Queen Mary
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Cross-section measurements in the NOvA Near Detector

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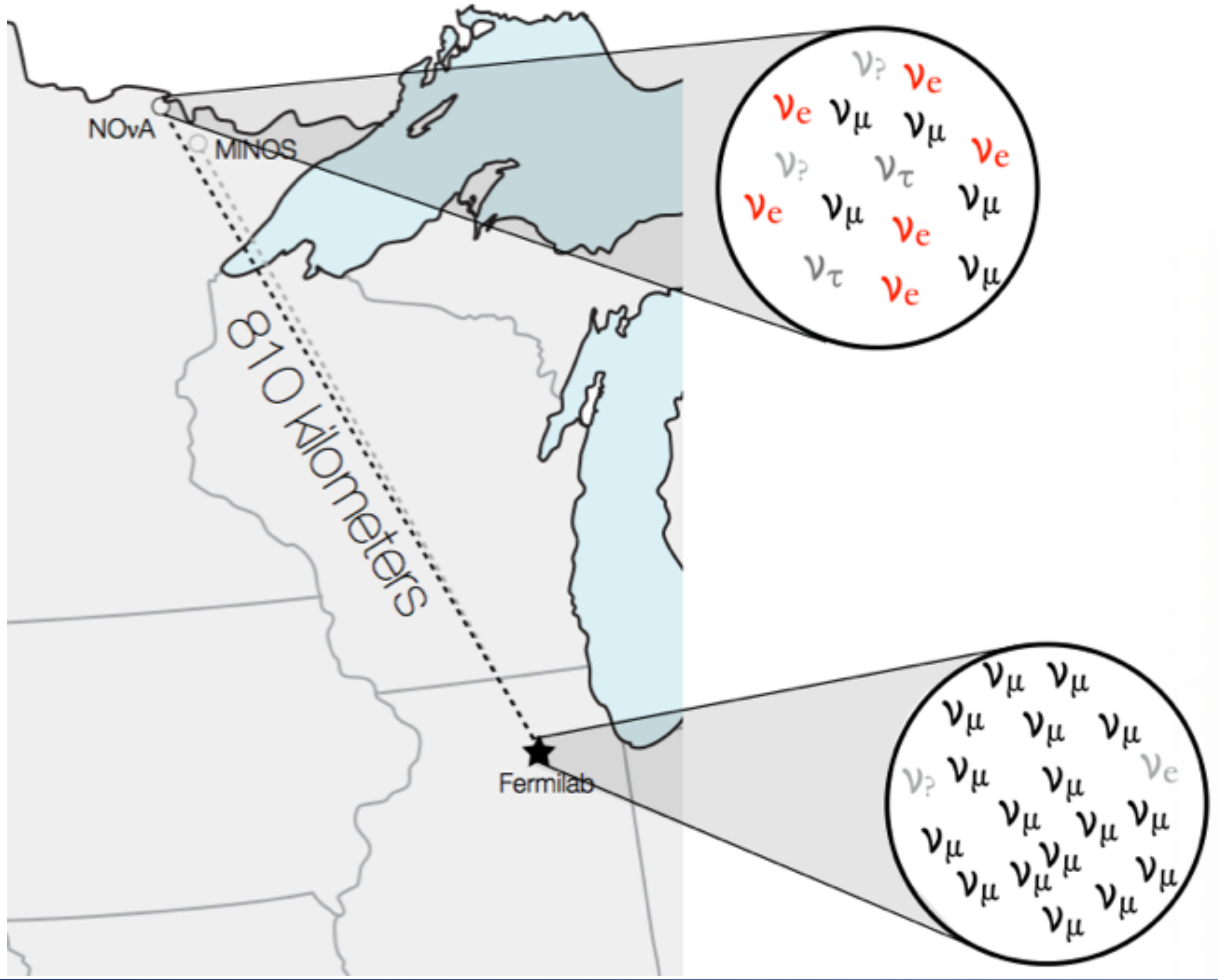
7th July 2022
International Conference on High Energy Physics (Bologna, Italy, 2022)

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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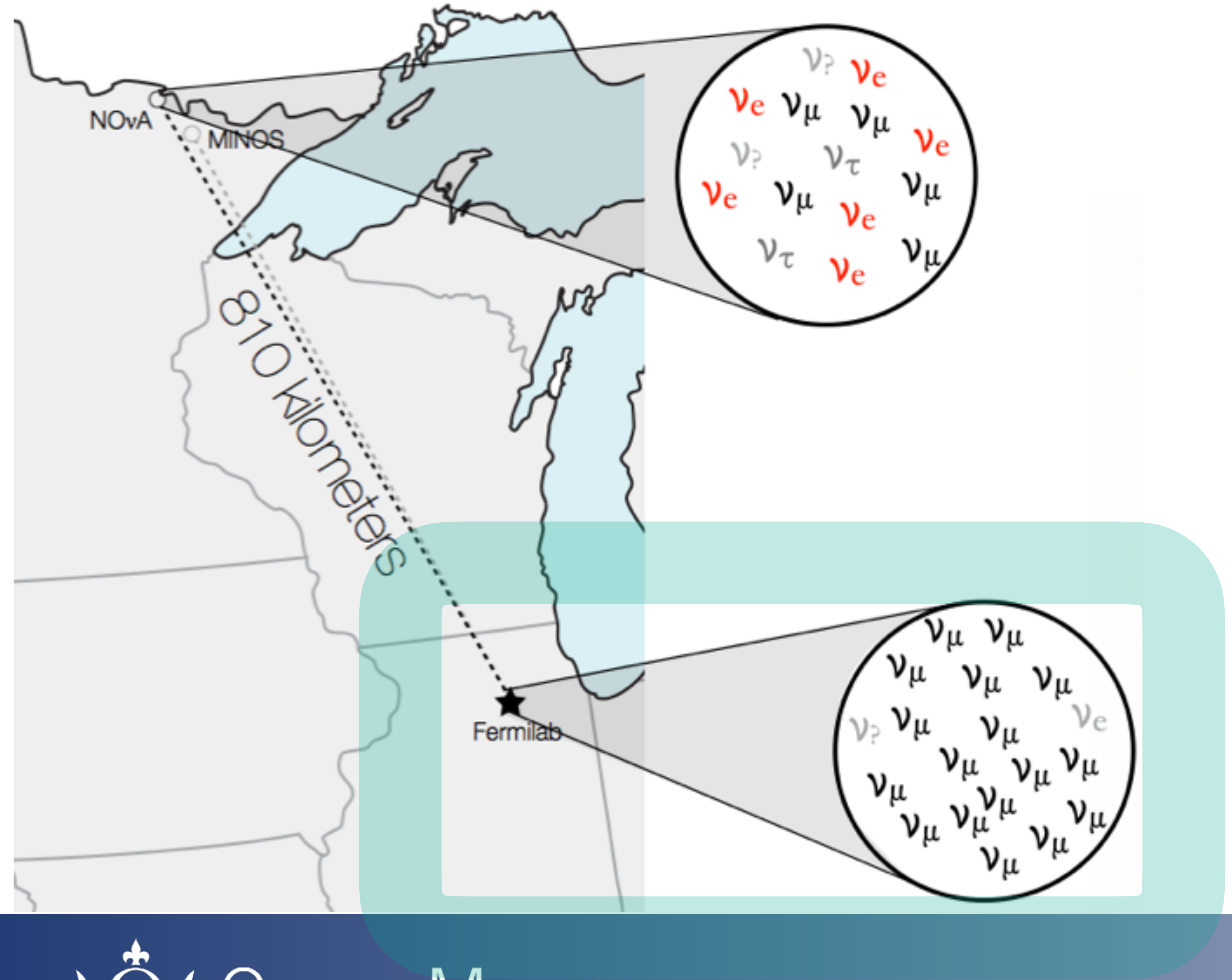
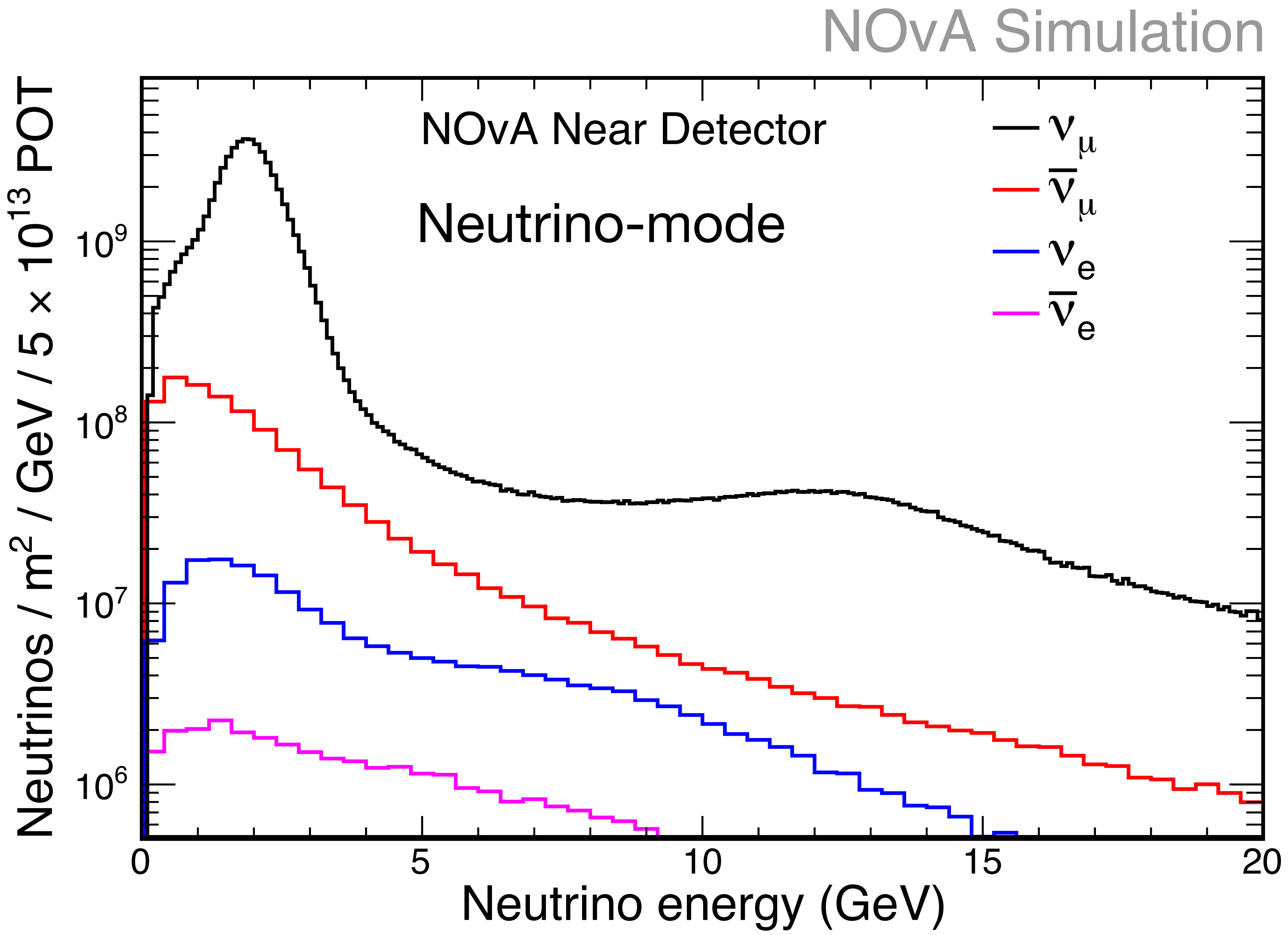
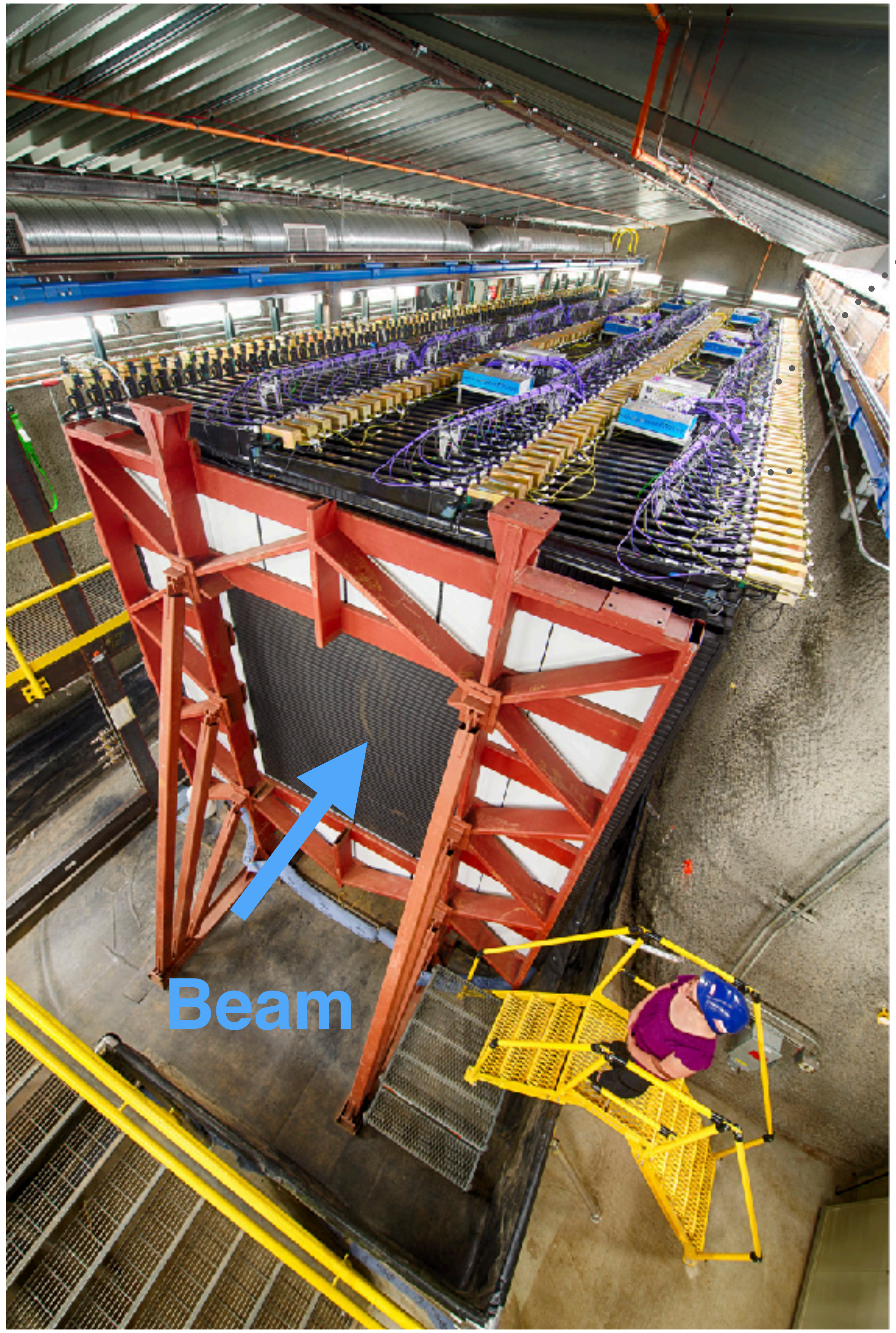


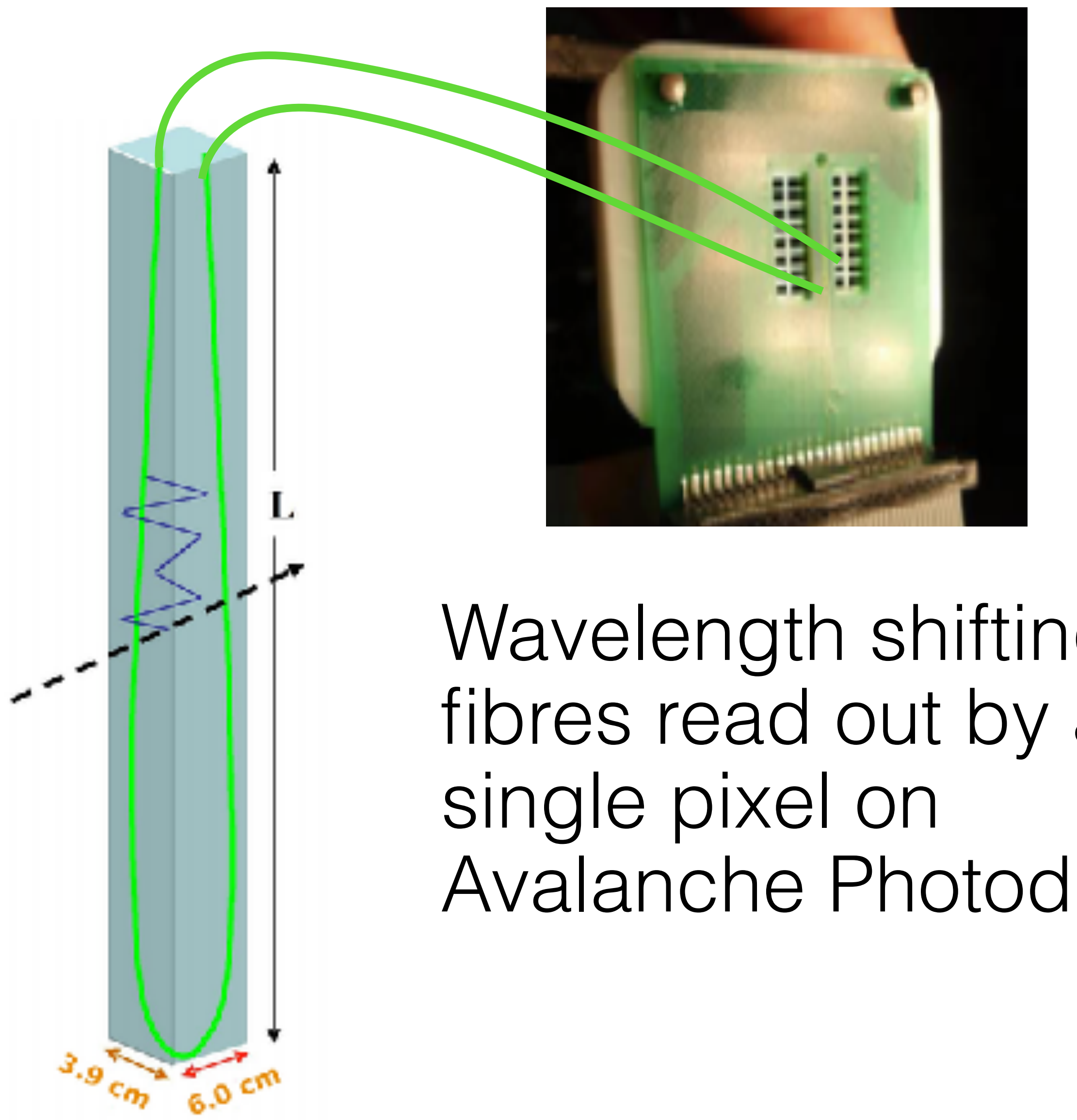
- High neutrino flux at Near Detector:
  - used as control for the oscillation analyses,
  - provides a rich data set for measuring cross sections.
- ND located 1km from the NuMI beam target.
- 96% pure ν_μ beam, 1% ν_e and $\bar{\nu}_e$



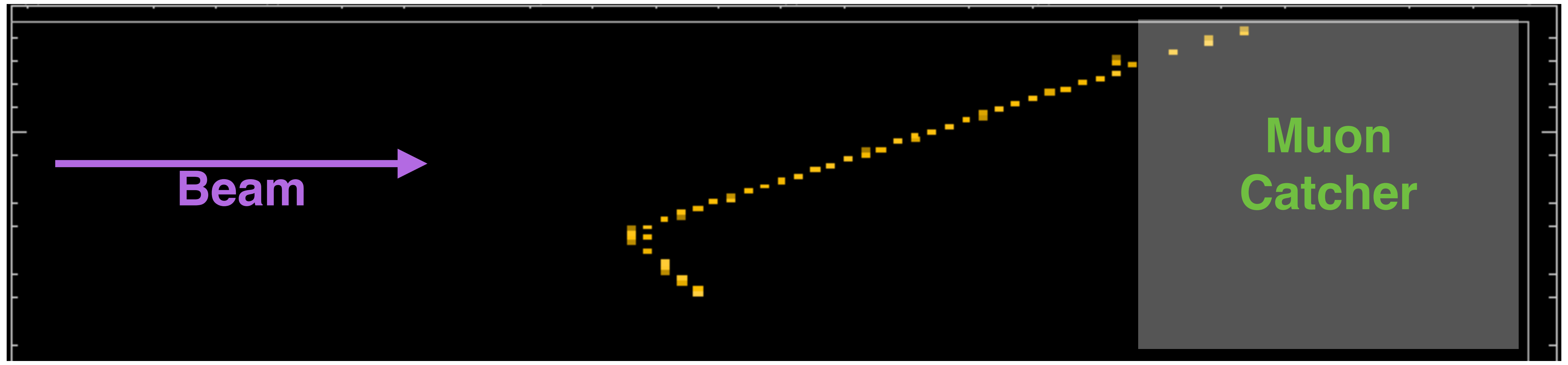
NOvA Near Detector



Alternating planes allow for 3D reconstruction

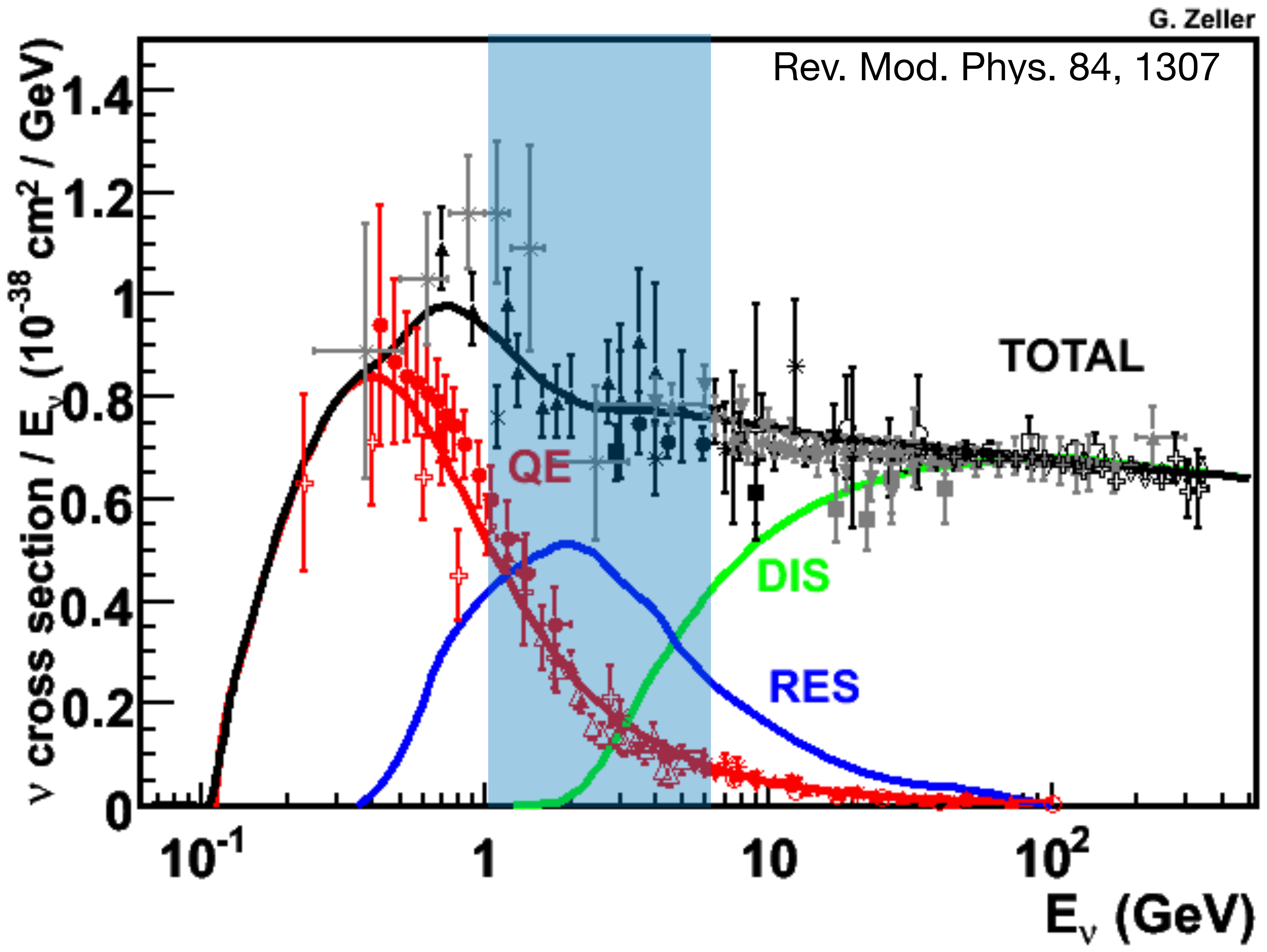


Wavelength shifting fibres read out by a single pixel on Avalanche Photodiode



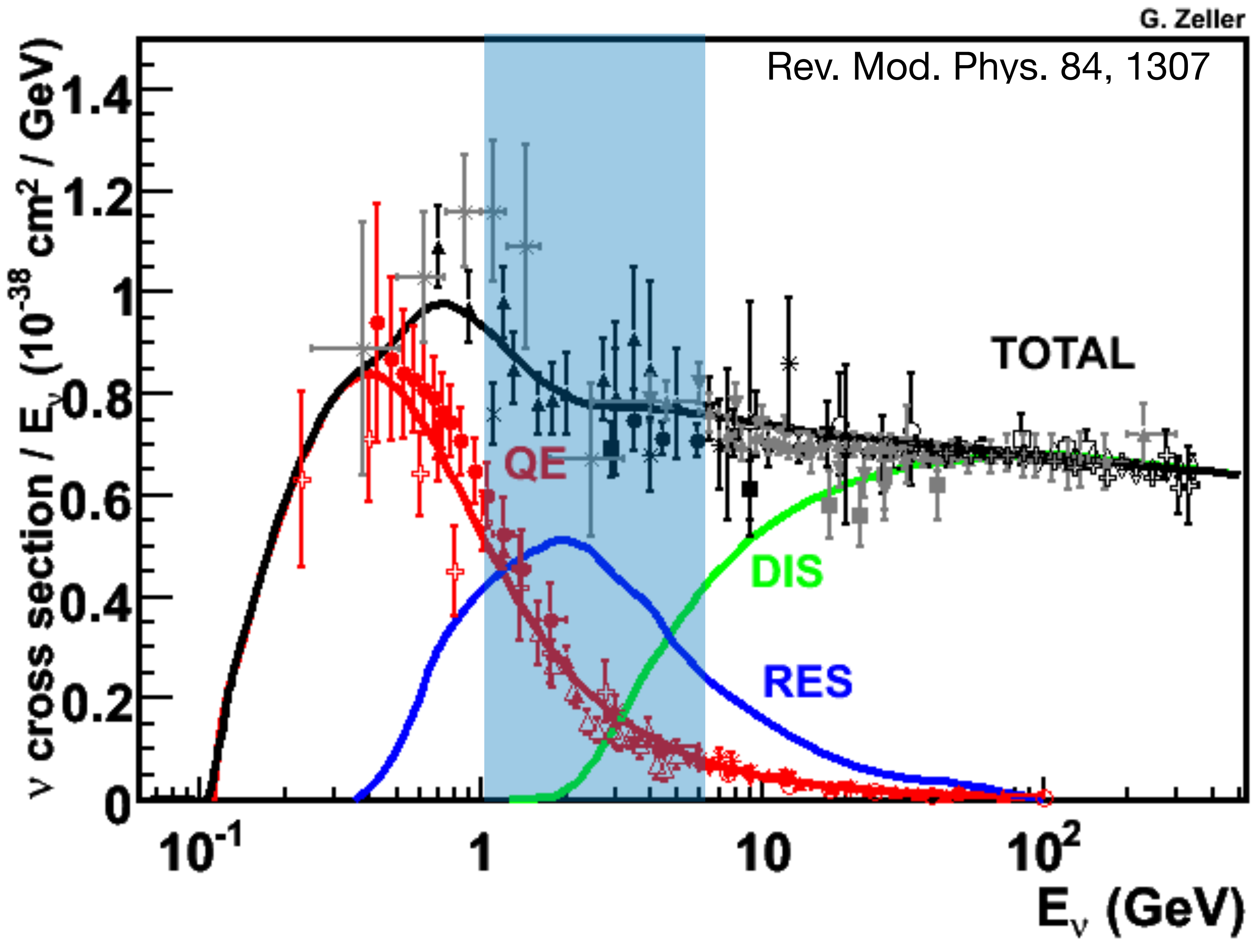
- 300t tracking calorimeter
- Extruded plastic cells, filled with liquid scintillator
- 0.17 X_0 per layer
- 77% hydrocarbon, 16% chlorine, 6% TiO_2 by mass
- Muon catcher (steel + NOvA cells) at downstream end to range out ~2GeV muons.

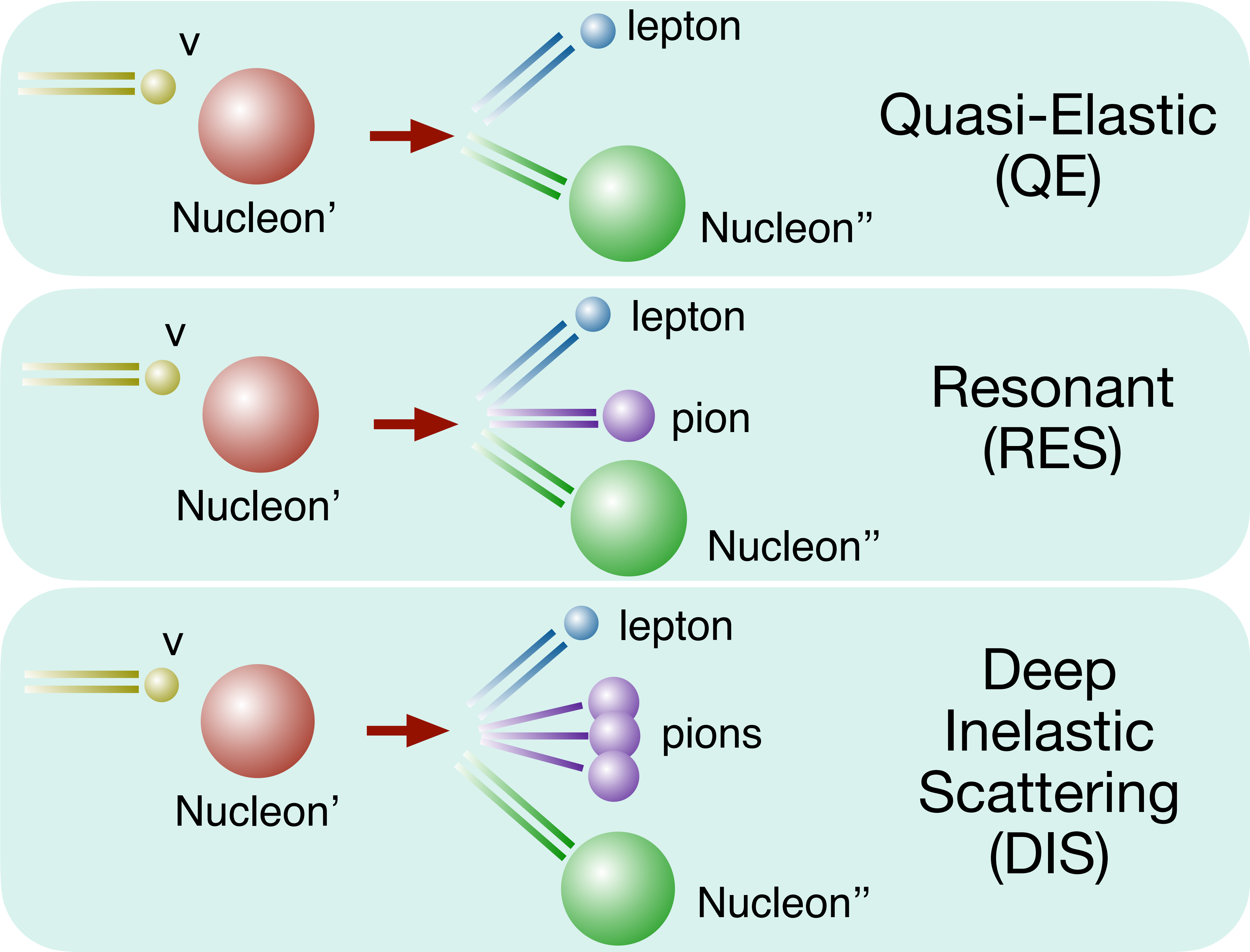
Neutrino CC interactions at NOvA



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

Neutrino CC interactions at NOvA





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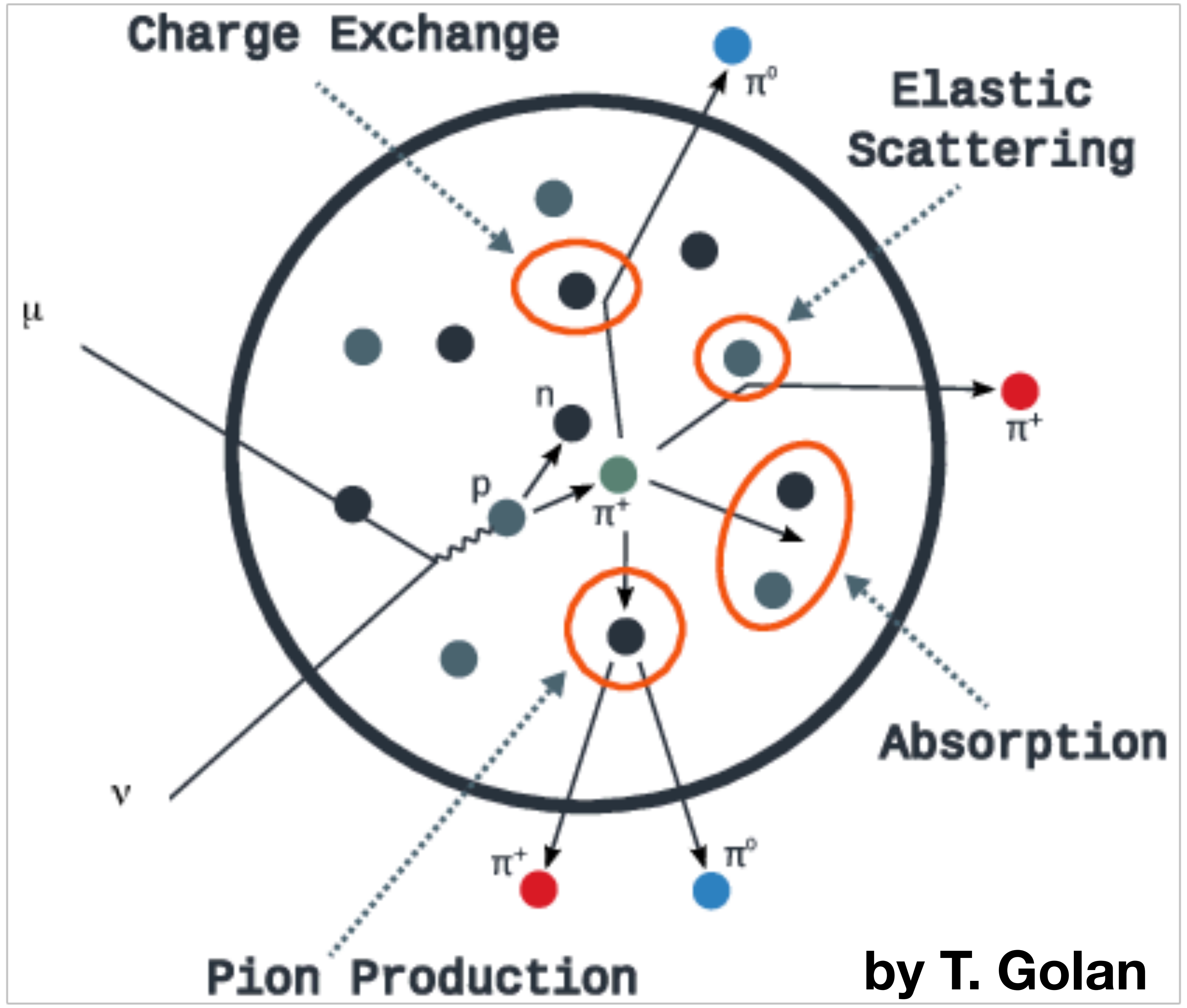
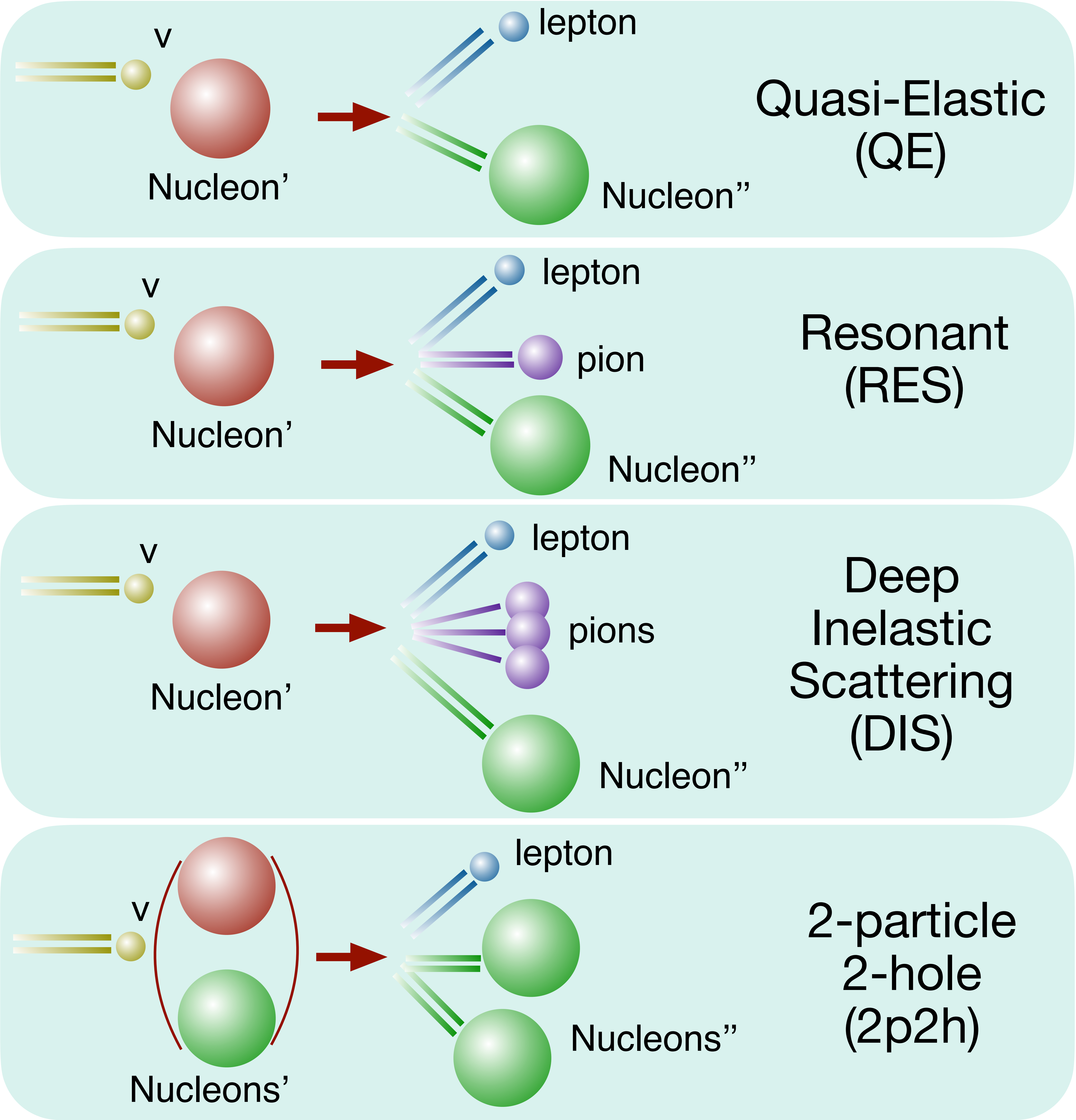
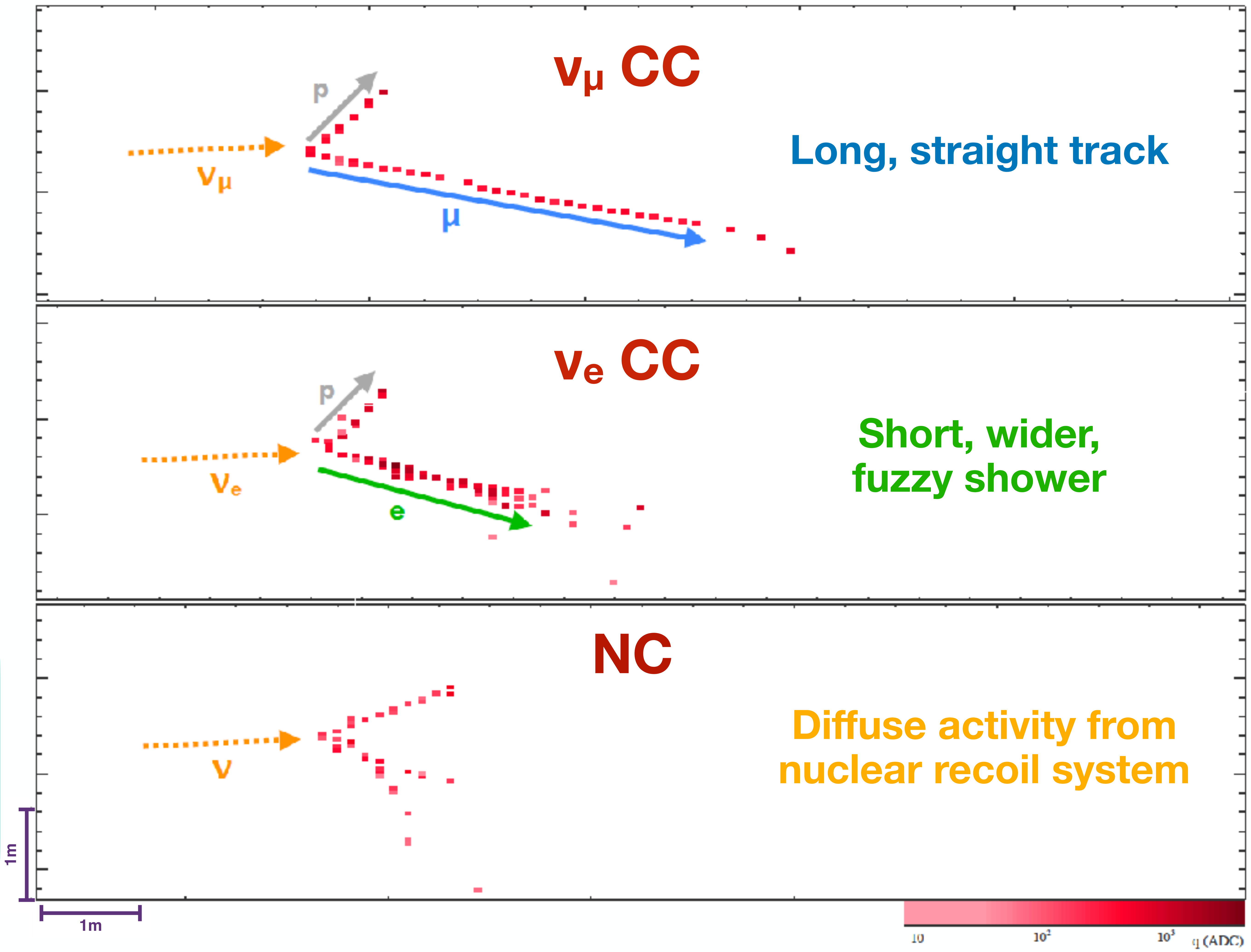


- These neutrino interactions happen inside the nuclear media.



Neutrino cross-section measurements at NOvA

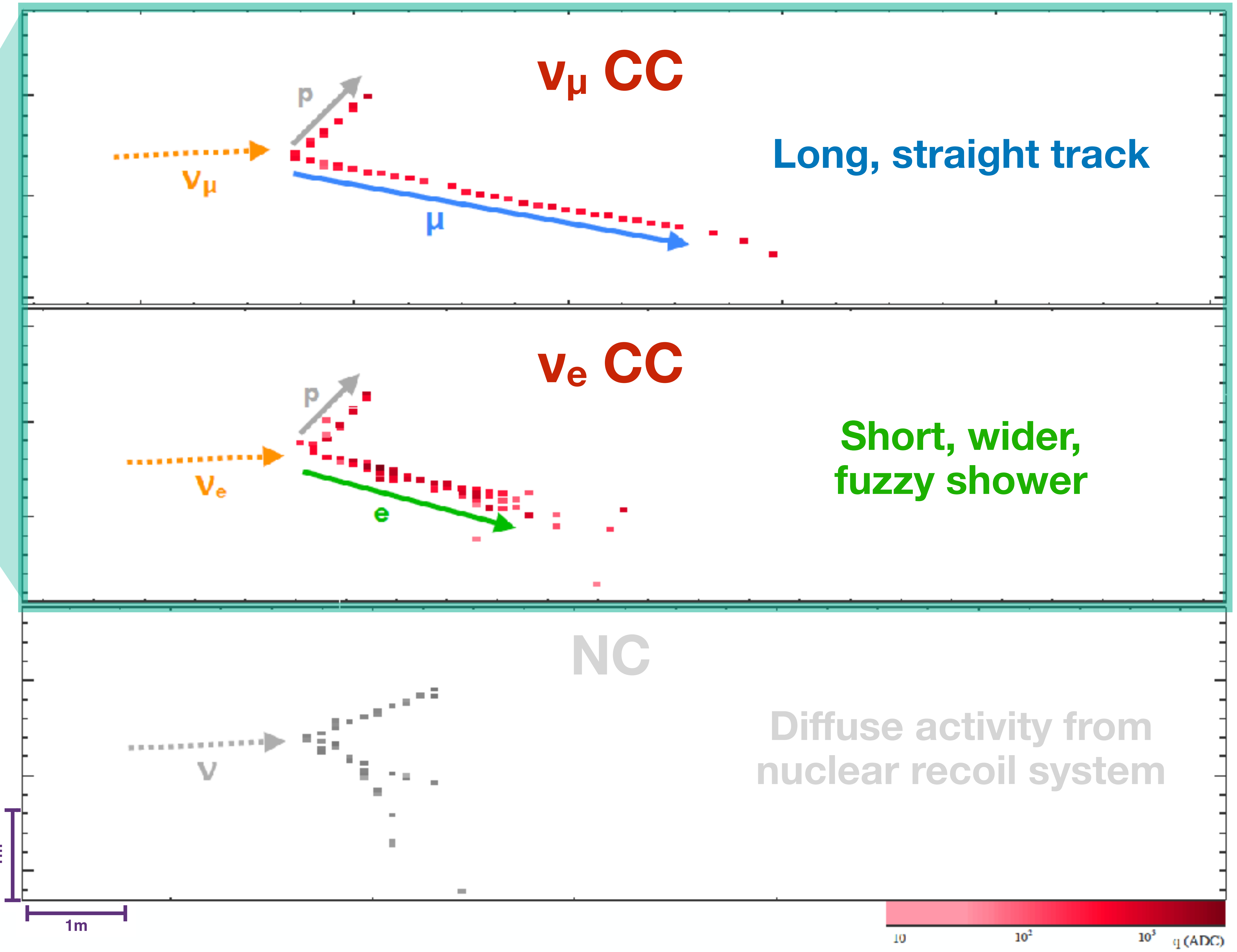


Energy range
Detector technology
Statistics

} Unique environment for cross section measurements

Neutrino cross-section measurements at NOvA

This talk

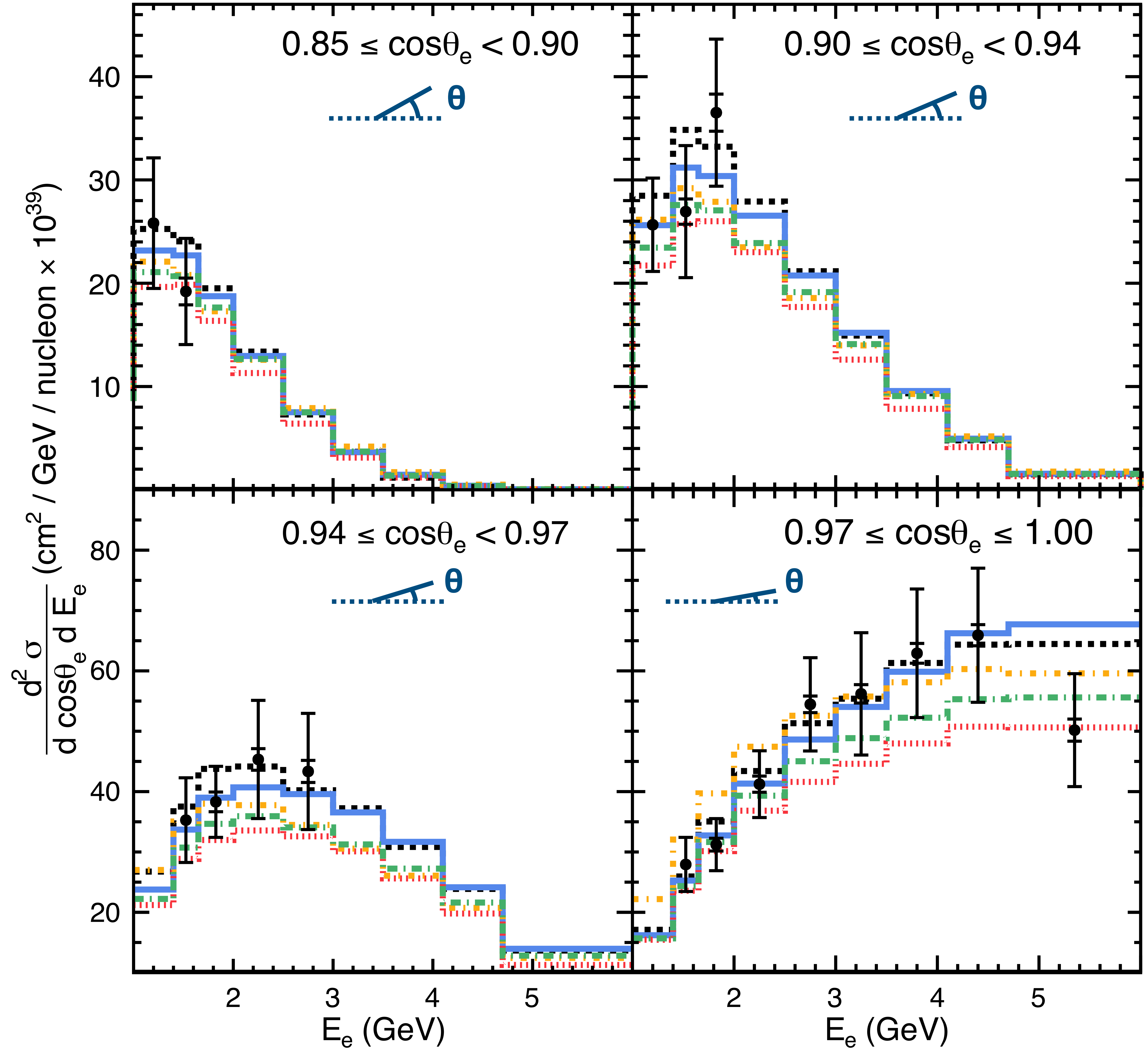


Energy range
Detector technology
Statistics

Unique environment for cross section measurements

ν_e CC inclusive

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



First ν_e CC inclusive double-differential measurement

- Data (Stat. + Syst.)
- GENIE v2 - NOvA-tune
- GENIE v3*
- GiBUU
- NEUT
- NuWro

https://arxiv.org/abs/2206.10585

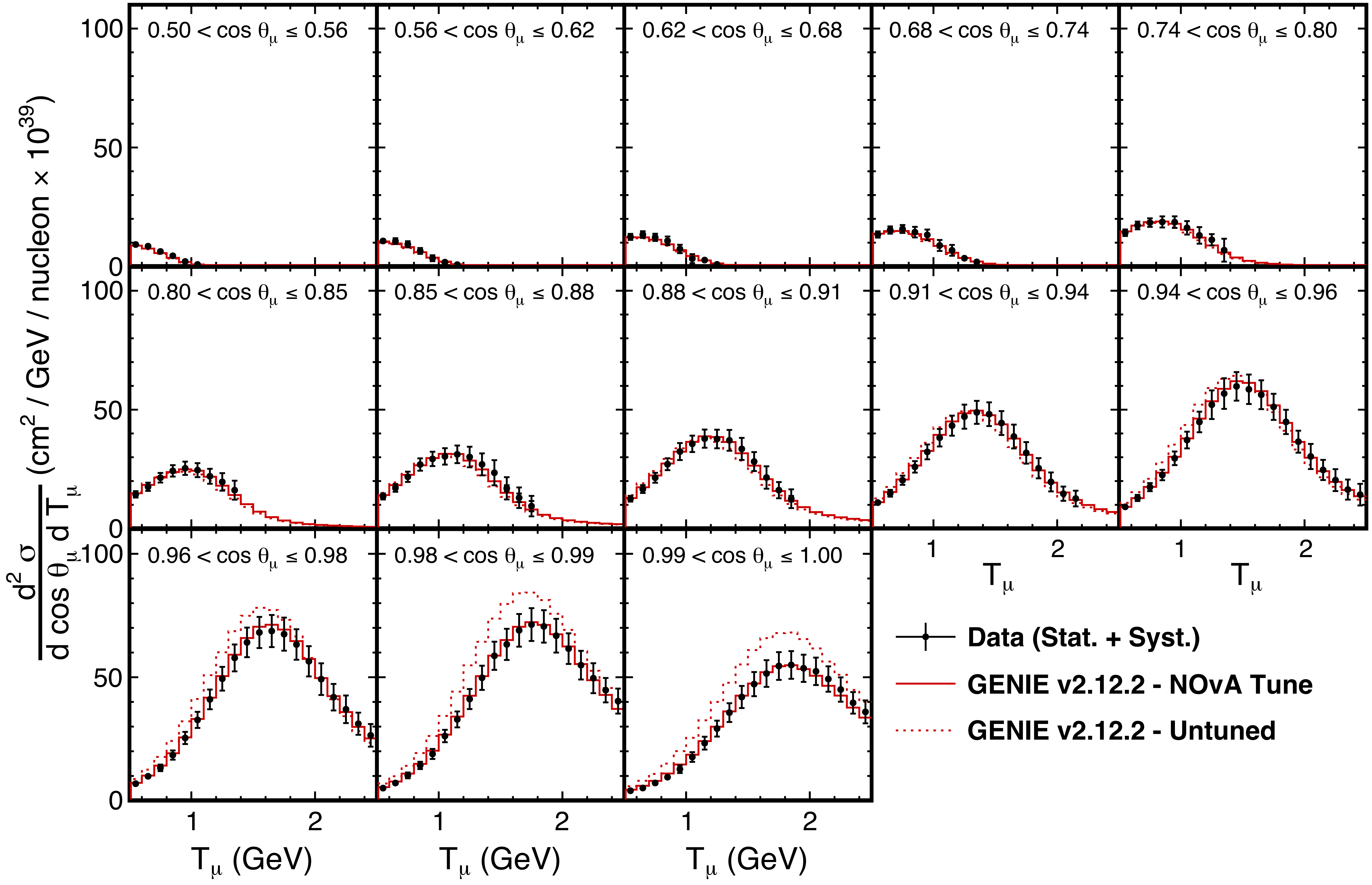
- Out of the box generator comparison.
- Measurement in good agreement with generator predictions.

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

ν_μ CC inclusive

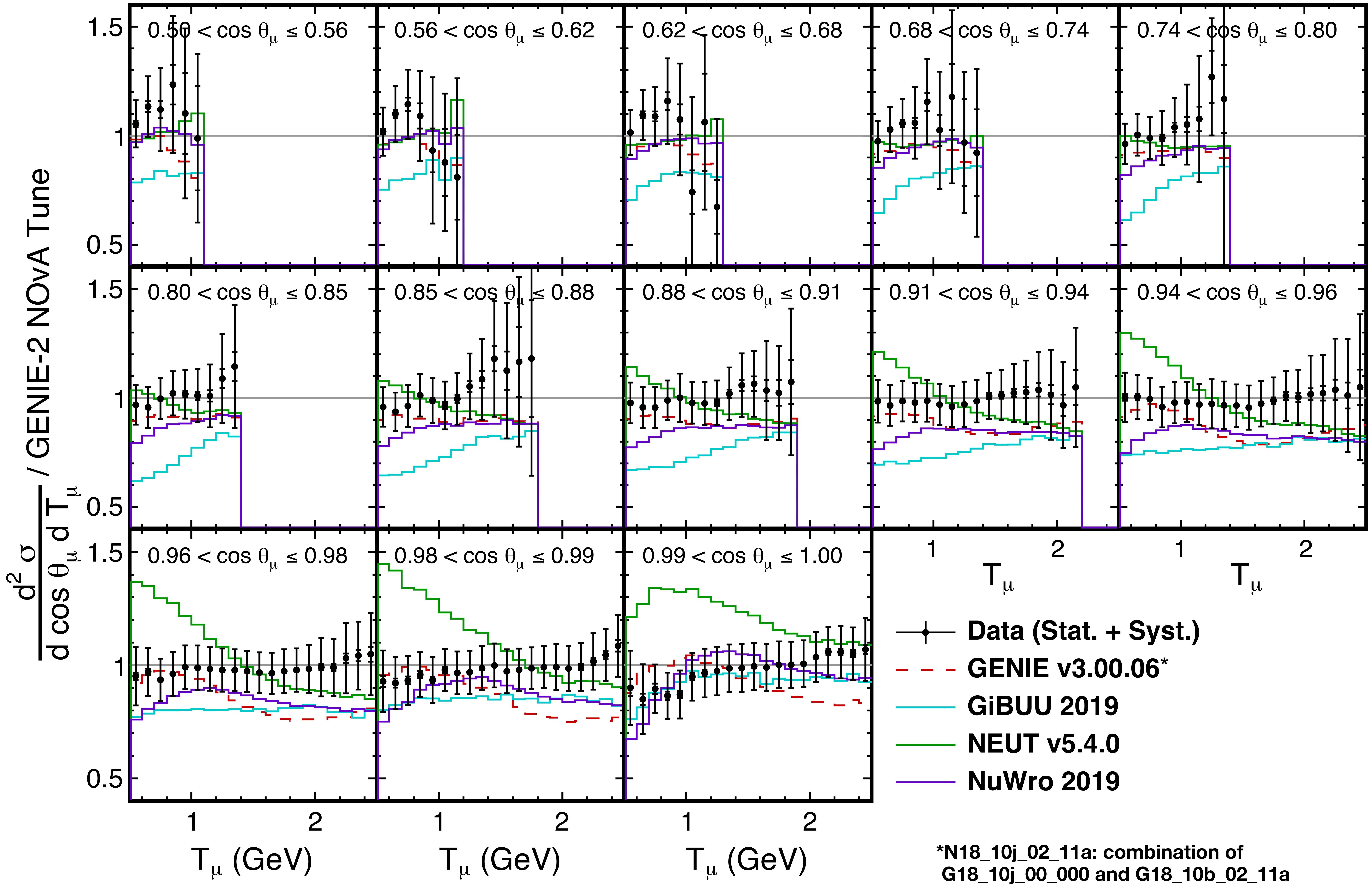
More than 1M ν_μ CC events in our selection

ν_μ CC inclusive double-differential measurement



https://arxiv.org/abs/2109.12220

- Cross section calculated at 172 kinematic points
- 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.

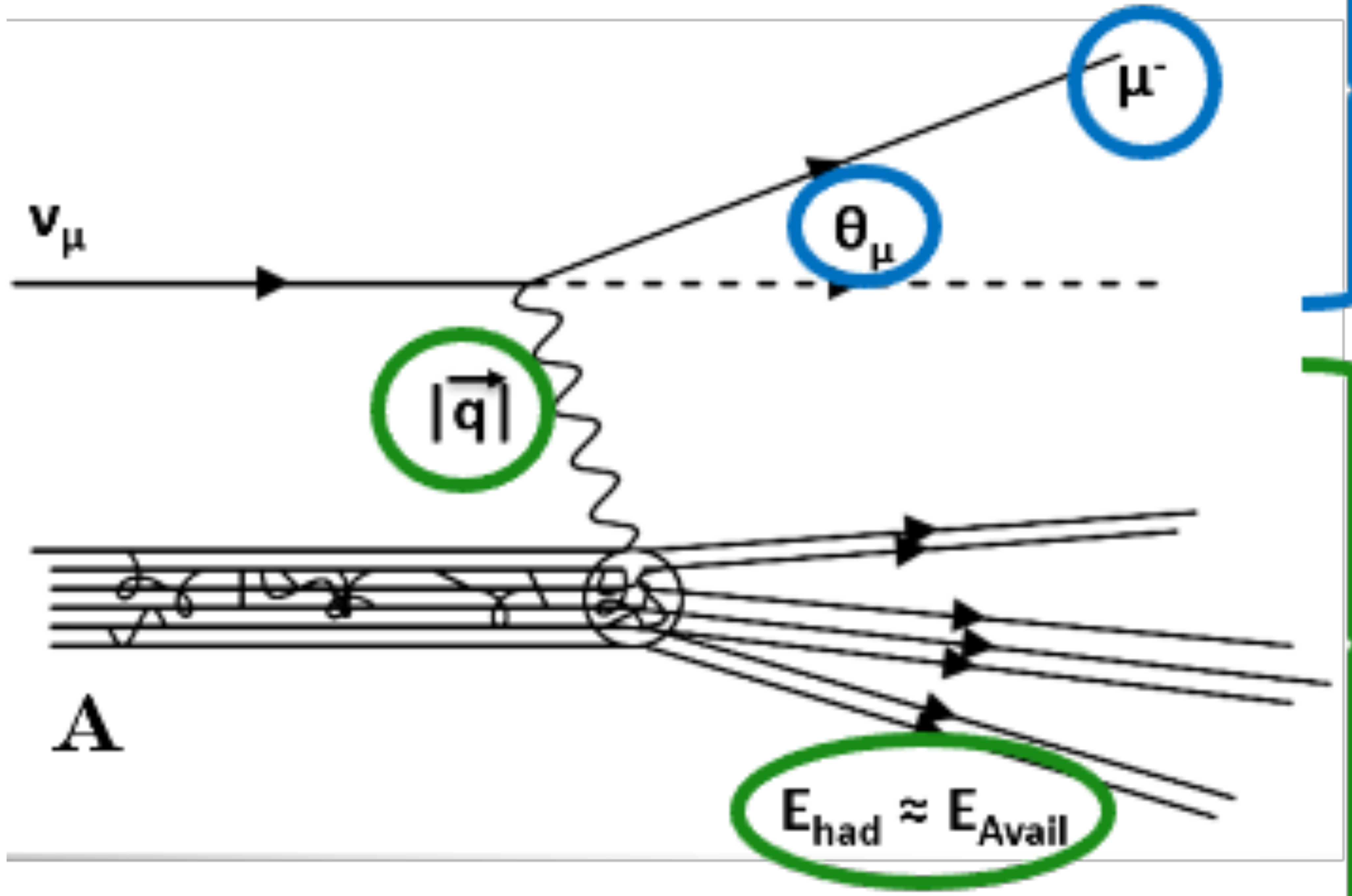


ν_μ CC inclusive double-differential measurement

https://arxiv.org/abs/2109.12220

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

Two new ν_μ double-differential results



Muon System ⇨ Energy vs angle

Exclusive
Select only events with low hadronic energy

Hadronic System ⇨ 3-momentum transfer $|\vec{q}|$ vs energy

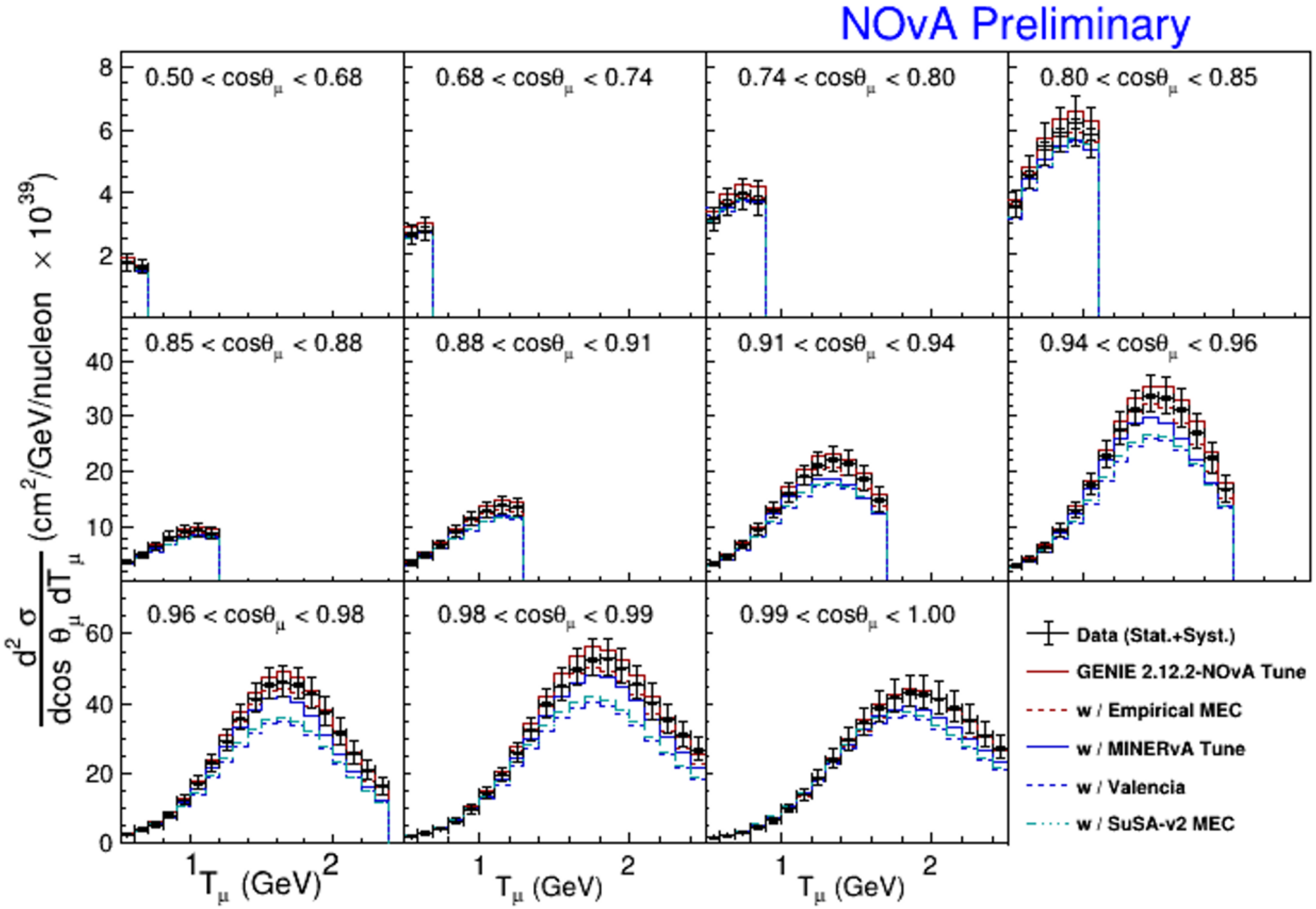
Inclusive
Select all ν_μ CC events

Muon System

ν_μ CC interactions:

- $T_p \leq 250$ MeV
- $T_\pi \leq 175$ MeV

- Events must have exactly one reconstructed track (low E_{had})
  - **Boosts 2p2h,** reduces DIS and RES
- Cross section reported at 115 kinematic points
- 12-15% uncertainty typically (dominated by flux systematic)

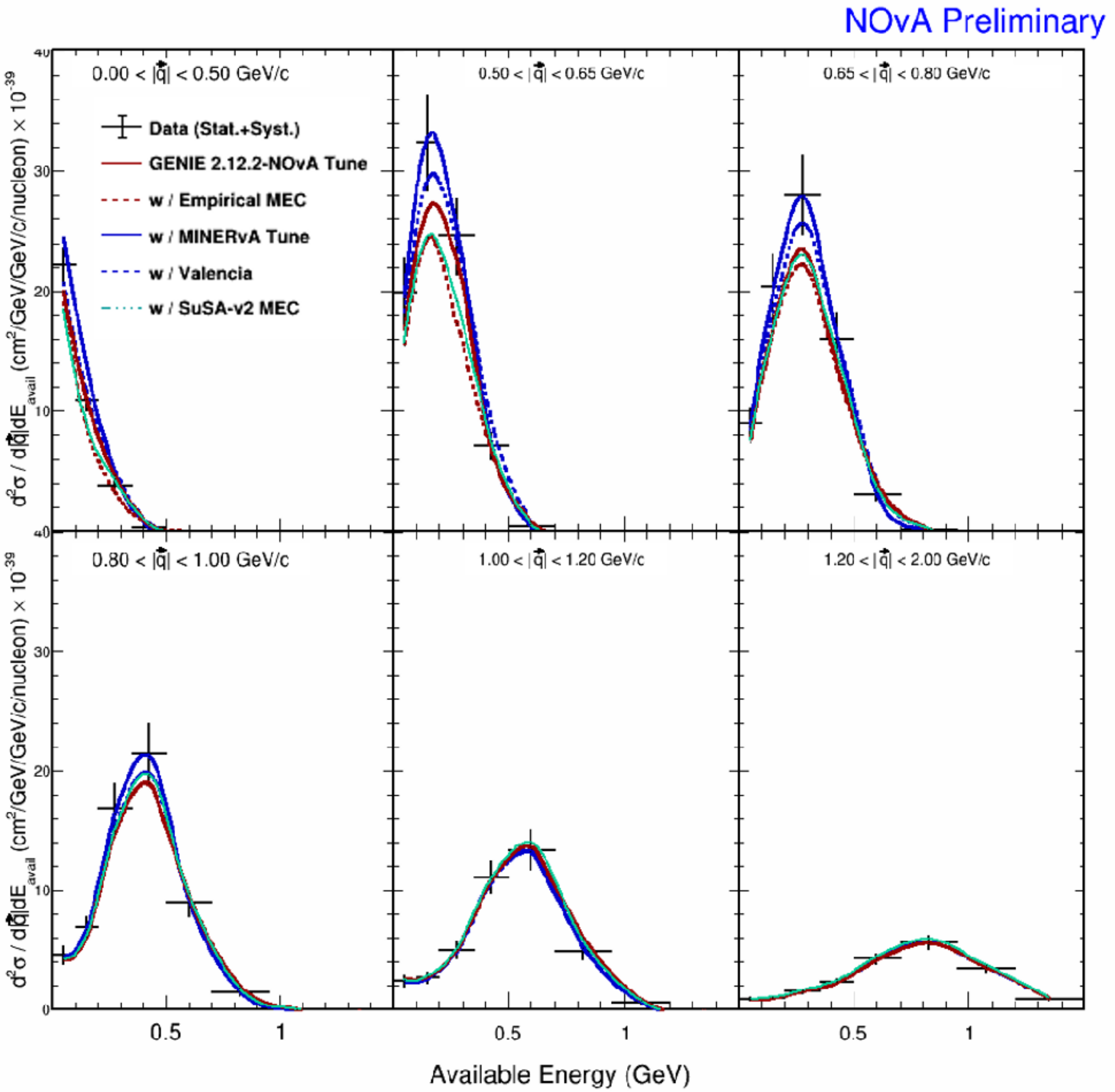


Hadronic System

ν_μ CC interactions:

- $|\vec{q}| \leq 2$ GeV/c
- $E_{Avail} \leq 2$ GeV

- Same selection as ν_μ CC inclusive analysis
- NOvA's first measurement in $|\vec{q}|$ and E_{Avail}
  - **2p2h concentrated at low values**
- Cross section reported at 67 kinematic points
- ~12% uncertainty typically (dominated by flux systematic)



Comparison of 2p-2h models to data

Large χ^2 values seen for all 2p2h models/tunes

Tuned models match data better than Valencia/SuSA-v2

2p2h Model	Muon System χ^2 (115 d.o.f.)	Hadron System χ^2 (67 d.o.f.)
GENIE v2.12.2 - NOvA Tune	200	320
Empirical MEC	190	460
Valencia w/ MINERvA Tune	340	420
Valencia	630	910
SuSA - v2	620	590

- χ^2 calculated for data vs. simulation with the various 2p2h models using full covariance matrix
- Correlations between bins are dominant contribution to χ^2
- Data release for these high-statistics analyses coming soon
  - Can explore many aspects of generator models beyond 2p2h with this data

Summary

ν_e CC inclusive

- First double differential measurement.
- Around 10k events.
- Uncertainties ~15-20% in each bin.

ν_μ CC inclusive

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

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Muon system analysis

- ~0.5M events.
- Enhanced low hadronic energy selection.
- Uncertainties ~12% in each bin.

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Future

- Active programme includes:
  - Antineutrino version of these analyses and ratios
  - Additional studies of semi-exclusive channels.
  - Data-driven techniques to reduce uncertainties.

ν_μ CC inclusive

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- 172 bins in muon kinematics.
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Hadronic system analysis

- NOvA's first measurement in $|\vec{q}|$ and E_{Avail} (2p2h concentrated at low values)
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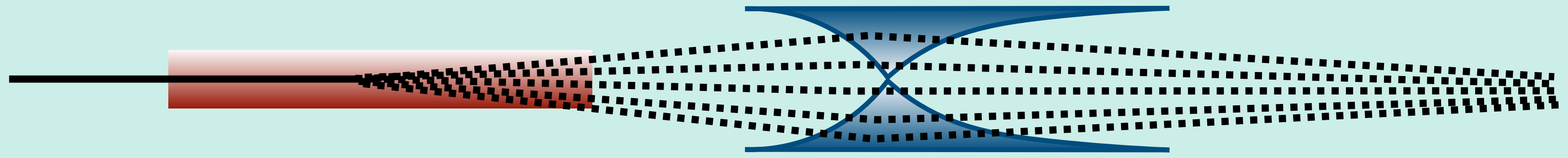
Thank you!

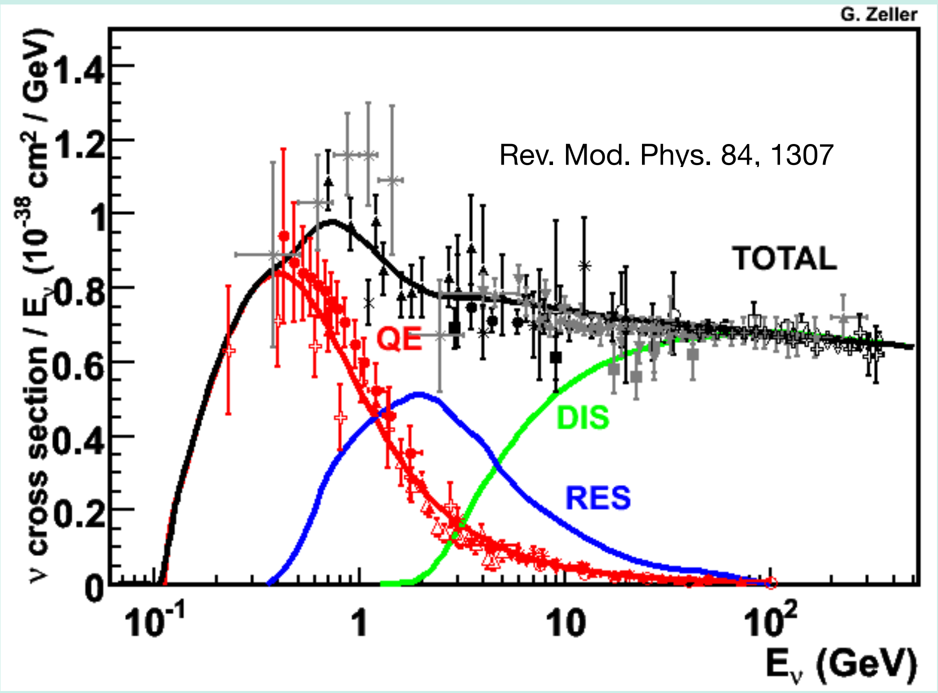
BACK UP

NOvA simulation

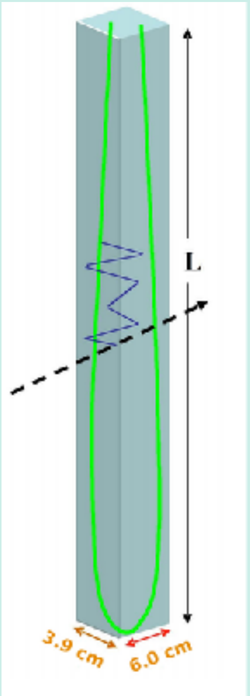


Beamline and Flux: G4NuMI

ν-A modelling: GENIE



Detector response: GEANT4

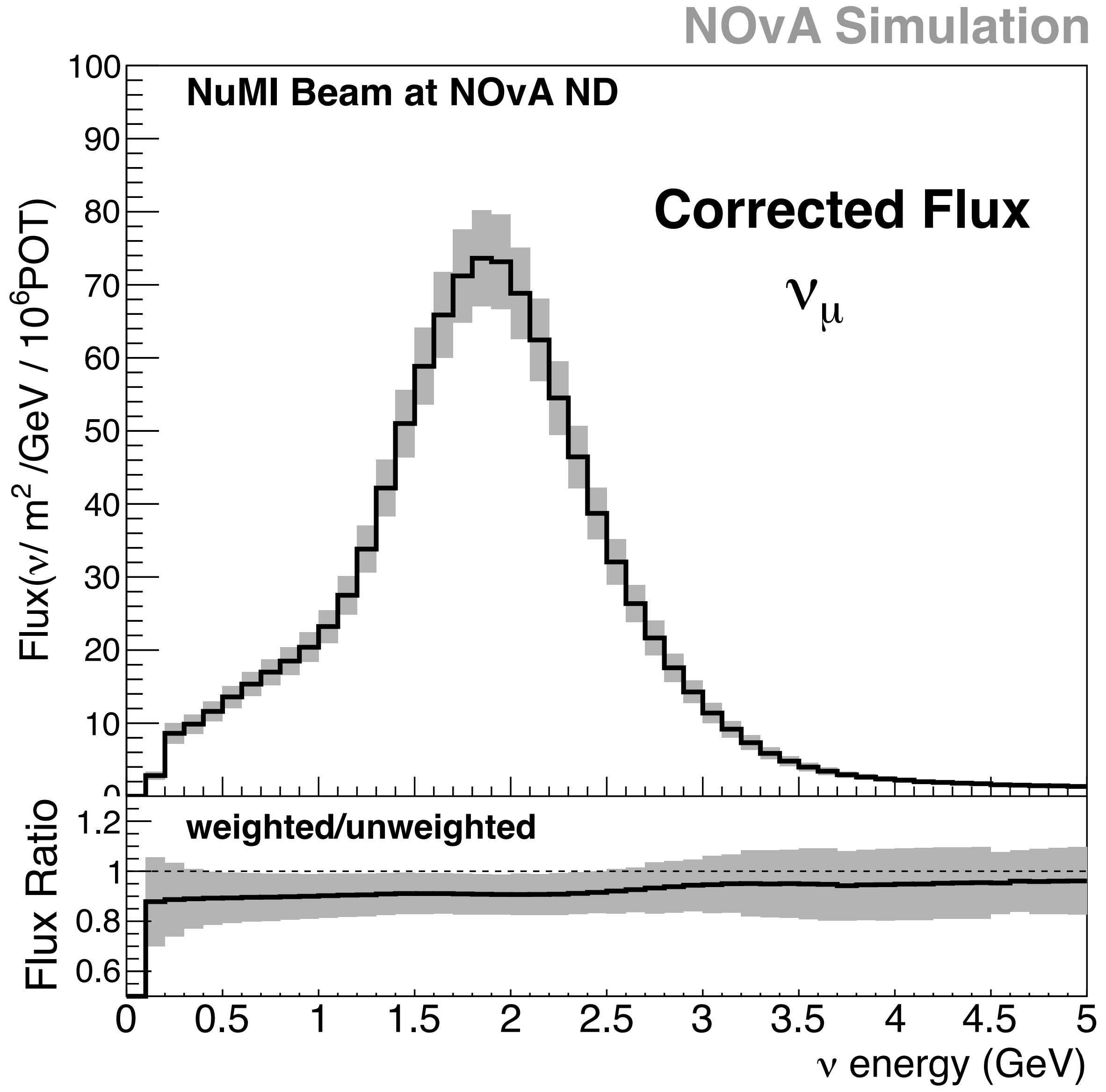


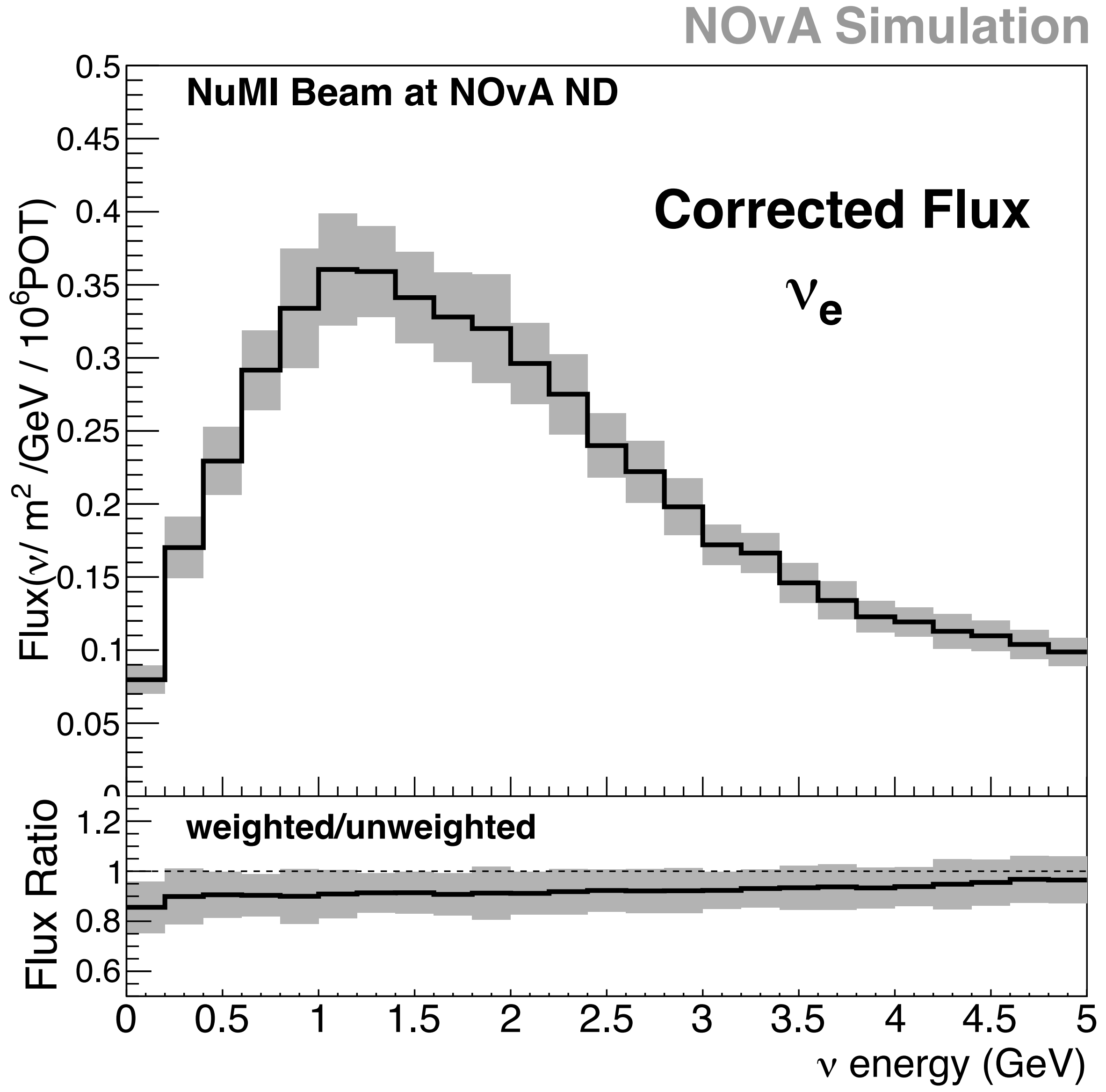
Readout electronics & DAQ: Custom simulation routines

Hadron production model constrained with external measurements on thin target.

Resulting uncertainty ~10% in normalisation.

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



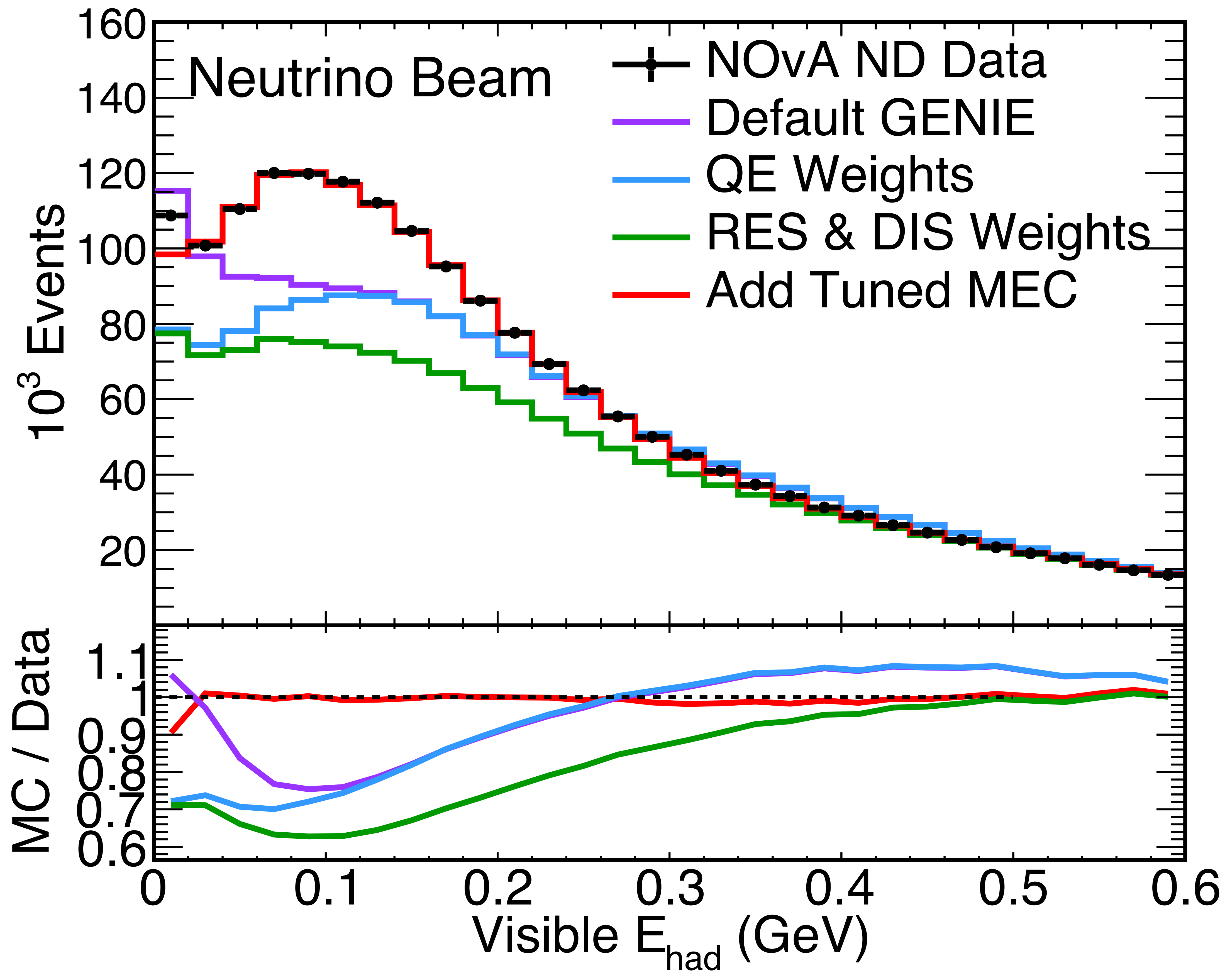


Cross section measurements

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

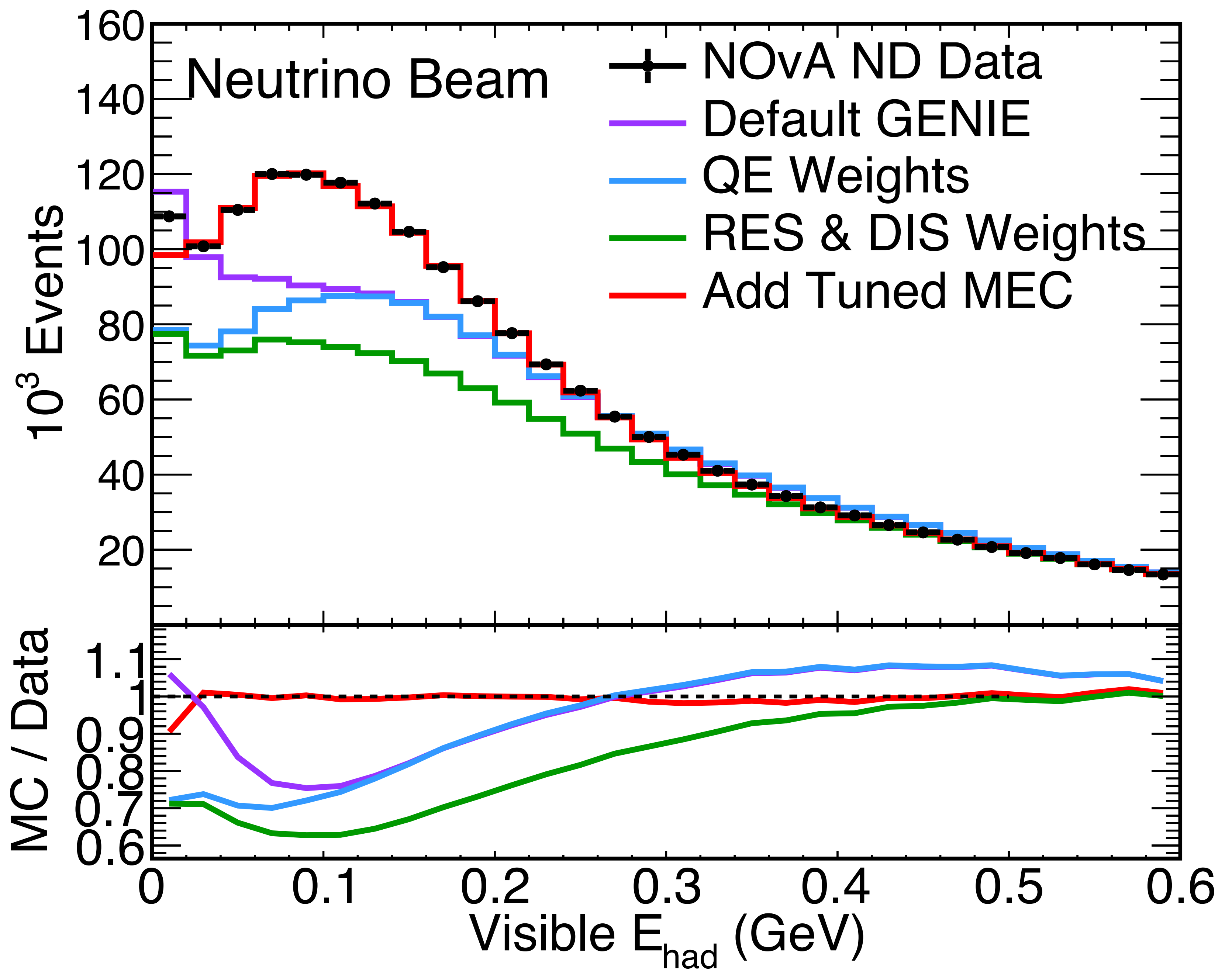
Cross Section	Events	Purity	Targets	Flux	Efficiency

- 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)

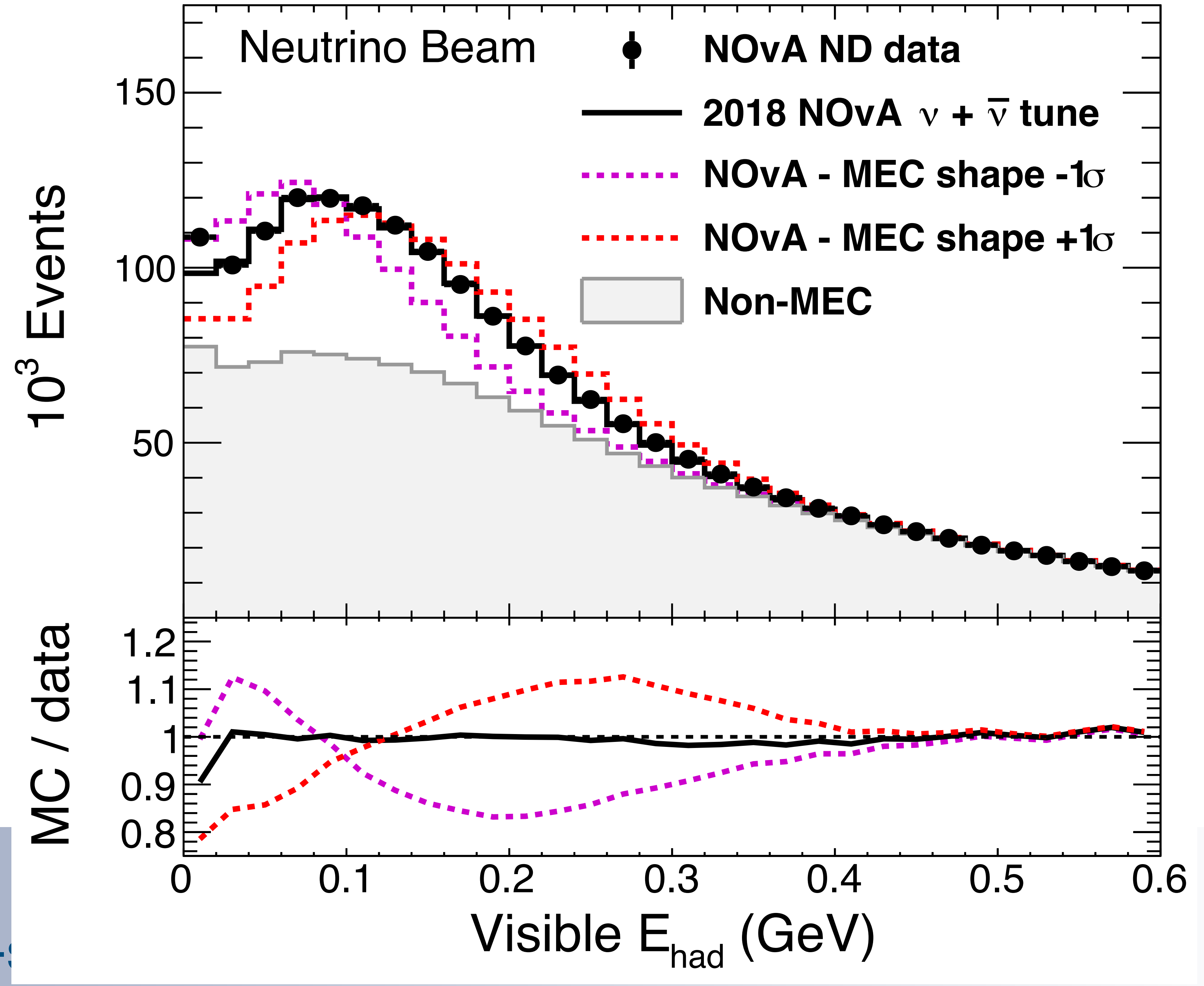


2018 NOvA tune

- 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.

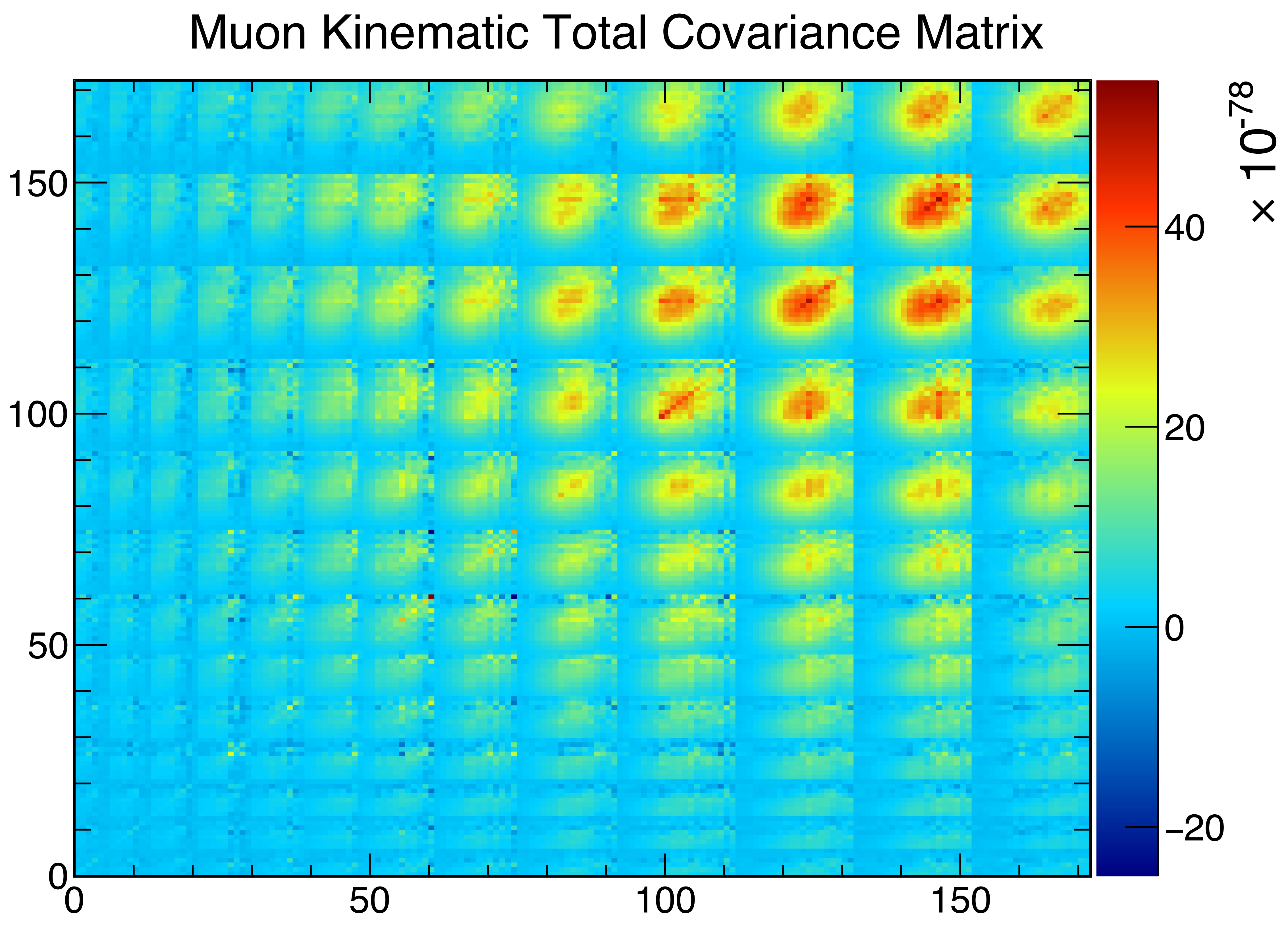


NOvA Preliminary



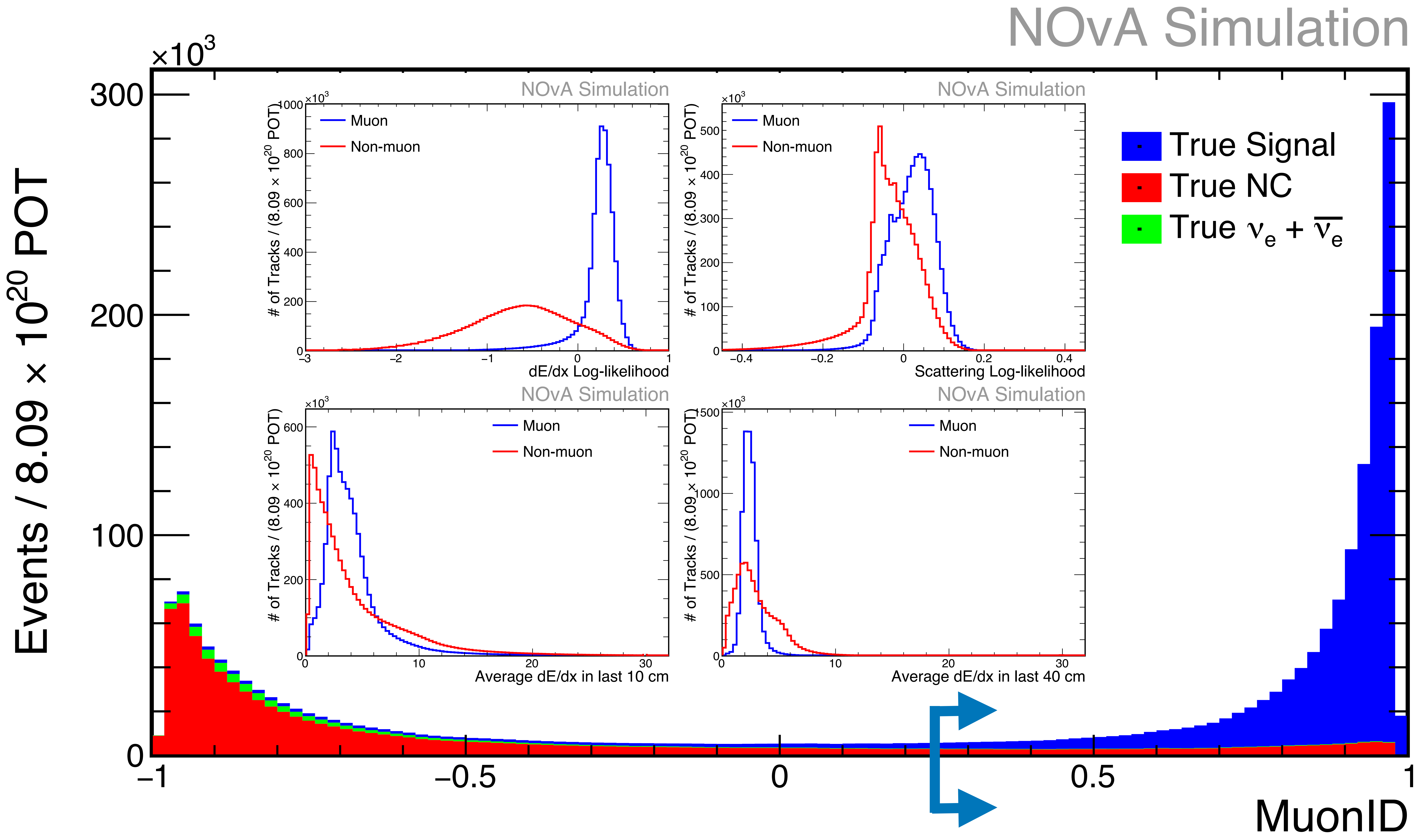
NuMu CC inclusive

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

Particle ID

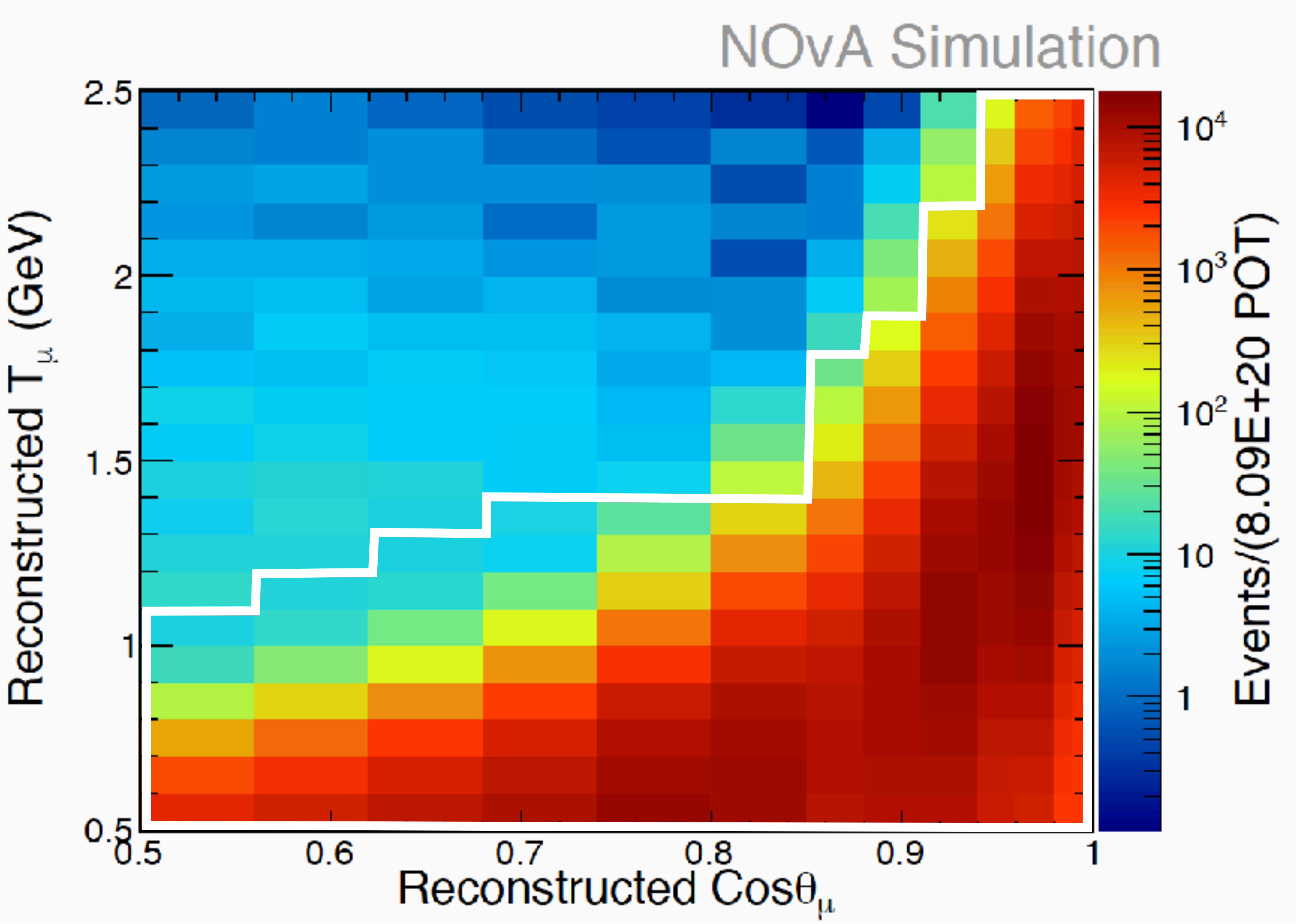


- Preselection: events fully contained and with vertex in fiducial volume.
- Muon ID calculated with a Boosted Decision Tree.
- Cut value corresponds to minimum uncertainties on cross section measurement.
- Resulting sample has 86% purity and ~90% efficiency with respect to preselection.

Measurement strategy

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

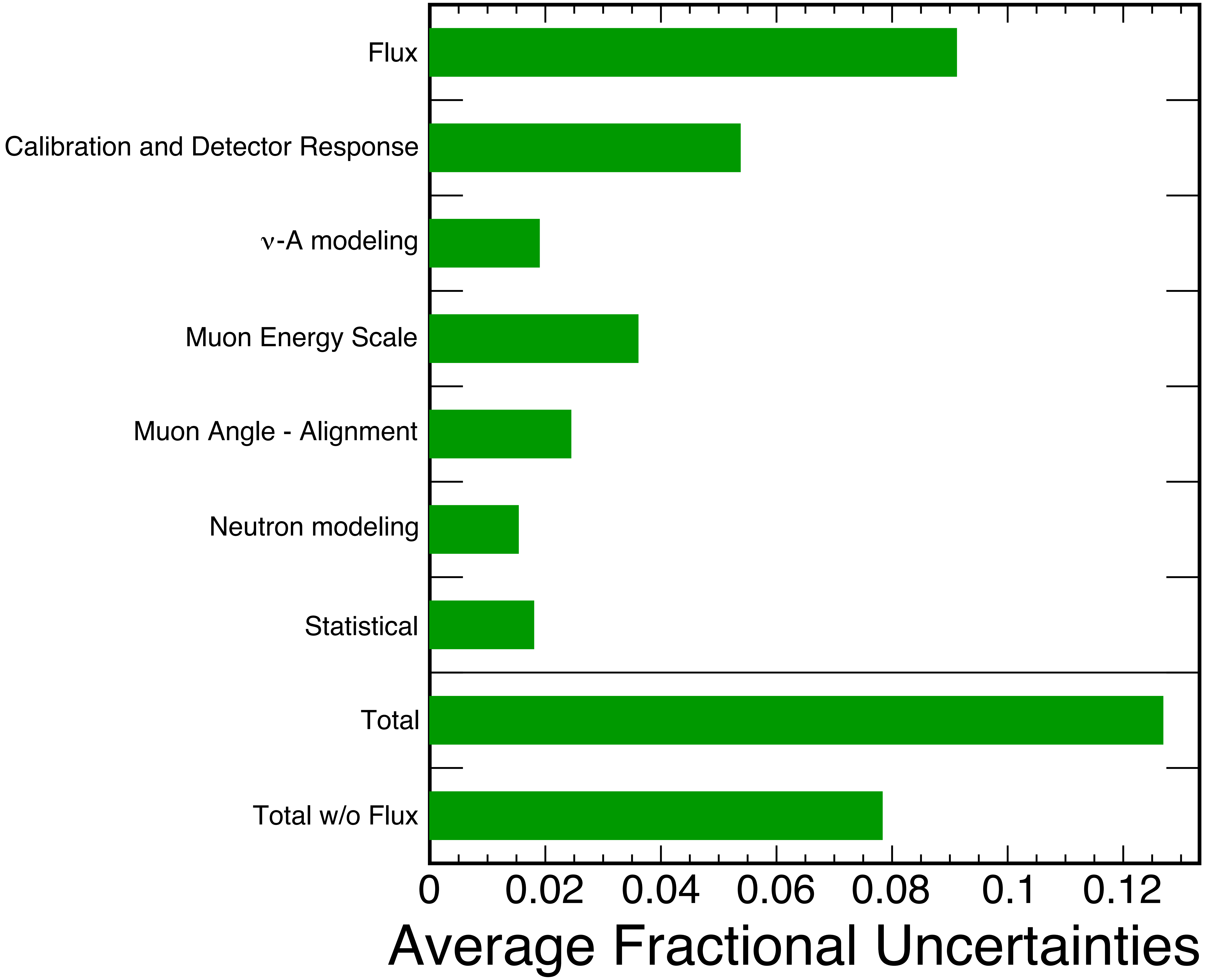
- Flux-averaged double differential cross section in 172 bins (white outline).
- Selection purity and efficiency corrections applied in 3D space (T_μ, $\cos\theta_\mu$, E_{avail}).
- E_{avail} (available energy): total energy of all observable final state hadrons.
- This reduces potential model dependence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



Fractional Uncertainties

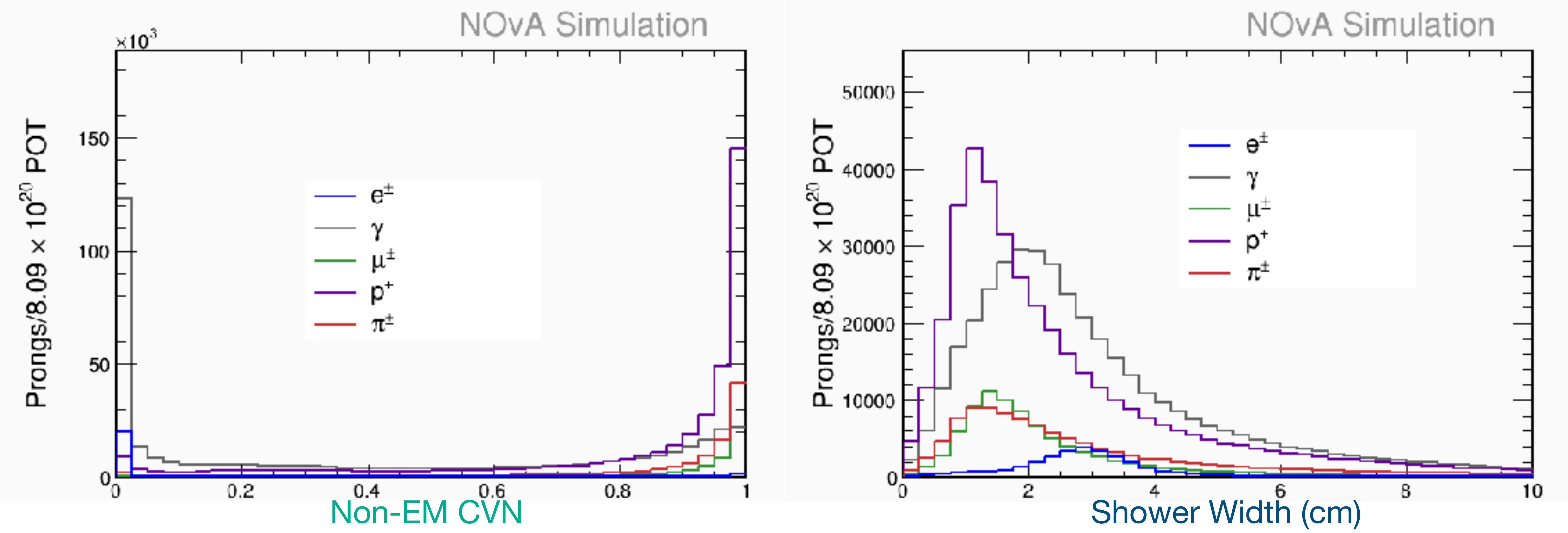
NOvA Preliminary

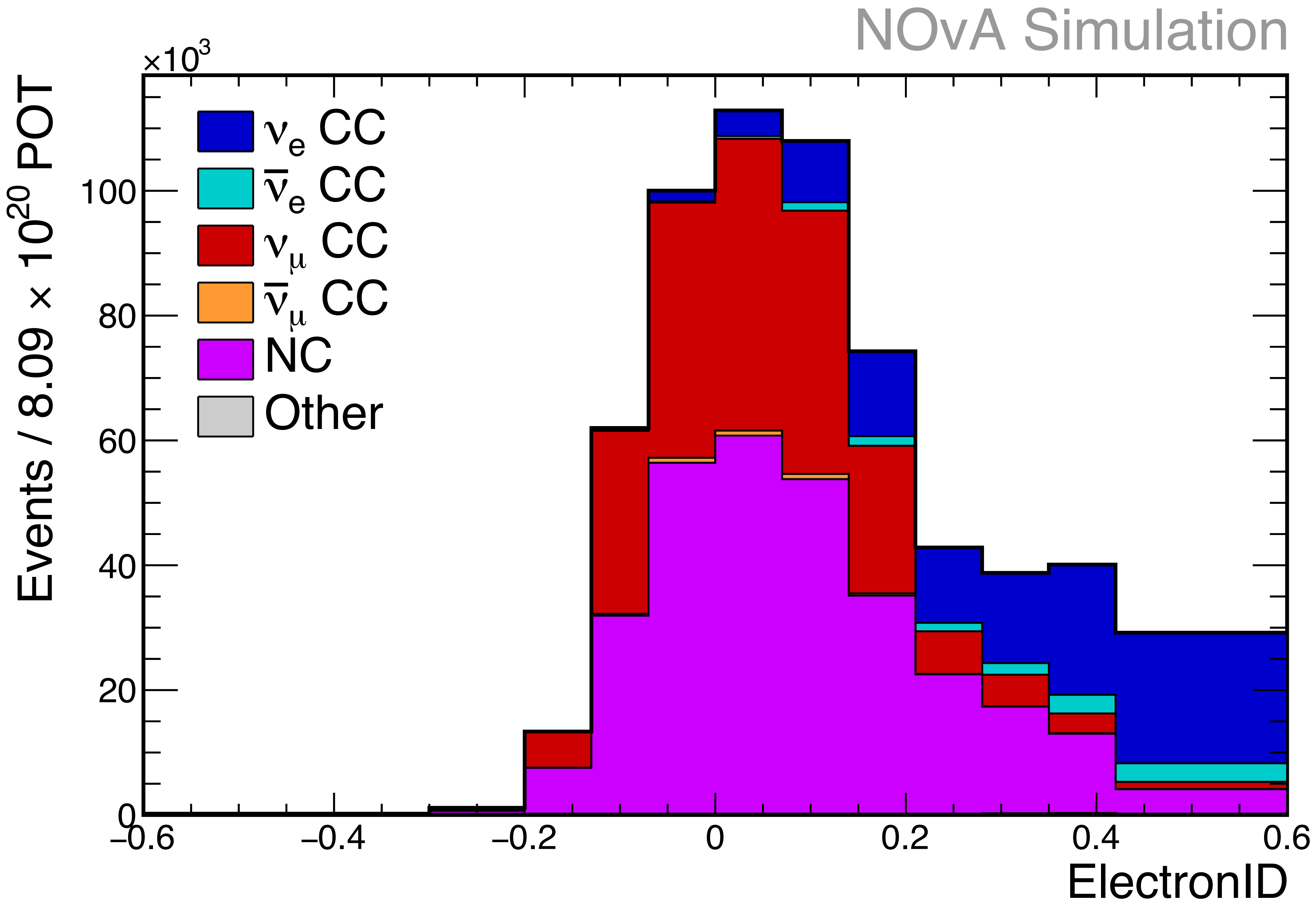
- Weighted average uncertainties to extracted cross section value.
- Flux is a normalisation uncertainty ~9%.
- Statistical uncertainties at level of a few %.
- Interaction modeling uncertainties are sub-dominant.
- Measurements has typical total uncertainties around 12% in each bin.



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.





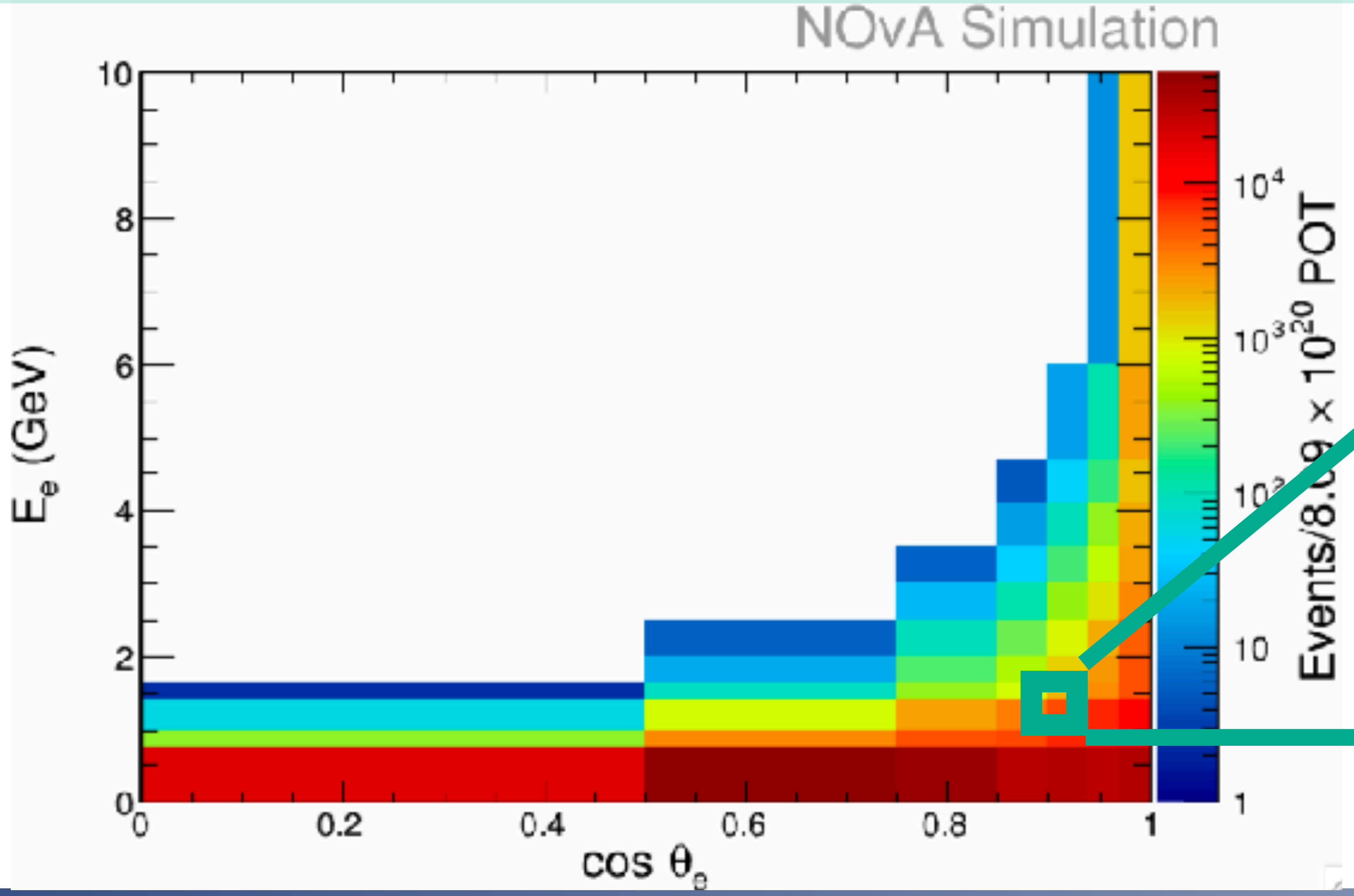
First ν_e CC double differential measurement

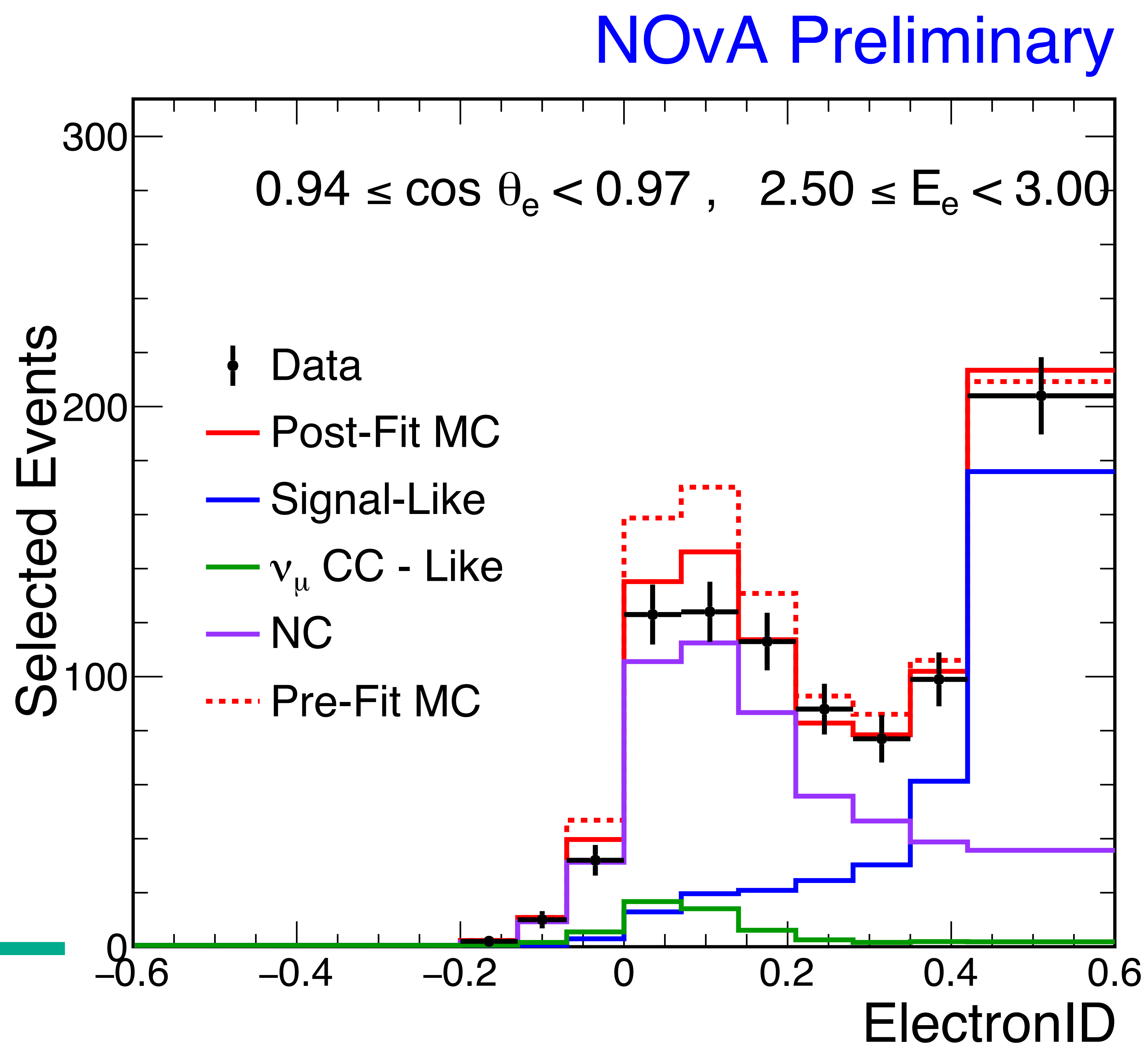
$$\left(\frac{d^2\sigma}{d\cos\theta_e dE_e}\right)_i = \sum_j \left(\frac{U^{-1}_{ij}(N^{\text{sel}}(\cos\theta_e, E_e)_j - N^{\text{bkg}}(\cos\theta_e, E_e)_j)}{N_t\Phi\epsilon(\cos\theta_e, E_e)_{ik}\Delta\cos\theta_{e_i}\Delta E_{e_i}}\right)$$

- 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.

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

$i = (E_e, \cos\theta_e, \text{ElectronID})$





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.