Exploring 2p2h signatures in muon-neutrino charged-current measurements at NOvA

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For the NOvA Collaboration

Joint Experimental-Theoretical Physics Seminar

February 2, 2024

Outline

- Introduction
- The NOvA experiment
- Measurement of muon-neutrino charged-current cross sections with low hadronic energy (L. Aliaga)
- Measurement of inclusive muon-neutrino charged-current cross sections and 2p2h contribution (T. Olson)
- Conclusions

Neutrino oscillations

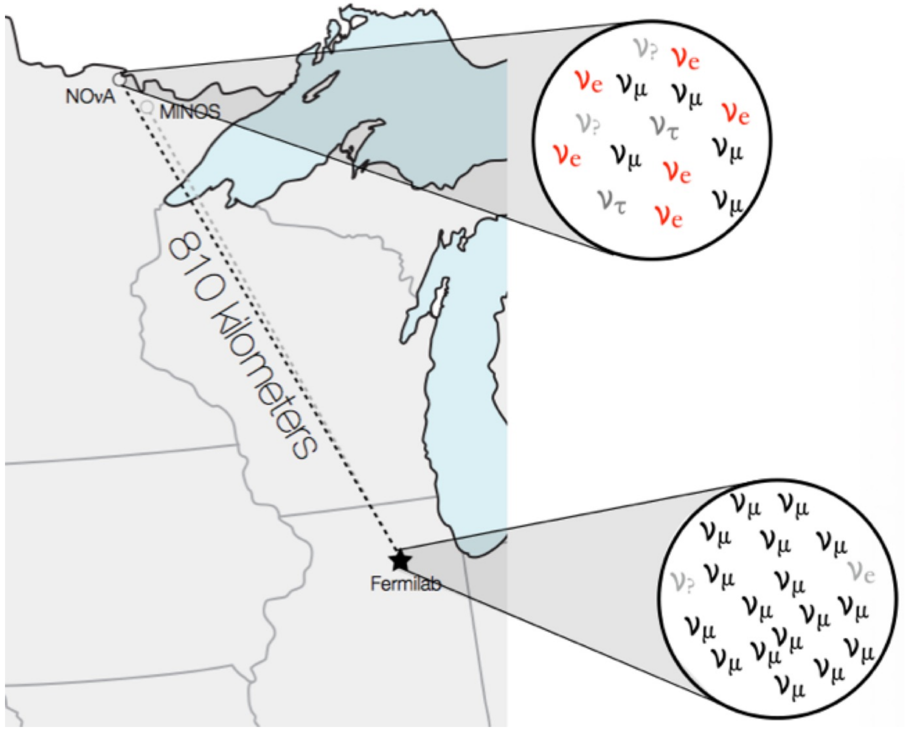
Neutrino experiments are addressing major questions in neutrino oscillations

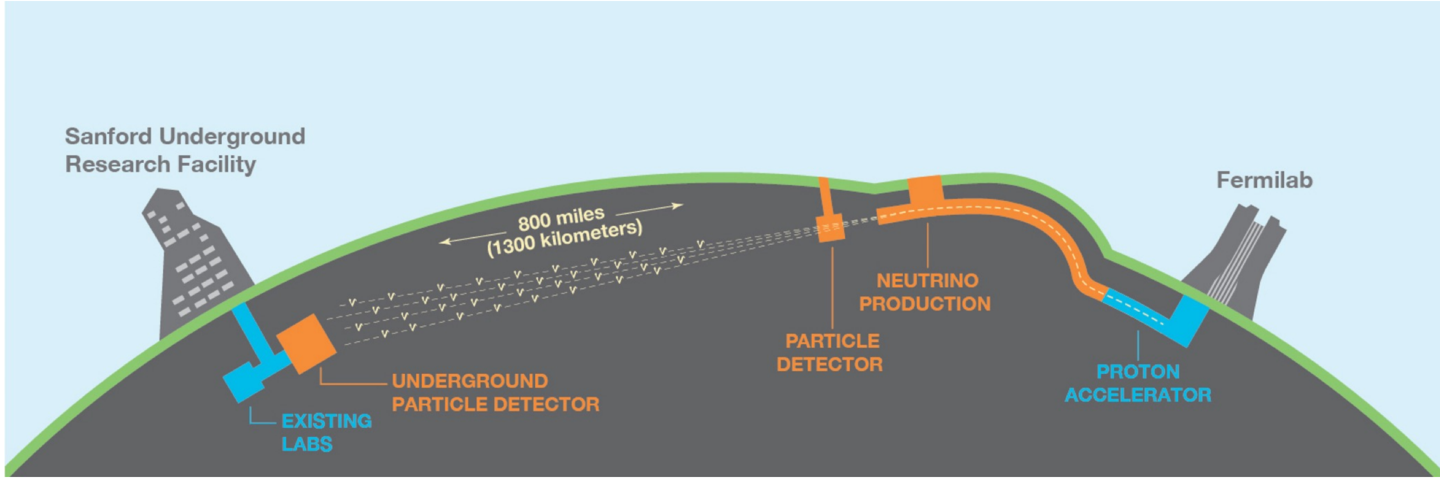
Is there a direct violation of CP symmetry by leptons ($\Delta P_{\nu\bar{\nu}} \sim \sin\delta_{CP}$)?

Is there a symmetry governing the ν_μ / ν_τ mixing into the mass states (is θ_{23} maximal?=45^0)

In the neutrino mass hierarchy normal or inverted?

Are there more than 3 neutrino states?





Neutrino scattering and oscillations

$E_\nu = E_{\mu/e} + E_{hadrons/showers}$: needs a good understanding of the final states of the reaction

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\ \sigma(E_\nu^{true})\ P(\alpha \to \beta, E_\nu^{true})\ \epsilon(E_\nu^{true})\ S(E_\nu^{true}, E_\nu^{reco})$$

$N_{pred}(E_\nu^{reco})$	: Expected events	$P(\alpha \to \beta, E_\nu^{true})$	: Oscillation probability
$\Phi(E_\nu^{true})$	: Neutrino flux	$\epsilon(E_\nu^{true})$	: Efficiency
$\sigma(E_\nu^{true})$	: Interaction cross section	$S(E_\nu^{true}, E_\nu^{reco})$	: Smearing matrix

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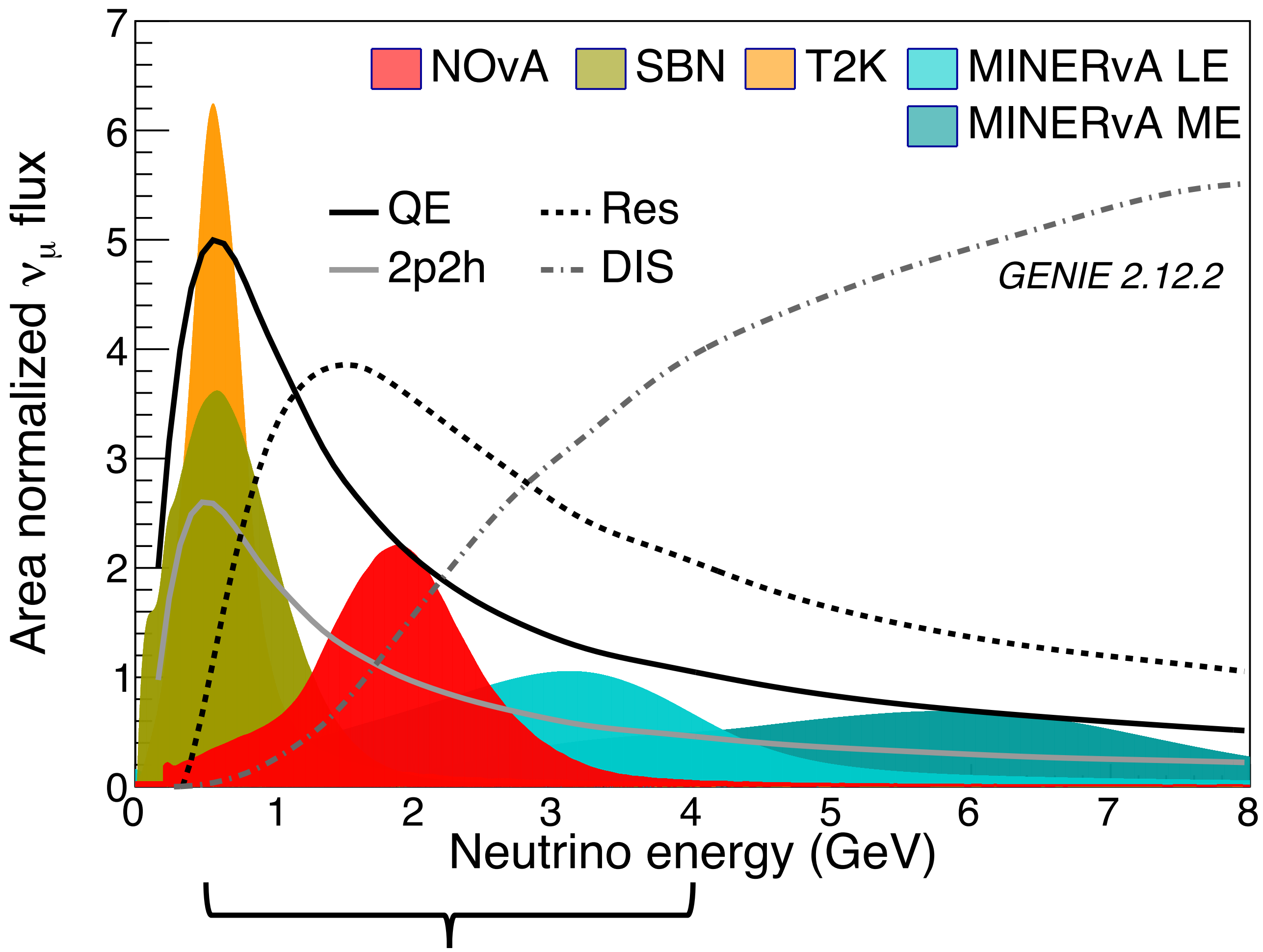
Accelerator neutrino experiments use an ***intense neutrino beam*** *and* ***near detector*** *(un-oscillated beam) and a* ***far detector*** *(oscillated beam) to address these questions*

→ ***expected mitigated uncertainties***

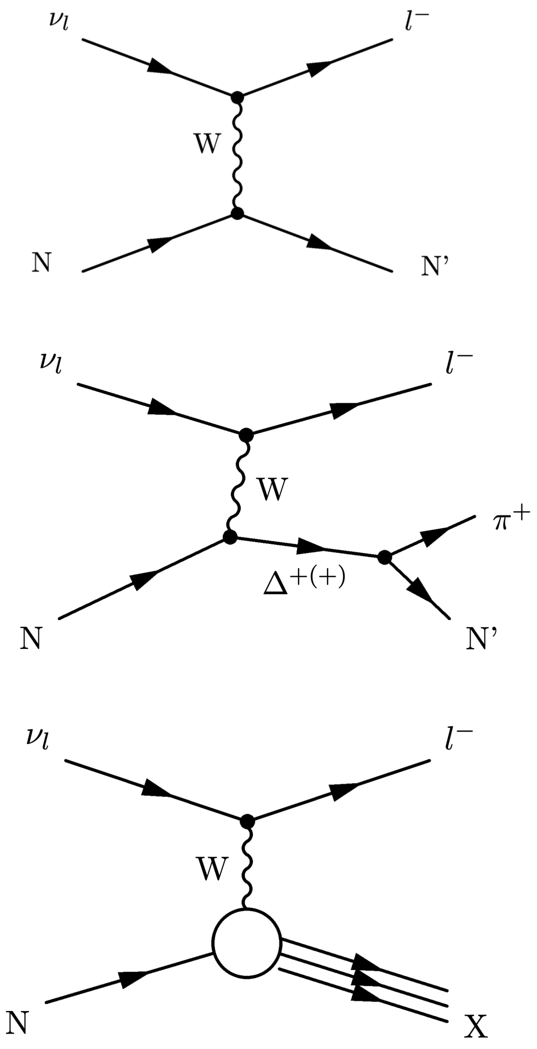
Near/Far do not fully cancel: different neutrino energy distributions, acceptances, etc.

We rely on models to make these corrections

Neutrino-nucleon interactions



The transition region between interaction processes

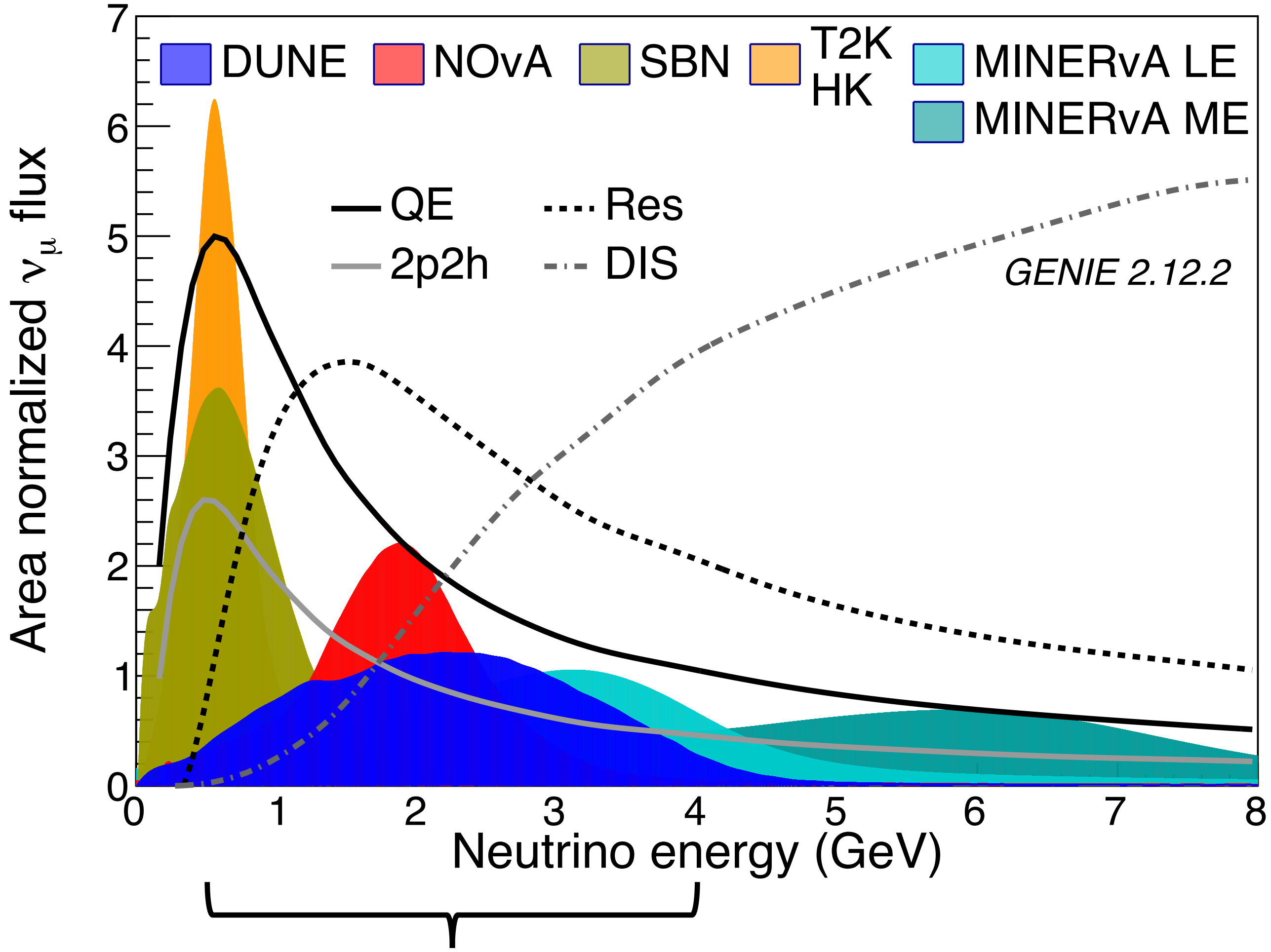


CC QE

CC Res

CC DIS

Neutrino-nucleon interactions



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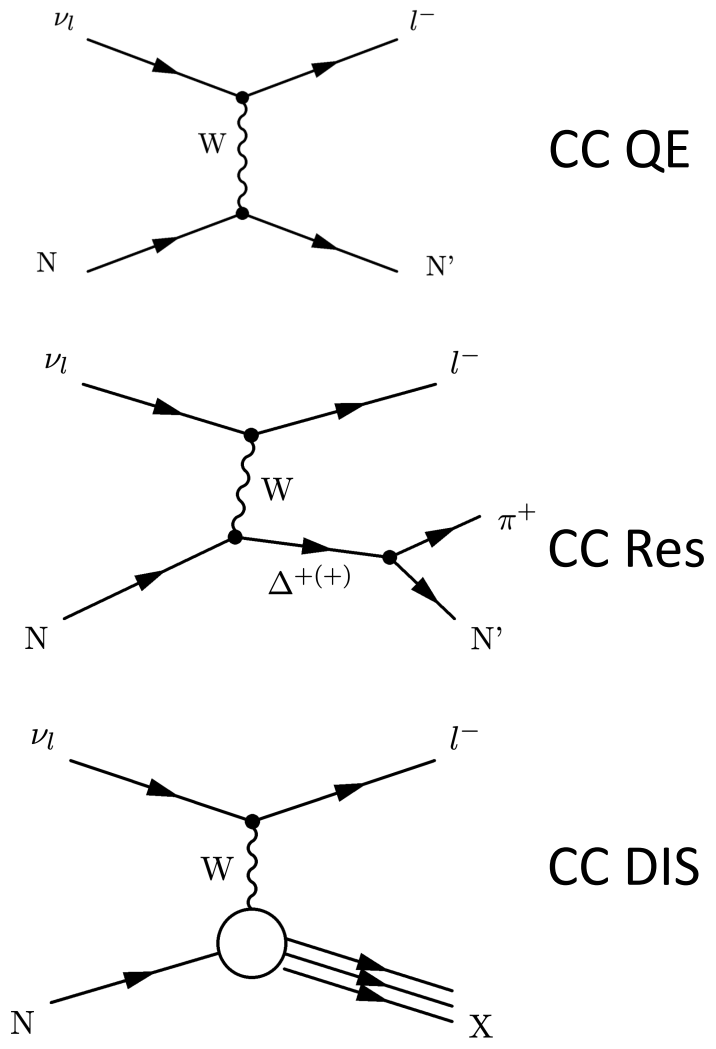
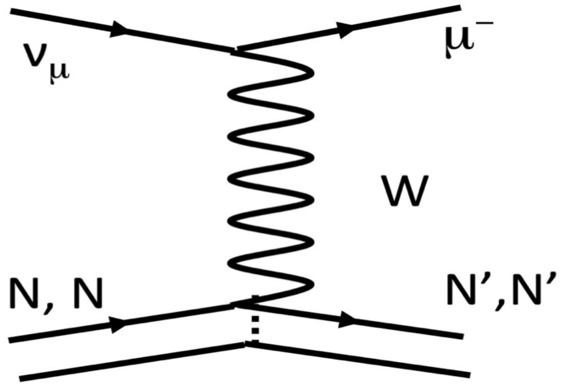


Multinucleon cross sections

2-particle 2-hole: neutrinos interact with a pair of nucleons

- 2p2h is well known in nuclear scattering
- Measuring 2p2h for neutrino experiments is challenging: unknown incoming beam, nuclear effects, etc.



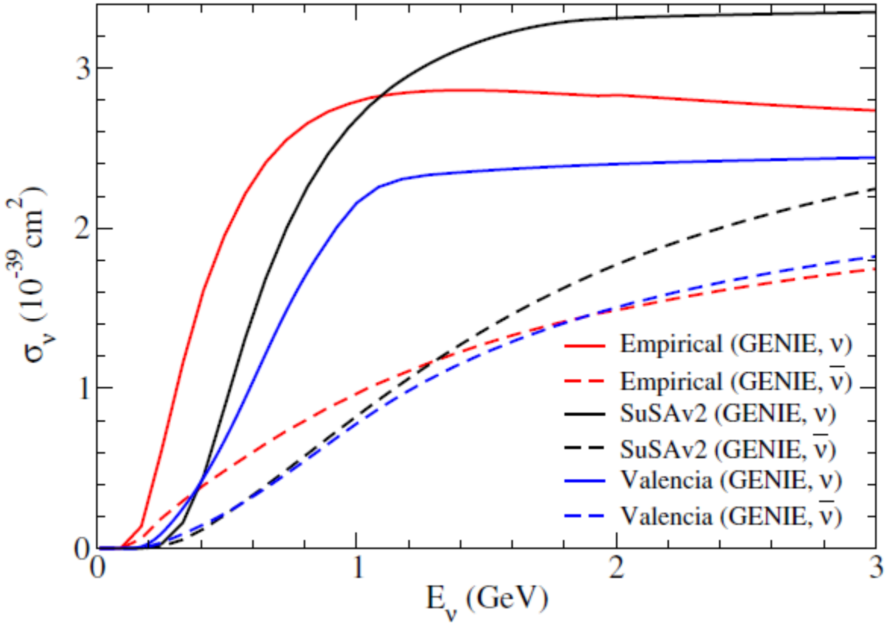
Models for this process have large disagreements:

GENIE Empirical MEC
GiBUU (Walecka)

MINERvA-tunes
NOvA-tunes

Valencia
SuSAv2

Phys. Rev. D 101, 033003 (2020).



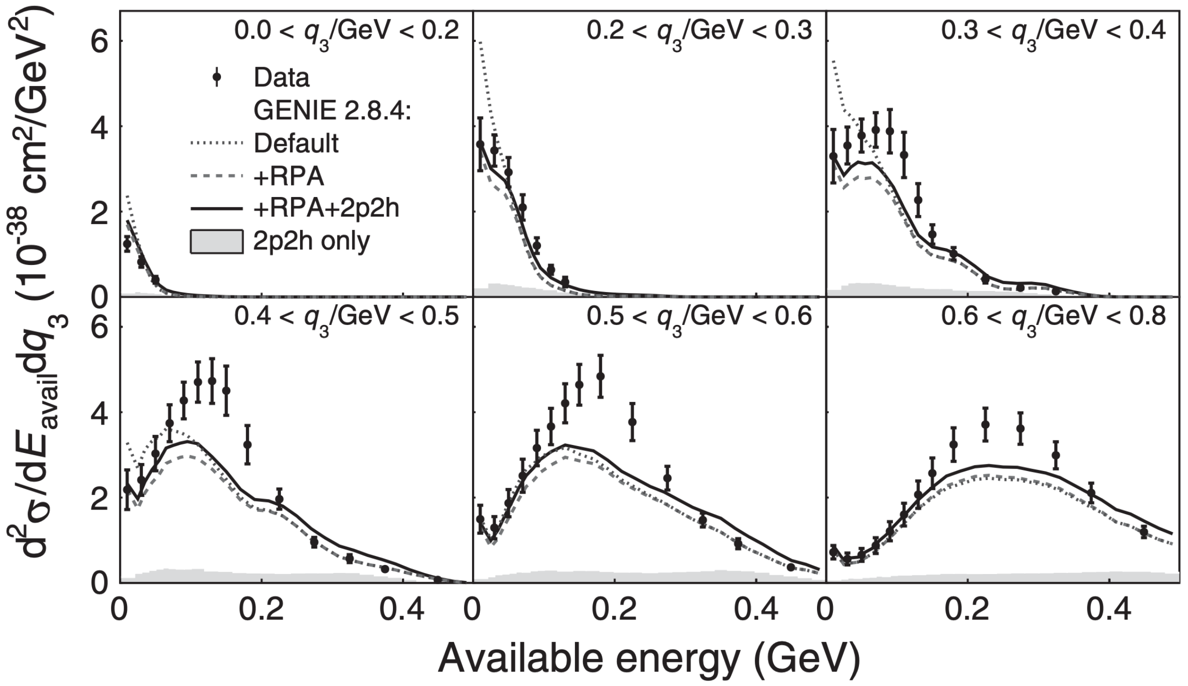
2p2h

Long standing efforts in the neutrino experiments to understand the 2p2h process

MINERvA pioneered measurements in kinematic regions with an enhanced population of multiproton final states

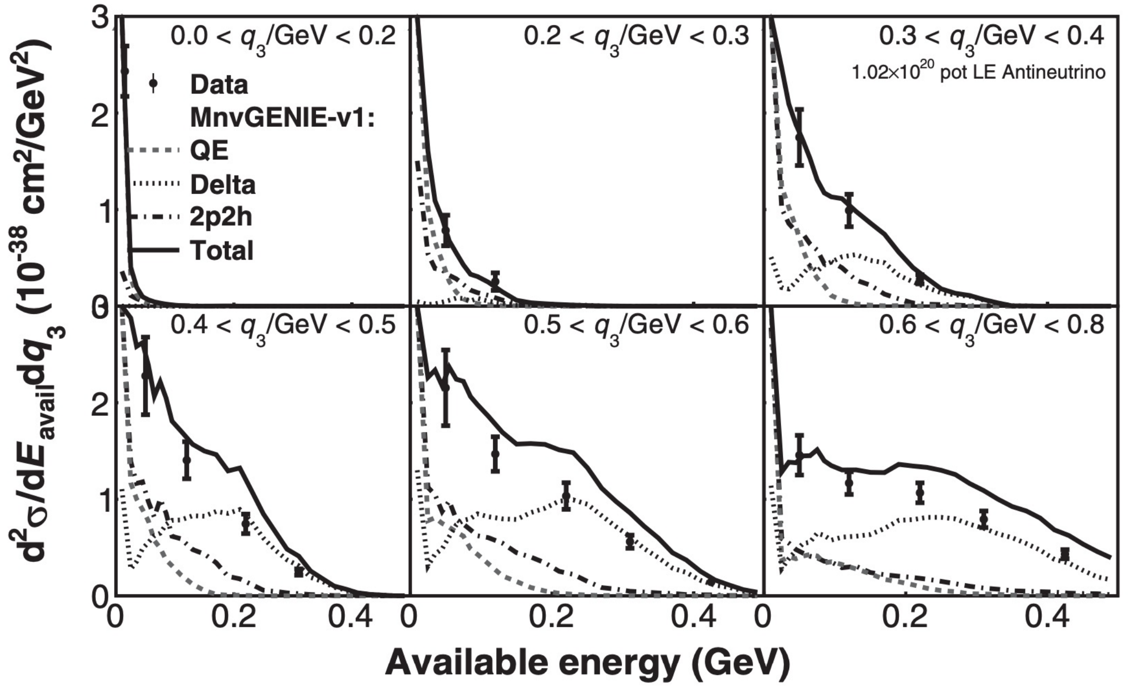
No model fully describes the data

ν_μ - *CC* measurement compared with default GENIE 2.8



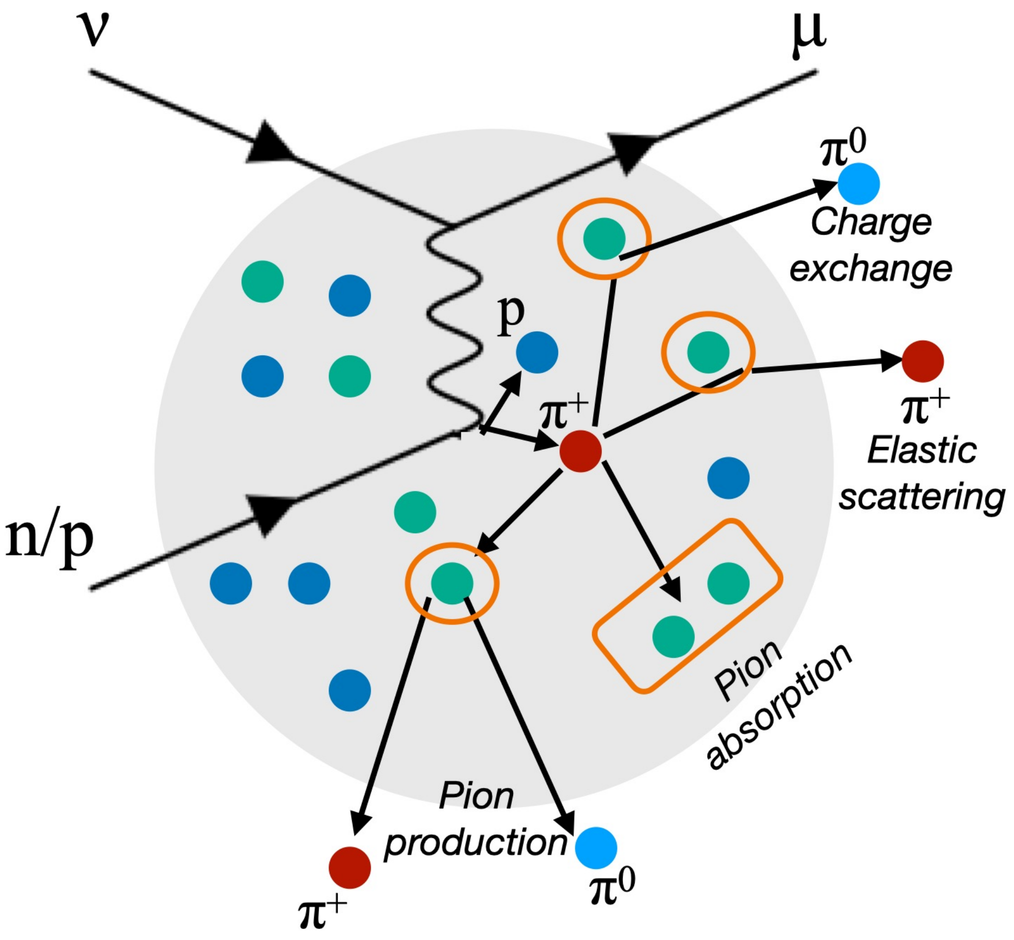
Phys. Rev. Lett. **116**, 071802

$\bar{\nu}_\mu$ - *CC* measurement compared to MINERvA-tune



Phys. Rev. Lett. **116**, 071802

Nuclear effects



Nucleons in motion inside the nucleus (Fermi motion) and binding energy

Final State Interactions: additional hadrons, new hadrons, hadrons absorption, hadron kinematics change, etc.

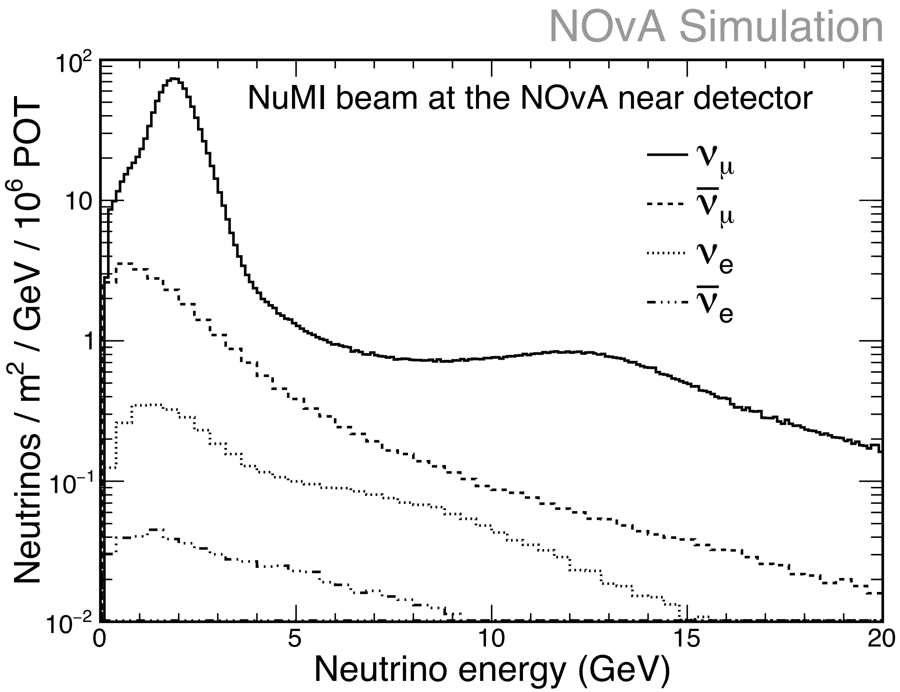
The NOvA experiment

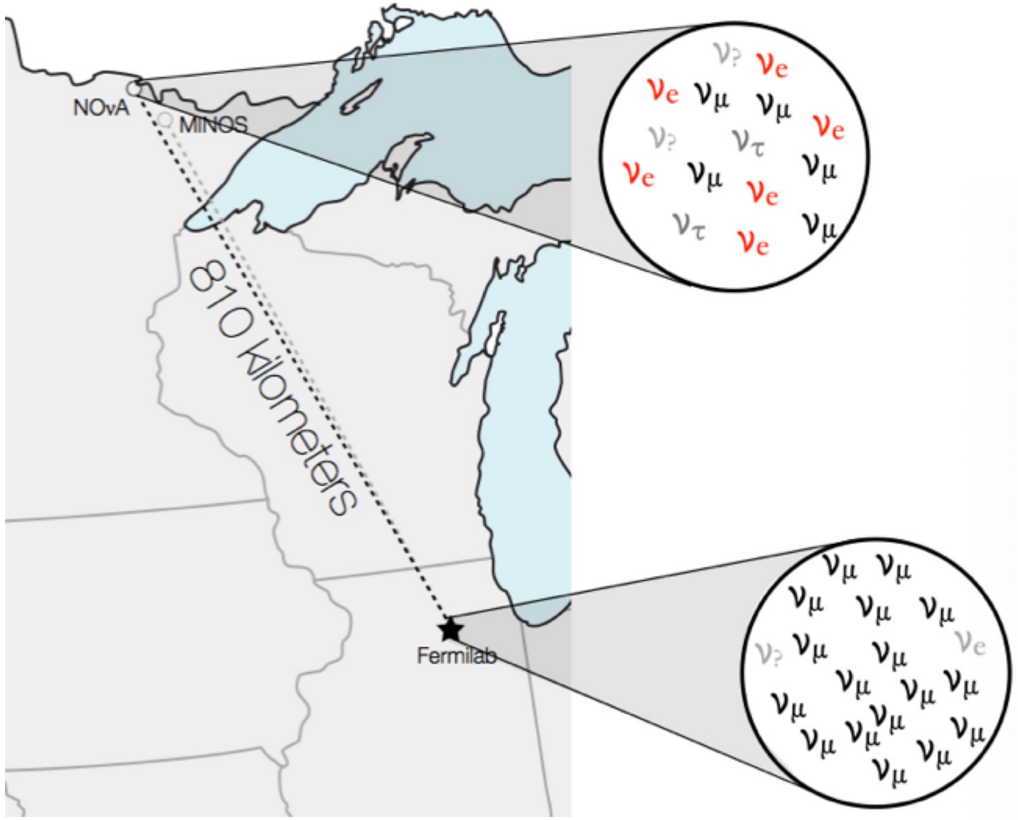
The NOvA experiment

NOvA is a long-baseline neutrino oscillation experiment

2 detectors: 14.6 mrad off-axis and 809 km apart

- *Designed to measure for $\nu_\mu \longrightarrow \nu_e$: detectors provide excellent imaging of both ν_μ and ν_e CC events*



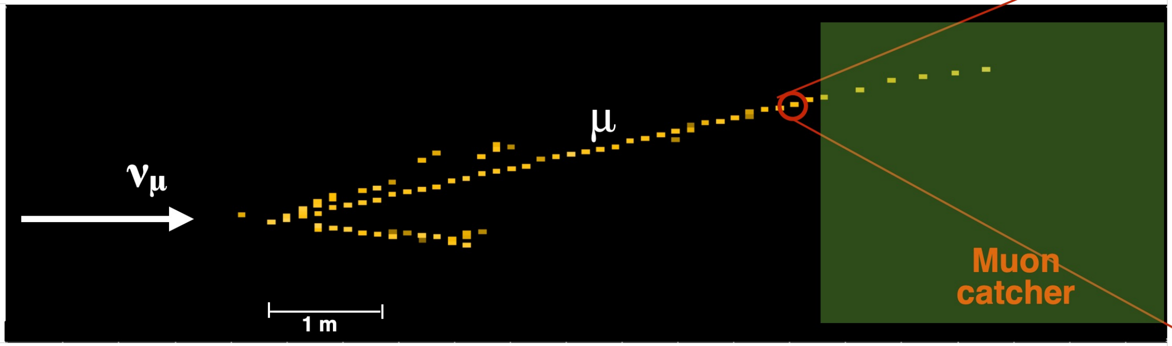


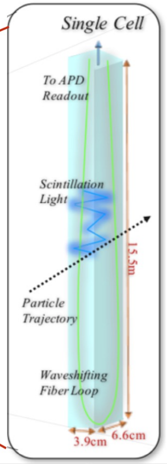
94% pure ν_μ, 5% $\bar{\nu}_\mu$, and 1% $\nu_e + \bar{\nu}_e$ in neutrino mode

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

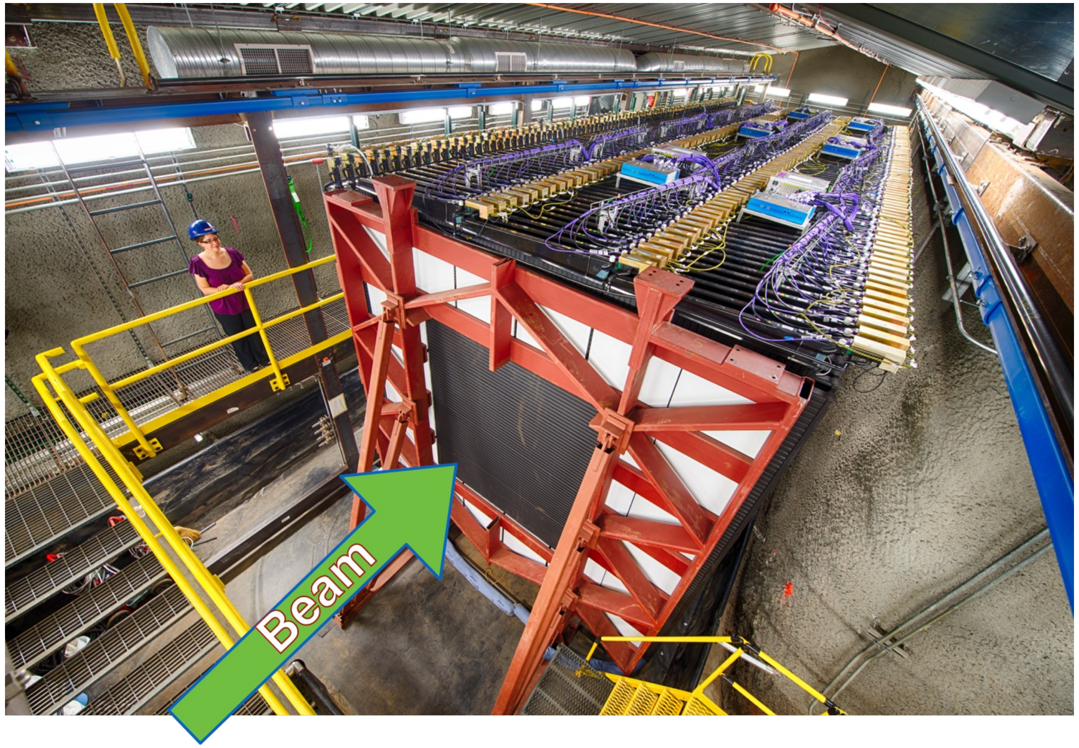
High neutrino flux at the Near Detector *provides a rich dataset for* ***cross-section measurements***

The NOvA near detector





The ND is **1 km** from source, **underground** at Fermilab



PVC cells filled with **liquid scintillator, 195 ton** fully active mass and 98-ton downstream muon catcher

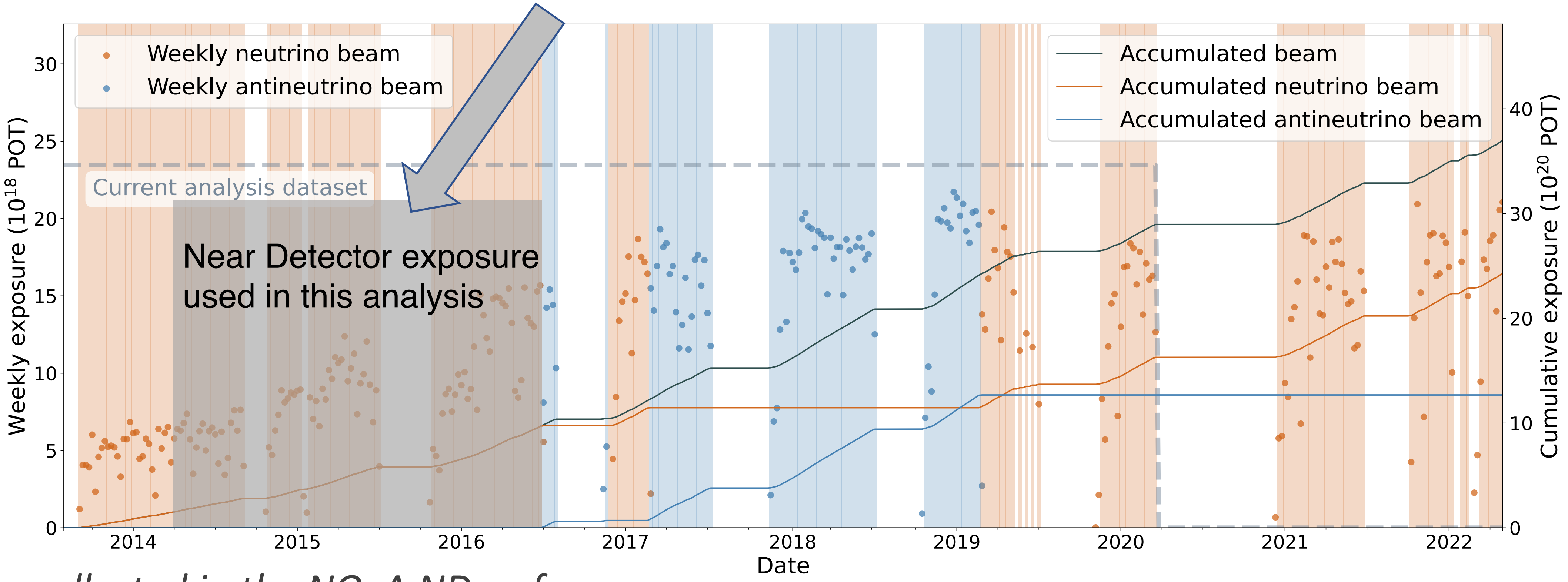
Alternating planes of orthogonal views

Low-Z, fine-grained: Composition by mass:

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

NOvA exposure to NuMI beam

*These analyses use **8.09 x 10^{20} POT FHC** data collected in the NOvA ND during the first couple of years*



Data collected in the NOvA ND so far:

26.76 x 10^{20} POT of neutrino-mode data and 12.76 x 10^{20} POT of antineutrino-mode

NuMI beam will aim 1MW in the next run!

Cross-section model

Neutrino interactions are simulated using GENIE 2.12.2

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

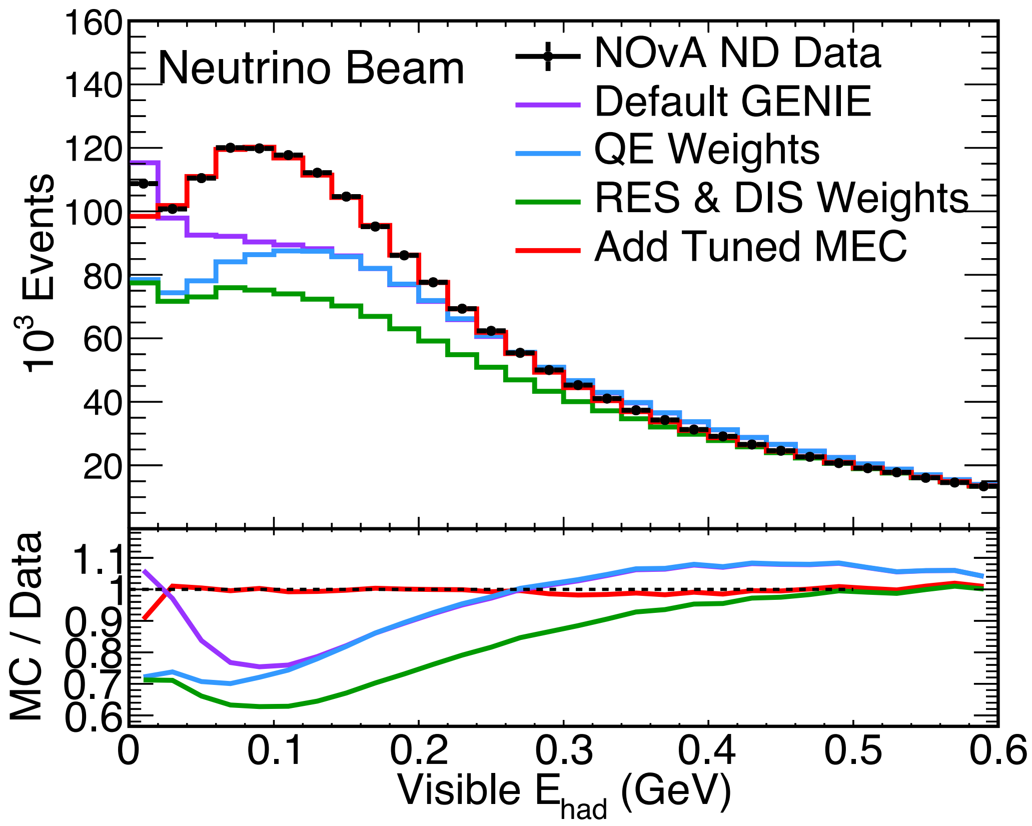
Cross-section model

Neutrino interactions are simulated using GENIE 2.12.2

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

NOvA ND and external data are used to tune the model

- Correct QE to account for low Q^2 suppression
- Apply low Q^2 suppression to Res baryon production
- Non resonant inelastic scattering (DIS) at W>1.7 GeV/c^2) weighted up 10% based on NOvA ND data
- **"Empirical MEC" based on NOvA ND data for 2p2h**



Our analyses are constructed to be insensitive to this tuning

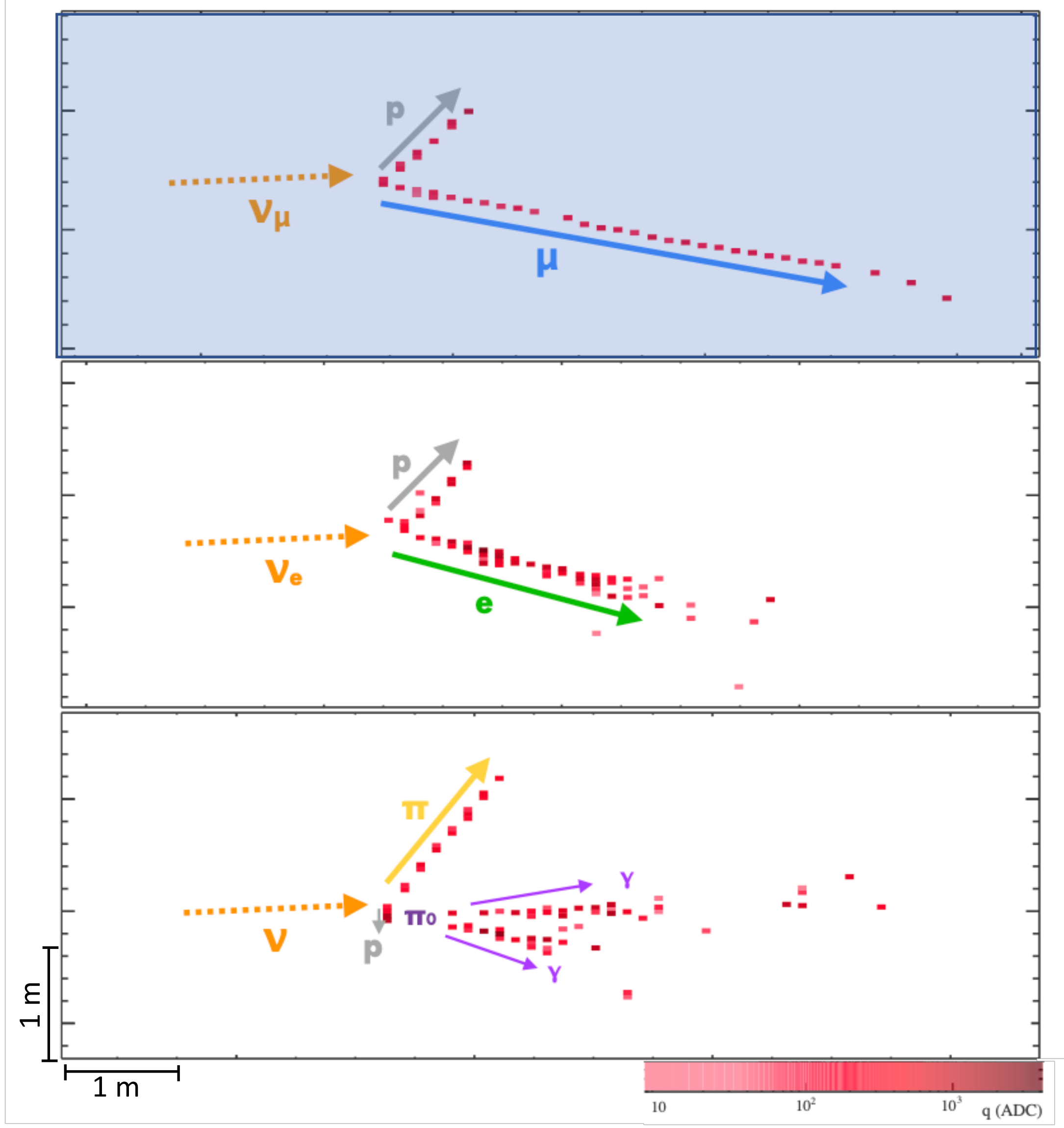
Previous tune that was used in the NOvA 2019 analysis

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

Neutrino interactions in the NOvA ND

Unique environment for cross-section measurements:

- Energy range
- Detector technology
- Statistics



ν_μ - CC

Long, straight muon track

ν_e - CC

Fuzzy shower from electron

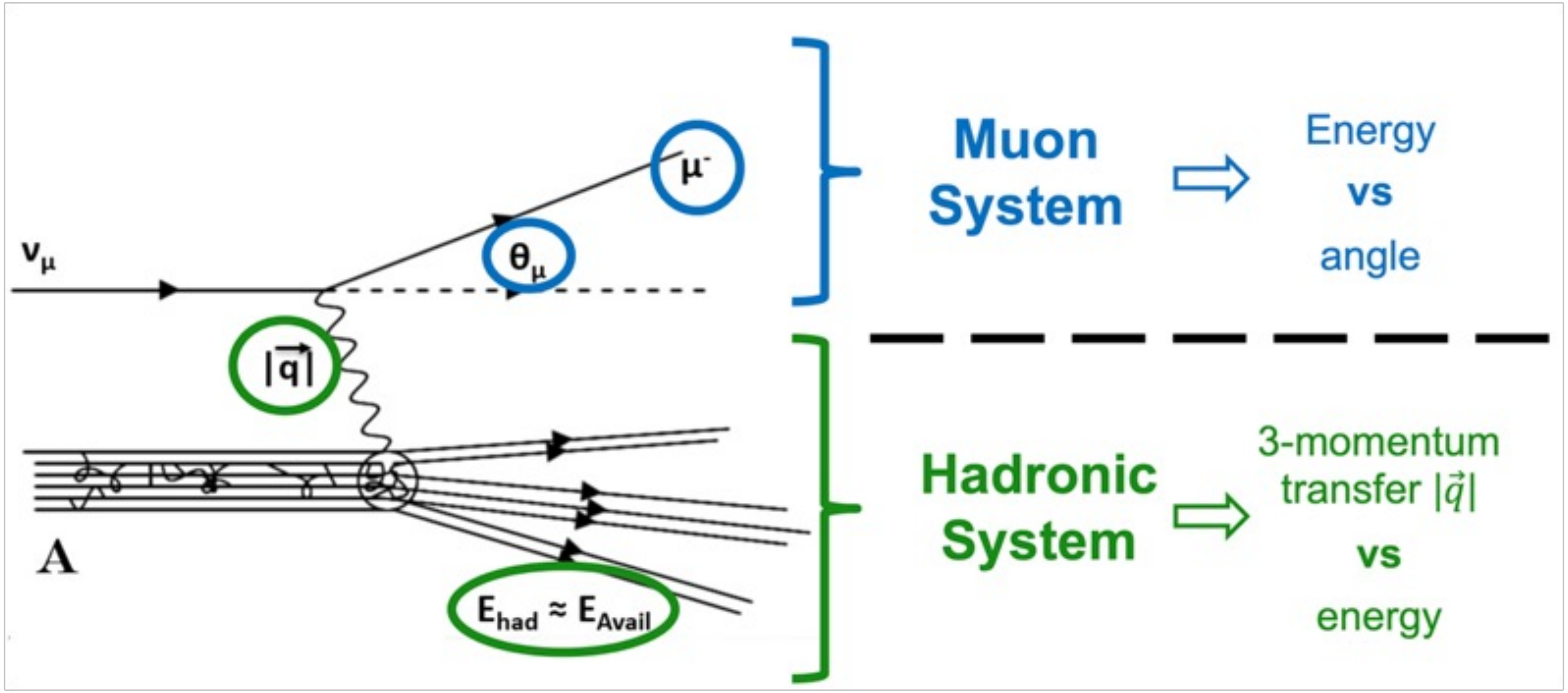
NC

Diffuse activity from nuclear recoil system

This talk

ν_μ – CC cross-section measurements: double differential results

Focusing on sensitivity to 2p2h events



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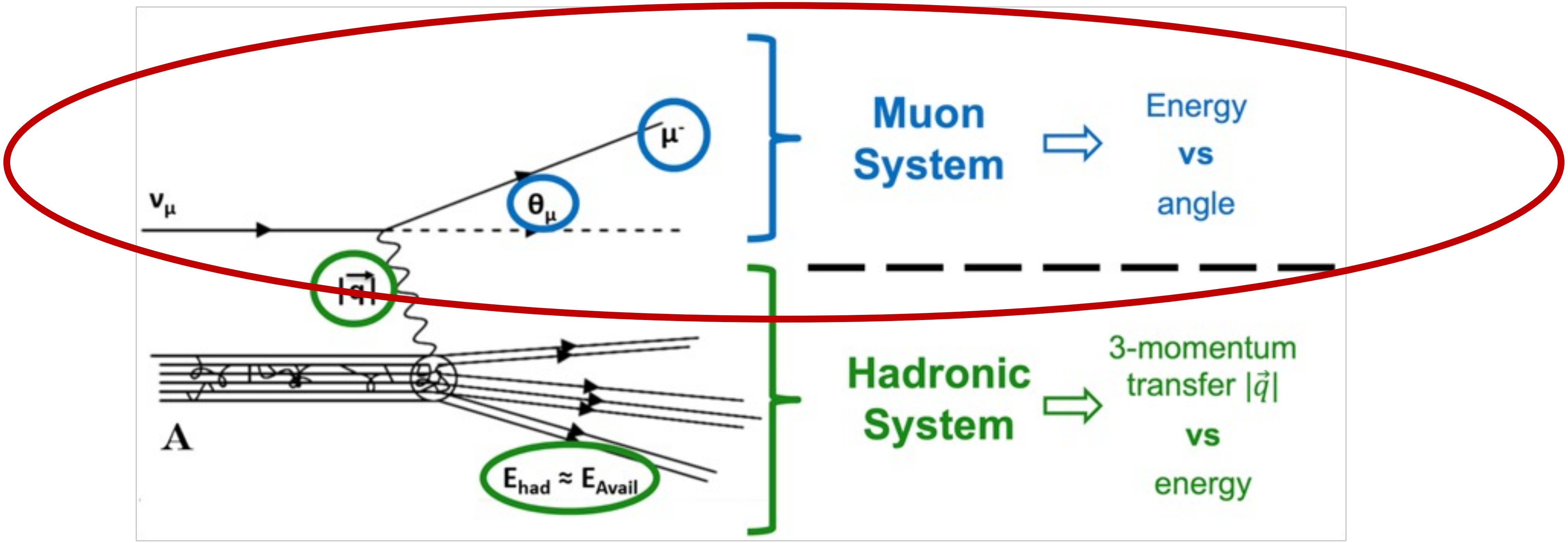
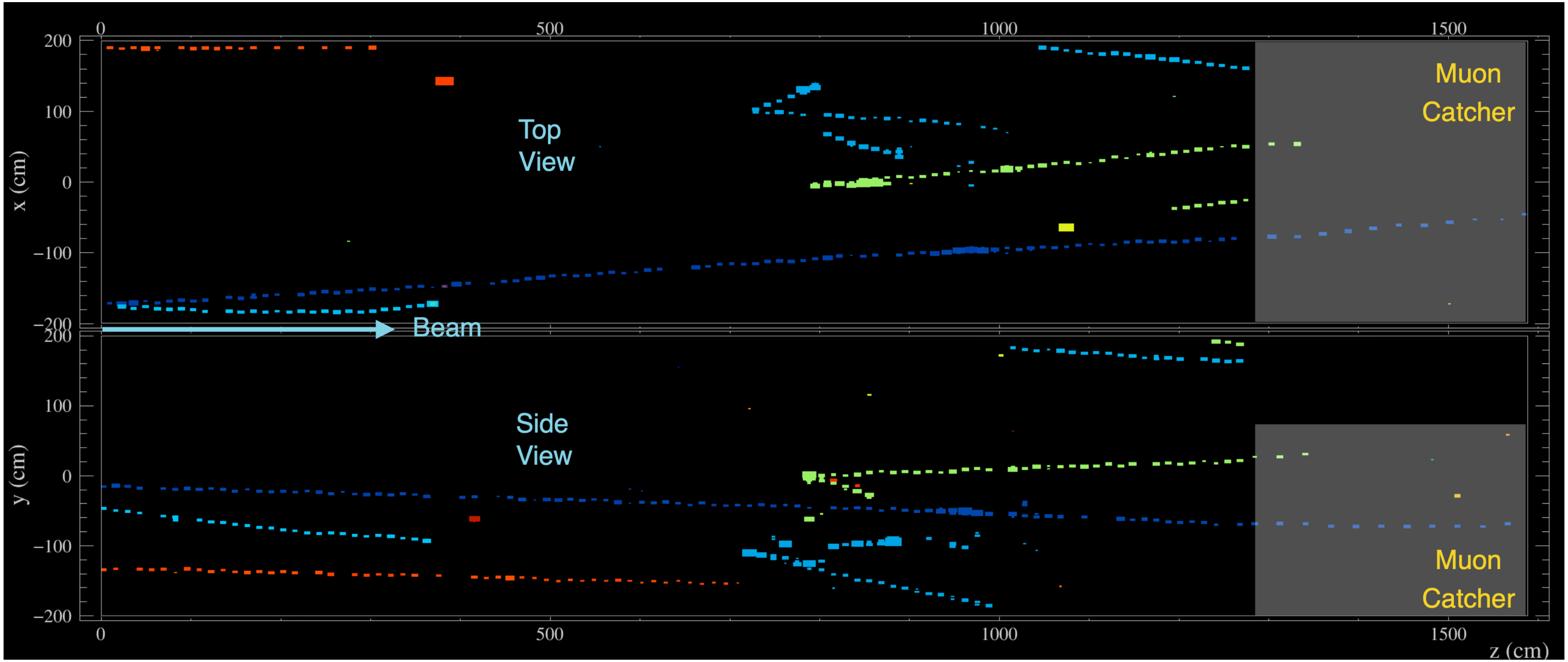
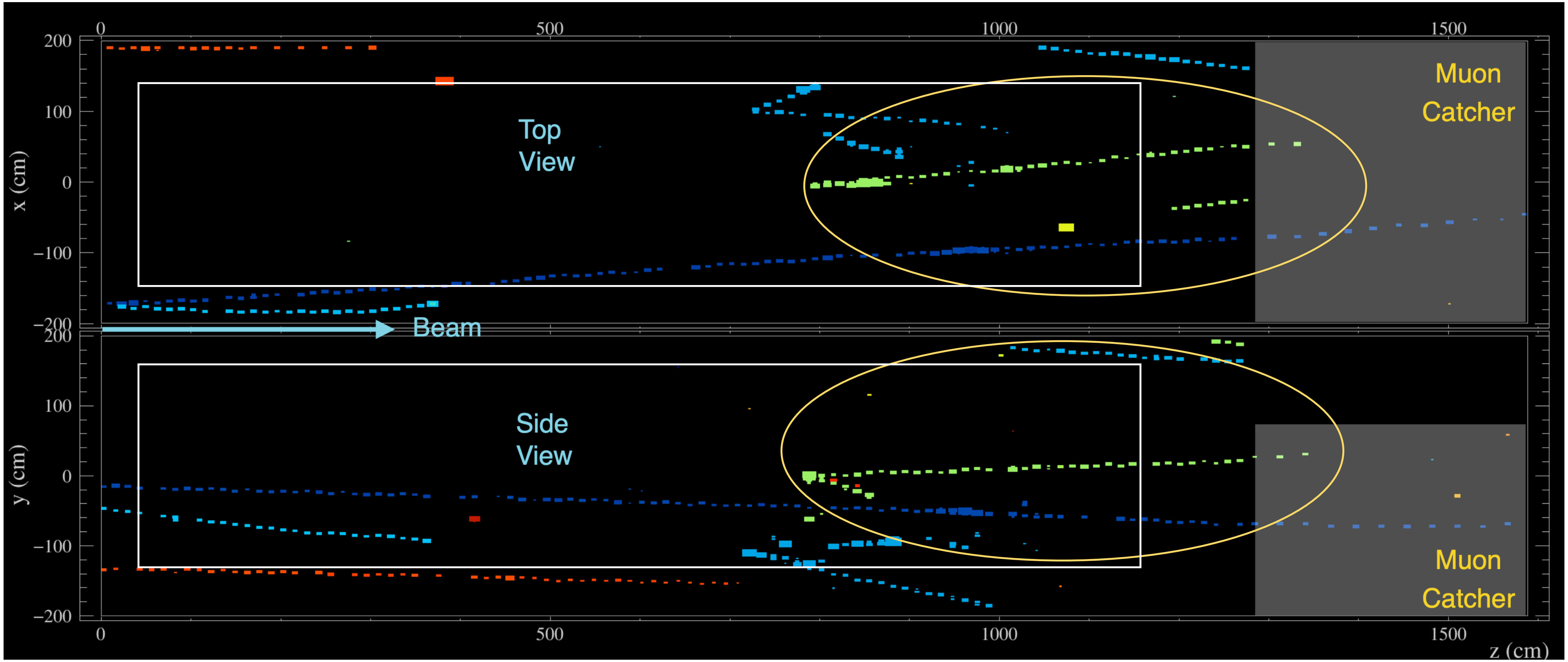


Preselection of event candidates



- Hits associated in time and space are used to form a candidate interaction
- Particle candidates (tracks) are formed from these hits

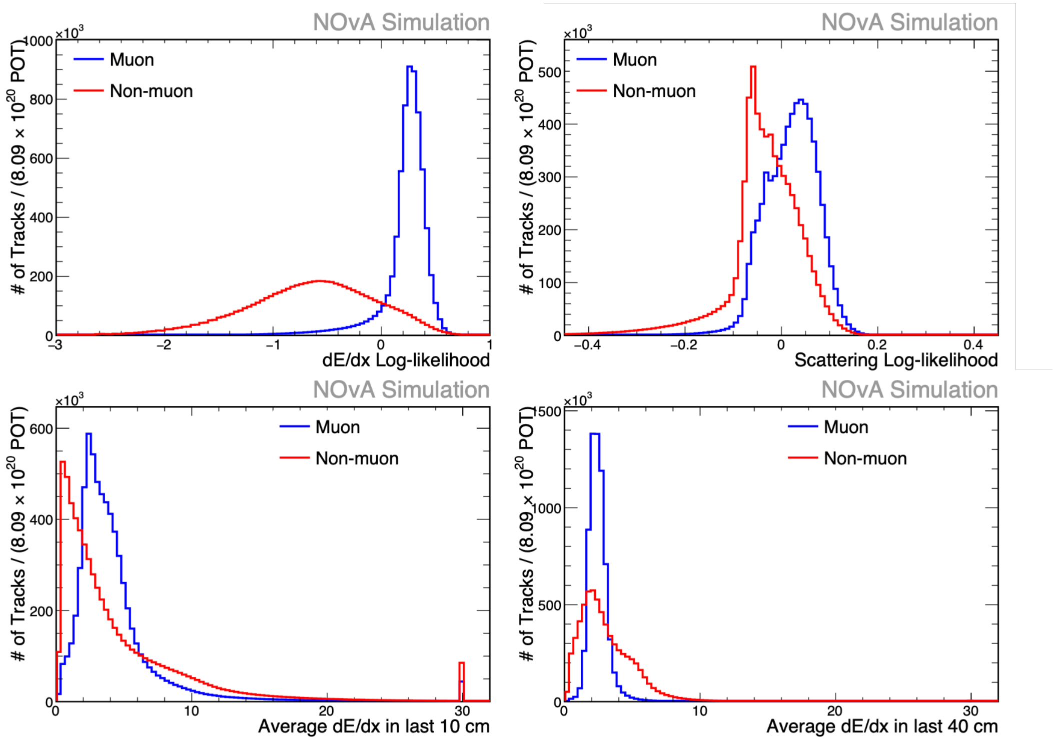
Preselection of event candidates



- Fiducial volume is inside the fully active region. Muons can traverse into the muon catcher.
- Events with hadronic activity in or close to the muon catcher are excluded

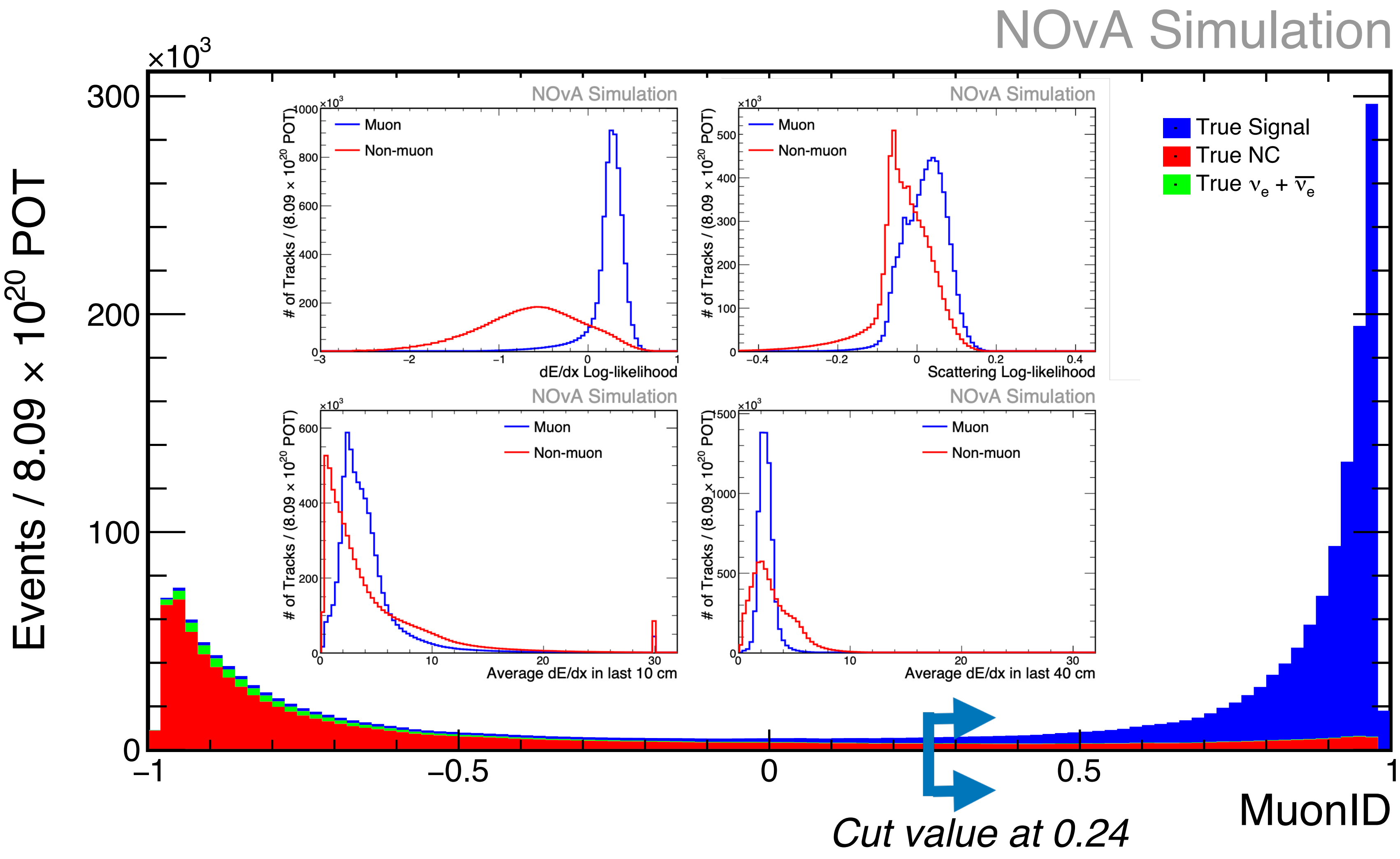
Muon identification

- **Muon ID** calculated with a Boosted Decision Tree



Muon identification

- **Muon ID** calculated with a Boosted Decision Tree
- Optimal cut value is determined to achieve the **minimum shape systematic uncertainty on cross-section** measurement
- Sample has **97% purity** and **~98% efficiency** with respect to preselection



More details in Phys. Rev. D 107, 052011:
(Measurement of ν_μ- CC Inclusive Cross Section in the NOvA ND)

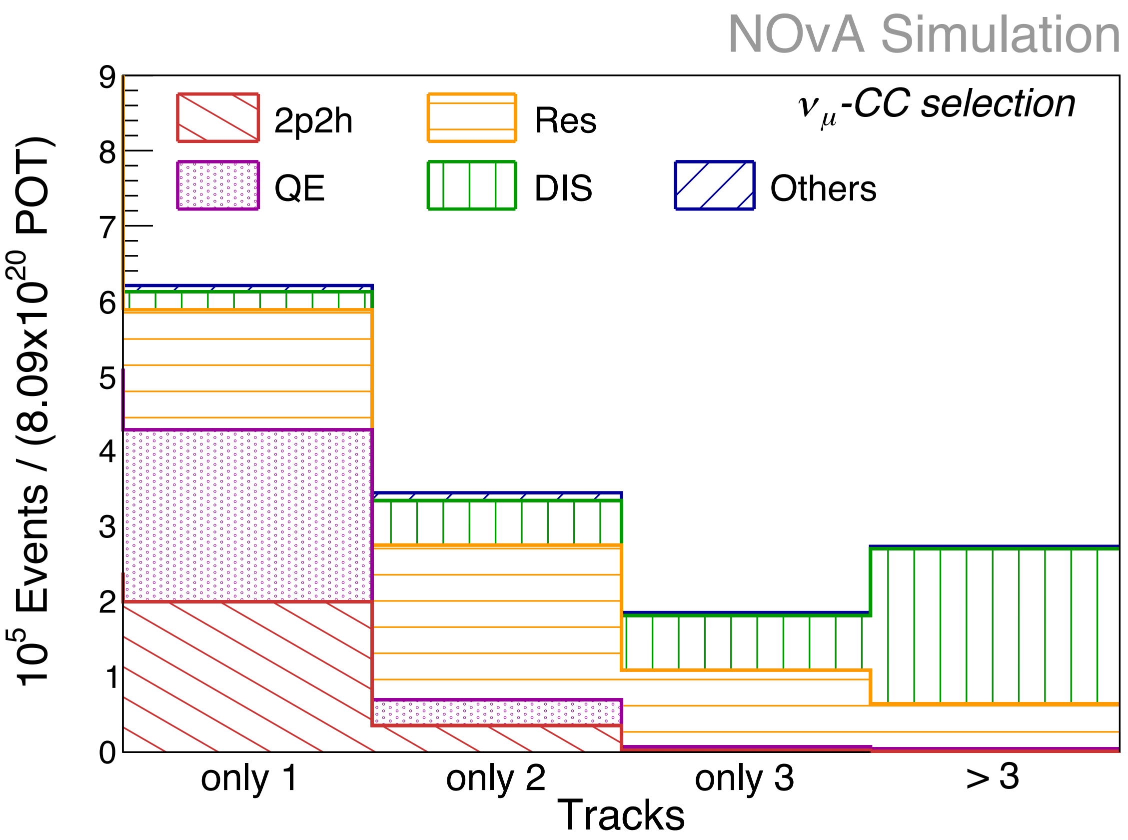
Low hadronic energy measurement

Selection and signal definition

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

We select events with **only a single track** (the muon candidate)

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



Selection:
ν_μ CC with 1 track

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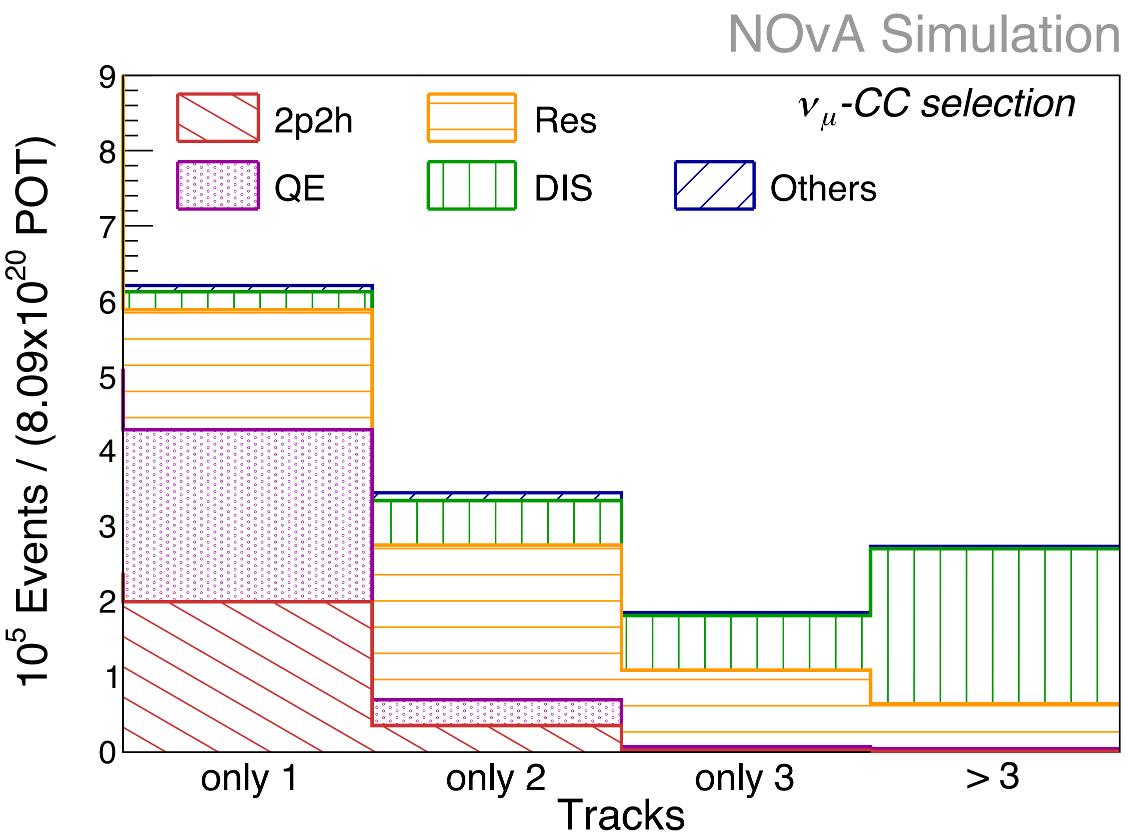
To find the signal definition:
A scan across all possible proton and pion energy thresholds is performed looking for the minimal uncertainty of the total cross section

Selection:
ν_μ CC with 1 track

Signal: *ν_μ CC in the fiducial volume with*
T_{proton}^{max} = 250 MeV
T_{pion}^{max} = 175 MeV



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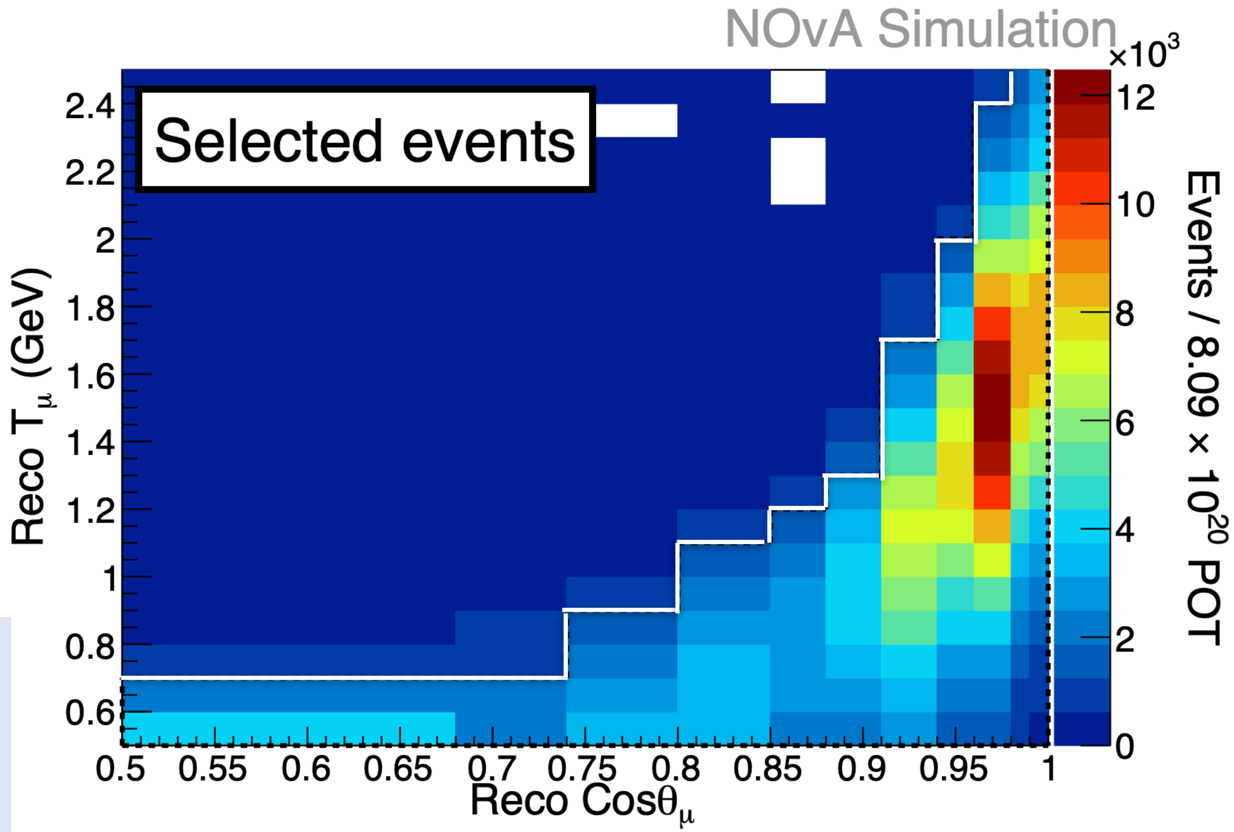


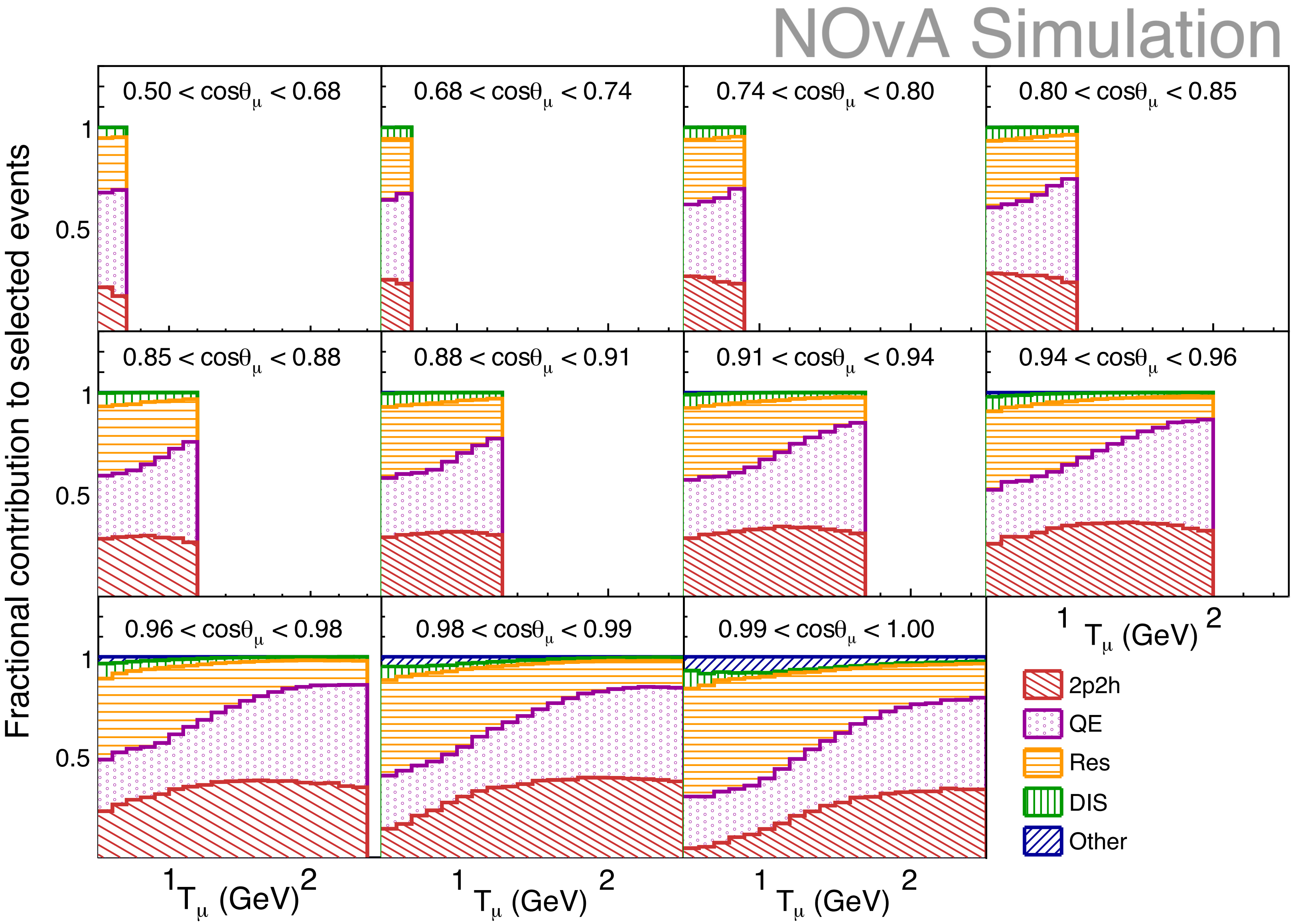
Selection by interaction modes

The selection enhanced **QE** and **2p2h**

Res is reduced with respect to the inclusive sample but still has large population, especially at lower muon energies

DIS is negligible

QE	2p2h	Res	DIS	COH
39.7%	33.7%	23.0%	2.5%	1.1%



Analysis

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu\, dT_\mu}\right)_i = \frac{1}{N_\mathrm{T}\,\phi} \sum_{E_{avail}} \frac{\sum_j U_{ij}^{-1}[N_{\mathrm{sel}\,j}\, P_j]}{\epsilon_i\, \Delta\cos\theta_{\mu_i}\, \Delta T_{\mu_i}}$$

Analysis is done in (T_μ, $\cos\theta_\mu$, E_{avail}) and then projected to ***muon kinematics***

Available energy (E_{avail}): *total energy of all observable final state hadrons*

- ***Variable pioneered by MINERvA (Phys. Rev. Lett. 116, 071802 (2016))***

Analysis

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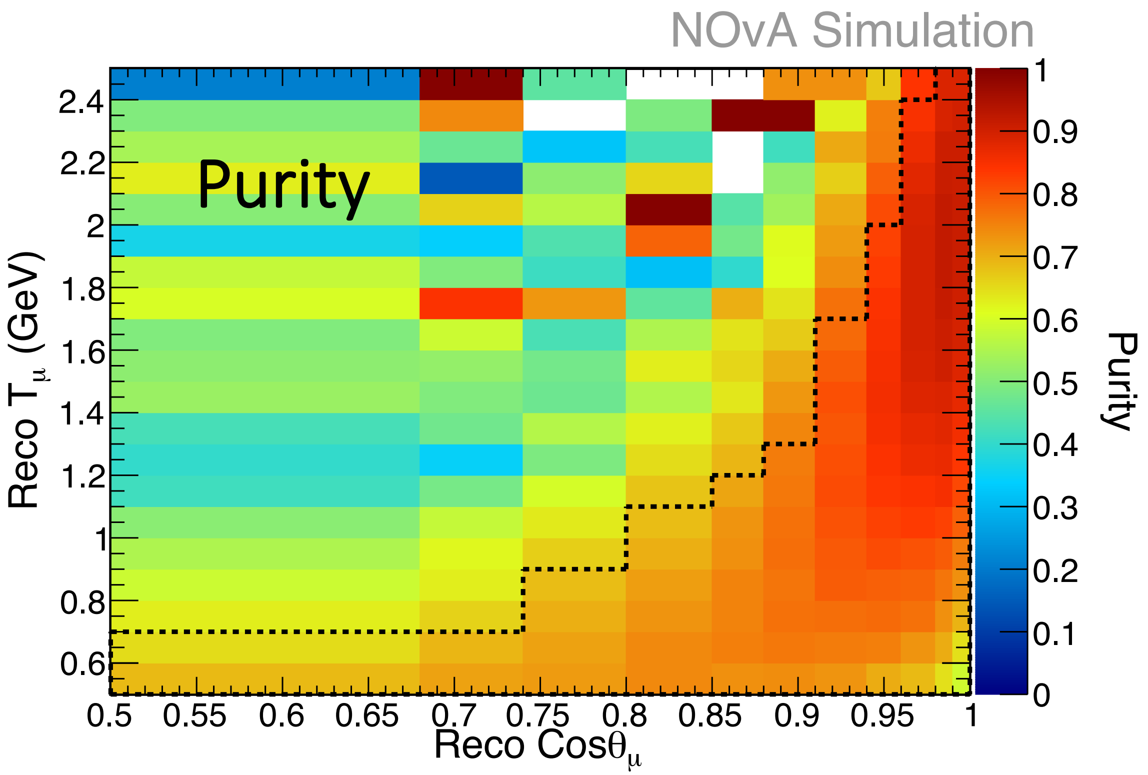
Purity ranges from 60% - 90%.

The background is estimated using the simulated purity

Main backgrounds are

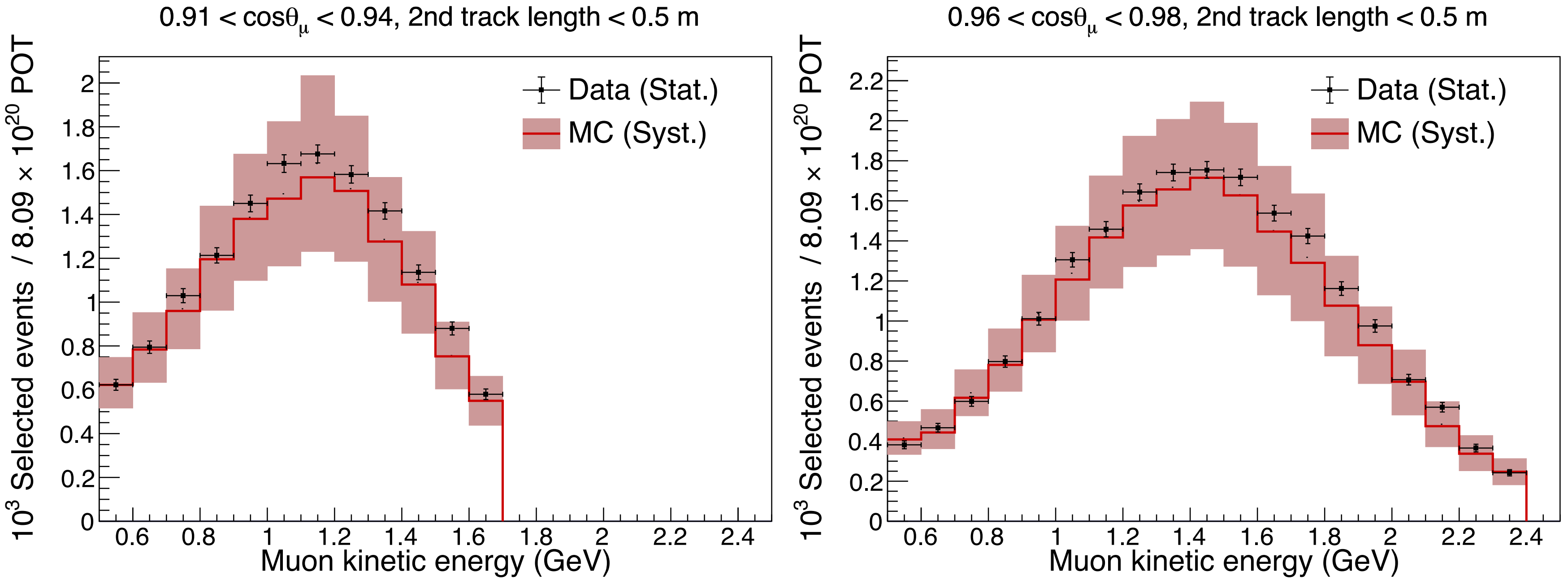
- *Events with at least 1 pion or 1 proton above the signal definition threshold*



Sideband (2 cosine slice samples)

The purity estimation was validated by sideband studies with **events with two Kalman tracks**:

- the muon candidate plus 1 short track (< 50 cm)
- shorter lengths are in the region where the Kalman algorithm is less efficient in forming a track



All data yield bins fall within the systematic error band and are close to the simulation's central value.

Composition:

Signal	Above threshold	$\bar{\nu}_\mu$ CC	NC + ν_e CC
31.4%	58.6%	11.5%	1.5%

Mostly Res (59.5%) and DIS (11.9%)

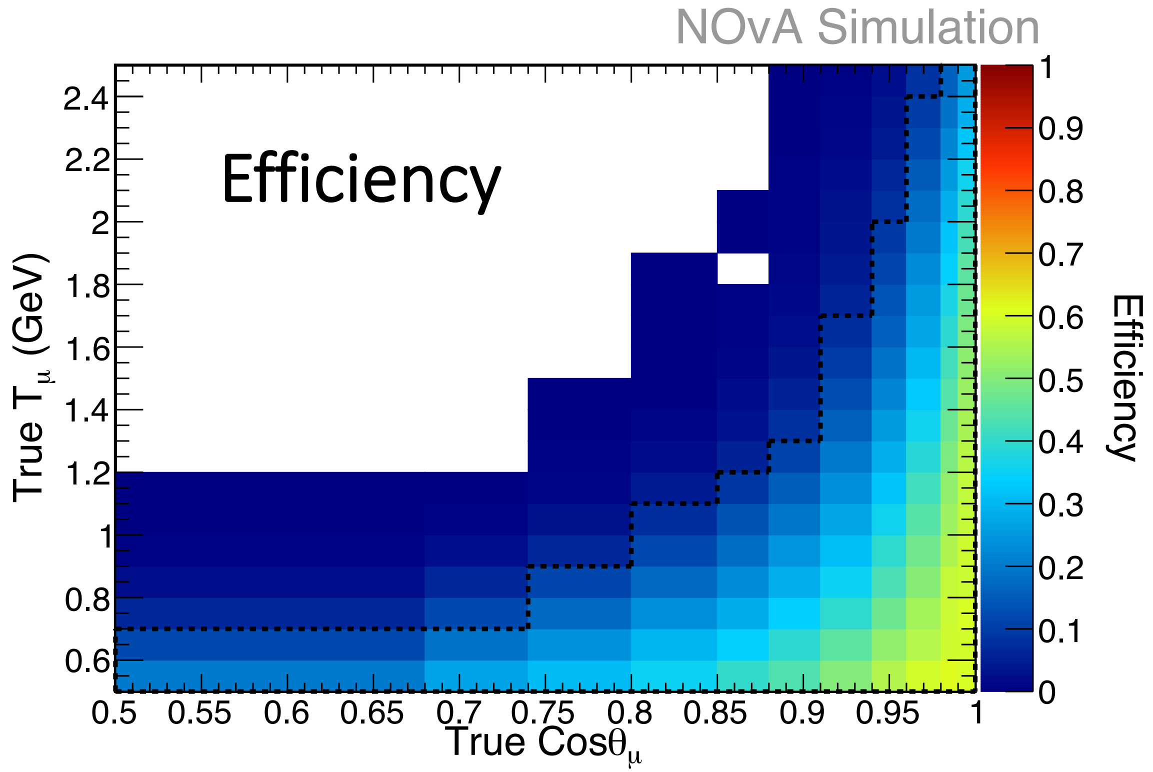
Analysis

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu\, dT_\mu}\right)_i = \frac{1}{N_\mathrm{T}\,\phi} \sum_{E_{avail}} \frac{\sum_j U^{-1}_{ij}[N_{\mathrm{sel}j}\, P_j]}{\epsilon_i \Delta\cos\theta_{\mu_i}\, \Delta T_{\mu_i}}$$

Unfolding technique (D'Agostini) is used to correct the smearing between bins due to detector and reconstruction effects

Correction of the efficiency is applied due to detector acceptance

Efficiency distribution is primarily due to the containment requirement (muon exiting)



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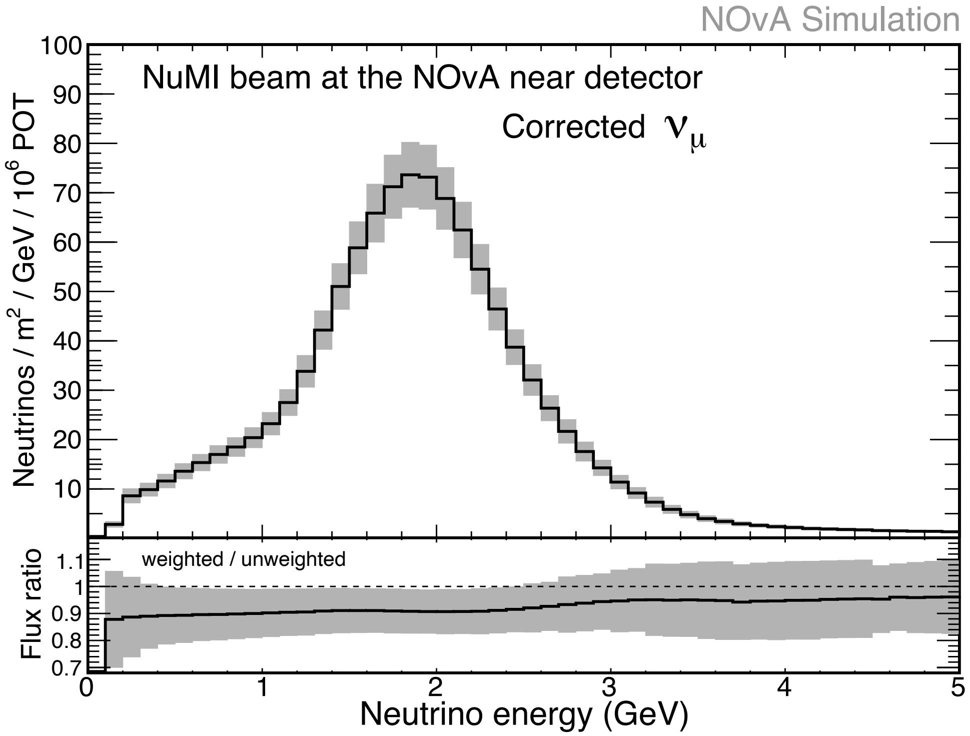
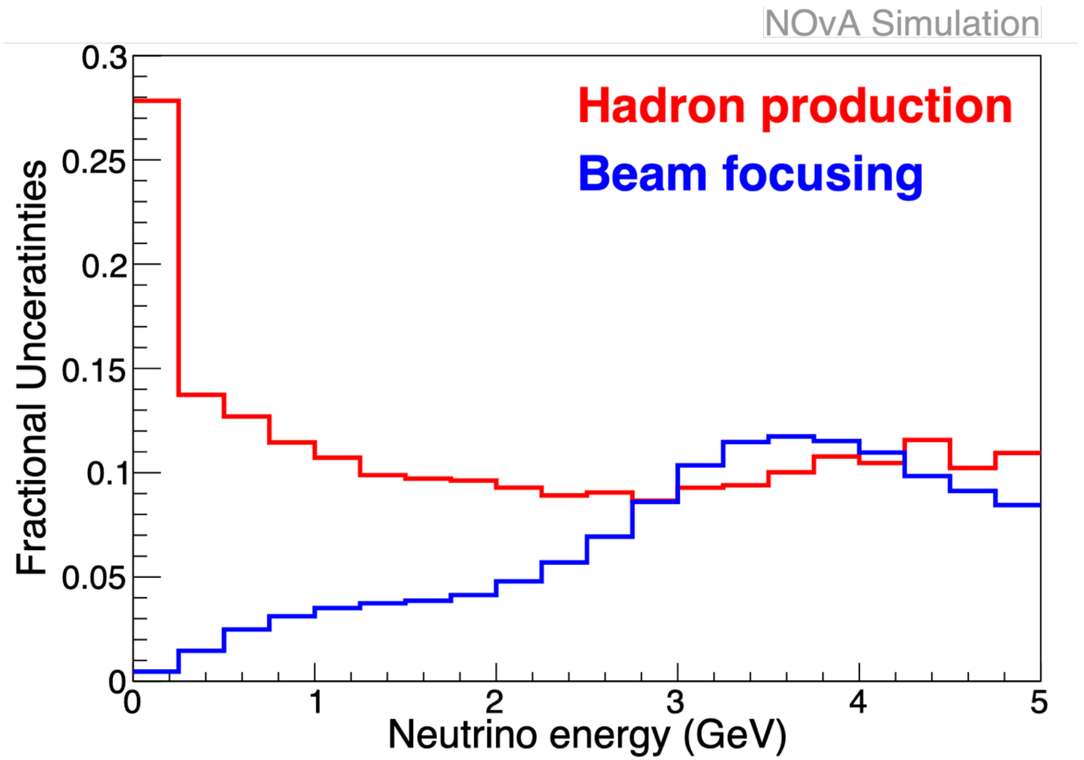
NuMI beam prediction

Hadron production model is constrained with external measurements on thin target data (NA49)

- *Same technique used by **MINERvA** (Phys. Rev. D94, 092005)*
- *The uncertainty based on these external measurements results in a **~10% normalization uncertainty***

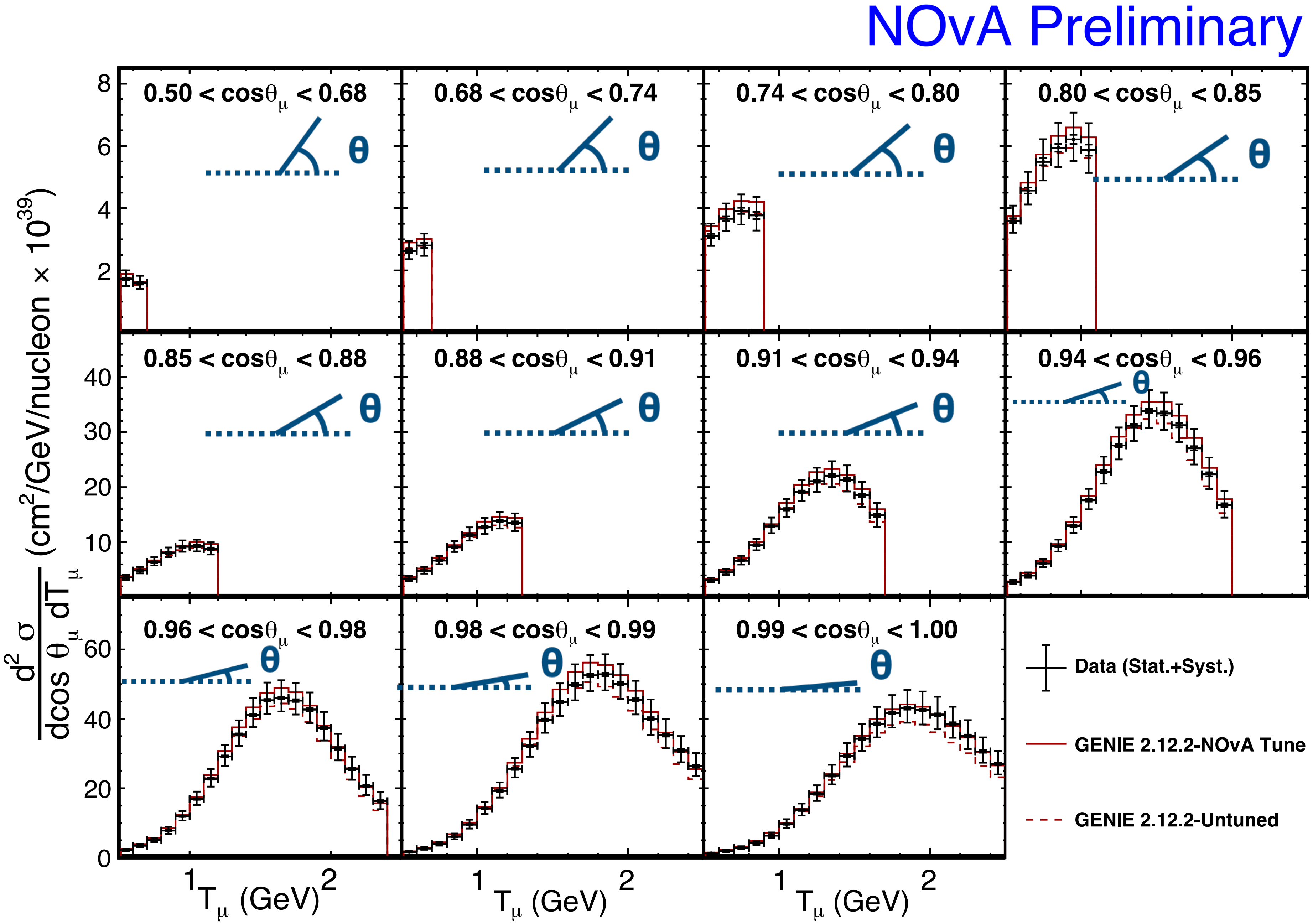
Beam focusing uncertainty is sub-dominant around the peak (below 2.5 GeV)





Results for the low hadronic measurements

Results in muon kinematic



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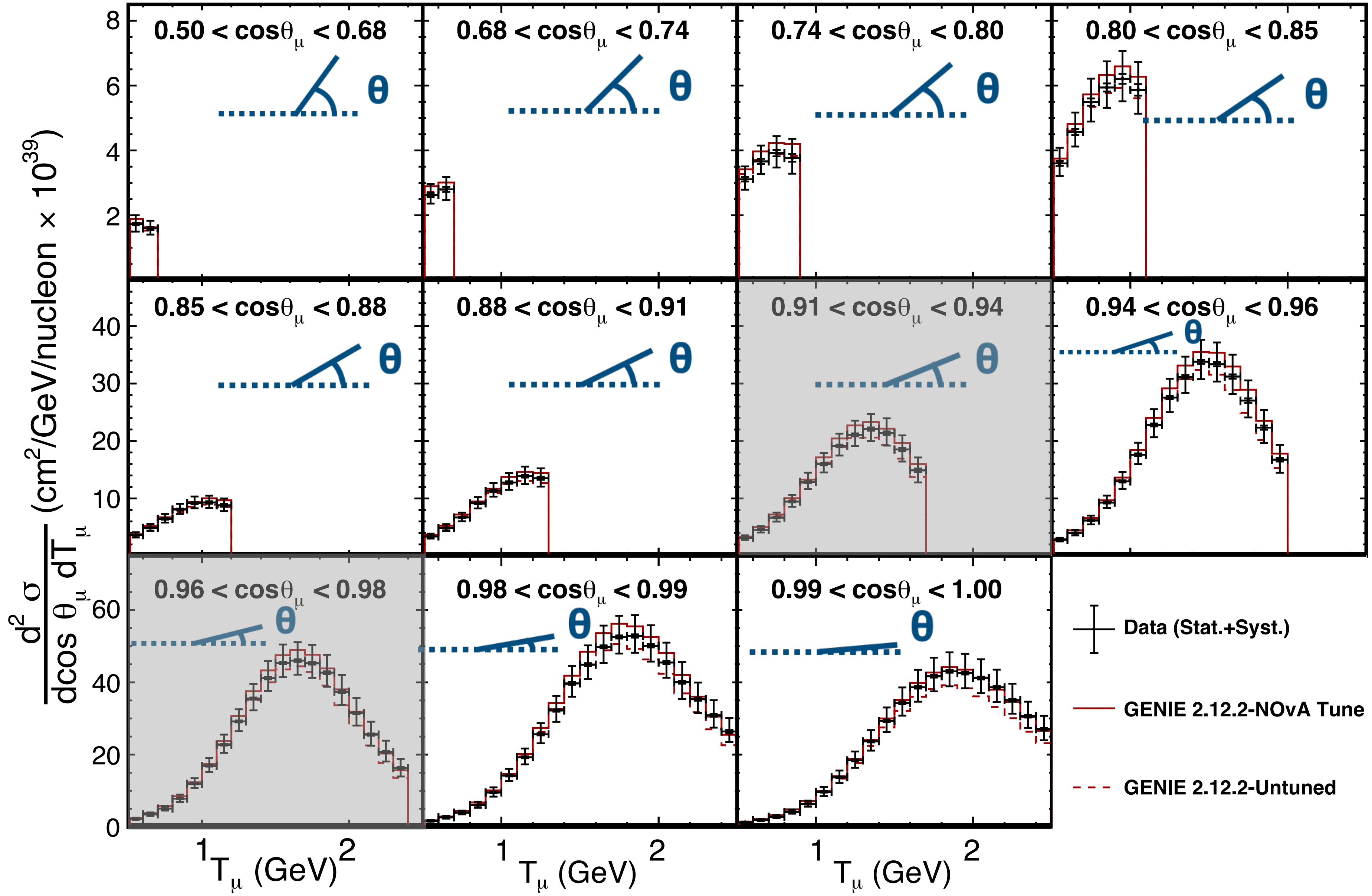
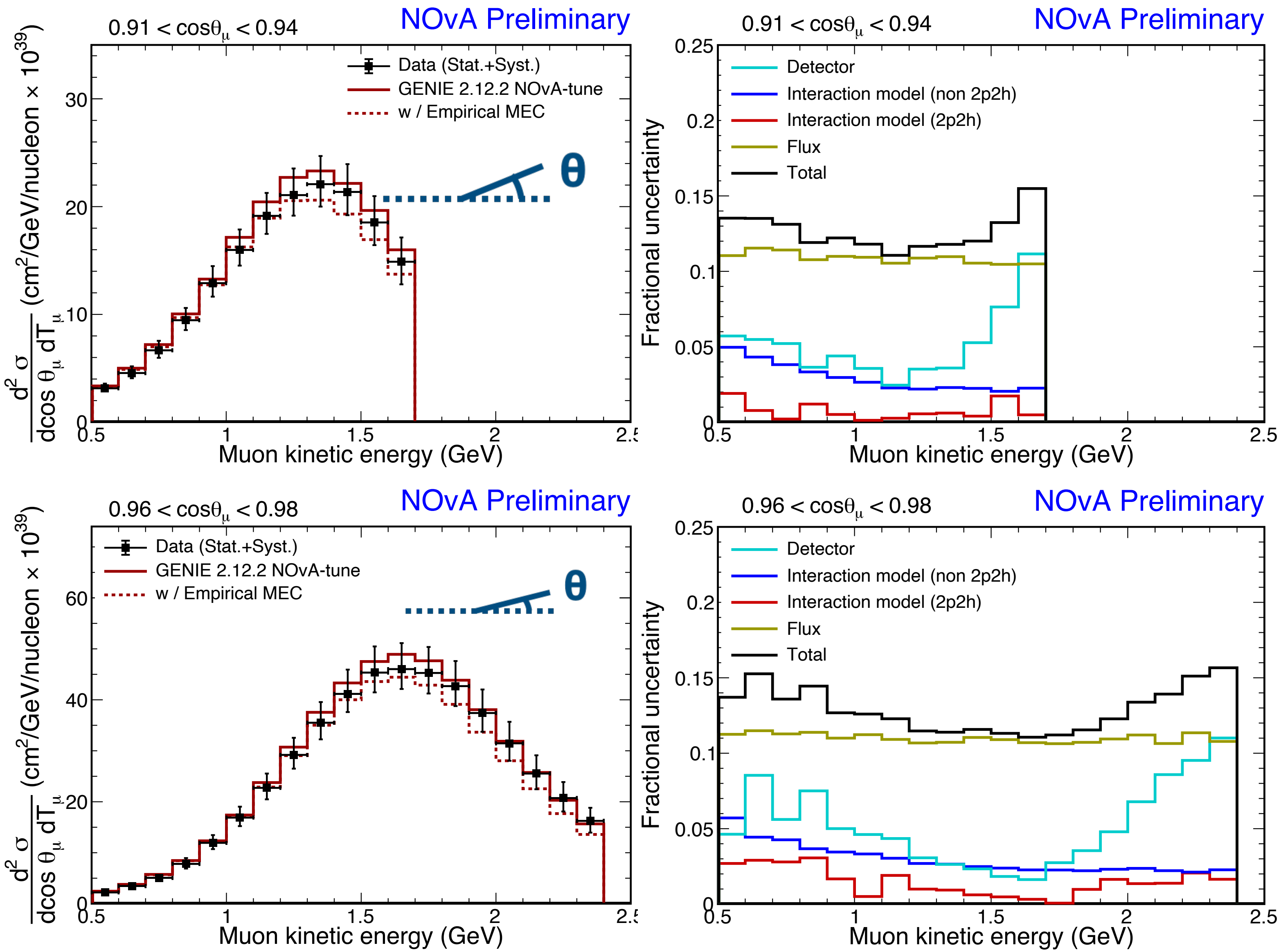


2 cosine slice samples



The dominant systematic is the **flux**:

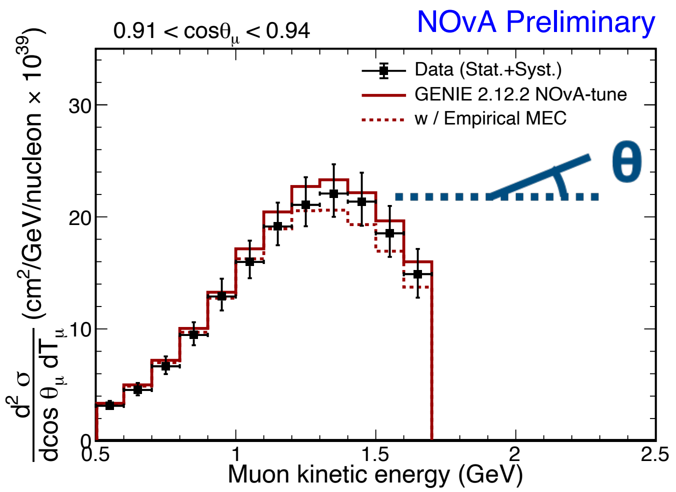
- hadron production (~10%)
- focusing uncertainties (~4%)

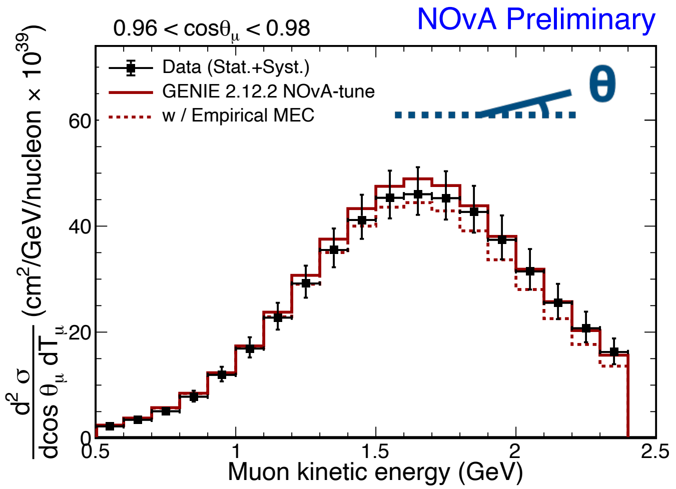
The non-2p2h neutrino interaction uncertainties are calculated with:

- GENIE tunable physics parameters
- shifts based on external data

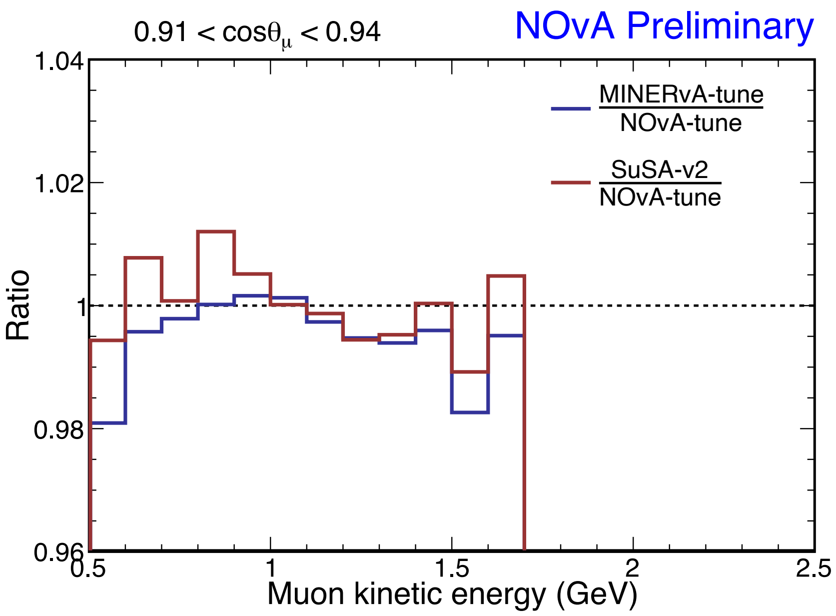
The **detector response** uncertainty comes from the calibration and the light model

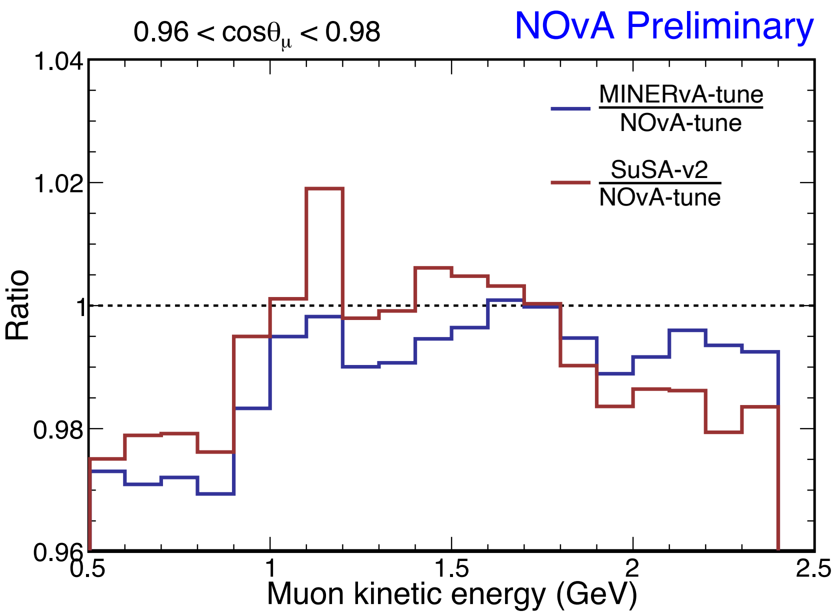
2 cosine slice samples





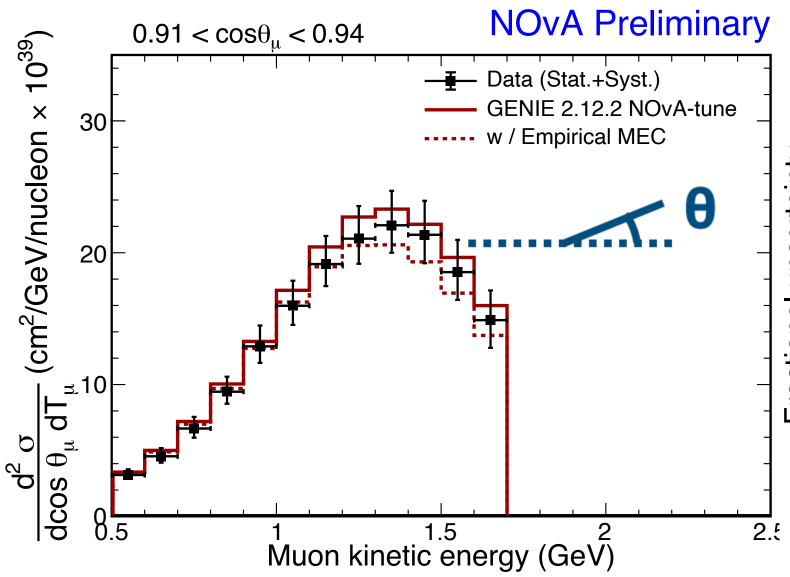
The 2p2h uncertainties are derived *as the spread when recalculating the cross section using SuSAv2 and the MINERvA-tune**

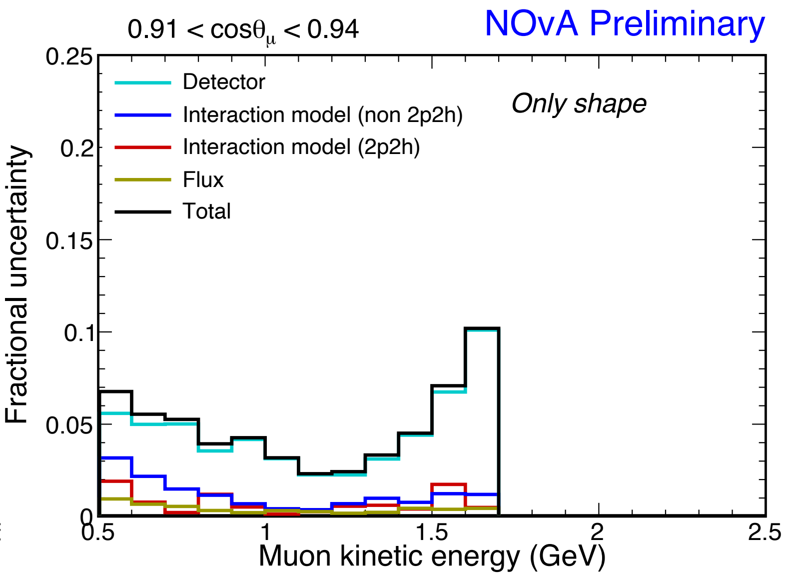


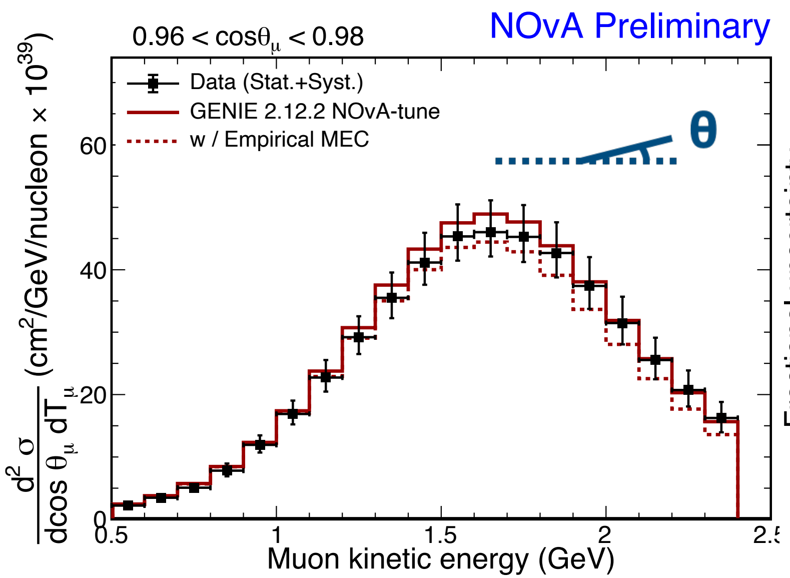


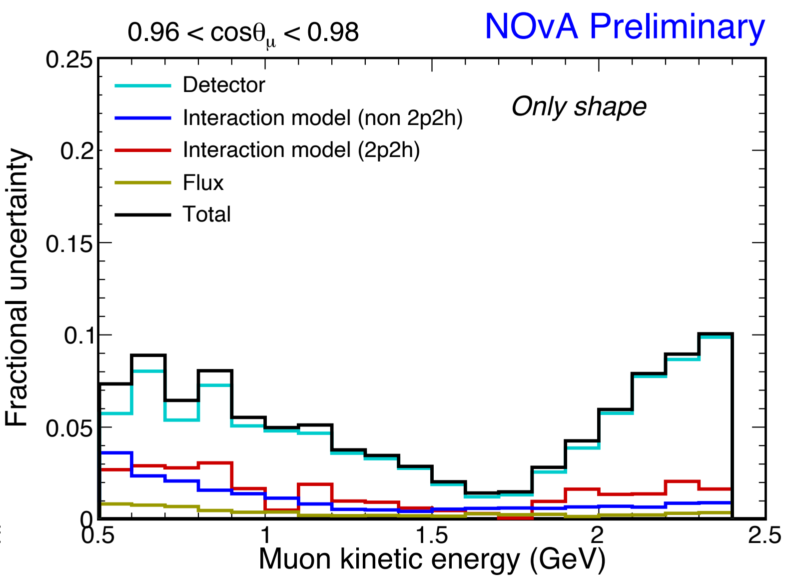
(*) We used MnvTune-v1.2

2 cosine slice samples (shape only uncertainties)









The flux uncertainties are negligible in the shape-only analyses

The neutrino interaction uncertainties are subdominant

The dominant uncertainty is the **detector response** uncertainty:
- especially at low and high muon energies

Comparison of our results using different 2p2h models

We implement new simulations by replacing the 2p2h NOvA-tune with 4 other models:

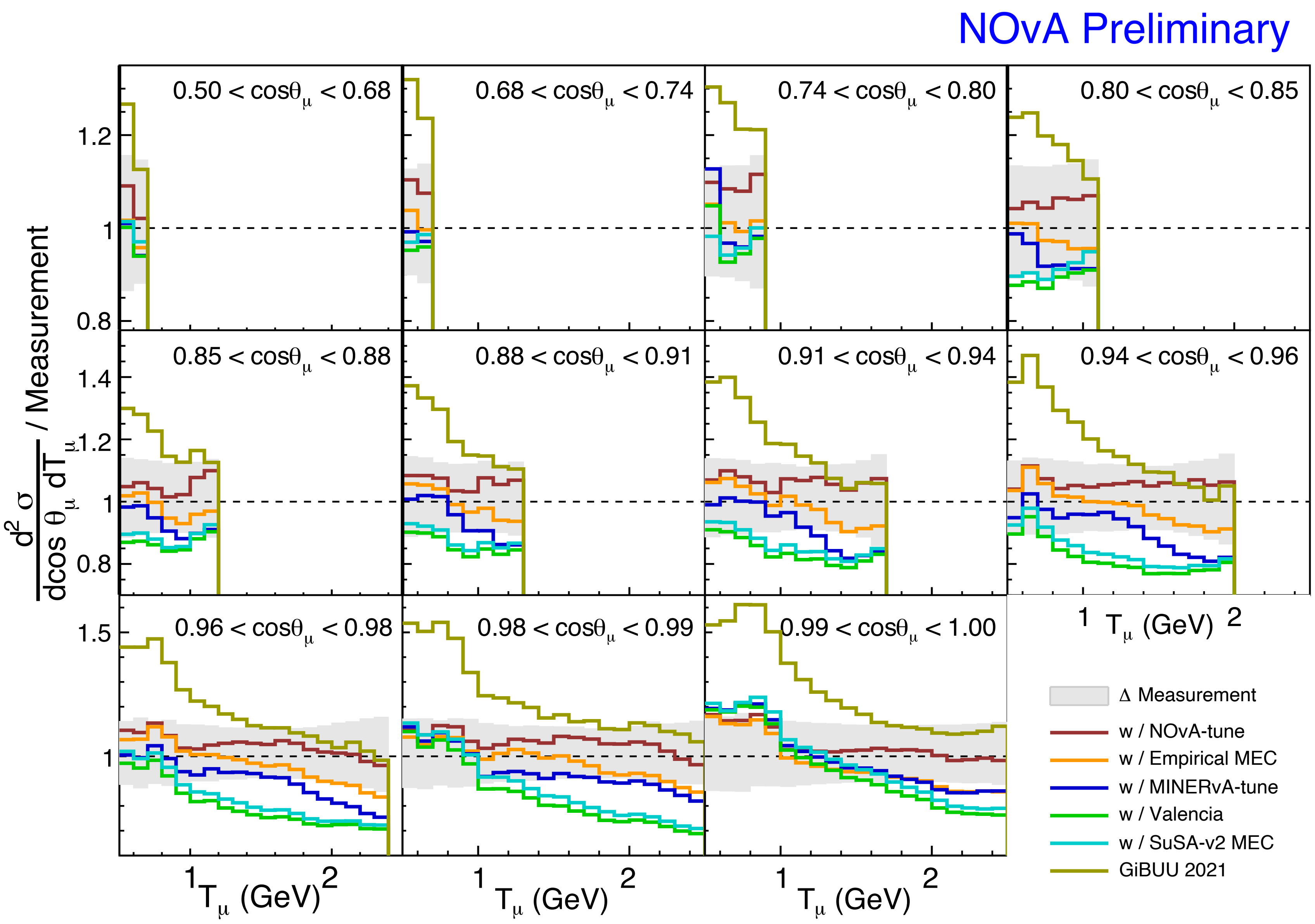
Empirical MEC, MINERvA-tune, SuSAv2 and Valencia

GiBUU 2021 is out-of-the-box

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

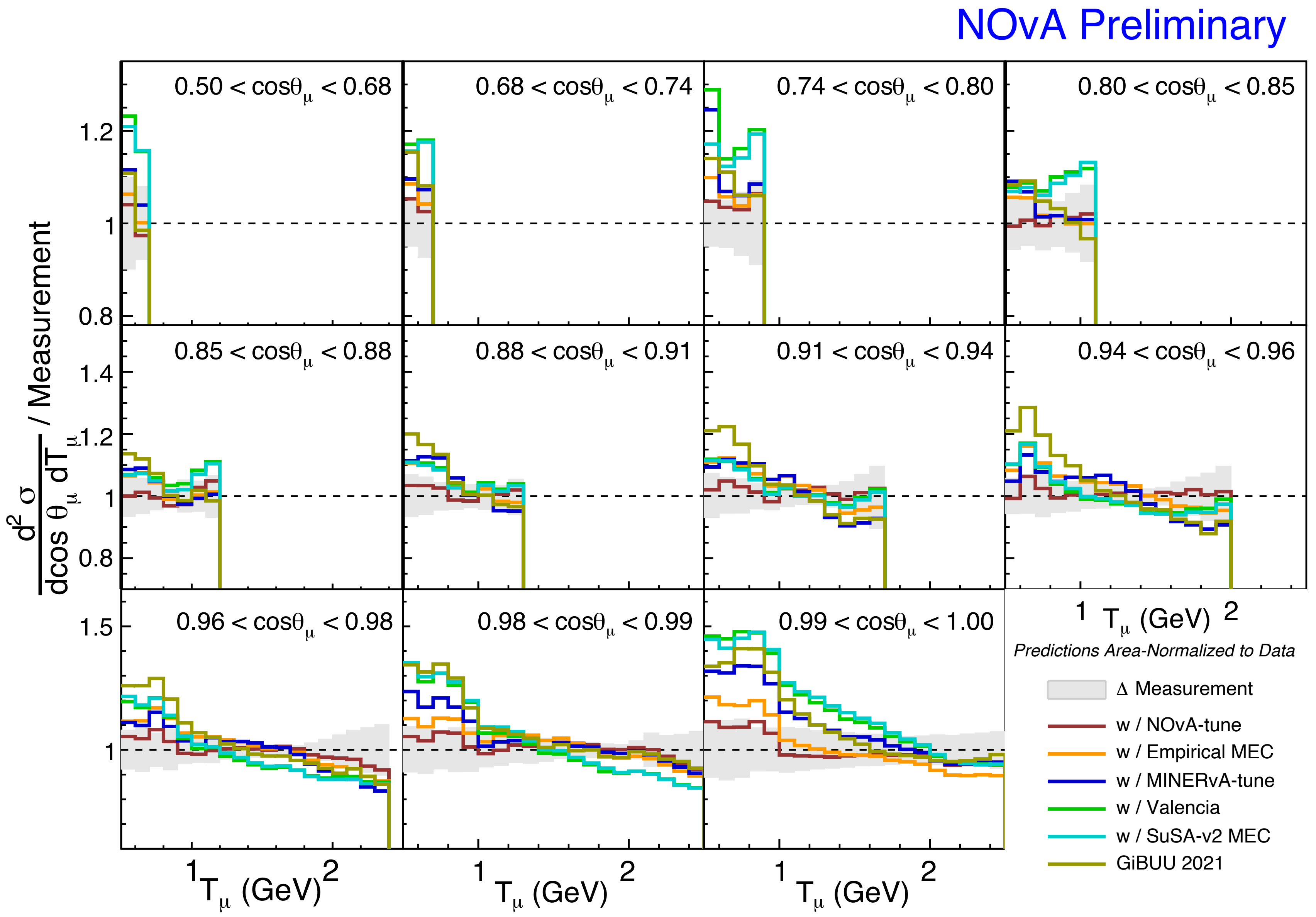


Comparison to 2p2h models

Shape only uncertainties

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

- Most of the models (except the NOvA-tune) predicts different cross-section shapes for this analysis

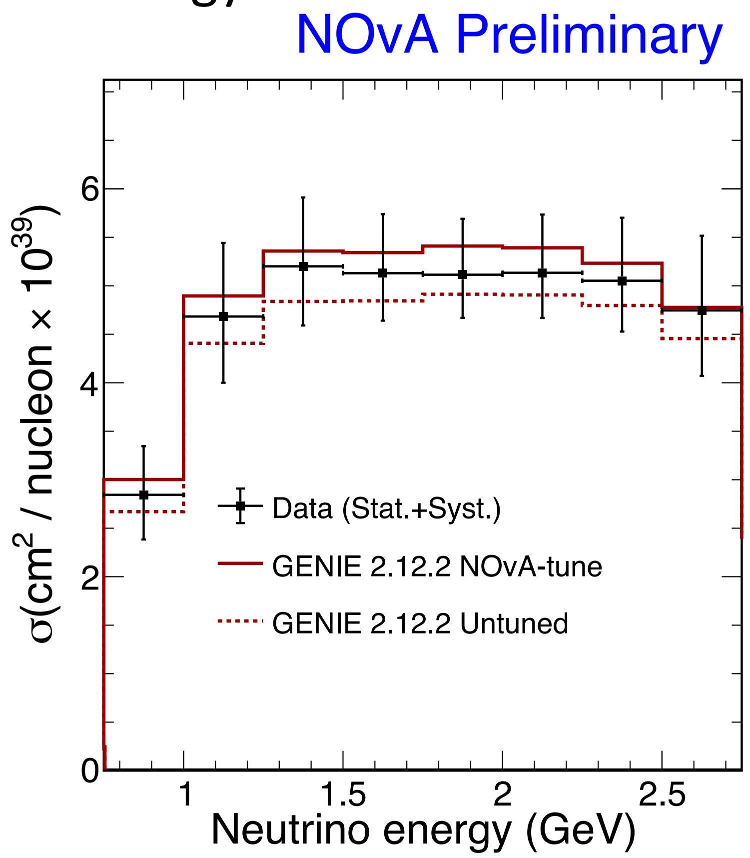


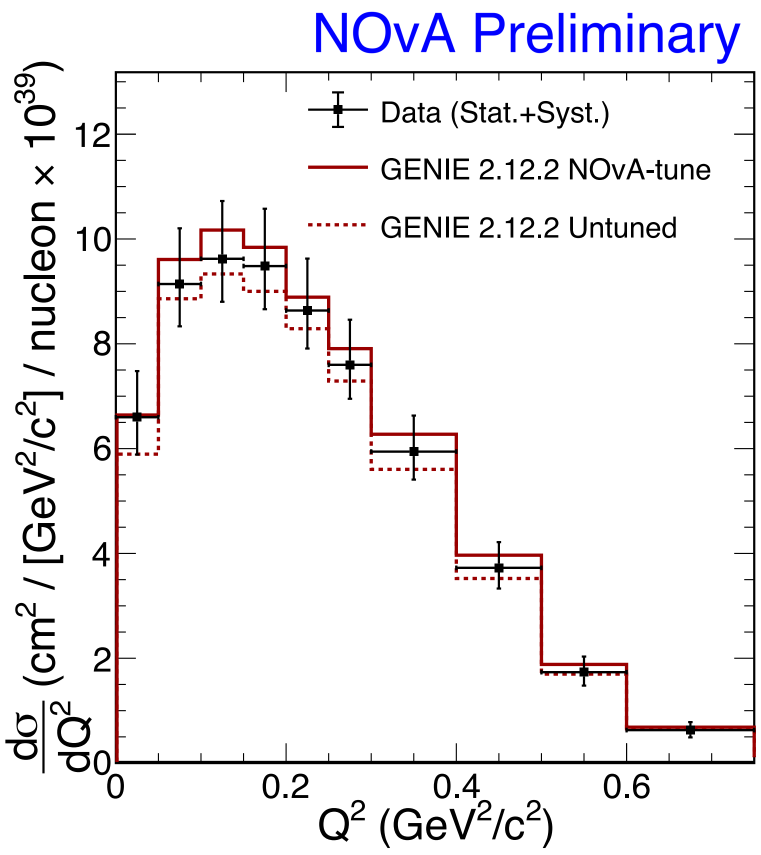
Results in 1-D derived variables

Results in derived variables

E_ν and Q^2 cross sections are limited to the phase space of the muon kinematic measurement

These are calculated as combinations of the reconstructed muon energy and the visible calorimetric energy



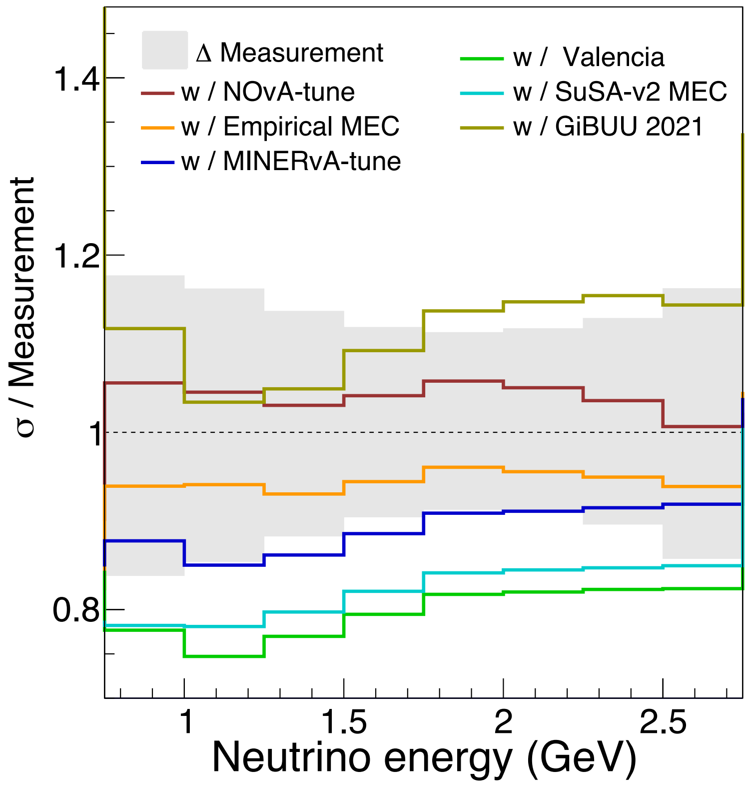


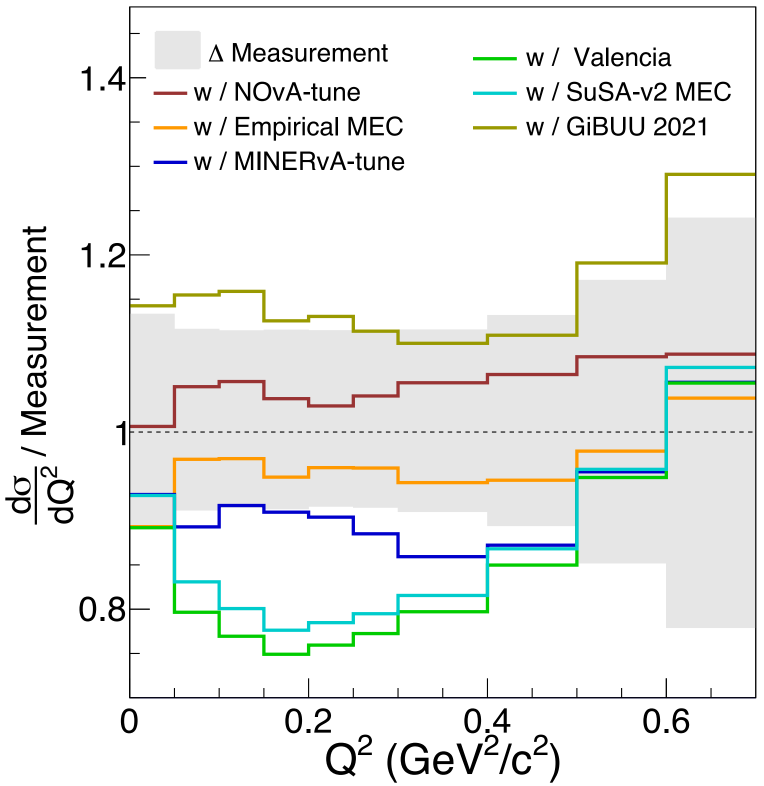
Comparison to 2p2h models

Empirical and NOvA-tune are in better agreement with the data within uncertainties

MINERvA-tune and SuSAv2 tend to underestimate our data

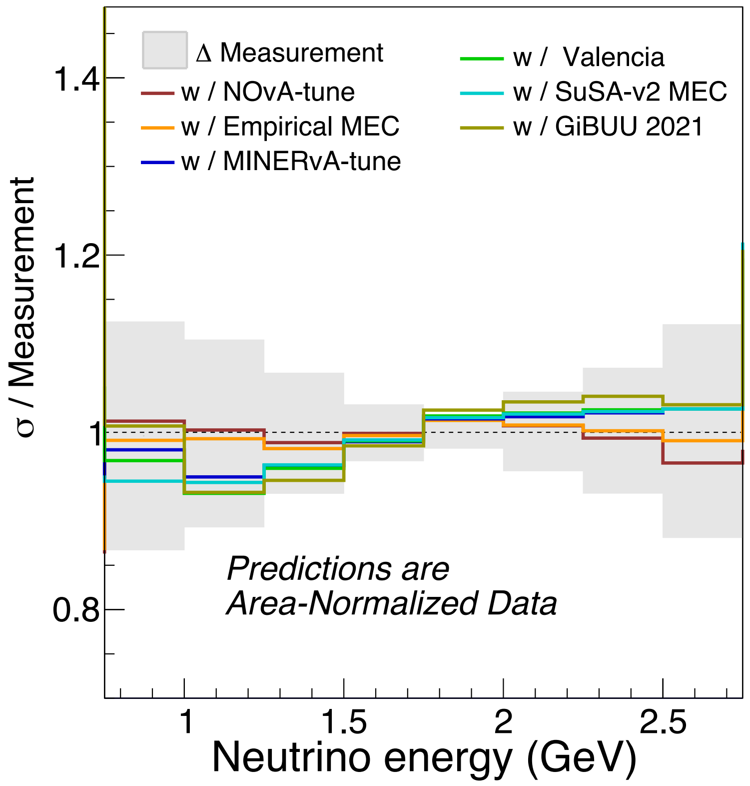
GiBUU tends to overestimate our data

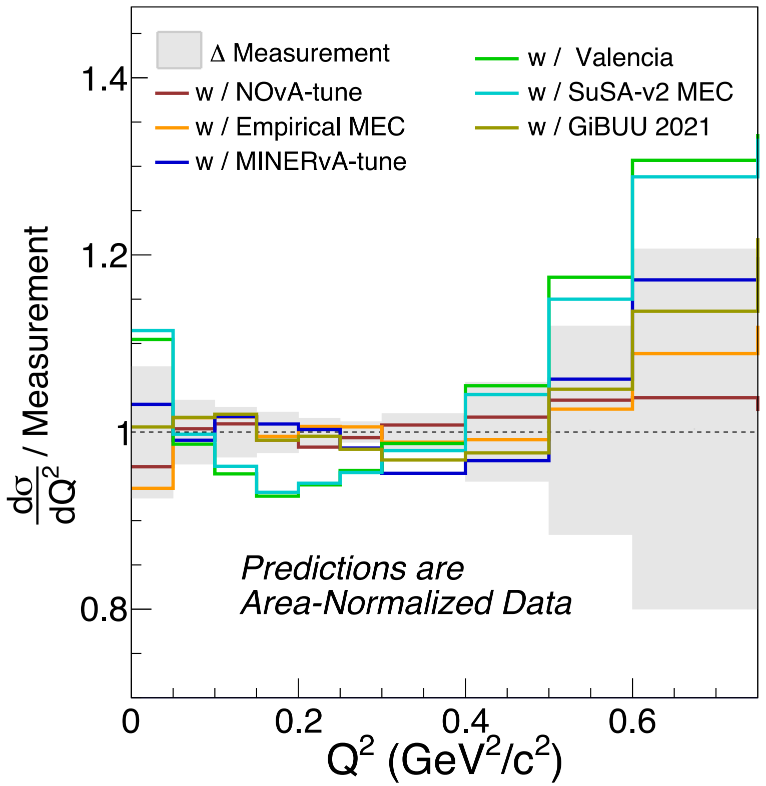




Comparison to 2p2h models (Shape only uncertainties)

In the shape only comparison most of the models except Valencia and SuSAv2 follow the shape of our measurement





χ^2 tests including bin-to-bin correlations

- They show different levels of agreement with respect to the ratio plots coming from the strength of the bin-to-bin correlations to model the data
- The Empirical MEC has the best performance modeling the data, followed by the tuned-based models and the theory-based models

2p2h implementation	Muon kinematics NDF: 115
Empirical MEC	190 (209)
NOvA-tune	197 (178)
MINERvA-tune	330 (386)
SuSAv2	499 (698)
Valencia	510 (756)
GiBUU	563 (501)

The values in parentheses are the shape-only $\chi 2$ calculations

χ^2 tests including bin-to-bin correlations

- They show different levels of agreement with respect to the ratio plots coming from the strength of the bin-to-bin correlations to model the data
- The Empirical MEC has the best performance modeling the data, followed by the tuned-based models and the theory-based models

2p2h implementation	Muon kinematics NDF: 115	Neutrino energy NDF: 8
Empirical MEC	190 (209)	4.5 (4.5)
NOvA-tune	197 (178)	7.5 (6.3)
MINERvA-tune	330 (386)	2.3 (2.6)
SuSAv2	499 (698)	4.0 (1.4)
Valencia	510 (756)	6.1 (3.1)
GiBUU	563 (501)	8.7 (7.8)

The values in parentheses are the shape-only χ2 calculations

χ^2 tests including bin-to-bin correlations

- They show different levels of agreement with respect to the ratio plots coming from the strength of the bin-to-bin correlations to model the data
- The Empirical MEC has the best performance modeling the data, followed by the tuned-based models and the theory-based models

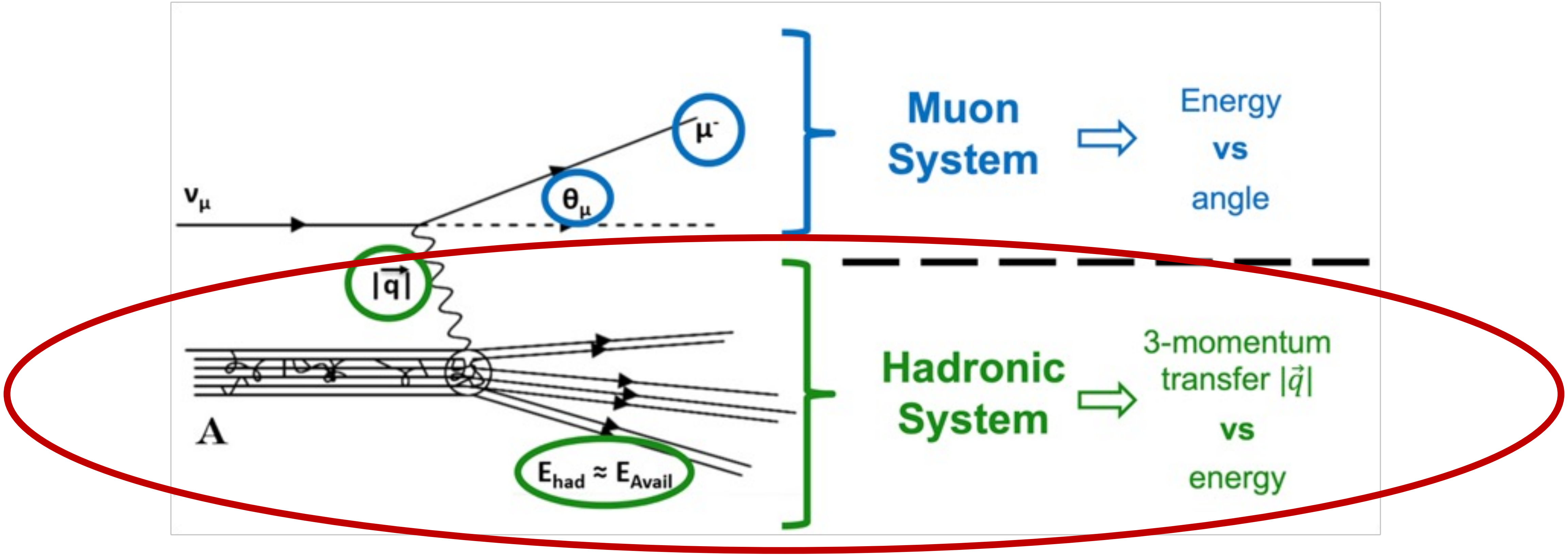
2p2h implementation	Muon kinematics NDF: 115	Neutrino energy NDF: 8	Four momentum square NDF: 10
Empirical MEC	190 (209)	4.5 (4.5)	20.8 (19.4)
NOvA-tune	197 (178)	7.5 (6.3)	24.2 (20.0)
MINERvA-tune	330 (386)	2.3 (2.6)	51.1 (63.2)
SuSAv2	499 (698)	4.0 (1.4)	41.6 (68.1)
Valencia	510 (756)	6.1 (3.1)	41.1 (64.9)
GiBUU	563 (501)	8.7 (7.8)	43.1 (27.5)

The values in parentheses are the shape-only χ2 calculations

This talk

ν_μ – CC cross-section measurements: double differential results

Focusing on sensitivity to 2p2h events



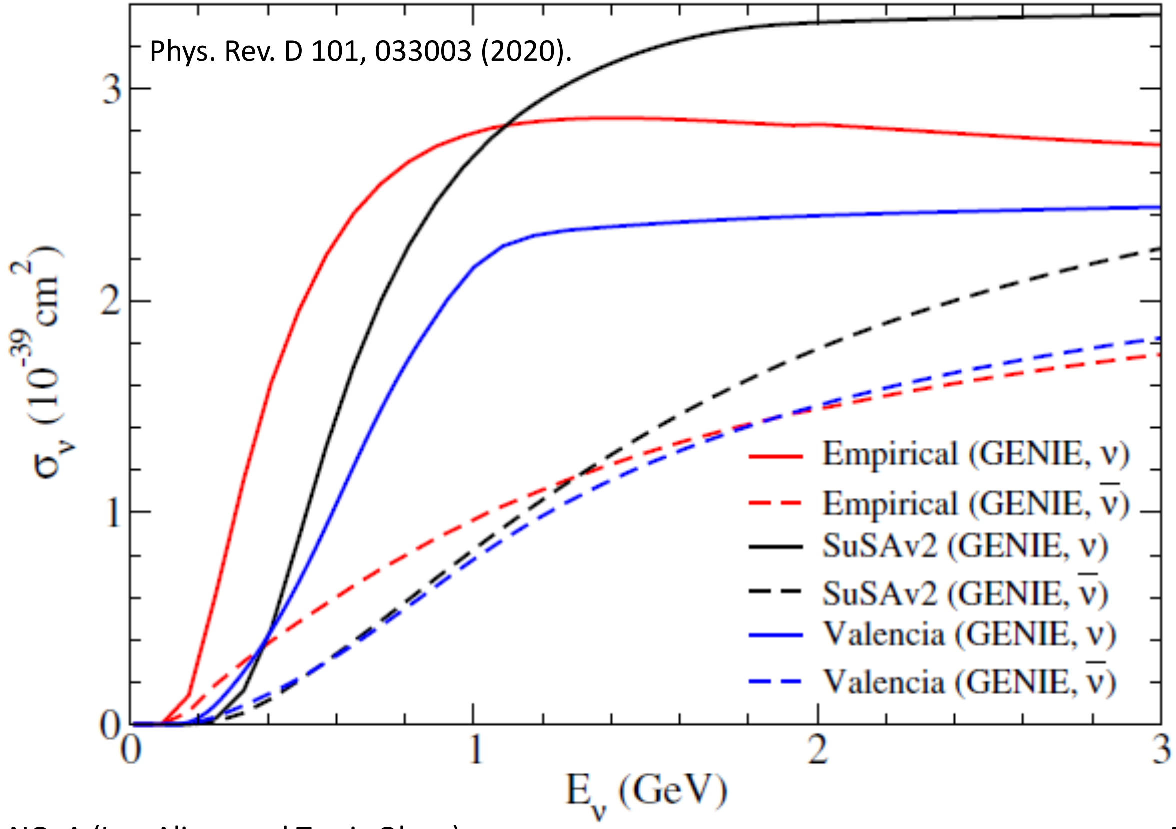
Measurement of ν_μ CC inclusive cross section and estimation of 2p2h

The 2p2h contribution to neutrino-nucleus charged-current scattering has received abundant experimental attention in recent times:

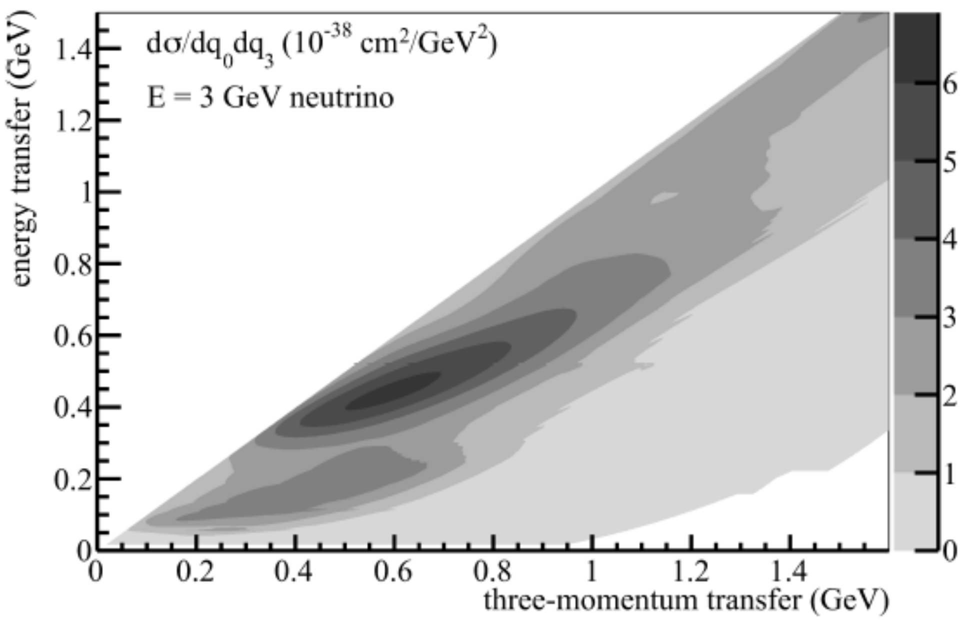
MINERvA: Phys. Rev. Lett. **116**, 071802 (2016), Phys. Rev. D **106**, 032001 (2022).
T2K: Phys. Rev. D **98**, 032003 (2018), Phys. Rev. D **108**, 112009 (2023).
MicroBooNE: Phys. Rev. D **102**, 112013 (2020), arXiv:2211.03734 (2022).

The NOvA measurements probe 2p2h with high statistics in the neutrino energy range 1.0 < Ev < 3.0 GeV.

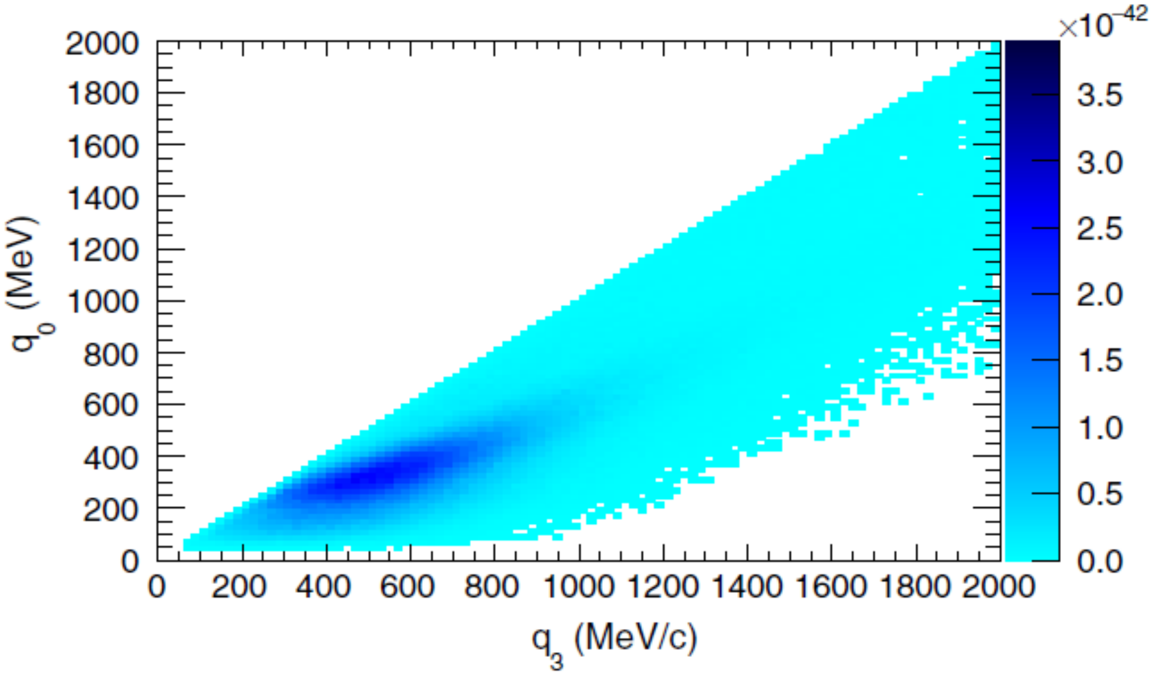
This range lies above the sub-GeV regime examined by MiniBooNE, T2K, and MicroBooNE, and on the lower edge of the few-to-multi-GeV range studied by MINERvA.



The **variables-of-choice** for most theoretical treatments of 2p2h are those which characterize 4-momentum transfer, namely magnitude of 3-momentum transfer $|\vec{\mathbf{q}}|$, and energy transfer, q_0 .



R. Gran et al. (Valencia), Phys. Rev. D 88, 113007 (2013).



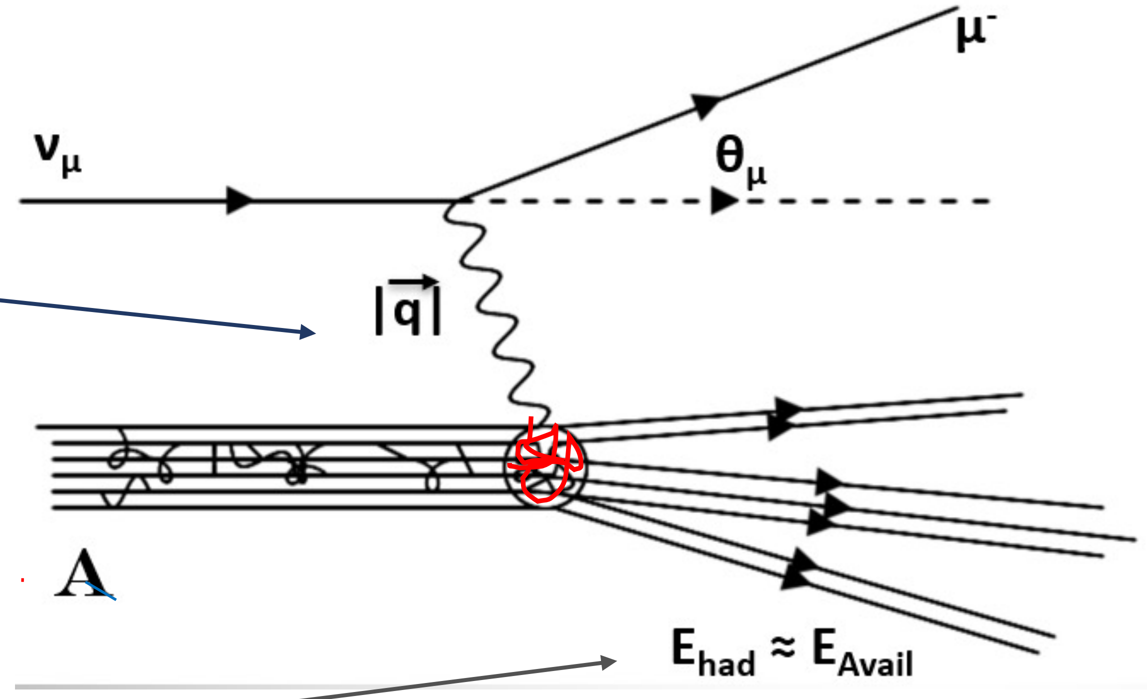
S. Dolan et al. (SuSAv2), Phys. Rev. D 101, 033003 (2020).

The analysis reported here uses variables which are as close to (q_0 , $|\vec{\mathbf{q}}|$) as we can achieve experimentally.

We can estimate $|\vec{\mathbf{q}}|$ directly; our proxy for q_0 is hadronic available energy, E_{avail} .

Analysis variables:

3-momentum transfer, $|\vec{q}|$



hadronic available energy, E_{avail}

Detectable hadronic energy
(neutron scattering is neglected)

Analysis variables:

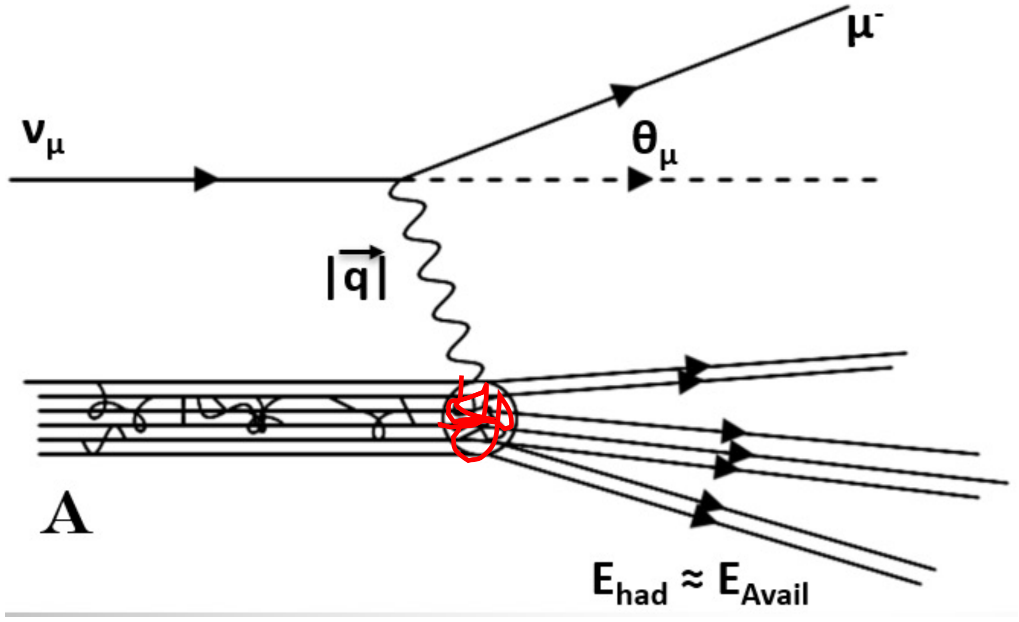
Neutrino energy: $E_{\upsilon} = E_{\mu} + E_{had}$

4-momentum transfer squared:

$$Q^2 = 2 * E_{\upsilon} * \left(E_{\mu} - P_{\mu} * \cos(\theta_{\upsilon})\right) - m_{\mu}^2$$

3-momentum transfer:

$$|\vec{q}| = \sqrt{Q^2 + (E_{\upsilon} - E_{\mu})^2}$$

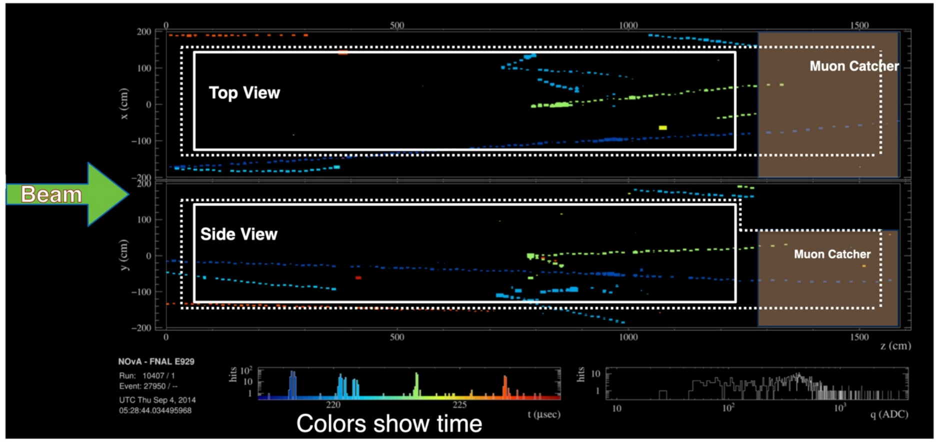


Available energy:

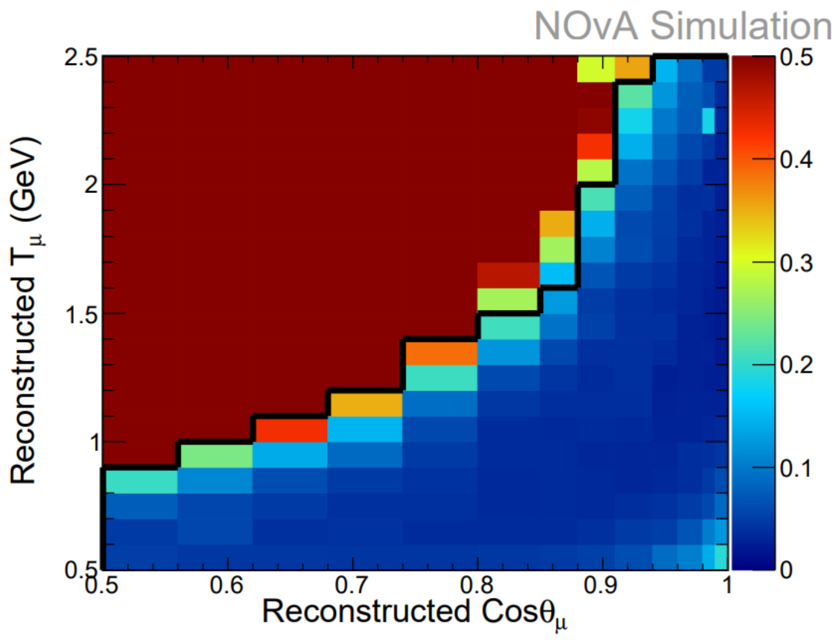
Kinetic energy: $p/\pi^{\pm}$
Total energy: $\pi^0/e/\gamma$
(neglect neutron energy)

Signal definition:

- **The event is a true ν_μ CC interaction.**
  (Backgrounds = neutral currents, antineutrino events and electron neutrino events, etc)
- **The interaction occurred within the fiducial volume.**
  (270 cm in X by 270 cm in Y by 900 cm in Z)



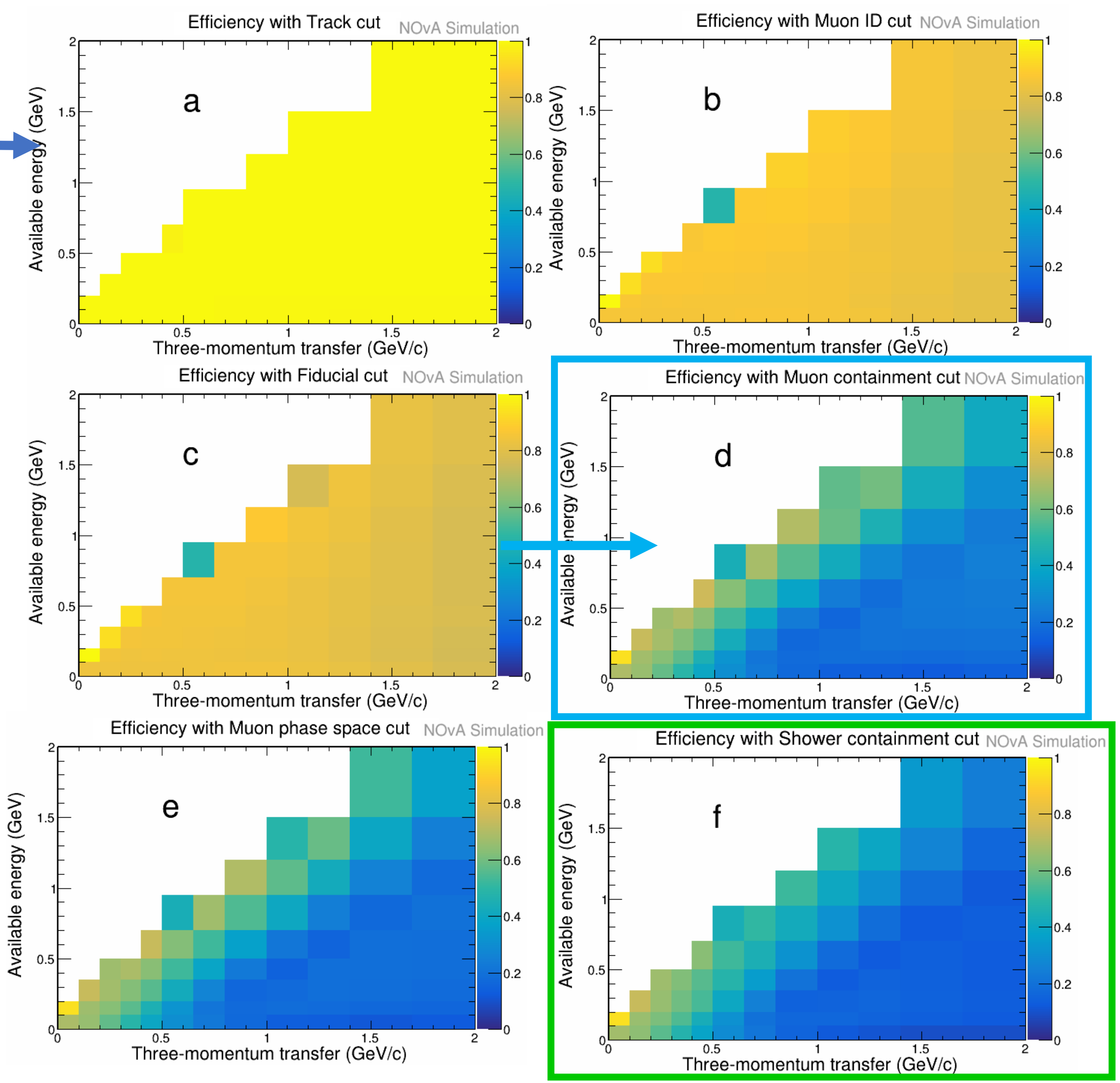
- **Event muon kinematics satisfy criteria that enhance selection efficiency and sample purity.**
  - True muon kinetic energy 0.5 GeV < T_μ < 2.5 GeV.
  - True 0.5 < $\cos(\theta_\mu)$ and has an increasing cut off as T_μ increases.



Efficiency versus selections:

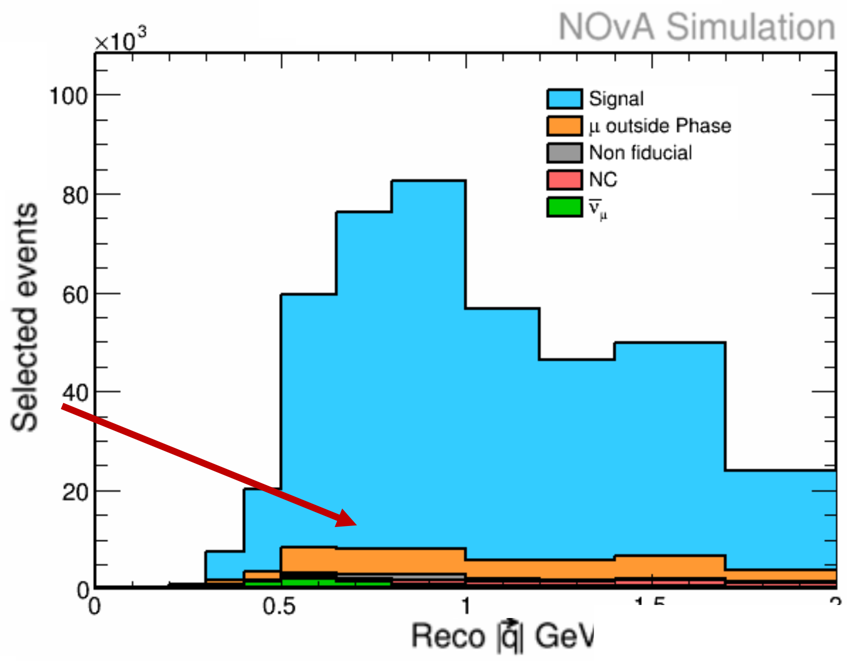
Selection sequence

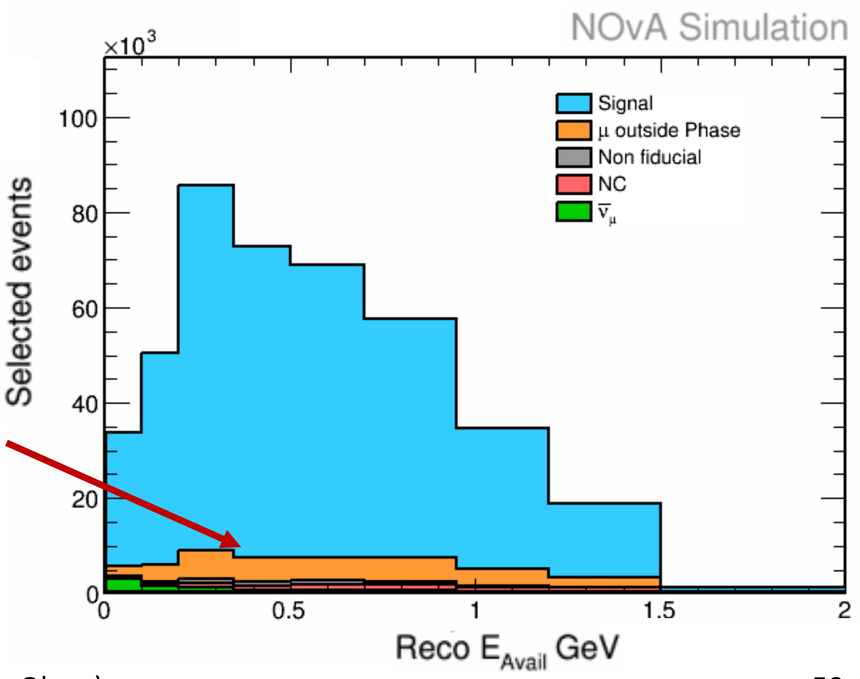
Selection cut	Efficiency
All true signal	100%
Quality	99.9%
Track reconstruction (a)	99.8%
Muon identification (b)	85.3%
Vertex fiducial (c)	82.3%
Muon containment (d)	24.7%
Muon phase space (e)	22.1%
Shower containment (f)	18.7%



Background events in sample:

Process	Event fraction
Signal	91.8%
Total background	8.2%
Outside phase space	3.7%
Non-fiducial	1.8%
CC Anti-neutrino	1.5%
Neutral current	1.1%
Electron neutrino	0.1%





Double differential cross section in $|\vec{q}|$ and E_{avail}:

$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta} U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$

$N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}$ is the selected data minus the estimated background in reco bins $\alpha\beta$

$U_{ij,\alpha\beta}$ is unfolding matrix that maps bins of reco variables $\alpha\beta$ to bins of true variables ij

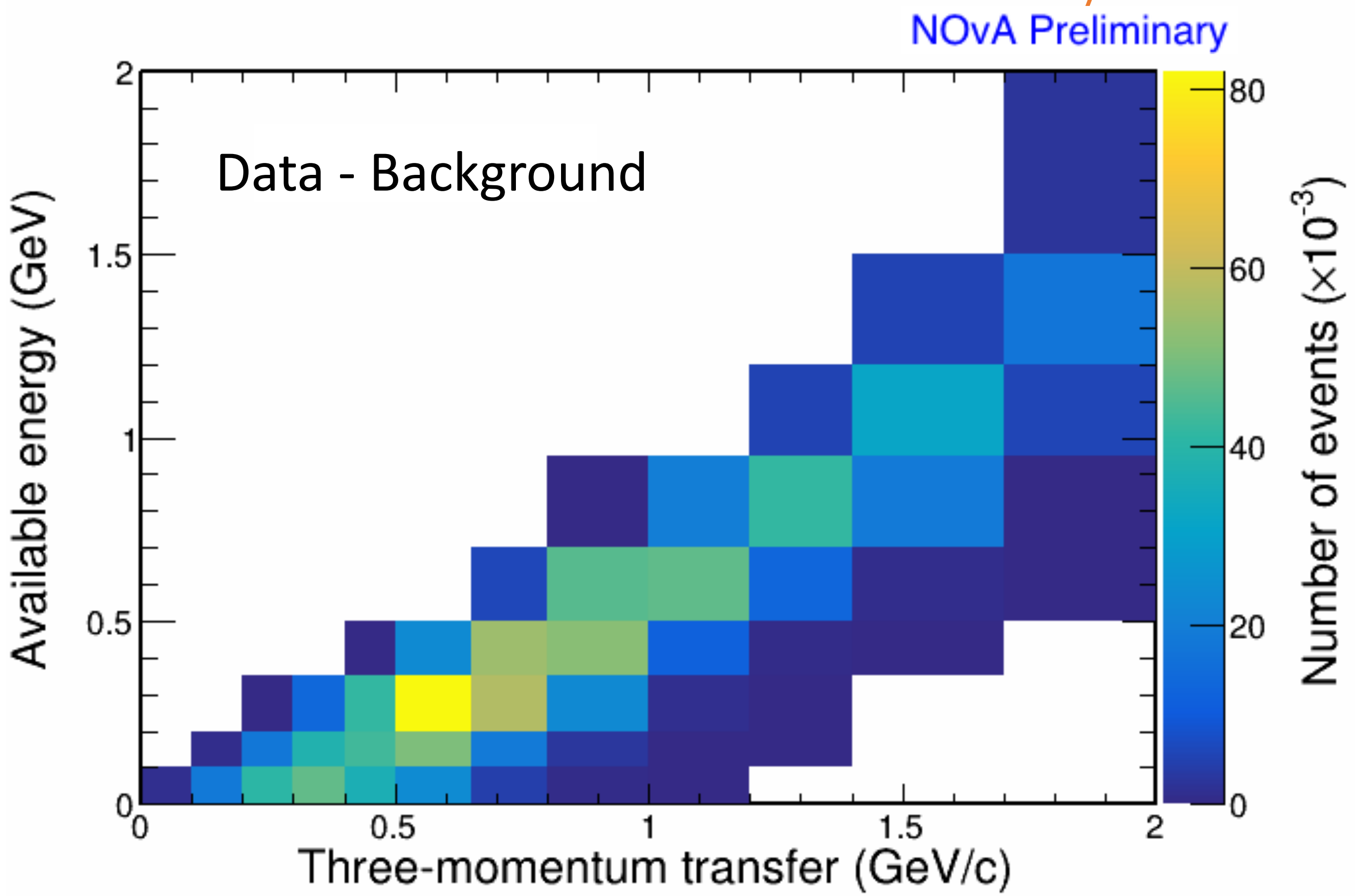
ε_{ij} is the detection efficiency for bin ij

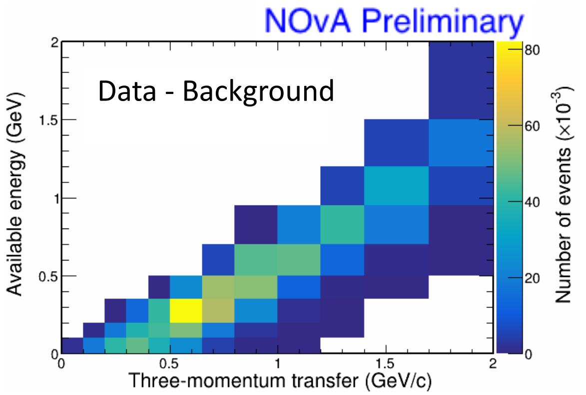
ϕ_ν is the integrated neutrino flux

T_N is the number of target nucleons

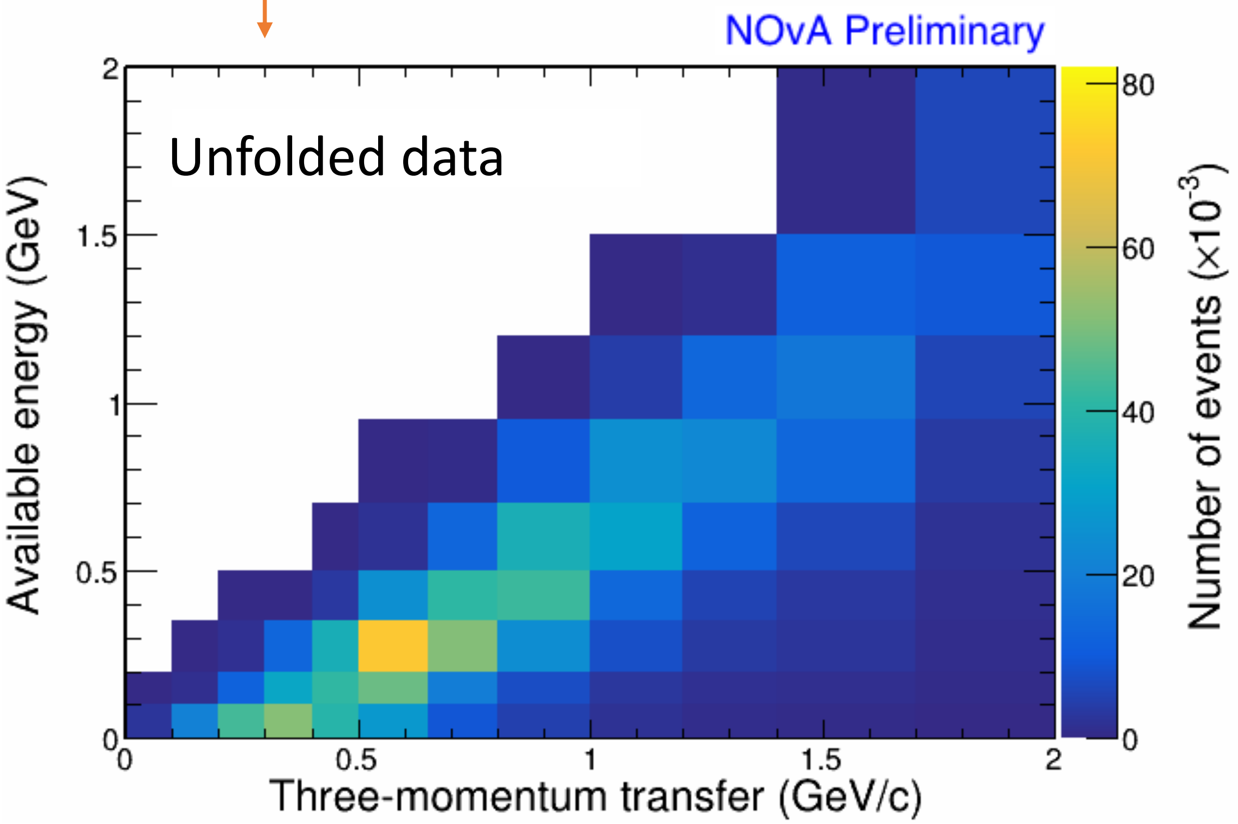
$(\Delta|\vec{q}|)_i(\Delta E_{avail})_j$ are the bin widths for the ith bin of |q| and the jth bin of E_{avail}

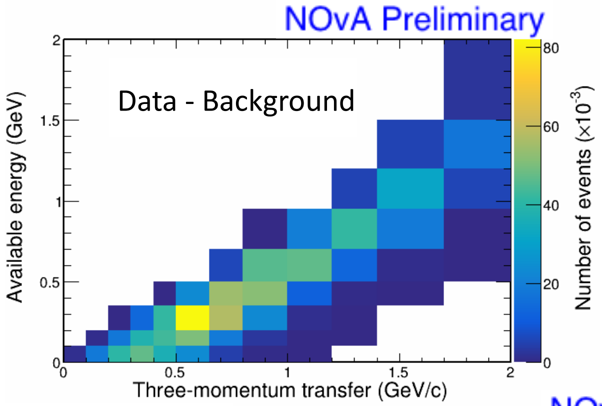
$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta} U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$

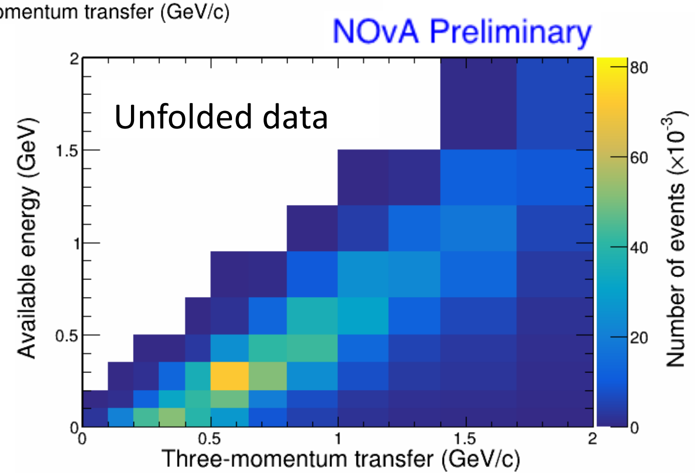




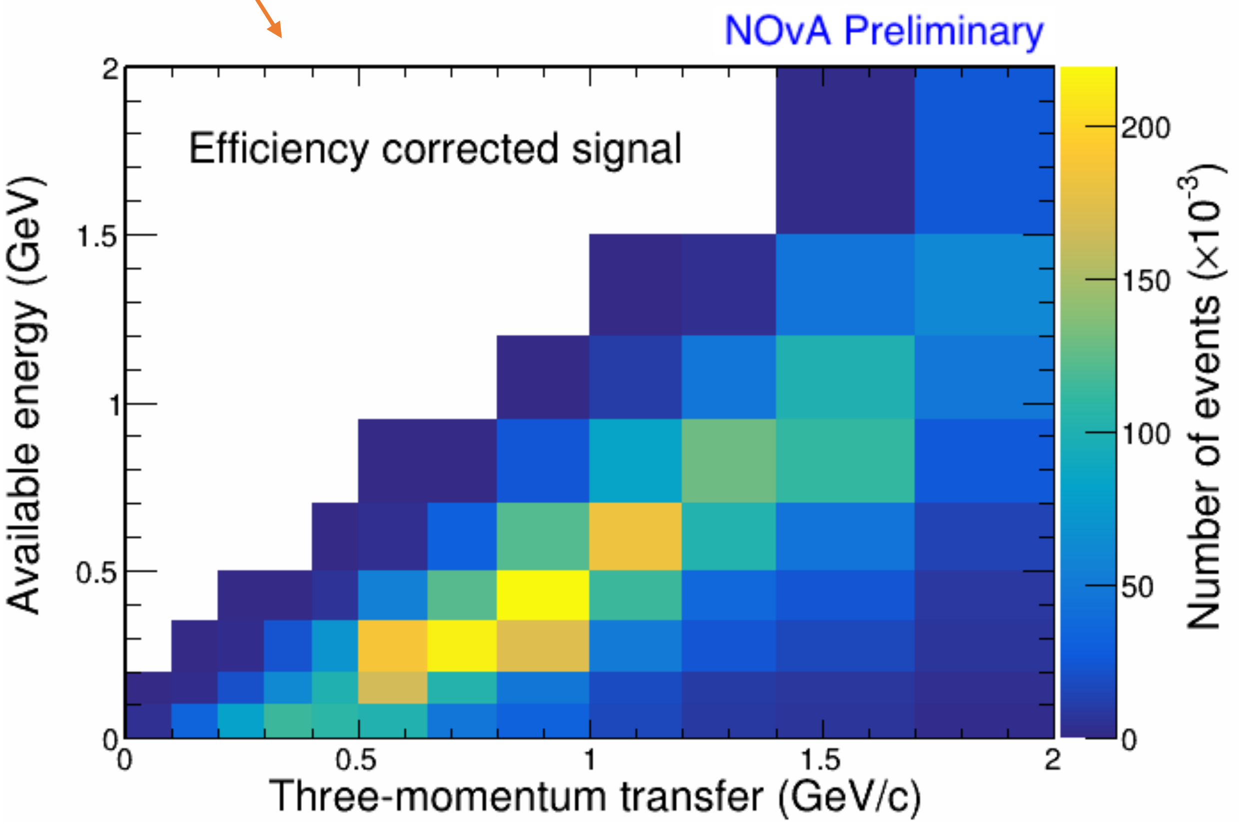
$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta}U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$



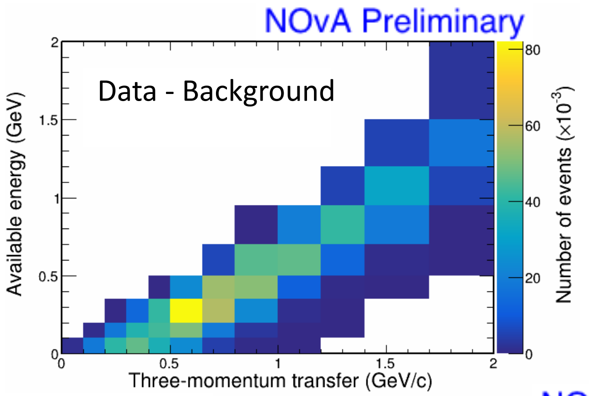


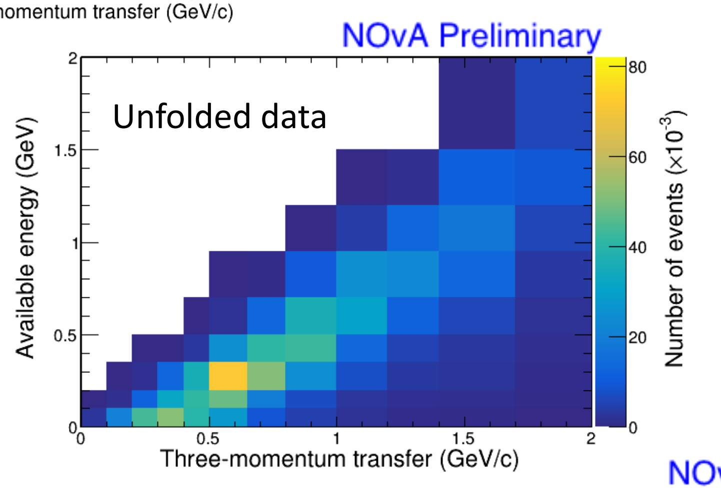


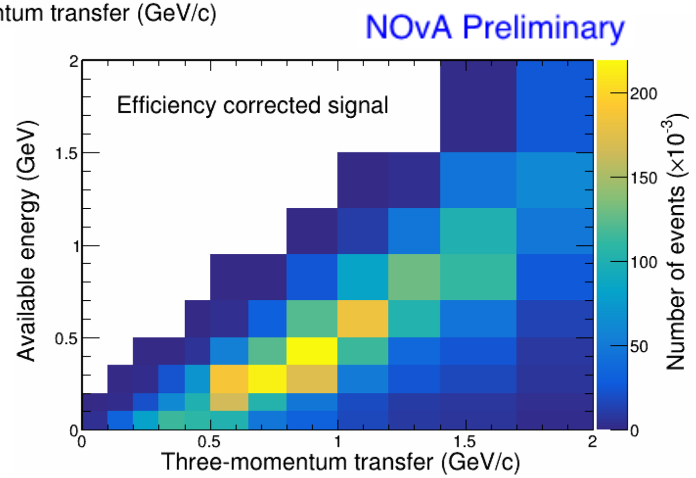
$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta} U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$

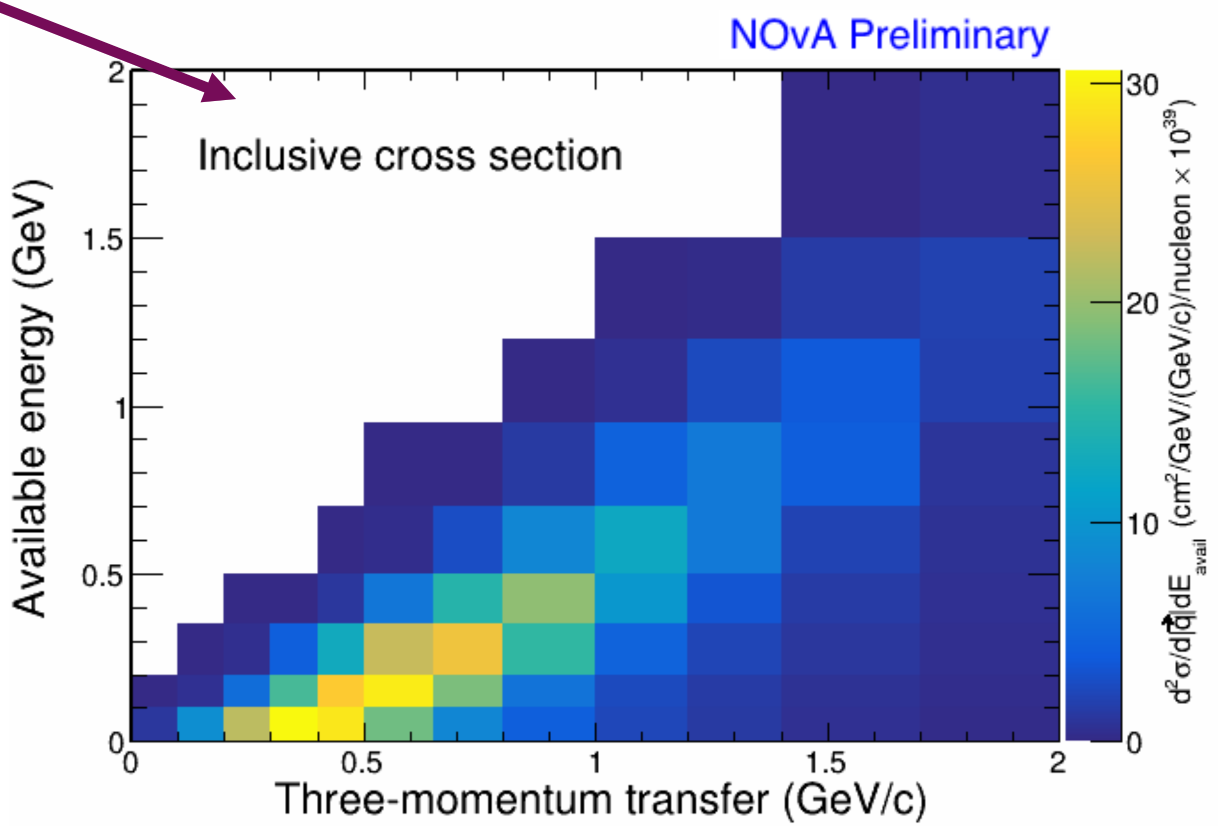


$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta}U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$







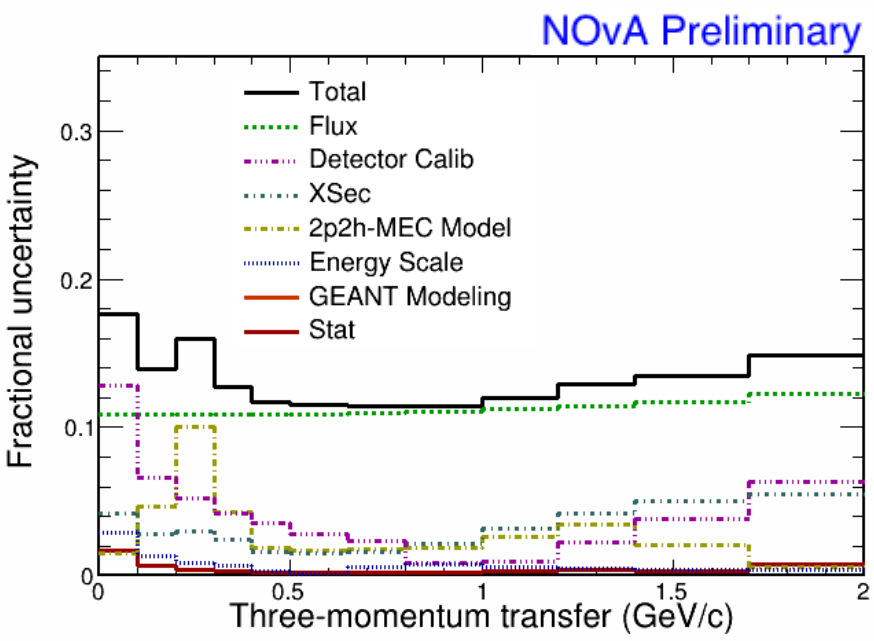


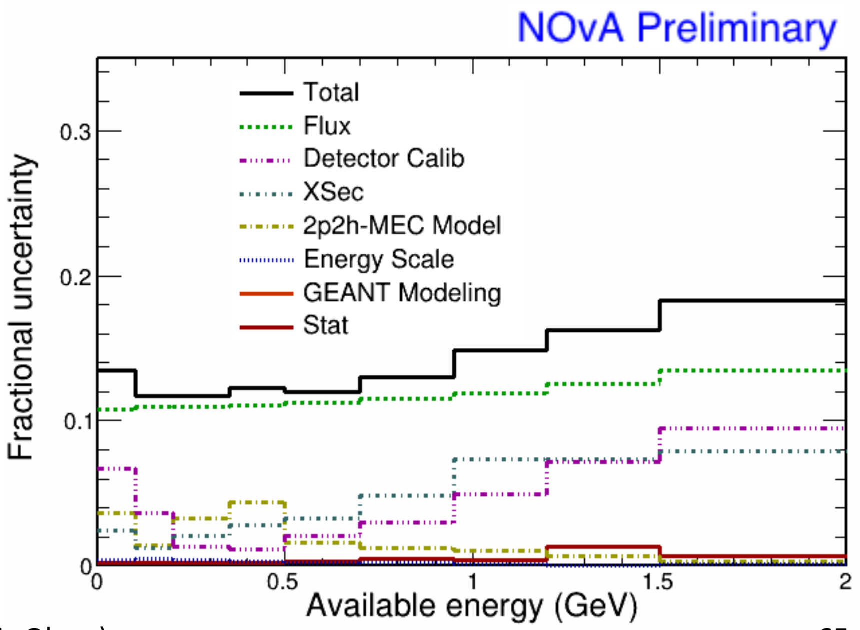
Cross-section Uncertainty:

The dominant uncertainty arises from the neutrino flux, however 2p2h modeling, cross-section models, and detector calibration are significant sources at low $|\vec{q}|$ and high E_{avail}.

As with the low hadronic energy analysis, the 2p2h modeling uncertainty is based on the cross-section spread observed using alternative 2p2h models in the reference simulation.

Source of uncertainty	Weighted avg fractional uncertainty	Weighted avg correlation
Flux	11 %	1.0
2p2h-MEC model	7.1 %	0.6
Cross section model	5.6 %	0.2
Detector calibration	3.7 %	0.6
Energy scale	0.9 %	0.6
Event statistics	0.5 %	0.4
Total	17 %	0.5

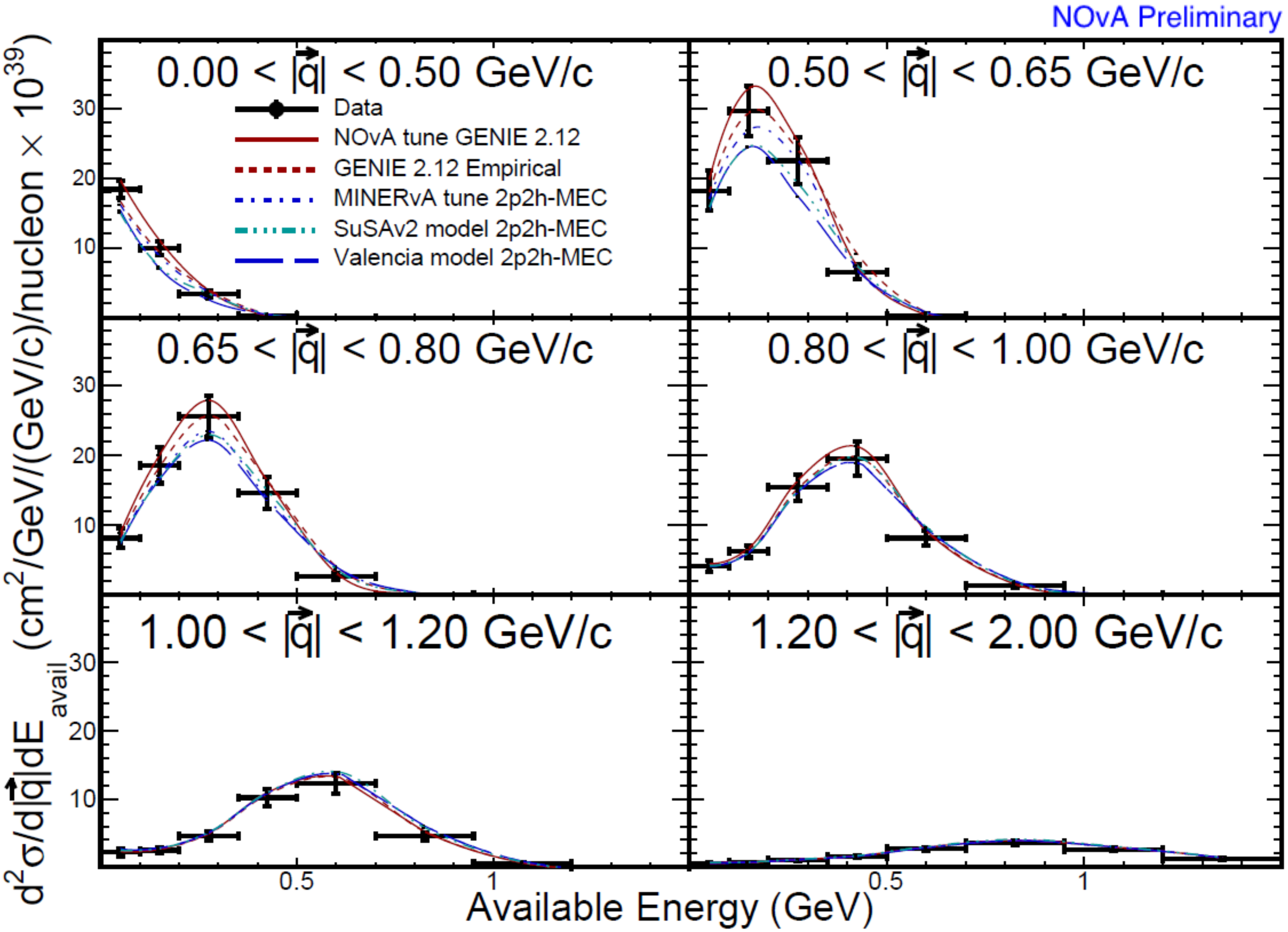




Cross section per analysis bins:

Cross section evolves in a regular way with increasing 3-momentum transfer.

Similar pattern reported previously by MINERvA:
PRL **116**, 071802 (2016).

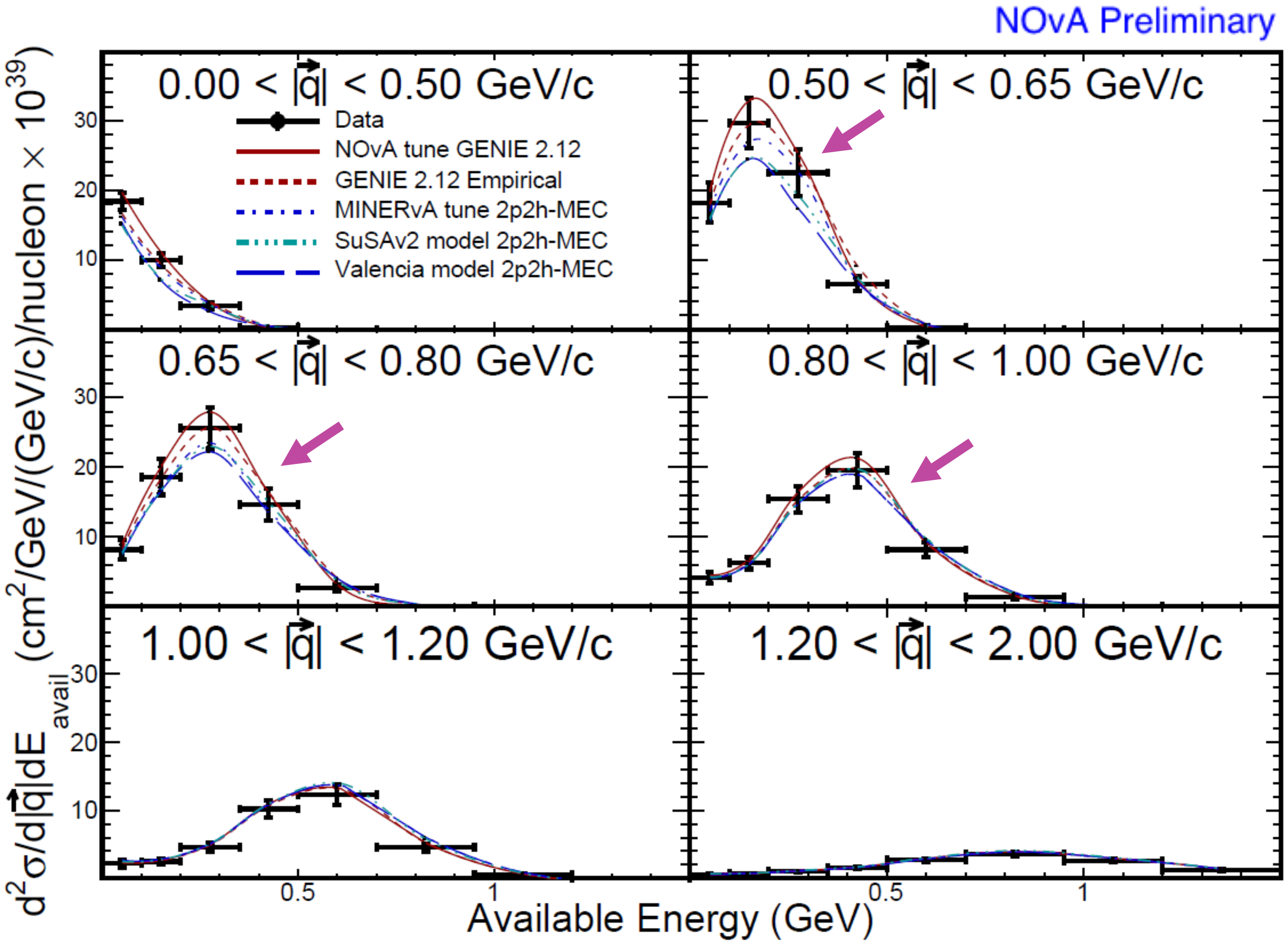


Cross section versus 2p2h models with GENIE 2.12:

Models predict large 2p2h contribution between $0.50 < |\vec{q}| < 1.00$ GeV/c and $0.2 < E_{avail} < 0.5$ GeV.

NOvA tune 2p2h gives best description of data.

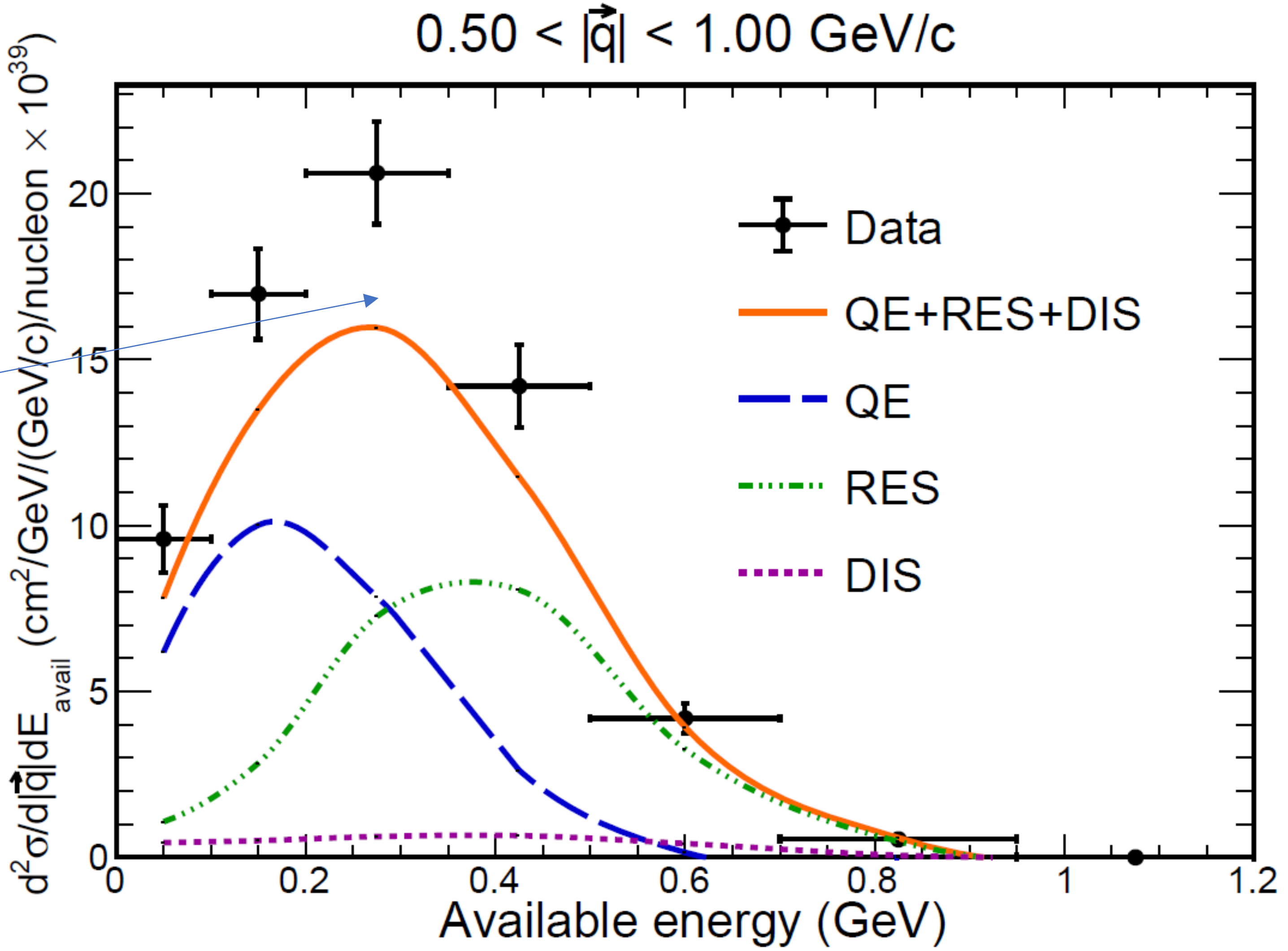
SusAv2 and Valencia models under-predict the data rate.



Data excess relative to neutrino-nucleon processes:

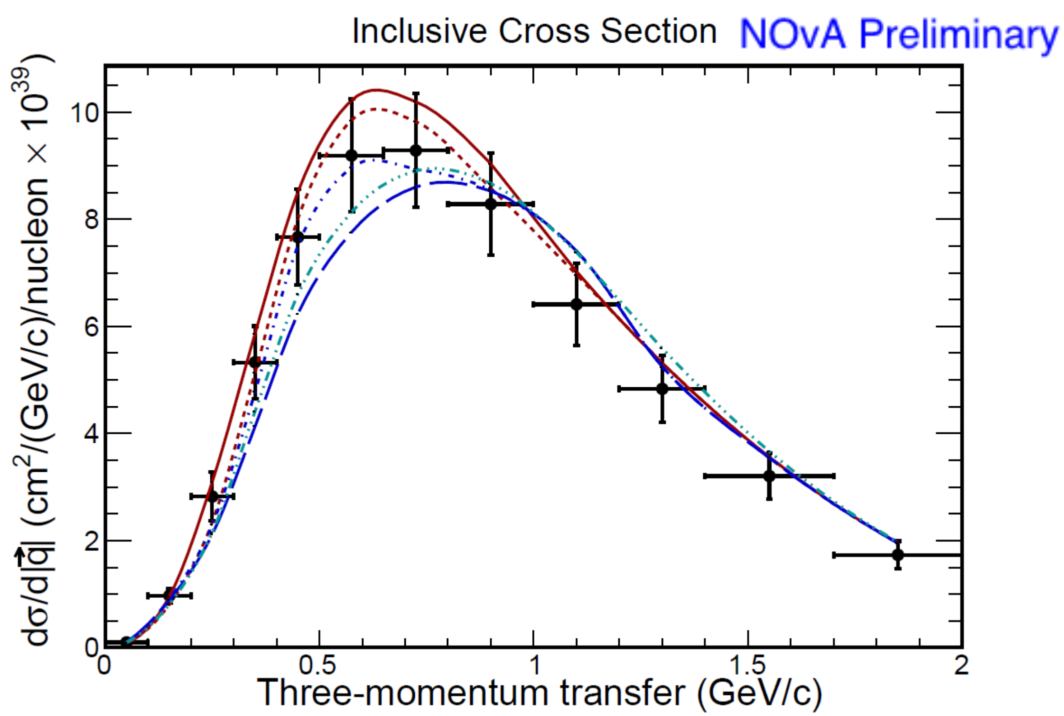
From electron nucleous scattering and theory 2p2h is expected to occur between QE and RES excitation.

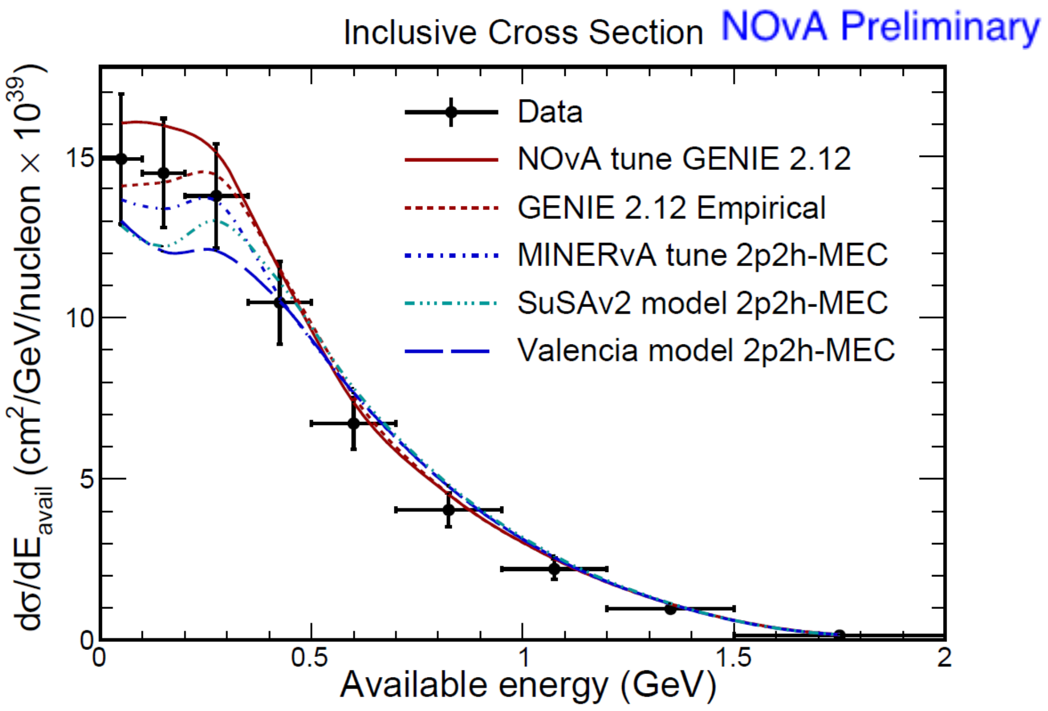
The data does indeed show an excess in that region above expectation for ν_μ CC single-nucleon scattering.



Differential cross sections in $|\vec{q}|$ and E_{avail} :

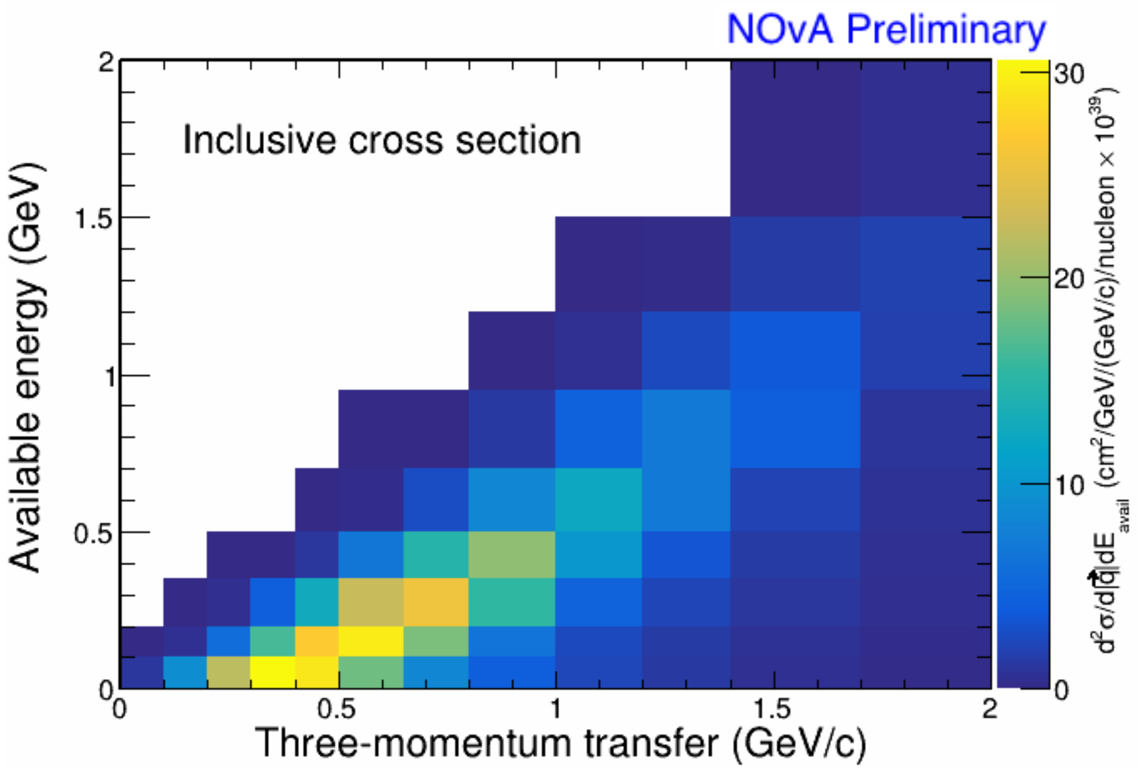
Data comparison with models:





Better alignment with the data is obtained with NOvA tune and GENIE 2p2h than with theory-based models or the MINERvA tune.

χ^2 comparison of inclusive double-differential cross section using different 2p2h models within the GENIE framework:



Model	χ^2 NDF: 61
NOvA tune	51 (50)
GENIE Empirical	514 (545)
MINERvA tune	1220 (1390)
SuSAv2 model	1610 (876)
Valencia model	2065 (2654)

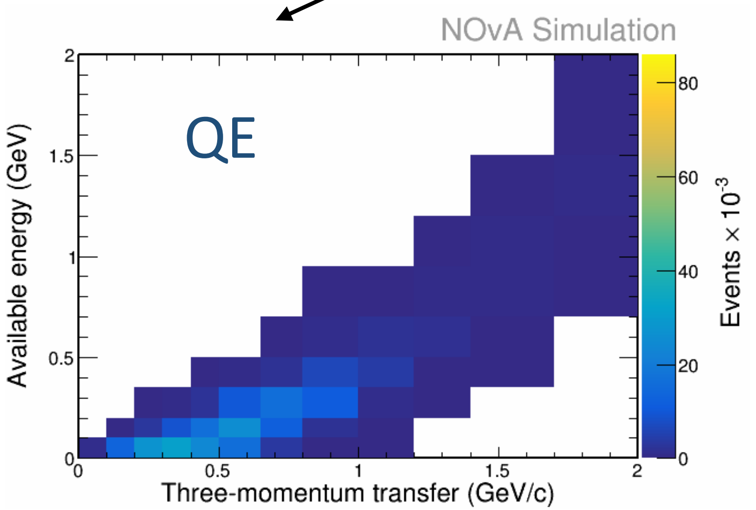
The values in parentheses are the shape-only χ2 calculations

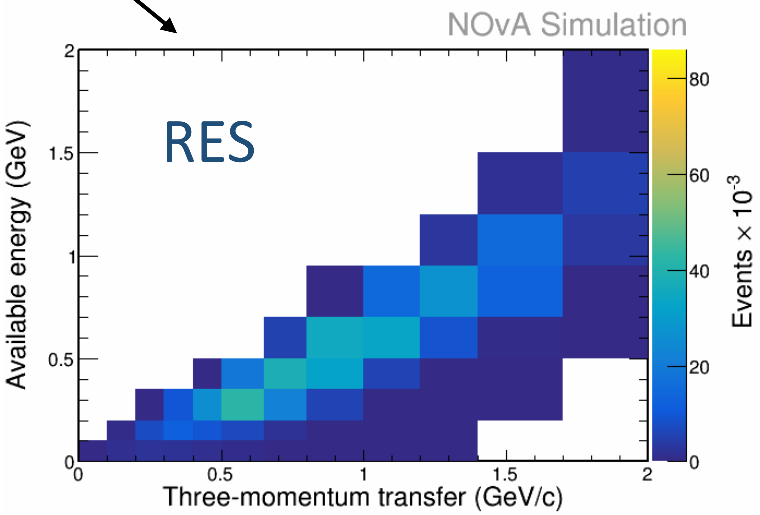
The NOvA tune and GENIE empirical 2p2h give better agreement with the data than the theory-based models or the MINERvA tune.

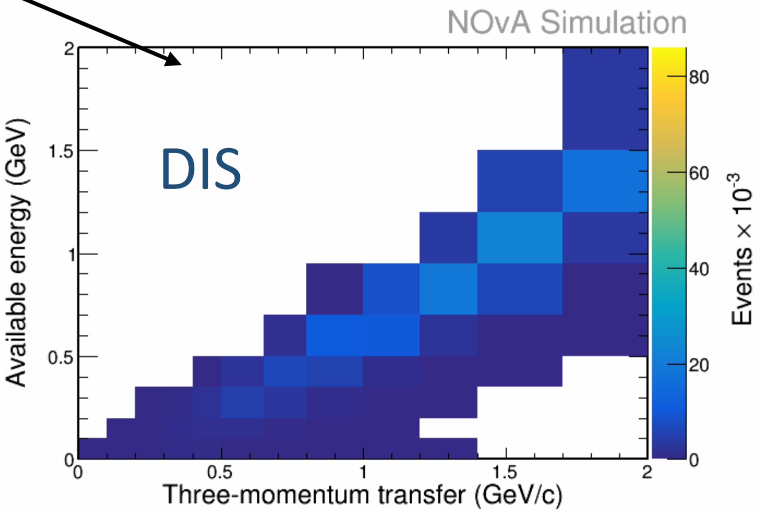
Estimation of 2p2h contribution to CC inclusive scattering

GENIE 2.12 based templates

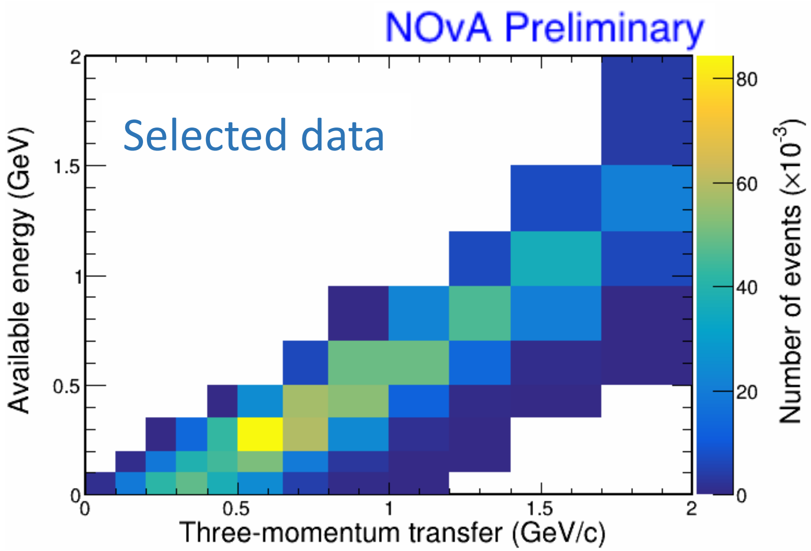
are used to estimate distribution of CC 1p1h reactions:







Template for CC coherent plus background is low population (not shown)



The data excess that lies above the sum of 1p1h templates is taken to be 2p2h.

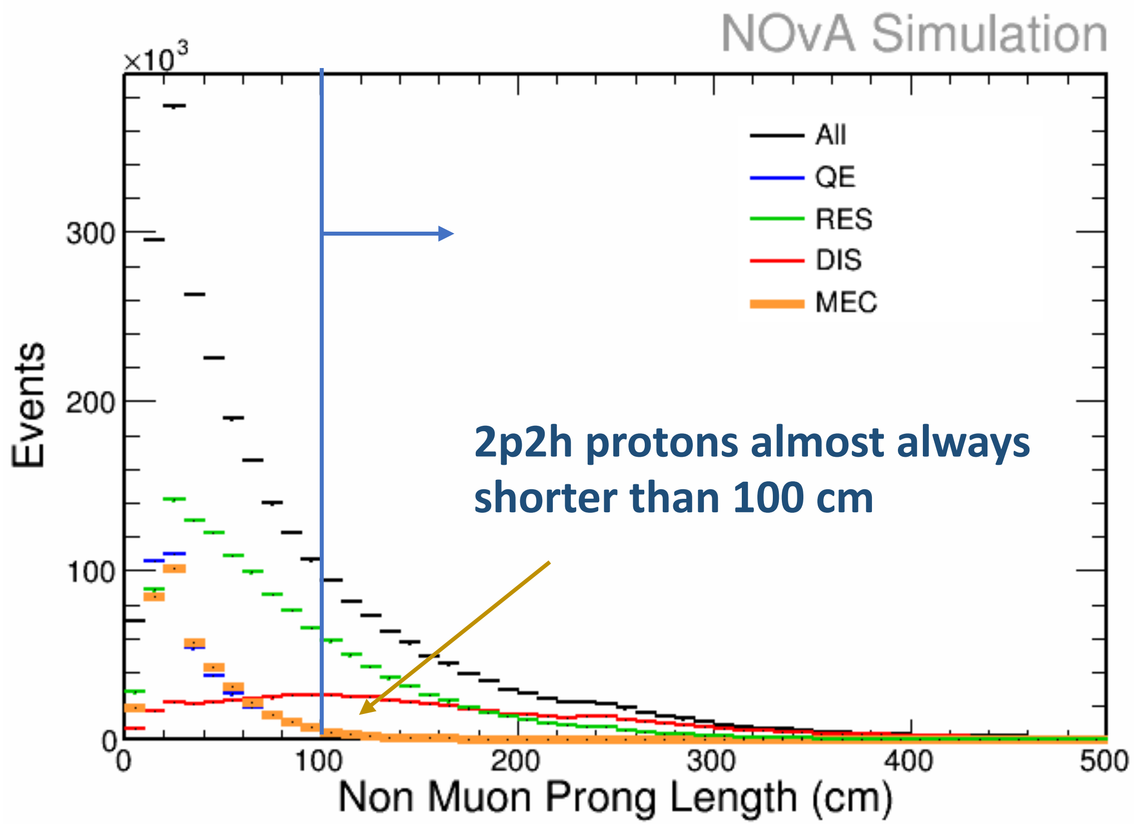
Control sample:

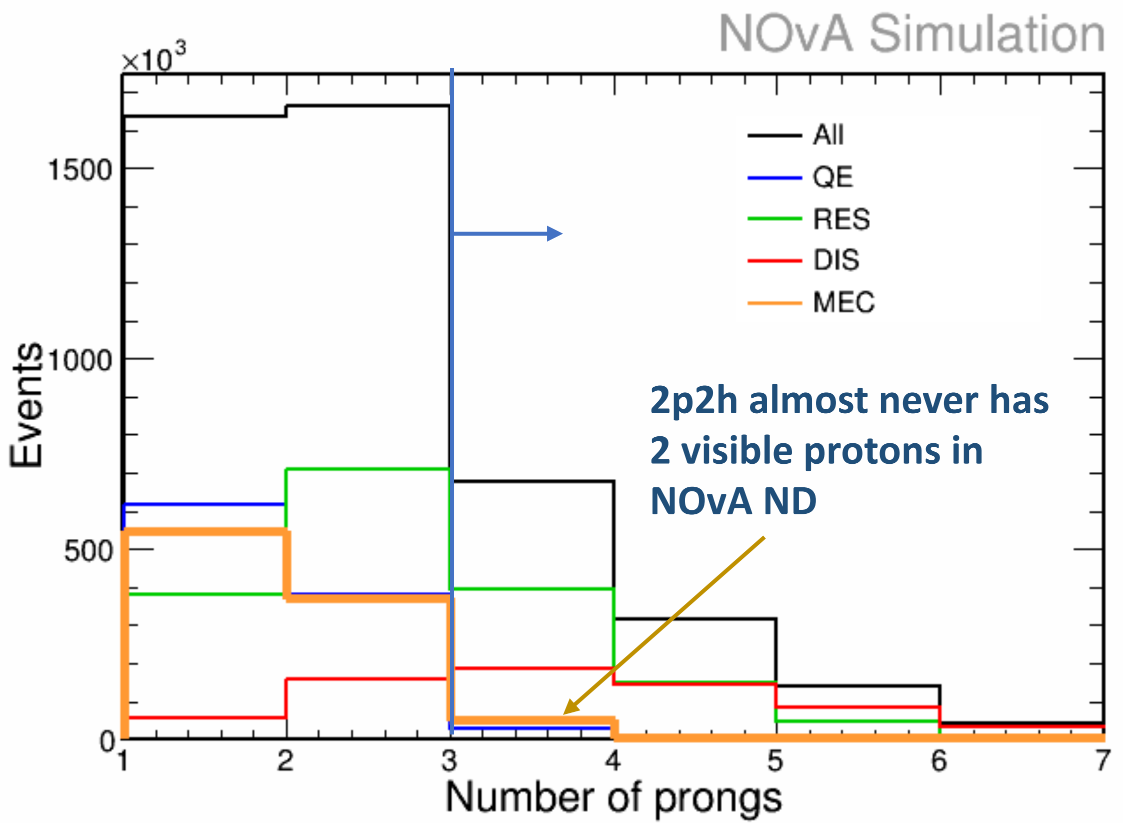
Select a subsample of events that have

1) A non-muon track of length > 100 cm (Protons of CCQE and 2p2h almost never reach that length)

or

2) Number of tracks + track-like clusters ≥ three (CCQE and 2p2h almost never have 3 visible tracks in NOvA ND)





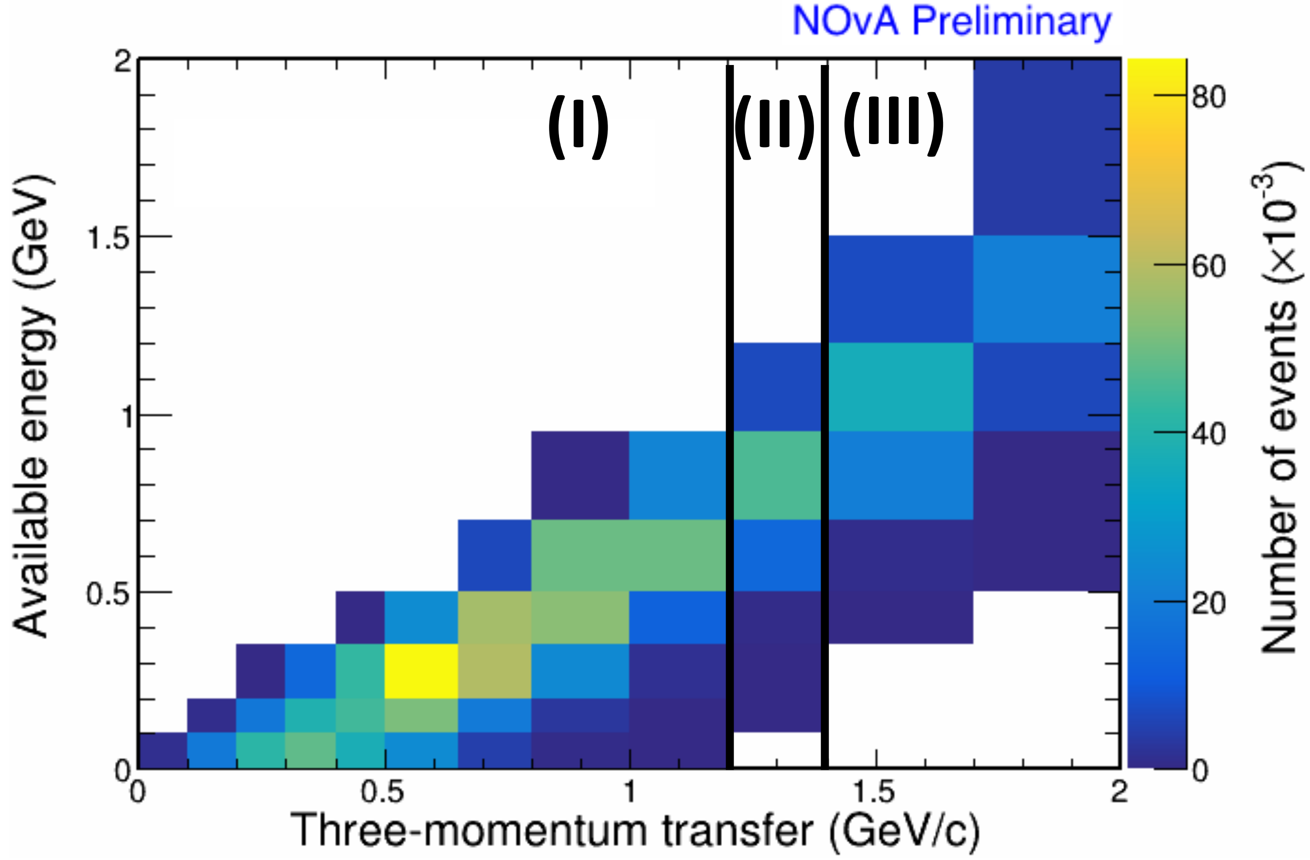
The **Control Sample** contains RES and DIS events, and is devoid of CCQE and 2p2h

The reference MC predictions for RES and DIS in the **Control Sample** are fit to that sample, and the resulting normalizations are assigned to the inclusive RES and DIS templates.

The fit is carried out separately in regions (I) and (III) which are chosen to make optimal use of the Control Sample: Region (I) is dominated by RES, while Region (III) has abundant DIS.

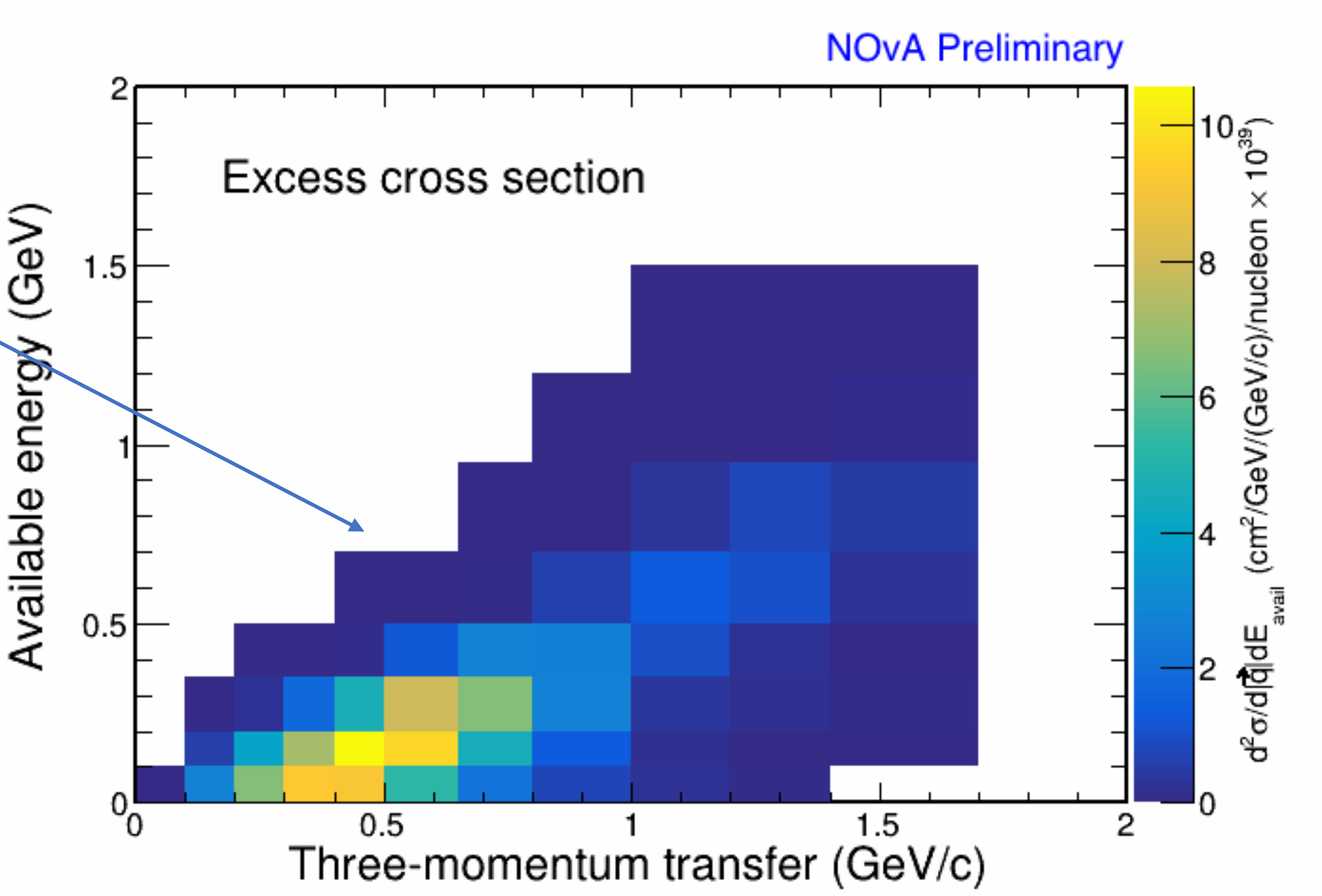
Template normalizations in Region (II) are set to the averages of normalizations for Regions (I) and (III).

The **QE template** is calculated using Llewellyn Smith formalism, relativistic Fermi gas nucleus with high-momentum tail plus RPA correction.



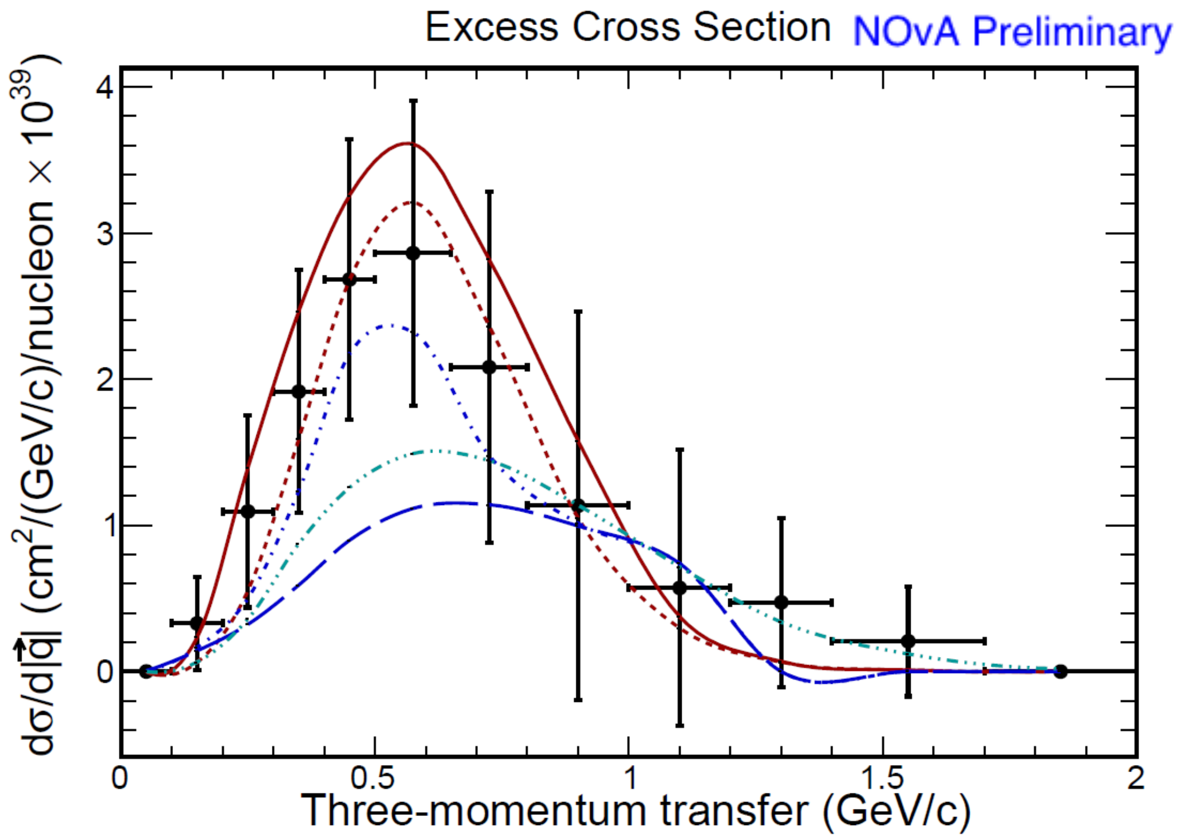
Estimated 2p2h cross section:

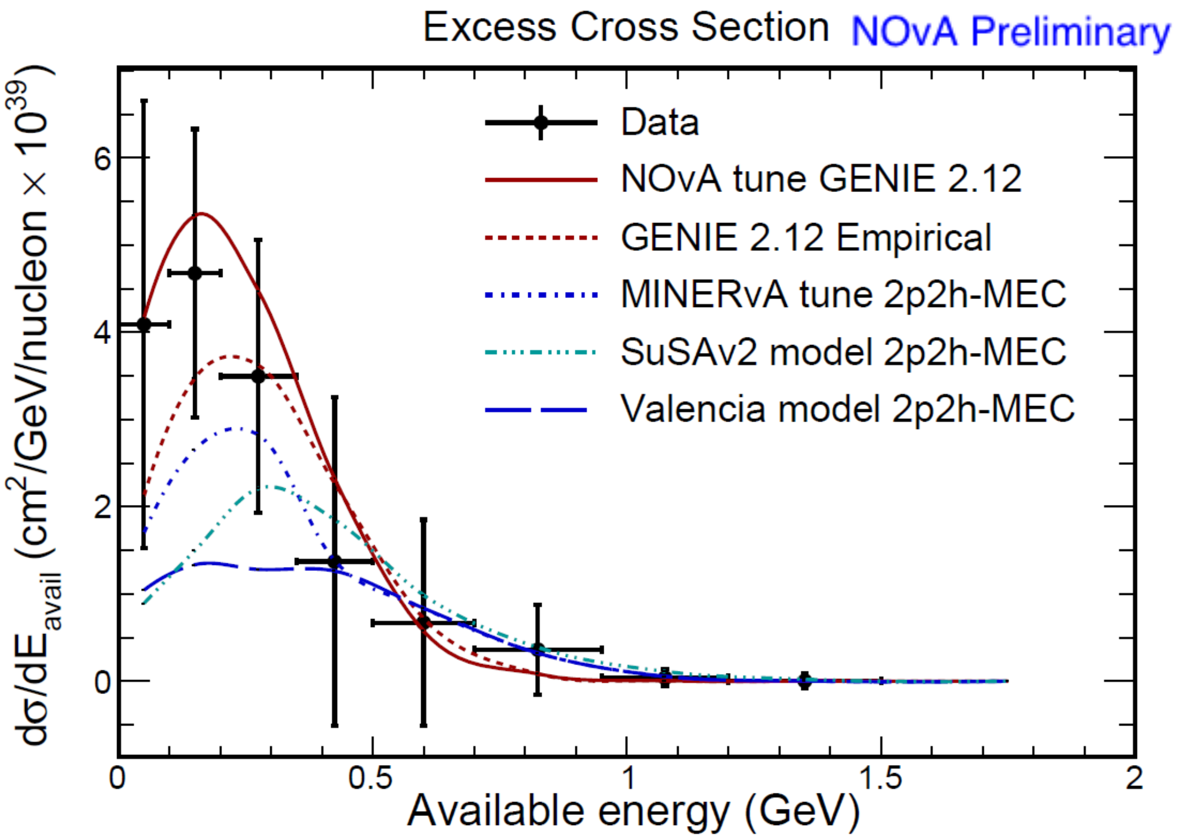
2p2h contribution is taken to be the data excess above the sum of the 1p1h templates.



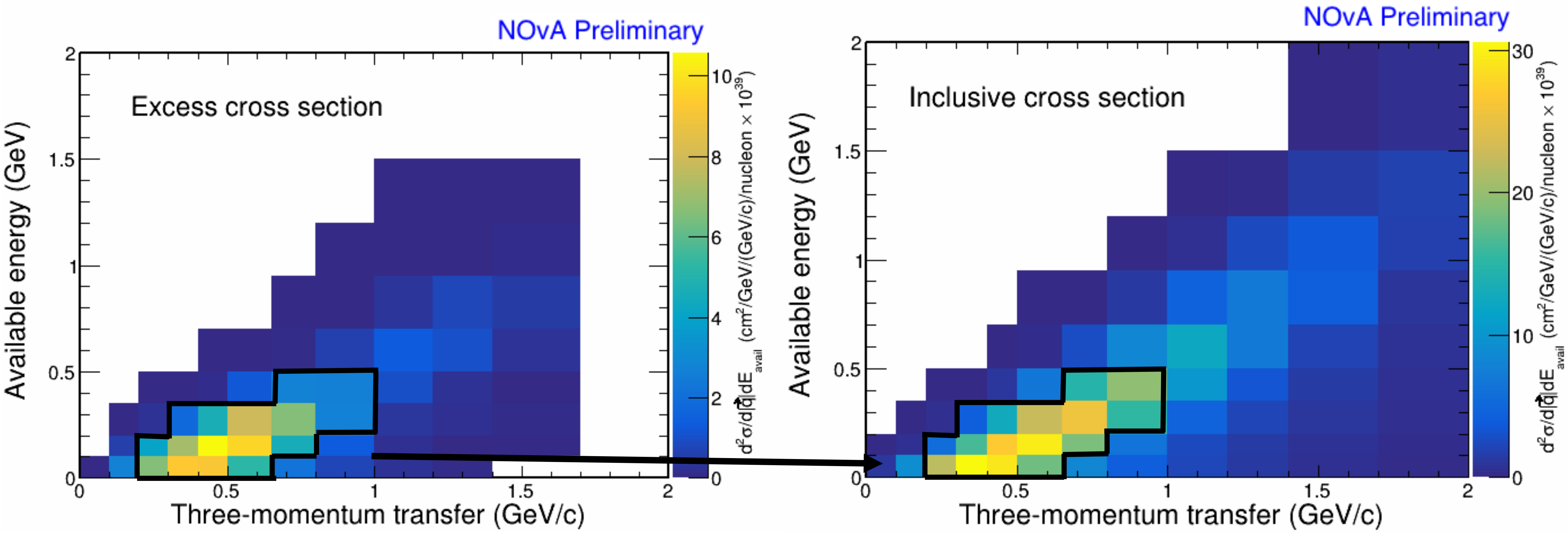
Estimated 2p2h cross section

Differential cross sections in $|\vec{q}|$ and E_{avail} :





Excess cross section defines 2p2h active region of the measured ν_μ CC inclusive cross section:



χ^2 now focuses on the 2p2h active region of the inclusive sample.

χ^2 comparison of 2p2h models using active region of the ν_μ CC inclusive cross section:

Predictions for 2p2h models in GENIE 2.12 framework are compared to ν_μ CC inclusive data in the active region using χ^2 with covariances.

Model	X^2 NDF:16
NOvA tune	6.3 (6.2)
GENIE Empirical	93 (102)
MINERvA tune	36 (43)
SuSAv2 model	70 (87)
Valencia model	104 (137)

The values in parentheses are the shape-only χ2 calculations

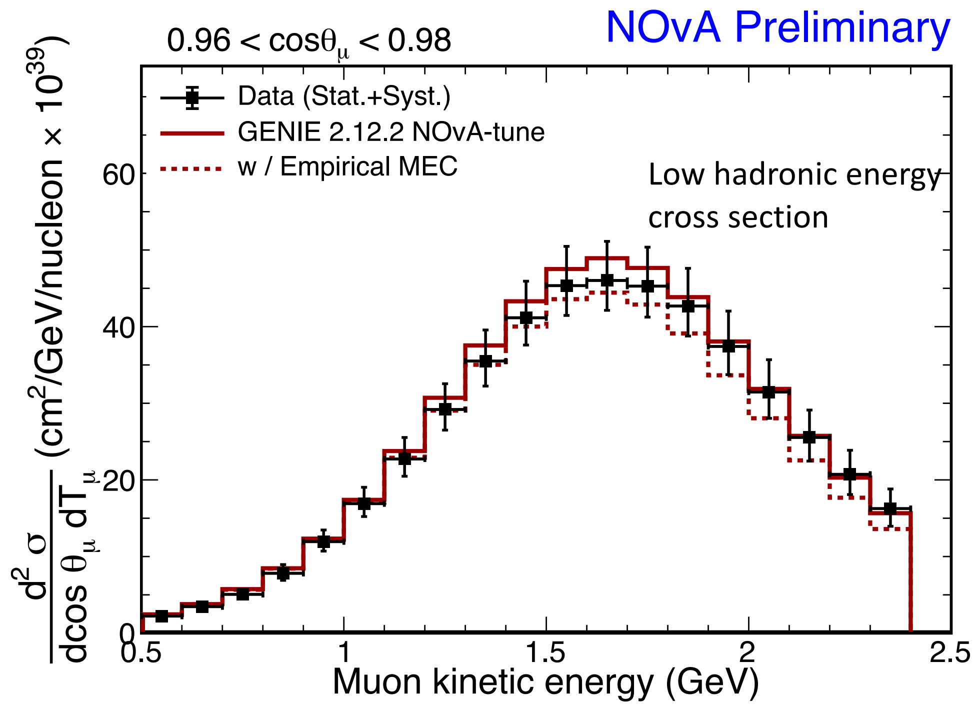
Only the NOvA tune 2p2h describes the data.
The theory-based models give poor descriptions of the data.

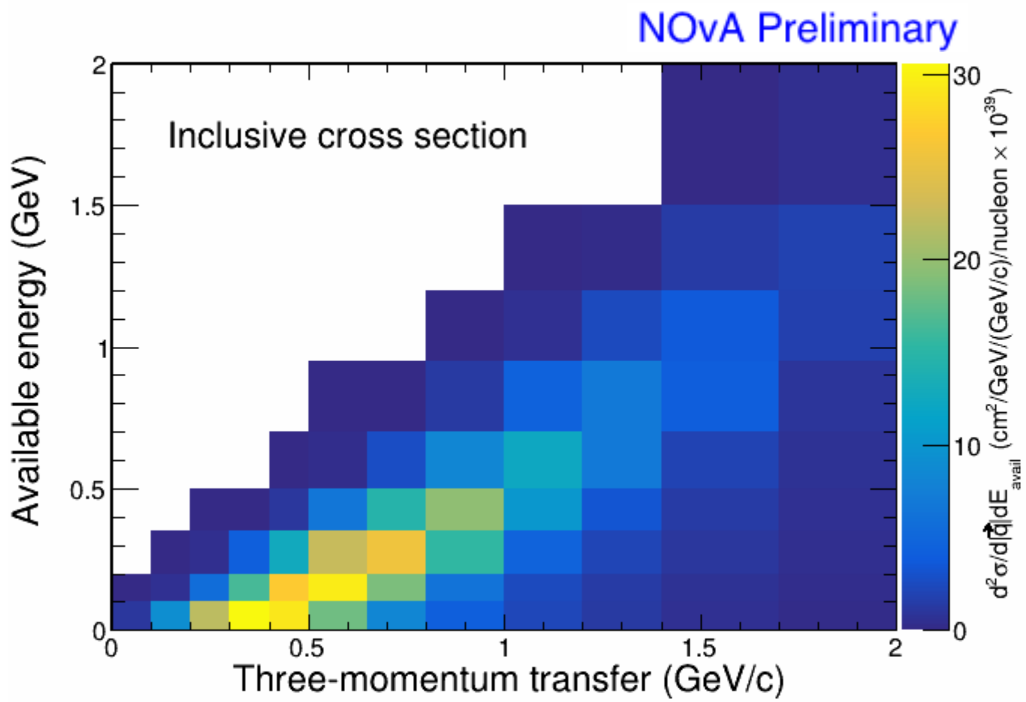
In conclusion:

We report new high-statistics neutrino cross-section measurements at $< E_\nu > \approx 1.9$ GeV

Cross-sections of low-hadronic energy interactions with respect to muon kinematics, neutrino energy, and Q^2.

Measurement of flux-integrated $\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}$

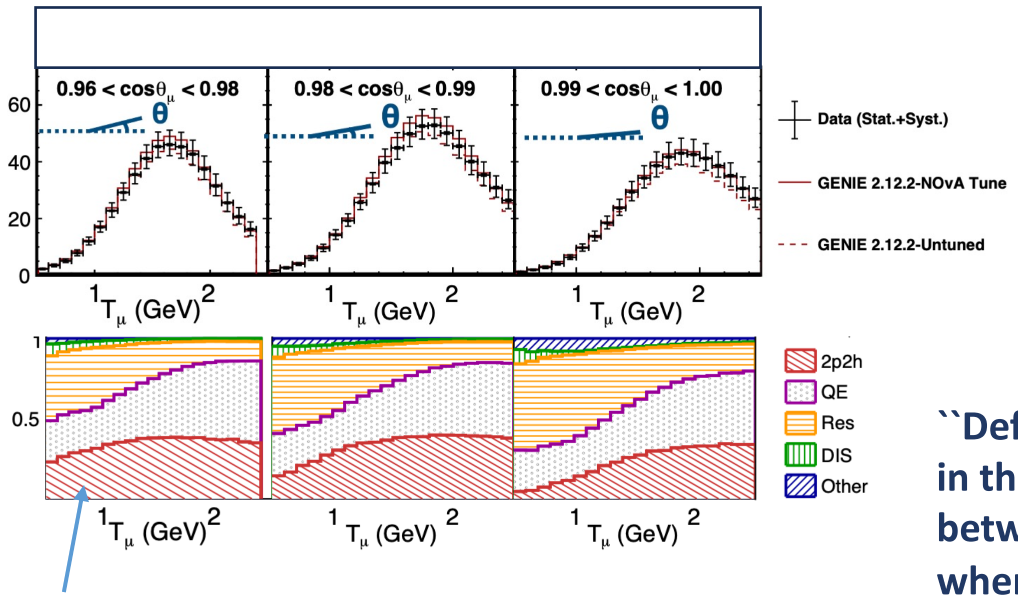




The analyses present complementary views of kinematic regions enhanced in 2p2h and CCQE events:

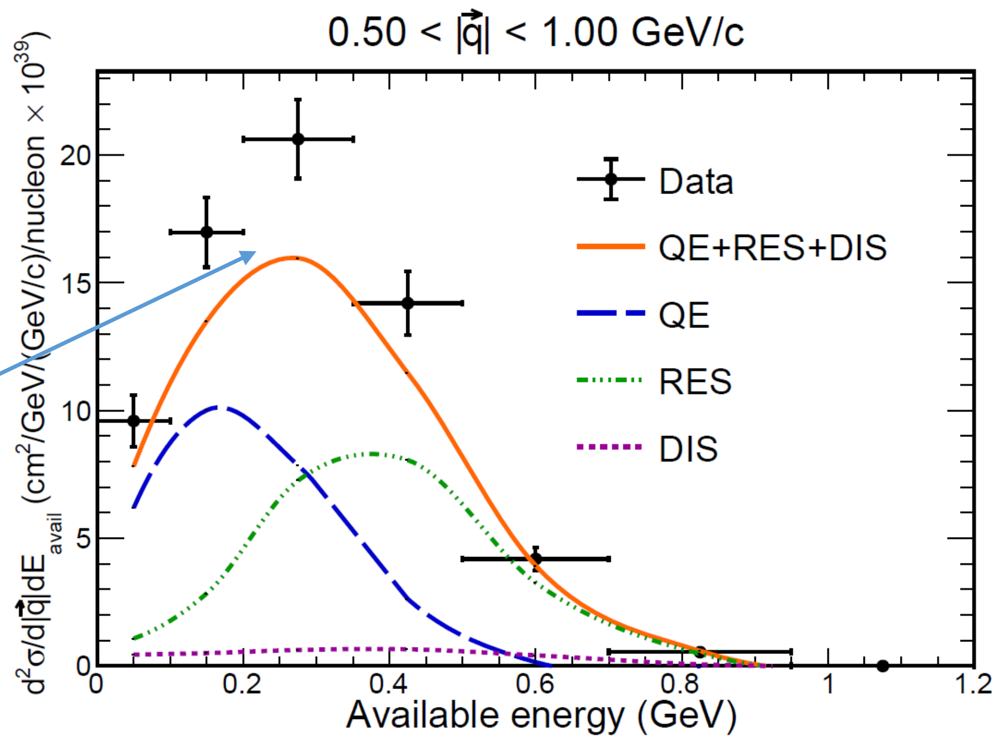
One analysis focused on **lepton kinematics**,
the other on **energy-momentum transfer** to the hadronic system.

Both analyses observe 2p2h to have a significant presence:

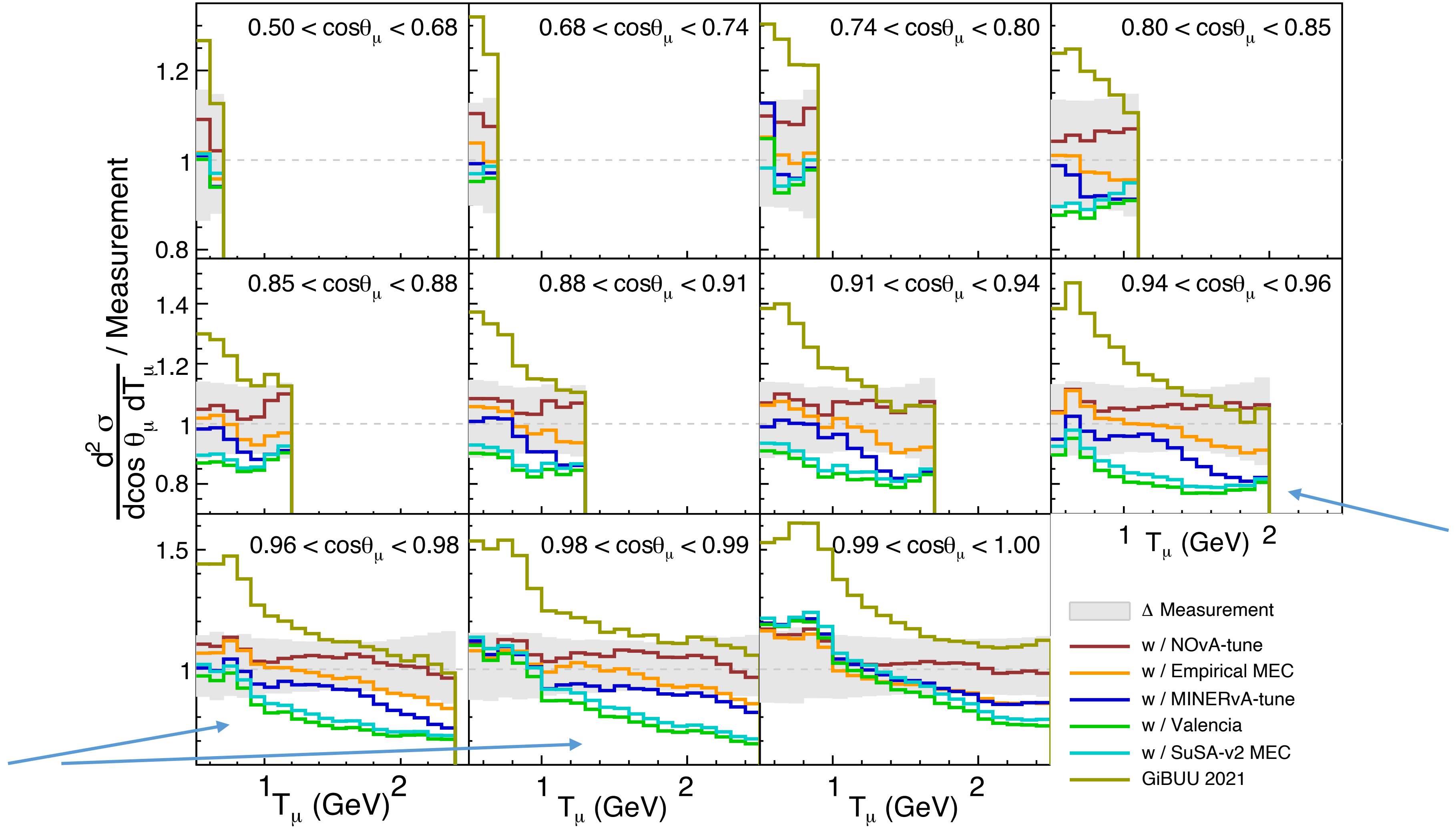


Data description requires large fraction of 2p2h.

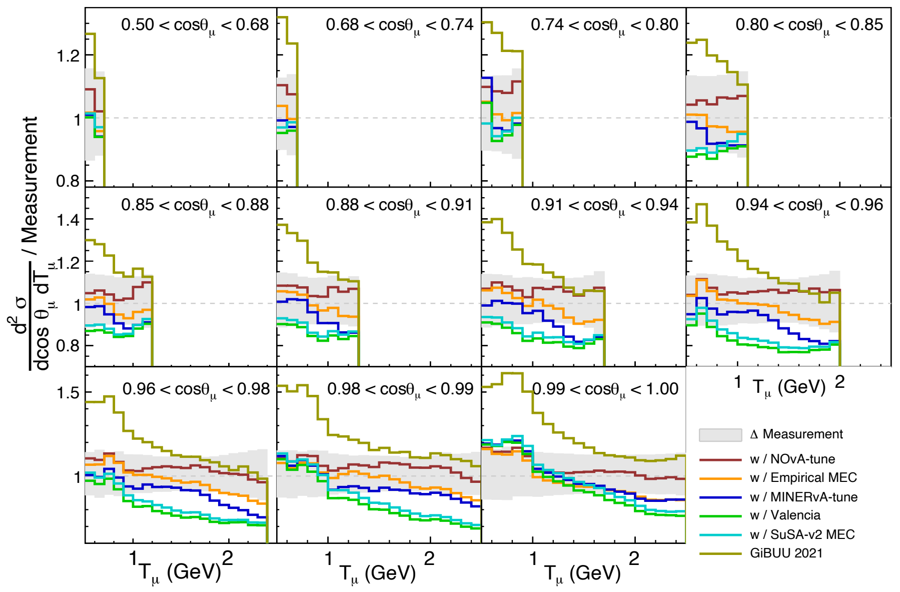
``Deficit" occurs in the transition region between CCQE and RES where 2p2h is predicted to occur.

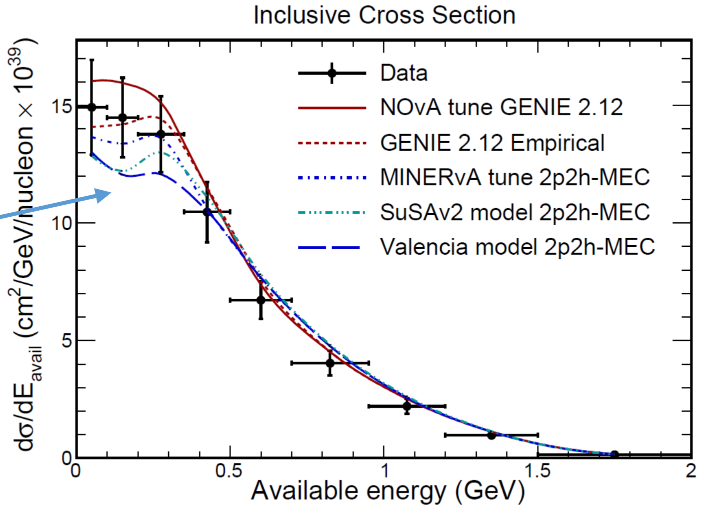


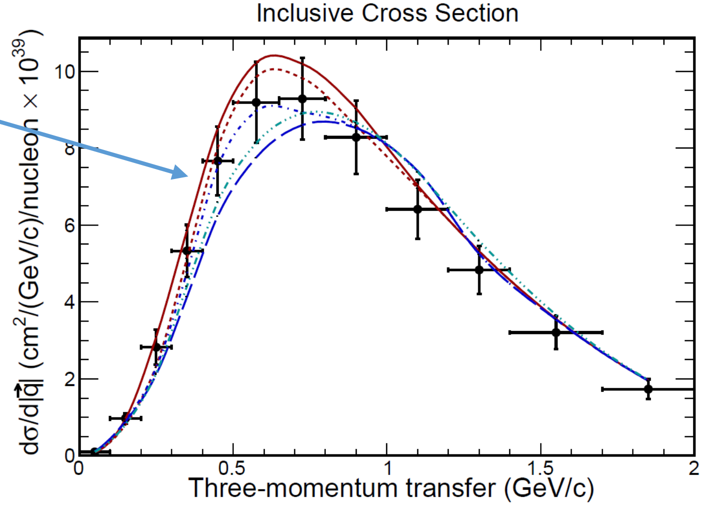
From the muon kinematic analysis, we see that the cross-section predictions (which include 2p2h contributions from various models) tend to under-predict in bins that are more forward and at higher muon momenta.



In the hadronic analysis, one sees a similar trend in which the modeling under-predicts in bins of lower available energy and 3-momentum transfer.







This is a region of kinematic phase space where 2p2h is degenerate with QE events.

The measurements indicate shortfalls with modeling of QE (1p1h) and 2p2h processes in this region.

RESULTS:

Double-differential cross-section measurements of ν_μ CC scattering at *$< E_\nu > \approx 1.9$ GeV*

ν_μ CC scattering with low hadronic energy using **lepton kinematics** (L. Aliaga)
Inclusive ν_μ CC scattering using **energy-momentum transfer** to the hadronic system (T. Olson)

**Analyses provide complementary views of kinematic regions enhanced in 2p2h and CCQE events.
Cross-section predictions, which include 2p2h contributions from various models,
tend to under-predict in bins that are**

1) **more forward-going and at higher muon momenta: $\cos\theta_\mu > 0.80$, $T_\mu > 0.80$ GeV.**
2) **of lower available energy and 3-momentum transfer: $E_{avail} < 0.4$ GeV, $|\vec{q}| < 0.8$ GeV/c.**

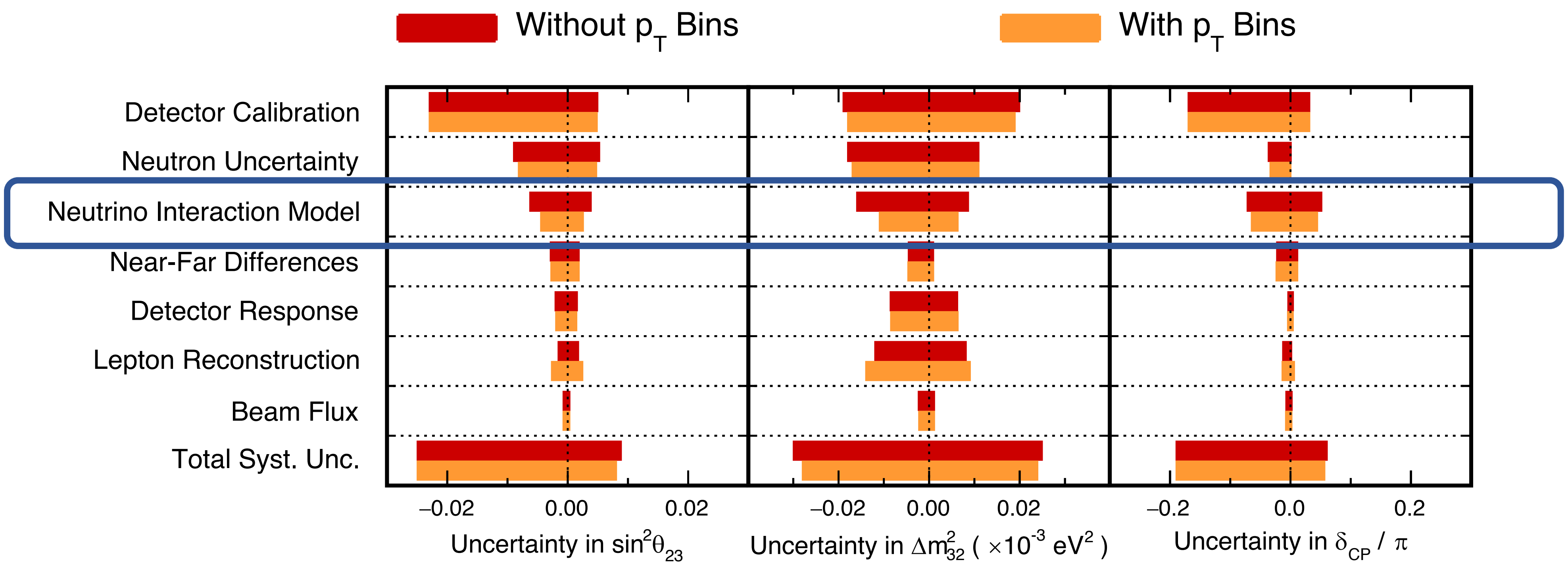
**Measurements indicate shortfalls with modeling of QE and 2ph2 reactions
that populate this region of phase space.**

Thanks for your attention!

Backup

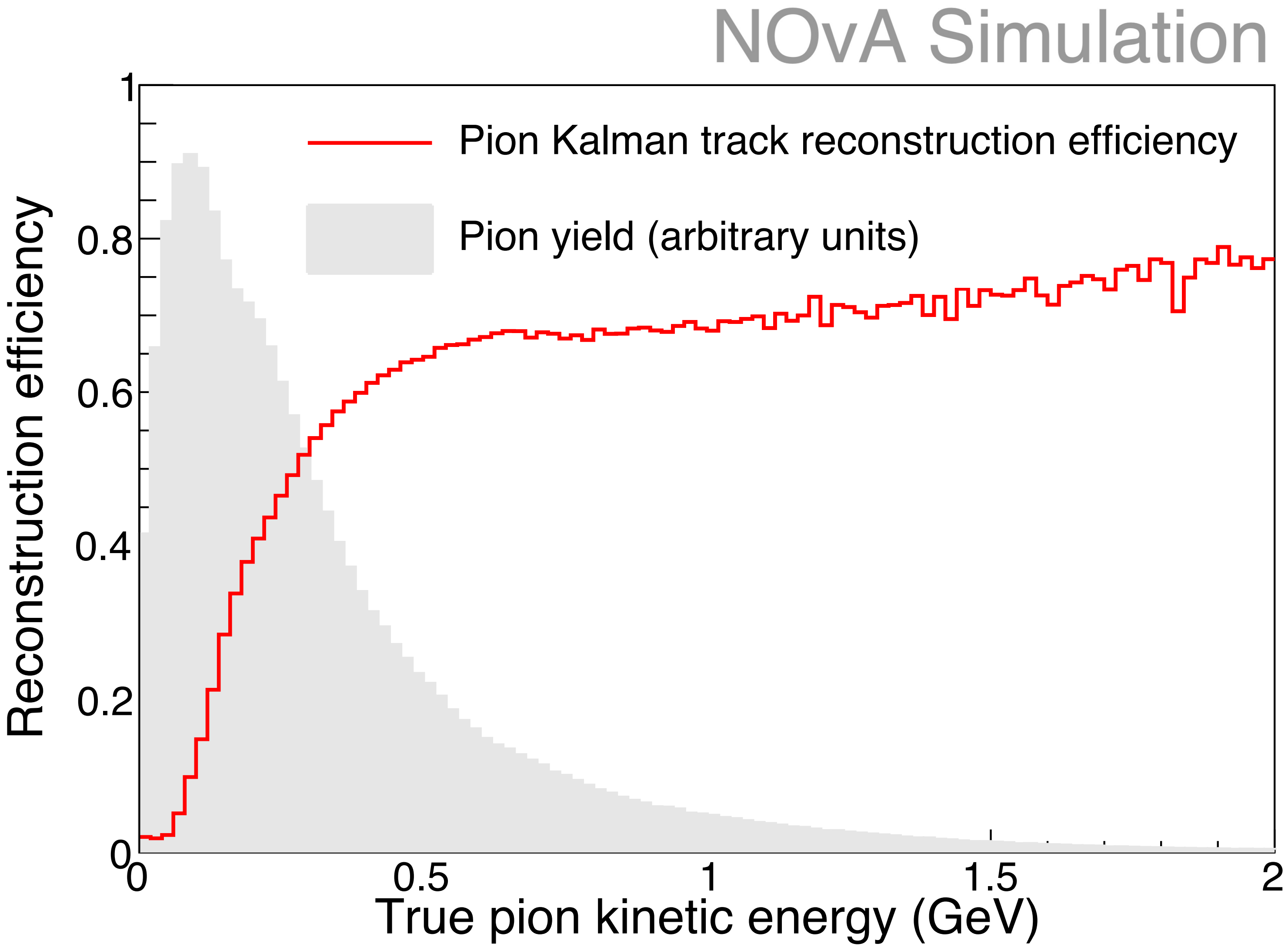
Uncertainties in neutrino oscillations

Neutrino cross-section model is one of the largest uncertainties in all oscillation parameters neutrino oscillation experiments measure



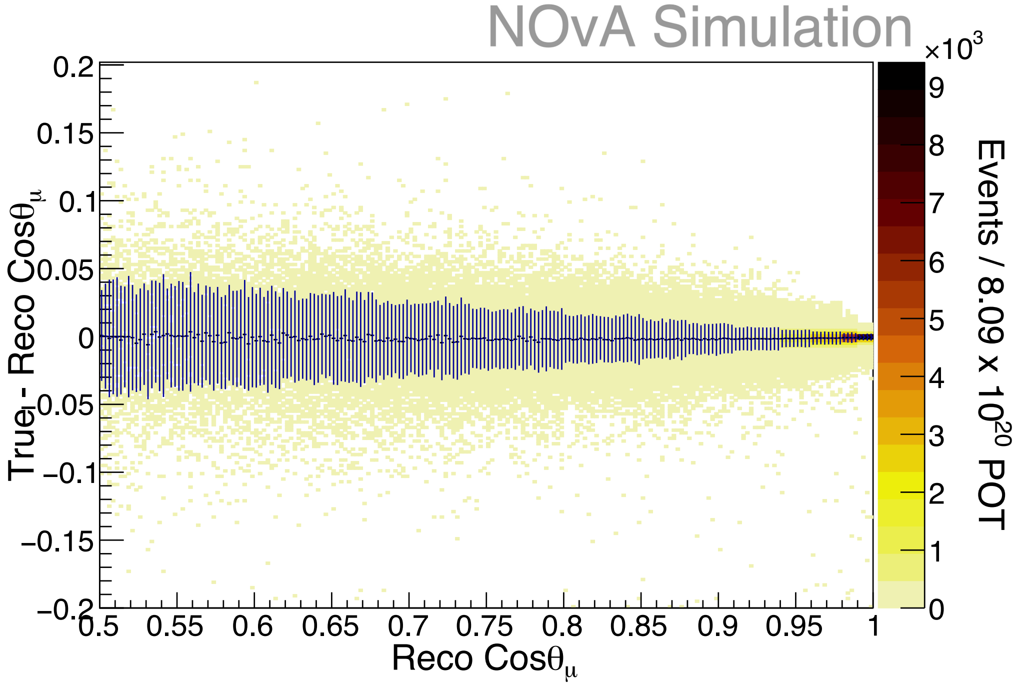
"An Improved Measurement of Neutrino Oscillation Parameters by the NOvA Experiment" Phys. Rev. D 106, 032004 (2022)

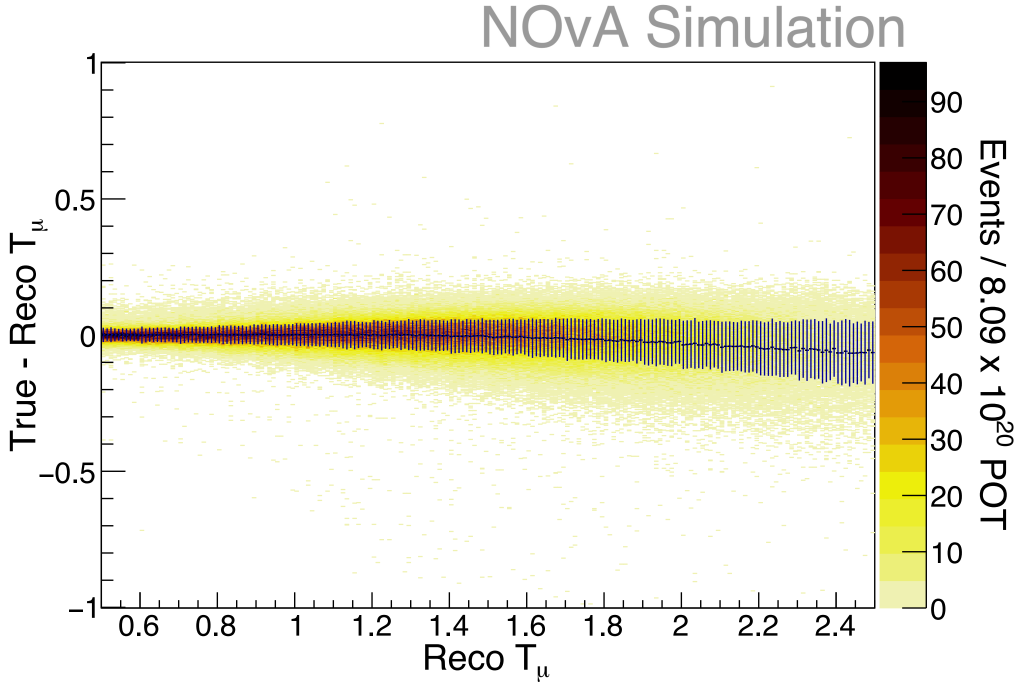
Pion reconstruction efficiency



Binning

Binning is determined considering resolution, statistical and systematic uncertainties

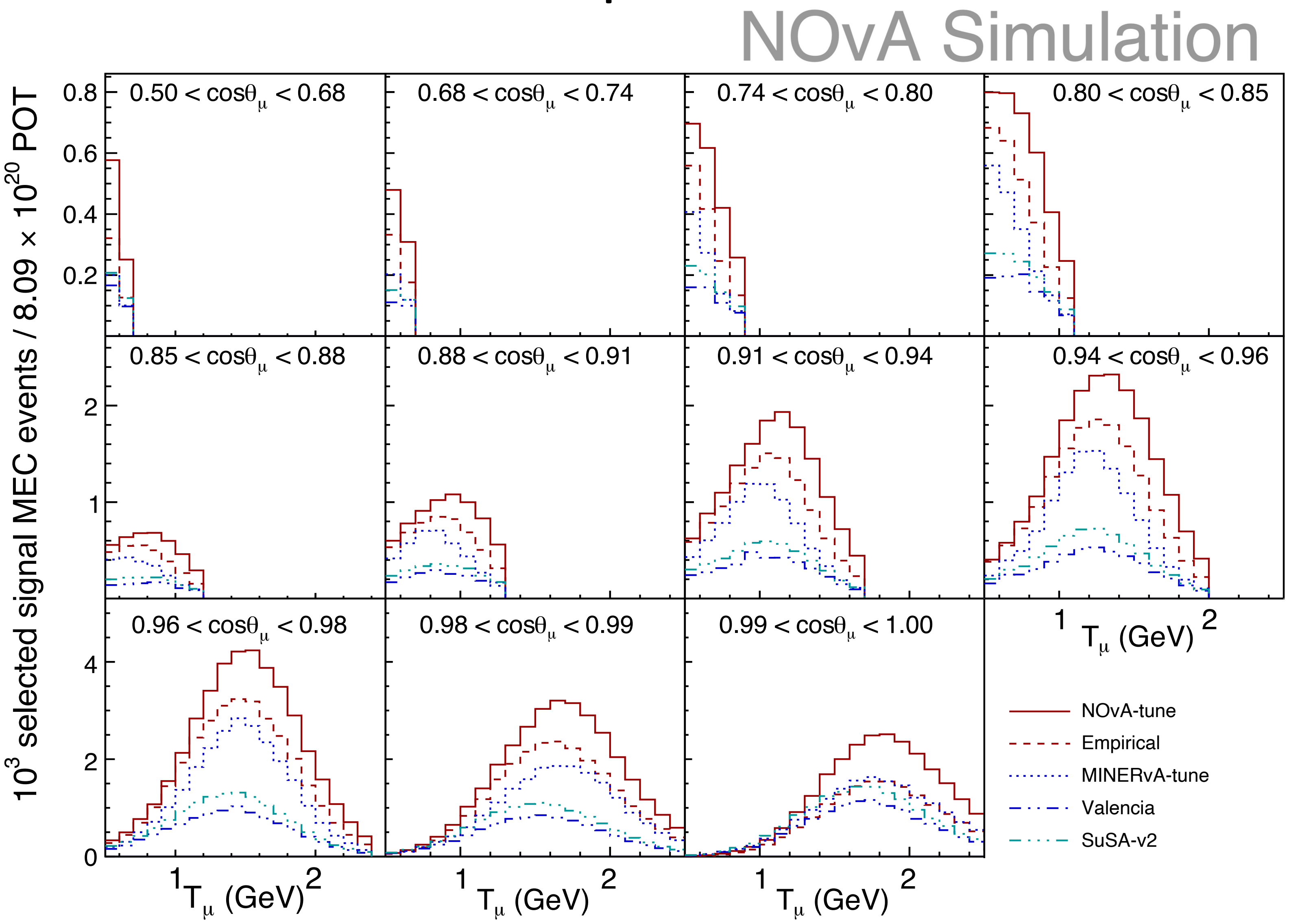




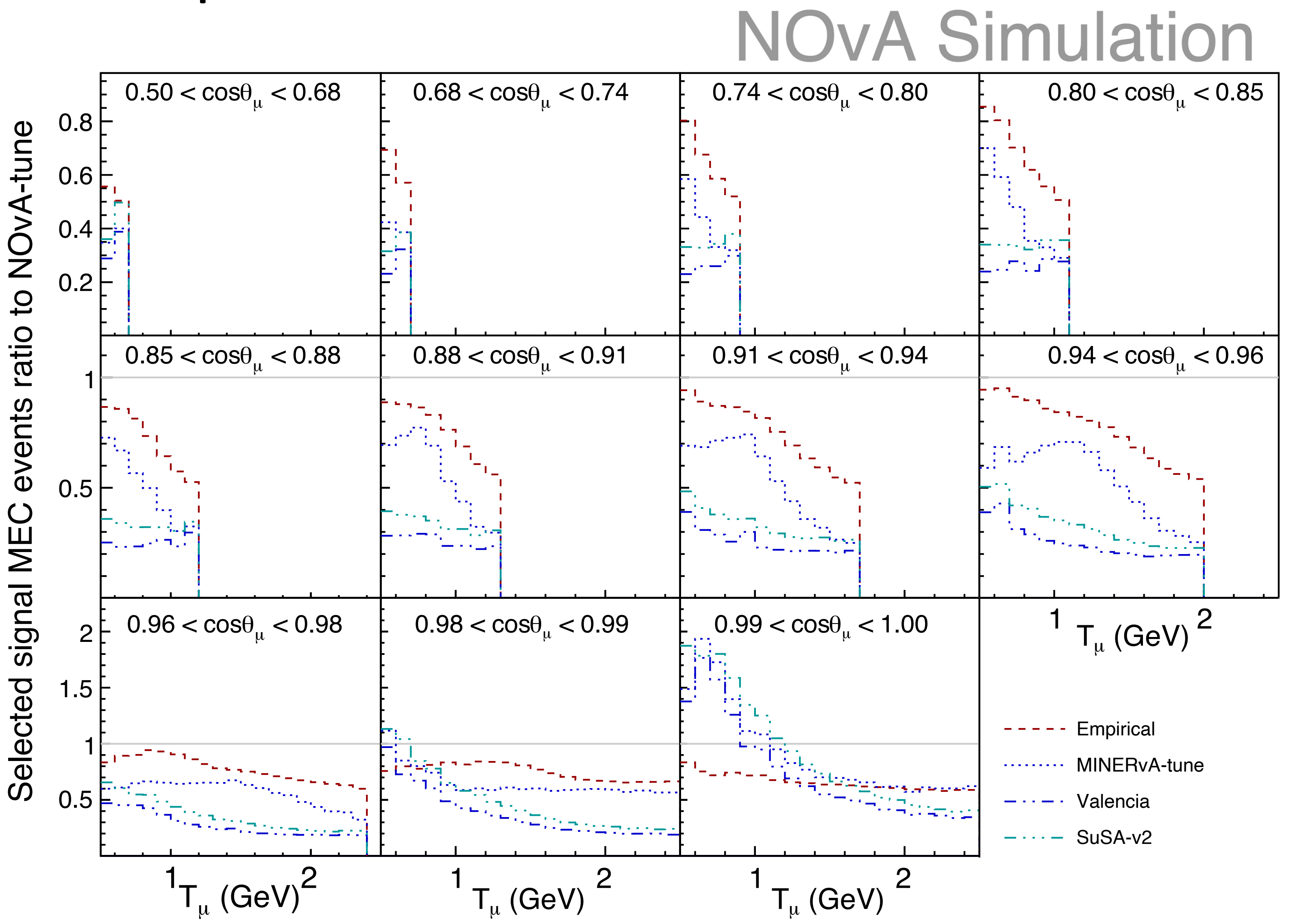
The muon energy is estimated by track length and has a resolution of approximately 4%

The muon angle resolution is < 0.1^0 at forward-going angles and < 3^0 at high angles

Selected 2p2h distributions



2p2h contribution in selection

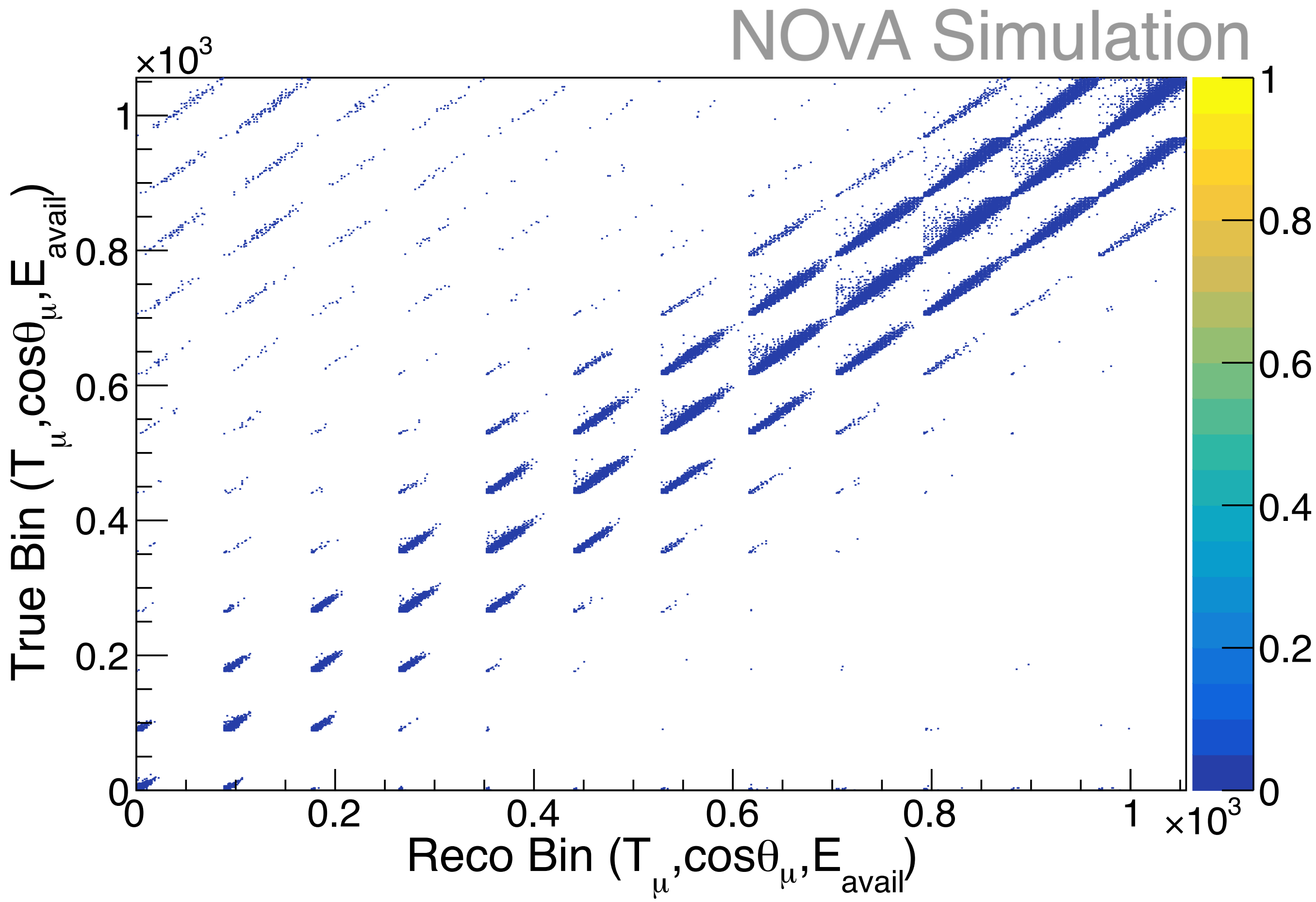


Unfolding

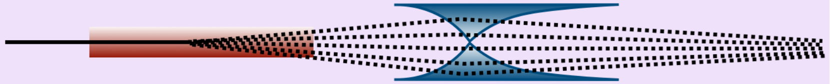
Unfolding technique (D'Agostini) is used to correct the smearing between bins due to detector and reconstruction effects:

- Smearing level is small: 0.46% of the off-diagonal bins in the migration matrix are larger than 20% of their diagonal element.

- We use the minimal Mean Square Error and several shifted fake data to optimize the number of iterations.

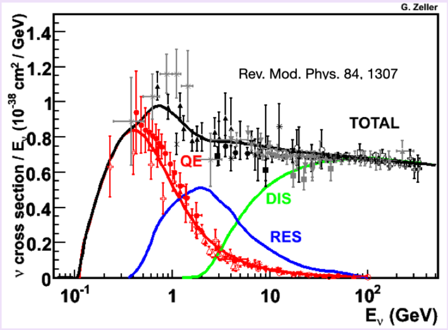


NOvA simulation

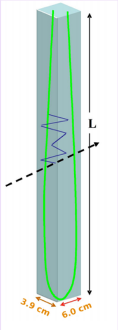


Beamline and Flux: G4NuMI

ν-A modelling: GENIE



Detector response: GEANT4



Readout electronics & DAQ: Custom simulation routines

Interaction mode in the inclusive selection

QE	2p2h	Res	DIS	COH
20.8%	18.5%	38.7%	20.2%	1.8%

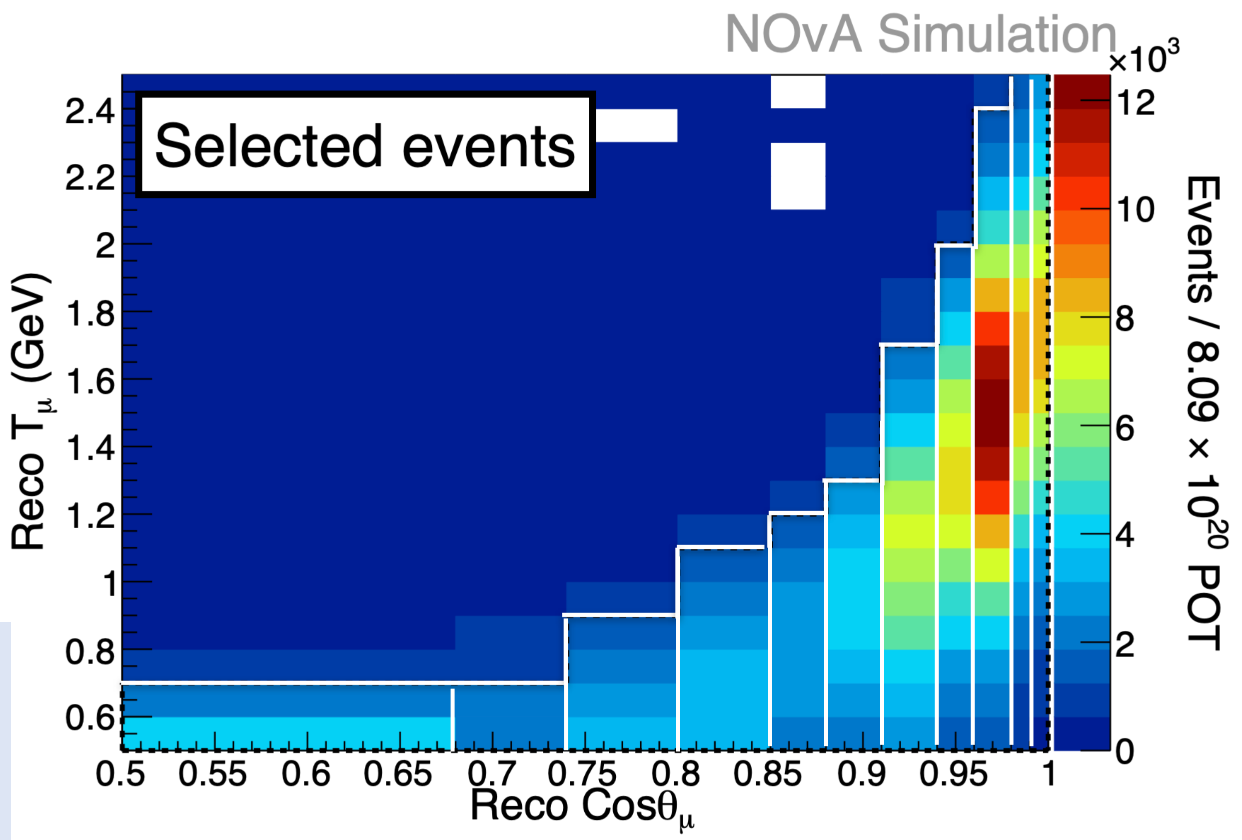
Selection and signal definition

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

We select events with **only a single track** (the muon candidate)

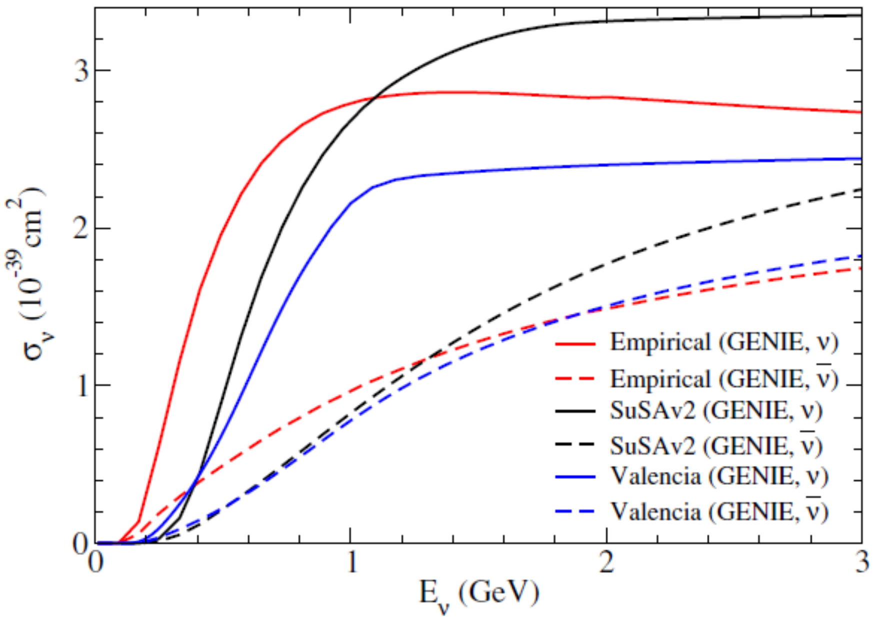
Res and DIS are more likely to produce events with > 1 track

To find the signal definition:
A scan across all possible proton and pion energy thresholds is performed looking for the minimal uncertainty of the total cross section

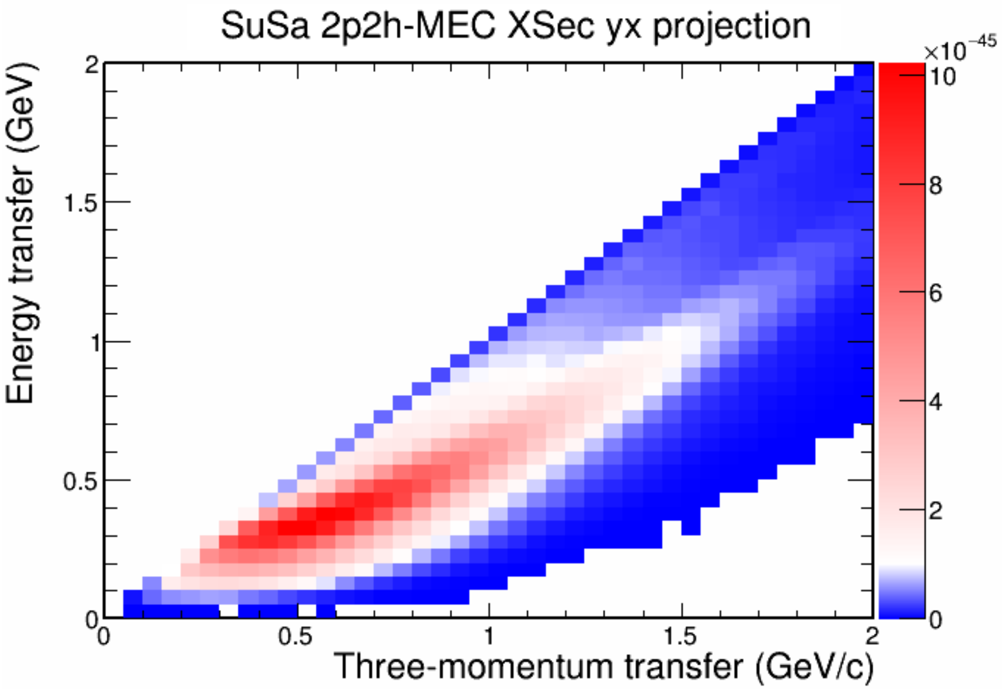


Selection:
ν_μ CC with 1 track

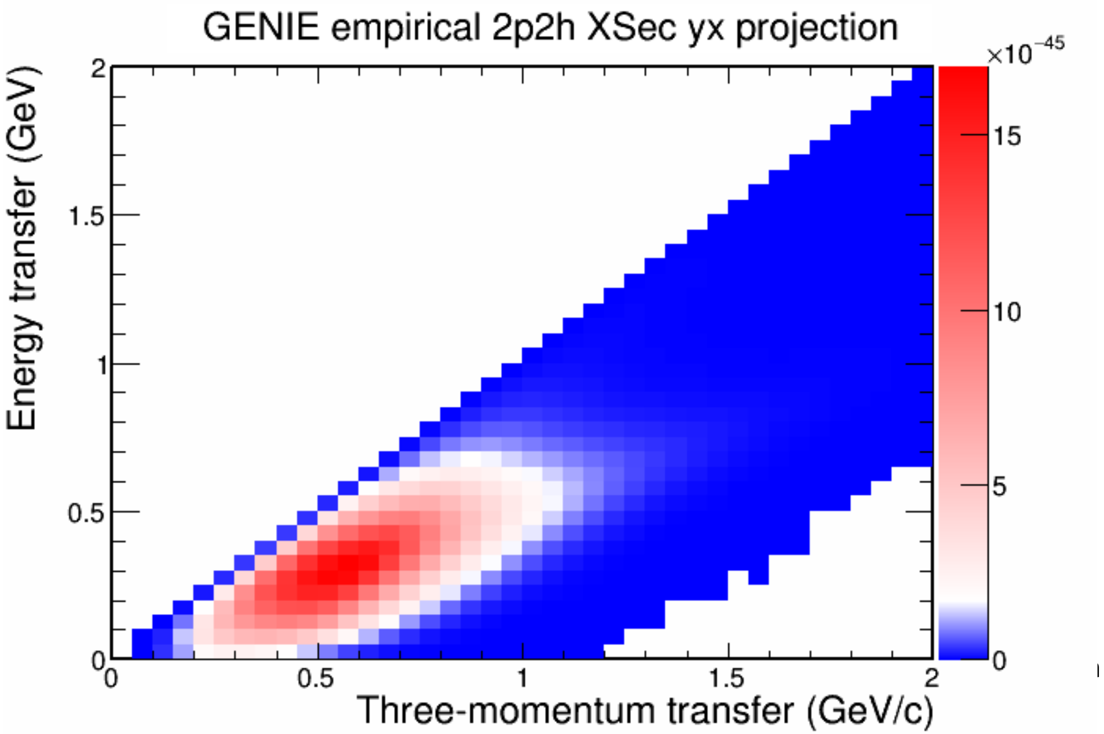
Signal: *ν_μ CC in the fiducial volume with*
T_{proton}^{max} = 250 MeV
T_{pion}^{max} = 175 MeV



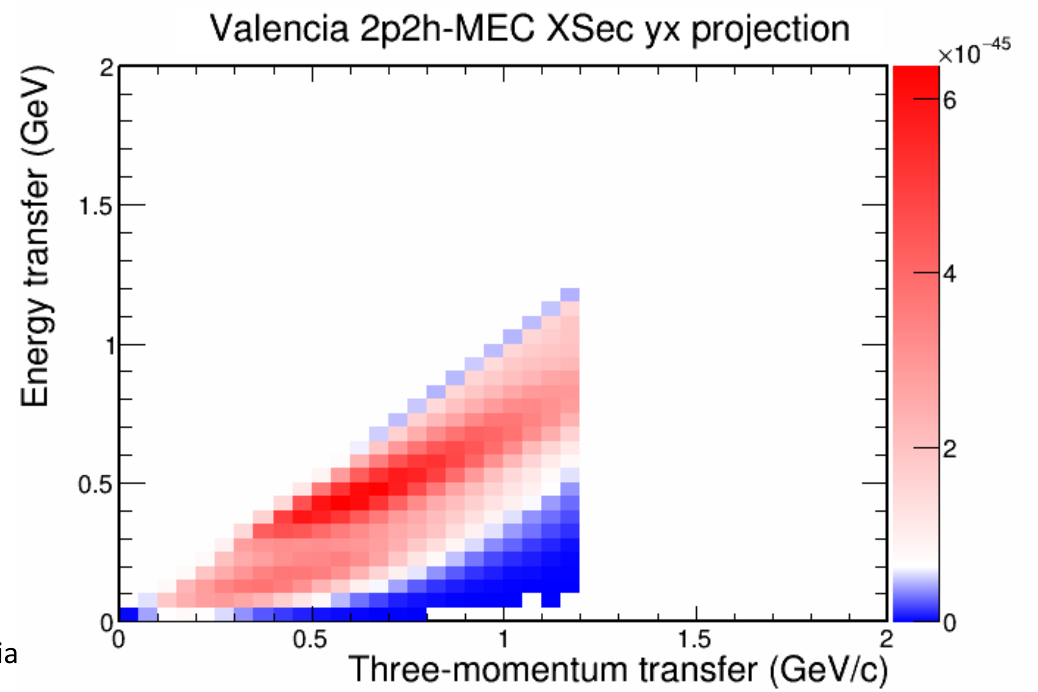
σ_ν (10^{-39} cm^2)
E_ν (GeV)
Empirical (GENIE, ν)
Empirical (GENIE, $\bar{\nu}$)
SuSAv2 (GENIE, ν)
SuSAv2 (GENIE, $\bar{\nu}$)
Valencia (GENIE, ν)
Valencia (GENIE, $\bar{\nu}$)



SuSa 2p2h-MEC XSec yx projection
Energy transfer (GeV)
Three-momentum transfer (GeV/c)
$\times 10^{-45}$



GENIE empirical 2p2h XSec yx projection
Energy transfer (GeV)
Three-momentum transfer (GeV/c)
$\times 10^{-45}$



Valencia 2p2h-MEC XSec yx projection
Energy transfer (GeV)
Three-momentum transfer (GeV/c)
$\times 10^{-45}$

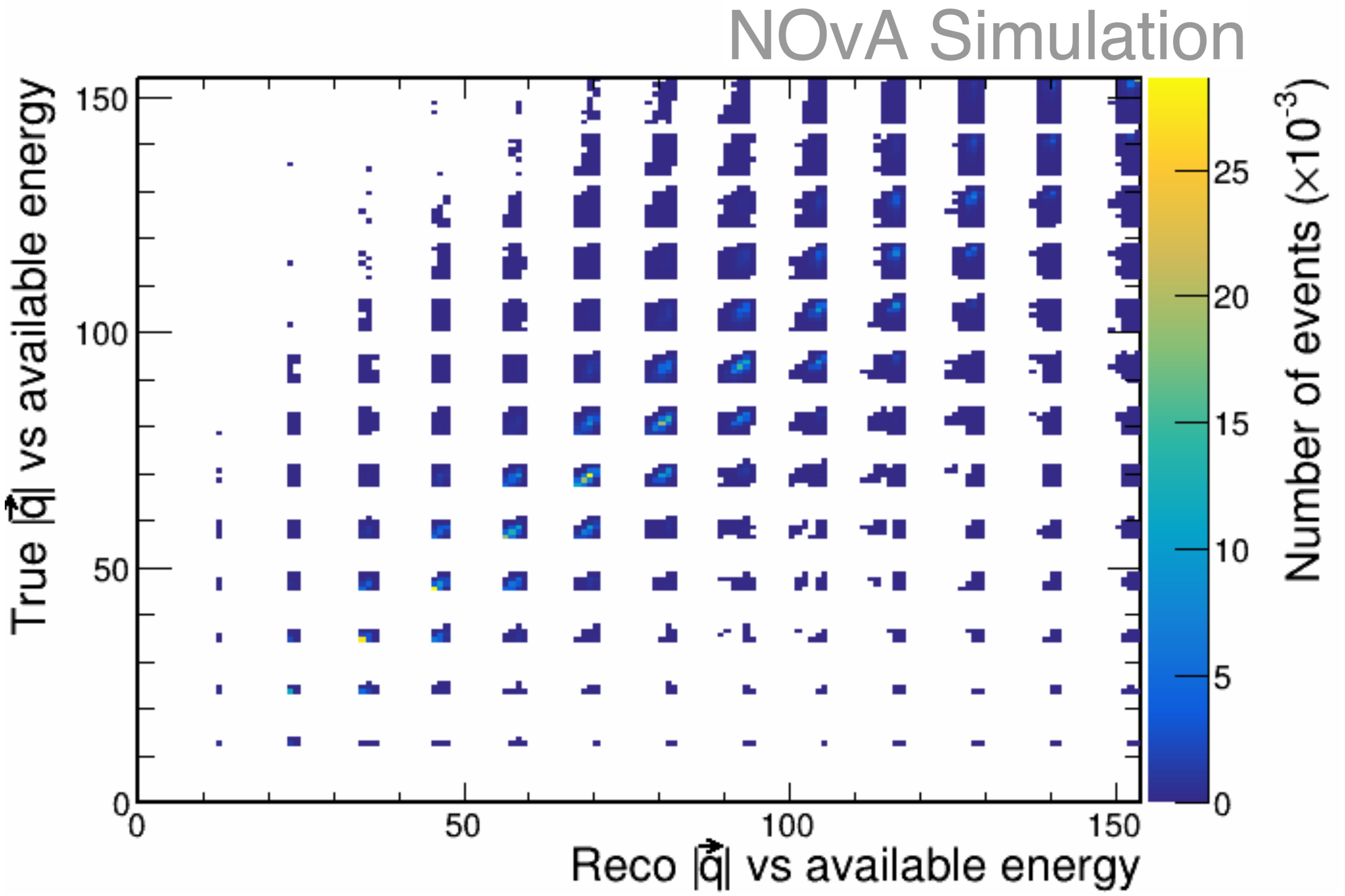
- **The event passes initial quality cuts**
- **The event has a reconstructed muon.**
- **The vertex is reconstructed within the fiducial volume.**
  (270 cm in X by 270 cm in Y by 900 cm in Z)
- **No particle leaves the detector, only muons go into the muon catcher**
- **Event muon kinematics satisfy criteria that enhance selection efficiency and sample purity.**
  - Reco muon kinetic energy 0.5 GeV < T_μ < 2.5 GeV.
  - Reco 0.5 < $\cos(\theta_\mu)$ and has an increasing cut off as T_μ increases.

Unfolding Hadronic Variables

Unfolding technique (D'Agostini) is used to correct the smearing between bins due to detector and reconstruction effects:

- We use the minimal Mean Square Error and several shifted fake data to optimize the number of iterations.

- Use 2 iterations of unfolding



Covariance and correlation hadronic variables