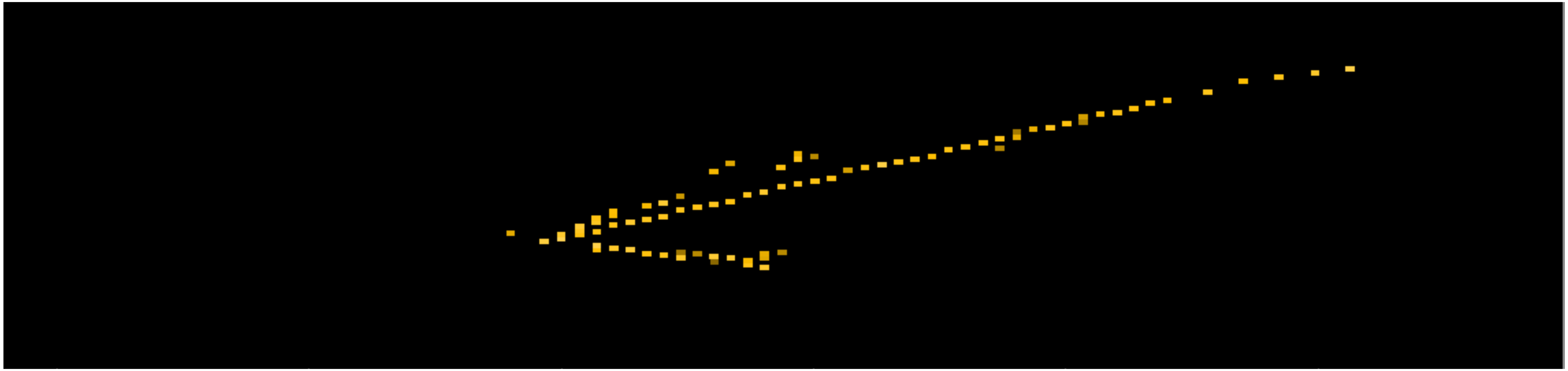
Cross-section measurement program in NOvA



Leonidas Aliaga (on behalf of the NOvA Collaboration)

New Directions in Neutrino-Nucleus Scattering (NUSTEC Workshop)

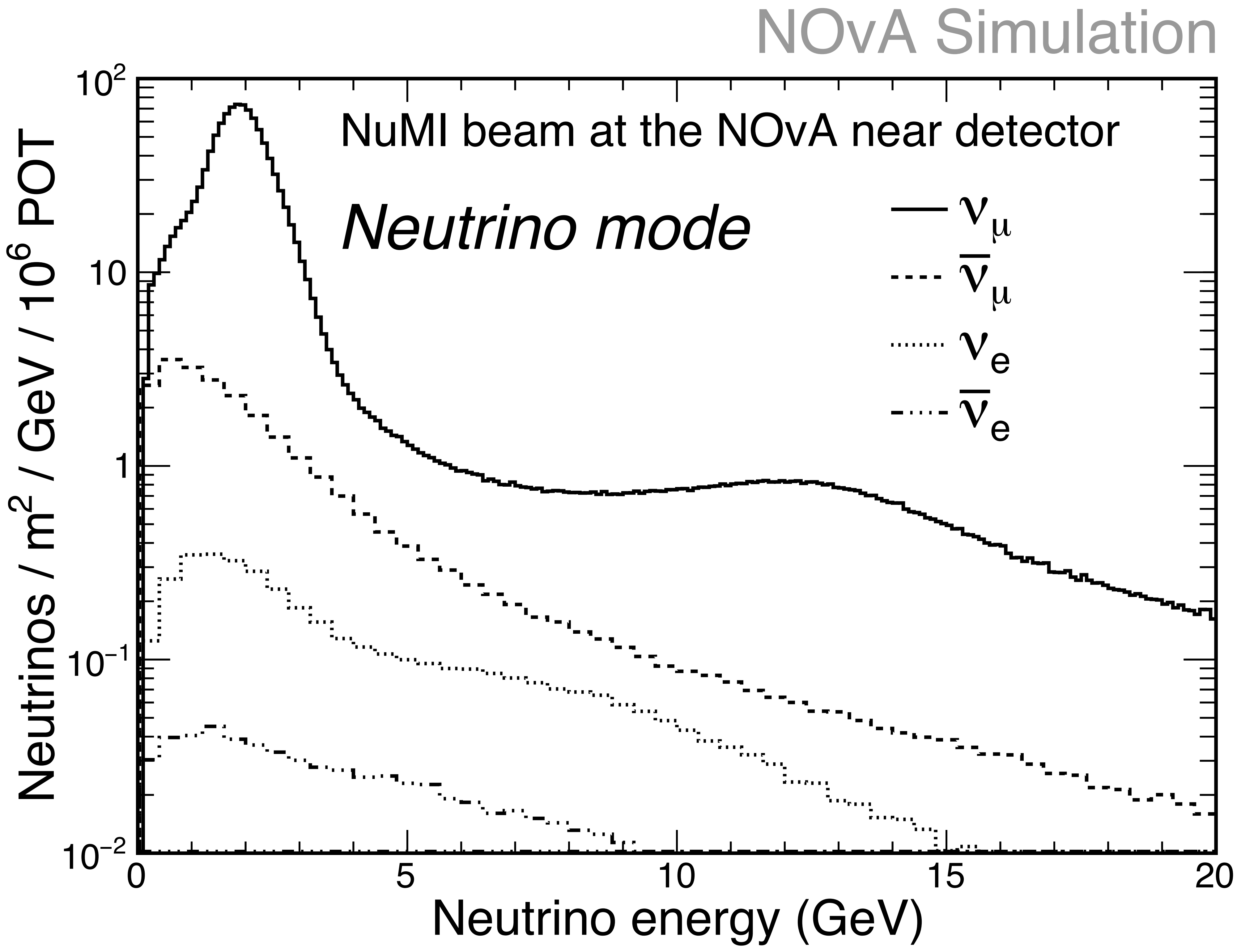
March 15, 2021

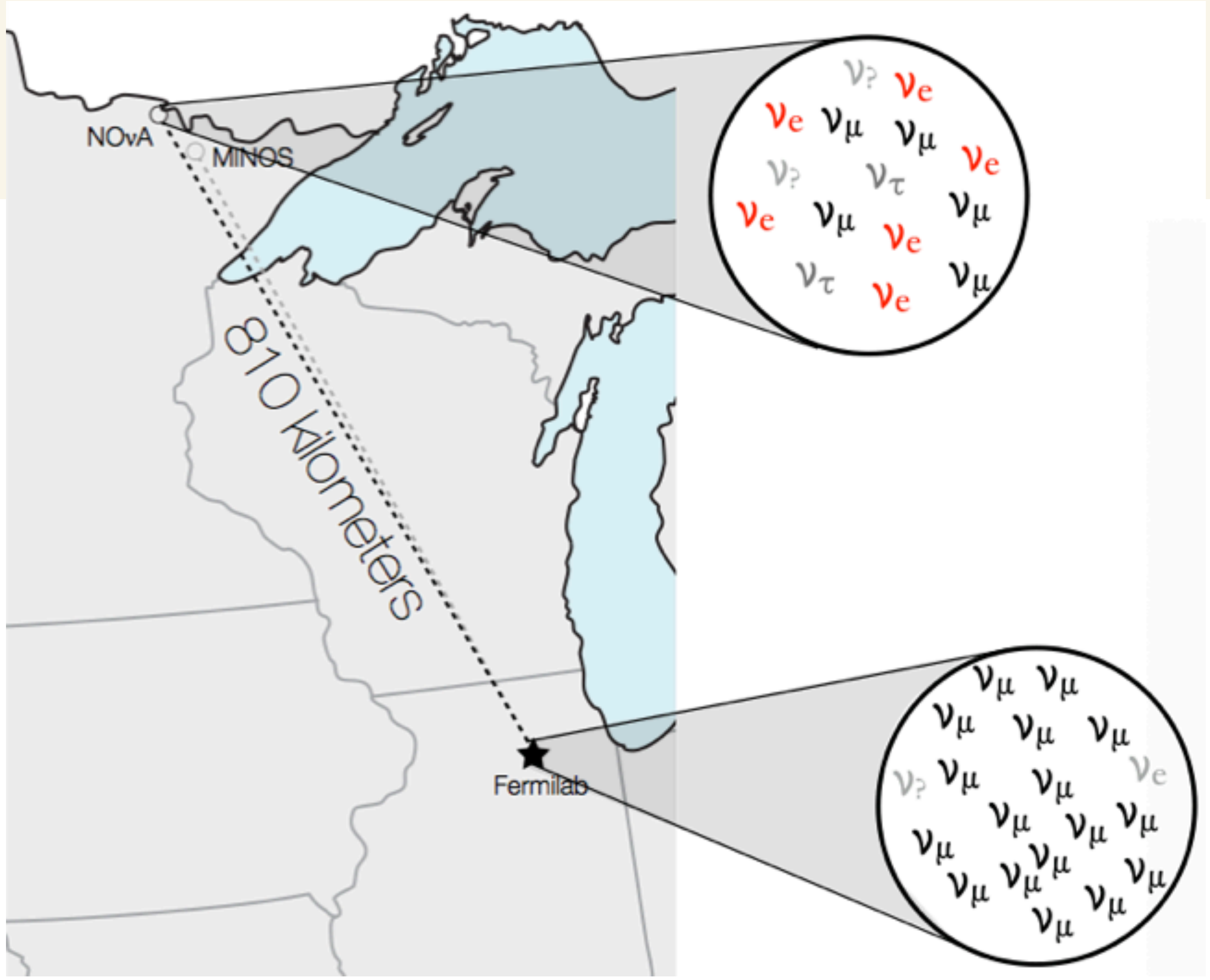
The NOvA experiment

» NOvA is a long-baseline neutrino experiment

» 2 detectors: 14 mrad off-axis and 810 km apart

- *Designed to measure for $\nu_\mu \longrightarrow \nu_e$: detectors provide excellent imaging of both ν_μ and ν_e CC events*



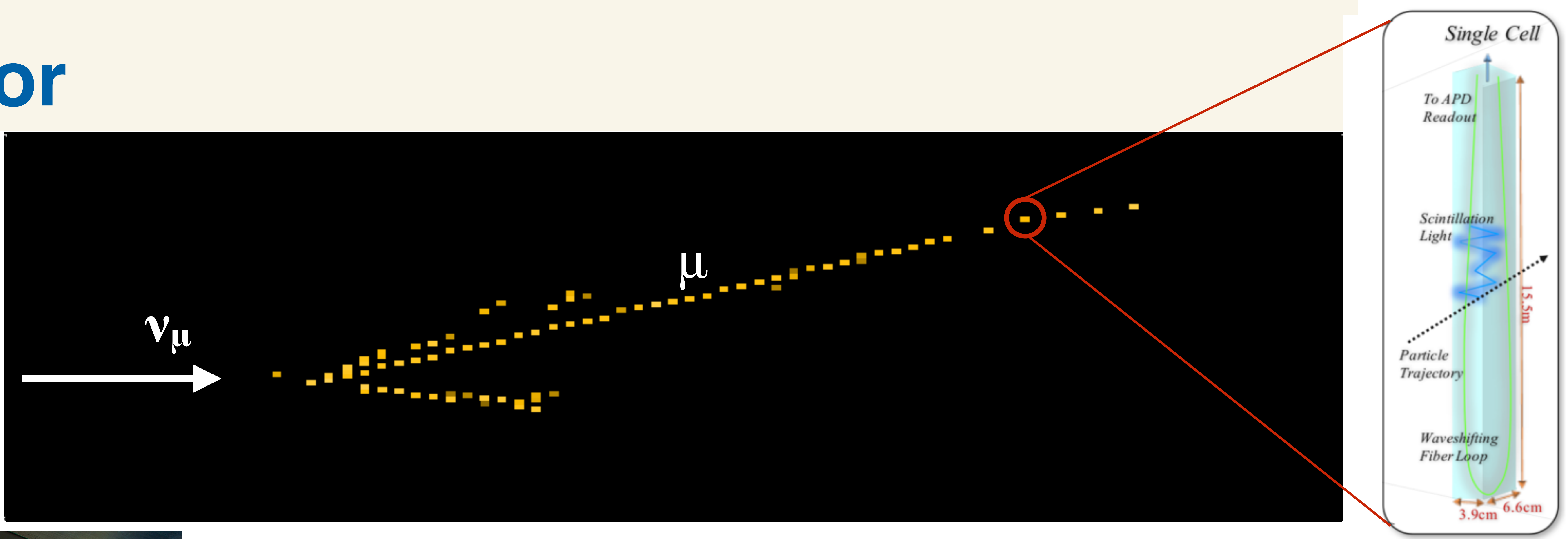


» **96% pure ν_μ beam**, 1% ν_e and $\bar{\nu}_e$

» **High neutrino flux at the Near Detector** provides a rich data set for **cross-section measurements**

NOvA Near Detector

The ND is **1 km** from source, **underground** at Fermilab.



PVC cells filled with **liquid scintillator, 193 ton** fully active mass and 97 ton downstream muon catcher

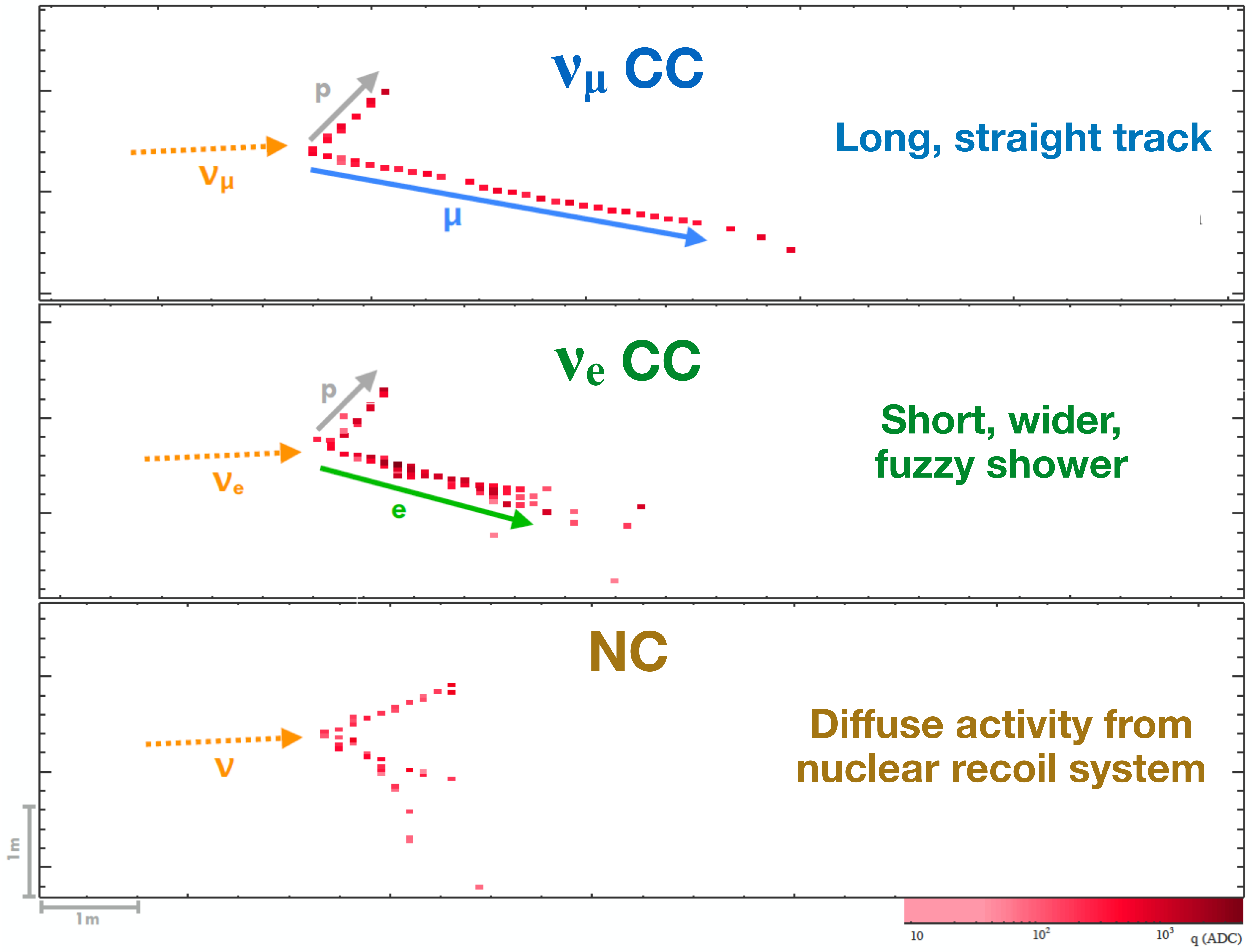
Alternating planes of orthogonal views

Low-Z, fine-grained: 1 plane ~ 0.15 X_0

C	Cl	H	O	Ti
65.9%	16.1%	10.7%	3.0%	2.4%

Neutrino cross-section measurements at NOvA

Energy range Detector technology Statistics	}	Unique environment for cross-section measurements



Neutrino cross-section measurements at NOvA

Energy range
Detector technology
Statistics

} Unique environment for cross-section measurements

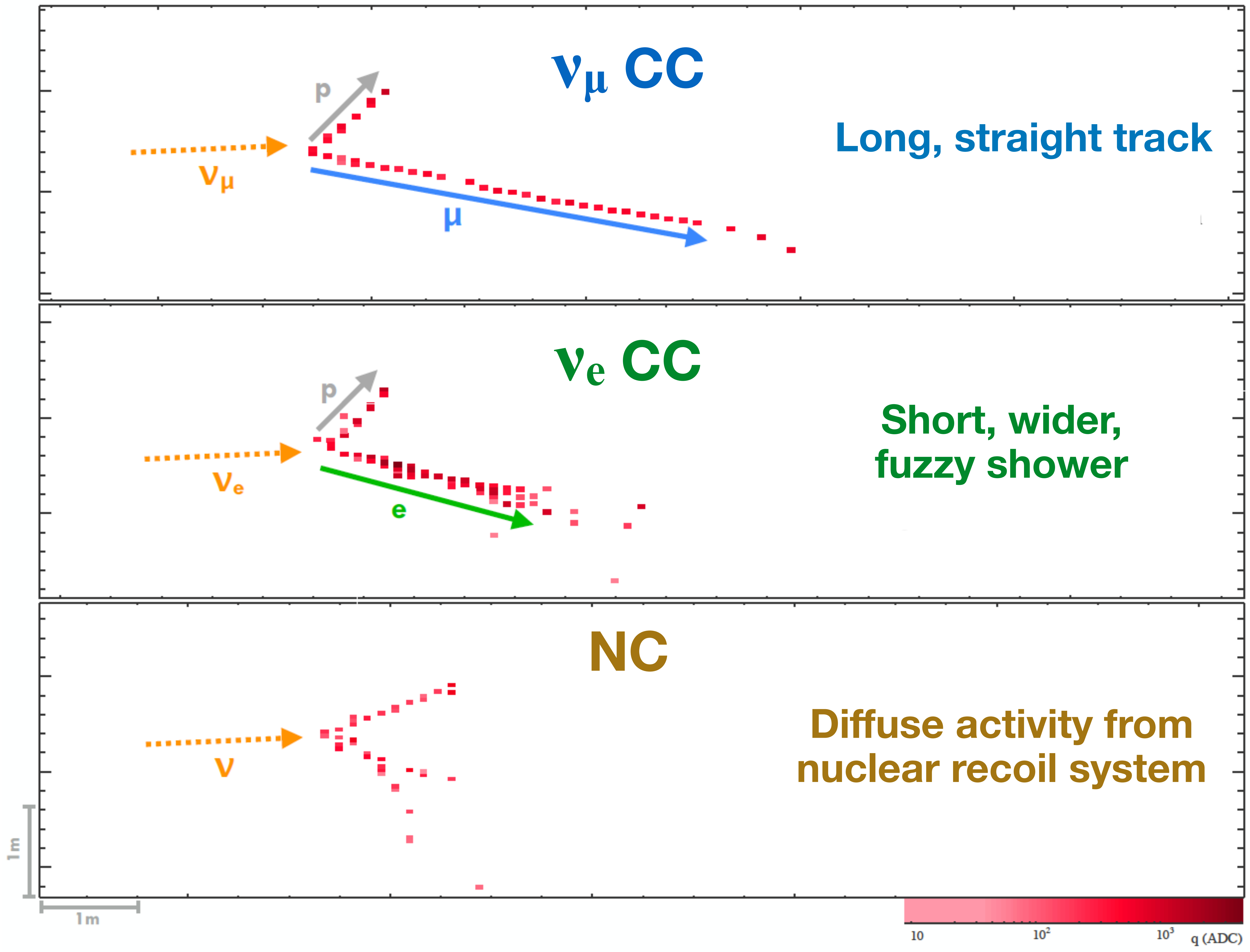
This talk

» **Inclusive analyses**

» **Exclusive analyses**

- CC low hadronic activity
- Pion production
  - $\bar{\nu}_\mu$ - CC π^0

» **Other analyses**



Inclusive CC analyses

ν_μ CC Inclusive

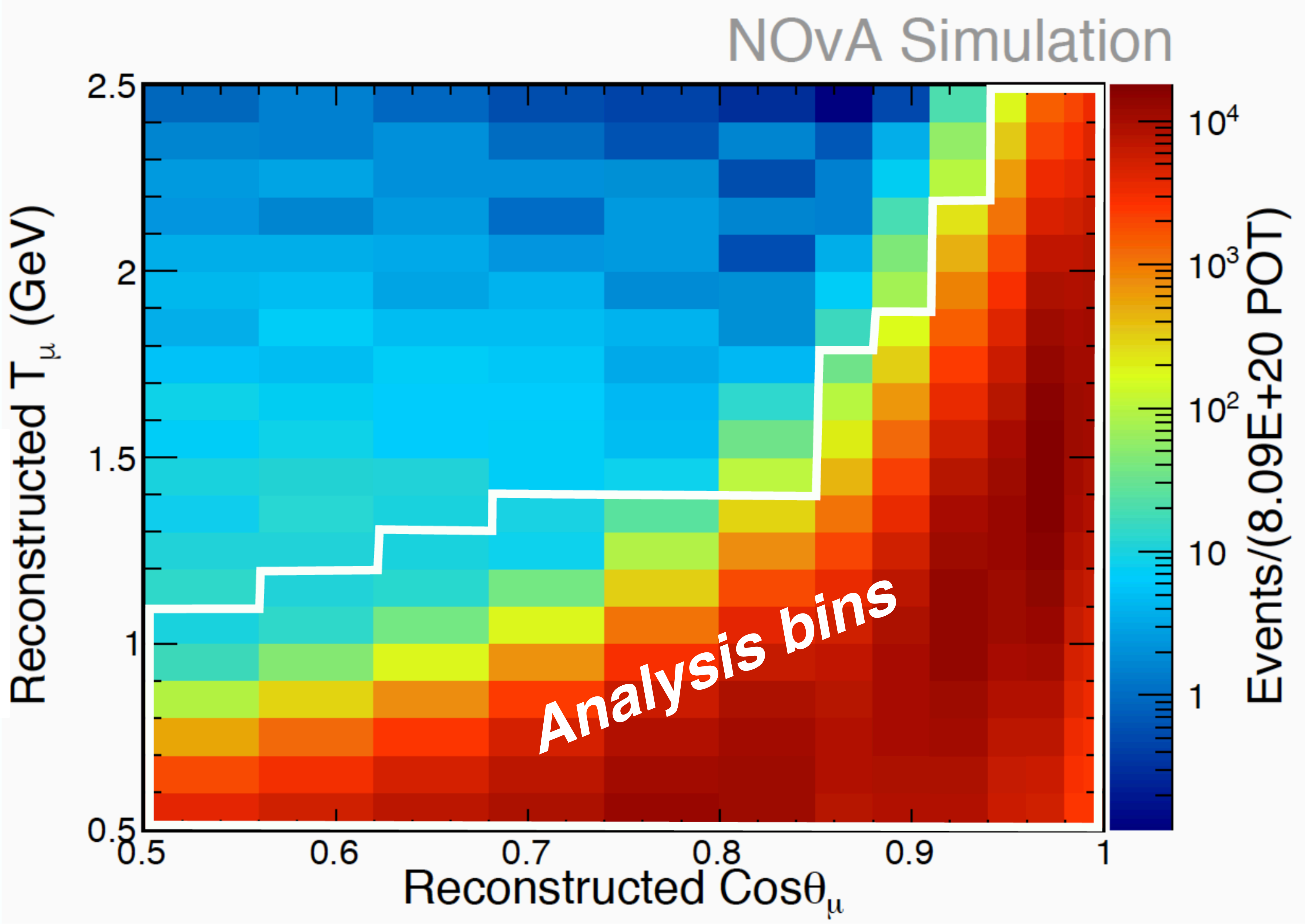
$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \left(\frac{\sum_j U^{-1}_{ijk}(N^{\rm sel}(\cos\theta_\mu, T_\mu, E_{\rm avail})_j P(\cos\theta_\mu, T_\mu, E_{\rm avail})_j)}{N_{\rm t}\Phi\epsilon(\cos\theta_\mu, T_\mu, E_{\rm avail})_{ik}\Delta\cos\theta_{\mu_i}\Delta T_{\mu_i}}\right)$$

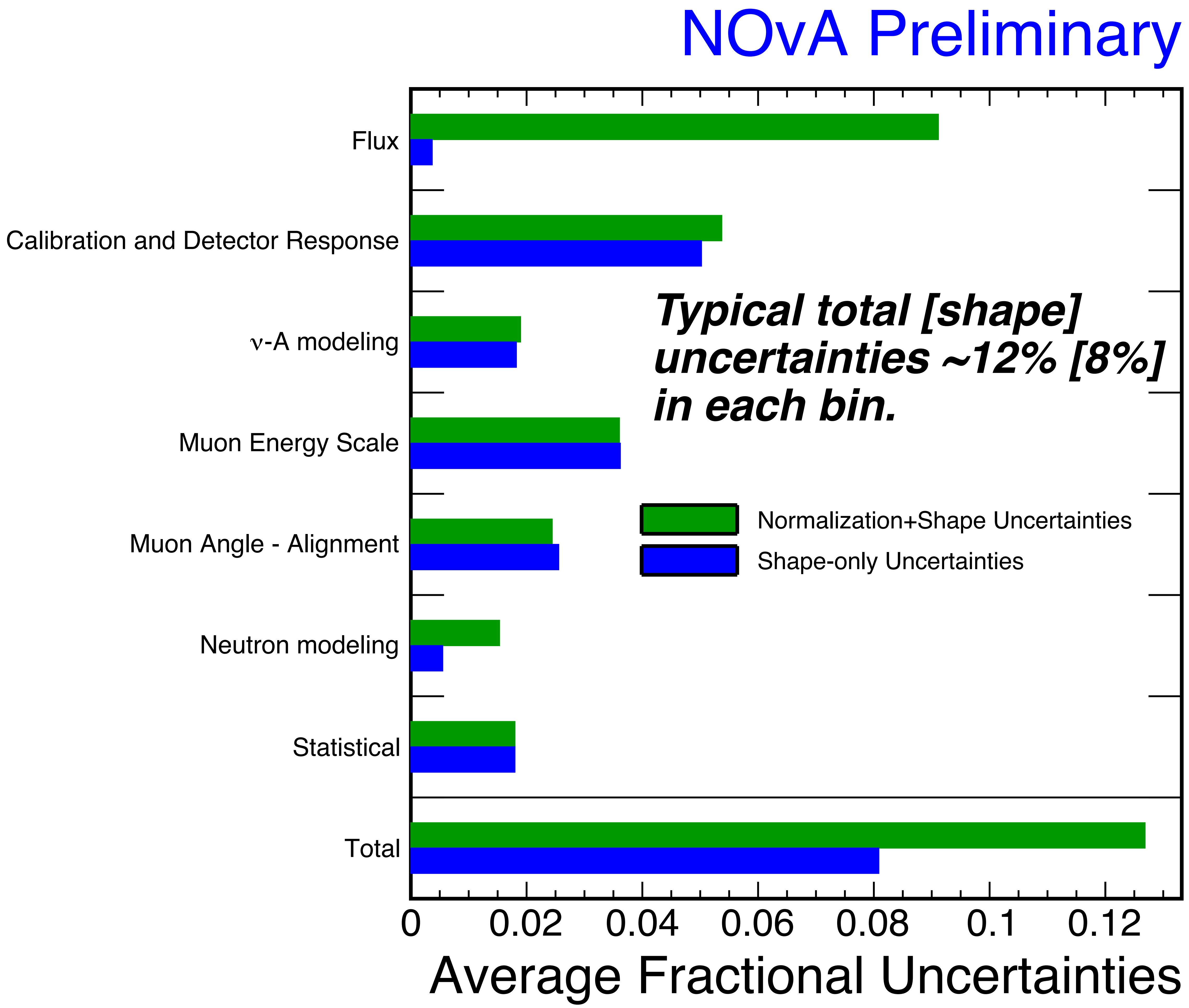
*Analysis is done in (T_μ, $\cos\theta_\mu$, E_{avail}) and then projected to **muon kinematics***

***E_{avail}**: total energy of all observable final state hadrons*

ν_μ CC Inclusive

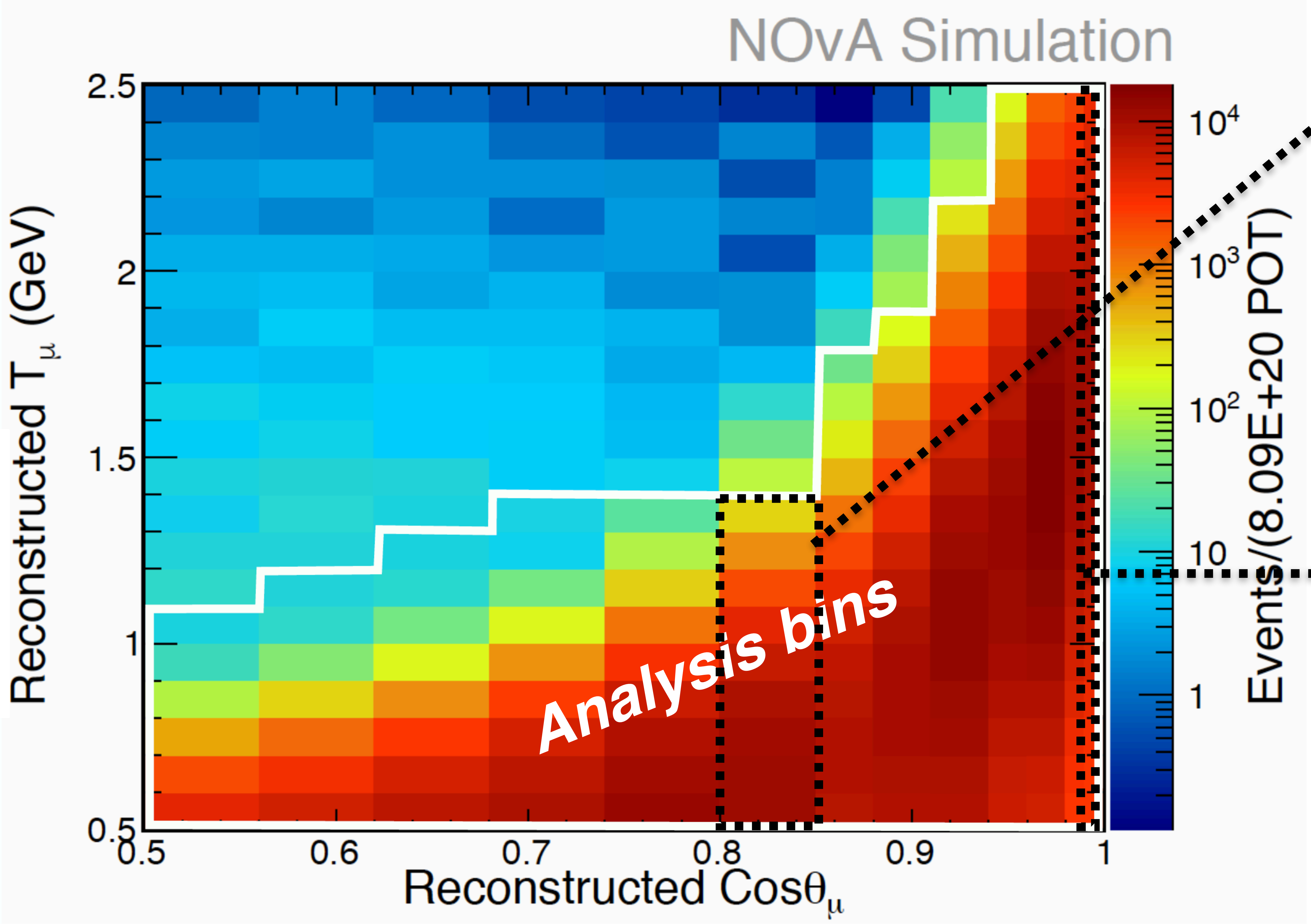
$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \left(\frac{\sum_j U^{-1}_{ijk}(N^{\text{sel}}(\cos\theta_\mu, T_\mu, E_{\text{avail}})_j P(\cos\theta_\mu, T_\mu, E_{\text{avail}})_j)}{N_t \Phi \epsilon(\cos\theta_\mu, T_\mu, E_{\text{avail}})_{ik} \Delta\cos\theta_\mu \Delta T_\mu}\right)$$



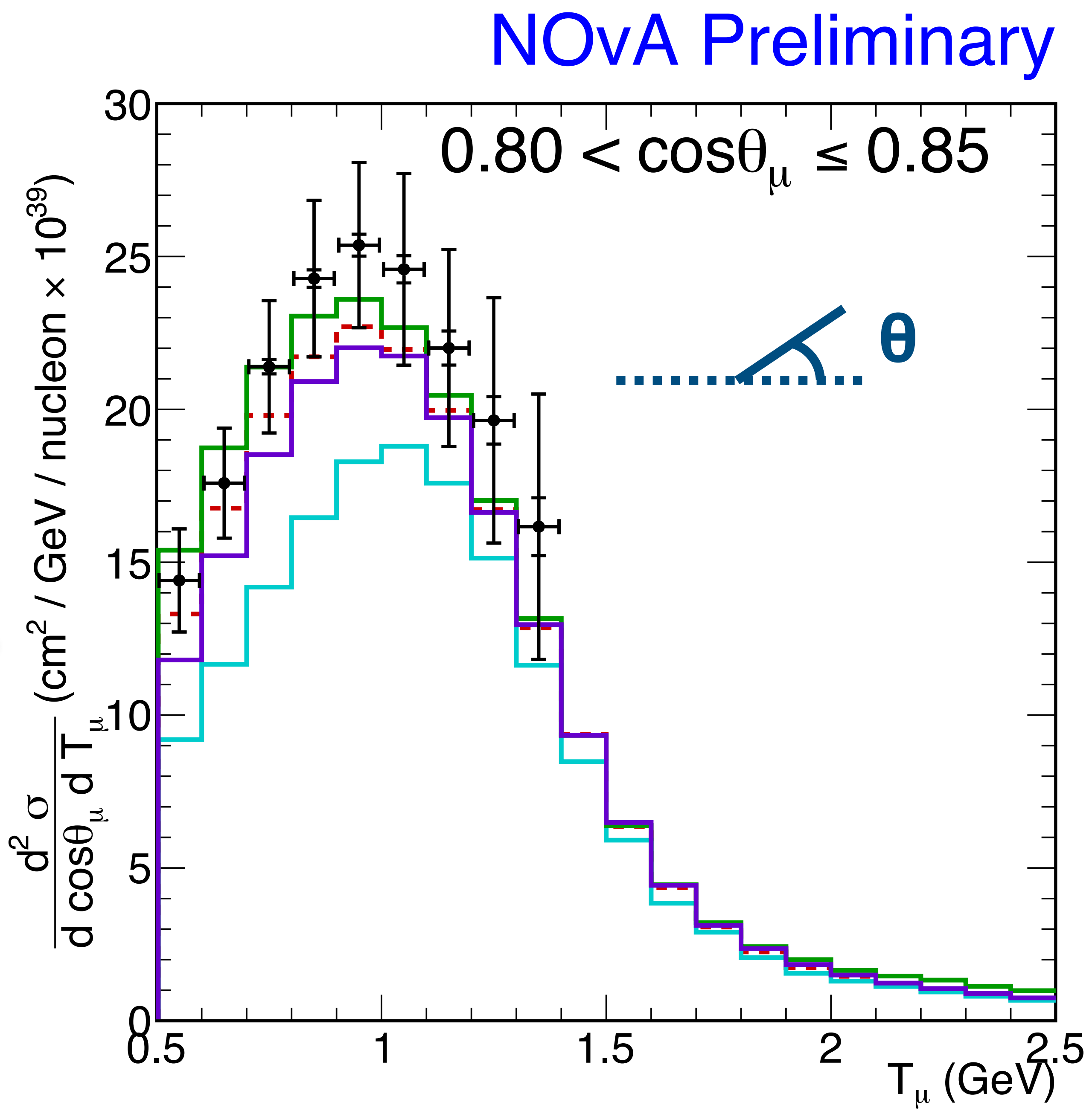


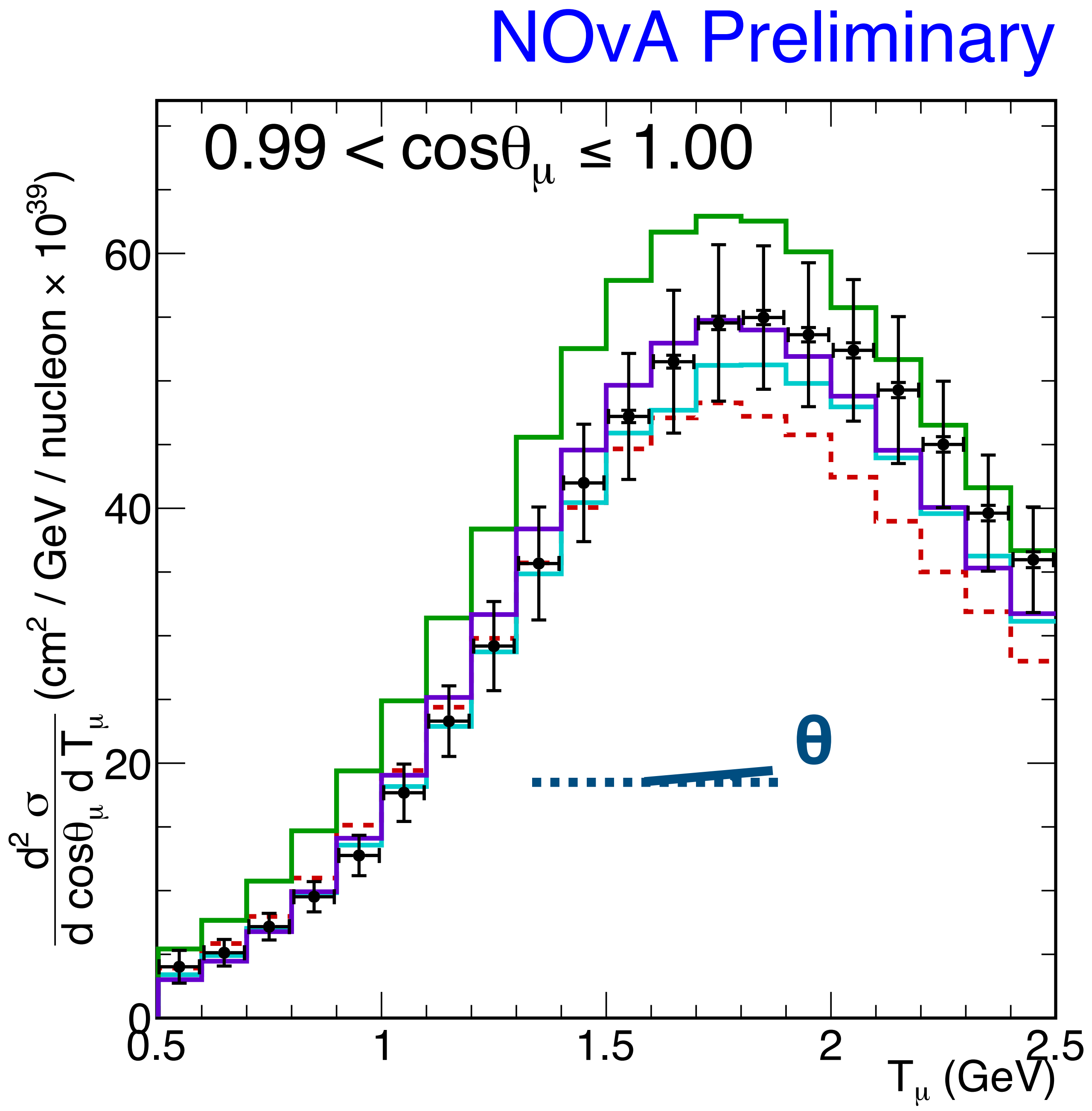
ν_μ CC Inclusive: Example of 2 cosine slices

Draft publication is under Collaboration review



<u>*Presented in Fermilab JETP Seminar, July, 2020*</u>





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

Generator	p-value
GENIE 2.12.2 - Tuned	0.93
GENIE 2.12.2 - Untuned	0.24
GENIE 3.00.06*	0.26
GiBUU 2019	0.03
NEUT 5.4.0	0.52
NuWro 2019	0.22

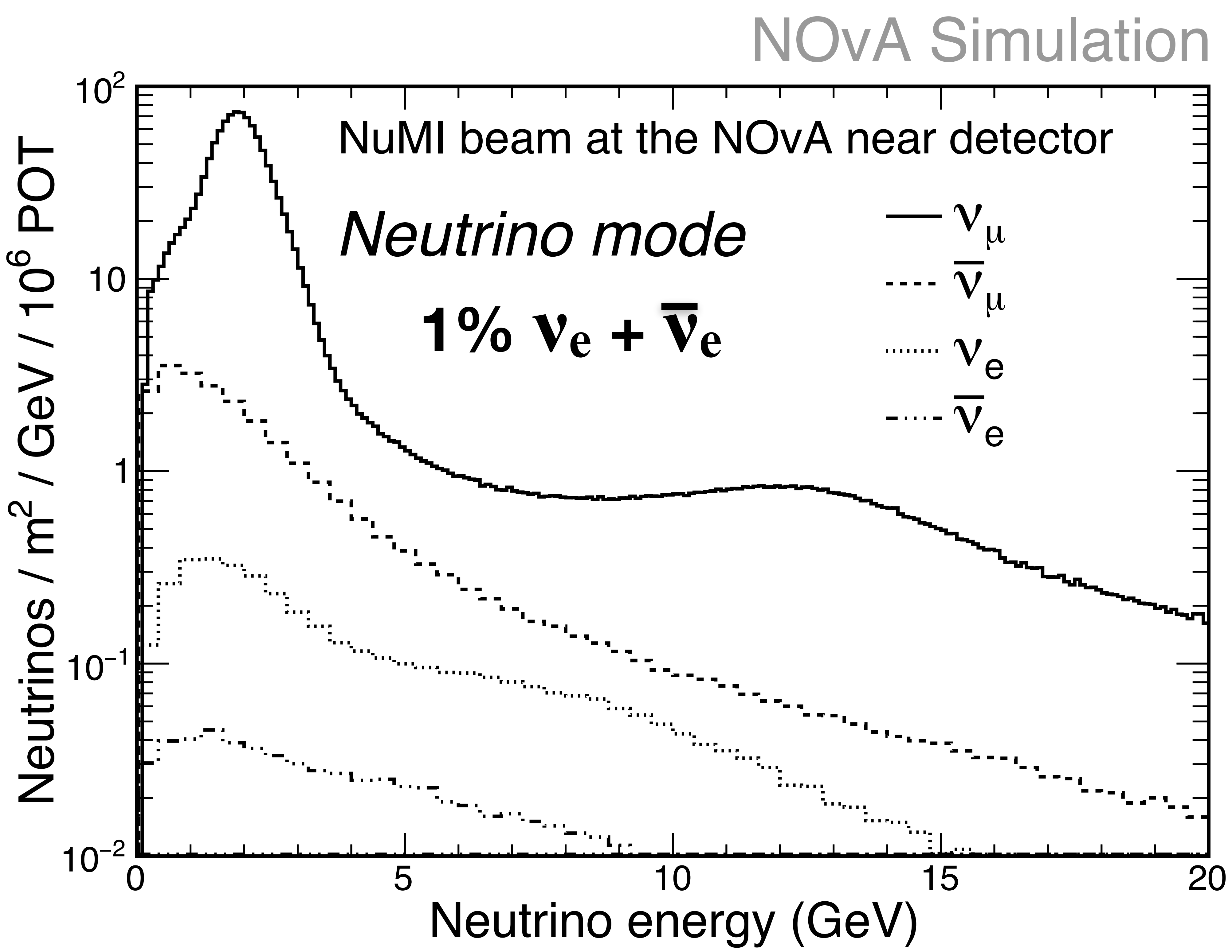
***N18_10j_02_11a:**
G18_10j_00_000 and G18_10b_02_11a

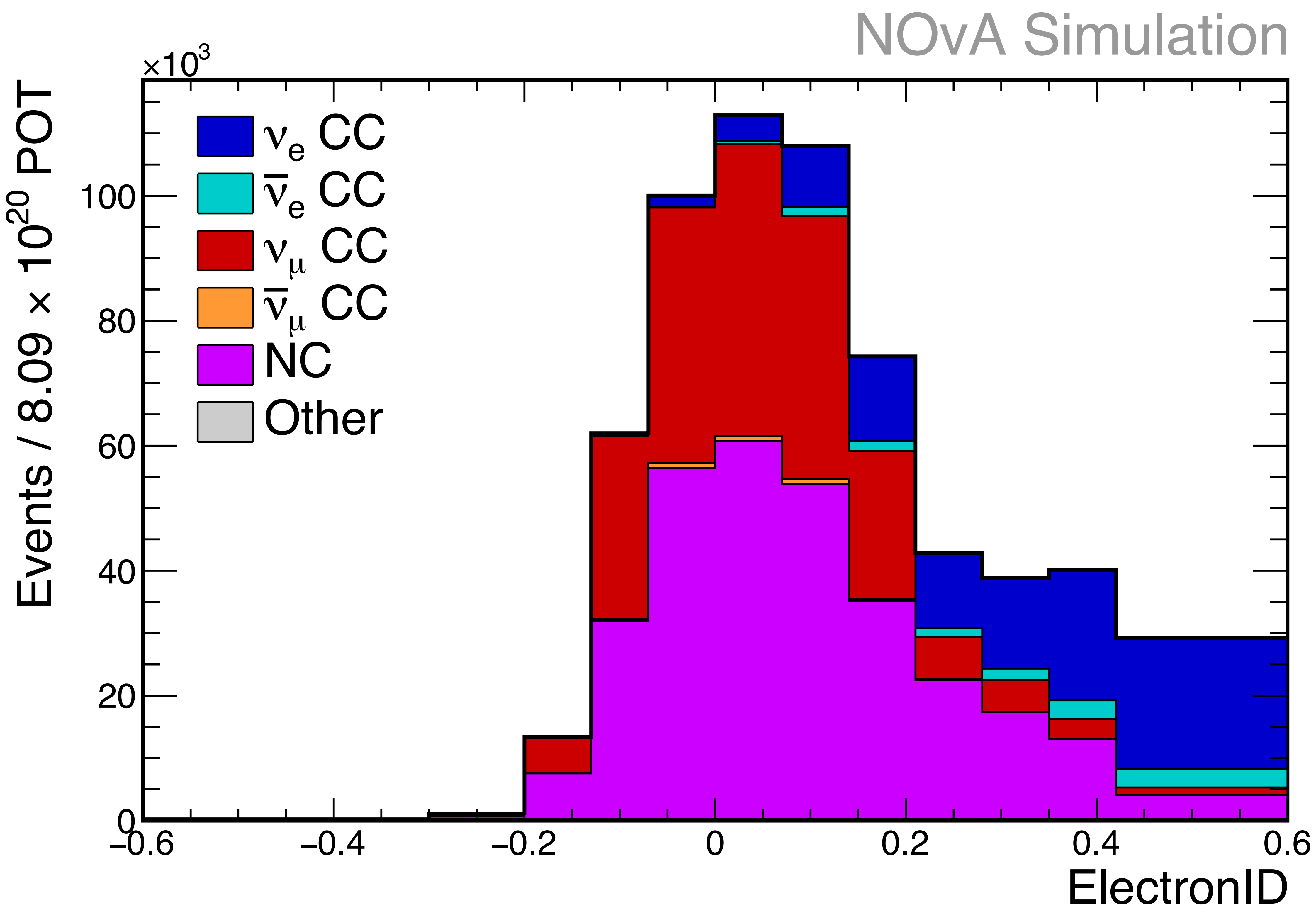
Fermilab

First ever ν_e CC double differential

$$\left(\frac{d^2\sigma}{d\cos\theta_e dE_e}\right)_i = \sum_j \left(\frac{U_{ij}^{-1}(N^{\mathrm{sel}}(\cos\theta_e, E_e)_j - N^{\mathrm{bkg}}(\cos\theta_e, E_e)_j)}{N_t \Phi \epsilon(\cos\theta_e, E_e)_{ik} \Delta\cos\theta_{e_i} \Delta E_{e_i}}\right)$$

Cross section as a function of the electron kinematics





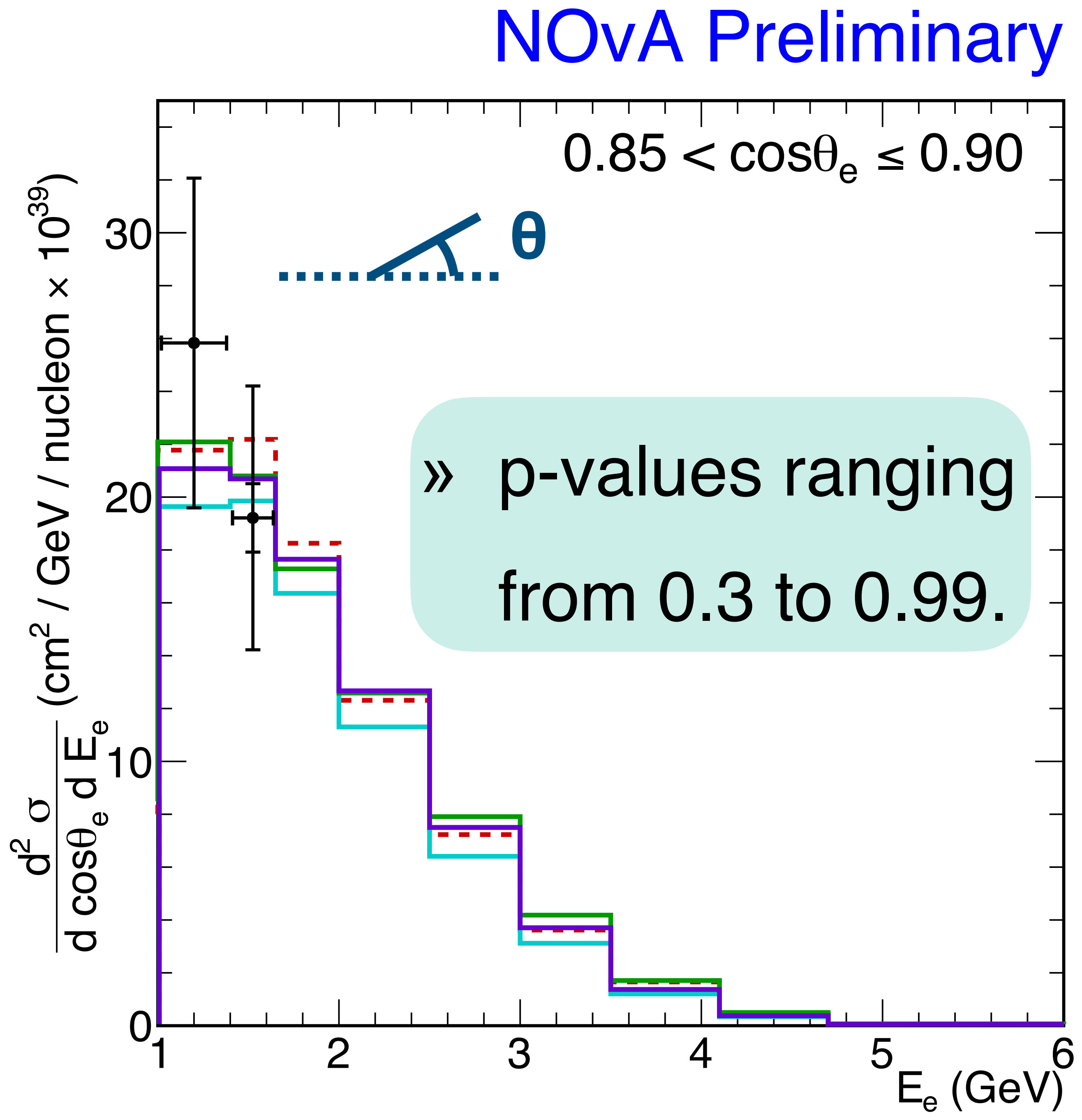
Background estimate in each electron kinematic bin is done via a template fit of the ElectronID distribution

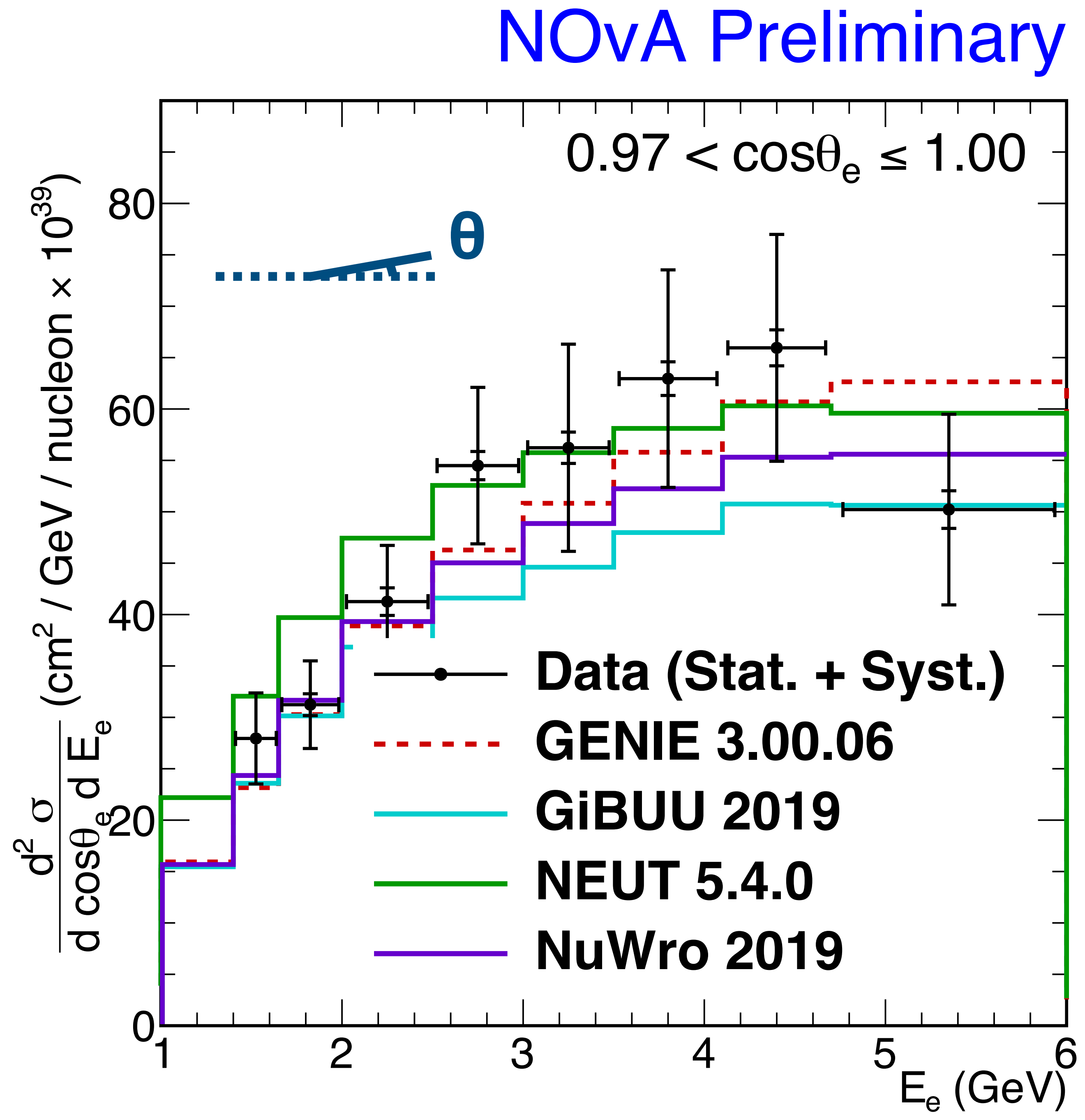
Electron ID uses deep convolutional network, reconstructed shower width and gap to reconstructed vertex

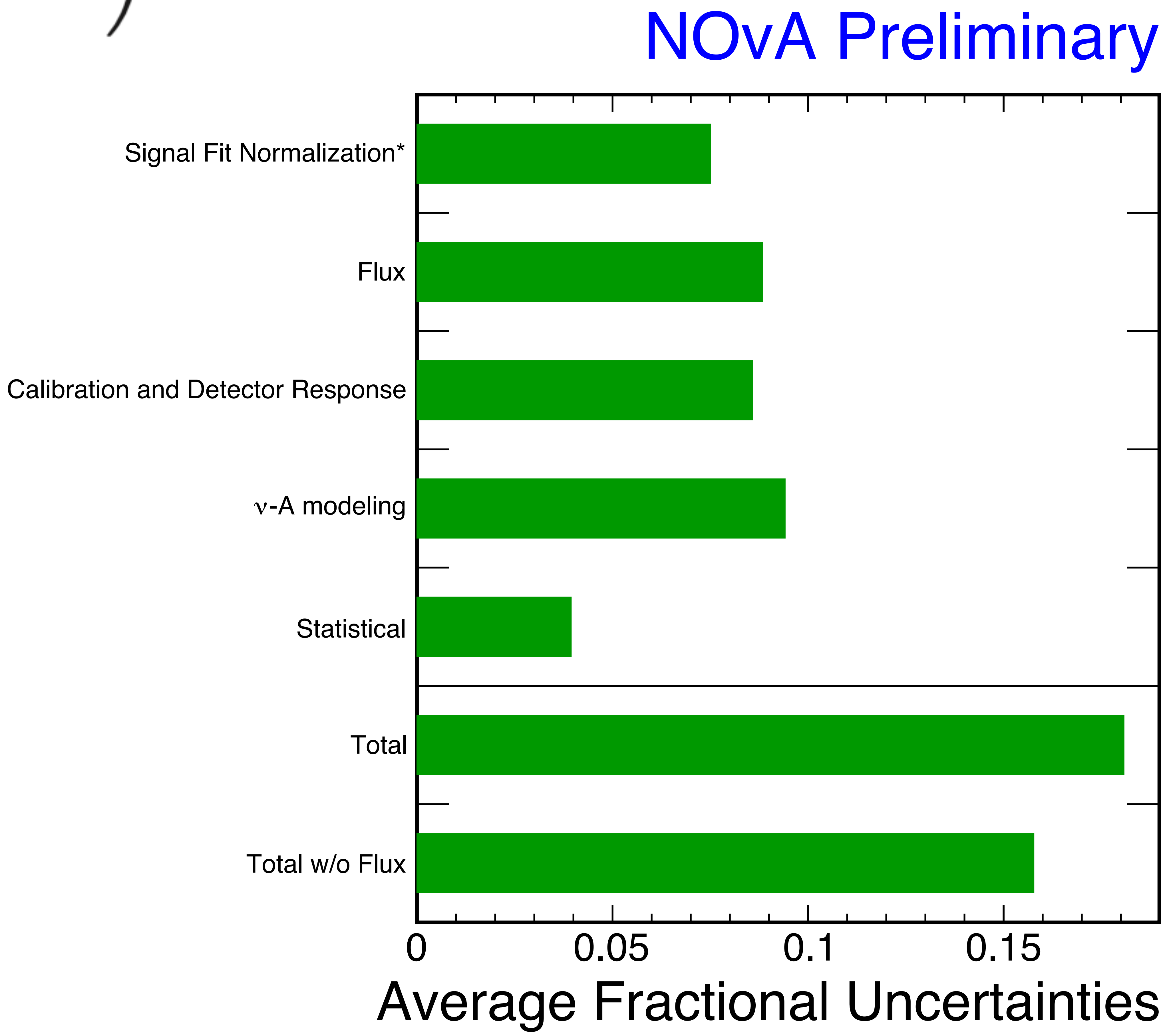
First ever ν_e CC double differential

$$\left(\frac{d^2\sigma}{d\cos\theta_e dE_e}\right)_i = \sum_j \left(\frac{U_{ij}^{-1}(N^{\mathrm{sel}}(\cos\theta_e, E_e)_j - N^{\mathrm{bkg}}(\cos\theta_e, E_e)_j)}{N_t \Phi \epsilon(\cos\theta_e, E_e)_{ik} \Delta\cos\theta_{e_i} \Delta E_{e_i}}\right)$$

Draft publication is under Collaboration review





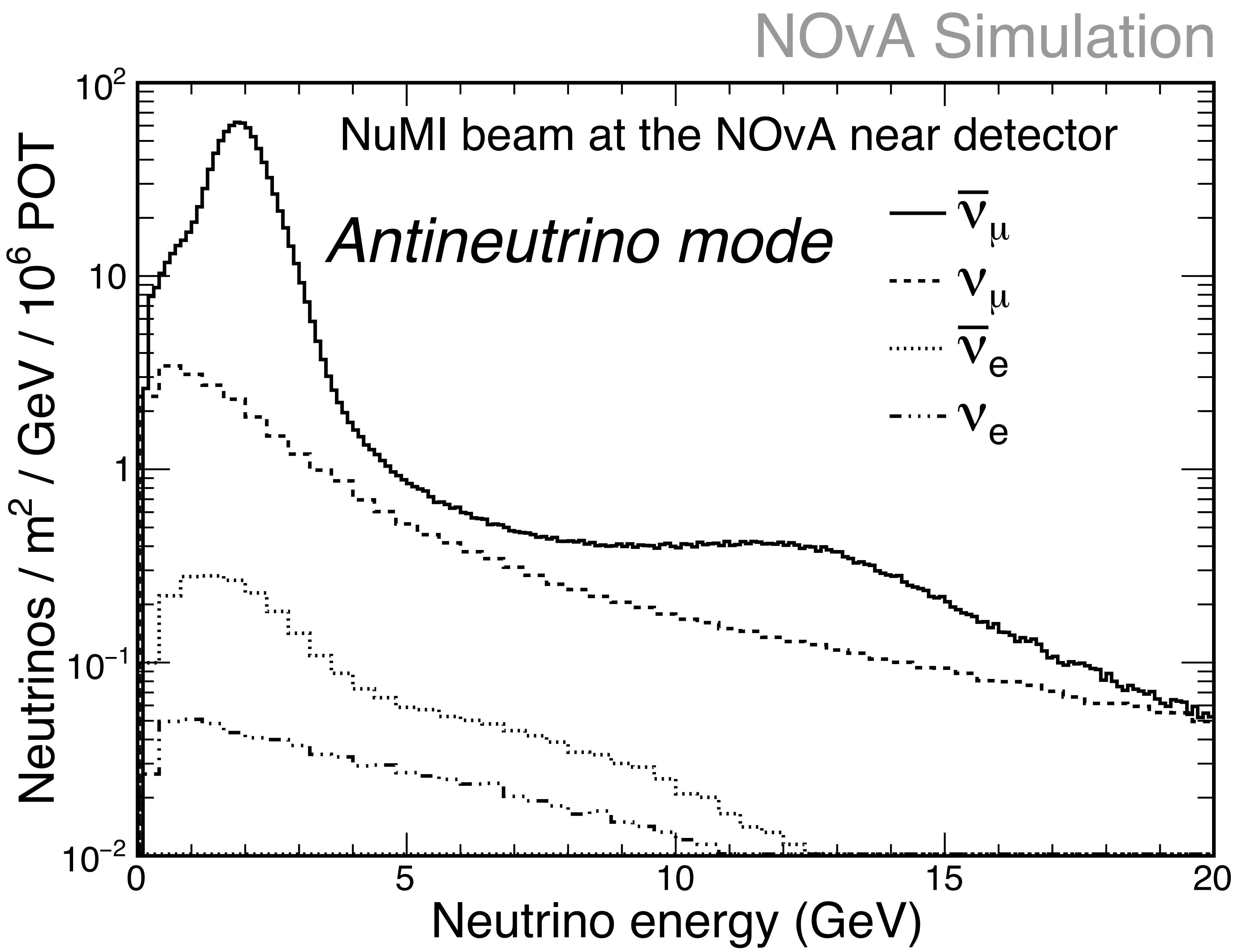


Presented in Fermilab JETP Seminar, August, 2020

Inclusive analyses in the antineutrino beam

- $\bar{\nu}_\mu$ CC Inclusive
  - *We are investigating a measurement in 3D: (T_μ, $\cos\theta_\mu$, E_{avail})*
- $\bar{\nu}_e$ CC Inclusive
  - *We plan to measure in 2D: (E_e, $\cos\theta_e$)*

Ratios $\bar{\nu}_\mu / \nu_\mu$ and $\bar{\nu}_e / \bar{\nu}_\mu$ will be calculated



Inclusive analyses in the antineutrino beam

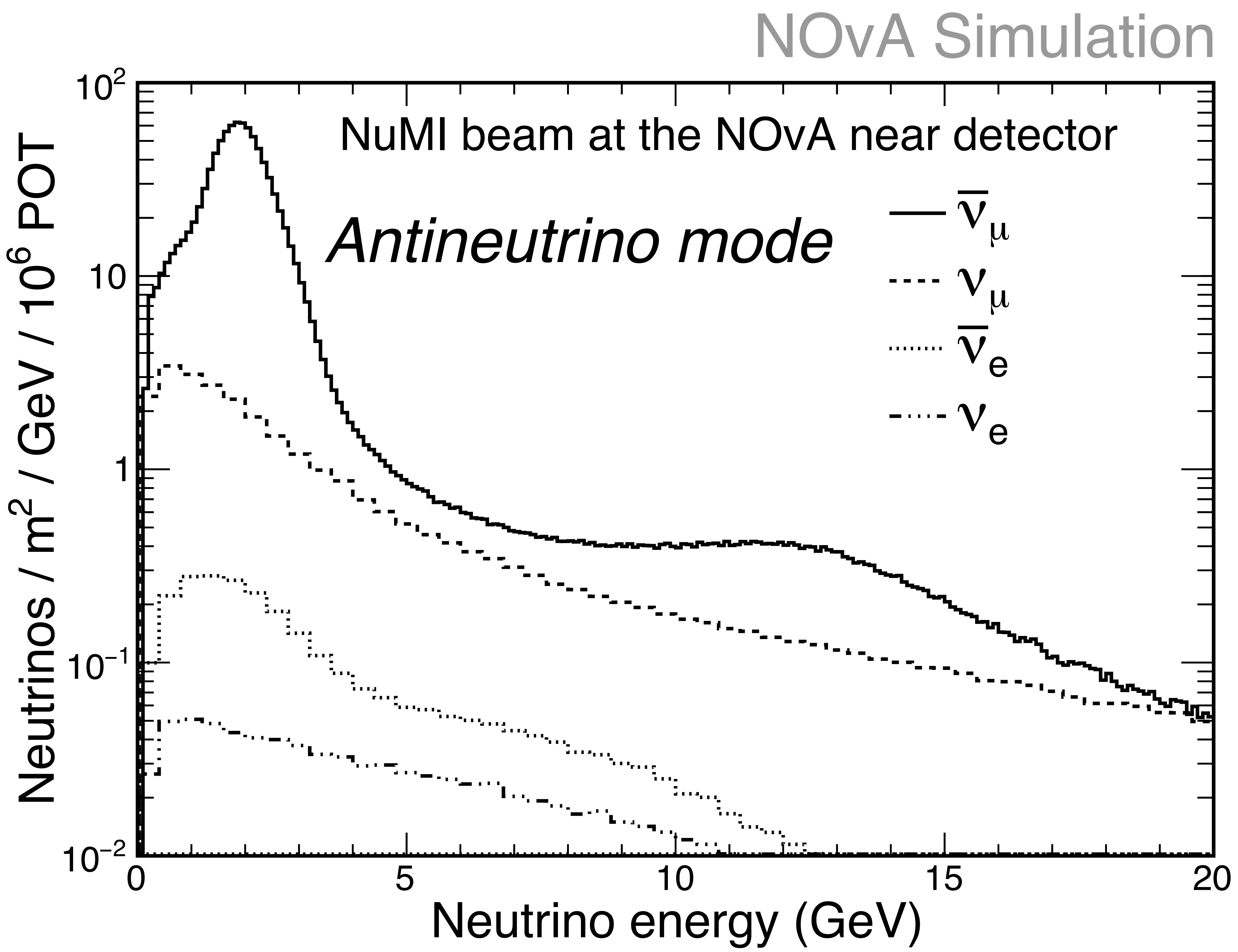
» $\bar{\nu}_\mu$ CC Inclusive

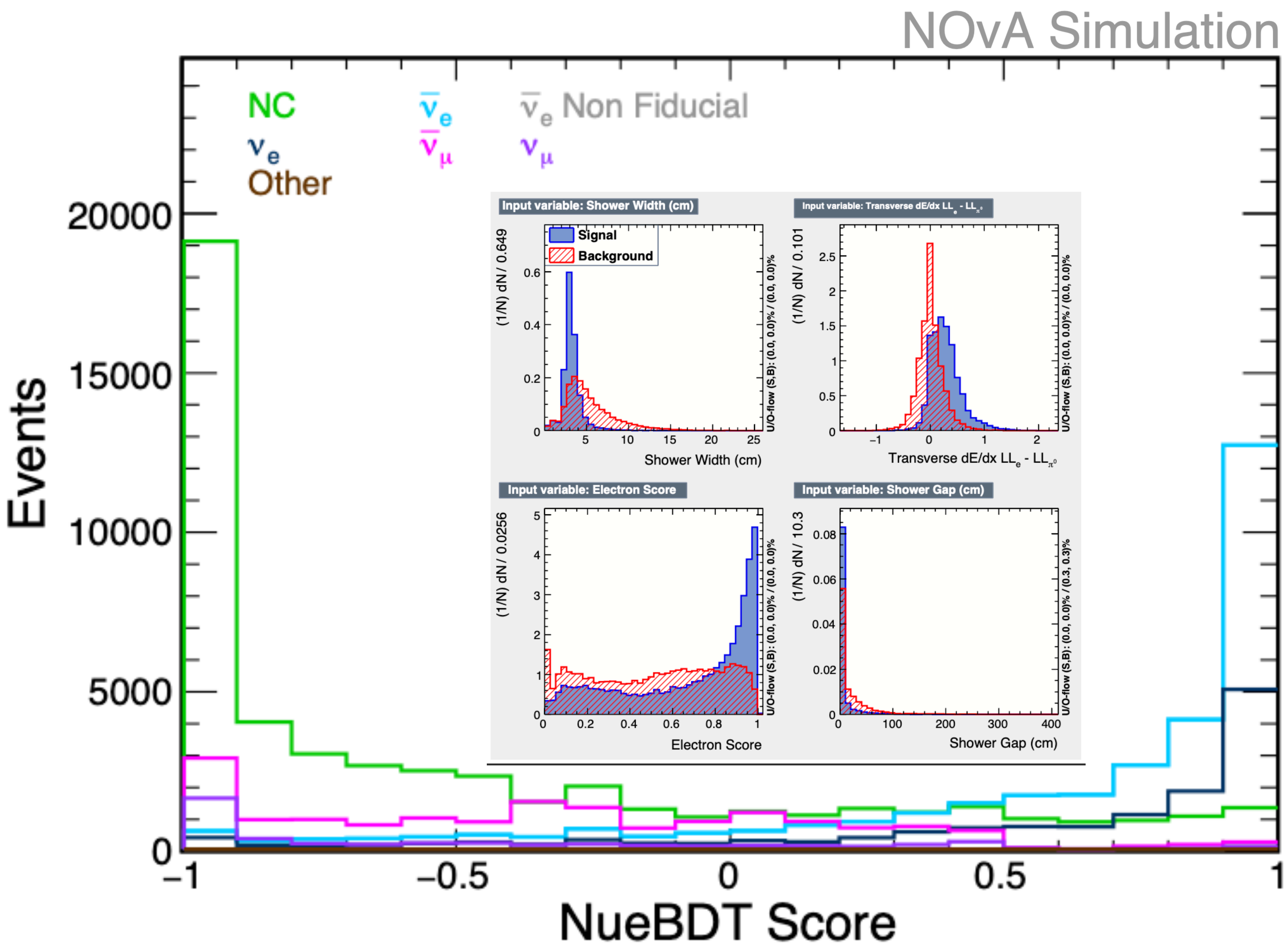
- *We are investigating a measurement in 3D: (T_μ, $\cos\theta_\mu$, E_{avail})*

Ratios $\bar{\nu}_\mu / \nu_\mu$ and $\bar{\nu}_e / \bar{\nu}_\mu$ will be calculated

» $\bar{\nu}_e$ CC Inclusive

- *We plan to measure in 2D: (E_μ, $\cos\theta_e$)*





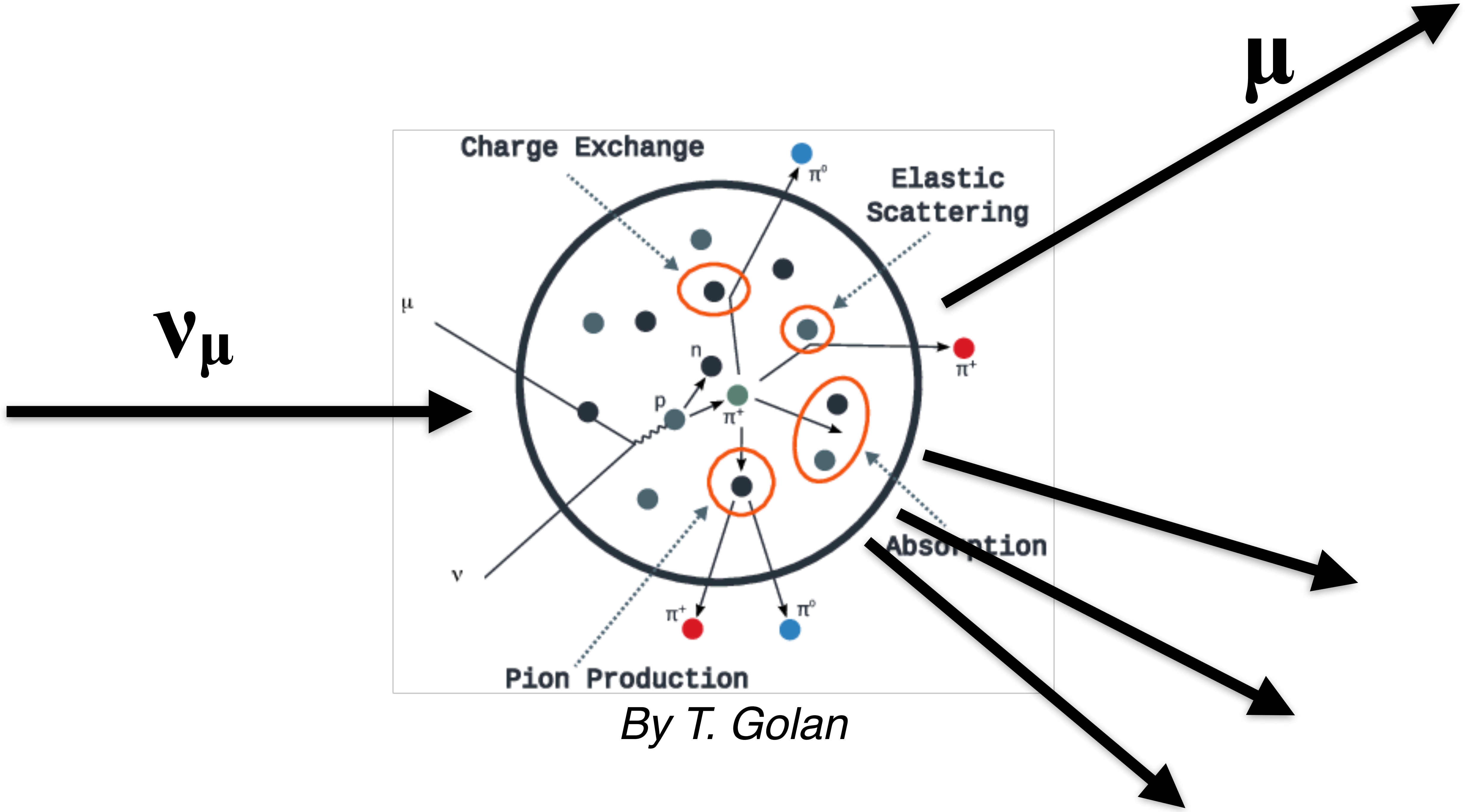
Exclusive analyses

Beyond the inclusive measurements

I showed the status of the inclusive CC cross sections in NOvA

$$\sigma_{CC}^{\text{inclusive}}(E_\nu) = \sigma_{CC}^{\text{QE}} + \sigma_{CC}^{\text{MEC}} + \sigma_{CC}^{\text{Res}} + \sigma_{CC}^{\text{DIS}} + \sigma_{CC}^{\text{Coh}}$$

NOvA is actively working on different exclusive channels with neutrino and antineutrino for CC and NC



By T. Golan

Beyond the inclusive measurements

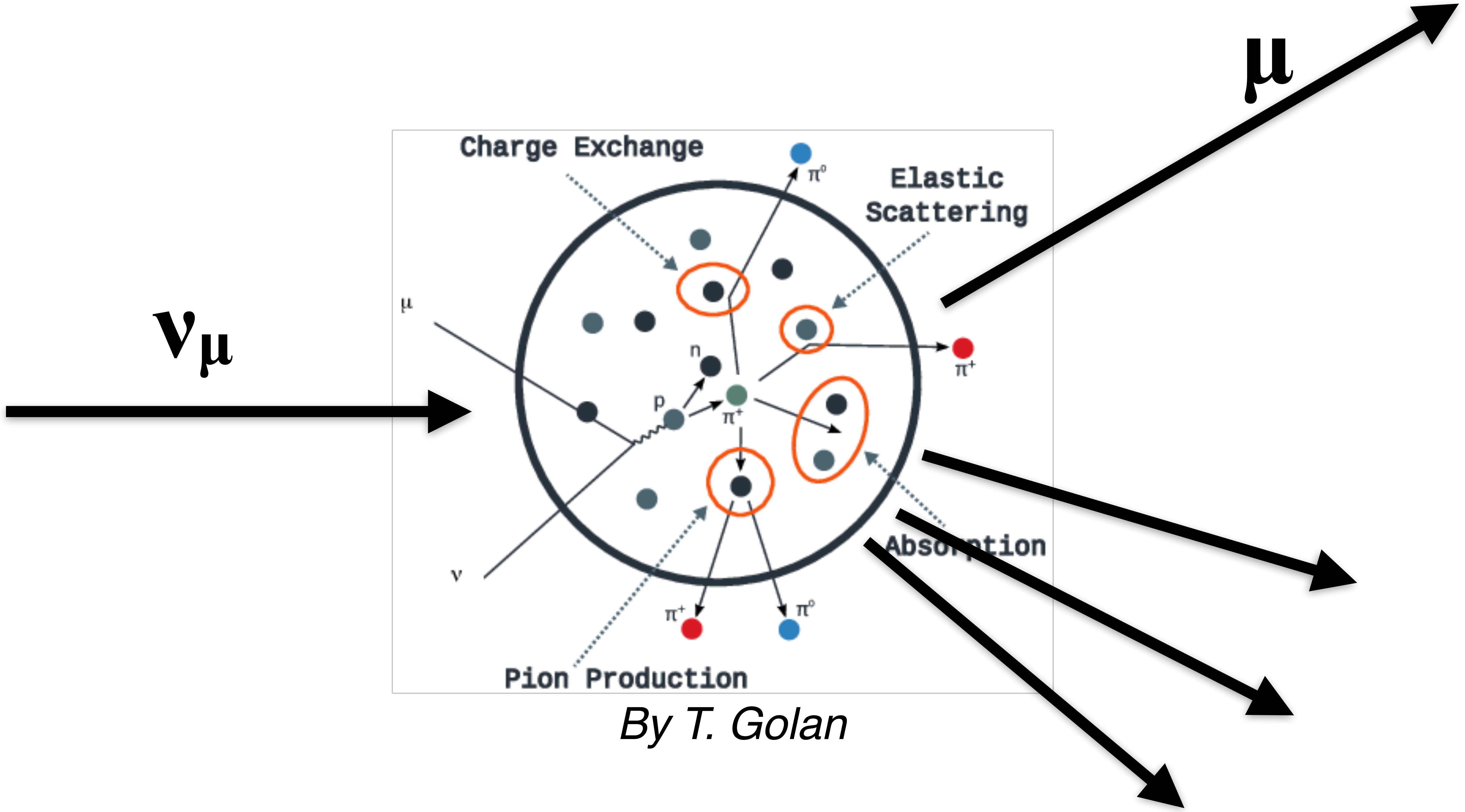
I showed the status of the inclusive CC cross sections in NOvA

$$\sigma_{\rm CC}^{\rm inclusive}(E_\nu) = \sigma_{\rm CC}^{\rm QE} + \sigma_{\rm CC}^{\rm MEC} + \sigma_{\rm CC}^{\rm Res} + \sigma_{\rm CC}^{\rm DIS} + \sigma_{\rm CC}^{\rm Coh}$$

NOvA is actively working on different exclusive channels with neutrino and antineutrino for CC and NC

There are two areas of analyses:

- **ν_μ-CC with low hadronic activity (ν_μ-CC low-had):** suitable for nuclear effect studies
- Different channels of semi in[ex]clusive **pion / pion-less / proton** production for CC and NC



By T. Golan

ν_μ-CC low-had: why is this measurement interesting?

It is sensitive to MEC contributions

It characterizes neutrino interactions with pion and proton with low kinetic energies

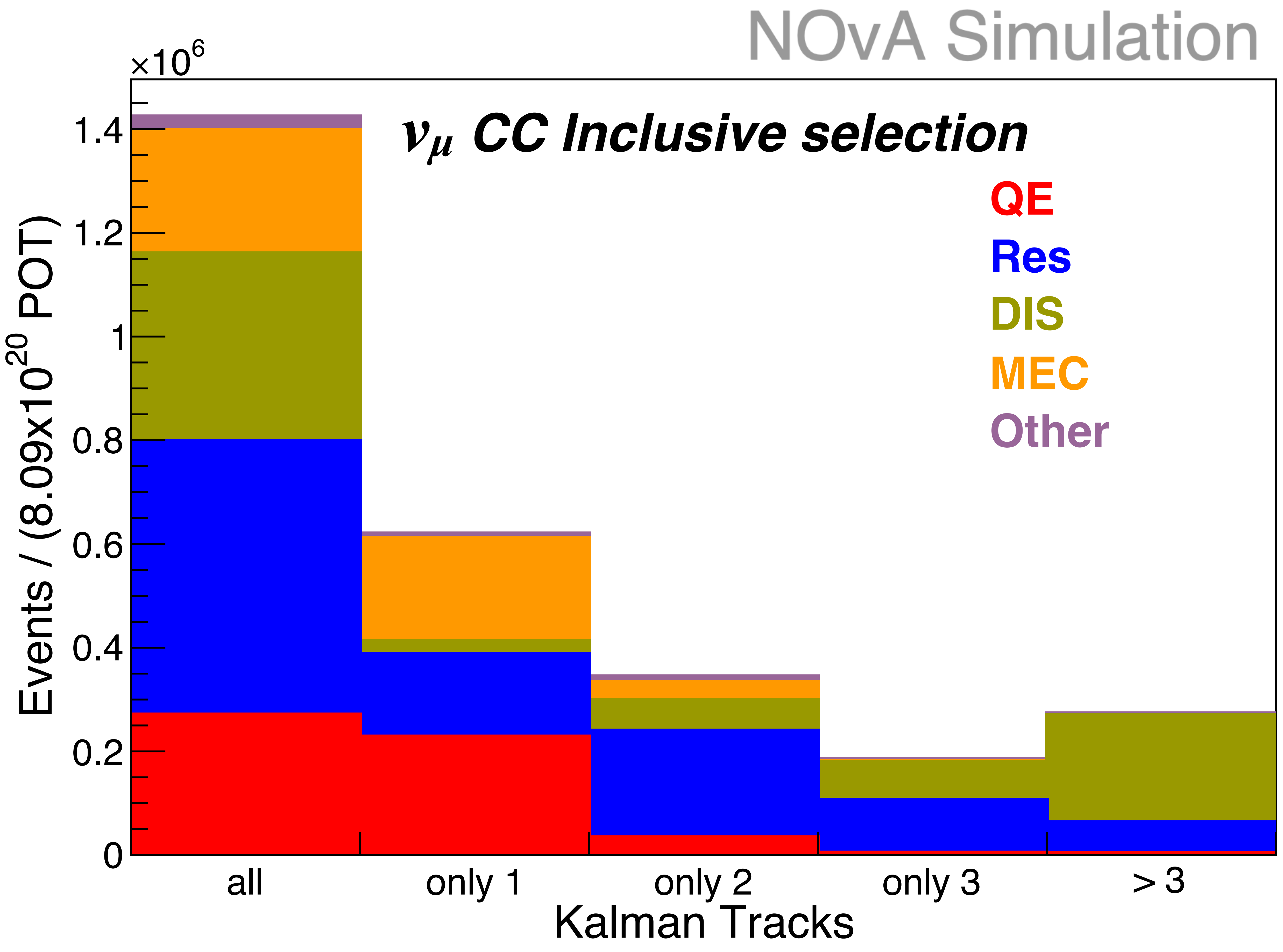
We plan to measure

» Cross sections of ν_μ - CC interactions with low hadronic activity in 3D: ($\cos\theta_\mu$, T_μ, E_{avail})

- *Total and shape comparison of measurements with generators*
- *Close examination to the phase space regions that are sensitive to MEC*

» Test of nuclear effects by comparing the energy estimation using the QEL hypothesis w.r.t the calorimetric calculation on the selected sample (QEL and MEC enriched distribution)

ν_μ-CC low-had: selection of low hadronic activity



Composition in percentages

Selection \ Interaction	QE	MEC	Res	DIS	COH
ν_μ-CC Incl.	20.9%	18.9%	38.7%	19.8%	1.8%
ν_μ-CC 1-track	39.7%	33.7%	23.0%	2.5%	1.1%

For this sample:

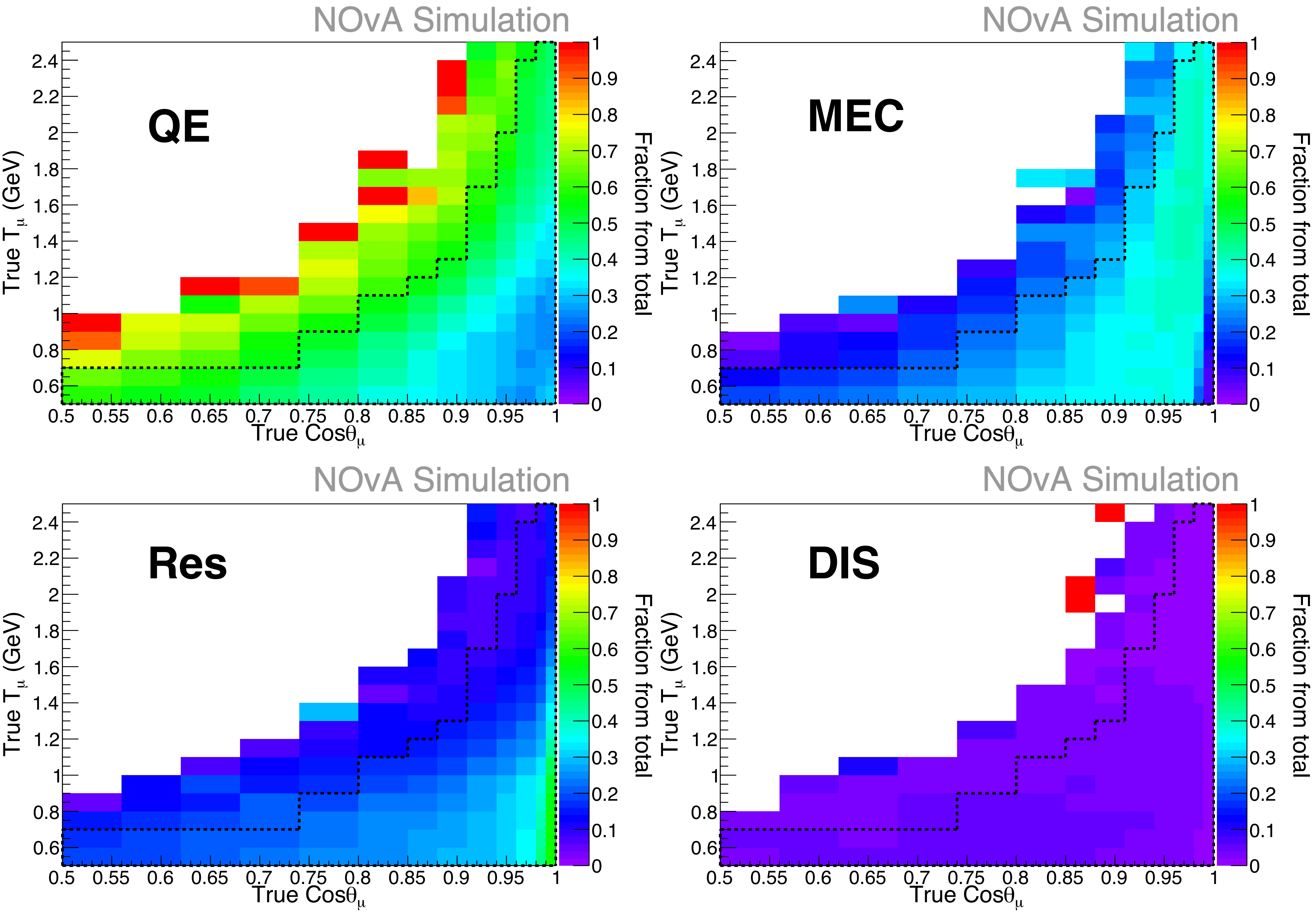
- ***QE** and **MEC** are enhanced*
- ***Res** is reduced*
- ***DIS** is almost negligible*

Selection:

ν_μ CC with 1 track

ν_μ-CC low-had: interaction modes

Fraction of interactions to total selected events



QE	MEC	Res	DIS	COH
39.7%	33.7%	23.0%	2.5%	1.1%

We defined low hadronic activity by optimizing the minimum uncertainty on the total cross section:

Signal:

***ν_μ CC** with*

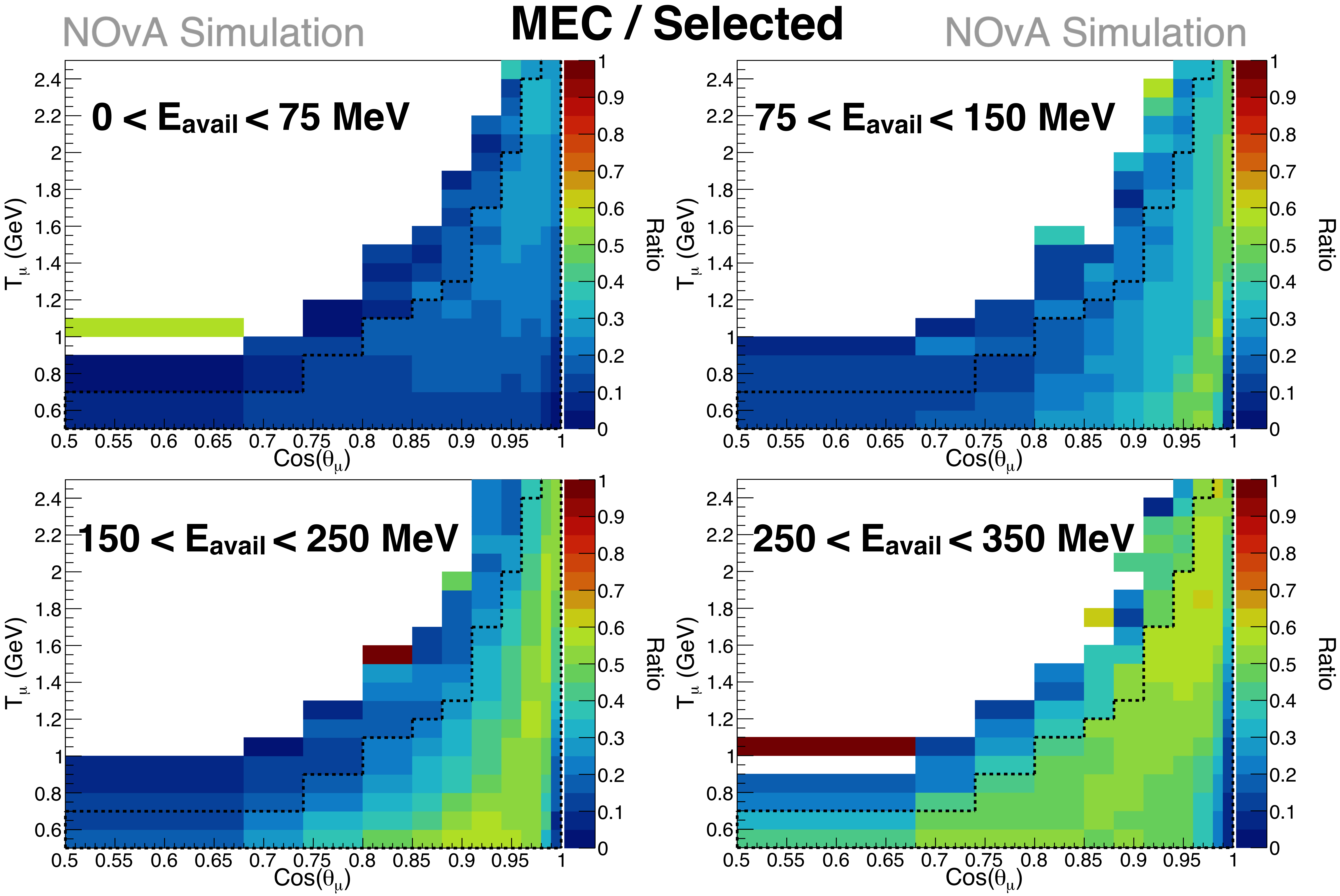
T_{proton}^{max} = 250 MeV, T_{pion}^{max} = 175 MeV

ν_μ-CC low-had: MEC component

MEC fraction increases with the E_{avail} bins

The cross sections will have regions of **enhanced MEC**

Total and shape comparisons will help to test different models



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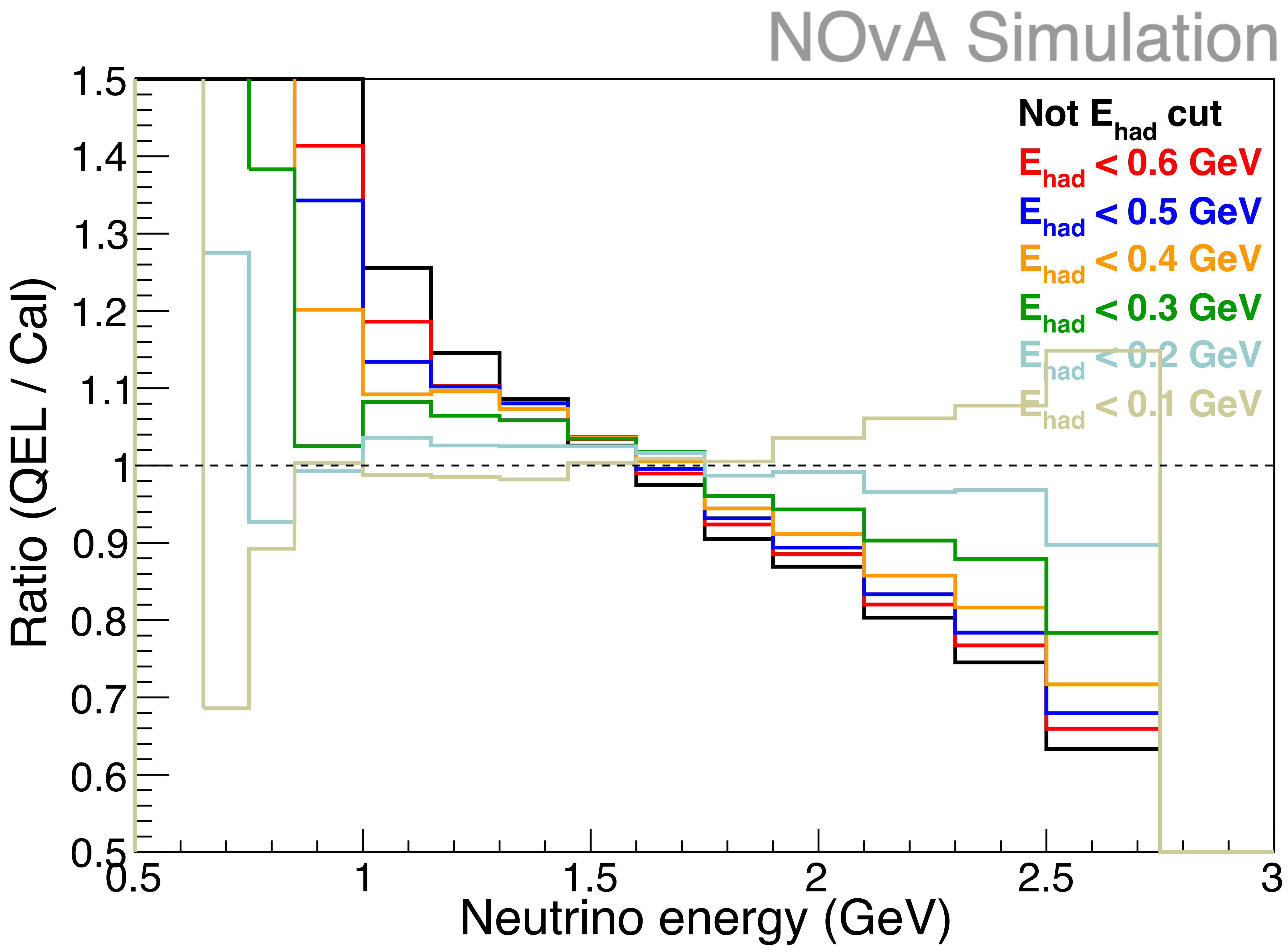
ν_μ-CC low-had: testing the QE hypothesis

Another study we can perform with this MEC + QE enhanced sample is to test the QE hypothesis

We want to observe the differences between the neutrino energy estimated by our calorimetric technique (Cal) vs the QE hypothesis

- ***We want to compare this ratio using different models with the ratio using real data***



Work on the low hadronic activity channel is in progress and we expect results soon

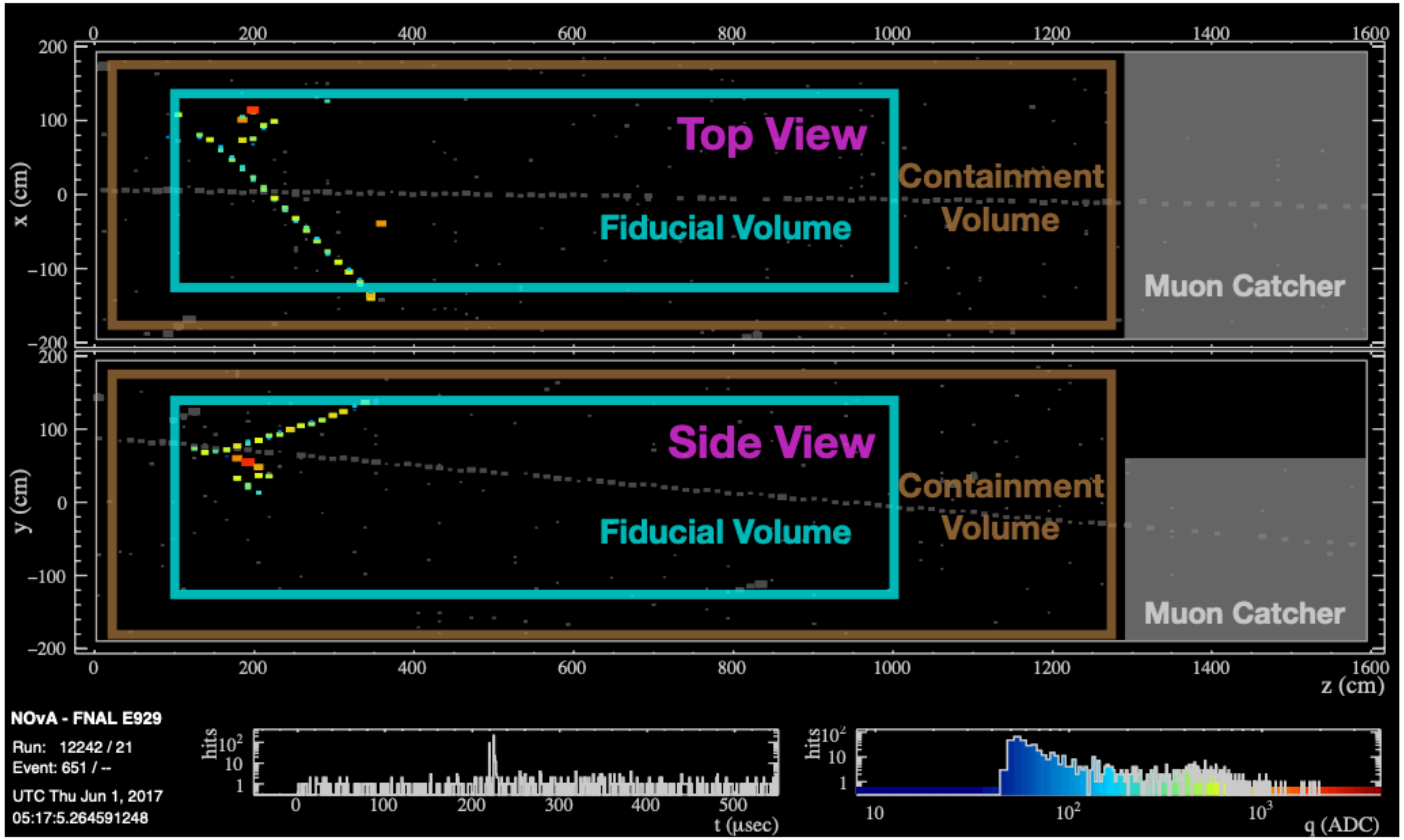
$\overline{\nu}_\mu$ CC π^0

We plan to measure: cross sections of $\overline{\nu}_\mu$ - CC interactions with at least 1 π^0 w.r.t. P_{π^0} and θ_{π^0}

Motivation

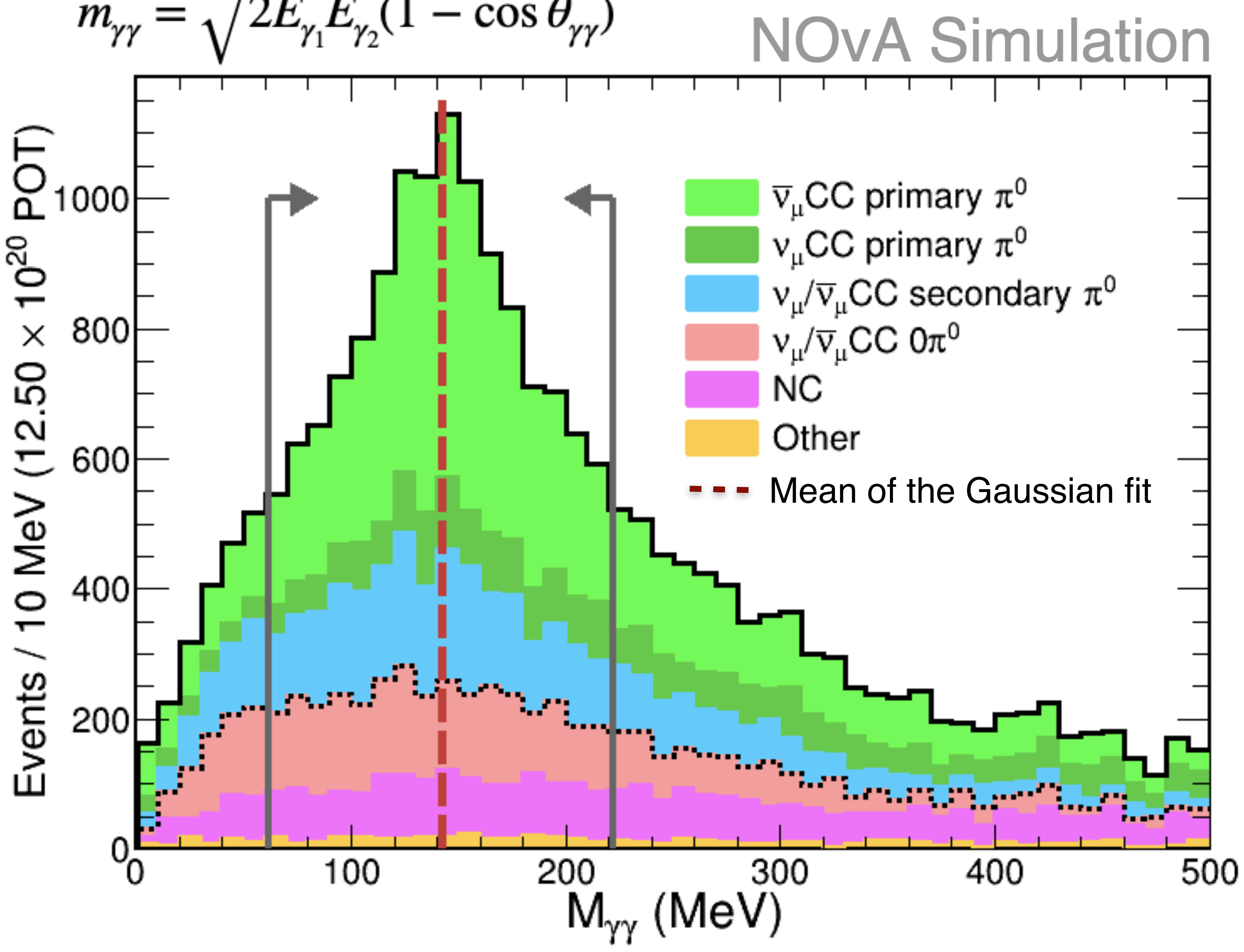
» It provides insight on background to ν_e / $\overline{\nu}_e$ appearance

» It constrains systematic uncertainties for neutrino interaction models



ν_μ CC π^0: invariant mass distribution

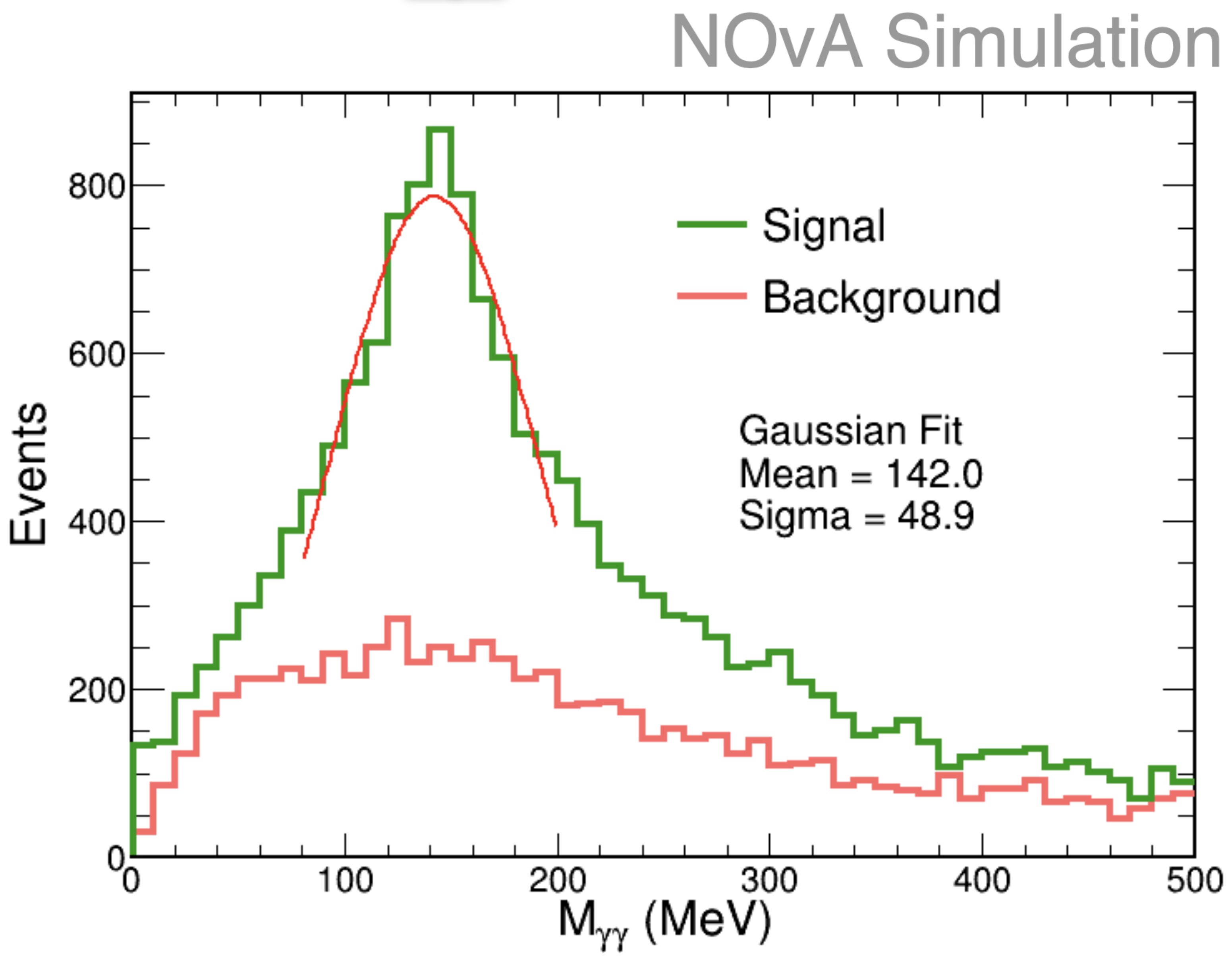
$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma\gamma})}$$



Invariant mass peak cut — [62, 222] MeV

Selected event components

- **Signal**: $\bar{\nu}_\mu$ CC with primary π^0
- **CC π^0 Background**
  - Wrong sign: ν_μ CC π^0
  - $\bar{\nu}_\mu$ CC with secondary / tertiary… π^0
- **Non-CC or Non—π^0 Background**
  - $\bar{\nu}_\mu$ CC with zero-π^0
  - NC
  - Other



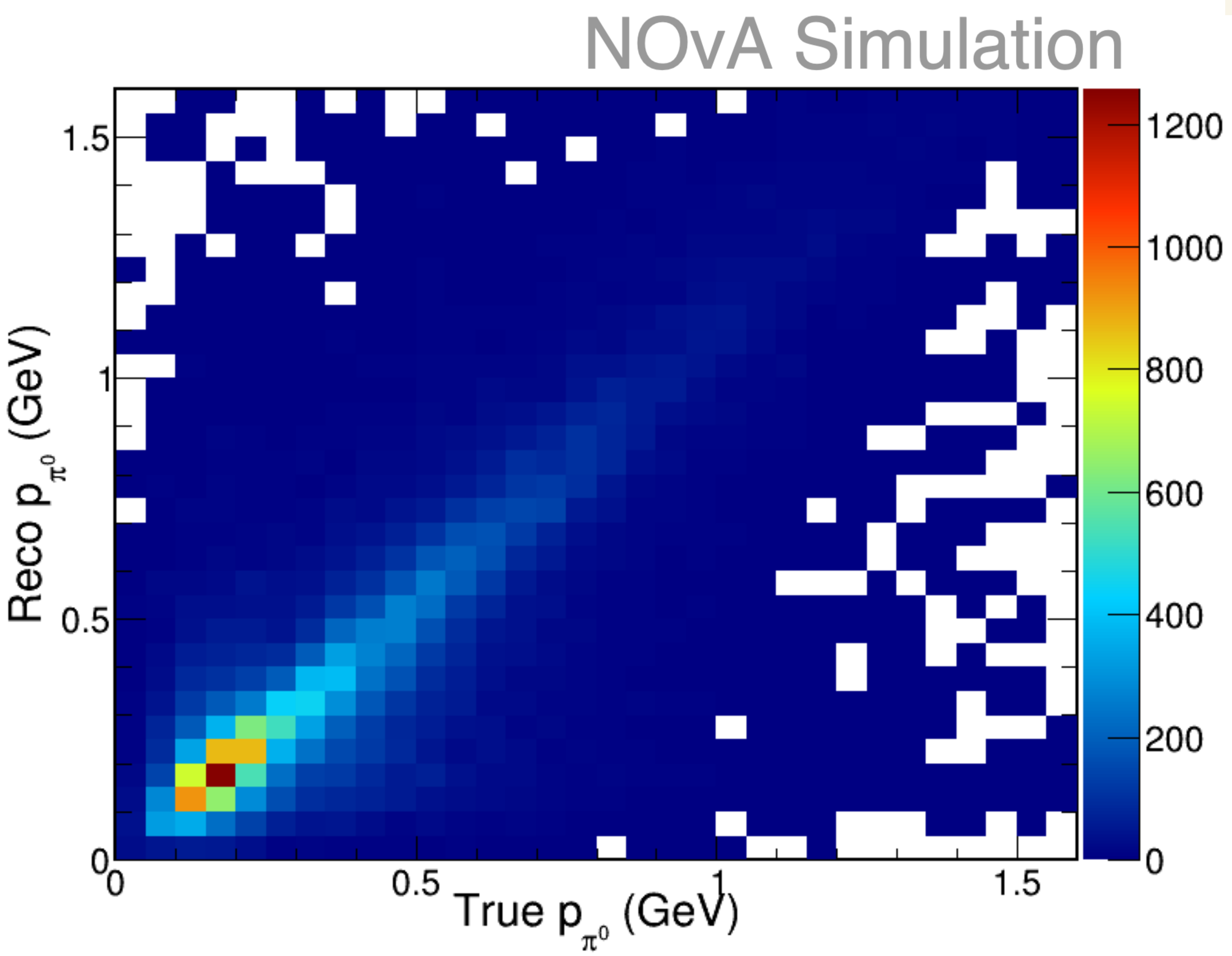
ν_μ CC π^0: resolution and particle id

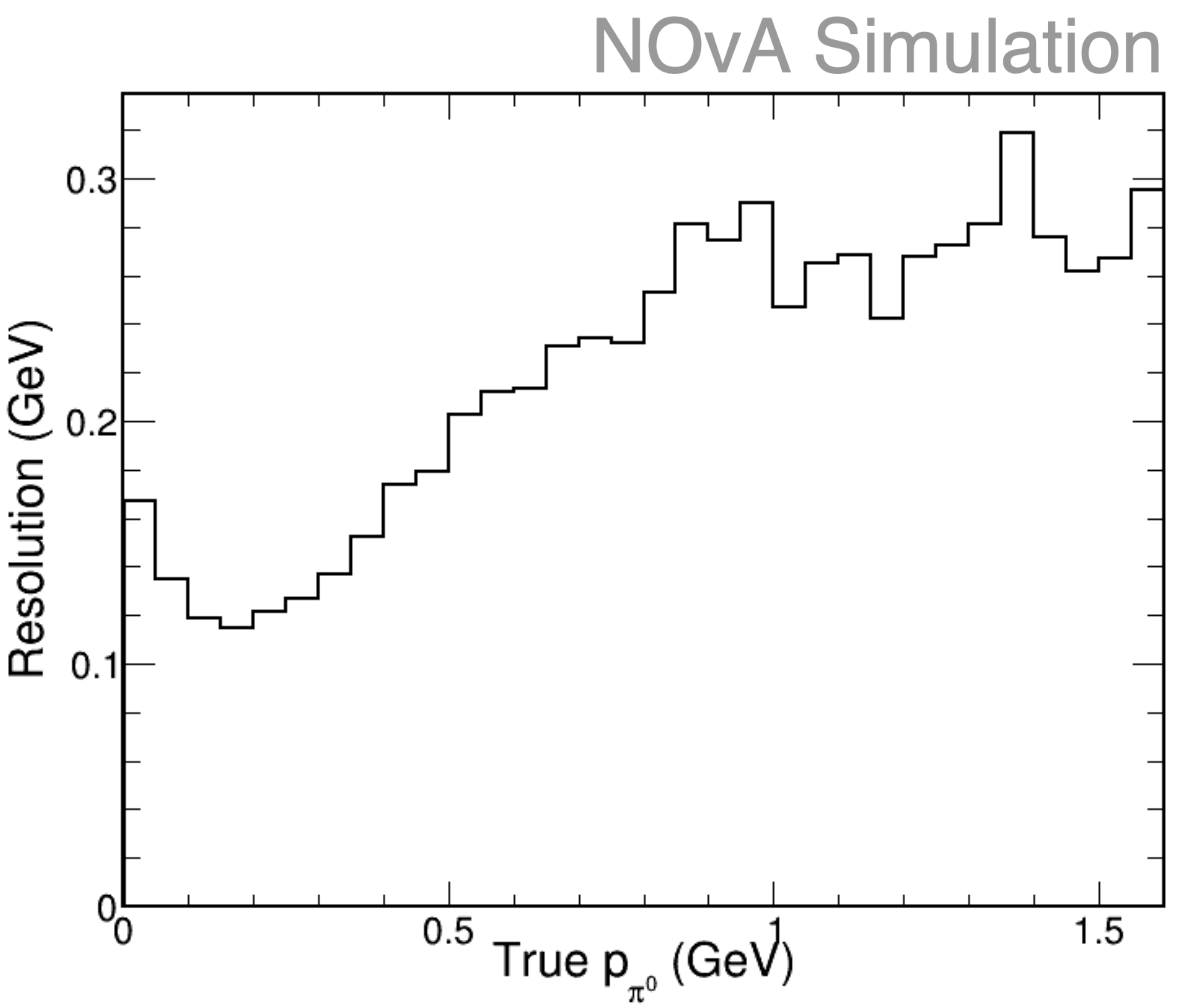
Cross sections w.r.t

π^0 momentum and angle

$$| \vec{P}_{\pi^0} | = | \vec{P}_{EM1} + \vec{P}_{EM2} |$$

$$Cos\,\theta_{\pi^0} = Cos(\vec{P}_{\pi^0}, Beam)$$





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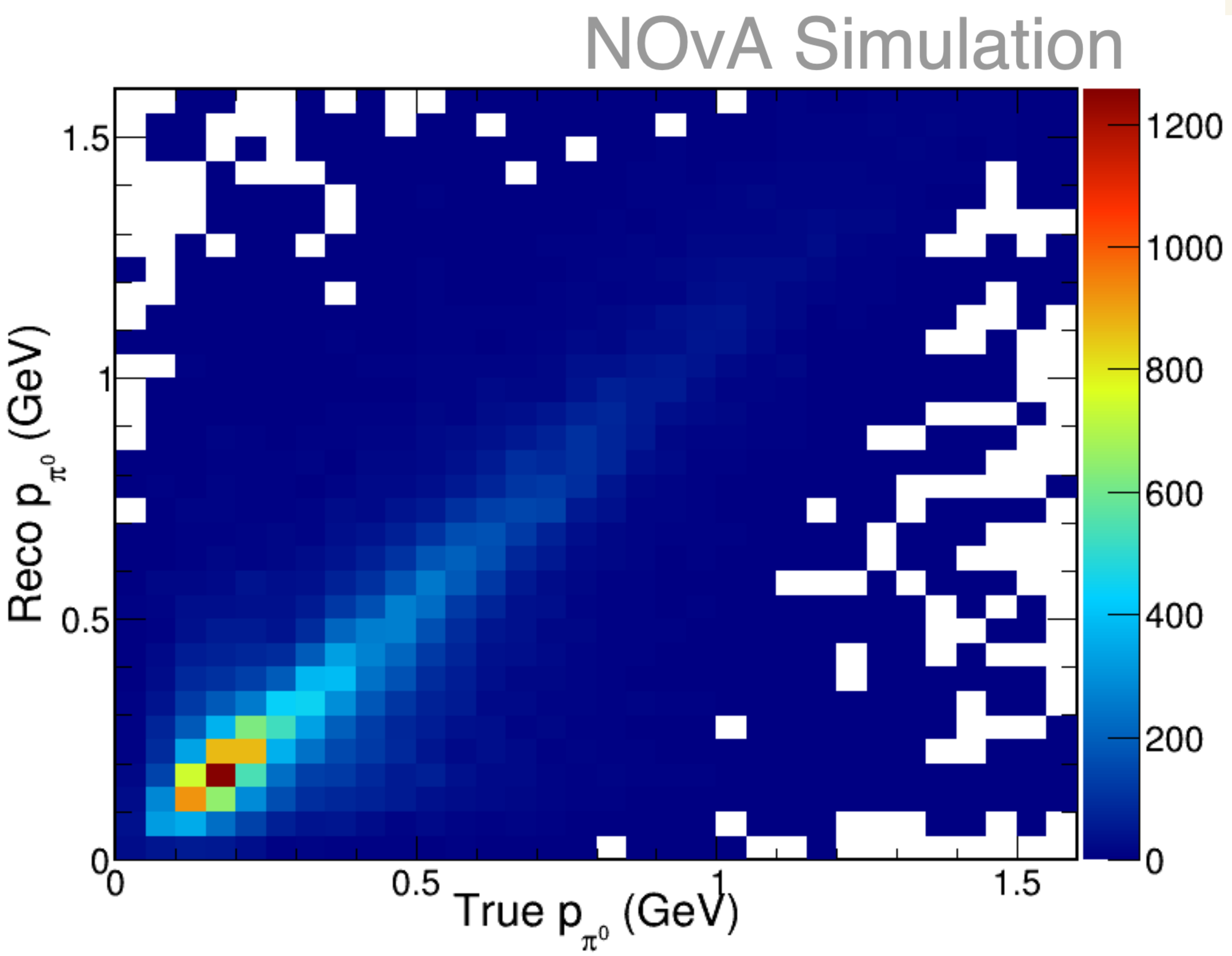
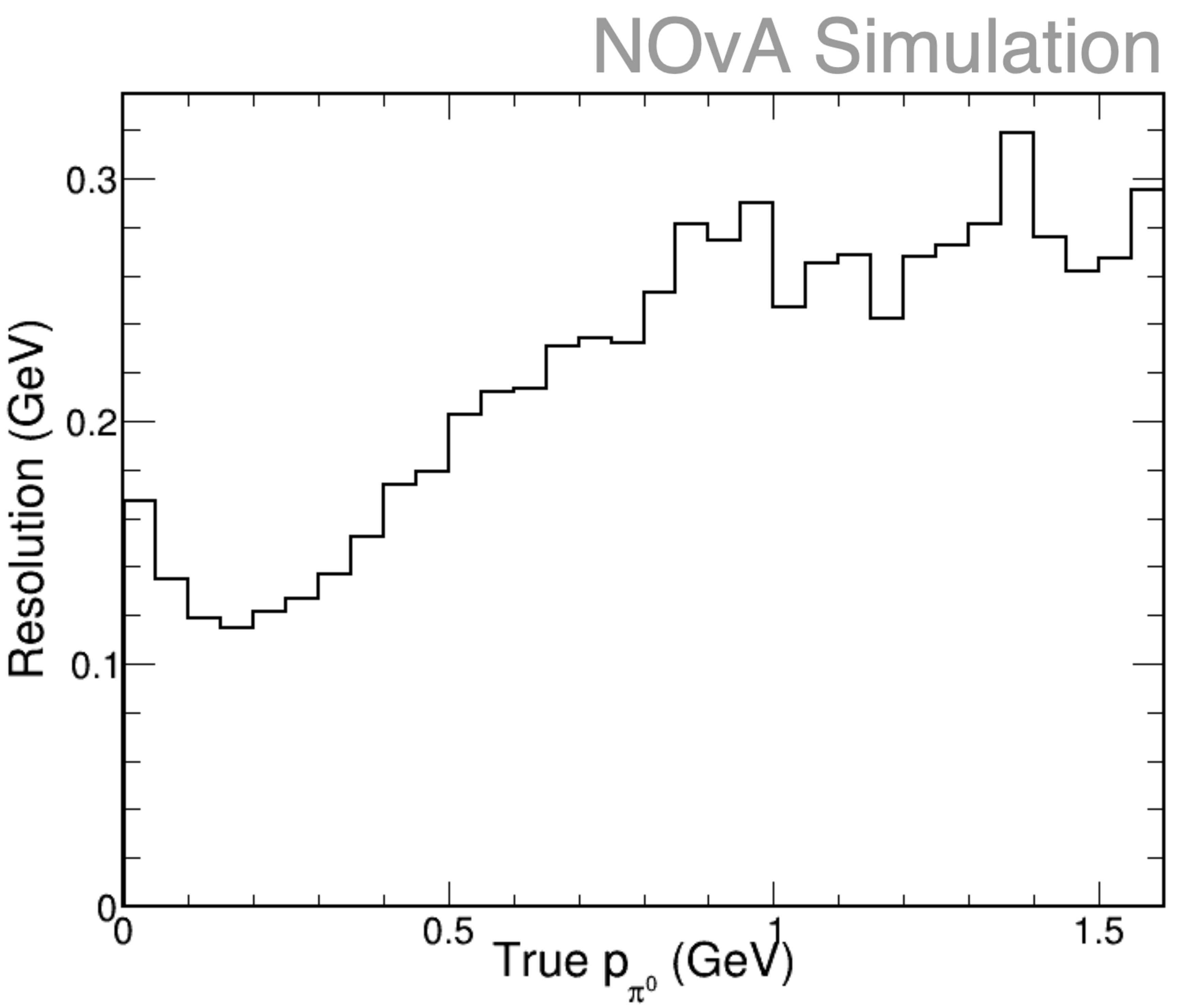




Work is in progress finalizing selection and completing the cross-section calculation chain

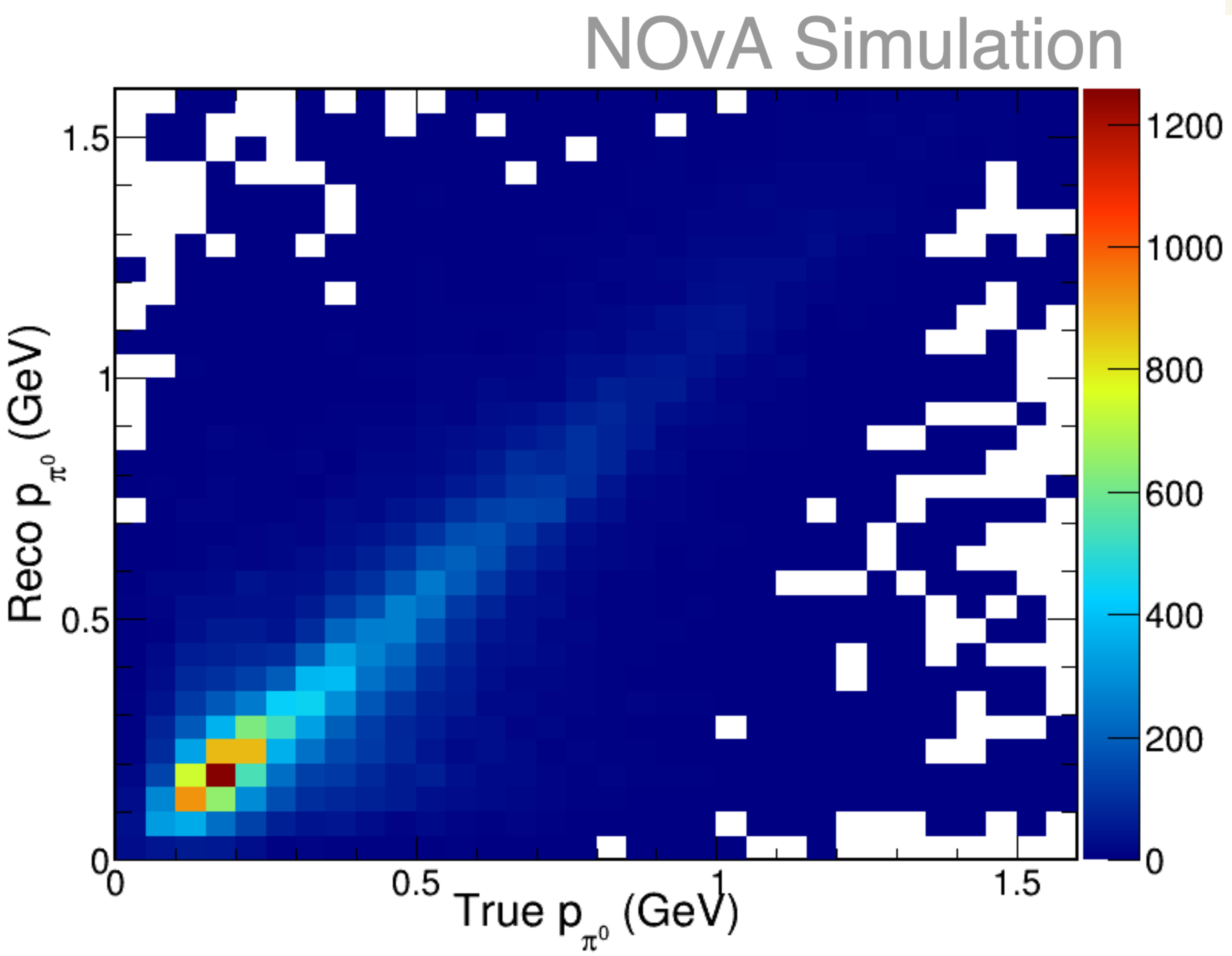
ν_μ CC π^0: resolution and particle id

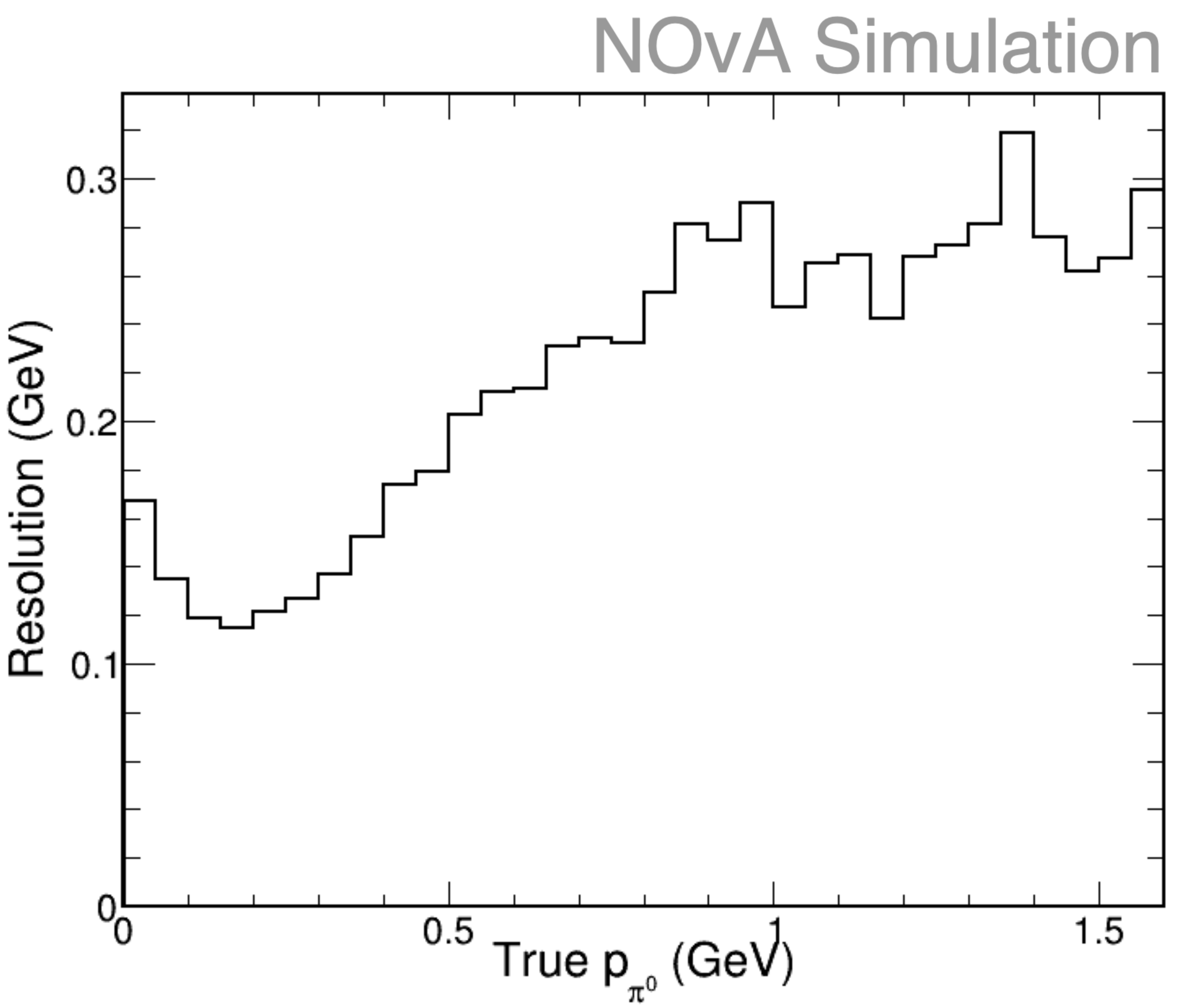
Cross sections w.r.t

π^0 momentum and angle

$$|\vec{P}_{\pi^0}| = |\vec{P}_{EM1} + \vec{P}_{EM2}|$$

$$Cos\,\theta_{\pi^0} = Cos(\vec{P}_{\pi^0}, Beam)$$





Work is in progress finalizing selection and completing the cross-section calculation chain

» We are improving the particle identification for all analyses by using Convolutional Visual Network (CVN):

- *It is trained in single particle candidates as an attempt to minimize model bias*
- *We use uniform distributions (momentum, angle, position) of e, γ, π^{+-}, p, μ*

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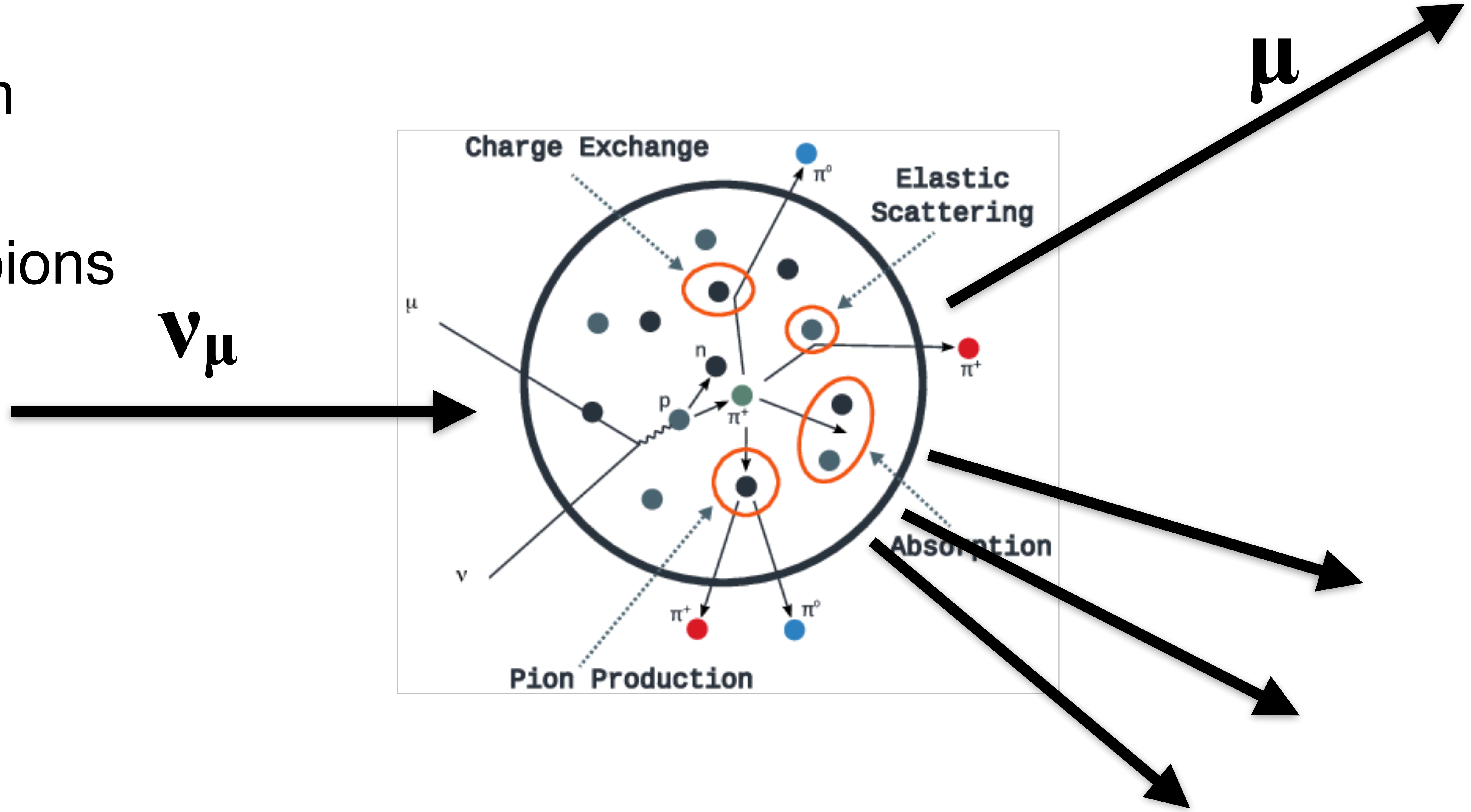
NOvA is pursuing other analyses

- ν_μ and $\bar{\nu}_\mu$ CC excess events (2p2h)
- NC π^0 production in neutrino and antineutrino beam
- ν_μ CC exclusive final state with pions and without pions
- ν_μ CC Coherent pion production
- Neutrino-electron scattering
- CC low hadronic activity in antineutrino beam



Summary and conclusions

» The NOvA experiment has an excellent opportunity to make a high precision and a broad set of neutrino-nucleus cross-section measurements

» The ν_μ - CC and ν_e - CC were recently presented and the publications will follow soon

» Exclusive channels such as ν_μ - CC with low hadronic activity and $\bar{\nu}_\mu$ - CC π^0, and other pion final states measurements are actively being analyzed and we expect results in a short term

» We will calculate ratios of inclusive channels and exclusive over inclusive measurements

Summary and conclusions

- In parallel, we are making improvements to allow more precise measurements:
  - *Improvement in the particle identification by CVN, dedicated neutron and pion reconstruction groups, etc*
  - *The NOvA Test Beam experiment, currently in-progress, aims to reduce the calibration and detector response uncertainties*

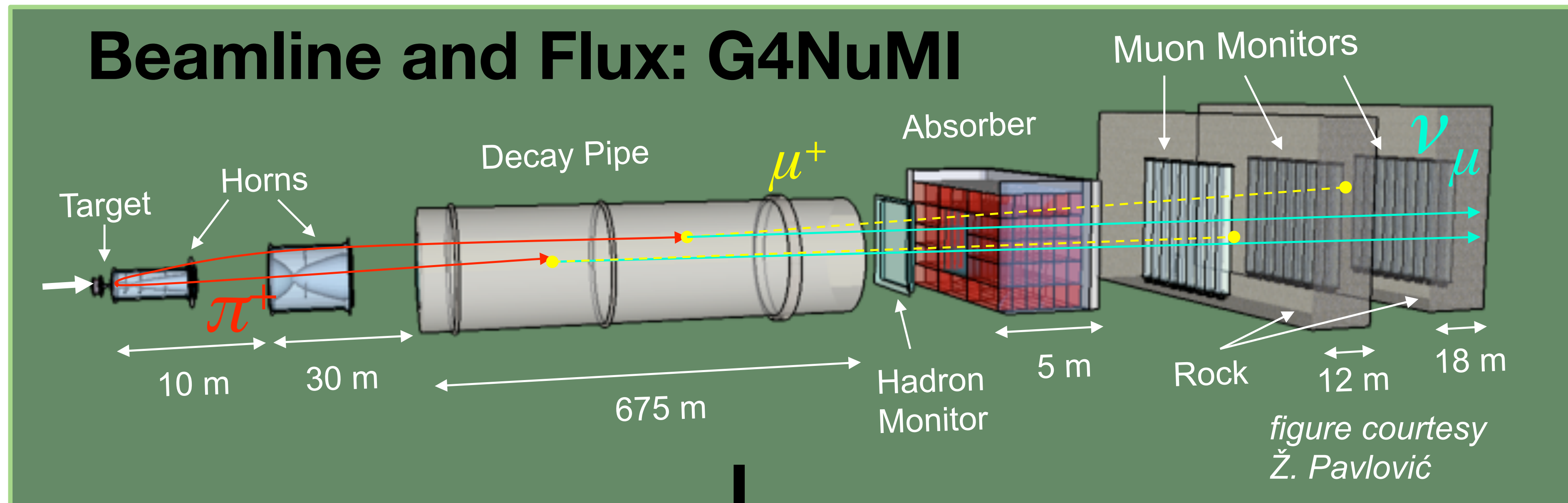
- We are collecting more neutrino and antineutrino data. We expect to have good statistics and finer resolution to make higher dimensional cross-section measurements

Thank you!

Backup

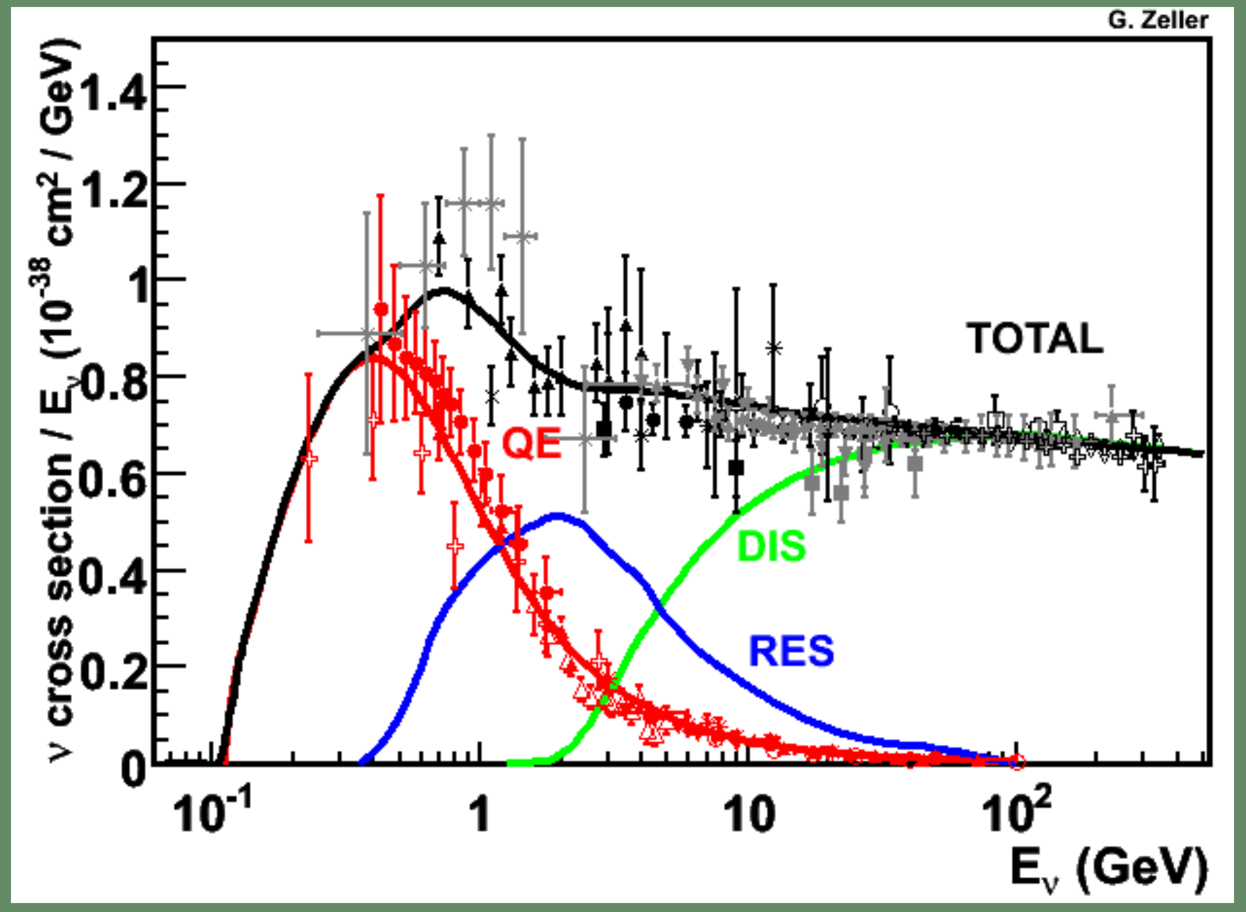
NOvA simulation

Beamline and Flux: G4NuMI

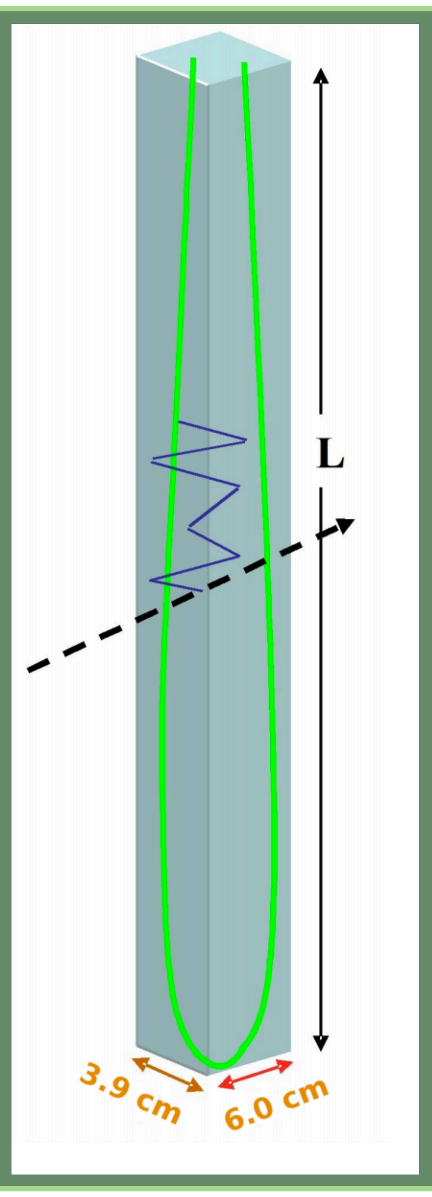


Systematic uncertainties coming from each of these steps are **assessed** and **propagated** to the final results.

ν-A modelling: GENIE

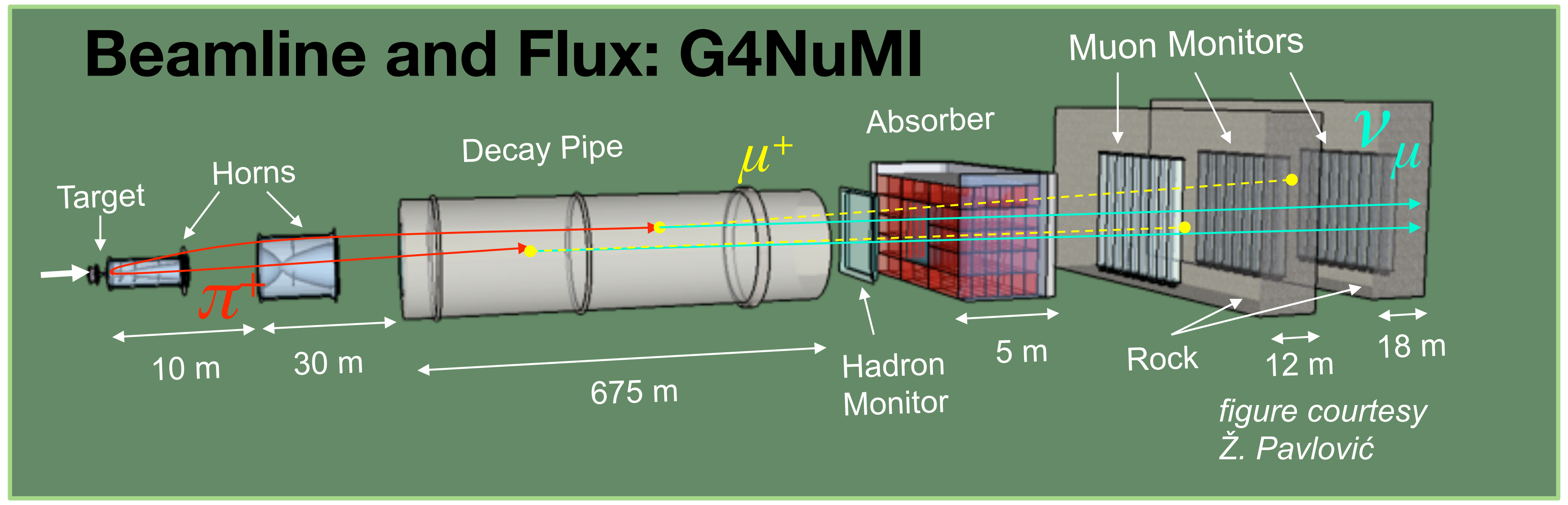


Detector response: GEANT4



Readout electronics & DAQ

Neutrino flux prediction



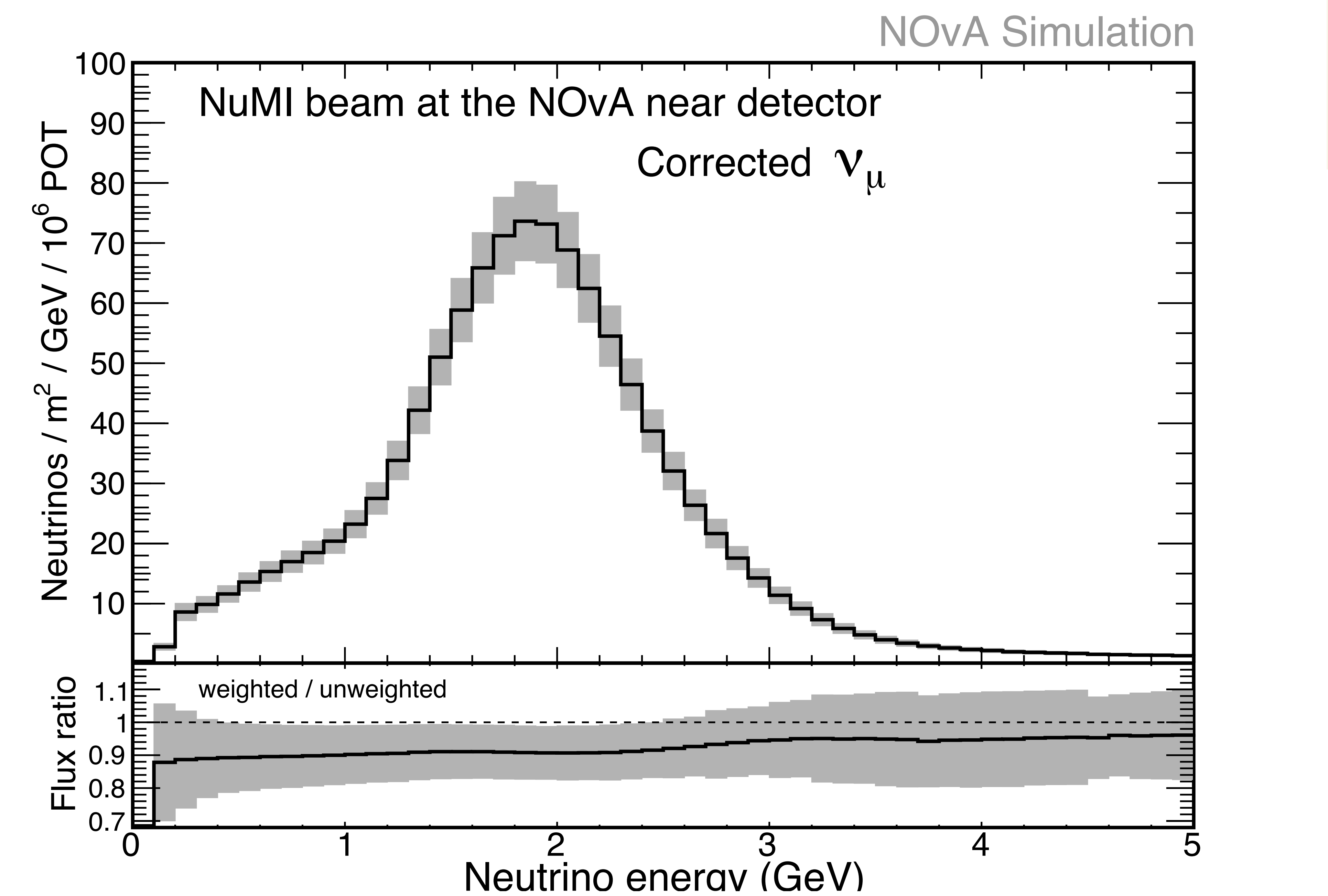
Begin with Geant4 simulation of neutrino beam production and transport.

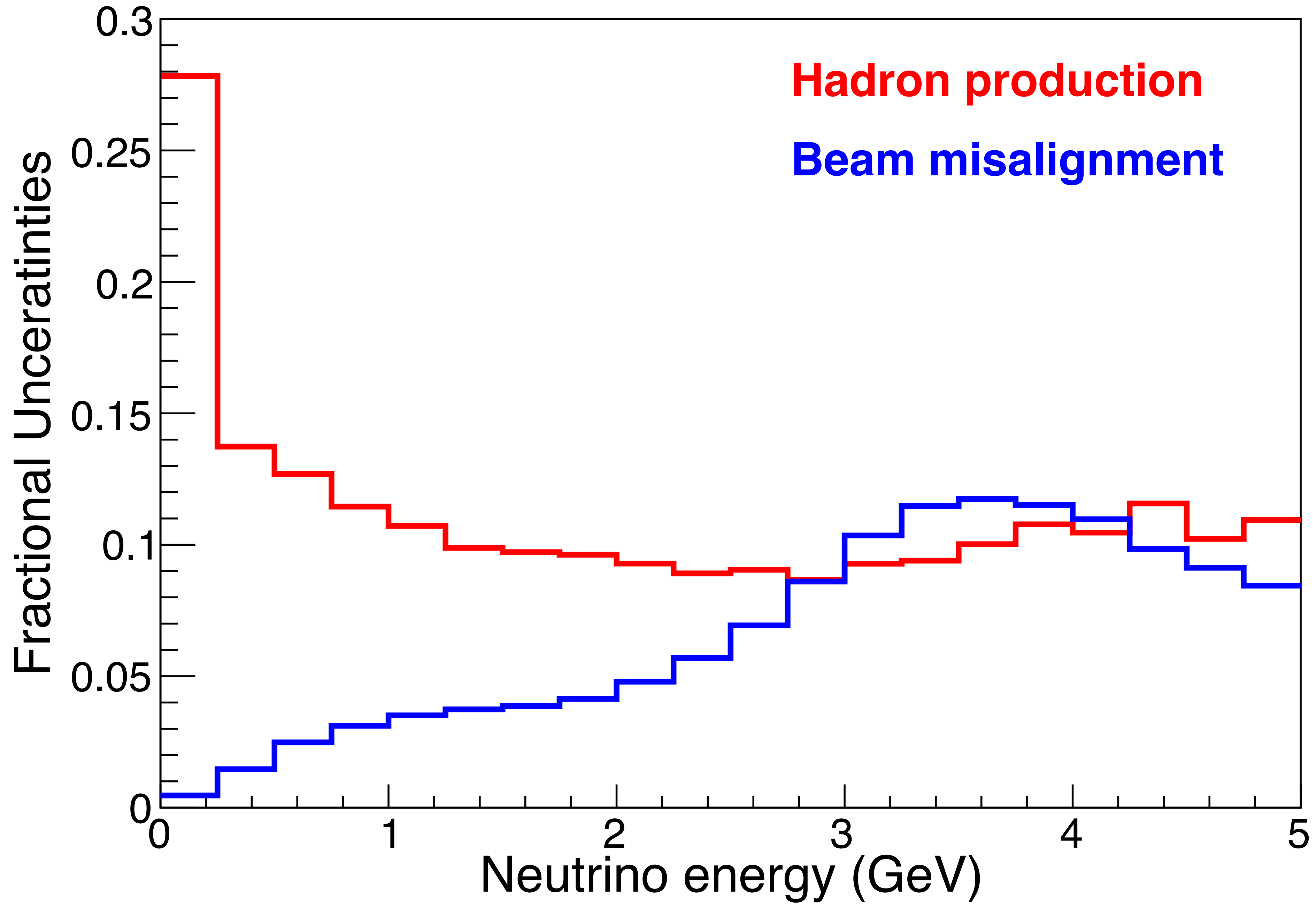
Hadron production model is constrained with external measurements on thin target data (mainly from **NA49**, CERN).

» Same technique developed by **MINERvA** (Phys. Rev. D94, 092005)

» The uncertainty based on these external measurements results in a ~10% normalization uncertainty.

Beam misalignment is sub-dominant around the peak (~2GeV)





The NOvA 2019 GENIE Tune

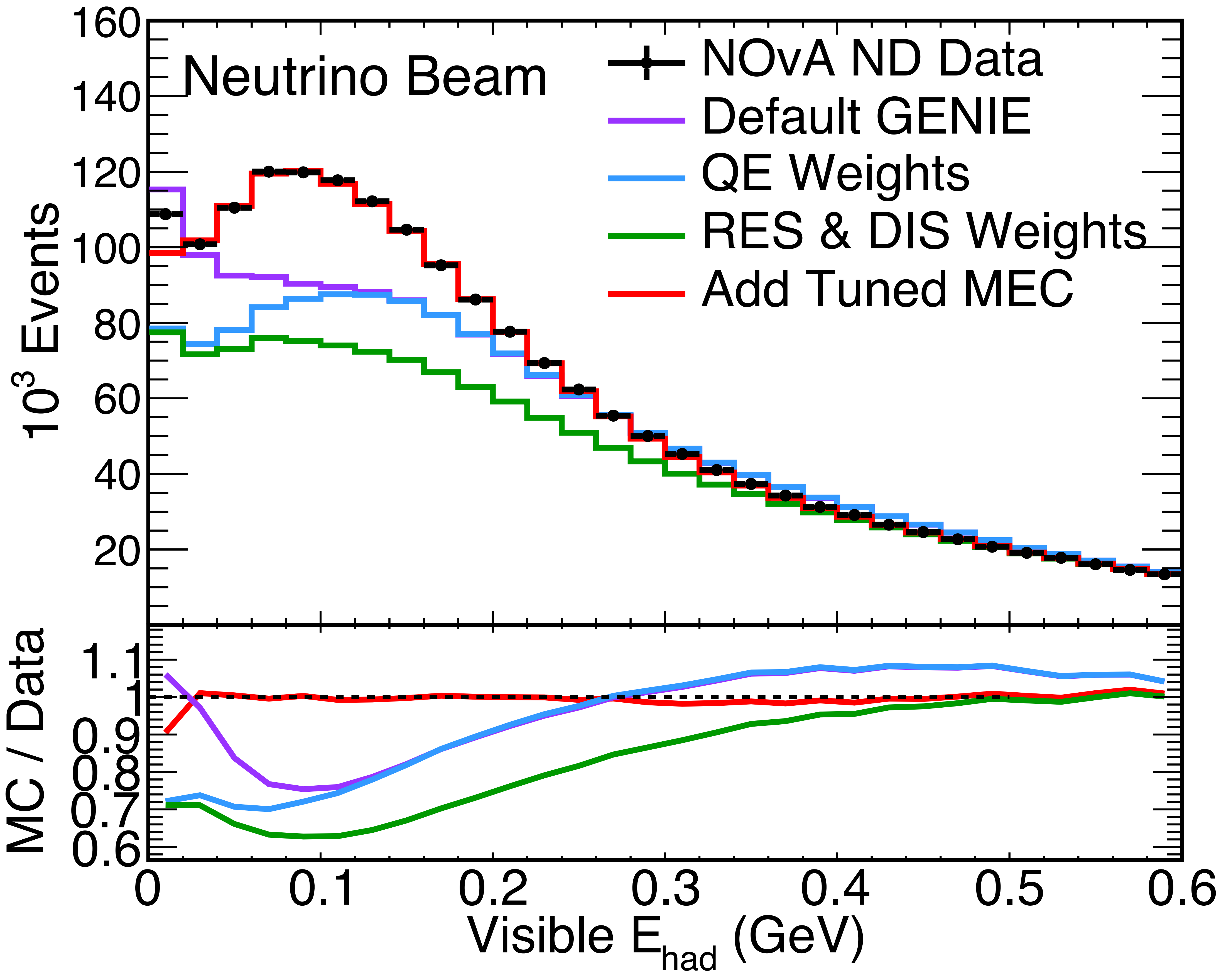
- We use NOvA and external data to tune interaction model.
- These analyses use GENIE 2.12.2

» Correct QE to account for low Q^2 suppression.

» Apply low Q^2 suppression to Res baryon production.

» Nonresonant inelastic scattering (DIS) at W>1.7 GeV/c²) weighted up 10% based on NOvA data.

» "Empirical MEC" based on NOvA ND data to account for multinucleon knockout (2p2h).



Same tune that was used in the NOvA 2019 analysis (arXiv:2006.08727)

Cross-section measurements

Differential cross-section measurement recipe:

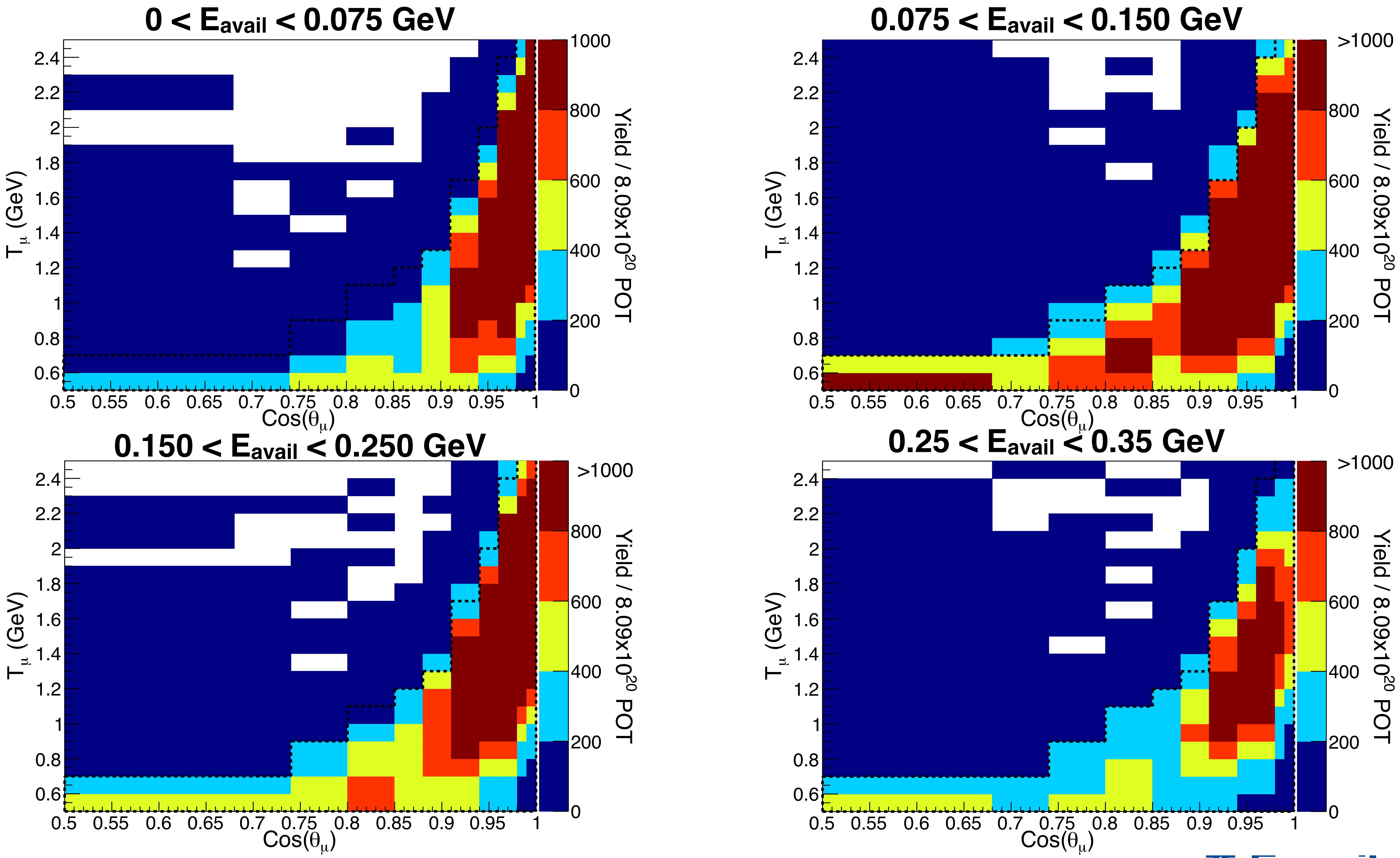
$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1} (N_j^{\mathrm{sel}} \times P_j)}{\epsilon_i N_{\mathrm{T}} \Phi \Delta x_i}$$

We rely on simulations for optimizing the selection, applying corrections for the background, smearing and efficiency and for the flux normalization.

1. Selection of the reconstructed signal event candidates optimally with minimal model bias.
2. Subtraction of the backgrounds in the selection.
3. Correction of the detector smearing to move from reconstructed to true distributions.
4. Correction of the efficiency in the selection.
5. Normalization by the neutrino flux.
6. Normalization by the number of targets.

Selected signal events: 4 E_{avail} slices

Good statistics for forward-going muons



ν_μ-CC low-had: efficiency and purity for $75 < E_{avail} < 150$ MeV

» Efficiency drops as the muon energy and angle increase due to containment

» Purity > 0.9 in the whole phase space