Recent NOvA cross section results

Travis Olson

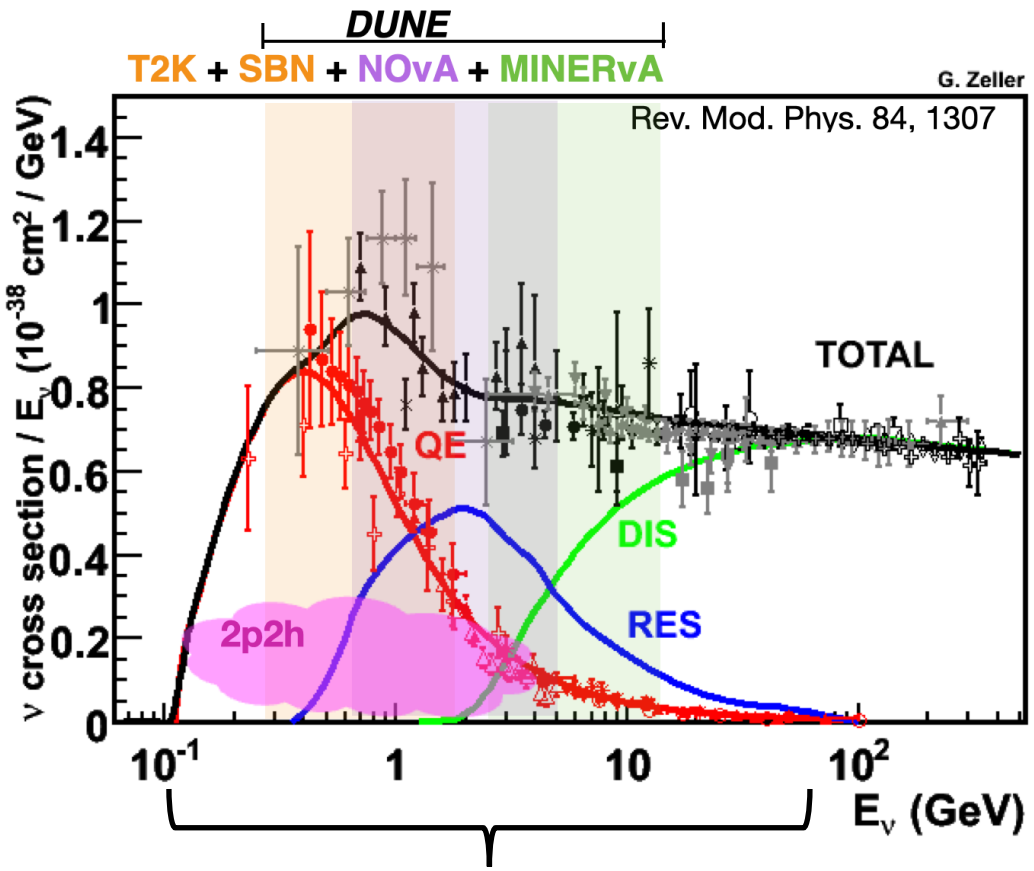
for the NOvA collaboration

WIN 25

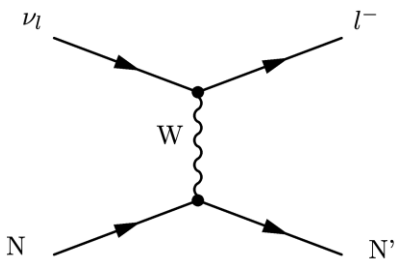
Overview

- Neutrino
  - 2D low hadronic energy semi-inclusive cross section in leptonic variables
  - 2D inclusive cross section in hadronic and leptonic variables
- Anti-neutrino
  - 3D Inclusive cross section in leptonic and hadronic variables

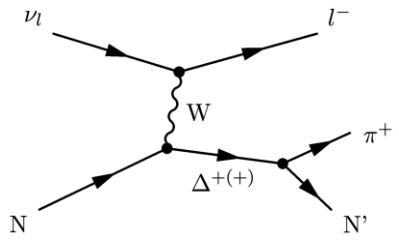
Neutrino-nucleon interactions



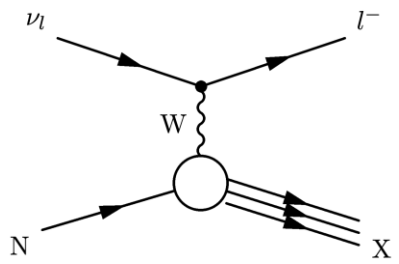
The transition region between interaction processes



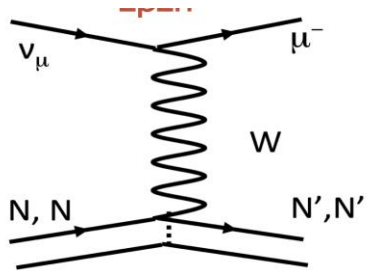
CC QE



CC Res



CC DIS



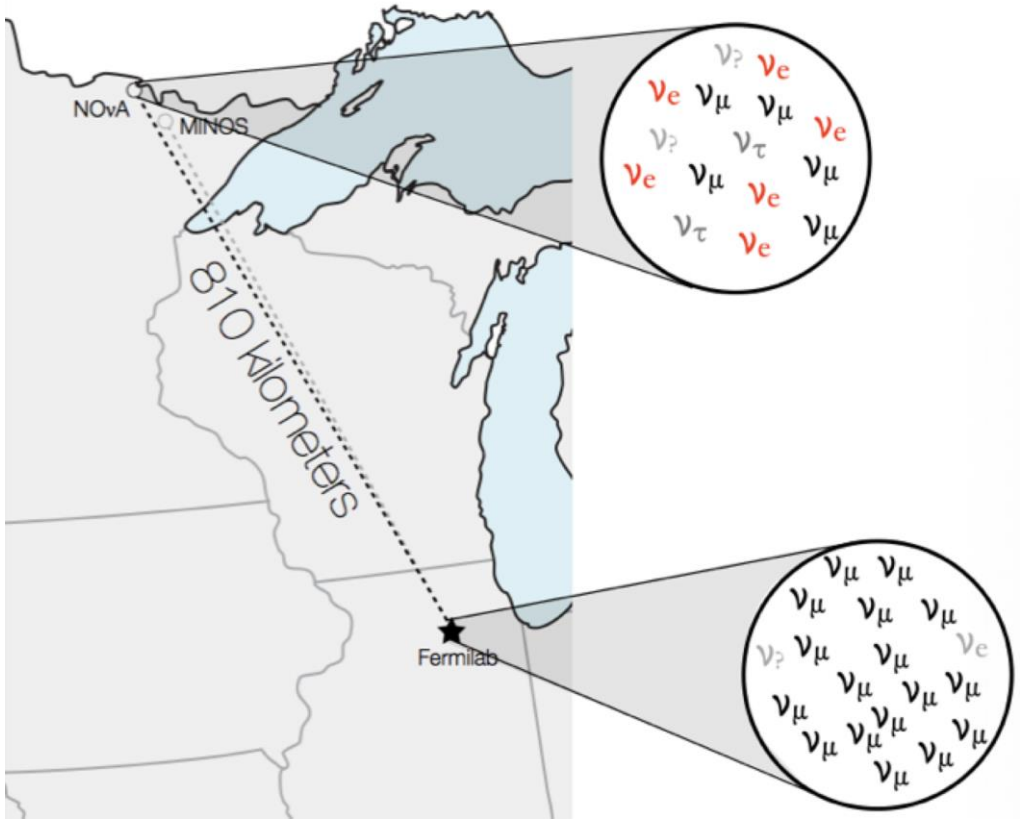
CC 2p2h

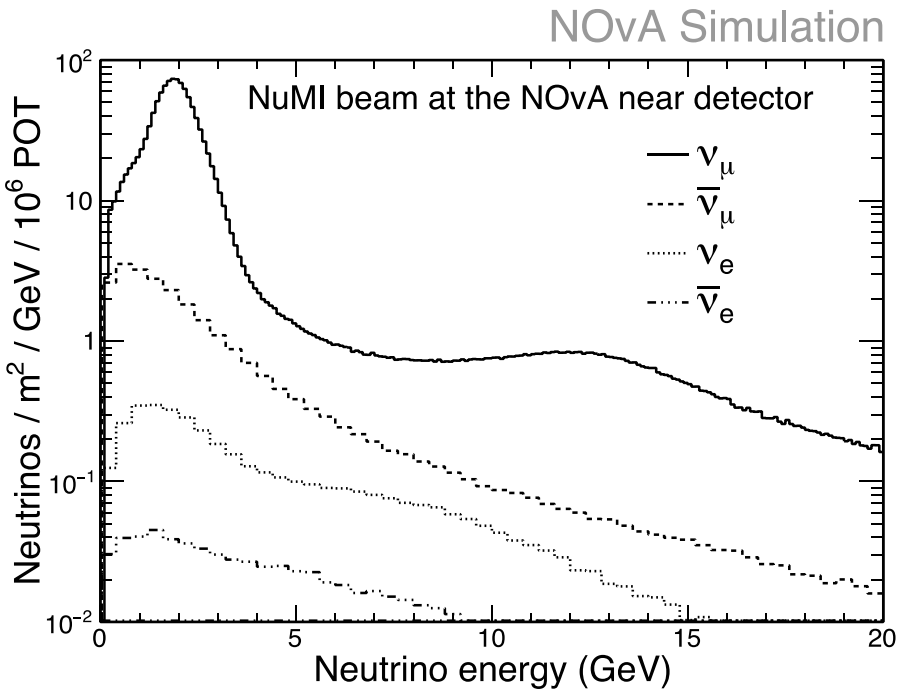
The NOvA experiment

NOvA is a long-baseline neutrino oscillation experiment

2 detectors: 14.6 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





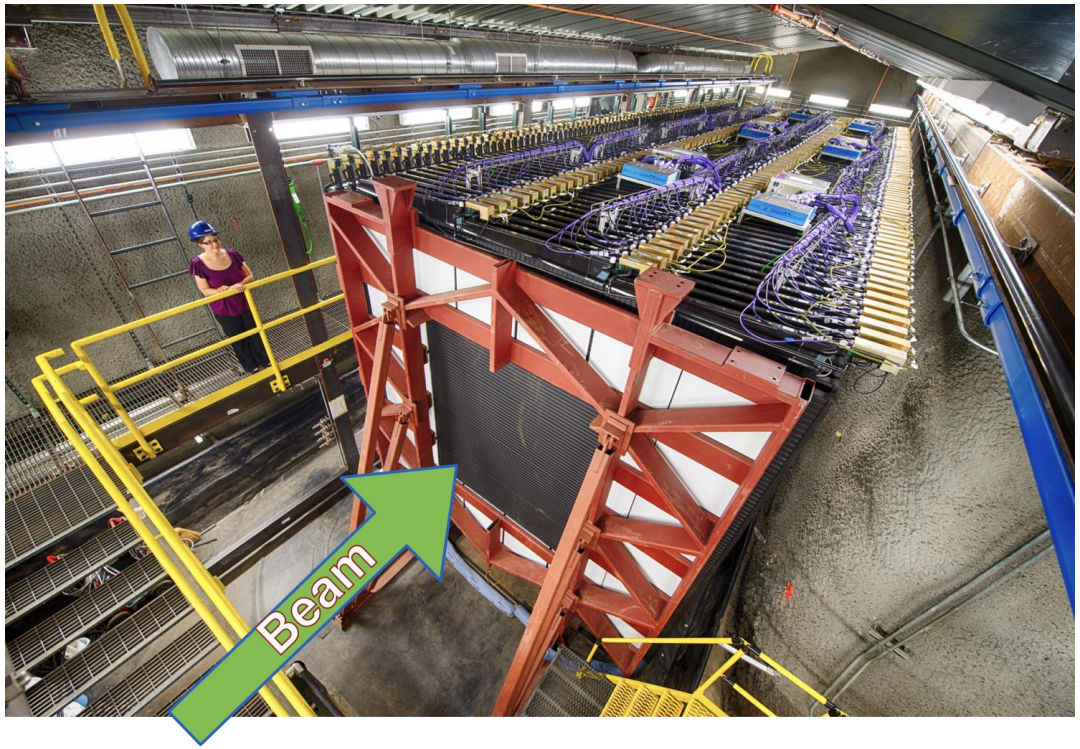
94% pure ν_μ, 5% $\bar{\nu}_\mu$, and 1% $\nu_e + \bar{\nu}_e$ in neutrino mode

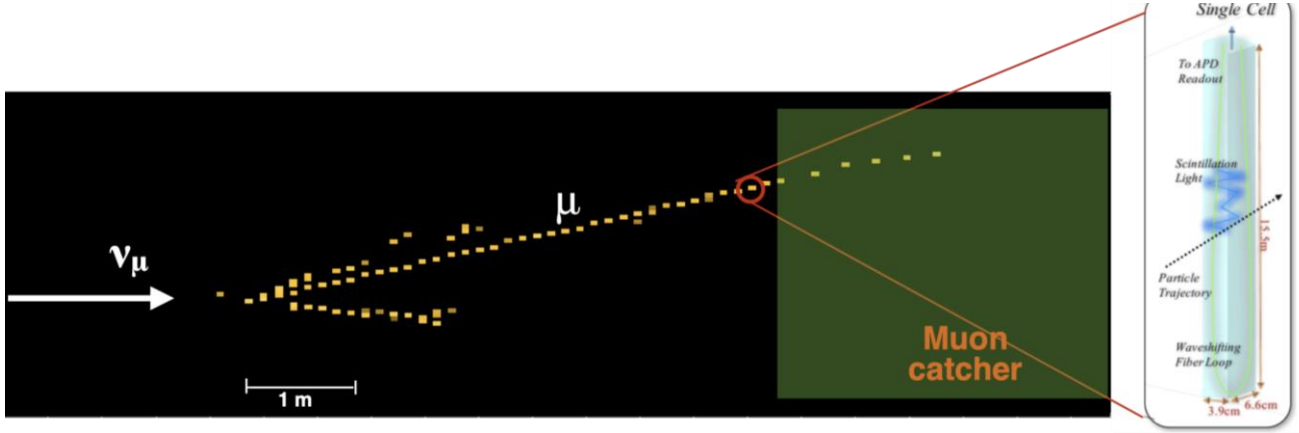
92% pure $\bar{\nu}_\mu$, 7% ν_μ, and 1% $\bar{\nu}_e + \nu_e$ in antineutrino mode

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

The 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

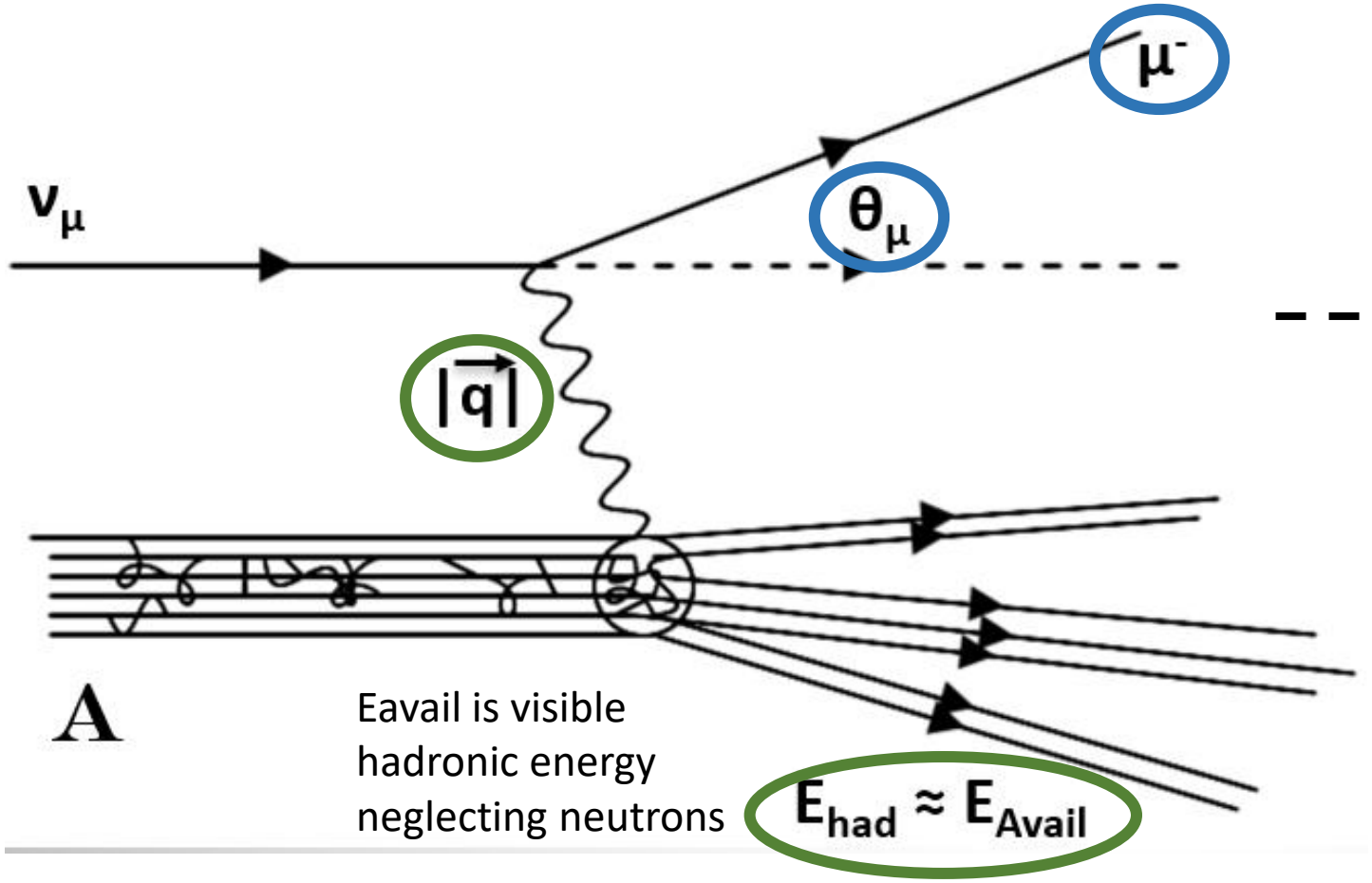
Low-Z, fine-grained: 1 plane ~ 0.15 X_0

C	Cl	H	O	Ti
67%	16%	11%	3%	3%

Two Complimentary ν_μ CC Cross Section results:

Both double differential

Both built on previous ν_μ CC Cross Section results: Phys. Rev. D **107**, 052011 https://doi.org/10.1103/PhysRevD.107.052011



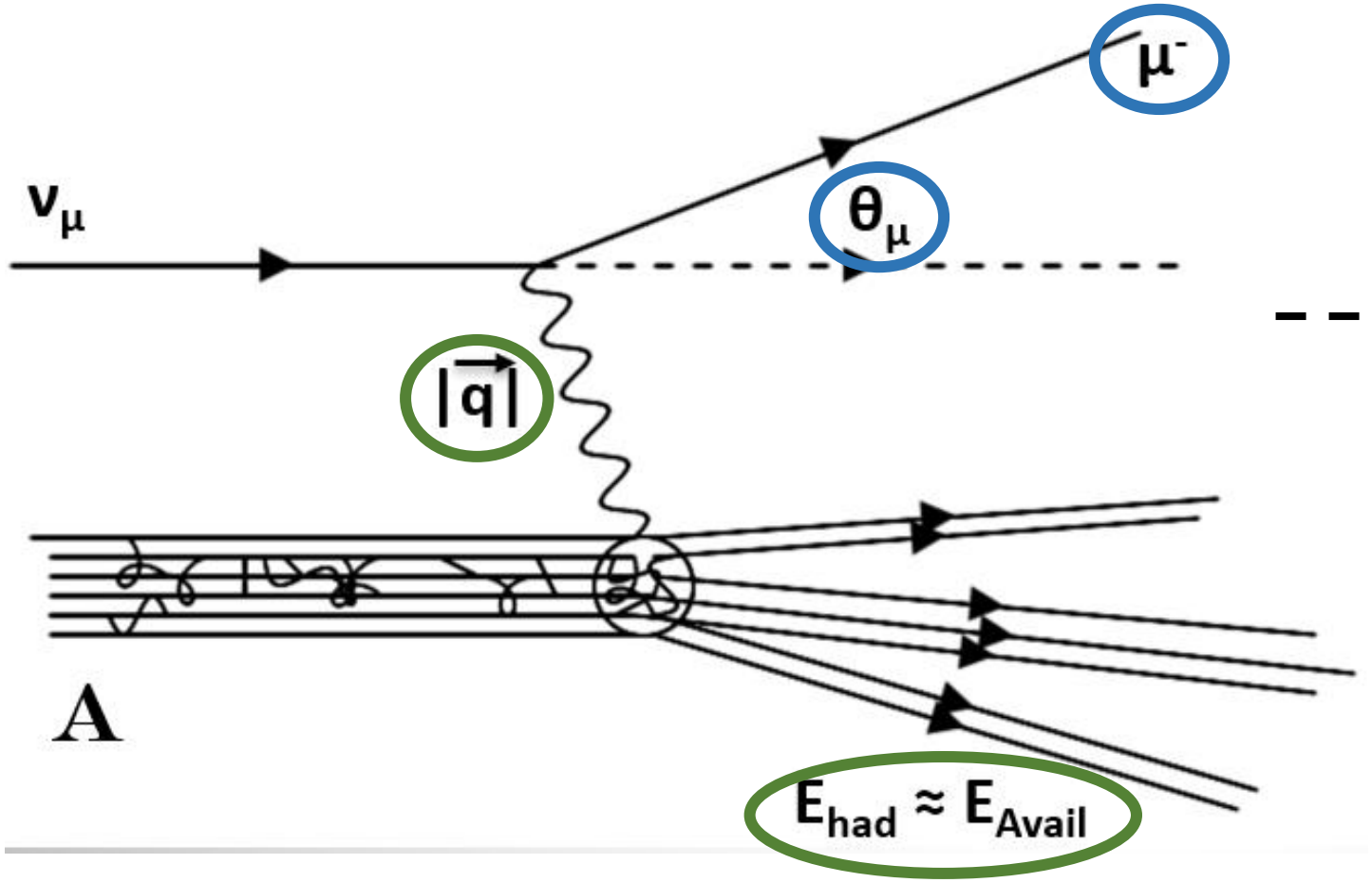
https://arxiv.org/abs/2410.10222

Leptonic system	Muon Energy Vs Muon Angle

https://doi.org/10.1103/PhysRevD.111.052009

Hadronic system	3-momentum transfer Vs Available energy

Two complimentary νμ CC ross section results:



https://arxiv.org/abs/2410.10222

Leptonic system	Semi-Inclusive Selects events with low hadronic energy

https://doi.org/10.1103/PhysRevD.111.052009

Hadronic system	Inclusive Select all events with a muon

ν_μ CC low hadronic energy in muon variables

This analysis aims to select a sample of ν_μ CC interactions with enhanced QE and 2p2h components

Res and DIS processes are more likely to produce events with > 1 track

Signal: *ν_μ CC in the fiducial volume with*

T_{proton}^{max} = 250 MeV

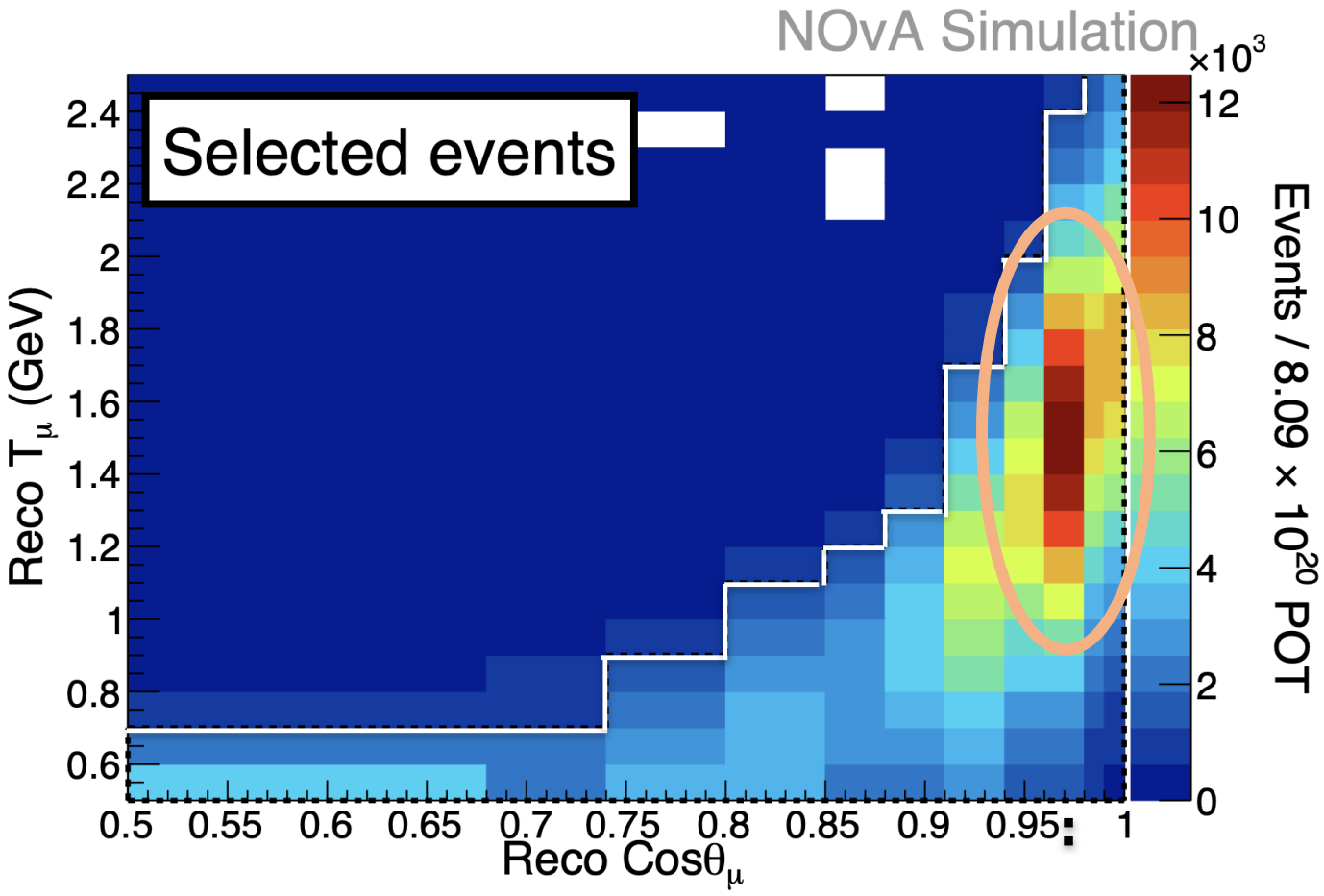
T_{pion}^{max} = 175 MeV

Selection:

ν_μ CC with 1 track

In the fiducial volume

Contained within the detector

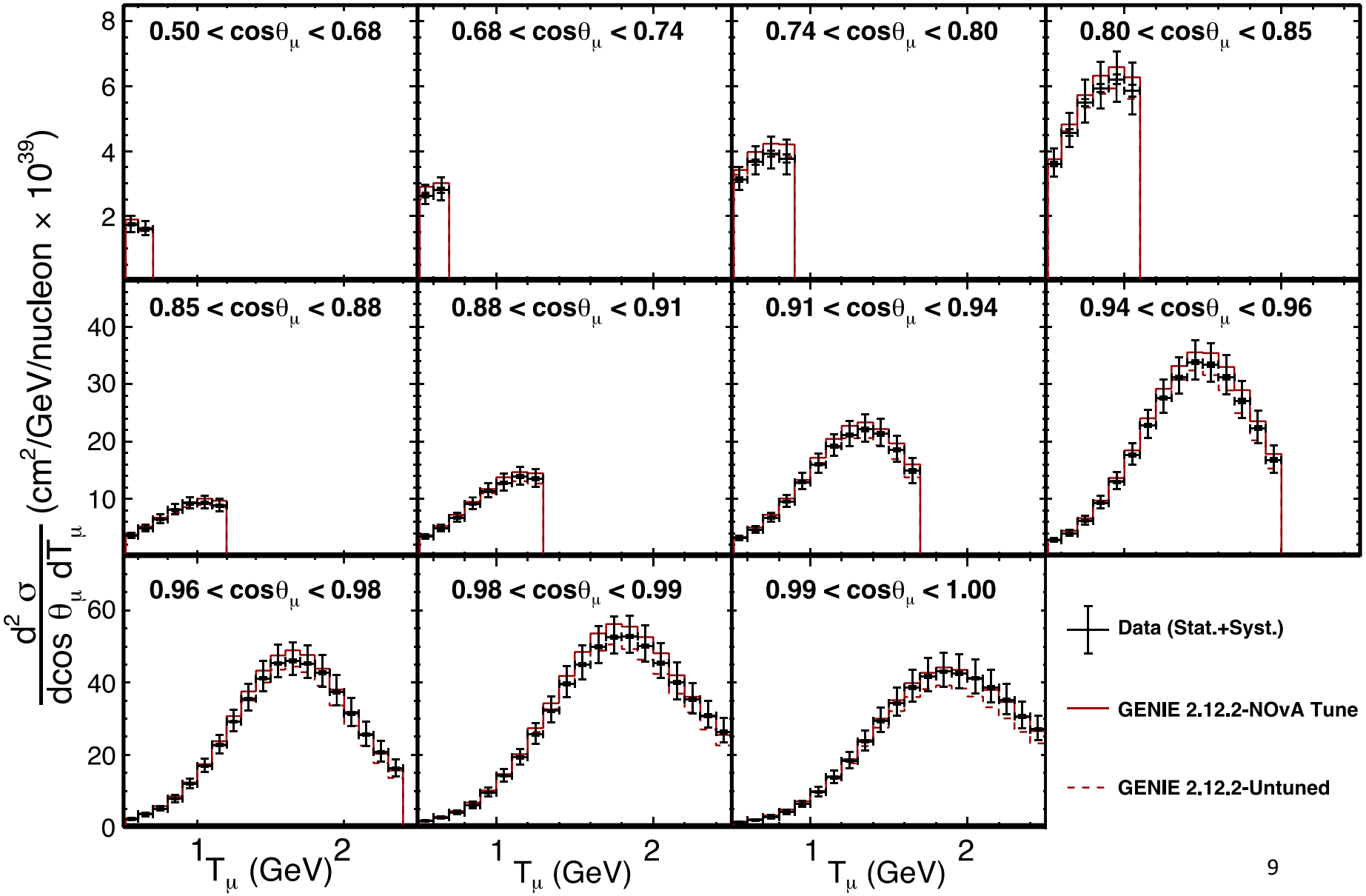


Muon kinematic variable results

Cross section is reported in 115 kinematic bins

12-15% uncertainty

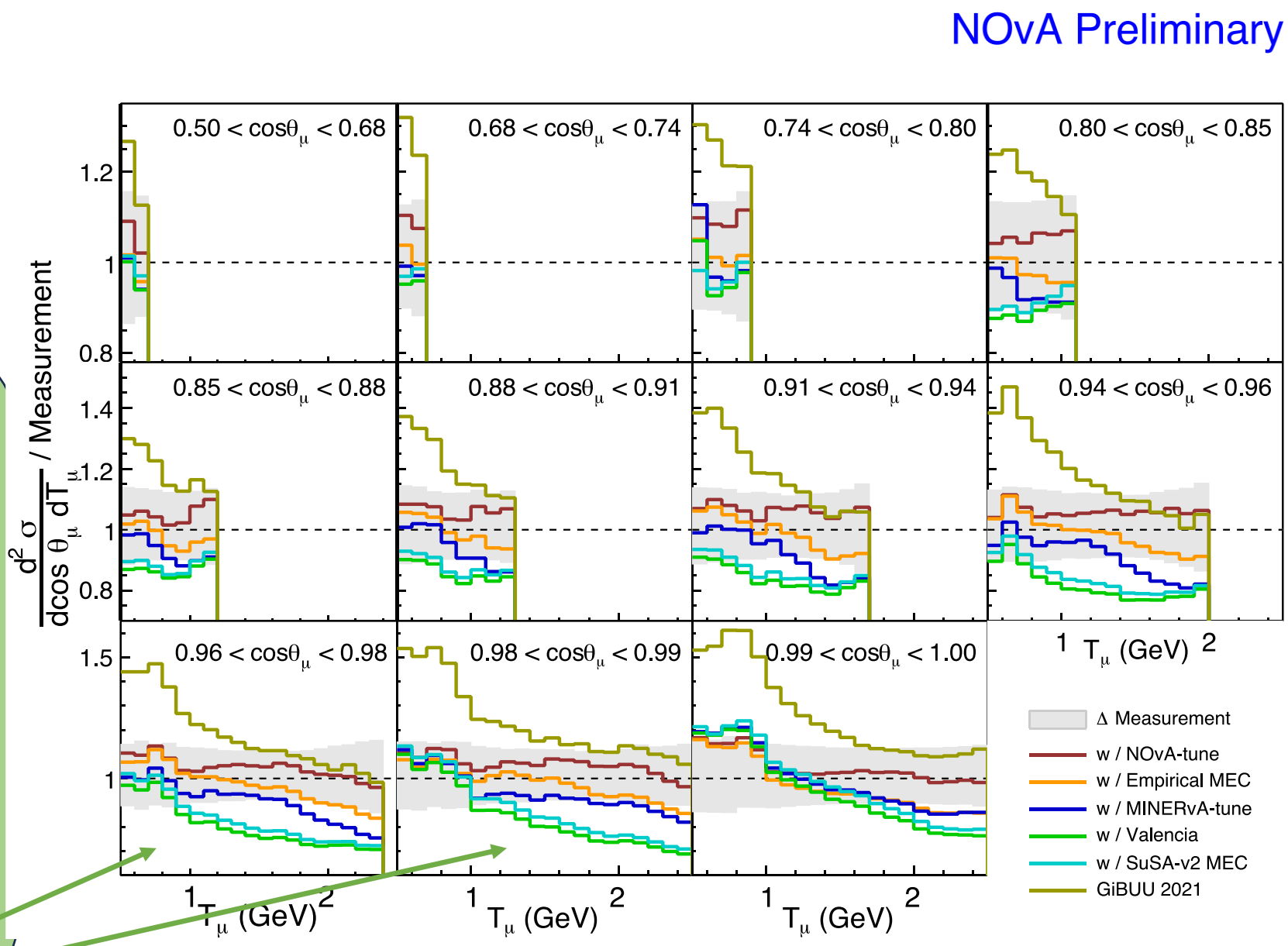
Flux is the dominant systematic



Comparison to 2p2h models

Ratio of simulations over the measured data: no model reproduces our measurement

- The NOvA-tune overestimates most bins' data
- The MINERvA-tune, Empirical MEC, Valencia, and SuSAv2 tend to predict lower values
- GiBUU overestimates most of the data
- Models tend to under-predict in bins that are more forward and at higher muon momenta.



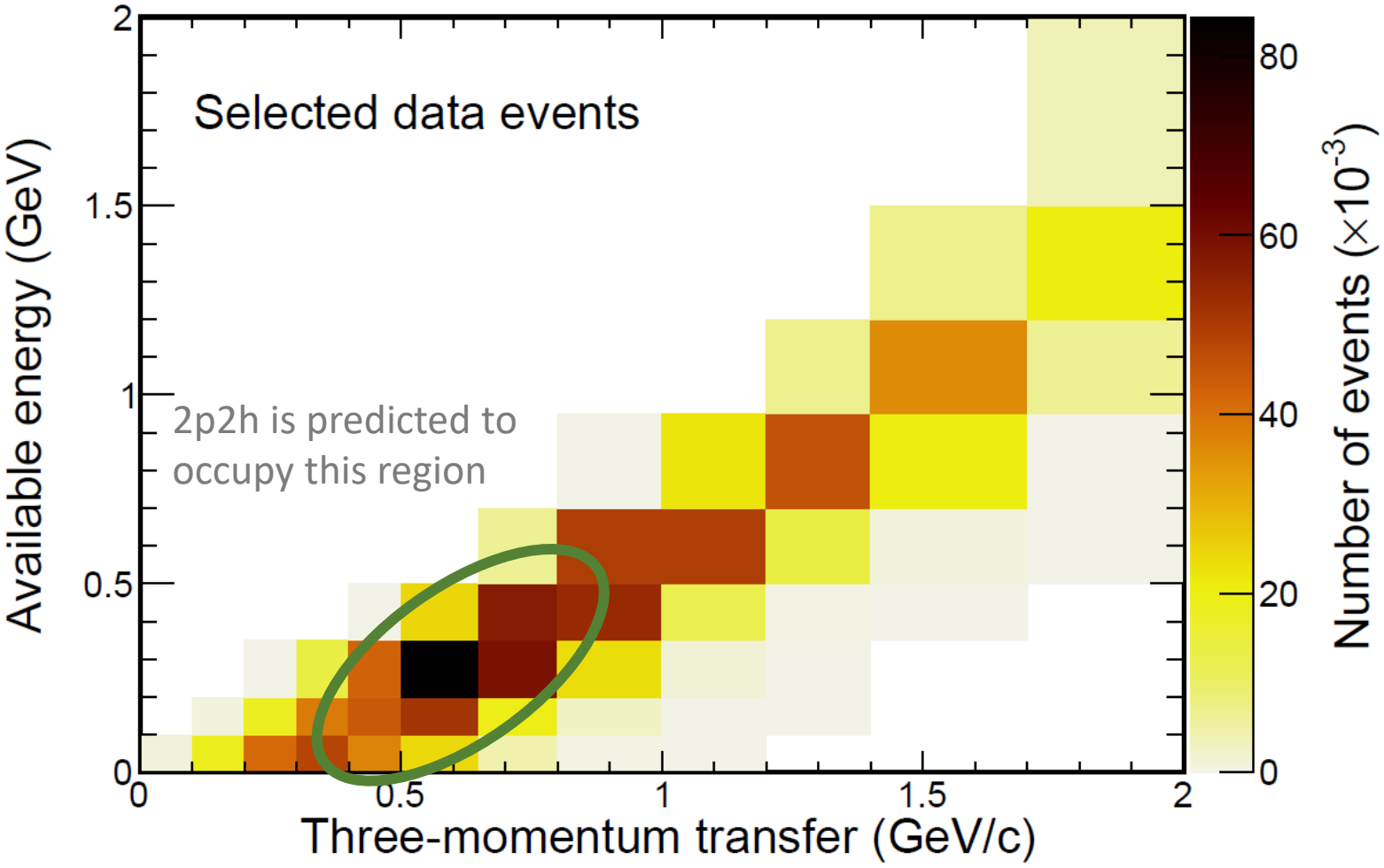
ν_μ CC in hadronic variables

NOvA's first measurement in |q| vs E_{Avail}

Signal: *ν_μ CC in the fiducial volume with*

Selection:
ν_μ CC
In the fiducial volume
Contained within the detector

~1 Million data events selected



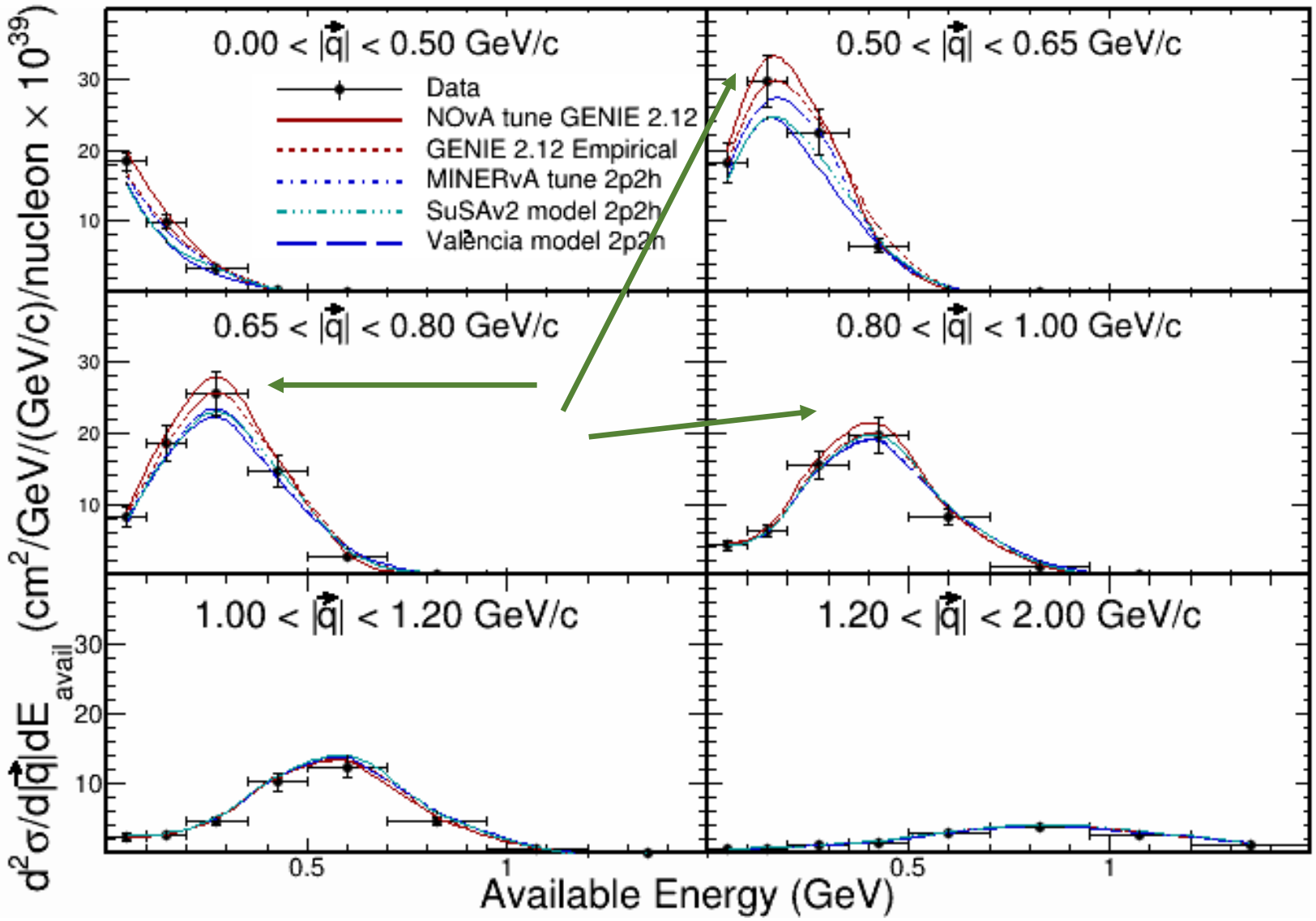
Hadronic variables results

Cross section is reported in 61 kinematic bins

~12% uncertainty

Flux is the dominant systematic

- The NOvA-tune overestimates most bins' data
- The MINERvA-tune, Empirical MEC, Valencia, and SuSAv2 tend to predict lower values

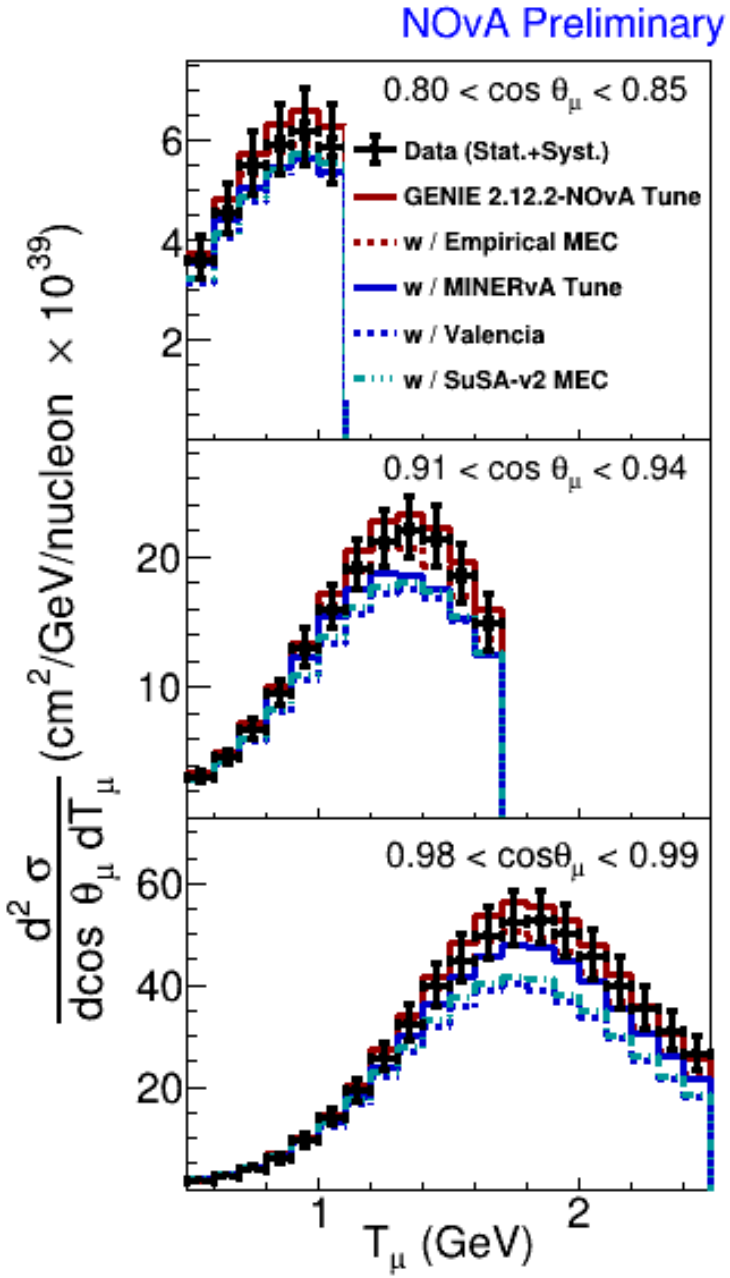


The results are compared to various 2p2h implementations using the same underlying GENIE models for other 1p1h processes

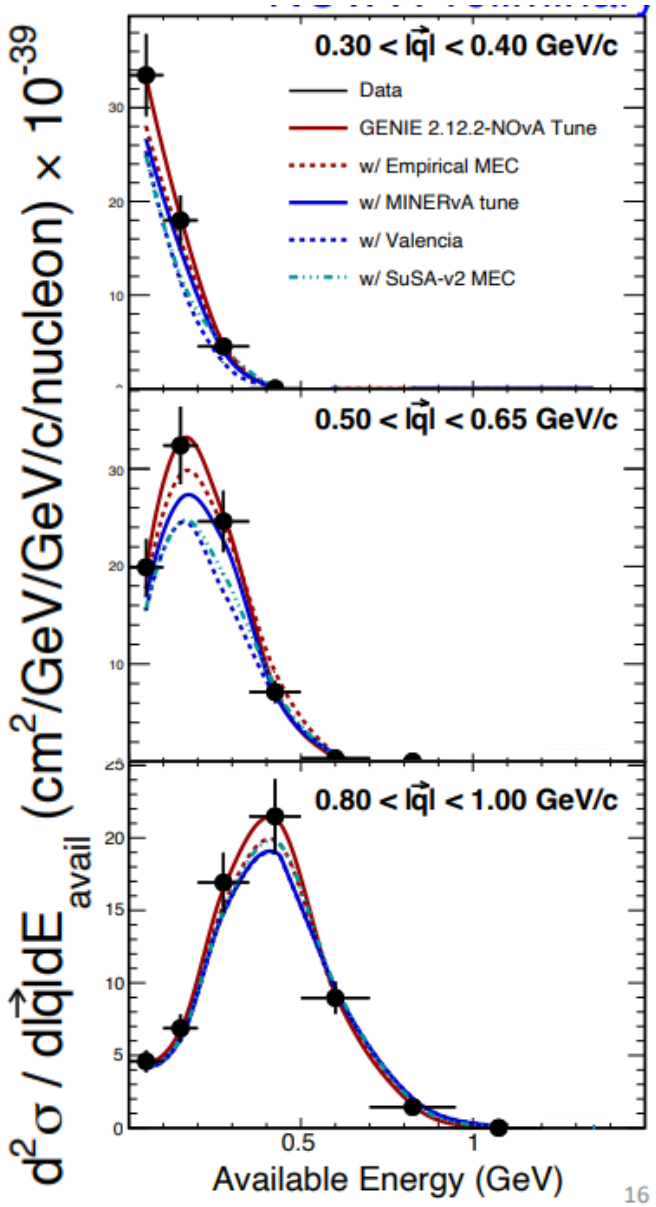
2p2h Model/tune	Muon kinematics NDF: 115	Hadronic Variables NDF: 61
Empirical MEC	190 (209)	514 (545)
MINERvA-tune	330 (386)	1220 (1390)
NOvA-tune	197 (178)	51 (50)
Valencia	510 (756)	2065 (2654)
SuSA-v2	499 (698)	1610 (876)

We see a preference for experimental tunes over theoretical models, but tension between everything.

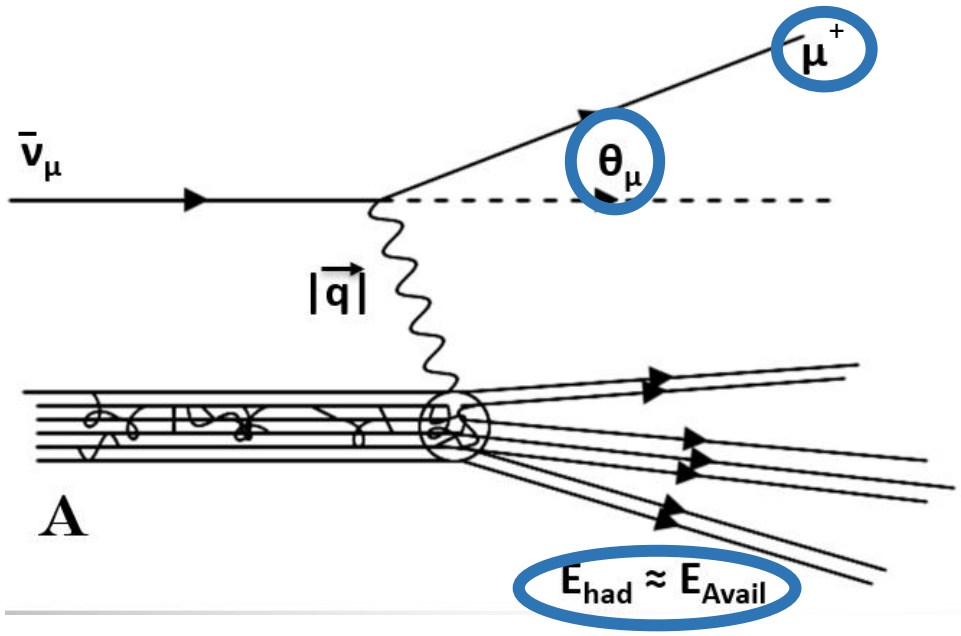
Muon kinematics



Hadronic variables



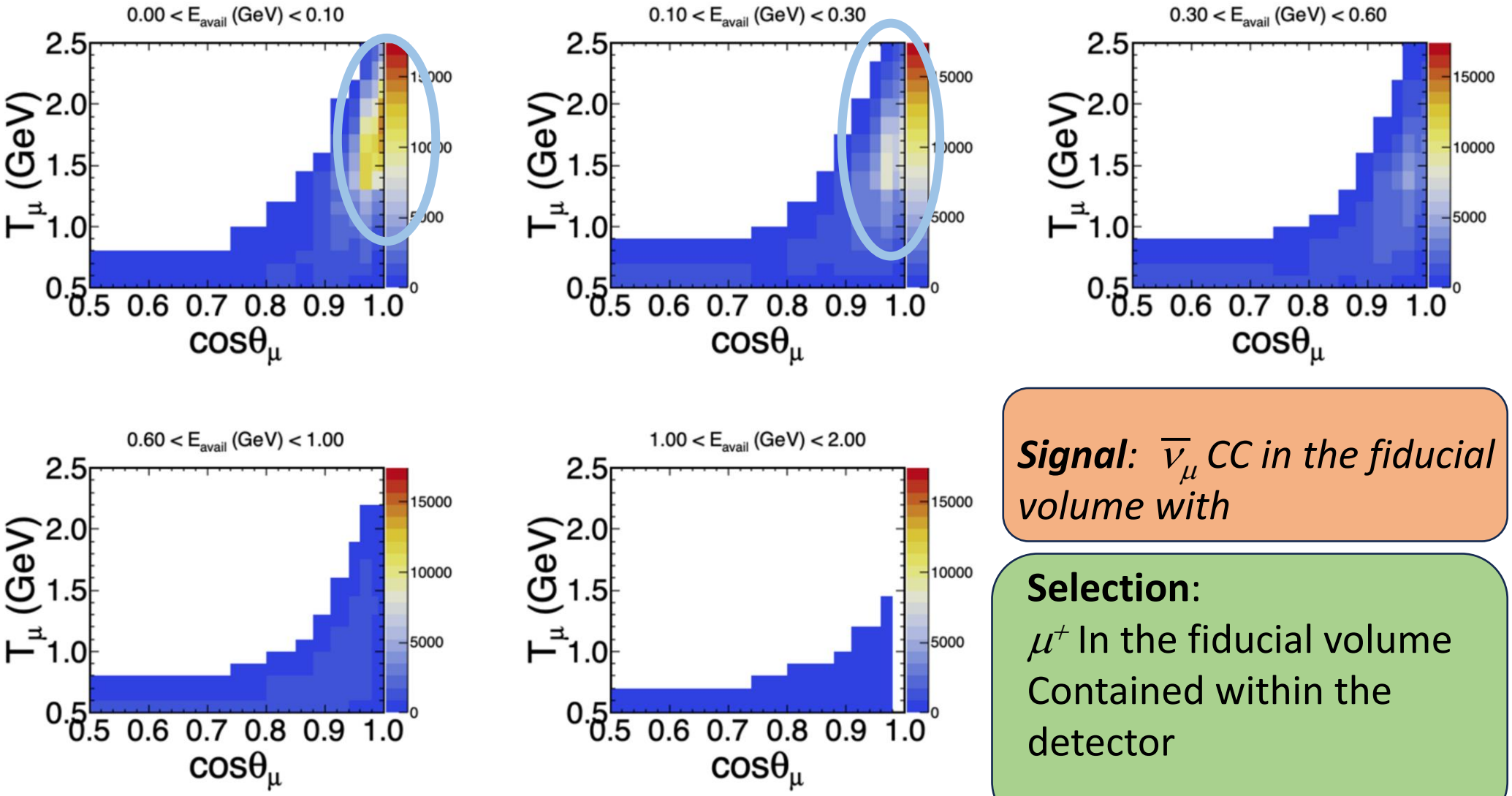
$\bar{\nu}_\mu$ CC Inclusive Cross Section results:



Inclusive
Select all events
with an anti-muon

Triple differential!
Muon kinetic energy
Vs
Muon angle
Vs
Available energy

NOvA Simulation



First triple differential antineutrino cross section measurement

Signal: *$\bar{\nu}_\mu$ CC in the fiducial volume with*

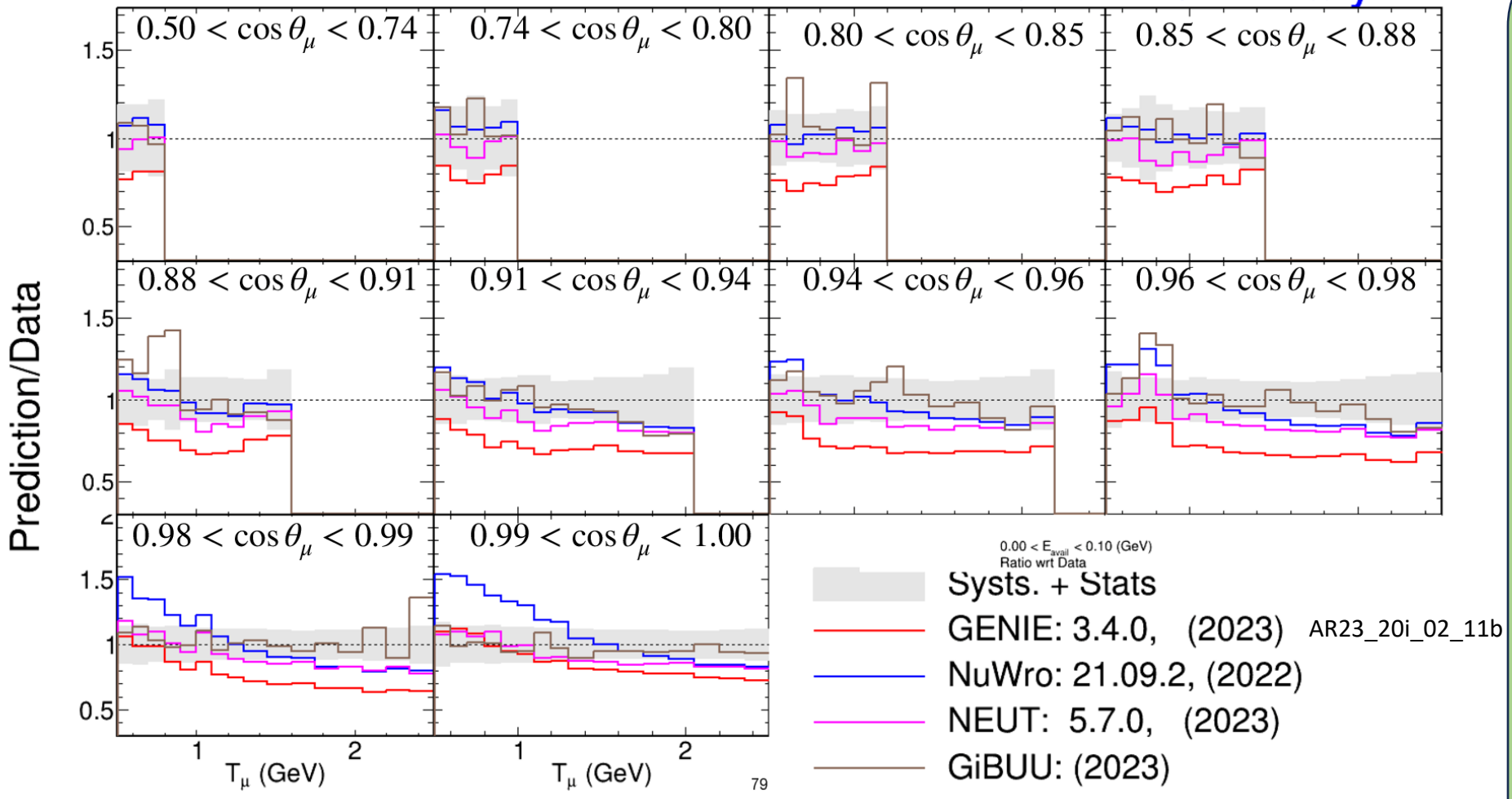
Selection:
μ^+ In the fiducial volume
Contained within the detector

Select > 900K events!

Largest antineutrino sample ever!

0.00 < Eavail < 0.10 (GeV) QE/MEC region

NOvA Preliminary



AR23_20i_02_11b

Cross section is reported in 459 kinematic bins

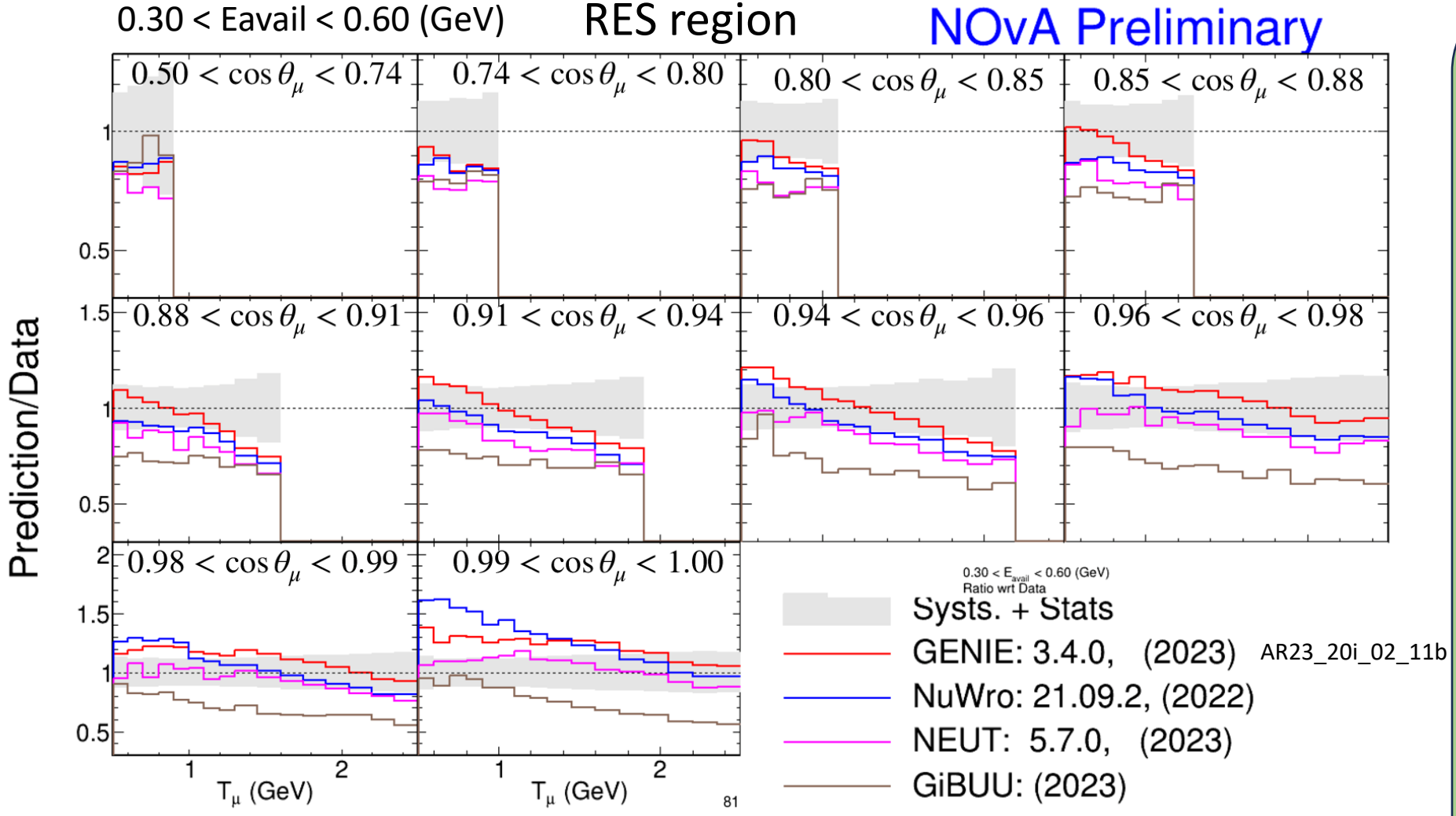
~12.6% uncertainty Flux is the dominant systematic

In the QE/MEC region GiBUU does a very good job.

NuWro has a very different shape and uses Llewellyn-Smith

GENIE and NEUT both use Valencia for QE but differ in FSI tune.

0.30 < Eavail < 0.60 (GeV) RES region



In the RES region we see all models have very different predictions.

GENIE and NuWro overpredict the data.

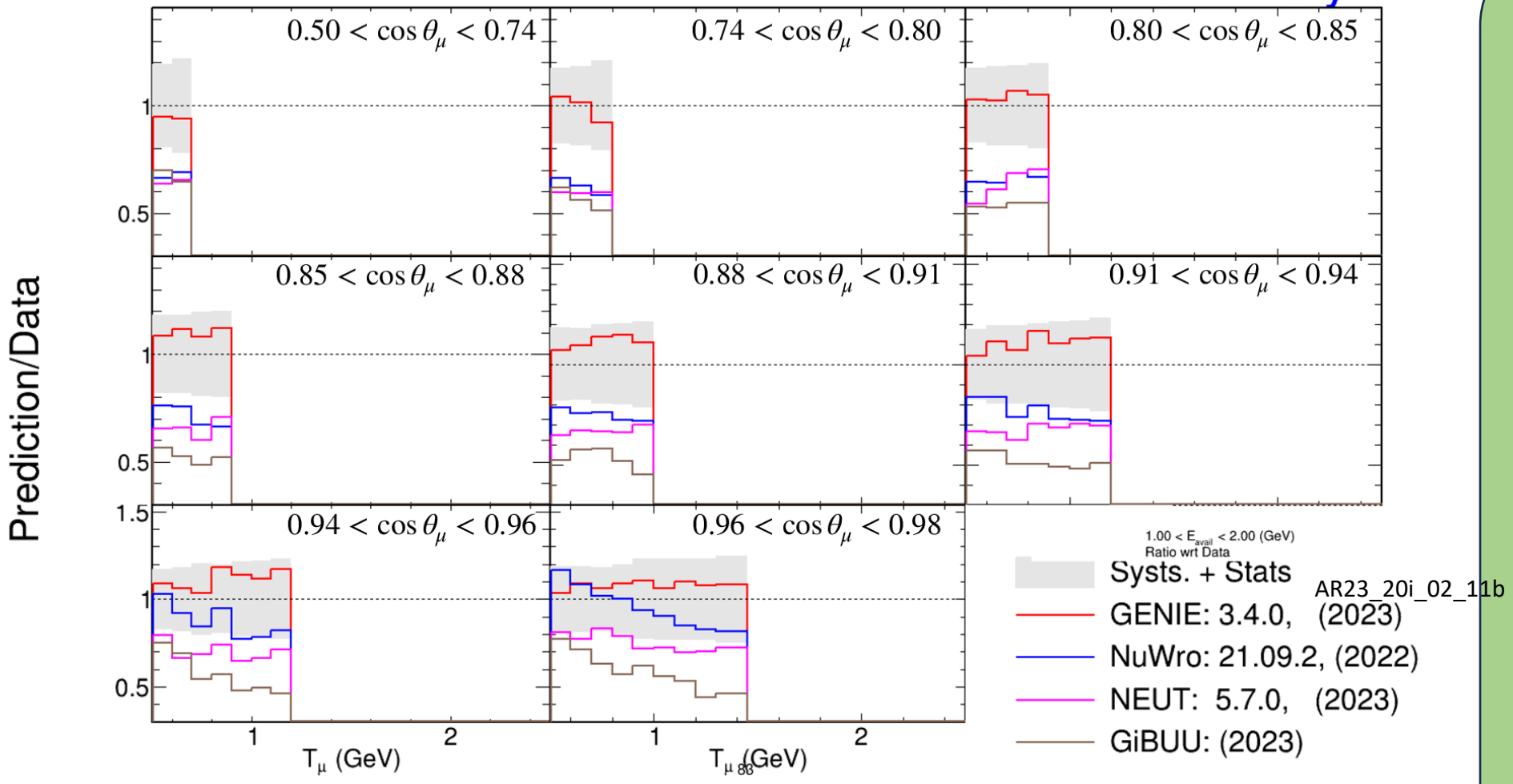
GiBUU underpredicts the data.

NEUT gets the RES region fairly well

1.00 < Eavail < 2.00 (GeV)

DIS region

NOvA Preliminary



AR23_20i_02_11b

NuWro, NEUT, and GENIE all do a good job in DIS

In the DIS region GiBUU mostly underpredicts

GENIE, NEUT and NuWro all use Bodek-Yang for DIS but different FSI tunes

GENIE's hA2018 tune seems to be doing the best job.

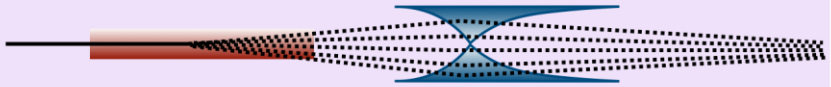
Summary

- Two Complimentary ν_μ CC Cross Section results focused on 2p2h
  - Low Hadronic energy in muon kinematics (Muon energy vs Angle)
    - https://arxiv.org/abs/2410.10222
  - Inclusive with hadronic variables (Available energy vs Momentum transfer)
    - DOI: https://doi.org/10.1103/PhysRevD.111.052009
- Disagreement between different MEC models in forward going high momentum muons, and $|q| \approx E_{avail}$.
- Triple differential ν_μ CC Cross section results (Available energy, vs Muon energy vs Angle)
  - Highly granular and shows model comparisons in regions dominated in many different areas of phase space.
- Look forward to future results!

Thank you for you attention!

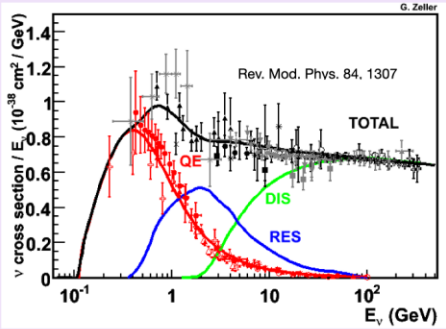
Backup

NOvA simulation

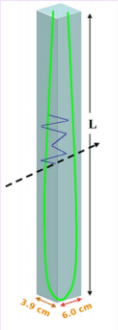


Beamline and Flux: G4NuMI

v-A modelling: GENIE

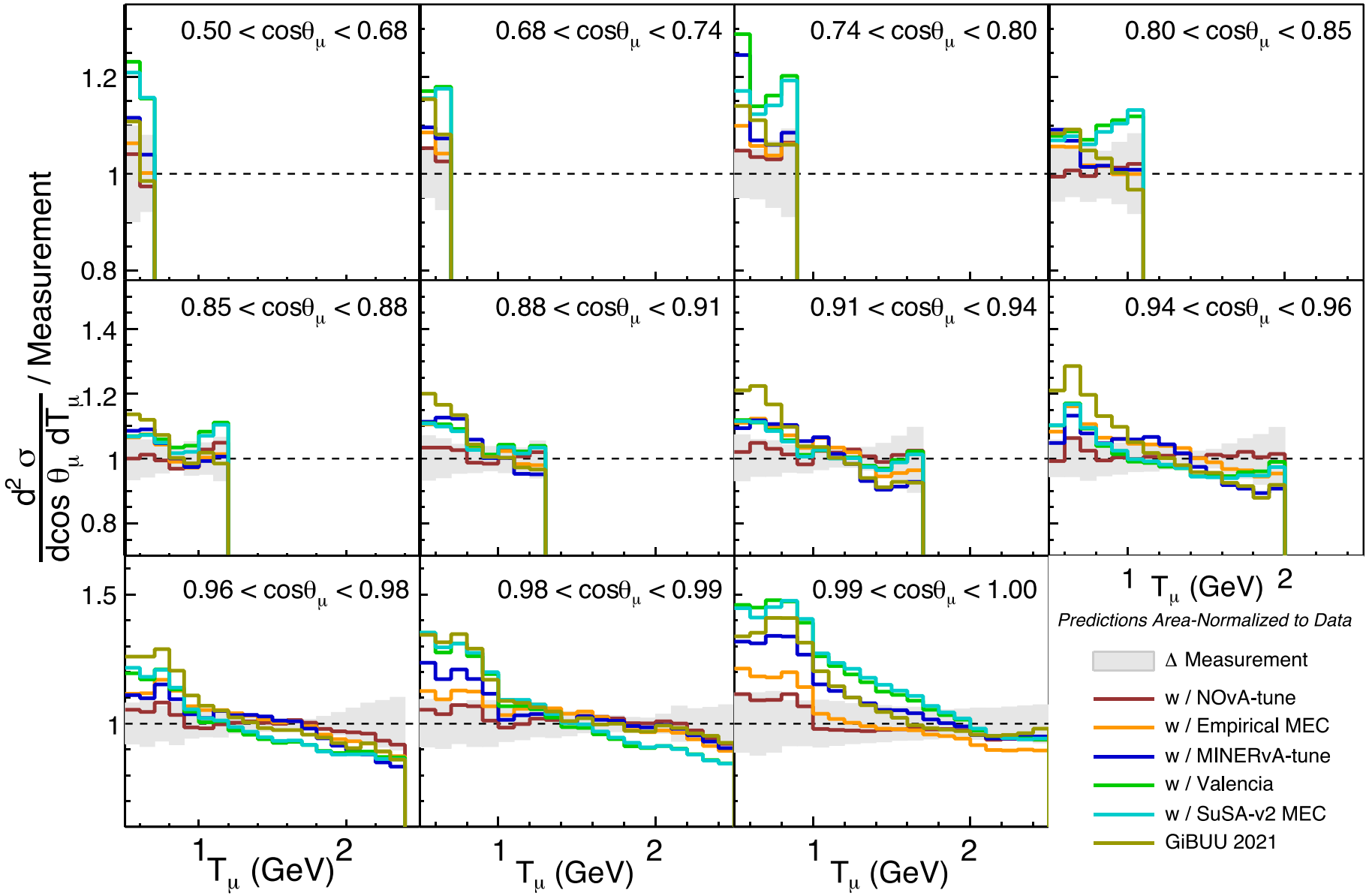


Detector response: GEANT4

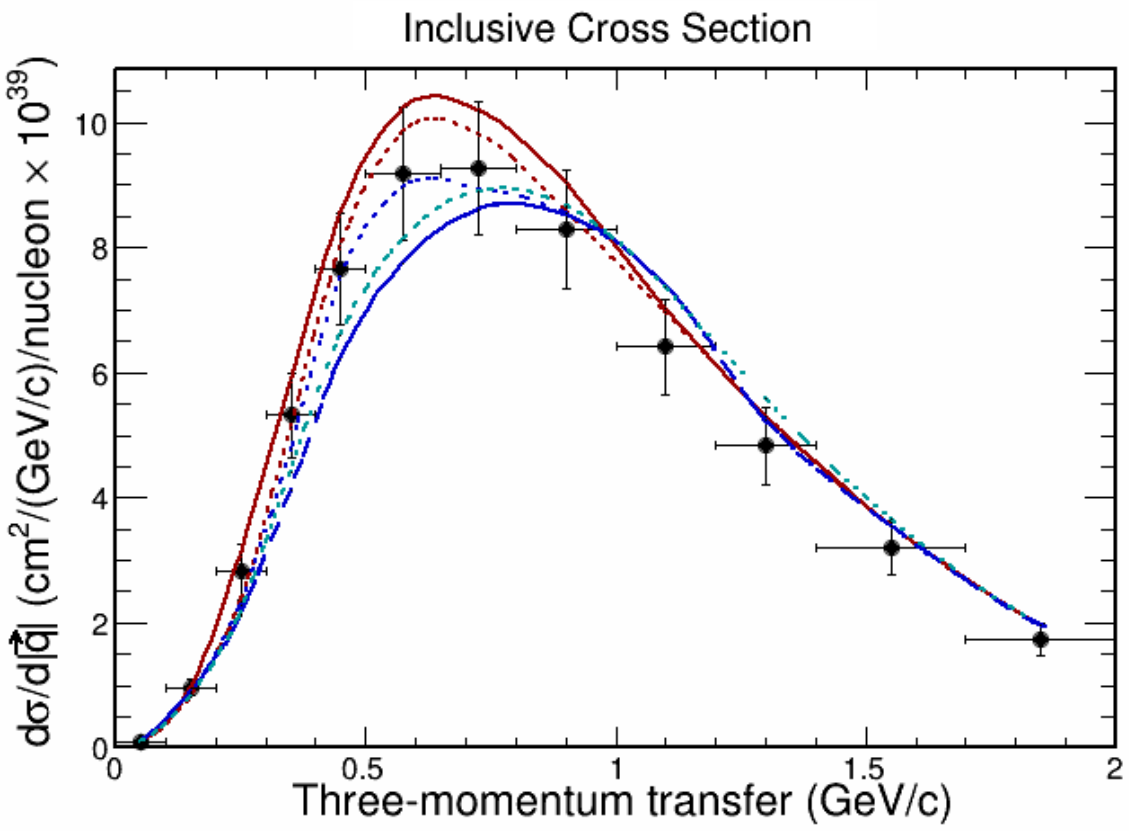


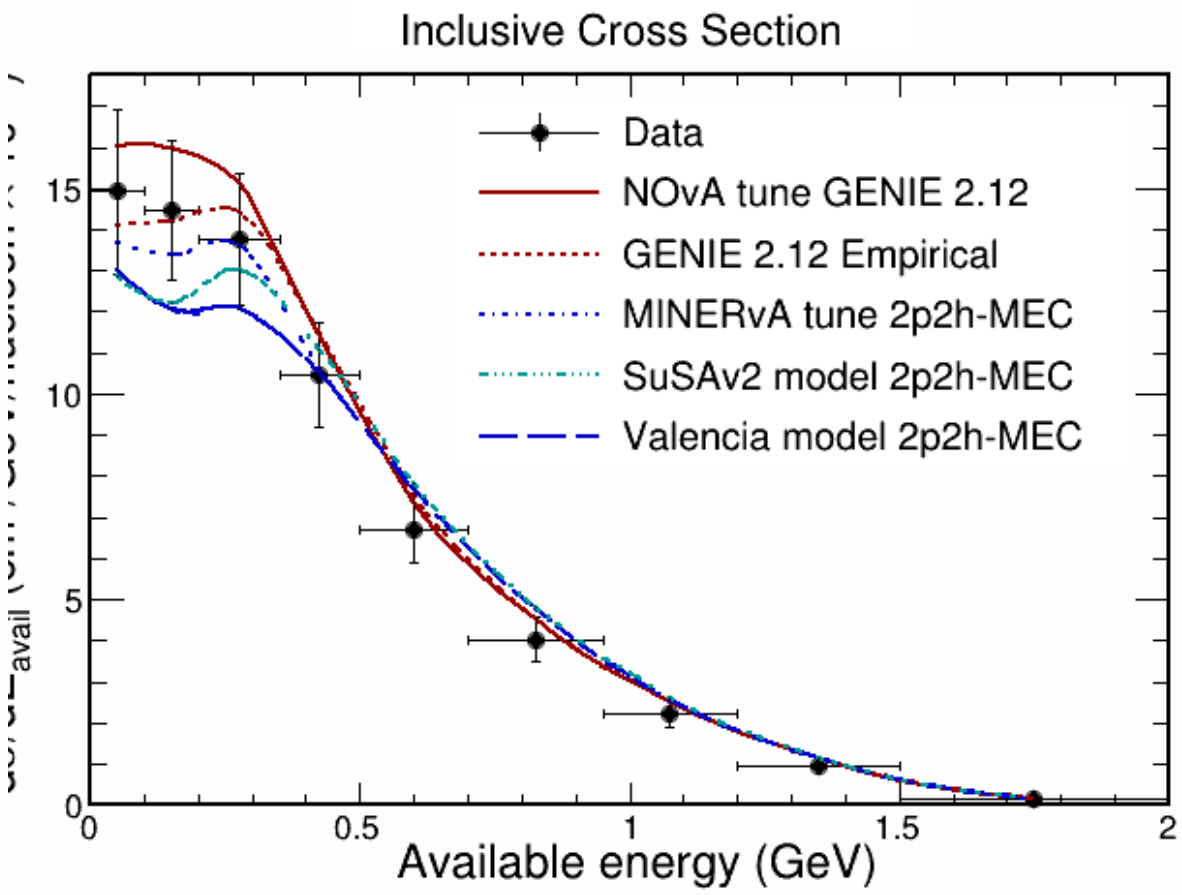
Readout electronics & DAQ: Custom simulation routines

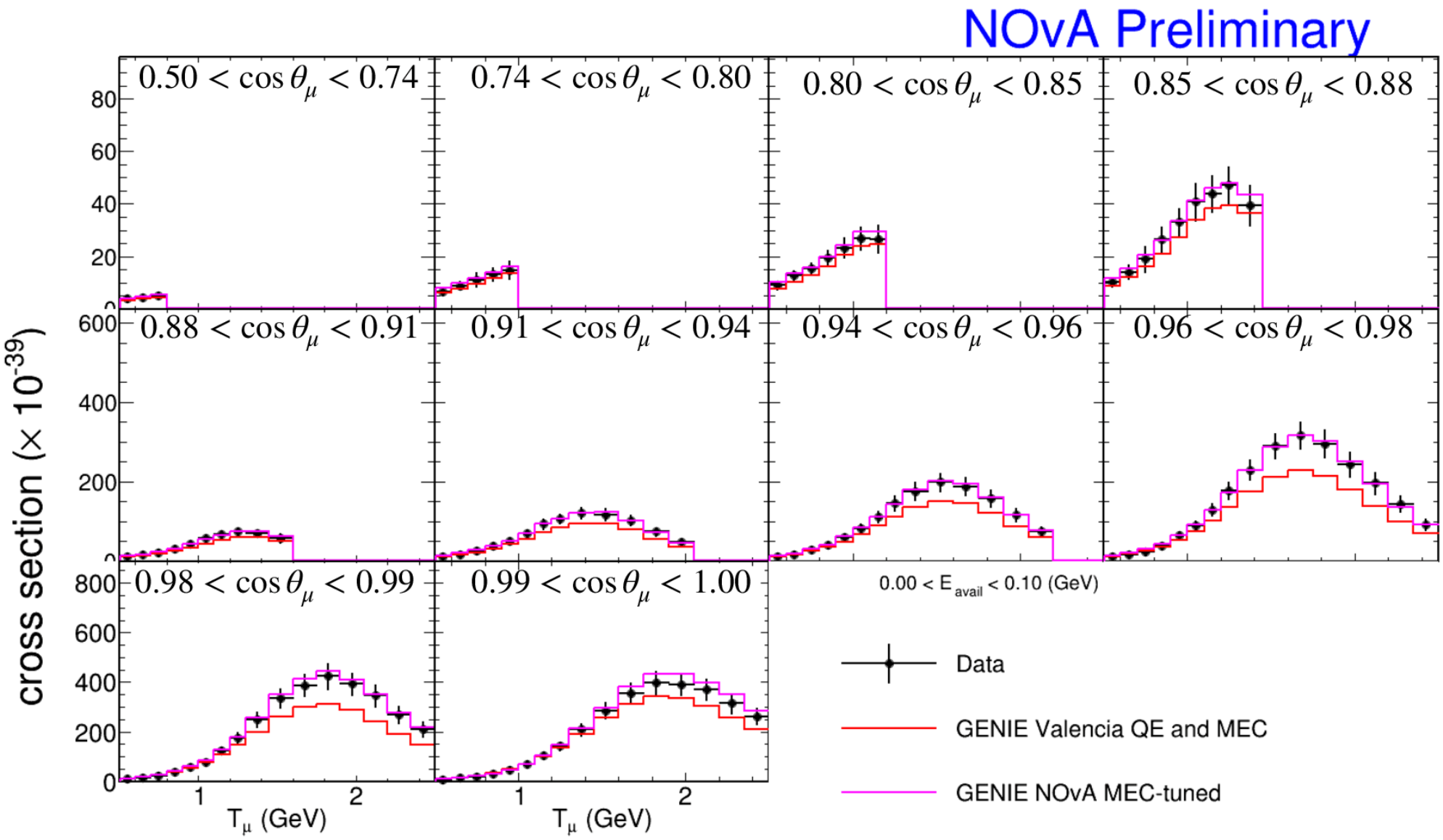
Low EHad


0.50 < cosθμ < 0.68
0.68 < cosθμ < 0.74
0.74 < cosθμ < 0.80
0.80 < cosθμ < 0.85
0.85 < cosθμ < 0.88
0.88 < cosθμ < 0.91
0.91 < cosθμ < 0.94
0.94 < cosθμ < 0.96
0.96 < cosθμ < 0.98
0.98 < cosθμ < 0.99
0.99 < cosθμ < 1.00
d²σ / dcosθμ dTμ / Measurement
Tμ (GeV)
Predictions Area-Normalized to Data
Δ Measurement
w / NOvA-tune
w / Empirical MEC
w / MINERvA-tune
w / Valencia
w / SuSA-v2 MEC
GiBUU 2021

Hadronic variables






NOvA Preliminary
0.50 < cos θμ < 0.74
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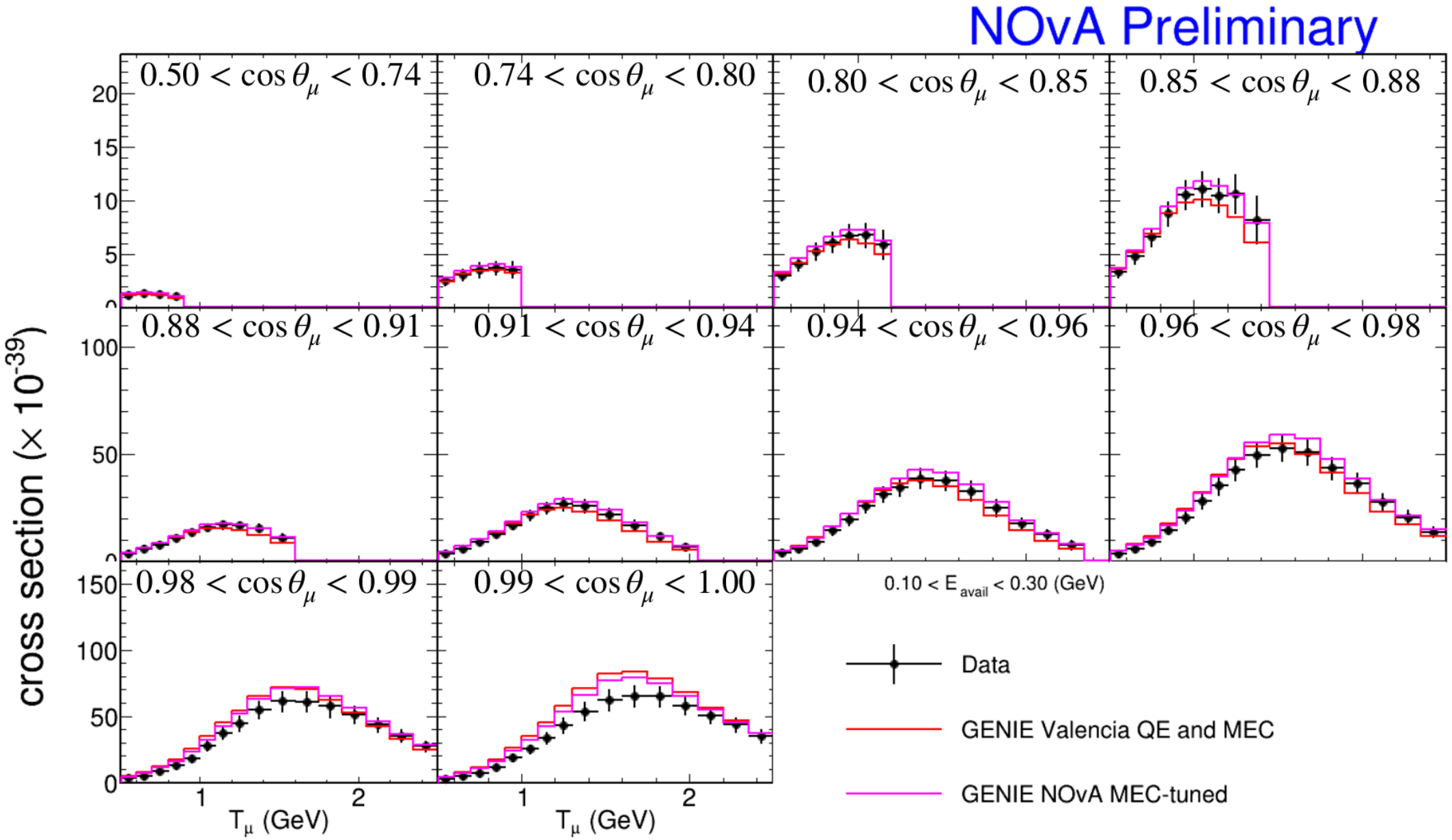
0.96 < cos θμ < 0.98
0.98 < cos θμ < 0.99
0.99 < cos θμ < 1.00
cross section (× 10^-39)
Tμ (GeV)
0.00 < E avail < 0.10 (GeV)
Data
GENIE Valencia QE and MEC
GENIE NOvA MEC-tuned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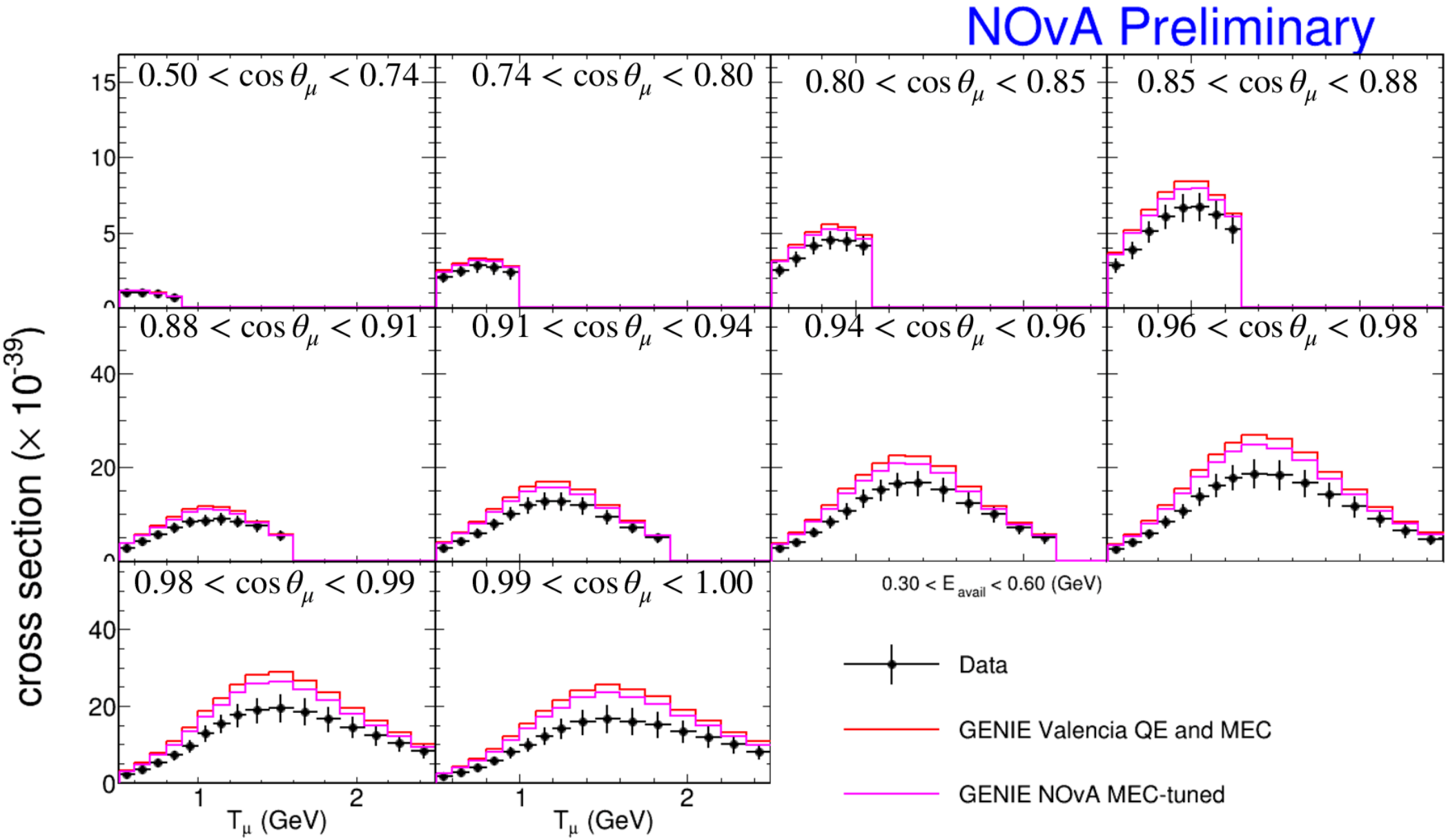
0.99 < cos θμ < 1.00
cross section (× 10^-39)
Tμ (GeV)
0.10 < E avail < 0.30 (GeV)
Data
GENIE Valencia QE and MEC
GENIE NOvA MEC-tuned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cross section (× 10^-39)
Tμ (GeV)
0.30 < E avail < 0.60 (GeV)
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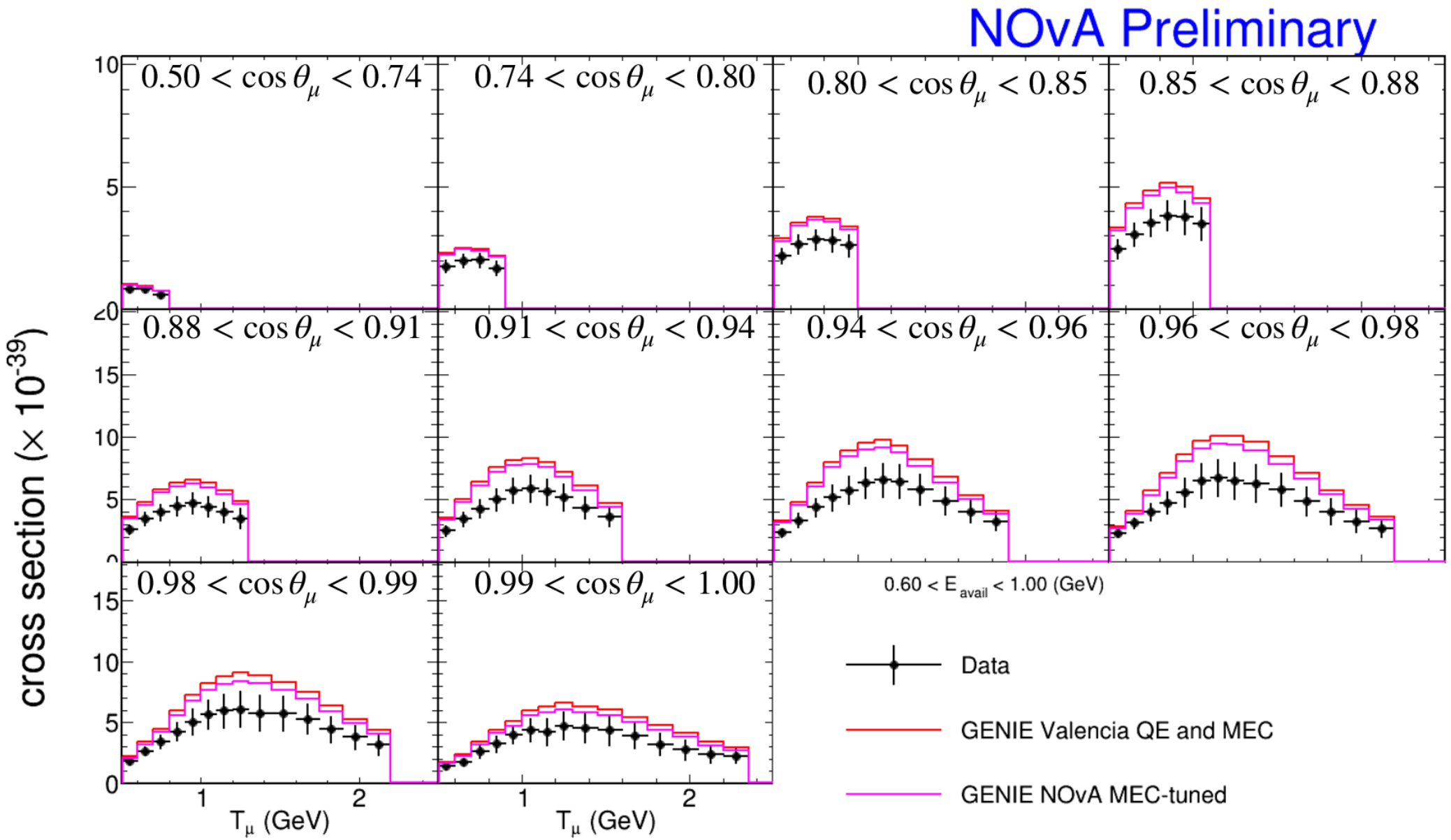
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cross section (× 10^-39)
Tμ (GeV)
0.60 < E avail < 1.00 (GeV)
Data
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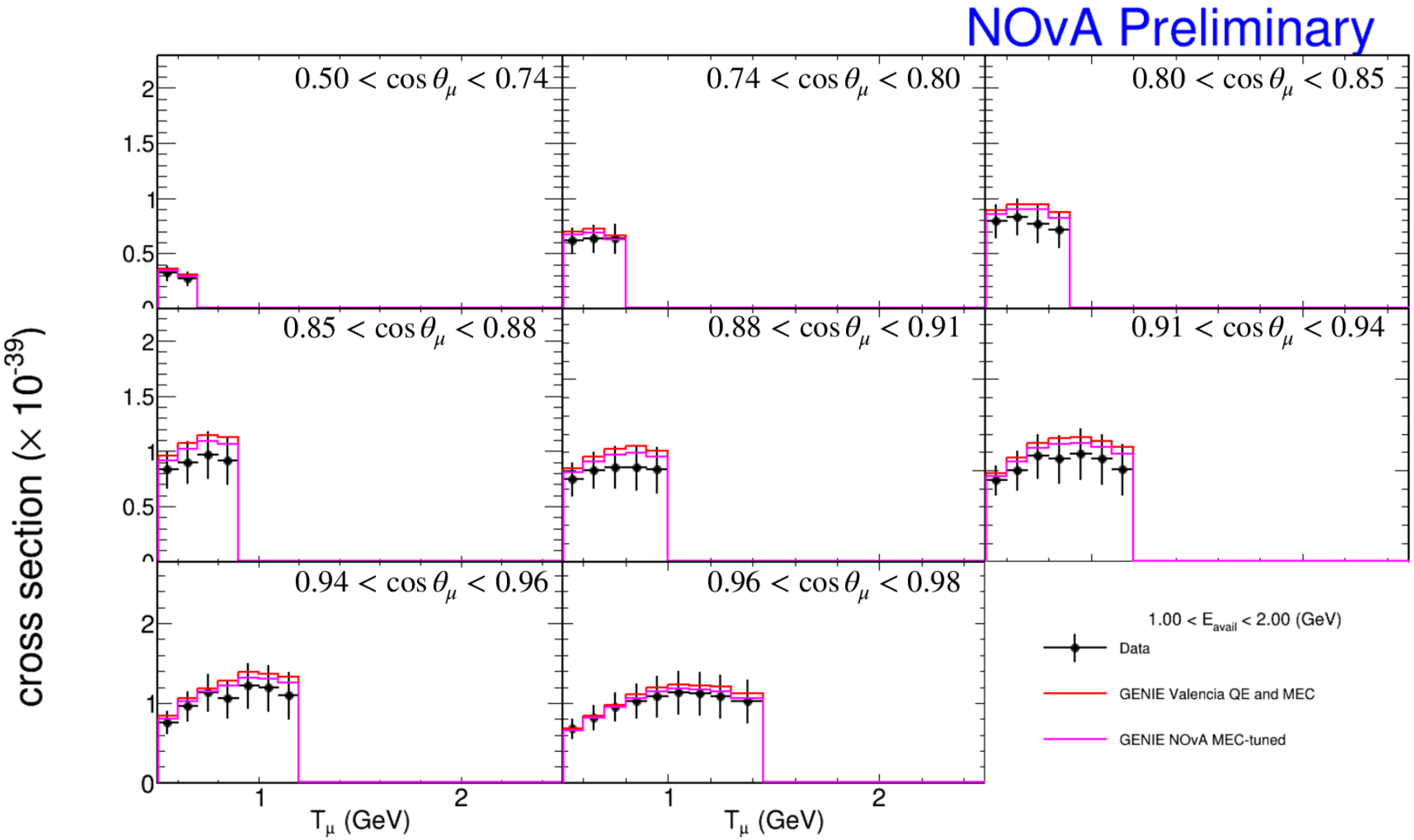
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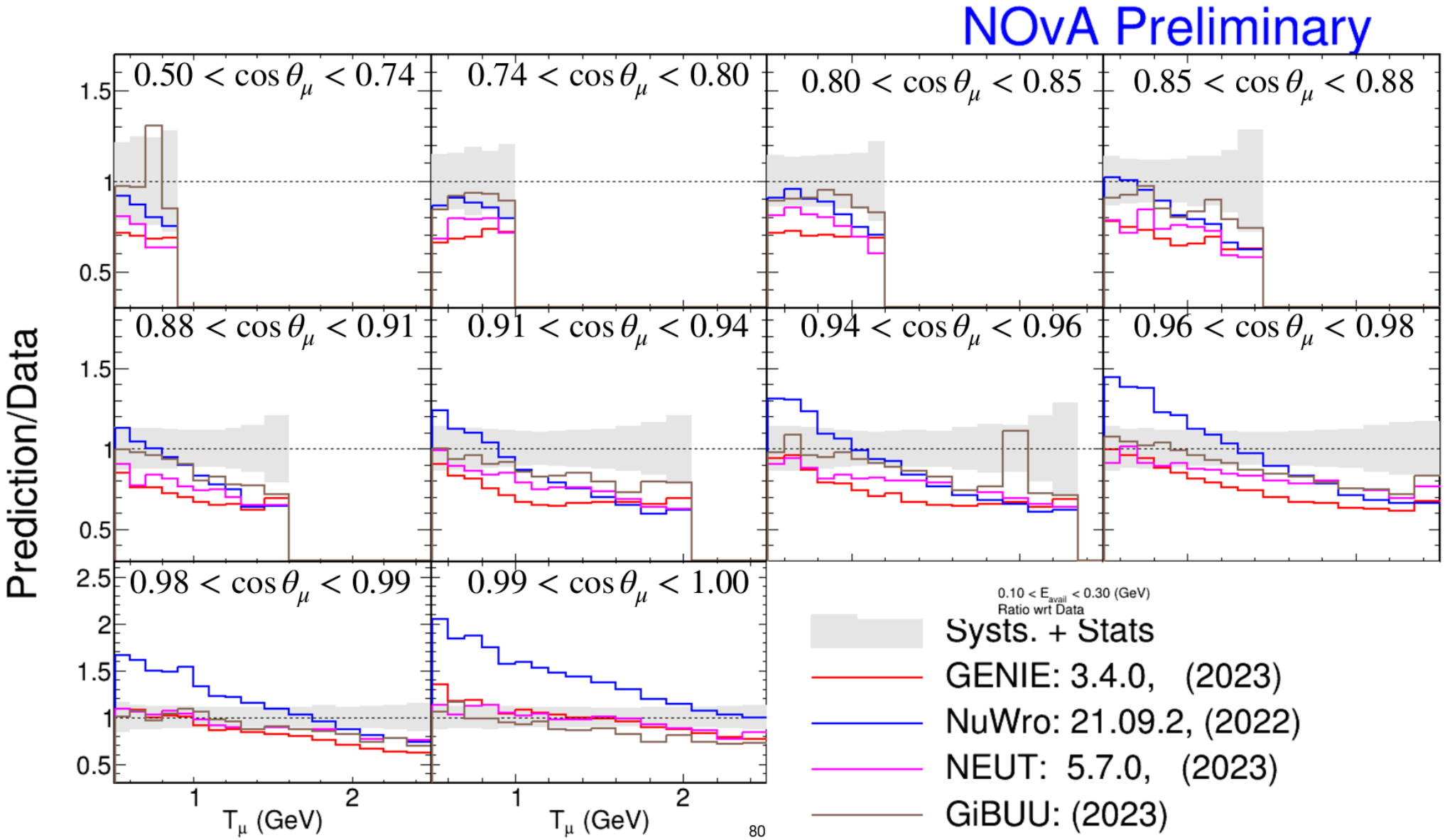
$0.96 < \cos\theta_\mu < 0.98$
cross section ($\times 10^{-39}$)
T_μ (GeV)
$1.00 < E_{avail} < 2.00$ (GeV)
Data
GENIE Valencia QE and MEC
GENIE NOvA MEC-tuned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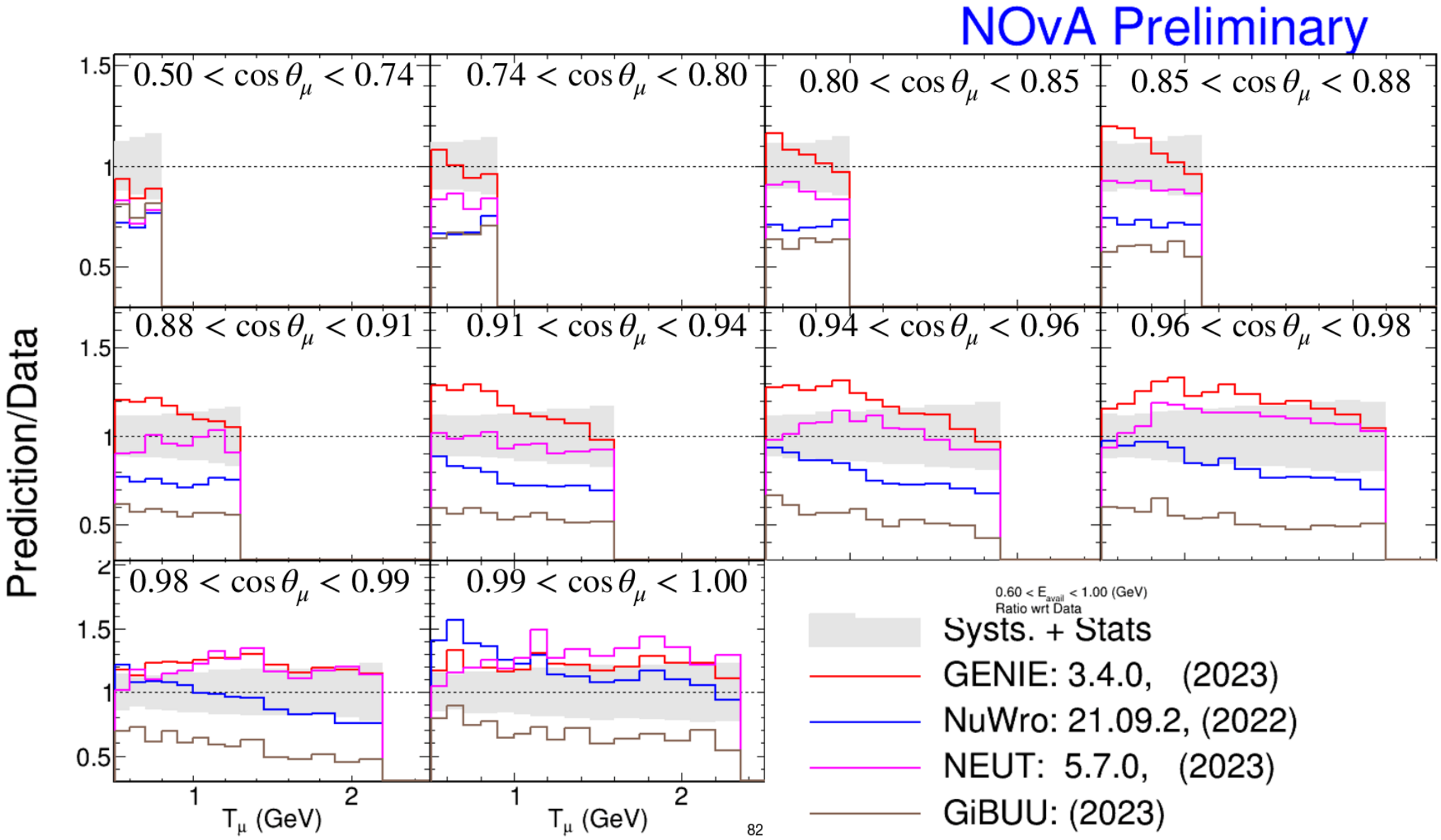
0.91 < cos θμ < 0.94
0.94 < cos θμ < 0.96
0.96 < cos θμ < 0.98
0.98 < cos θμ < 0.99
0.99 < cos θμ < 1.00
Prediction/Data
Tμ (GeV)
0.10 < Eavail < 0.30 (GeV)
Ratio wrt Data
Systs. + Stats
GENIE: 3.4.0, (2023)
NuWro: 21.09.2, (2022)
NEUT: 5.7.0, (2023)
GiBUU: (2023)
80


NOvA Preliminary
Prediction/Data
0.50 < cos θμ < 0.74
0.74 < cos θμ < 0.80
0.80 < cos θμ < 0.85
0.85 < cos θμ < 0.88
0.88 < cos θμ < 0.91
0.91 < cos θμ < 0.94
0.94 < cos θμ < 0.96
0.96 < cos θμ < 0.98
0.98 < cos θμ < 0.99
0.99 < cos θμ < 1.00
Tμ (GeV)
0.60 < Eavail < 1.00 (GeV)
Ratio wrt Data
Systs. + Stats
GENIE: 3.4.0, (2023)
NuWro: 21.09.2, (2022)
NEUT: 5.7.0, (2023)
GiBUU: (2023)
82