Neutrino Cross Section Measurements in the NOvA Near Detector

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For the NOvA Collaboration

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Outline

- Introduction to the NOvA ND and flux.
- Neutral pion measurements
- Inclusive Measurements
- Summary

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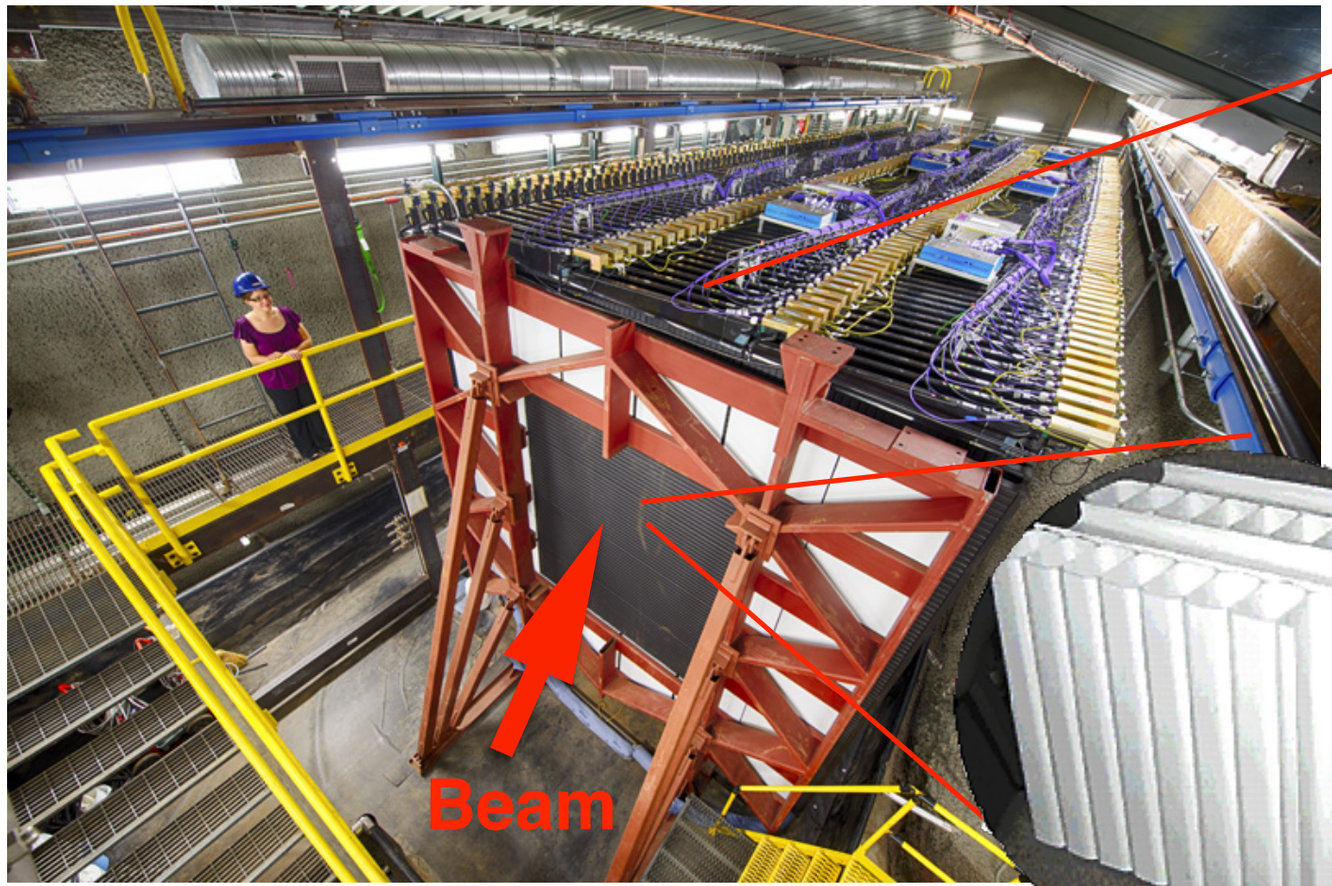
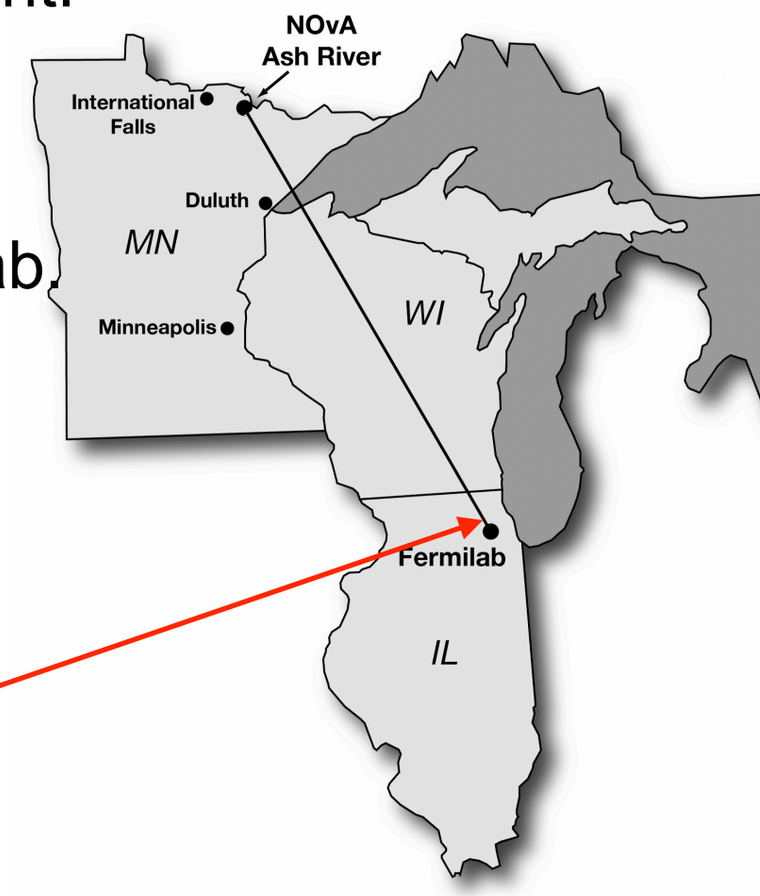
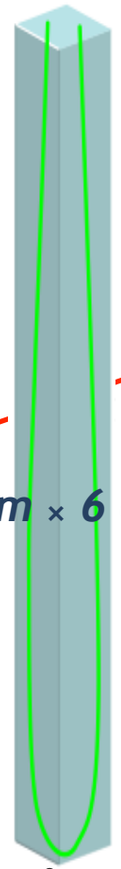
The NOvA Near Detector

- NOvA is a Long-baseline neutrino oscillation experiment:
  - See Erica Smith and Steven Calvez's talk for the latest oscillation results!
- The ND is **1 km** from source, **underground** at Fermilab.
- PVC cells filled with **liquid scintillator**.
- Alternating planes of orthogonal view.
- **193 ton** fully active mass.
- 97 ton downstream muon catcher.



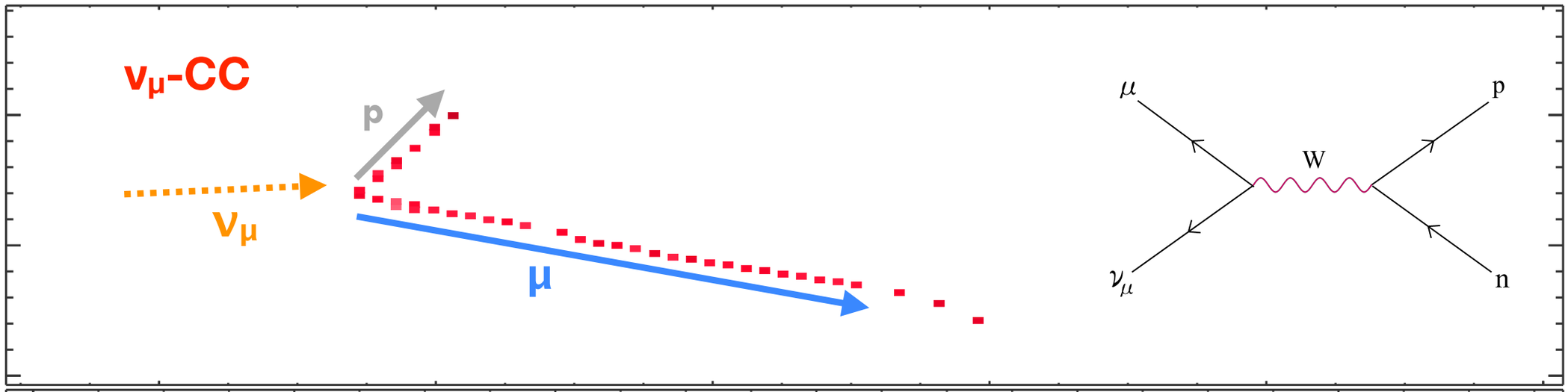


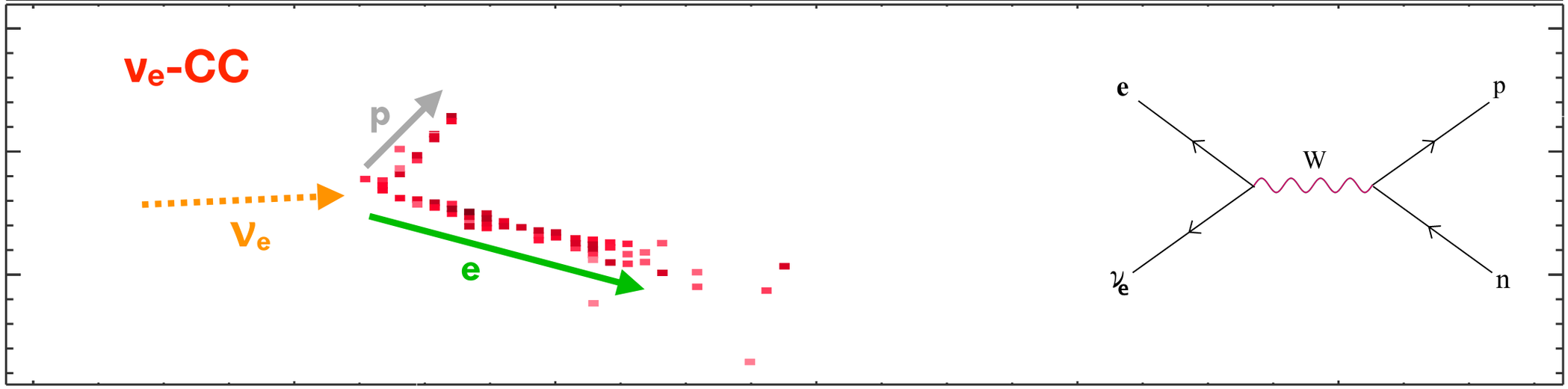


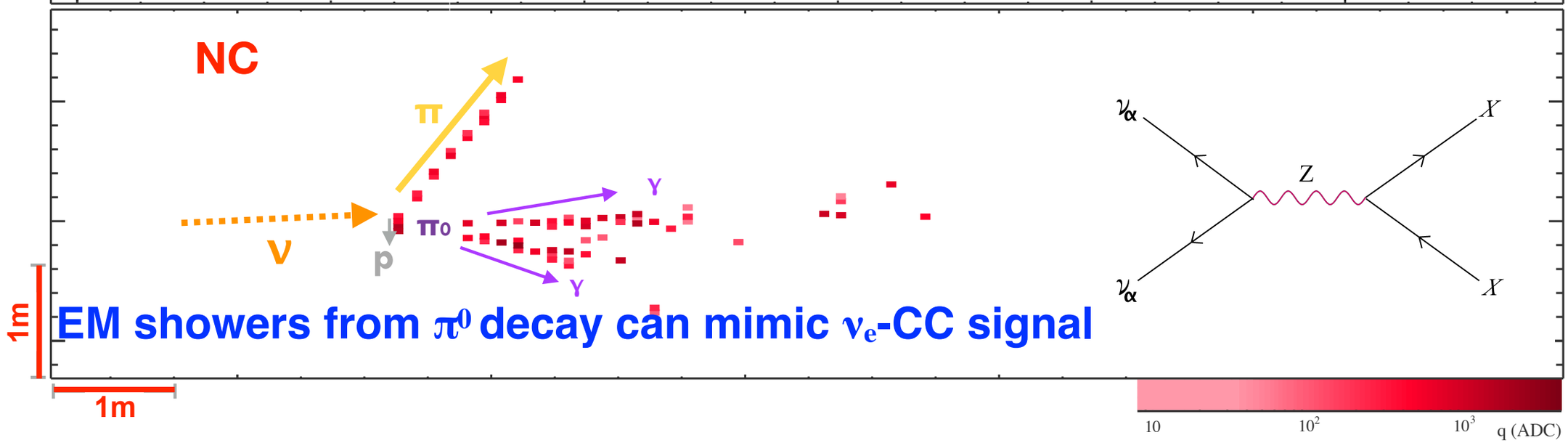
- **Low-Z, fine-grained**
  1 plane ~0.15X_0 (38 cm).
-

C	Cl	H	Cl	O	Ti
65.9%	12.0%	10.7%	4.1%	3.0%	2.4%

Event Topology



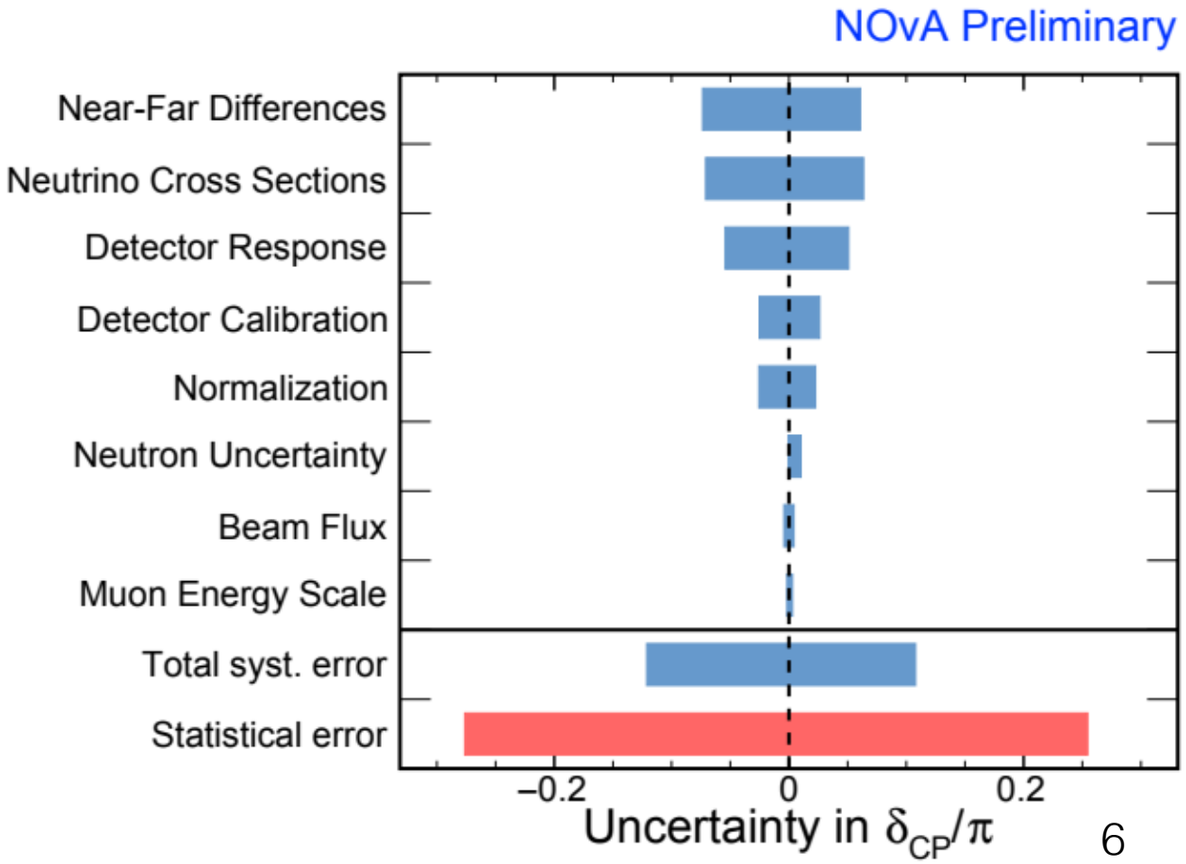


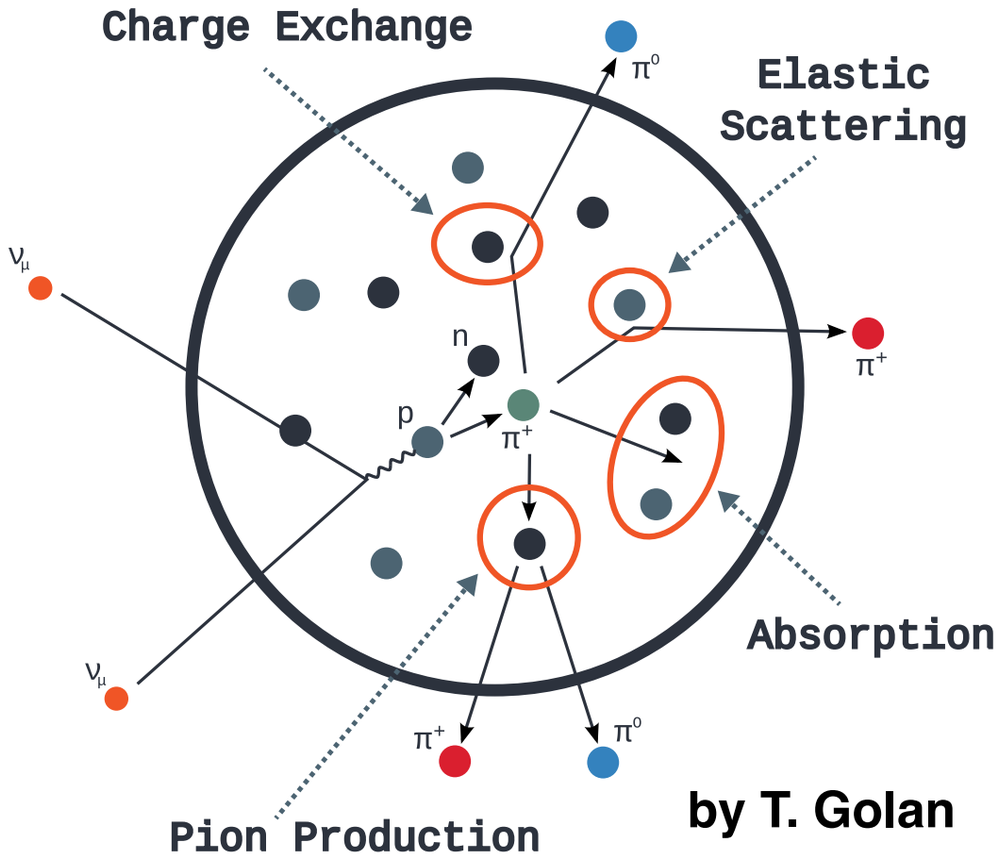


EM showers from π^0 decay can mimic ν_e-CC signal

Motivation

- Cross-sections are rich in **physics themselves**.
- Also important to **oscillation systematic uncertainties**:
  - **Signals** and **backgrounds** to the oscillation analysis.
  - Oscillations are measured as function of neutrino energy: need to reconstruct E_ν correctly.
    - **Nuclear effects** (fermi motion, nucleon correlation, final-state interaction…) are important.



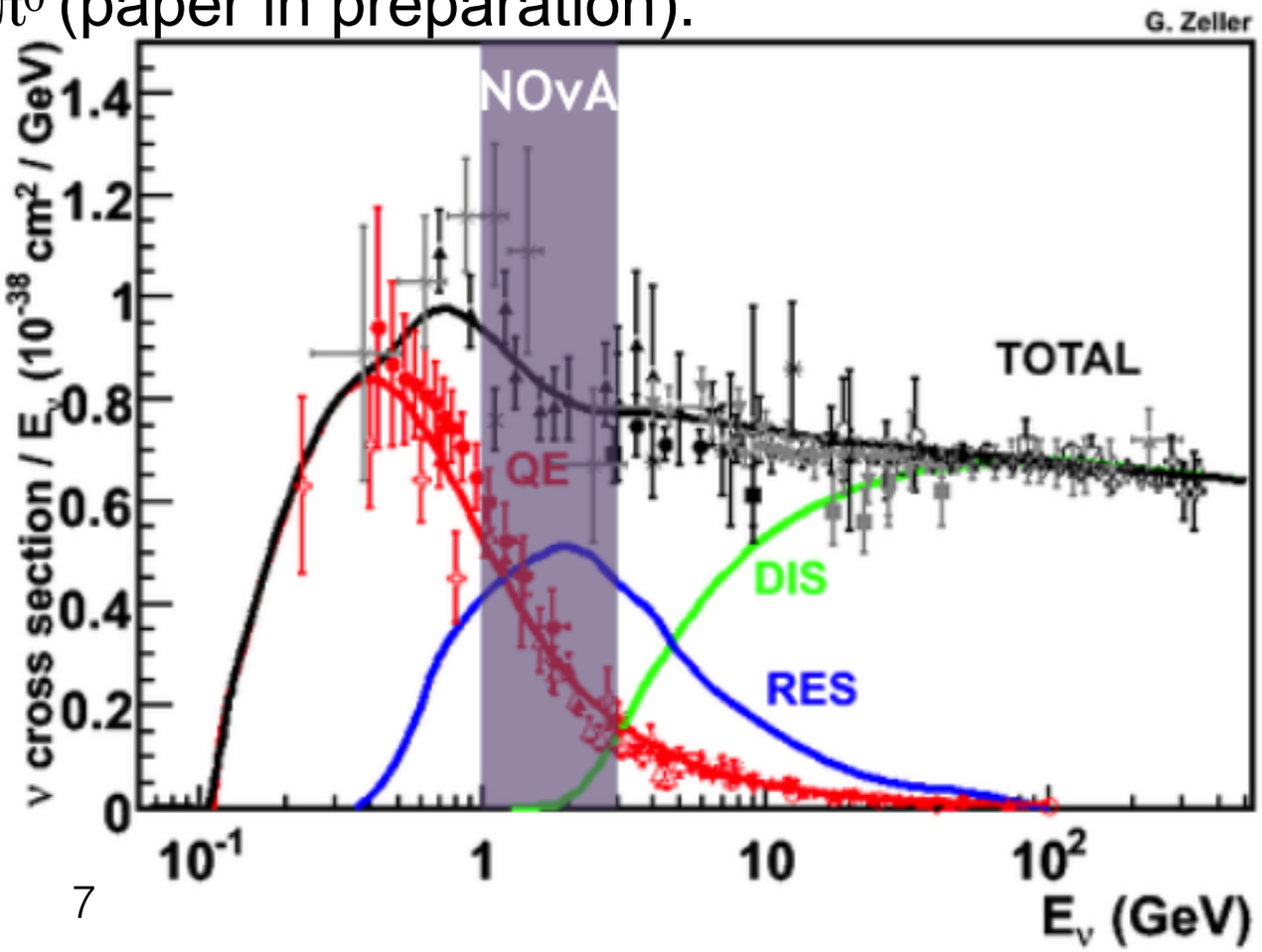


by T. Golan

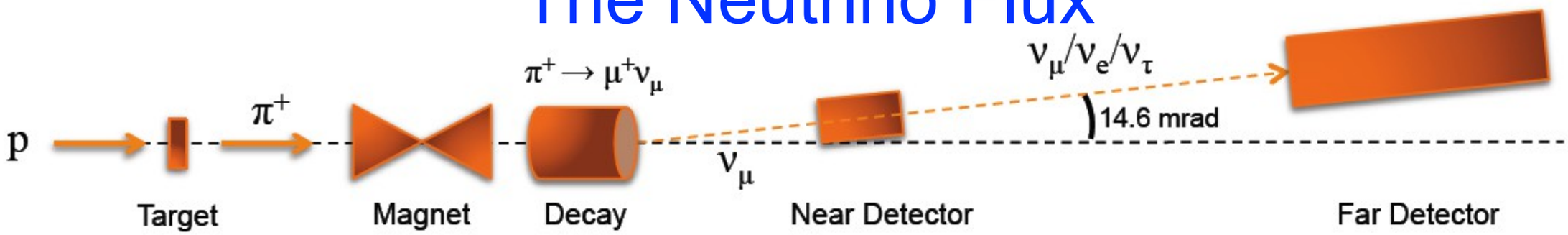
We want to understand those issues in our own detector

NOvA Cross-Section Measurements Overview

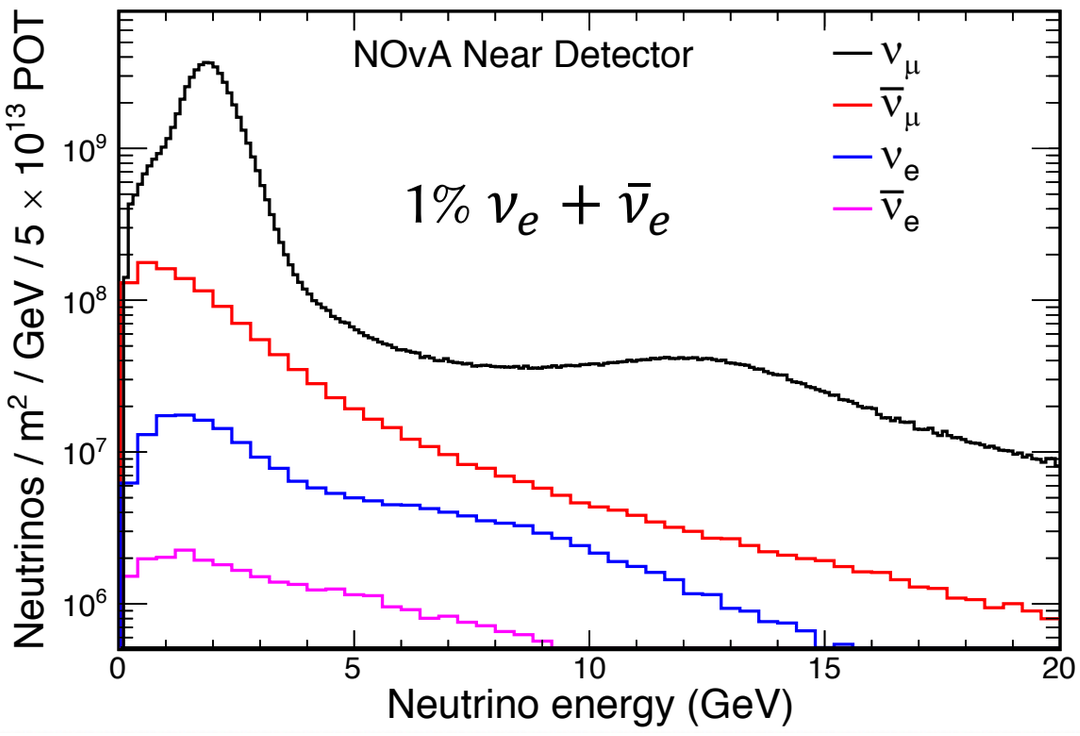
- Both neutrino and anti-neutrino modes.
- Excellent statistics from 193 ton of fully-active tracking region.
- Inclusive measurements:
  - ν_μ-CC inclusive
  - ν_e-CC inclusive
- Neutral pion measurements:
  - Neutral current coherent π^0 (Submitted to PRD).
  - Charged current semi-inclusive π^0 (paper in preparation).
  - NC π^0 inclusive.
- Charged pion measurements
- Others
  - ν_μ-CC 0π
  - ν_μ-CC 2p2h
  - And more



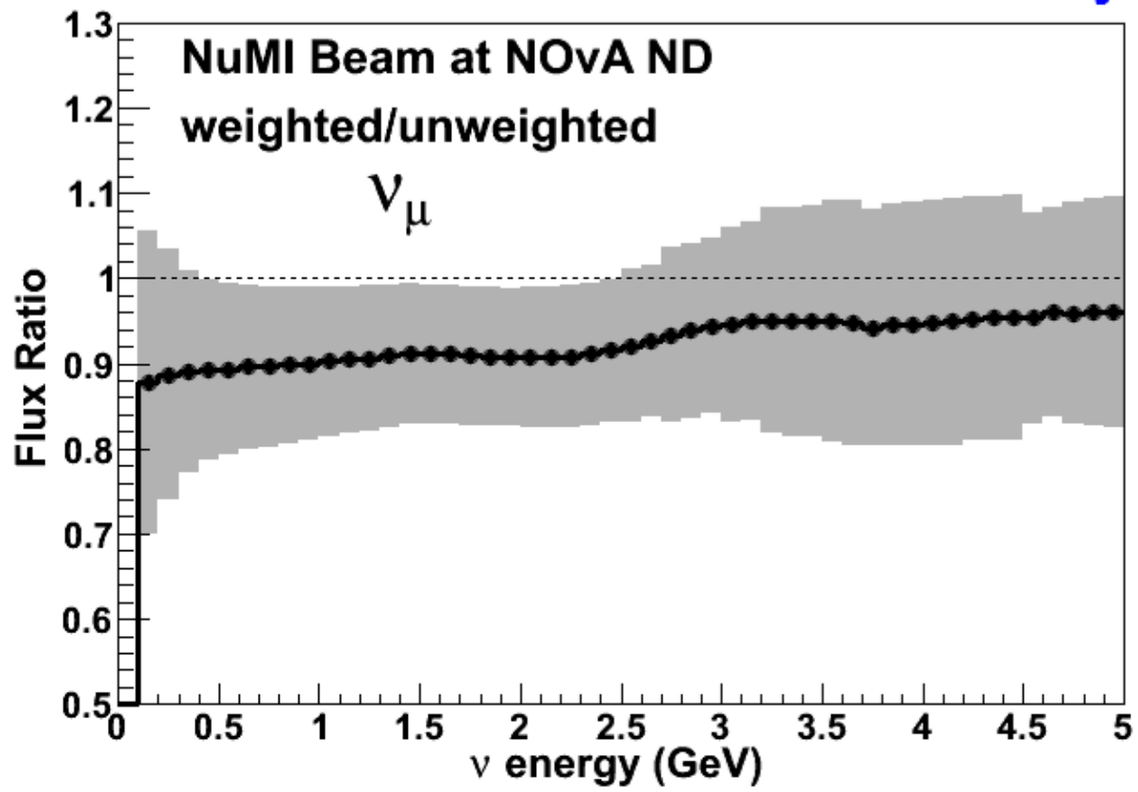
The Neutrino Flux



NOvA Simulation



NOvA Preliminary



- Narrow band neutrino beam 1~3GeV peak at ~2GeV, dominated by ν_μ (94%)
  - Right on the DUNE 1st oscillation maximum.
- Both neutrino mode and anti-neutrino mode.
- Hadron production uncertainty constraint by external hadron production data.

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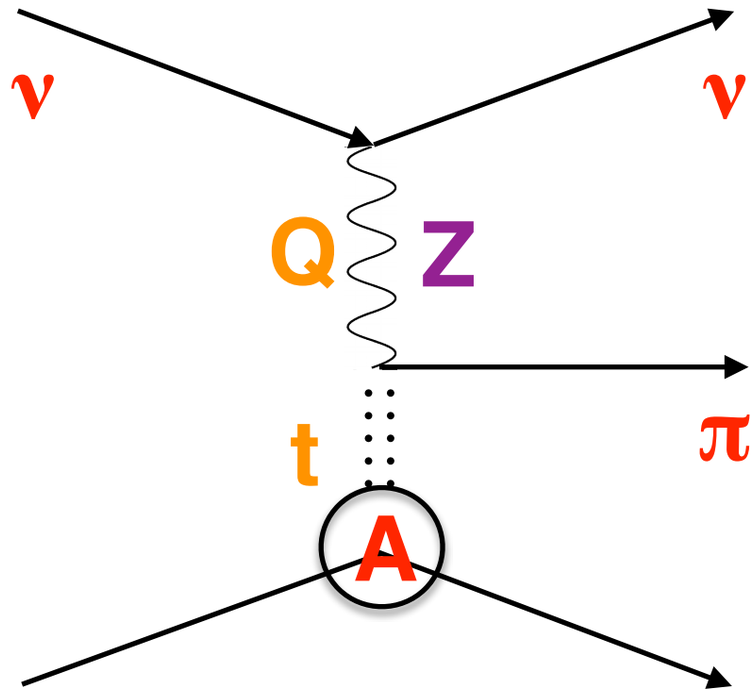
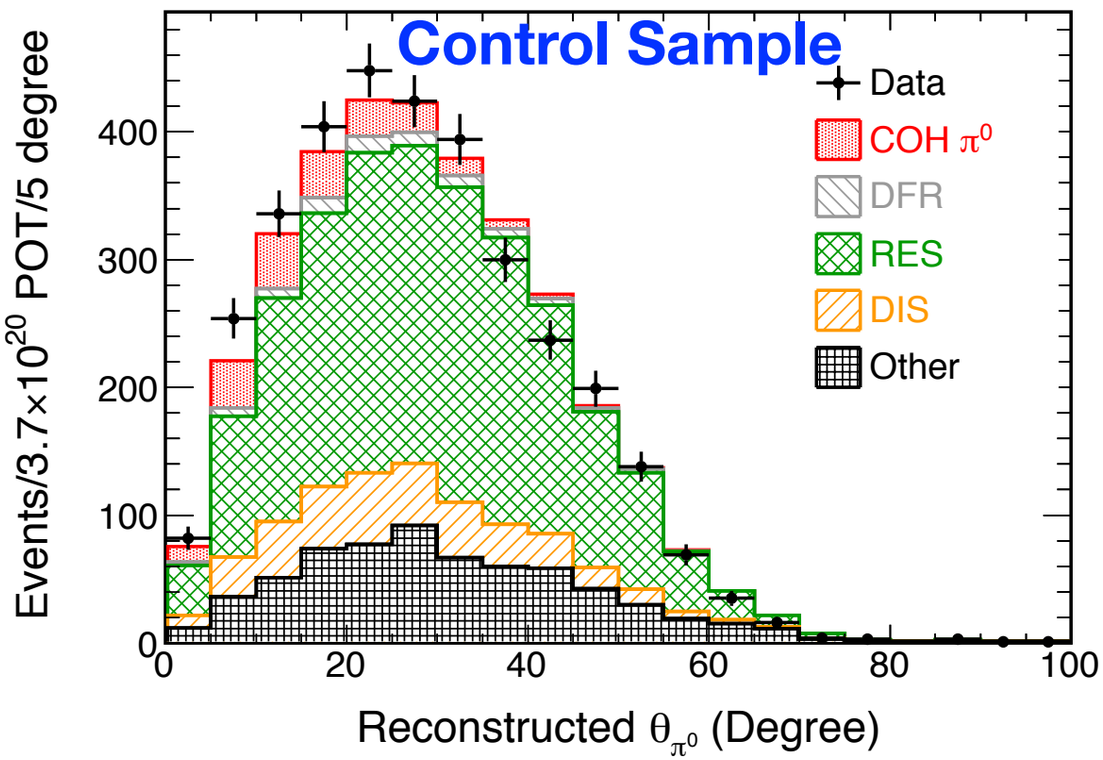
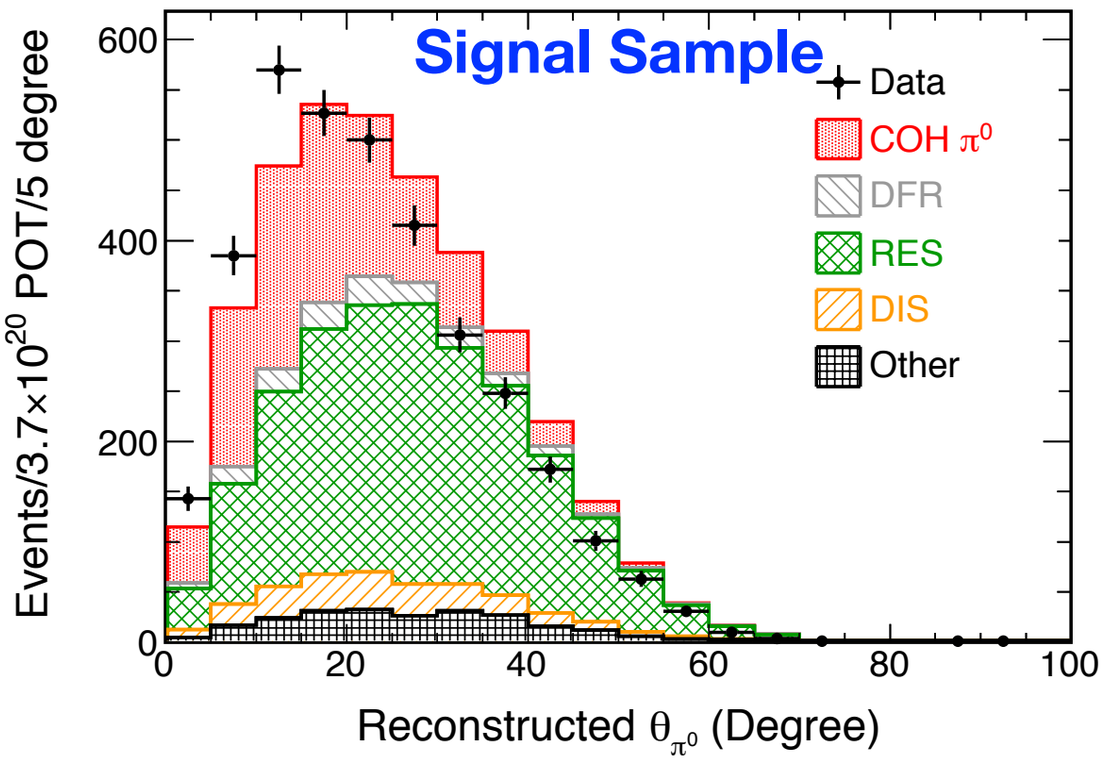
NC Coherent π^0

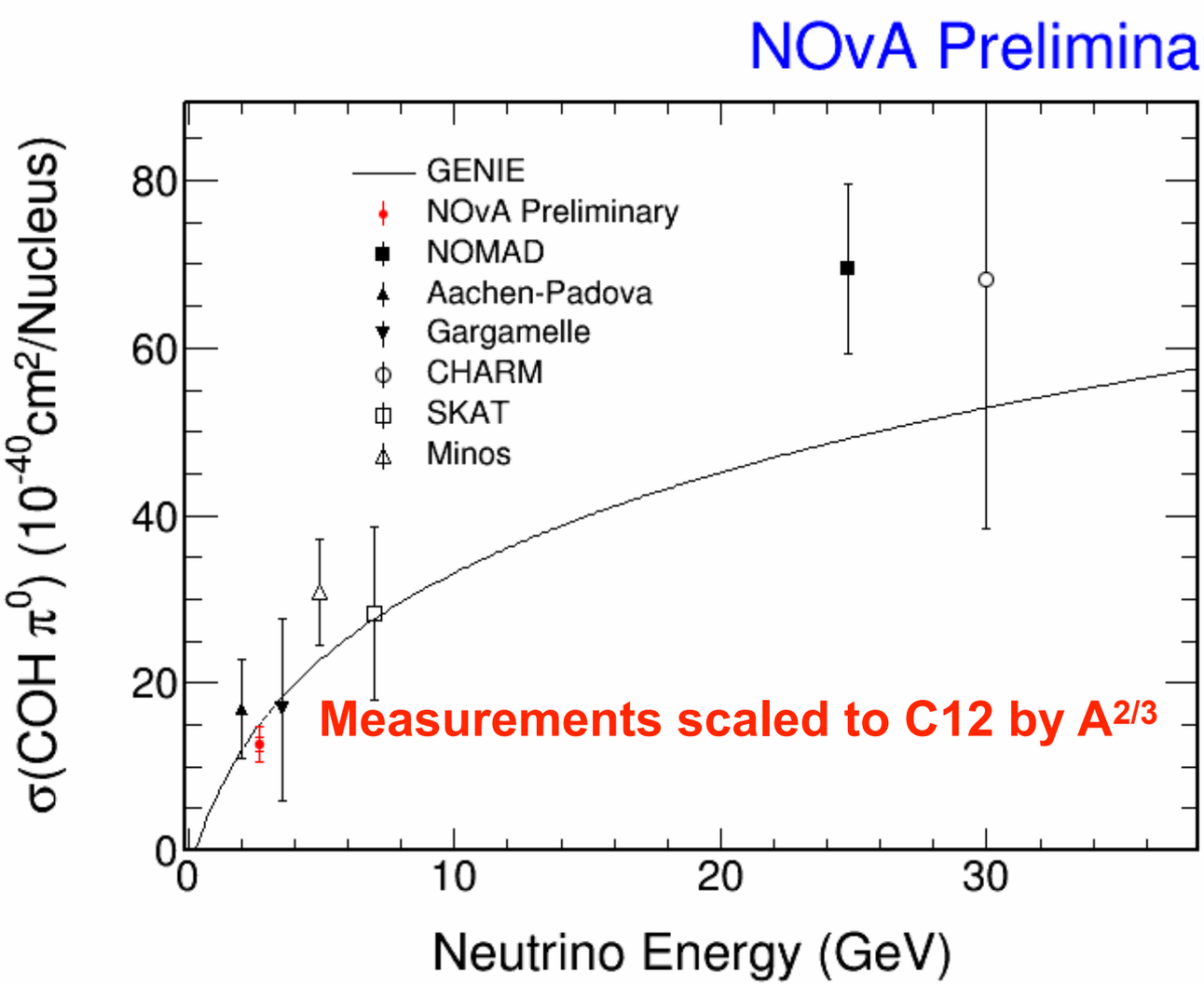




- Neutrinos coherently scatter on whole nucleus and produce pions.
- Background to ν_e appearance
- Small cross section compares with other pion production channels.
- Data-driven background prediction:
  - A control sample defined by large vertex energy and extra energy deposition than the photon showers.
  - A template fit method to normalize backgrounds



NC Coherent π^0

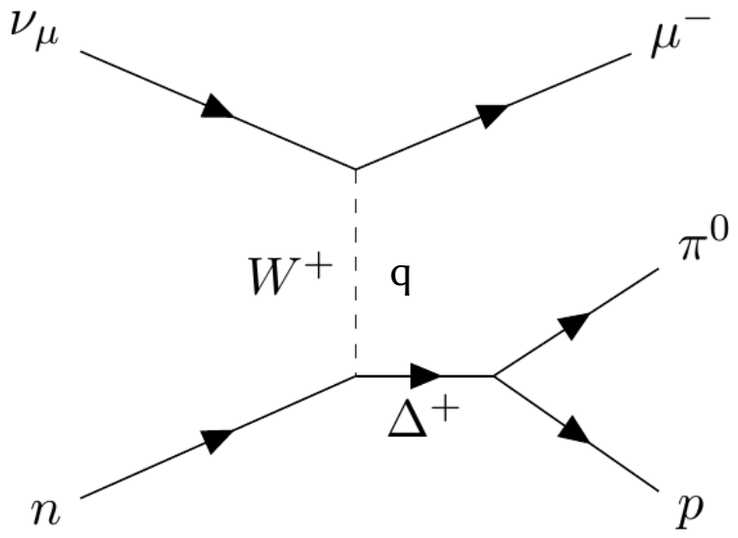


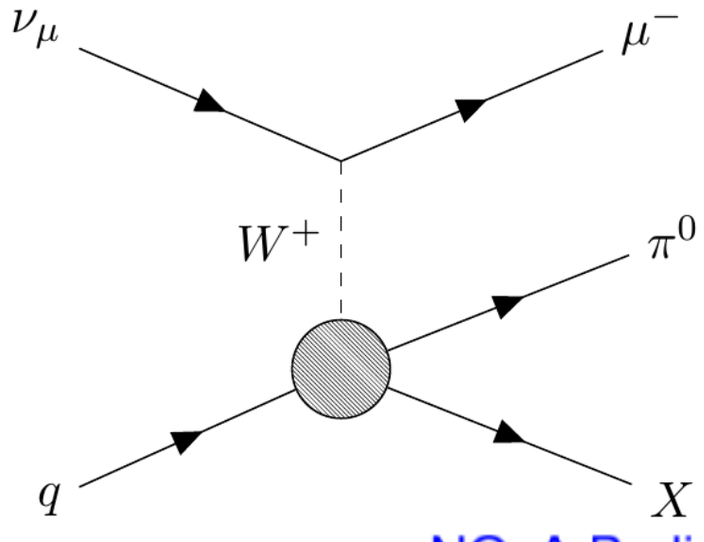
Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

- Coherent signal measurement by subtracting normalized background from data in energy and angle 2D space.
- Measured flux-averaged cross-section:
  $\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40}\text{cm}^2/\text{nucleus}$
- Total uncertainty 16.7%, systematic dominant.
- For more details see arXiv: 1902.00558 (submitted to PRD).

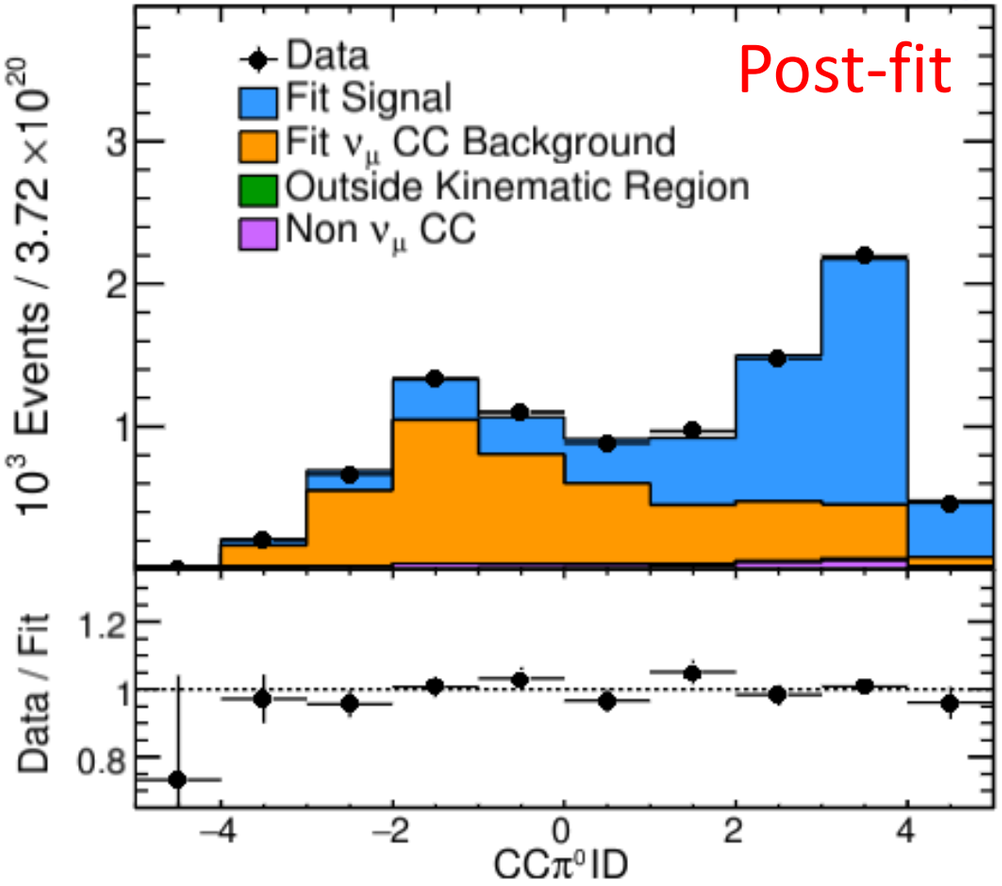
ν_μ-CC π^0

Signal: ν_μ-CC events with at least one primary π^0 in the final state.

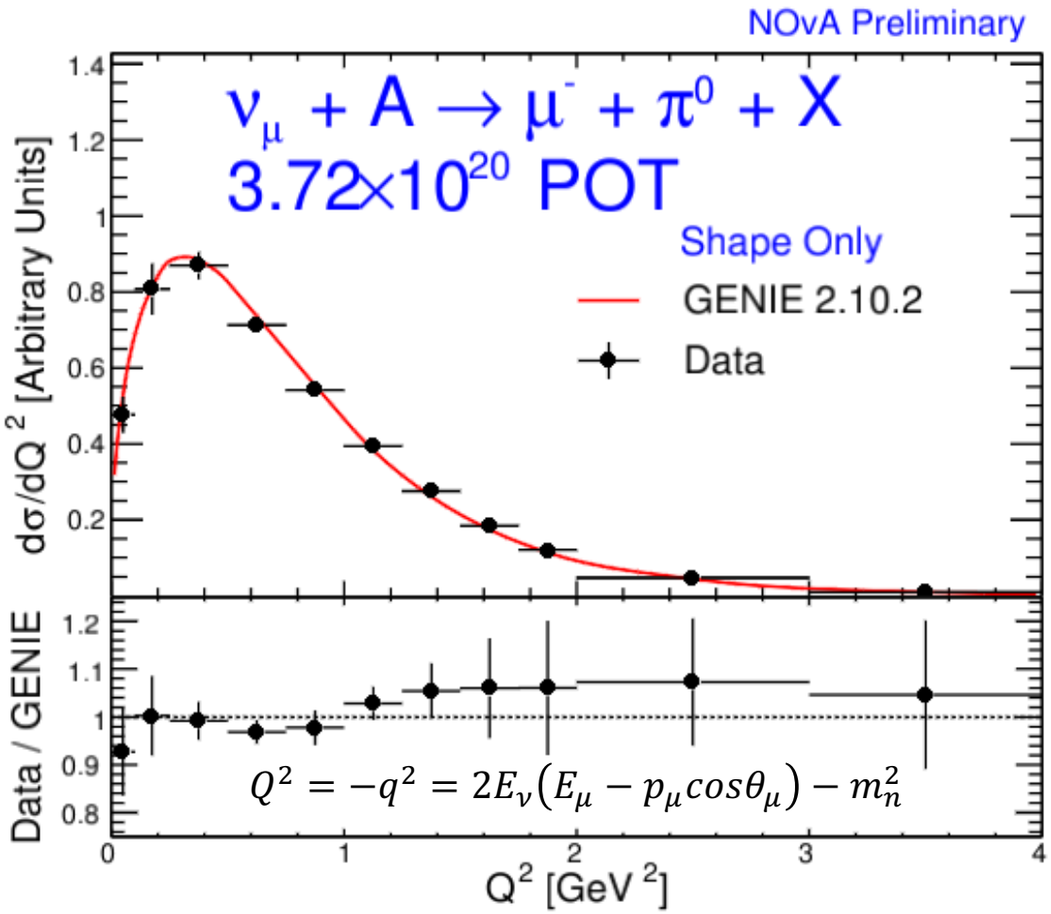


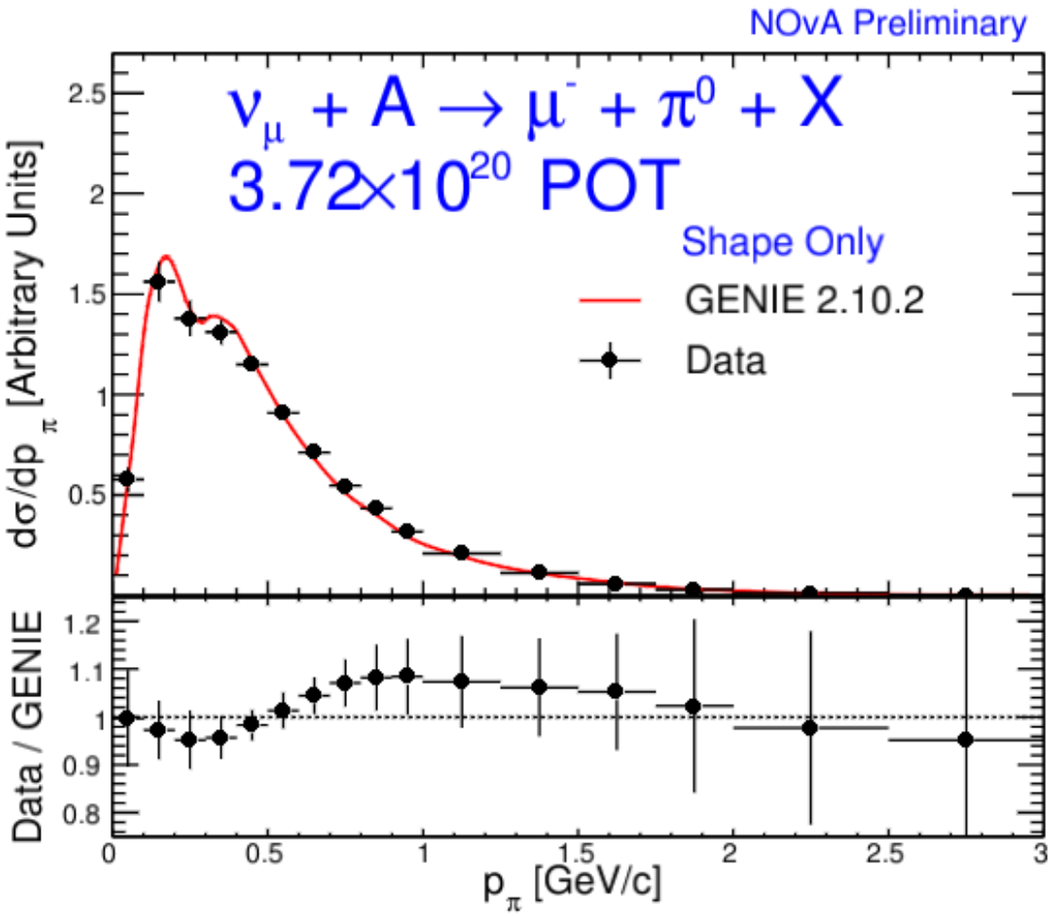


- Use non-muon shower variables to form a π^0 identifier:
  - Bragg peak identifier.
  - Energy per hit.
  - Photon gap from vertex.
  - Number of missing planes.
- Fit signal and background MC to data in each kinematic bin.



ν_μ-CC π^0





- Reporting result as differential cross section as function of Q2 and muon/pion kinematics.
- In general consistent with GENIE.
- Paper in preparation. For more details see **https://theory.fnal.gov/events/event/results-from-nova-2/**

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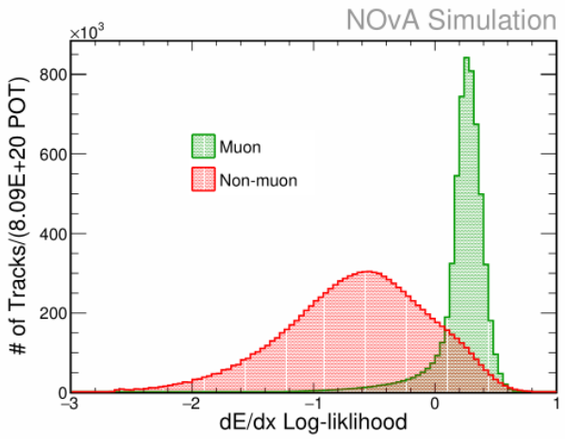
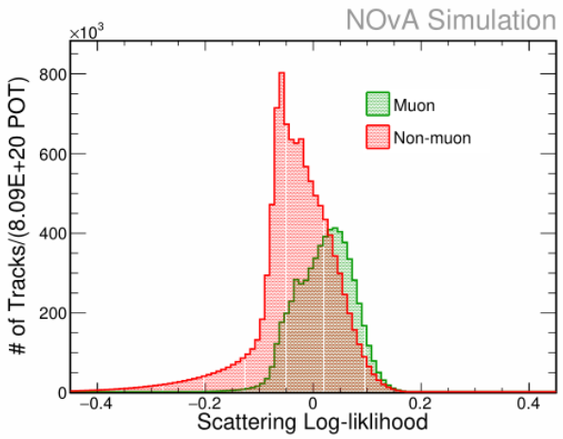
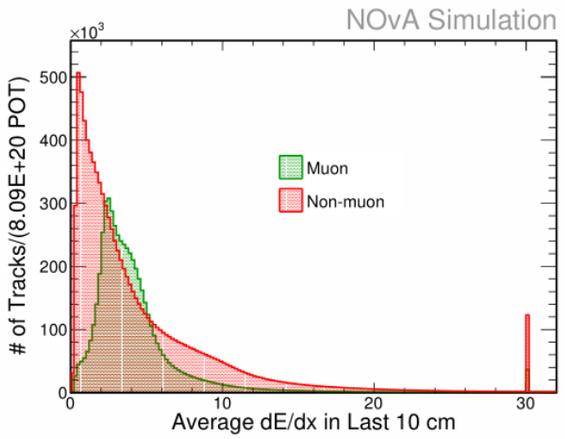
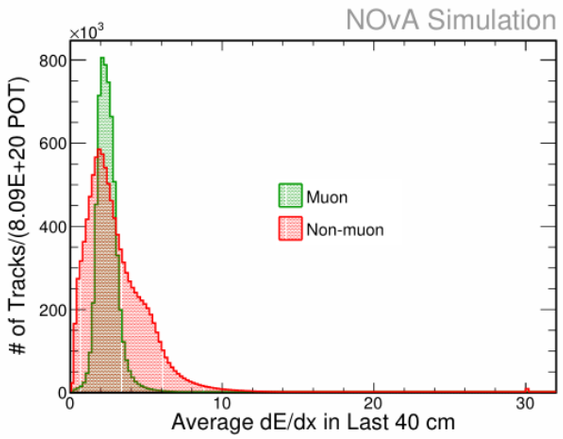
ν_μ-CC Inclusive



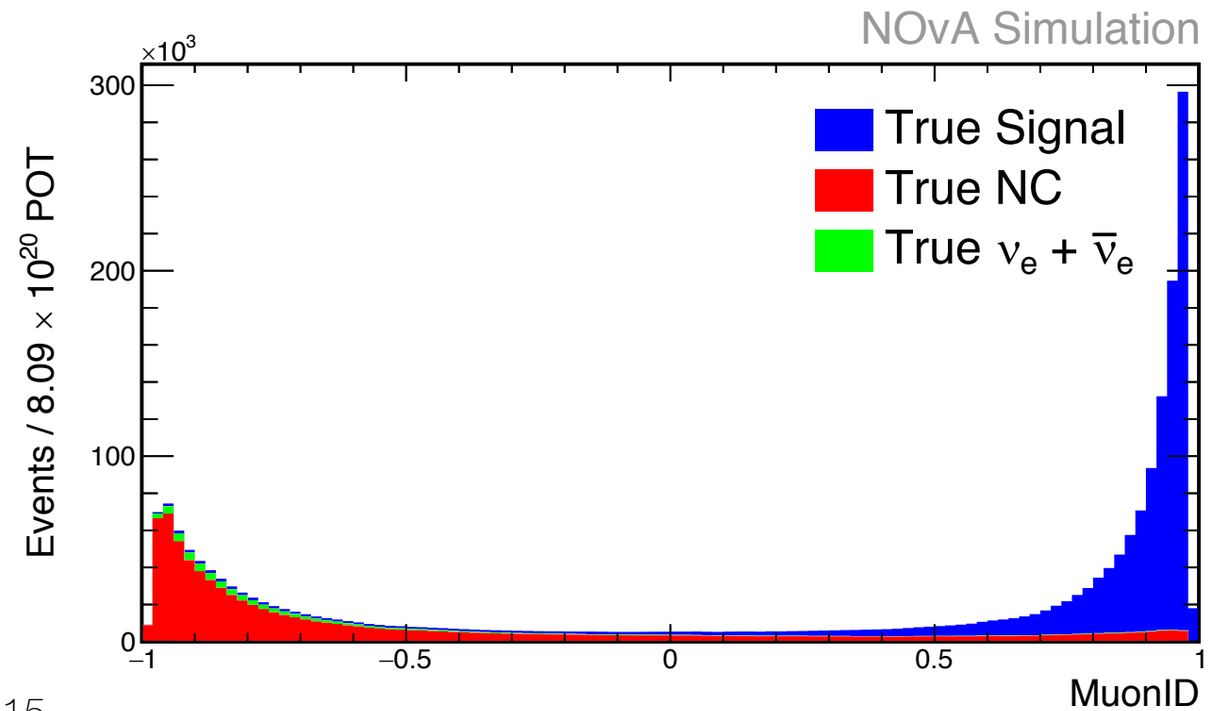




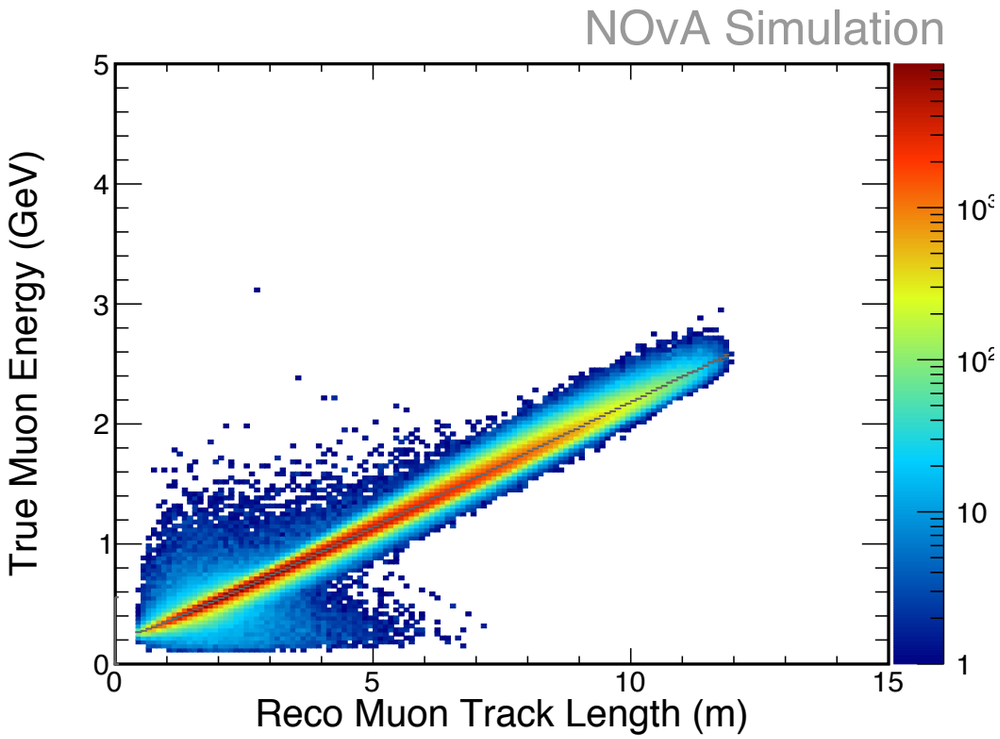


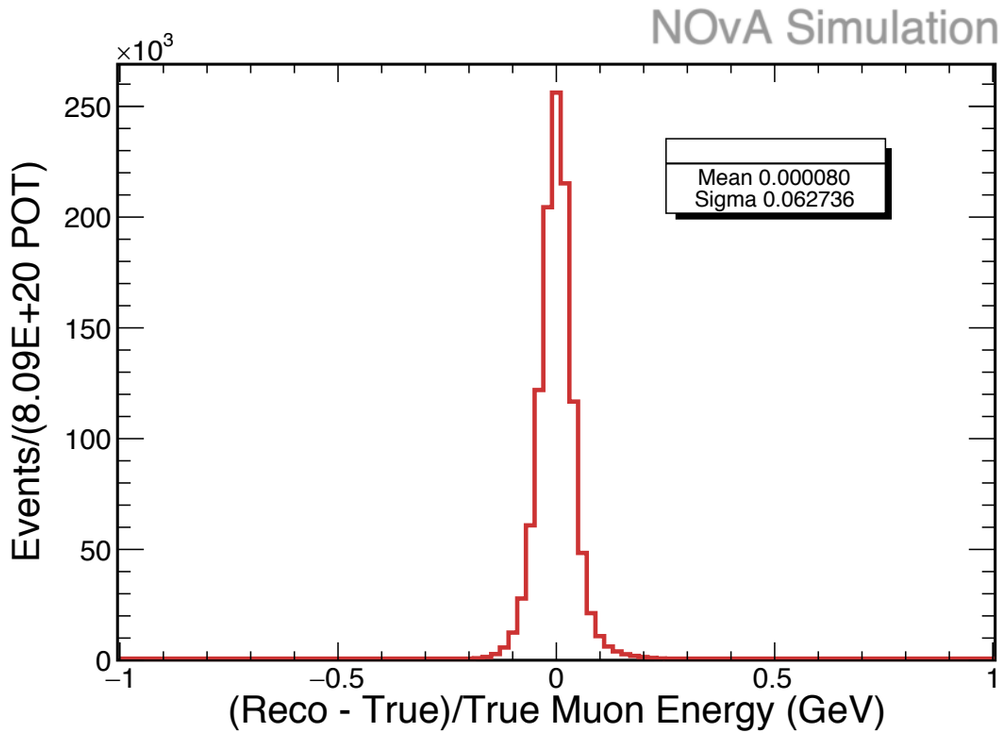
- Goal: double differential cross section as function of muon kinematics.
- Backgrounds: neutral current events and ν_e.

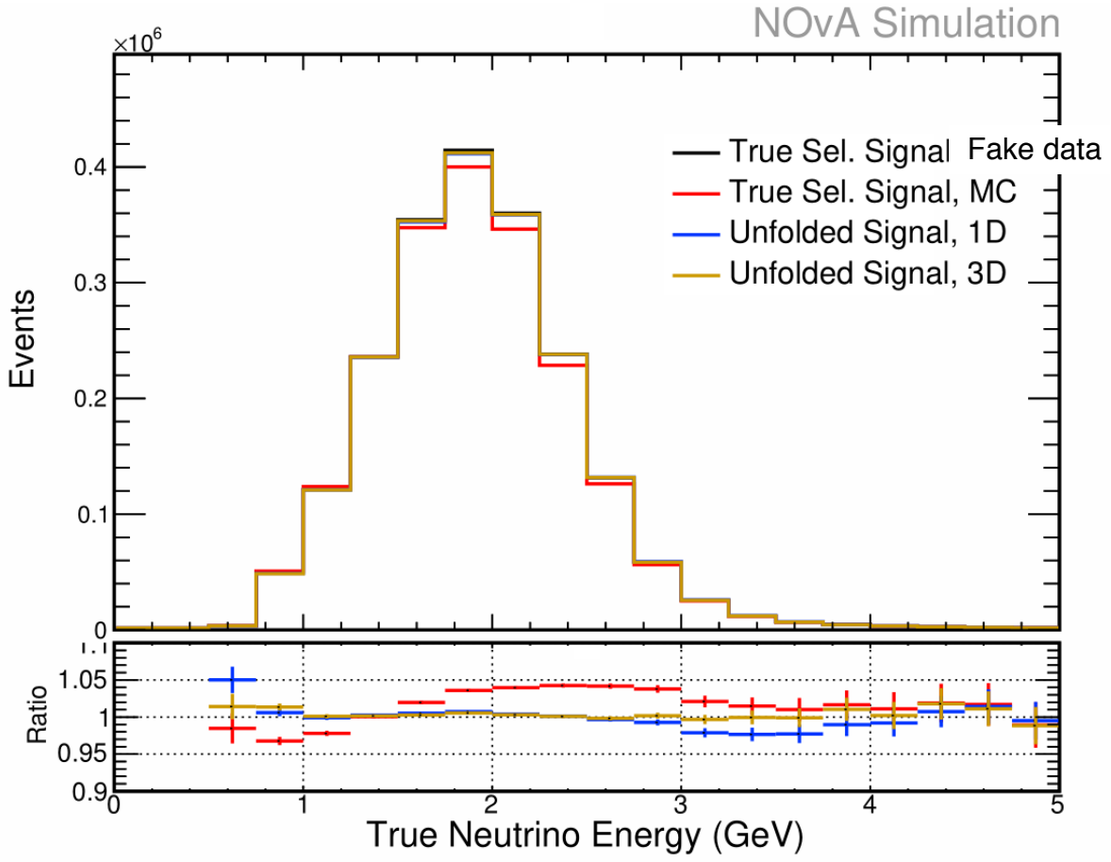
- A boosted decision tree (BDT) based upon dE/dx and scattering information is trained to identify the muons.
- Cut value optimized by minimizing uncertainties.



ν_μ-CC Inclusive

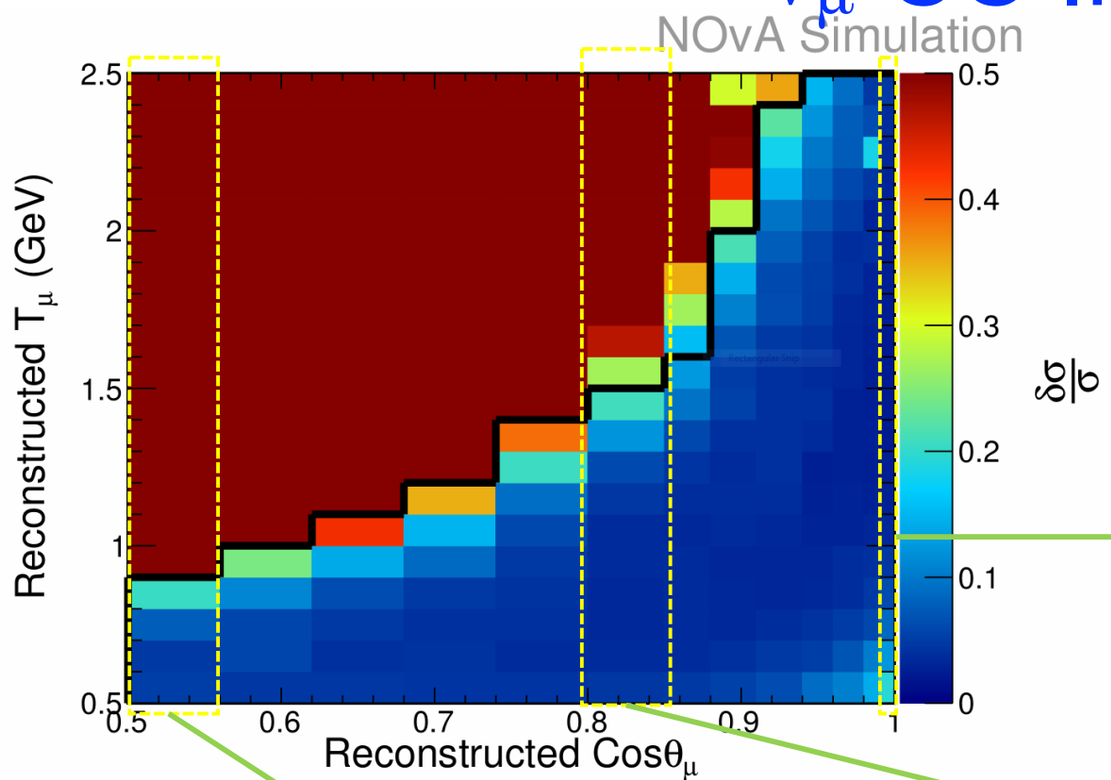


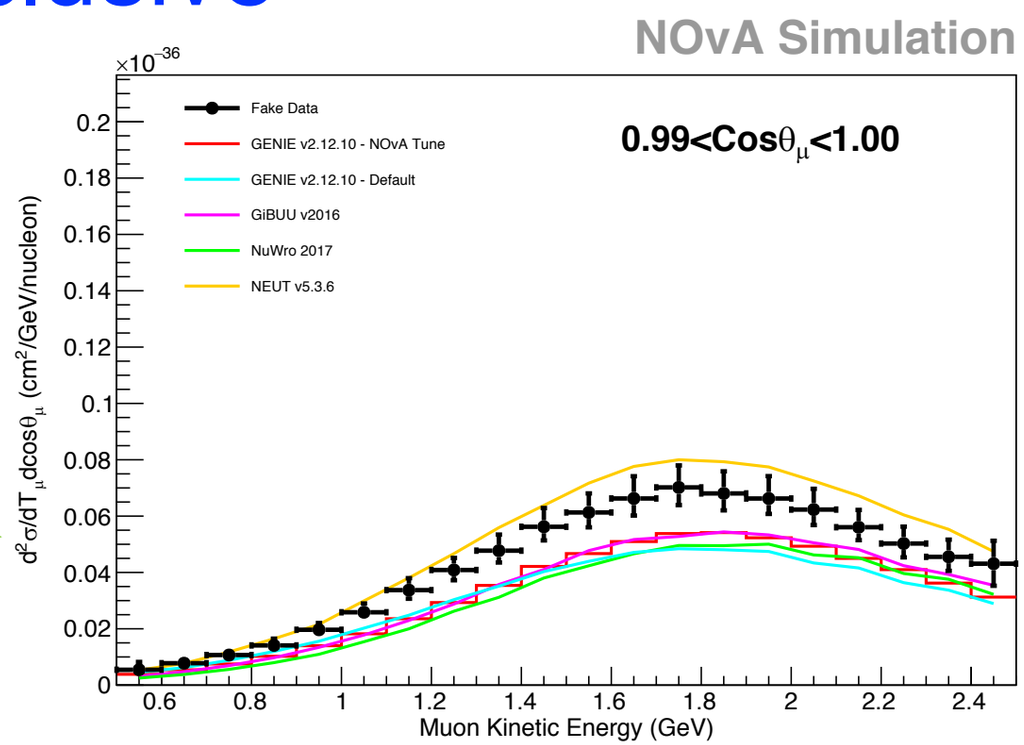


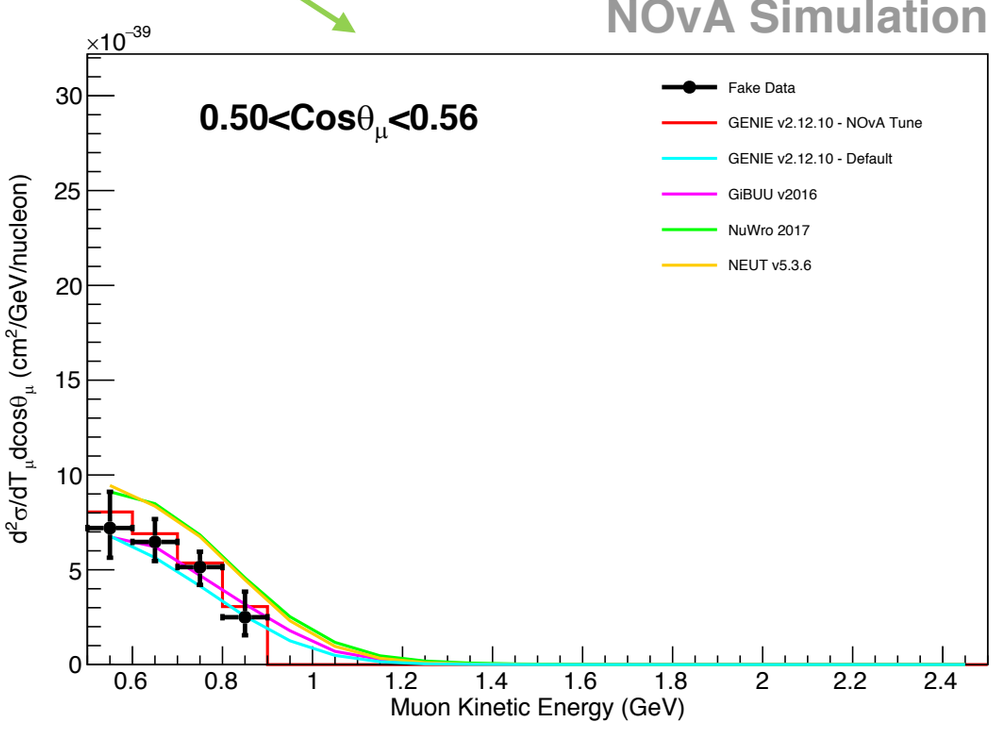


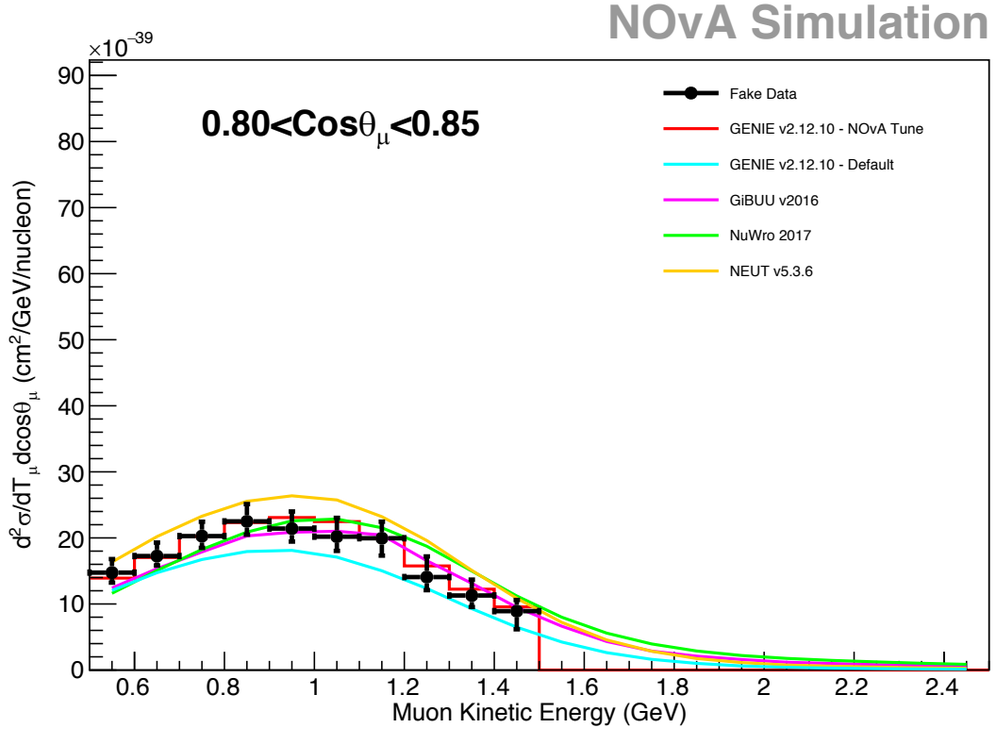
- Muon energy measured by range.
- Perform unfolding and efficiency correction in ($\cos\theta_\mu$, T_μ, E_{avail}) 3D space to take into account correlations between lepton and hadron kinematic variables.
- Projection to 1D or 2D space for the differential cross-section measurement.

ν_μ-CC Inclusive



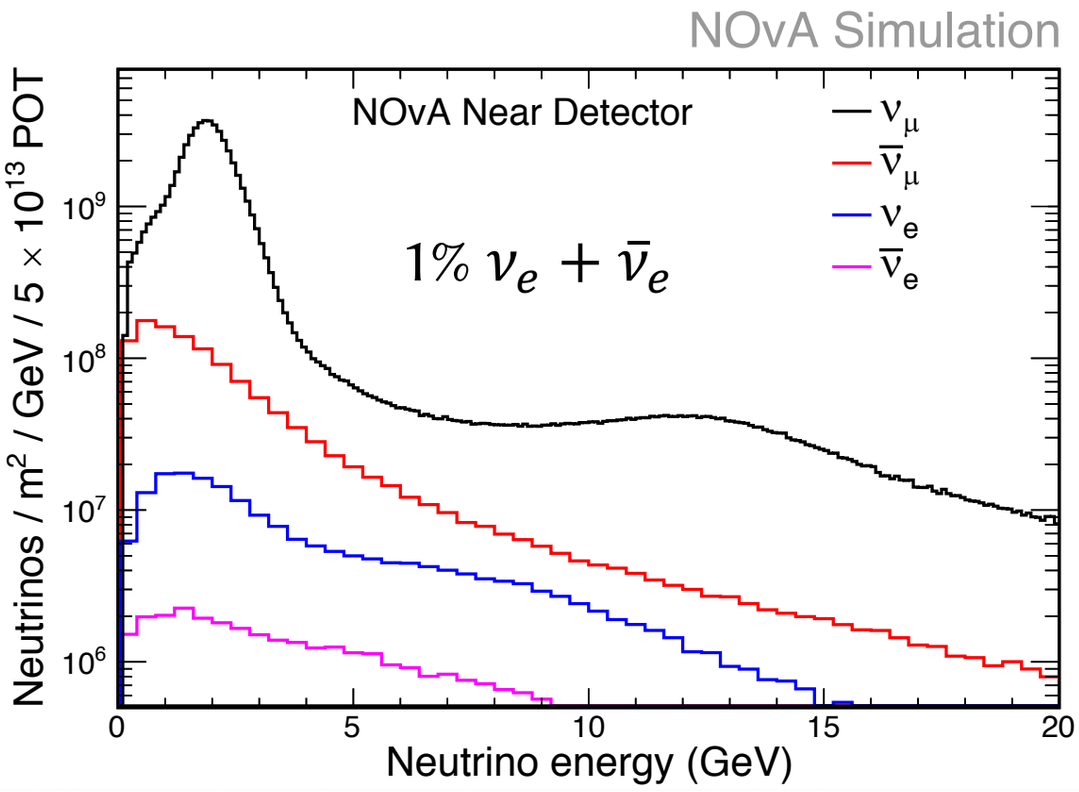


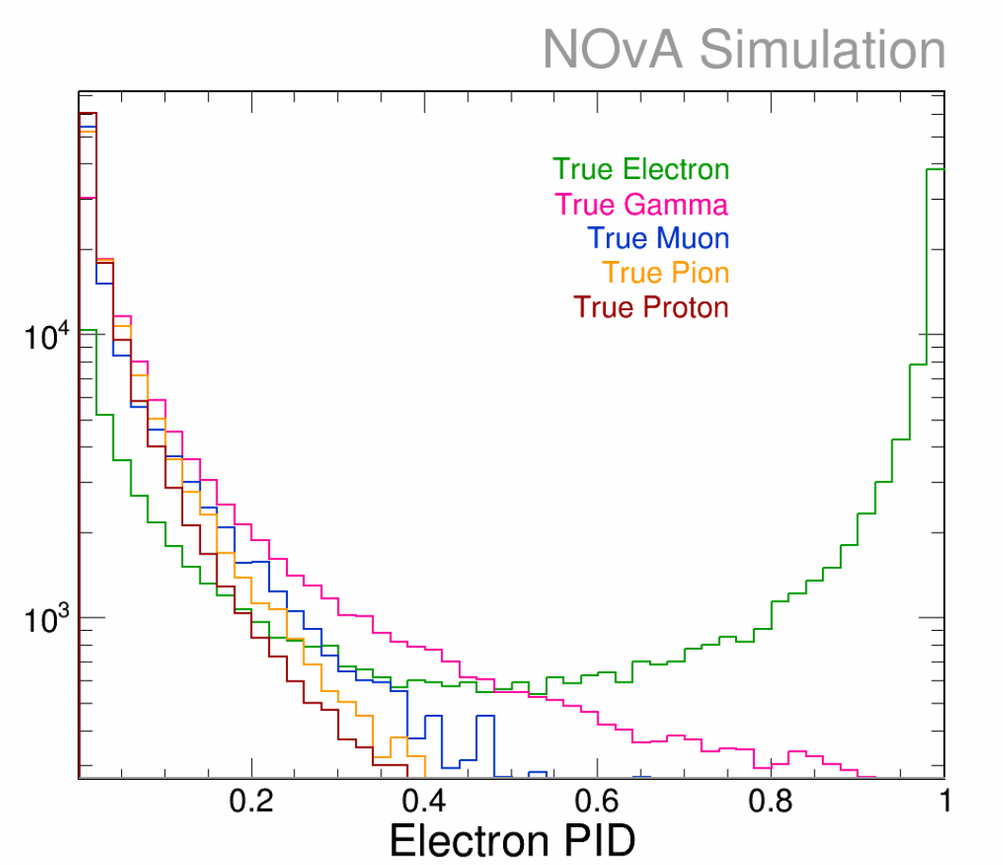




- Showing a mock data study. Real result coming soon.

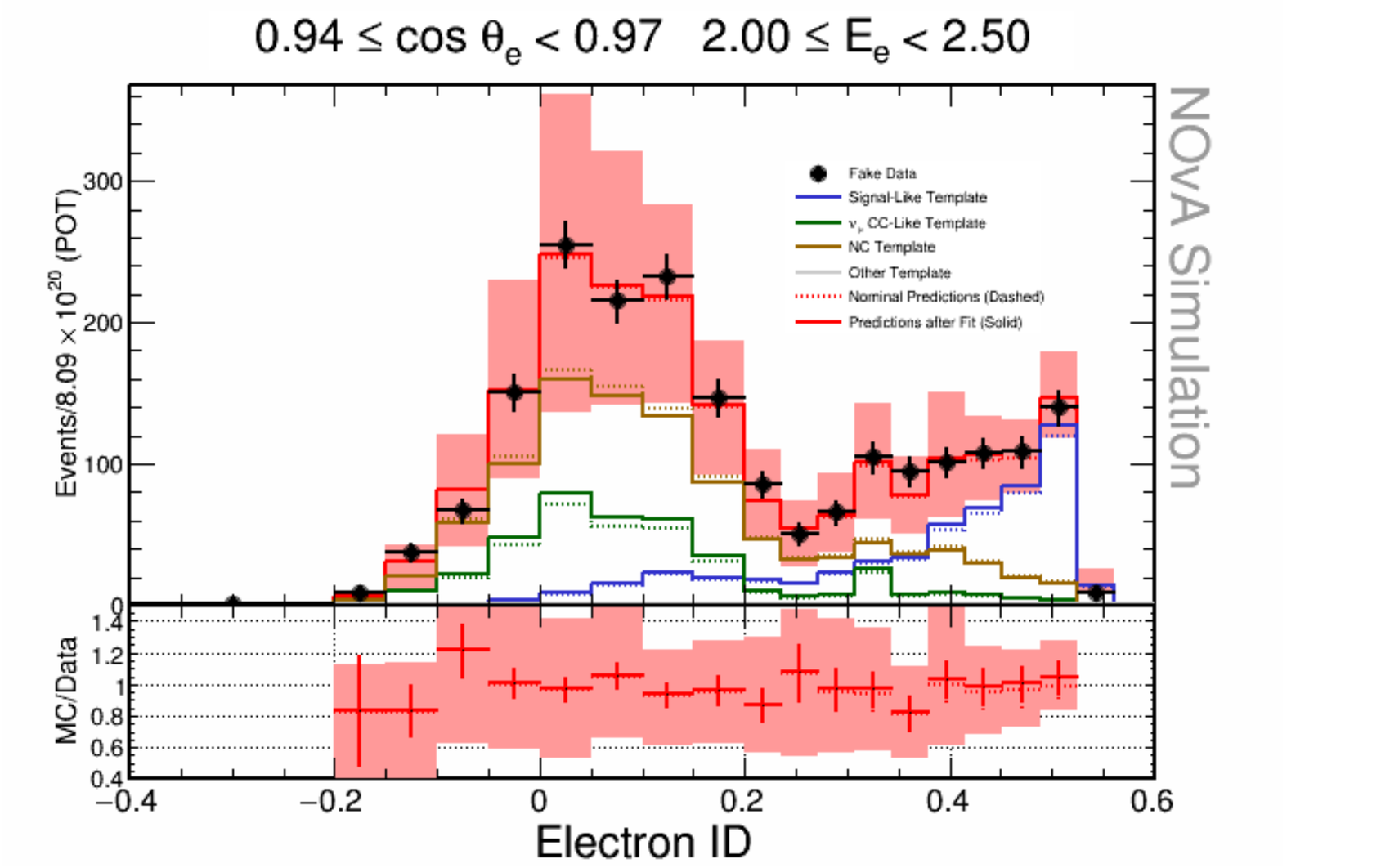
ν_e-CC Inclusive





- Signal of ν_e appearance oscillation measurement.
- Challenge: ν_e is only 1% of the flux. Overwhelming background from ν_μ CC and NC.
- A convolutional neural network (CVN) trained to identify the signal by topology features.
- Cut optimized by minimizing uncertainties.

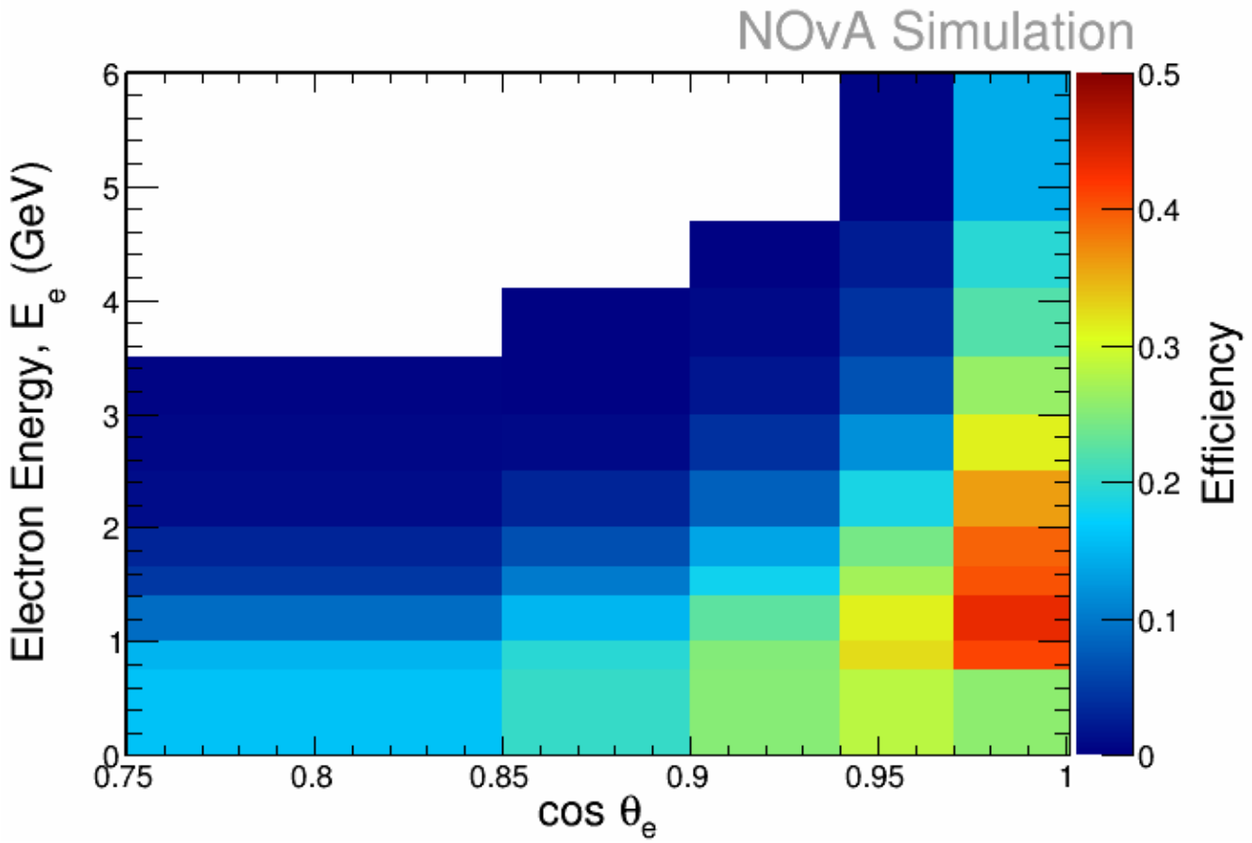
ν_e-CC Inclusive

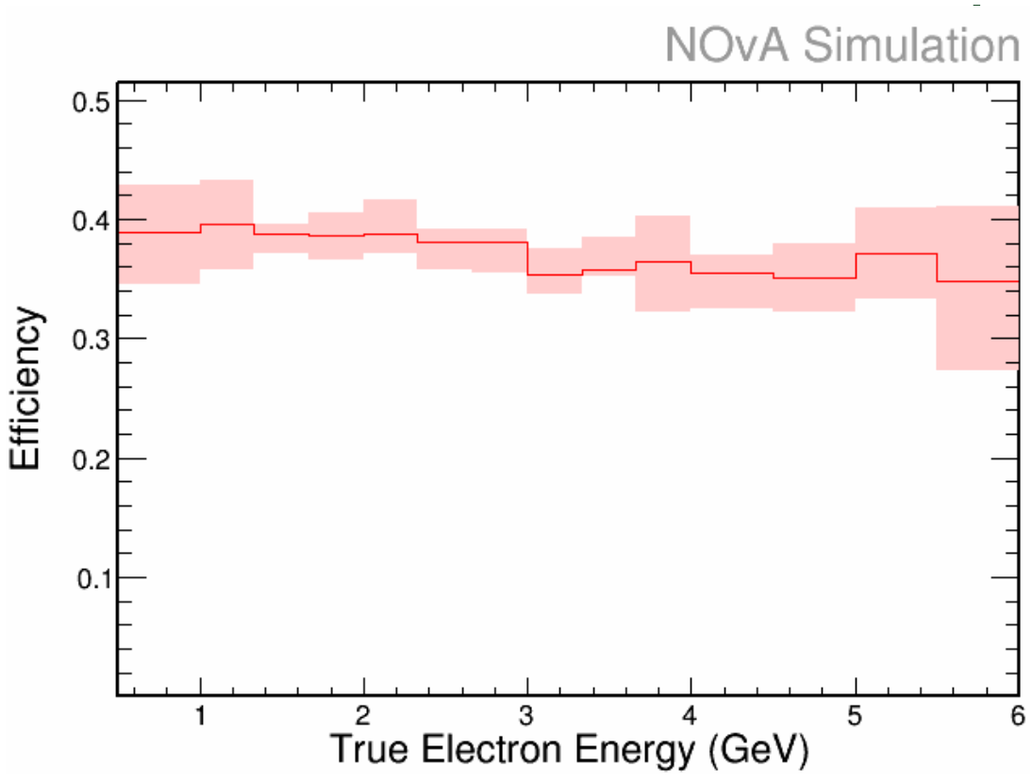


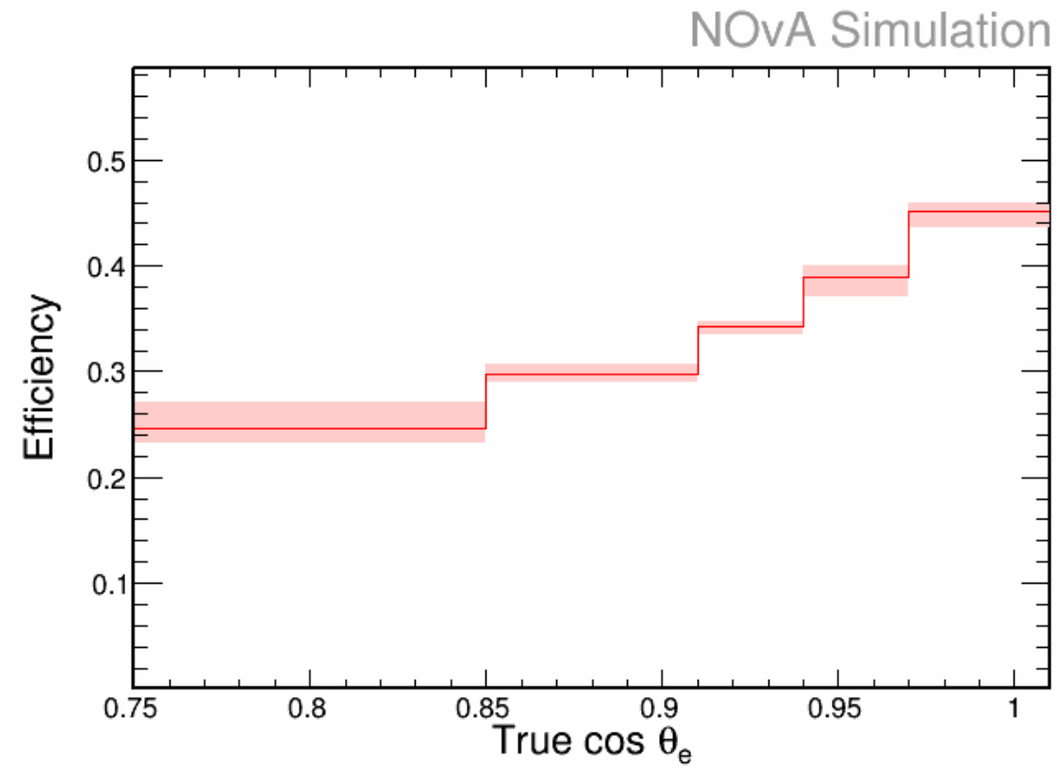
- A template fit method is used to measure signal and background.
  - Templates: signal, ν_μ-CC, NC.
- Fit to data as function of CVNe in each measurement bin.

ν_e-CC Inclusive

- High and flat signal efficiency thanks to CVNe and the template fit method.
- The goal is to report double differential cross sections as function of electron kinematics which has never been measured before.
- Also very interesting to see the ratio to ν_μ inclusive.
- Work under internal review.







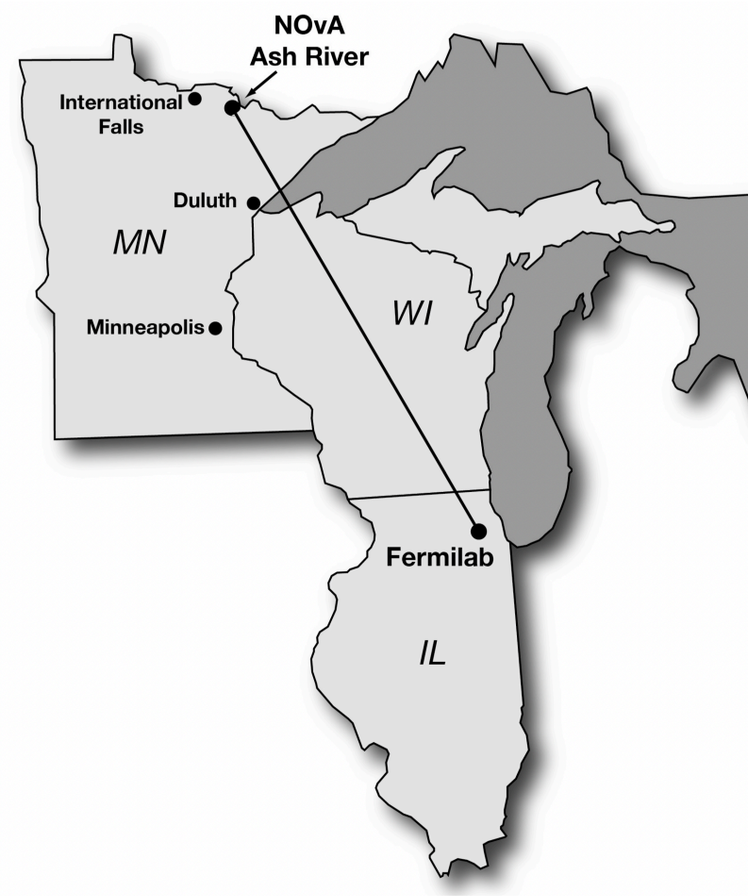
Summary

- The NOvA ND has an very active cross section physics program.
- 2 publications coming:
  - NC coherent π^0
  - CC π^0
- Inclusive measurements in the final stage.
- Lots of other measurements.
- And expect more in the near future.

Back up slides

The NOvA Experiment

- Long-baseline neutrino oscillation measurements:
  - ν_μ to ν_e appearance & ν_μ disappearance
    - Mass hierarchy, θ_{23} octant, δ_{cp}
  - NC disappearance sterile neutrino search
  - See Erica Smith and Steven Calvez's talk for the latest oscillation results!



ν_μ-CC Inclusive Systematic Uncertainties