FERMILAB-SLIDES-24-0053-PPD-V

Measurement of the Triple Differential Muon-Antineutrino Charged-Current Inclusive Cross Section in the NOvA Near Detector

Prabhjot Singh, on behalf of the NOvA Collaboration

Fermilab Joint Experimental-Theoretical Physics Seminar

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Why Neutrino Cross sections are Important? - Oscillations

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

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

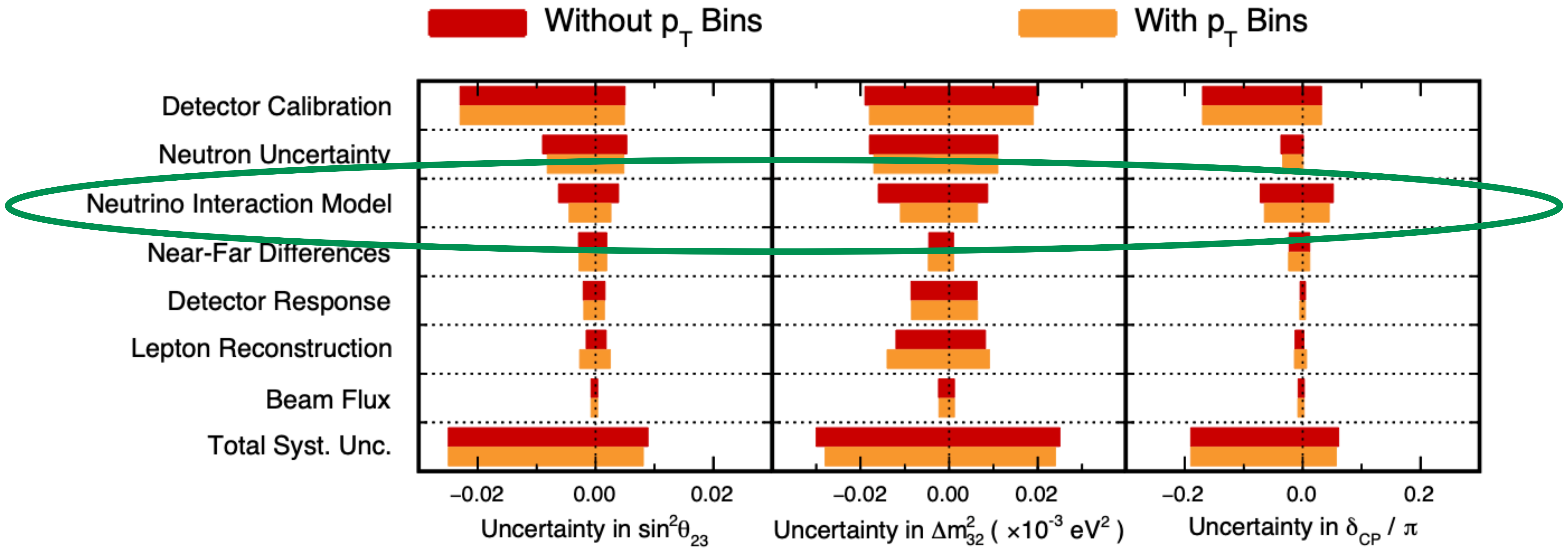
Why Neutrino Cross sections are Important? - Uncertainties

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



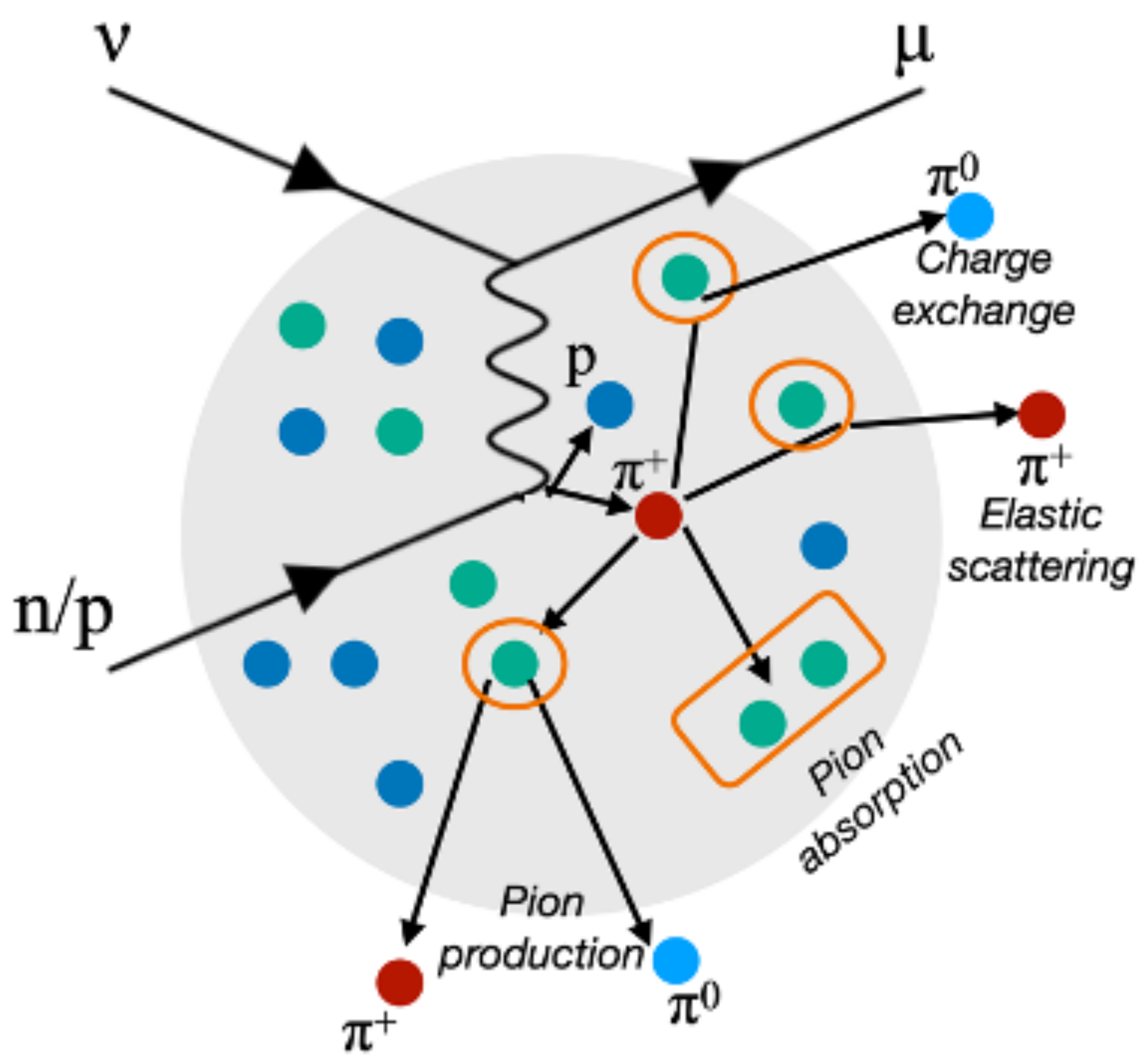
Why Neutrino Cross sections are Important? - Nuclear Physics

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

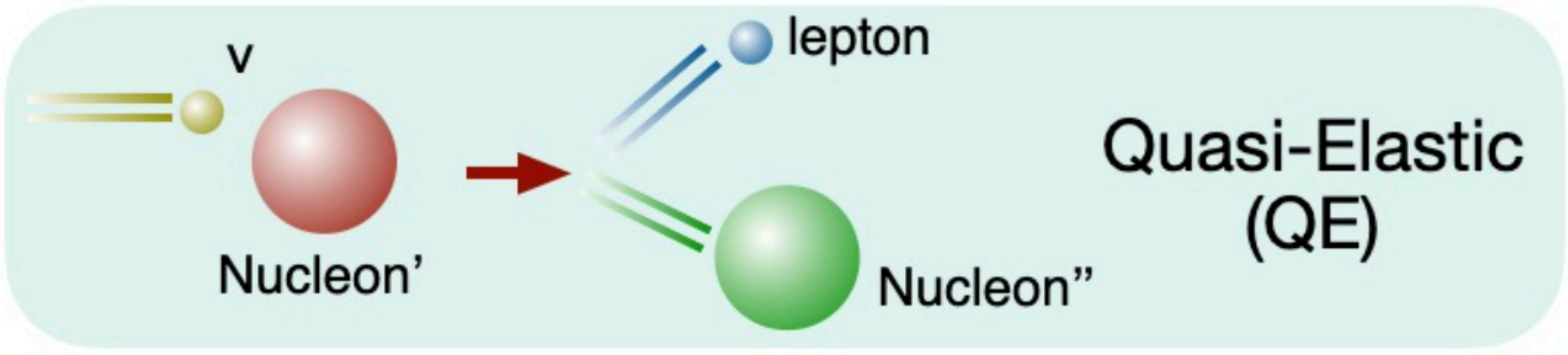
Physics conclusion can be drawn by comparing various nuclear physics models to the cross section measurement results

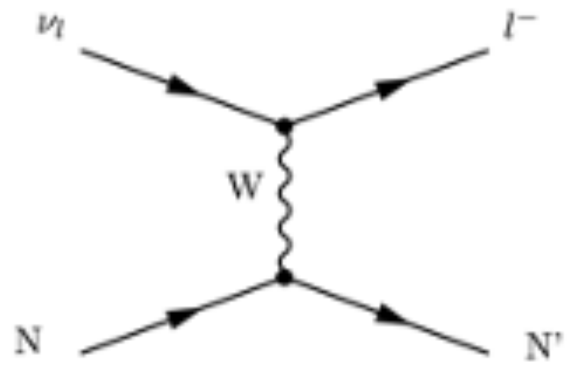
This can further help us to reduce neutrino interaction uncertainties in the future neutrino experiments



By T. Golan

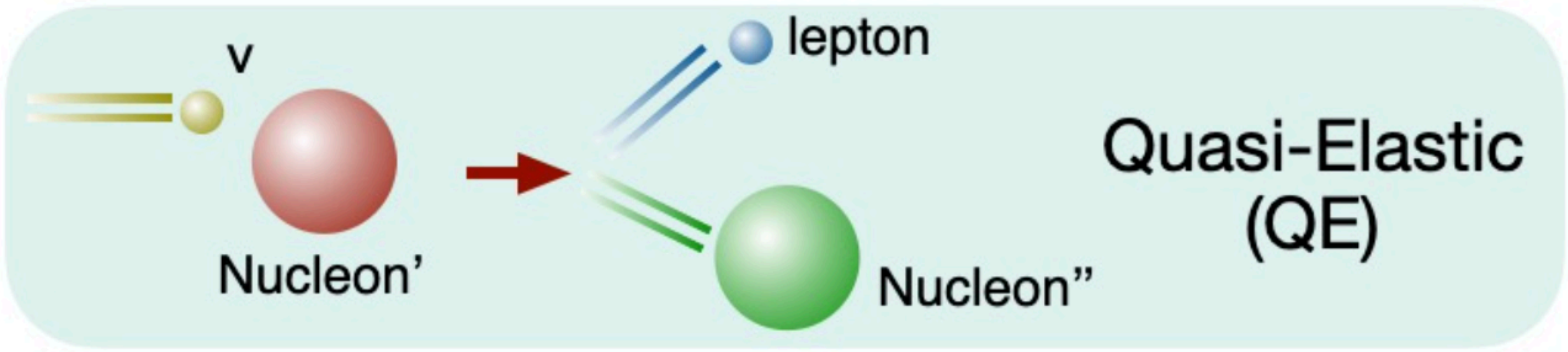
Neutrino Interactions

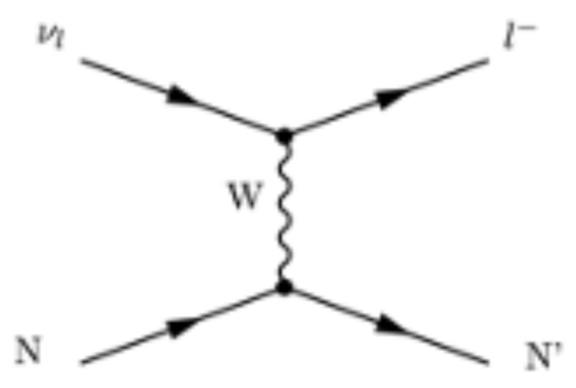


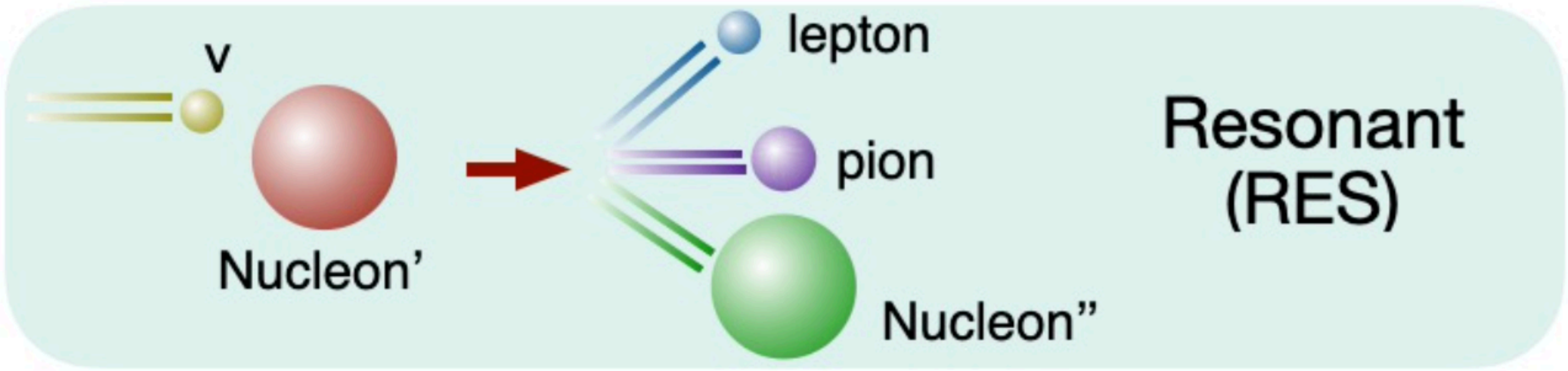


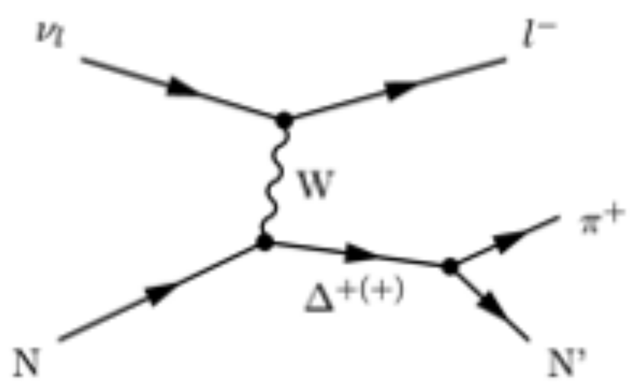
By Linda Cremonesi, [Neutrino 2020]

Neutrino Interactions









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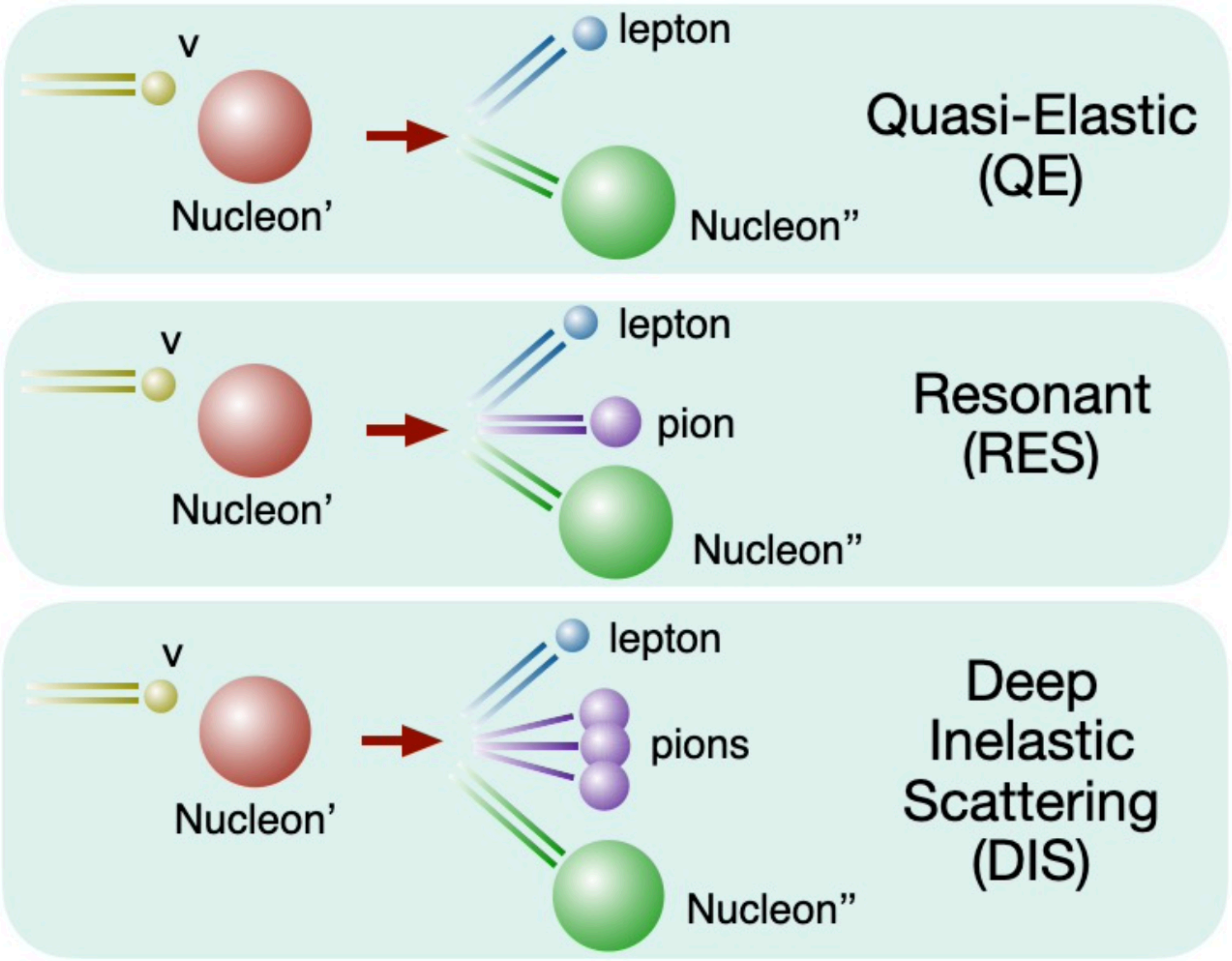

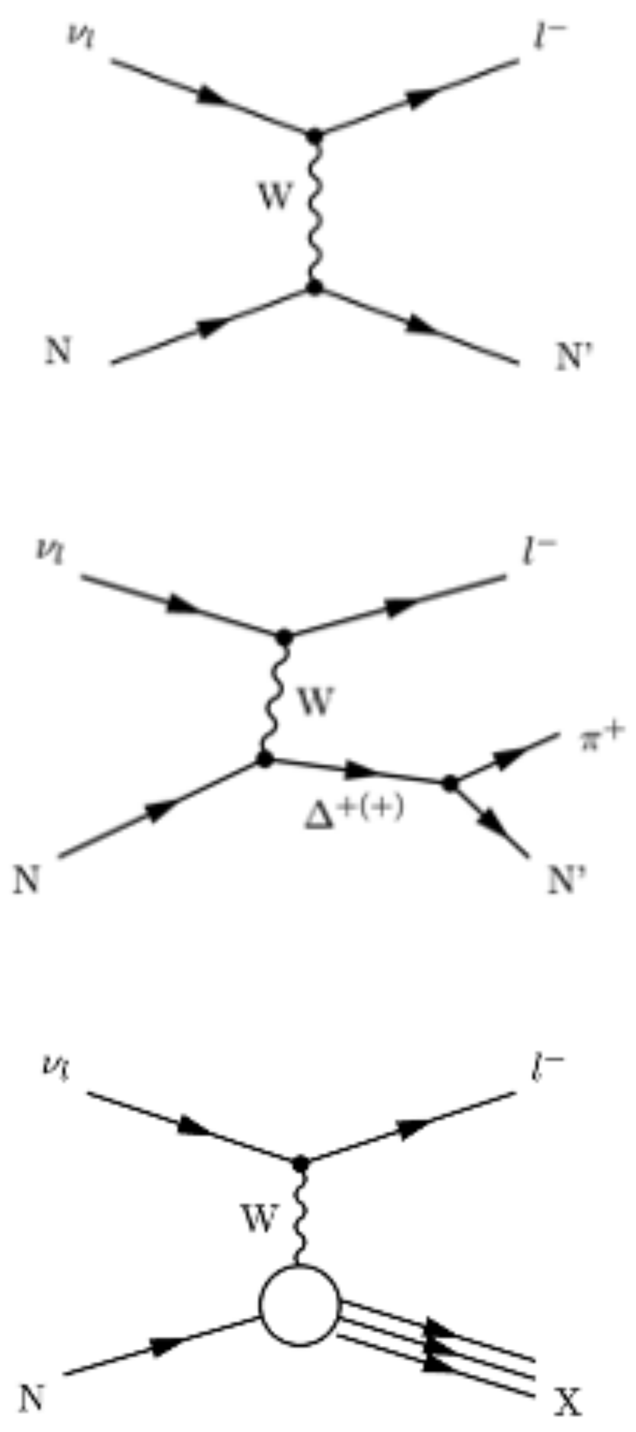

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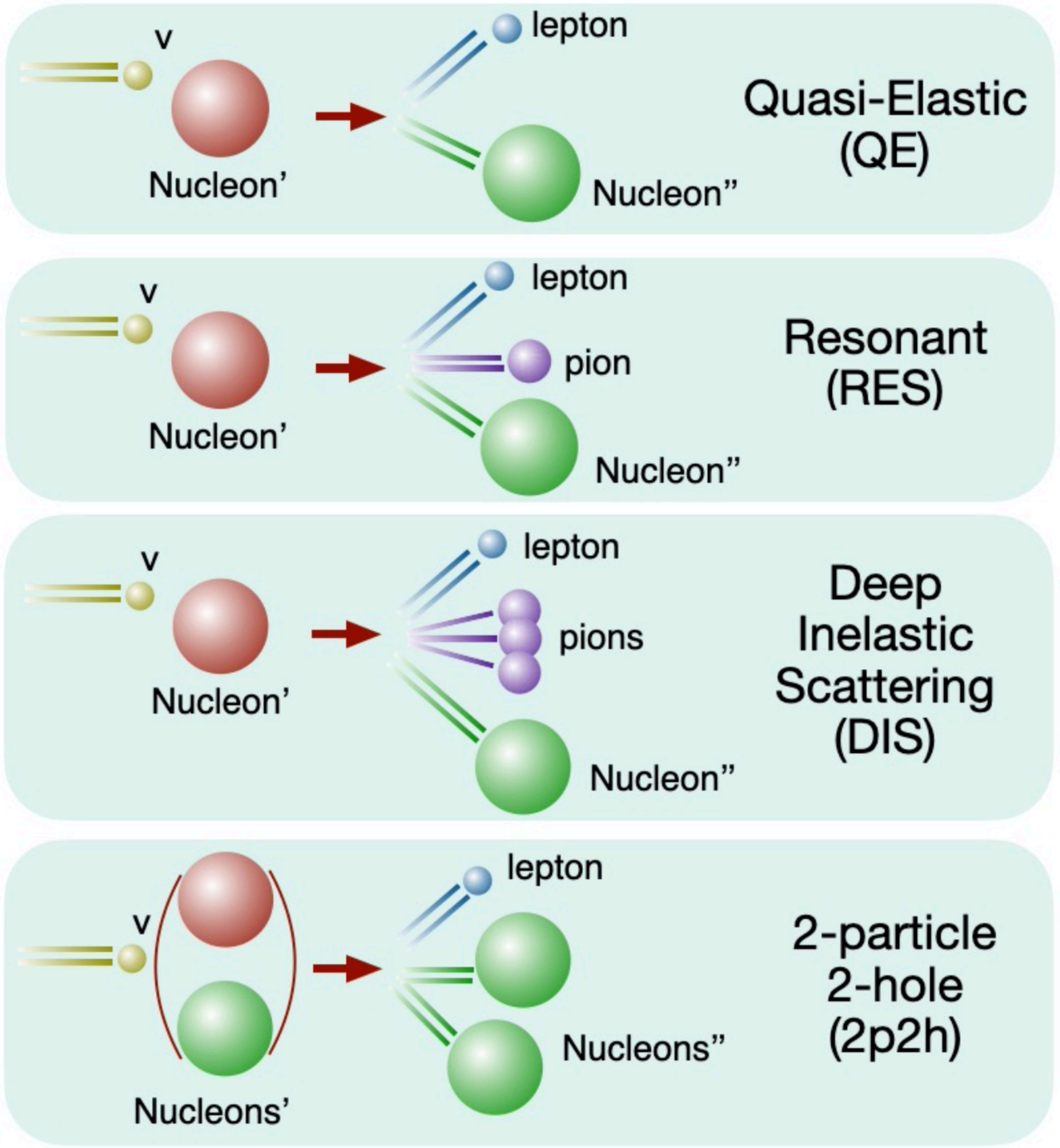
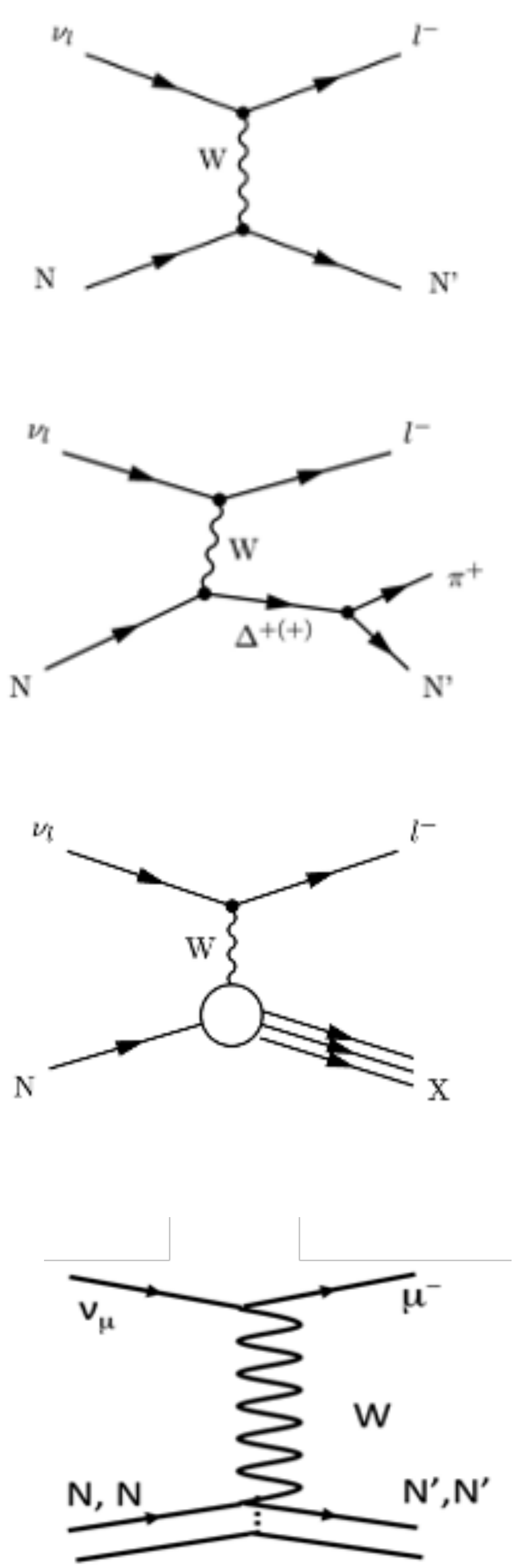
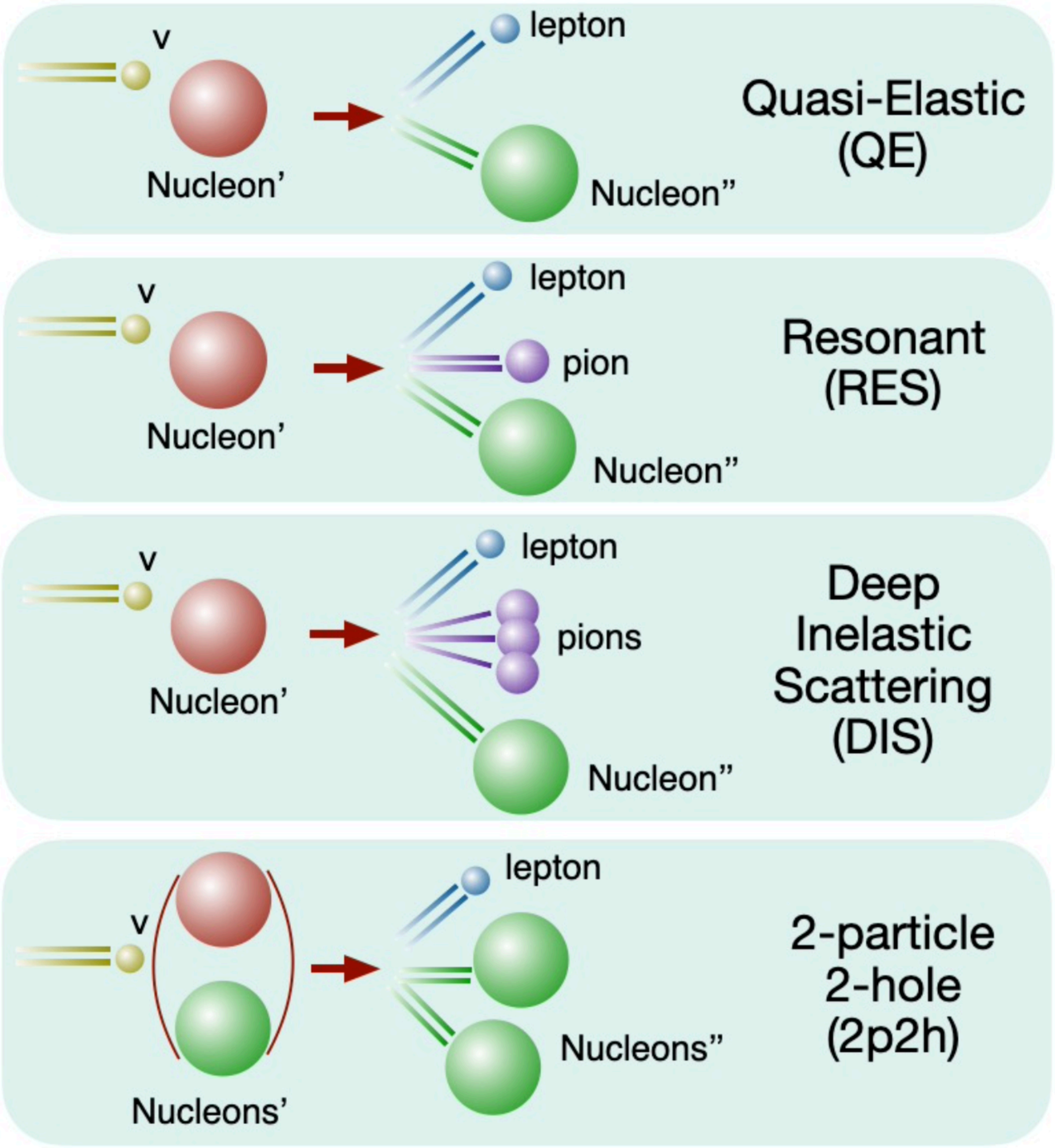




By Linda Cremonesi, Neutrino 2020

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

Neutrino Interactions - Nuclear Effects



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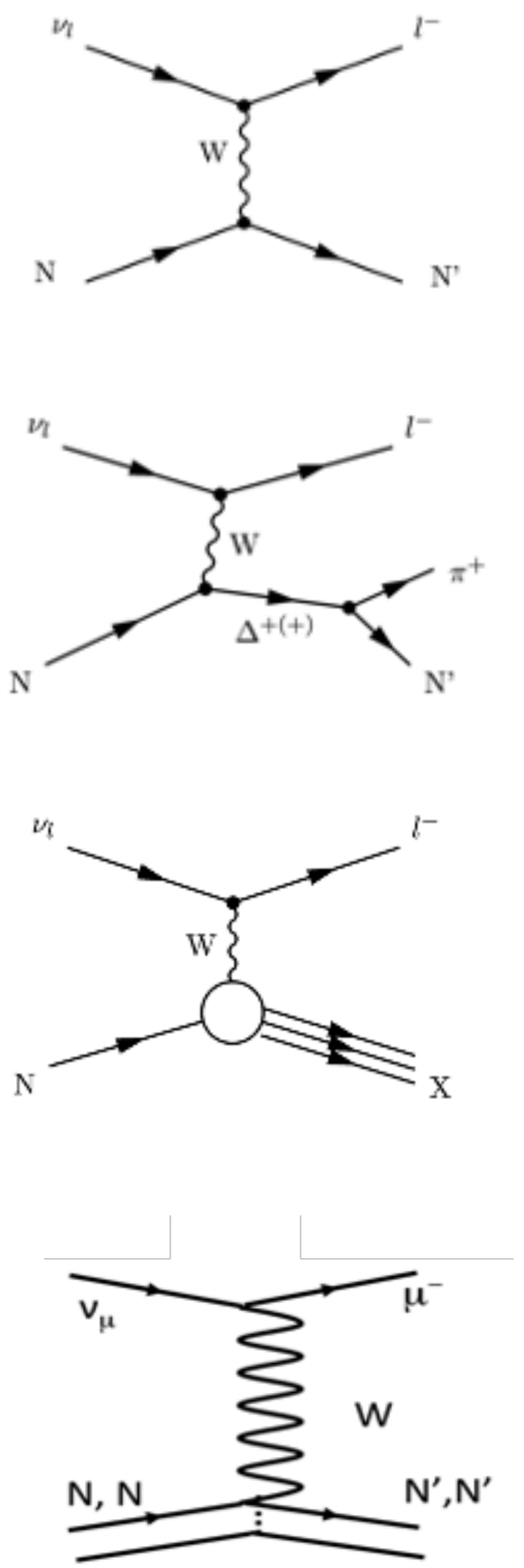

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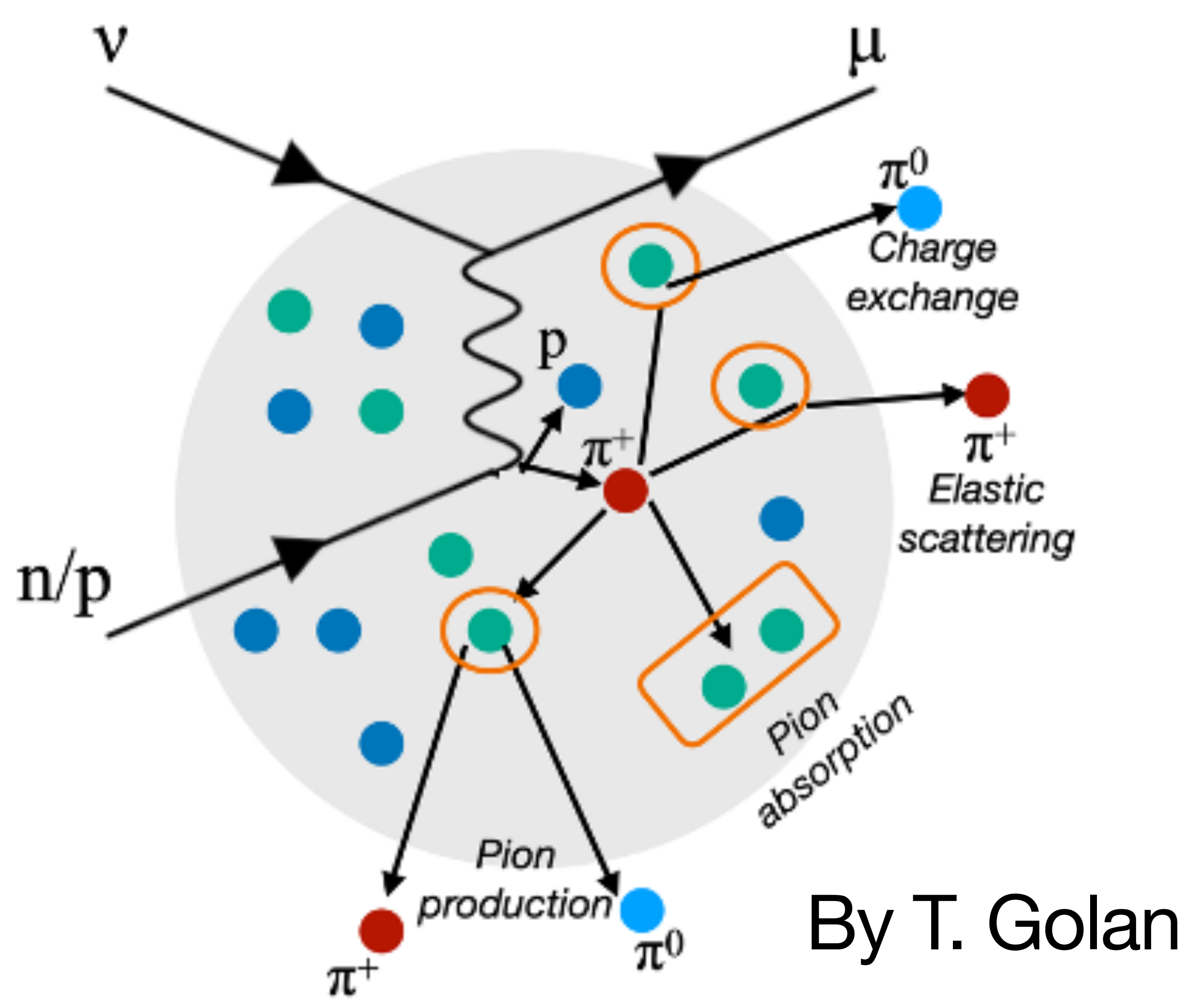
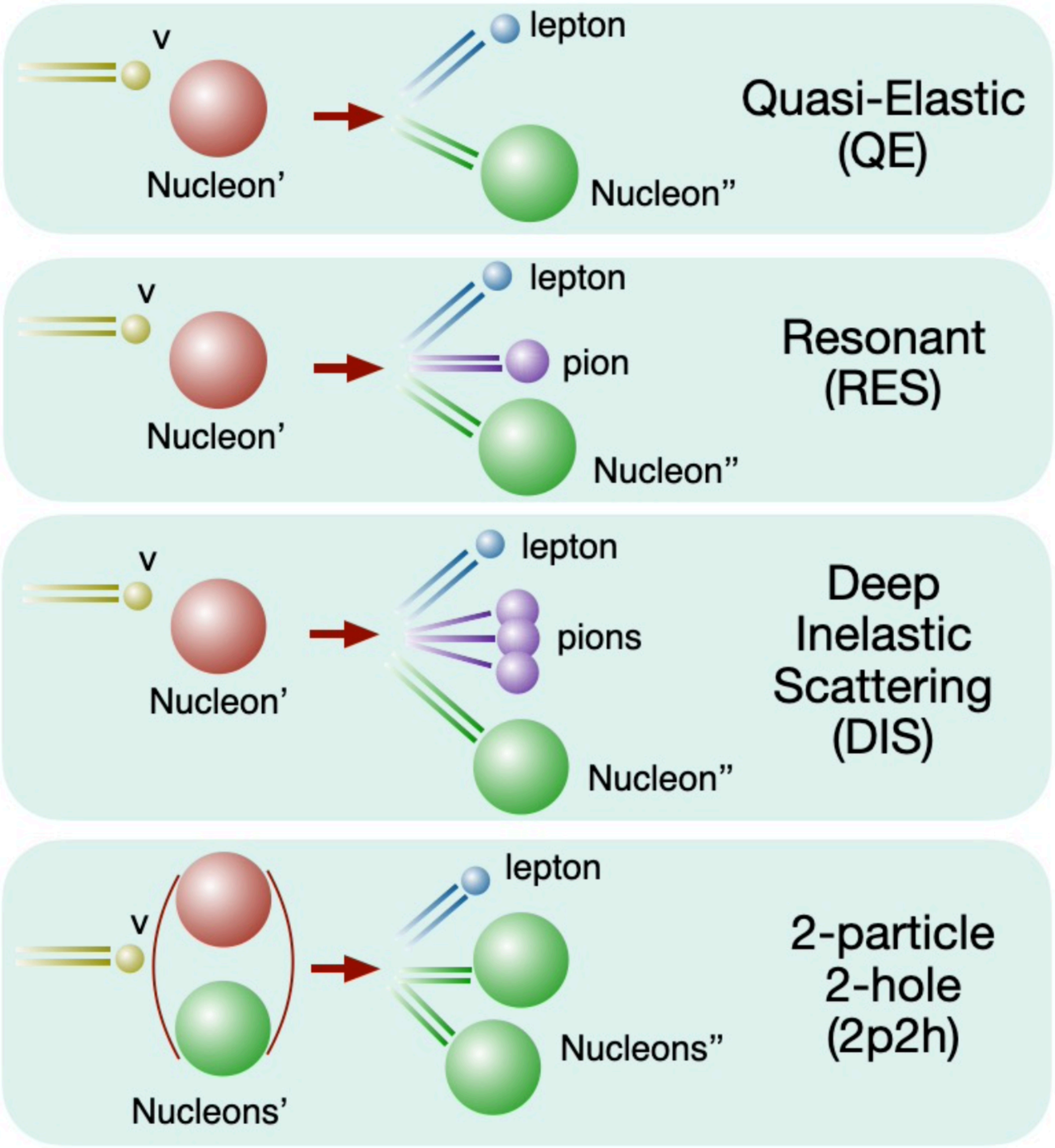


By T. Golan

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

Neutrino Interactions in NOvA ND



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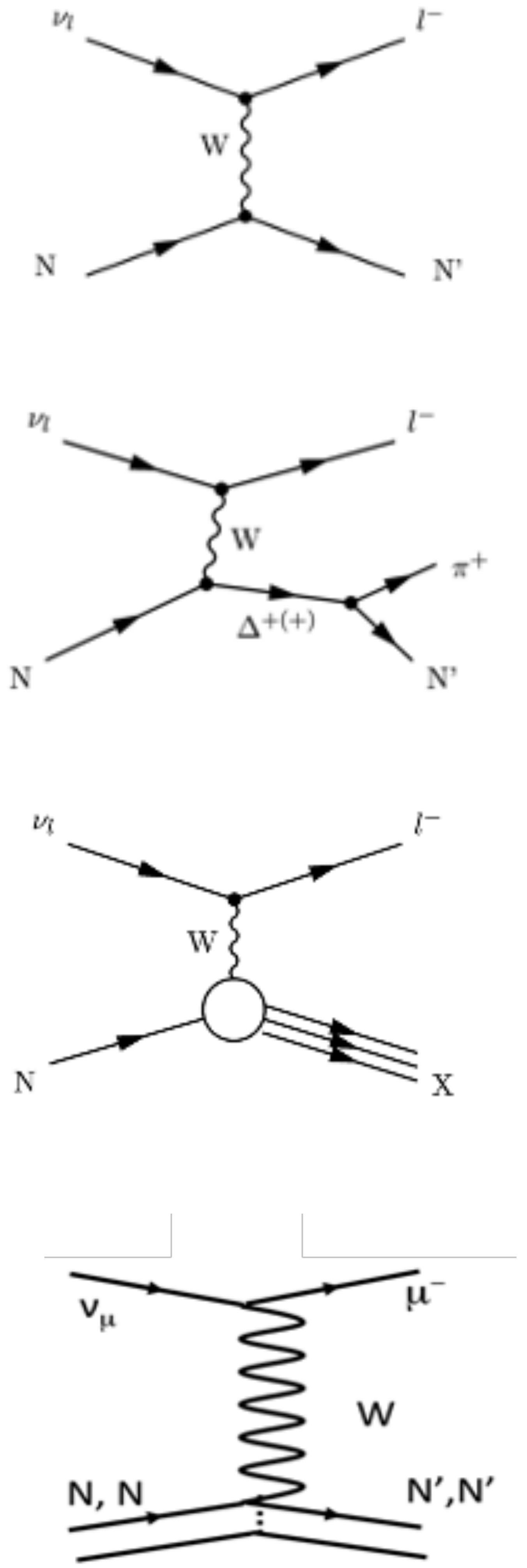
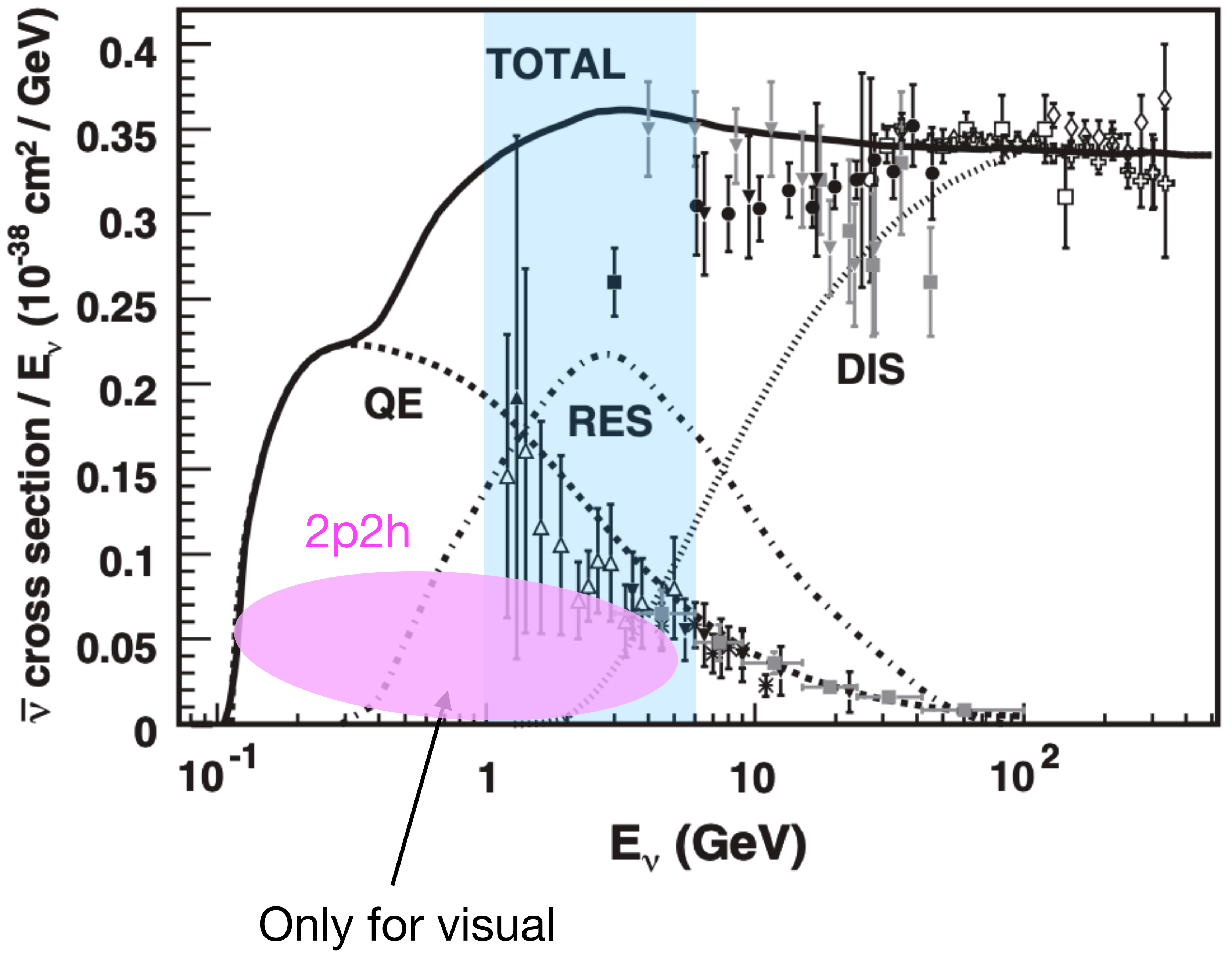


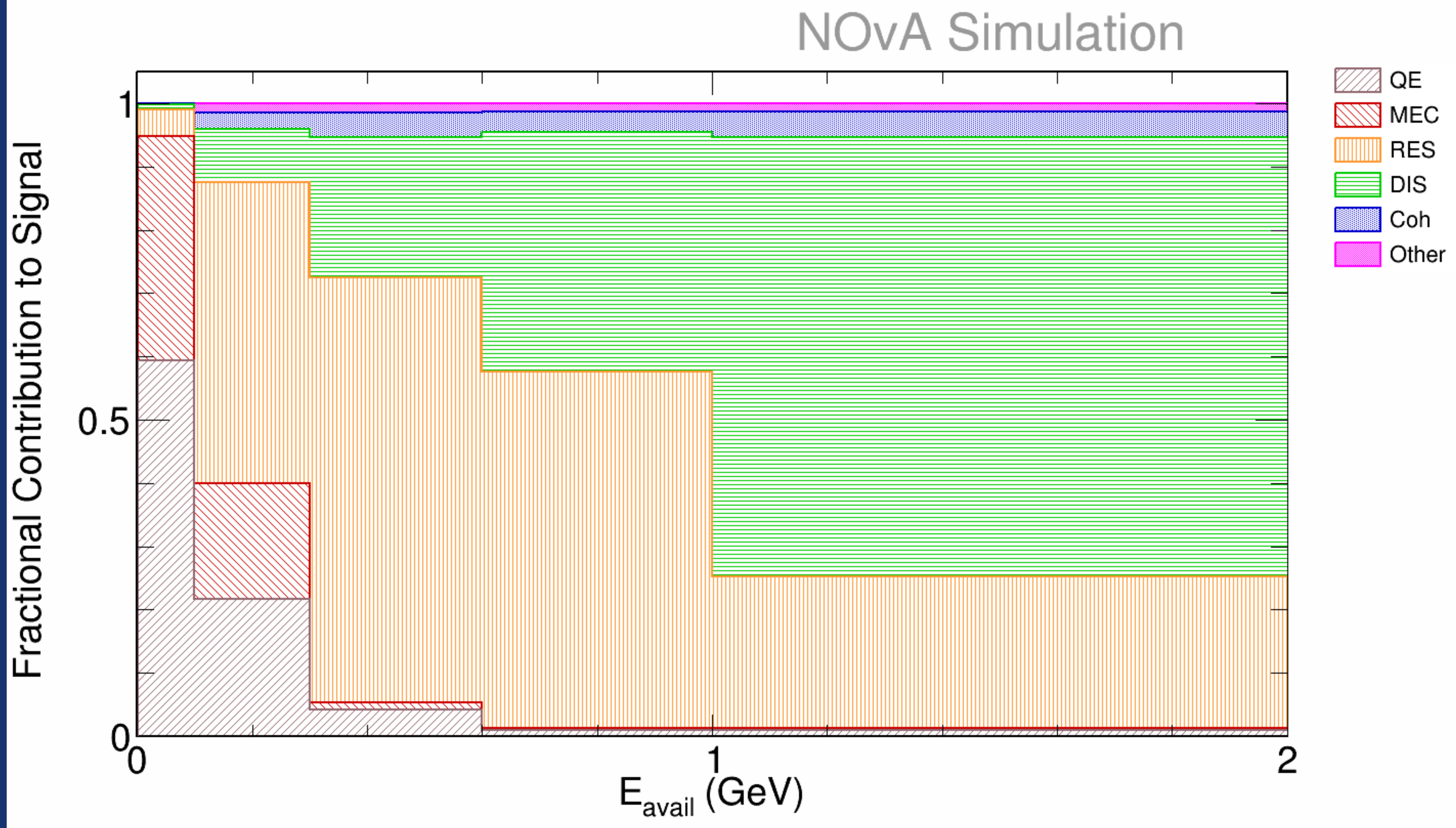
Meson exchange currents (MEC) is a dominating model to describe 2p2h process

RevModPhys.84.1307



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

Available Energy - E_{avail}



- 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 including daughter particles of the primary neutrons
- E_{avail} < 100 MeV is dominated by QE
- E_{avail} > 1GeV mostly has DIS
- 0.1 to 1 GeV are dominated by RES

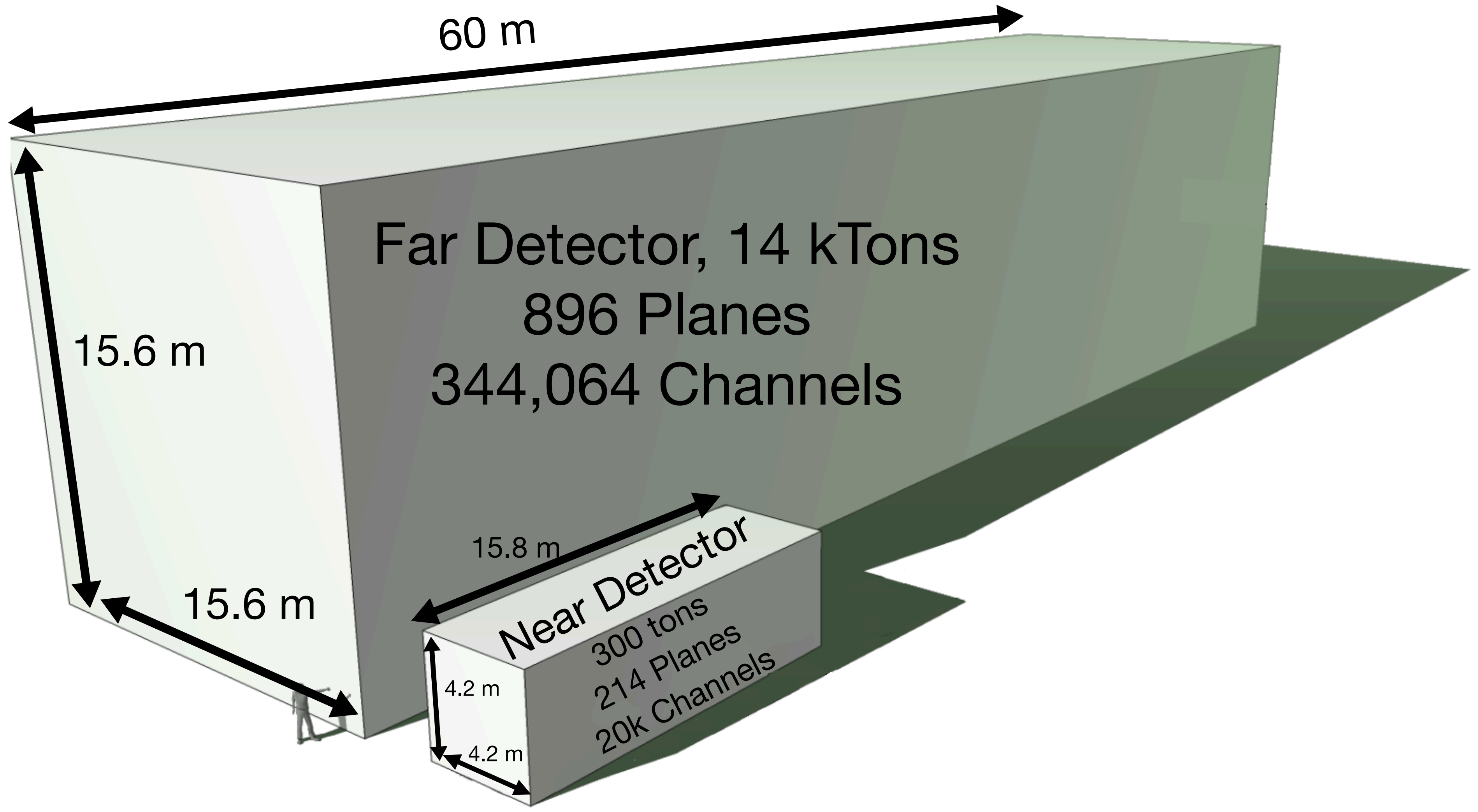
Pioneered by MINERvA (Phys. Rev. Lett. 116, 071802 (2016))

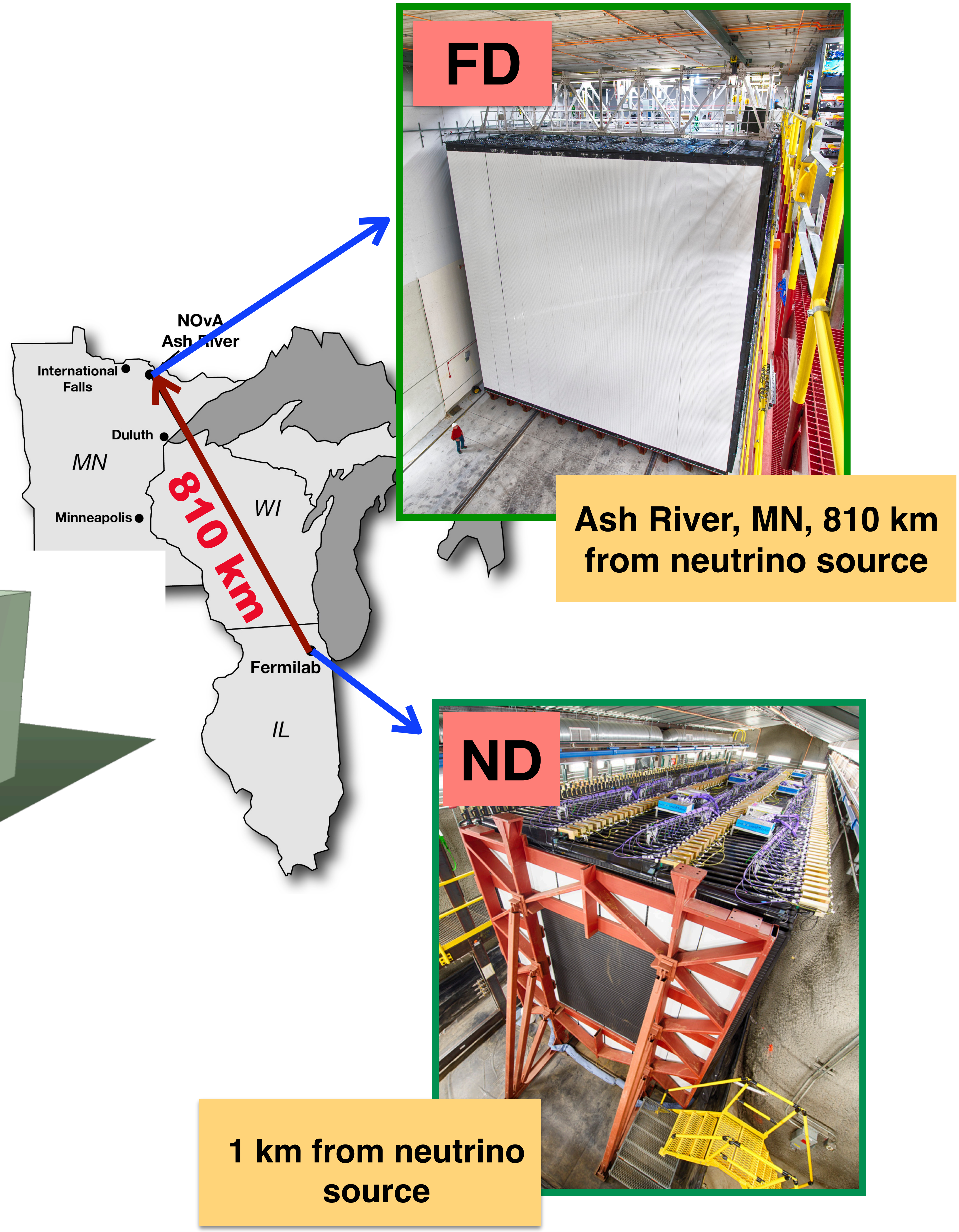
NOvA Experiment

- 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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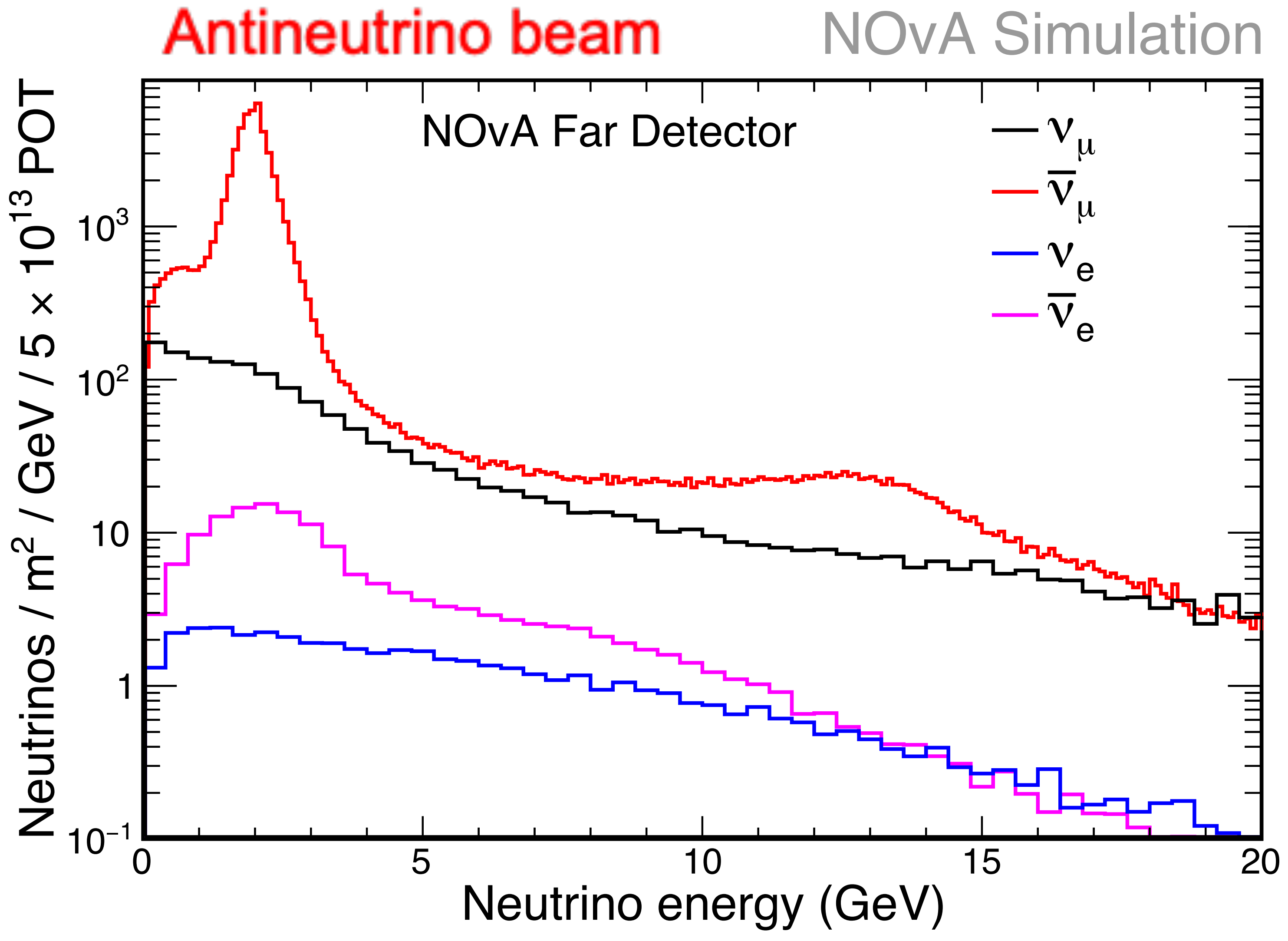
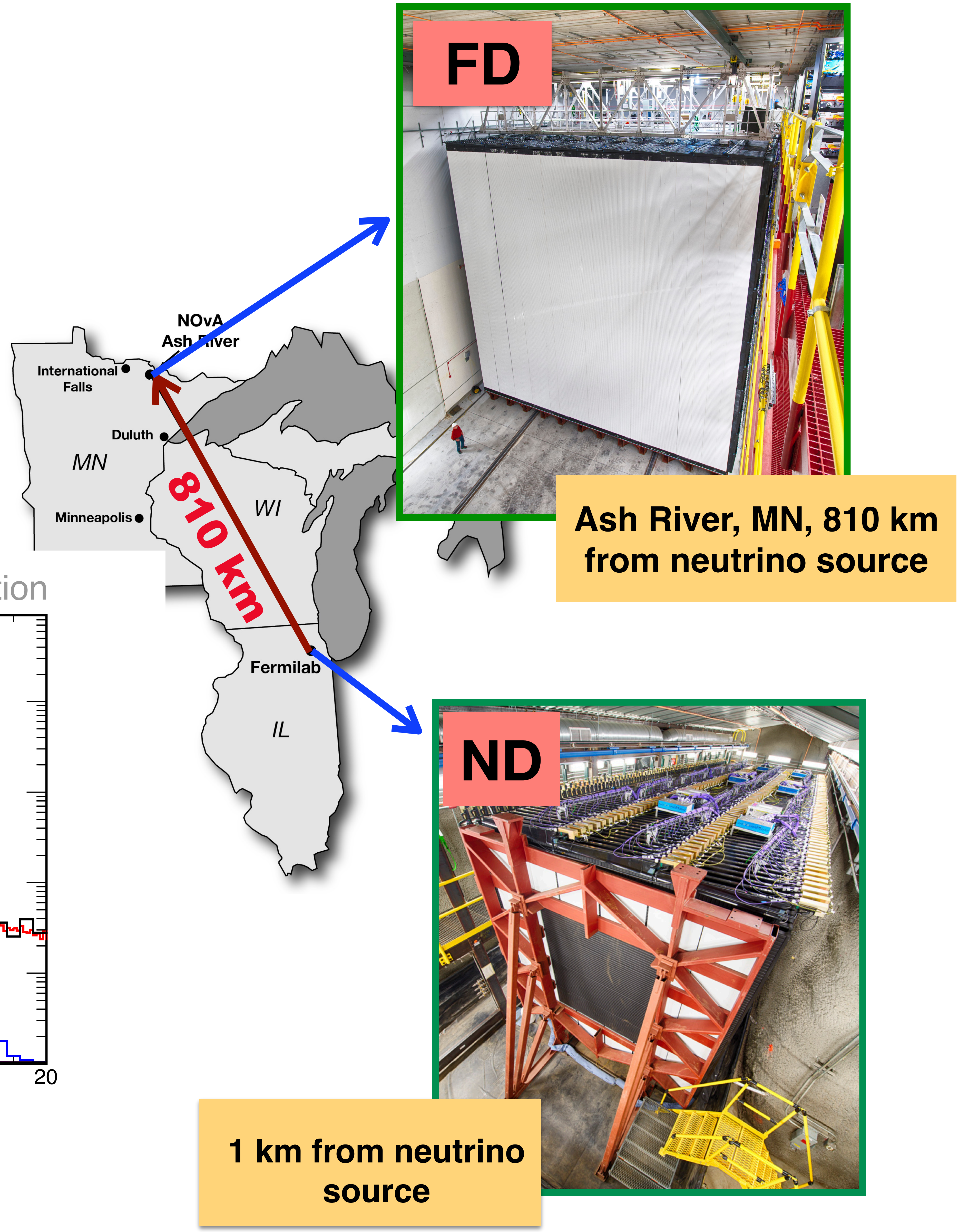
- Both detectors are filled with liquid scintillator and composed of 67% C, 16% chlorine, 11% H, 3% O, 3% Ti by mass
- Functionally identical detectors to reduce systematic uncertainties
- 14.6 mrad off-axis detectors
- Neutrino beam peaks around 2 GeV



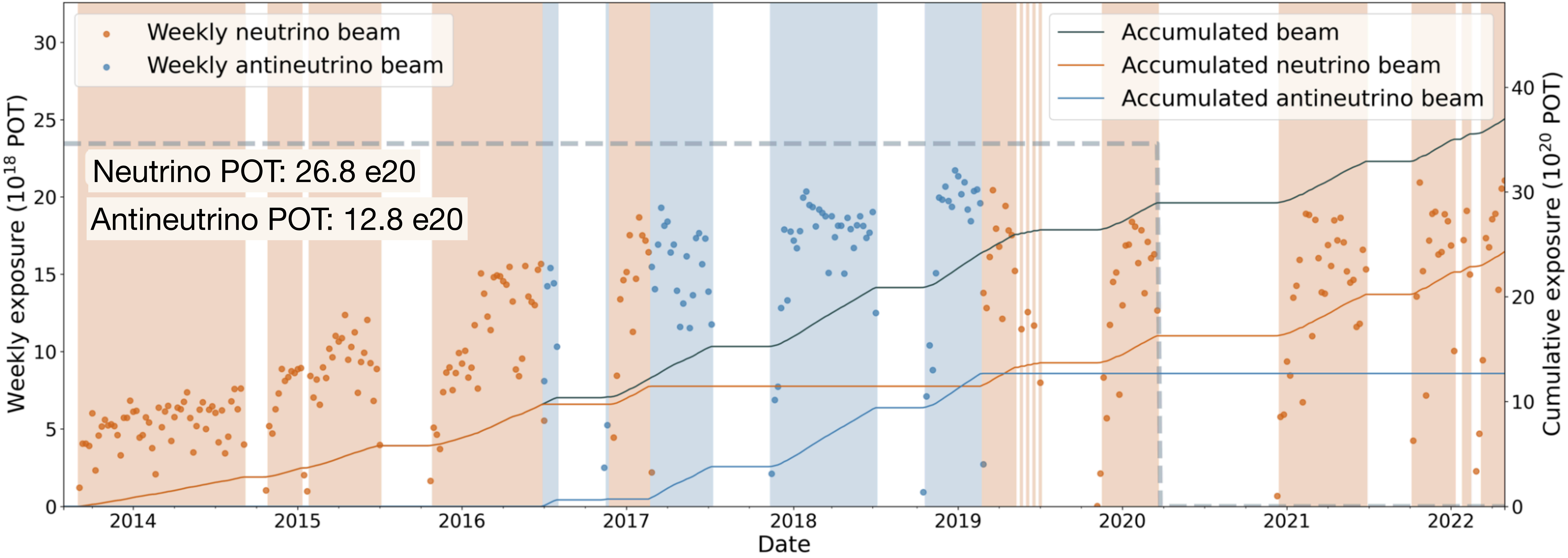
High purity $\bar{\nu}_\mu$ beam



Beam Exposure

Current Analysis Dataset

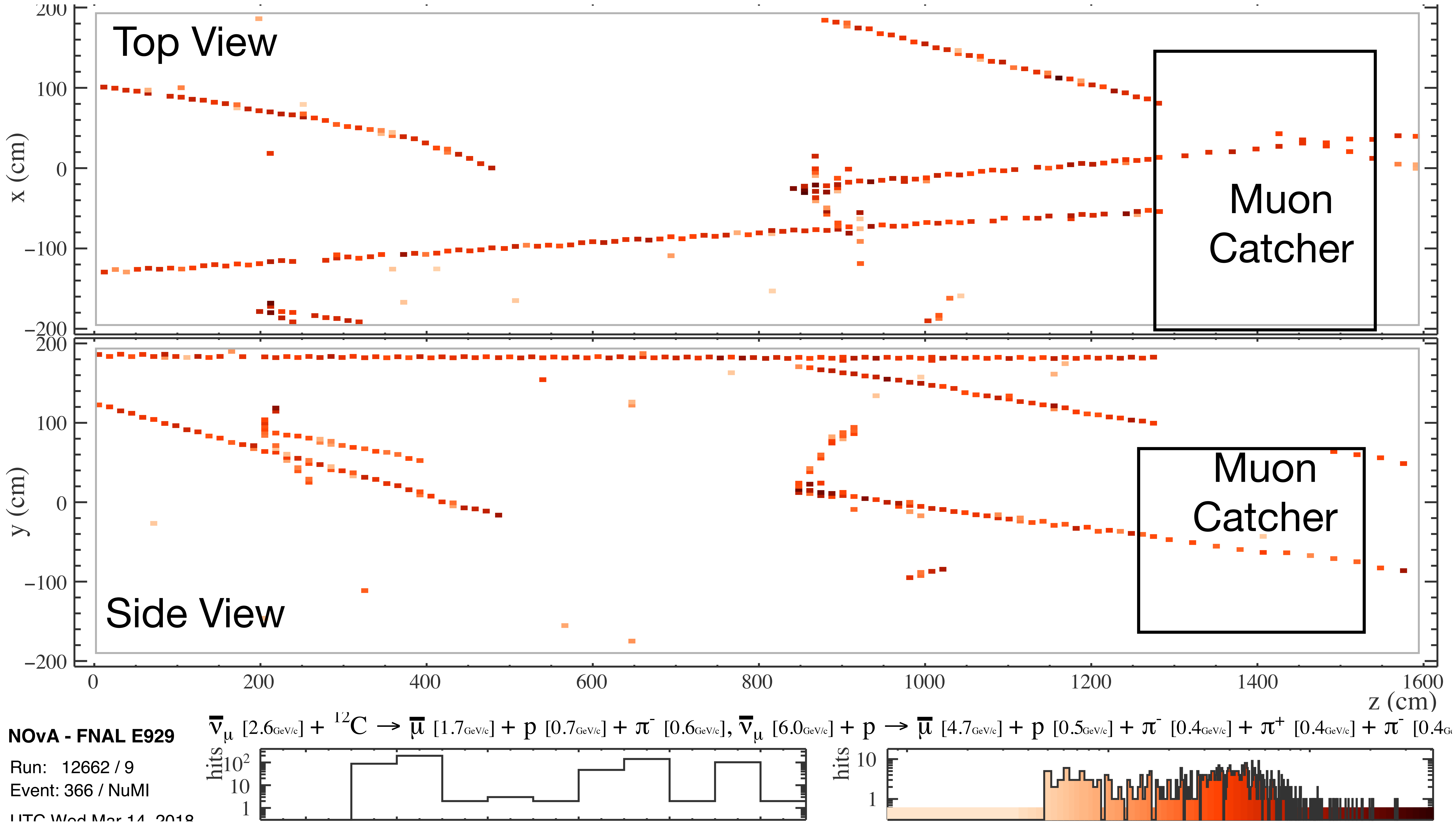
Antineutrino POT 12.5×10^{20} in ND



- 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

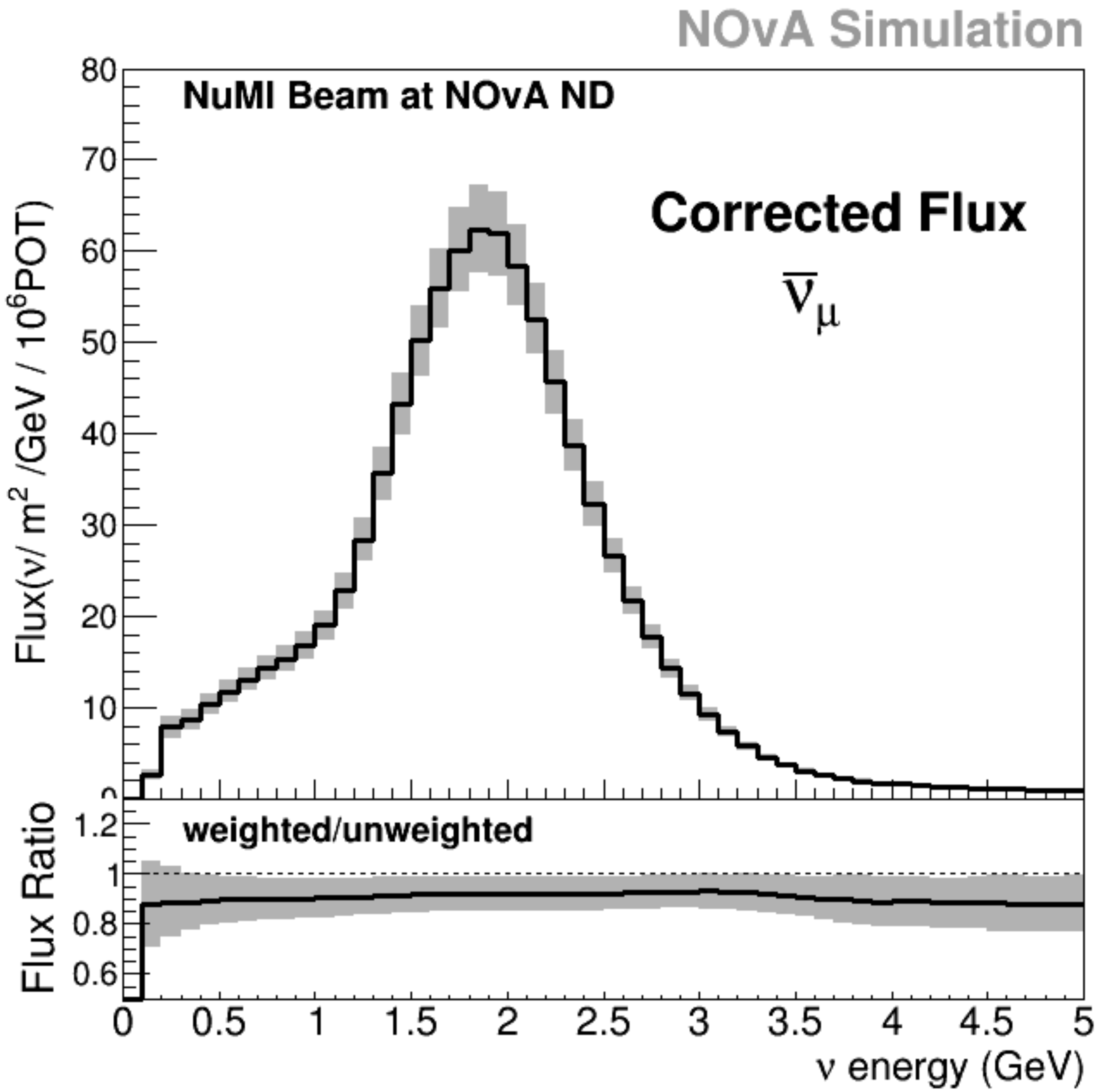
Initial State Interactions	QE	MEC	Res/Coh	DIS	FSI
Local Fermi Gas (LFG)	Valencia + Z-expansion	Valencia	Berger-Sehgal (BS)	Bodek-Yang + Pythia	hN semi-classical intranuclear cascade mode

- 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

- 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: To describe scattering at low momentum transfers by modeling deep inelastic cross sections in the few GeV regions
- hN (FSI): Calculate cross section for many possible interactions inside nucleons

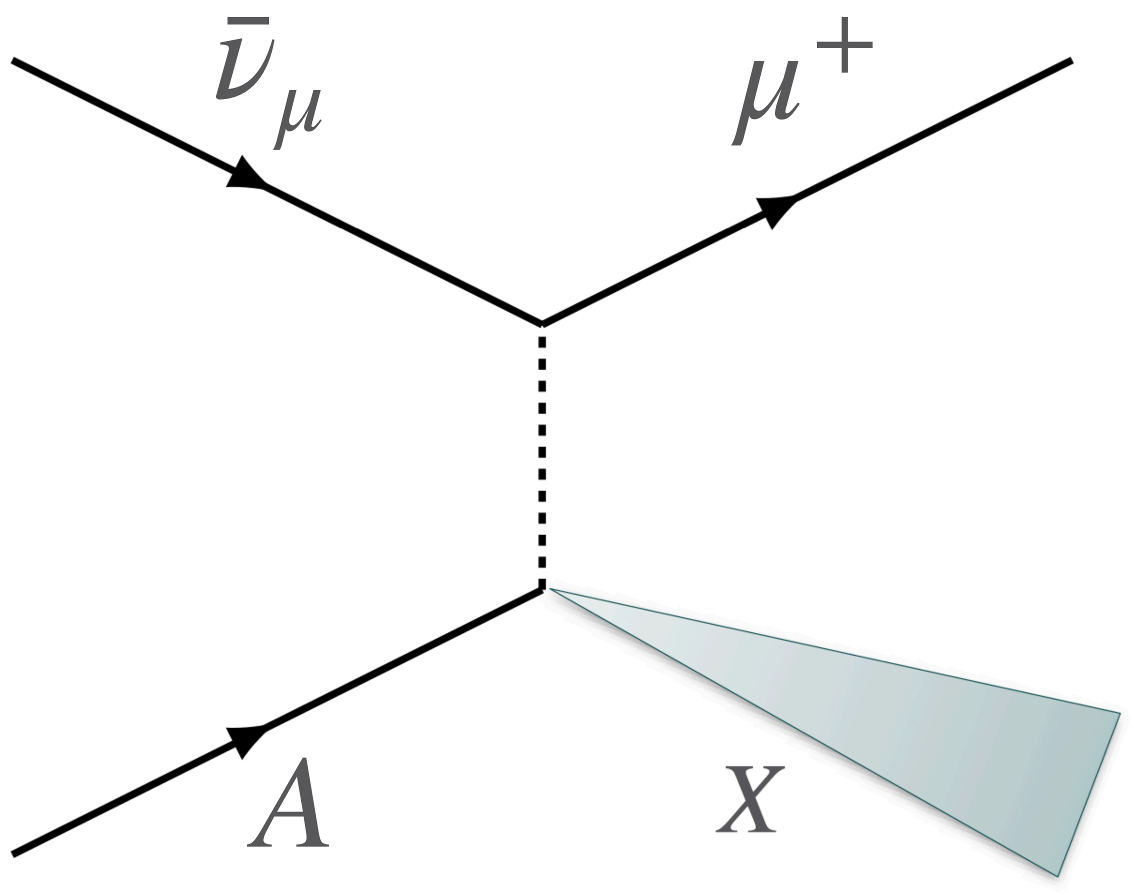
Beam Flux

- 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)
  - 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



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
- Benefit of inclusive analysis:
  - High statistics
  - Unaffected by the final state interactions inside nucleons



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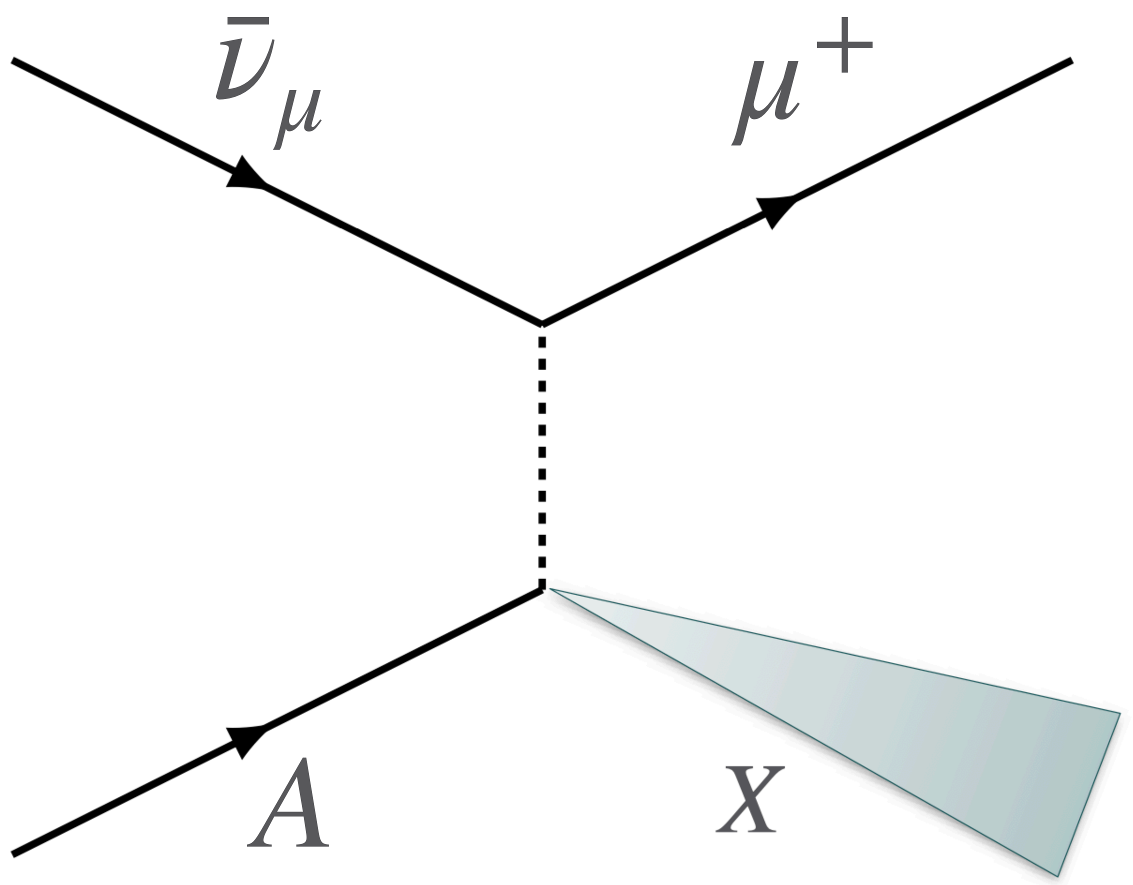
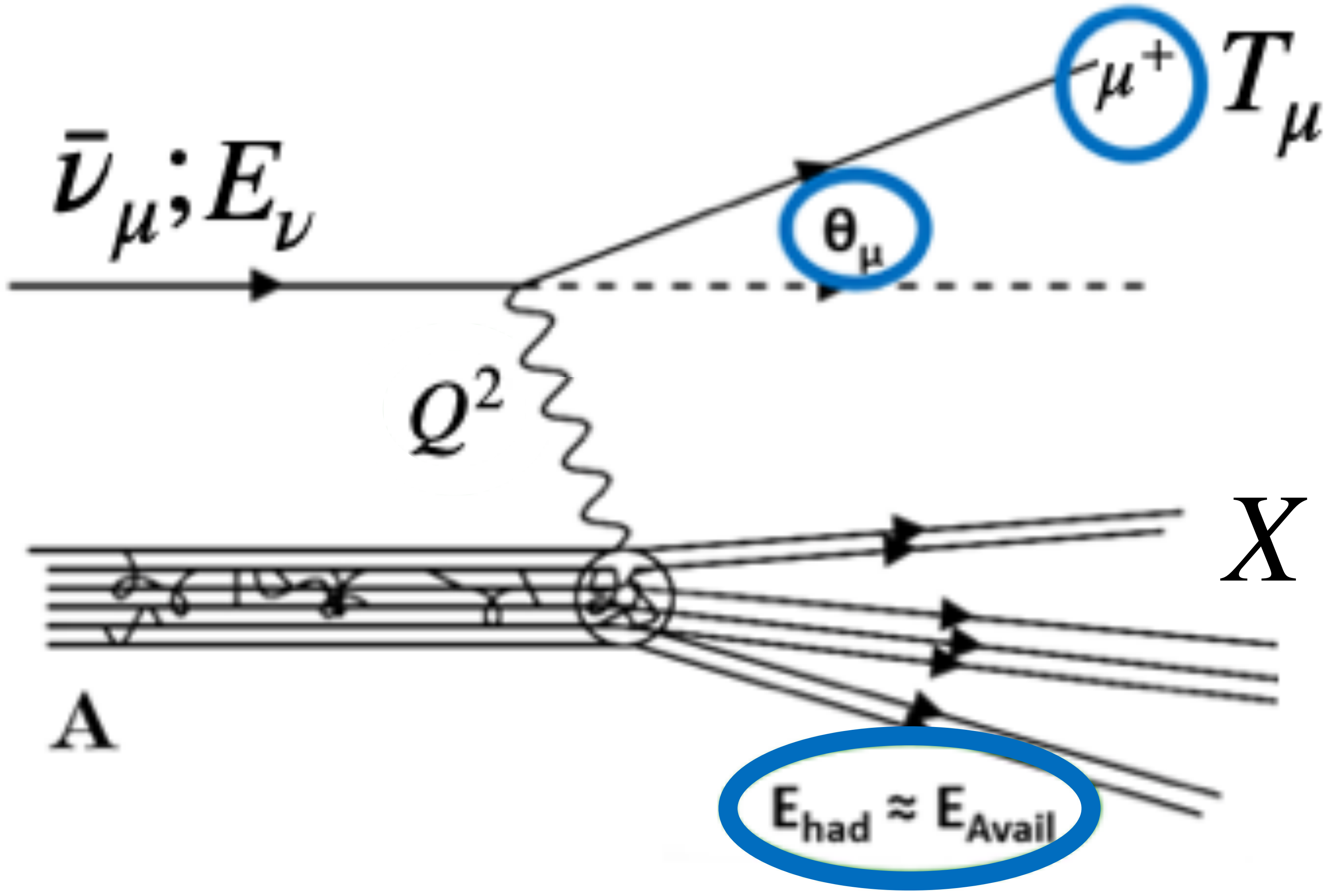
- Deliverables are

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





By Travis Olson

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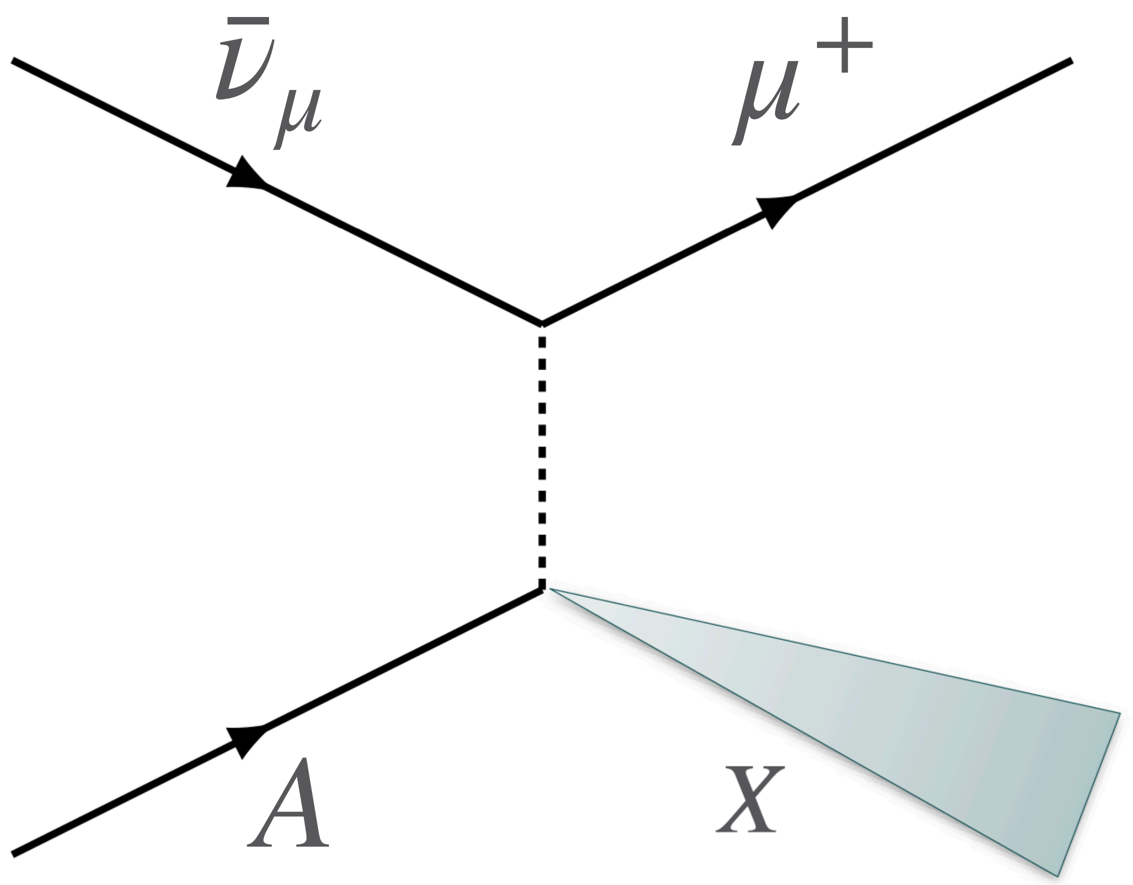
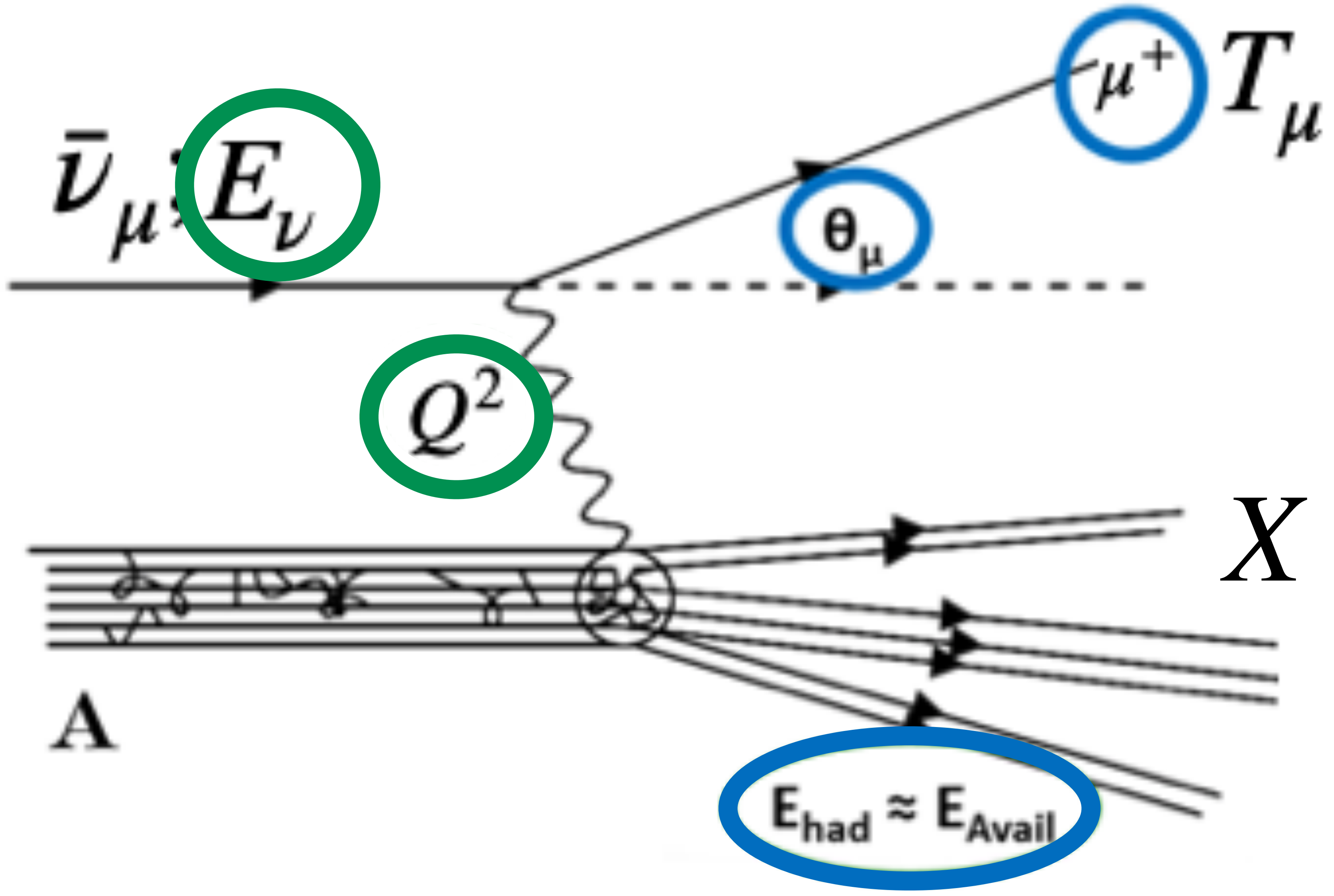
- Process is $\bar{\nu}_\mu + A \rightarrow \mu^+ + X$, A is the target nucleus and X represents all other final state particles

- Benefits of inclusive analysis:
  - High statistics
  - Unaffected by the final state interactions inside nucleons

- 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





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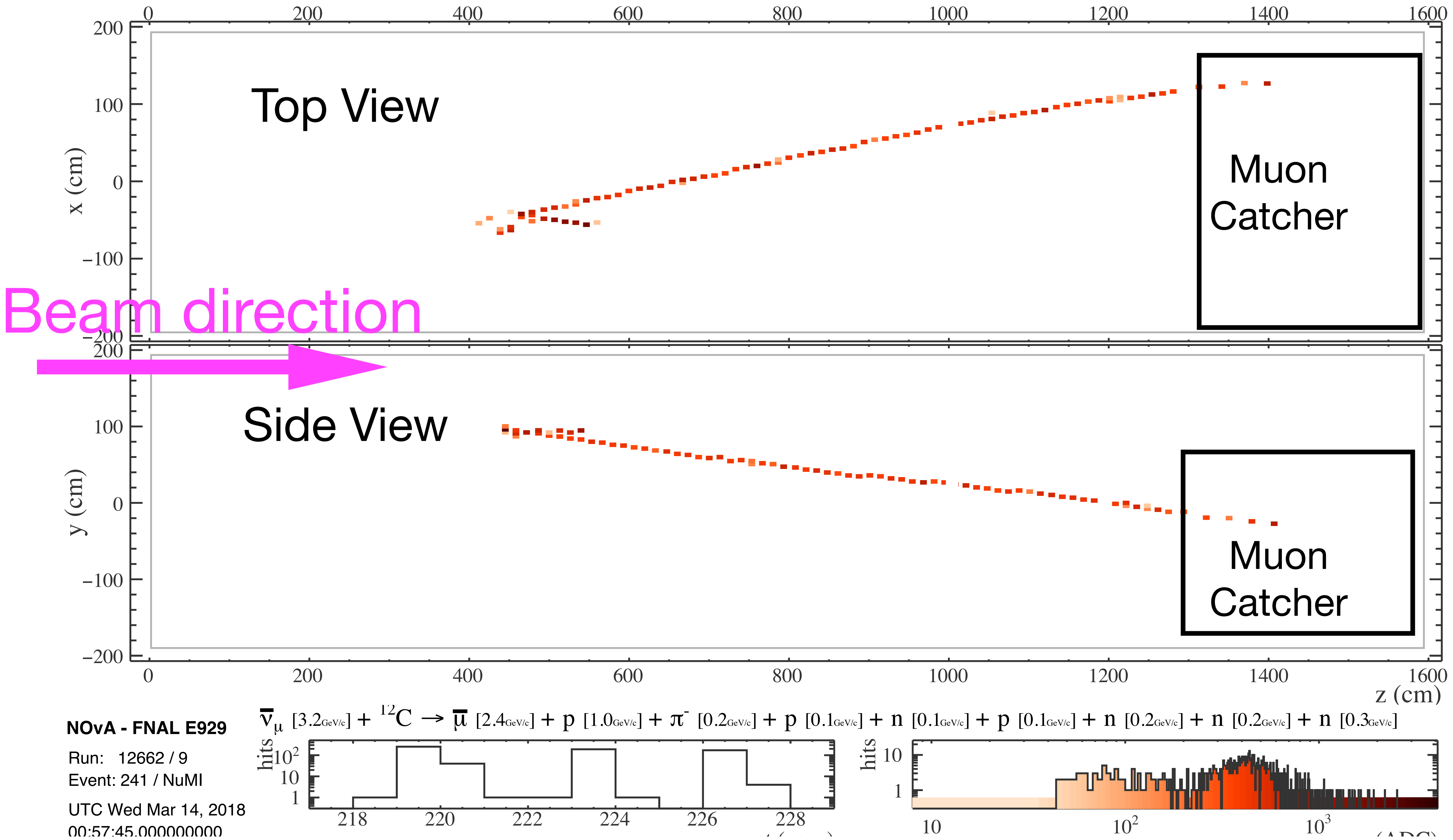
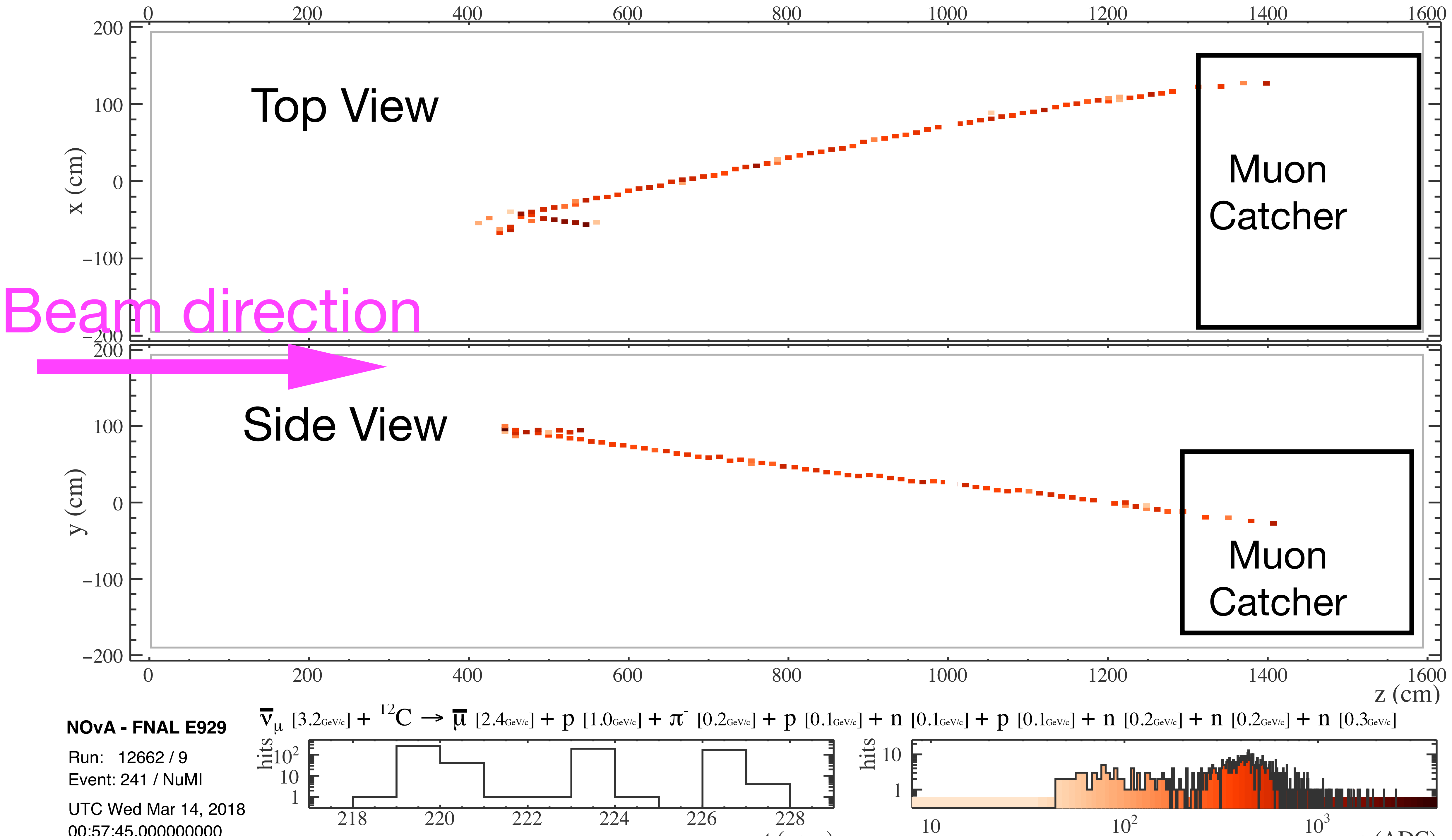
Selections



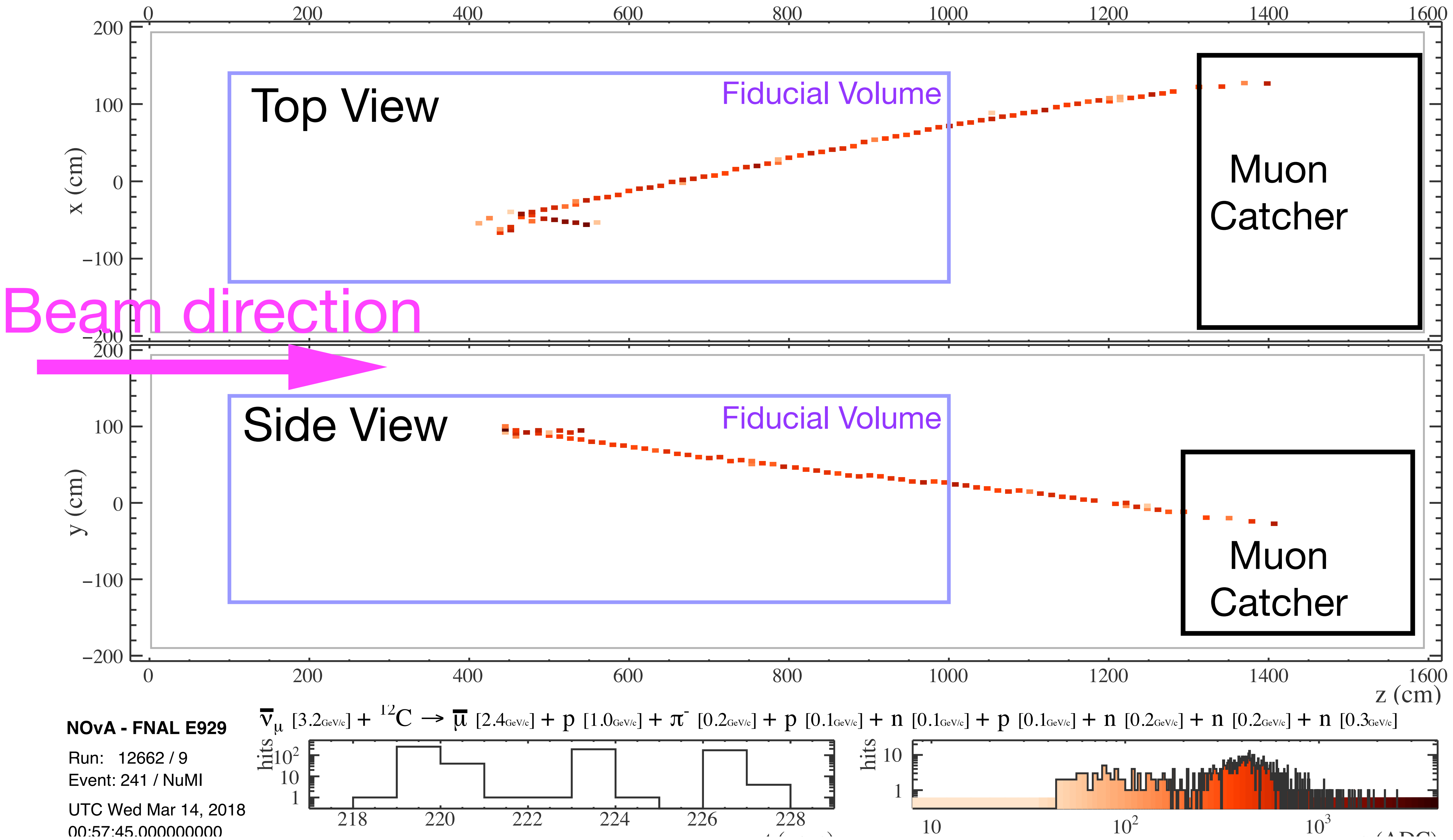
- Hits associated in time and space are used to reconstruct tracks and showers

Selections



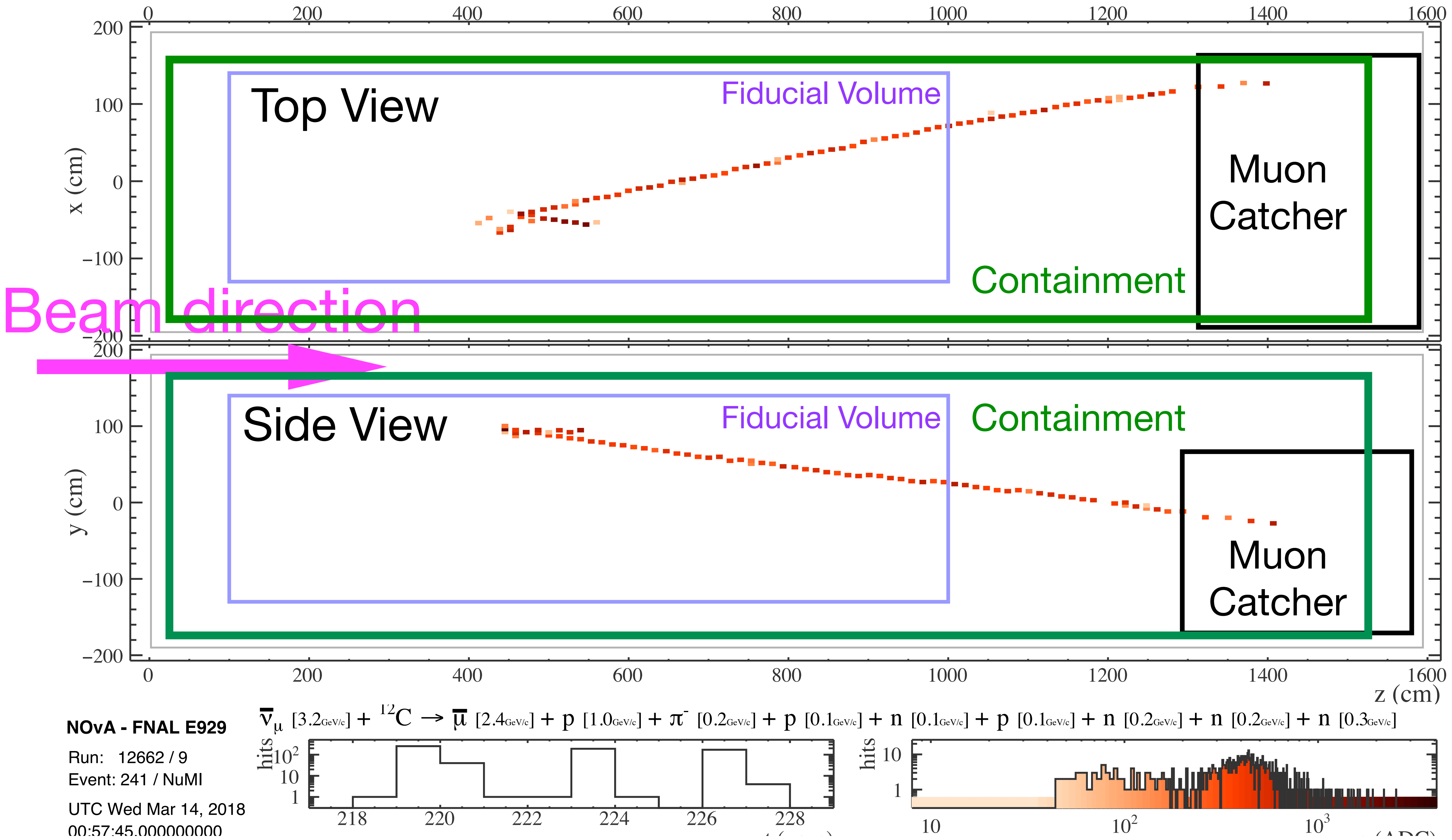
- Quality: 1+ tracks, >20 hits, >4 contiguous planes

Selections



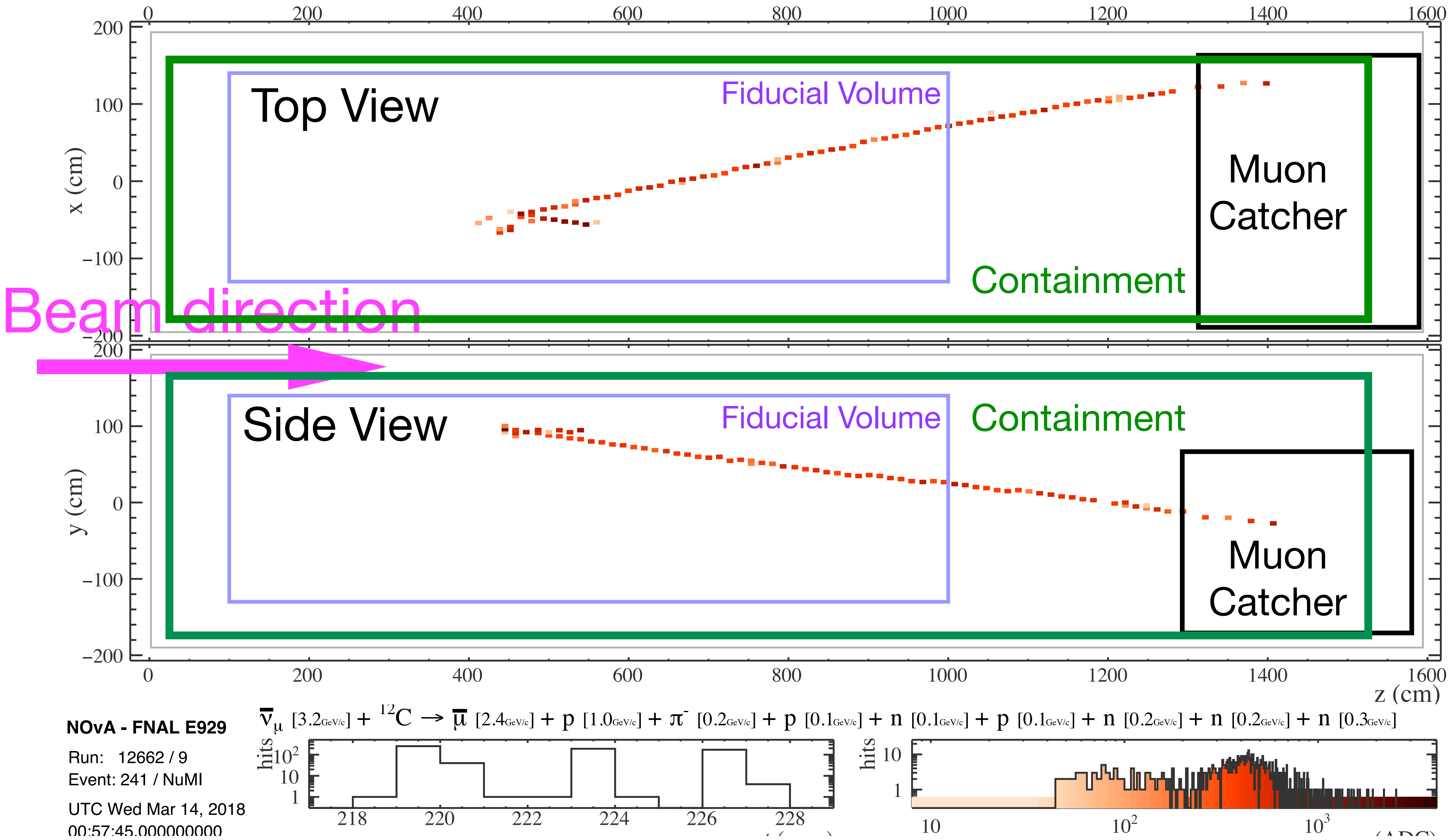
- Quality: 1+ tracks, >20 hits, >4 contiguous planes
- Interaction vertex in the fiducial volume

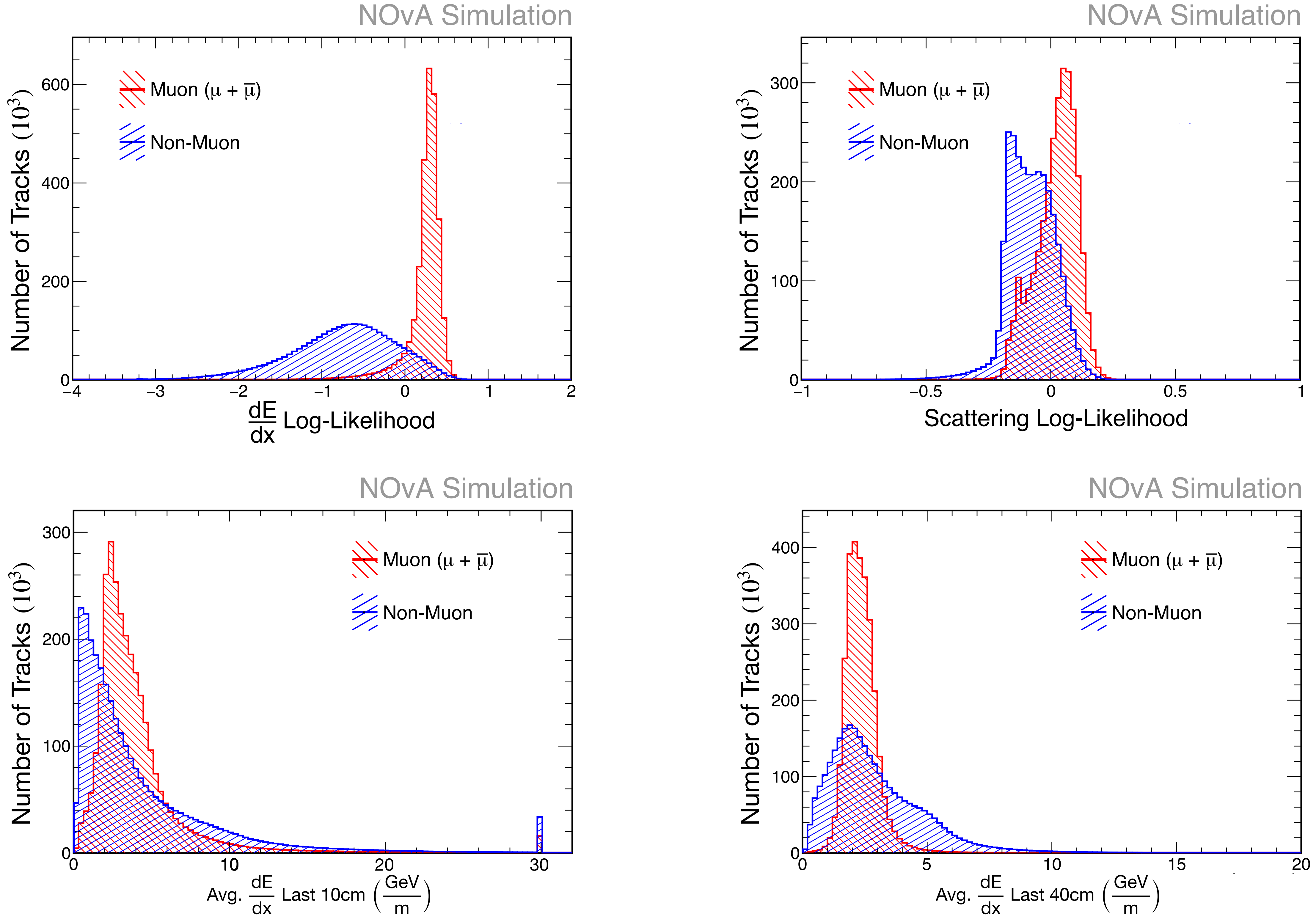
Selections



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

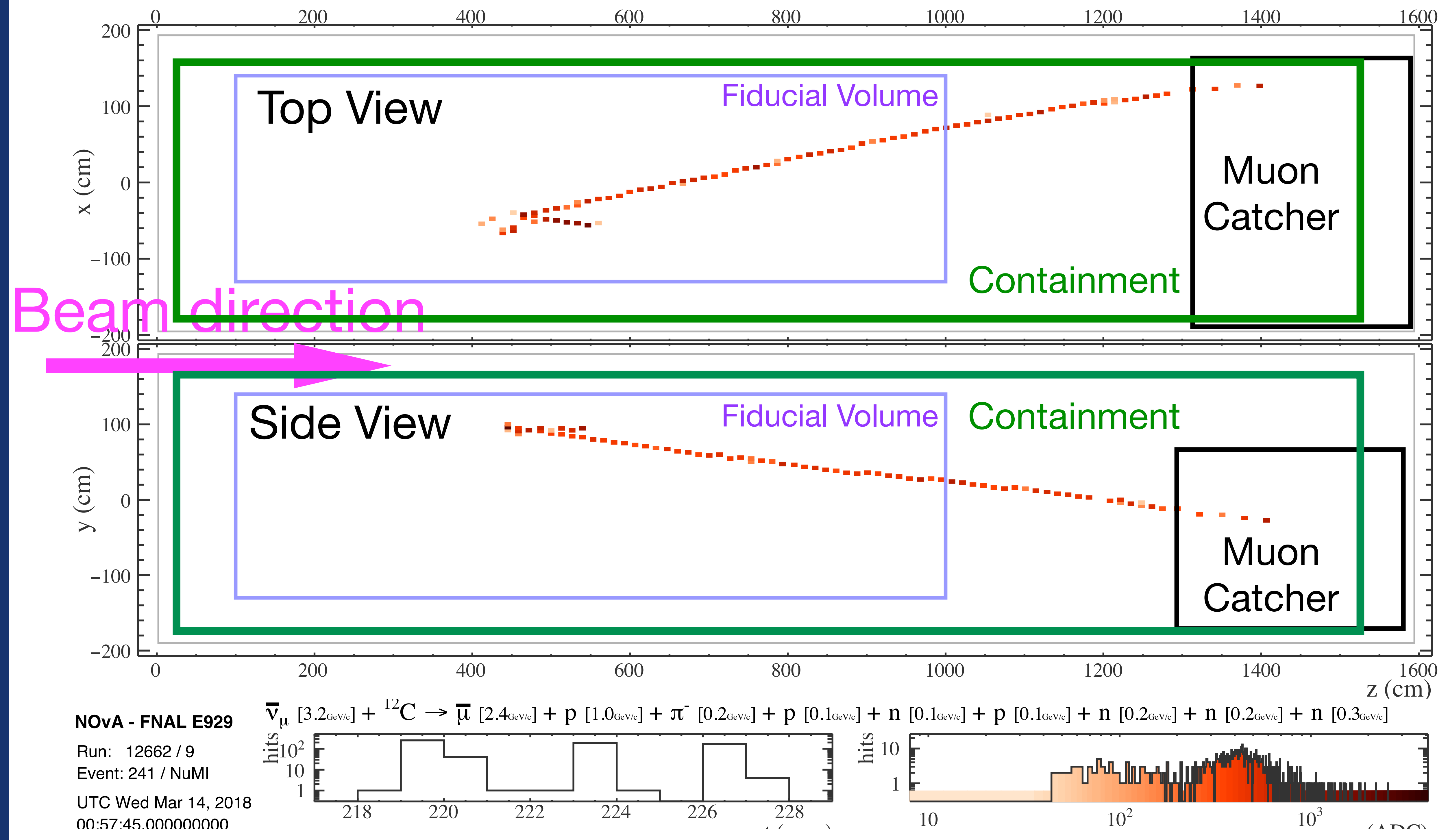
Selections

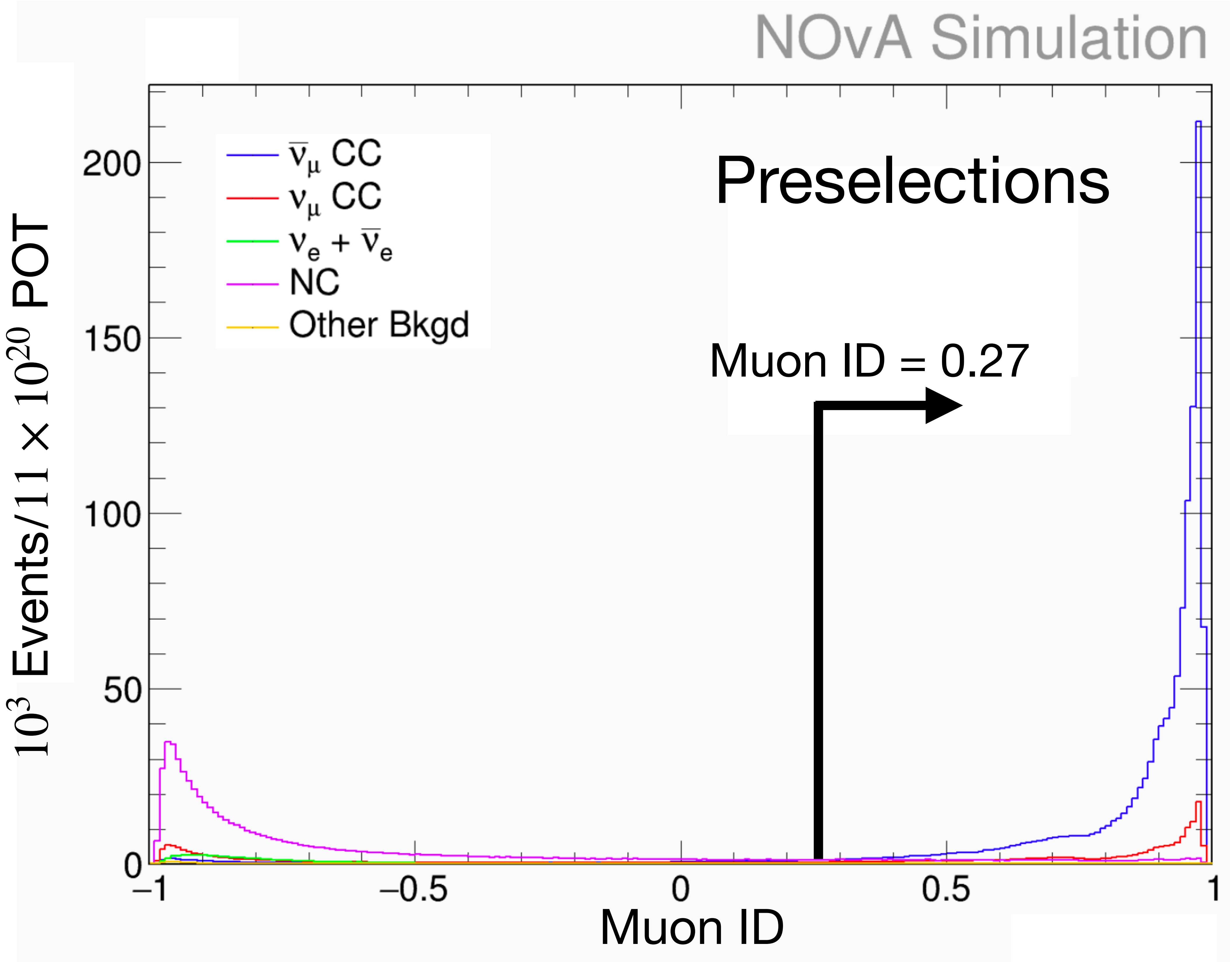




- Boosted decision tree with muon dE/dx and scattering input variables is used to select candidate muons

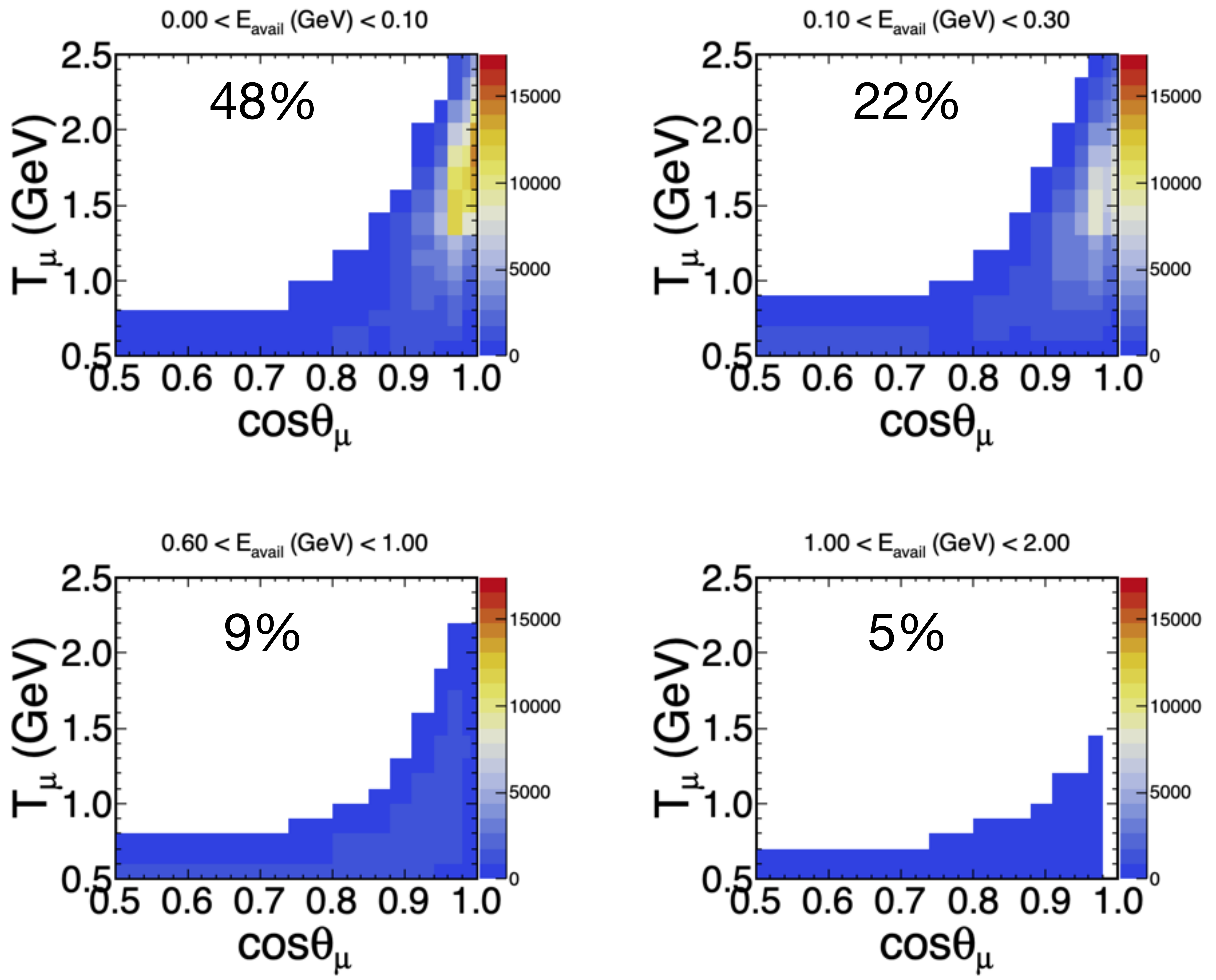
Selections





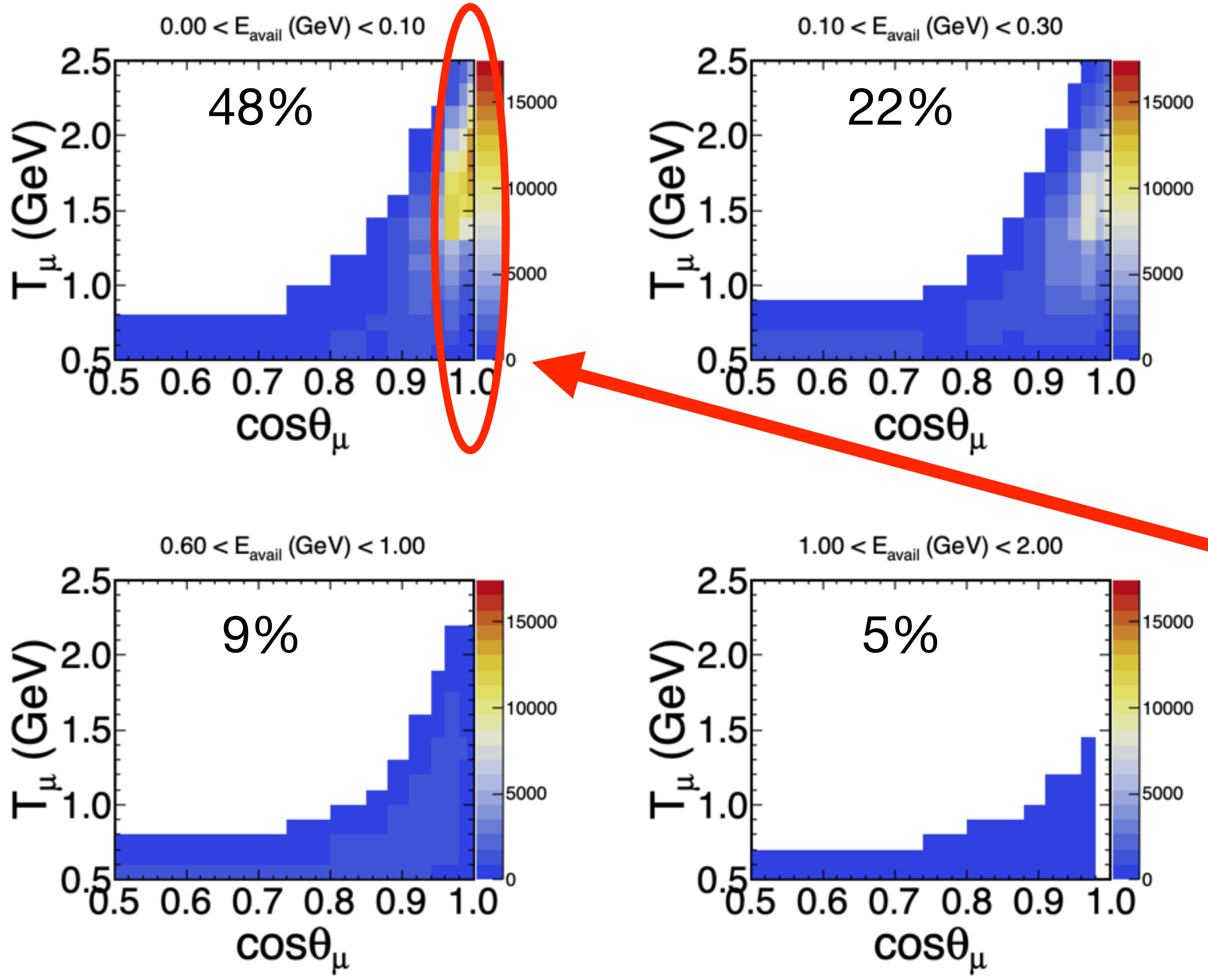
- Boosted decision tree with muon dE/dx and scattering input variables is used to select candidate muons
- BDT provides excellent separation of signal from backgrounds

Selections



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

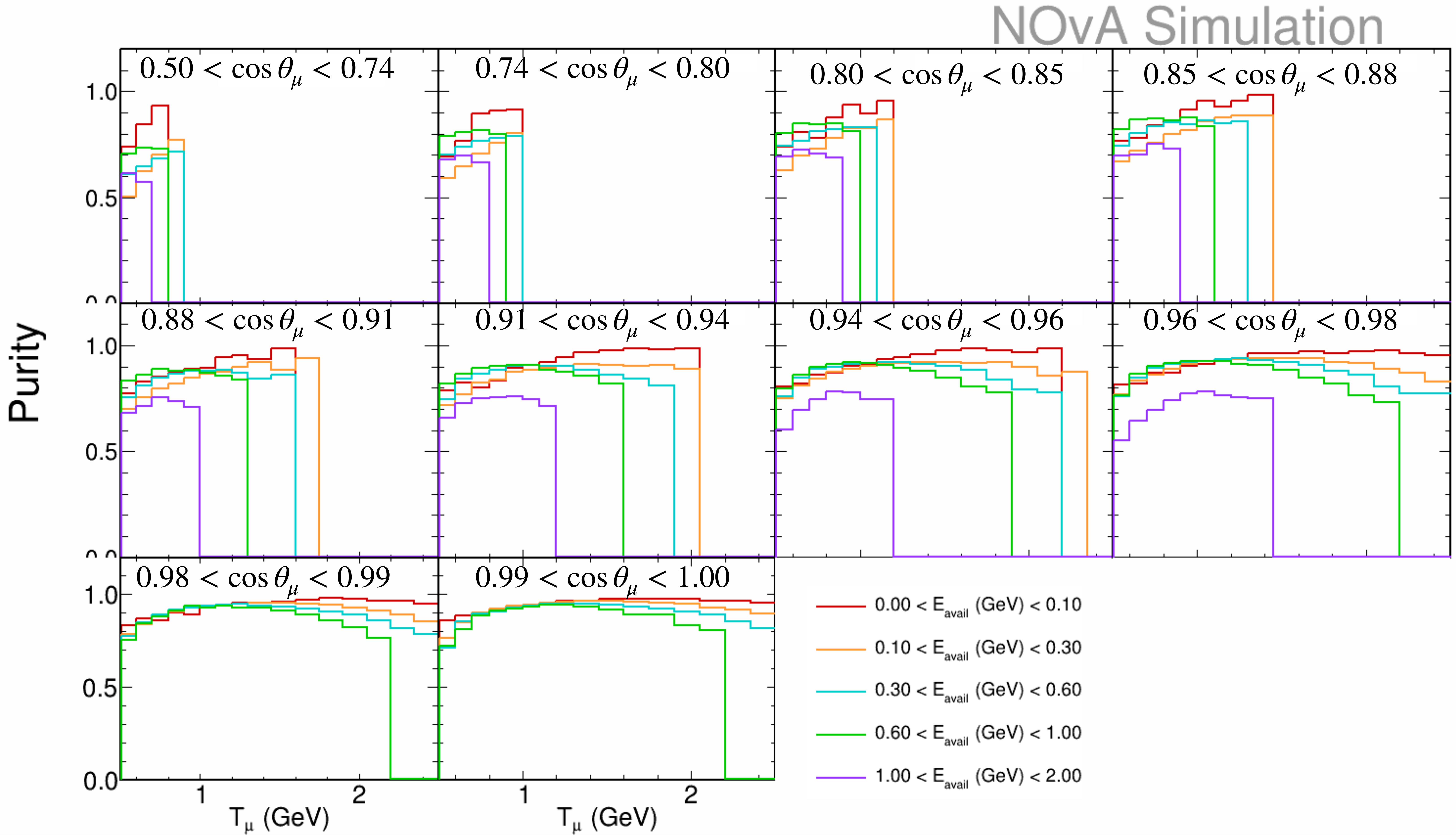
Selections



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

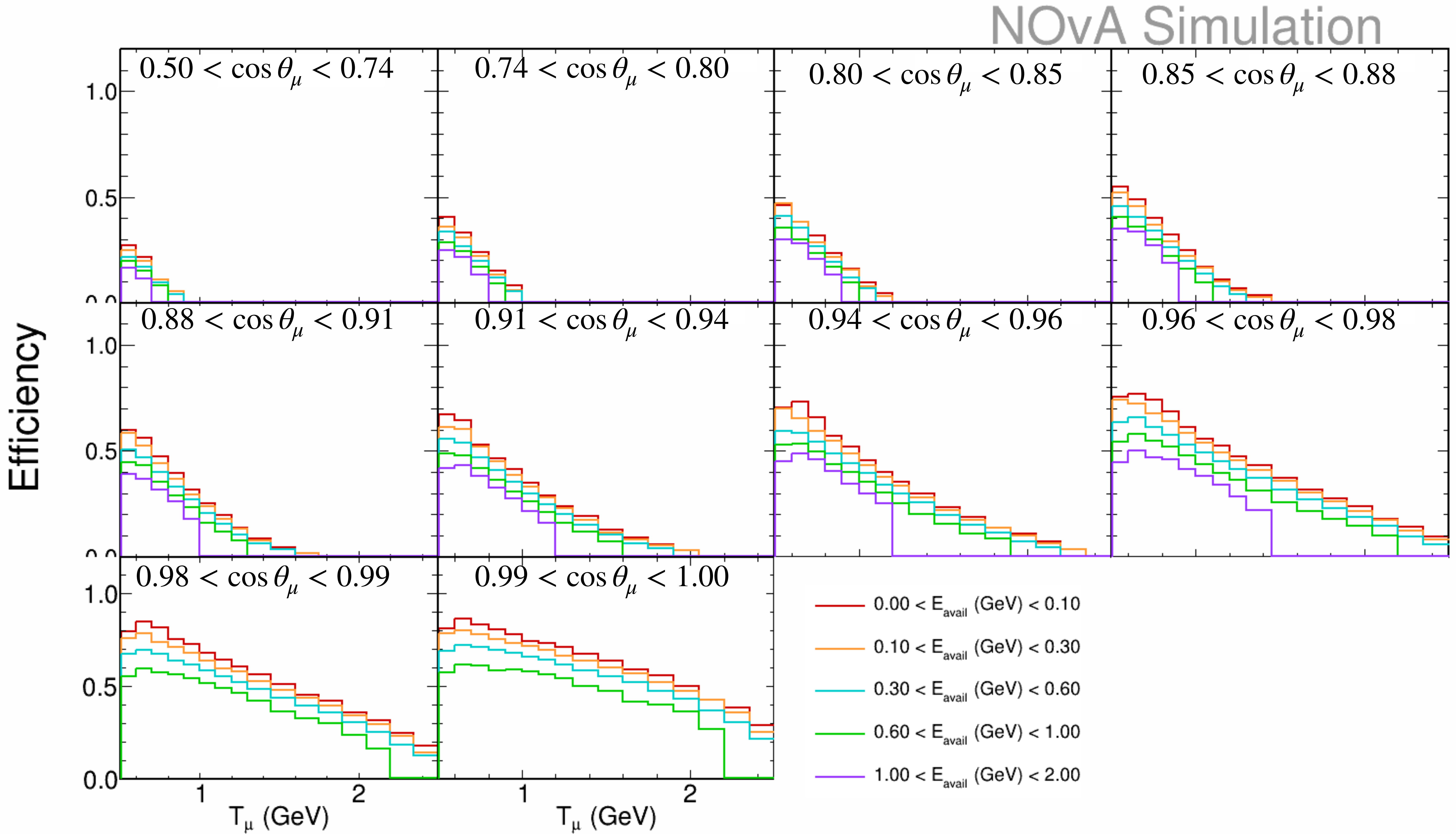


Selection Efficiency

- 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



Measurement Strategy

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

- For differential cross section measurements in T_μ, $\cos\theta_\mu$, and E_{avail}, we need
  - Selected candidate signal events

Measurement Strategy

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- For differential cross section measurements in T_μ, $\cos\theta_\mu$, and E_{avail}, we need
  - Selected candidate signal events, sample purity

Measurement Strategy

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  - 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

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  - Selection efficiencies

Cross sections

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

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  - 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

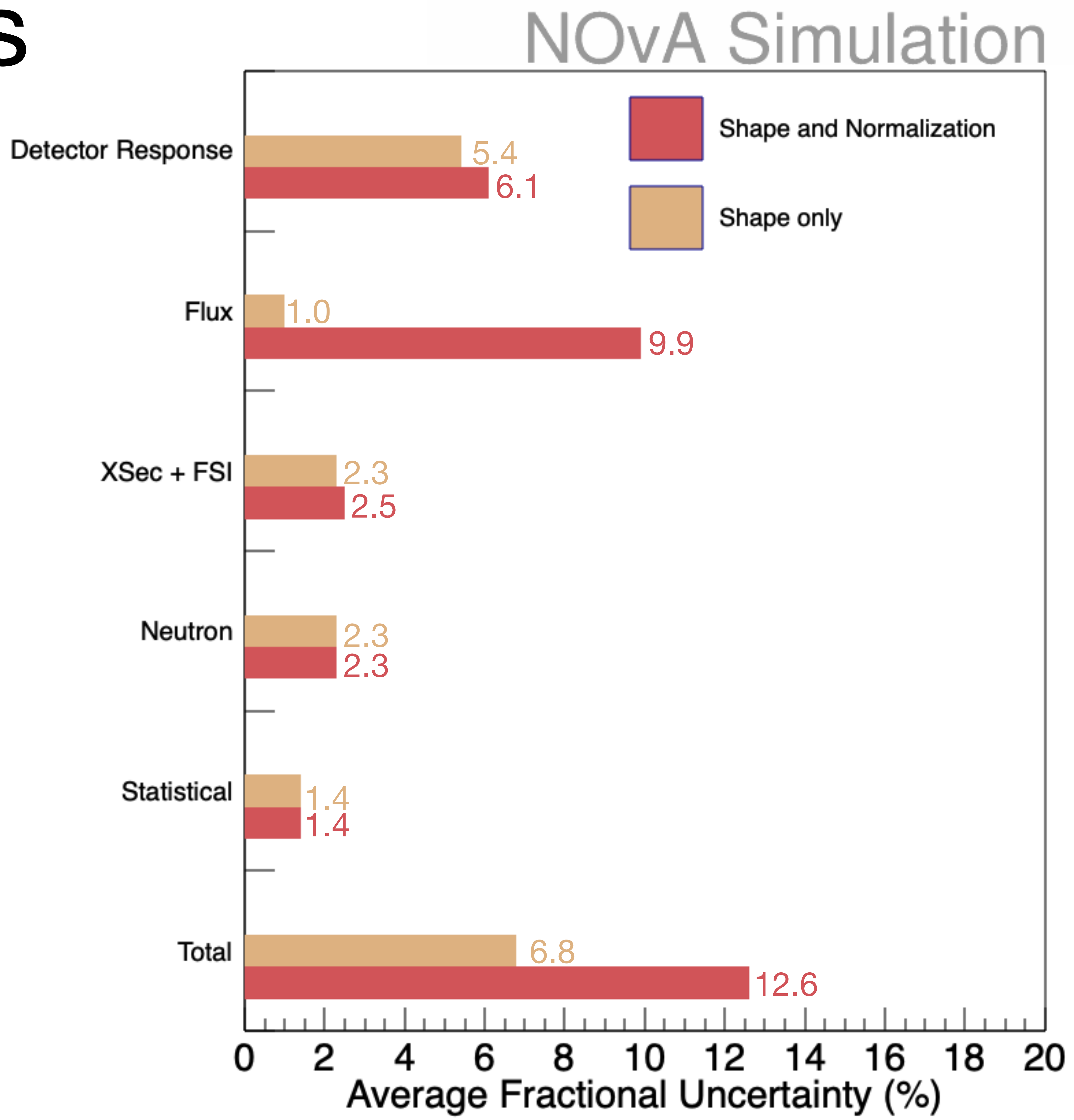
Cross sections

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

- 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 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 within 14%



Results for the Triple Differential Measurements

GENIE Comprehensive Model Configurations (CMC)

GENIE CMC	Initial State Interactions	QE	MEC	RES/Coh	DIS	FSI
GENIE 3.0.6 (Base Model) (G18_10j_00_000)	Local Fermi Gas (LFG)	Valencia + Z-expansion	Valencia	Berger-Sehgal (BS)	Bodek-Yang (BY) + Pythia	hN semi-classical intranuclear cascade mode
G18_10a_02_11a	LFG	Valencia	Valencia	BS	BY	hA2018
G18_10a_02_11b	LFG	Valencia	Valencia	BS	BY	hA2018
G21_11a_00_000	LFG	SuSAv2	SuSAv2	BS	BY	hA2018
AR23_20i_02_11b (DUNE)	Spectral function LFG	Valencia	SuSAv2	BS	BY	hA2018

Special thanks to Kevin Vockerodt, and Colin Weber for generating GENIE CMC predictions

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

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

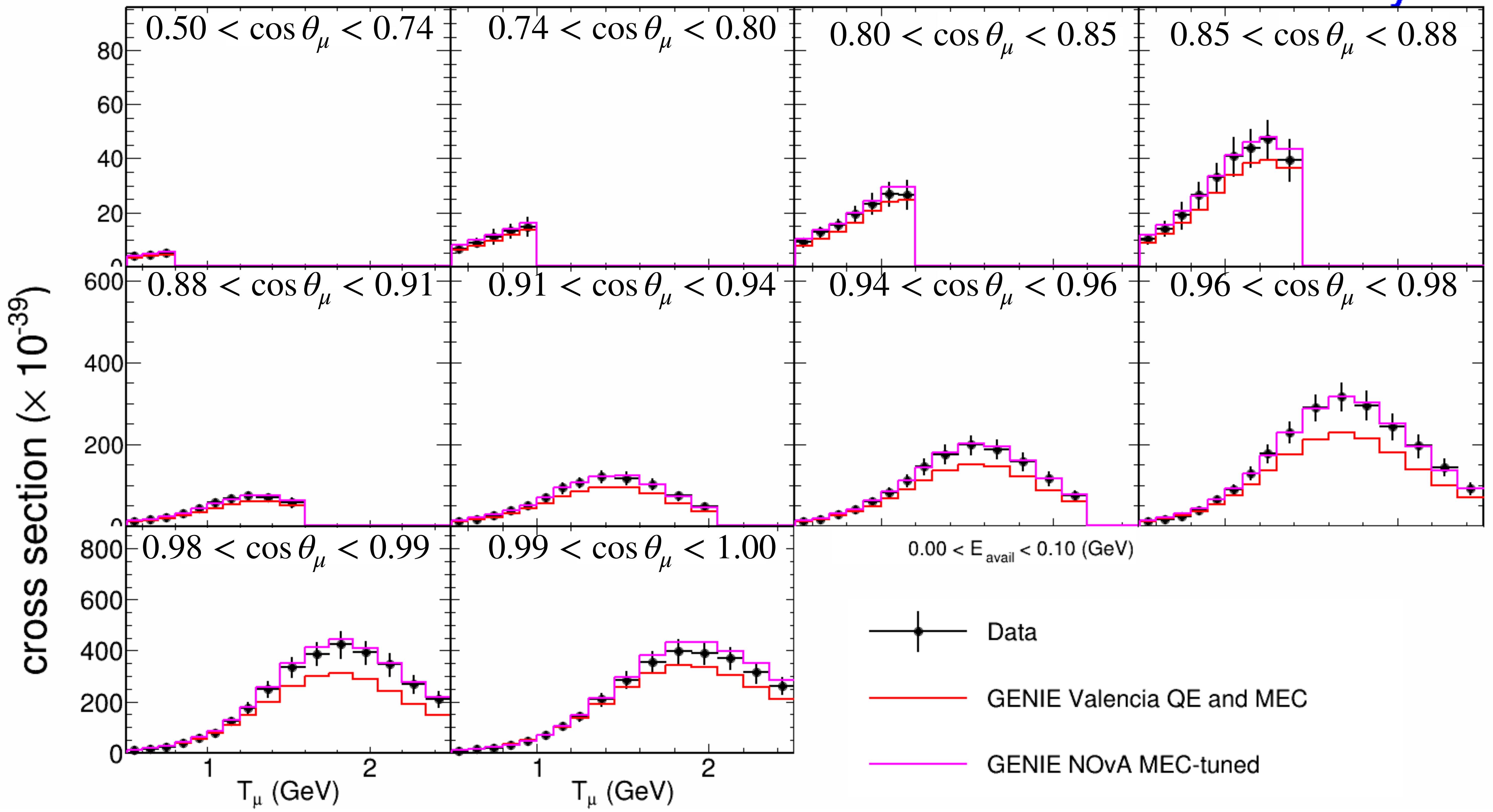
Events: 48%

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

NOvA Preliminary

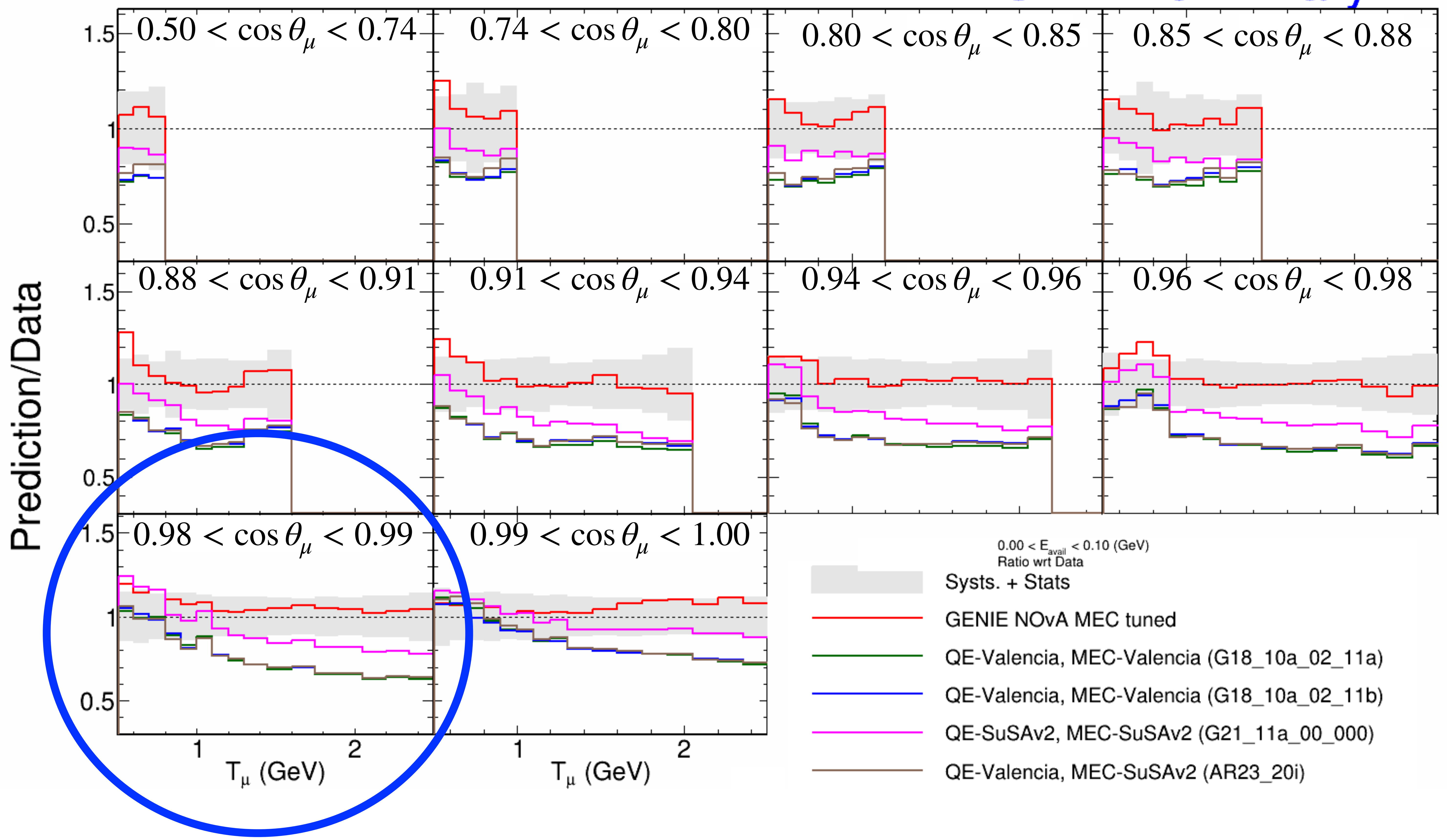


Ratios GENIE CMC to Data Results: $0 < E_{avail} < 100$ MeV

Events: 48%

- GENIE CMC ratios to data are useful to draw conclusions about the performance of different interaction models
- Though no model reproduces our measurement but the SuSA-v2 model for QE agrees better than the Valencia model for QE
- For MEC interactions, both SuSA-v2 and Valencia performs the same

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



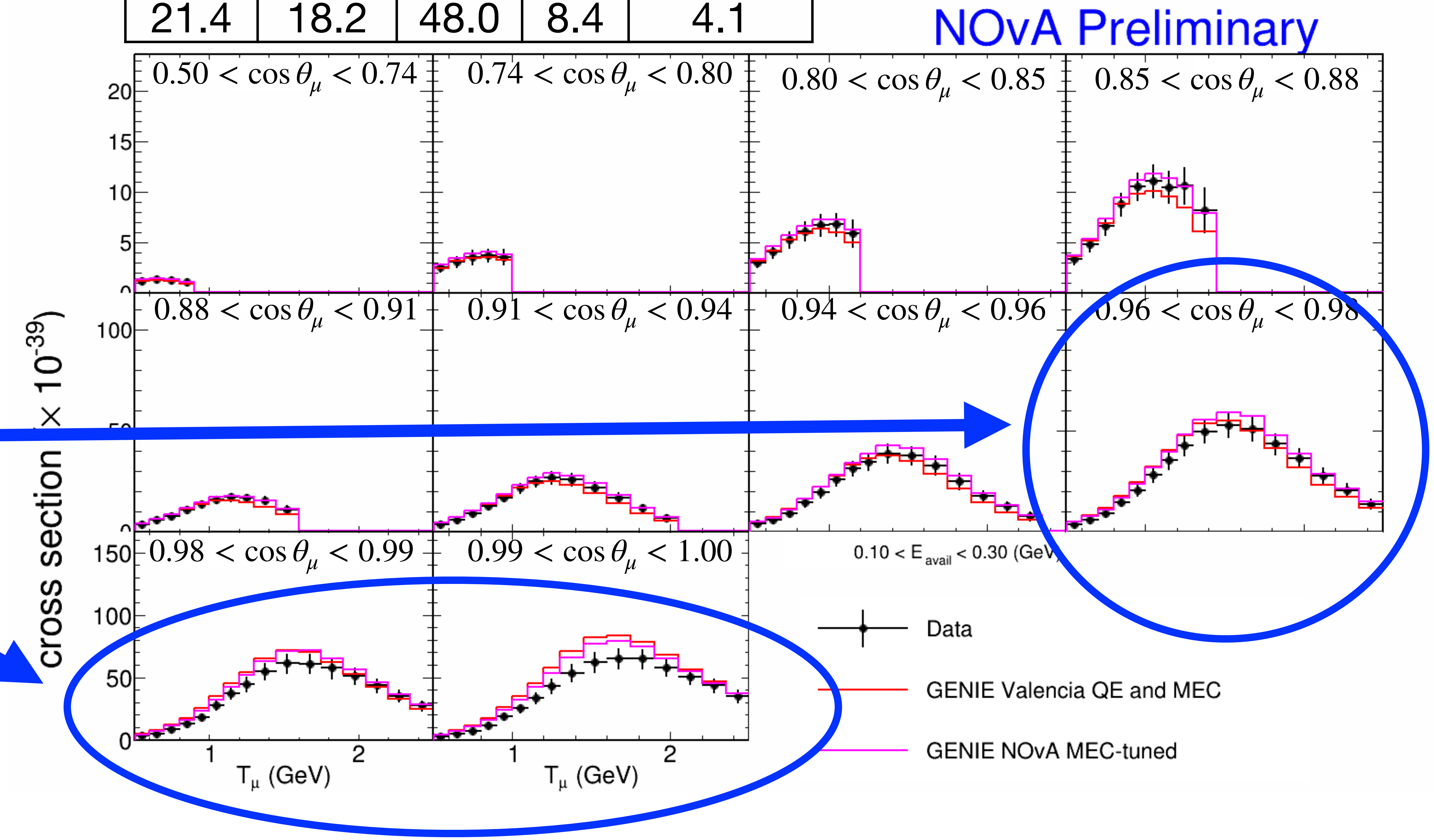
Data Results: $100 < E_{avail} < 300$ MeV

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

Events: 22%

- 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

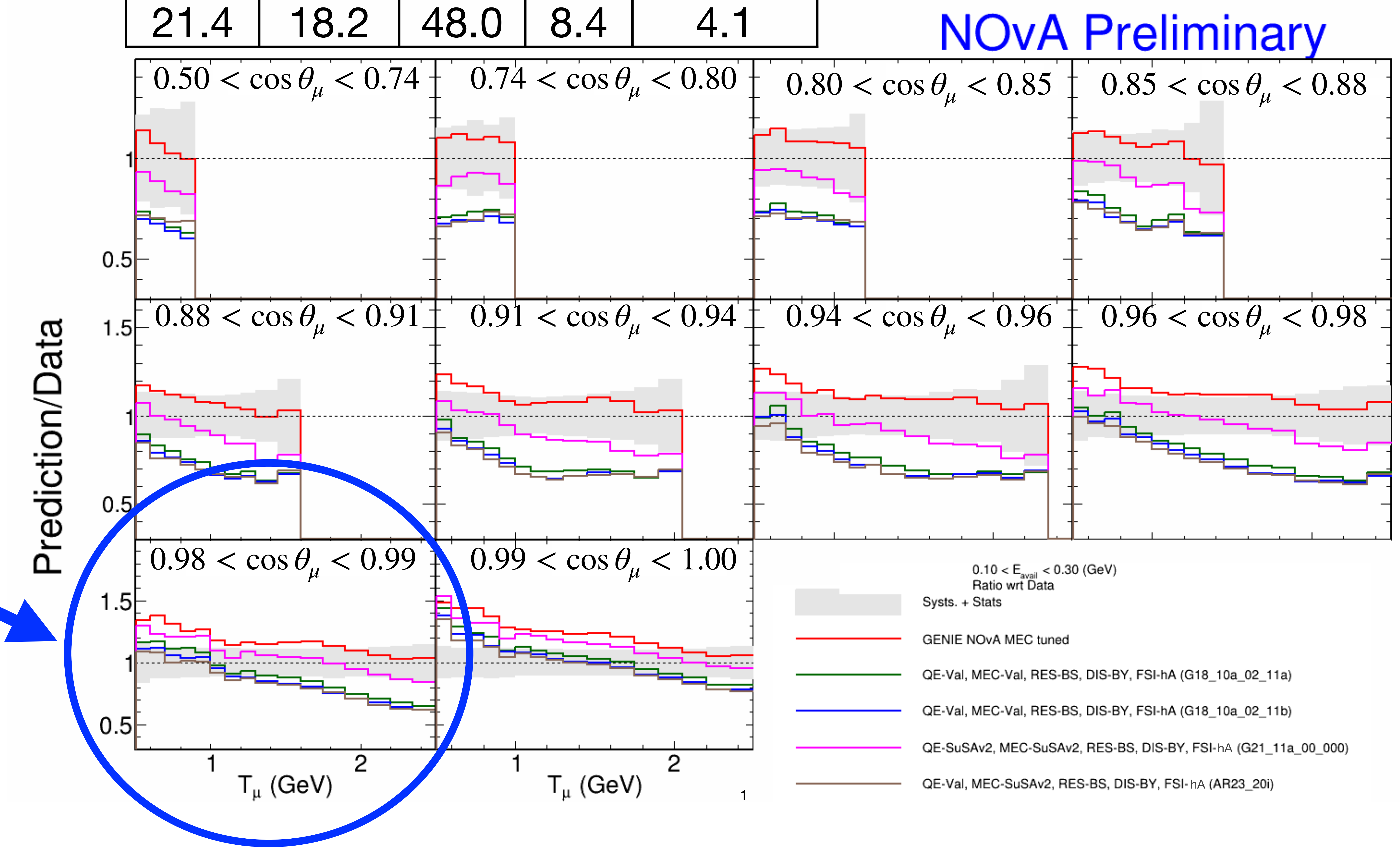


Ratios GENIE CMC to Data Results: $100 < E_{avail} < 300$ MeV

Events: 22%

- Same conclusions here that SuSA-v2 for QE is performing better than Valencia for QE
- For MEC, both SuSA-v2, and Valencia show similar performance

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



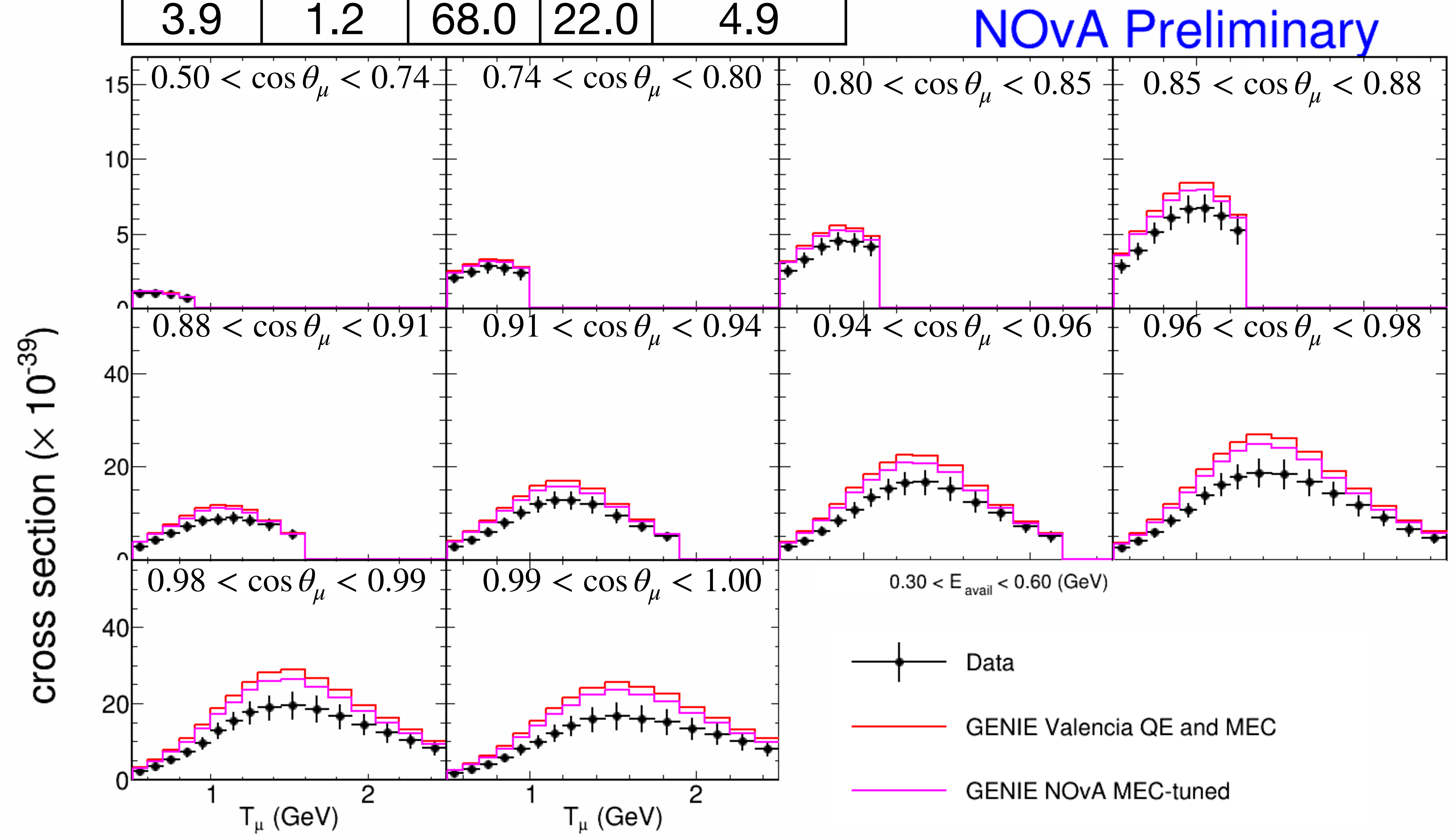
Data Results: $300 < E_{avail} < 600$ MeV

- In 300-600 MeV E_{avail}, phase-space is rich in RES and DIS interactions with RES dominating

- Here everywhere GENIE predictions are overestimating data

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

Events: 14%

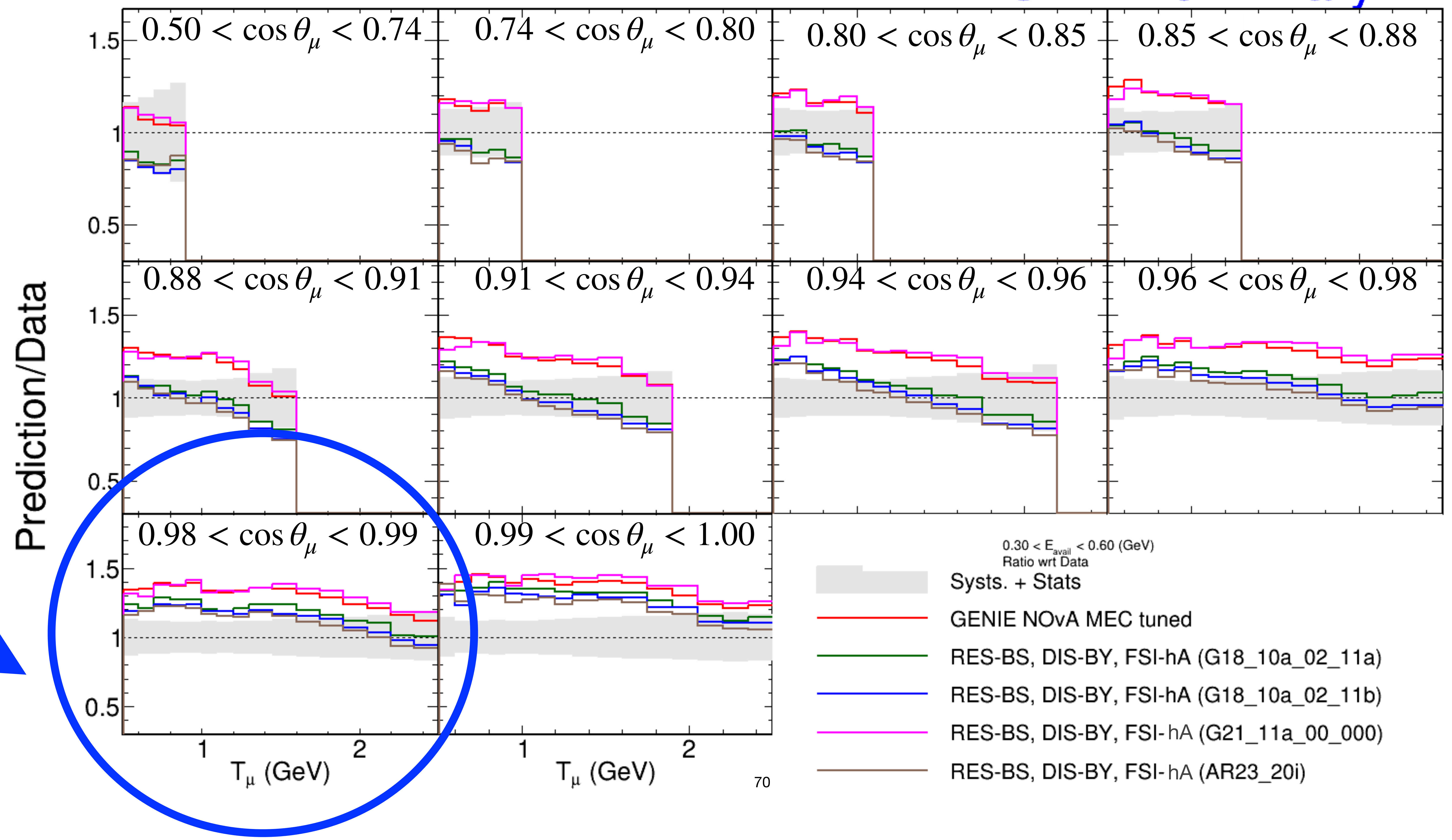


Ratios GENIE CMC to Data Results: $300 < E_{avail} < 600$ MeV

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

Events: 14%

In the RES enhanced regions, GENIE tunes 02_11a, and 02_11b are performing better than all zero tunes to describe RES interactions in data

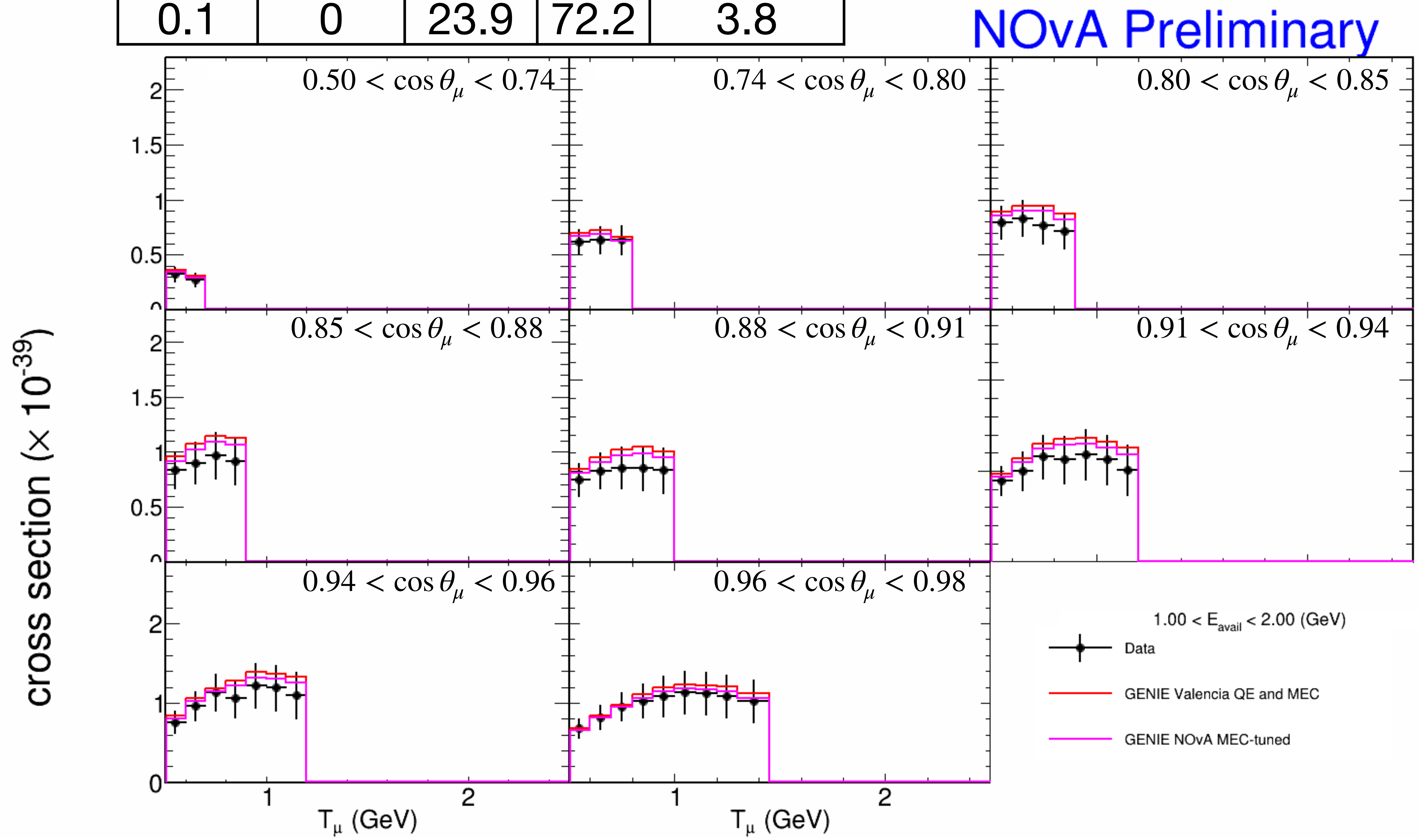


Data Results: $1 < E_{avail} < 2$ GeV

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

Events: 5%

- 1-2 GeV E_{avail} region has only 5% sample of selected events
- This region is dominated by the DIS interaction
- GENIE predictions are within uncertainties to data



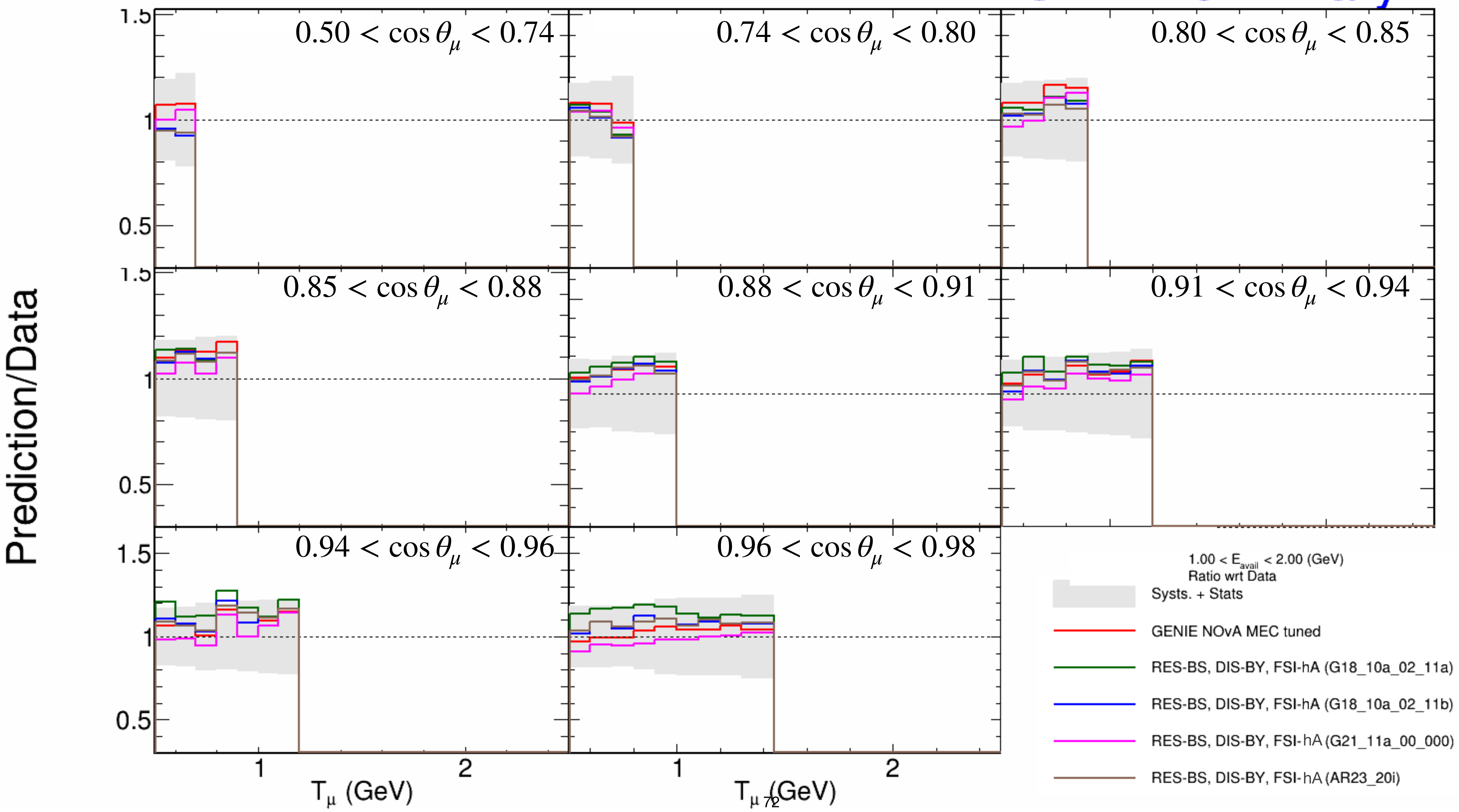
Ratios GENIE CMC to Data Results: $1 < E_{avail} < 2$ GeV

- 1-2 GeV E_{avail} region has only 5% sample of selected events
- This region is dominated by the DIS interaction
- GENIE predictions are within uncertainties to data
- Bodek-Yang + Pythia is doing a good job in modeling DIS interactions

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

Events: 5%

NOvA Preliminary



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	hA2018
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
GiBUU p3 (2023)	Modified LFG	Dipole Form Factor, RPA corrections	Christy	MAID	Data	BUU transport model

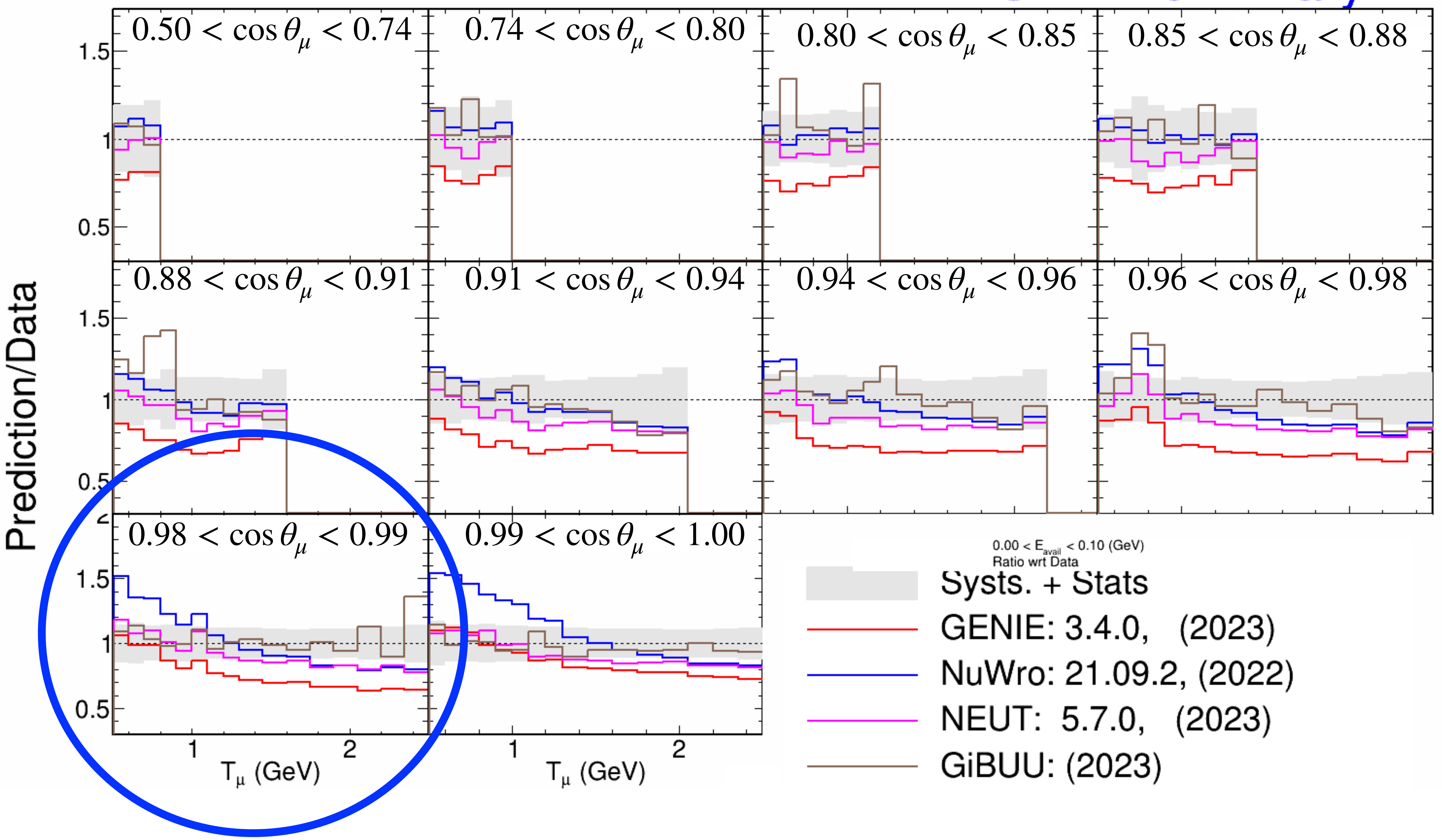
Special thanks to Kevin Vockerodt, and Colin Weber for generating various generator predictions

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

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

Events: 48%

- In the QE enhanced regions, NuWro has a very different shape and NuWro is the only one that is using Llewellyn-Smith (LS) models for QE interactions
- Both GENIE 3.4.0, and NEUT are using Valencia for QE, only there FSI tunes are different and NEUTs tune seems to be doing better
- GiBUU seems to be doing a good job in modeling QE in data

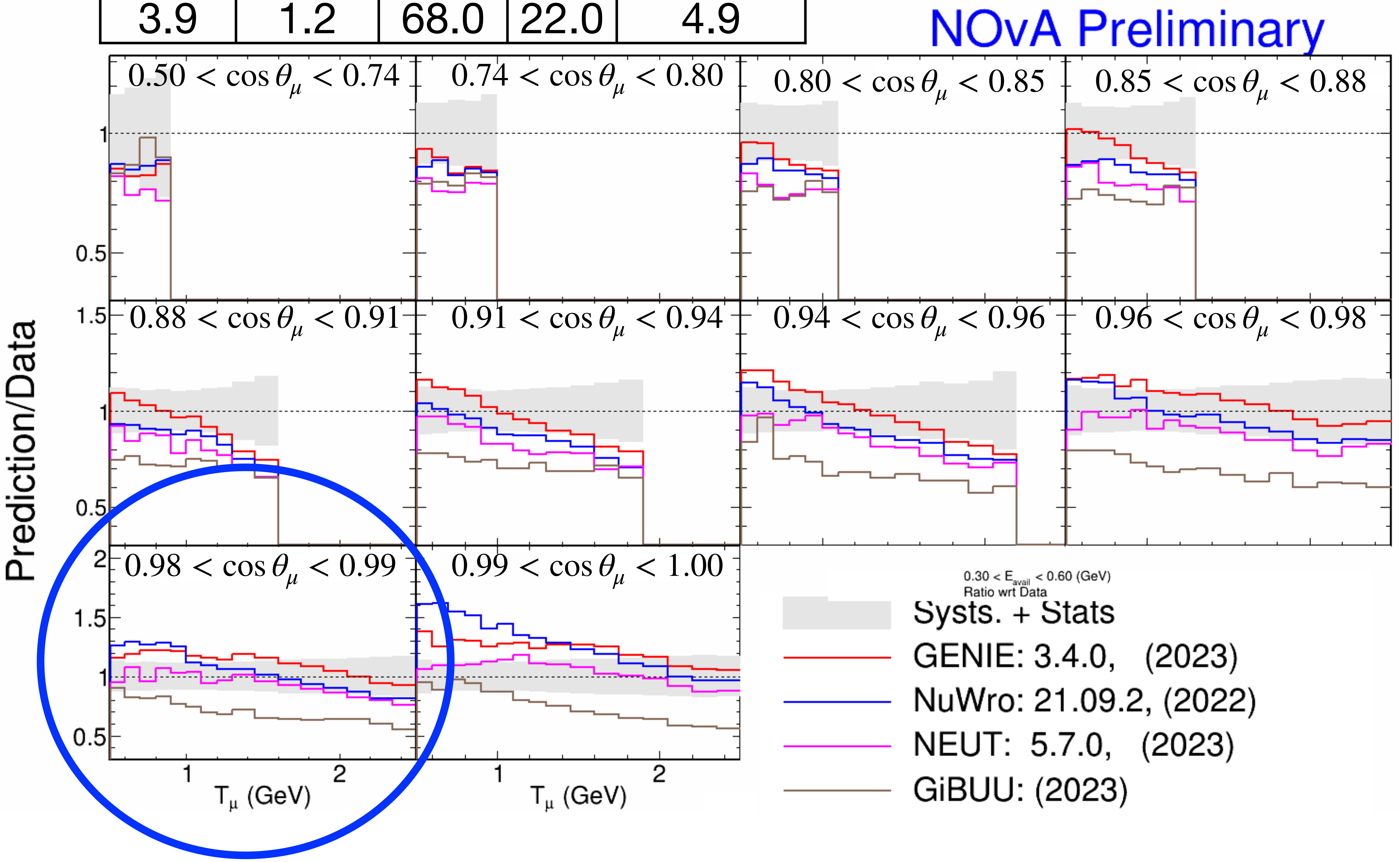


Generators to Data Results: $300 < E_{avail} < 600$ MeV

- In the RES rich regions, all generators are performing differently
- GiBUU is mostly under-predicting
- NEUT is generally closer to the data. It is using BY for modeling DIS along with its custom semi-classical intranuclear cascade tune for FSI

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

Events: 14%

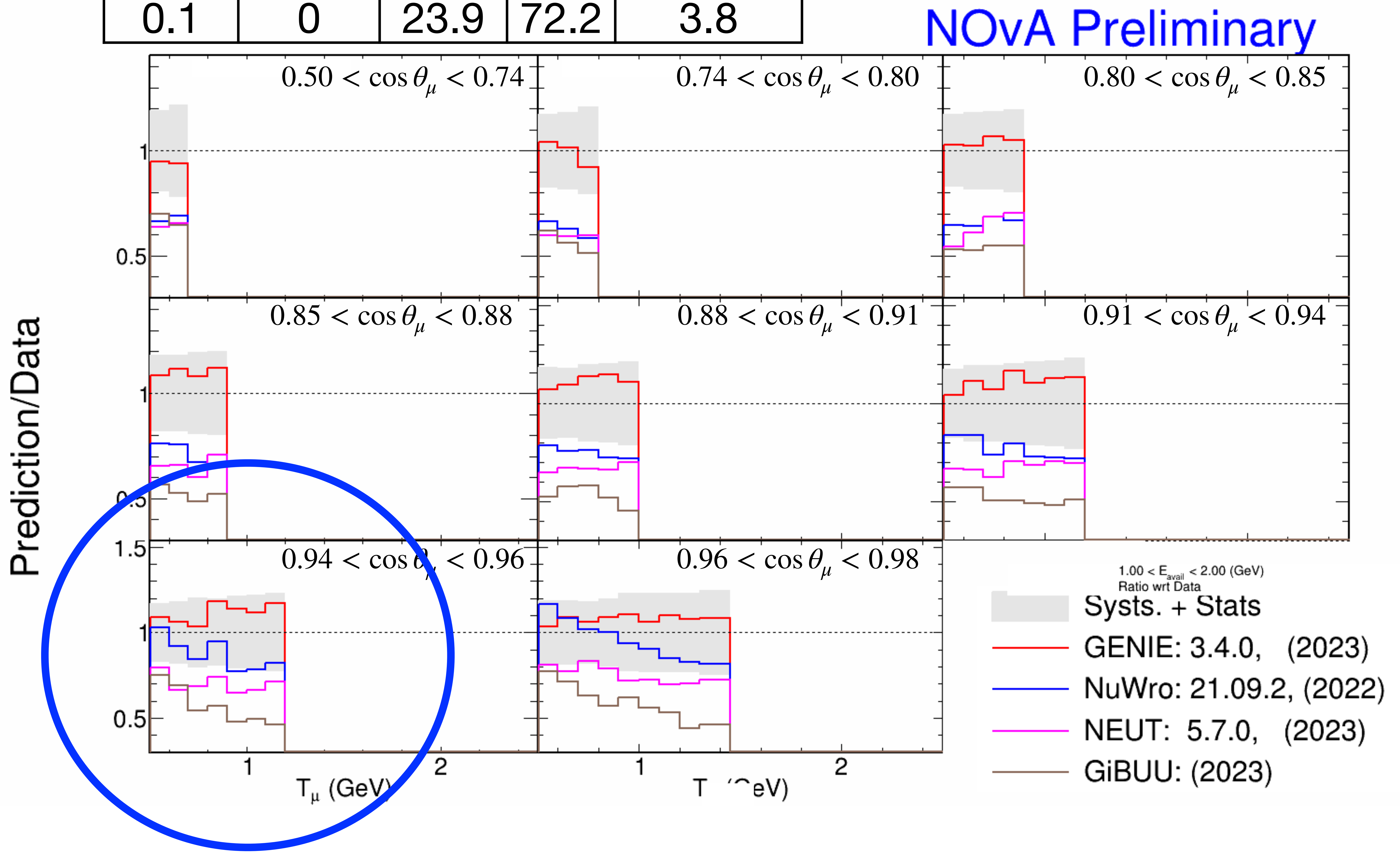


Generators to Data Results: $1 < E_{avail} < 2$ MeV

- 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 hA2018 tune seems to be doing a better job in modeling DIS interactions

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

Events: 5%

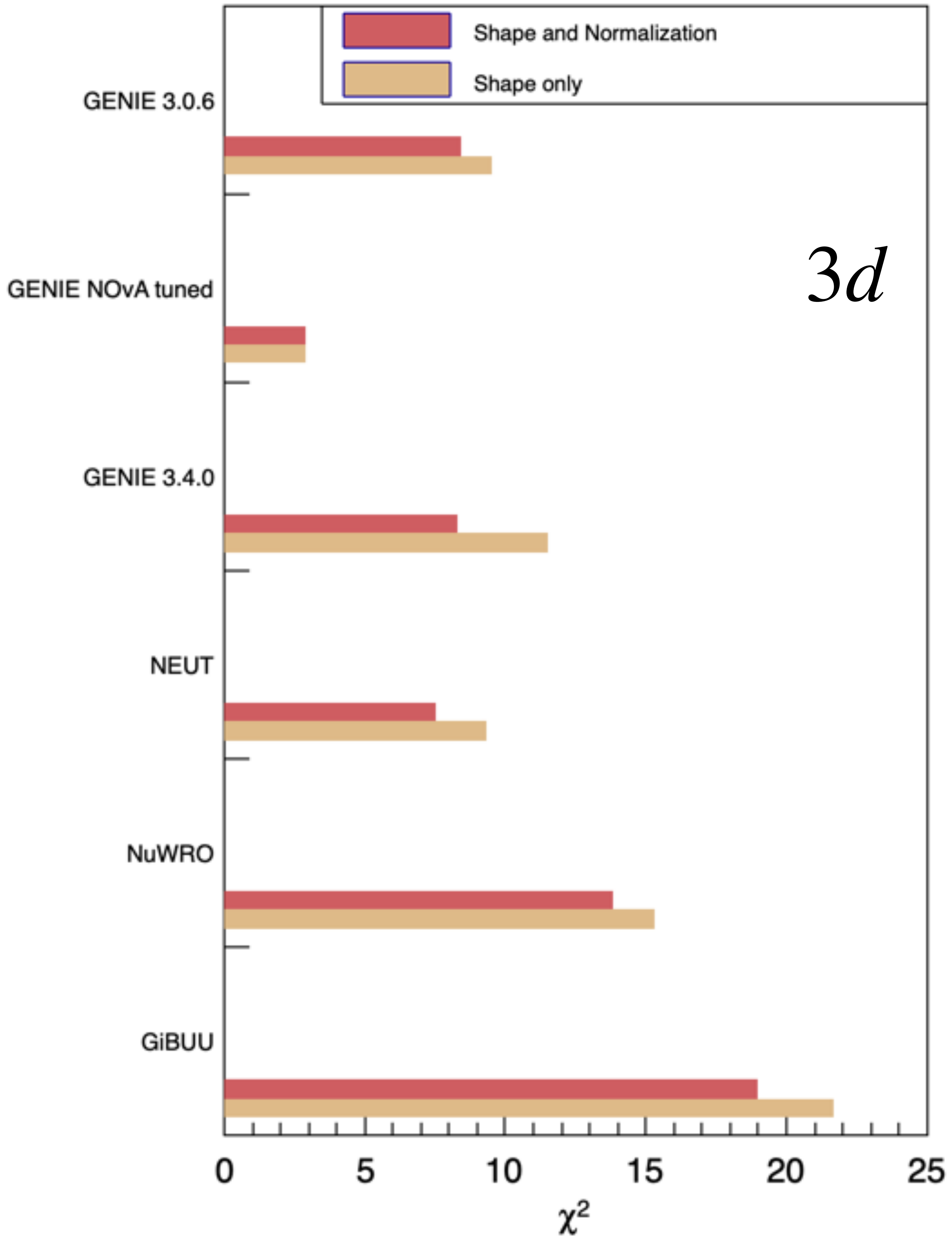


χ^2

- Different generators seems to show different level of agreements in the T_μ, $\cos\theta_\mu$, and E_{avail} phase space

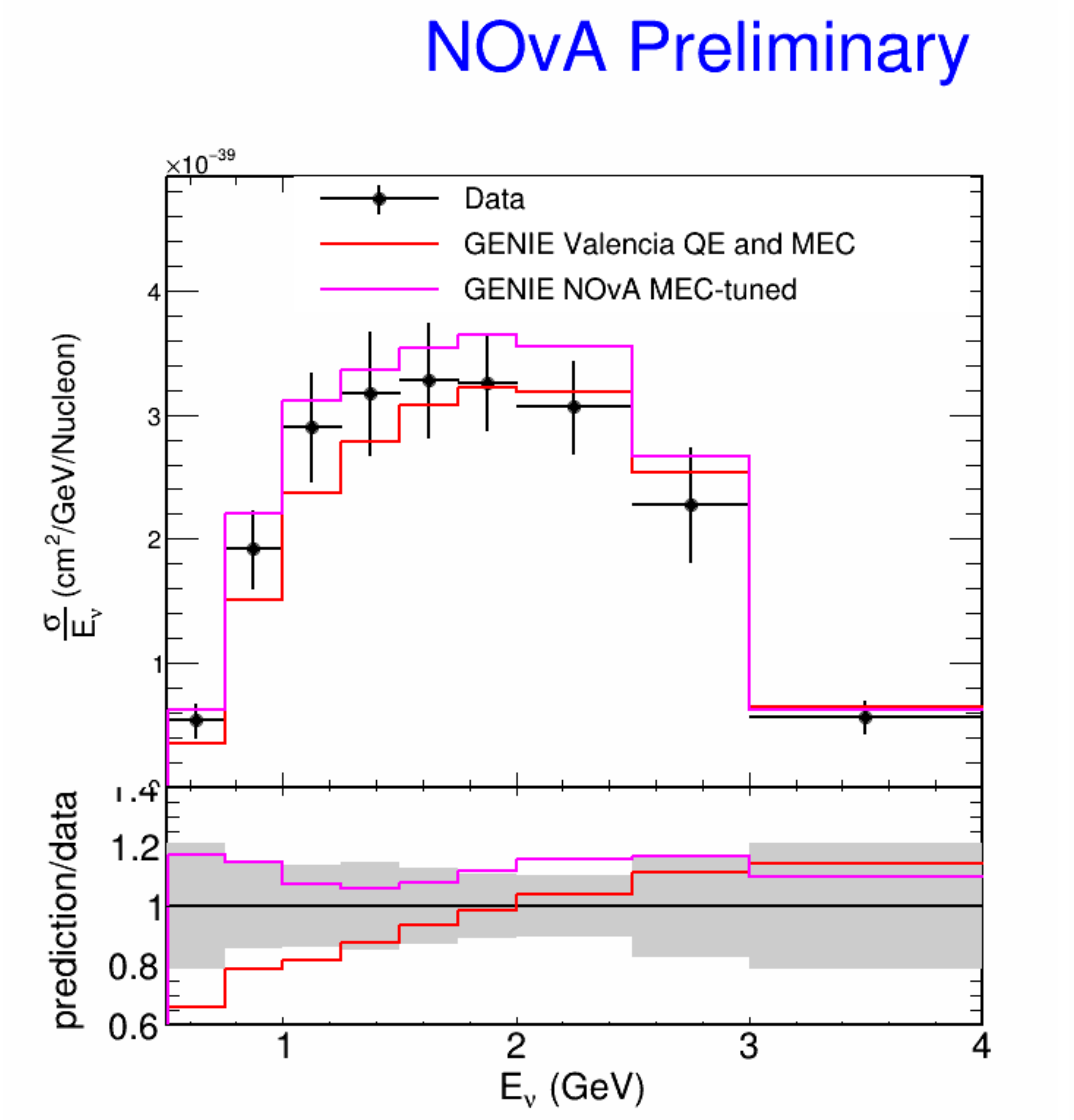
- χ^2 are calculated using covariance matrices to account the bin to bin correlations for different generators

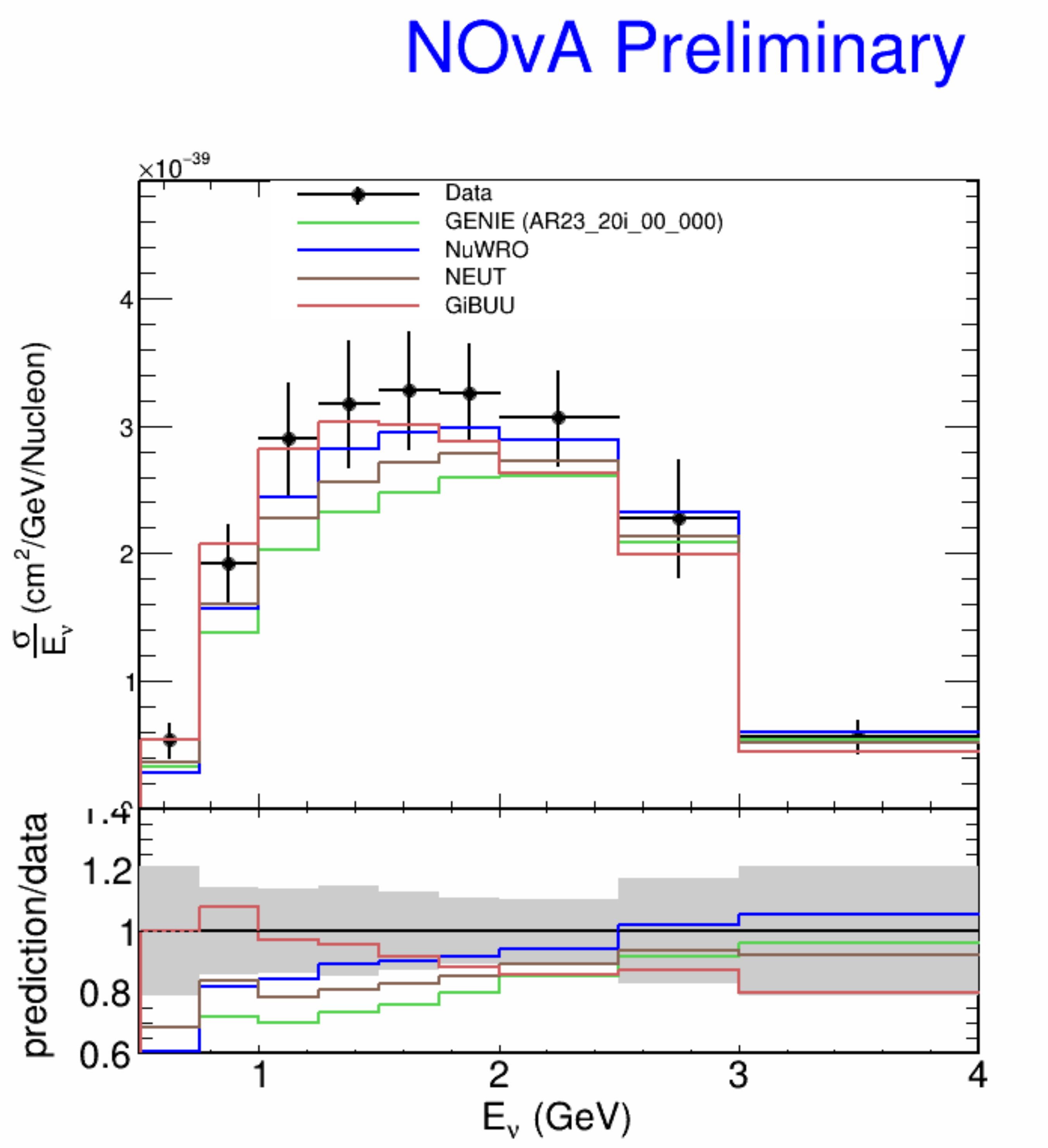
- Overall NEUT seems to be doing a better job in modeling data in the overall phase-space

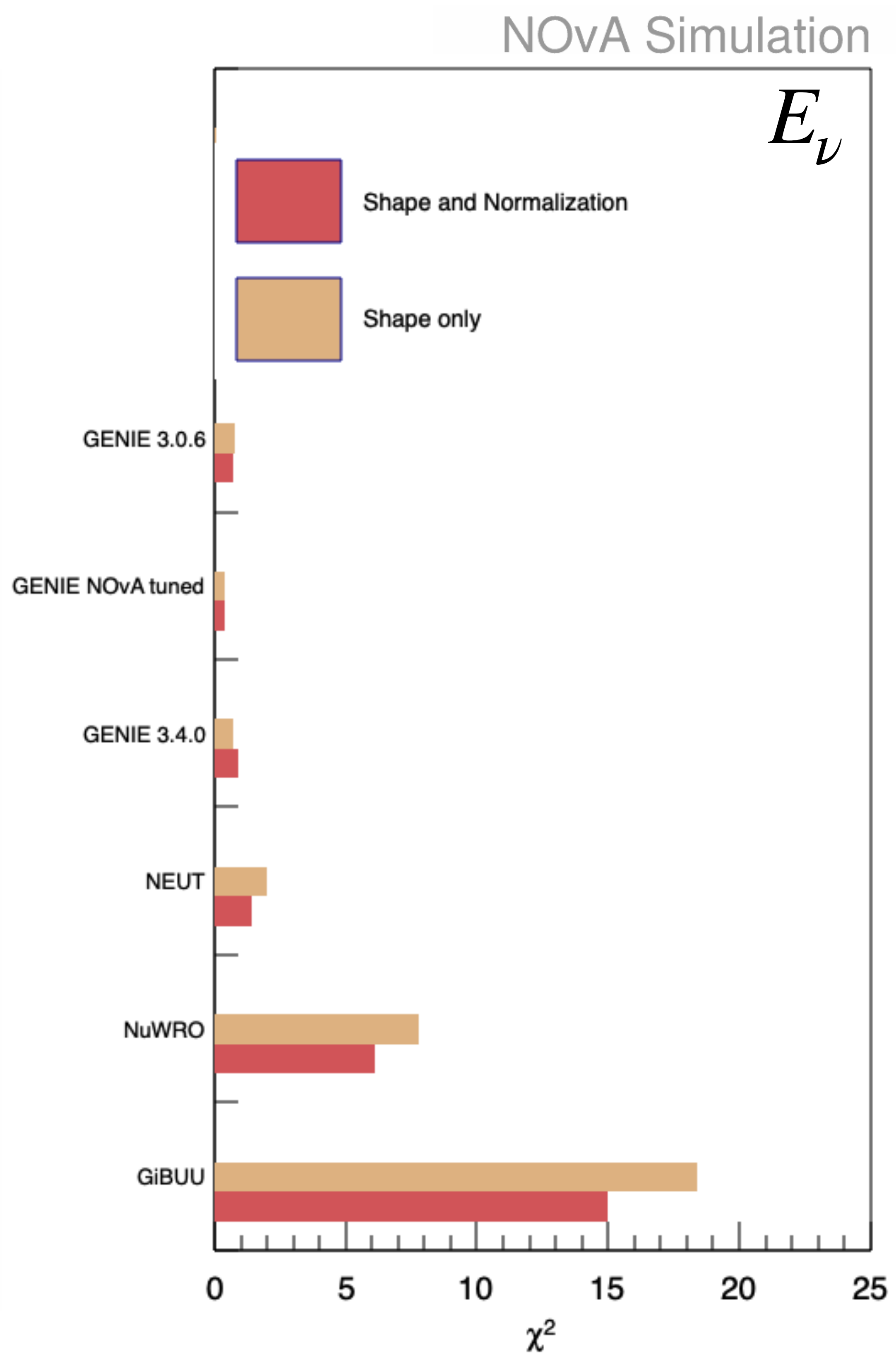


Single Differential E_ν and Q^2 Measurements

Data Results and Generator Predictions - E_ν

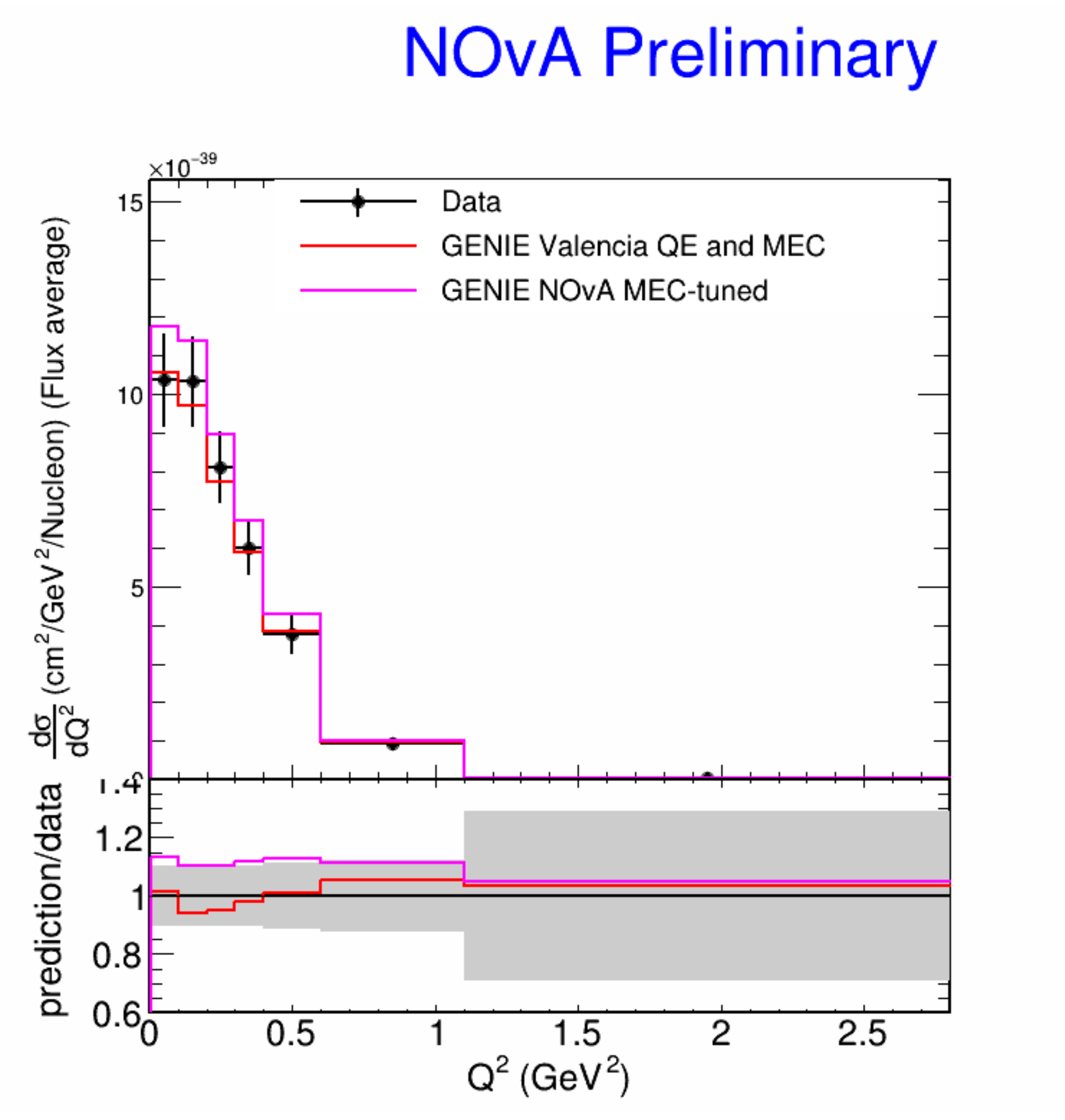


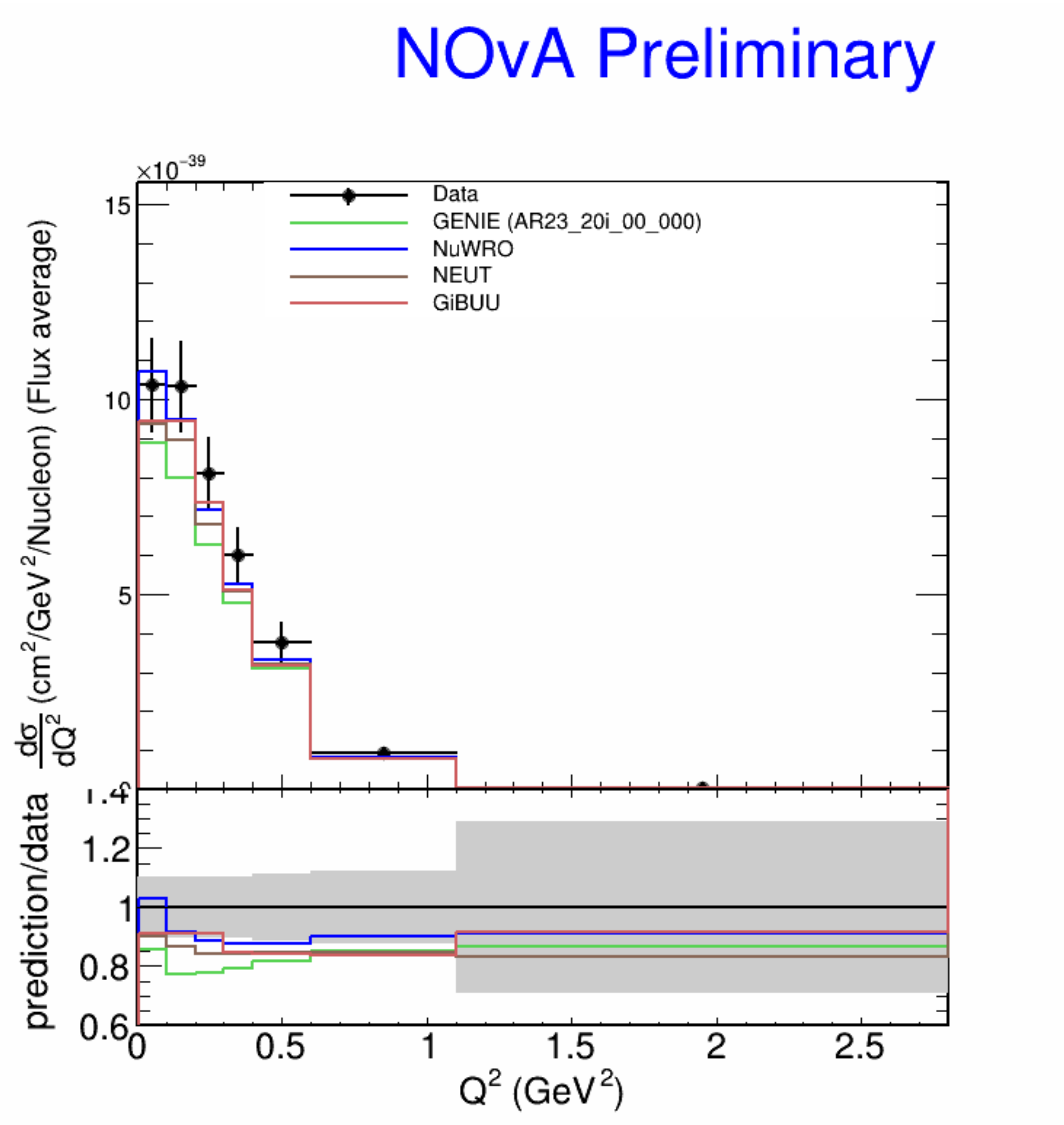


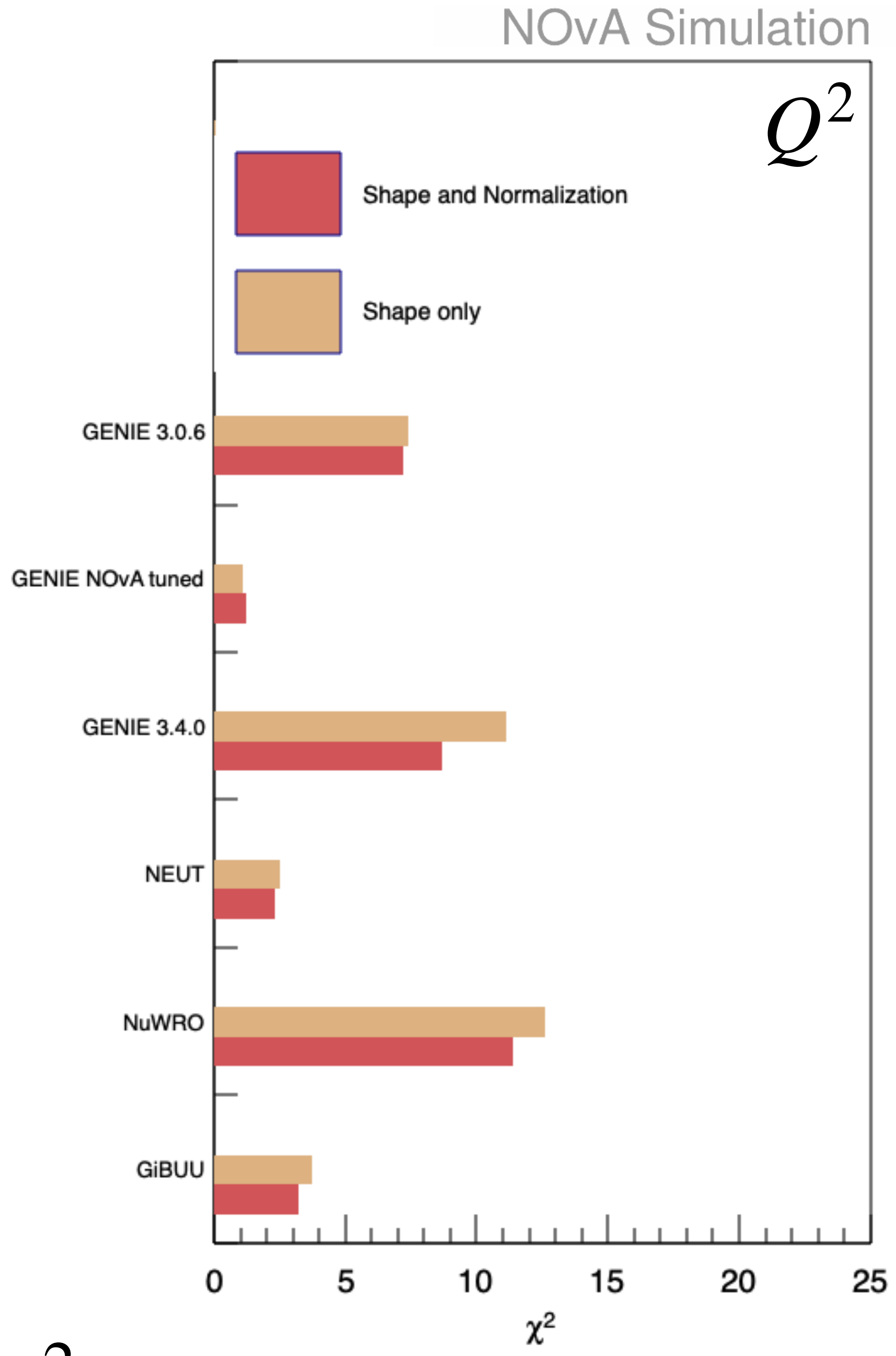


- At low E_ν, all generators are under predicting data
- GENIE 3.4.0, with QE-Valencia and MEC-SuSAv2 are modeling data well according to the χ^2

Data Results and Generator Predictions - Q^2







- For Q^2, GENIE, NEUT, and GiBUU, are under-predicting at low Q^2
- NEUT, with QE-Valencia and MEC-Valencia are modeling data well according to the χ^2

Conclusions

- We have presented a high statistic Muon-Antineutrino Charged-Current Inclusive Cross Section in the NOvA Near Detector
- Triple differential cross sections in T_μ, $\cos\theta_\mu$, and E_{avail} and single differential cross sections in E_ν and Q^2 are reported
- Available energy gives us a good handle of dealing with different interaction types
- Current GENIE predictions are able to predict data results in the 0-100 MeV E_{avail} region where QE and MEC interactions are dominating. From $E_{avail} > 100$ MeV, current GENIE predictions are not able to predict data results due to increase in resonance interaction
- All other generators, show different level of agreement with data in different phase-spaces
- We are very excited about our new results and encourage neutrino-interaction model builders to use our data (when released) for model building

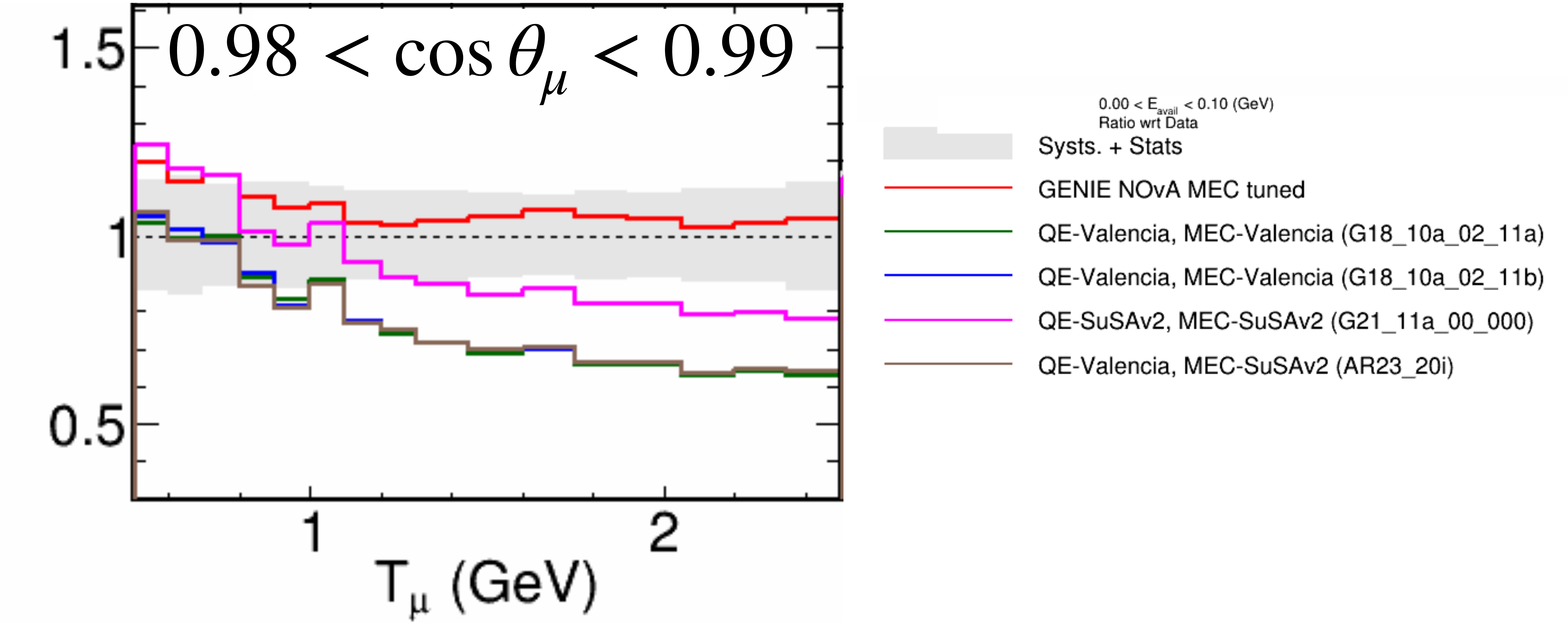
Backup

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

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

Events: 48%

- GENIE CMC ratios to data are useful to draw conclusions about the performance of different interaction models
- Though no model reproduces our measurement but the SuSA-v2 model for QE agrees better than the Valencia model for QE
- For MEC interactions, both SuSA-v2 and Valencia performs the same



χ^2

Tune	Chisq/NDF		
	Muon Kinematics and Available Energy	Neutrino Energy	Four Momentum Square
GENIE 3.0.6	8.4	0.7	7.2
GENIE NOvA Tune	2.9	0.4	1.2
GENIE 3.4.0	8.3	0.9	8.7
NEUT	7.5	1.4	2.3
nuWRO	13.8	6.1	11.4
GiBUU	19.0	15.0	3.2