FERMILAB-SLIDES-24-0183-PPD

Triple Differential Muon Antineutrino Charge Current Inclusive Cross Section Measurement in NOvA

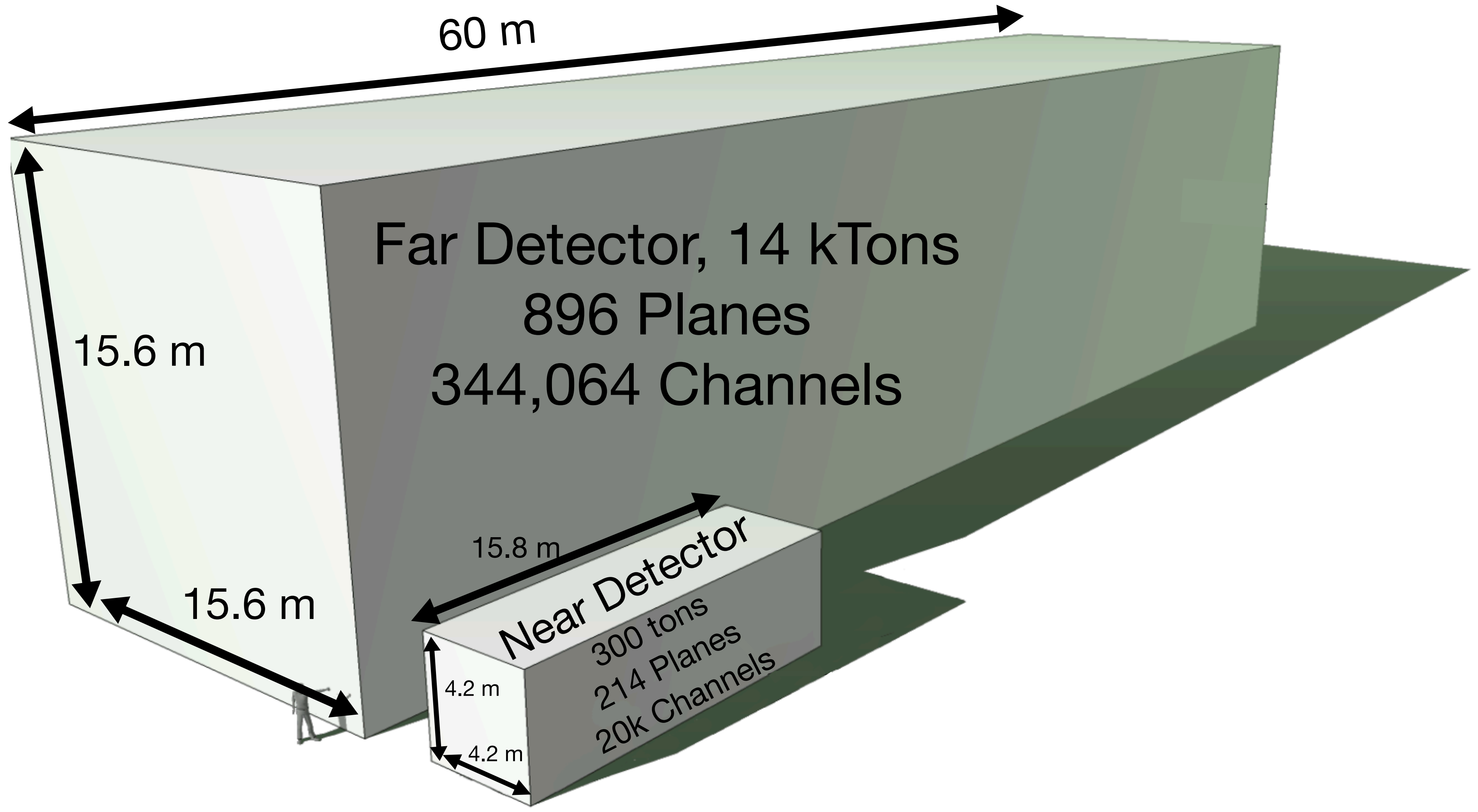
Prabhjot Singh, on behalf of the NOvA Collaboration

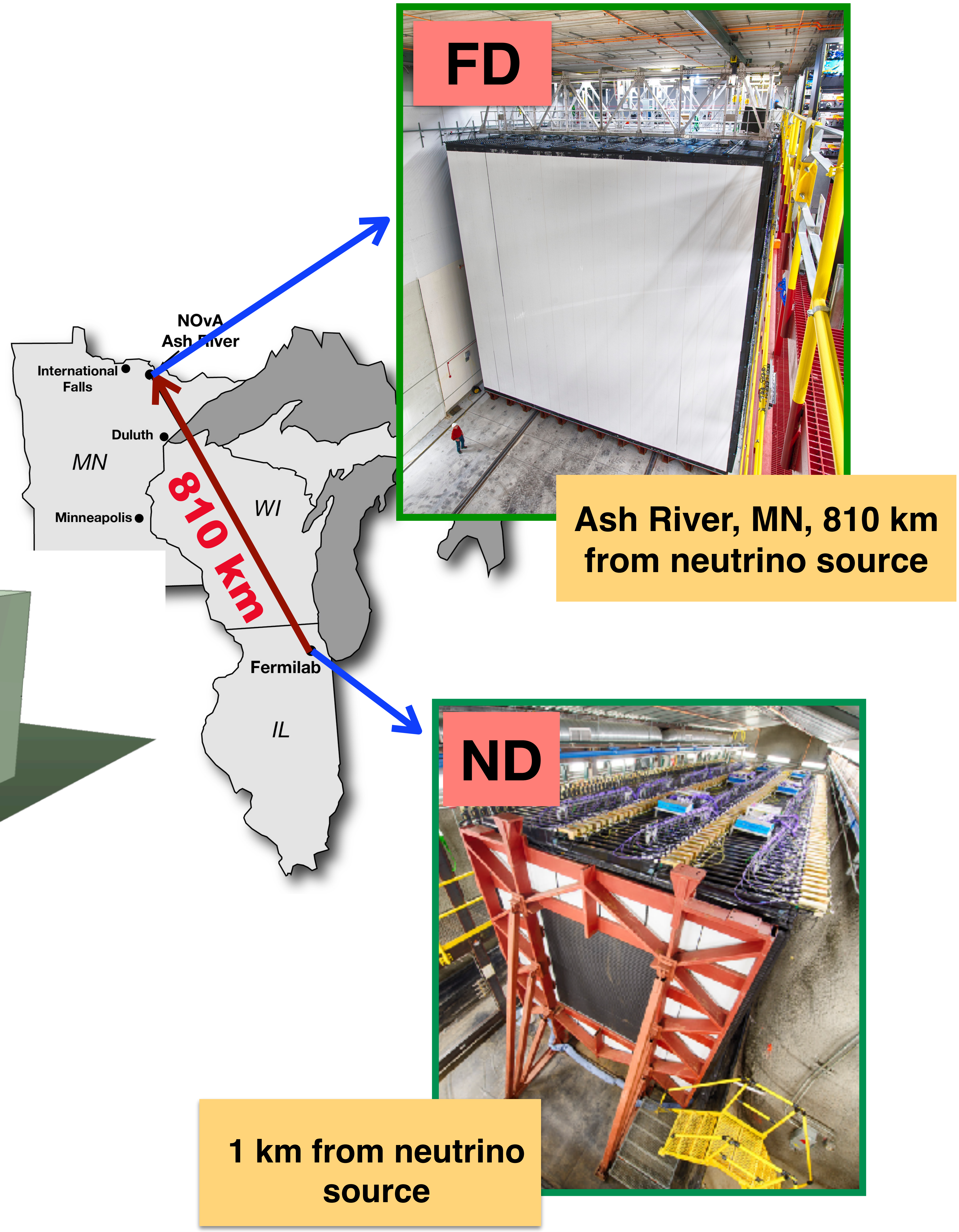
42nd International Conference On High Energy Physics (ICHEP 2024), Prague, Czech Republic

July 18, 2024

NOvA Experiment

- NOvA is a long-baseline two-detector neutrino oscillation experiment
- Both detectors are filled with liquid scintillator and composed of 67% C, 16% chlorine, 11% H, 3% O, 3% Ti by mass
- Functionally identical detectors to reduce systematic uncertainties





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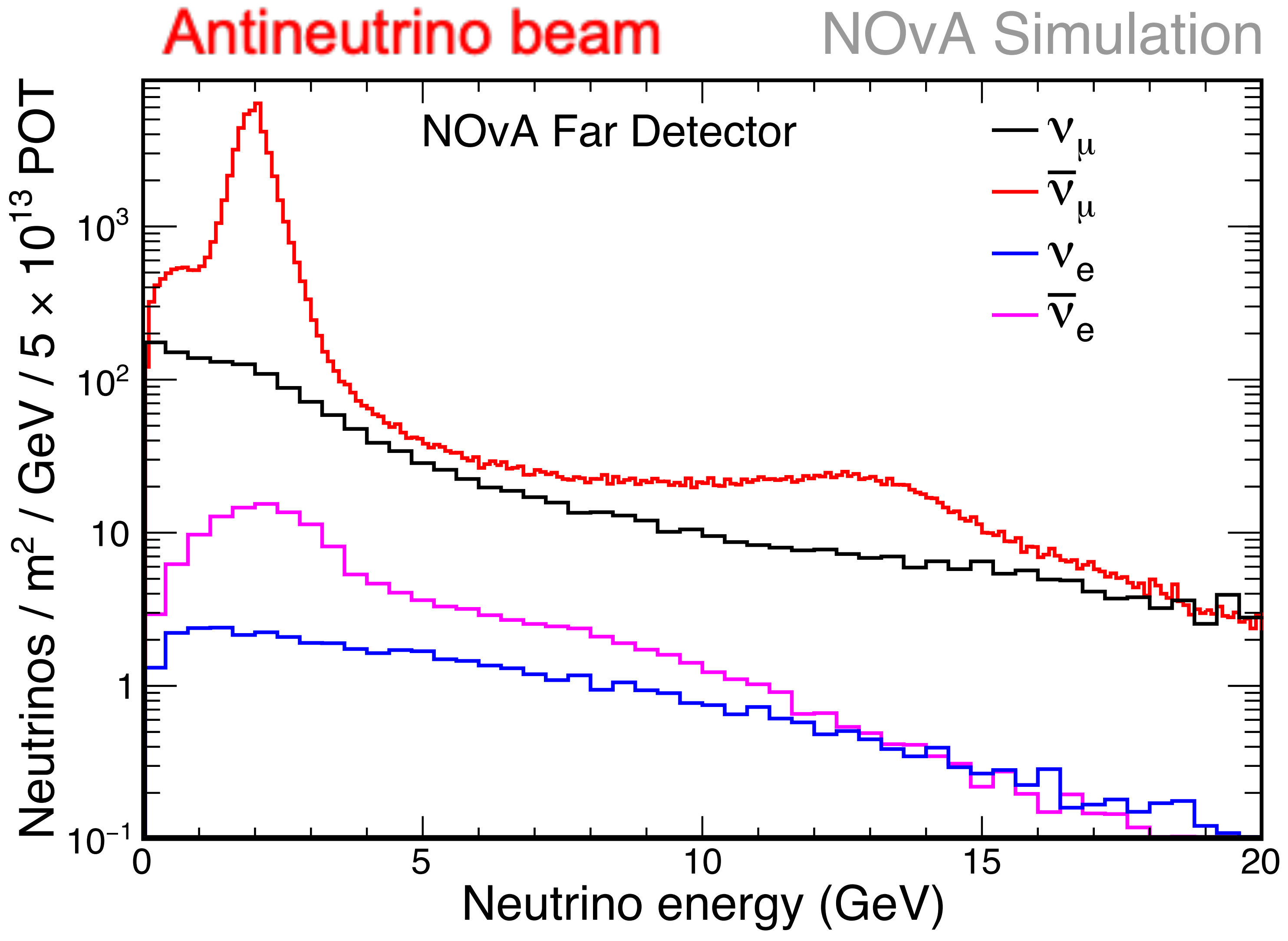
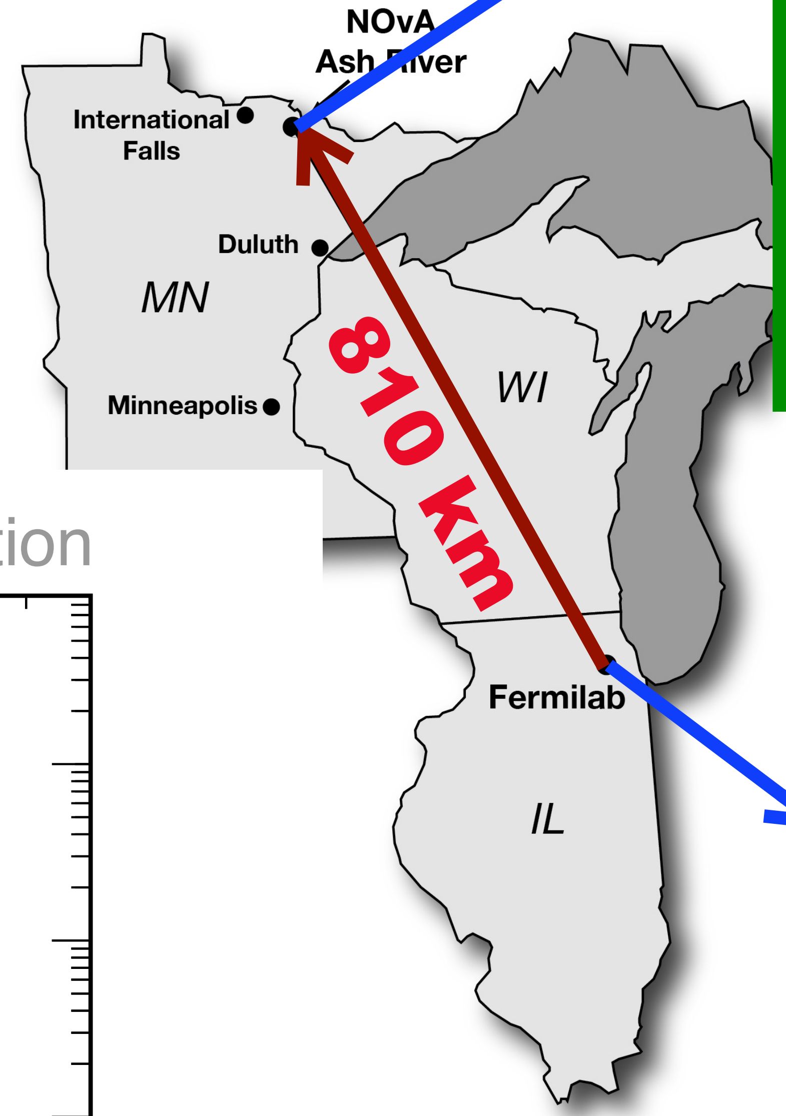
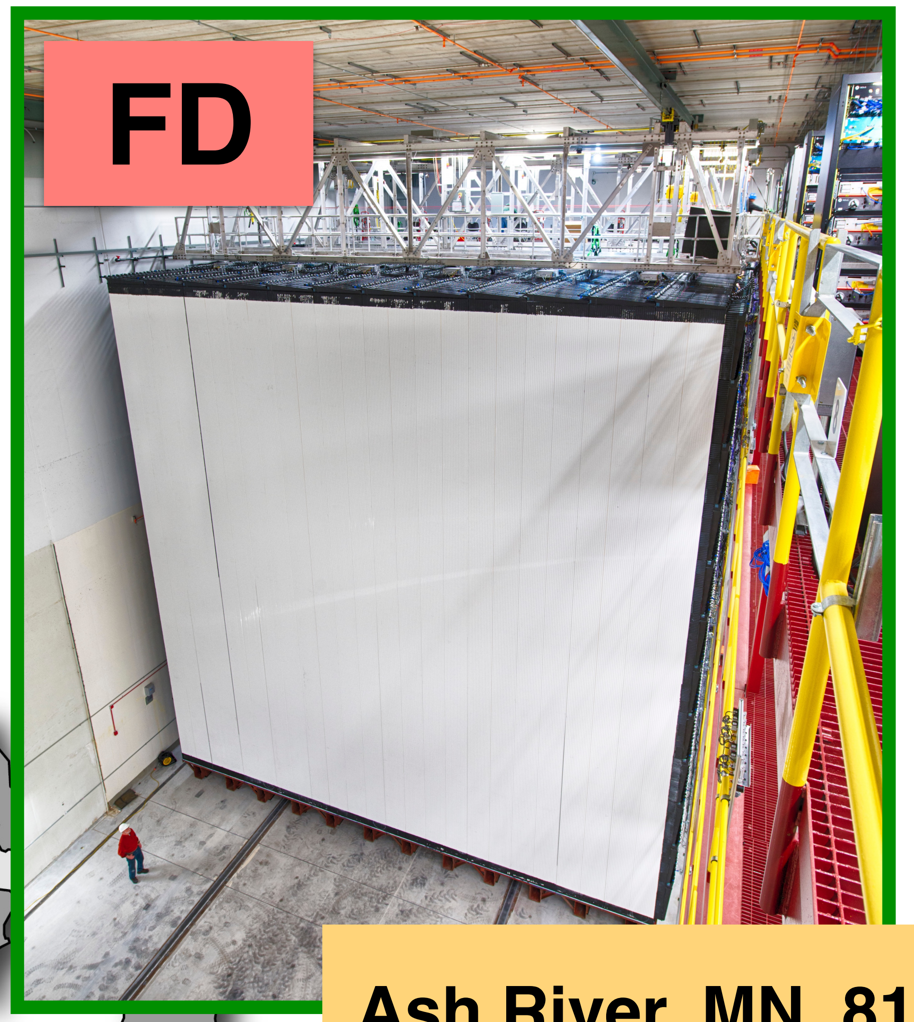
- Functionally identical detectors to reduce systematic uncertainties
- 14.6 mrad off-axis detectors
- Neutrino beam peaks around 2 GeV



High purity $\bar{\nu}_\mu$ beam





Ash River, MN, 810 km from neutrino source

1 km from neutrino source

NOvA Experiment

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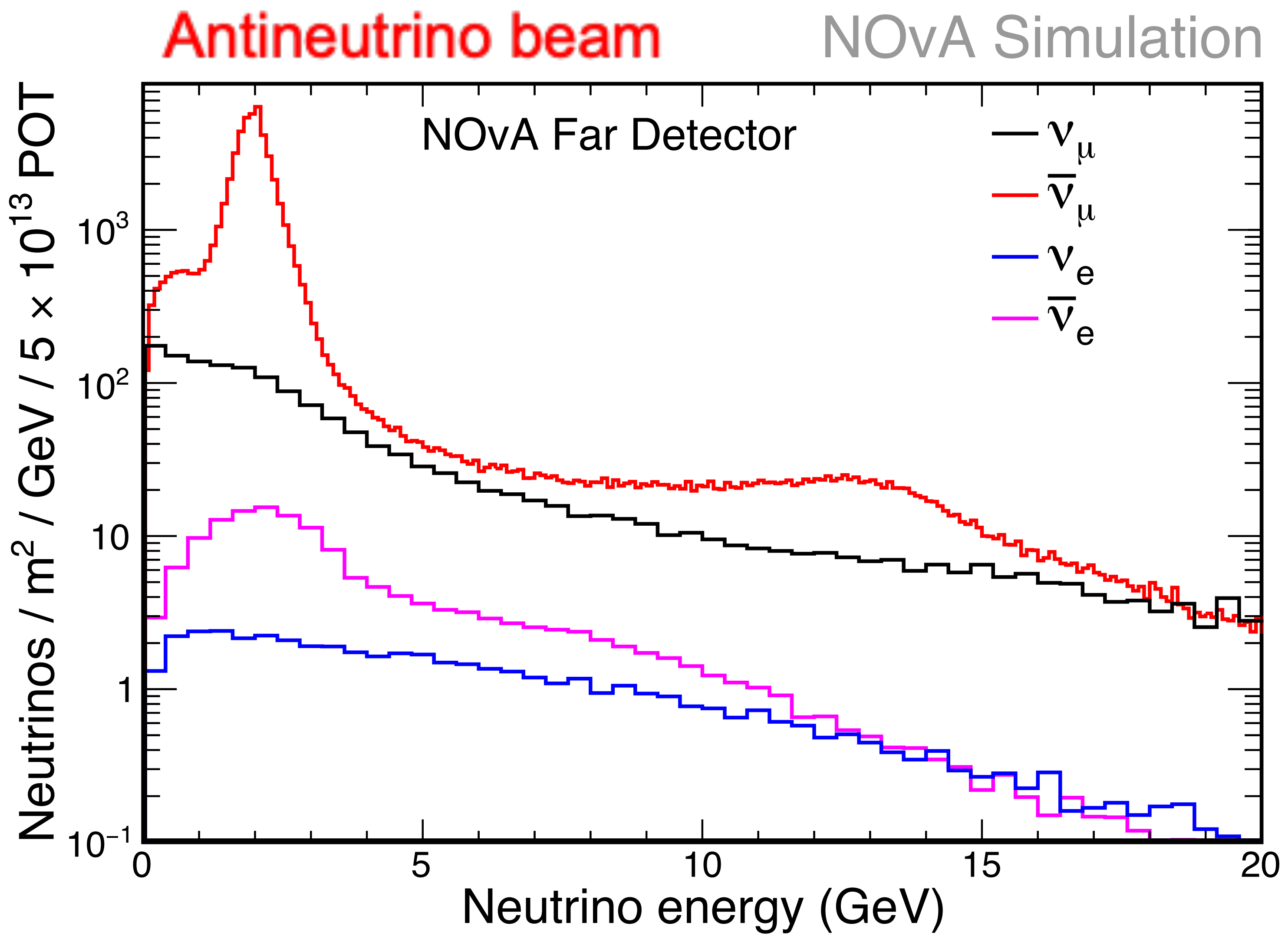
- Both detectors are filled with liquid scintillator and composed of 67% C, 16% chlorine, 11% H, 3% O, 3% Ti by mass

- Functionally identical detectors to reduce systematic uncertainties

- We use high statistics in the ND to do multi-differential cross section measurements



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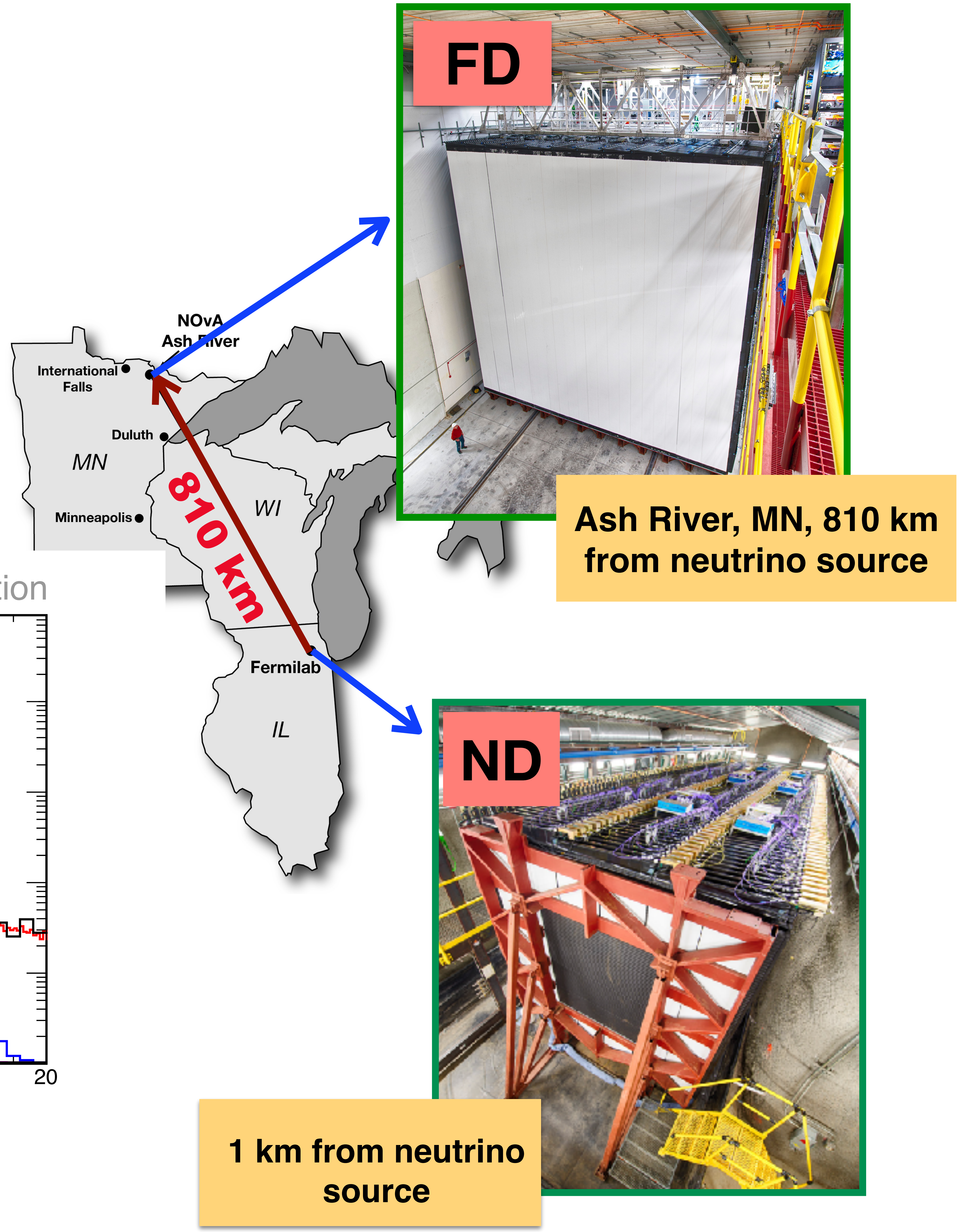
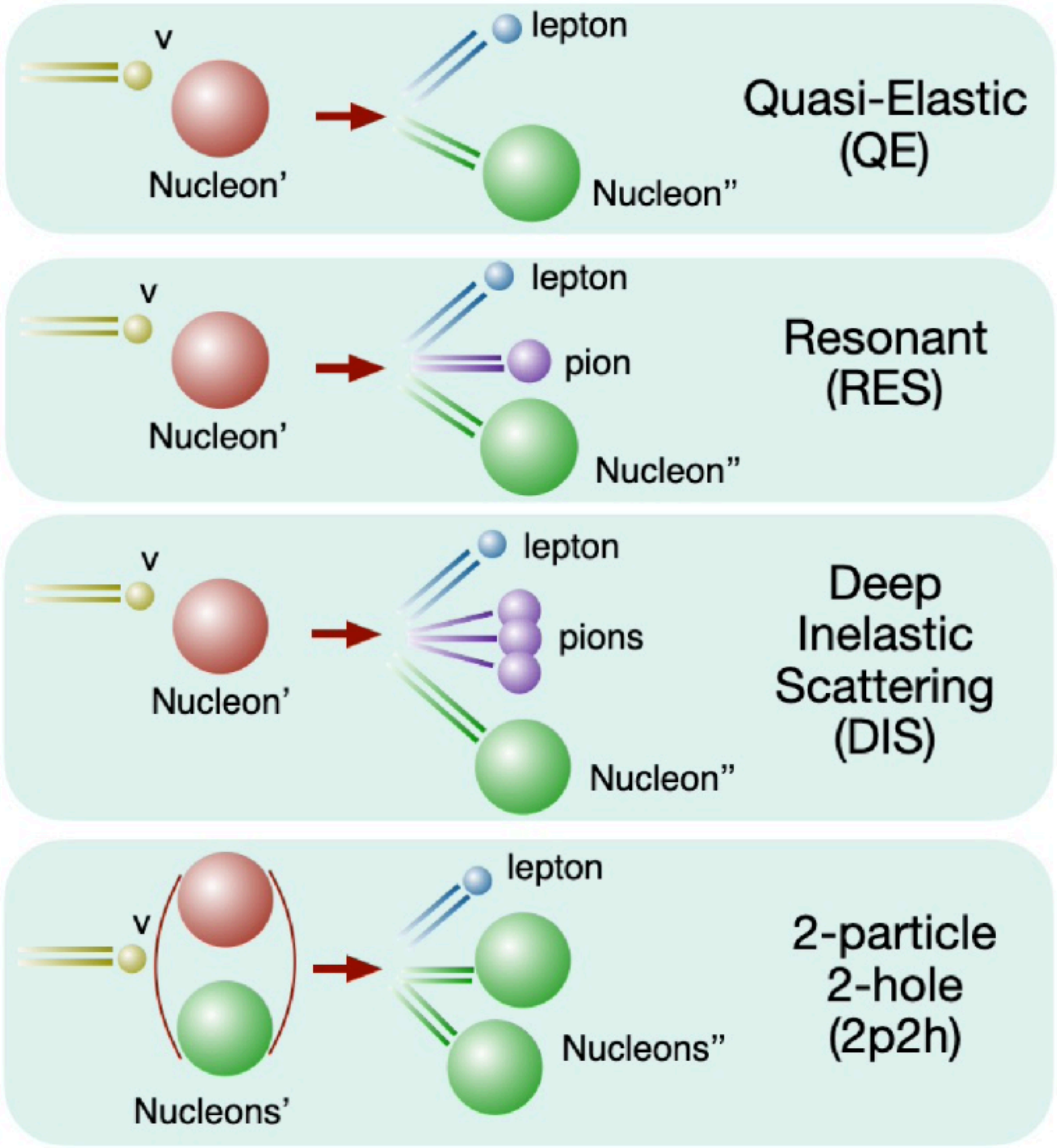


Neutrino Interactions in NOvA ND



By Linda Cremonesi, Neutrino 2020

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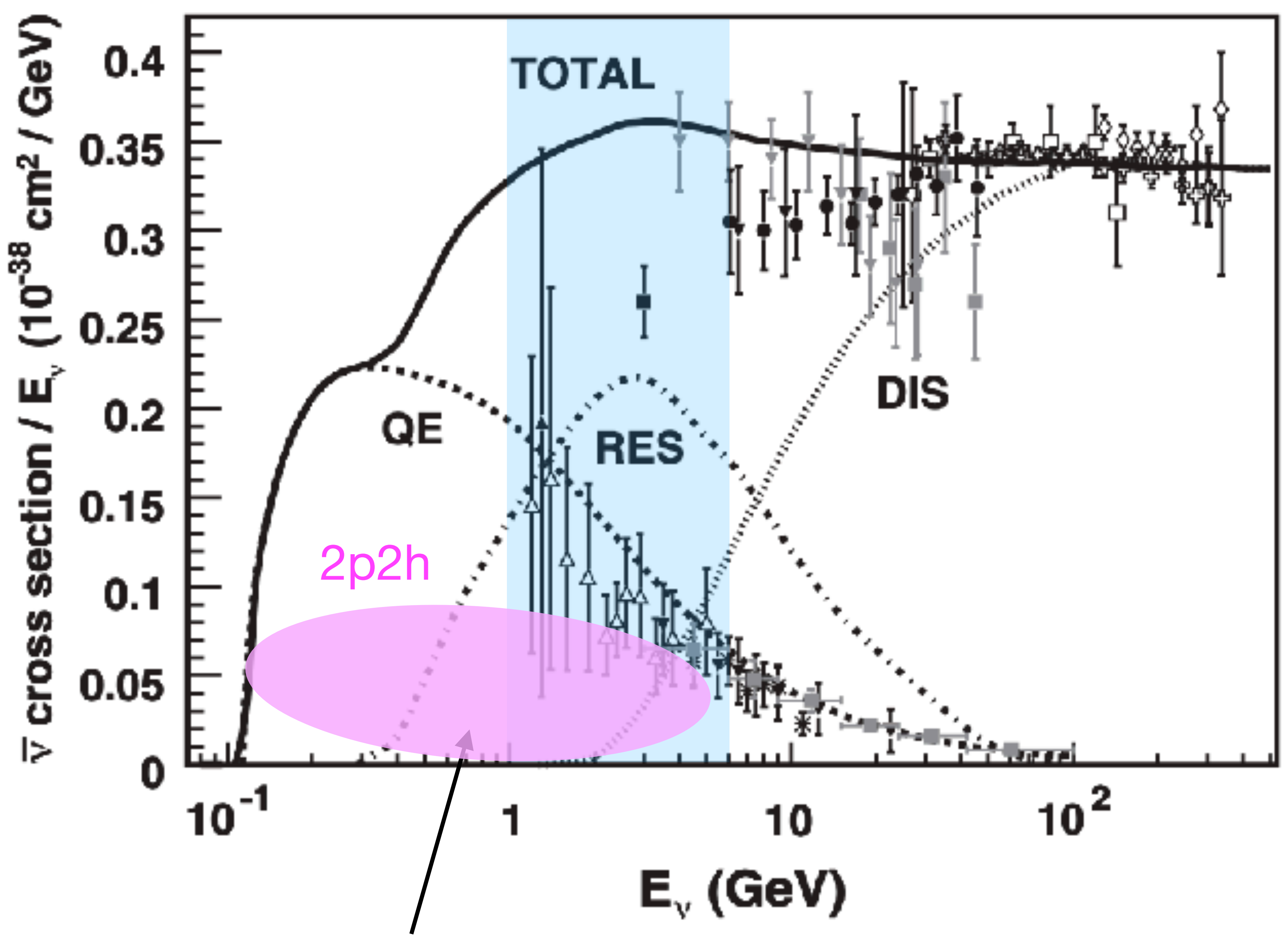
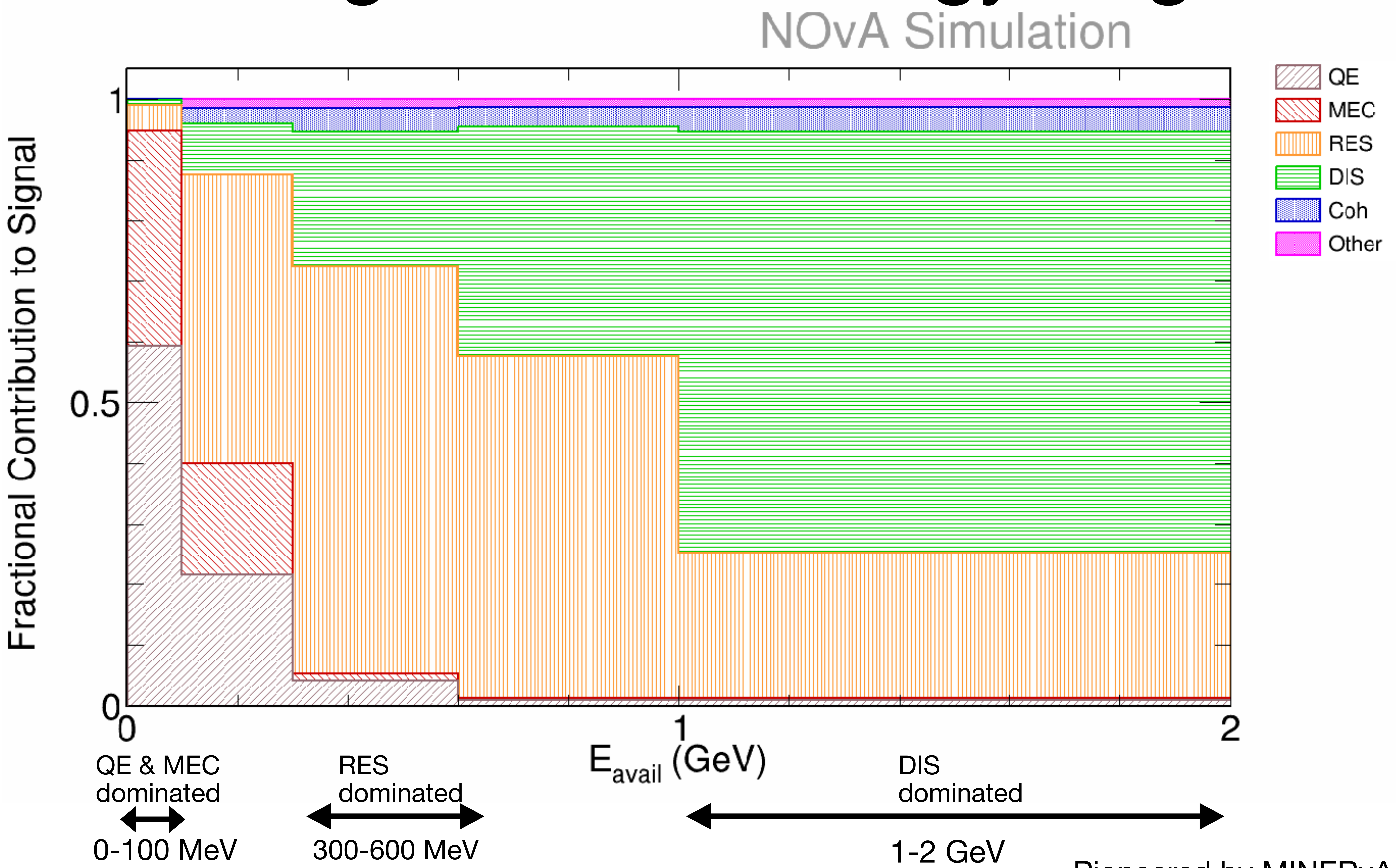


NOvA sits in the transition region of all interaction types, thus we have an opportunity to measure cross sections for these processes

Meson exchange currents (MEC) is a dominating model to describe 2p2h process

Interesting Available Energy Regions

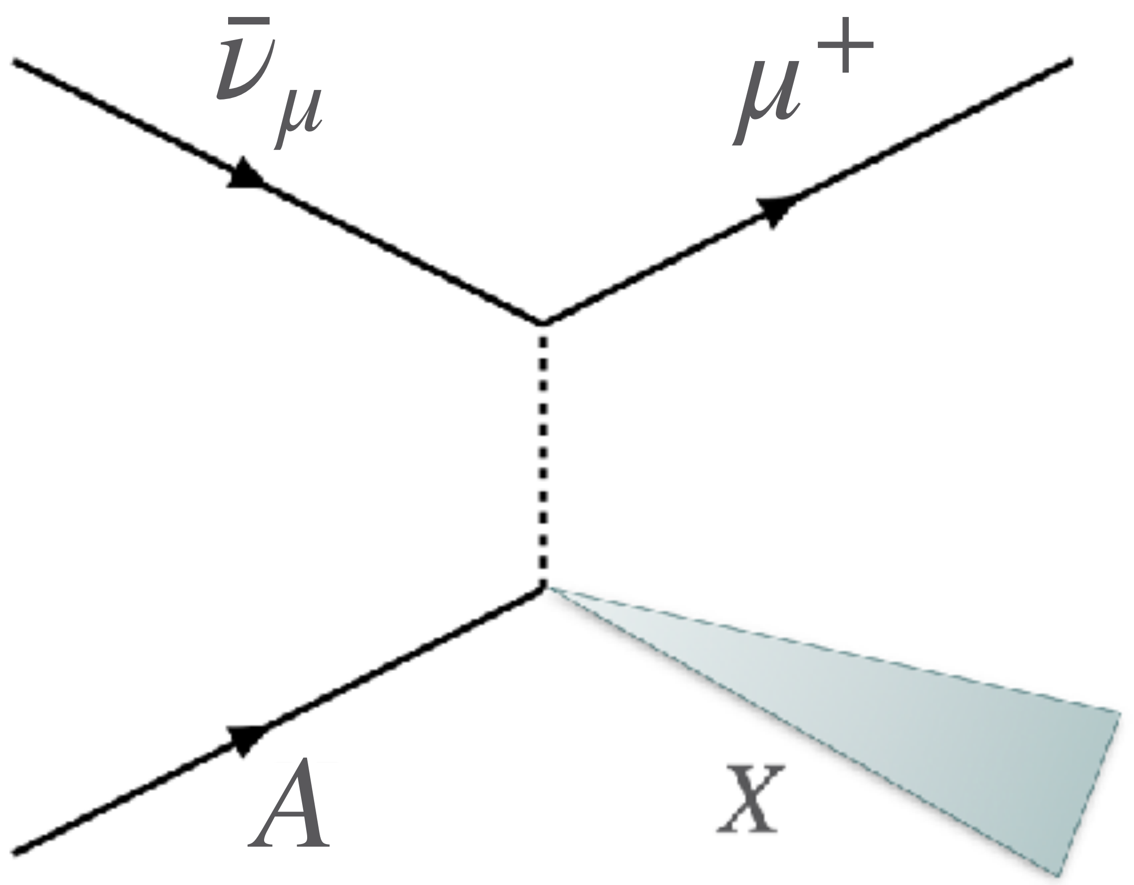


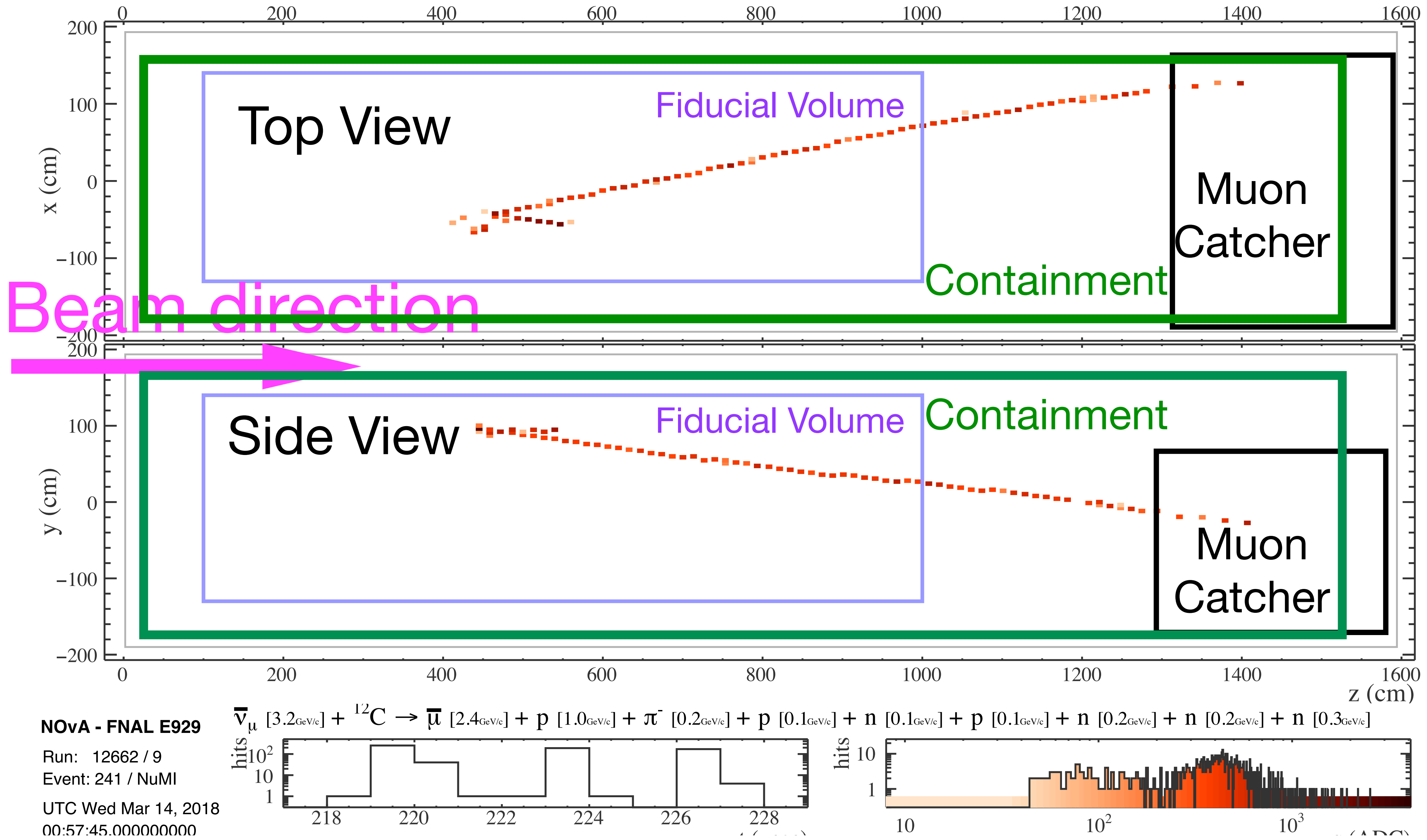
- NOvA uses total energy of all observable final state hadrons to distinguish various interaction types
- All particles that deposit visible energy in the detector contribute to the available energy

Pioneered by MINERvA (Phys. Rev. Lett. 116, 071802 (2016))

Overview of the Analysis

- Signal is $\bar{\nu}_\mu$ CC interaction having interaction vertex in the fiducial volume of the Near Detector
- Process is $\bar{\nu}_\mu + A \rightarrow \mu^+ + X$, A is the target nucleus and X represents all other final state particles
- Benefits of inclusive analysis:
  - High statistics (>900k events)
  - Ties together all neutrino-interaction models





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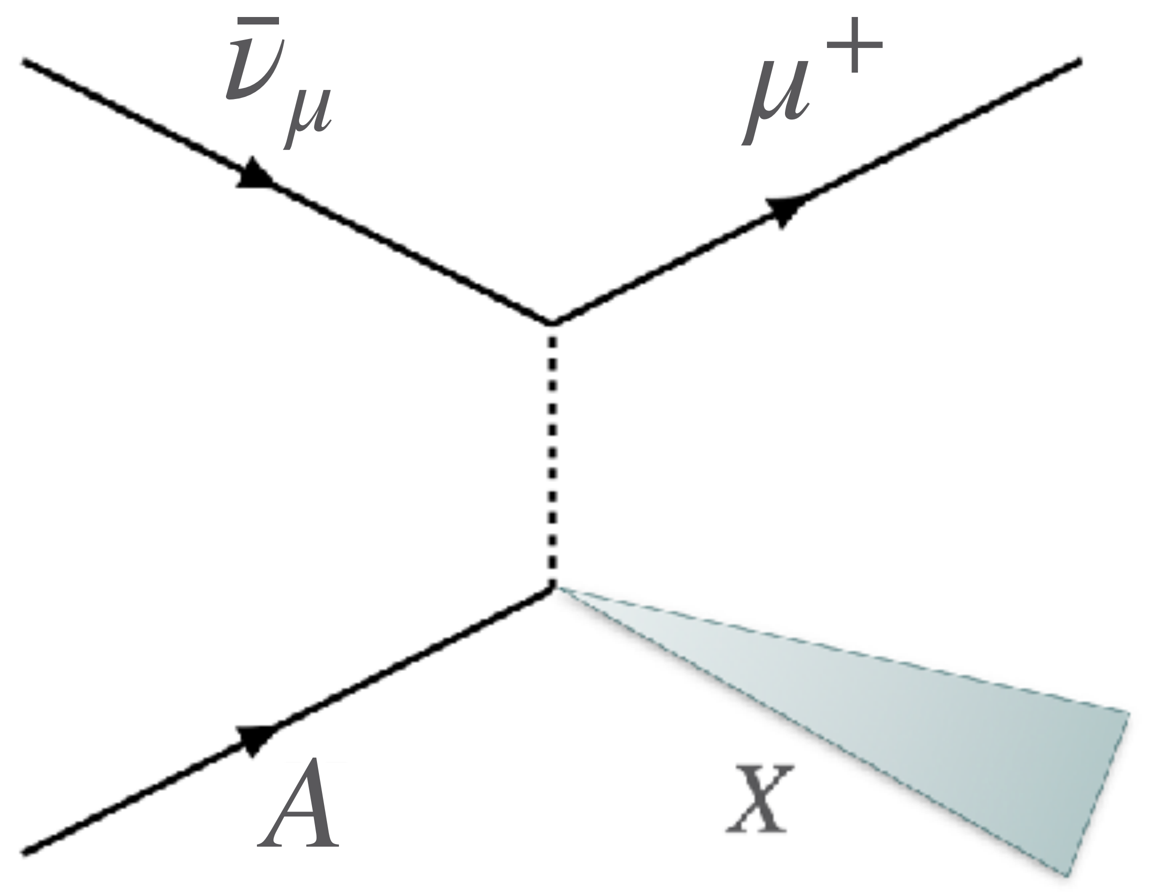
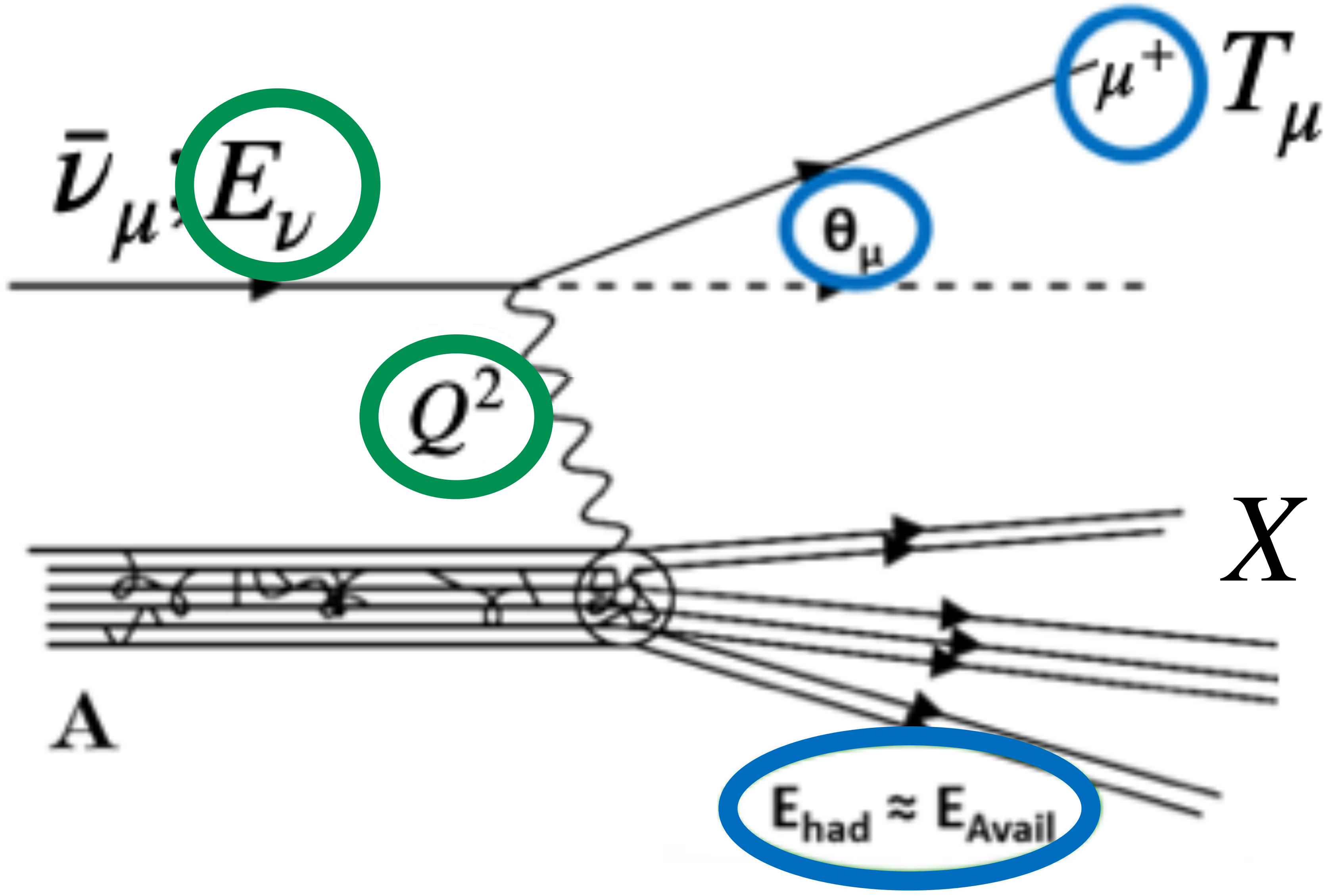
- Deliverables are

✓ triple differential cross section in T_μ, $\cos\theta_\mu$, and E_{avail}

✓ single differential cross section in E_ν and Q^2





By Travis Olson

Data Results: $0 < E_{avail} < 100$ MeV

First E_{avail} bin is enhanced in QE, and MEC interactions

GENIE 3.0.6 out of the box is under-predicting data at forward angle angles and higher T_μ

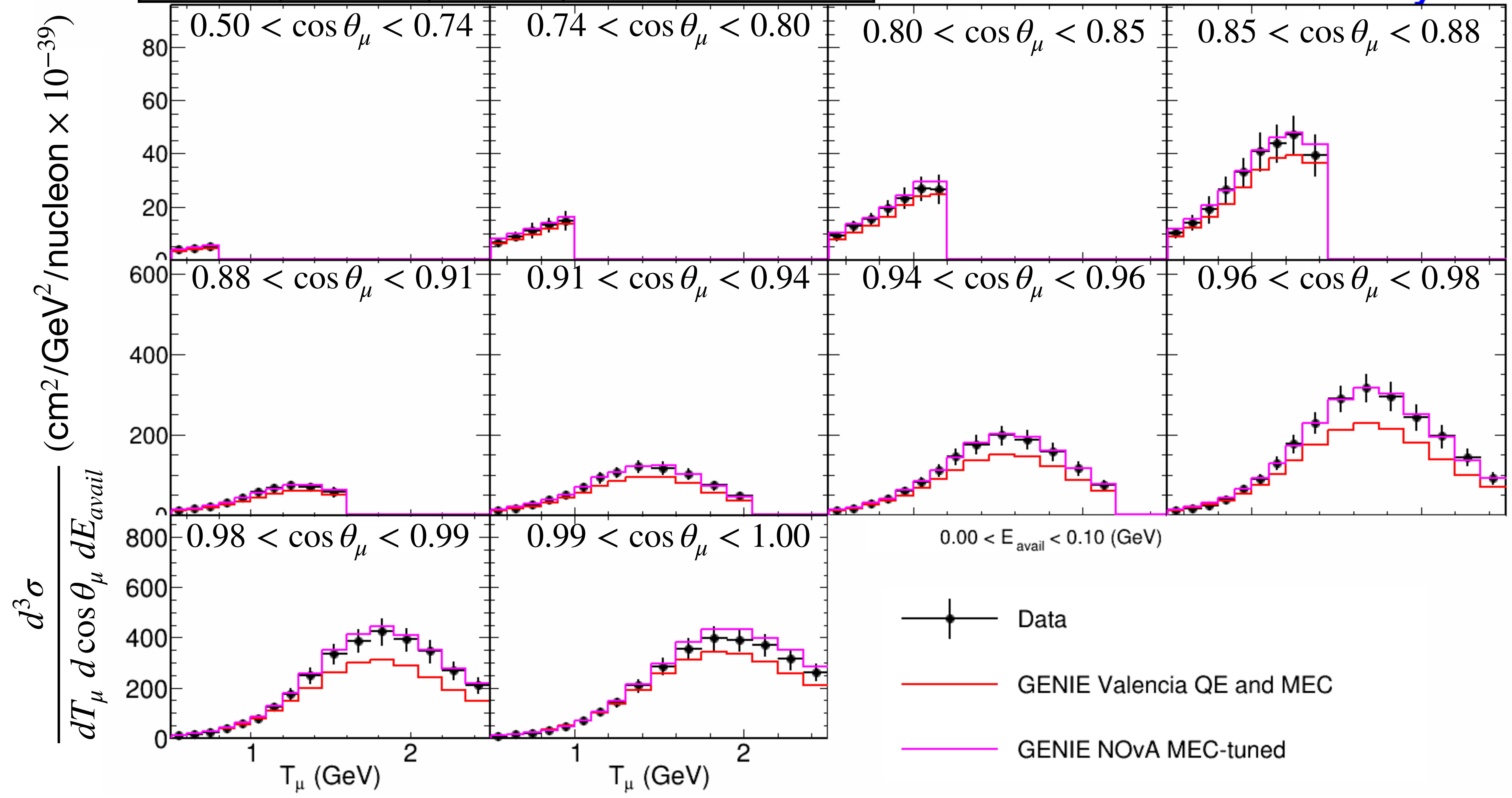
GENIE predictions tuned to NOvA-data are able to model data because NOvA tune is MEC enhanced

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
59.4	35.4	4.4	0.6	0.2

Events: 48%

NOvA Preliminary



Ratios GENIE CMC to Data Results: $0 < E_{avail} < 100$ MeV

- No theory-based model reproduces our measurement
- For QE, SuSA-v2 model is better than the Valencia model
- For MEC, differences between the SuSA-v2 and Valencia are very small and they both perform poorly to model data

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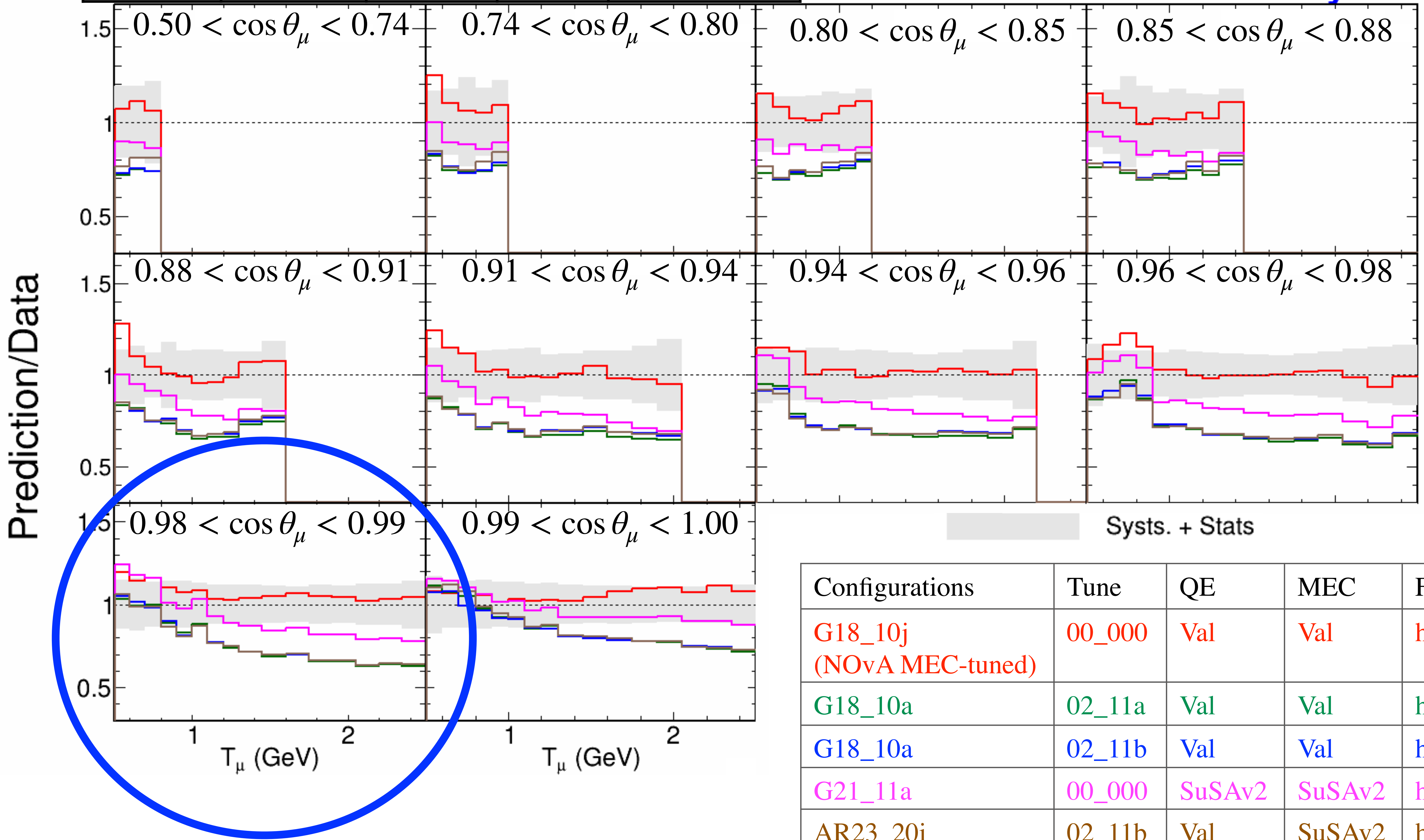


Configurations	Tune	QE	MEC	FSI
G18_10j (NOvA MEC-tuned)	00_000	Val	Val	hN
G18_10a	02_11a	Val	Val	hA
G18_10a	02_11b	Val	Val	hA
G21_11a	00_000	SuSAv2	SuSAv2	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	hA

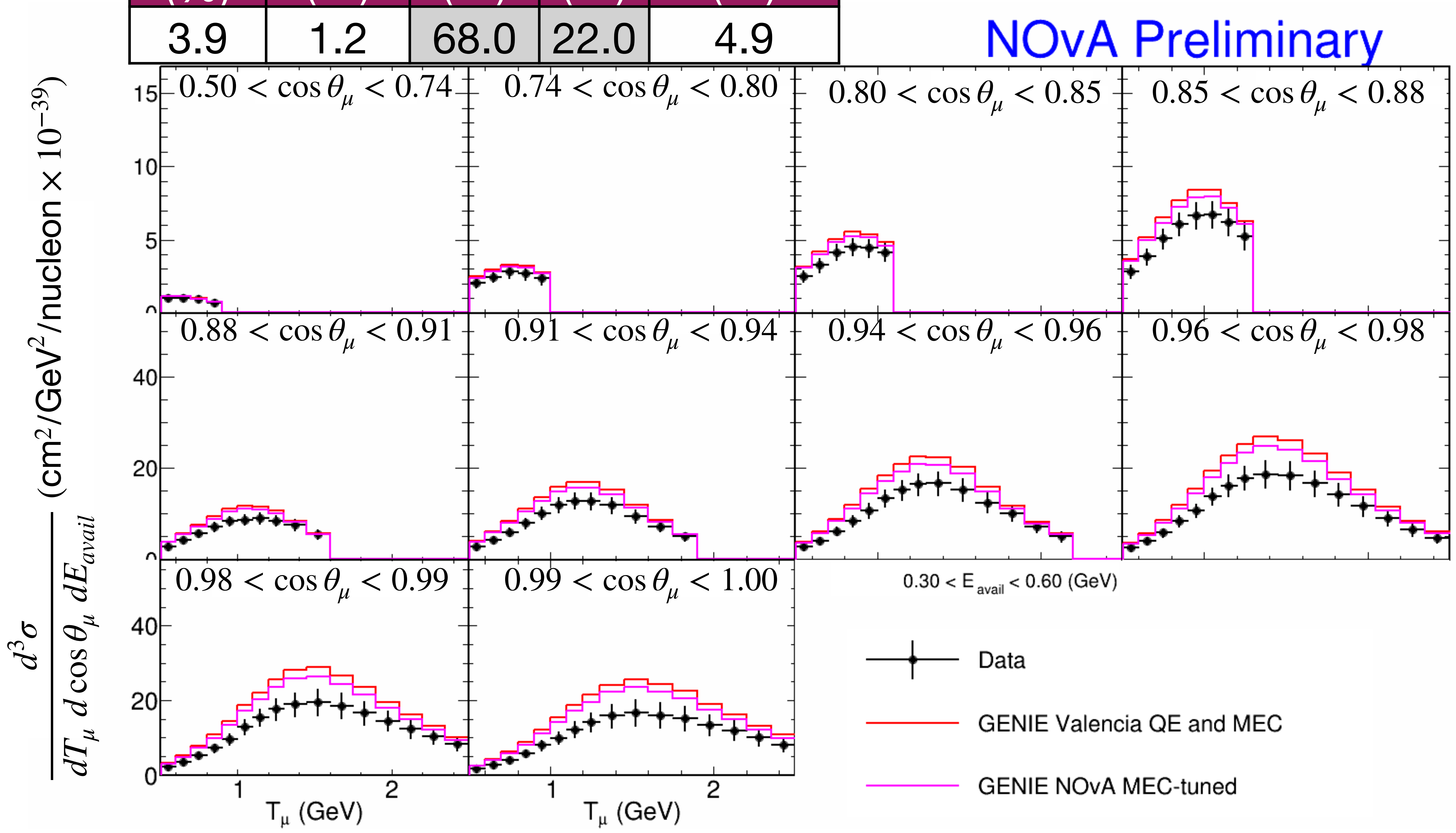
Data Results: $300 < E_{avail} < 600$ MeV

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
3.9	1.2	68.0	22.0	4.9

Events: 14%

- Available energy phase-space from 300-600 MeV is rich in RES and DIS interactions with RES dominating
- Here everywhere GENIE predictions are overestimating data



Ratios GENIE CMC to Data Results: $300 < E_{avail} < 600$ MeV

- GENIE tune 00_000 is a default tune based on previous GENIE developments
- 02_11a/b tunes are GENIE-only tunes to free-nucleon data that only affects RES/DIS events
- GENIE tunes 02_11a, and 02_11b are performing better than 00_000 tune to model RES dominated interactions in data

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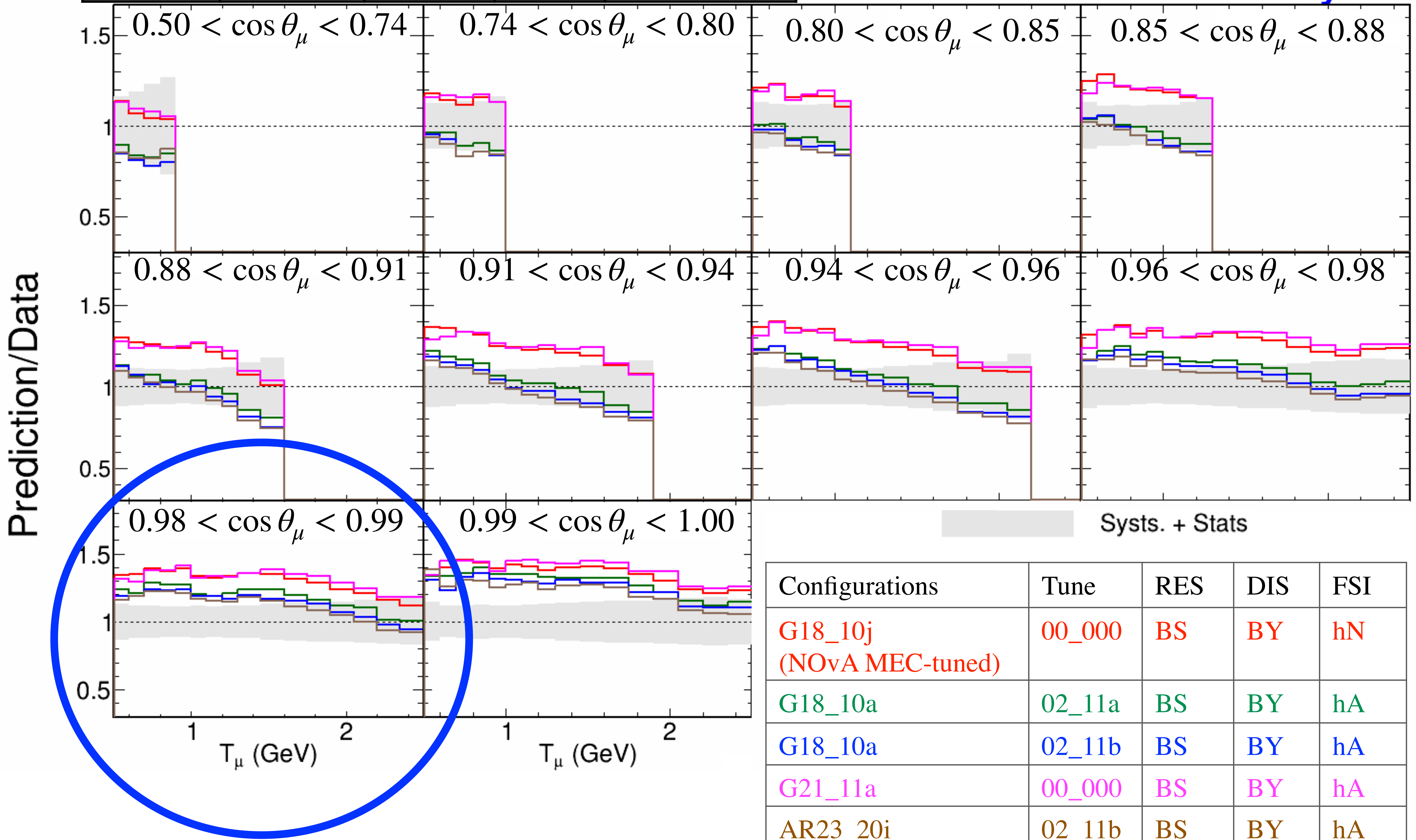


Configurations	Tune	RES	DIS	FSI
G18_10j (NOvA MEC-tuned)	00_000	BS	BY	hN
G18_10a	02_11a	BS	BY	hA
G18_10a	02_11b	BS	BY	hA
G21_11a	00_000	BS	BY	hA
AR23_20i (DUNE)	02_11b	BS	BY	hA

Data Results: $1 < E_{avail} < 2$ GeV

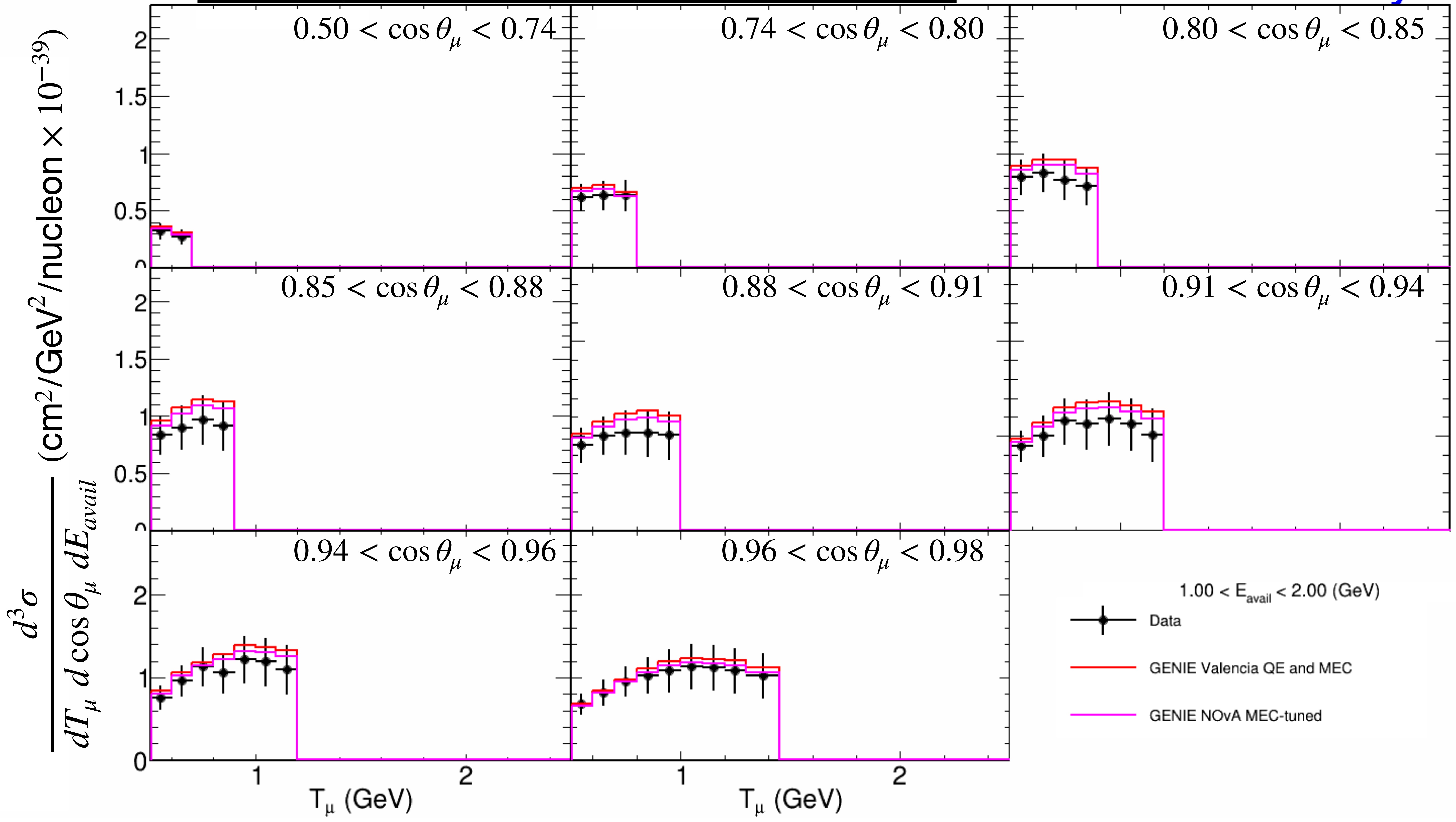
- Region is dominated by DIS interactions
- GENIE is doing a reasonable modeling of DIS interactions

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
0.1	0	23.9	72.2	3.8

Events: 5%

NOvA Preliminary



Ratios GENIE CMC to Data Results: $1 < E_{avail} < 2$ GeV

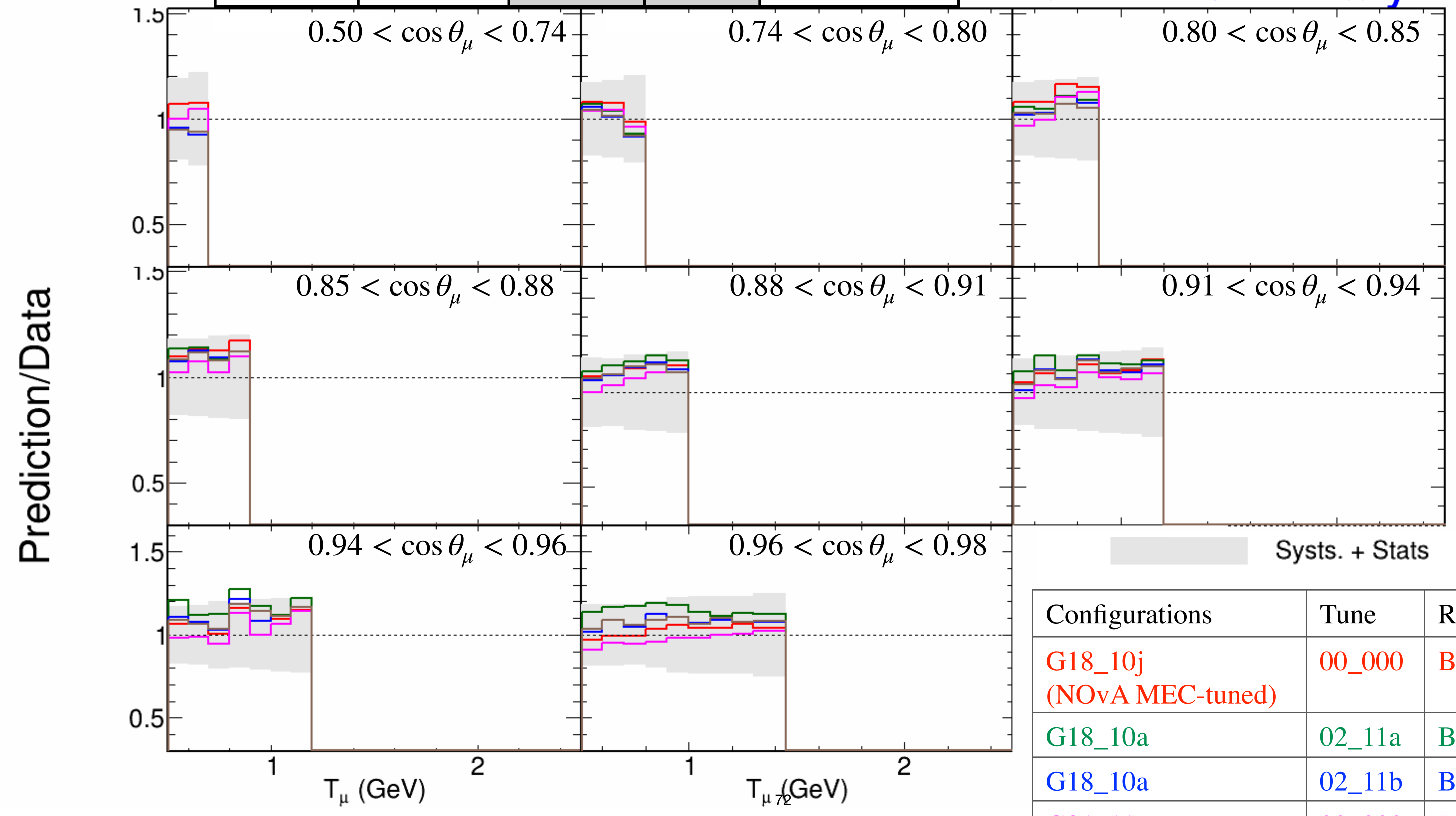
Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
0.1	0	23.9	72.2	3.8

Events: 5%

NOvA Preliminary

- Bodek-Yang + Pythia is doing a good job in modeling DIS interactions



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G18_10a	02_11b	BS	BY	hA
G21_11a	00_000	BS	BY	hA
AR23_20i (DUNE)	02_11b	BS	BY	hA

Results
Neutrino Generator Comparisons

Generators to Data Results: $0 < E_{avail} < 100$ MeV

- GiBUU is doing a good job in modeling QE/MEC interactions

- Both GENIE 3.4.0, and NEUT uses Valencia for QE, only their FSI tunes are different and NEUTs tune is doing better

Table from NOvA-tuned GENIE

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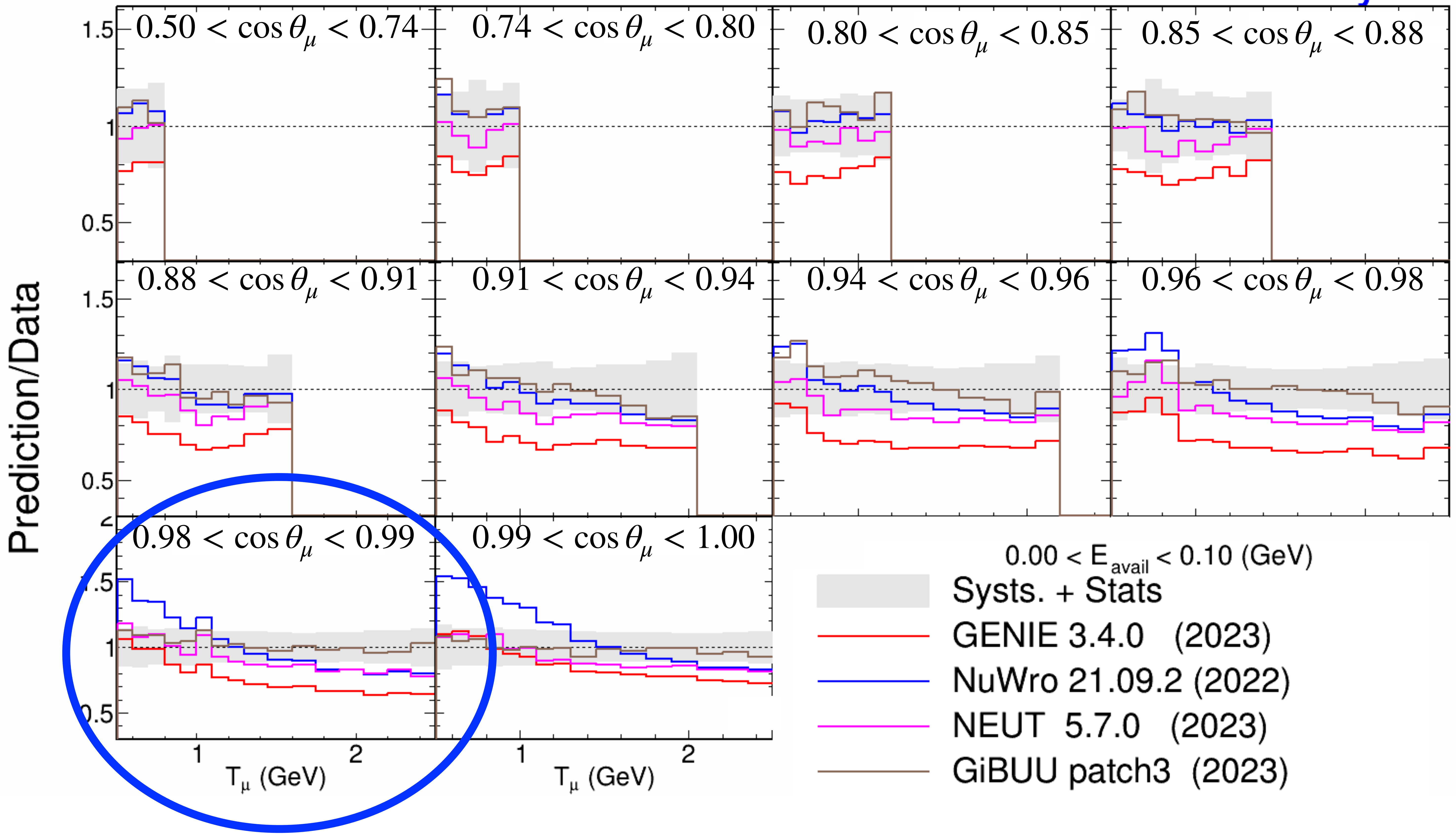
NOvA Preliminary



Generators to Data Results: $300 < E_{avail} < 600$ MeV

- In the RES enhanced regions, all generators are performing differently
- GiBUU is mostly under-predicting
- NEUT is generally closer to the data. It uses BS for modeling RES along with its custom tune for FSI

Table from NOvA-tuned GENIE

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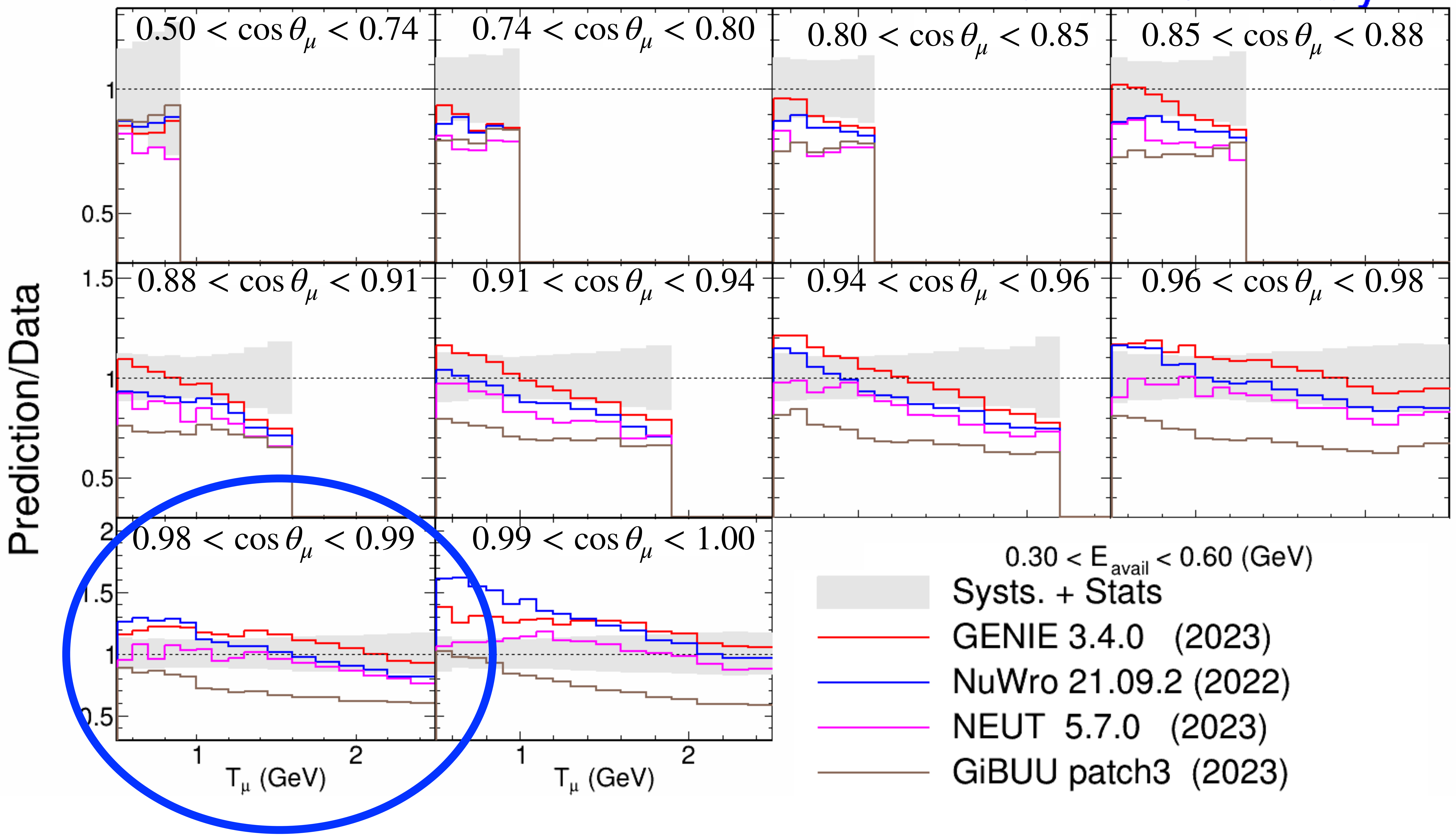

Generators to Data Results: $1 < E_{avail} < 2$ GeV

- In the DIS rich regions, GiBUU is mostly under-predicting
- GENIE, NuWro, and NEUT are using Bodek-Yang model for DIS but all three have different FSI tunes
- GENIE's FSI tune seems to be doing a better job in modeling DIS interactions

Table from NOvA-tuned GENIE

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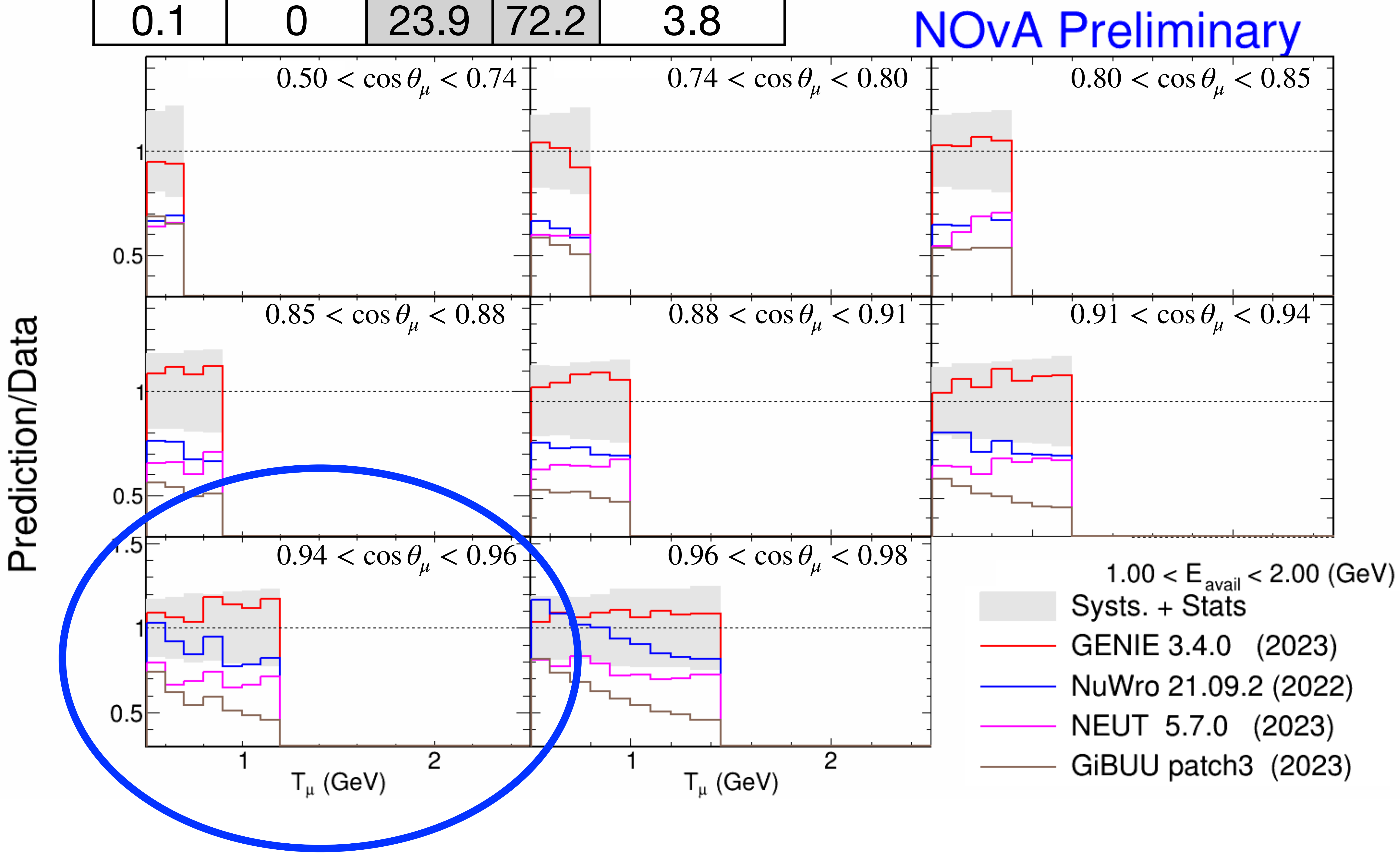
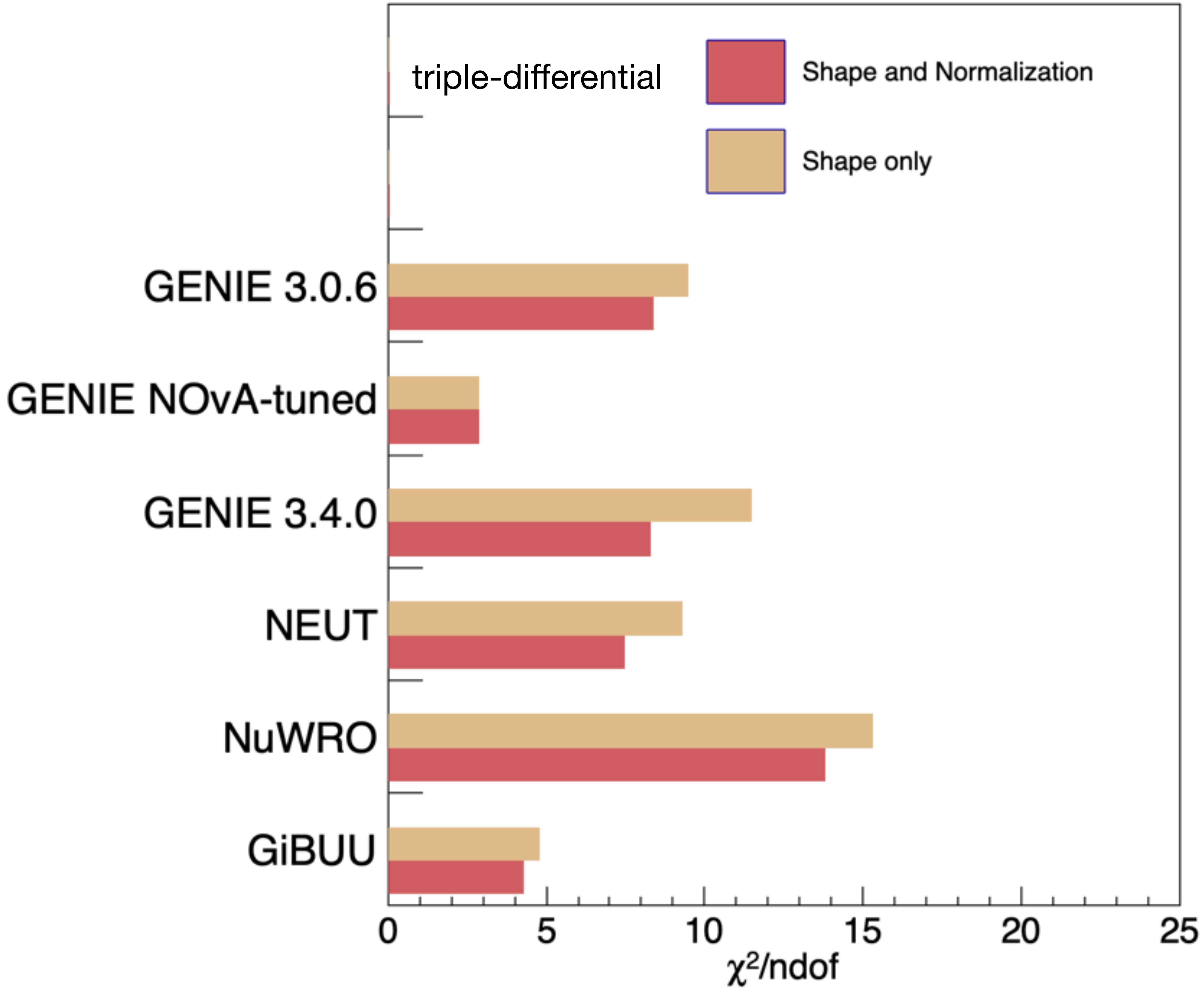
Events: 5%



χ^2/ndof

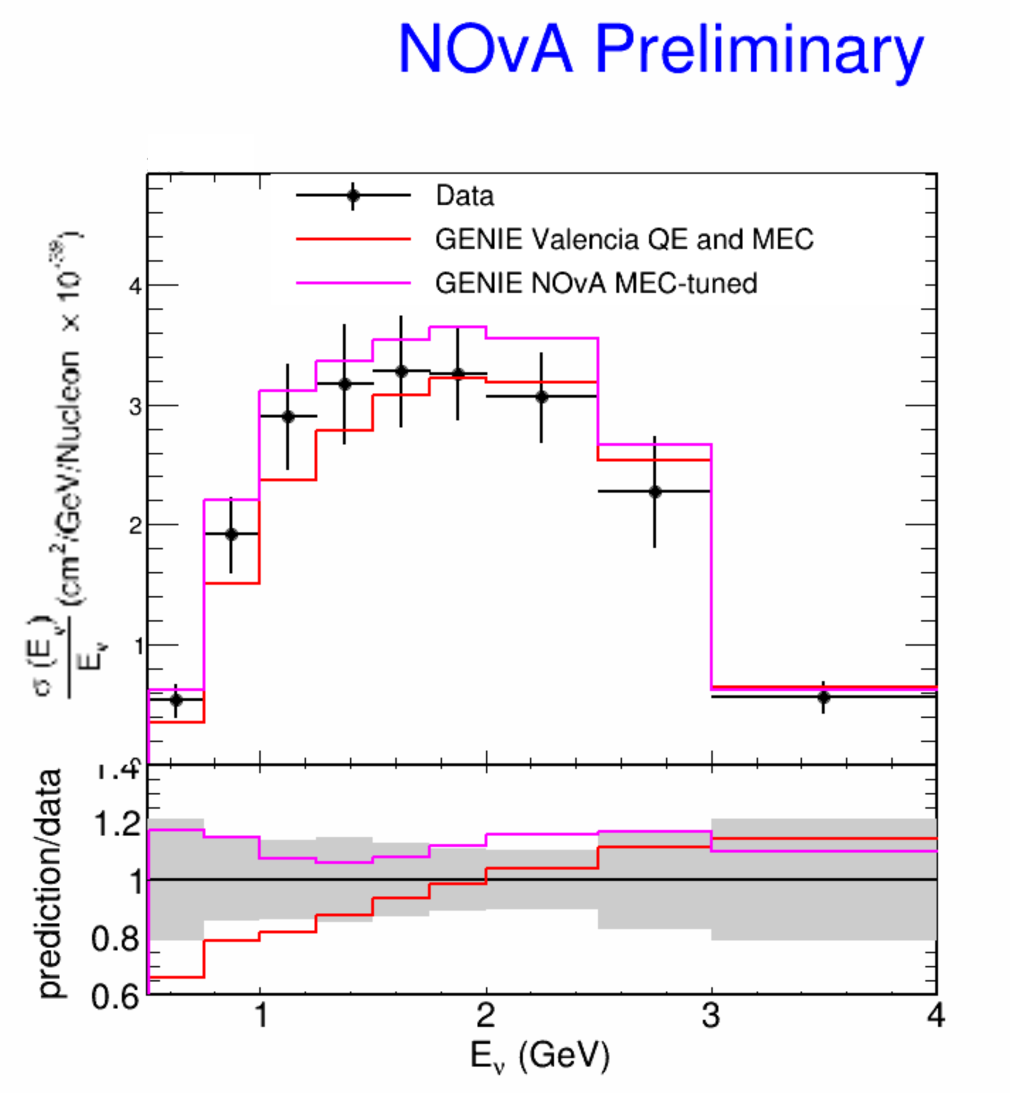
- χ^2 are calculated using covariance matrices to account for bin-to-bin correlations
- Overall χ^2 are driven strongly by the 0-100 MeV available energy region which has about half of our signal events
- Generators show varying level of agreements to data in different regions of available energy

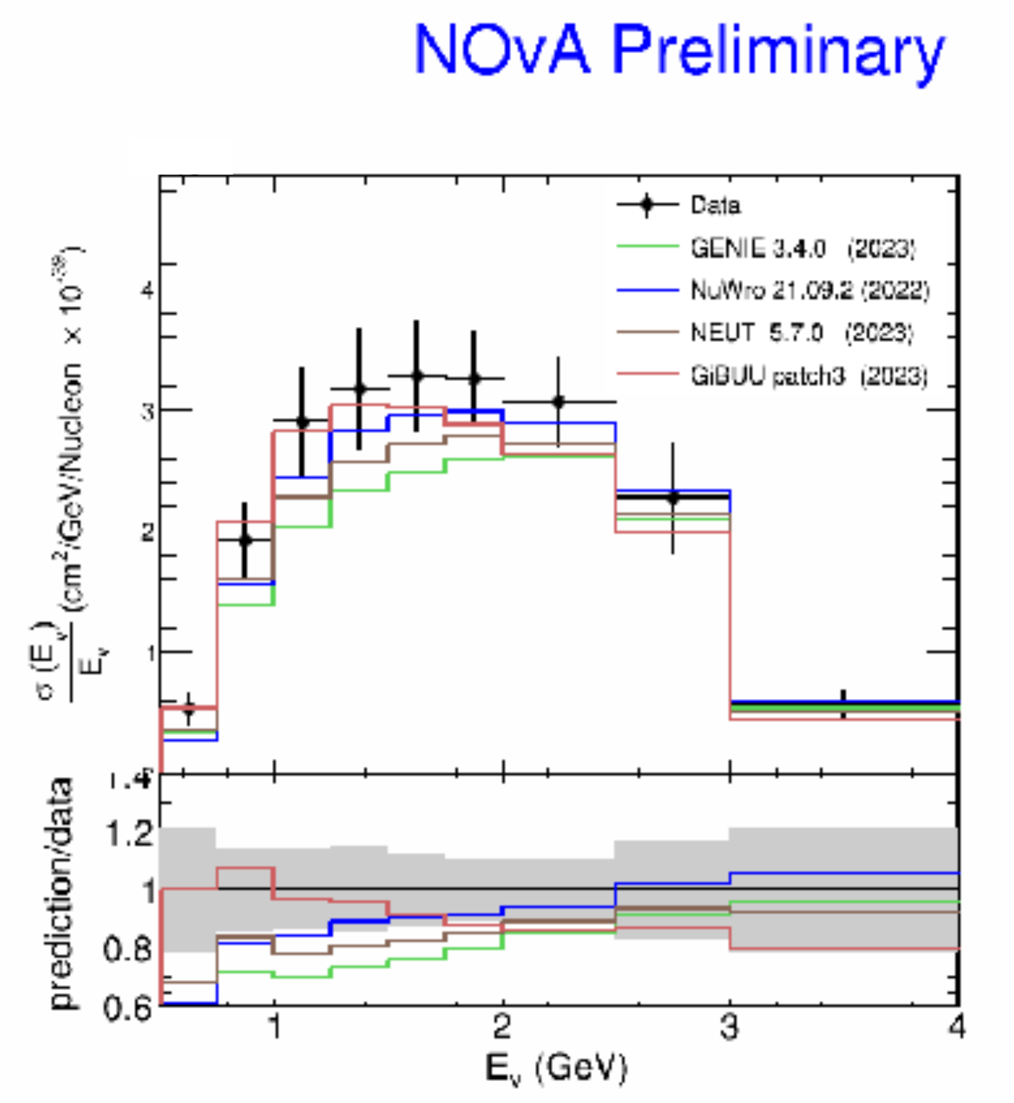
NOvA Preliminary

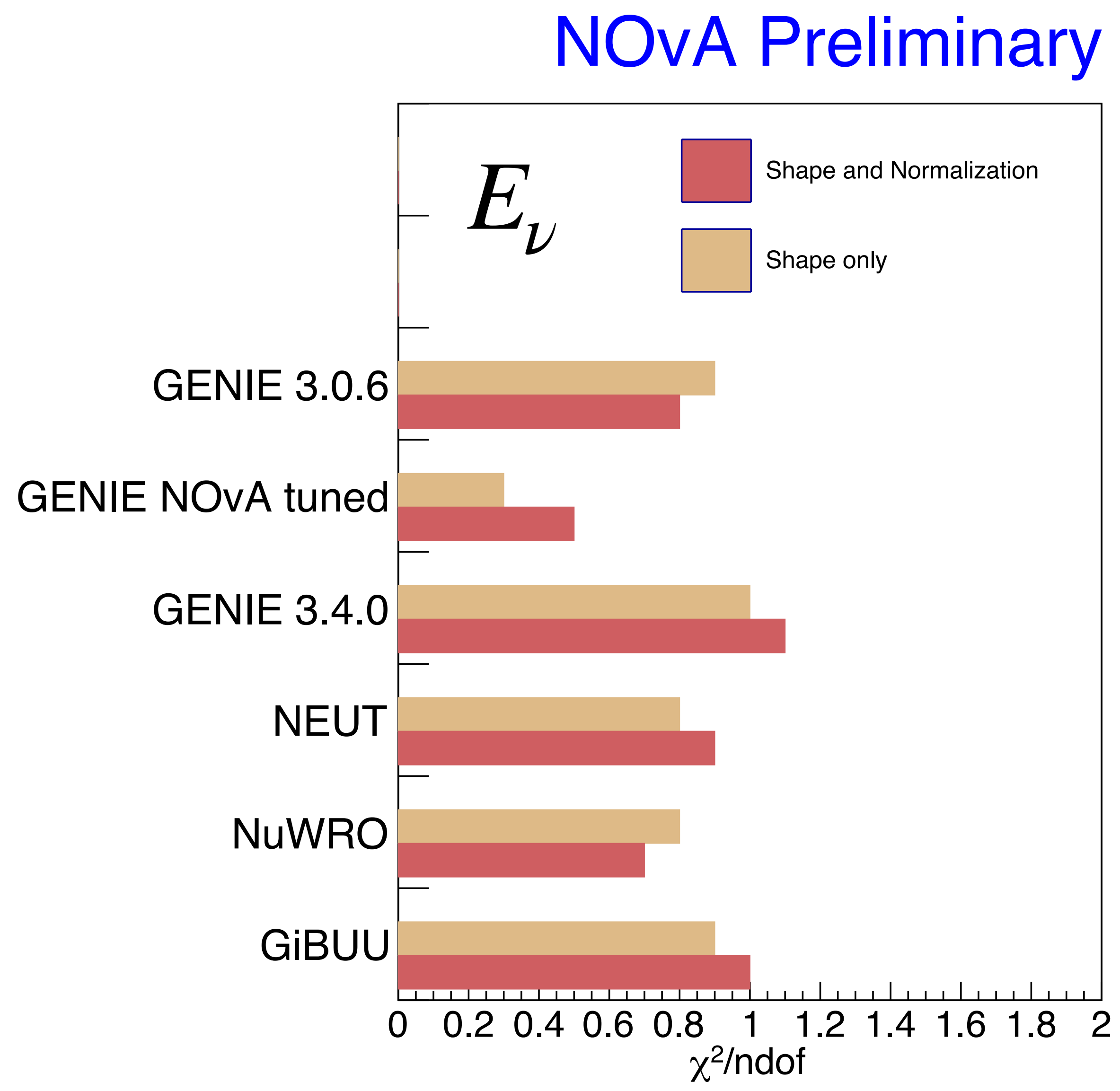


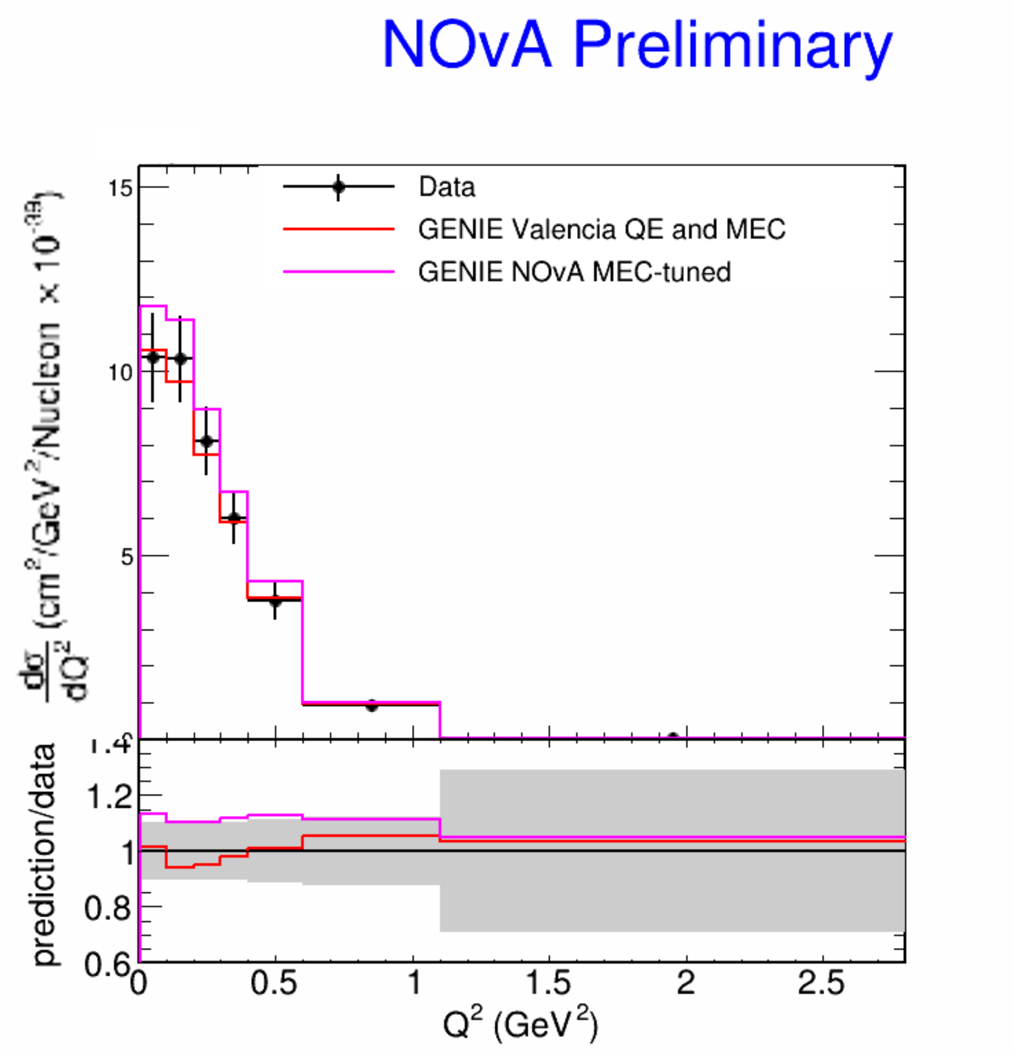
Single Differential Results

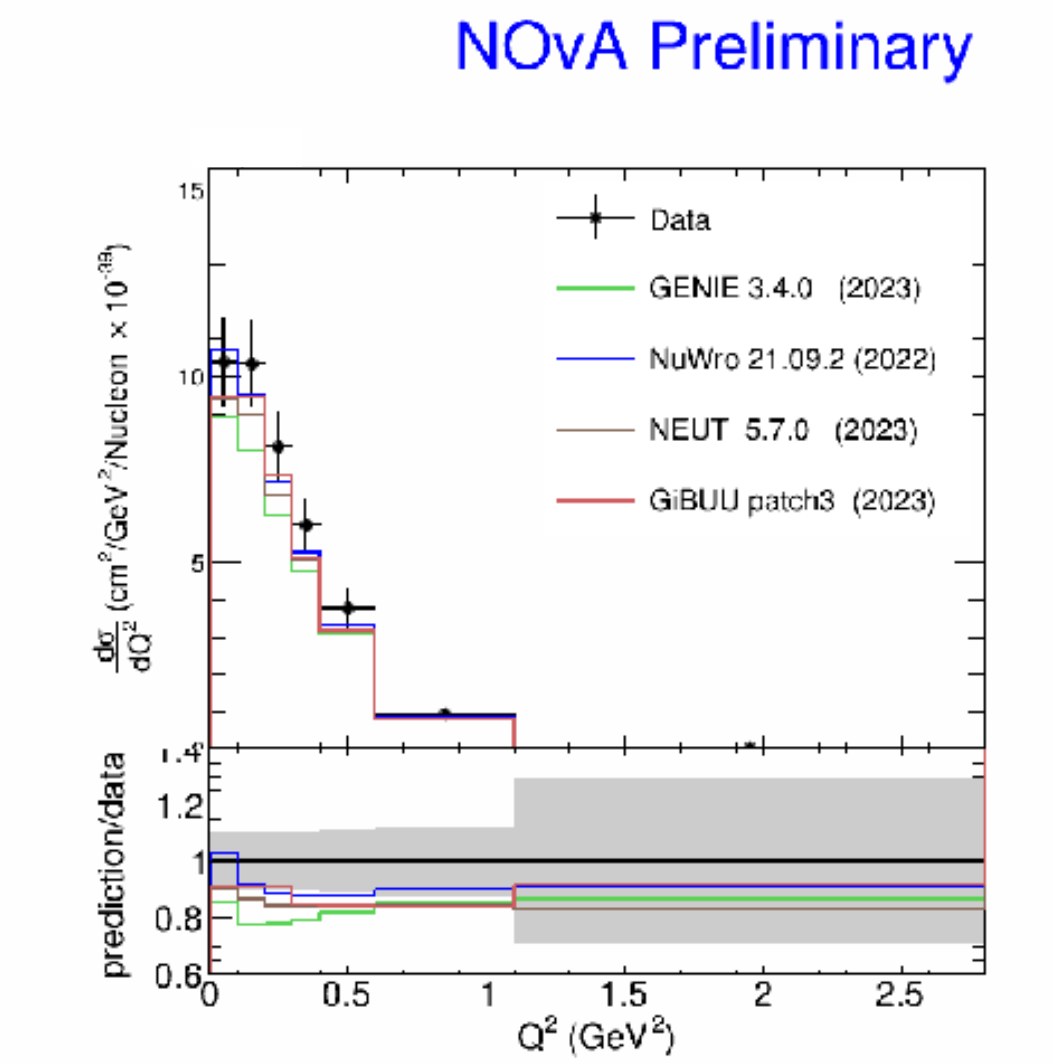
- At low E_ν, all generators are under predicting data except GiBUU
- For generators shape agreement in energy is good and disagreements are mostly in normalization
- For Q^2, GENIE 3.4.0, NEUT, NuWRO, and GiBUU, are under-predicting data

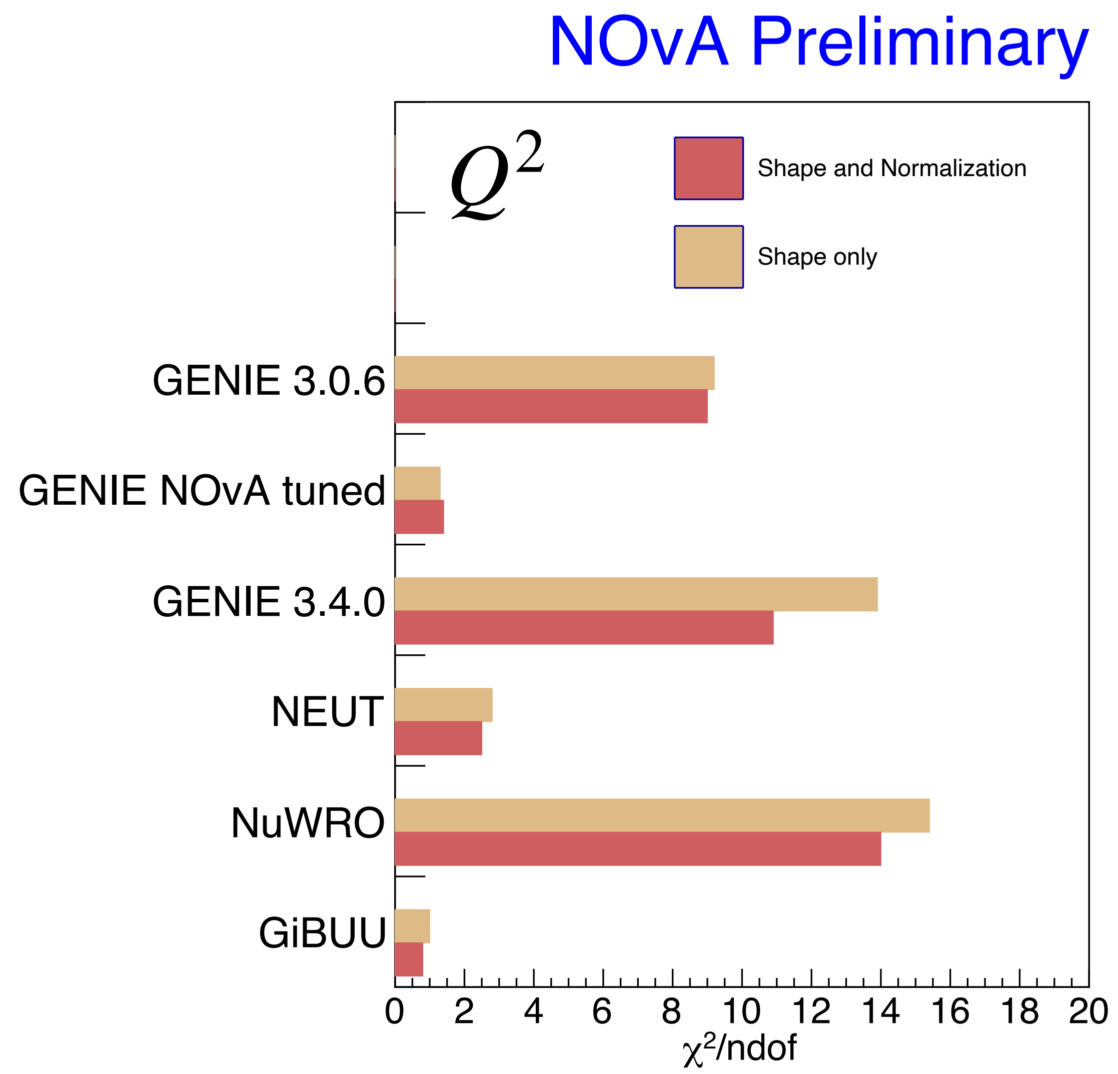












Conclusions

- No theory based model reproduces our measurement
  - ✓ QE: SuSA-v2 agrees better than the Valencia
  - ✓ MEC: differences between Valencia, and SuSA-v2 are very small though both performs equally poorly
  - ✓ RES: GENIE predictions are over-predicting data. We need more neutrino interaction models to understand these regions
- Various neutrino generators, have different strengths in different regions of available energy
- We plan to release our data to enable model builders to tune interaction models, look forward to it when released with paper

NOvA Collaboration

> 240 people, ~ 50 institutions, 7 countries

Thank You

Backup

Why Neutrino Cross sections are Important? - Oscillations

$$R(x) = \phi(E_\nu) \times \sigma(E_\nu, x) \times \epsilon(x) \times P(\nu_\alpha \rightarrow \nu_\beta)$$

- $R(x)$: Event rate (Measured in detector)
- $\phi(E_\nu)$: Neutrino flux
- $\sigma(E_\nu, x)$: Neutrino-nucleus interaction cross section
- $\epsilon(x)$: Detector response
- $P(\nu_\alpha \rightarrow \nu_\beta)$: Oscillation probability ($\alpha \rightarrow \beta$ neutrino flavor oscillation)

To deduce physics observations, such as the CP-violation by neutrinos (δ_{cp}), oscillation mixing angles, and the mass ordering of neutrino masses, we need to infer neutrino oscillation probabilities from the event rate

This can be done with a good understanding of:
- neutrino beam flux
- detector responses (selection efficiencies)
- neutrino-nucleus cross section modeling

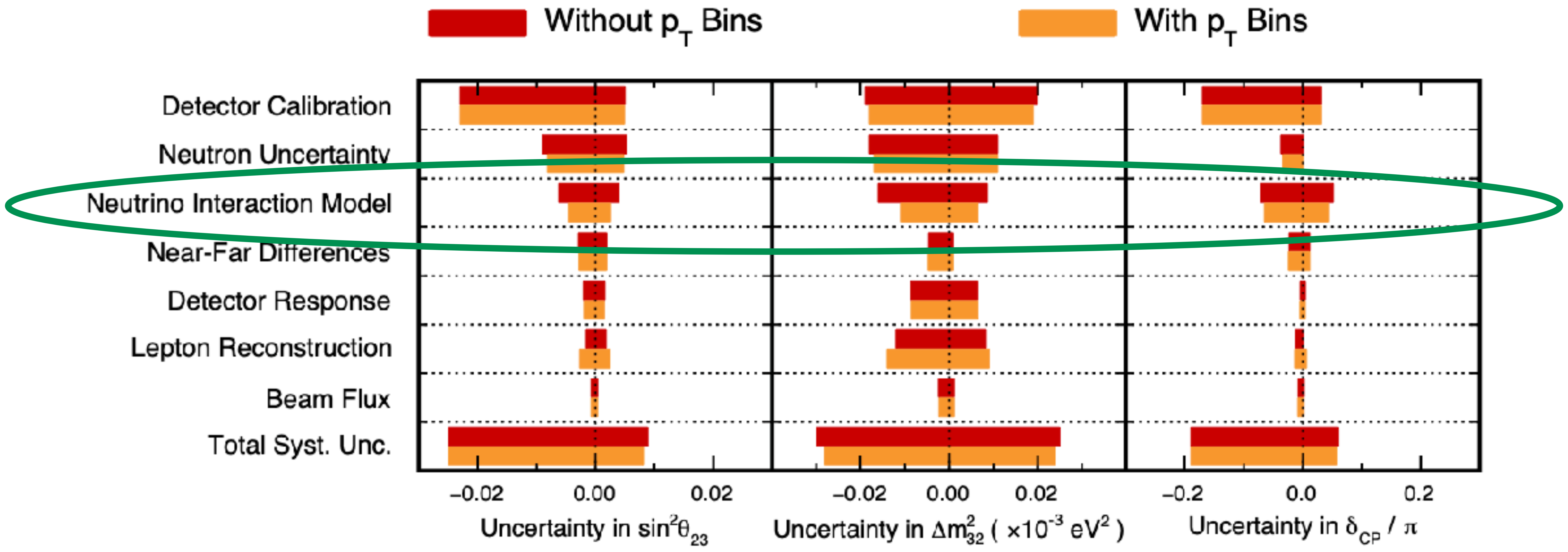
Why Neutrino Cross sections are Important? - Uncertainties

In the current era of neutrino experiments, we are no longer statistically-limited

Systematic uncertainties have become very important to derive physics conclusions from the data collected by the experiments

Uncertainties due to neutrino interaction modeling is one of the dominant source of uncertainties and can be reduced by the cross section measurements

NOvA: PhysRevD.106.032004



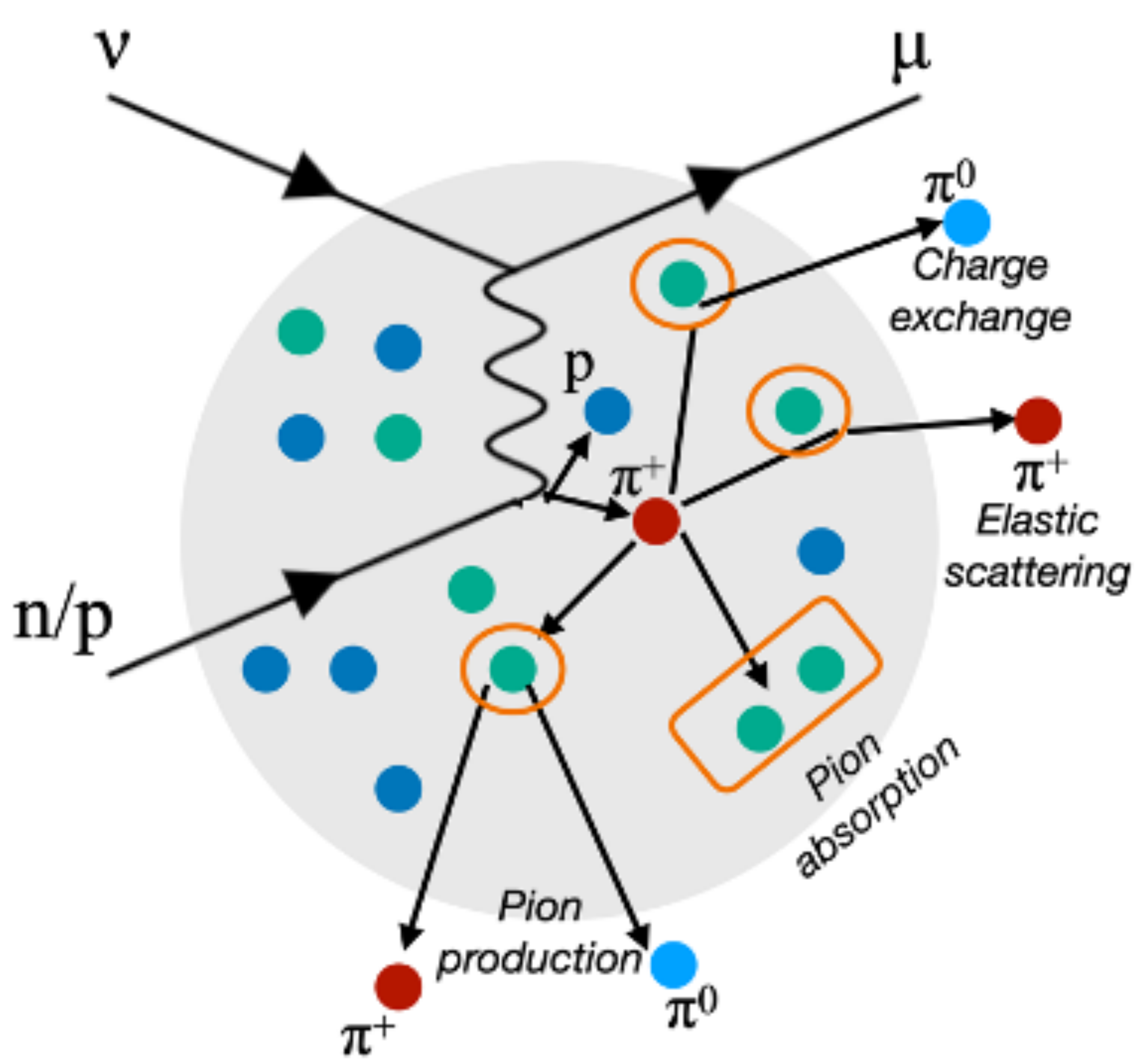
Why Neutrino Cross sections are Important? - Nuclear Physics

Neutrino cross section measurements can be used to study nuclear physics

In heavy nuclei, the interactions of nucleons within the nucleus affect the neutrino scattering by the nucleus

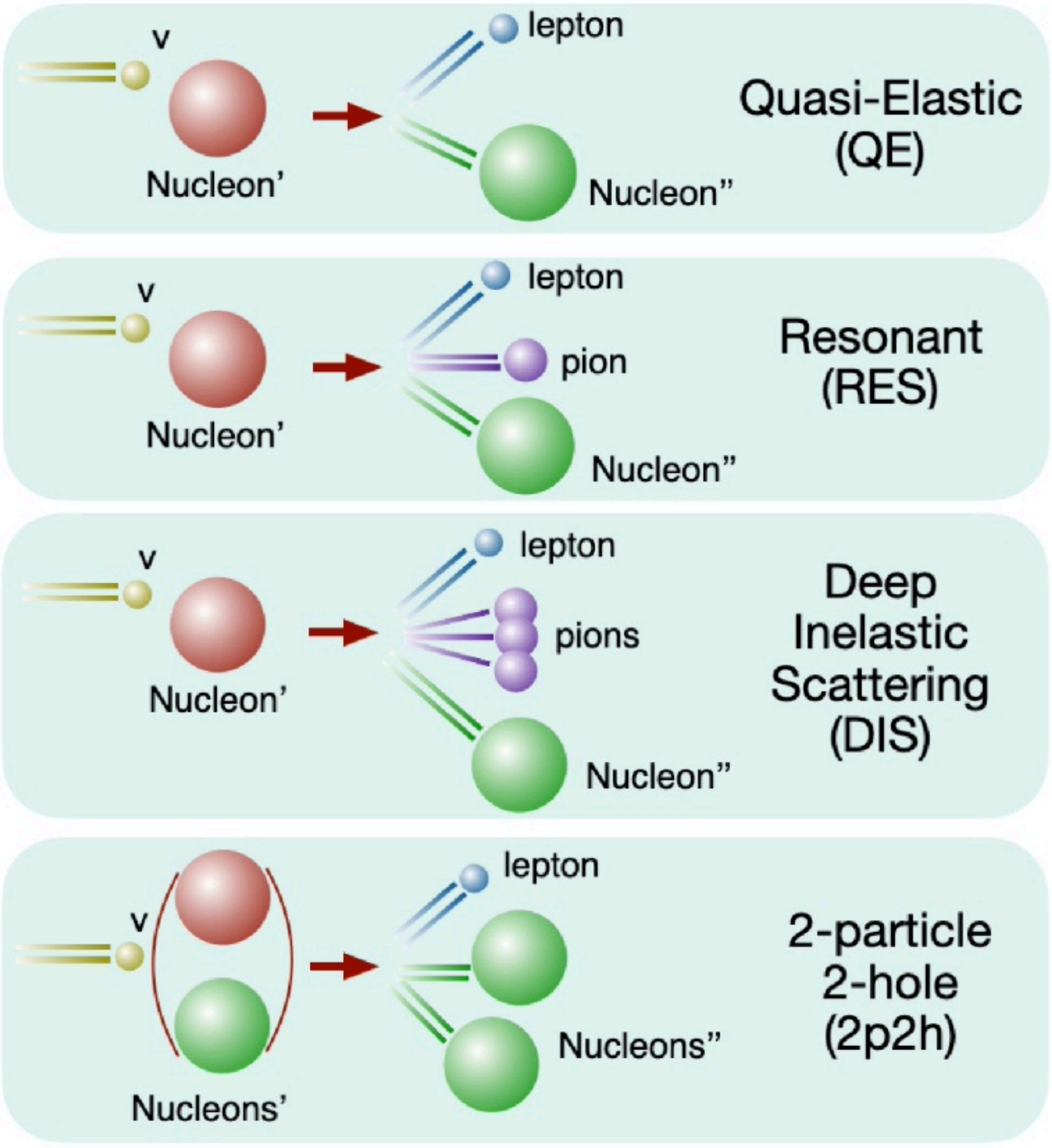
Physics conclusion can be drawn by comparing various nuclear physics models to the cross section measurement results

This can further help us to reduce neutrino interaction uncertainties in the future neutrino experiments

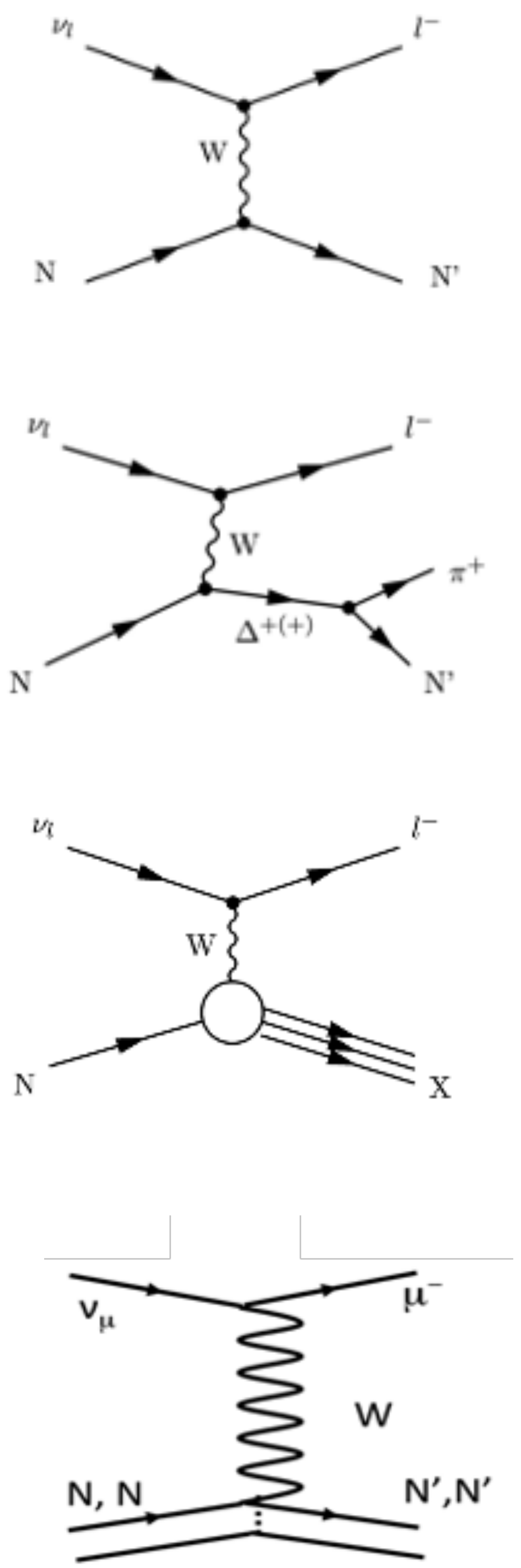


By T. Golan

Neutrino Interactions and Nuclear Effects



By Linda Cremonesi, [Neutrino 2020]



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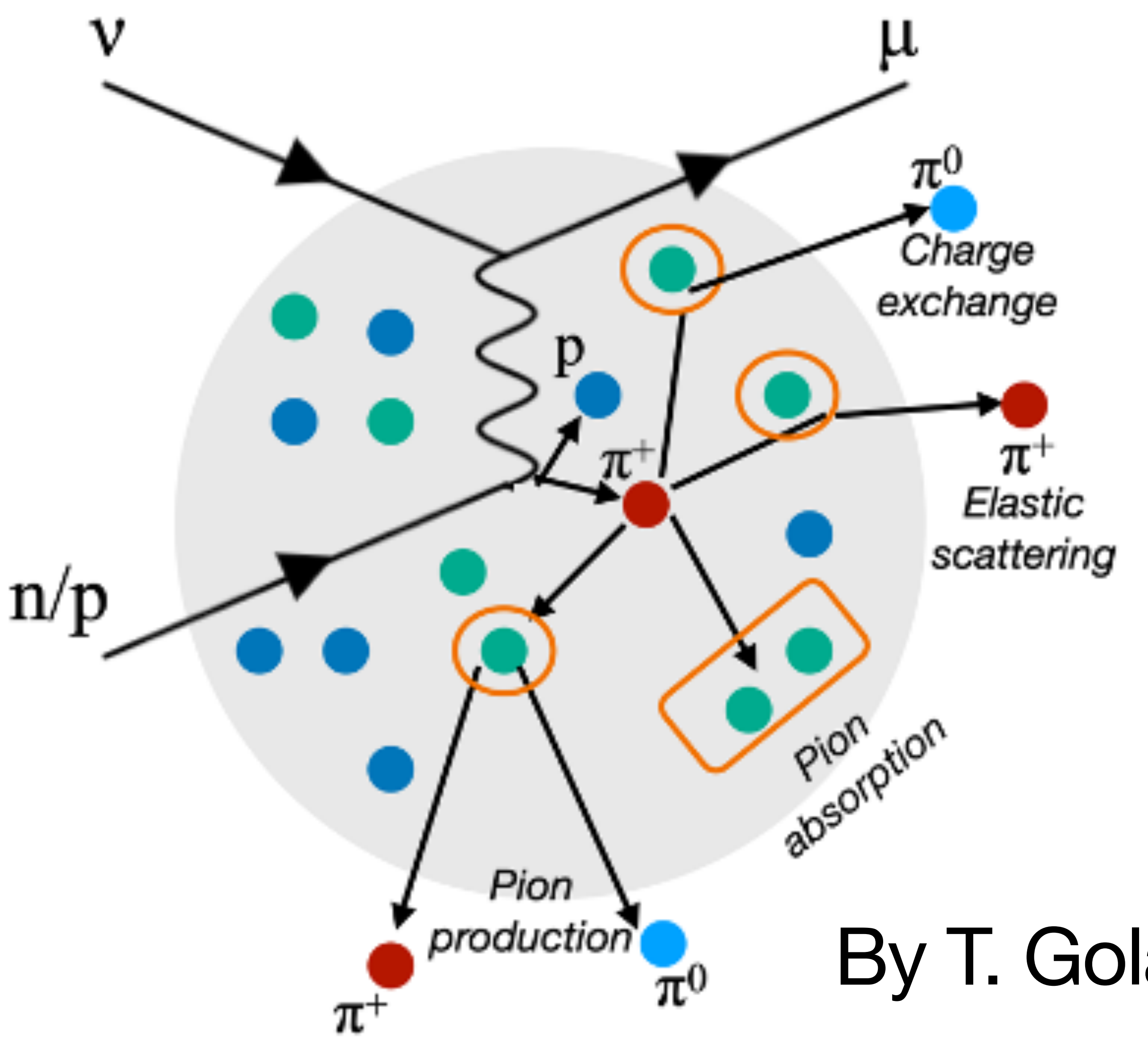


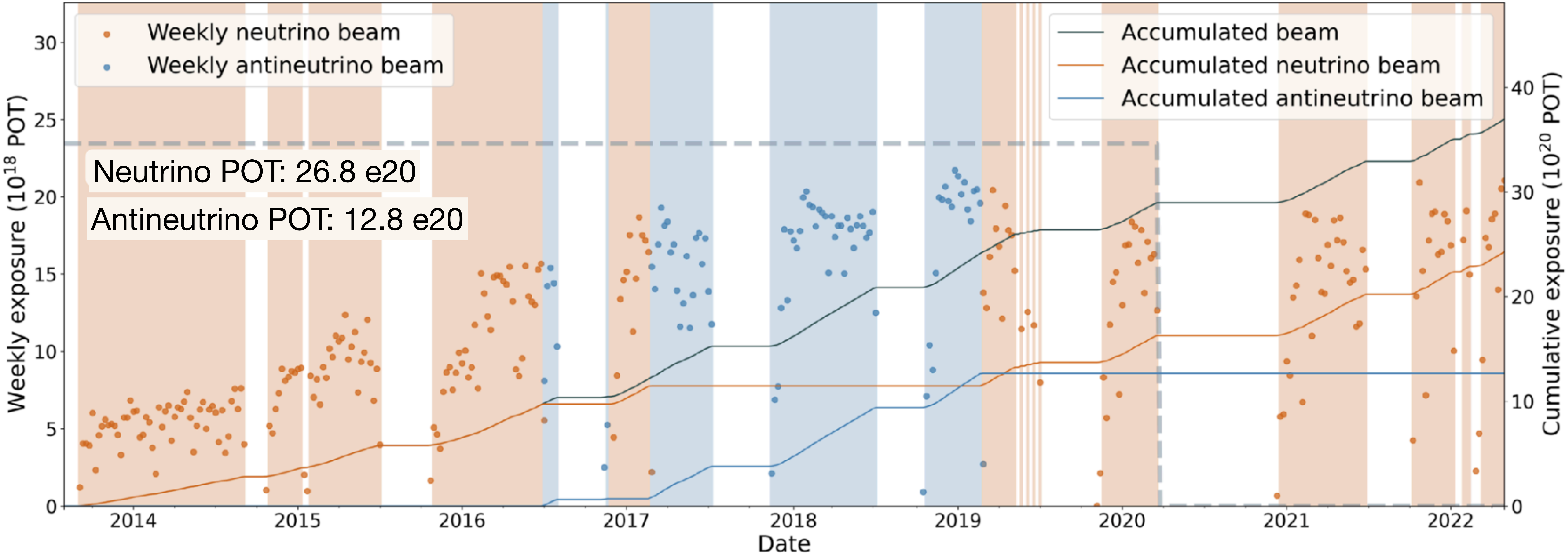
By T. Golan

Final state interactions due to intra-nuclear re-scattering can change the hadron kinematics of the outgoing particles

Beam Exposure

Current Analysis Dataset

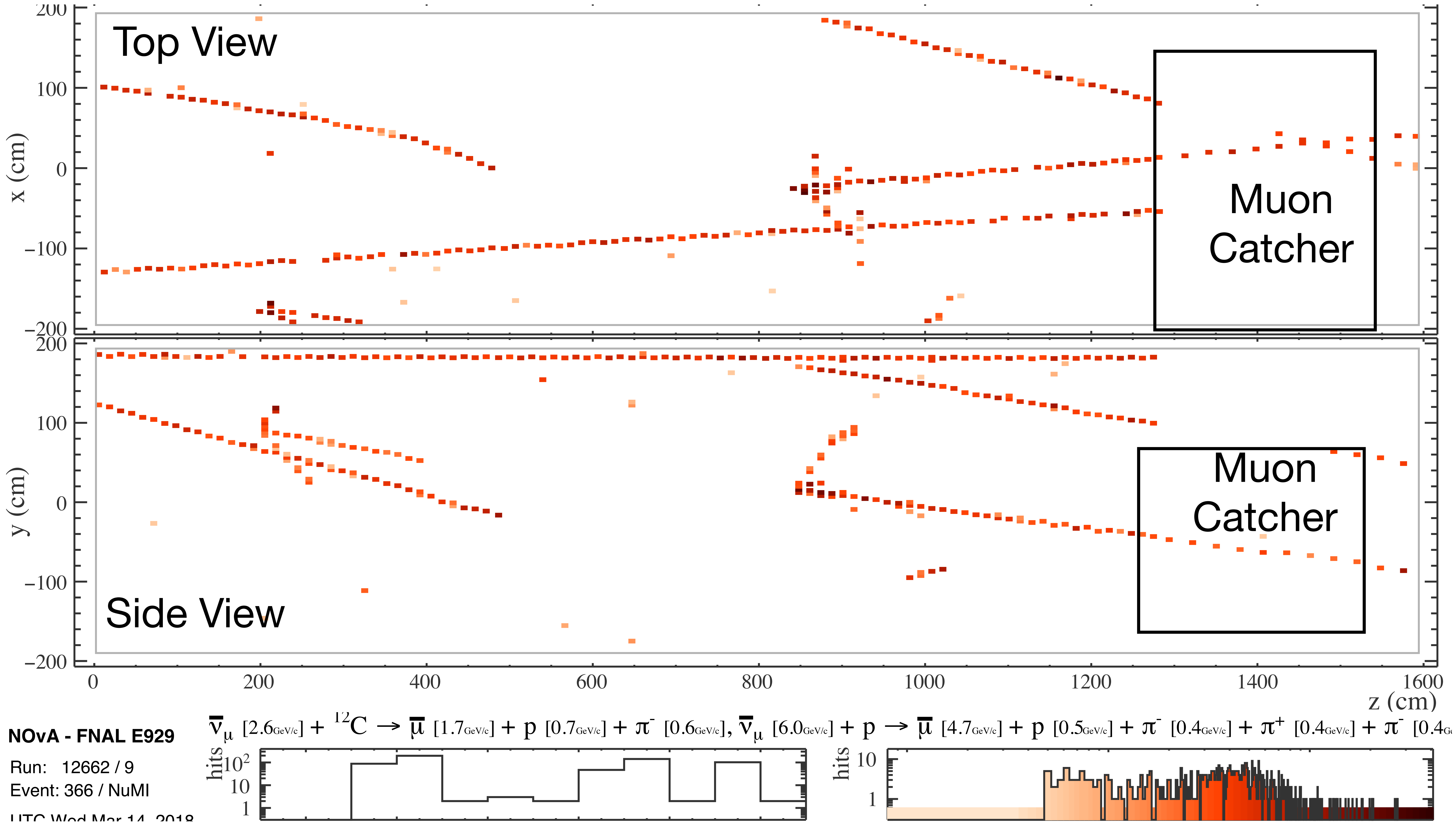
Antineutrino POT 12.5×10^{20} in ND



- Total protons on target recorded so far 39.6e20
- New power record 950+ kW in FY23

1MW, here we come! - Thanks to the hard work of many people, in front and behind the scenes

Event Display - Near Detector



Near Detector sees high intensity neutrino beam due to its close proximity to the neutrino target

We use this opportunity to do high statistics cross-section measurements

Simulation Model - GENIE 3.0.6

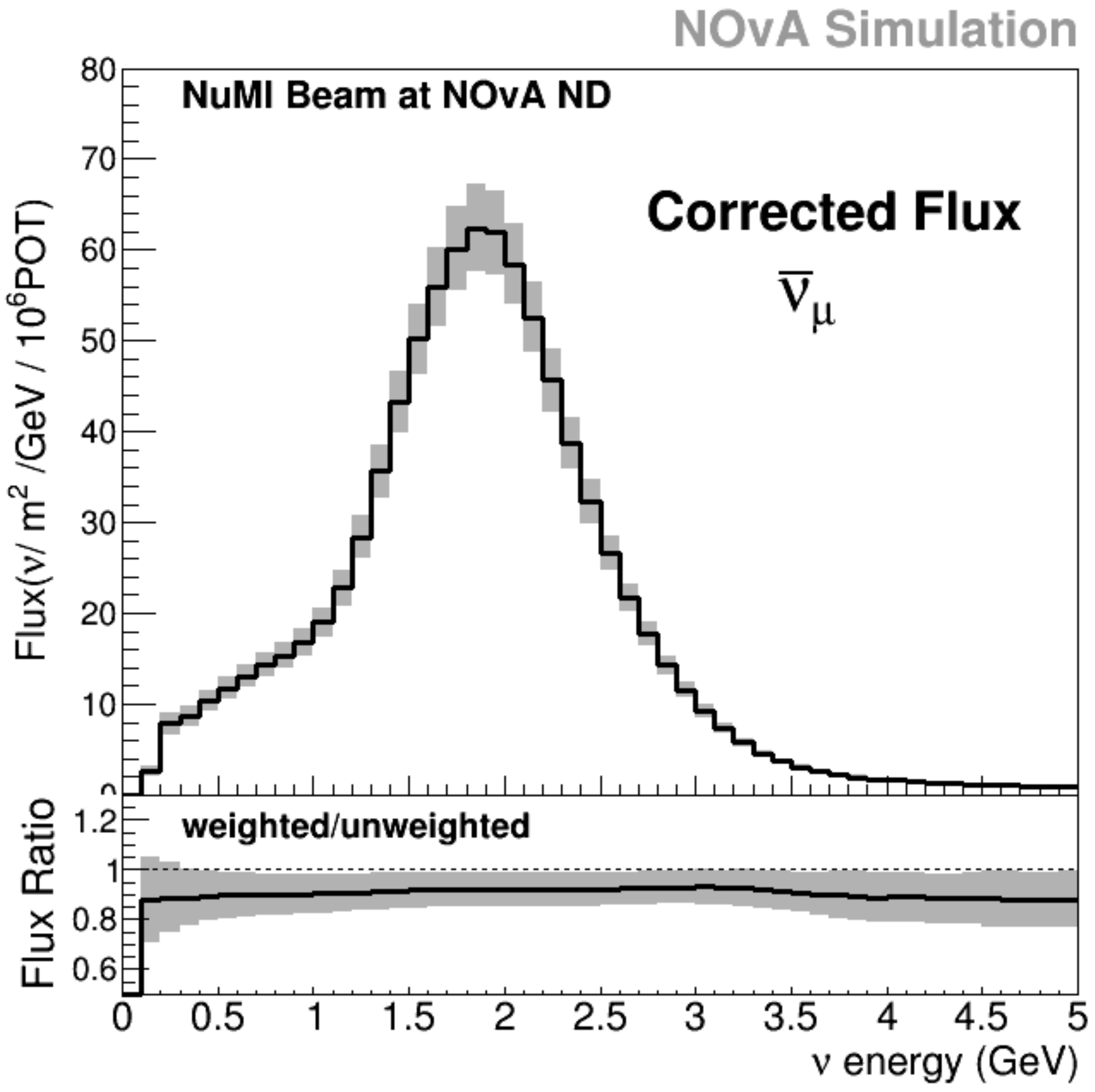
Initial State Interactions	QE	MEC	Res/Coh	DIS	FSI
Local Fermi Gas (LFG)	Valencia + Z-expansion	Valencia	Berger-Sehgal (BS)	Bodek-Yang + Pythia	hN (many possible interactions)

- We simulate neutrino interactions using a custom model configuration of GENIE 3.0.6 tuned to external and NOvA ND data
- MEC and FSI are adjusted to produce a NOvA-specific neutrino interaction model tune
- NOvA-tuning is performed in variables that are different from this analysis
- MEC tune developed using neutrino data and applied to anti-neutrino

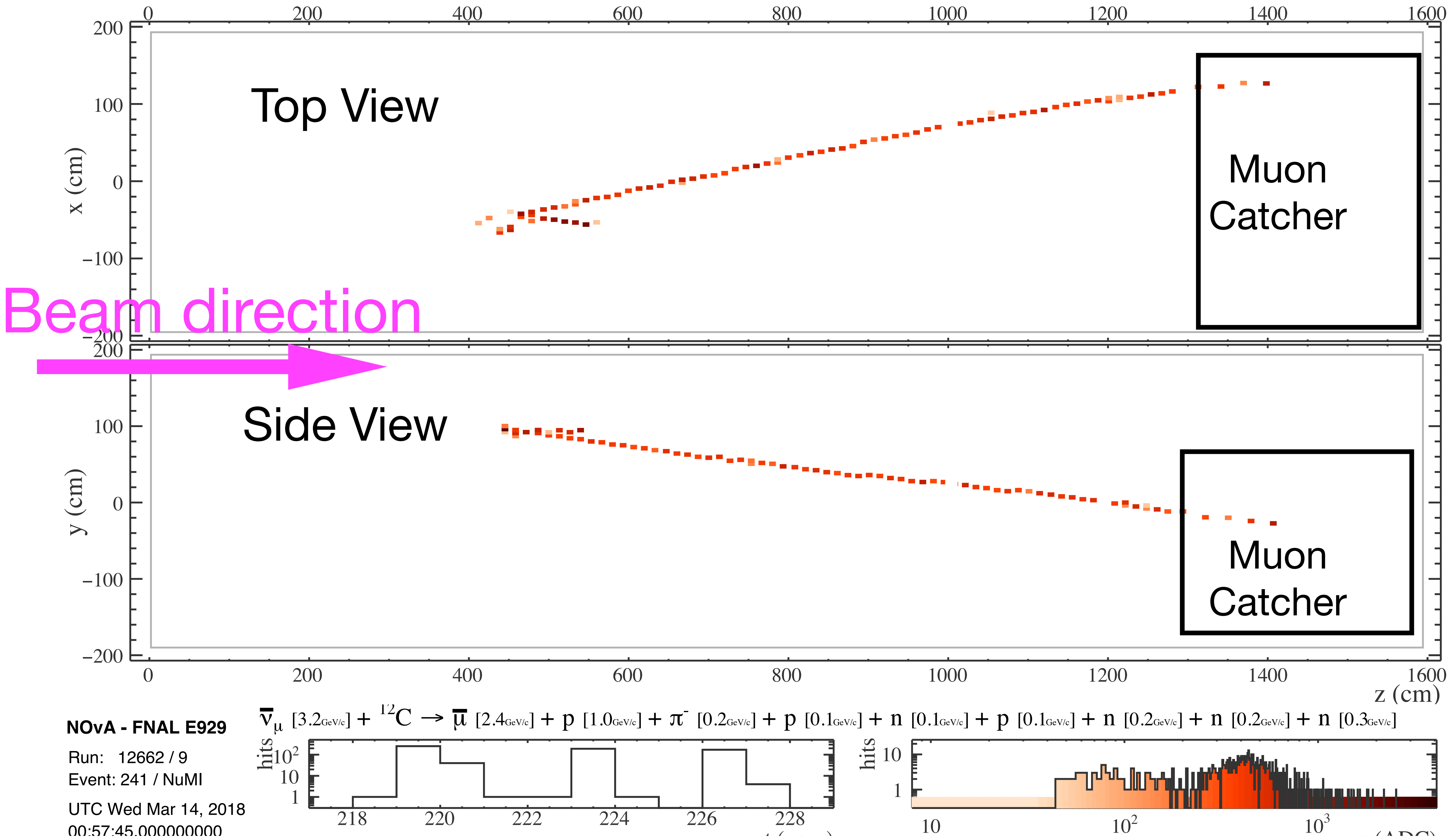
- Local Fermi Gas (LFG): spherical symmetric density of nucleons. Degenerate gas up to Fermi momentum
- Valencia model: includes random phase approximation
- Berger-Sehgal: lepton mass effects in single pion production by neutrinos
- Bodek-Yang: describes scattering at low momentum transfers by modeling deep inelastic cross sections in the few GeV regions
- hN (FSI): calculates cross section for many possible interactions inside nucleons

Beam Flux

- Uncertainties from the hadron production
  - Hadron production model is constrained with external measurements on thin target data (NA49)
  - We use Package to Predict the Flux (PPFX) to evaluate Hadron production uncertainties (Phys. Rev. D94, 092005)
  - It results into a ~10% normalization effect
- Beam focusing (hardware related)
  - Includes uncertainties such as the horn current amperage, the beam spot size on target, the beam position on target, uncertainties related to the magnetic field used in the beam, and so on
  - Sub-dominant

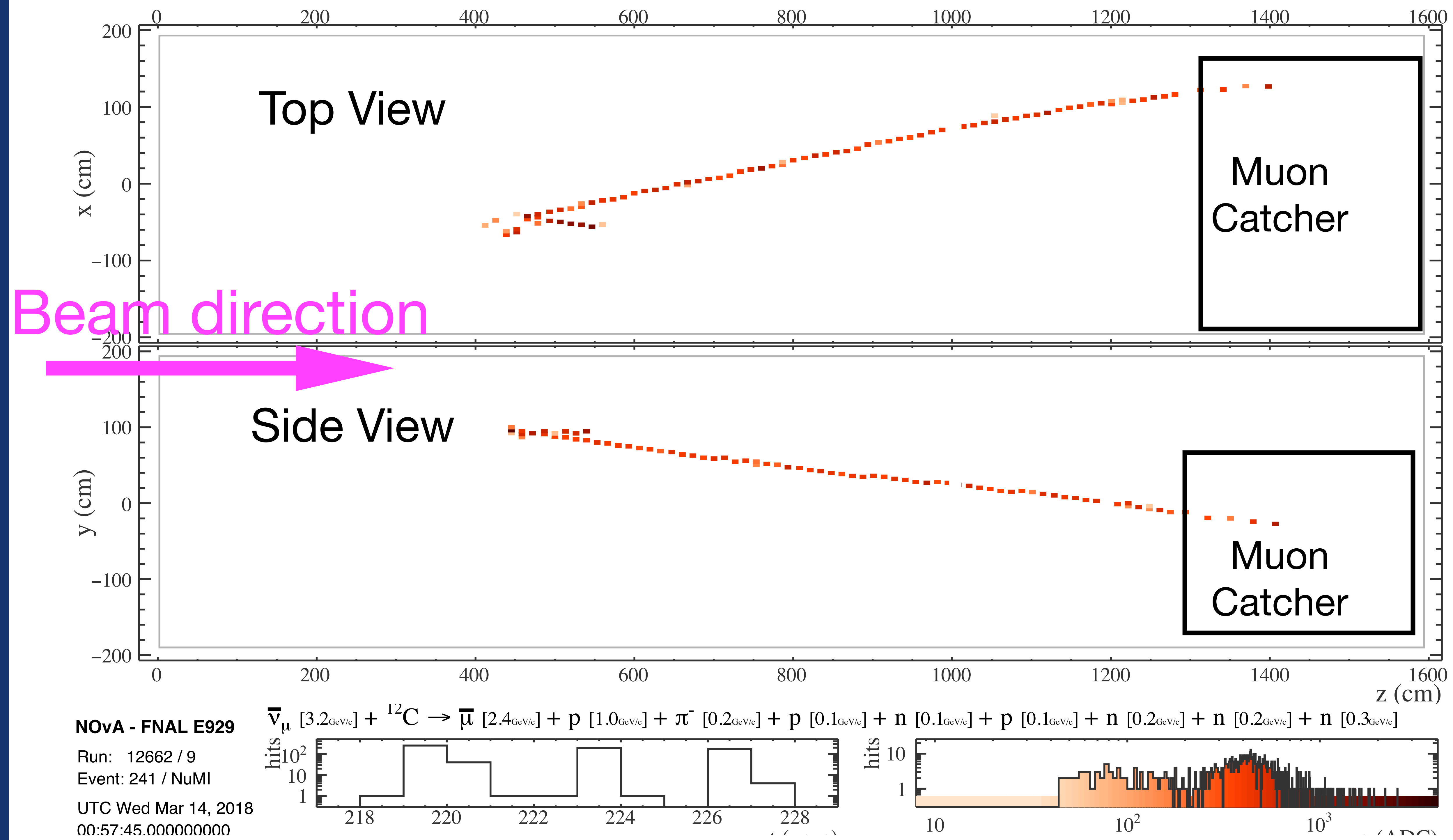


Selections



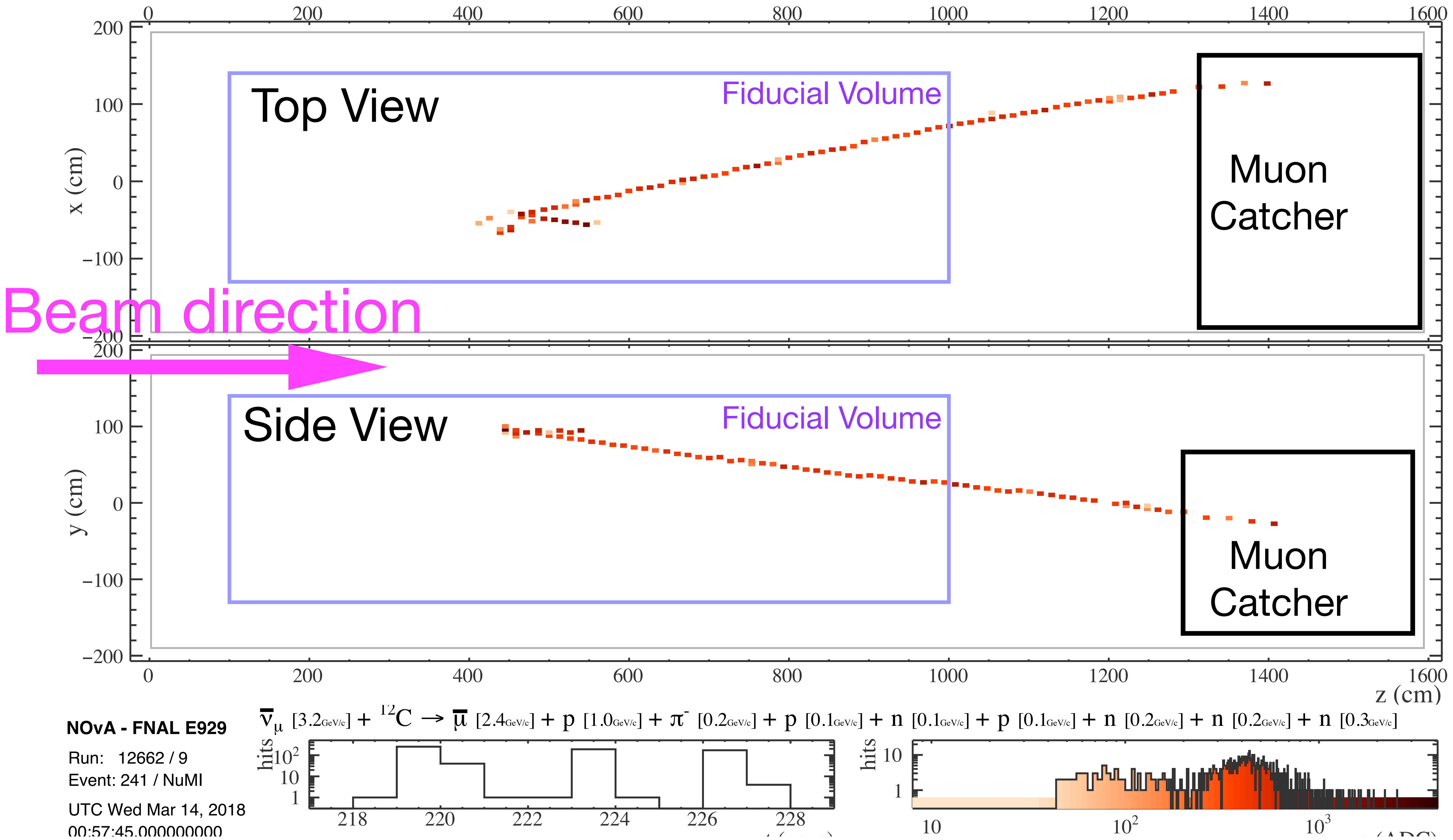
- Hits associated in time and space are used to reconstruct tracks and showers

Selections



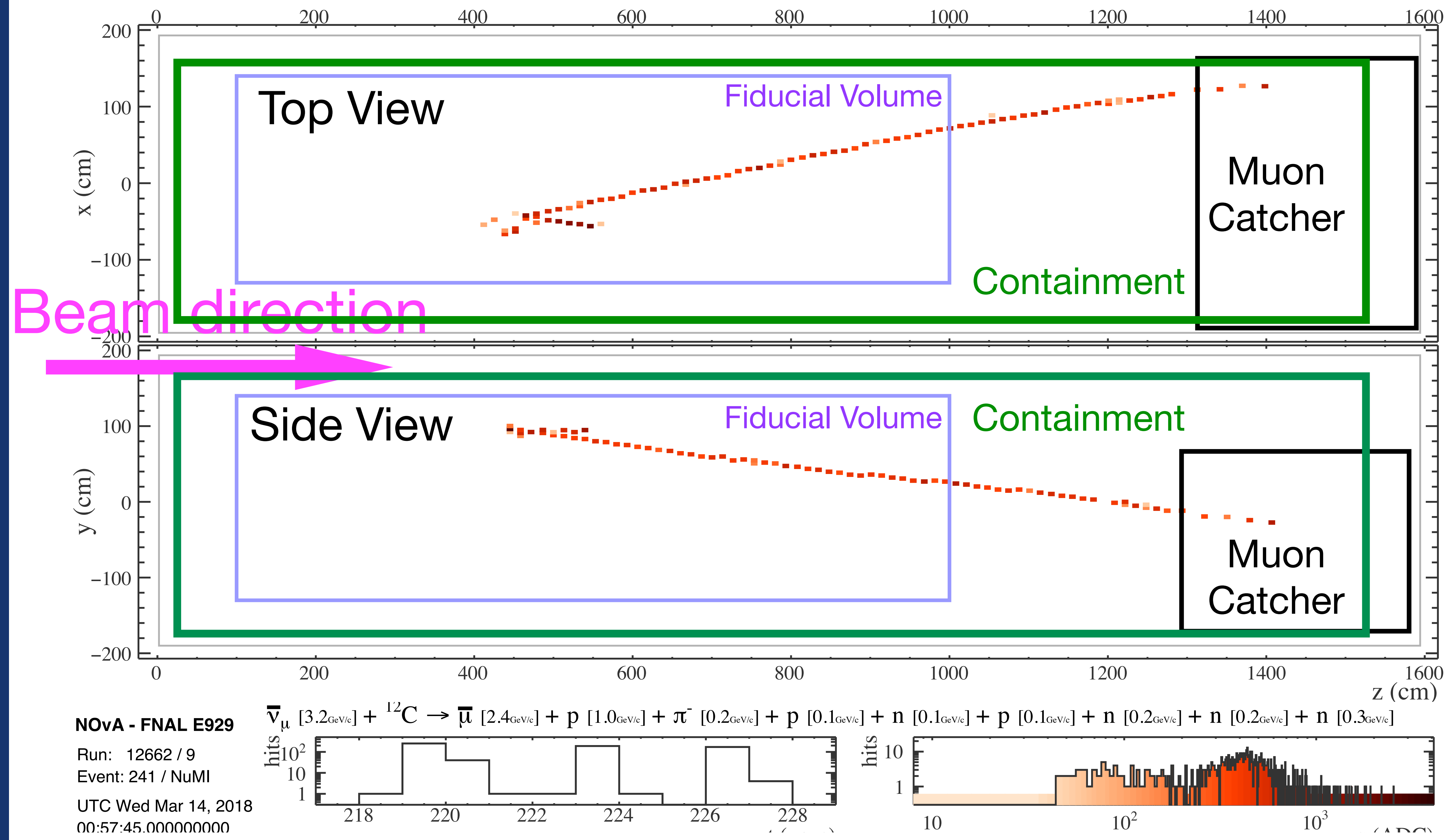
- Quality: 1+ tracks, >20 hits, >4 contiguous planes

Selections



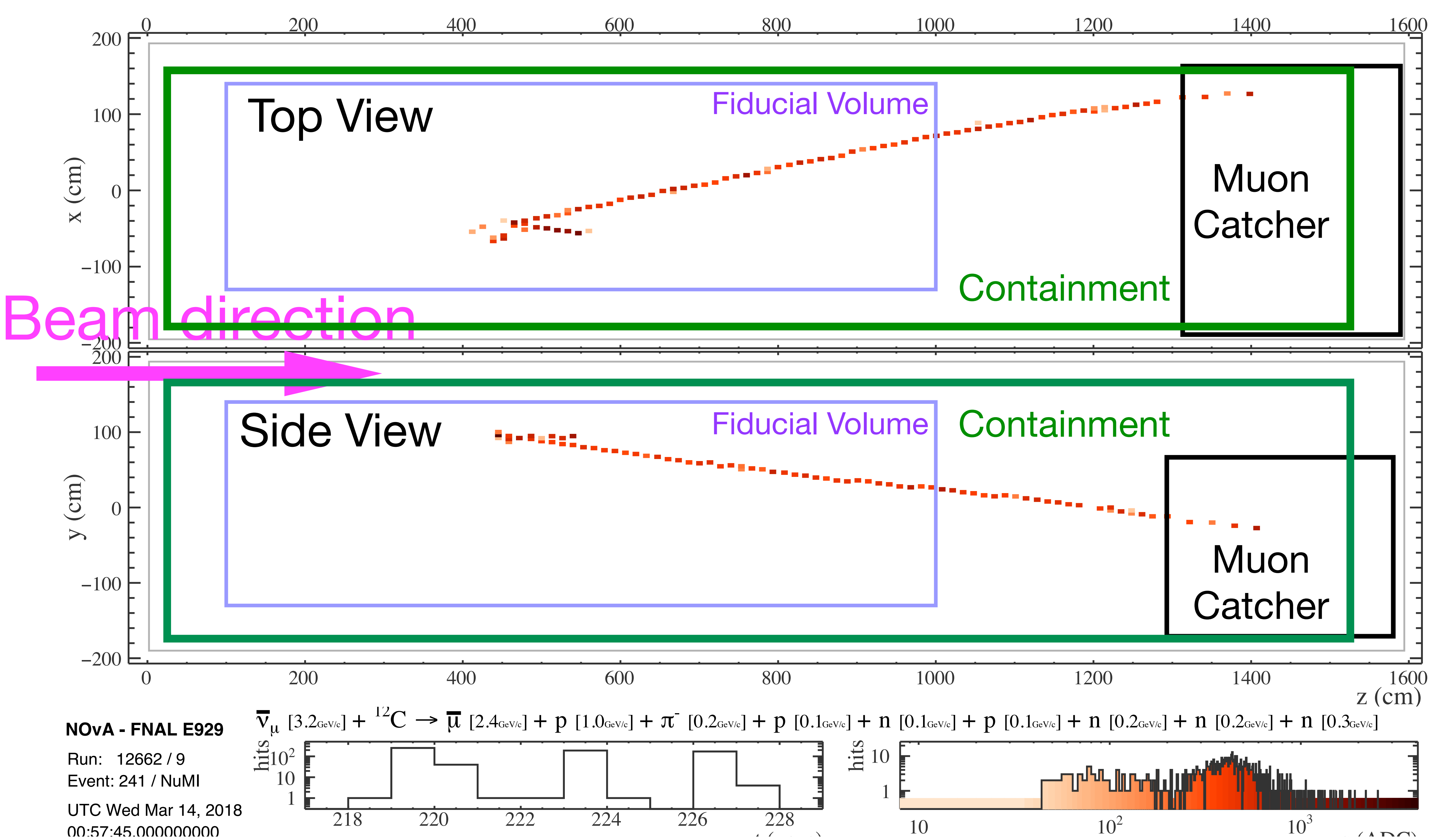
- Quality: 1+ tracks, >20 hits, >4 contiguous planes
- Interaction vertex in the fiducial volume

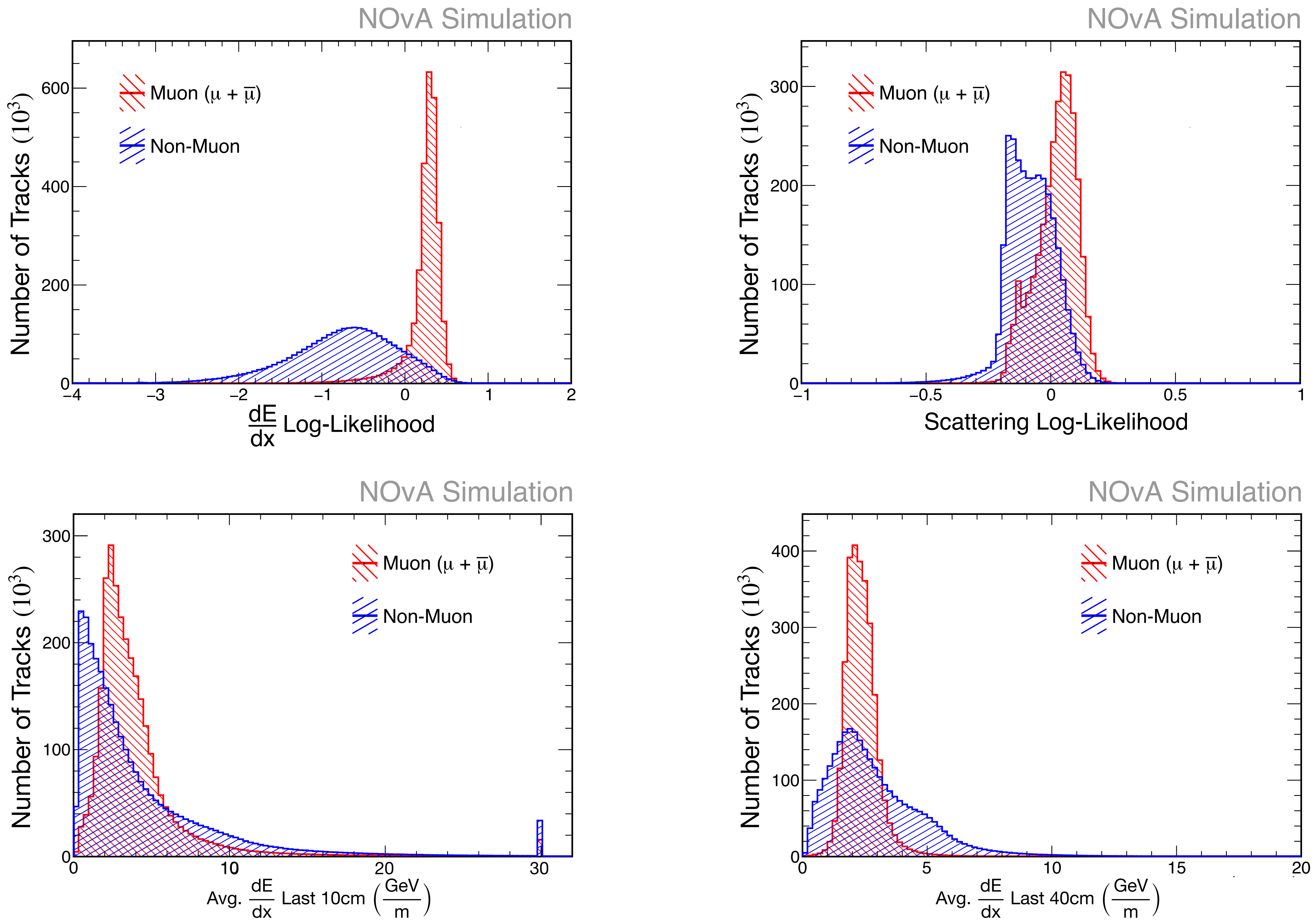
Selections



- Quality: 1+ tracks, >20 hits, >4 contiguous planes
- Interaction vertex in the fiducial volume
- Fully contained tracks and showers are selected

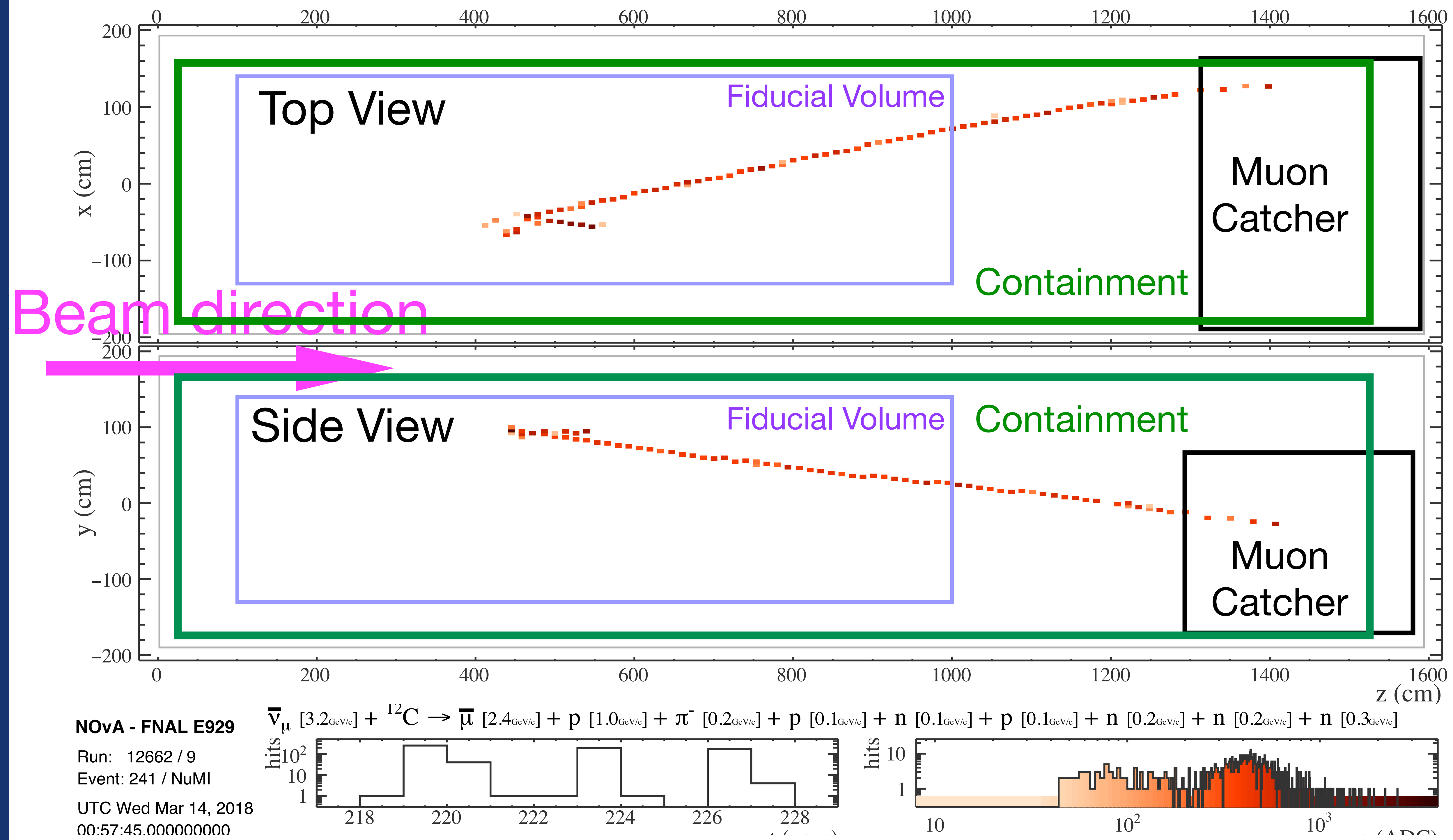
Selections

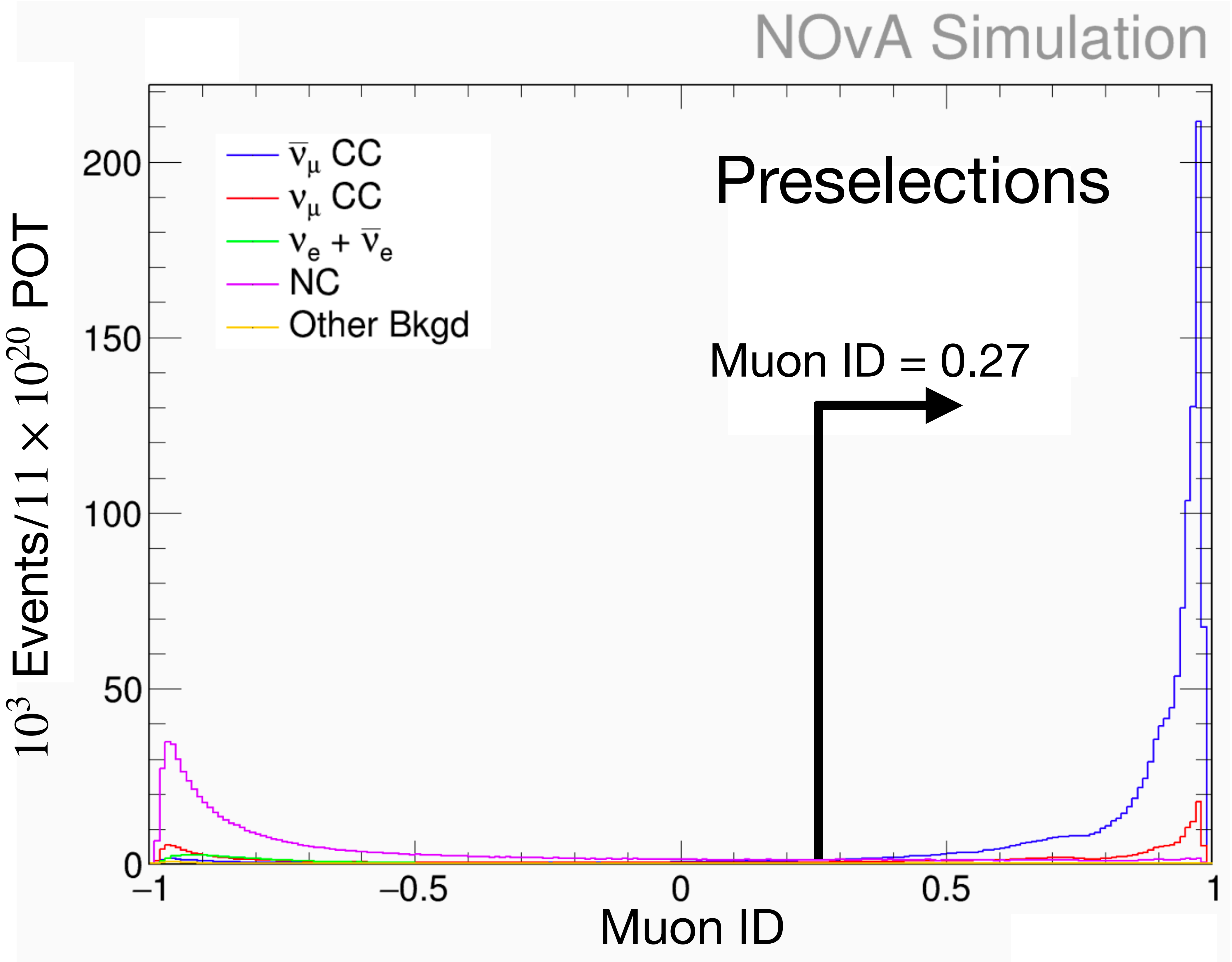




- Boosted decision tree with muon dE/dx and scattering input variables is used to select candidate muons

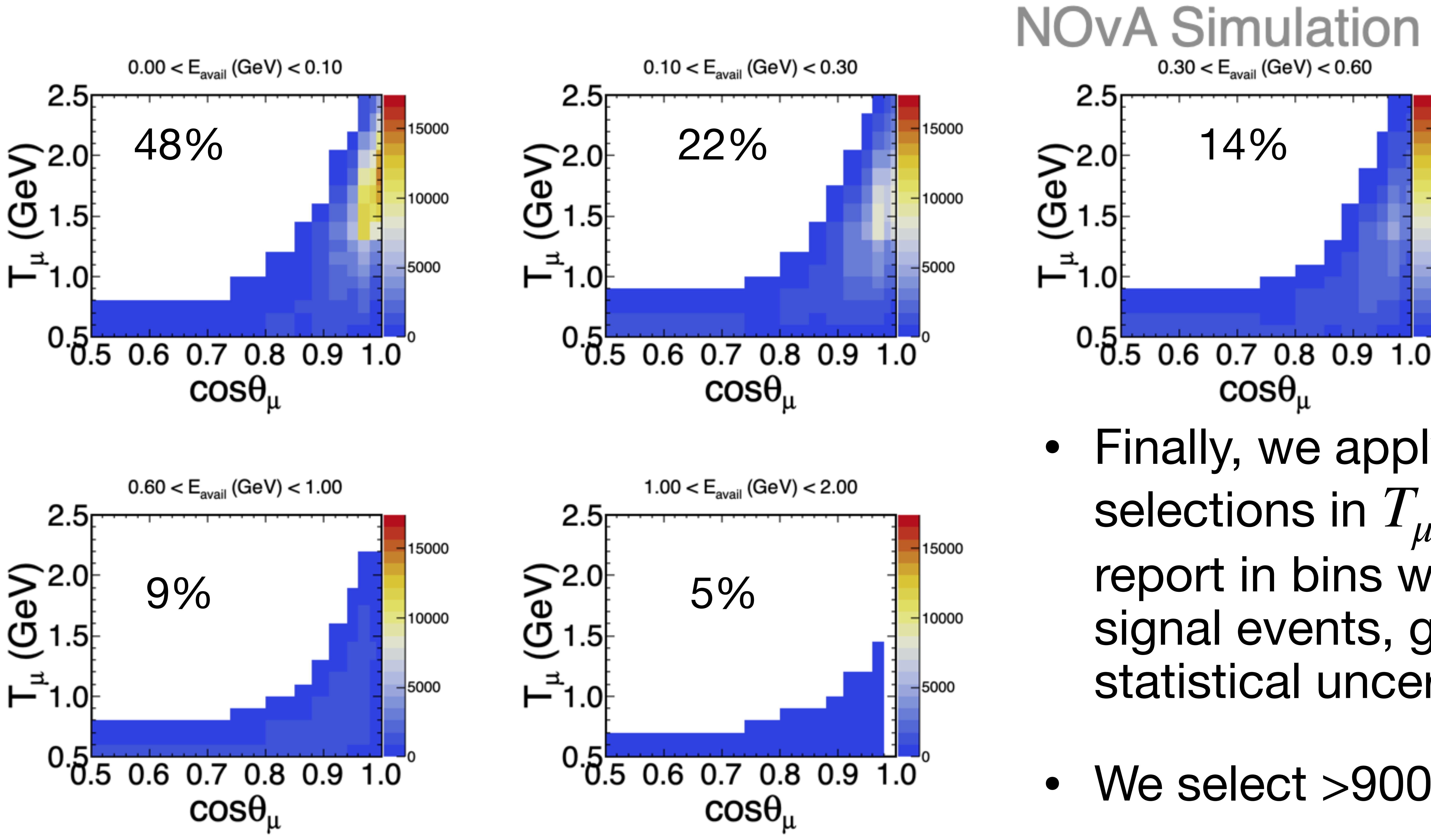
Selections





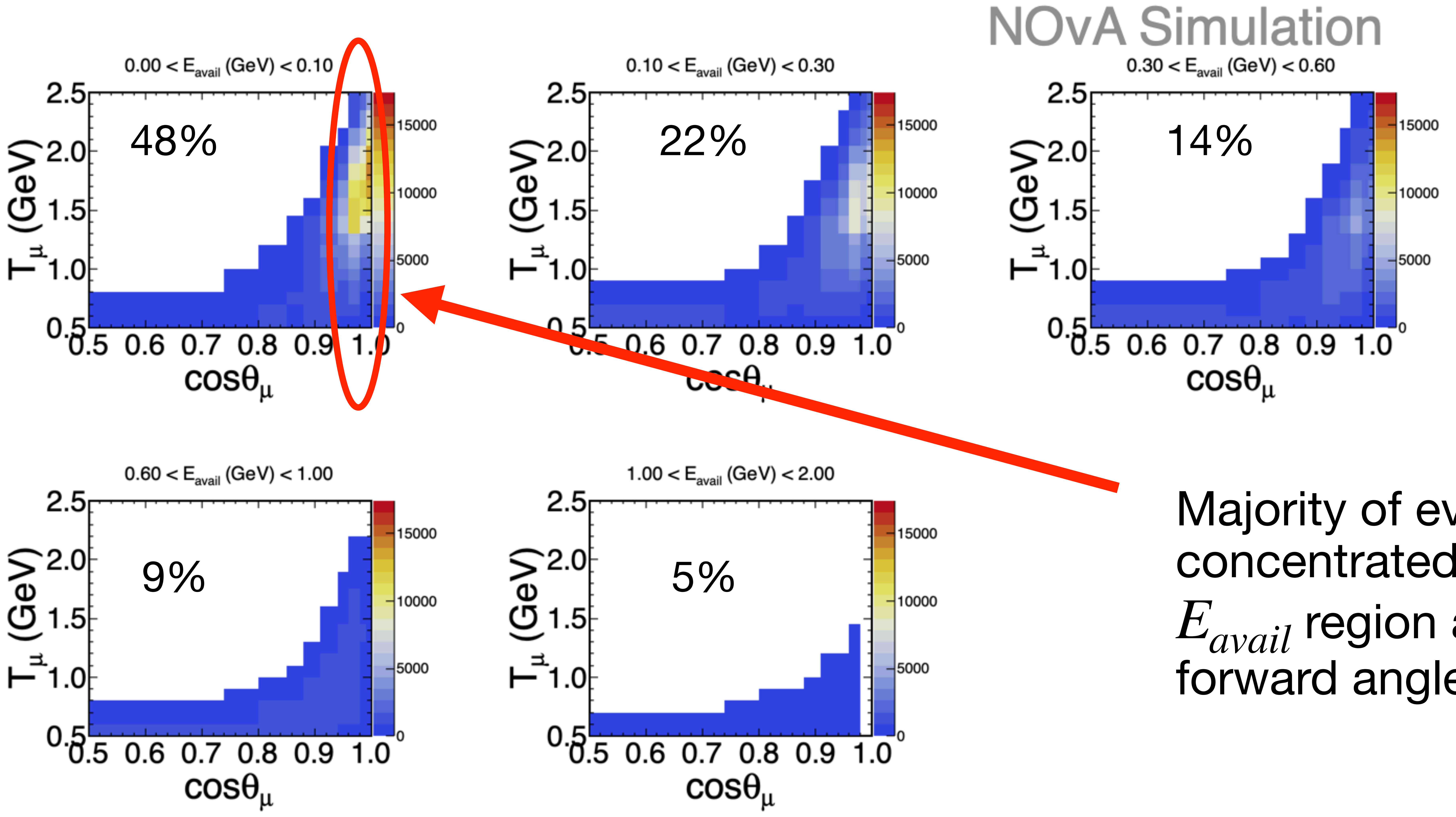
- Boosted decision tree with muon dE/dx and scattering input variables is used to select candidate muons
- BDT provides excellent separation of signal from backgrounds

Selections



- Finally, we apply phase-space selections in T_μ and $\cos\theta_\mu$ to only report in bins with at least 200 signal events, giving at most 7% statistical uncertainty
- We select >900k events

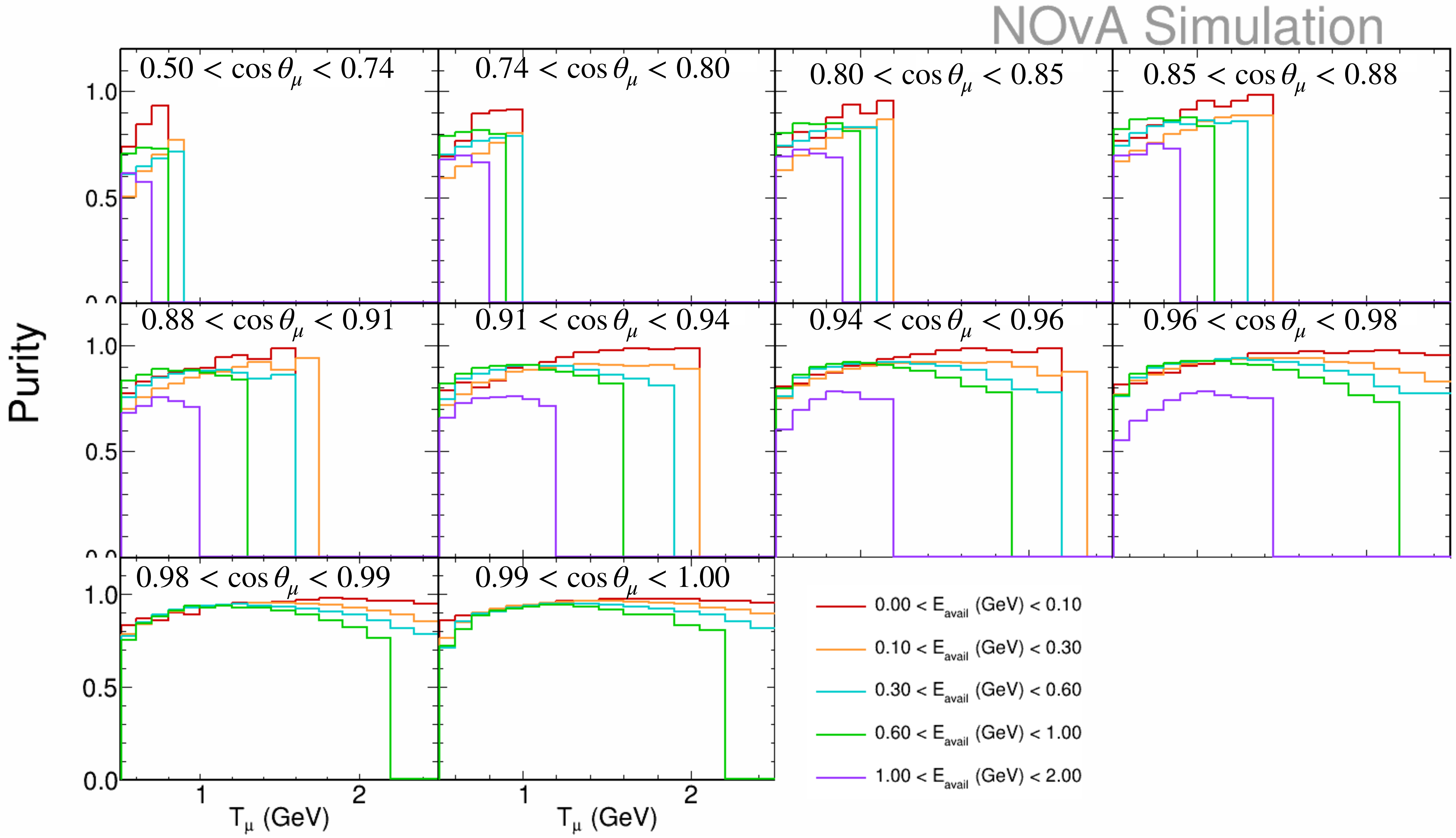
Selections



Majority of events are concentrated in the lowest E_{avail} region and at high forward angles

Purity

- Purity is shown only in the phase-space region
- It reduces with E_{avail} because the wrong sign component increase at higher E_{avail}
- Further reduction in purity in the 1-2 GeV E_{avail} is because of the presence of NC interactions at higher E_{avail}
- Overall it is a high purity sample with 90% purity

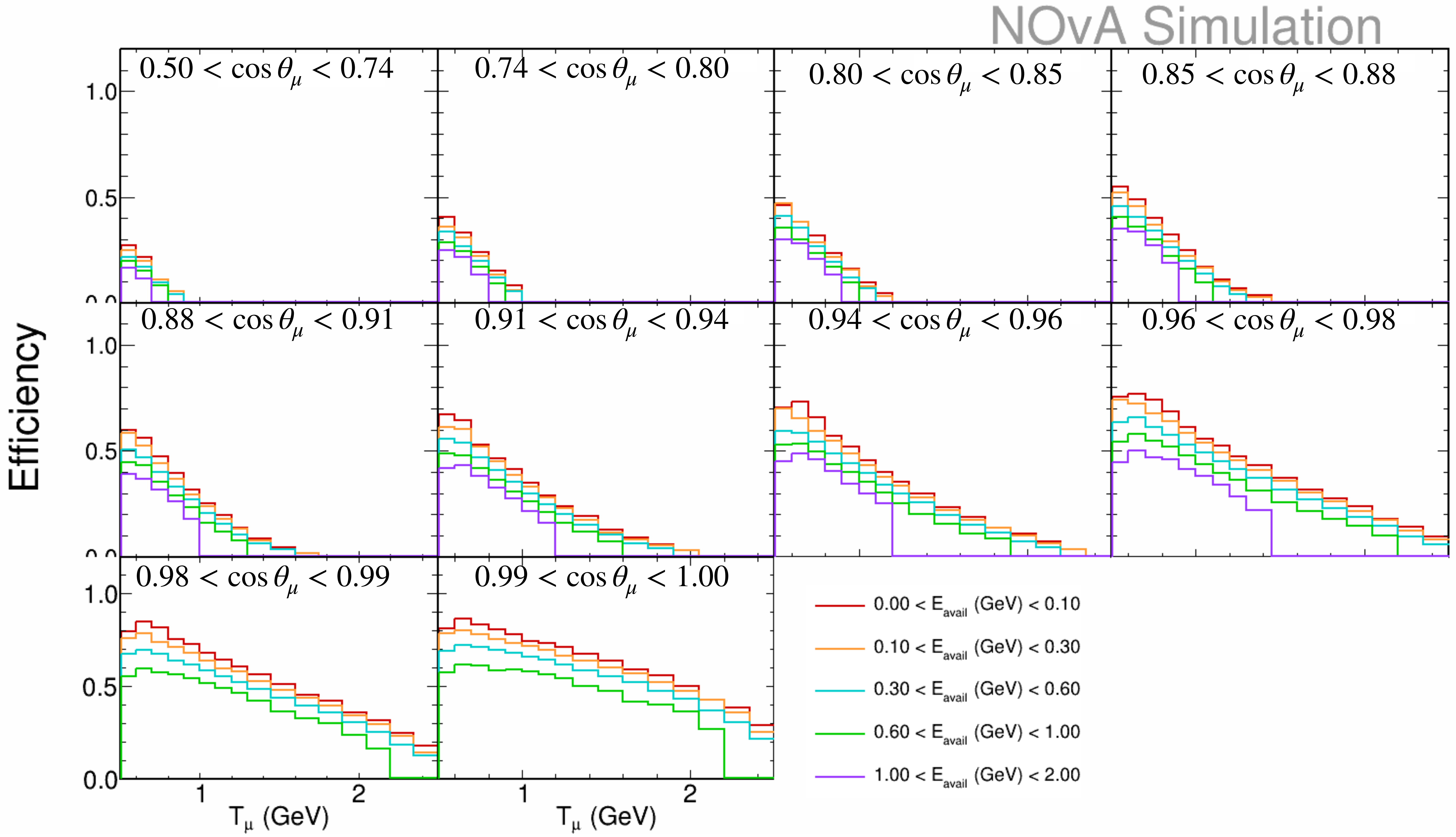


Selection Efficiency

- Efficiency reduction with T_μ, and at higher scattering angles due to muons escaping containment

- Reduction at higher E_{avail} because there is more hadronic activity and showers in the detector making it harder for the muon to be properly reconstructed

- Overall, 32% selection efficiency



Cross sections

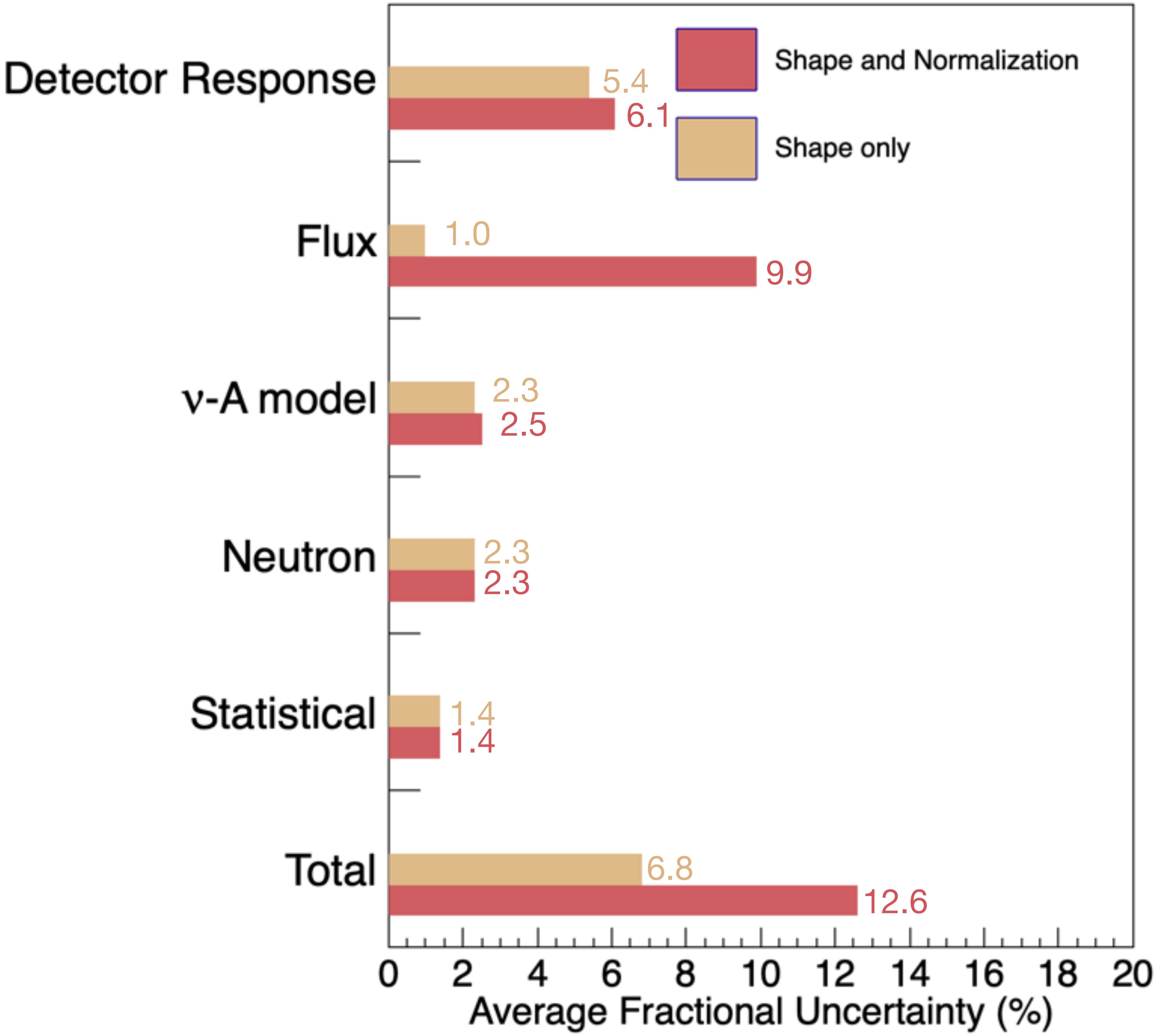
$$\left(\frac{d^3\sigma}{d\cos\theta_\mu dT_\mu dE_{avail}}\right)_i = \frac{\sum_j U_{ij}(N^{\text{sel}}(\cos\theta_\mu, T_\mu, E_{avail})_j P(\cos\theta_\mu, T_\mu, E_{avail})_j)}{\epsilon(\cos\theta_\mu, T_\mu, E_{avail})_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i(\Delta E_{avail})_i N_{\text{target}}\phi}$$

- For differential cross section measurements in T_μ, $\cos\theta_\mu$, and E_{avail}, we need
  - Selected candidate signal events, sample purity
  - The unfolding matrix (reco to true migration): transitions events from reconstructed space to the true space. We use improved D'Agostini iterative unfolding method to unfold events
  - Selection efficiencies
  - Integrated beam flux, and number of target nucleons
  - Normalization by bin widths

Systematic Uncertainties

- Flux is dominating systematics, followed by detector response (biggest contributor detector calibration)
- Neutrino cross section and neutron uncertainties are also significant
- Shape-only shows that flux is mostly a normalization systematics while other uncertainties have a shape effect
- Overall average fractional uncertainty is within 14%

NOvA Simulation



Results of the Triple Differential Measurements

Results of the Triple Differential Measurements

- Categories of results in different regions of available energies

  ✓ Absolute data cross section comparisons to GENIE 3.0.6 untuned and tuned (NOvA MEC-tune) cross sections

  ✓ Ratios of various GENIE configurations to the data cross sections

  ✓ Ratios of GENIE, NEUT, NuWro, and GiBUU neutrino generators to data cross sections

GENIE Comprehensive Model Configurations (CMC)

GENIE versions	**Configurations**	Initial State Interactions	QE	MEC	RES/ Coh	DIS	FSI
3.0.6 (Our Base Model)	**G18_10j_00_000**	Local Fermi Gas (LFG)	Valencia + Z-expansion	Valencia	Berger-Sehgal (BS)	Bodek-Yang (BY) + Pythia	hN (many possible interactions)
3.4.0	**G18_10a_02_11a**	LFG	Valencia	Valencia	BS	BY	hA (one effective interaction)
3.4.0	**G18_10a_02_11b**	LFG	Valencia	Valencia	BS	BY	hA
3.4.0	**G21_11a_00_000**	LFG	SuSAv2	SuSAv2	BS	BY	hA
3.4.0	**AR23_20i_02_11b (DUNE)**	Spectral function LFG	Valencia	SuSAv2	BS	BY	hA

Data Results: $100 < E_{avail} < 300$ MeV

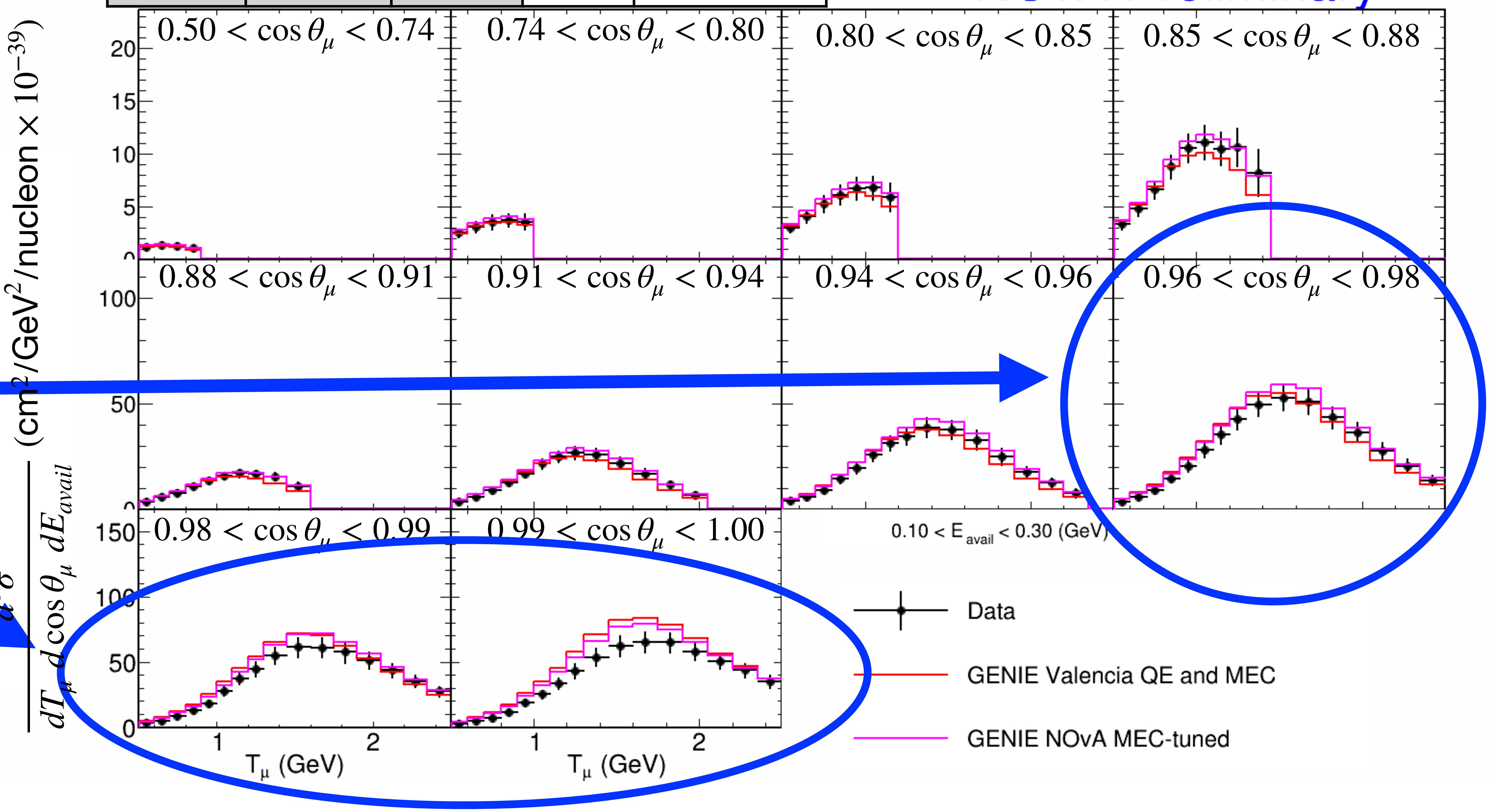
- In 100-300 MeV E_{avail}, there is a significant mixture of QE, MEC, and RES interactions
- At high forward angles, GENIE predictions, both tuned and un-tuned start to over-estimate data

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
21.4	18.2	48.0	8.4	4.1

Events: 22%

NOvA Preliminary



Ratios GENIE CMC to Data Results: $100 < E_{avail} < 300$ MeV

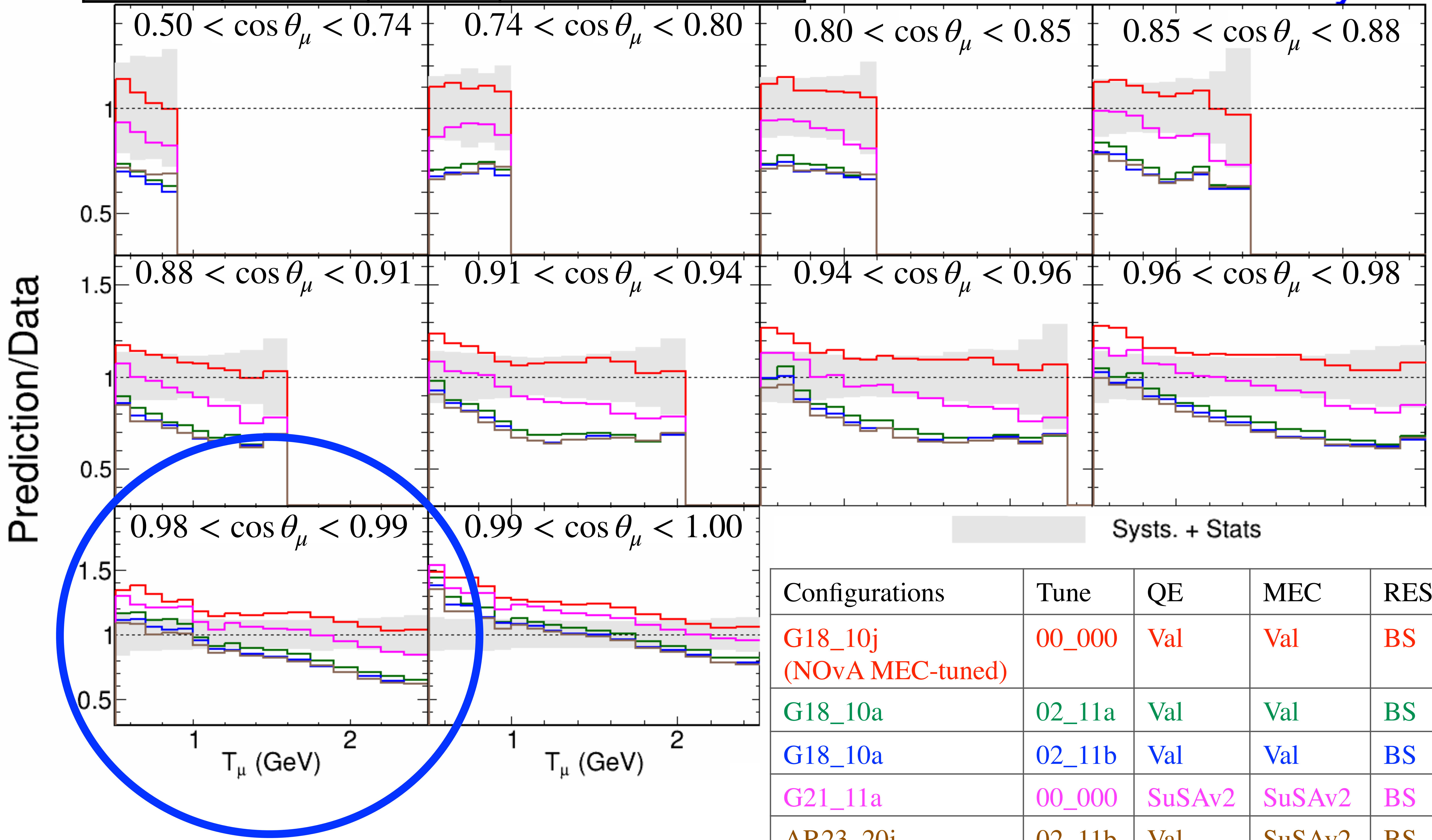
- Same conclusions, for QE, SuSA-v2 model is better than the Valencia mode
- For MEC, differences between the SuSA-v2 and Valencia are very small and they both perform poorly to model data

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
21.4	18.2	48.0	8.4	4.1

Events: 22%

NOvA Preliminary



Configurations	Tune	QE	MEC	RES	FSI
G18_10j (NOvA MEC-tuned)	00_000	Val	Val	BS	hN
G18_10a	02_11a	Val	Val	BS	hA
G18_10a	02_11b	Val	Val	BS	hA
G21_11a	00_000	SuSAv2	SuSAv2	BS	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	BS	hA

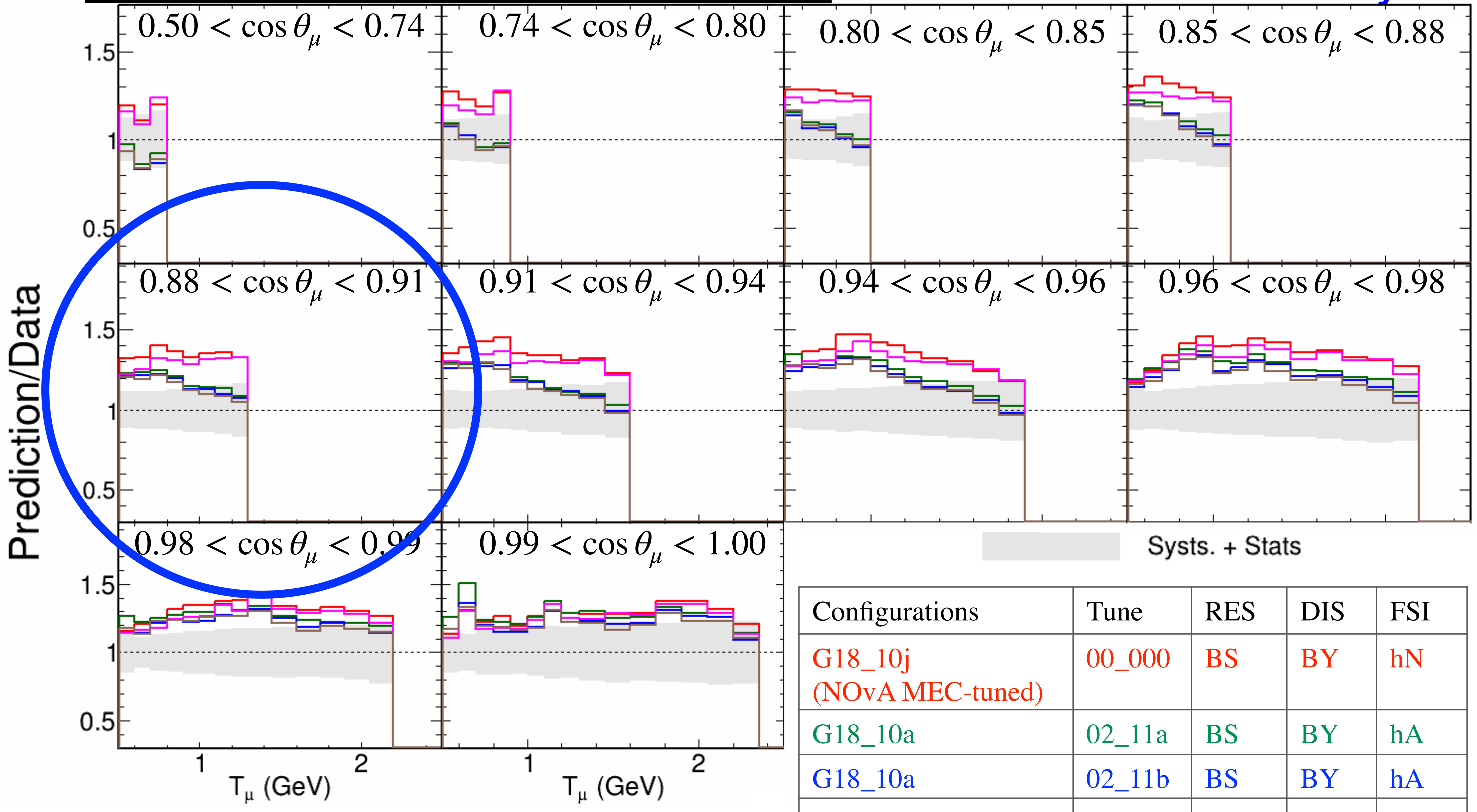
Ratios GENIE CMC to Data Results: $0.6 < E_{avail} < 1.0$ GeV

- Available energy region from 0.6-1.0 GeV is also dominated by the RES interactions and gives same conclusions
- GENIE tunes 02_11a, and 02_11b are performing better than 00_000 tune to model RES interactions

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
0.7	0.4	58.0	37.1	3.8

Events: 9%



Configurations	Tune	RES	DIS	FSI
G18_10j (NOvA MEC-tuned)	00_000	BS	BY	hN
G18_10a	02_11a	BS	BY	hA
G18_10a	02_11b	BS	BY	hA
G21_11a	00_000	BS	BY	hA
AR23_20i (DUNE)	02_11b	BS	BY	hA

Neutrino Generators

Generators	Initial State Interactions	QE	MEC	RES/Coh	DIS	FSI
GENIE 3.4.0 (2023) (DUNE) AR23_20i_02_11b	Spectral function LFG	Valencia	SuSAv2	BS	BY	hA
NuWro 21.09.02 (2022)	LFG	Llewellyn-Smith (LS)	Valencia	NuWro RES model	BY	NuWro FSI model
NEUT 5.7.0 (2023)	LFG	Valencia	Valencia	BS/RS	BY	Custom semi-classical intranuclear cascade (INC) model
GiBUU patch3 (2023)	Modified LFG	Dipole Form Factor, RPA corrections	Semi-inclusive electron scattering data	MAID (electromagnetic form factors)	Data driven GiBUU model	BUU transport model

For generator comparisons, we only show the available energy regions which are enhanced either in QE/MEC or RES, or DIS interactions

Other exciting cross section analyses

- Two 2p2h focused papers: Exploring 2p2h signatures in muon-neutrino charged-current measurements at NOvA. Presented in W&C on 2 Feb 2024
- ν-on-e analysis: goal is to measure neutrino flux
- ν_μ CC low-hadronic energy triple differential
- ν_μ CC zero mesons
- $\bar{\nu}_\mu$ CC π^0 analysis
- $\bar{\nu}_\mu$ CC on hydrogen
- $\bar{\nu}_e$ CC inclusive analysis
- Beyond single differential charge pion analyses

Binning

$$T_\mu \text{ (GeV)} = \{0.50, 0.60, 0.70, 0.80, 0.90, 1.00, 1.10, 1.20, 1.30, 1.45, 1.60, 1.75, 1.90, 2.05, 2.20, 2.35, 2.50, 120\}$$

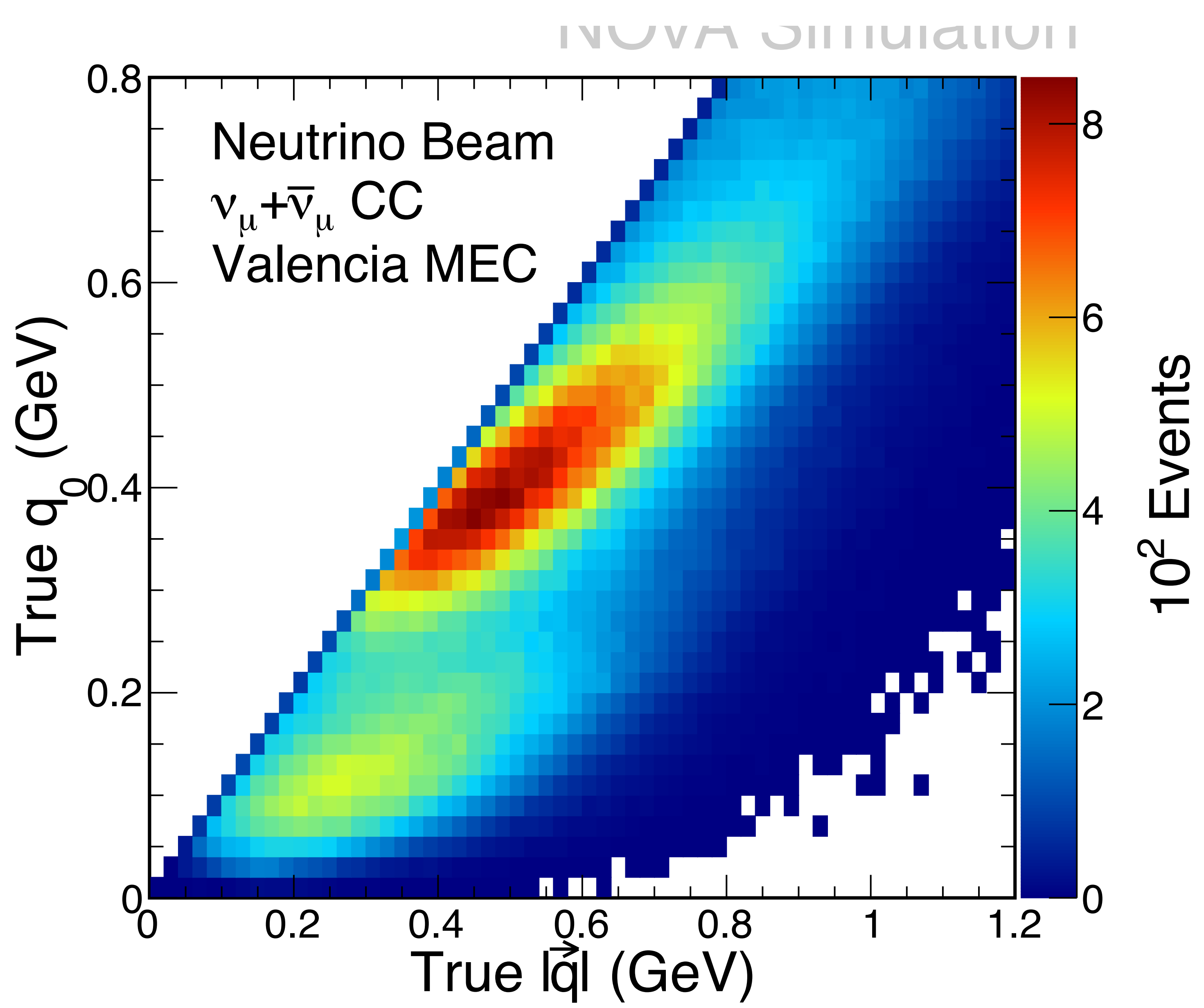
$$\cos\theta_\mu = \{0.50, 0.74, 0.80, 0.85, 0.88, 0.91, 0.94, 0.96, 0.98, 0.99, 1.0\}$$

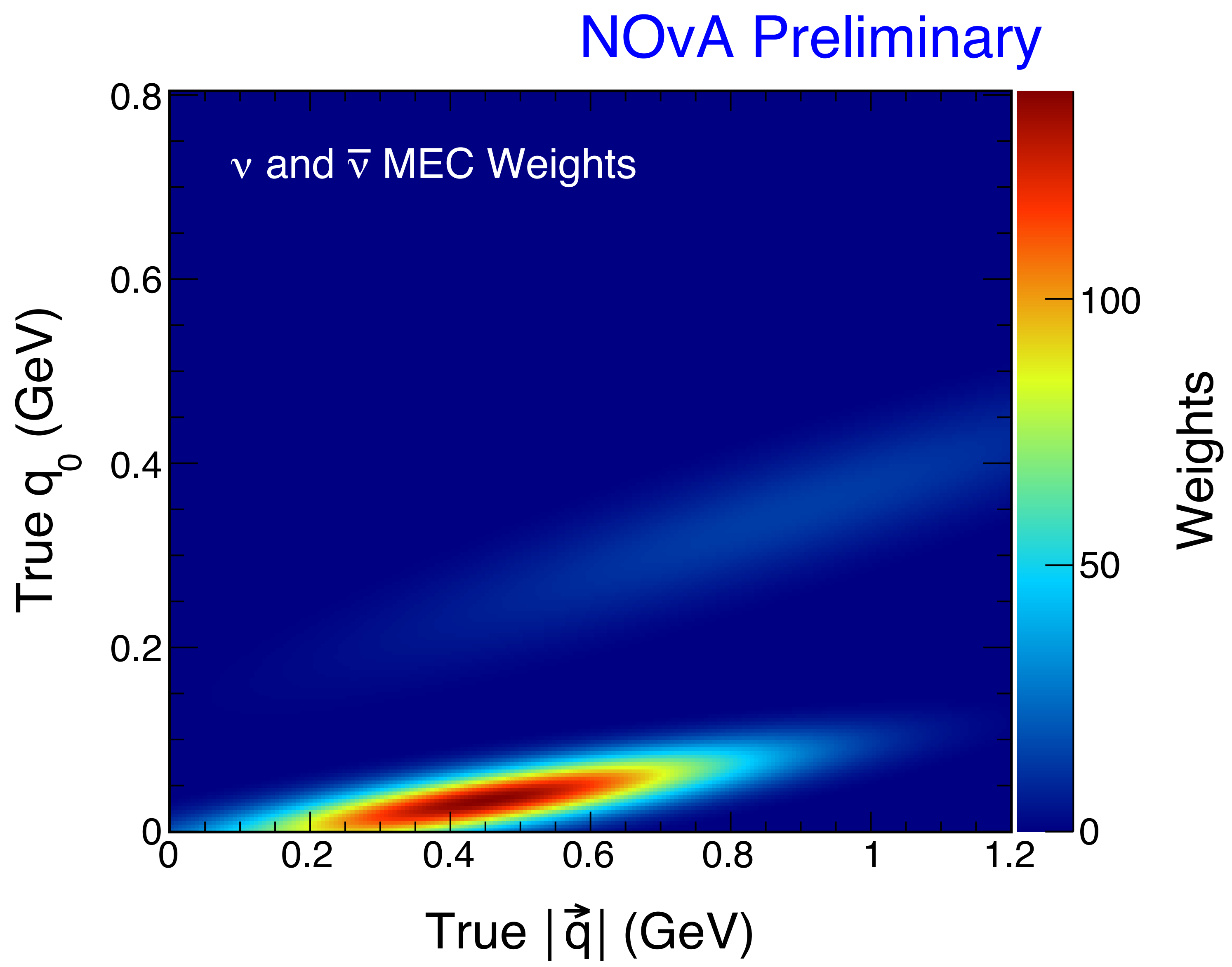
$$E_{avail} \text{ (GeV)} = \{0.0, 0.10, 0.30, 0.60, 1.0, 2.0, 120.0\}$$

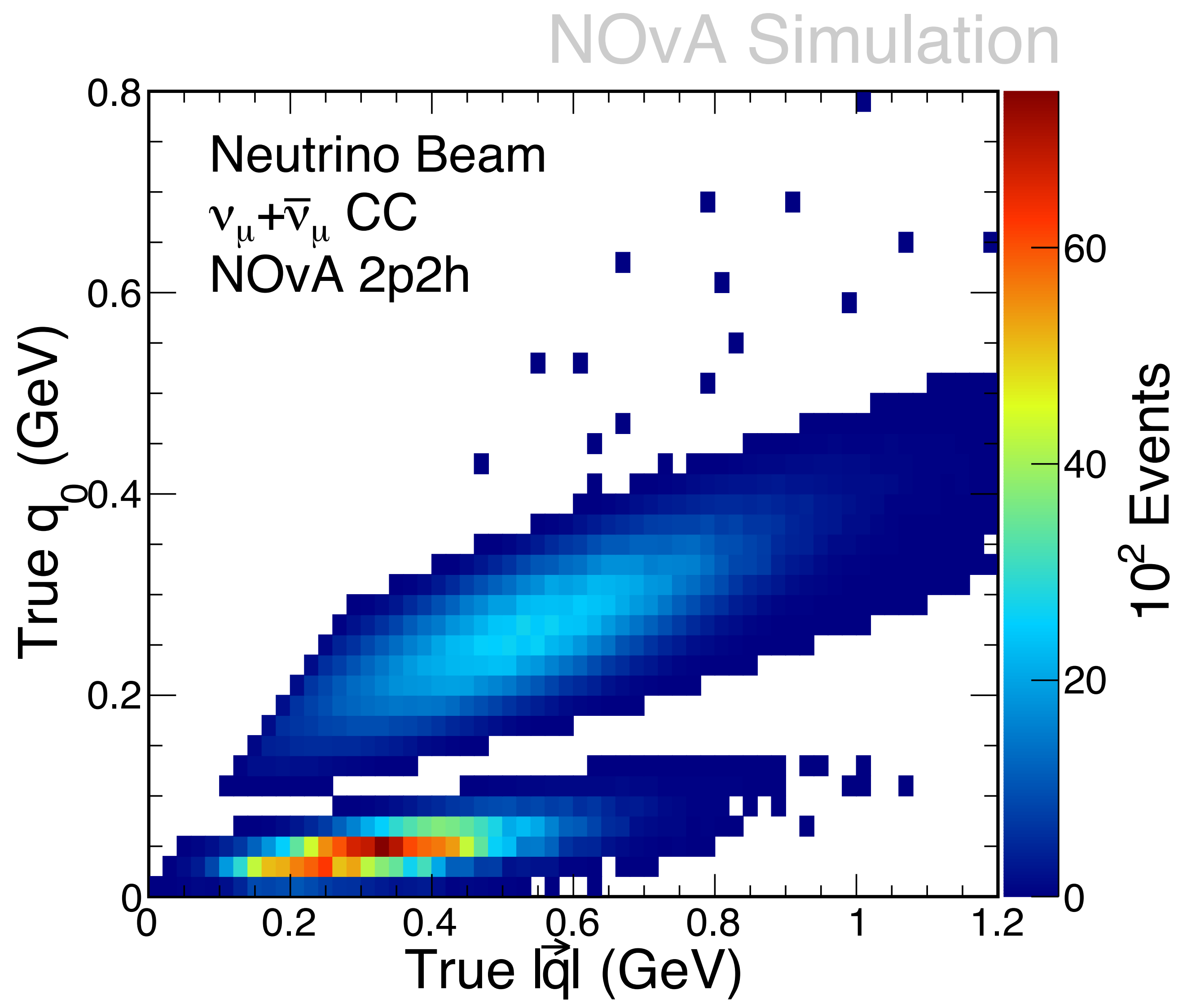
$$E_\nu \text{ (GeV)} = \{0.0, 0.50, 0.75, 1.0, 1.25, 1.50, 1.75, 2.0, 2.50, 3.0, 4.0, 120\}$$

$$Q^2 \text{ (GeV}^2\text{)} = \{0.0, 0.10, 0.20, 0.30, 0.40, 0.60, 1.10, 2.8, 120\}$$

NOvA-MEC Tuning

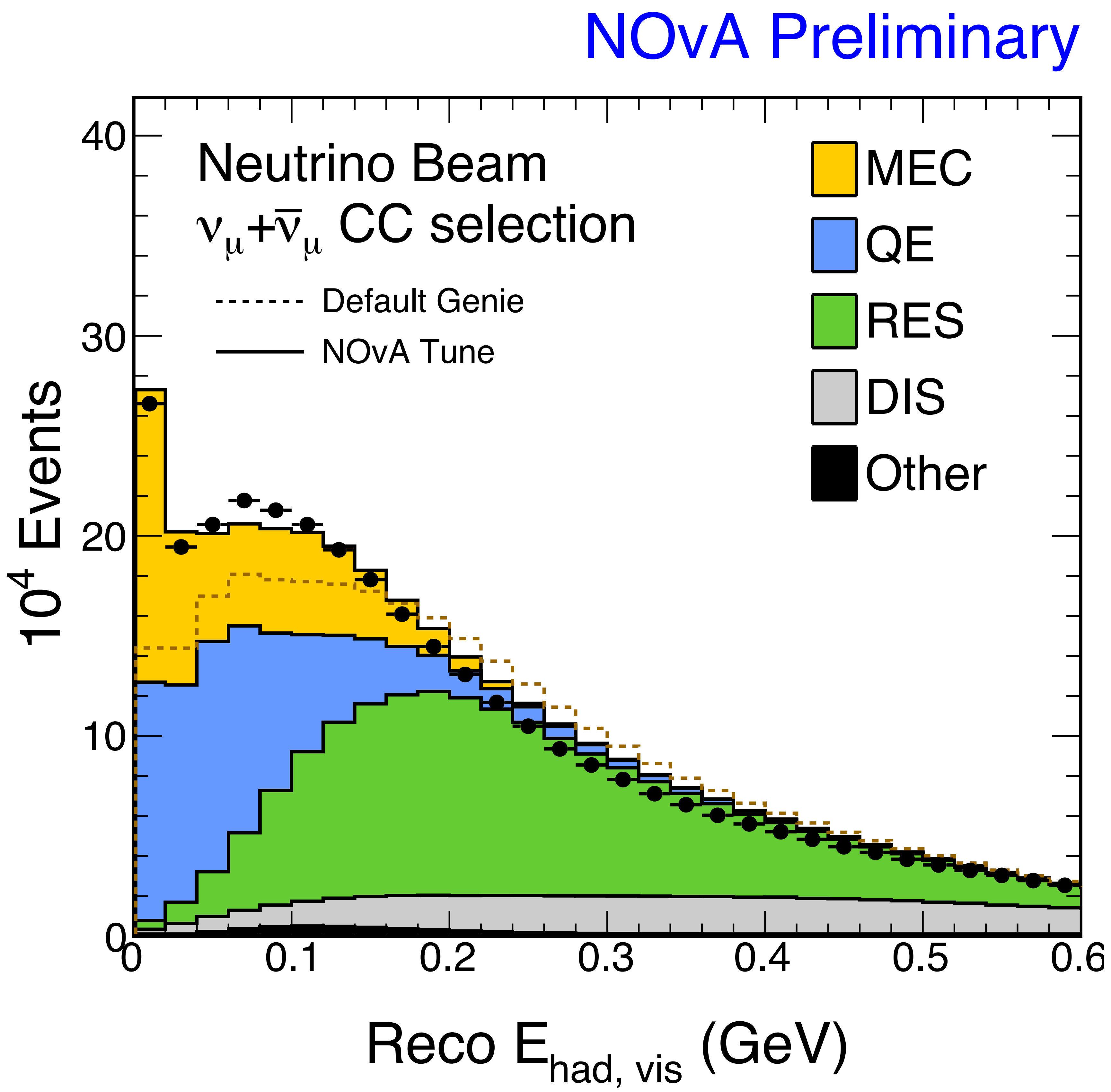


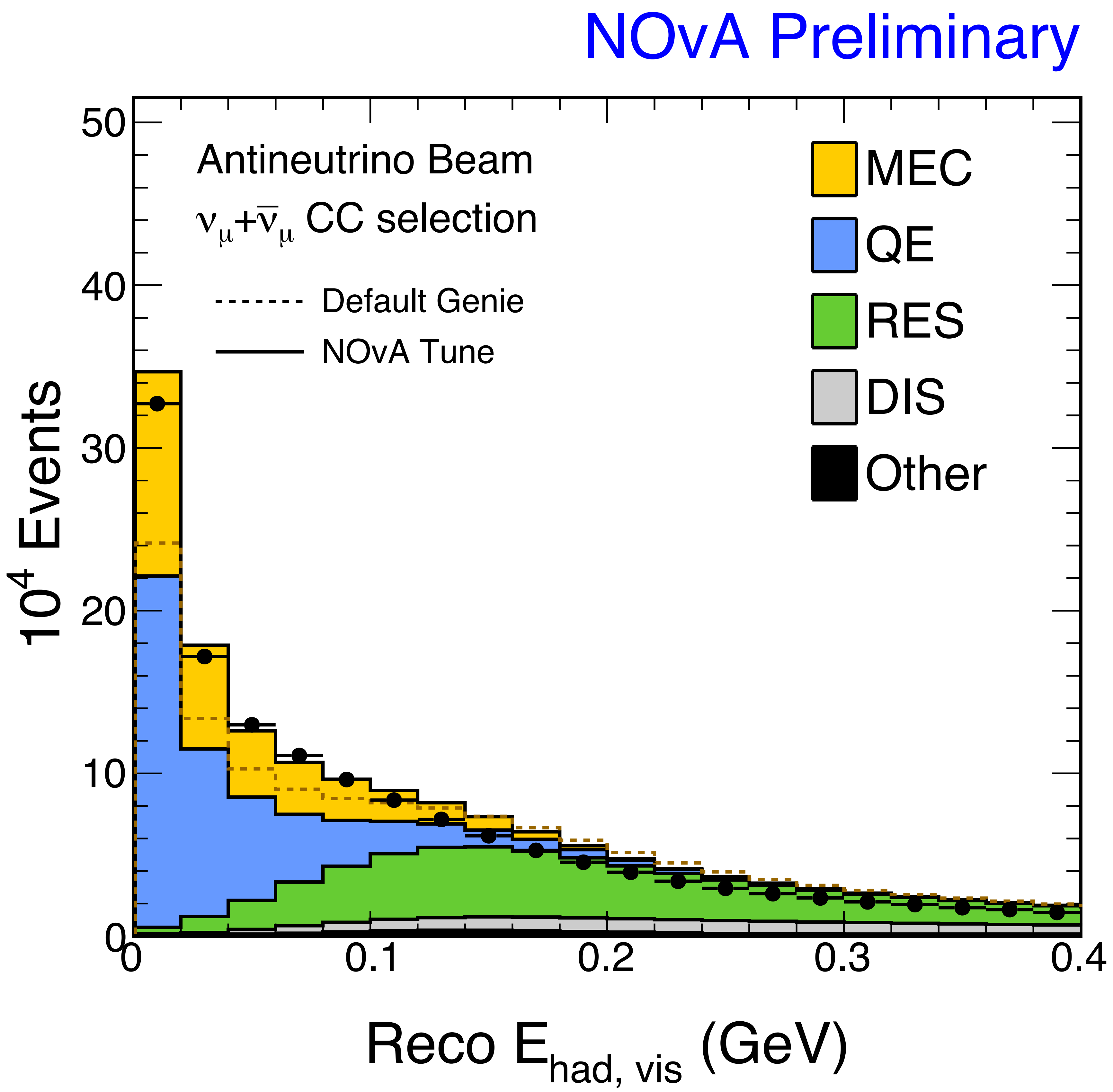




- Fit is performed to the Near Detector using dual 2D-Gaussians in energy and momentum transfer space
- CV shifted upward by 50%
- Systematics are applied to assess remaining differences

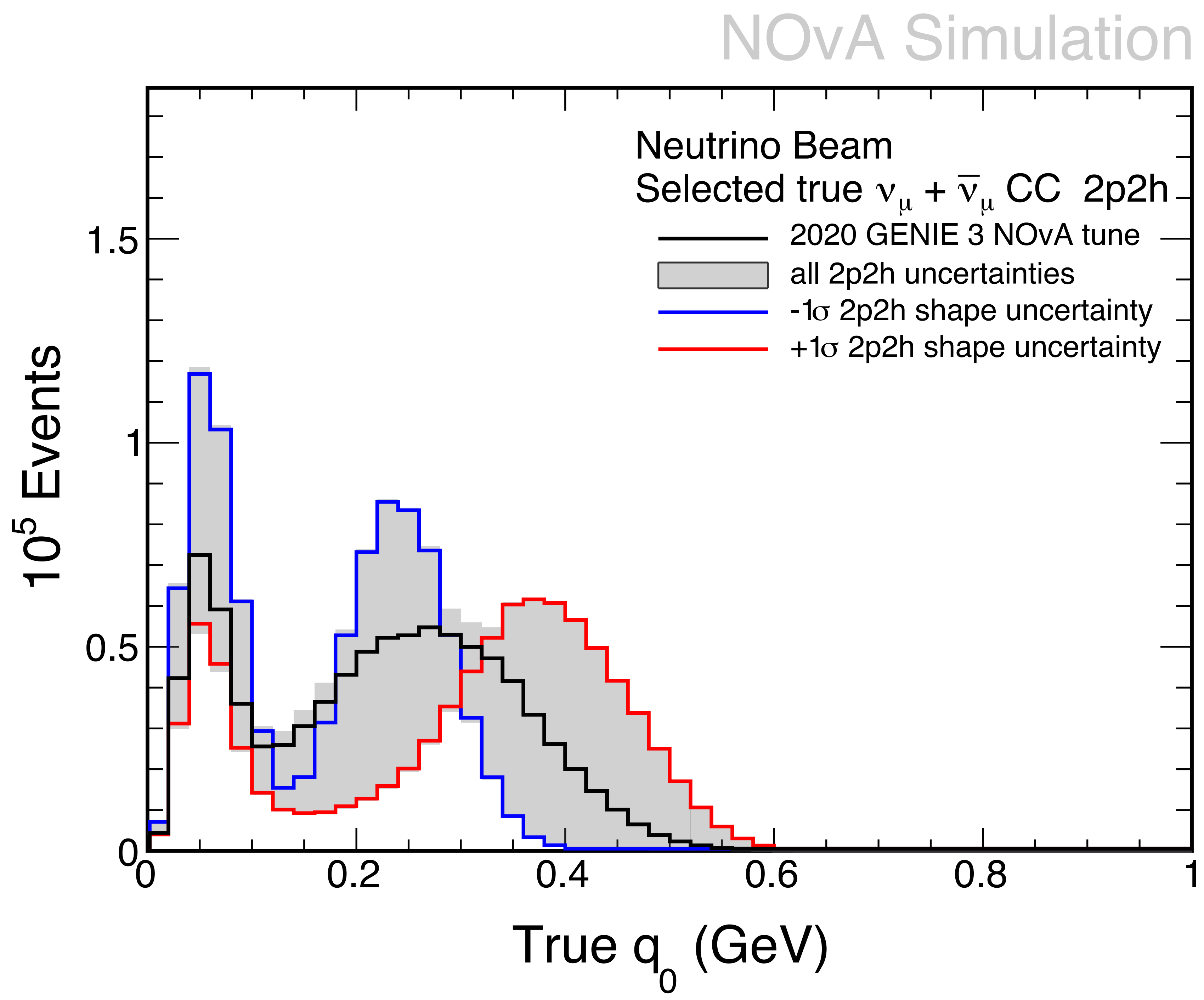
NOvA-MEC Tuning

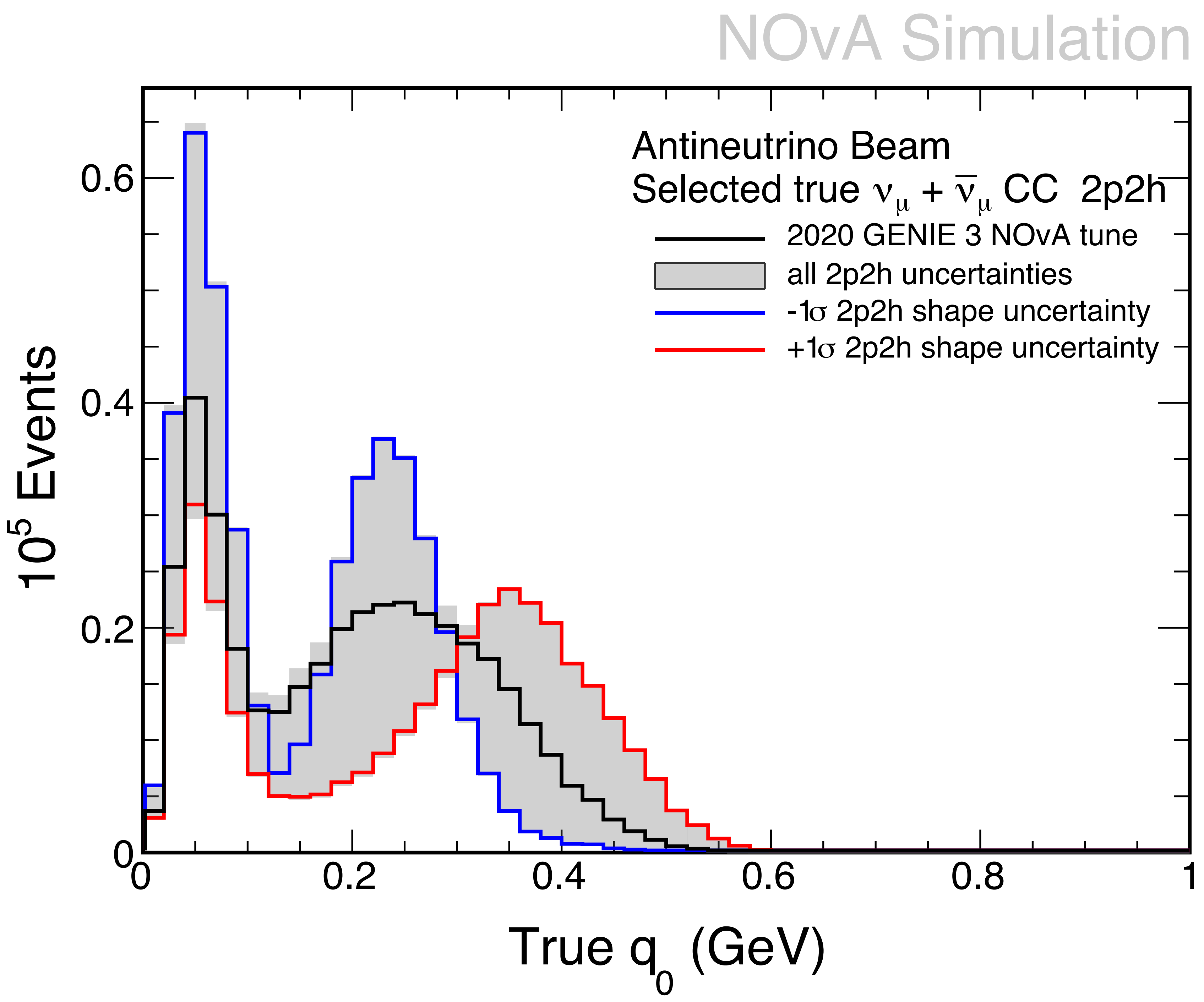




MEC weights from neutrino sample also improves MEC fractions in the the anti-neutrino sample

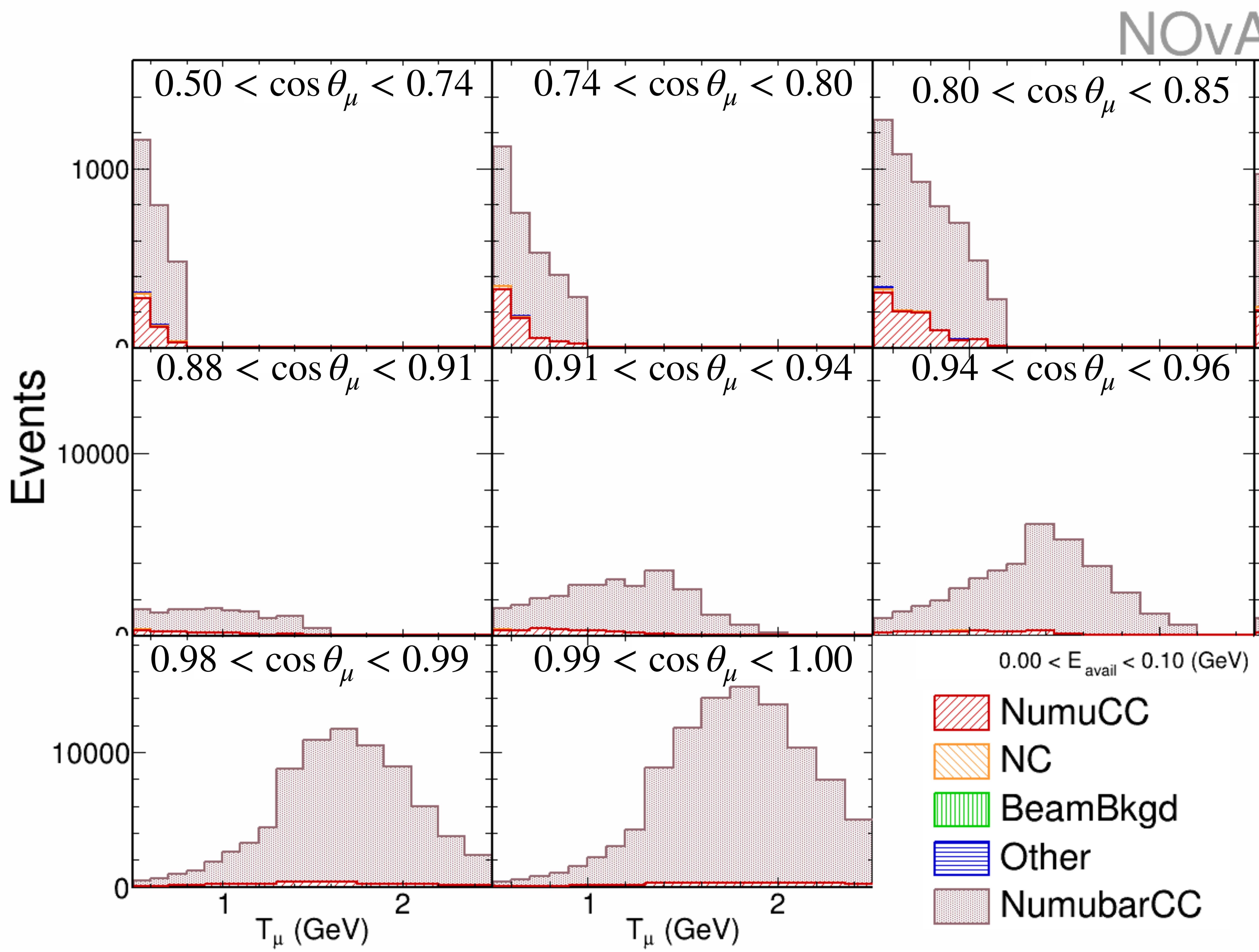
MEC Tuning Uncertainty



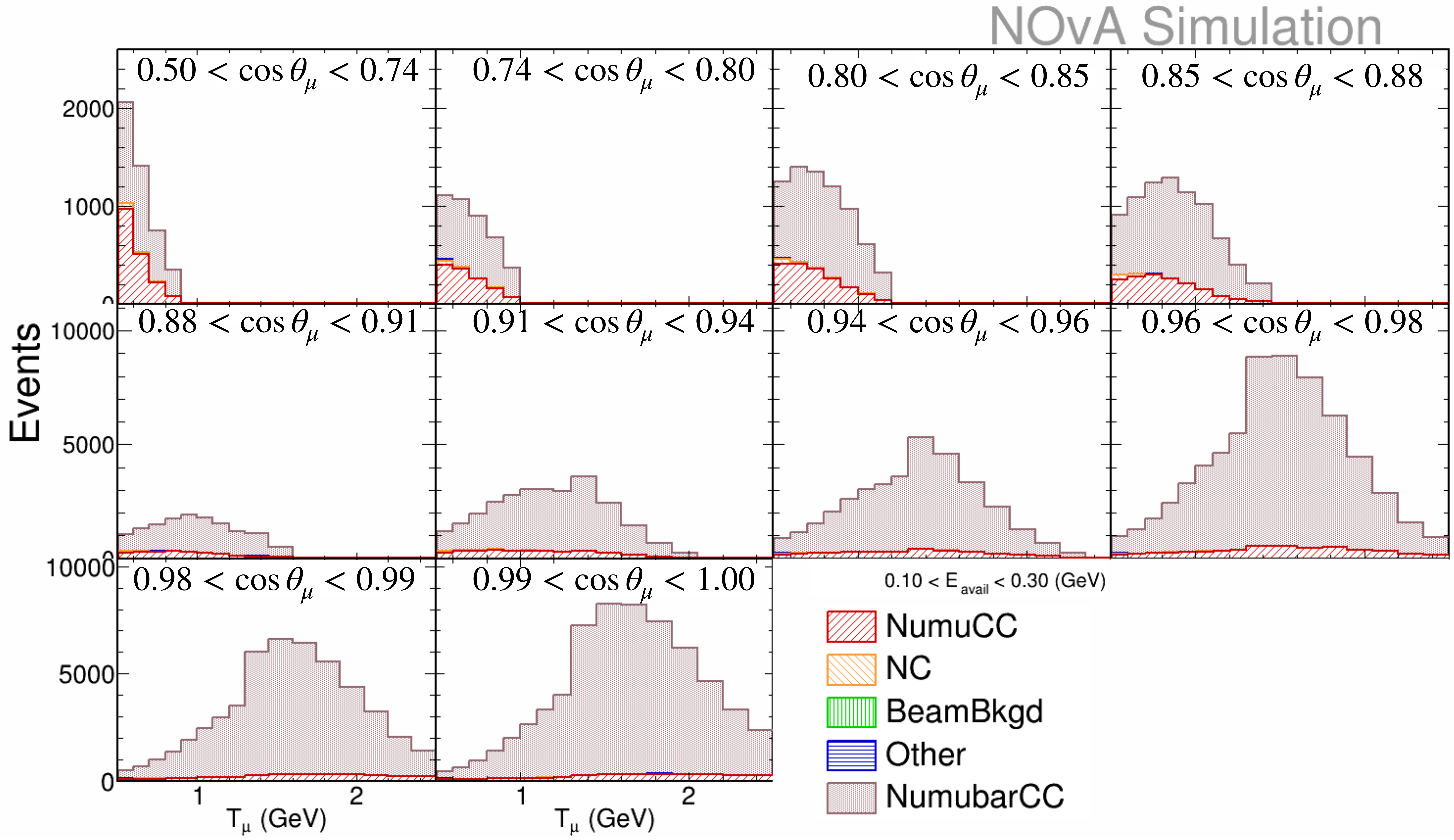


We alter other cross-section parameters by 1σ in conjunction to make things more 'QE-like' and 'RES-like' to support our possible uncertainty.

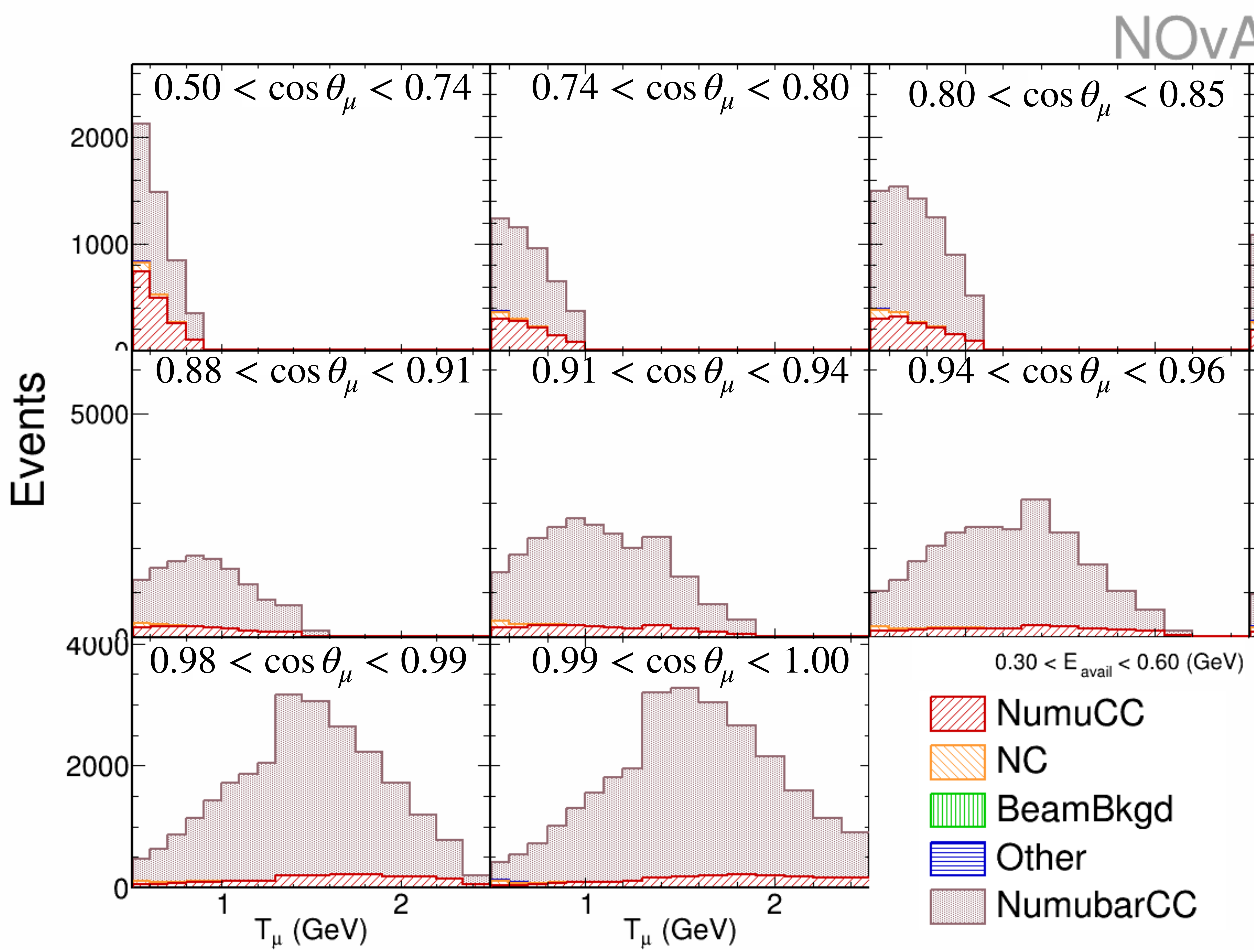
Signal and Backgrounds: $0 < E_{avail} < 100$ MeV



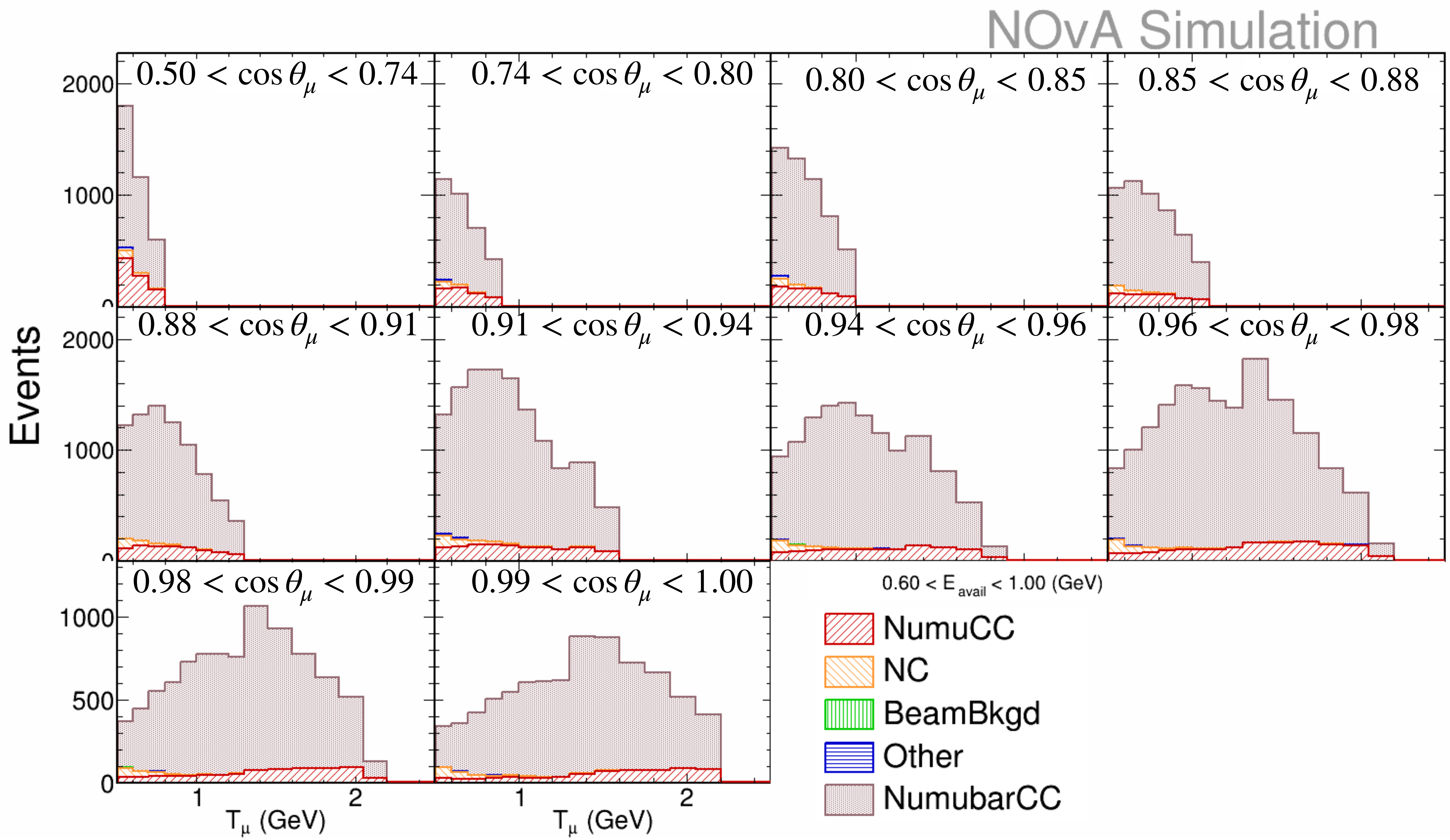
Signal and Backgrounds: $100 < E_{avail} < 300$ MeV



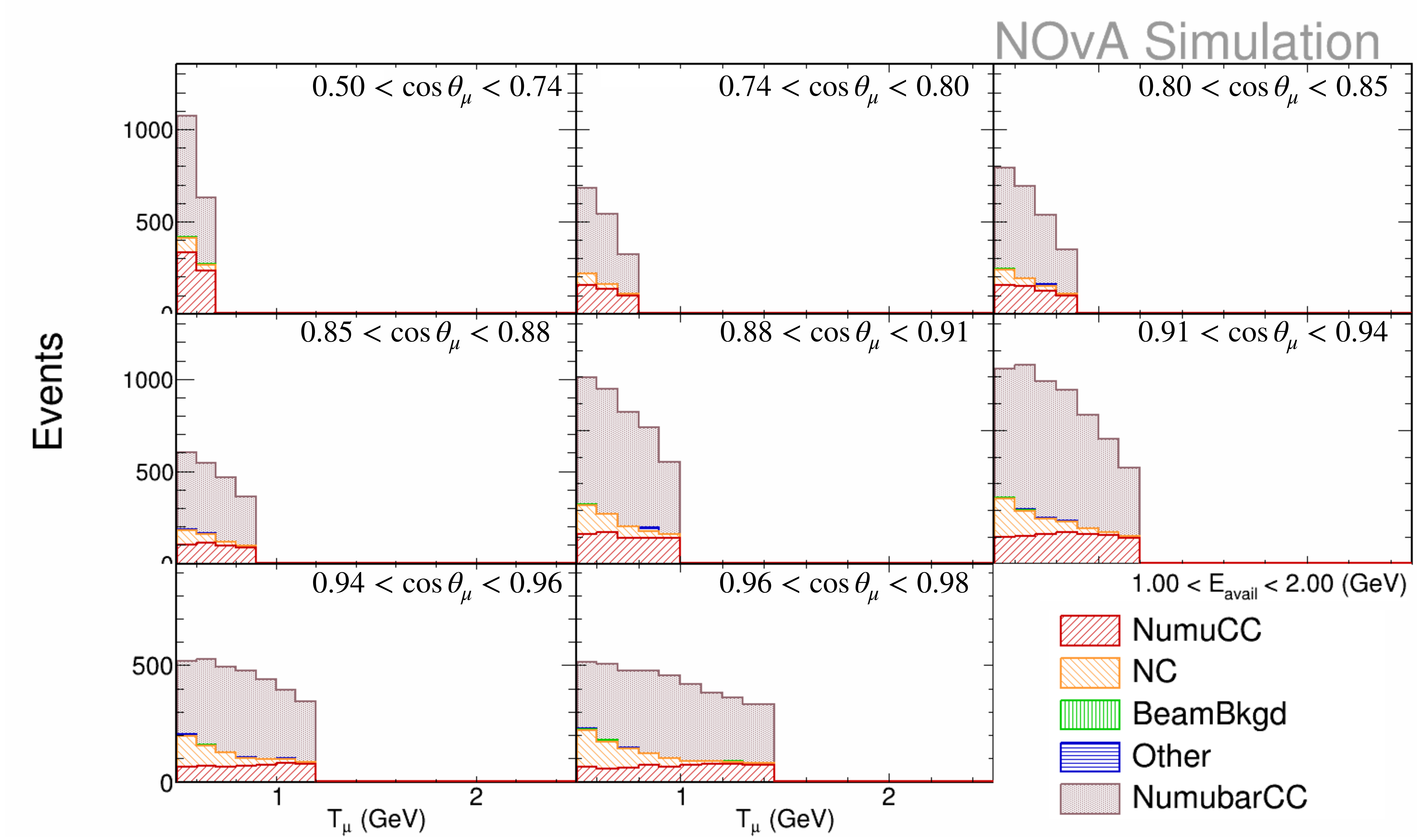
Signal and Backgrounds: $300 < E_{avail} < 600$ MeV



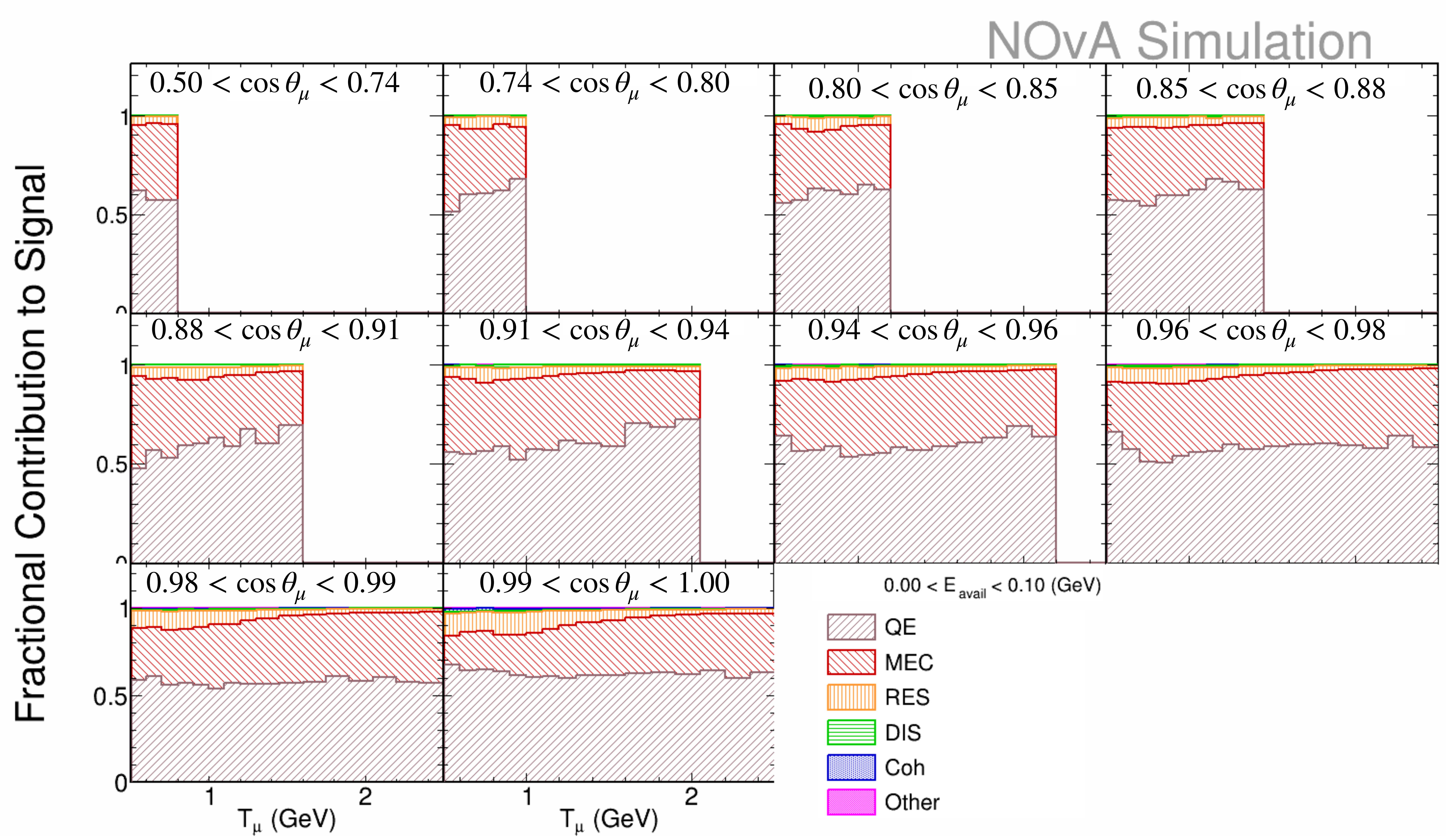
Signal and Backgrounds: $0.6 < E_{avail} < 1.0$ GeV



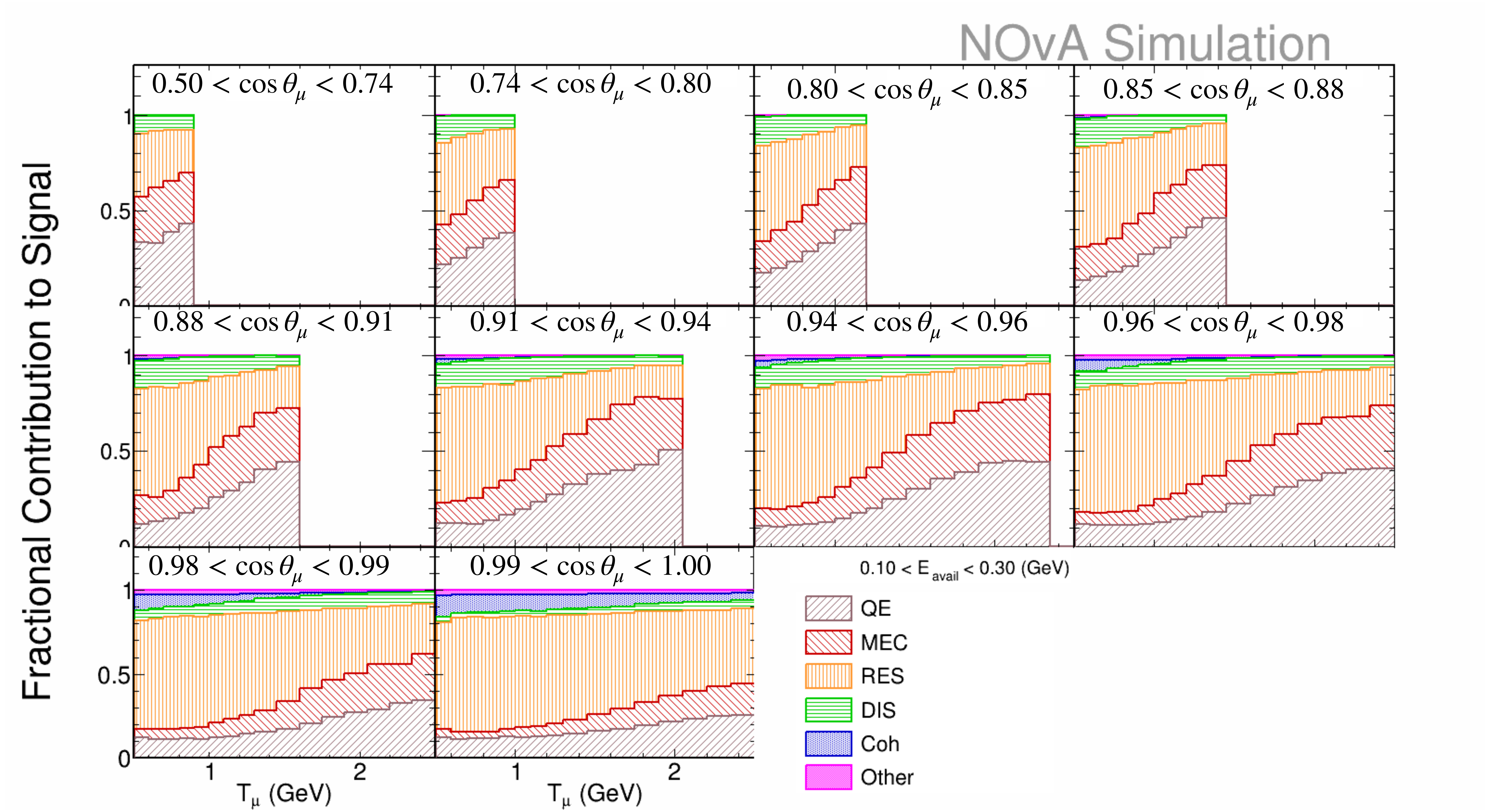
Signal and Backgrounds: $1.0 < E_{avail} < 2.0$ GeV



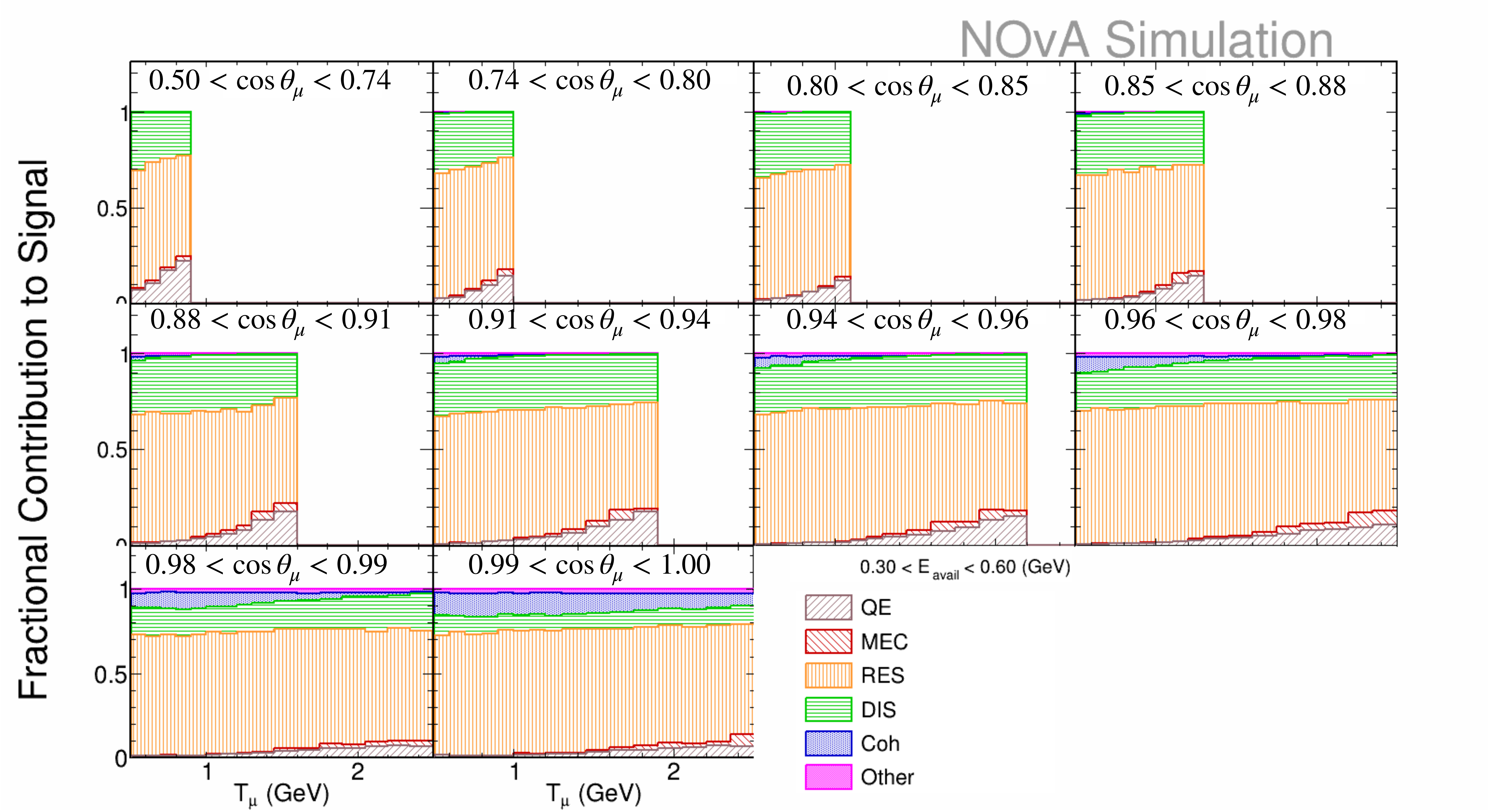
Interaction Modes: $0 < E_{avail} < 100$ MeV



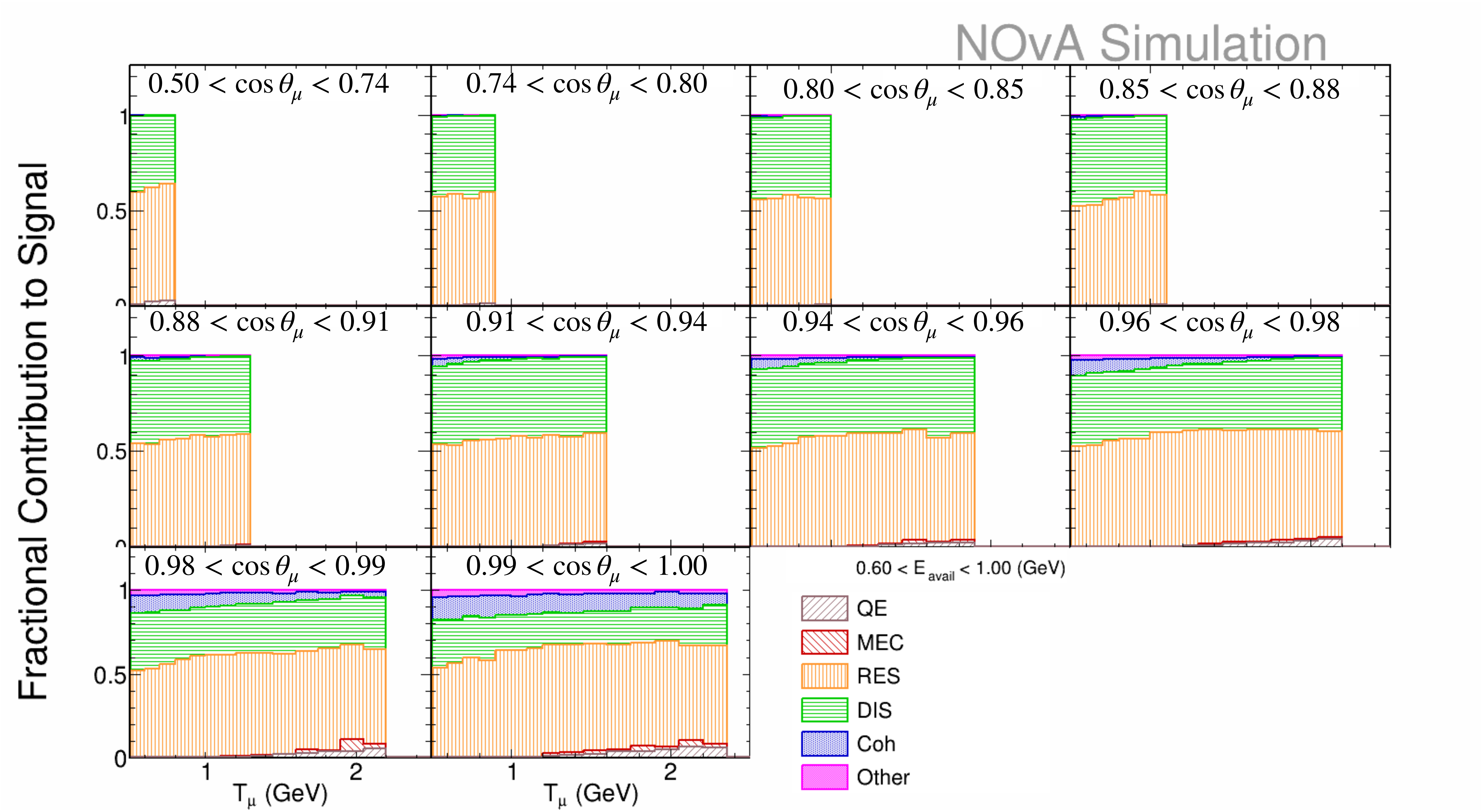
Interaction Modes: $100 < E_{avail} < 300$ MeV



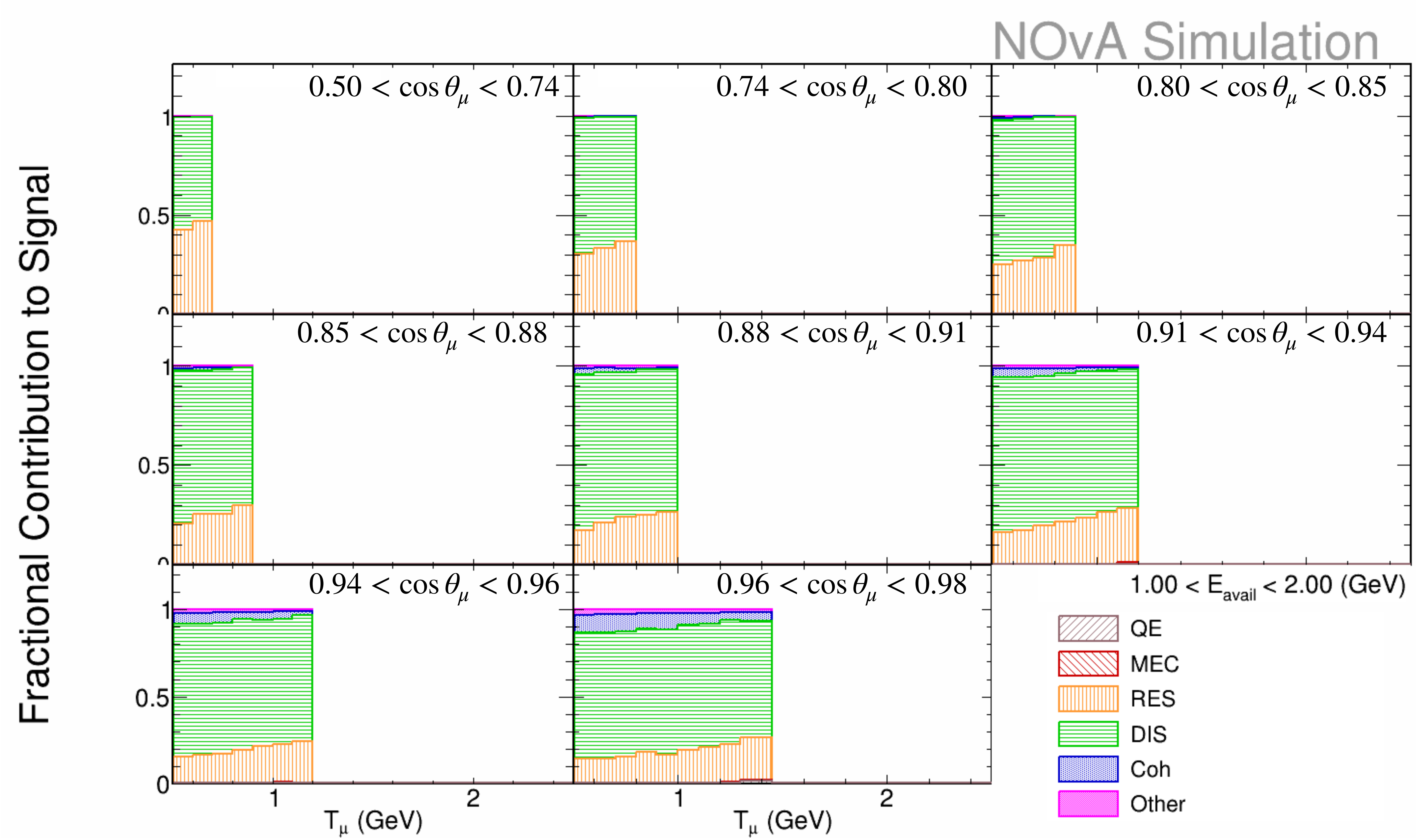
Interaction Modes: $300 < E_{avail} < 600$ MeV



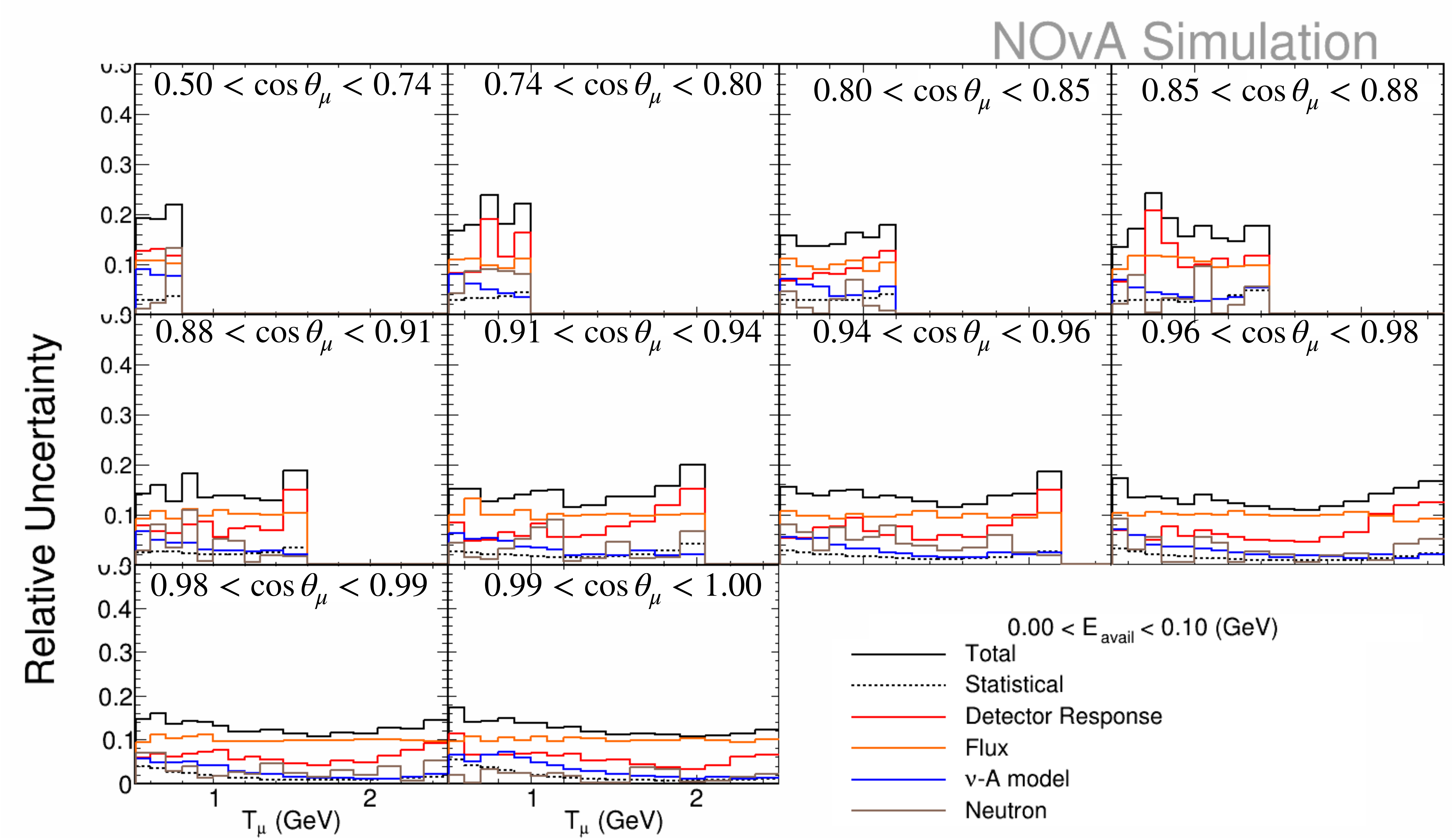
Interaction Modes: $0.6 < E_{avail} < 1.0$ GeV



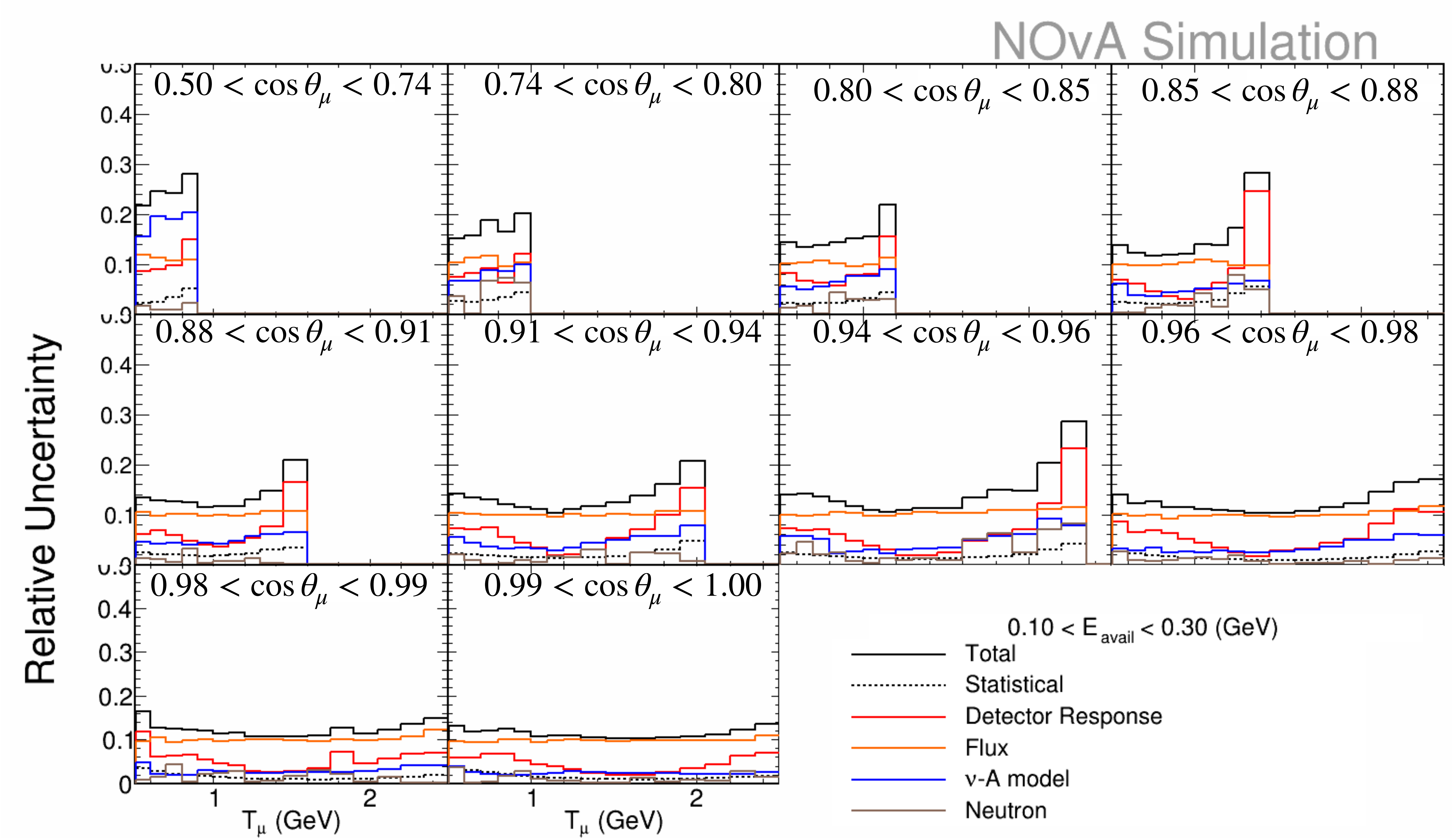
Interaction Modes: $1.0 < E_{avail} < 2.0$ GeV



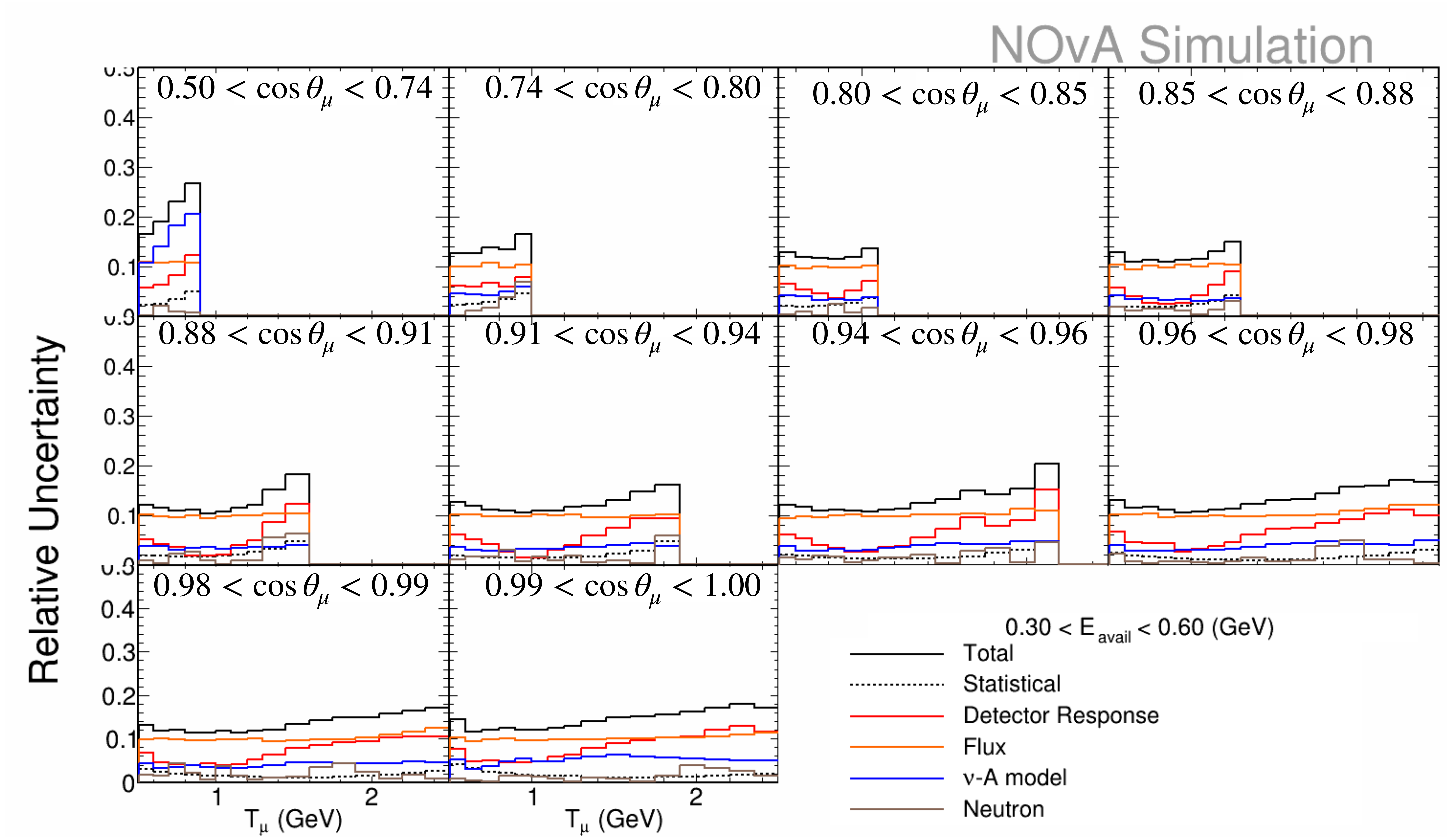
Systematic Uncertainties: $0 < E_{avail} < 100$ MeV



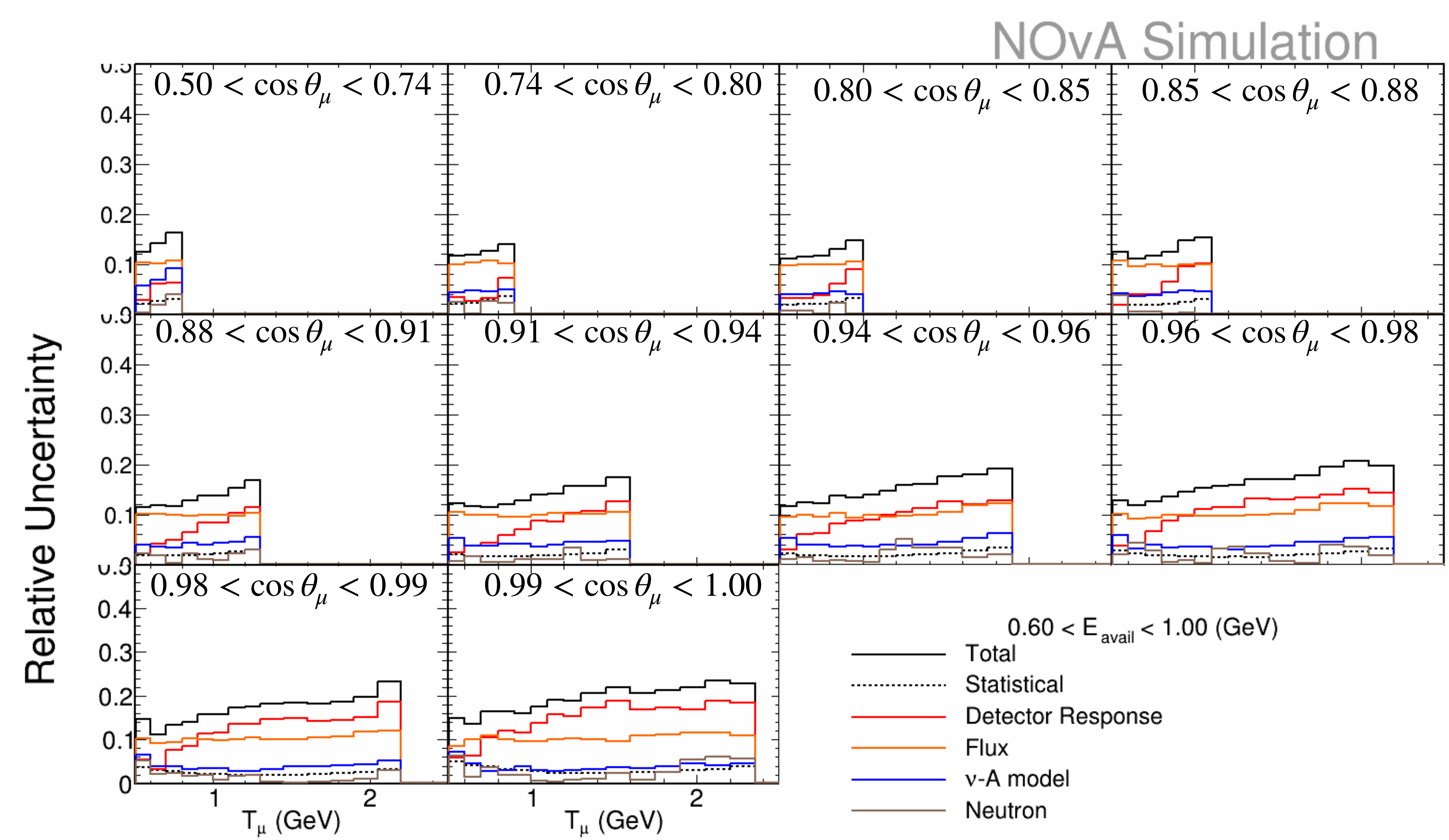
Systematic Uncertainties: $100 < E_{avail} < 300$ MeV



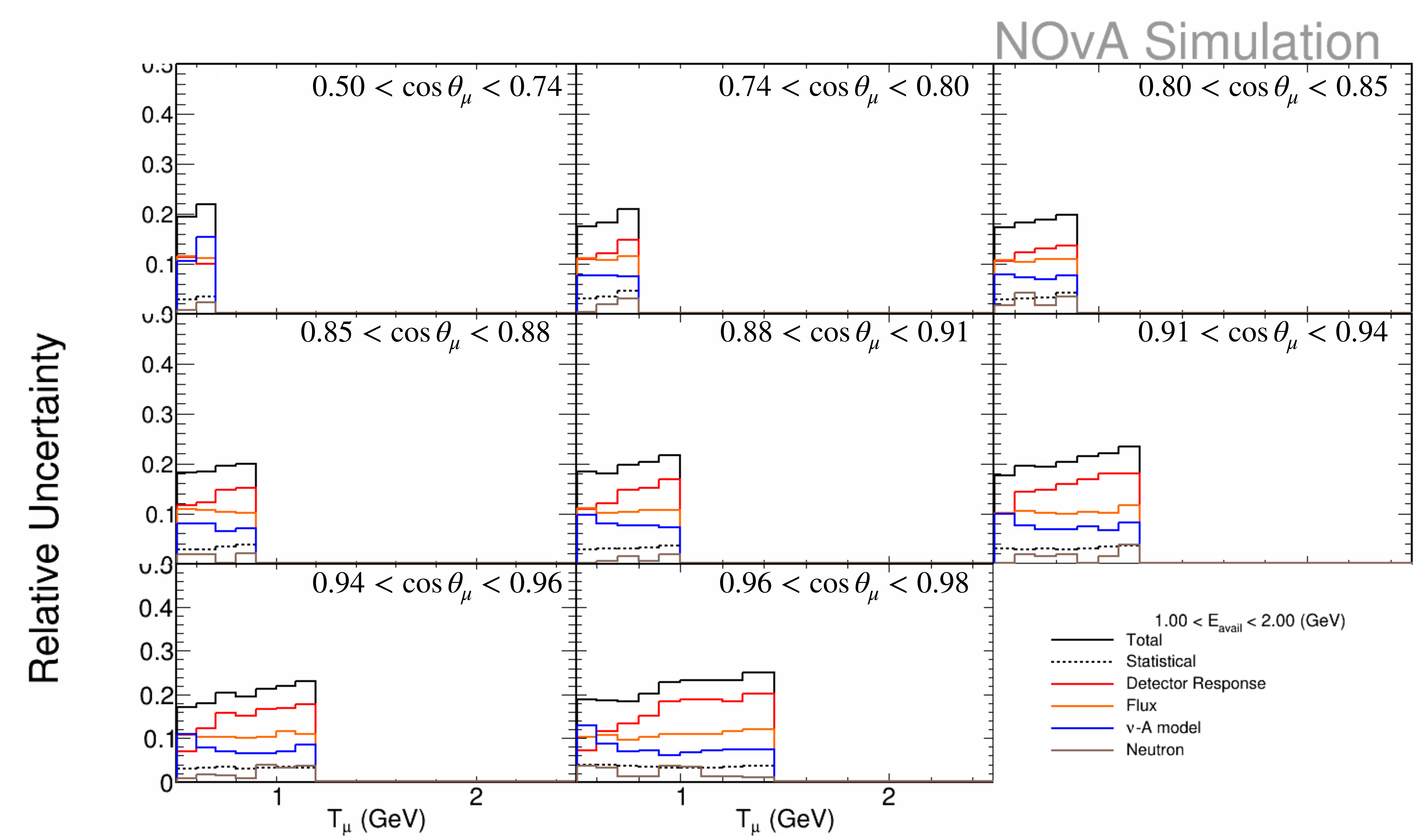
Systematic Uncertainties: $300 < E_{avail} < 600$ MeV



Systematic Uncertainties: $0.6 < E_{avail} < 1.0$ GeV

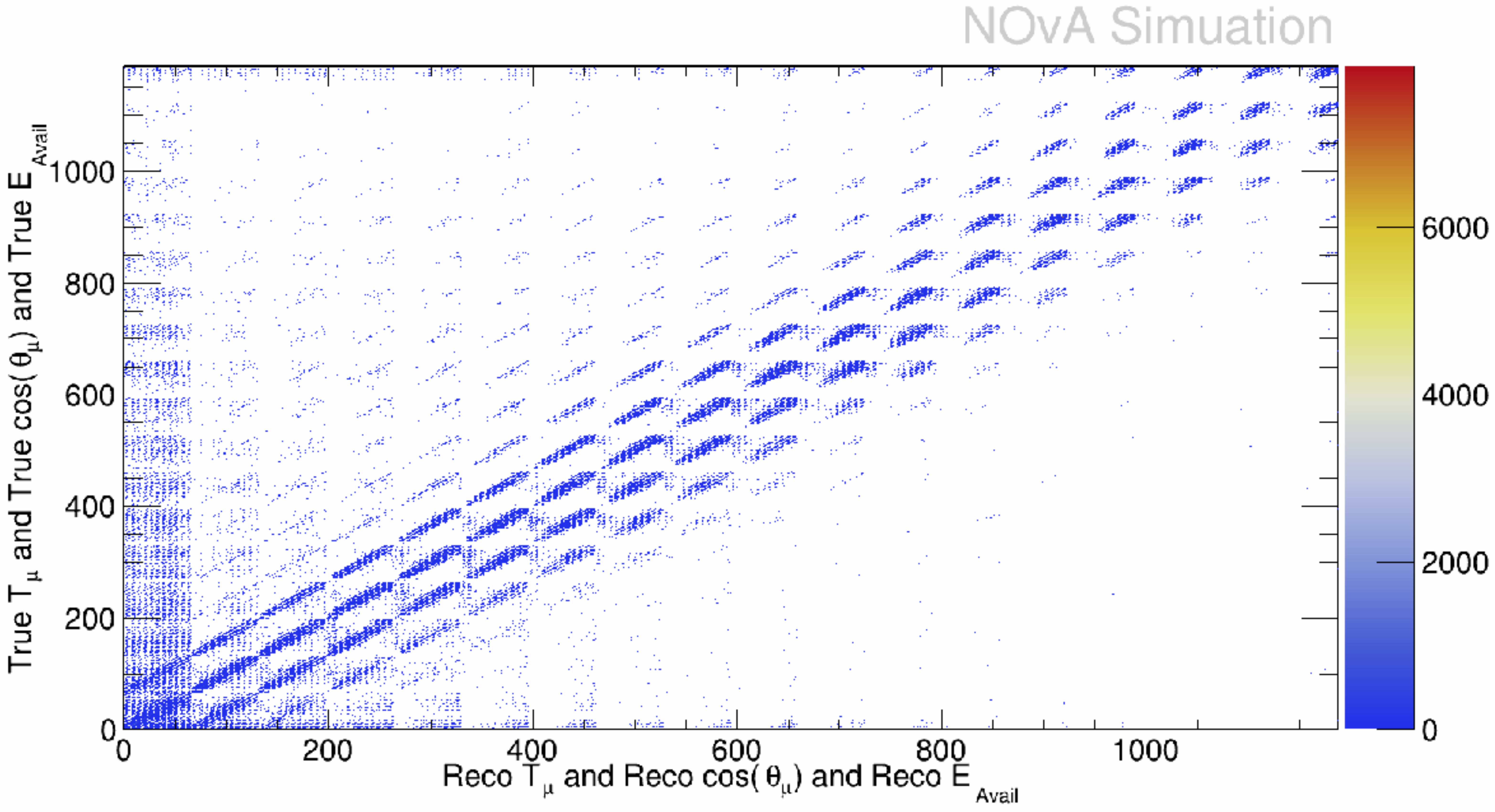


Systematic Uncertainties: $1.0 < E_{avail} < 2.0$ GeV

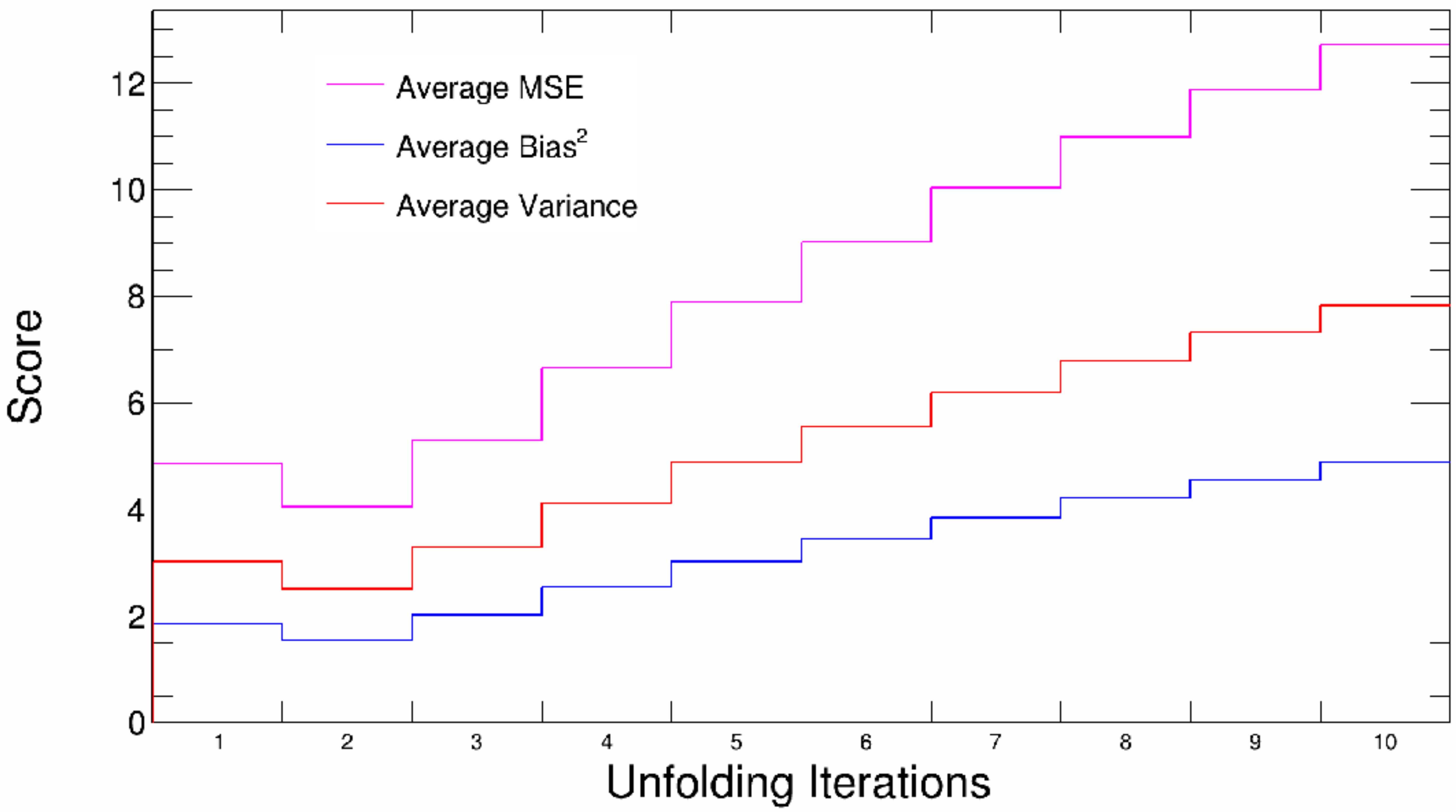


Unfolding Matrix and Technique

- Unfolding is performed in 3D space of T_μ, $\cos\theta_\mu$, and E_{avail}
- Unfolding transitions events from reconstructed space to the true space
- We use D'Agostini iterative unfolding method to unfold events



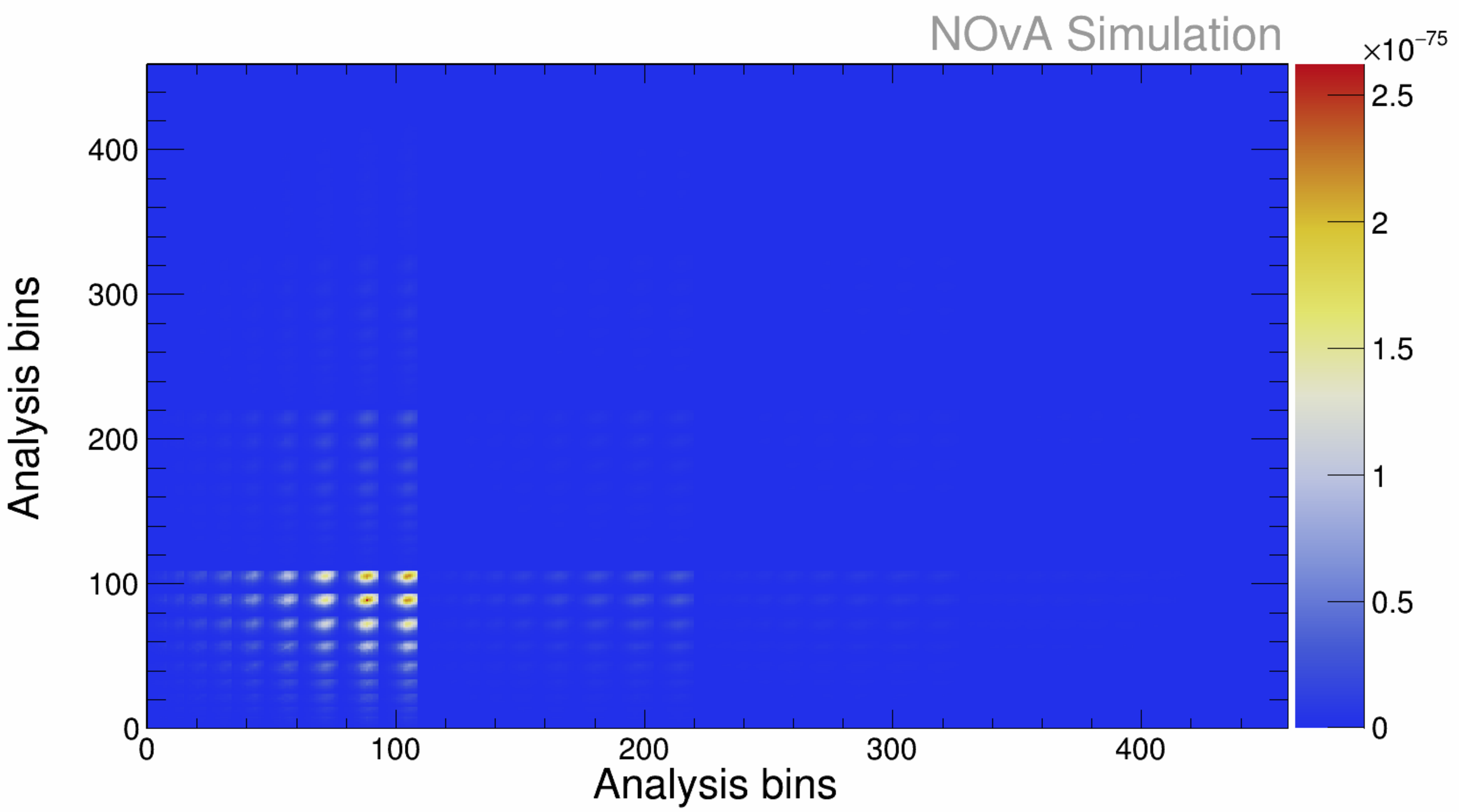
Number of Unfolding Iteration

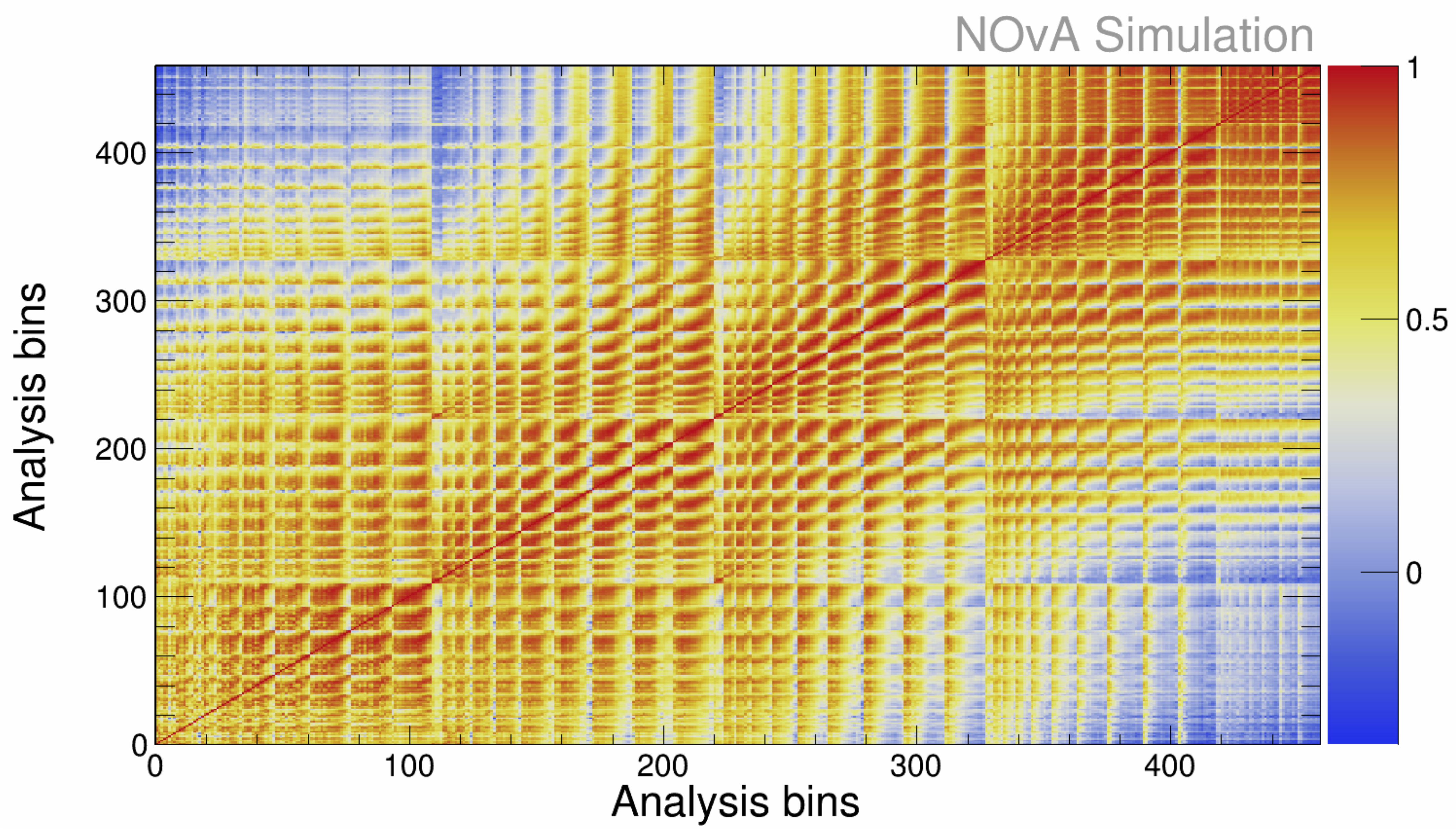


Systematic Uncertainties

- Statistical: includes statistical uncertainties from both the data and MC samples. Evaluated using multi Poisson universes
- Detector response: energy calibration, light levels, Cherenkov light, detector aging, muon energy and angle shifts, GEANT4 secondary interactions
- Flux: PPFX and beam systematics
- Neutrino-interaction model: NOvA "custom" systematics, with
    - updates to RPA CCQE with Valencia as base model
    - RES "RPA" replaced by smaller, better motivated low-Q^2 suppression knob
    - Retuned MEC systs based on previous NOvA data
    - Custom Formation Zone and FSI knobs using "BDT reweight" method
- Neutron systematics: based on neutron–carbon inelastic reactions defined by MENATE_r model within GEANT4

Covariance and Correlation Matrices

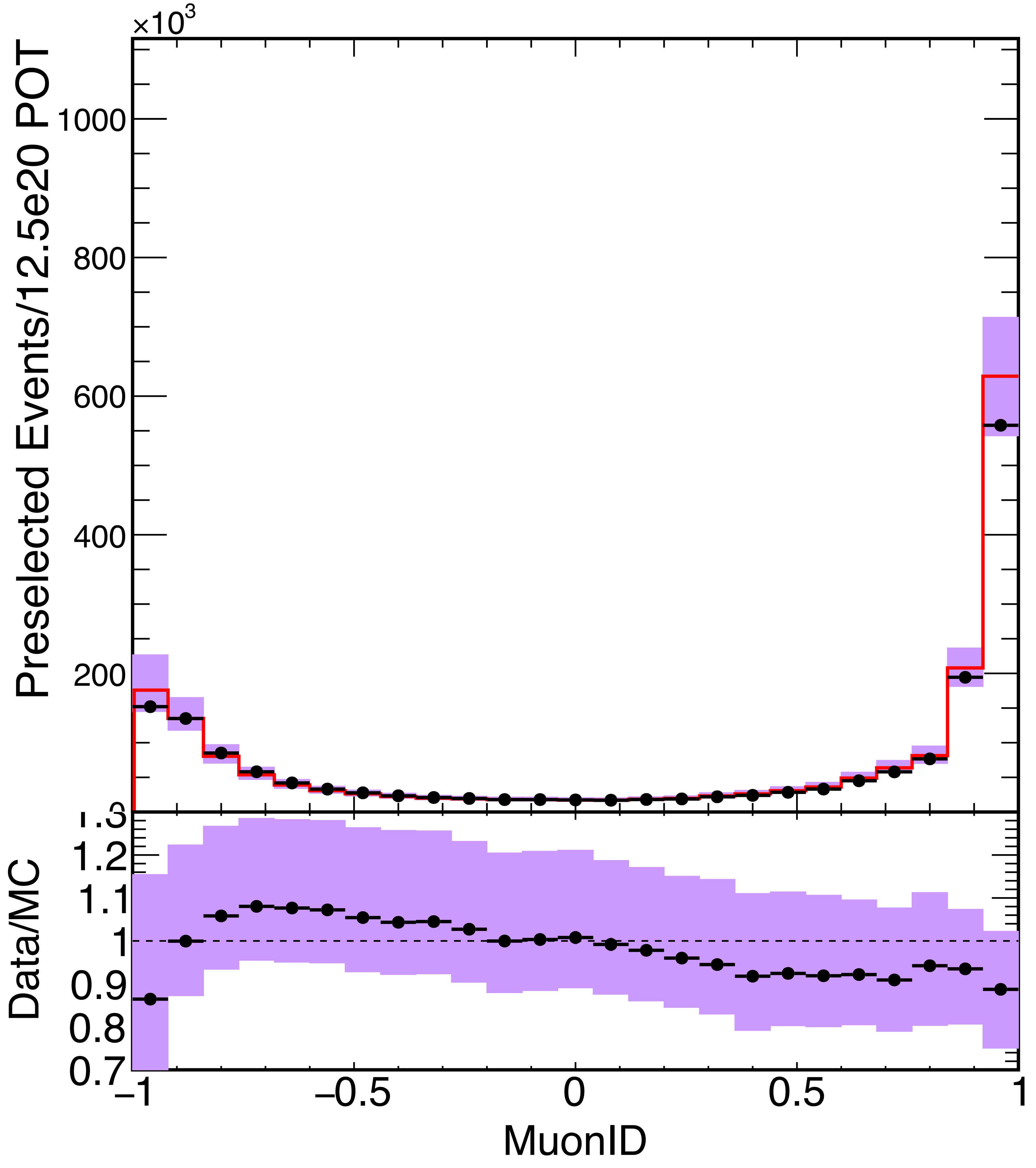




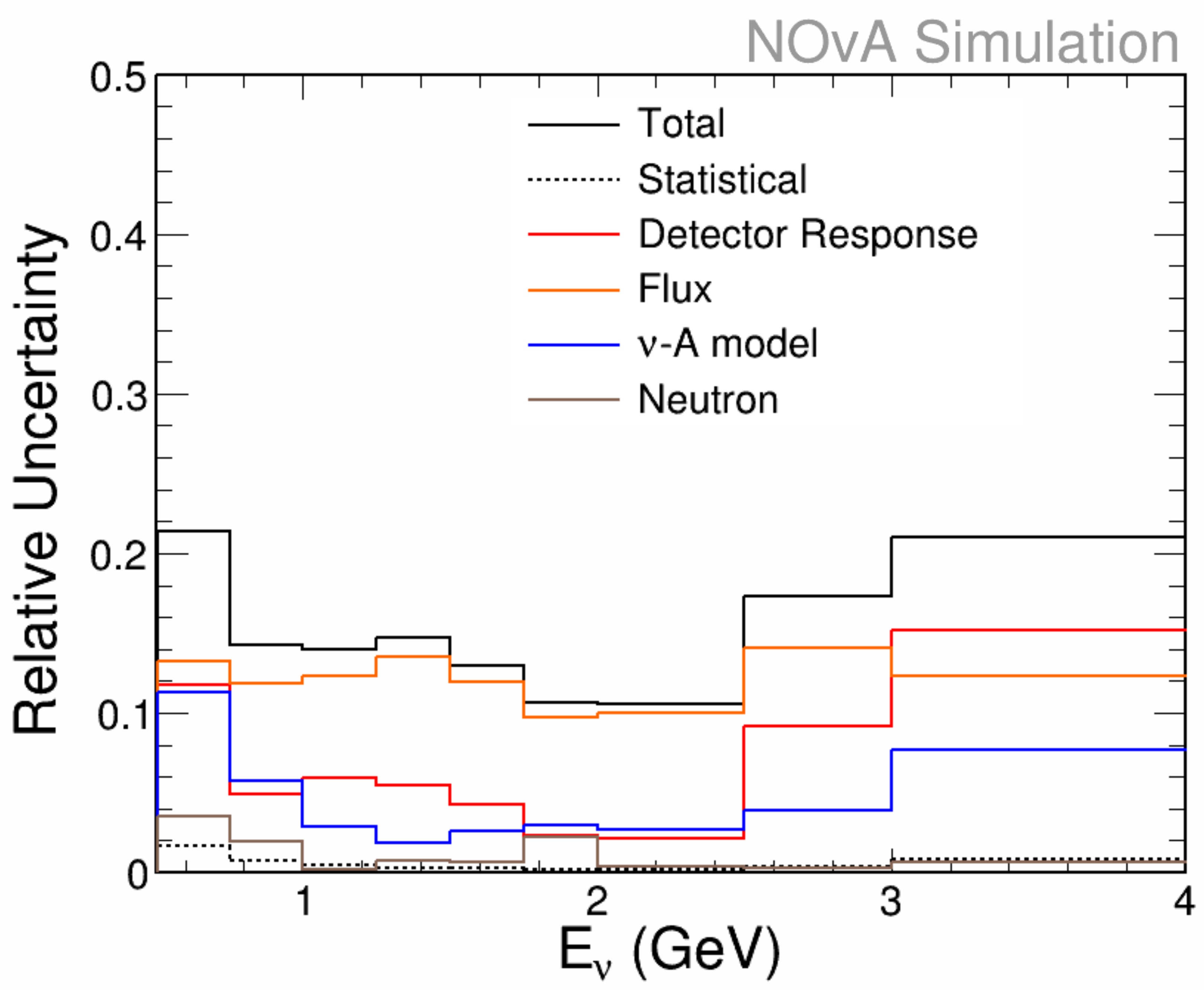
- Cross sections are calculated for nominal and each source of systematic uncertainty
- Covariance matrix is evaluated using the nominal and the shifted cross sections

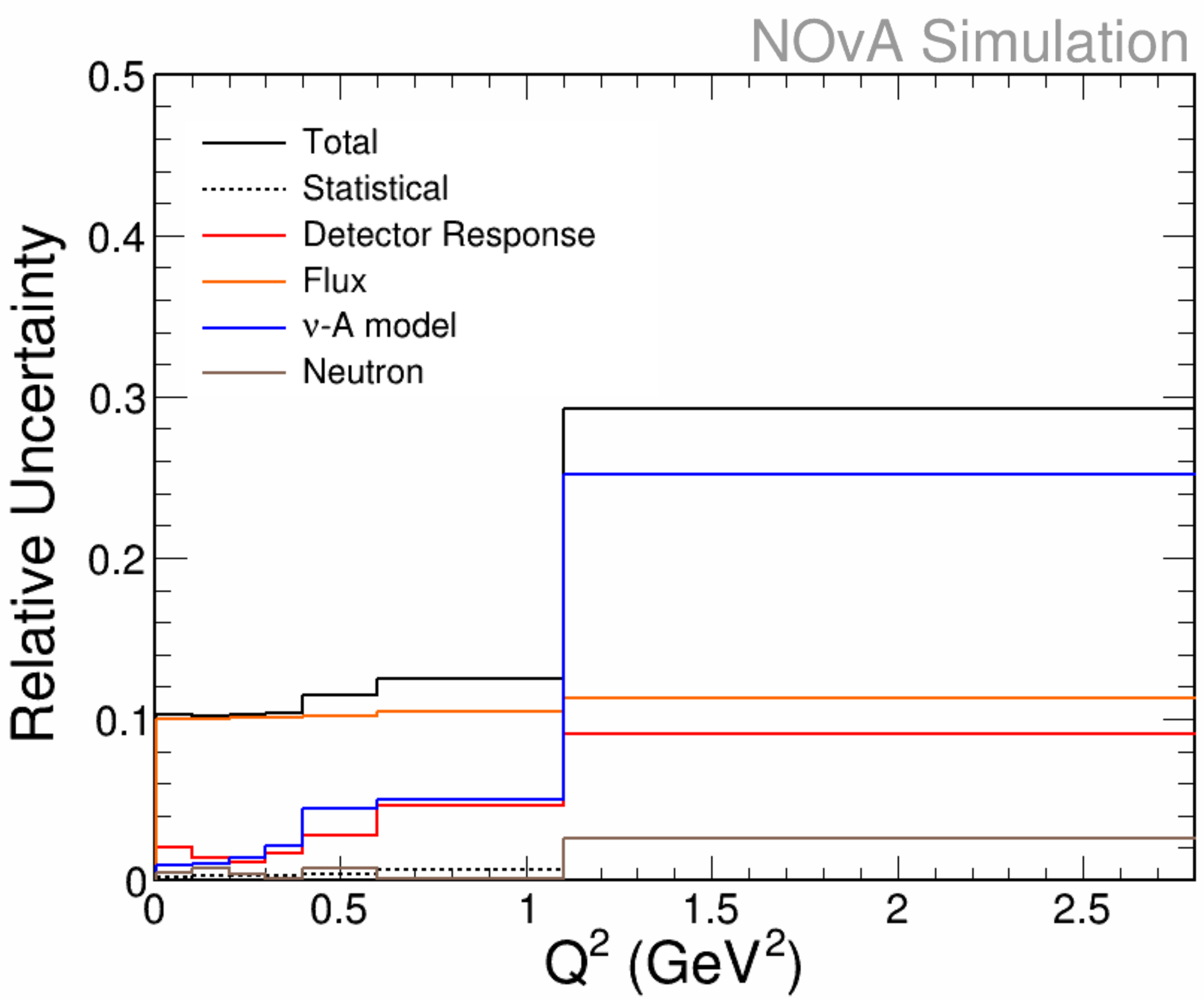
- Correlation matrix shows that the large phase-space region is highly correlated between analysis bins
- Bin-by-bin correlations are picked up by the covariance matrix

Muon ID: Data/MC



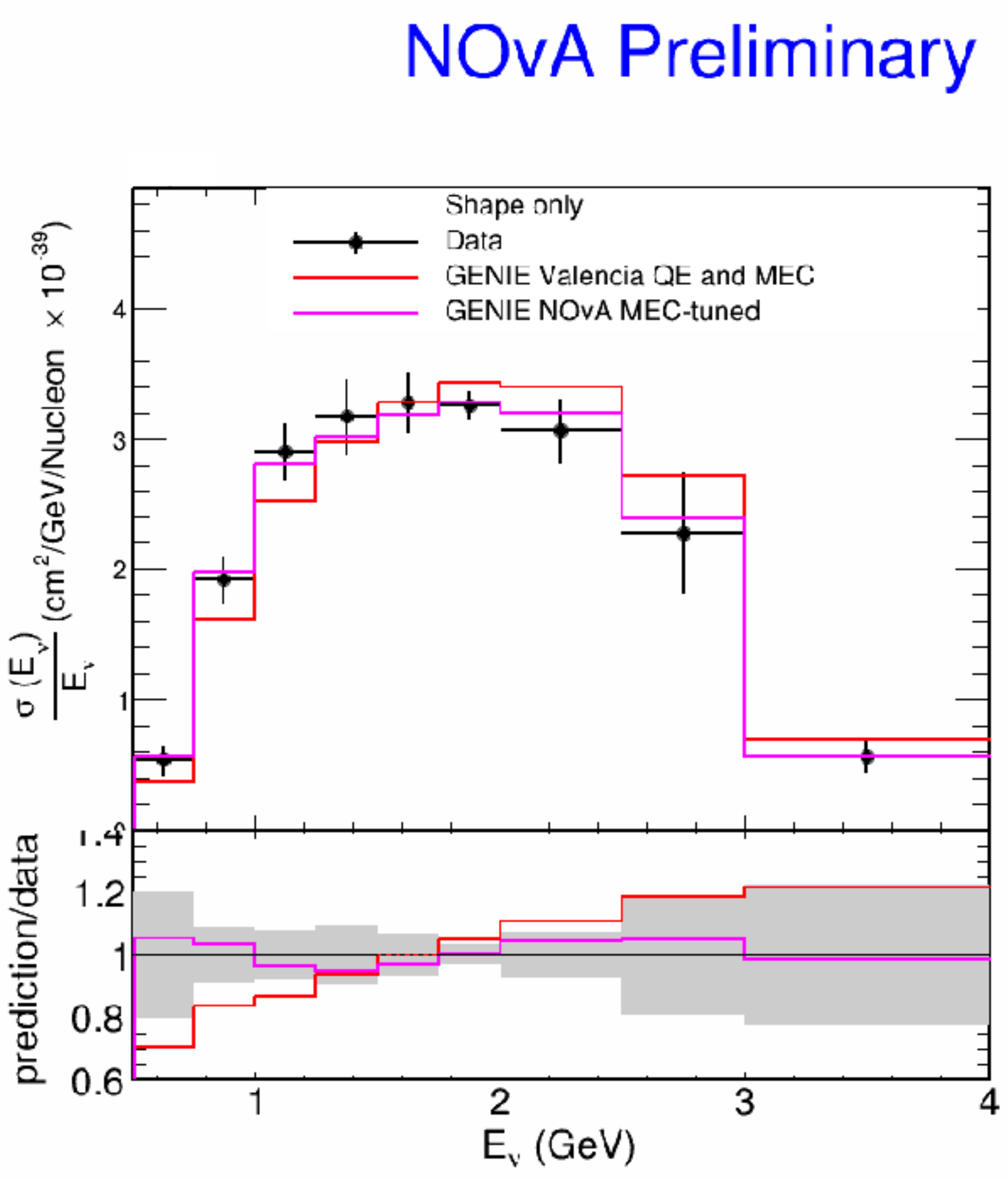
Systematic Uncertainties

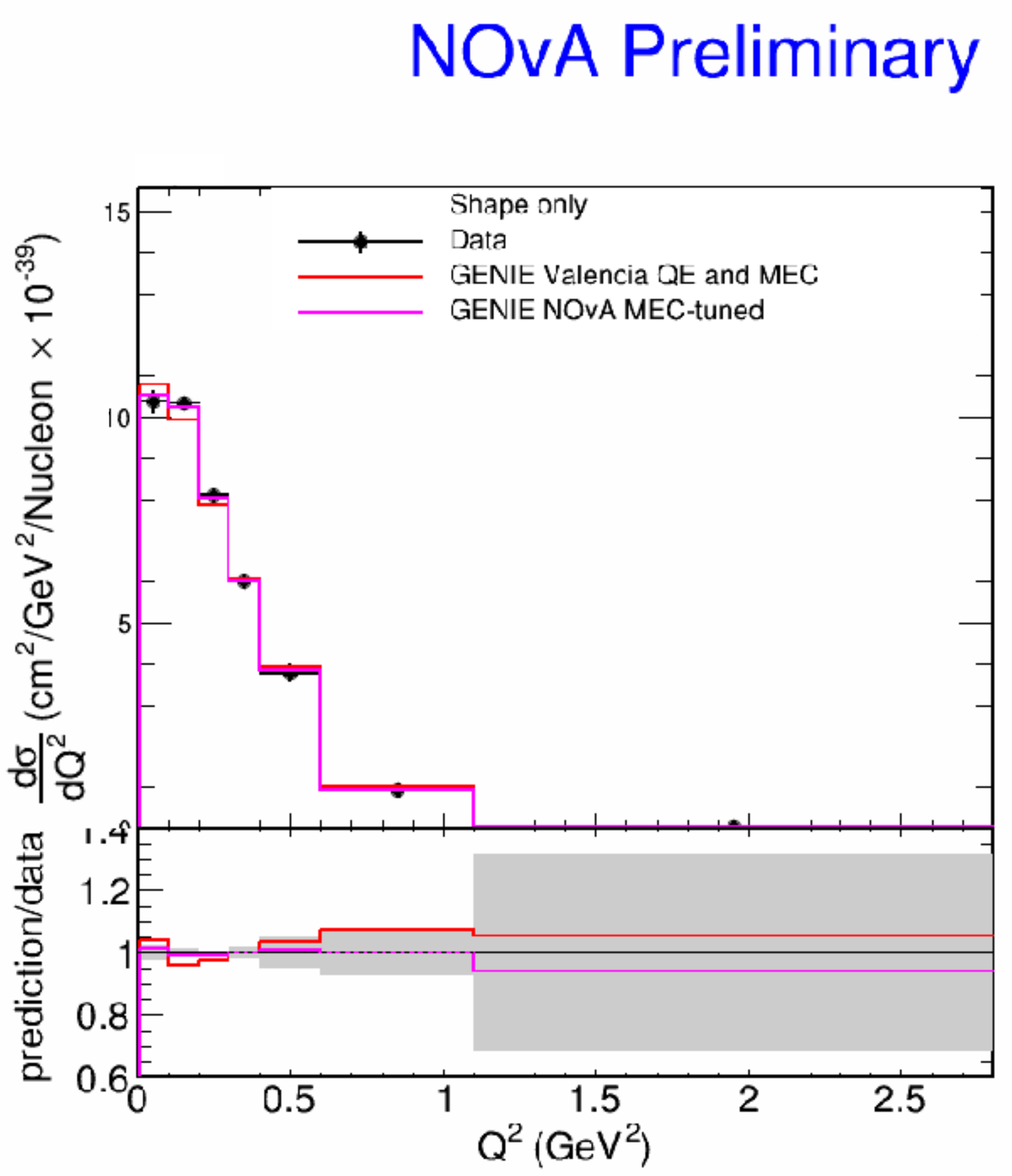




Sources	Avg. fractional uncertainty (%)	
	Enu	Q2
Detector Response	4.8	1.8
Flux	11.8	10.0
ν-A model	3.2	1.7
Neutron	1.0	0.5
Statistical	0.3	0.3
Total	13.4	10.4

Shape only Results





Shape only Results