Queen Mary
University of London

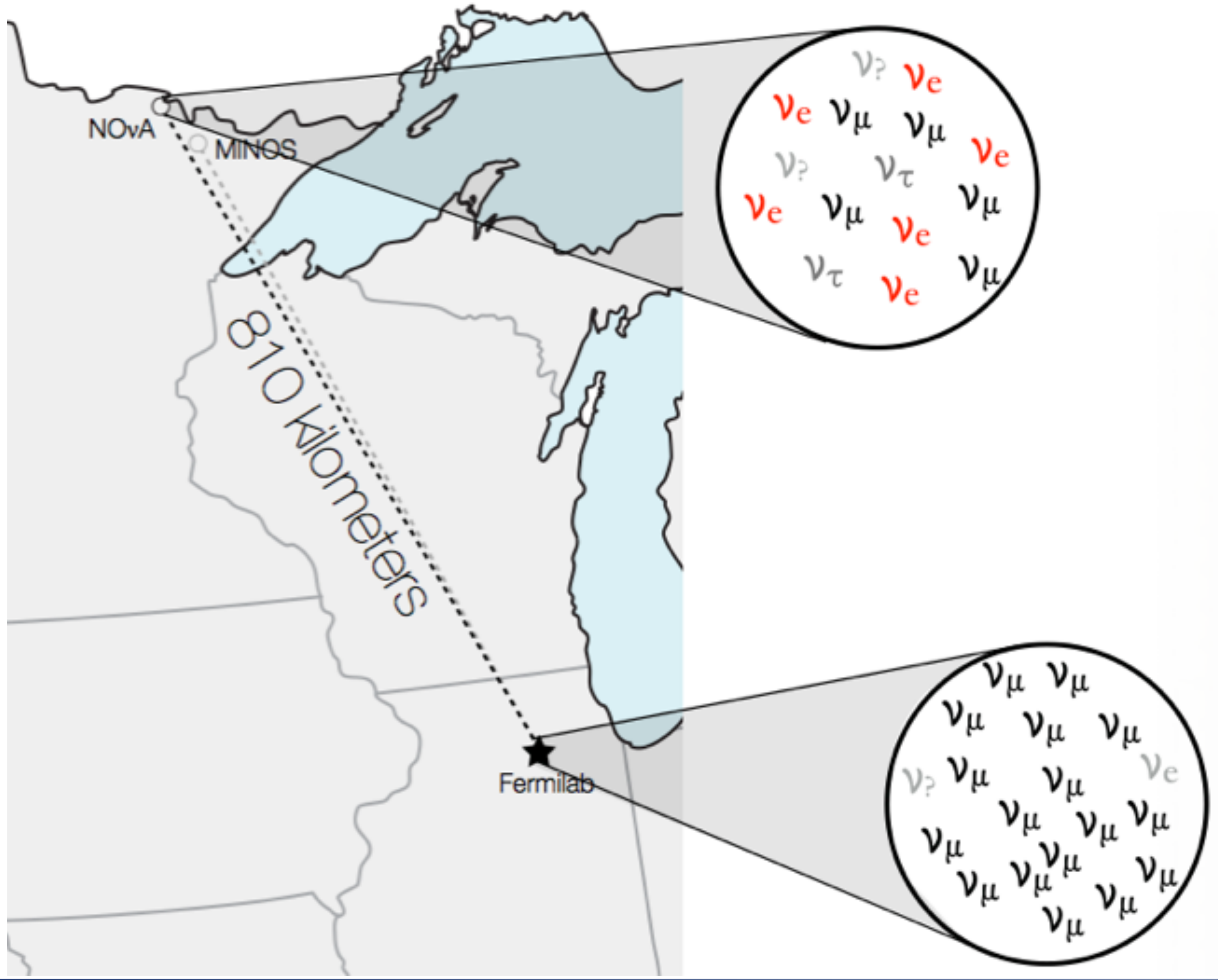
Cross-section measurements in the NOvA Near Detector

Dr Linda Cremonesi

IPPP topical meeting on physics with high-brightness stored muon beams
10-11 February 2021

The NOvA experiment

- NOvA is a long-baseline neutrino experiment:
  - 2 detectors, 14 mrad off-axis, 809 km apart.
  - Designed to measure for $\nu_\mu \rightarrow \nu_e$ oscillations: detectors provide excellent imaging of both ν_μ and ν_e CC events.
- NOvA can run in neutrino-mode or antineutrino-mode.



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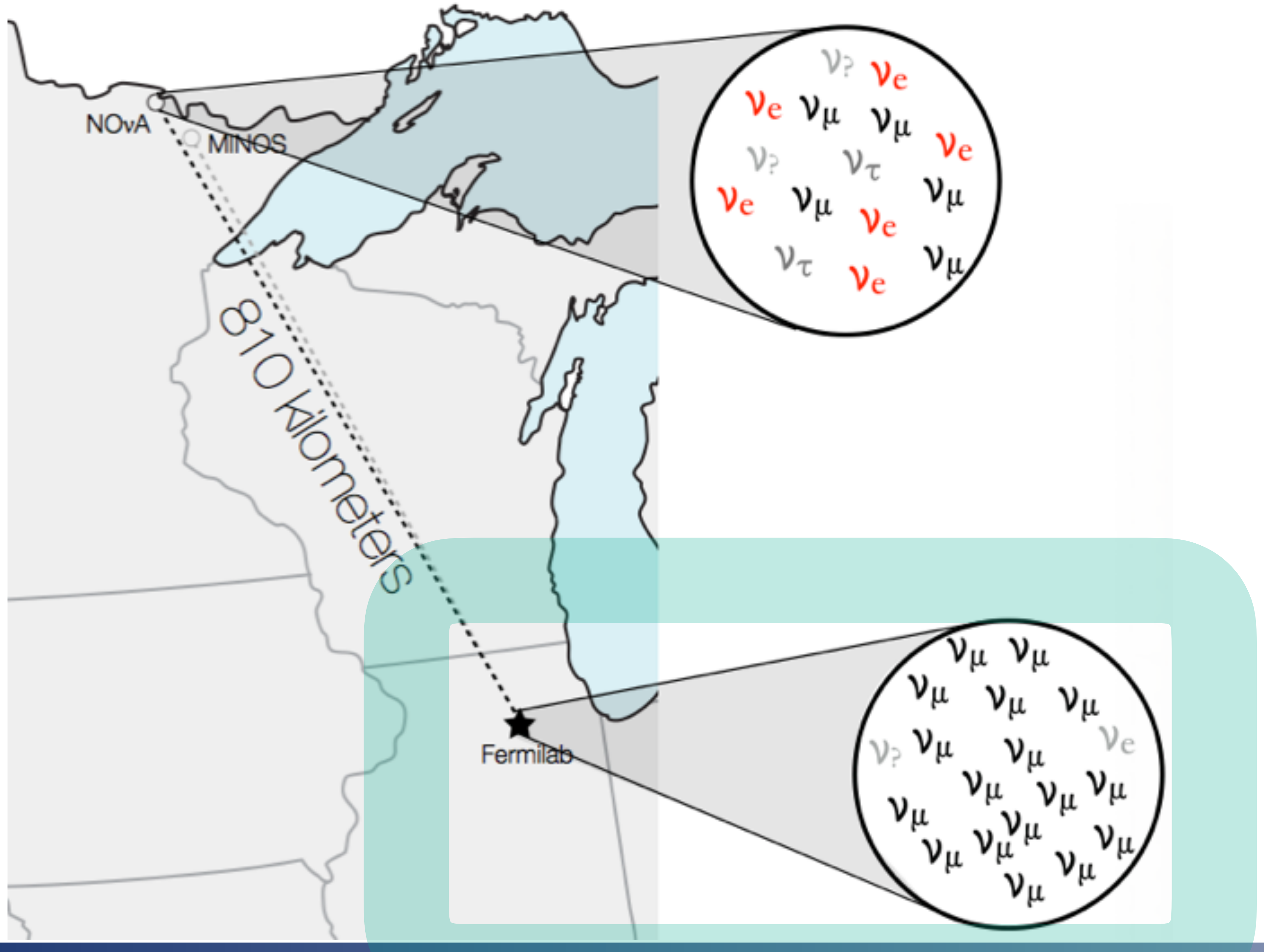
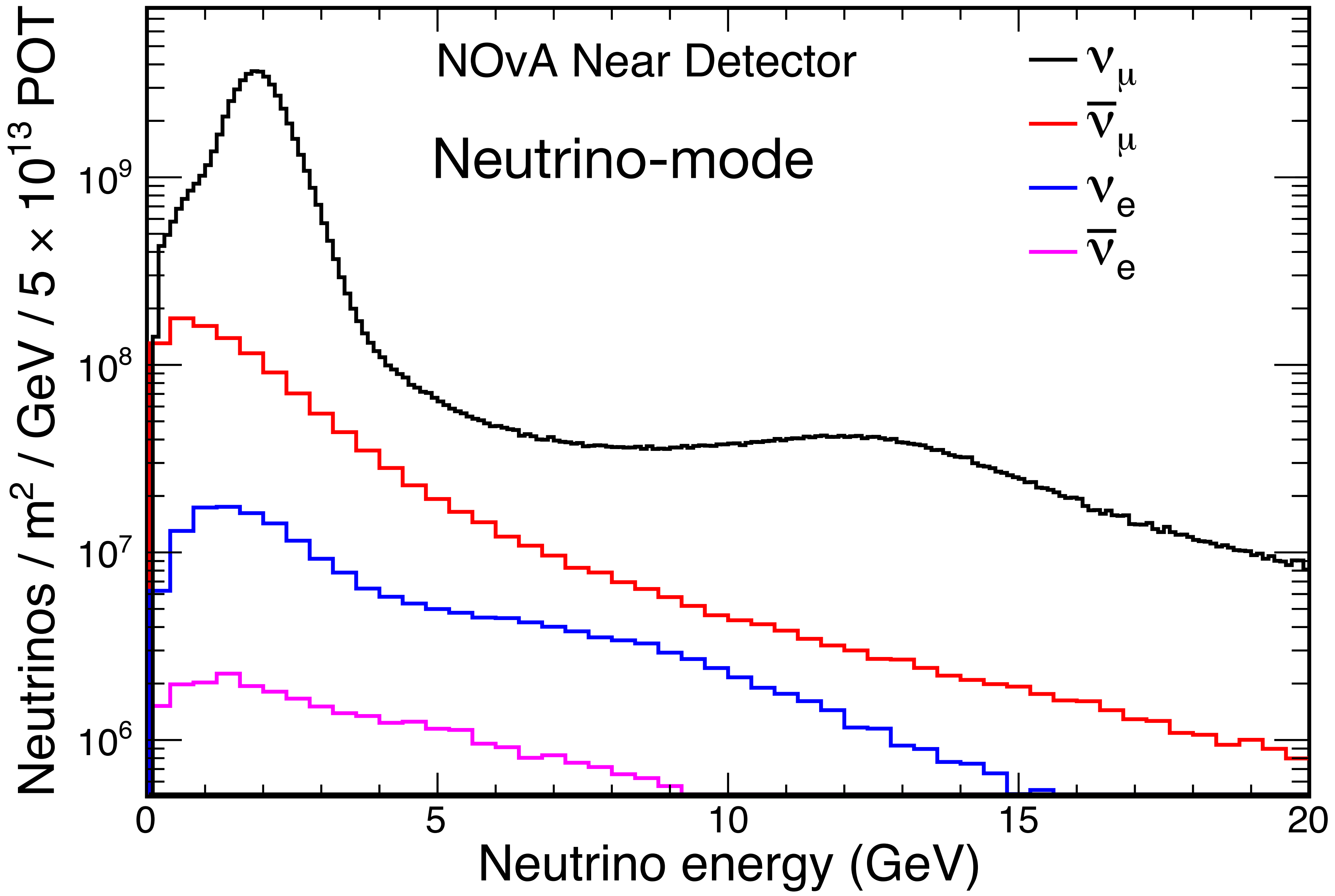
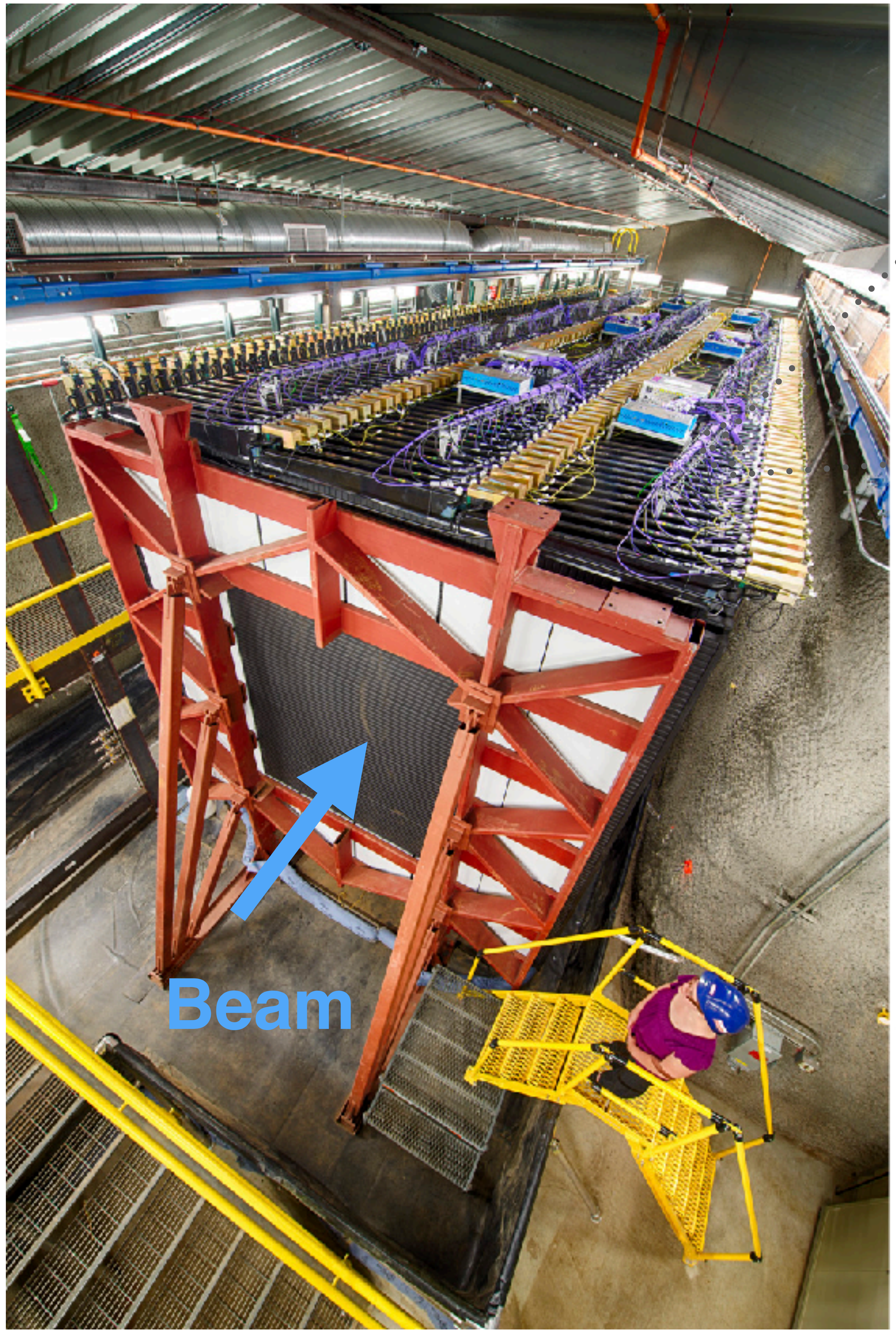


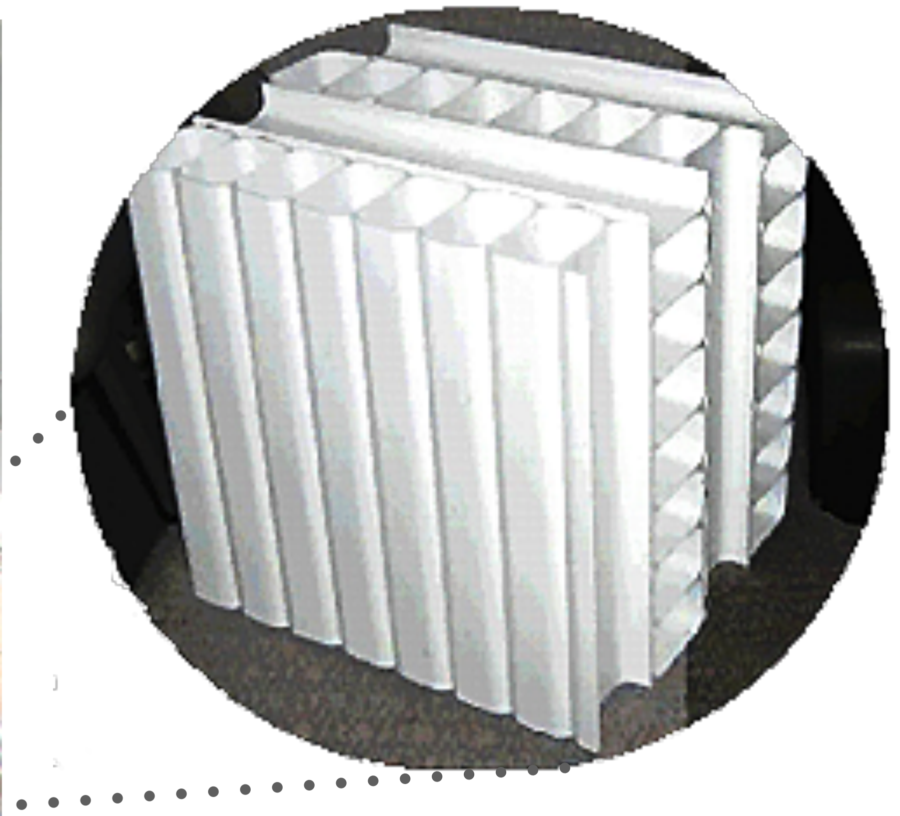
- High neutrino flux at Near Detector:
  - used as control for the oscillation analyses,
  - provides a rich data set for measuring cross sections.
- ND located 1km from the NuMI beam target.
- 96% pure ν_μ beam, 1% ν_e and $\bar{\nu}_e$

NOvA Simulation

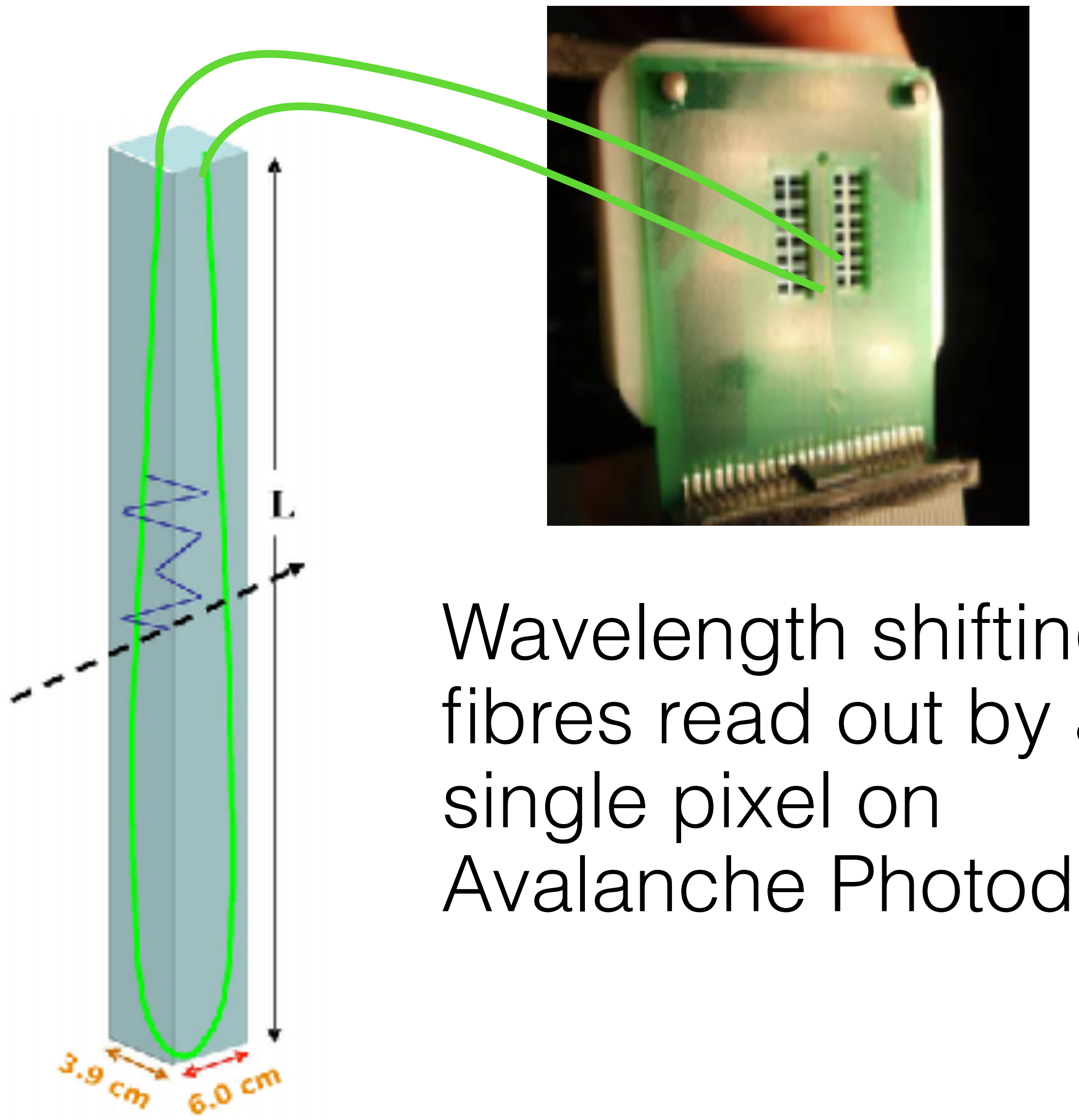


NOvA Near Detector

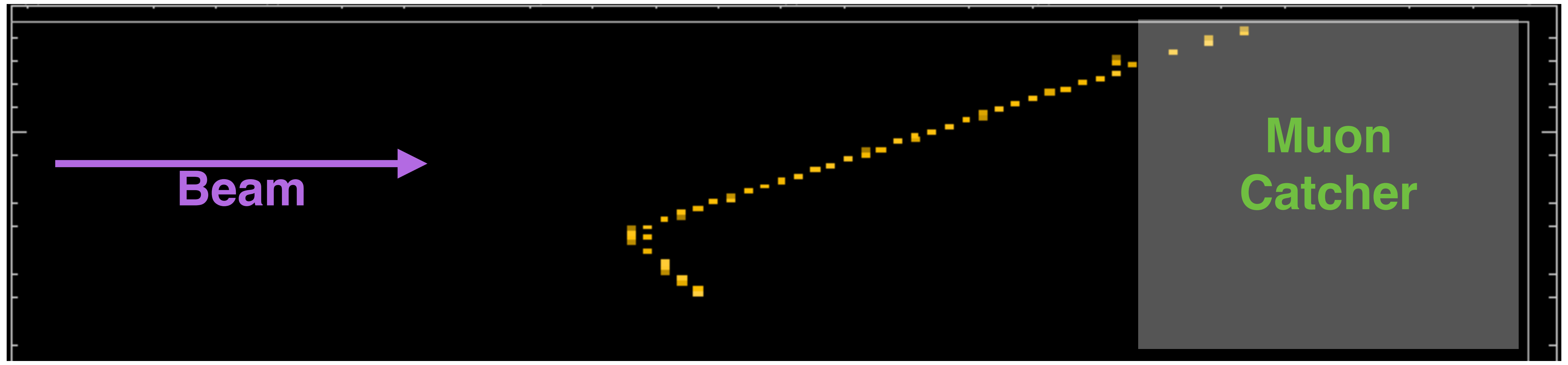




Alternating planes allow for 3D reconstruction

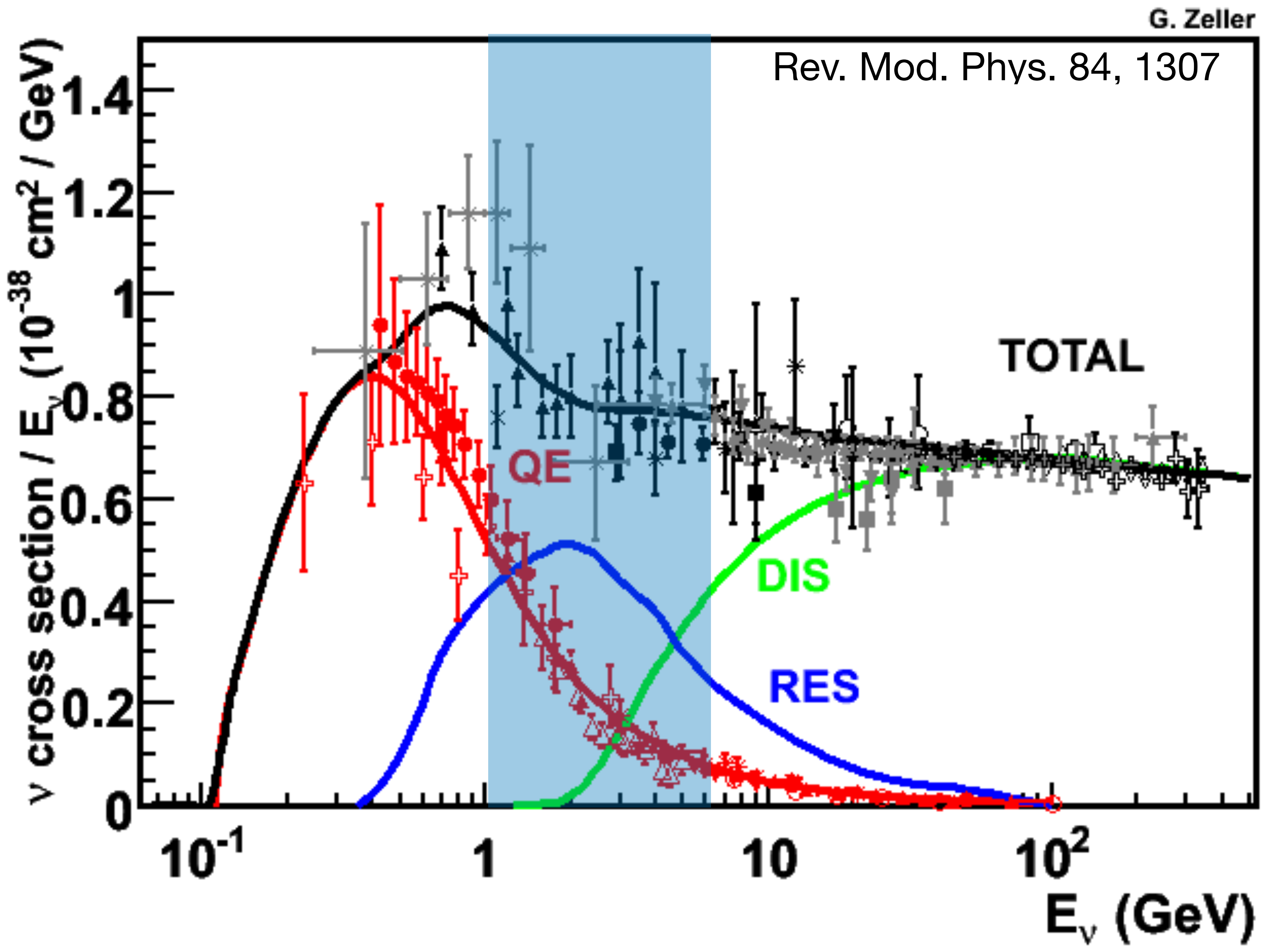


Wavelength shifting fibres read out by a single pixel on Avalanche Photodiode



- 300t tracking calorimeter
- Extruded plastic cells, filled with liquid scintillator
- 0.17 X_0 per layer
- 77% hydrocarbon, 16% chlorine, 6% TiO_2 by mass
- Muon catcher (steel + NOvA cells) at downstream end to range out ~2GeV muons.

Neutrino CC interactions at NOvA



- NOvA flux peaks between 1 and 5 GeV: it sits in the transition region between different neutrino interaction processes.

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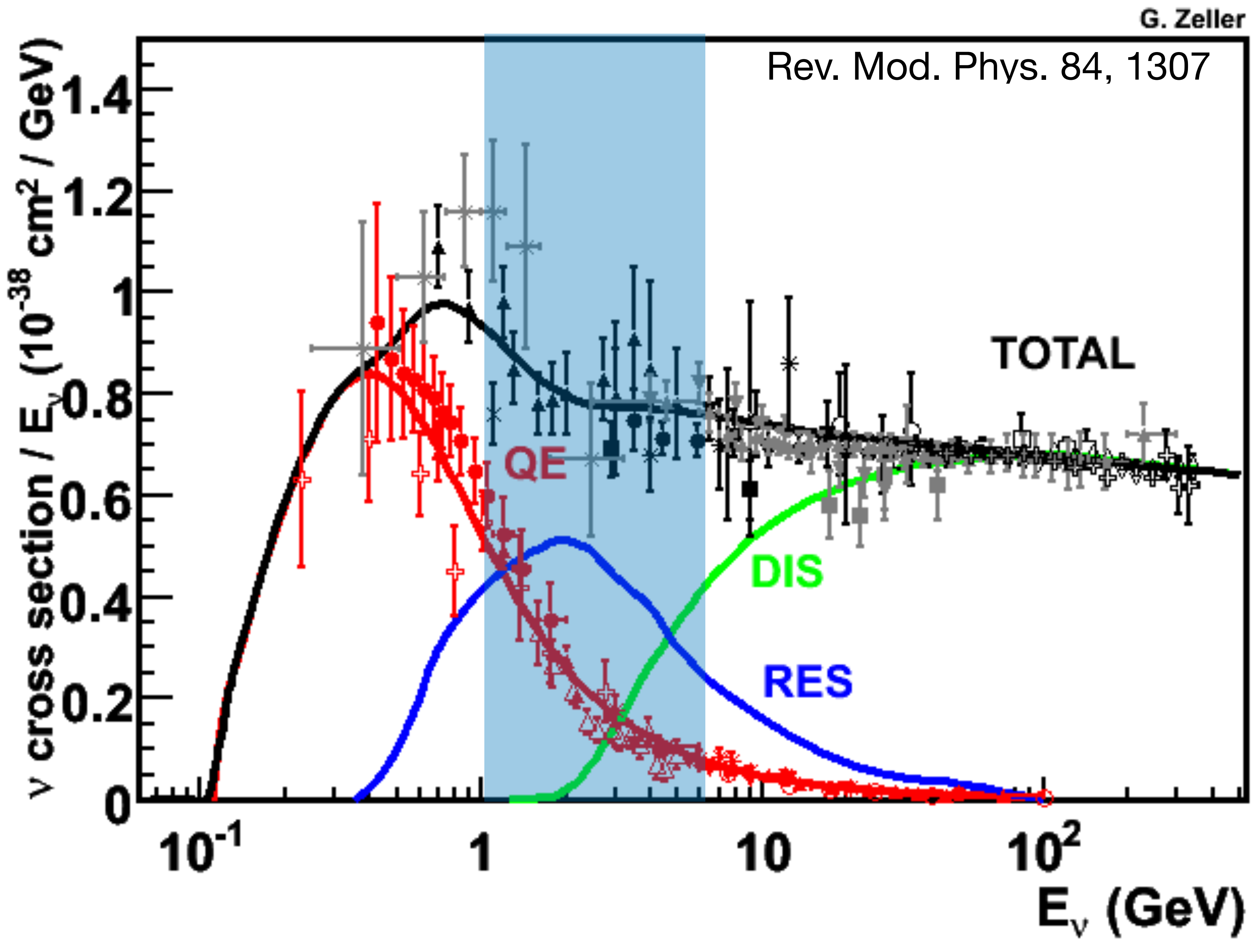

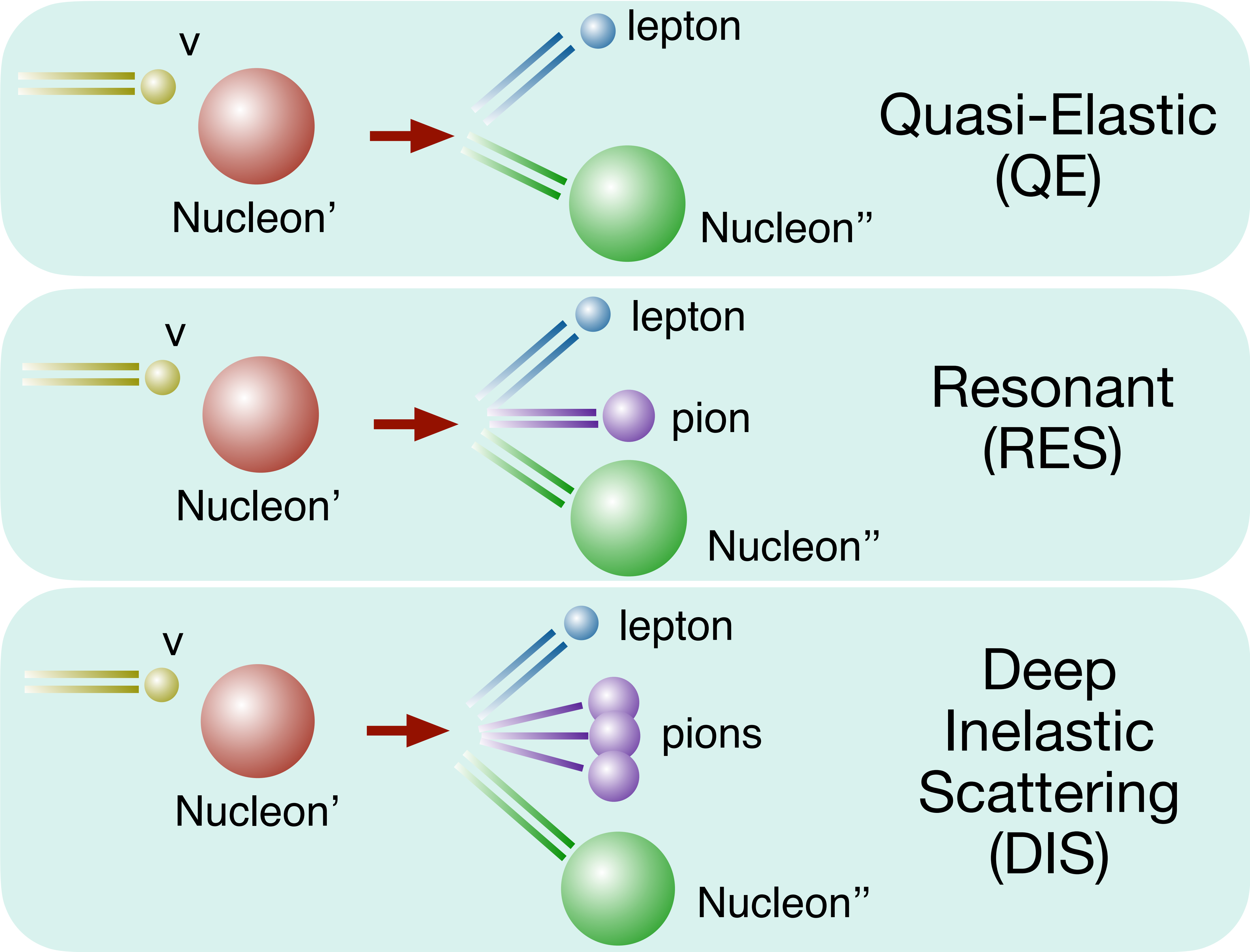

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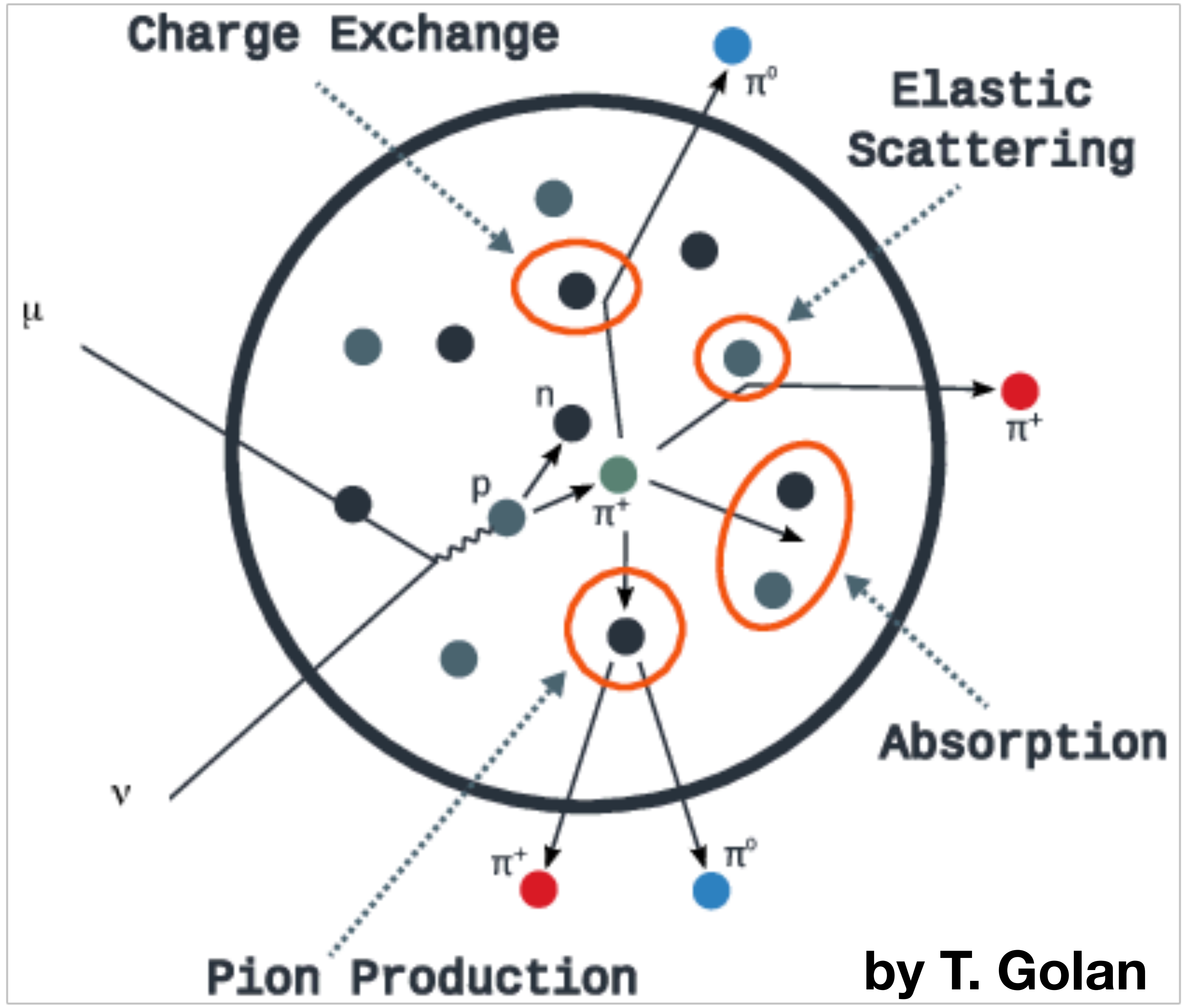
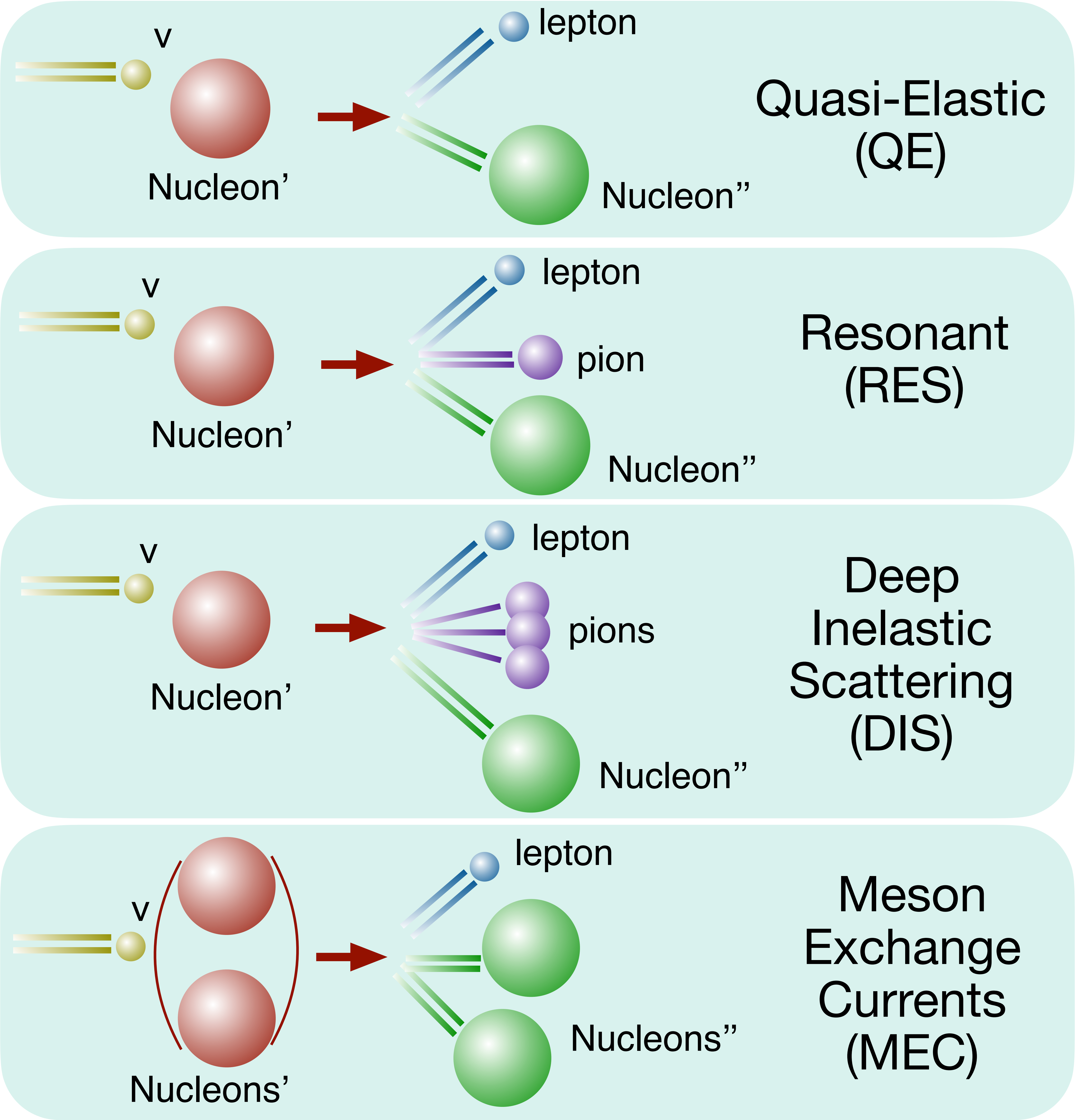
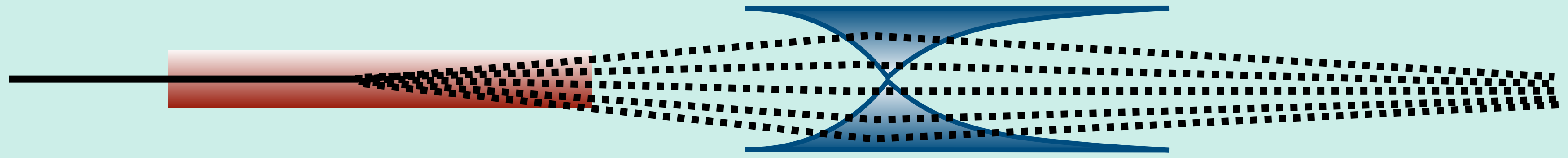


- These neutrino interactions happen inside the nuclear media.

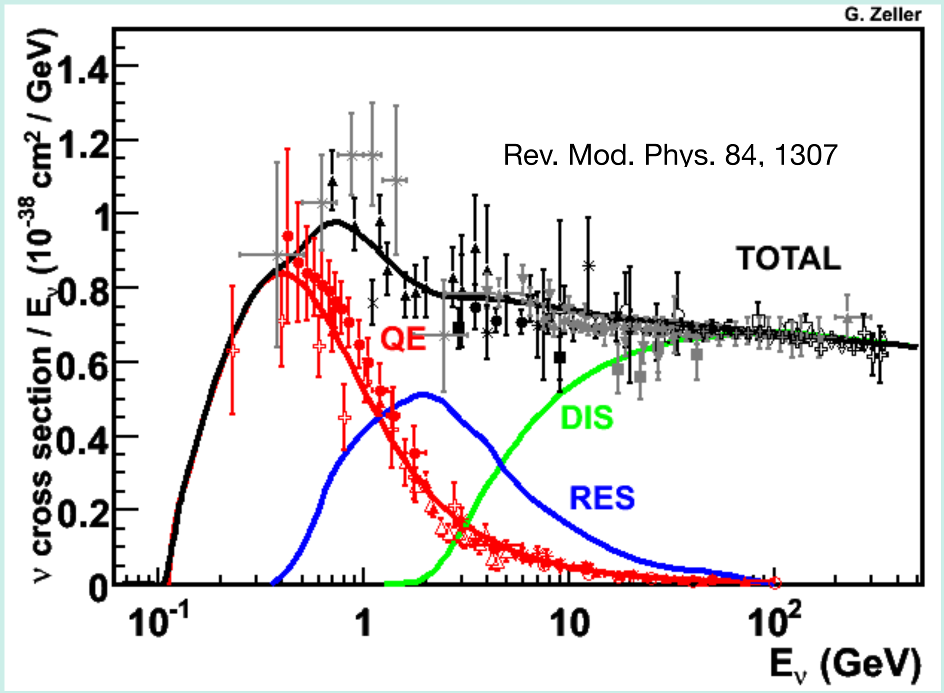


NOvA simulation

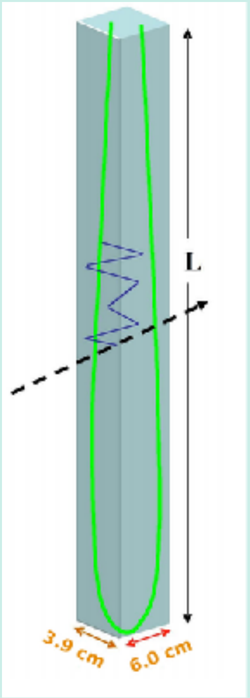


Beamline and Flux: G4NuMI

v-A modelling: GENIE

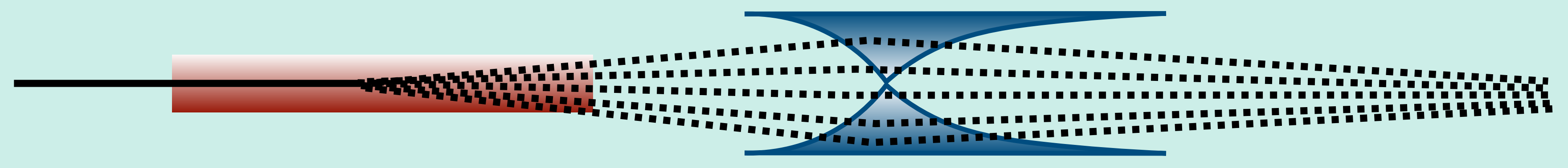


Detector response: GEANT4



Readout electronics & DAQ: Custom simulation routines

NOvA simulation



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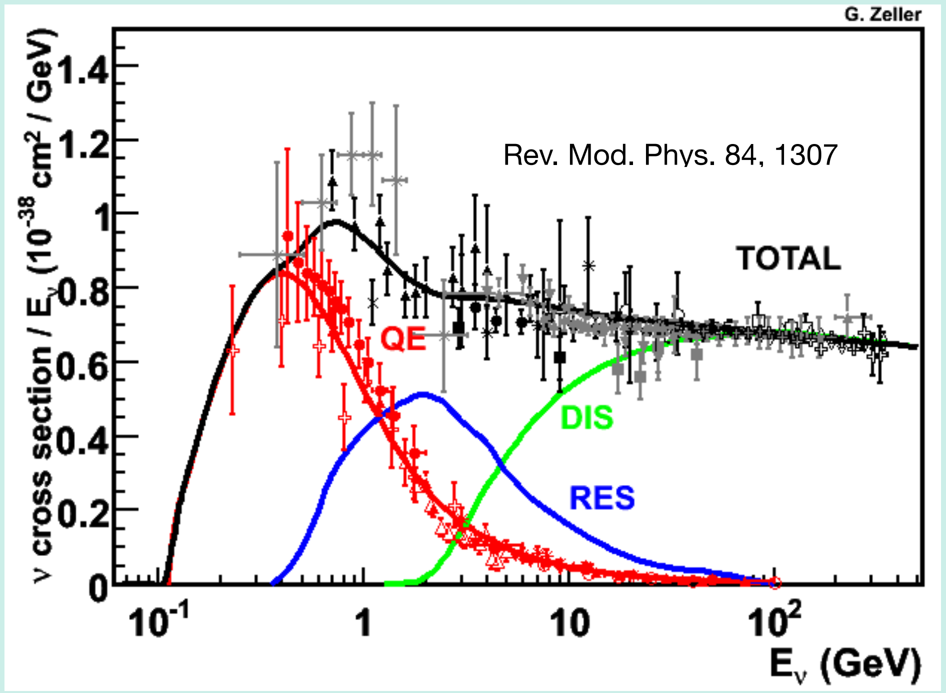

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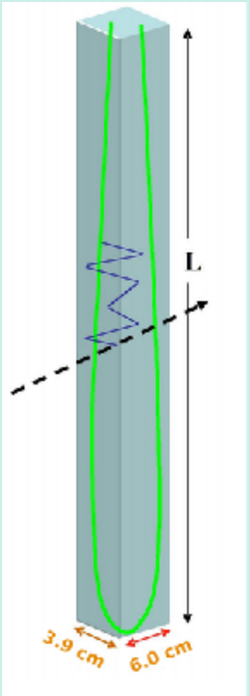
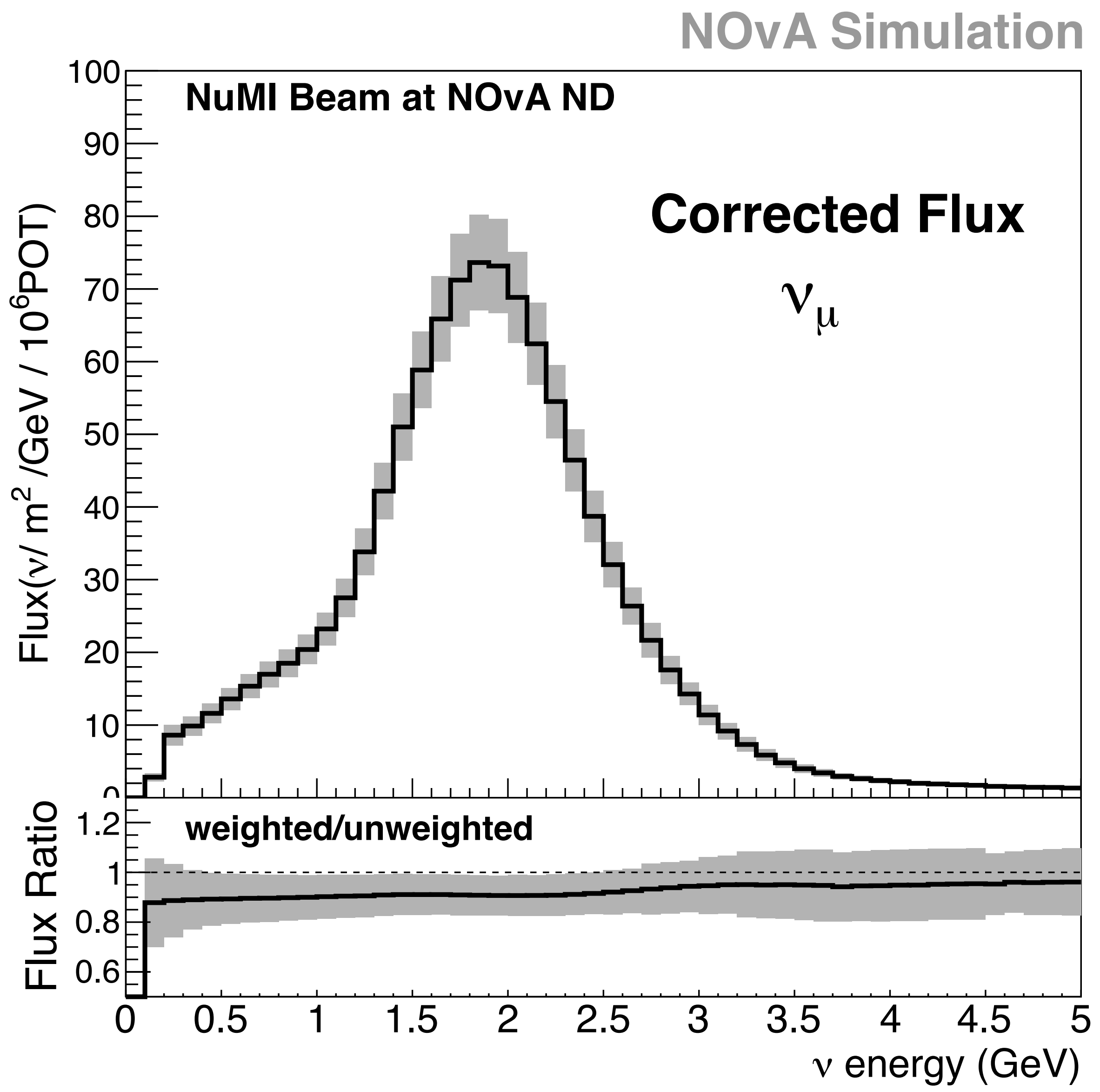


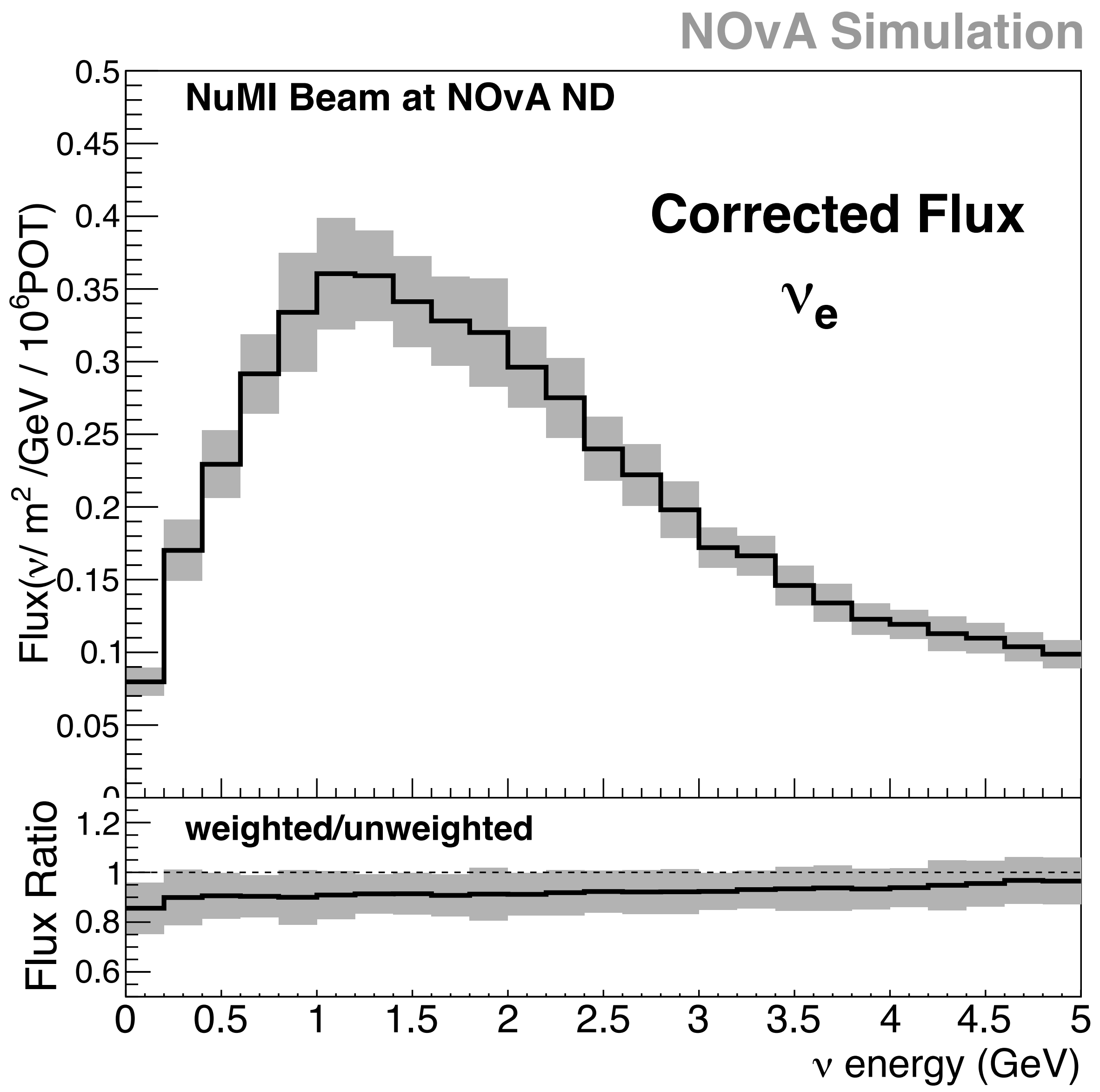
Readout electronics & DAQ: Custom simulation routines

Hadron production model constrained with external measurements on thin target.

Resulting uncertainty ~10% in normalisation.

Technique by MINERvA [Phys.Rev.D94, 092005]





Cross section measurements

$$\sigma = \frac{N^{\text{events}} P}{N_{\text{t}} \Phi \epsilon}$$

Cross Section	Events	Purity	Targets	Flux	Efficiency

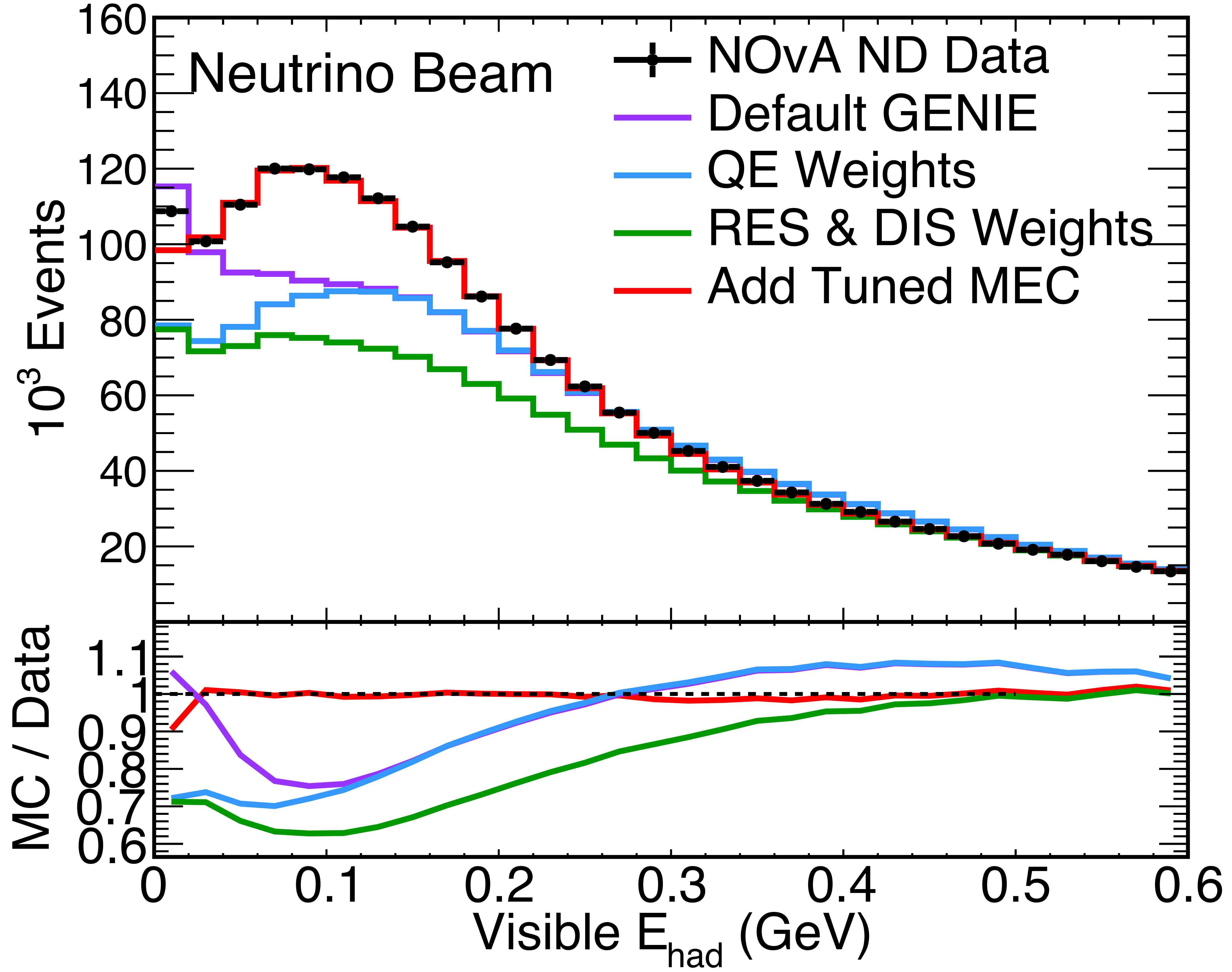
Cross section measurements

$$\sigma = \frac{N^{\text{events}} P}{N_t \Phi \epsilon}$$

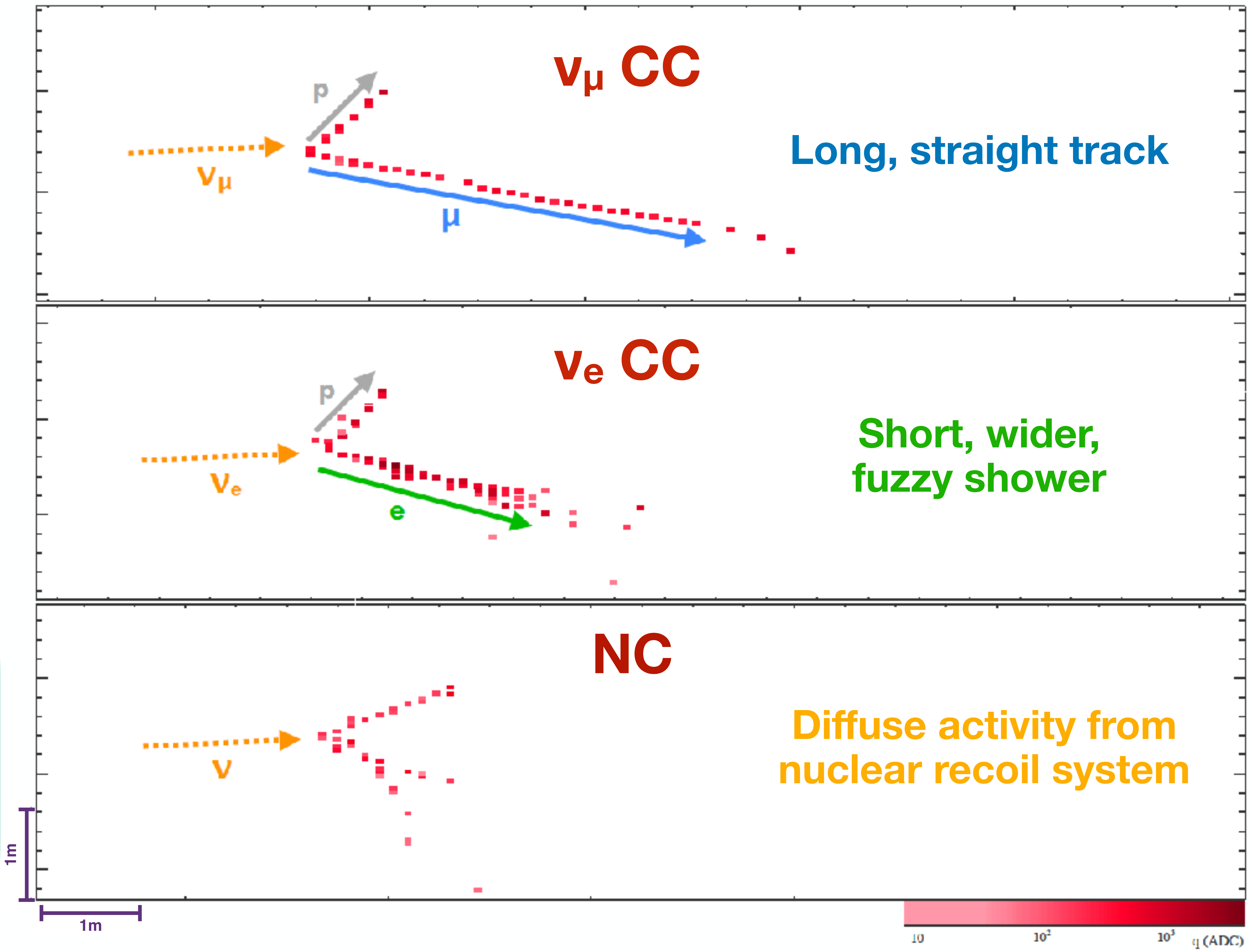
Cross Section	Events	Purity	Targets	Flux	Efficiency

- Measurements of neutrino cross sections depend on the **efficiency** and **purity** which are estimated from our simulation.
- We use NOvA and external data to tune interaction model (GENIE 2.12.2):
  - Suppress QE and RES,
  - Increase DIS,
  - Add MEC.
- Same tune that was used in the NOvA 2018 analysis

Eur. Phys. J. C 80, 1119 (2020)



Neutrino cross-section measurements at NOvA

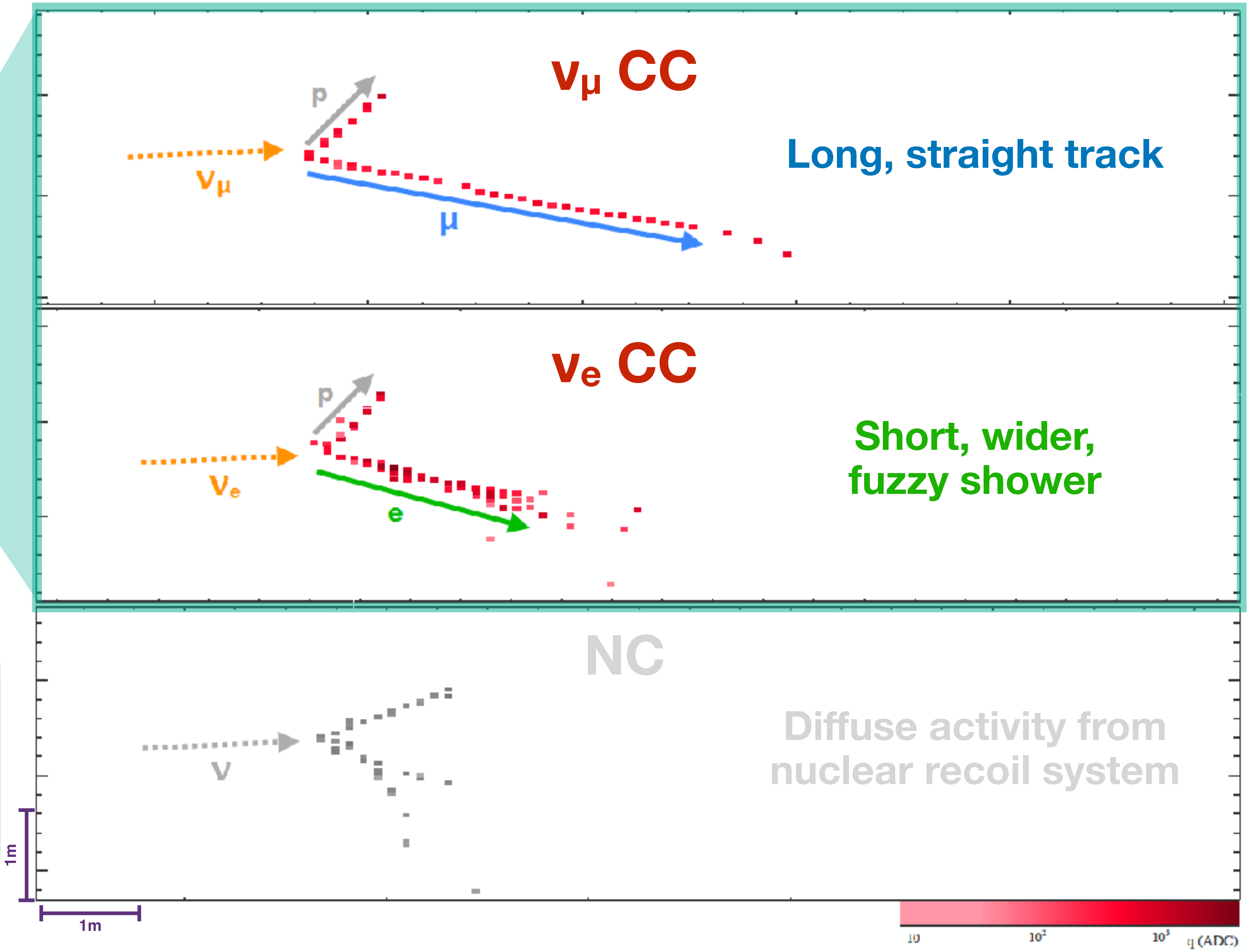


Energy range
Detector technology
Statistics

Unique environment for cross section measurements

Neutrino cross-section measurements at NOvA

This talk



Energy range

Detector technology

Statistics

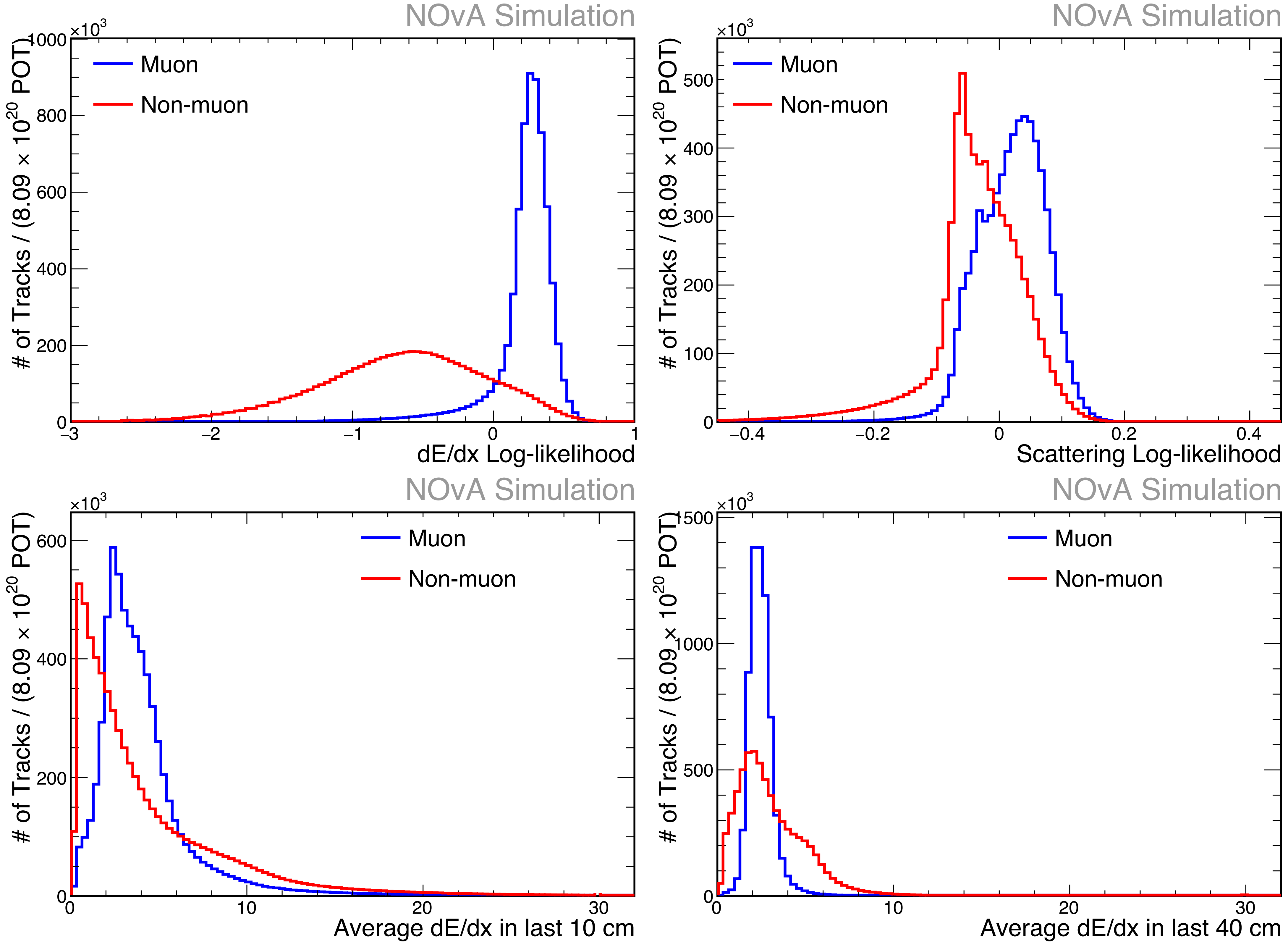
} Unique environment for cross section measurements

ν_μ CC inclusive

ν_μ CC inclusive

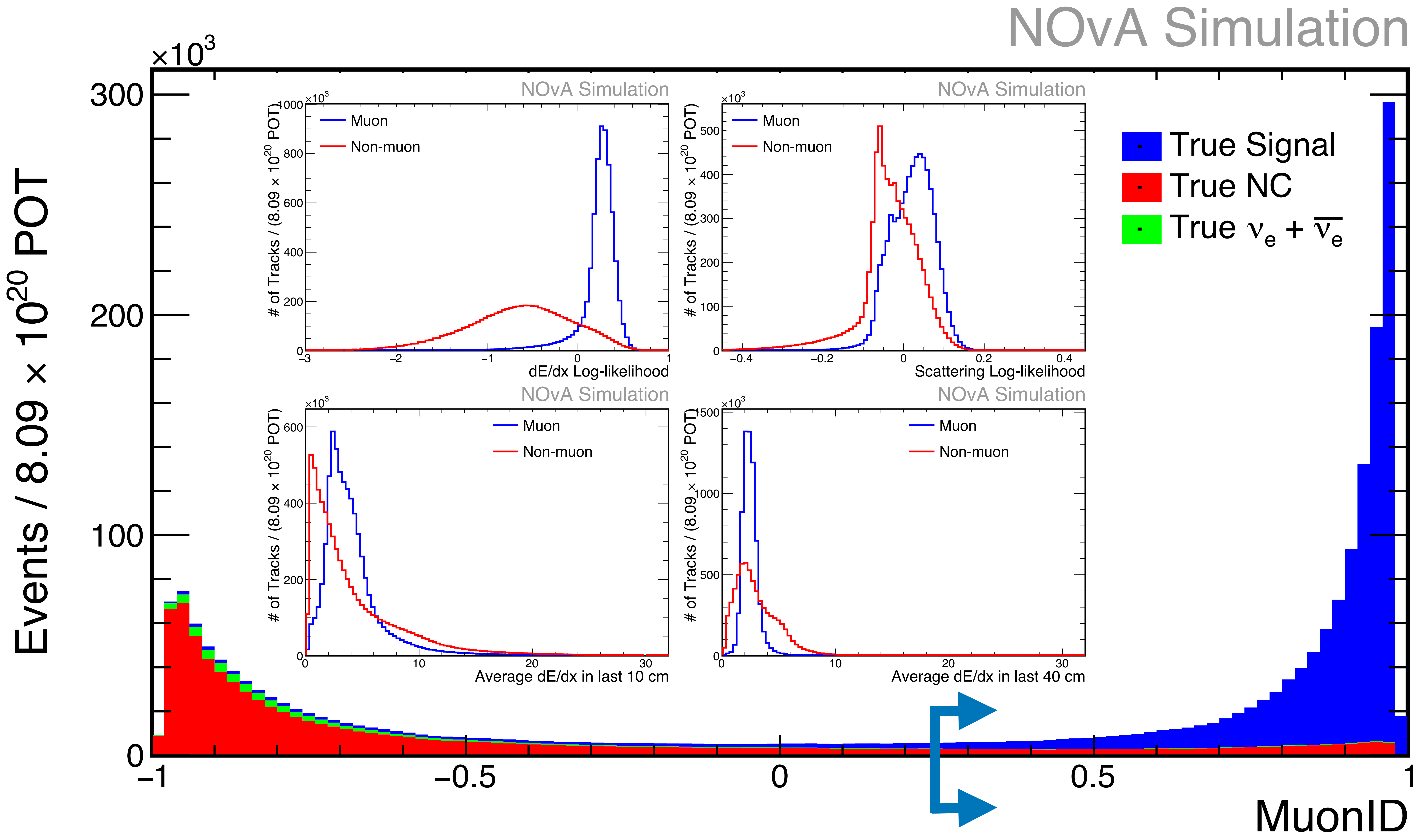
More than 1M ν_μ CC events in our selection

Particle ID



- Preselection: events fully contained and with vertex in fiducial volume.
- Muon ID calculated with a Boosted Decision Tree.

Particle ID

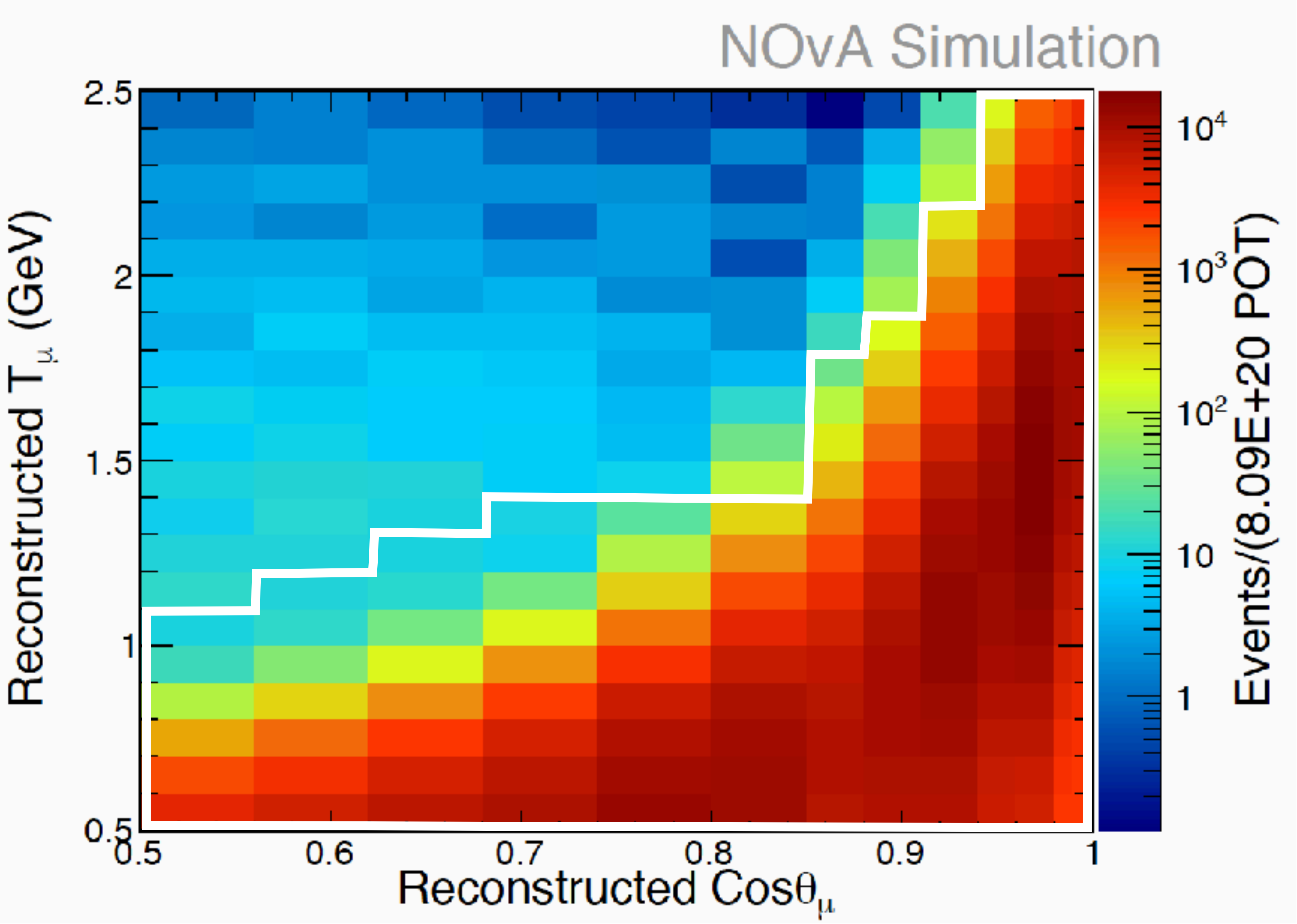


- Preselection: events fully contained and with vertex in fiducial volume.
- Muon ID calculated with a Boosted Decision Tree.
- Cut value corresponds to minimum uncertainties on cross section measurement.
- Resulting sample has 86% purity and ~90% efficiency with respect to preselection.

Measurement strategy

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

- Flux-averaged double differential cross section in 172 bins (white outline).



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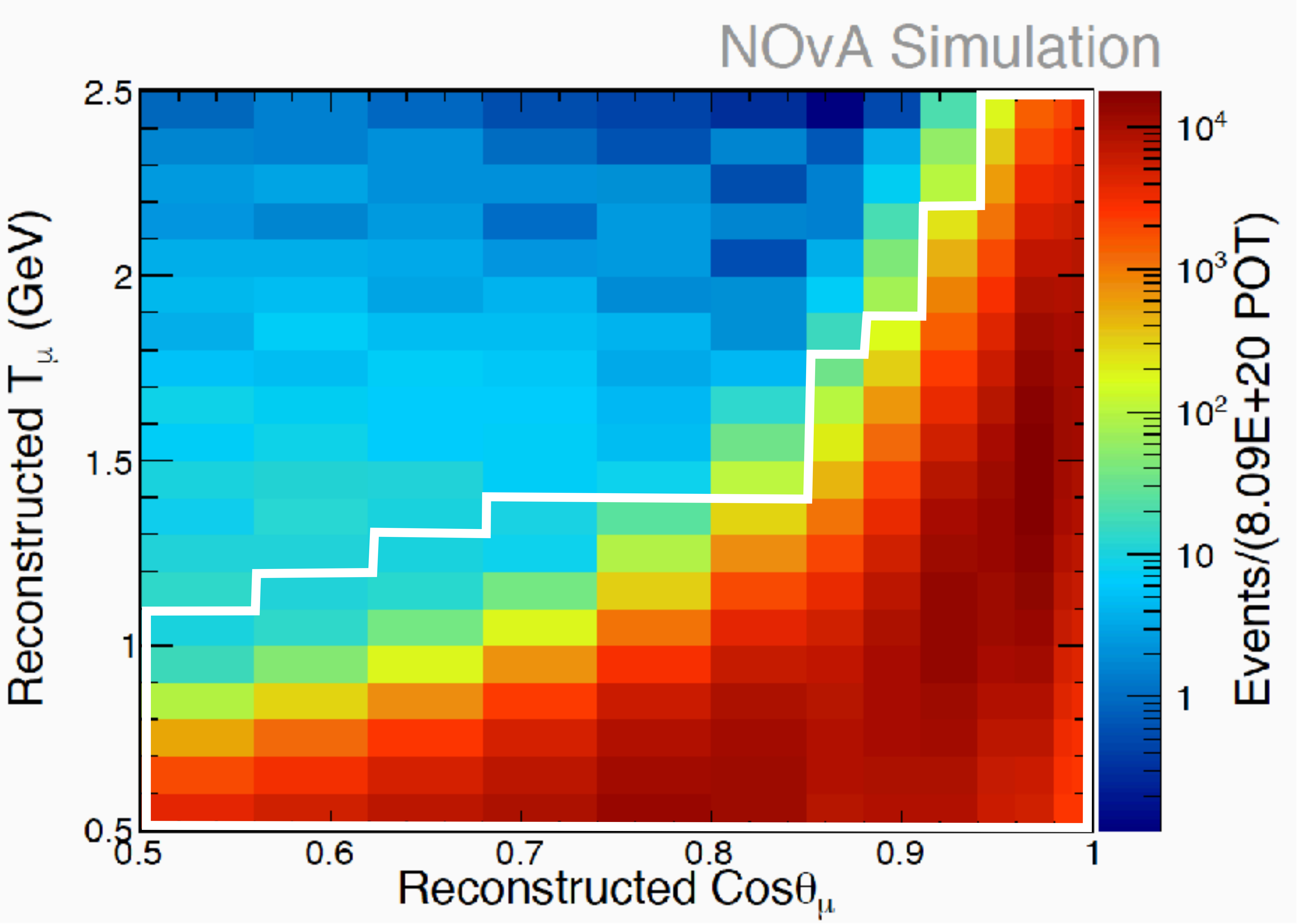
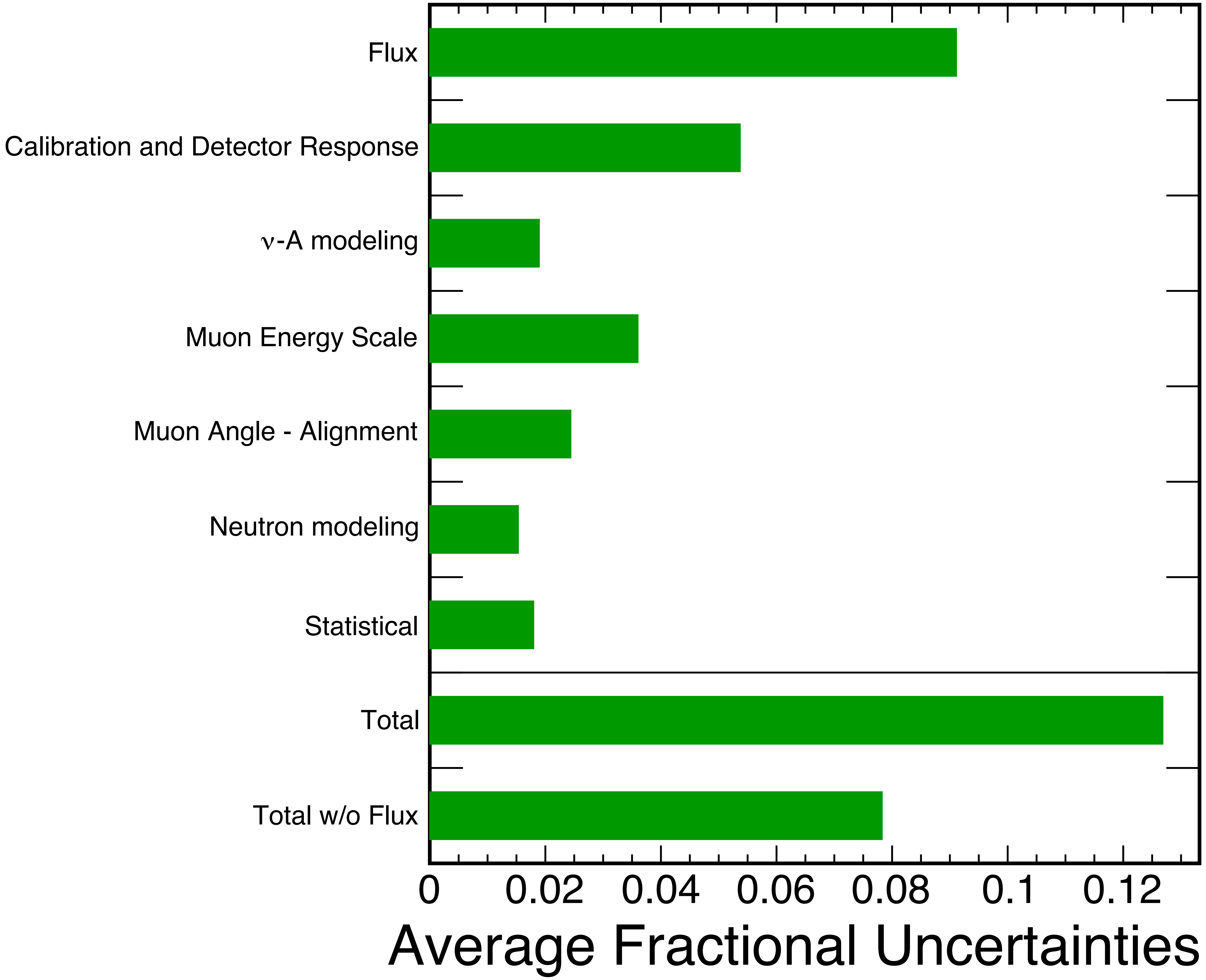
- Flux-averaged double differential cross section in 172 bins (white outline).
- Selection purity and efficiency corrections applied in 3D space (T_μ, $\cos\theta_\mu$, E_{avail}).
- E_{avail} (available energy): total energy of all observable final state hadrons.
- This reduces potential model dependence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



Fractional Uncertainties

NOvA Preliminary

- Weighted average uncertainties to extracted cross section value.
- Flux is a normalisation uncertainty ~9%.
- Statistical uncertainties at level of a few %.
- Interaction modeling uncertainties are sub-dominant.
- Measurements has typical total uncertainties around 12% in each bin.



Results in 1-page

ν_μ CC inclusive

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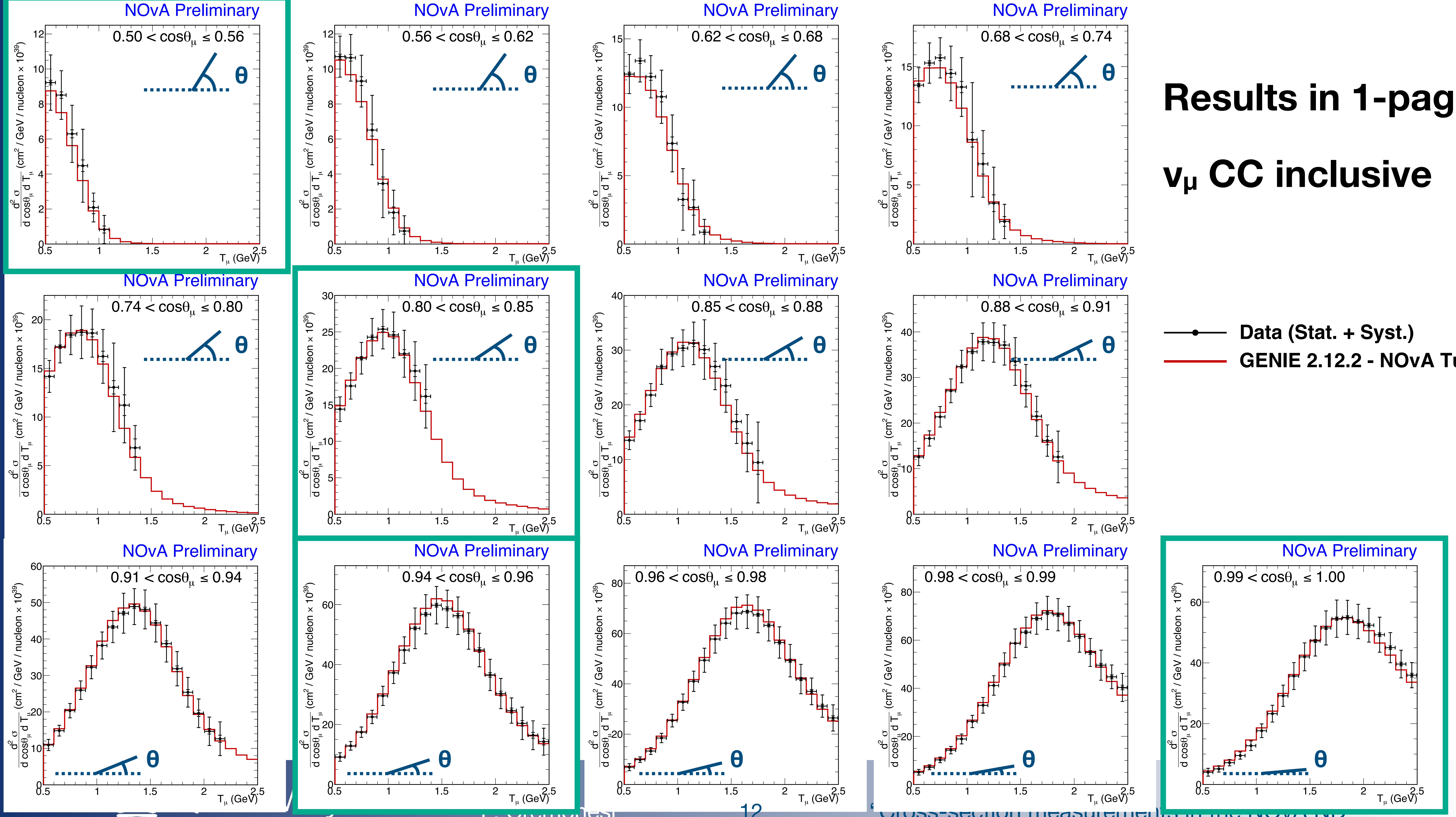
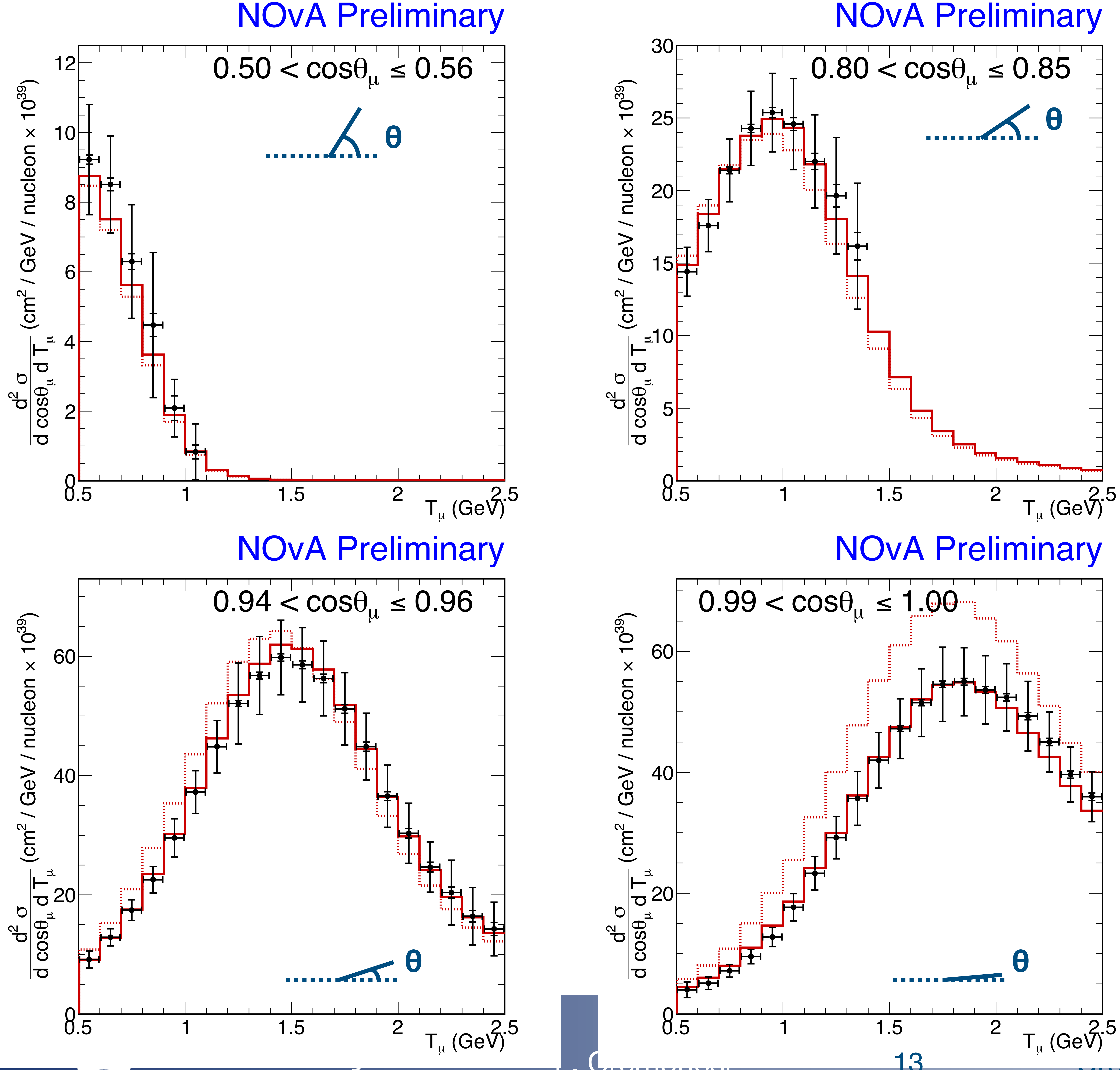


Data (Stat. + Syst.)

GENIE 2.12.2 - NOvA Tune

Example 4 cosine slices

ν_μ CC inclusive

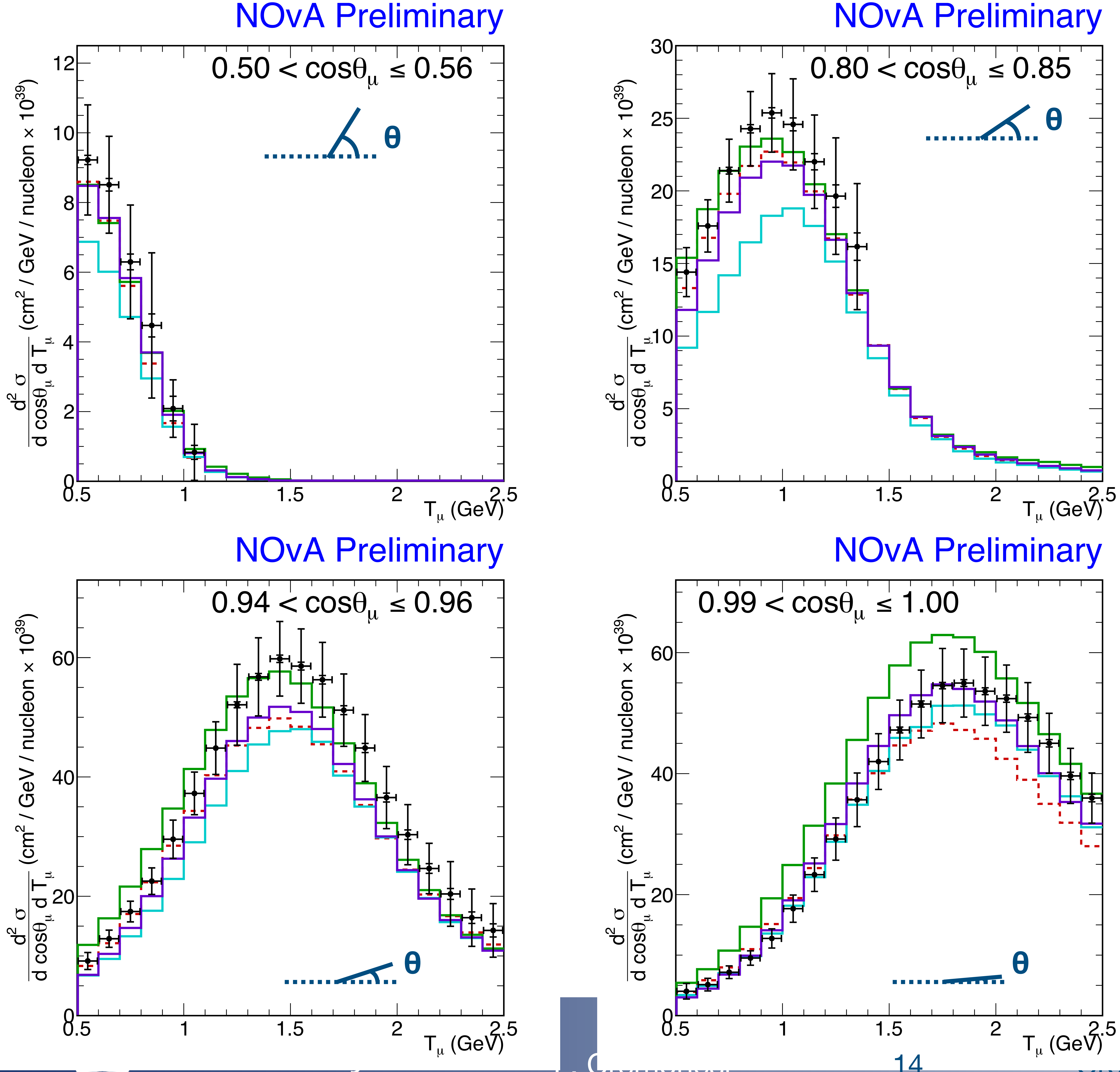


- Data (Stat. + Syst.)
- GENIE 2.12.2 - NOvA Tune
- GENIE 2.12.2 - Untuned

- Good agreement between tuned/untuned GENIE versions in high angle slices.
- At forward angle, where QE and MEC events dominate, the untuned GENIE 2 overshoots data.

Example 4 cosine slices

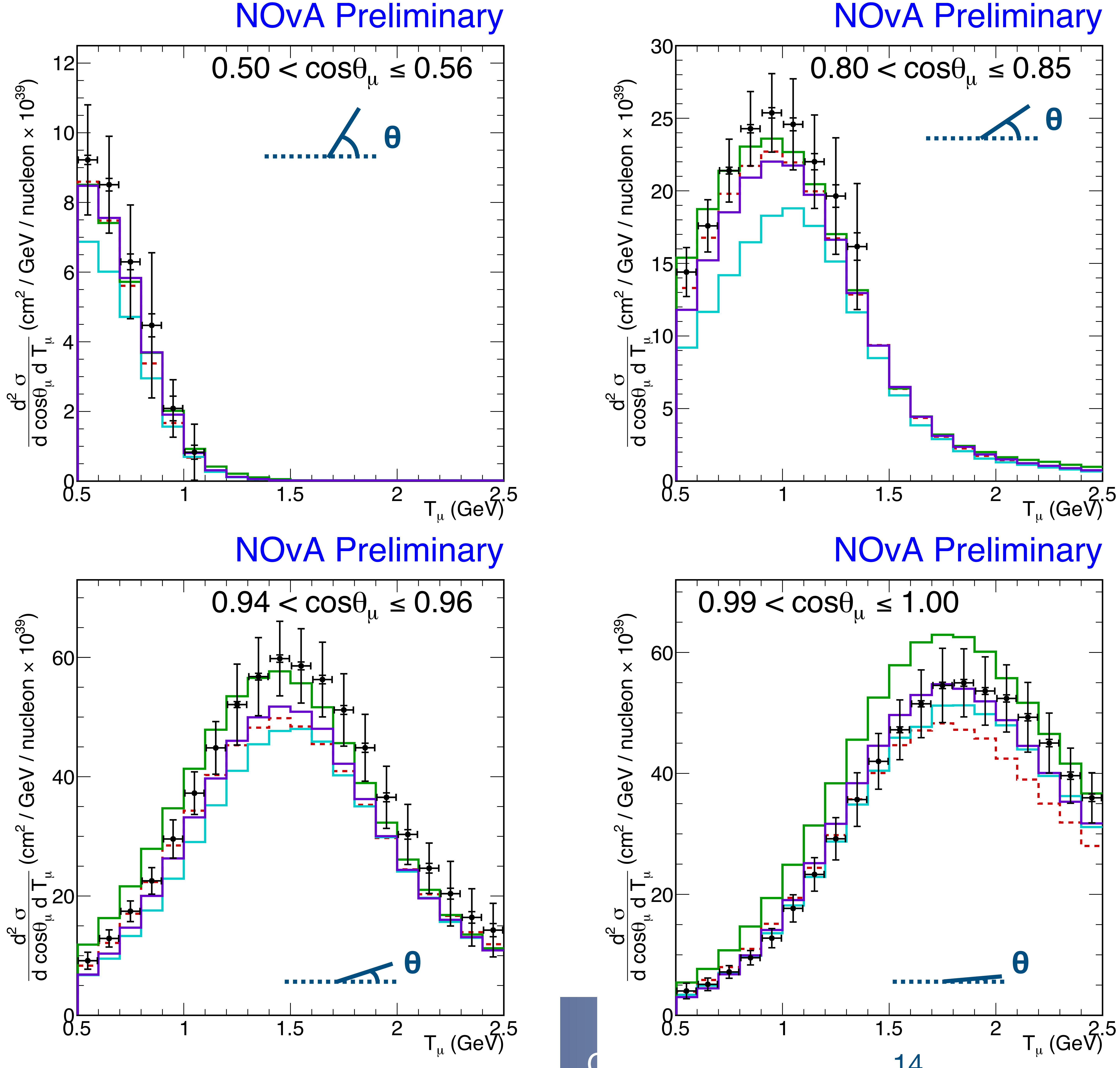
ν_μ CC inclusive



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

- Out of the box generator comparisons.
- All generators reproduce well the shape of our data.
- We notice an overall normalisation difference in GiBUU.

***N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a**



Example 4 cosine slices

ν_μ CC inclusive

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

We used the total covariance matrix to calculate p-values.

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

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ν_e CC inclusive

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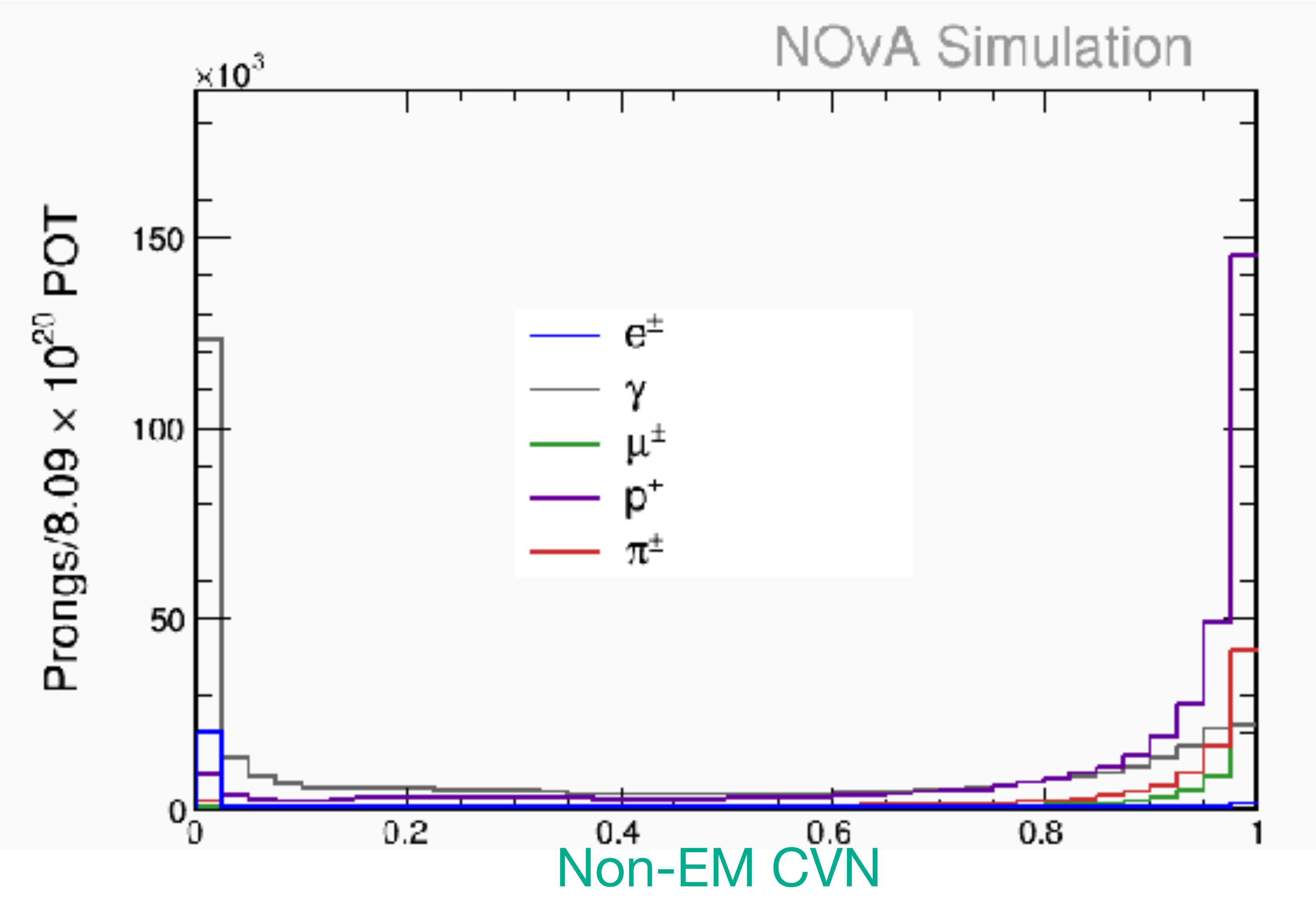
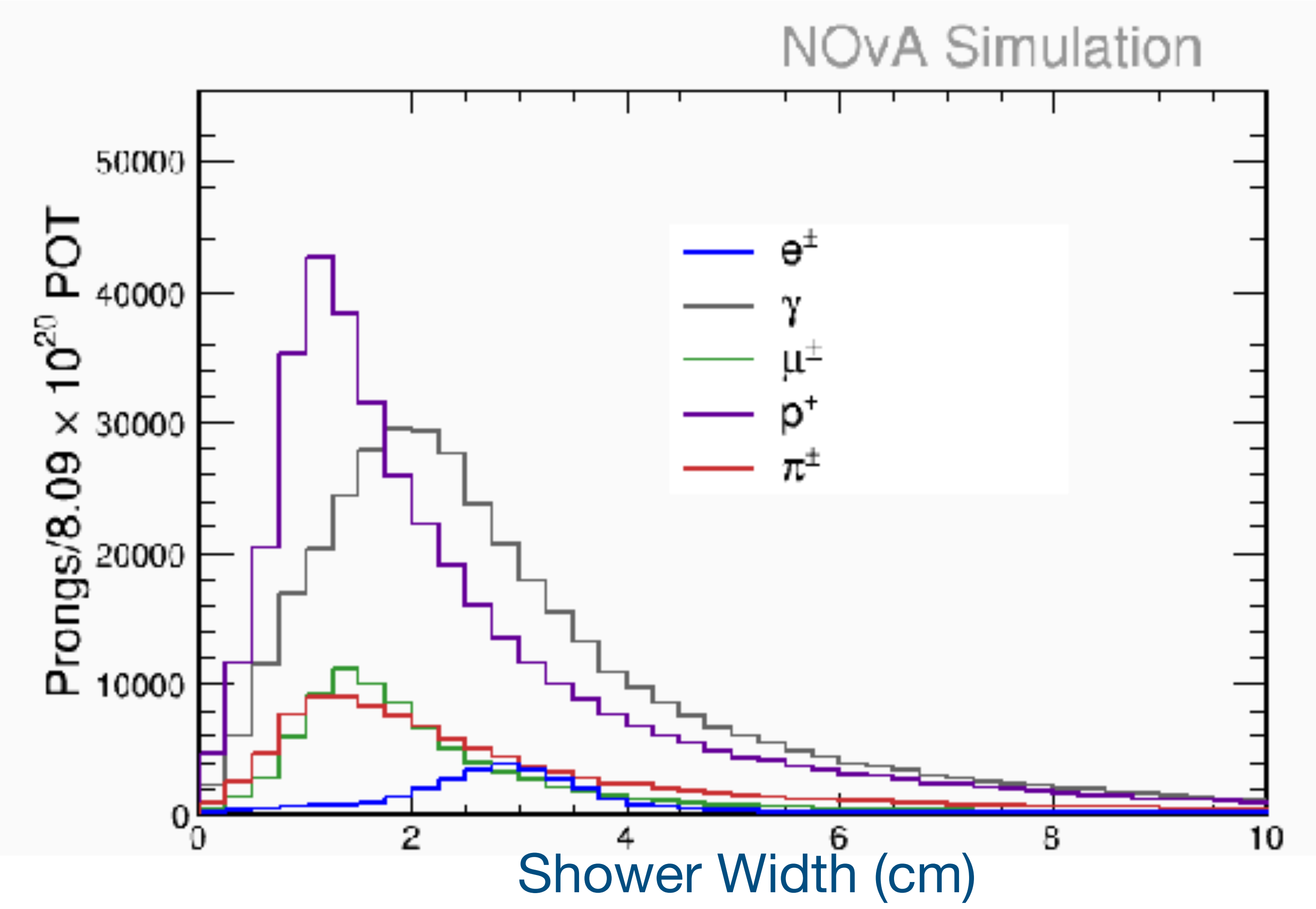
1% of our event rates, but still around 10k ν_e CC events in our selection

Analysis strategy

- High efficiency low purity selection and background constrained with template fit on ElectronID

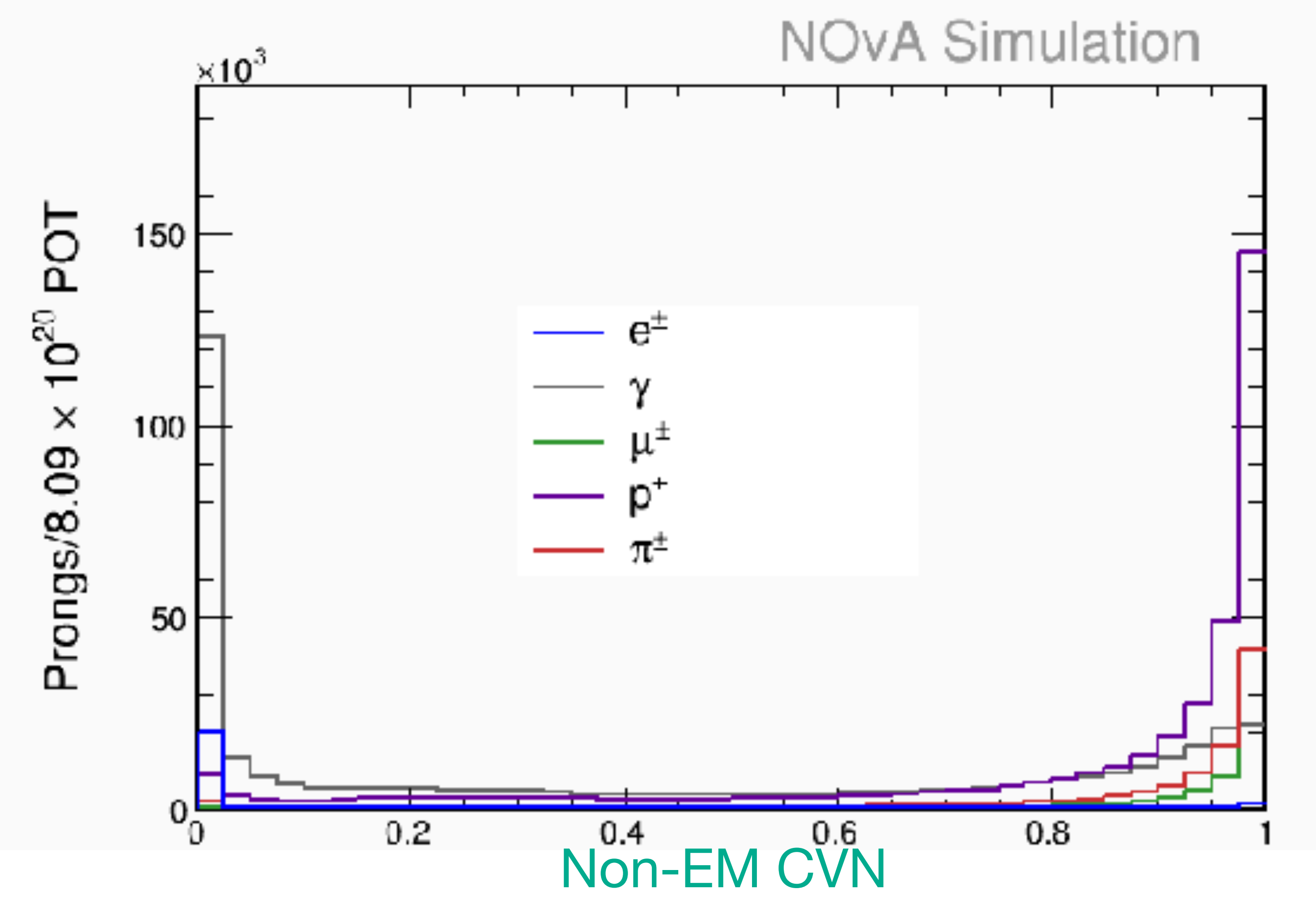
- Boosted Decision tree based on several inputs to distinguish electrons from other particles:
  - Deep convolution network PIDs based on single particle (CVN).
  - Event level information.

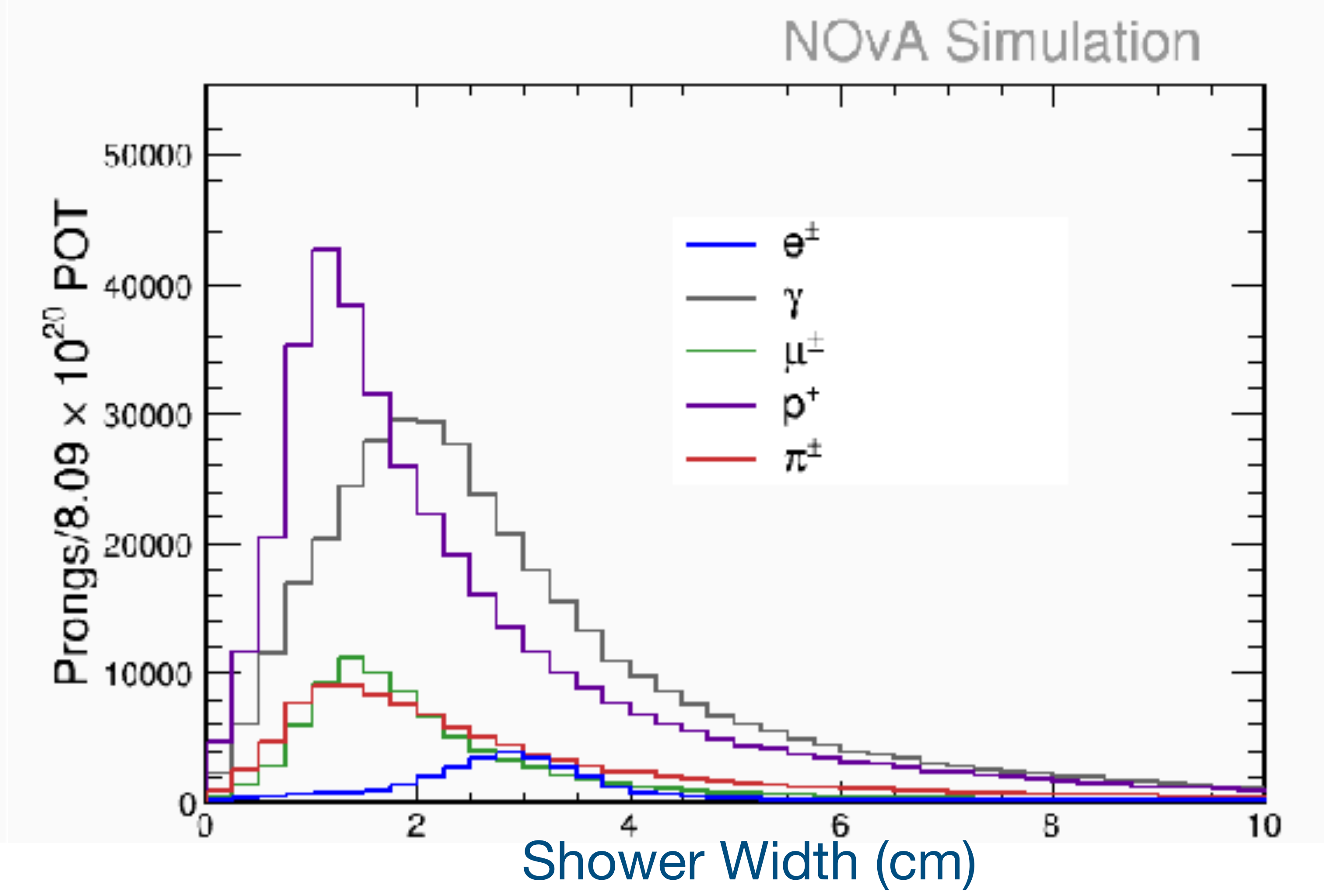


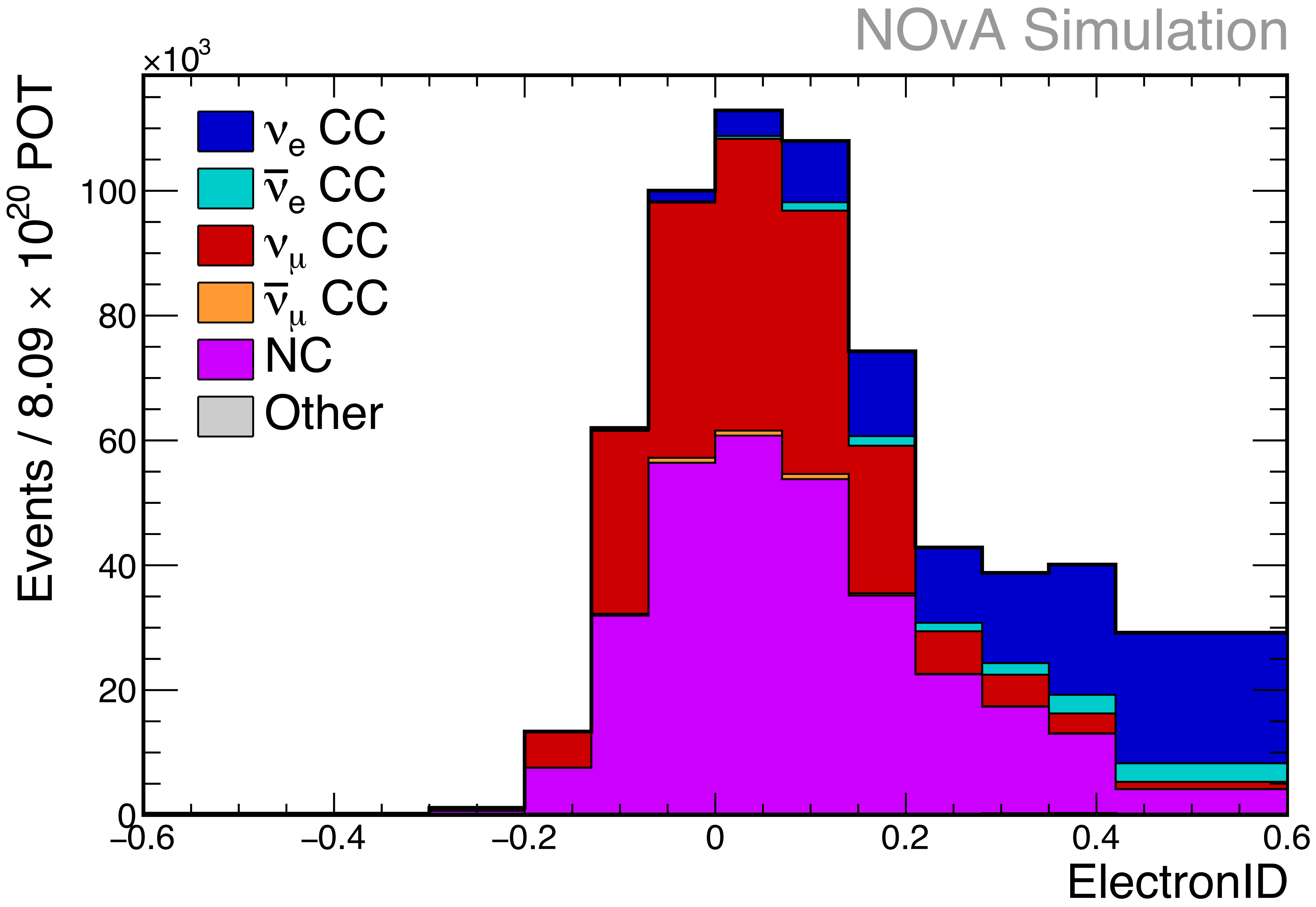


Analysis strategy

- High efficiency low purity 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 (CVN).
  - Event level information.
- ElectronID not as strongly discriminating as MuonID.



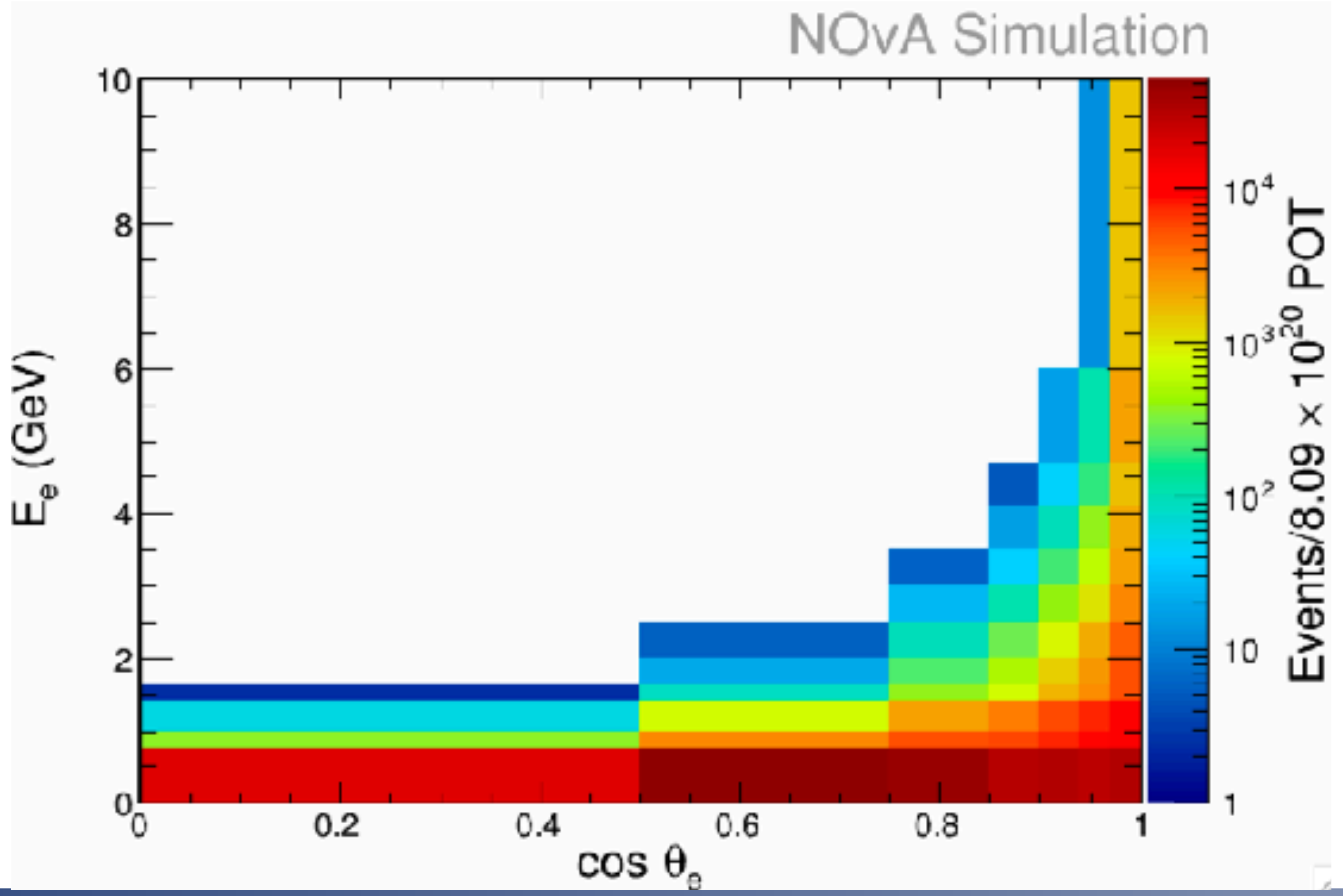




First ν_e CC double differential measurement

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

- Flux-averaged double differential cross section as a function of the electron kinematics.



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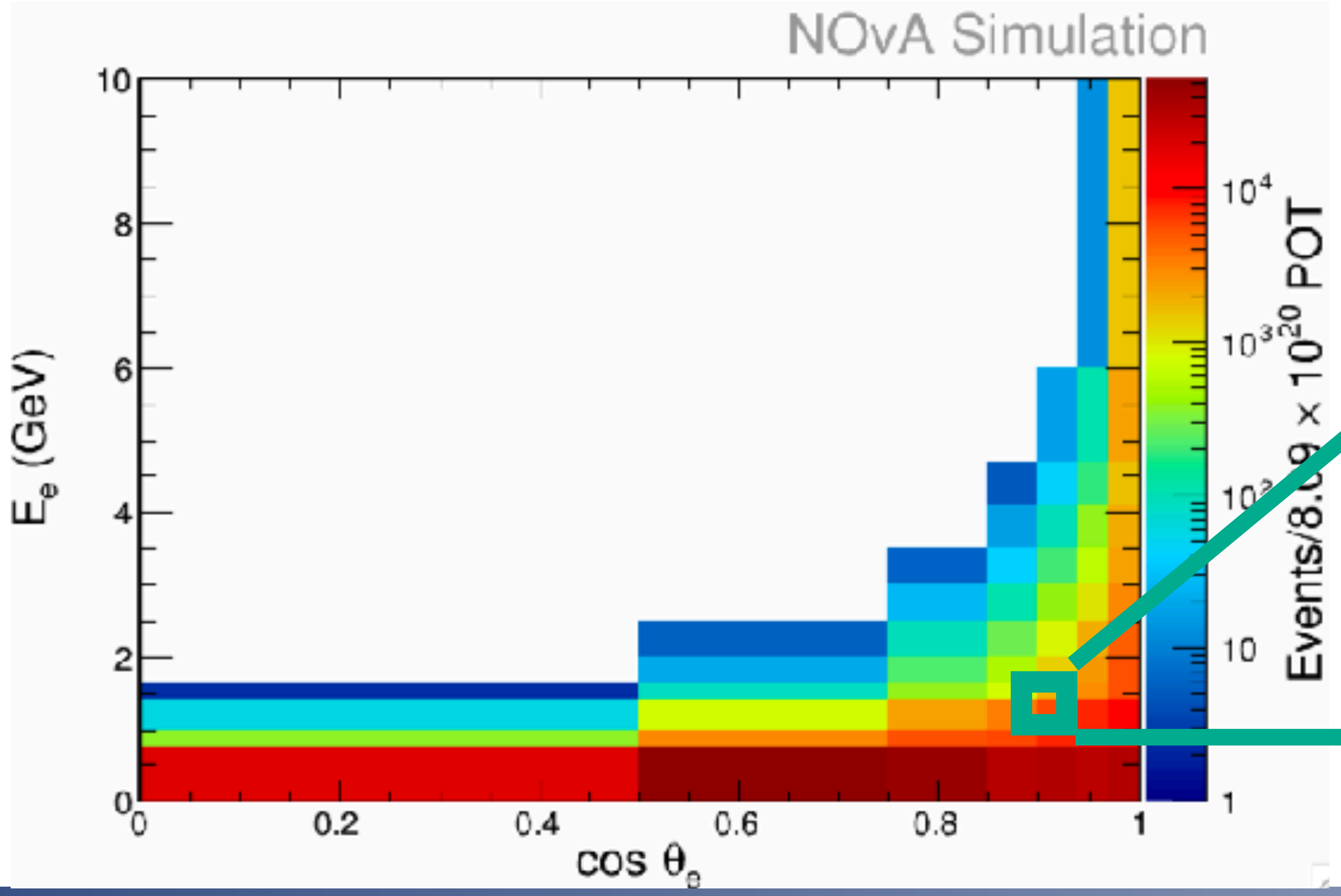
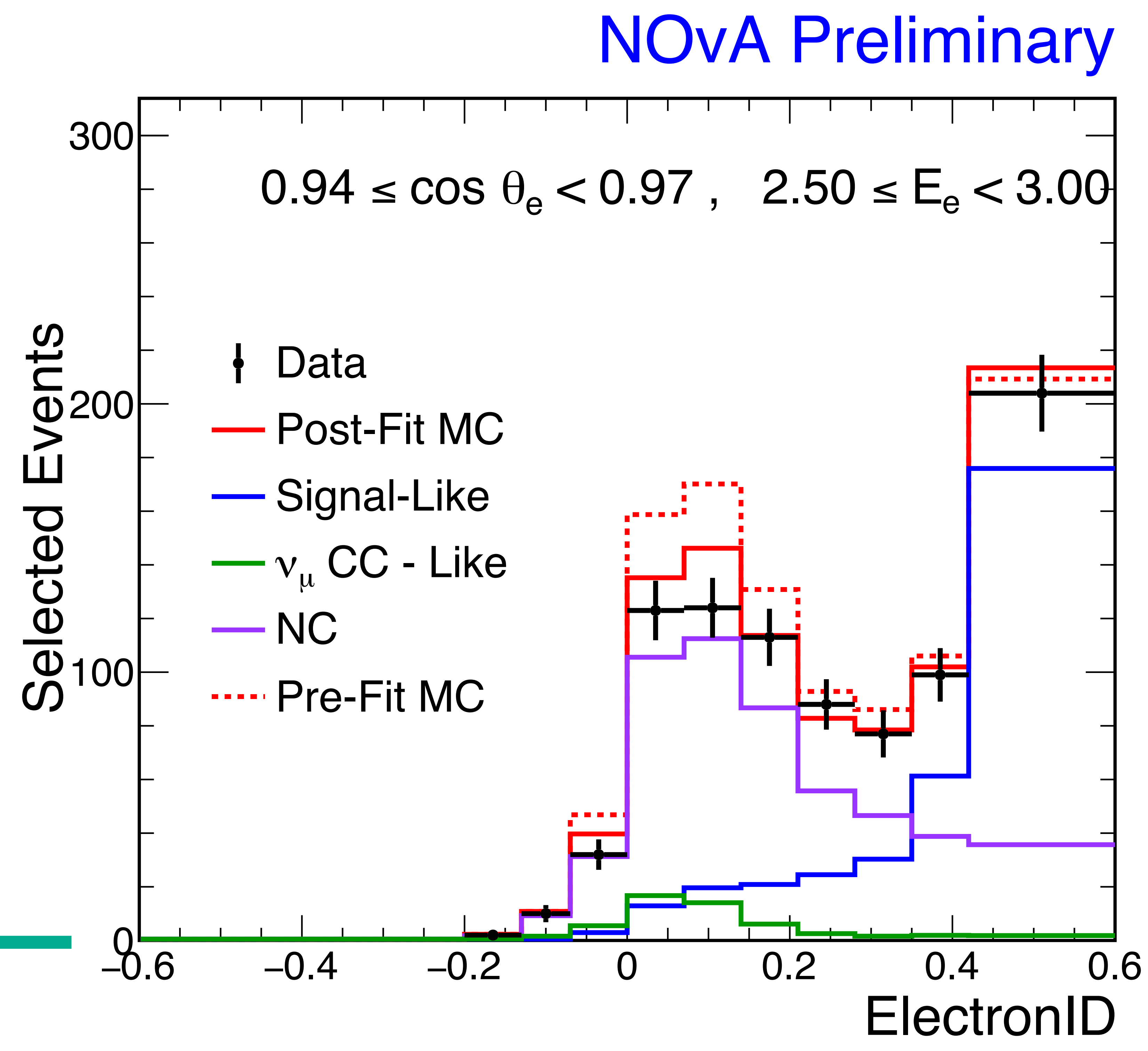
- Flux-averaged double differential cross section as a function of the electron kinematics.
- Background estimate in each electron kinematic bin is done via a template fit of the ElectronID distribution.





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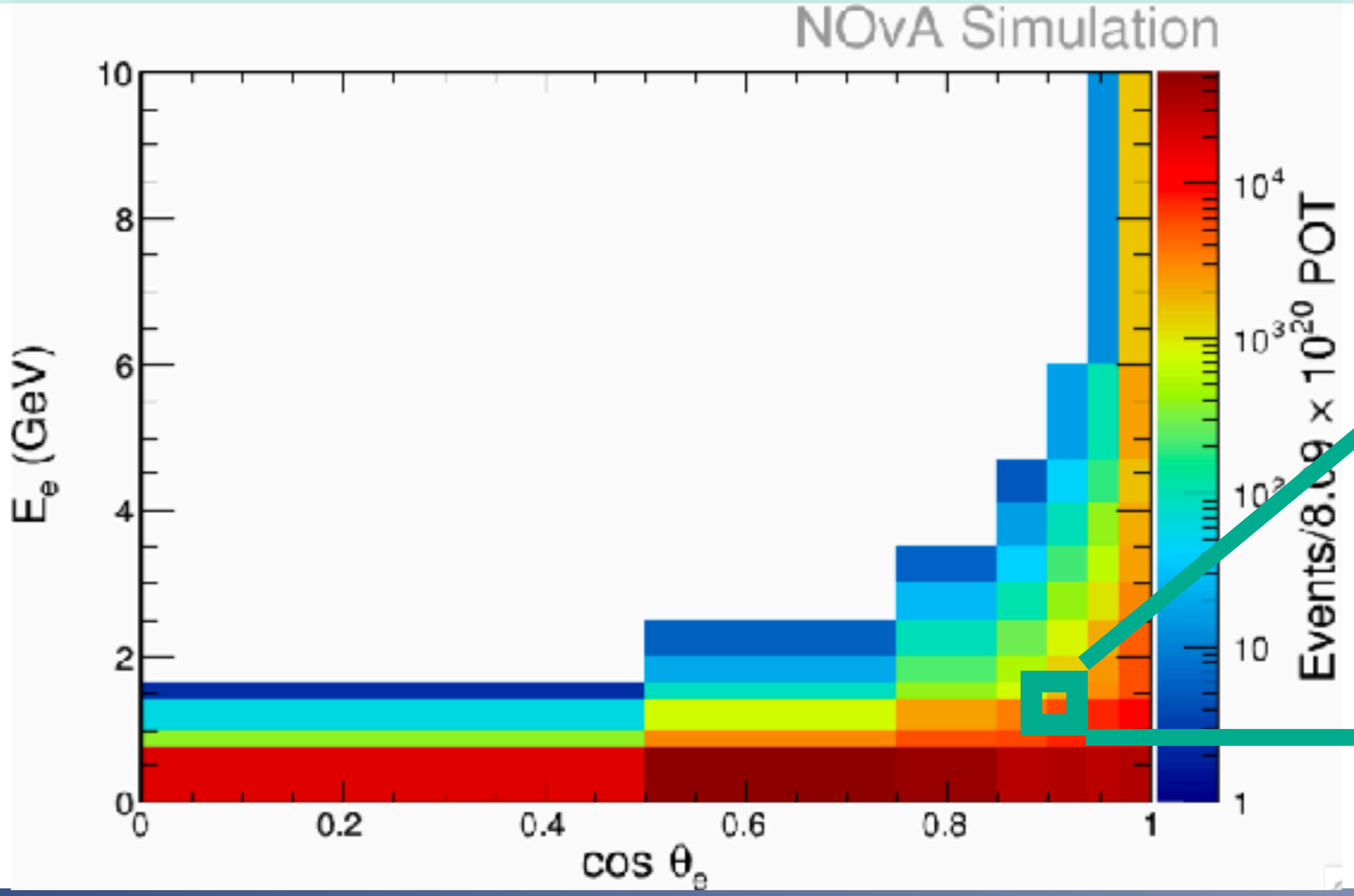
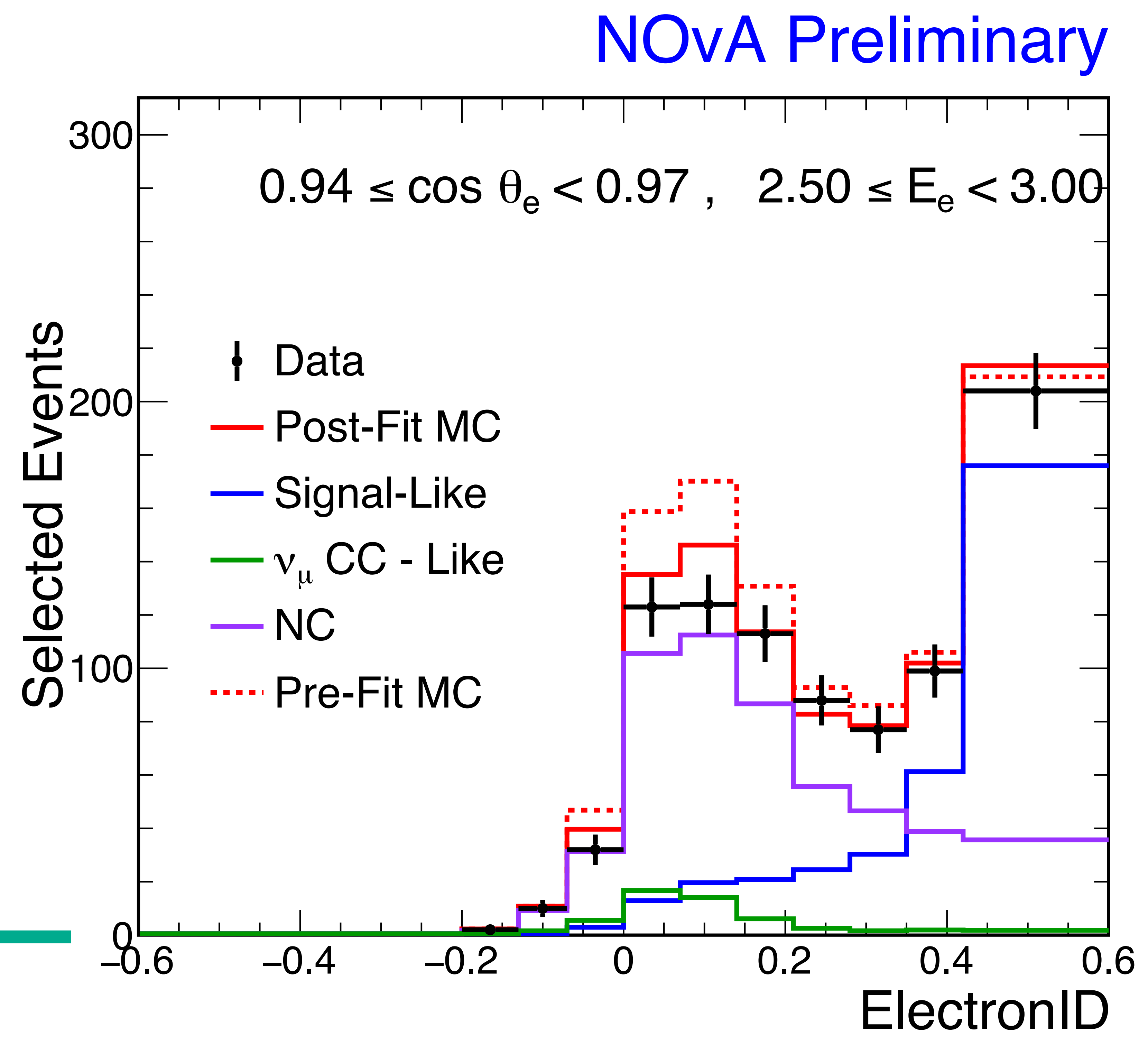
- Flux-averaged double differential cross section as a function of the electron kinematics.
- Background estimate in each electron kinematic bin is done via a template fit of the ElectronID distribution.
- Uncertainties in templates shape are accounted for using a covariance matrix.

$$\chi^2 = (x_i - \mu_i)^T V^{-1}_{ij} (x_j - \mu_j)$$

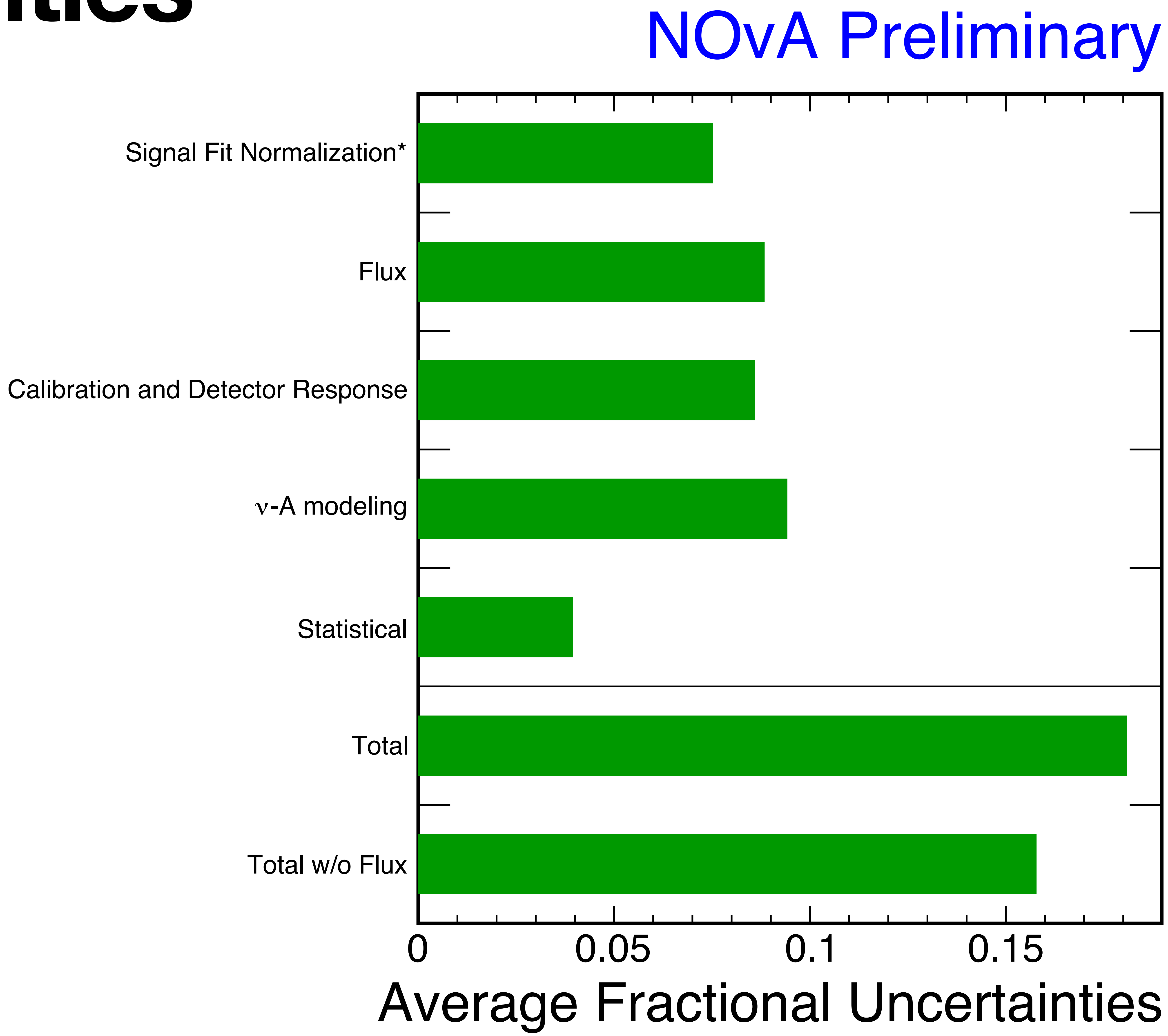
$i = (E_e , \cos\theta_e , ElectronID)$

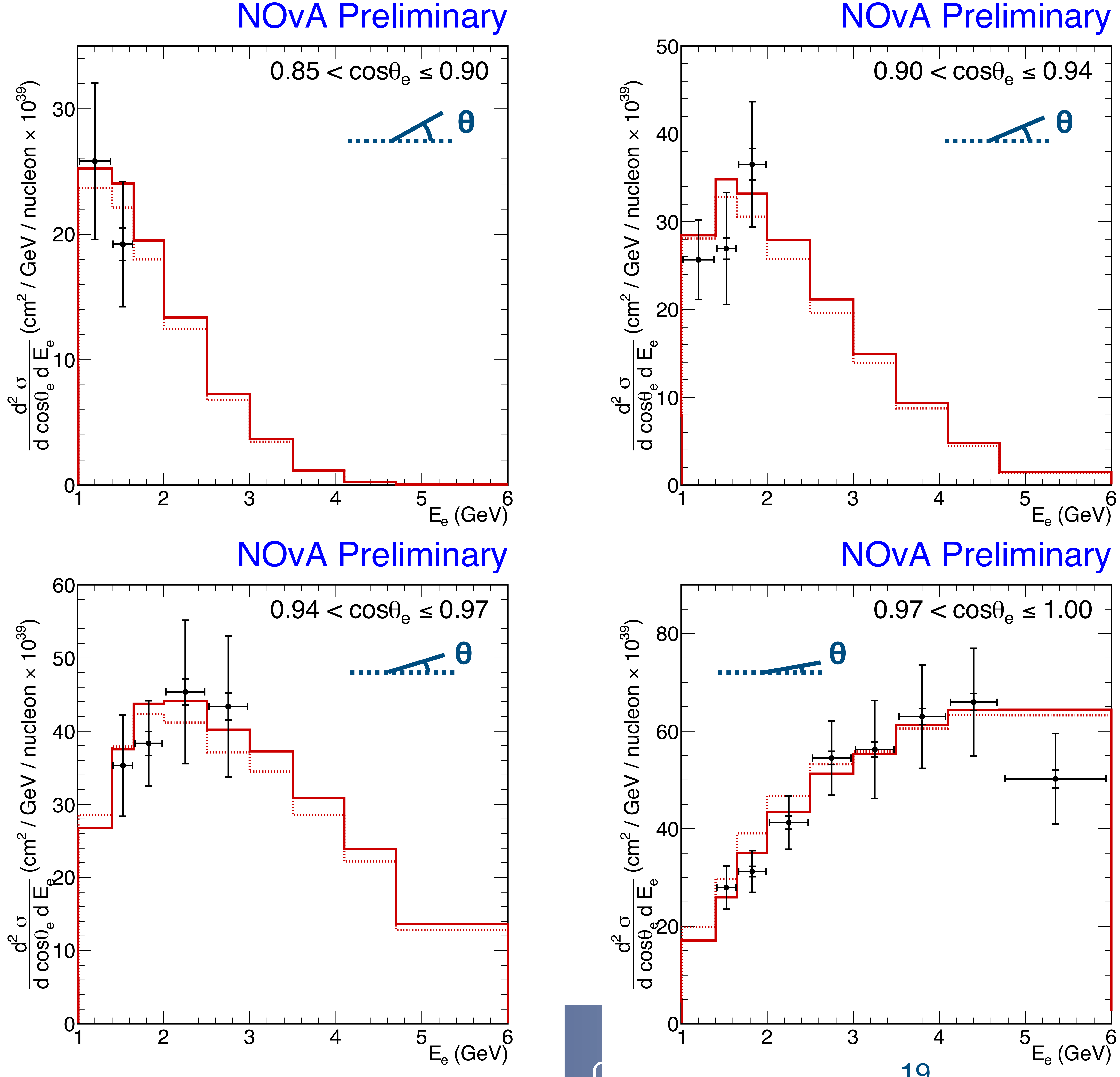




Fractional Uncertainties

- Average uncertainty is a weighted average to extracted cross section value.
- *Uncertainty output of the template fit.
- Main uncertainties are related to 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.
- Measurements have typical total uncertainties between 15% and 20% in each bin.

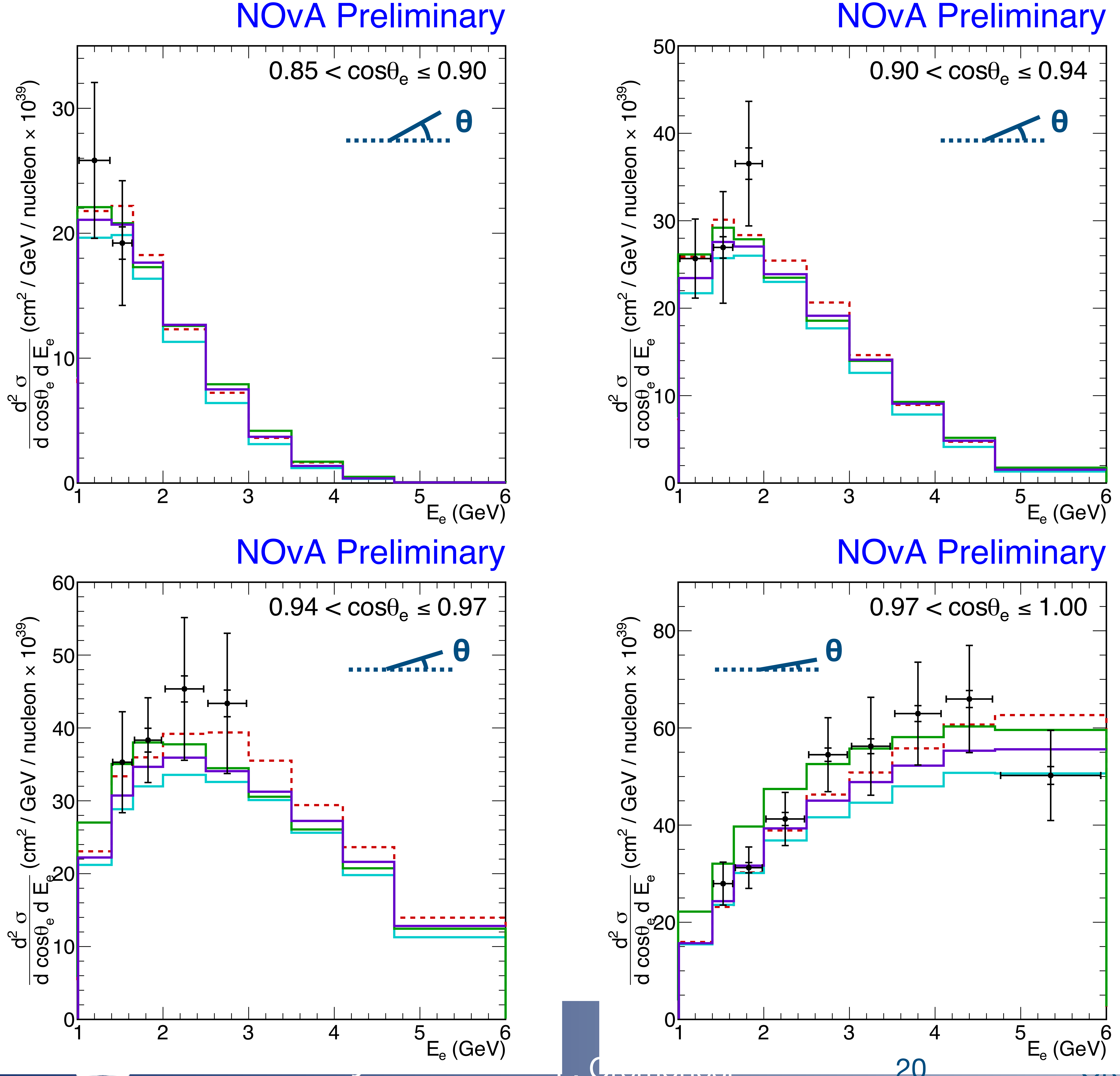




ν_e CC inclusive

- 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.



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- Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
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- Out of the box generator comparison.
- Measurement in good agreement with generator predictions.
- p-values ranging from 0.3 to 0.99.

*N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a.

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 10k events.
- Uncertainties ~ 15-20% in each bin.

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ν_e CC inclusive

- **First double differential measurement.**
- Around 10k events.
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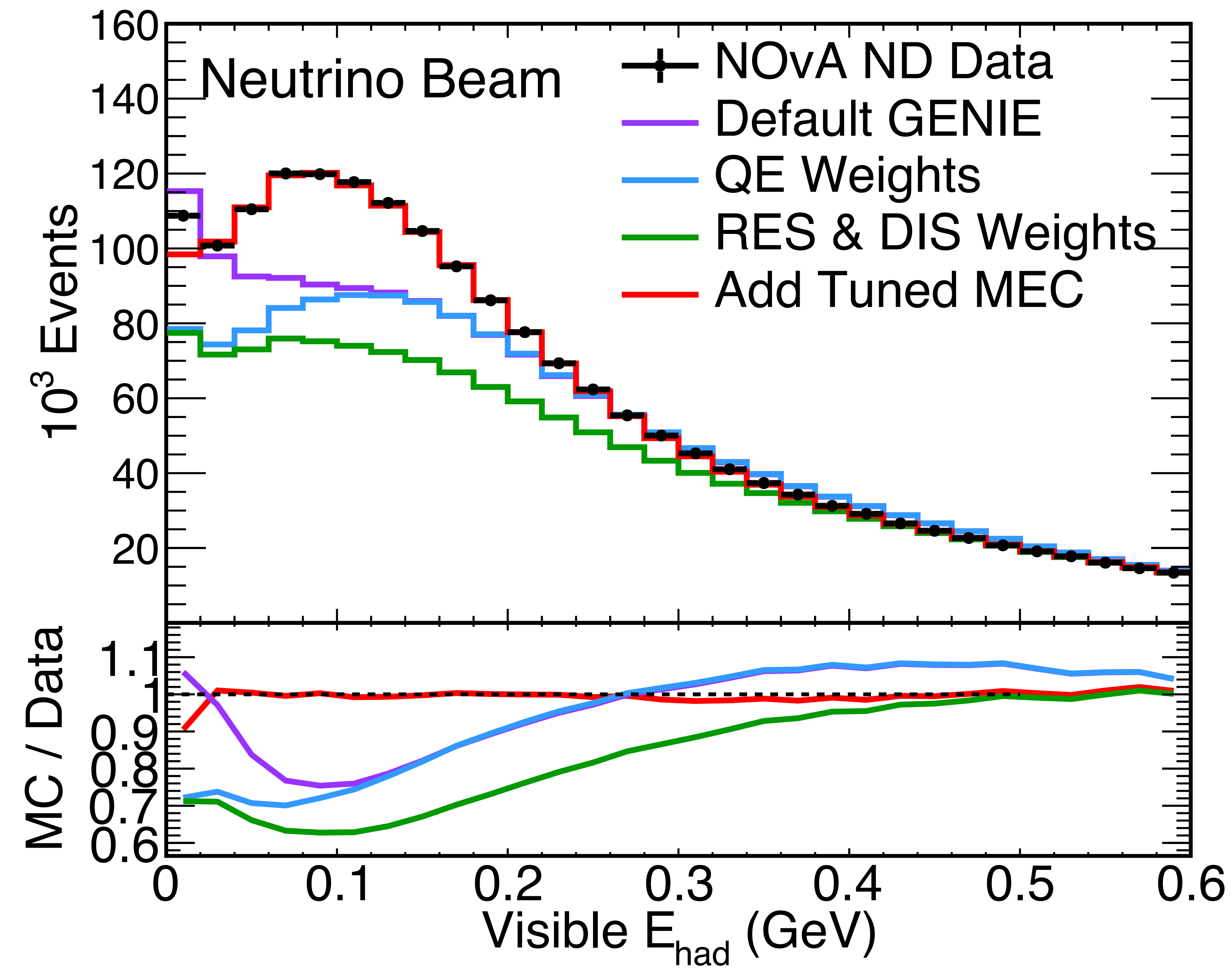
- Total covariance matrices and p-value calculations will be made available to the community.
- Active programme includes:
  - Ratio of ν_e to ν_μ cross sections.
  - Antineutrino version of these analyses and neutrino version of exclusive channels.
  - Data-driven techniques to reduce uncertainties.

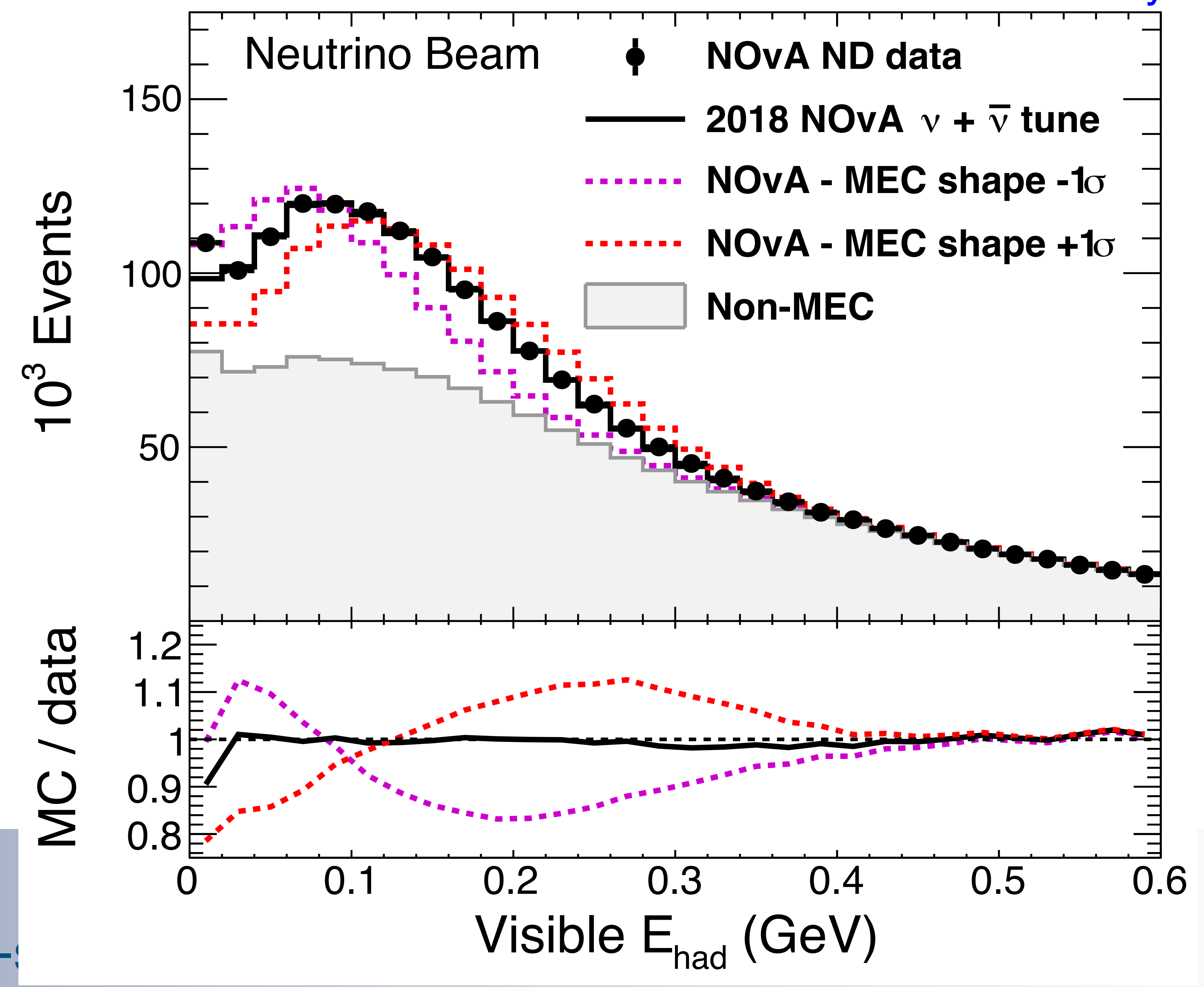
Thank you!

BACK UP

2018 NOvA tune

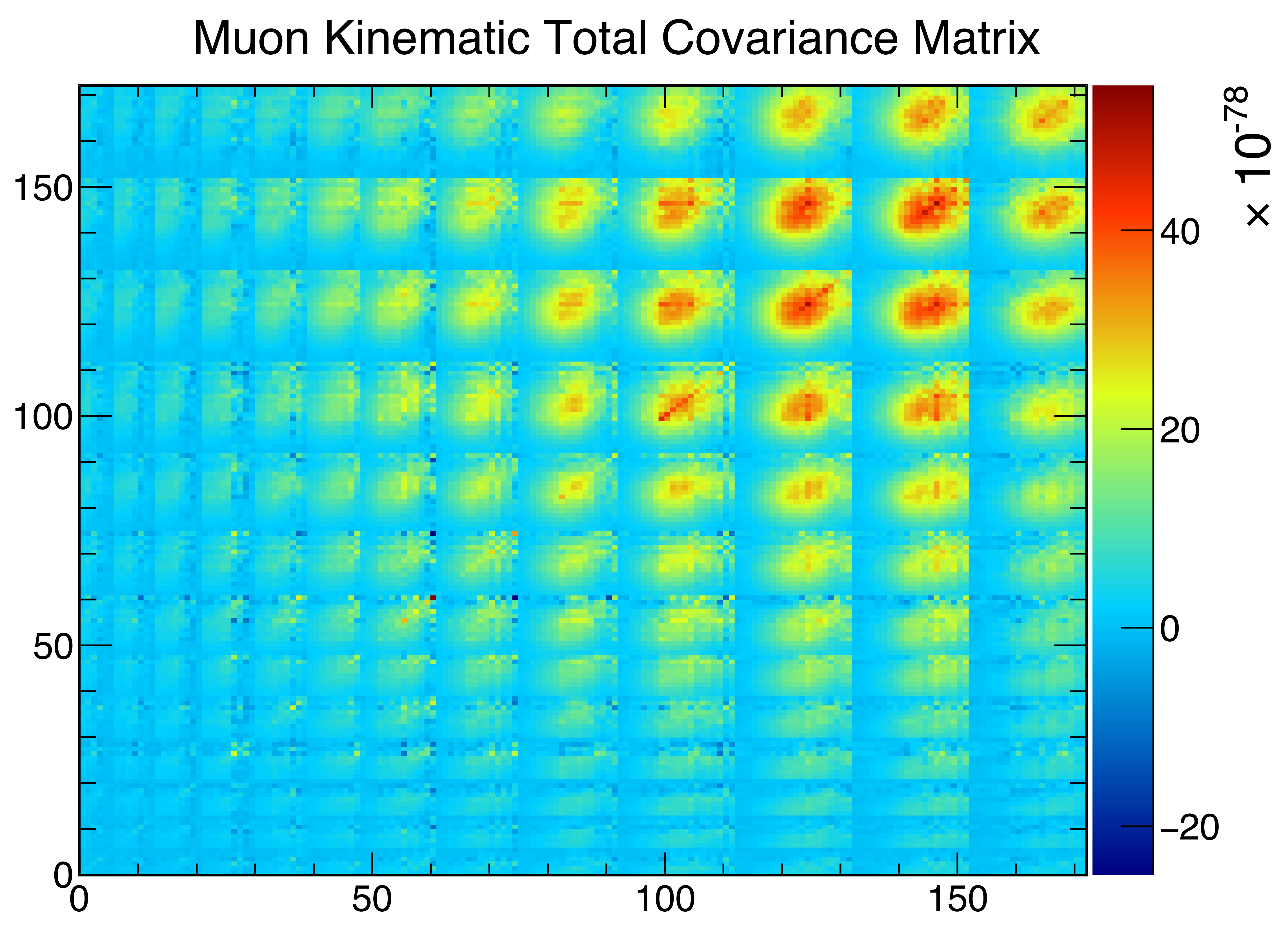
- We use NOvA and external data to tune interaction model
- Correct quasielastic (QE) component to account for low Q^2 suppression using model of Valencia group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
- Apply low Q^2 suppression to resonant (RES) baryon production.
- Nonresonant inelastic scattering (DIS) at high invariant mass ($W>1.7$ GeV/c^2) weighted up 10% based on NOvA data.
- "Empirical MEC" based on NOvA ND data to account for multinucleon knockout (2p2h). Tuning is done in bins of momentum transfer using the visible hadronic energy distribution.





NuMu CC inclusive

Covariance matrix

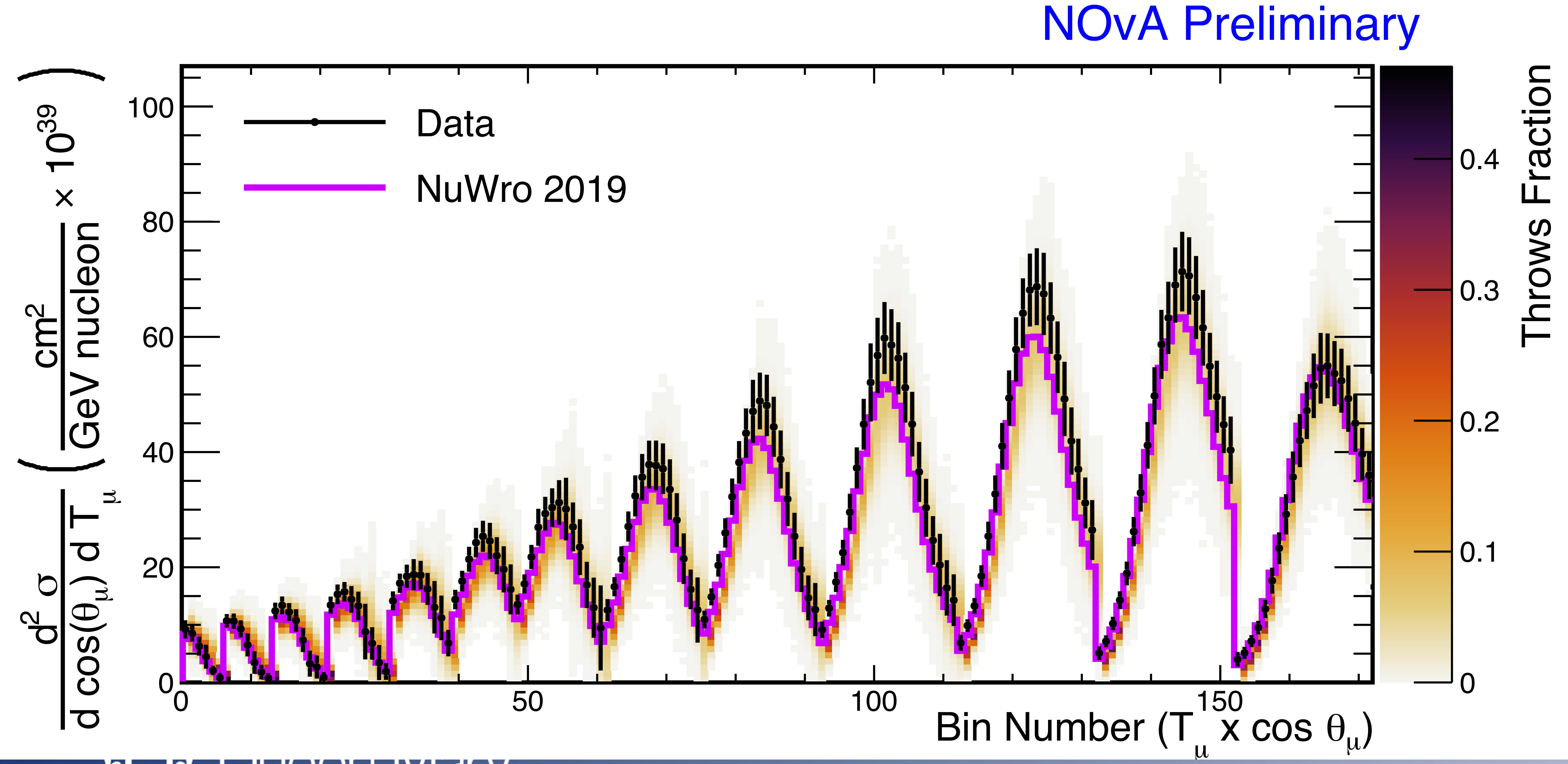


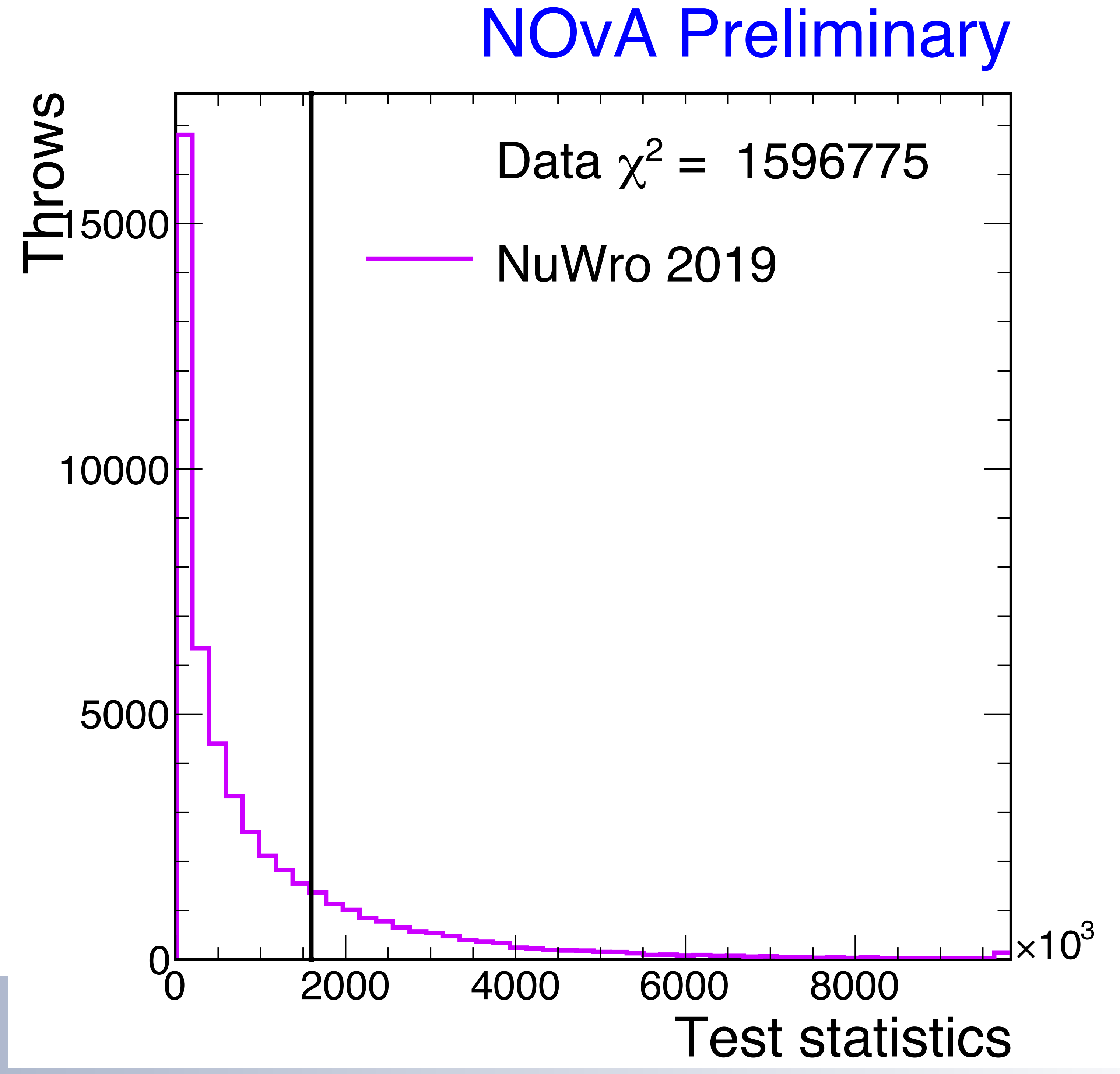
- We use a covariance matrix to calculate our final systematic uncertainties
- We generate 100k+ universes corresponding to different combinations of our systematic uncertainty samples to populate a covariance matrix
- One of the key deliverable of the analysis as it will allow users to access full treatment of our systematics

Comparison to generators

- We generate 100k+ universes corresponding to different combinations of our systematic uncertainty samples to populate a covariance matrix, which accounts for bin to bin correlations.
- We use this covariance matrix to calculate 50,000 throws from each generator prediction (RooFit).
- Compare test statistics of throws to data to find p-values.

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





Shape-only p-values

- Shape-only p-values are calculated using data-normalised generator predictions and shape-only covariance matrices.

ν_μ CC inclusive

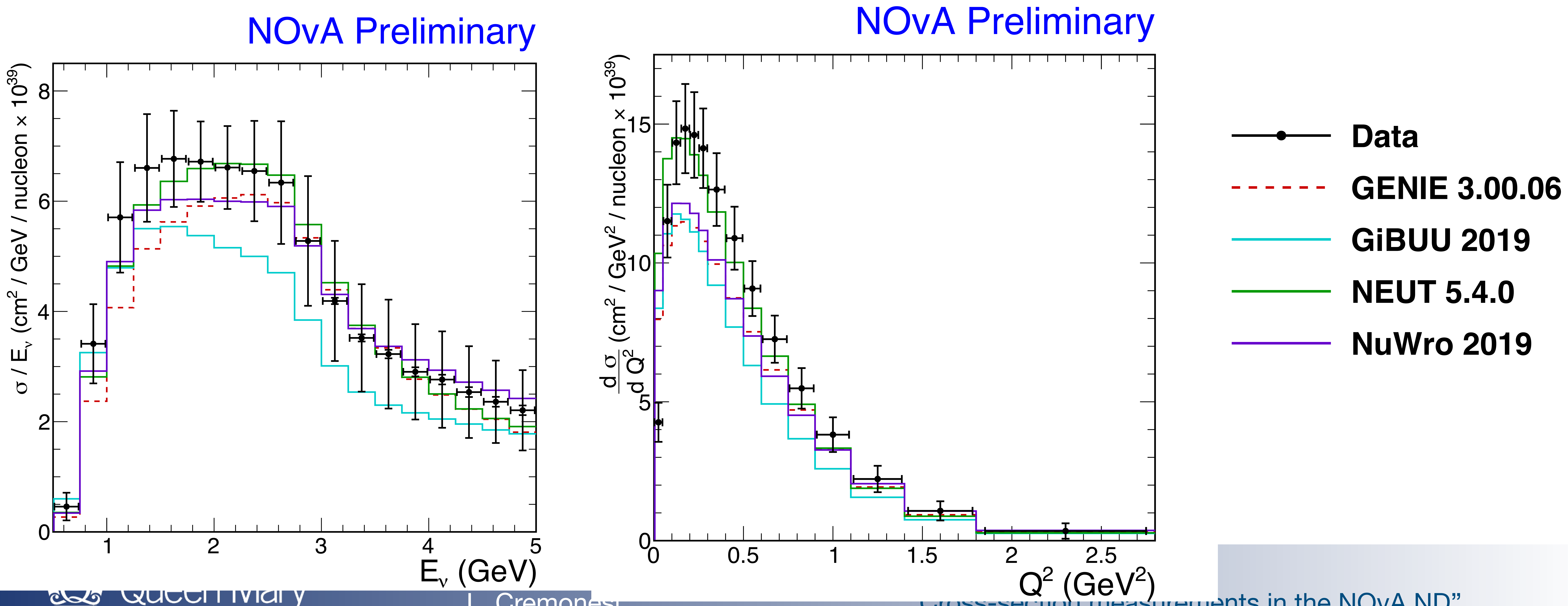
Generator	p-value
GENIE 2.12.2 - Tuned	0.54
GENIE 2.12.2 - Untuned	0.003
GENIE 3.00.06 - Untuned	0.31
GiBUU 2019	0.38
NEUT 5.4.0	0.004
NuWro 2019	0.54

ν_e CC inclusive

Generator	p-value
GENIE 2.12.2 - Tuned	0.95
GENIE 2.12.2 - Untuned	0.60
GENIE 3.00.06 - Untuned	0.95
GiBUU 2019	0.72
NEUT 5.4.0	0.40
NuWro 2019	0.78

NuMu CC Inclusive - single differential cross sections

Single differential derived variables (Enu and Q2) extracted only over the ranges of muon kinematics reported in the differential measurements



NuE CC Inclusive - single differential cross sections

Single differential derived variables (Enu and Q2) extracted only over the ranges of electron kinematics reported in the differential measurements