Measurement of ν_μ CC inclusive cross section and estimation of 2-particle 2-hole contribution

arxiv: 2410.05526

Complementary analysis arxiv: 2410.10222

Travis Olson

University of Houston

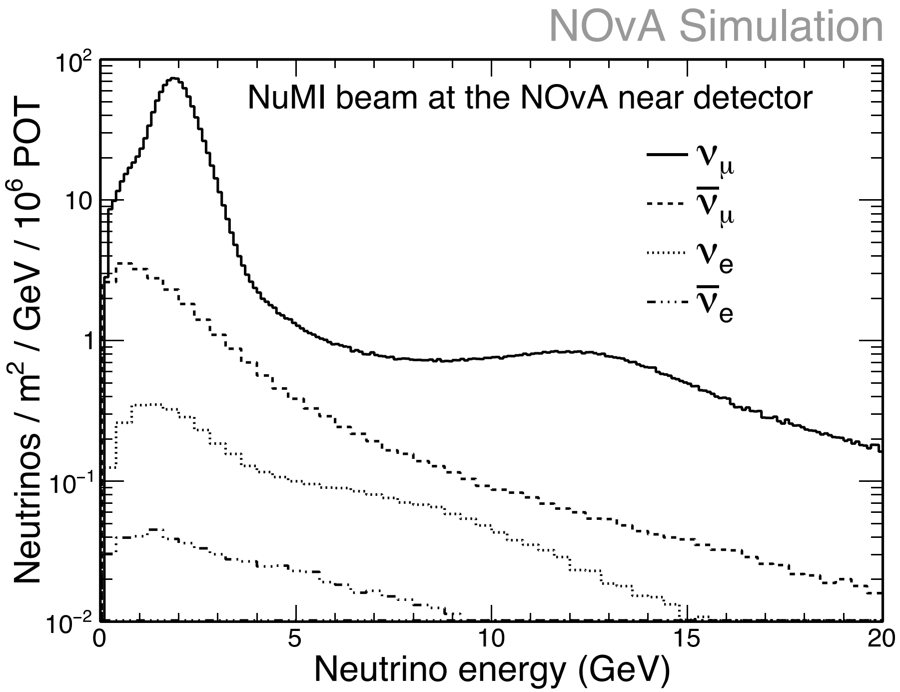
For the NOvA collaboration

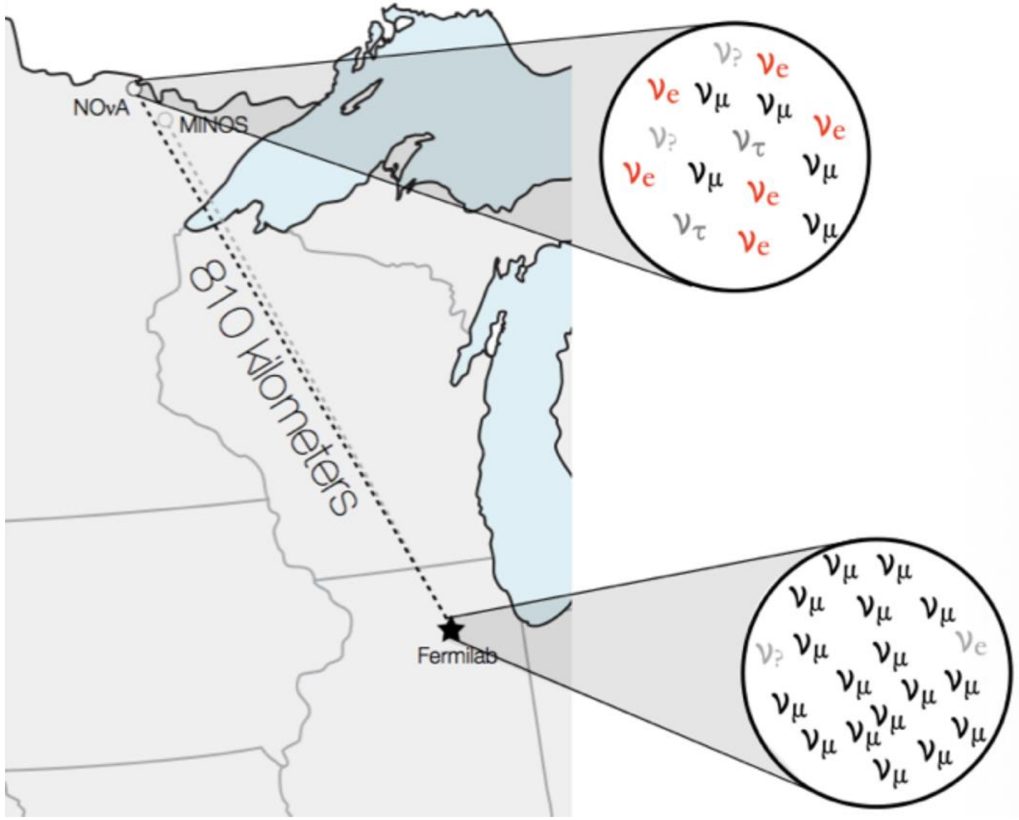
The NOvA experiment

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*



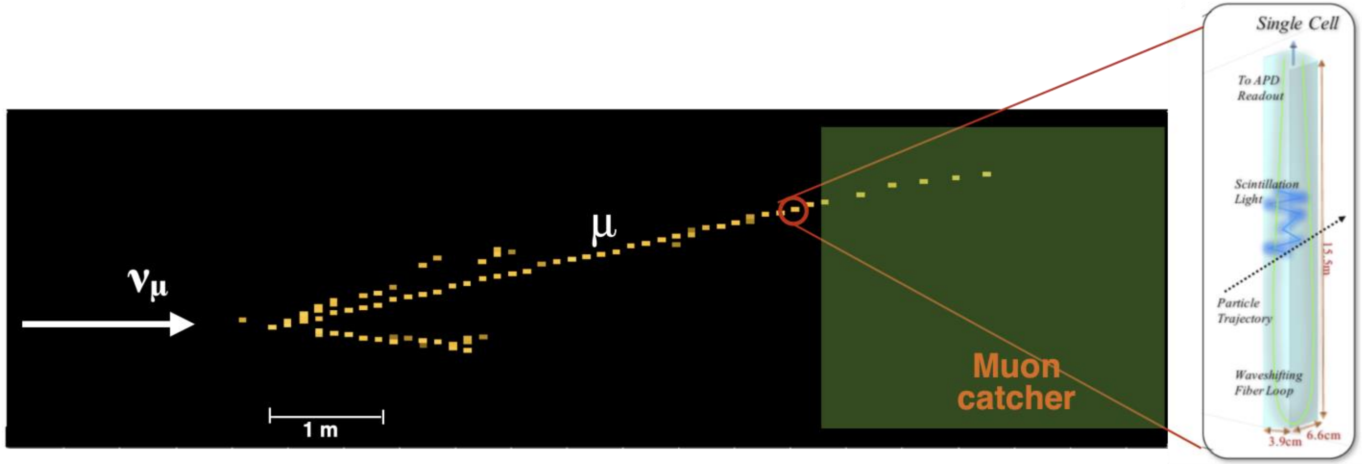


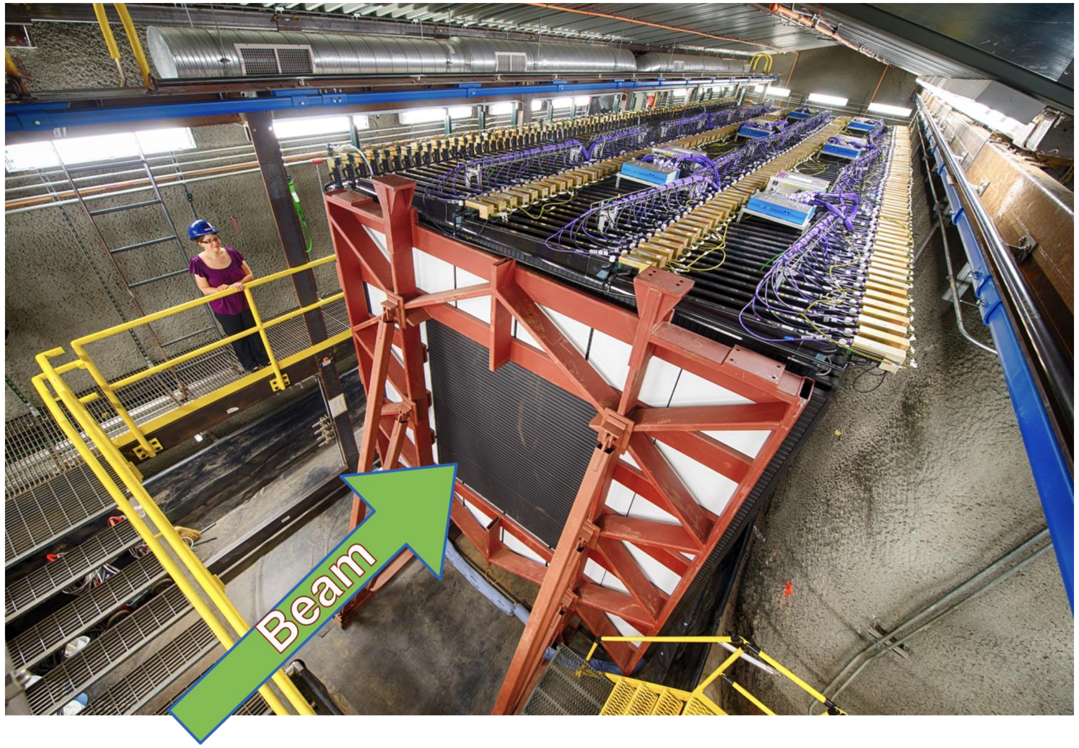
94% pure ν_μ, 5% $\bar{\nu}_\mu$, and 1% ν_e + $\bar{\nu}_e$ in neutrino mode

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.





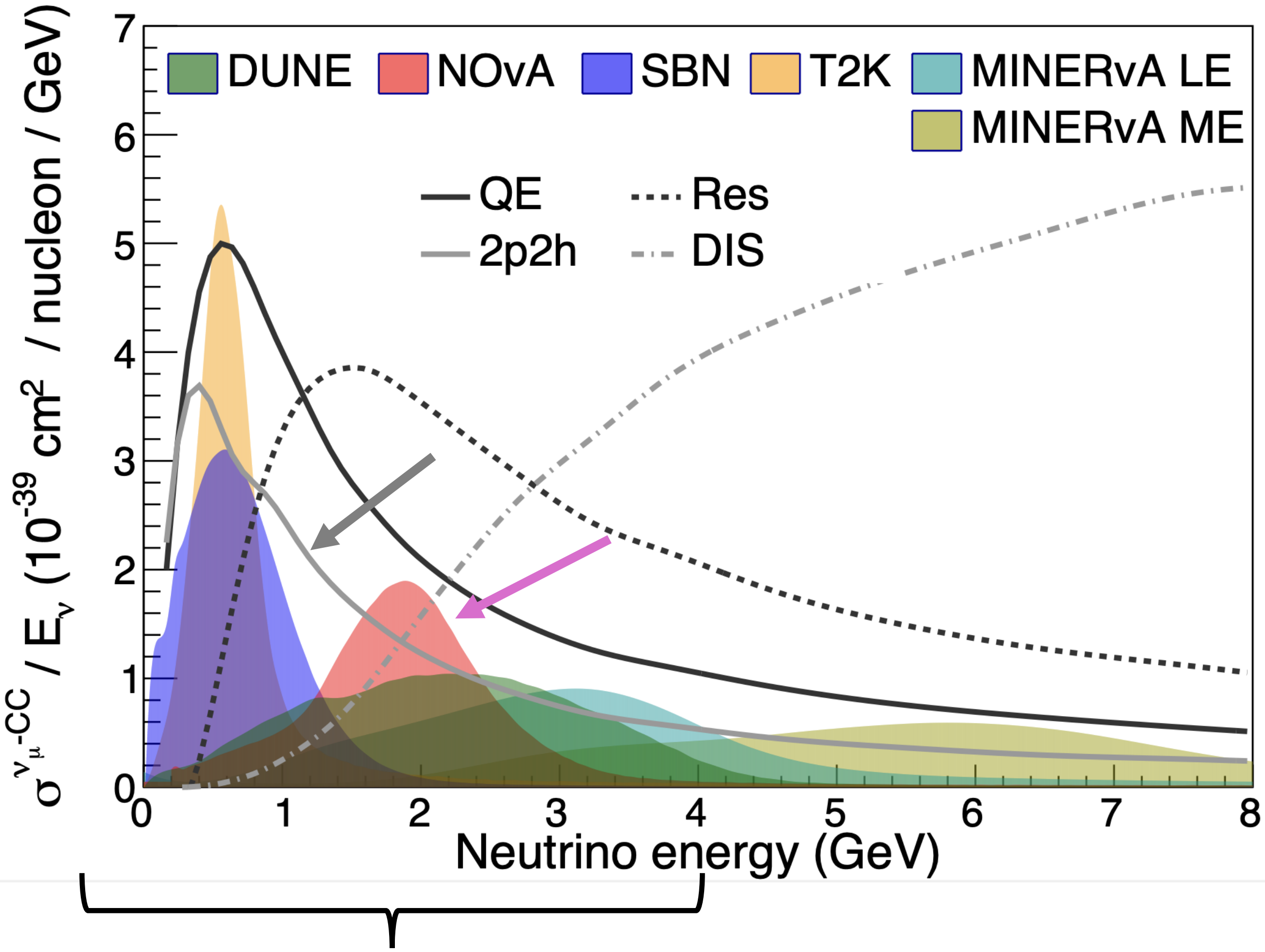
PVC cells filled with **liquid scintillator, 195 ton** fully active mass and 98-ton downstream muon catcher

Alternating planes of orthogonal views

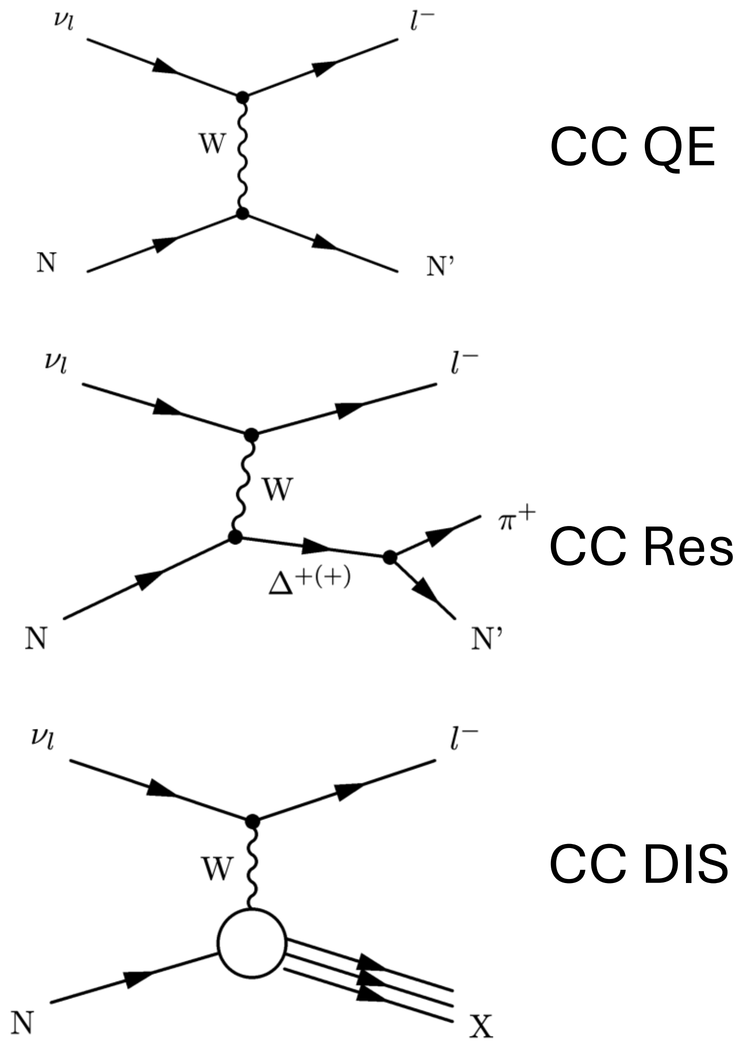
Low-Z, fine-grained: Composition by mass:

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

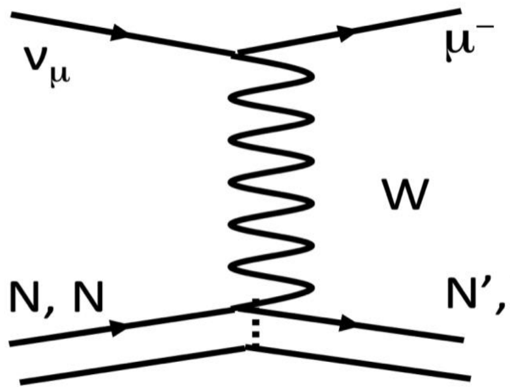
Neutrino-nucleon interactions



The transition region between interaction processes



In a nuclear medium, neutrinos can interact with two nucleons



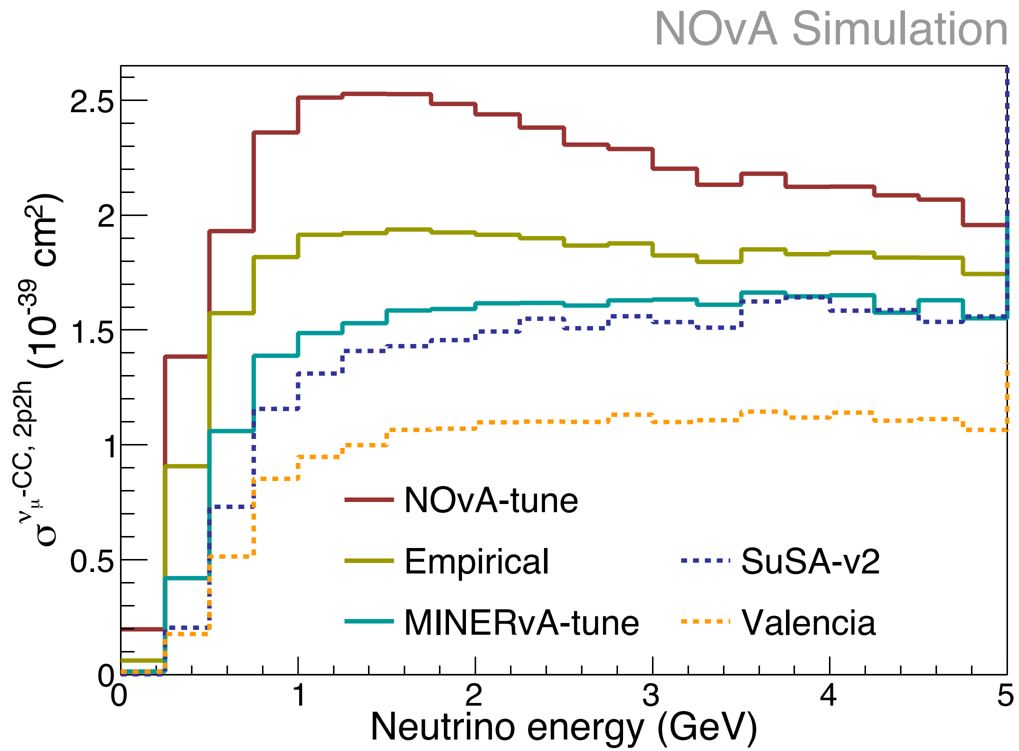
2-particle 2-hole processes:

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

Models for this process have large disagreements:

NOvA-tunes
GENIE Empirical MEC
MINERvA-tunes

SuSA-v2 model
Valencia model



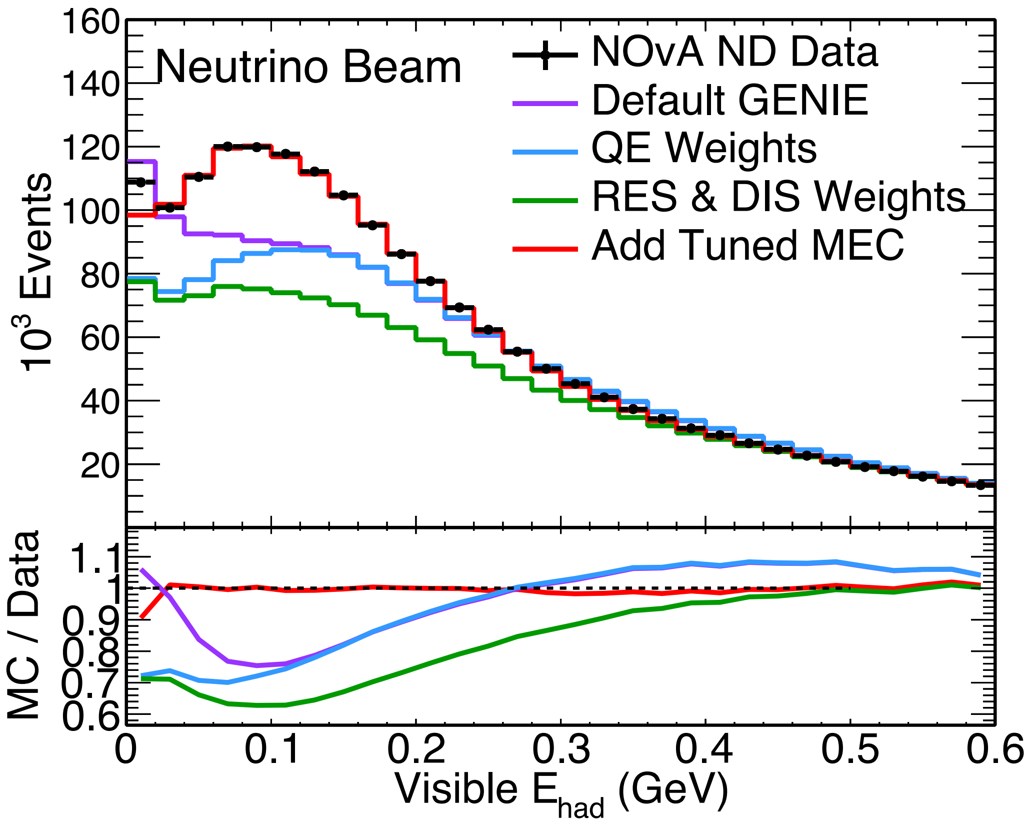
Cross-section model

Neutrino interactions are simulated using GENIE 2.12

ISI	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	Pythia6	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



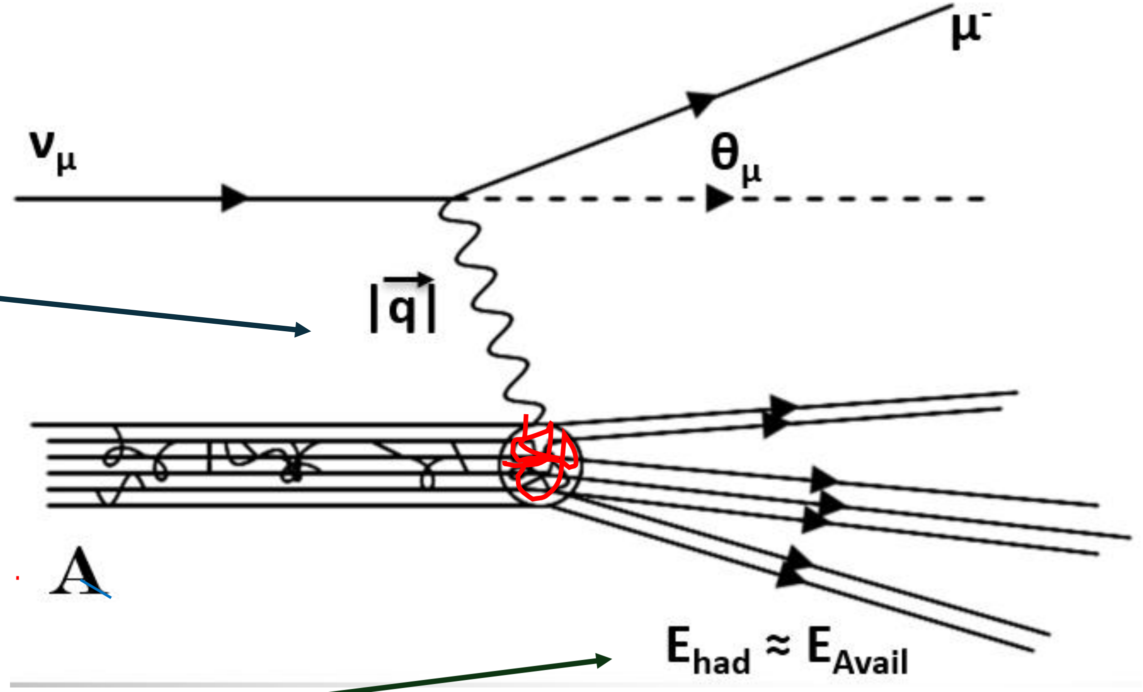
Our analyses are constructed to be insensitive to this tuning

Previous tune that was used in the NOvA 2019 analysis **Eur. Phys. J. C 80, 1119 (2020)**

Analysis variables:

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

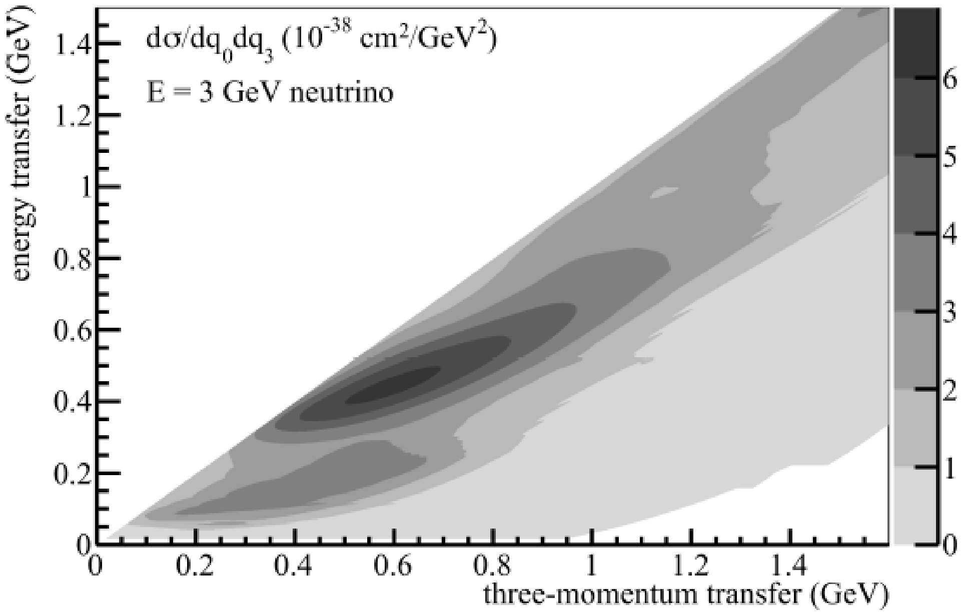
hadronic available energy, E_{avail}



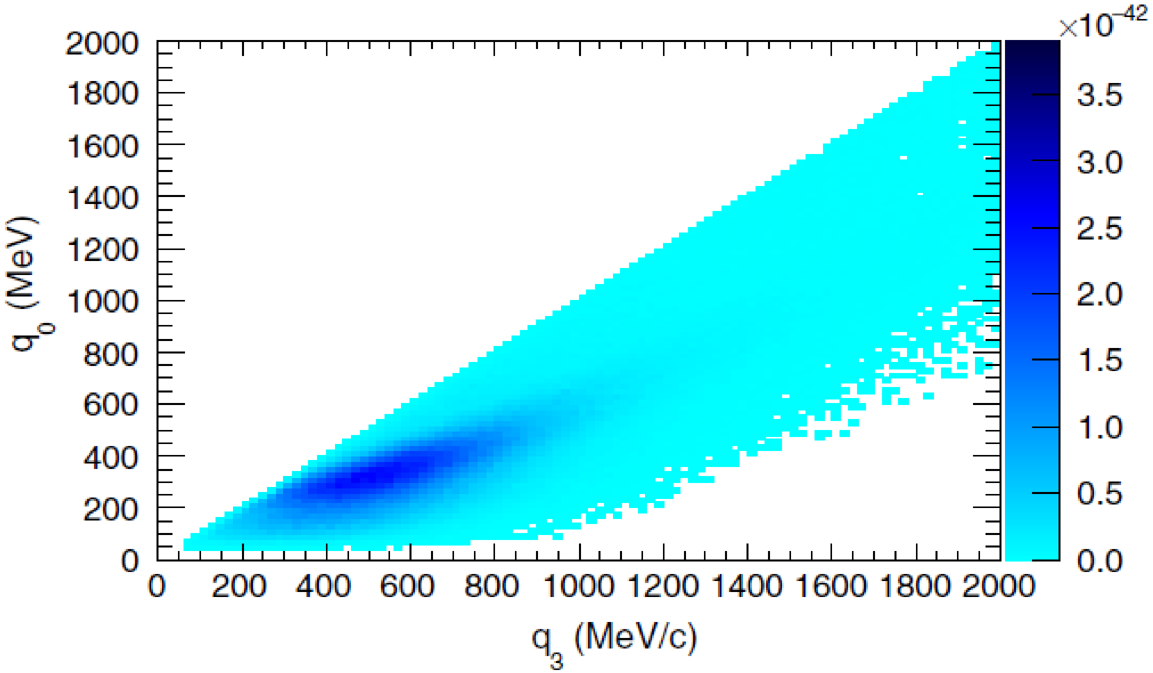
Available energy:

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

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).



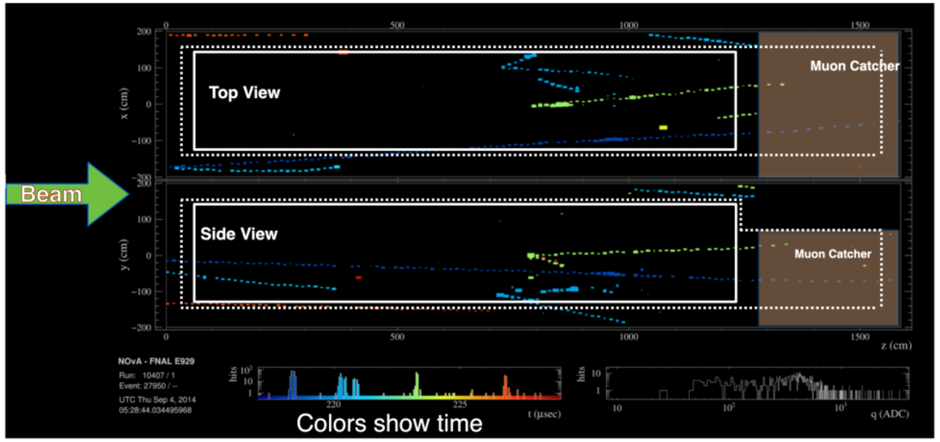
S. Dolan et al. (SuSAv2), Phys. Rev. D 101, 033003 (2020).

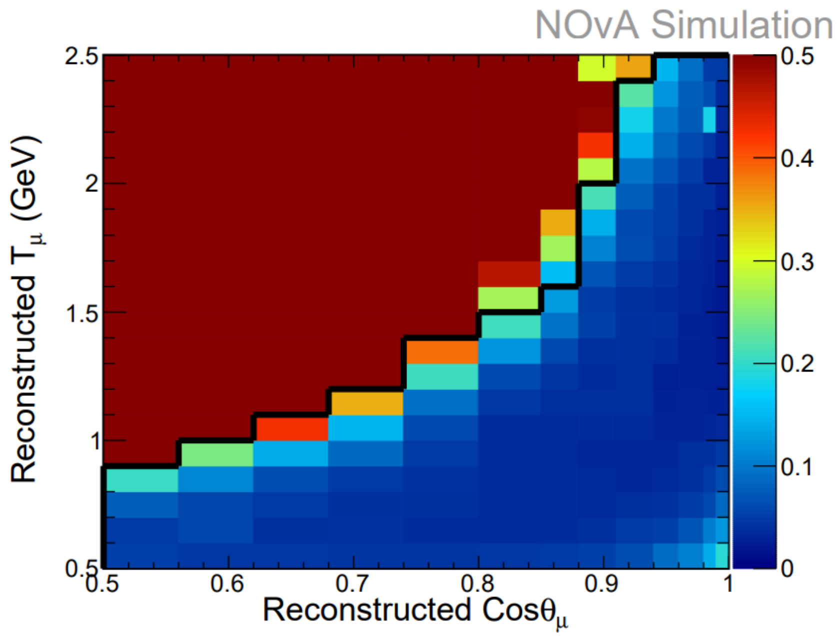
The analysis reported here uses variables which are as close to $(q_0, |\vec{\mathbf{q}}|)$ as we can achieve experimentally.

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

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)

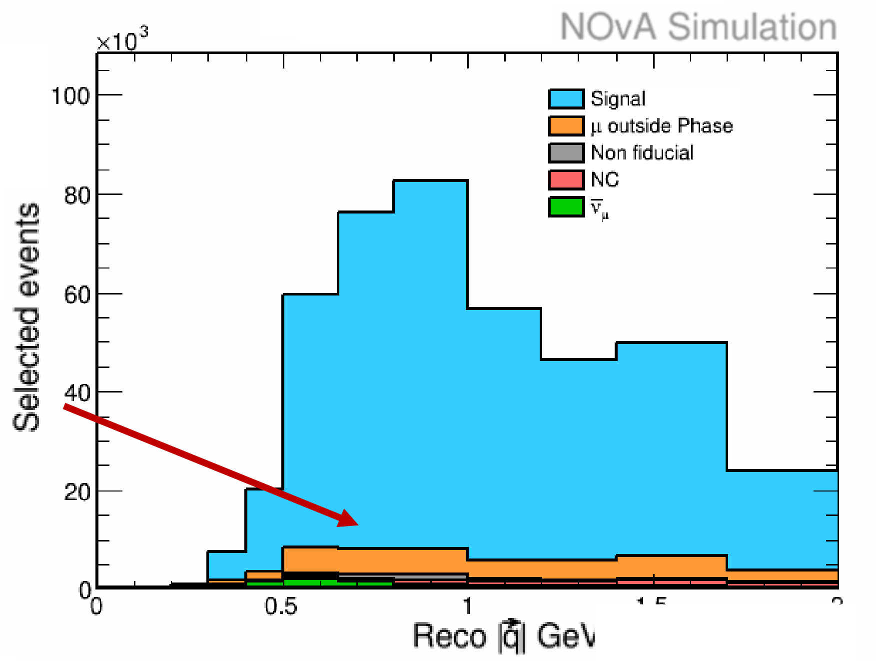


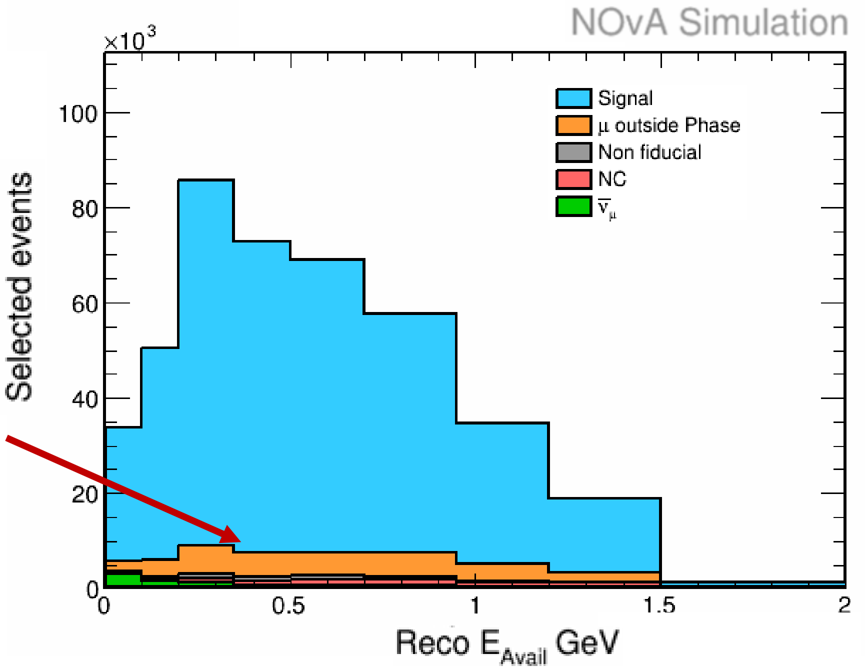


- **Event muon kinematics satisfy criteria that enhance selection efficiency and sample purity.**
  - True muon kinetic energy 0.5 GeV < T_μ < 2.5 GeV.
  - True 0.5 < $\cos(\theta_\mu)$ and has an increasing cut off as T_μ increases.

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

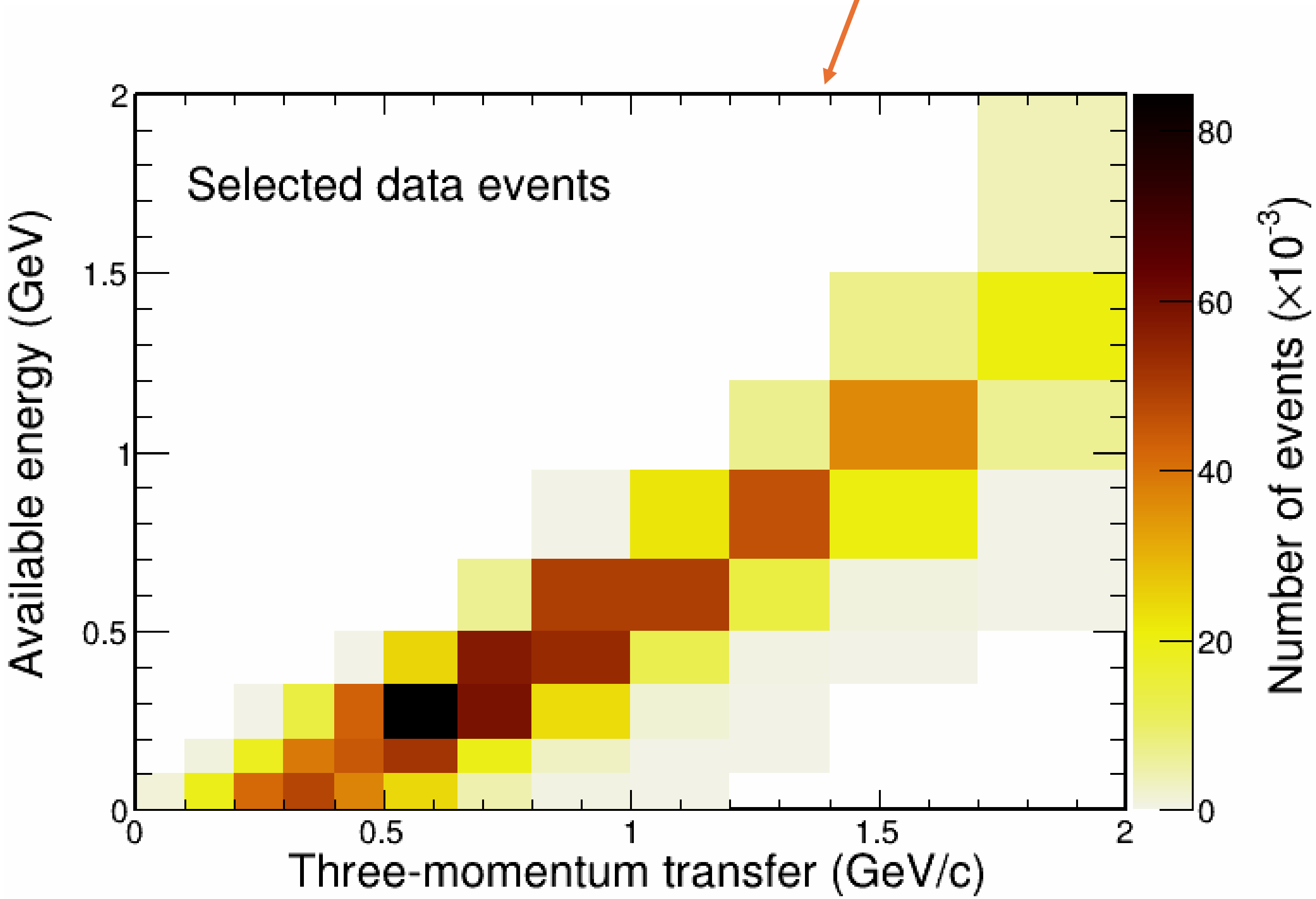
ϕ_ν is the integrated neutrino flux

T_N is the number of target nucleons

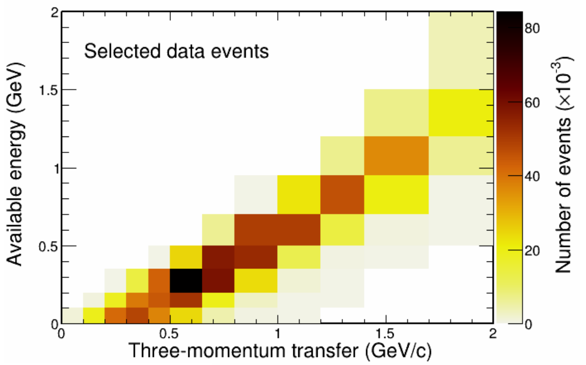
$(\Delta|\vec{q}|)_i(\Delta E_{avail})_j$ are the bin widths for the ith bin of |q| and the jth bin of E_{avail}

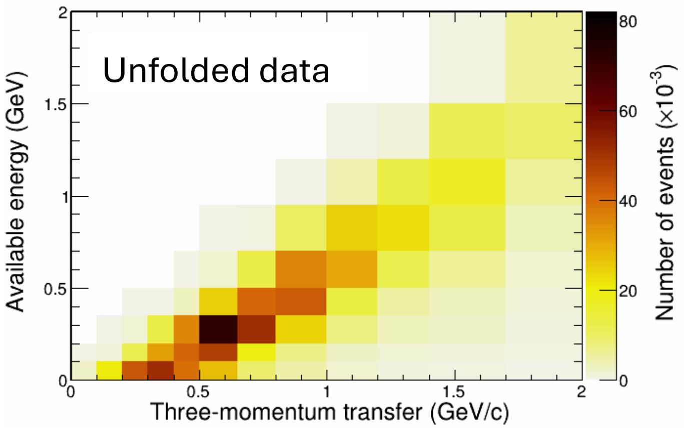
$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta} U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{Data} - N_{\alpha\beta}^{Bkgd}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$

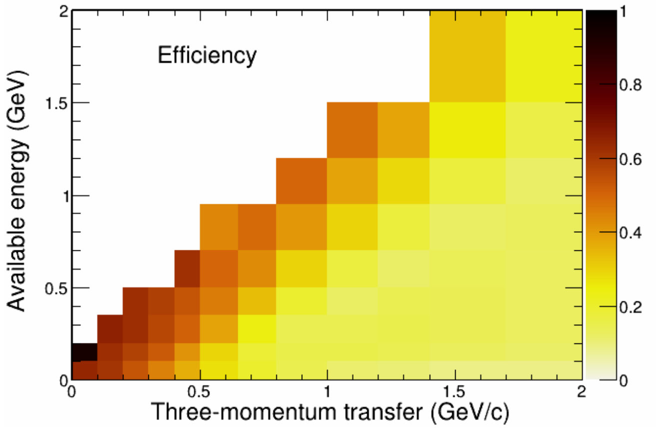
Almost 1 million selected neutrino events!

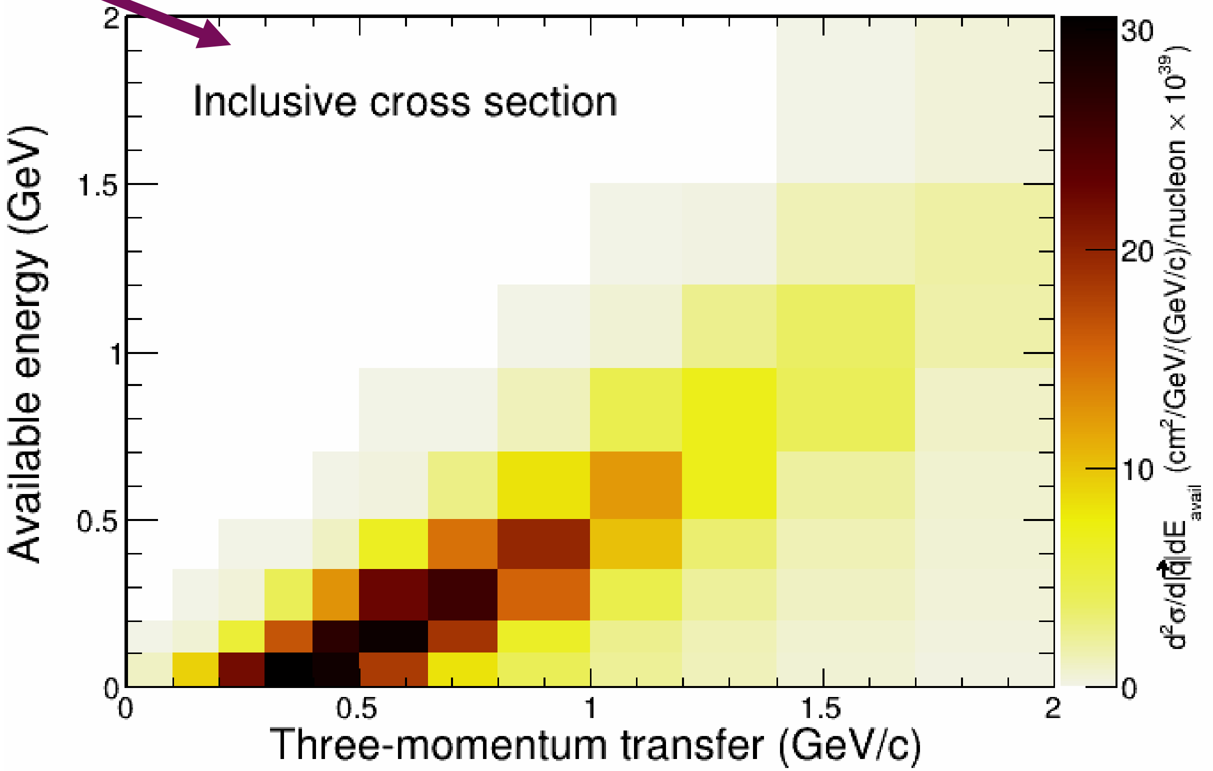


$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{avail}}\right)_{ij} = \frac{\Sigma_{\alpha\beta}U_{ij,\alpha\beta}\left(N^{Data}_{\alpha\beta} - N^{Bkgd}_{\alpha\beta}\right)}{\varepsilon_{ij}(\phi_\nu T_N)(\Delta|\vec{q}|)_i(\Delta E_{avail})_j}$$







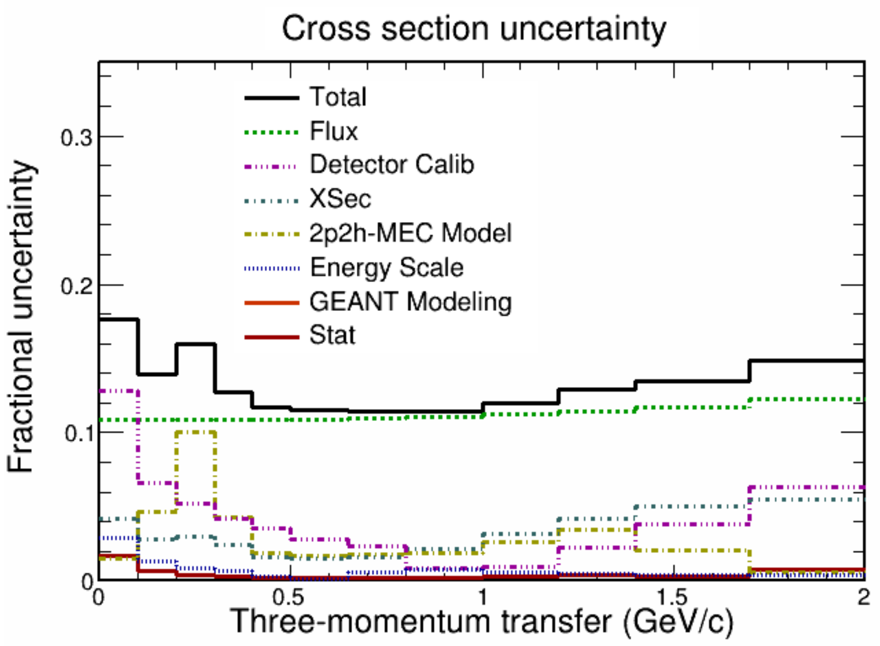


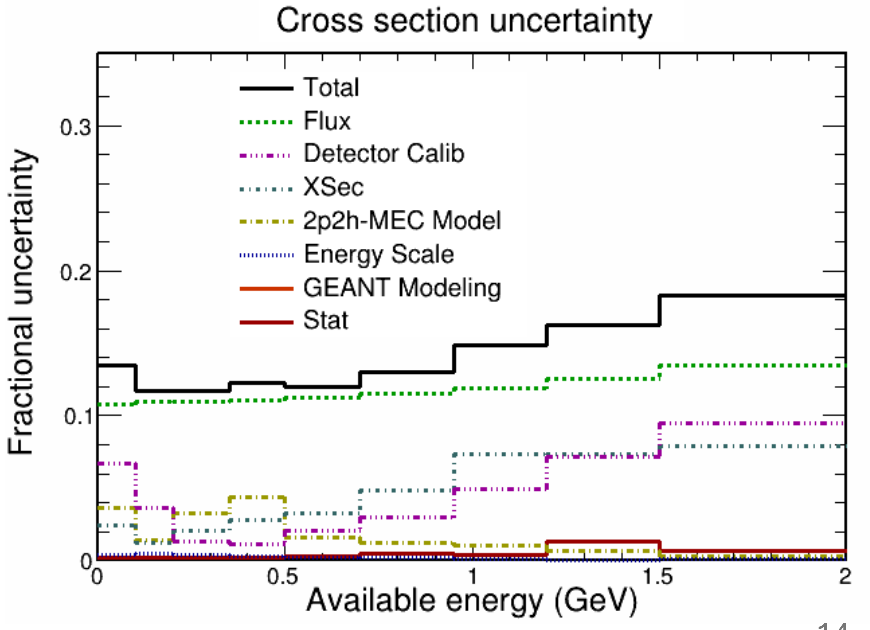
Cross-section Uncertainty:

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

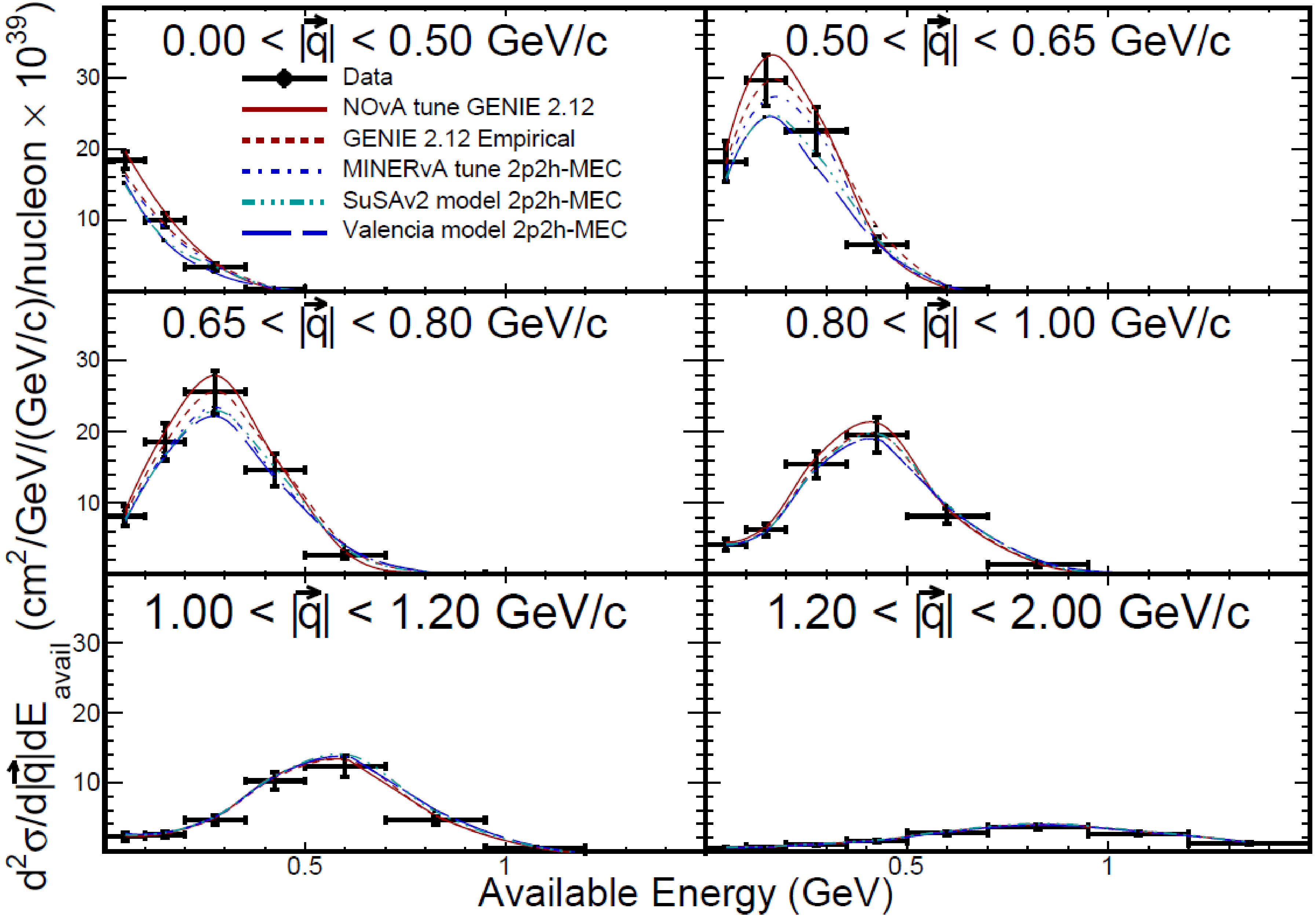




Cross section per analysis bins:

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

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

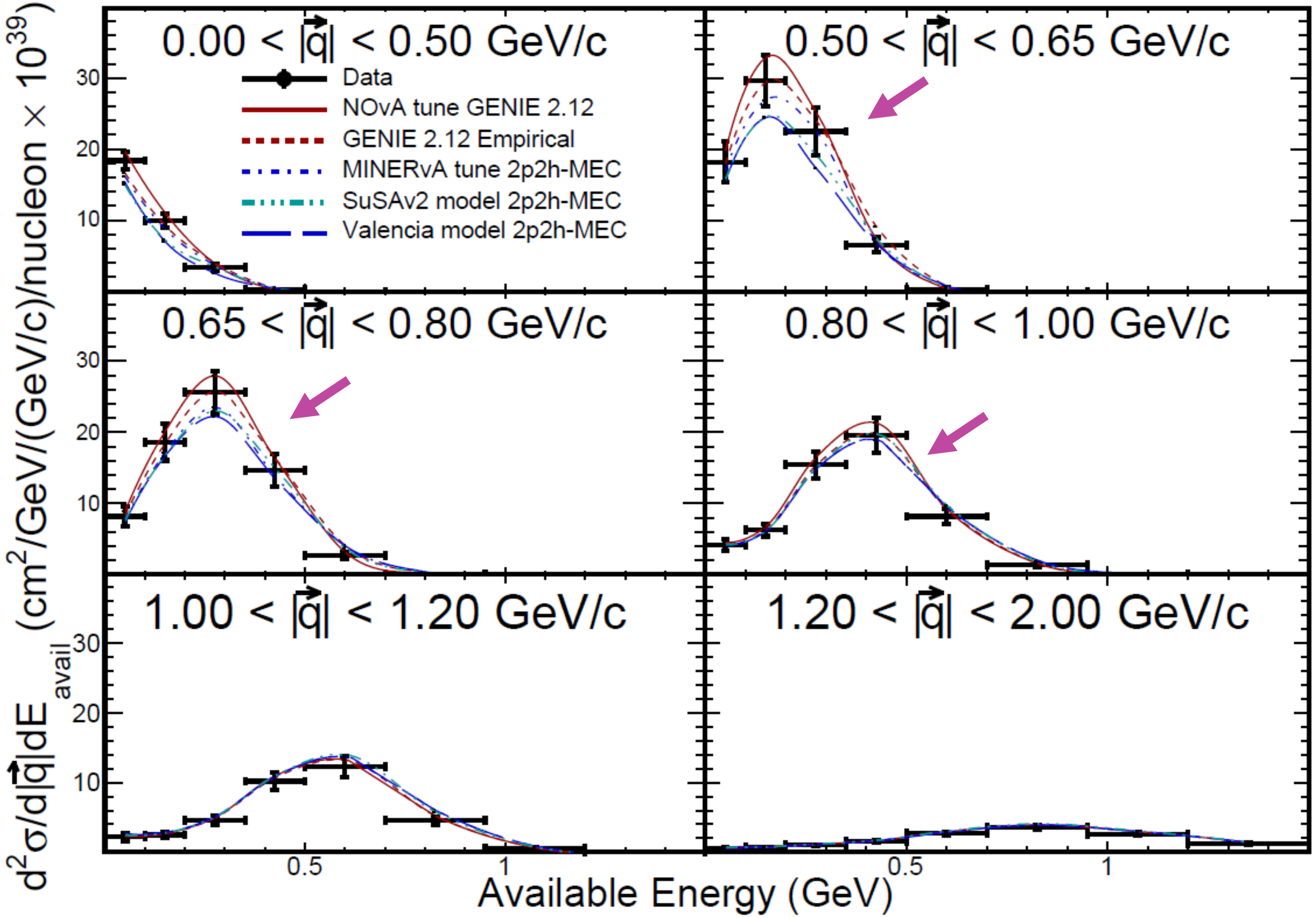


Cross section versus 2p2h models with GENIE 2.12:

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.

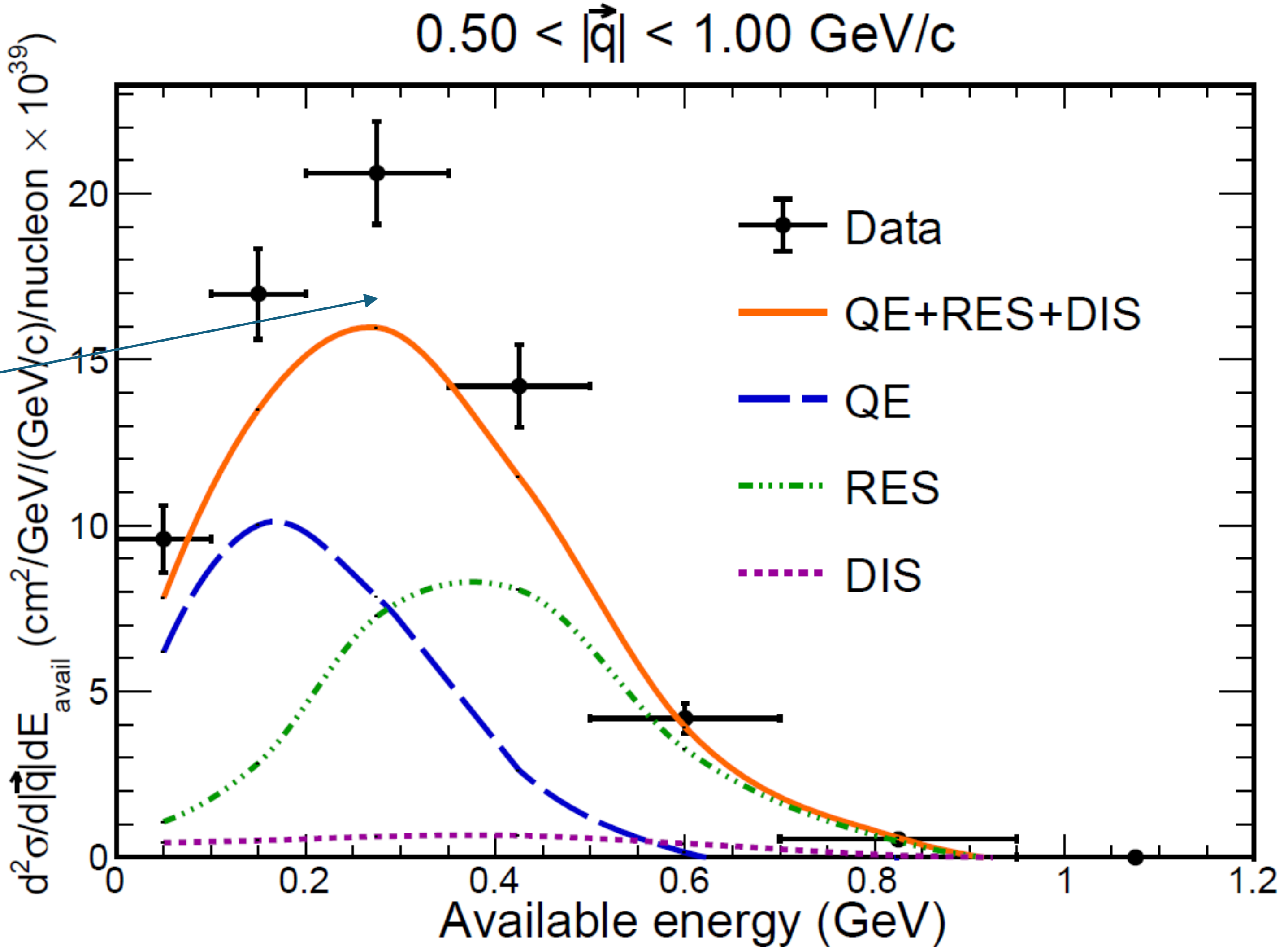
SuSAv2 and Valencia models under-predict the data rate.



Data excess relative to neutrino-nucleon processes:

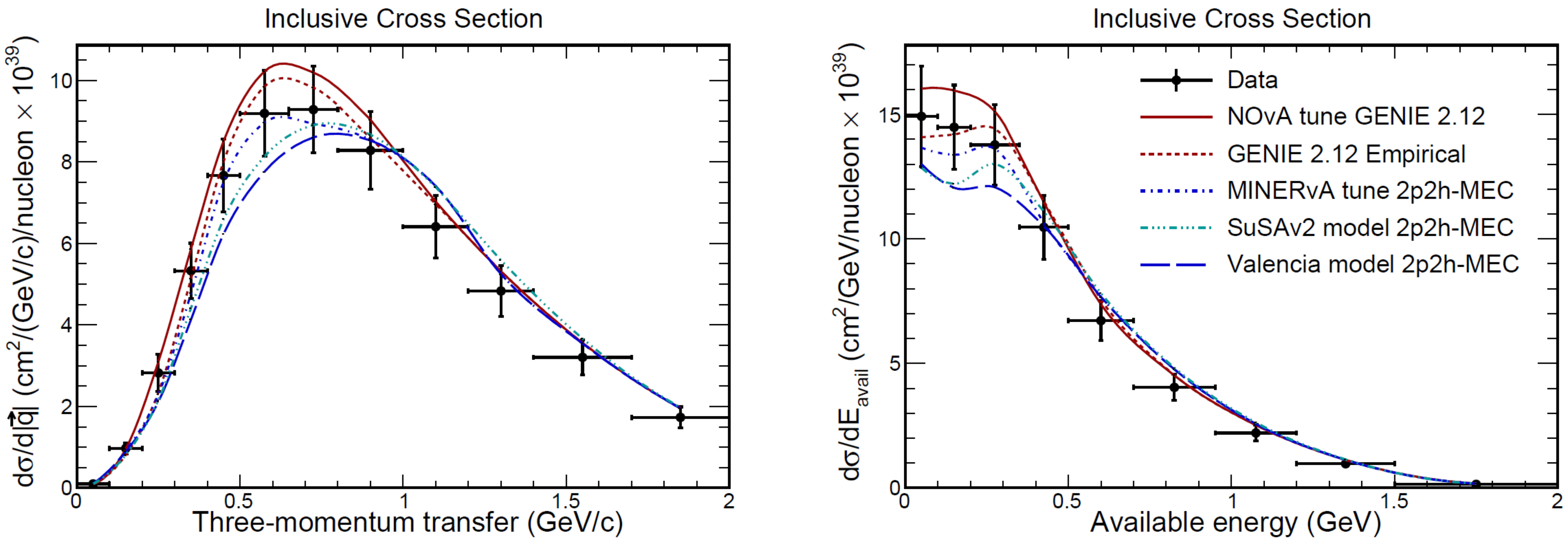
From electron nucleous scattering and theory 2p2h is expected to occur between QE and RES excitation.

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



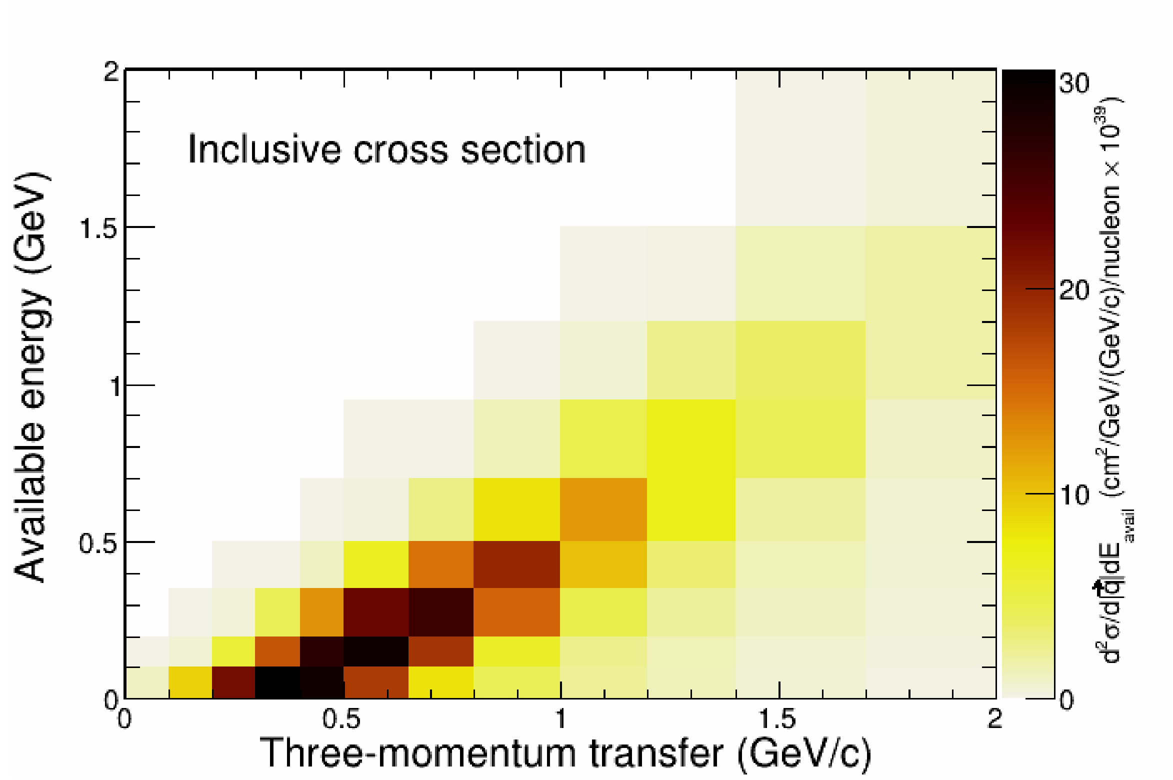
Differential cross sections in $|\vec{q}|$ and E_{avail}:

Data comparison with models:



Better agreement 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: 67
NOvA tune	270 (218)
GENIE Empirical	550 (493)
MINERvA tune	746 (784)
SuSAv2 model	766 (859)
Valencia model	1501 (1748)

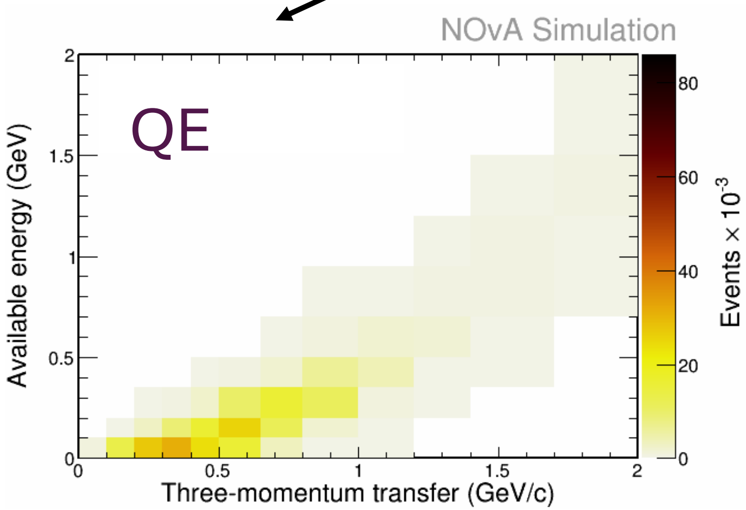
The values in parentheses are the shape-only χ2 calculations

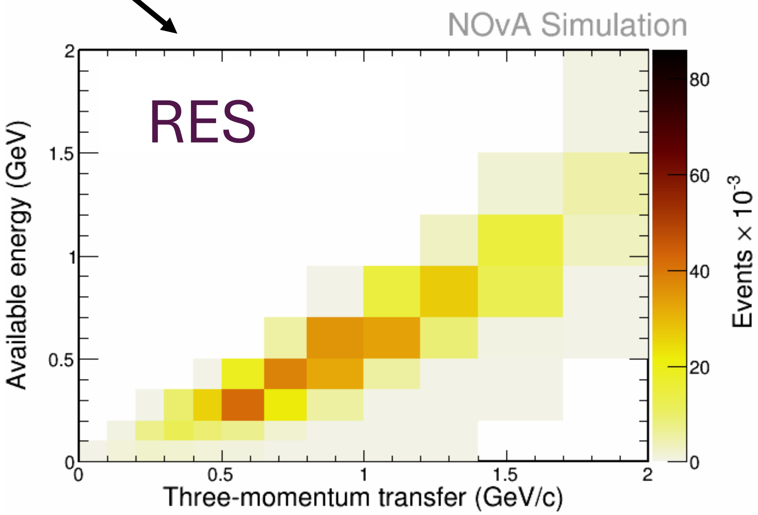
The NOvA tune and GENIE empirical 2p2h give better agreement with the data than the theory-based models or the MINERvA tune.

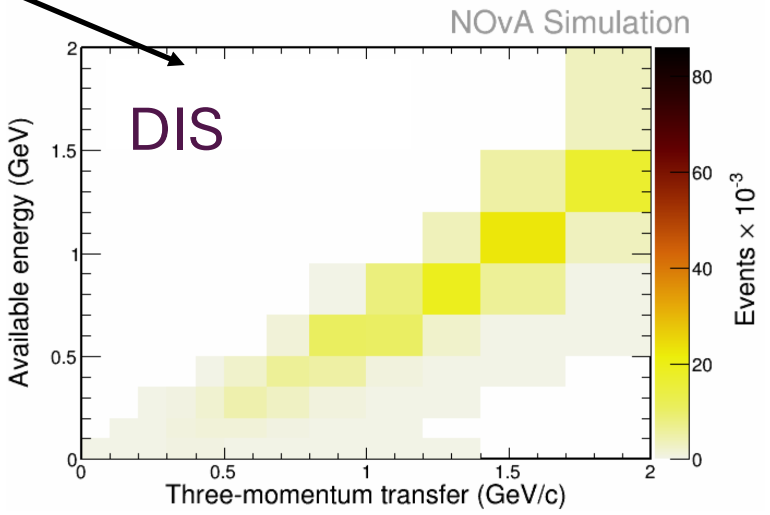
Estimation of 2p2h contribution to CC inclusive scattering

GENIE 2.12 based templates

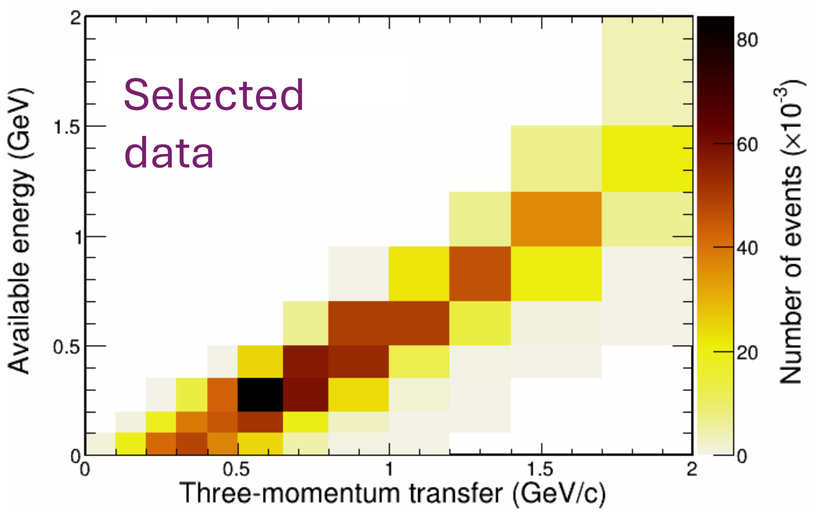
are used to estimate distribution of CC 1p1h reactions:







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



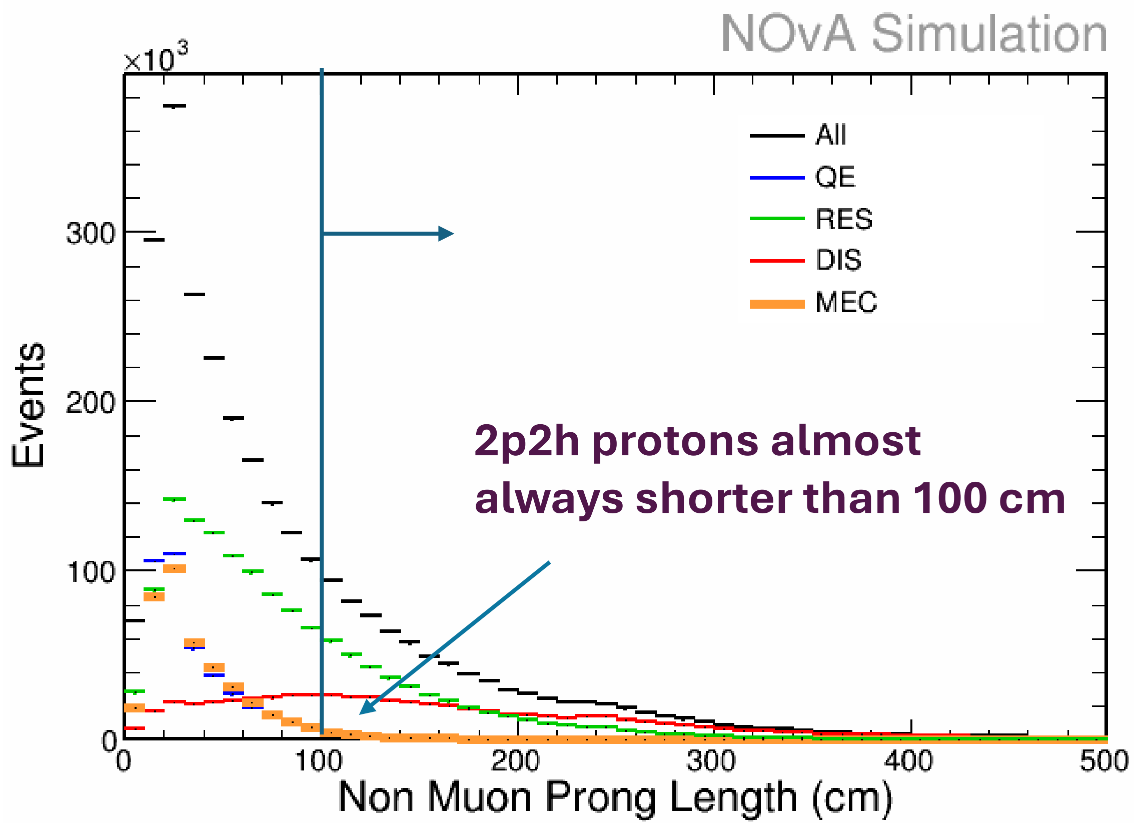
The data excess that lies above the sum of 1p1h templates is taken to be 2p2h.

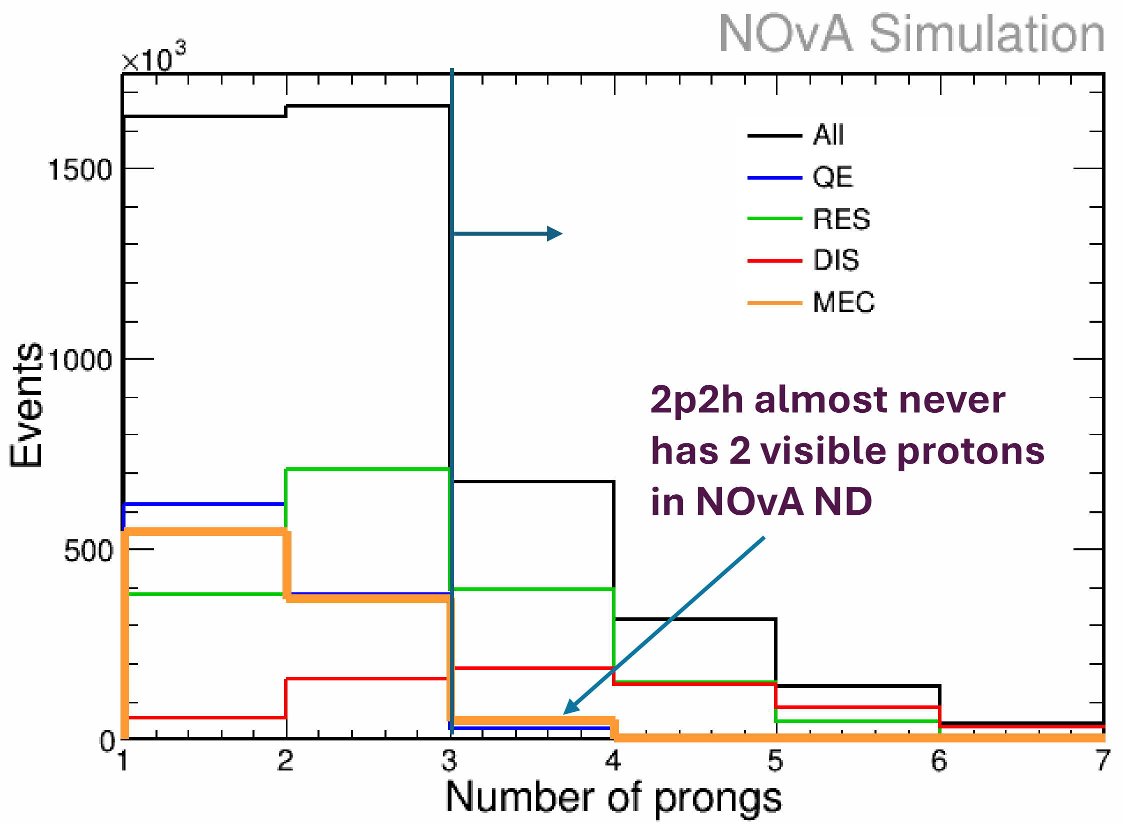
Control sample: Select a subsample of events that have

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)





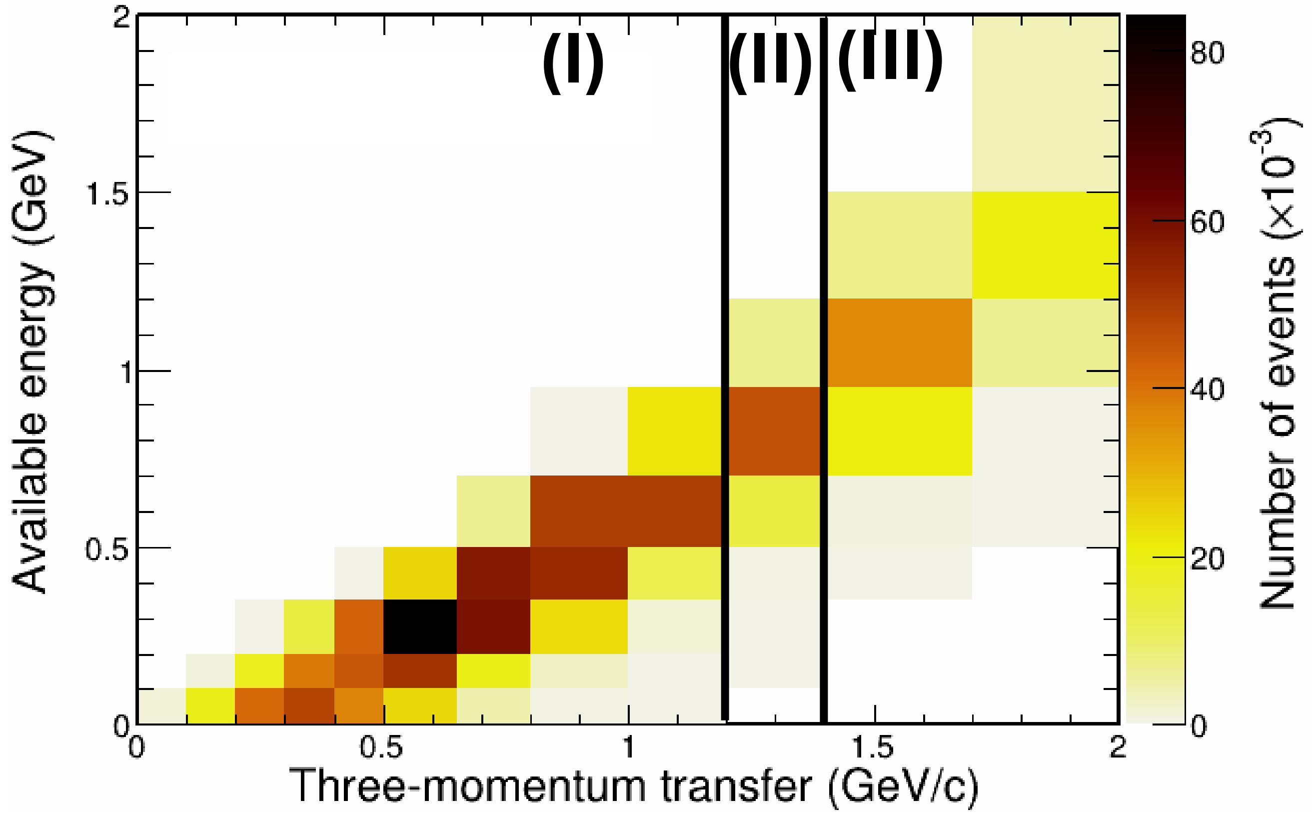
The **Control Sample** contains RES and DIS events, and is devoid of CCQE and 2p2h

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.

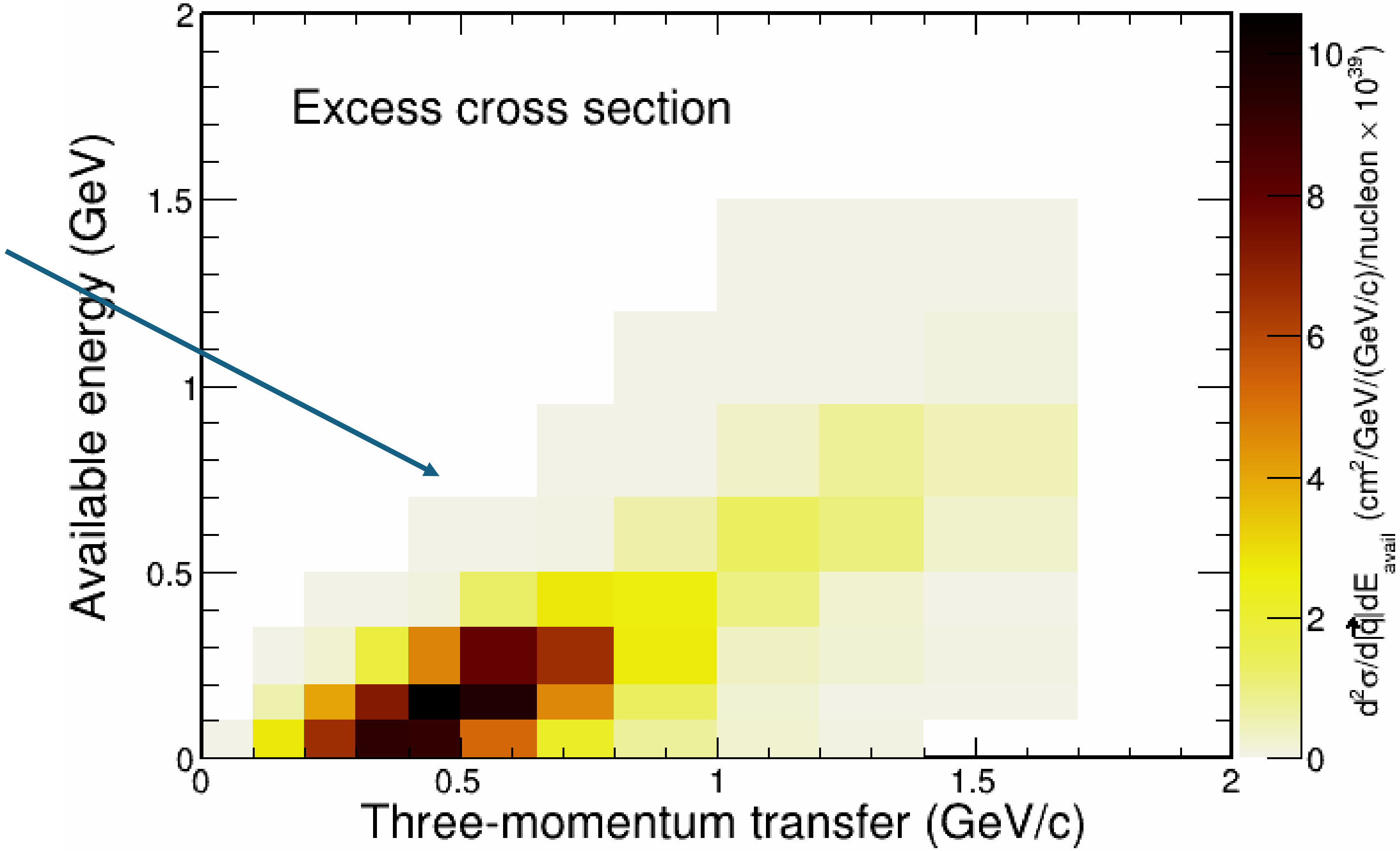
Template normalizations in Region (II) are set to the averages of normalizations for Regions (I) and (III).

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



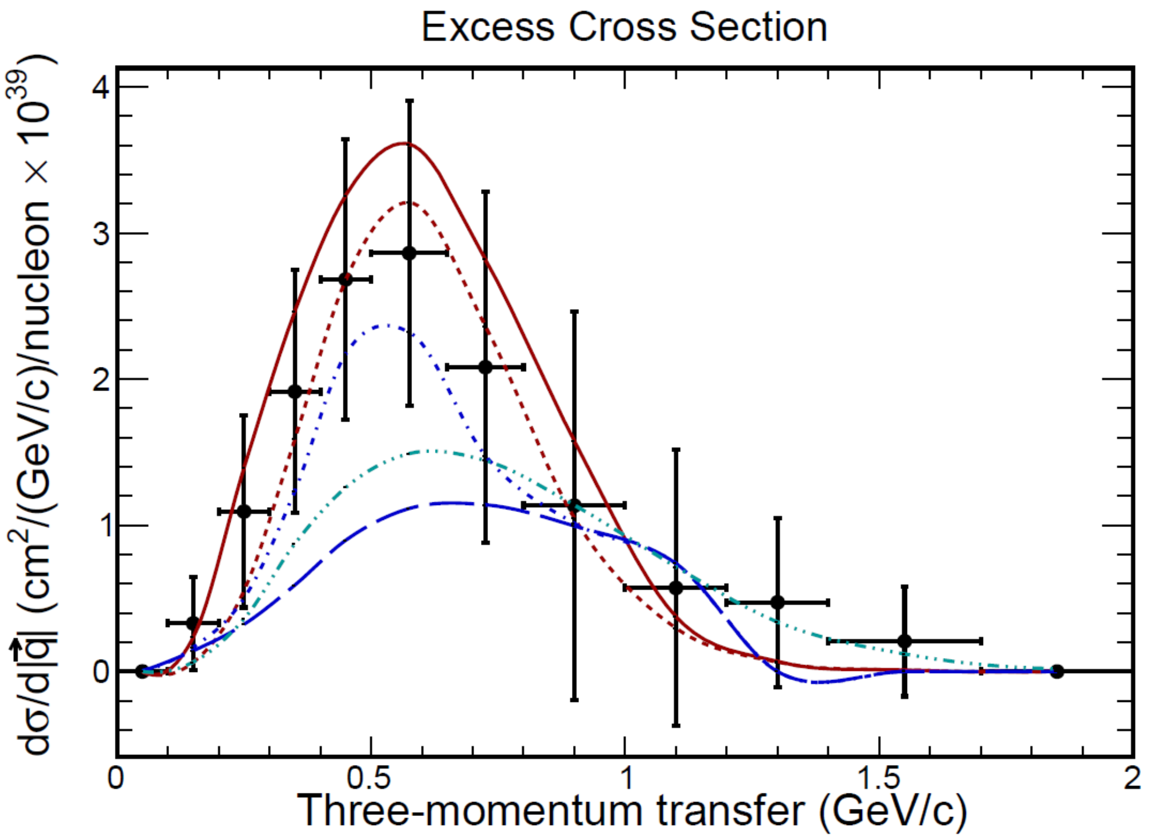
Estimated 2p2h cross section:

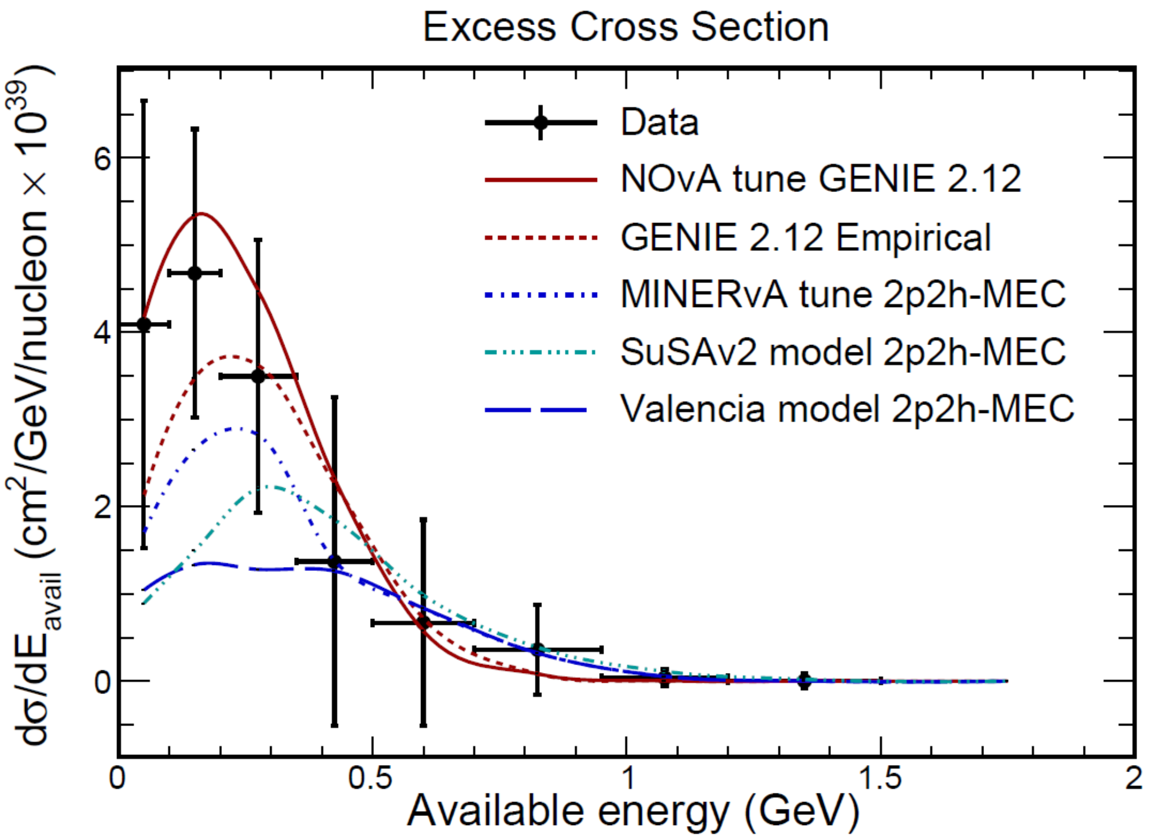
2p2h contribution is taken to be the data excess above the sum of the 1p1h templates.



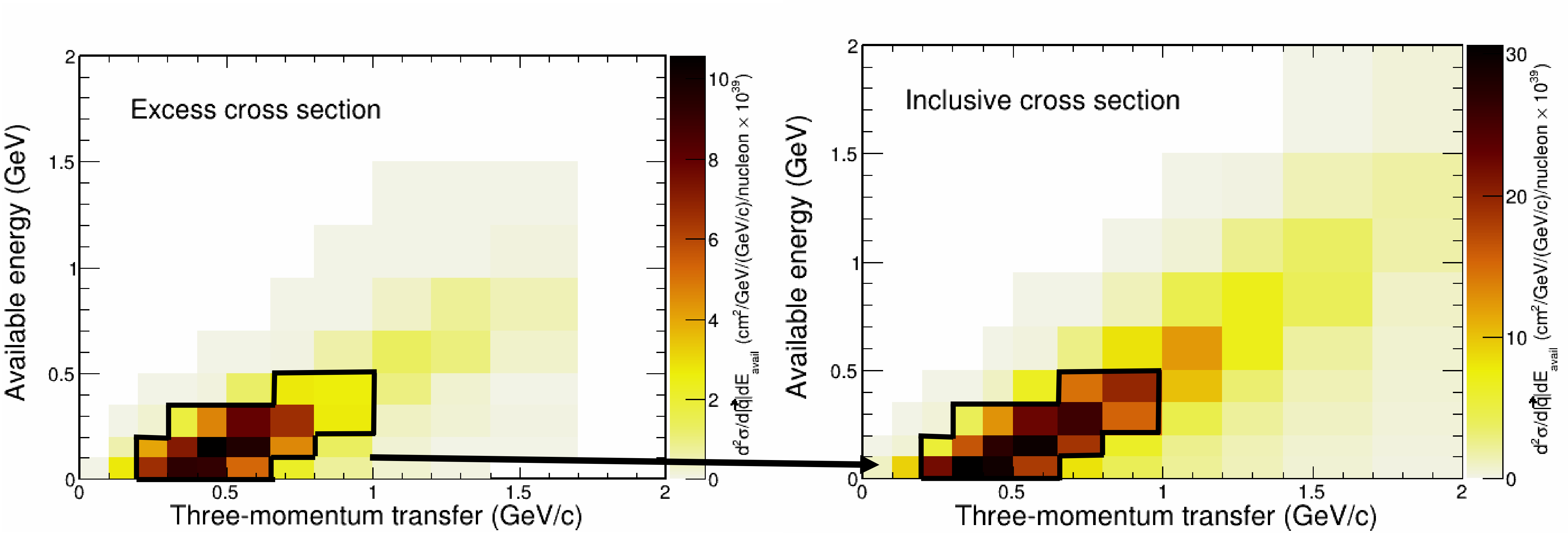
Estimated 2p2h cross section

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:22
NOvA tune	103 (81)
GENIE Empirical	184 (167)
MINERvA tune	84 (86)
SuSAv2 model	176 (192)
Valencia model	346 (391)

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:

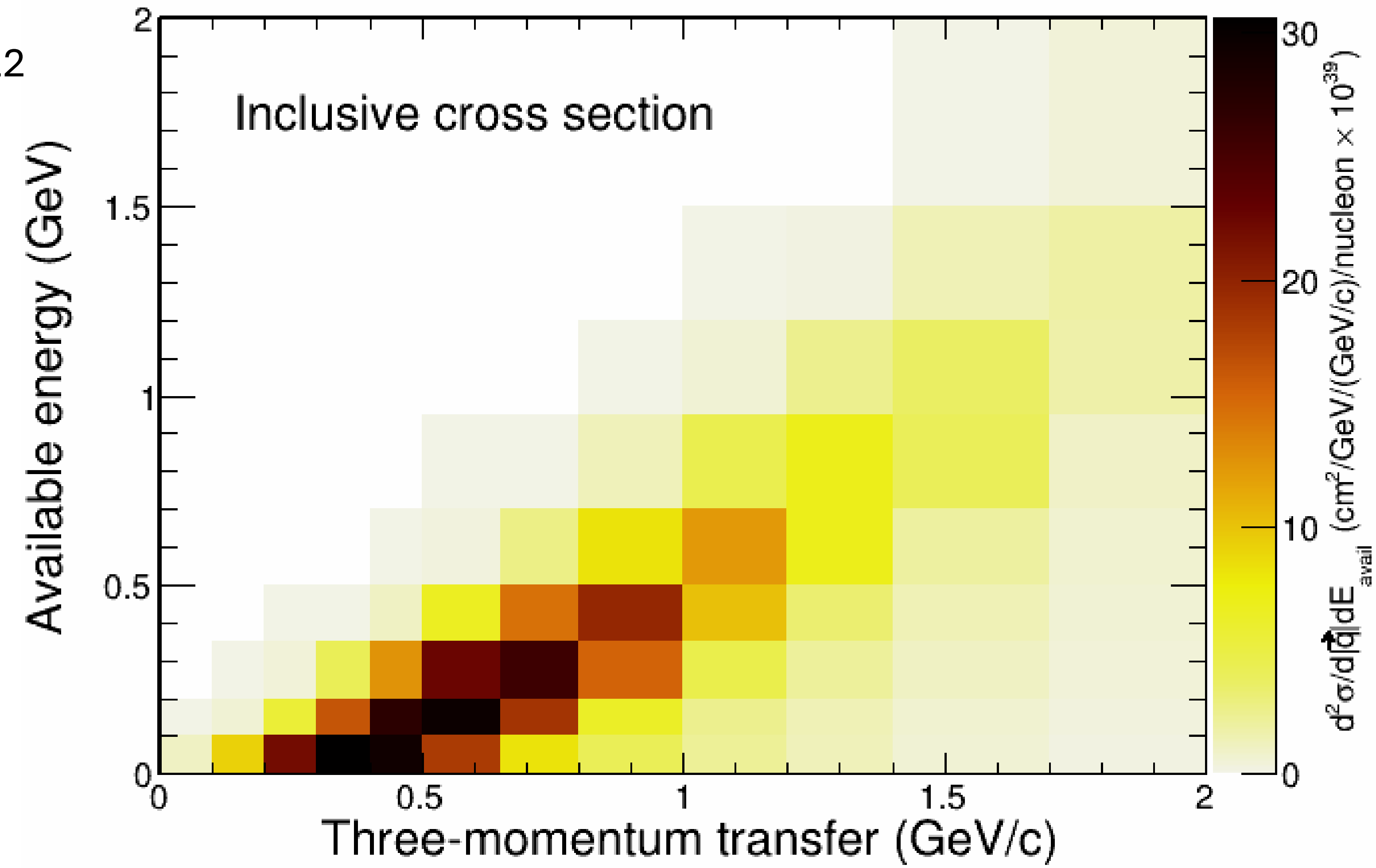
We report a new high-statistics neutrino cross-section measurement at $< E_\nu > \approx 1.9$ GeV using the variables |three-momentum transfer| and available energy

arxiv: 2410.05526

Complementary analysis arxiv: 2410.10222

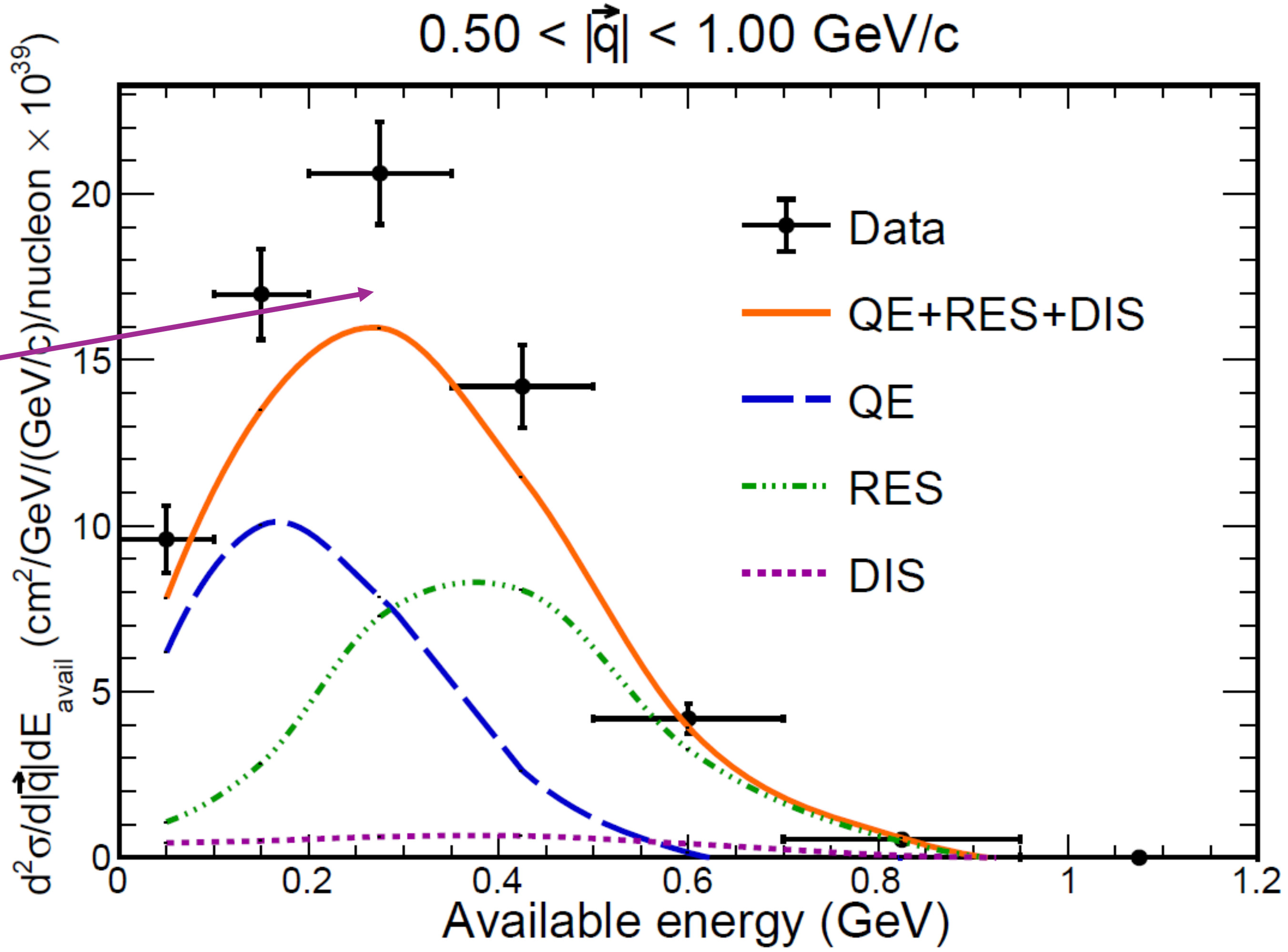
Measurement of flux-integrated

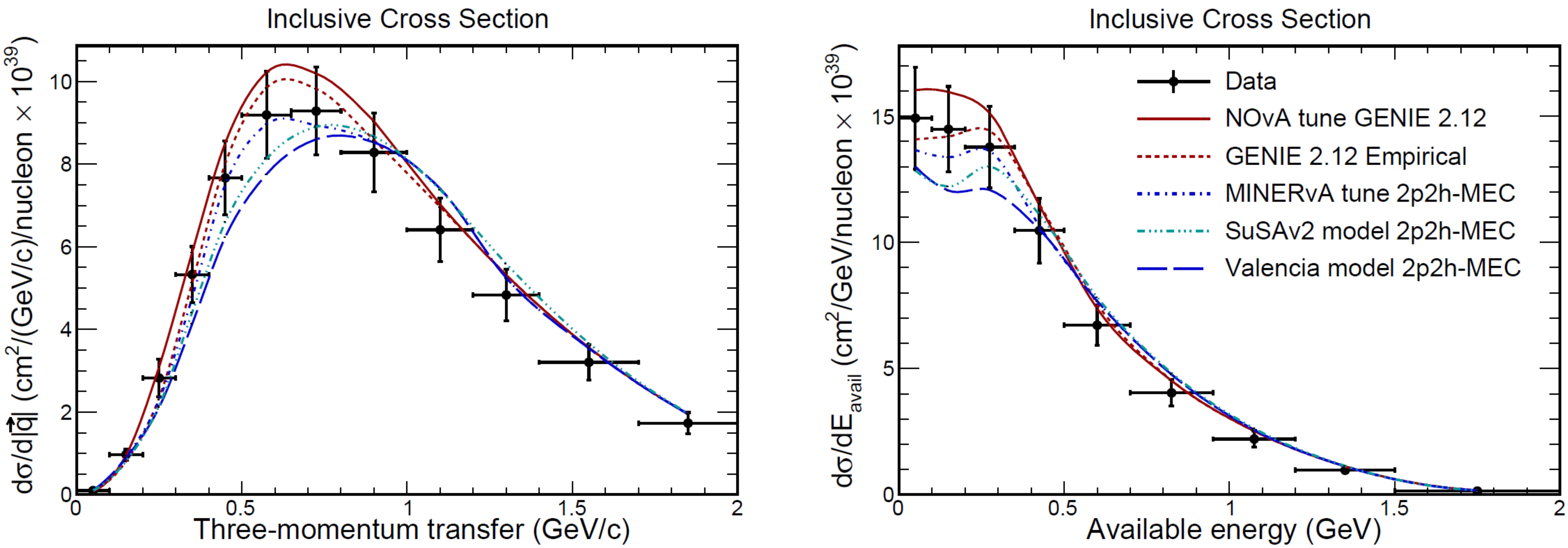
$$\frac{d^2\sigma}{d|\vec{q}|\, dE_{avail}}$$



Our analyses observes 2p2h to have a significant presence:

Data excess relative to the expectation from scattering on single nucleons occurs in the transition region between CCQE and RES where 2p2h is predicted to occur.





Model	X^2 NDF:22
NOvA tune	103 (81)
GENIE Empirical	184 (167)
MINERvA tune	84 (86)
SuSAv2 model	176 (192)
Valencia model	346 (391)

In general, the theory based models and the data tunes exhibit shortfalls with predictions in bins of lower 3-momentum transfer and available energy.

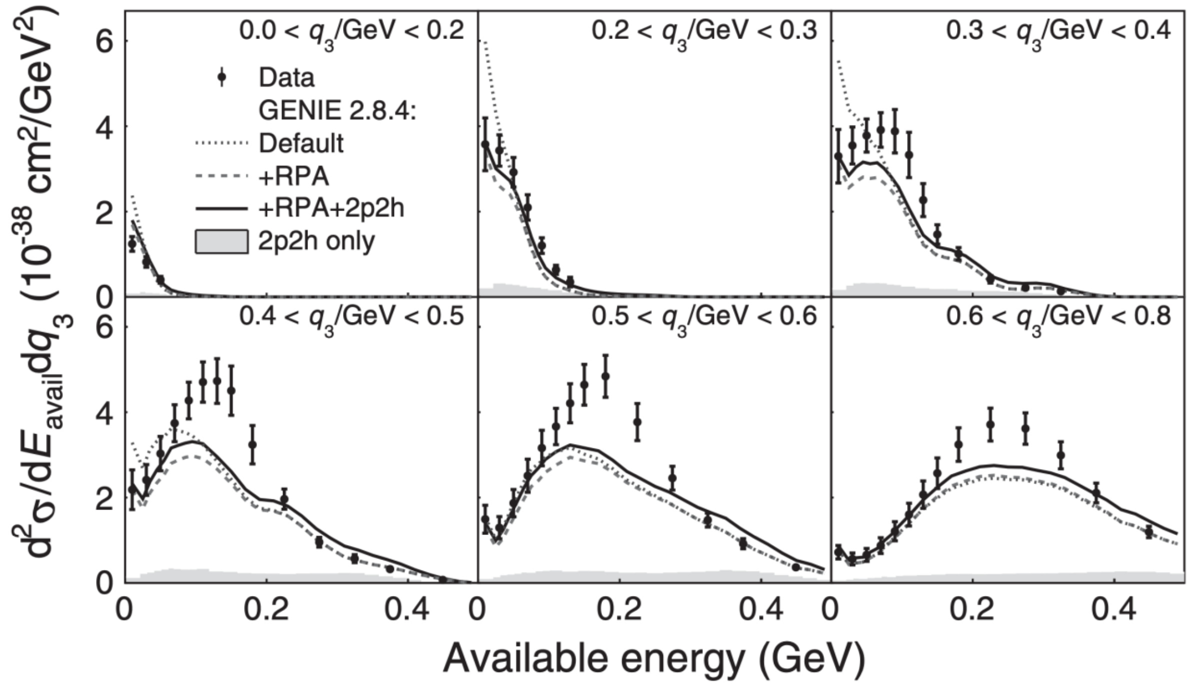
2p2h

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.

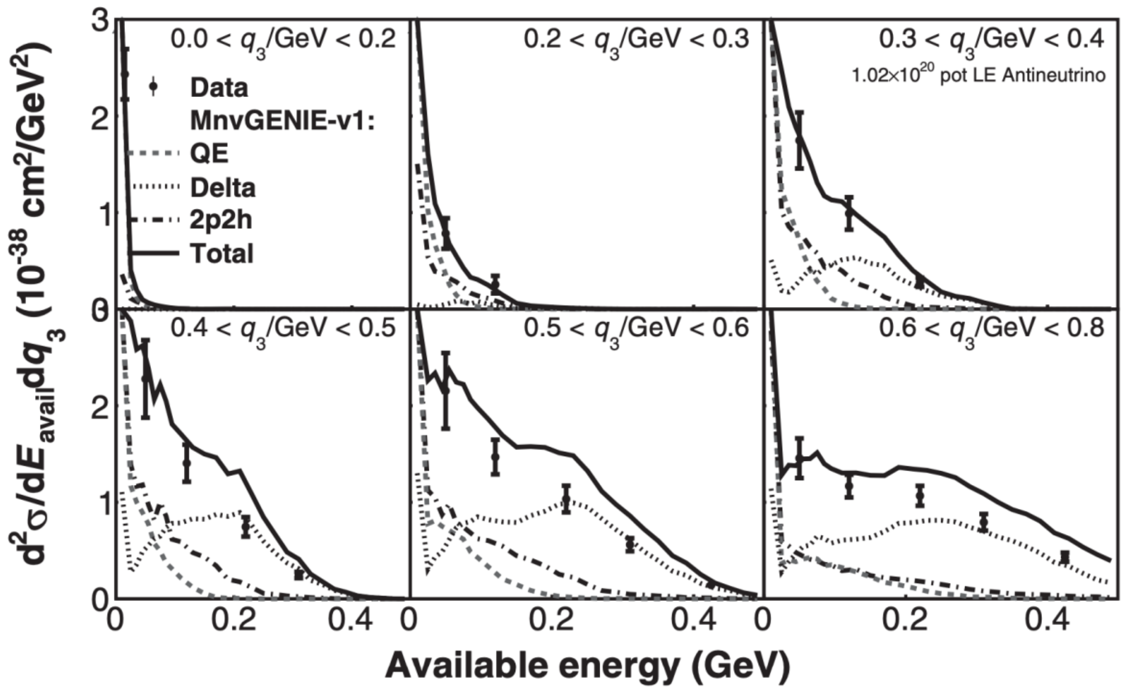
No model describes the data

ν_μ - *CC* measurement compare with default GENIE 2.8



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

$\overline{\nu}_\mu$ - *CC* measurement compare to MINERvA-tune



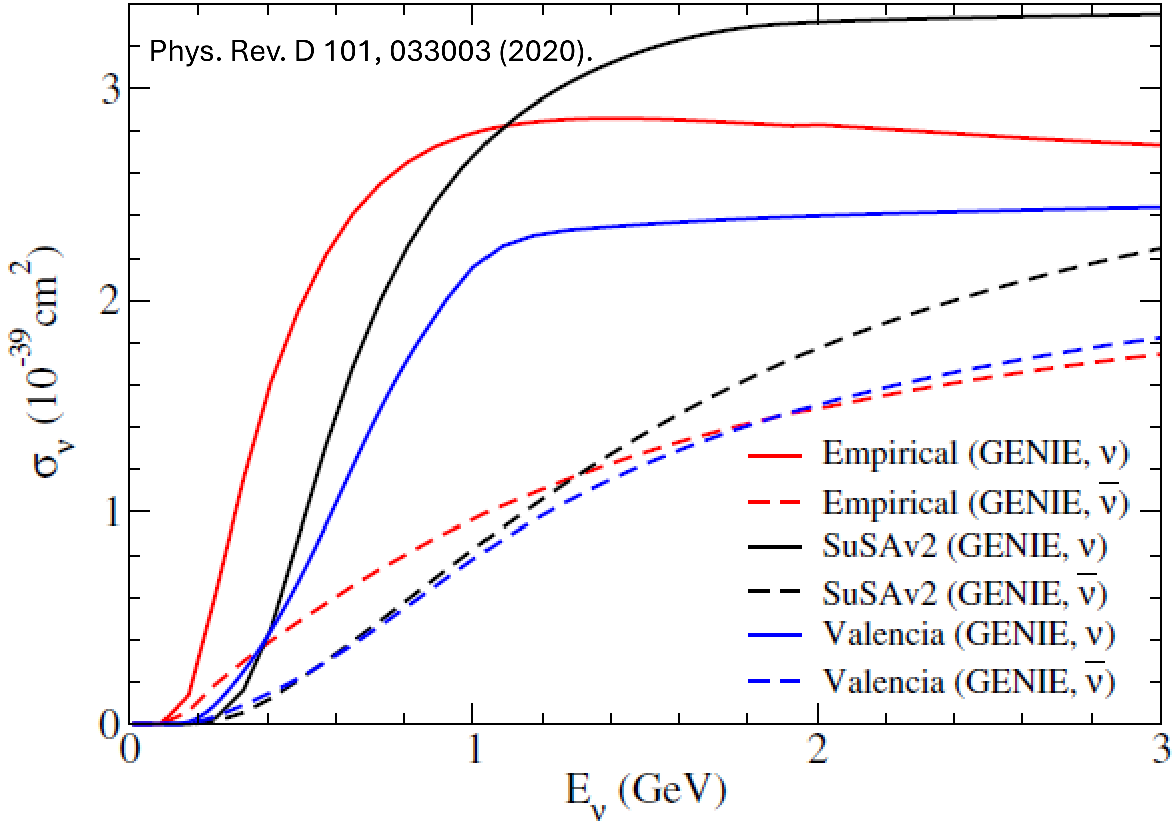
Phys. Rev. Lett. ***116***, *071802*

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

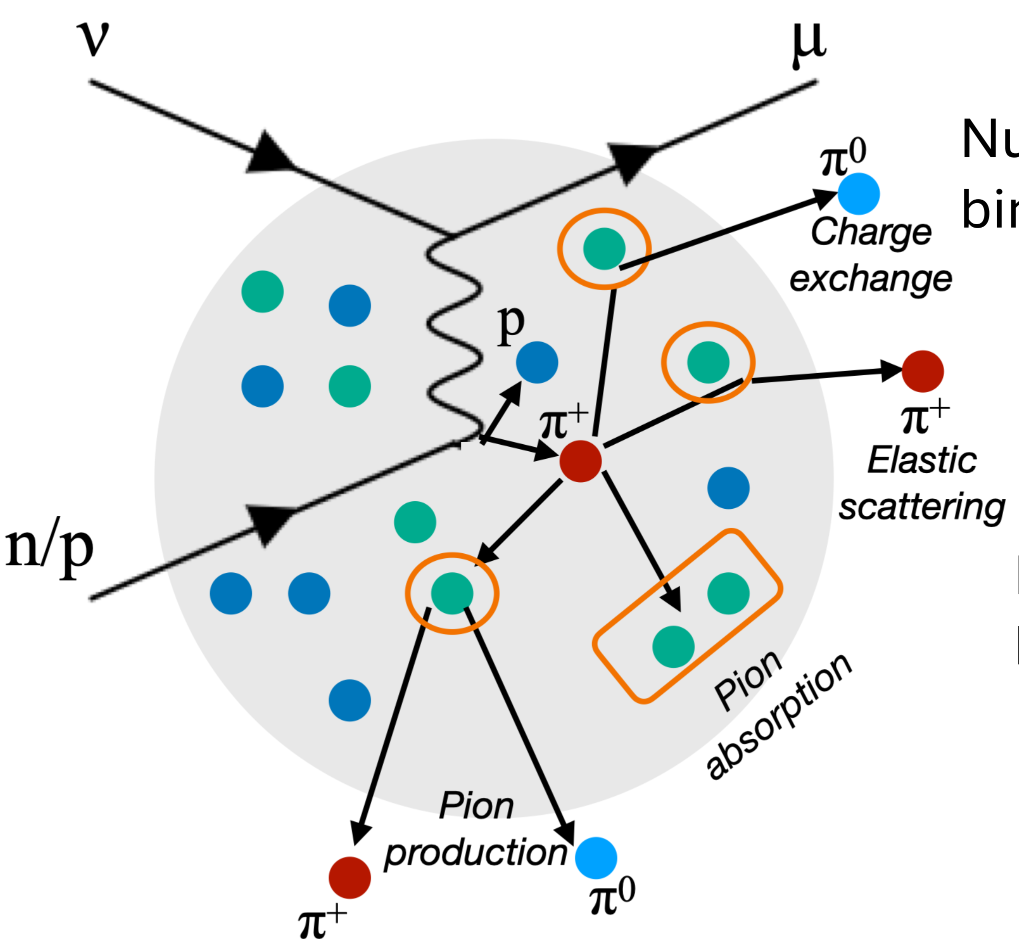
MINERvA: Phys. Rev. Lett. **116**, 071802 (2016), Phys. Rev. D **106**, 032001 (2022).
T2K: Phys. Rev. D **98**, 032003 (2018), Phys. Rev. D **108**, 112009 (2023).
MicroBooNE: Phys. Rev. D **102**, 112013 (2020), arXiv:2211.03734 (2022).

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.



Nuclear effects

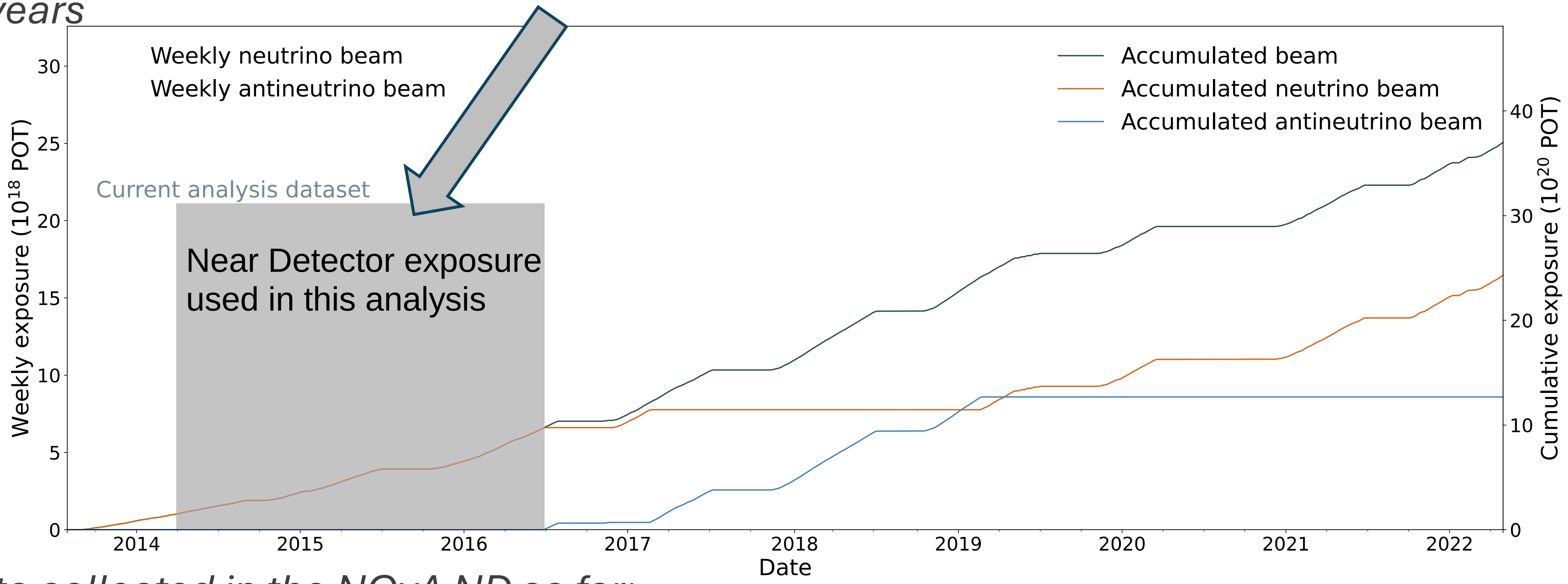


Nucleons on motion inside the nucleus (Fermi motion) and binding energy

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

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:

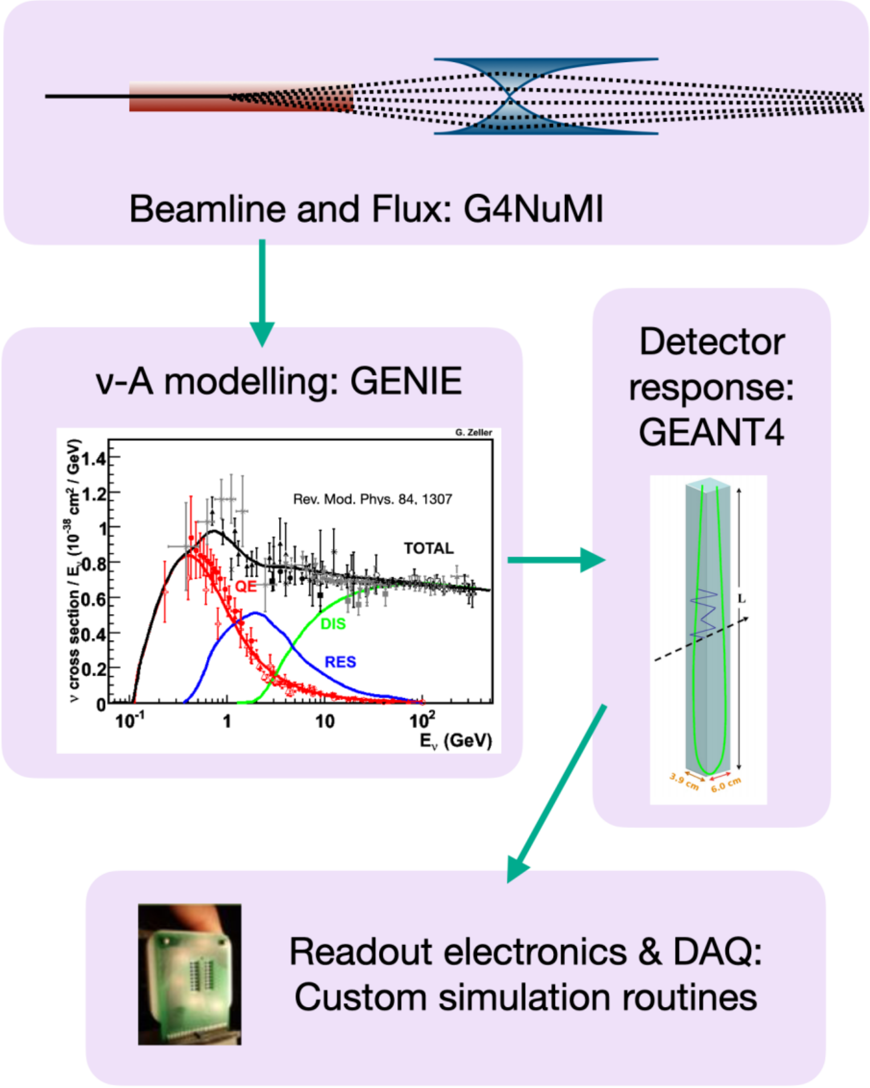
26.76 x 10^{20} POT of neutrino-mode data and 12.76 x 10^{20} POT of antineutrino-mode

NuMI beam will aim 1MW in the next run!

NOvA analysis

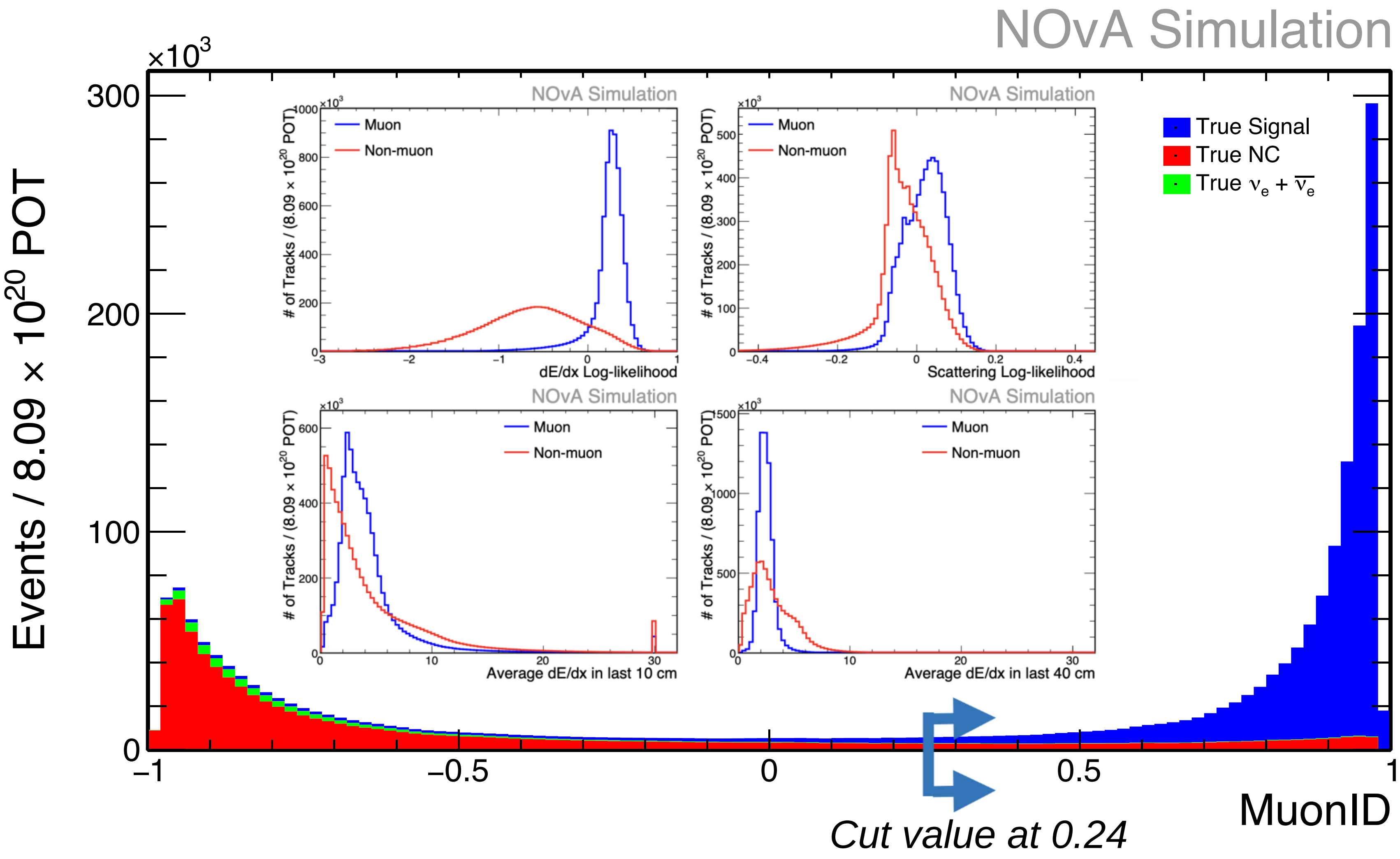
$$\frac{d\sigma}{dx_i} = \frac{\sum_j U^{-1}_{ij}\left(N^{\mathrm{sel}}_j \times P_j\right)}{\epsilon_i N_{\mathrm{T}}\, \Phi\, \Delta x_i}$$

We rely on simulations for optimizing the **selection**, applying **corrections for the background**, **smearing** and **efficiency** and for the **flux normalization**



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)

Analysis variables:

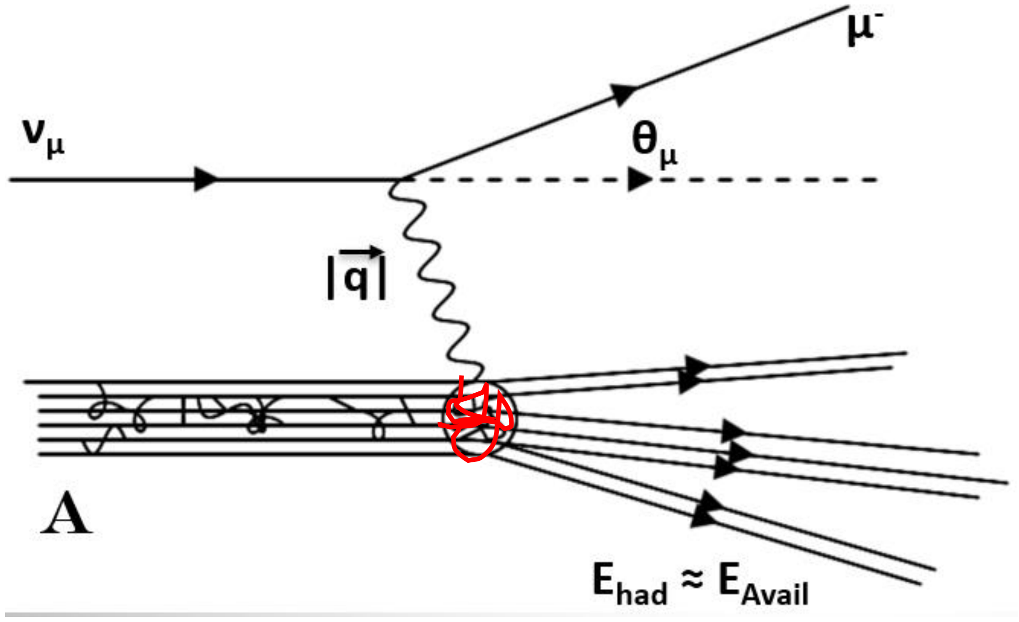
Neutrino energy: $E_{\upsilon} = E_{\mu} + E_{had}$

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: $p/\pi^{\pm}$

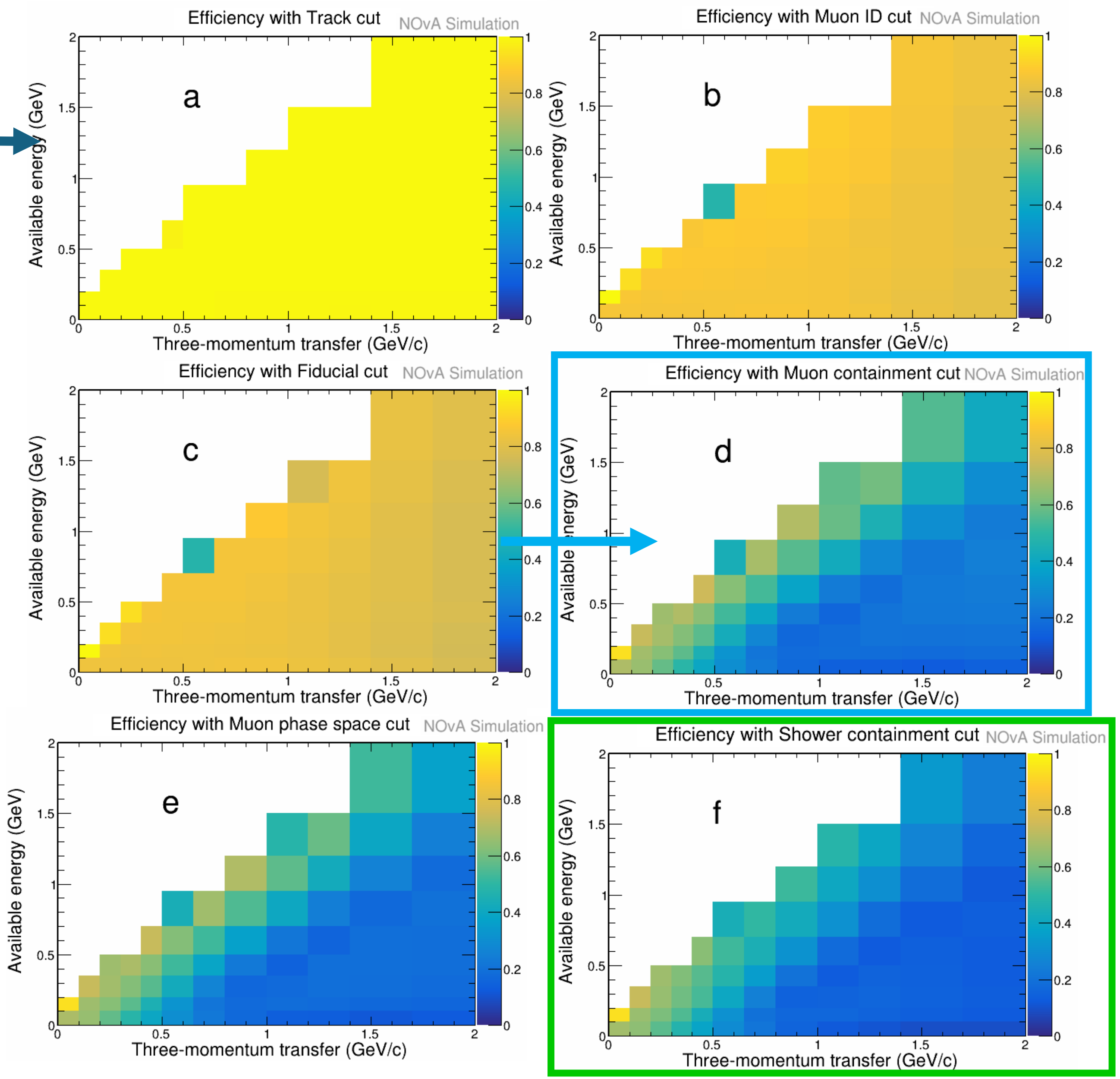
Total energy: $\pi^0/e/\gamma$

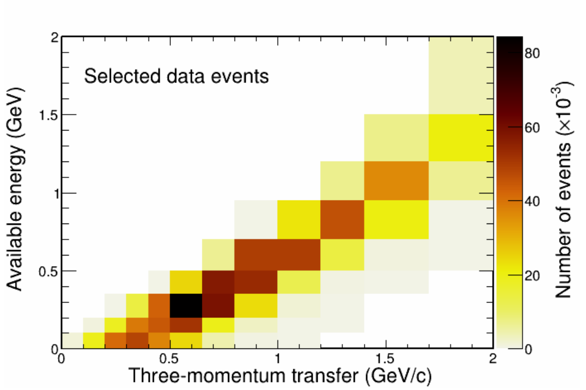
(neglect neutron energy)

Efficiency versus selections:

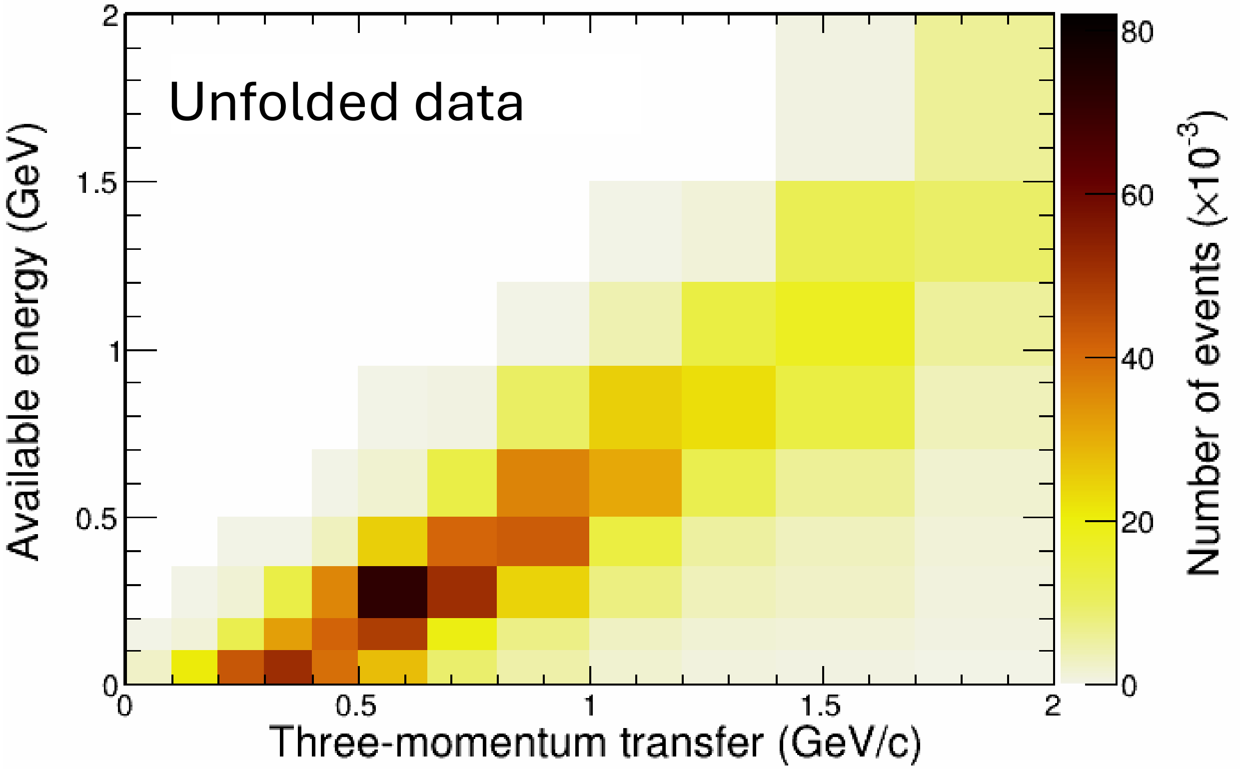
Selection sequence

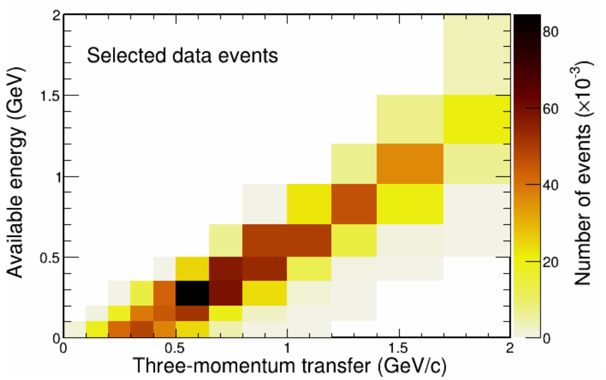
Selection cut	Efficiency
All true signal	100%
Quality	99.9%
Track reconstruction (a)	99.8%
Muon identification (b)	85.3%
Vertex fiducial (c)	82.3%
Muon containment (d)	24.7%
Muon phase space (e)	22.1%
Shower containment (f)	18.7%





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





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