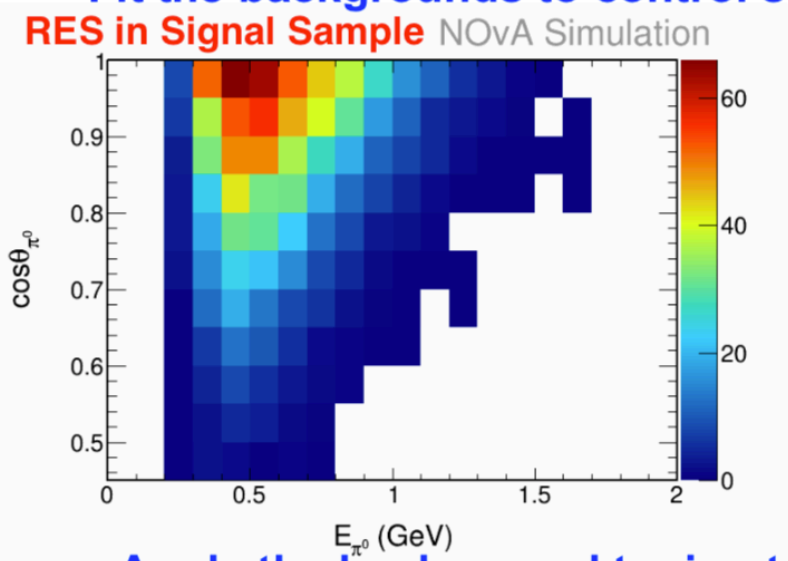
Coherent π^0 - Background Constraint

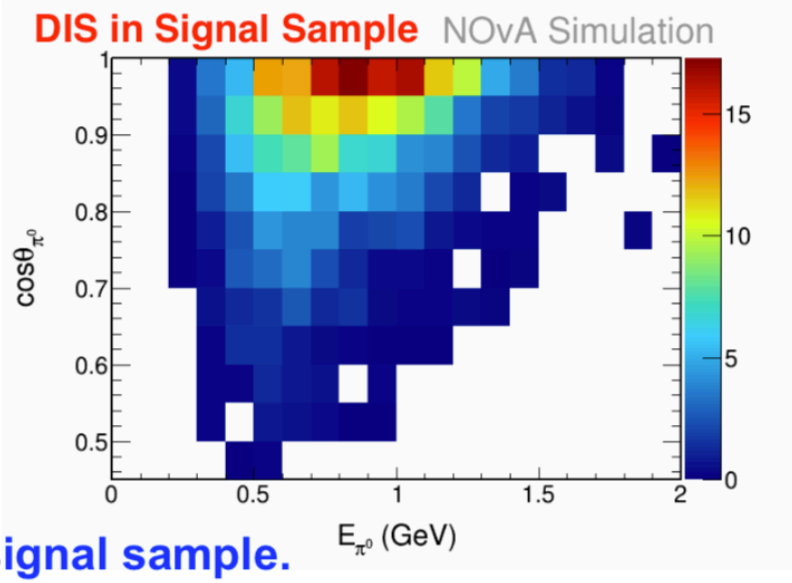




RES/DIS template fit in control sample

- **Fit the backgrounds to control sample data in π^0 energy vs angle 2D space.**



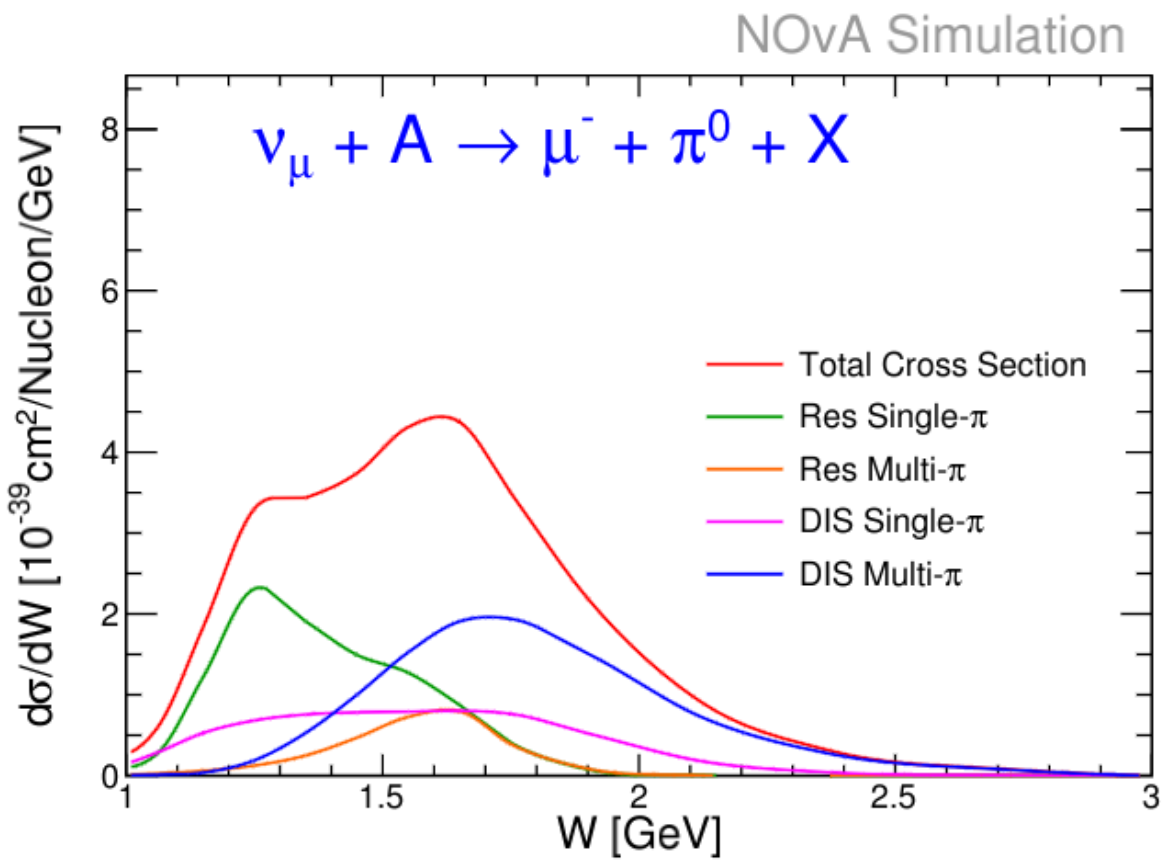


Apply fit results to signal sample

- **Apply the background tuning to the signal sample.**

ν_μ CC π^0 Semi-Inclusive Signal Composition

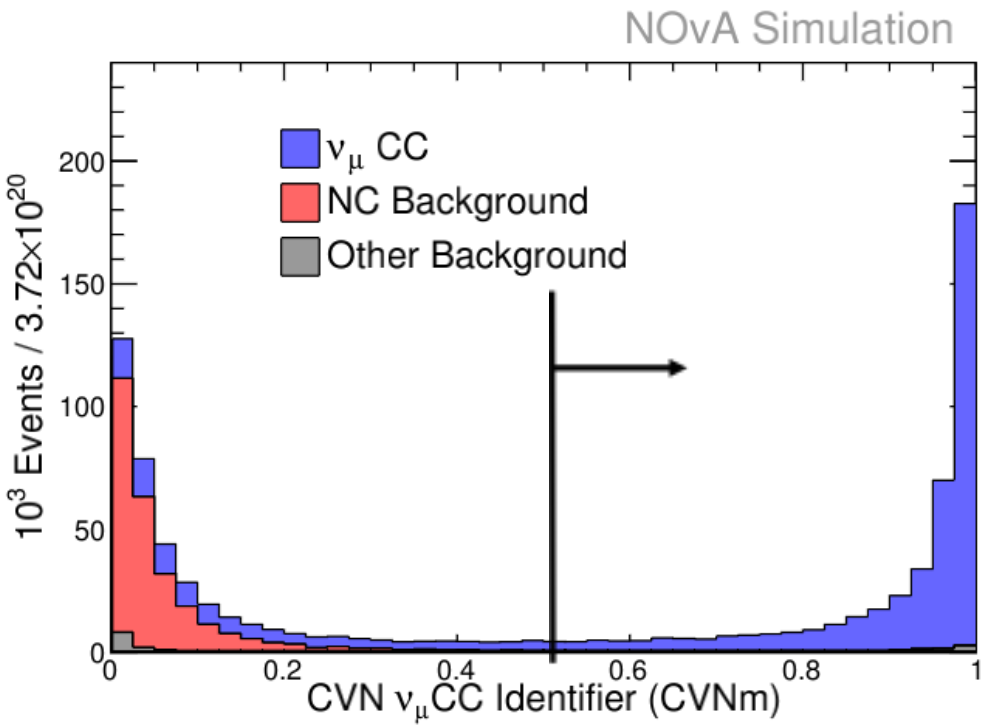
- Analysis signal has large contribution from both Res and DIS interactions
- There is a large multi-π component in ν_μ CC π^0 events which is included in the analysis signal



ν_μ CC π^0 Semi-Inclusive Event Selection

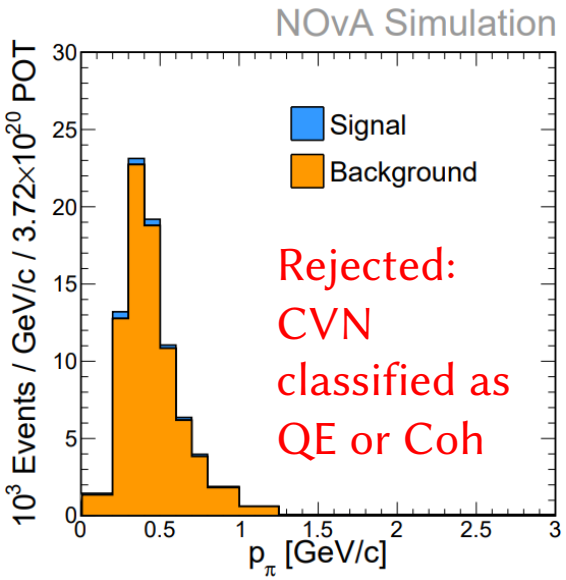
Neutral Current Rejection

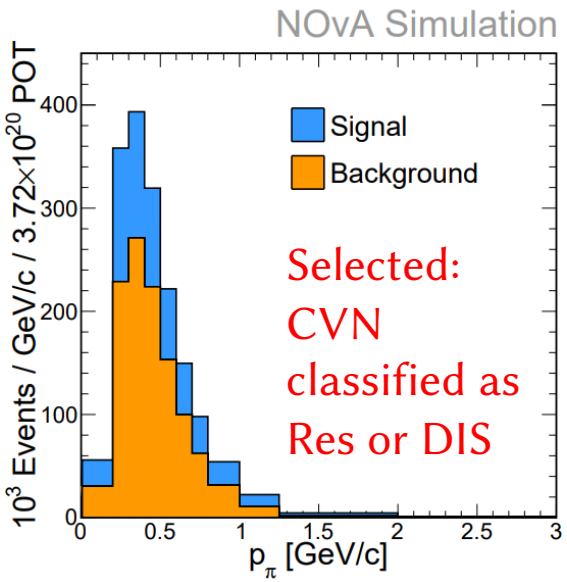
CVN effectively rejects neutral current background from sample



Signal Enhancement

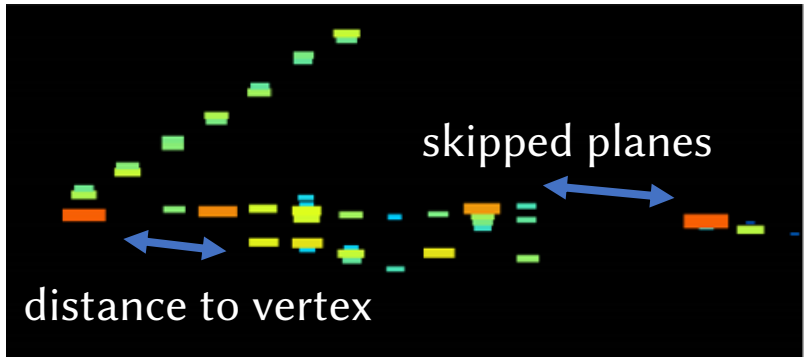
Select only events CVN classifies as RES or DIS
Reject background events classified as QE or Coh

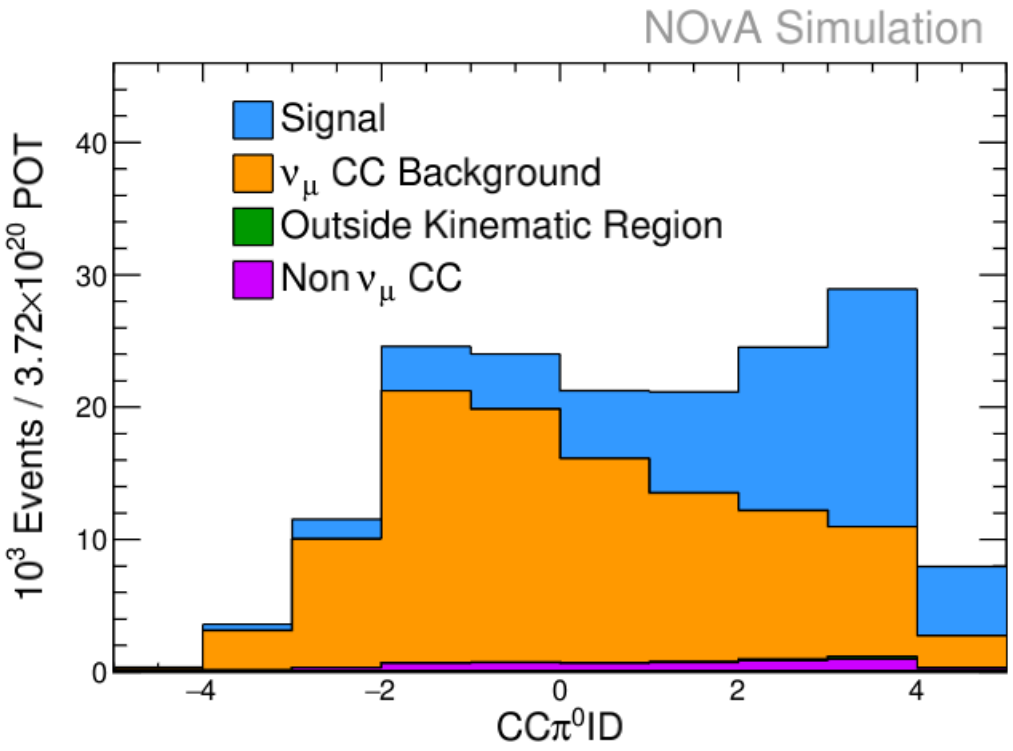




ν_μ CC π^0 Semi-Inclusive π^0 Identification

- A four-variable photon score based on ΔLL is developed
  - Two are related to dE/dx
  - Two are related to "gapiness"
- CCπ^0ID is defined as highest photon score in event
- Momentum estimate: function of prong calorimetric energy
- Direction estimate: reconstructed prong direction





ν_μ CC π^0 Semi-Inclusive Constraining Simulation: Template Fitting

- Apply a data-driven constraint to simulation: a template fit
- Procedure assumes the simulated CCπ0ID shape but allows signal and background normalization to float
- Measurement is differential: must perform template fit in every kinematic bin separately
- Test the accuracy of this procedure with systematic fake-data study
- After the fit, total adjusted simulation agrees with fake-data
- Apply to real data to extract signal.