Cross Section Measurements in the NOvA Near Detector

54th Annual Users (Virtual) Meeting

Wenjie Wu, for the NOvA Collaboration

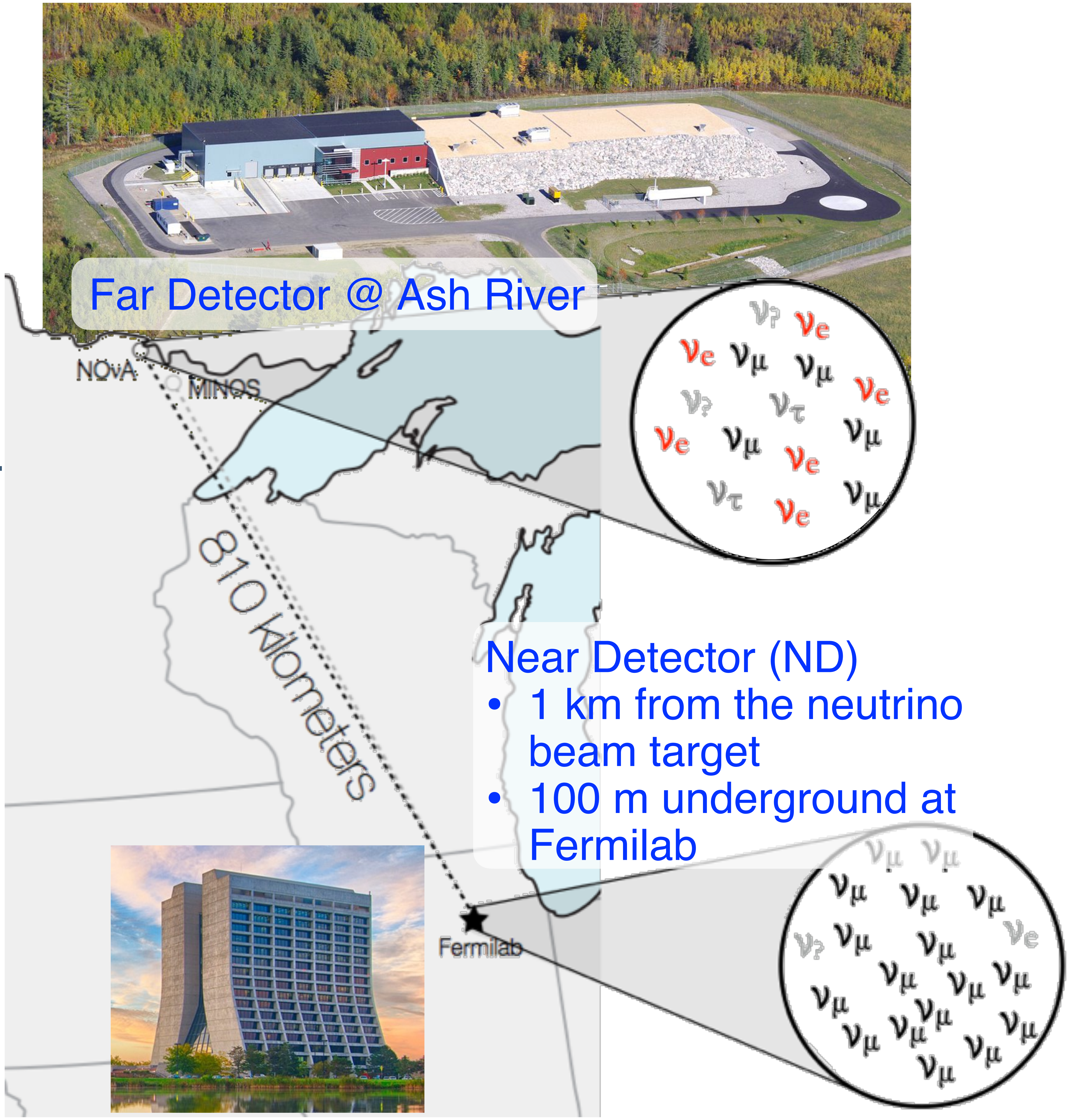
University of California, Irvine

August 5, 2021

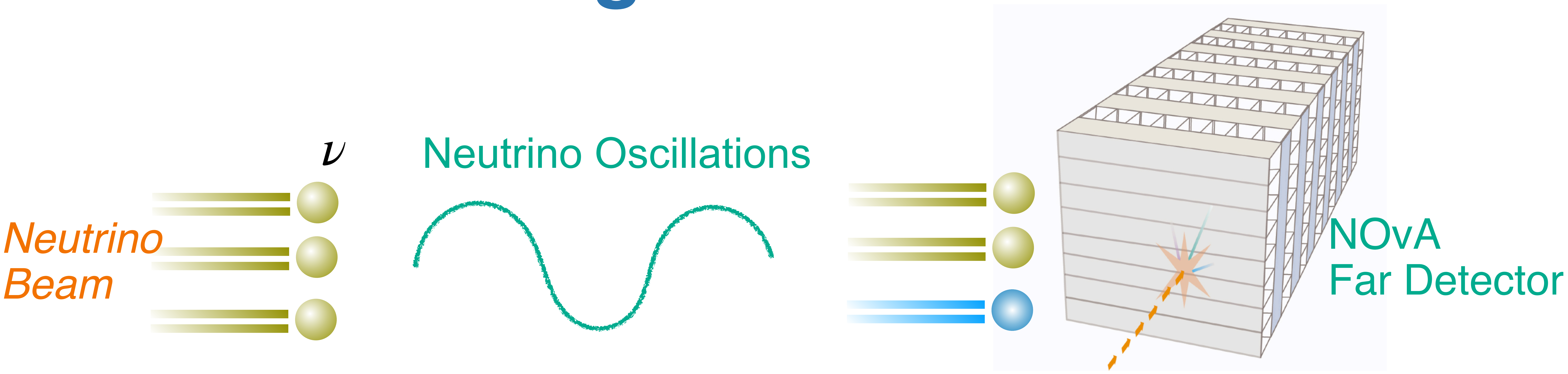
The NOvA Experiment

- NOvA is a long-baseline neutrino experiment
  - 2 functionally identical detectors, 14 mrad off-axis.
  - Designed to measure $\nu_\mu \to \nu_e$ oscillations: detectors provide excellent imaging for both ν_μ and ν_e CC events.
- NuMI beam

  NOvA 3-Flavor oscillation results by Erika Catano-Mur @ Aug. 4
  - Two running configurations: neutrino mode (ν_μ) and antineutrino mode ($\bar{\nu}_\mu$).
- **High-statistics dataset** of neutrino in the Near Detector
  - Used as a control for the oscillation analyses.
  - Provides a rich dataset for measuring neutrino cross sections.



Neutrino Scattering and Oscillation

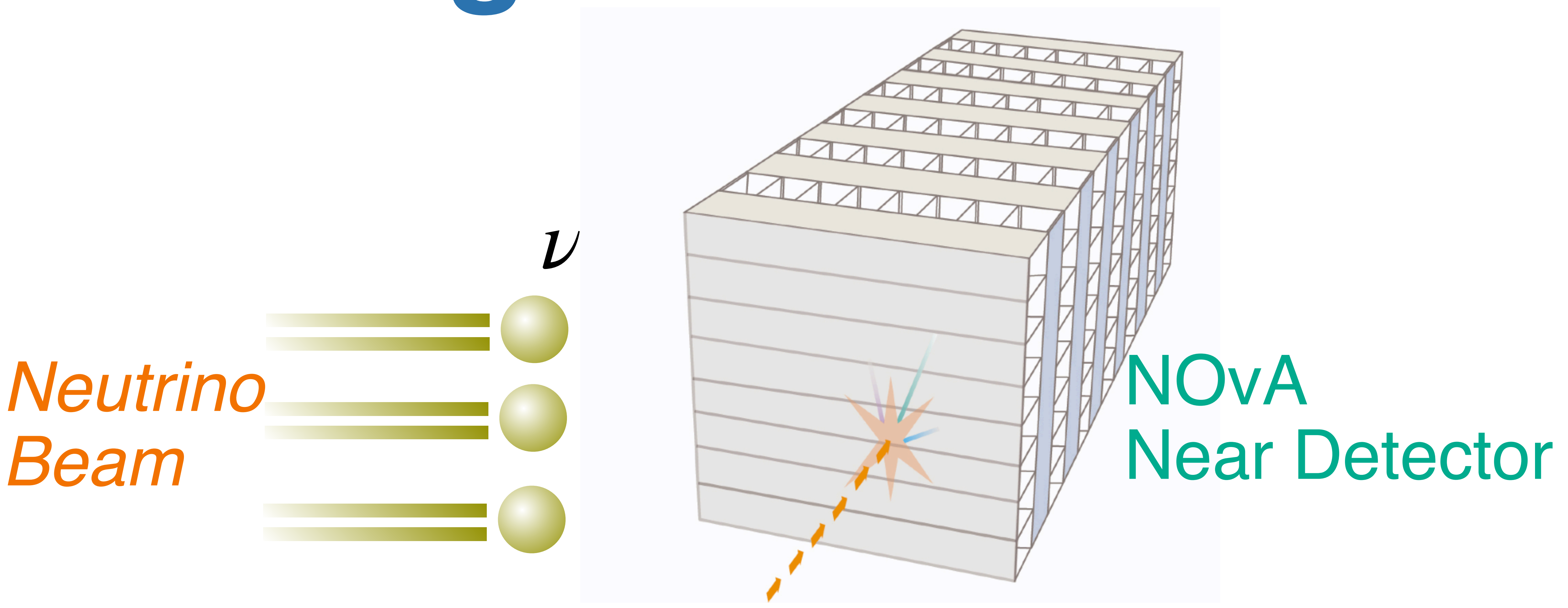


$\Phi \times P_{\nu\to\nu} \times \sigma \propto N_{\nu}^{\mathrm{obs}}$

Neutrino flux — Oscillation Probability — *Cross section* — Observed neutrinos

- Cross section is essential to accurately convert observed neutrinos in the detector into **measured oscillation parameters**.

Neutrino Scattering and Oscillation



$$\Phi \times \sigma \propto N_{\nu}^{\text{obs}}$$

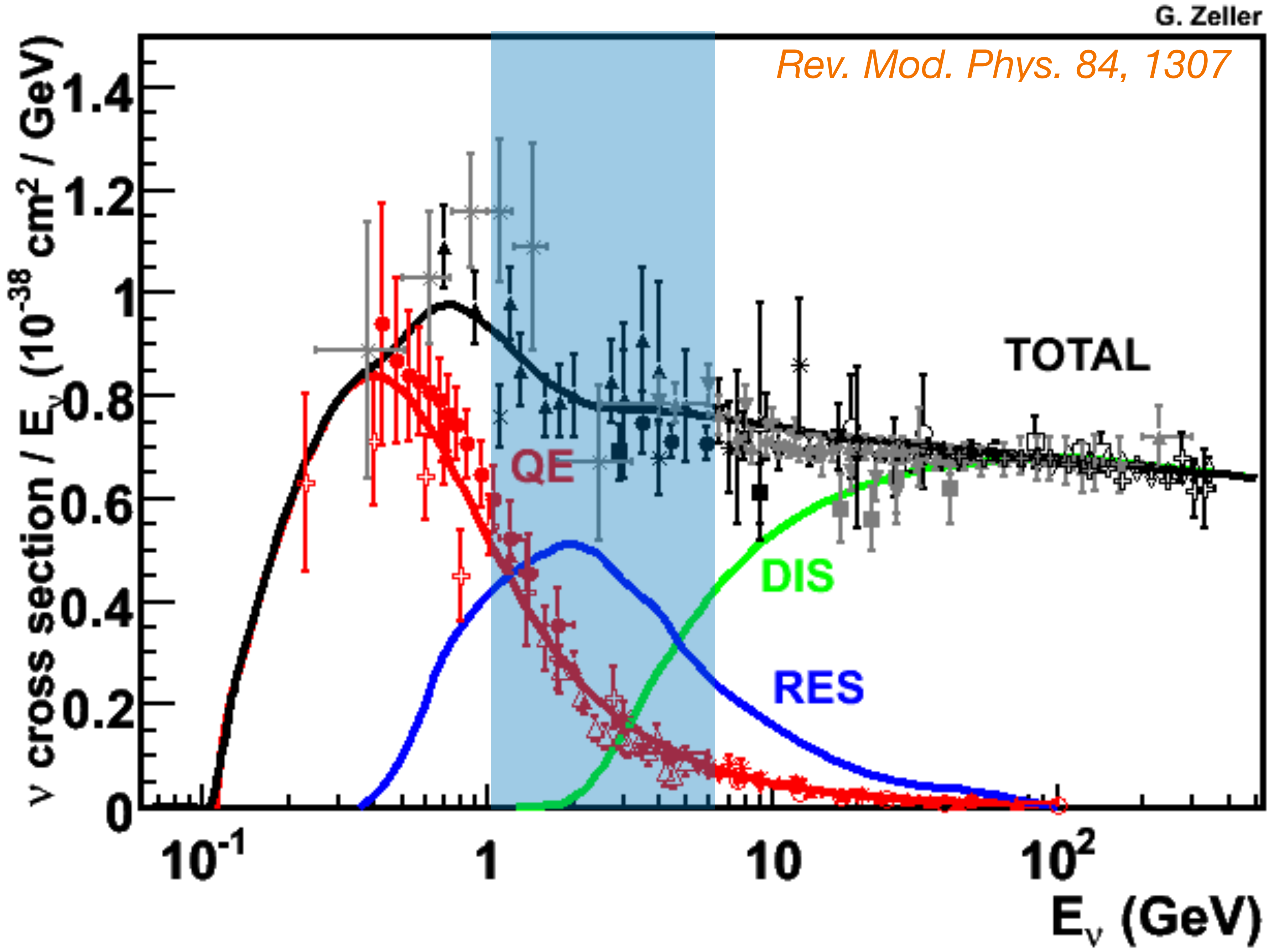
Neutrino flux *Cross section* Observed neutrinos

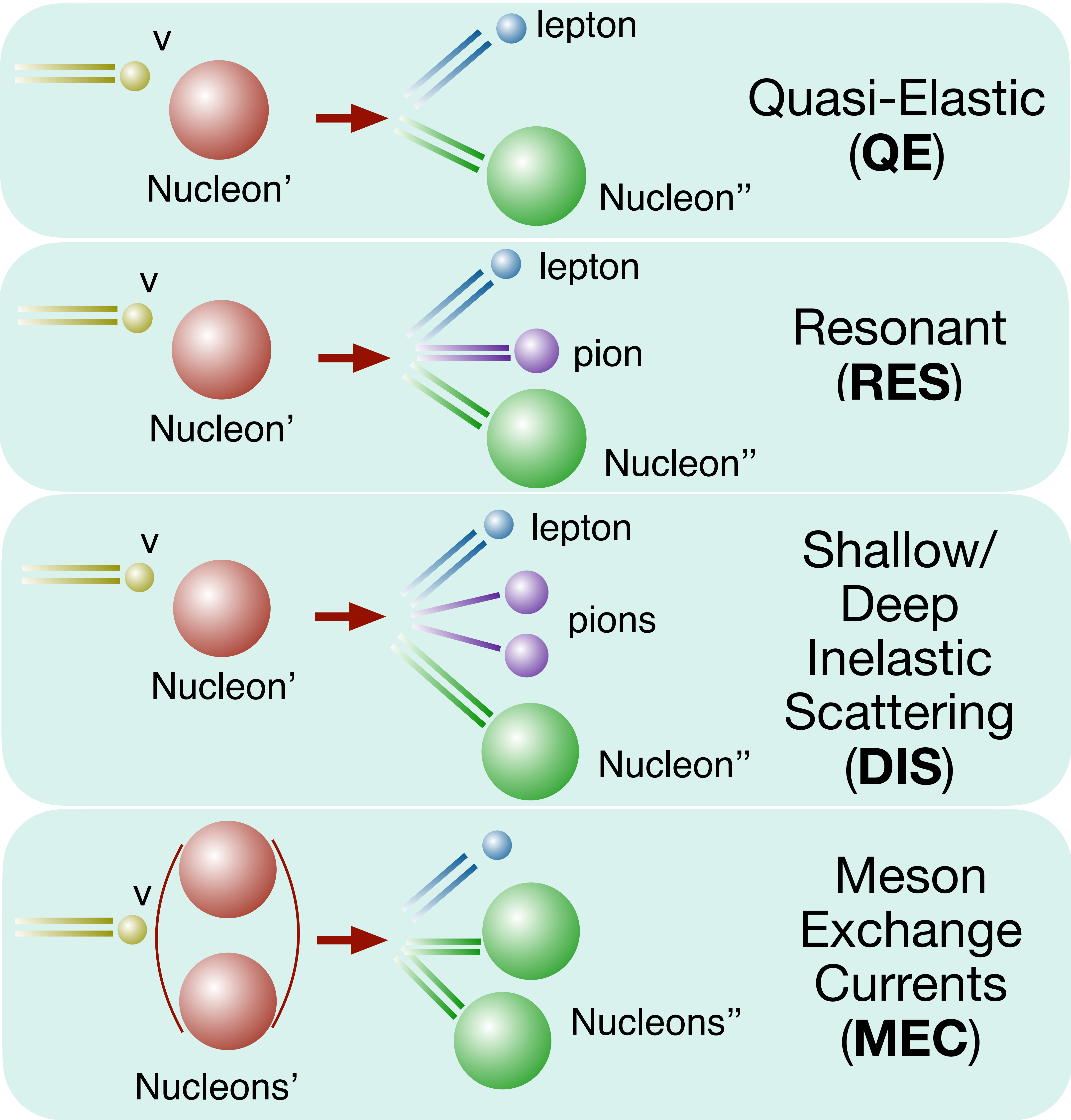
- Cross section is essential to accurately convert observed neutrinos in the detector into **measured oscillation parameters**.
- NOvA Near Detector can perform the cross-section measurements
  - It can also intrinsically deepen our understanding of **neutrino - nucleus interactions**.

Neutrino cross-sections theory by Noemi Rocco @ Aug. 5

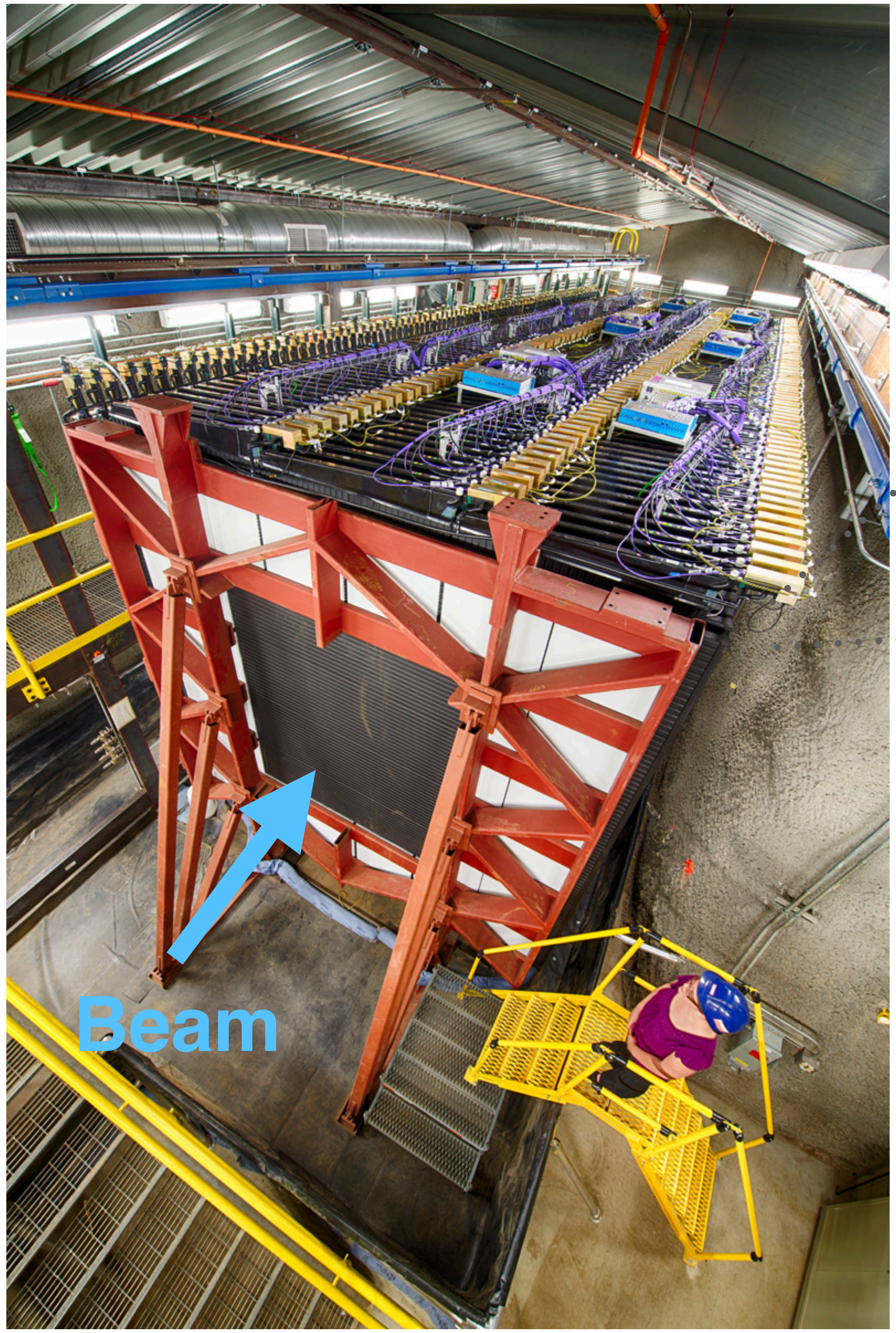
Neutrino Interactions in the NOvA Detector

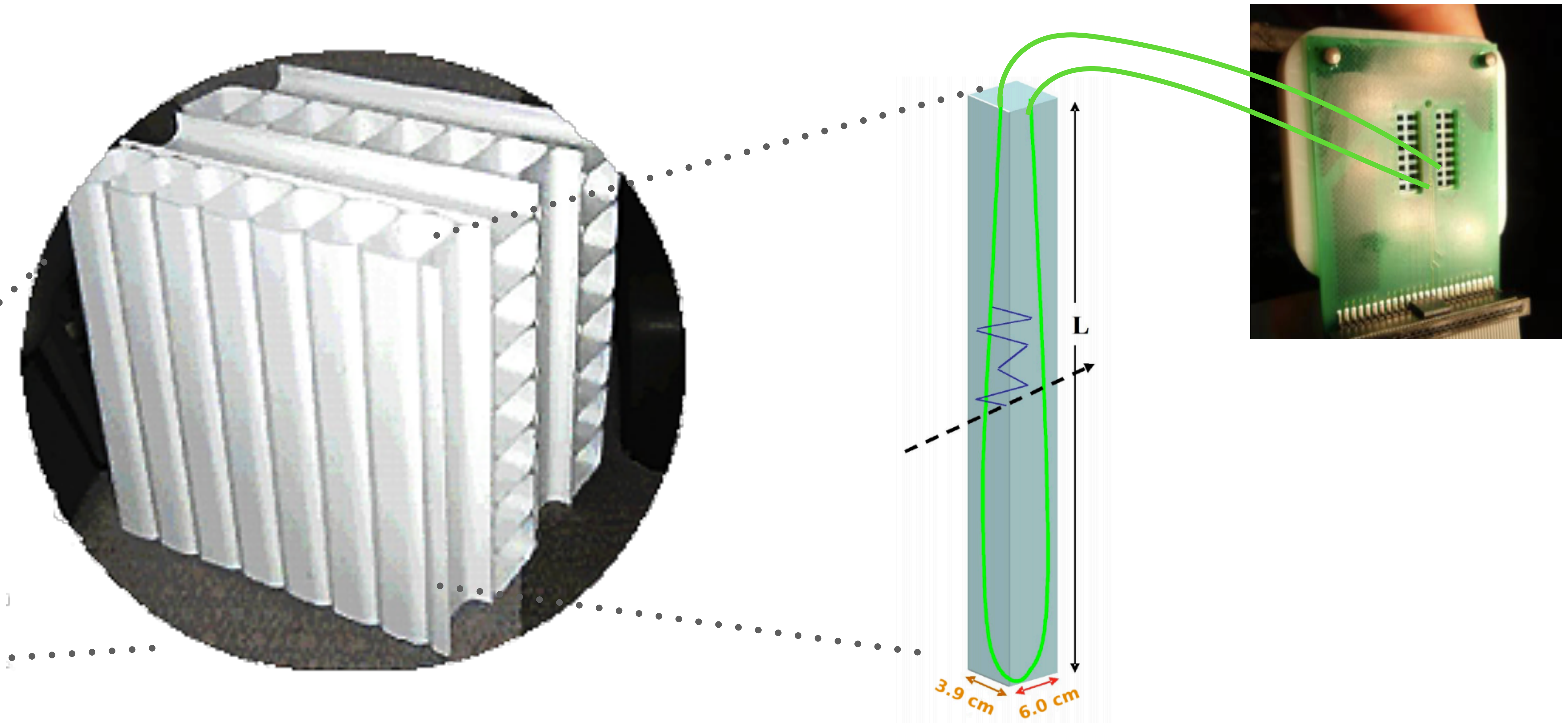
- NOvA flux peaks between **1 and 5 GeV**
  - Several types of interactions can occur.
  - All of this happens in a complex nuclear environment which impacts both initial state and what is observed in the final state.





The NOvA Near Detector





- 300 ton tracking calorimeter
- Extruded plastic cells, filled with liquid scintillator
- Scintillation light captured and routed to APDs via wavelength shifting fibers
- 77% hydrocarbon, 16% chlorine, 6% TiO_2 by mass

Cross Section Measurements

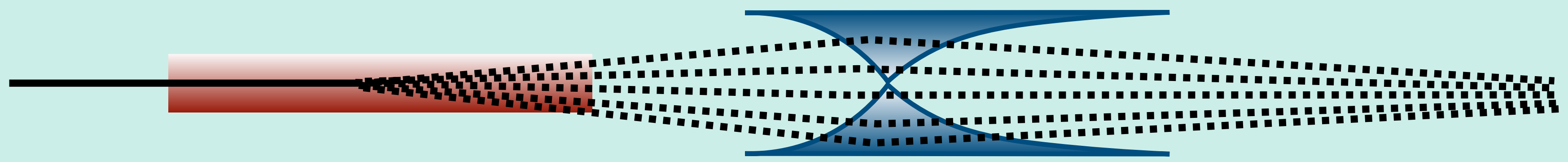
$$\sigma \propto \frac{N_\nu^{\text{obs}}}{\Phi} \quad \Longrightarrow \quad \sigma \propto \frac{N_\nu^{\text{obs}} \cdot p}{\Phi \cdot \epsilon}$$

Purity

Efficiency

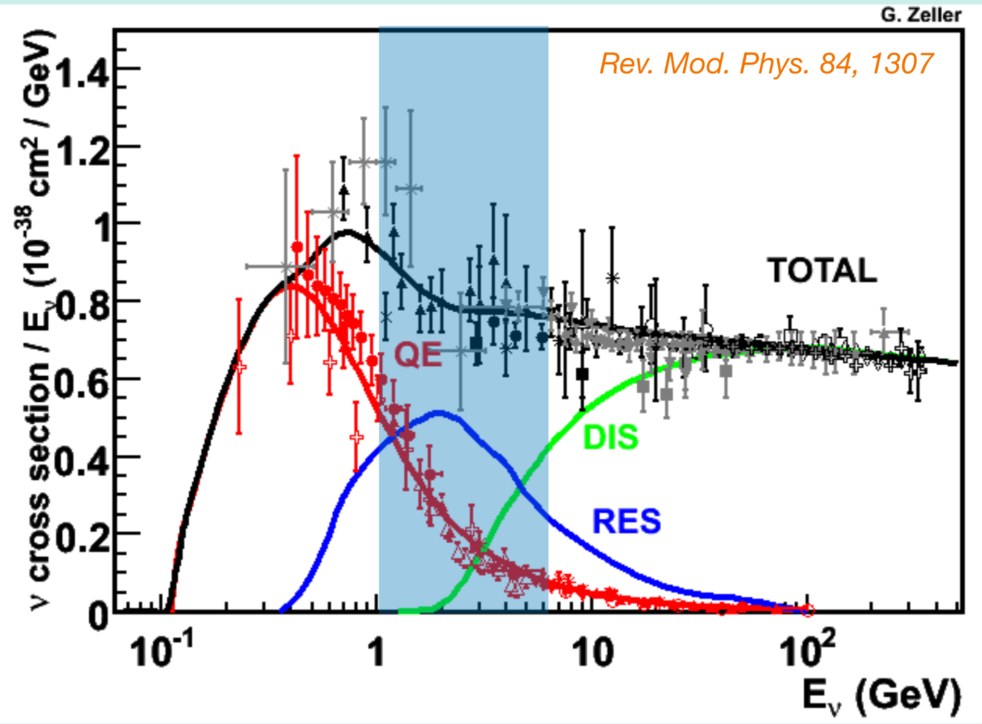
- Complex relationship between outgoing kinematics of final state particle and our ability to select them in the real experiment
  - **Purity** and **efficiency**.
- **We rely on models to determine these corrections**. As we move into the era of high-statistics neutrino oscillation measurements, systematic uncertainties associated with these models become very important.

NOvA Simulation

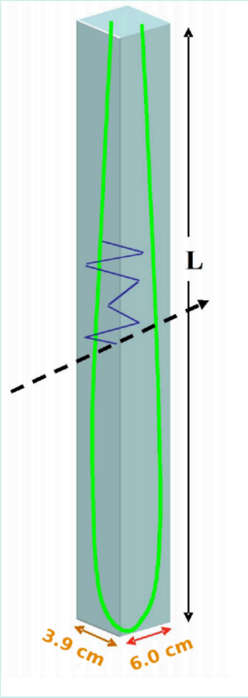


Beamline and Neutrino Flux: G4NuMI

ν-A modelling: GENIE



Detector response
Readout electronics & DAQ



GEANT4-based simulations of particle production and transportation

Neutrino - nucleus interactions are simulated based on a **neutrino event generator GENIE 2.12.2**

Different generators (*GENIE, NEUT, NuWro, GiBUU*) use very similar models but details can be quite different

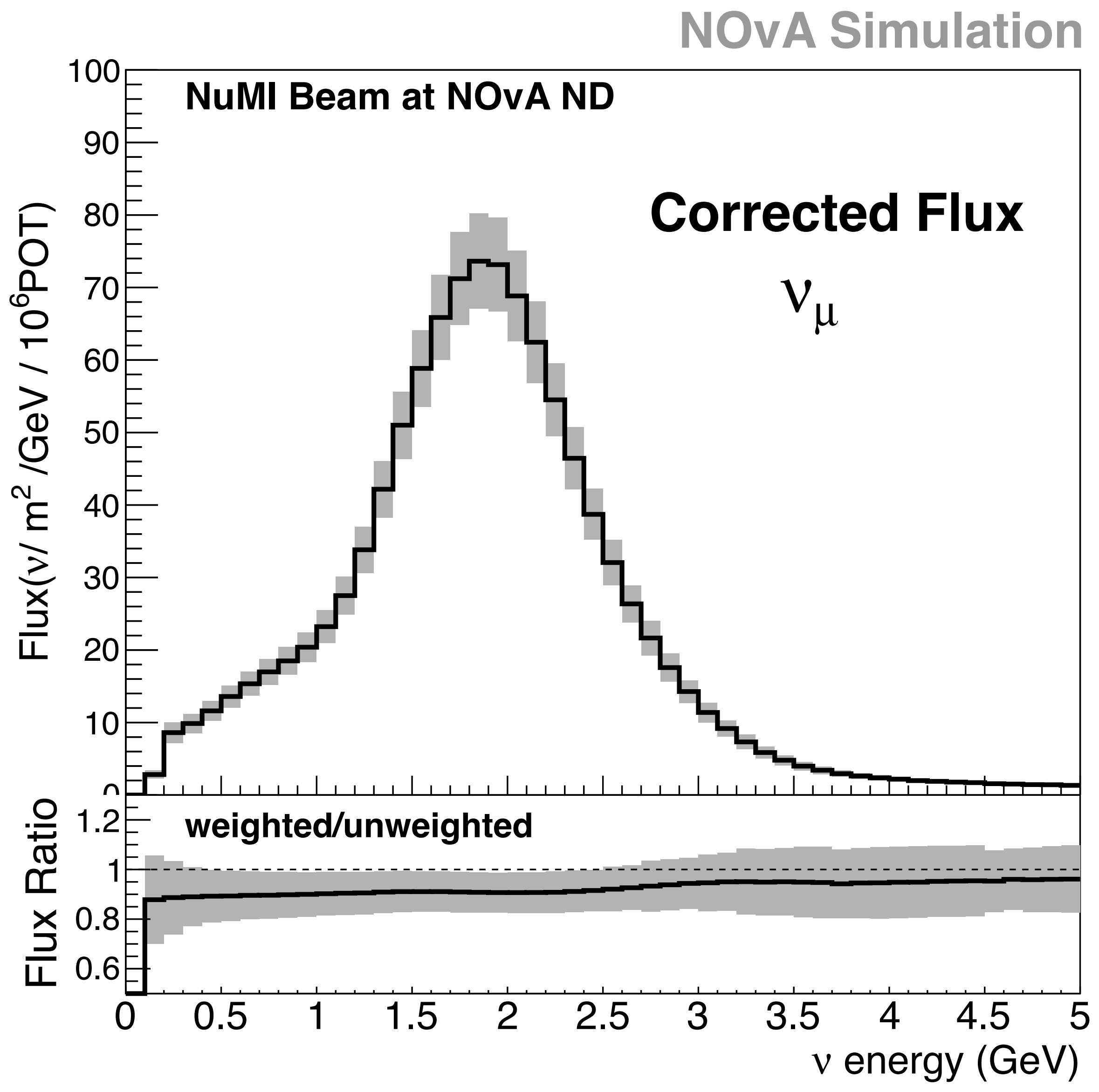
The detector response to the final state particles traversing the detector simulated with **GEANT4**

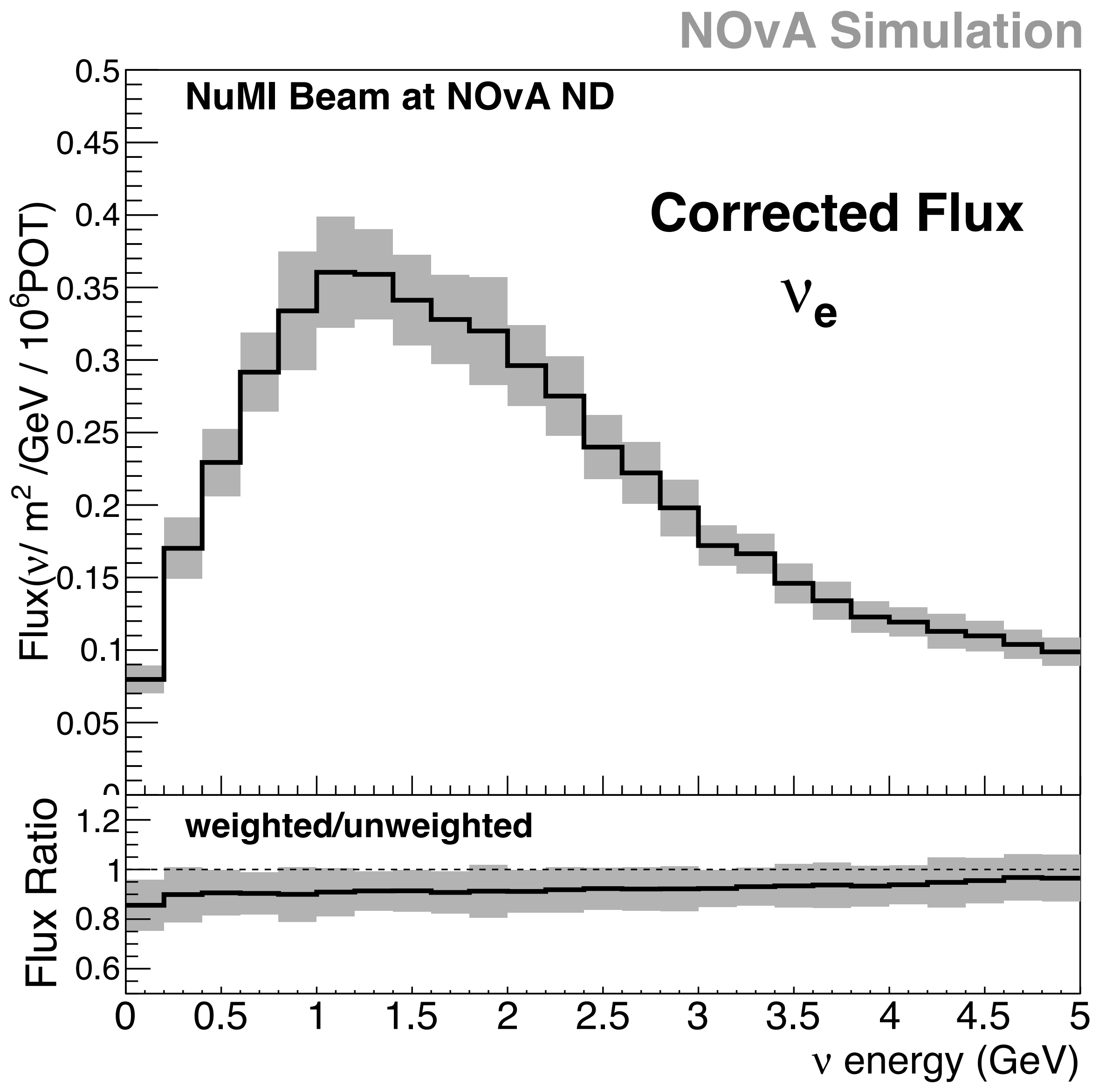
The response of readout electronics and DAQ use **custom simulation routines**

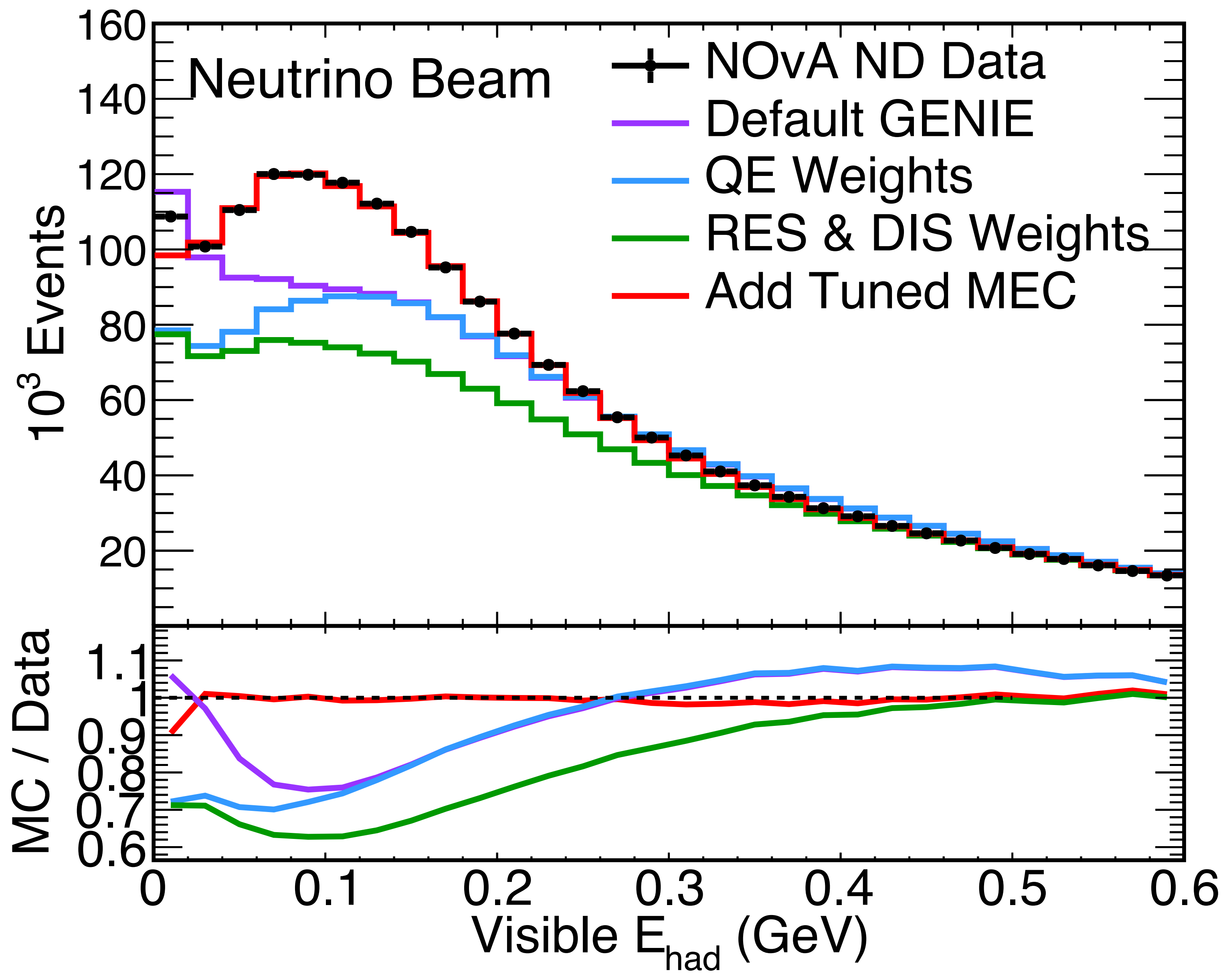
NOvA Simulation

- **Neutrino flux**: Hadron production model constrained with external measurements on thin target.
- Resulting uncertainty ~10% in normalization.
- Technique by MINERvA [Phys.Rev.D94, 092005]

- **Interaction model**: NOvA and external data to tune the simulation by GENIE 2.12.2 (**NOvA Tune)**
  - Suppress QE and RES, Increase DIS, Add MEC
- Details of tune procedure are in Eur. Phys. J. C 80, 1119 (2020).



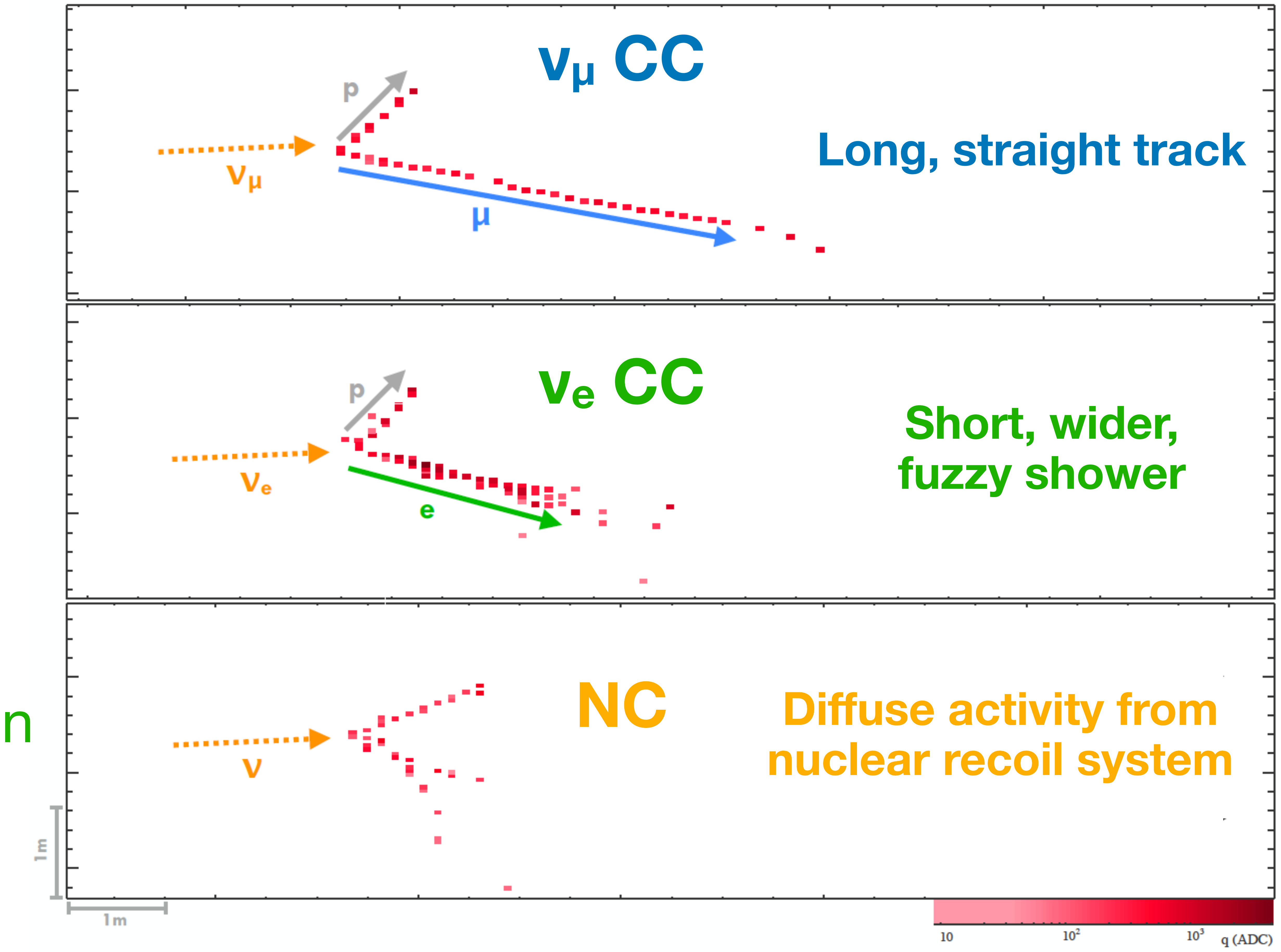




Neutrino Cross Section Measurements at NOvA

Energy range
Detector technology
Statistics

} Unique environment for cross section measurements



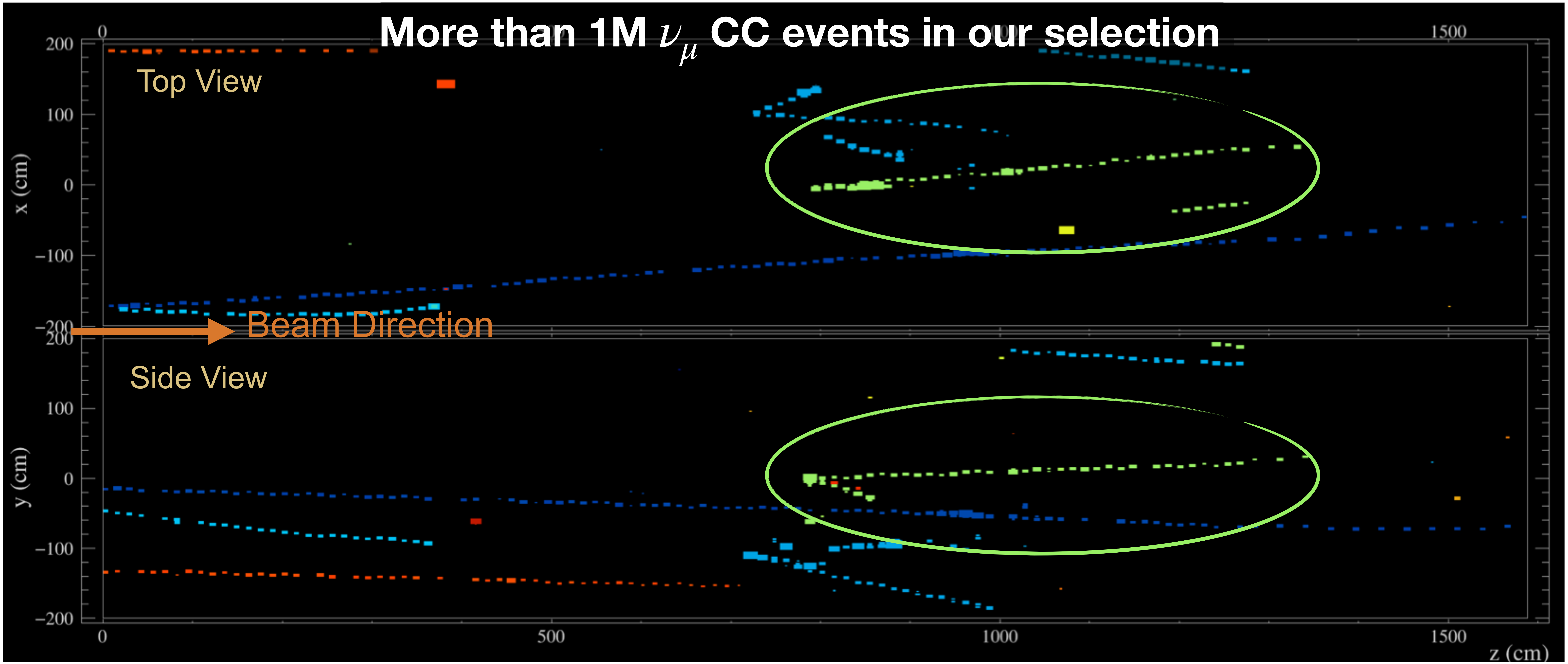
This talk

- ν_μ **CC Inclusive** *: with a final state muon
- ν_e **CC Inclusive** *: with a final state electron

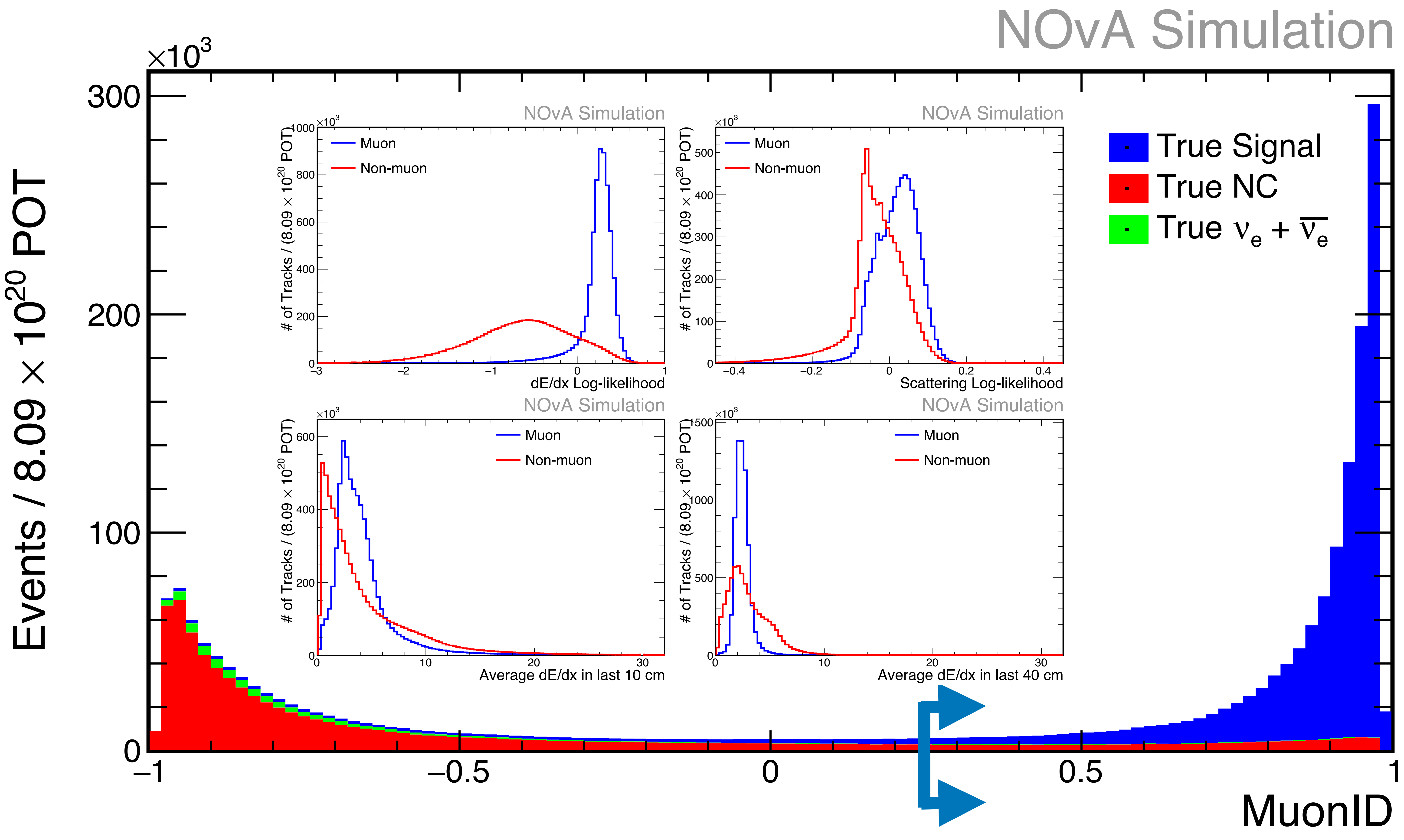
$$^{*}\ \sigma_{CC}^{inclusive} = \sigma_{CC}^{QE} + \sigma_{CC}^{MEC} + \sigma_{CC}^{Res} + \sigma_{CC}^{DIS} + \cdots$$

Inclusive cross section measurements provide insight and constraints on how all the pieces fit together

ν_μ CC Inclusive - with a final state muon



Muon Identification

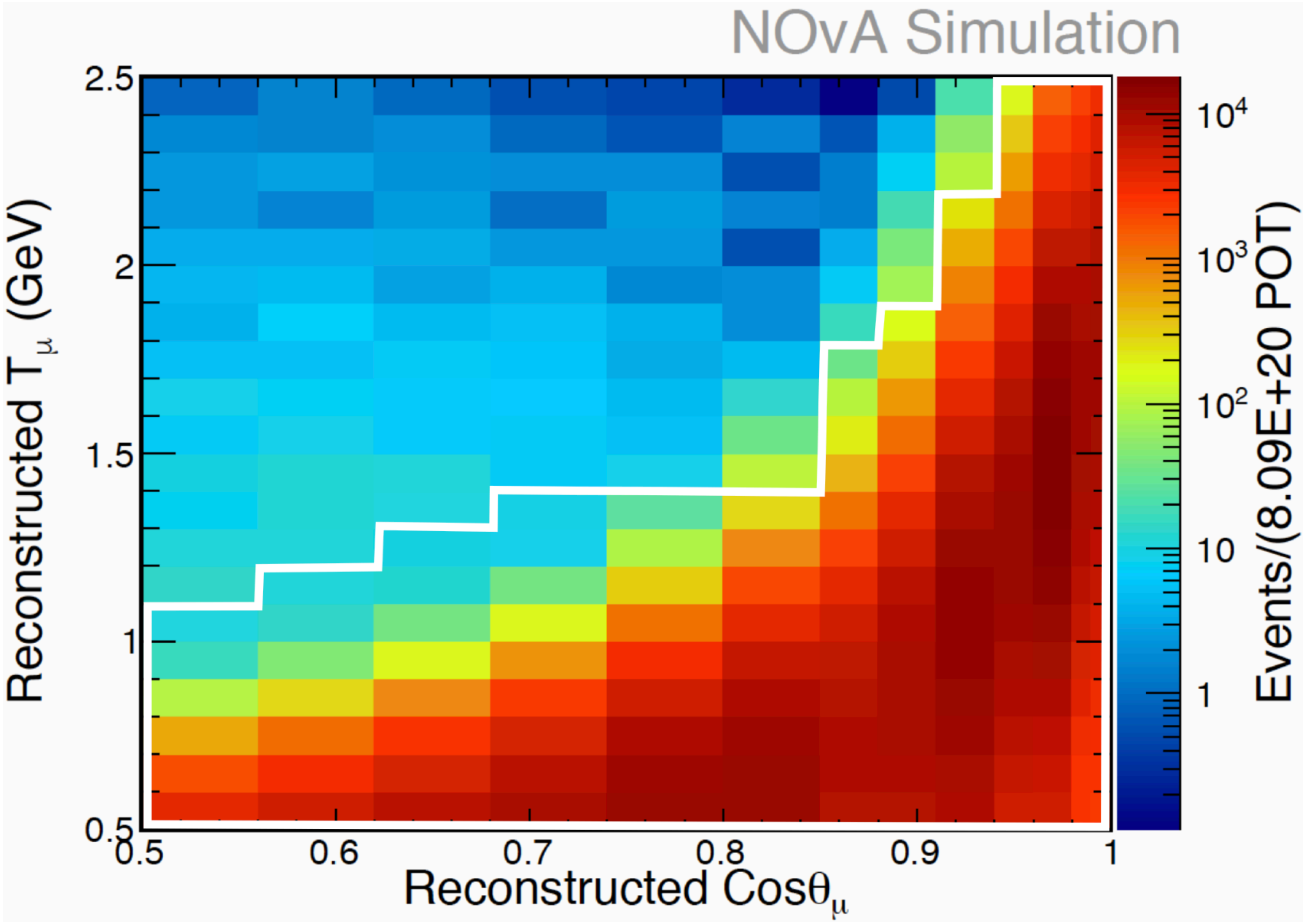


- MuonID derived using Boosted Decision Tree with muon dE/dx and scattering input observables.
- Cut value optimized based on minimizing uncertainty.
- Resulting sample has 86% purity and ~90% efficiency with respect to preselection.

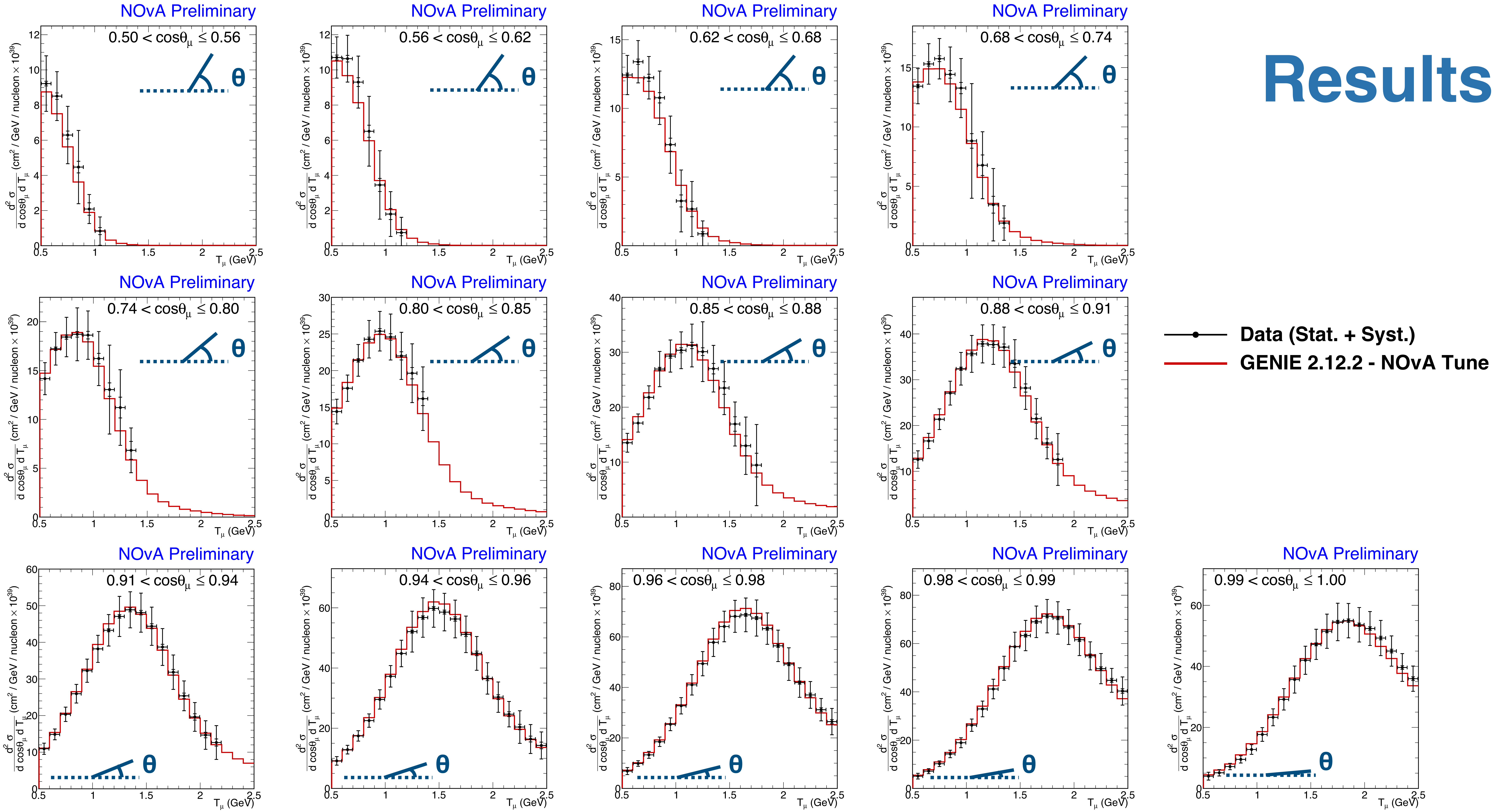
Measurement Strategy

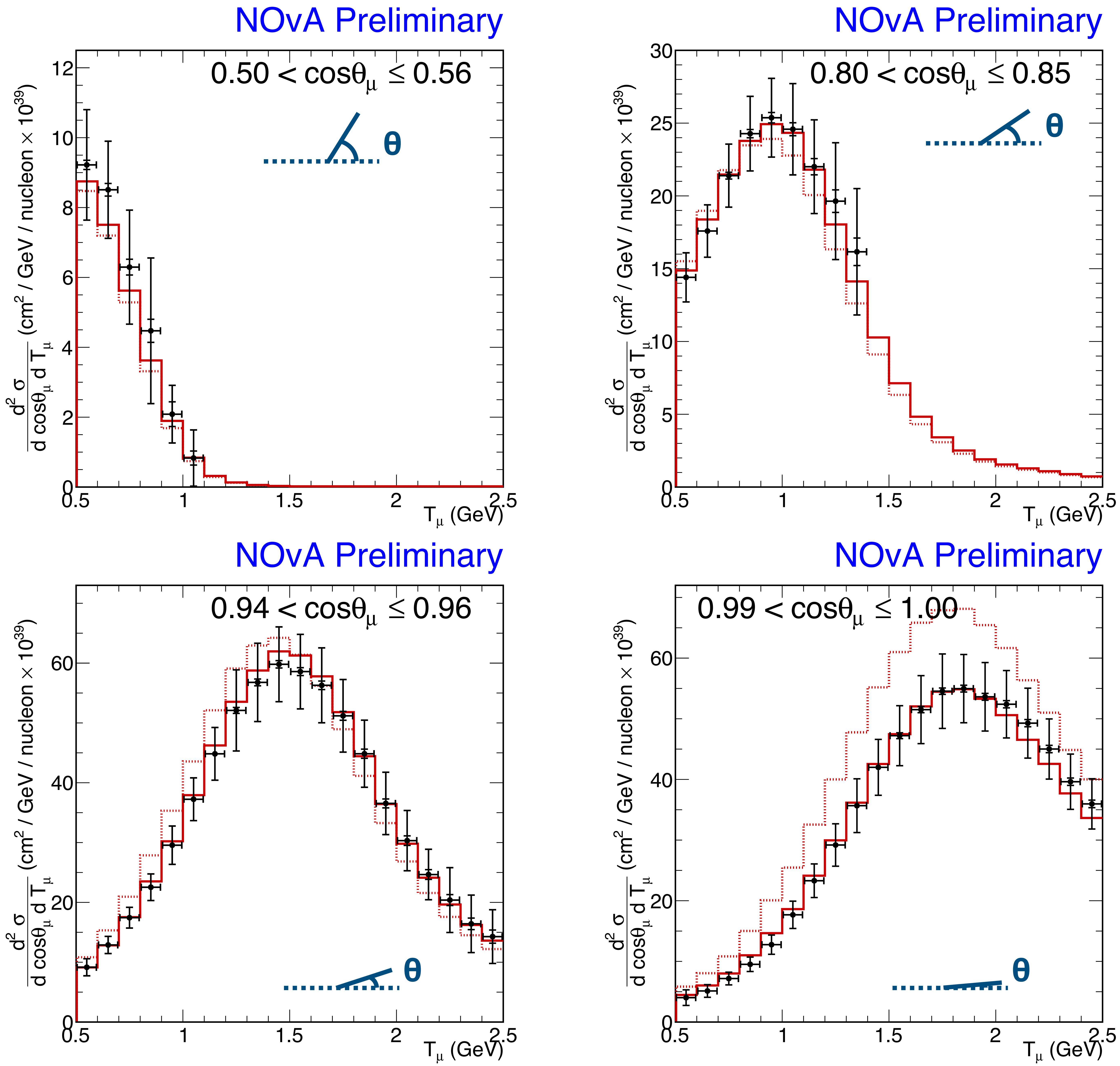
$$\sigma \propto \frac{N_\nu^{\text{obs}} \cdot p}{\Phi \cdot \epsilon} \;\Rightarrow\; \left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_{E_\text{avail}} \left(\frac{\sum_j U_{ij}^{-1} \left(N_\text{sel}\left(\cos\theta_\mu, T_\mu, E_\text{avail}\right)_j P\left(\cos\theta_\mu, T_\mu, E_\text{avail}\right)\right)_j}{N_\text{target}\phi\epsilon\left(\cos\theta_\mu, T_\mu, E_\text{avail}\right)_i \Delta\cos\theta_{\mu_i}\Delta T_{\mu_i}} \right)$$

- Flux-averaged **double-differential cross section** in 172 bins (white outline).
- Selection purity (P) and efficiency (ϵ) corrections applied in 3D space (T_μ, $\cos\theta_\mu$, E_avail).
- E_avail **(available energy): total energy of all observable final state hadrons.**
  - This reduces potential model dependence of the efficiency and purity corrections on the final state hadronic system.
- Unfolded 3D result is then integrated over E_avail.



Results


NOvA Preliminary
0.50 < cosθ_μ ≤ 0.56
0.56 < cosθ_μ ≤ 0.62
0.62 < cosθ_μ ≤ 0.68
0.68 < cosθ_μ ≤ 0.74
0.74 < cosθ_μ ≤ 0.80
0.80 < cosθ_μ ≤ 0.85
0.85 < cosθ_μ ≤ 0.88
0.88 < cosθ_μ ≤ 0.91
0.91 < cosθ_μ ≤ 0.94
0.94 < cosθ_μ ≤ 0.96
0.96 < cosθ_μ ≤ 0.98
0.98 < cosθ_μ ≤ 0.99
0.99 < cosθ_μ ≤ 1.00
θ
d²σ / d cosθ_μ d T_μ (cm² / GeV / nucleon × 10³⁹)
T_μ (GeV)
Data (Stat. + Syst.)
GENIE 2.12.2 - NOvA Tune

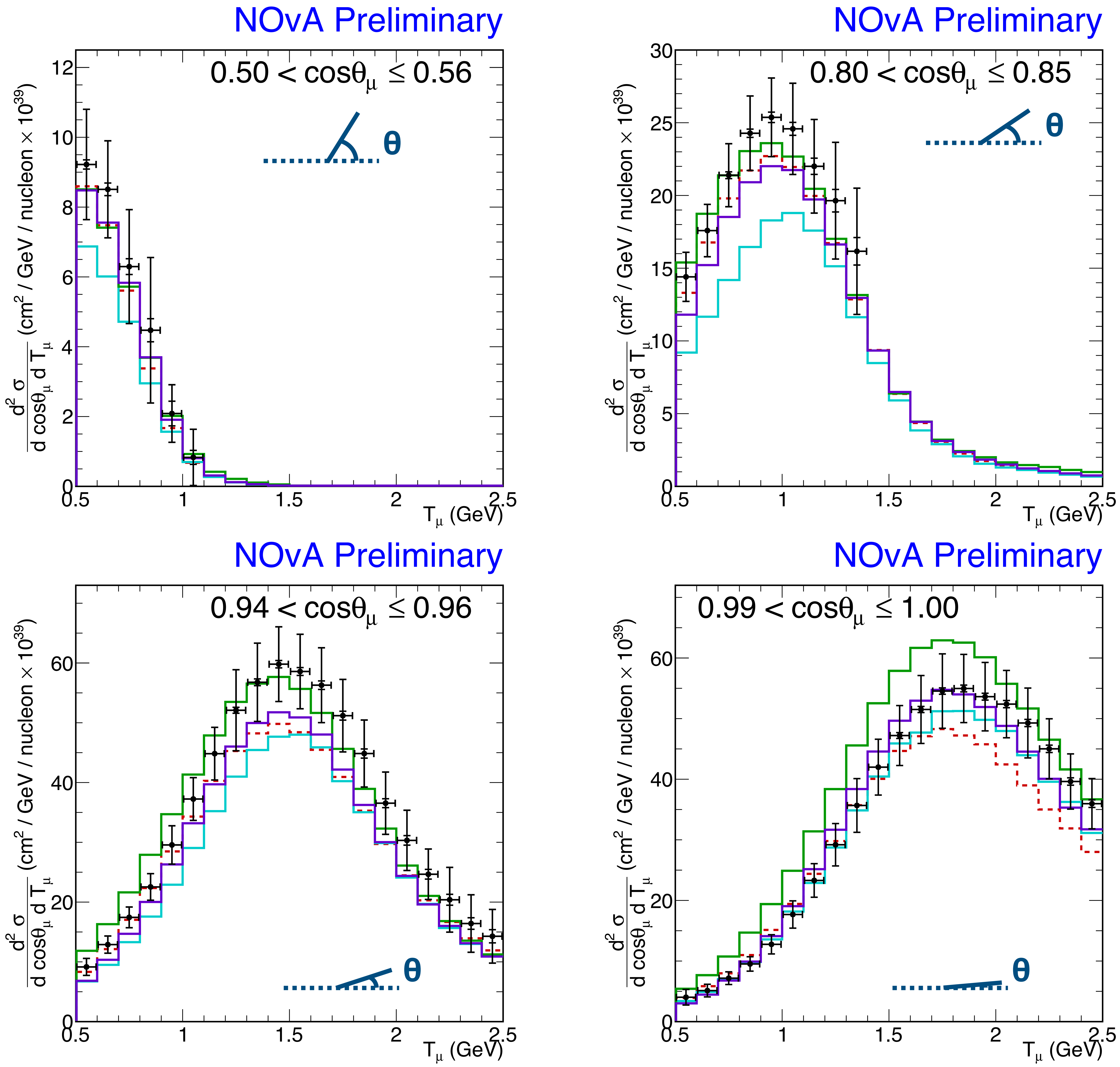


Example 4 cosine slices

- Data (Stat. + Syst.)
- GENIE 2.12.2 - NOvA Tune
- GENIE 2.12.2 - Untuned

- Good agreement between tuned /untuned GENIE versions in high angle slices.
- Untuned GENIE2 overshoots data at forward angle, where events are more elastic.

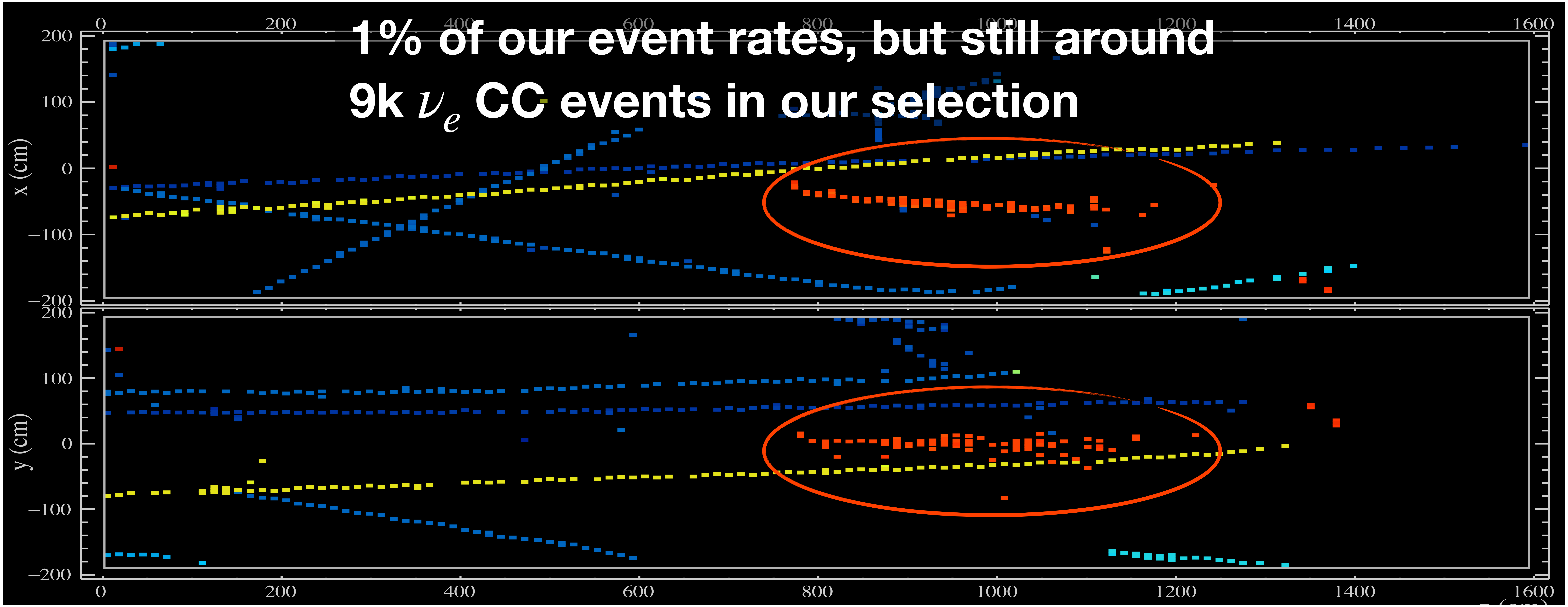
Example 4 cosine slices



- Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

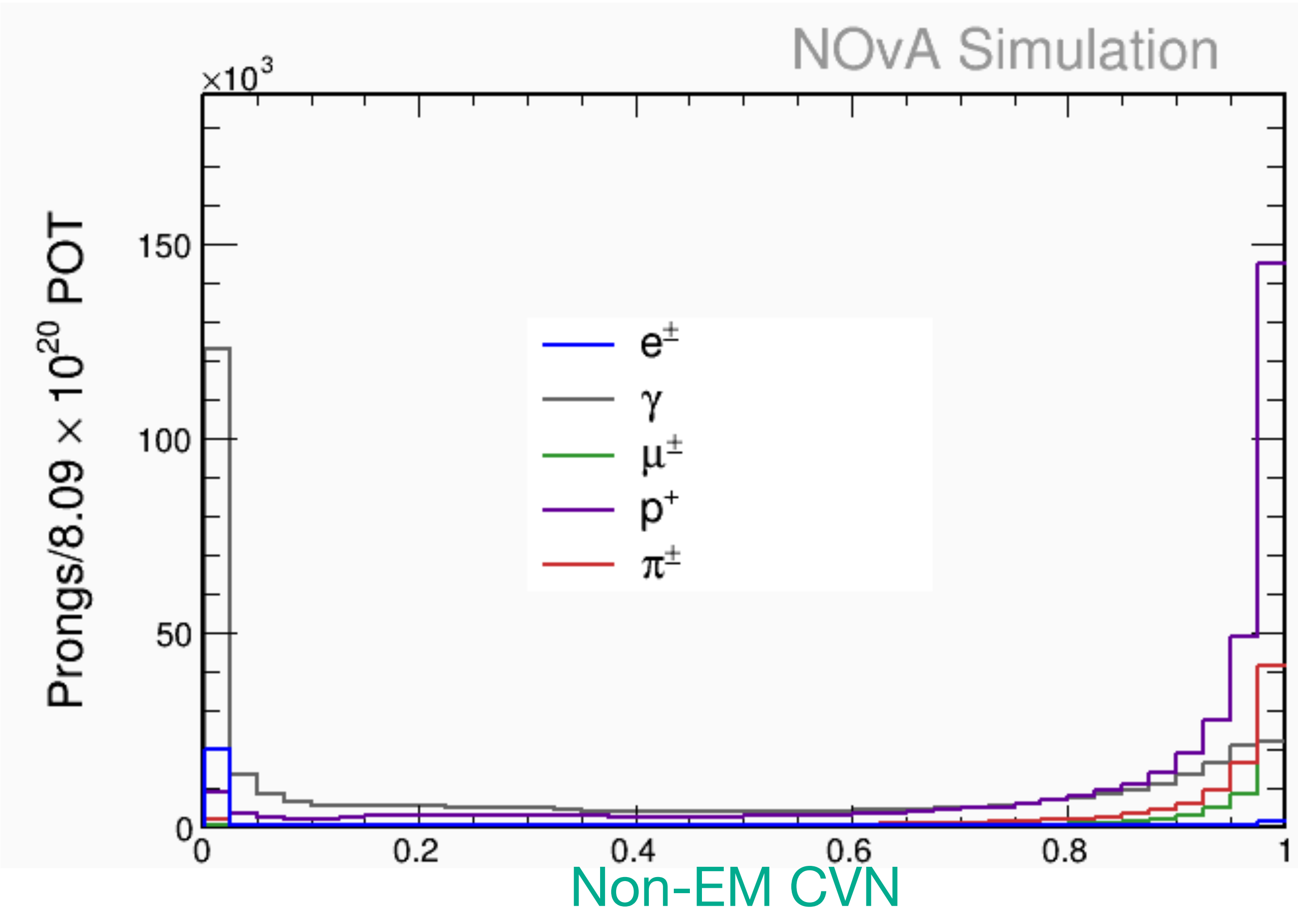
- Out of the box generator comparisons.
- Similar levels of agreement with data across all models.

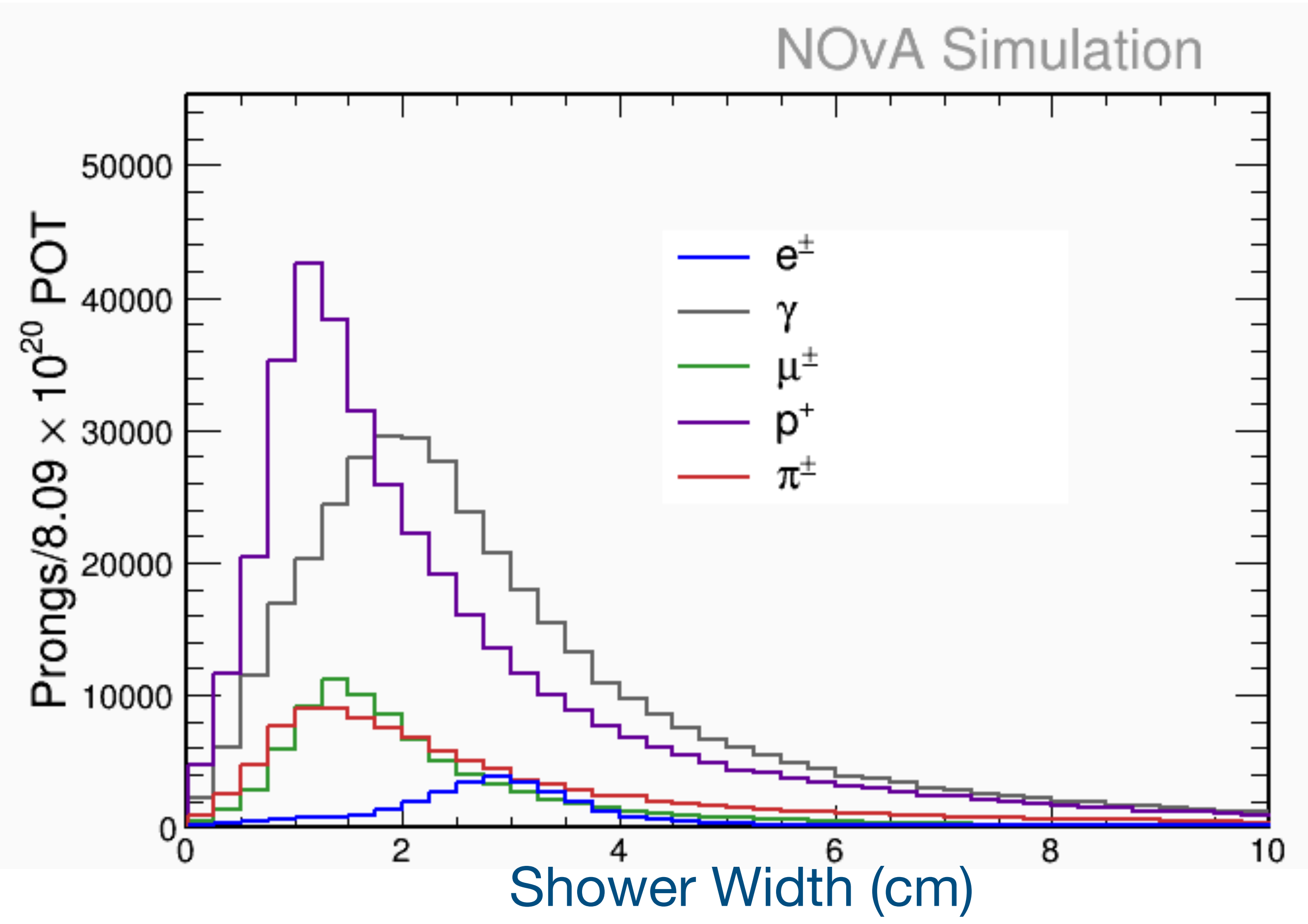
ν_e CC Inclusive: with a final state electron

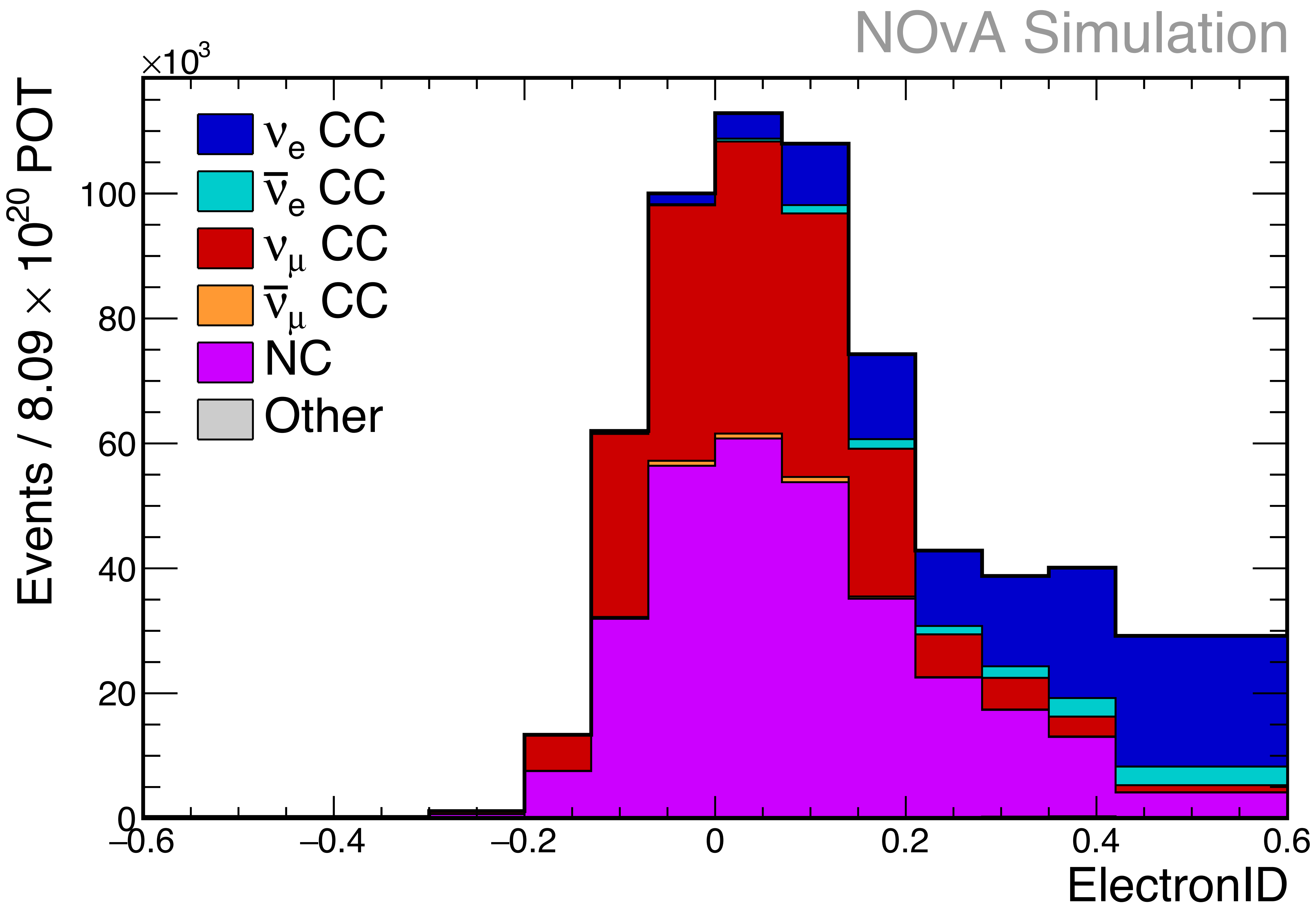


Analysis Strategy

- High efficiency (35%) low purity (12.6%) selection and background constrained with template fit on ElectronID.
- Boosted Decision tree based on several inputs to distinguish electrons from other particles
  - Deep convolution network PIDs based on single particle
  - Event level information



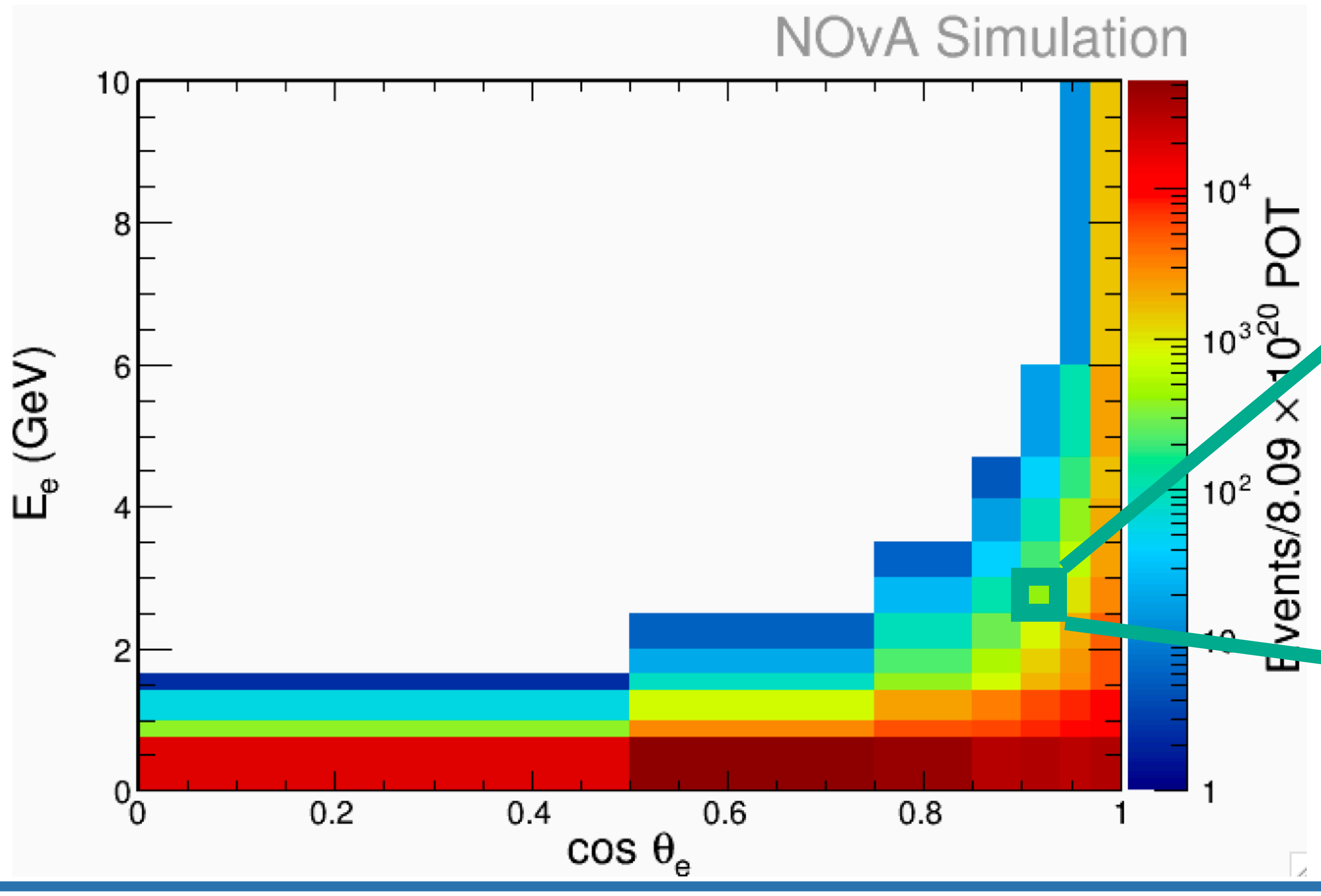


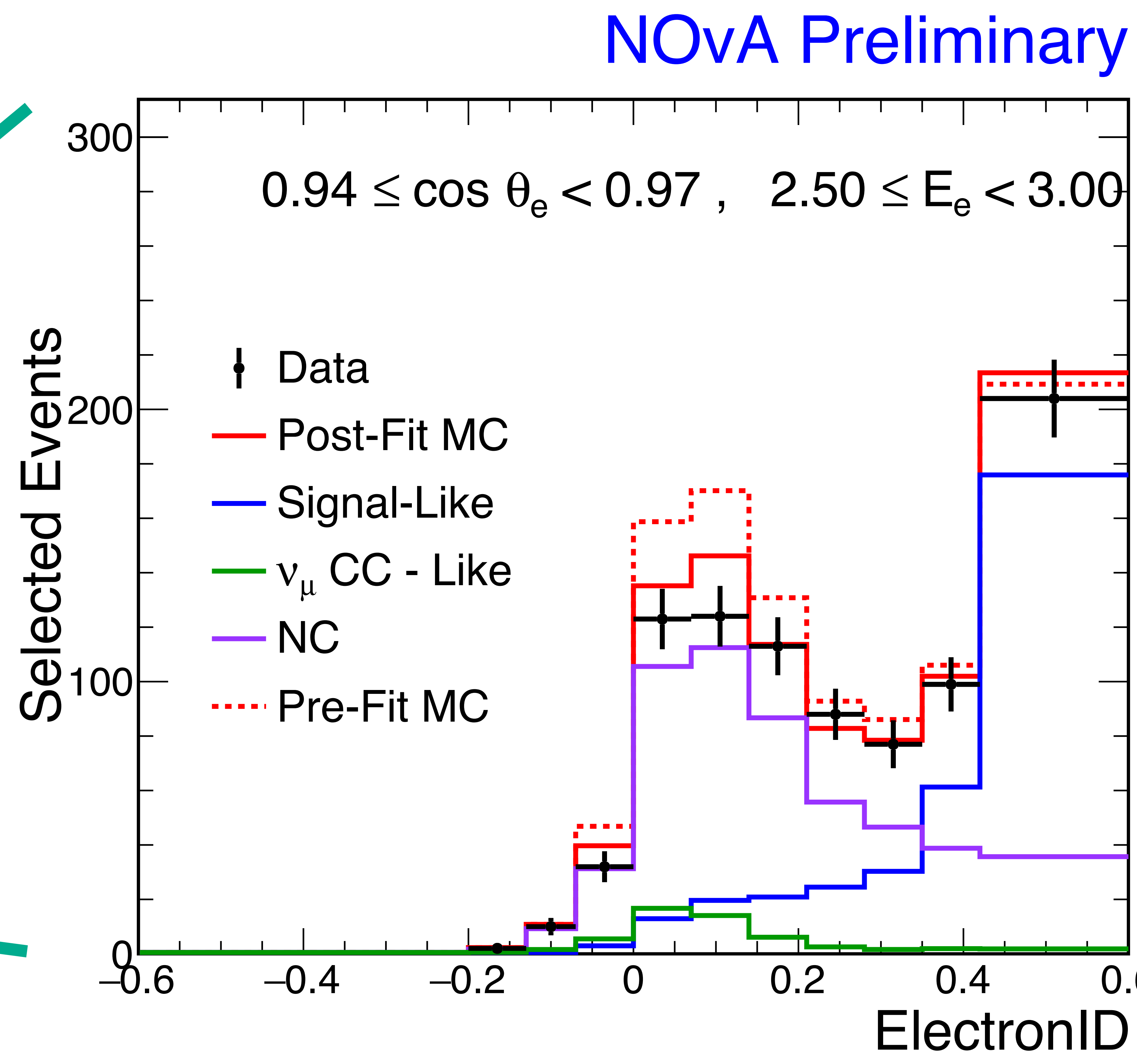


First ν_e CC Double-Differential Measurement

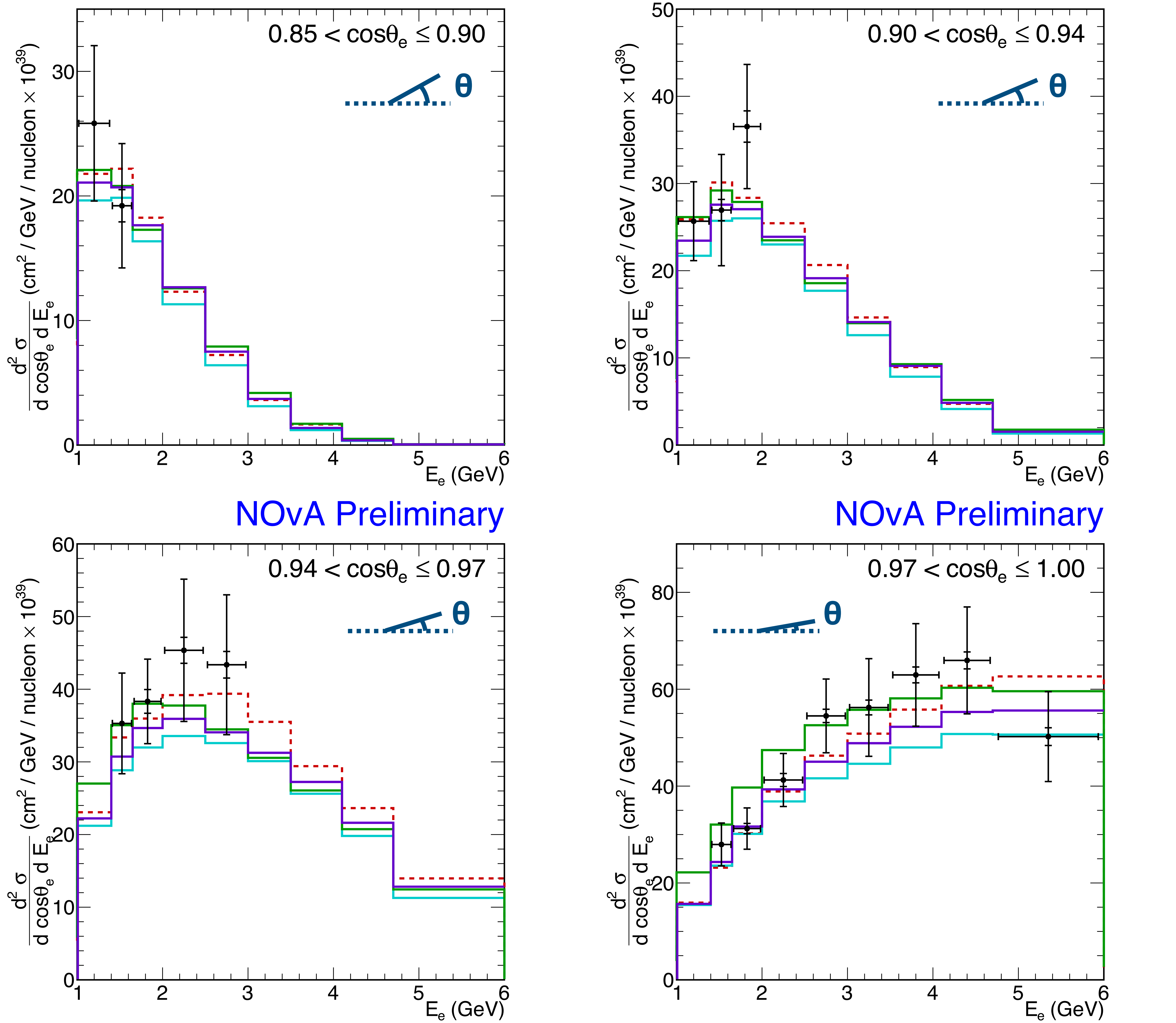
$$\left(\frac{d^2\sigma}{d\cos\theta_e dE_e}\right)_i = \frac{\sum_j U_{ij}^{-1} N_{\text{sig}}(\cos\theta_e, E_e)_j}{N_t \phi \epsilon(\cos\theta_e, E_e)_i \Delta\cos\theta_{ei} \Delta E_{ei}}$$

- **Flux-averaged double-differential cross section as a function of the electron kinematics ($\cos\theta_e$, E_e).**
- Background estimate in each electron kinematic bin is done via a template fit of the ElectronID distribution.





Results: ν_e CC Inclusive



- Out of the box generator comparison.
- Measurement in good agreement with generator predictions.

Summary

ν_μ CC Inclusive

- **More than 1M events**
- 172 bins in muon kinematics
- Uncertainties ~12% in each bin

ν_e CC Inclusive

- **First double-differential measurement**
- Around 9k events
- Uncertainties ~15-20% in each bin

- High-statistics neutrino dataset in NOvA ND enables double-differential cross section measurements for both ν_μ and ν_e CC interactions.
- NOvA is also working on many other measurements to advance our understanding of neutrino-nucleus interactions.
- **As part of the Fermilab's neutrino program, it takes everyone in the lab to achieve these results. And we're aiming for more results in the future.**

NOvA

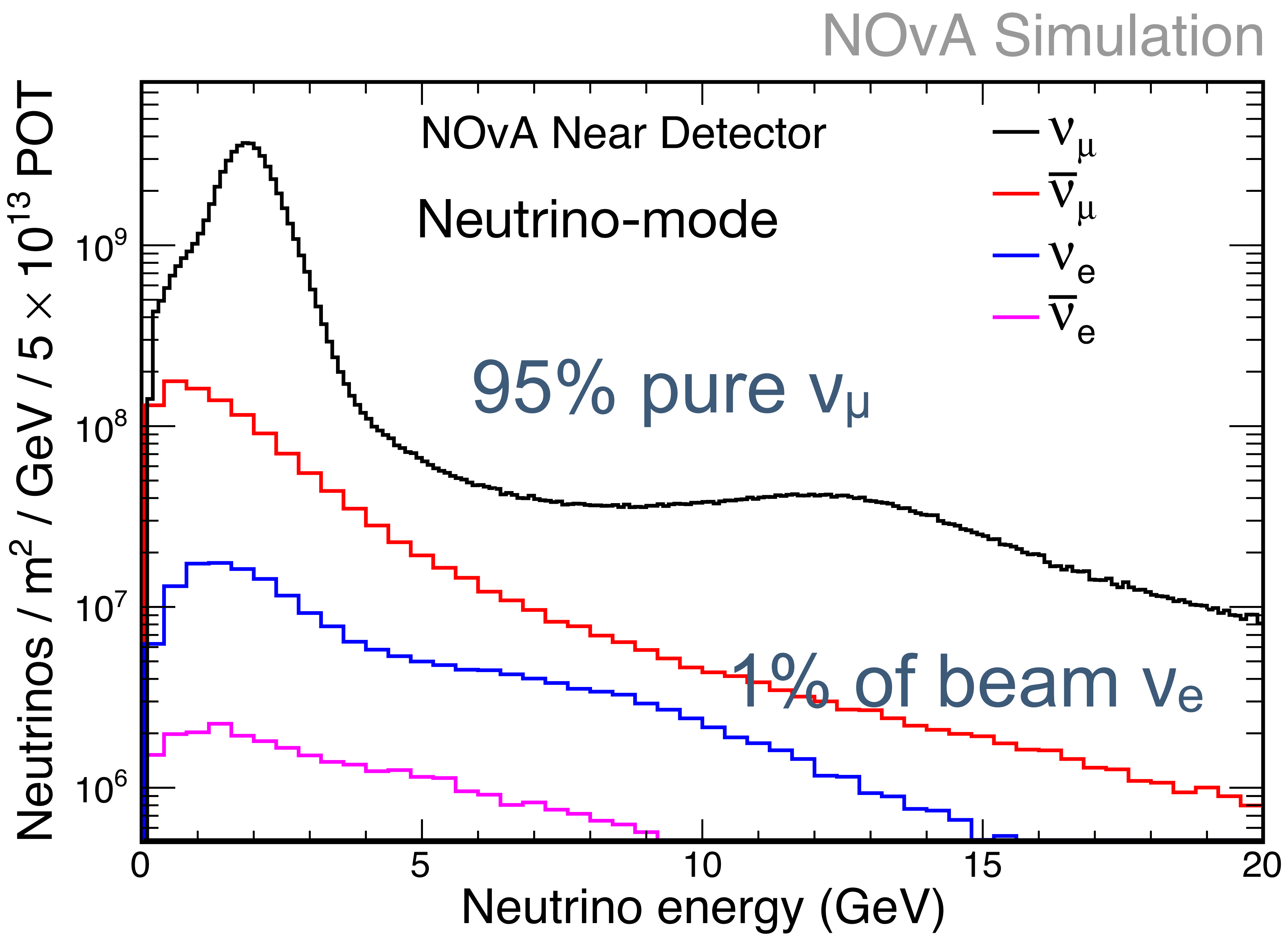
Thank you!

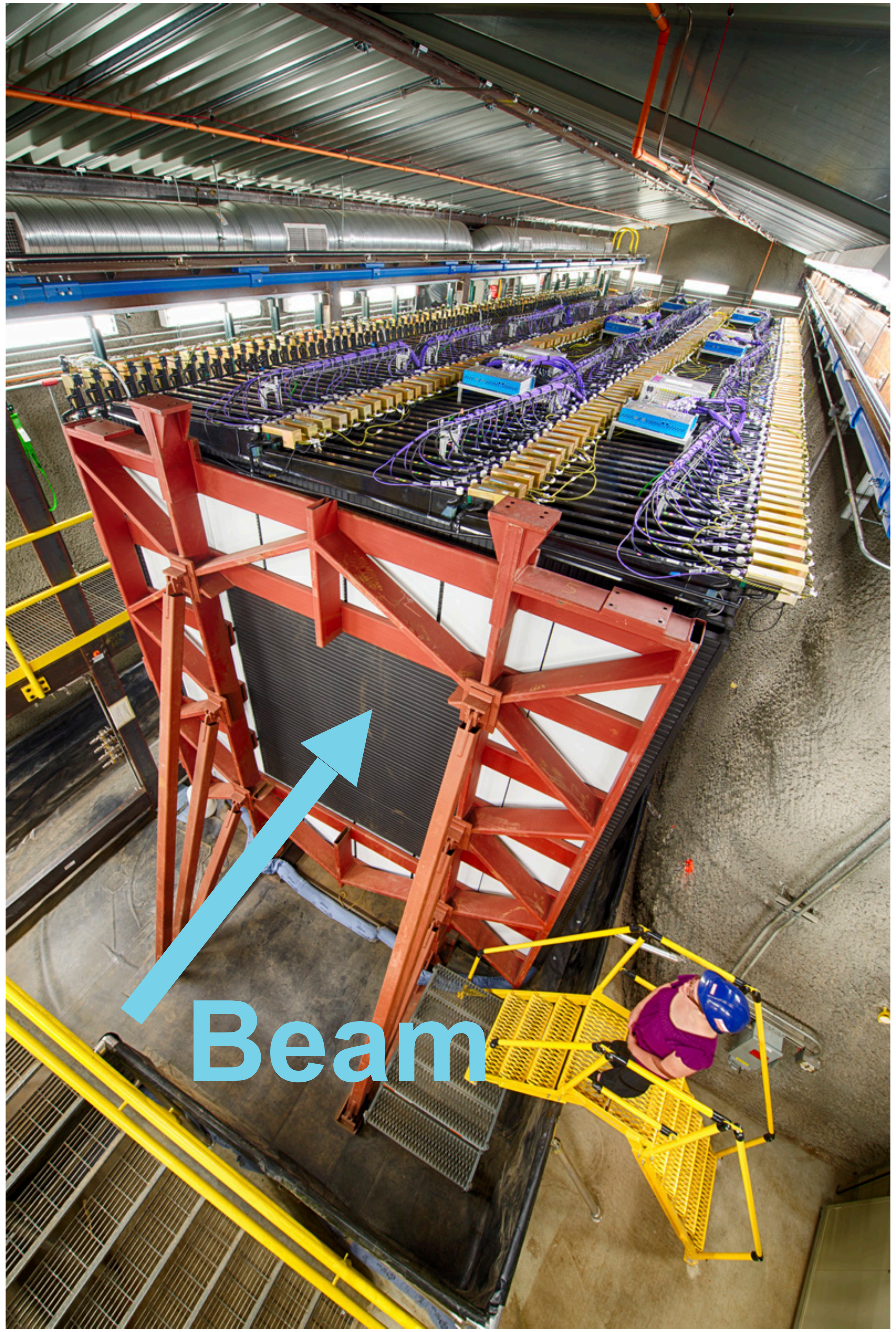
MAY 2020

Backup

The NuMI Beam at NOvA

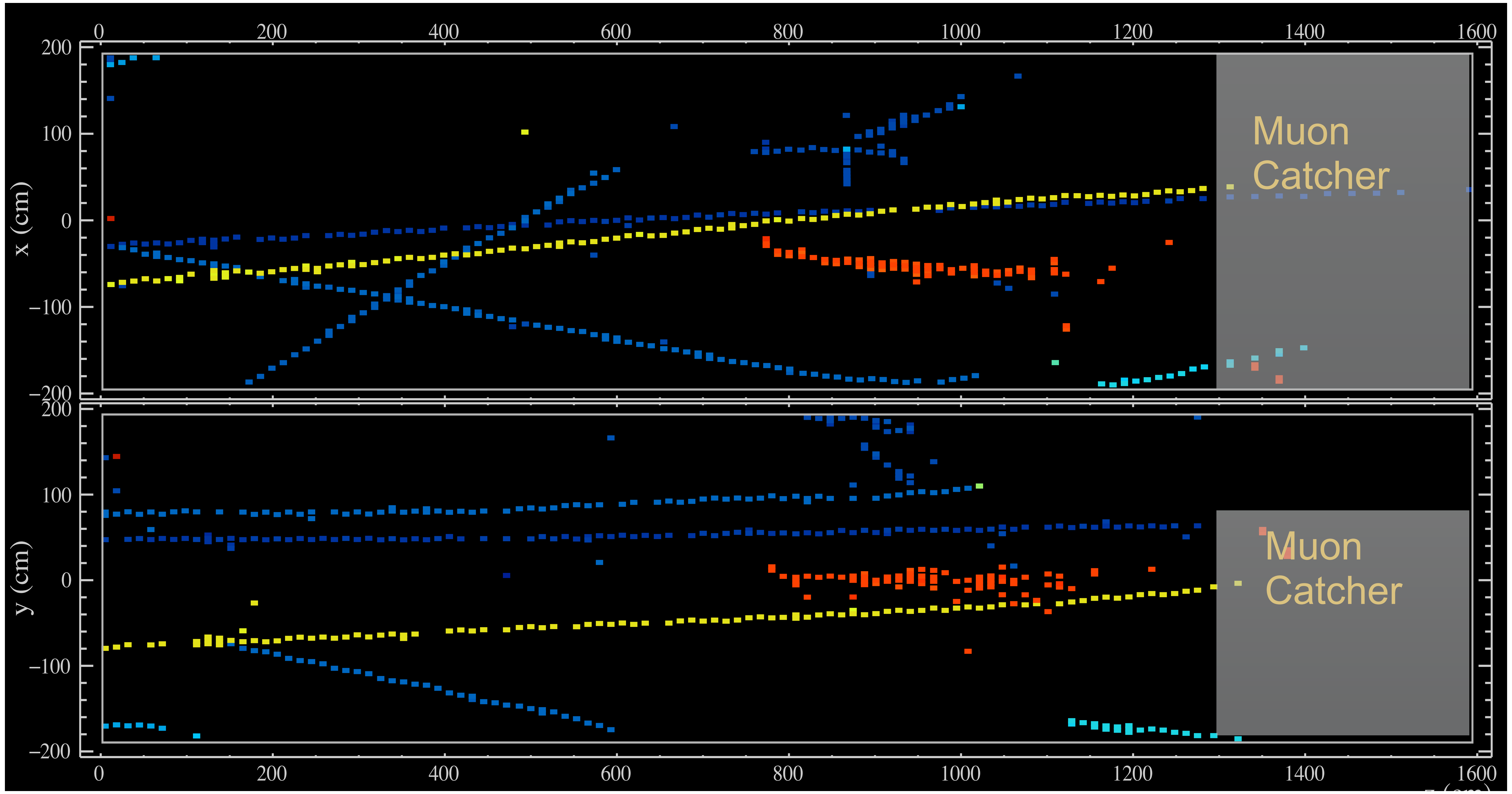
- The near detector (ND) is 1 km from the neutrino beam target and lies 100 m underground at Fermilab.
- It is located 14.6 mrad off-axis from the NuMI beam line, results a narrow-band neutrino flux peaked at ~2 GeV with ~1 GeV FWHM.





The NOvA Near Detector

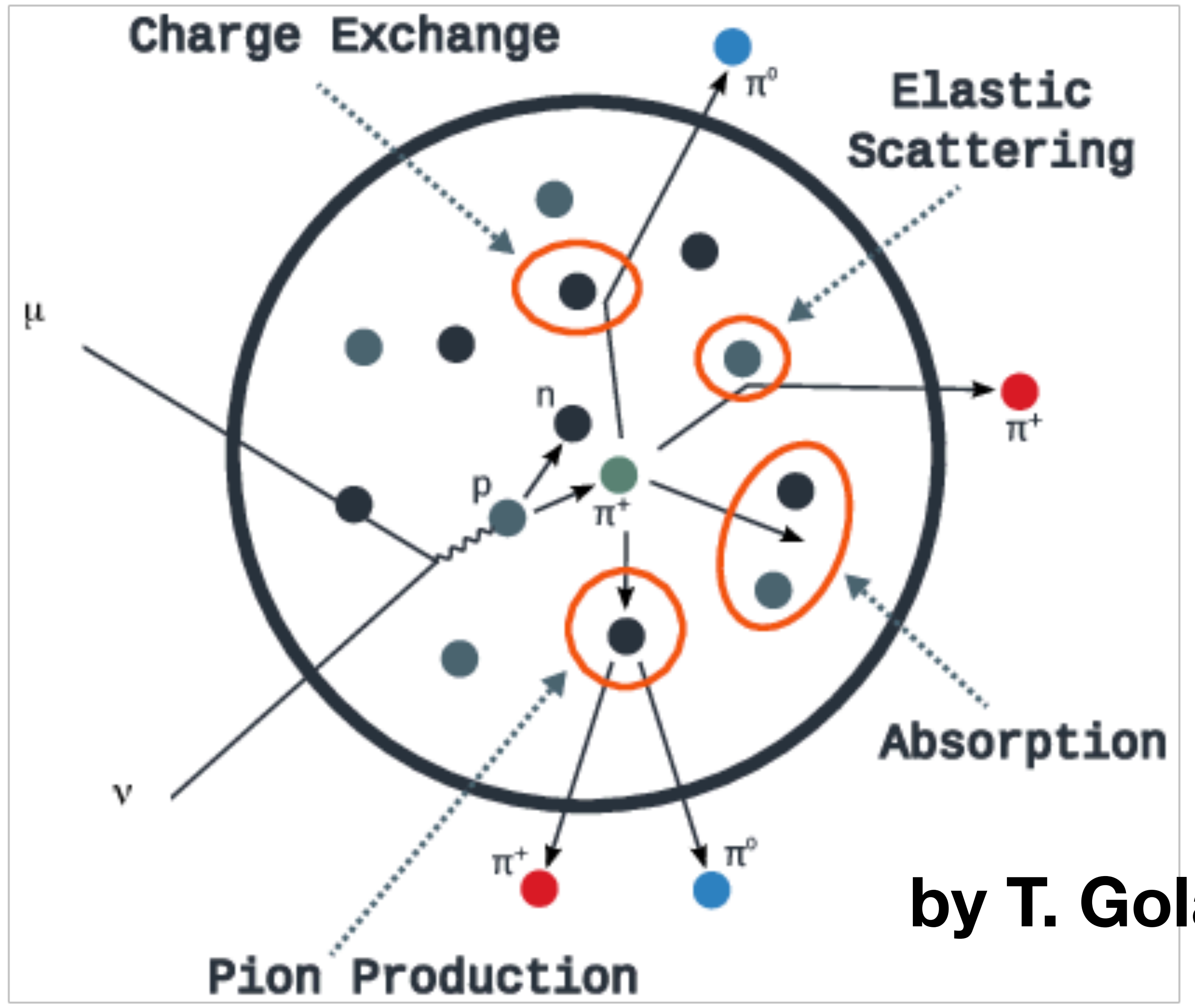
- Segmented liquid scintillator detectors provides 3D tracks and calorimetry.
- Optimized for electron shower measurements: X_0 = 38 cm (6 cell depth, 10 cell width).
- Muon catcher (steel + NOvA cell) at the downstream end designed to range out ~2 GeV muons.
- Good time resolution (~ 5 ns) and spatial resolution (~ few cm).
- Allow clear separation of interactions.



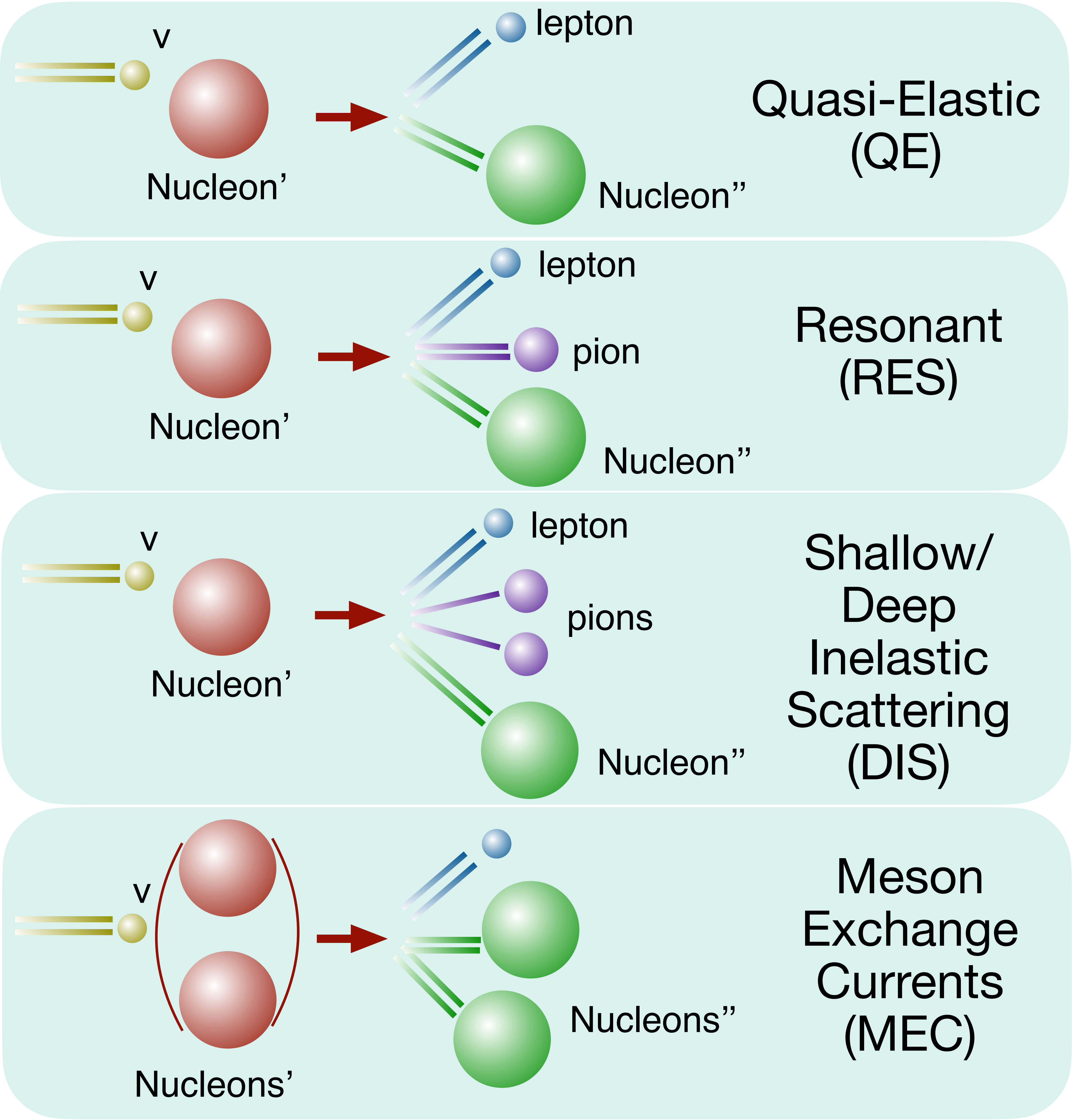
UCIRVINE

Neutrino Interactions

- Interactions at the ~GeV scale remain an active area of study.
  - Several types of interactions can occur.
  - All of which take place in a complex nuclear environment that impacts both initial conditions and what is observed in the final state.



by T. Golan



Neutrino Cross-section measurements at NOvA

$\nu_\mu(\bar{\nu}_\mu)$ CC 0π

$\nu_\mu(\bar{\nu}_\mu)$ CC π^0

$\nu_\mu(\bar{\nu}_\mu)$ CC $\pi^\pm$

$\nu_\mu(\bar{\nu}_\mu)$ CC COH π^+

ν_μ CC low-had

ν_μ CC 2p2h

ν_μ CC inclusive

$\bar{\nu}_\mu$ CC inclusive

$\nu_e(\bar{\nu}_e)$ CC 0π

$\nu_e(\bar{\nu}_e)$ CC $\pi^\pm$

ν_e CC inclusive

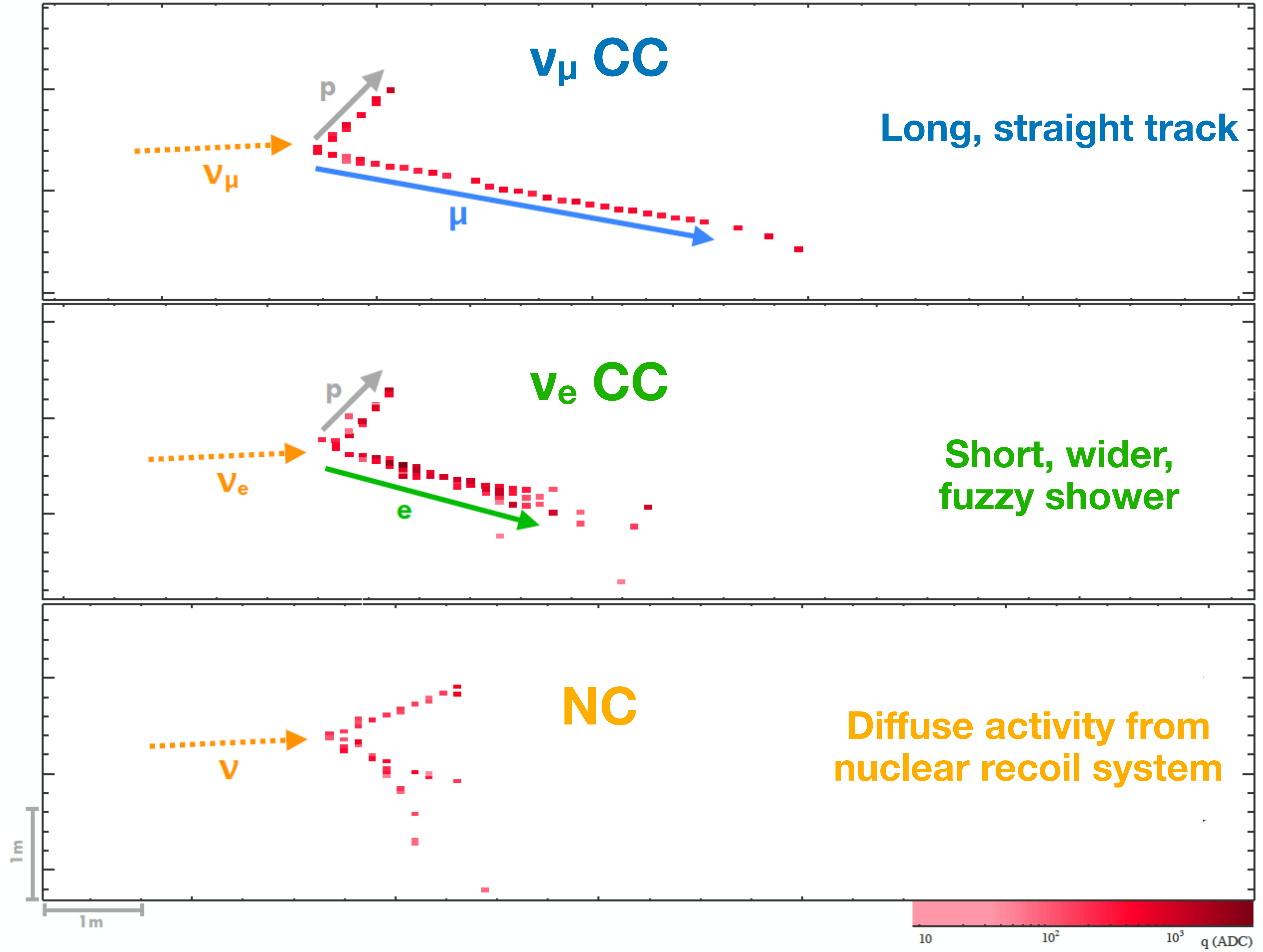
$\bar{\nu}_e$ CC inclusive

NC ν π^0

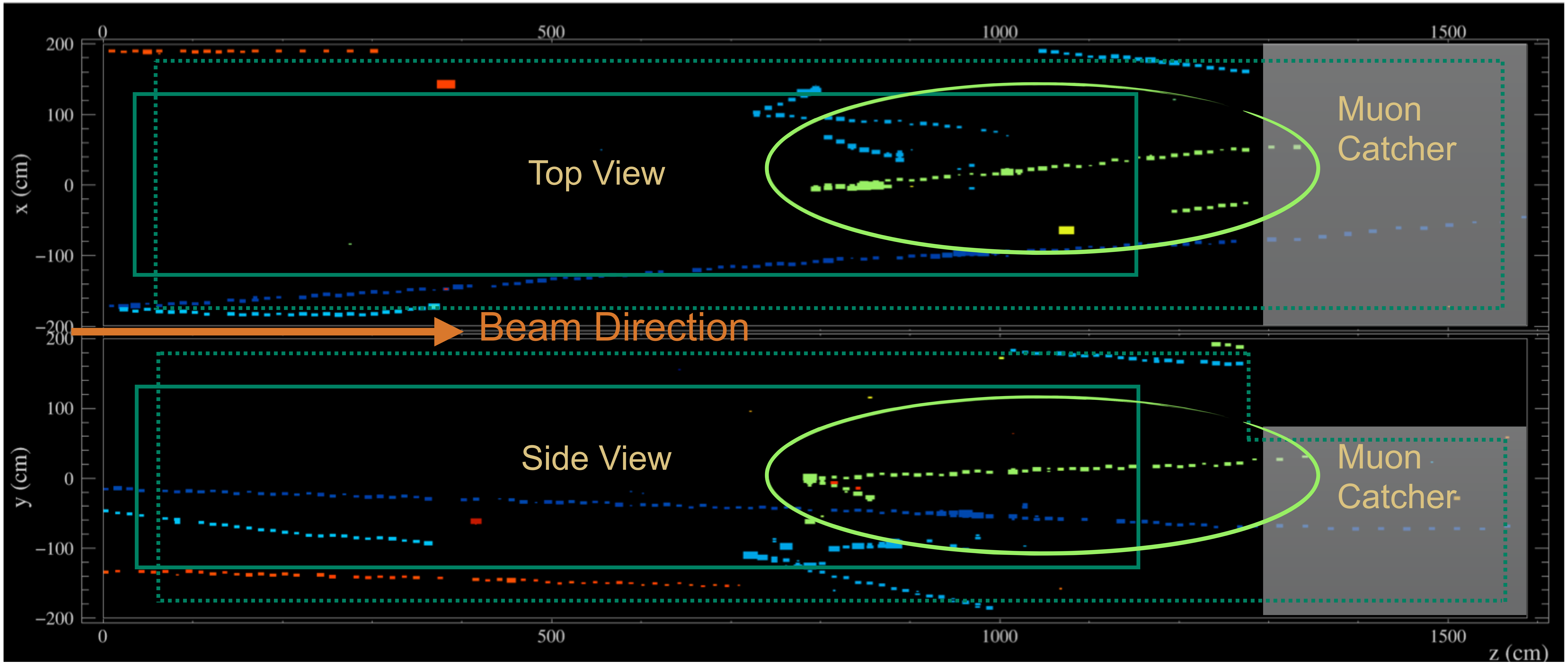
NC ν $\pi^\pm$

$\nu - e$ elastic scattering

……

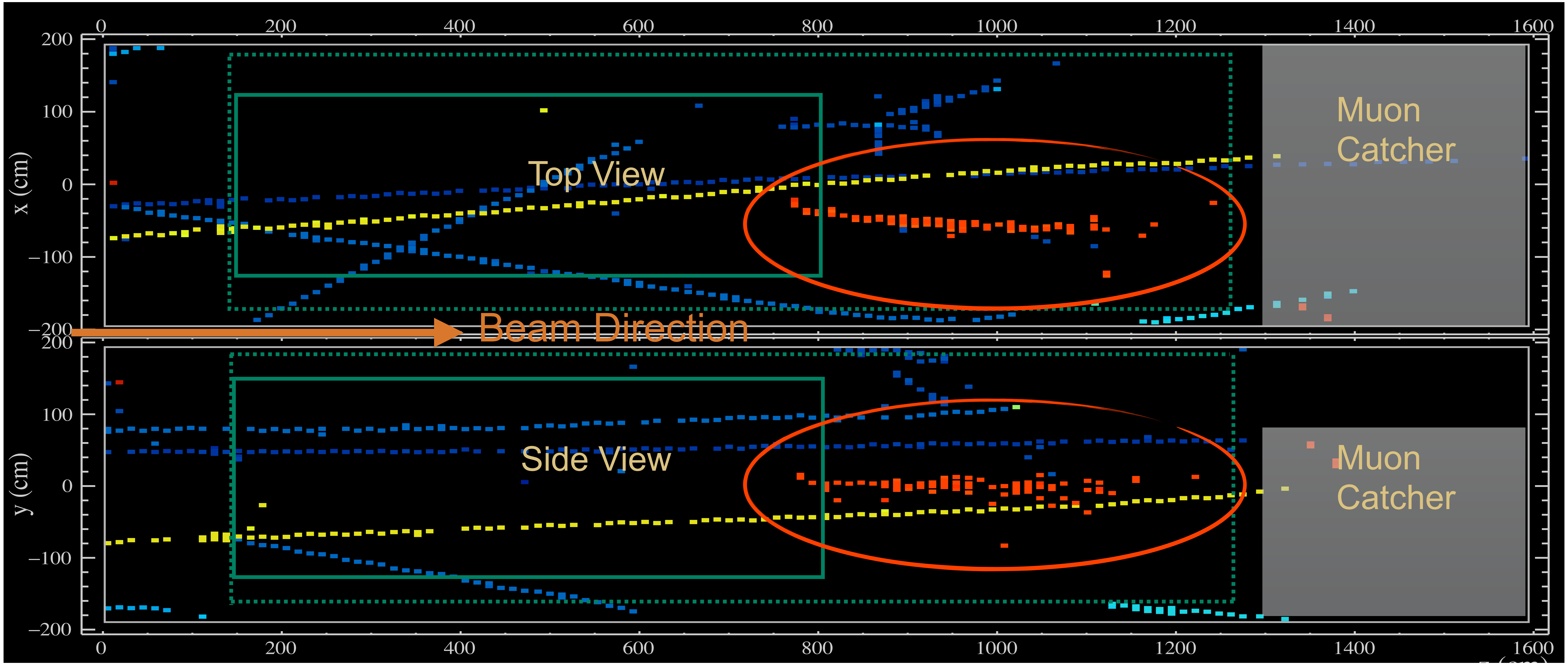


ν_μ CC Inclusive: with a final state muon



- Fiducial volume (solid) and containment volume (dashed) are defined as pre-selection of ν_μ CC events.

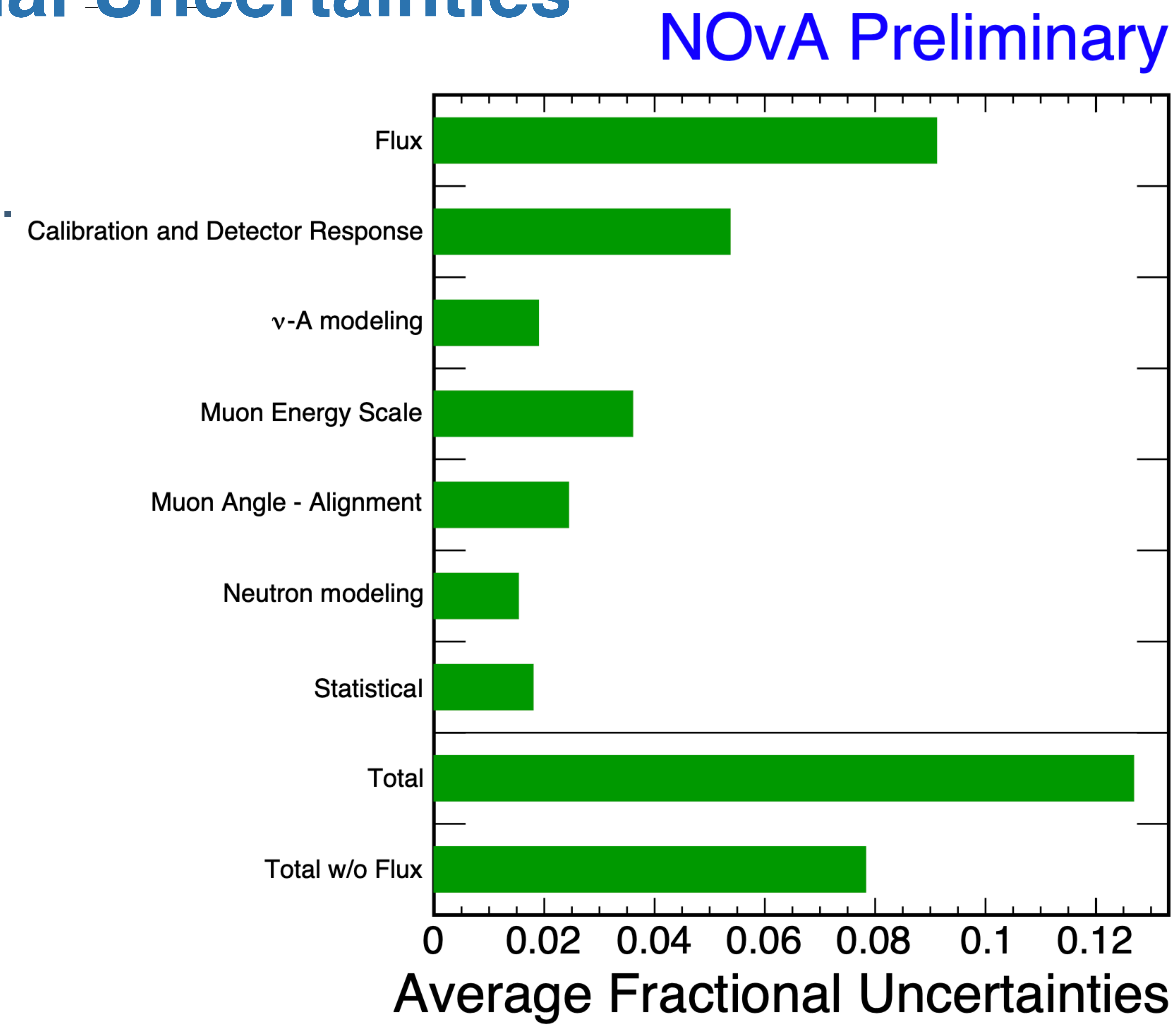
ν_e CC Inclusive: with a final state electron



- Fiducial volume (solid) and containment volume (dashed) are defined as pre-selection of ν_e CC events.

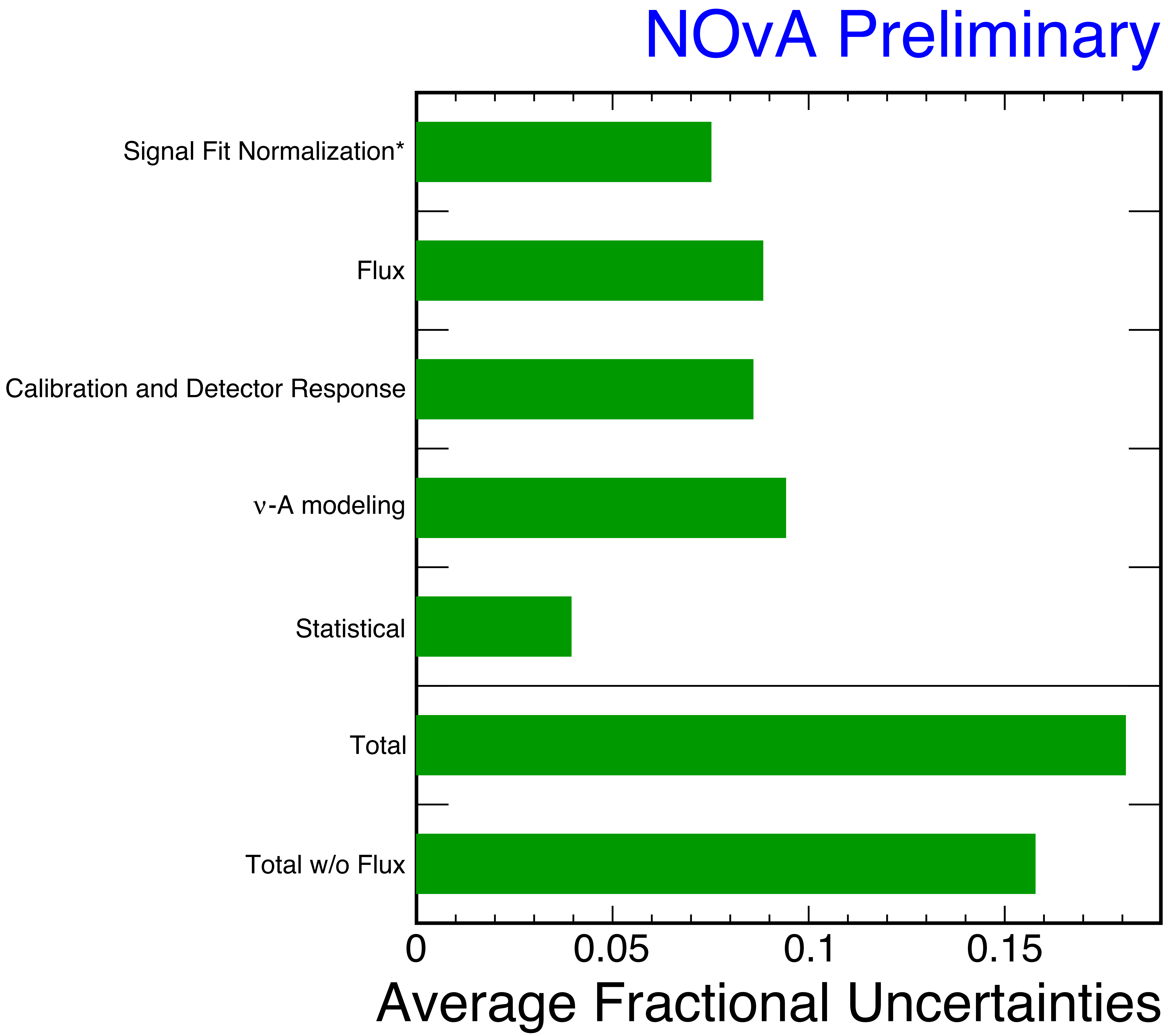
ν_μ CC Inclusive: Fractional Uncertainties

- Weighted average uncertainties to extracted cross section value.
- Flux is a normalization uncertainty ~ 9%.
- Statistical uncertainty: a few %
- Interaction modeling uncertainties are subdominant.
- Measurement has typical total uncertainties around 12% in each bin.

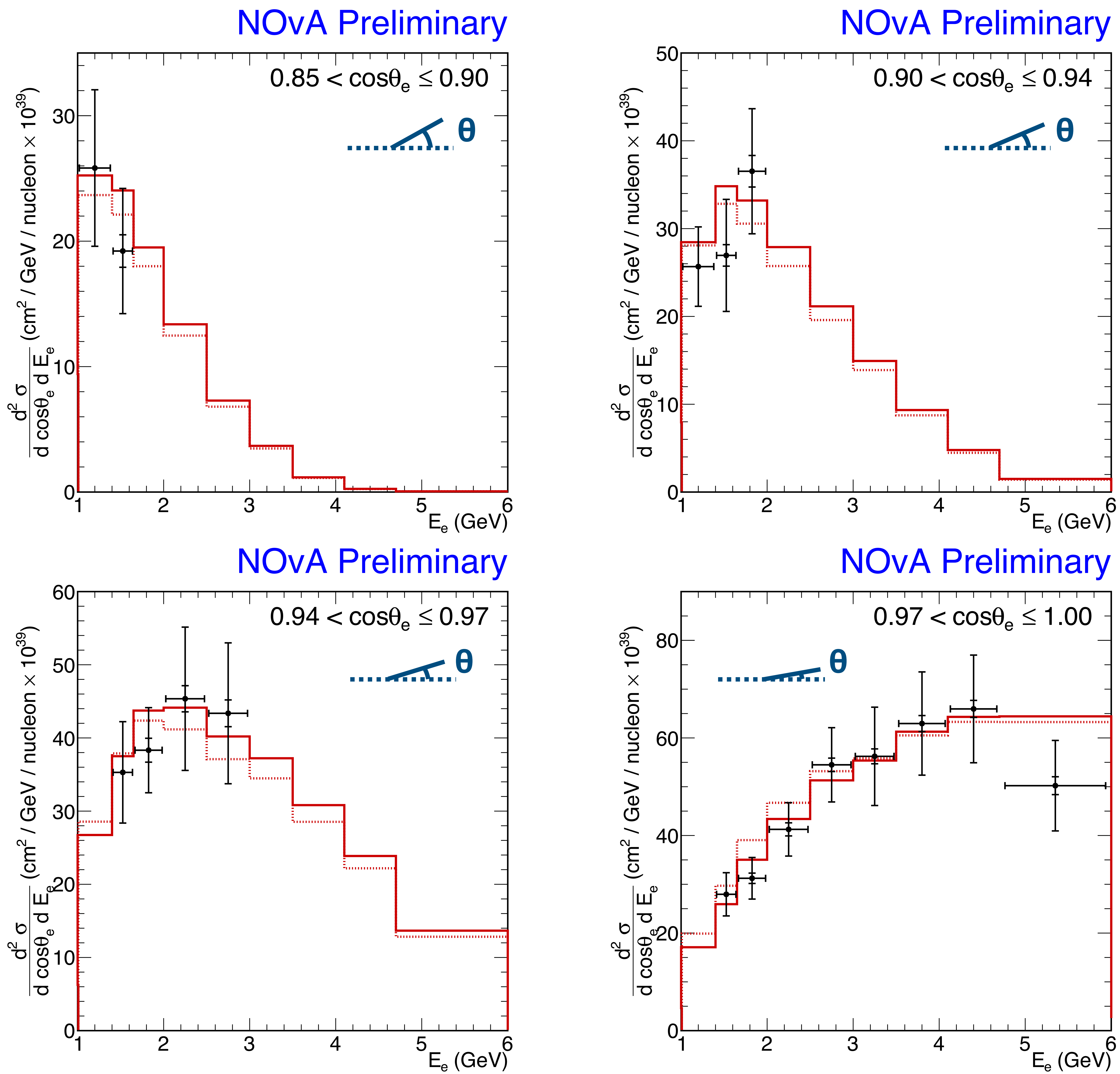


ν_e CC Inclusive: Fractional Uncertainties

- Weighted average uncertainties to extracted cross section value.
- *Uncertainty output of the template fit.
- Main uncertainties: calibration and detector response as Electron energy is calculated from calorimetry.
- Interaction modeling uncertainties play a substantial role as analysis has a large fraction of background.
- Measurement has typical total uncertainties between 15% and 20% in each bin.



Results: ν_e CC Inclusive



- Data (Stat. + Syst.)
- GENIE 2.12.2 - NOvA Tune
- GENIE 2.12.2 - Untuned

- Good agreement between tuned /untuned GENIE versions in all angle slices.
- The measurement is insensitive to the tune.