Zero Mesons/QE/2p2h-like ν-A interactions at the NOvA Near Detector

Results and prospects

Sebastian Sanchez-Falero,
on behalf of the NOvA collaboration

NuInt 2024

14th International Workshop on Neutrino-Nucleus Interactions

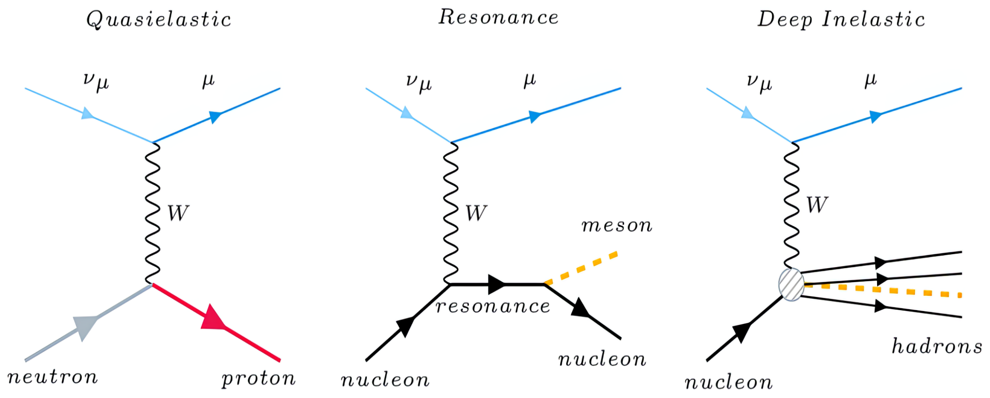
April 16th, 2024 – Instituto Principia, São Paulo, Brazil

Overview

What	**Analysis program** of **ZeroMesons/QE/2p2h-like** interactions
Why	• ZM/QE/2p-2h-like channels provide handles for **constraining models of neutrino interactions** and **nuclear structure models** • **NOvA Near Detector** is illuminated by a **high intensity and purity narrow-band beam** at $\langle E_\nu \rangle \sim 2$ GeV, a **highly dynamic region**
How	• **Focused analyses** on the **leptonic** and **hadronic products** of the ν-A interaction • Subsequently, extend to **greater exposures** and **greater detail** on the final state • Leverage a **strong muon reconstruction**; a combination of **traditional and Deep Learning** tools for event selection; and **data-driven background constrains**
Status	• **Two released analyses** on the lepton and hadronic aspects • **Three upcoming analyses** with extended exposure, improved systematics and detail on final state

Motivation

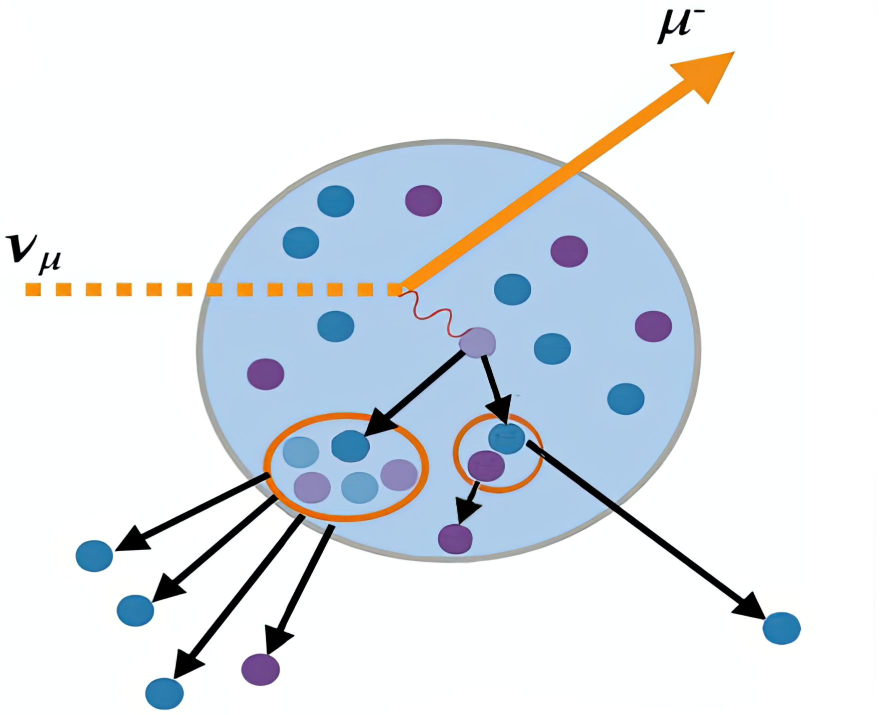
- Solving open questions in neutrino physics requires **accurate understanding of their interactions**
- **Reconstruction** of **closer-to-elastic** channels is more **transparent**



+ *(many) more diagrams…*

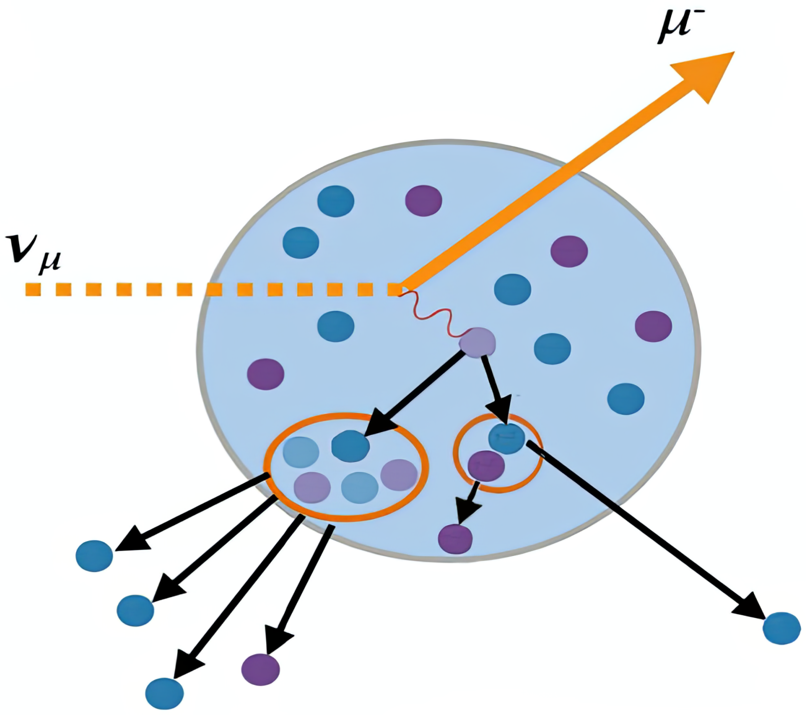
Motivation

- Solving open questions in neutrino physics requires **accurate understanding of their interactions**
- **Reconstruction** of **closer-to-elastic** channels is more **transparent**
- The **nuclear environment blurs** the underlying neutrino interactions
  - Only partially known initial state
  - Scattering off correlated nucleons (e.g. 2p2h)
  - Intranuclear rescattering



Motivation

- Solving open questions in neutrino physics requires **accurate understanding of their interactions**
- **Reconstruction** of **closer-to-elastic** channels is more **transparent**
- The **nuclear environment blurs** the underlying neutrino interactions
  - Only partially known initial state
  - Scattering off correlated nucleons (e.g. 2p2h)
  - Intranuclear rescattering
- Focus on **observable final states**, provide **experimentally-defined** cross sections
- **ZM/QE/2p2h-like** are **one of multiple complementary channels** valuable to elicit neutrino interaction unknowns

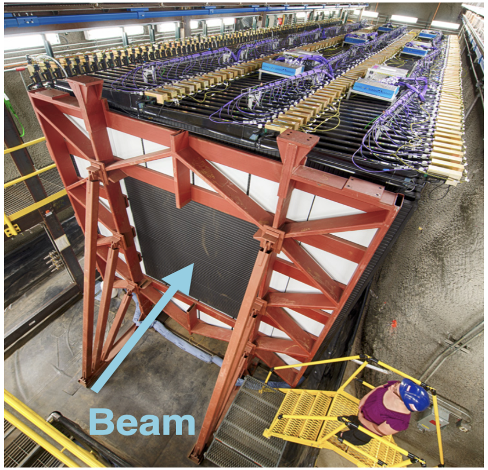


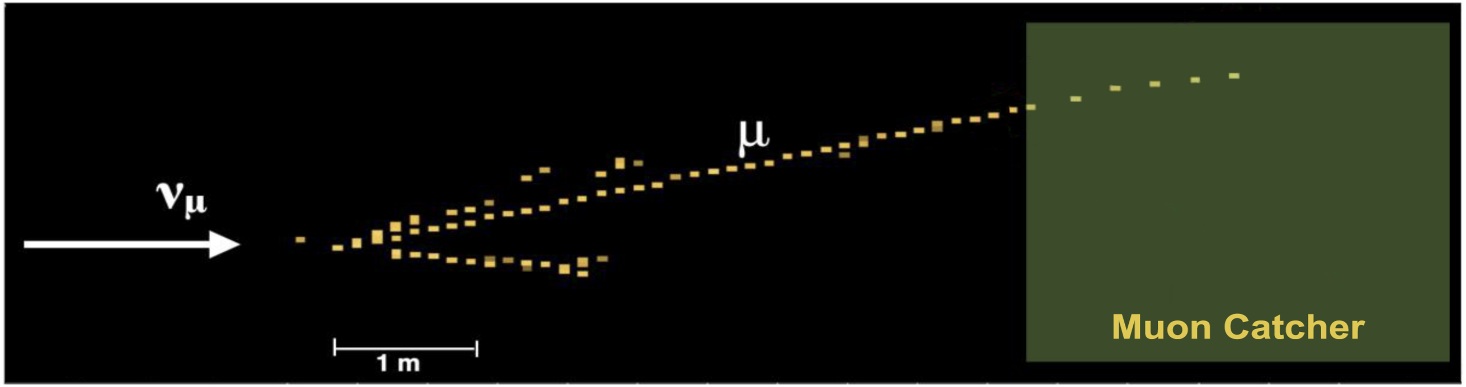
The NOvA Near Detector

A natural laboratory for cross section analyses:

- Fine-grained liquid scintillator tracking calorimeter
- 300 ton, 100m underground

Element Mass fraction				
C	Cl	H	O	Ti
67%	16%	11%	3%	3%





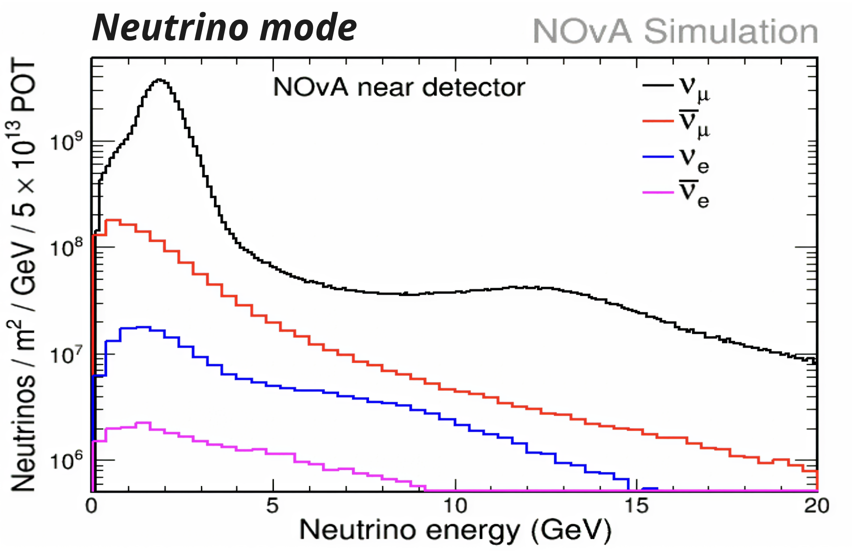
Scintillator layers

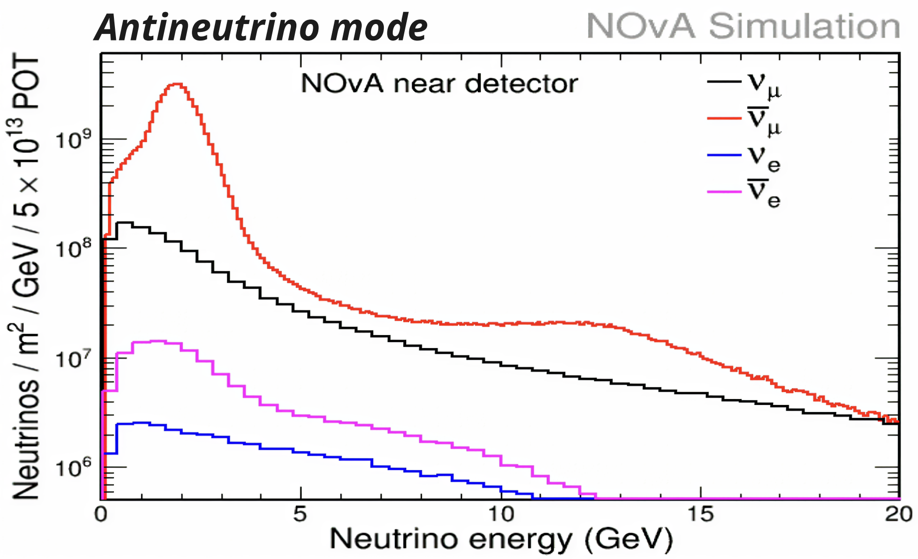
Scintillator + iron layers

The NOvA Near Detector

A natural laboratory for cross section analyses:

- High intensity and purity narrow-band beam at peak E_ν = 1.86 GeV



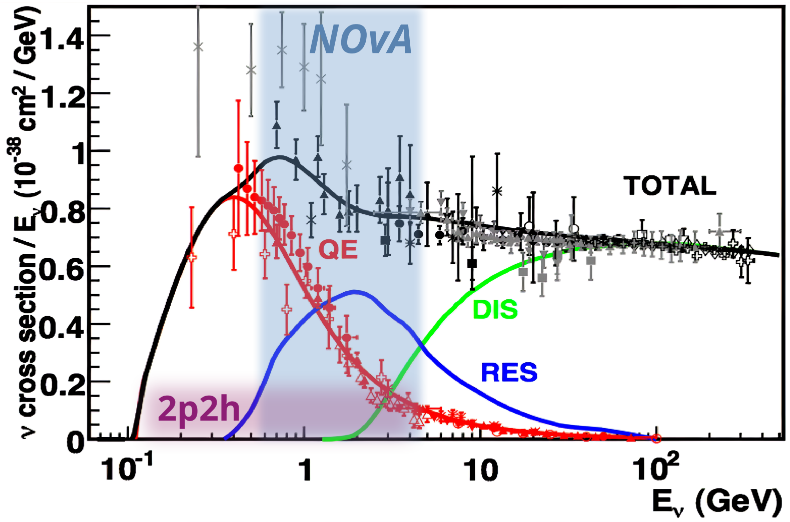


The NOvA Near Detector

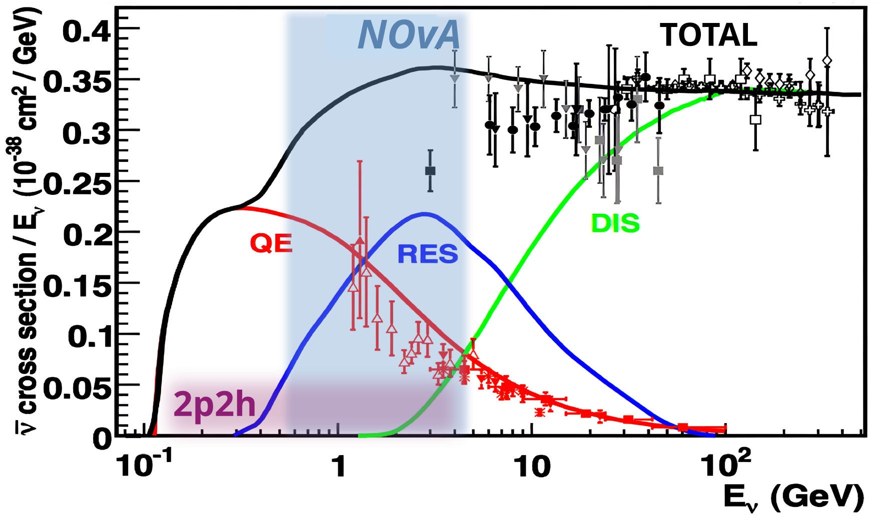
A natural laboratory for cross section analyses:

- Highly dynamic region for neutrino interaction modes

Neutrino CC cross sections

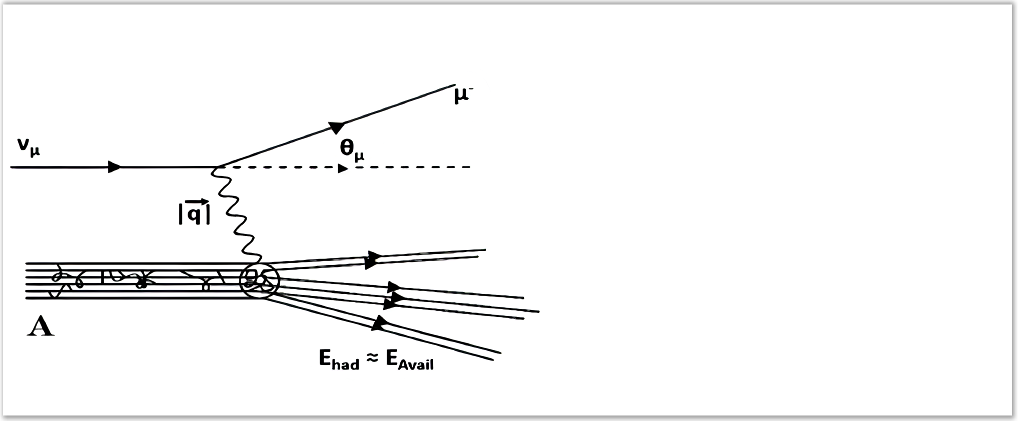


Antineutrino CC cross sections

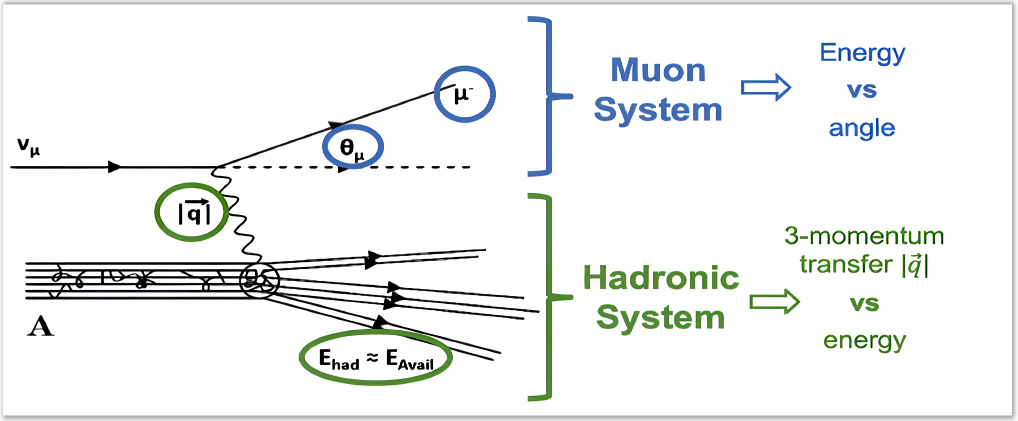


ZM/QE/2p2h-like

Analysis Program



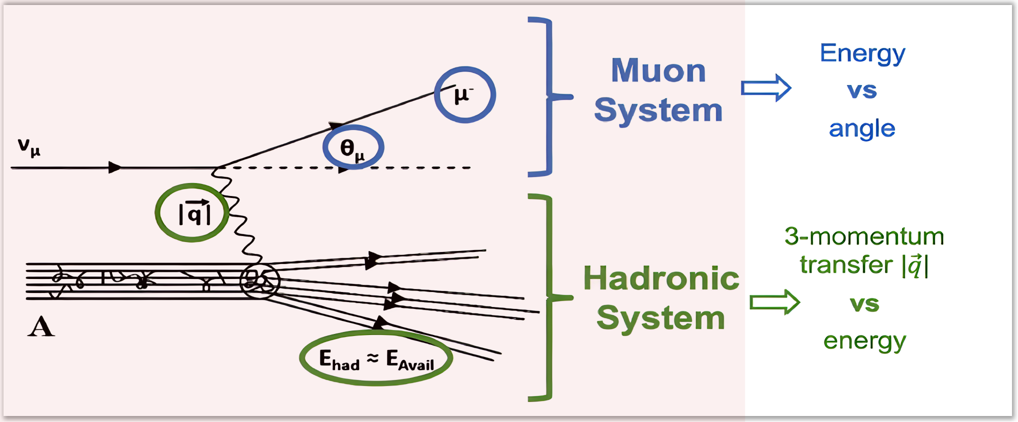
ZM/QE/2p2h-like
Analysis Program



ZM/QE/2p2h-like
Analysis Program

Two Released Analyses

ν_μ CC Low Hadronic Energy

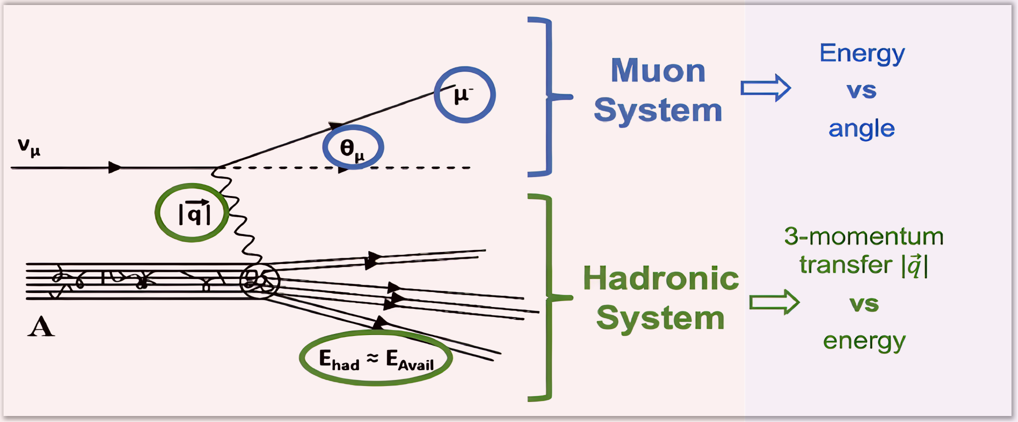


ν_μ CC inclusive and 2p2h estimation

Analysis Program

Two Released Analyses

ν_μ CC Low Hadronic Energy



ν_μ CC inclusive and 2p2h estimation

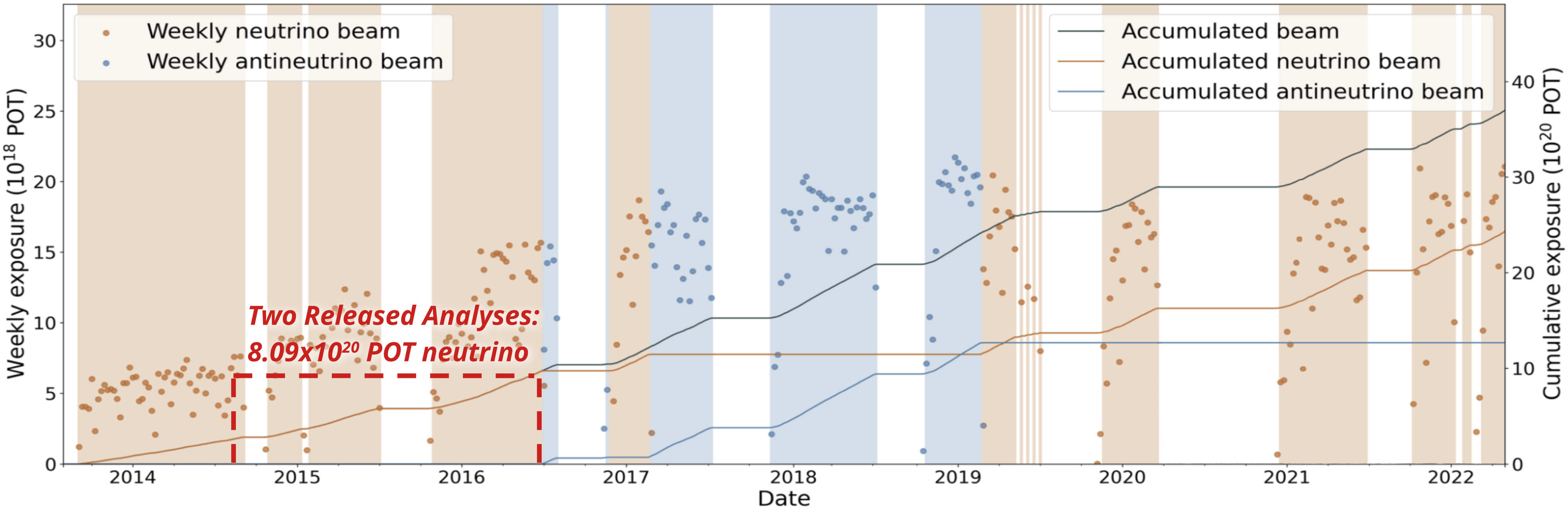
Three Upcoming Analyses

ν_μ CC Low Hadronic Energy in 3D (adds E_{avail})

ν_μ CC Zero Mesons

Anti-ν_μ CC Zero Mesons

Neutrino Beam Exposures



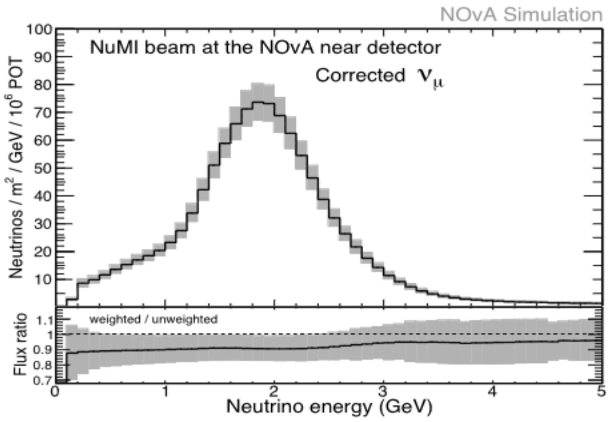
Total exposures to date are 27.8x10^{20} POT neutrino and 12.8x10^{20} antineutrino

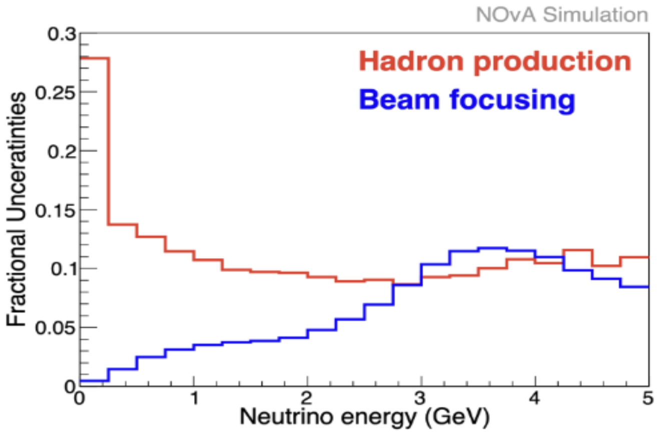
Neutrino Beam Simulation Uncertainties

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

- Technique developed by **MINERvA** *(Phys. Rev. D94, 092005)*
- About **10% normalization uncertainty**

Beam focusing uncertainty is subdominant around the peak (below 2.5 GeV)





ZM/QE/2p2h-like

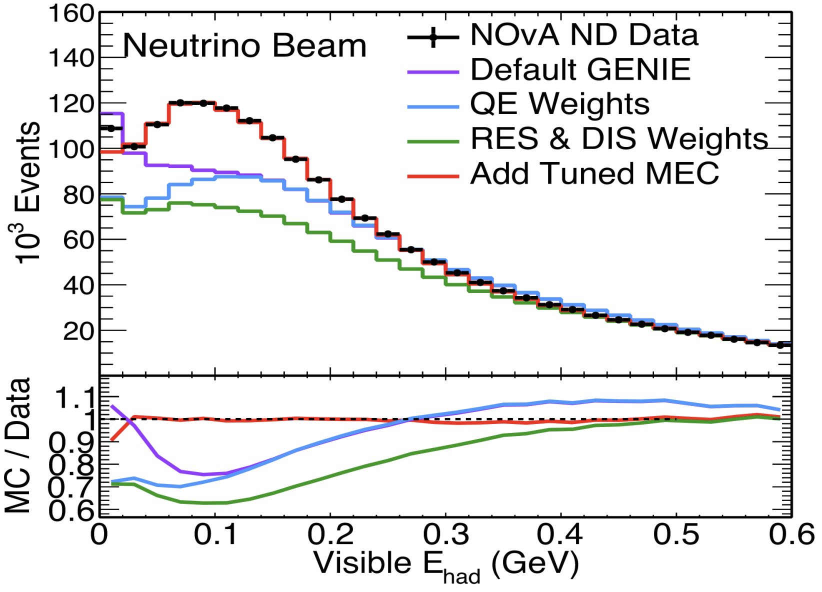
Neutrino Interaction Model

Released analyses: base model is **Genie 2.12.2**

ISA	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 Resonant baryon production
- DIS at W>1.7 GeV/c^2 is weighted up 10% based on NOvA ND data
- **Empirical MEC based on NOvA ND data for 2p2h**



All analyses are constructed to be insensitive to the tuning

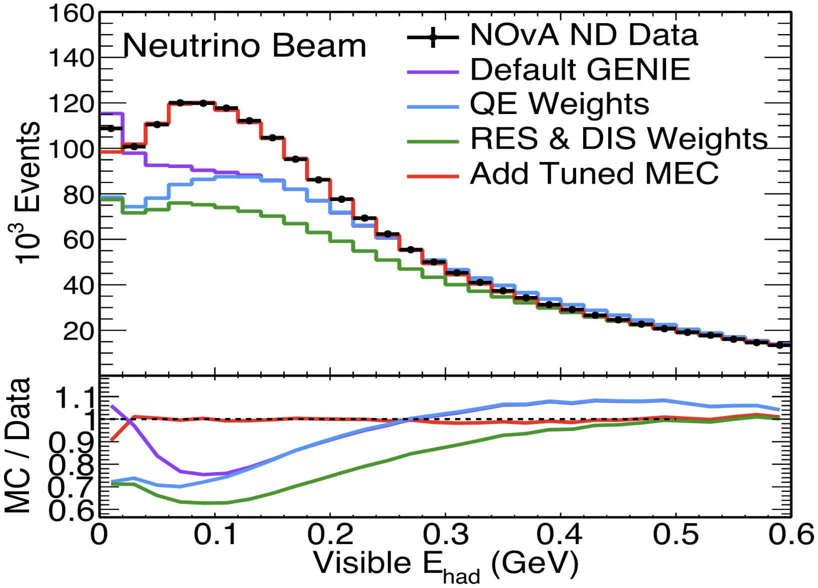
Neutrino Interaction Model

Released analyses: base model is **Genie 2.12.2**

ISA	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 Resonant baryon production
- DIS at W>1.7 GeV/c^2 is weighted up 10% based on NOvA ND data
- **Empirical MEC based on NOvA ND data for 2p2h**



Upcoming Analyses: base model is **Genie 3.0.6**

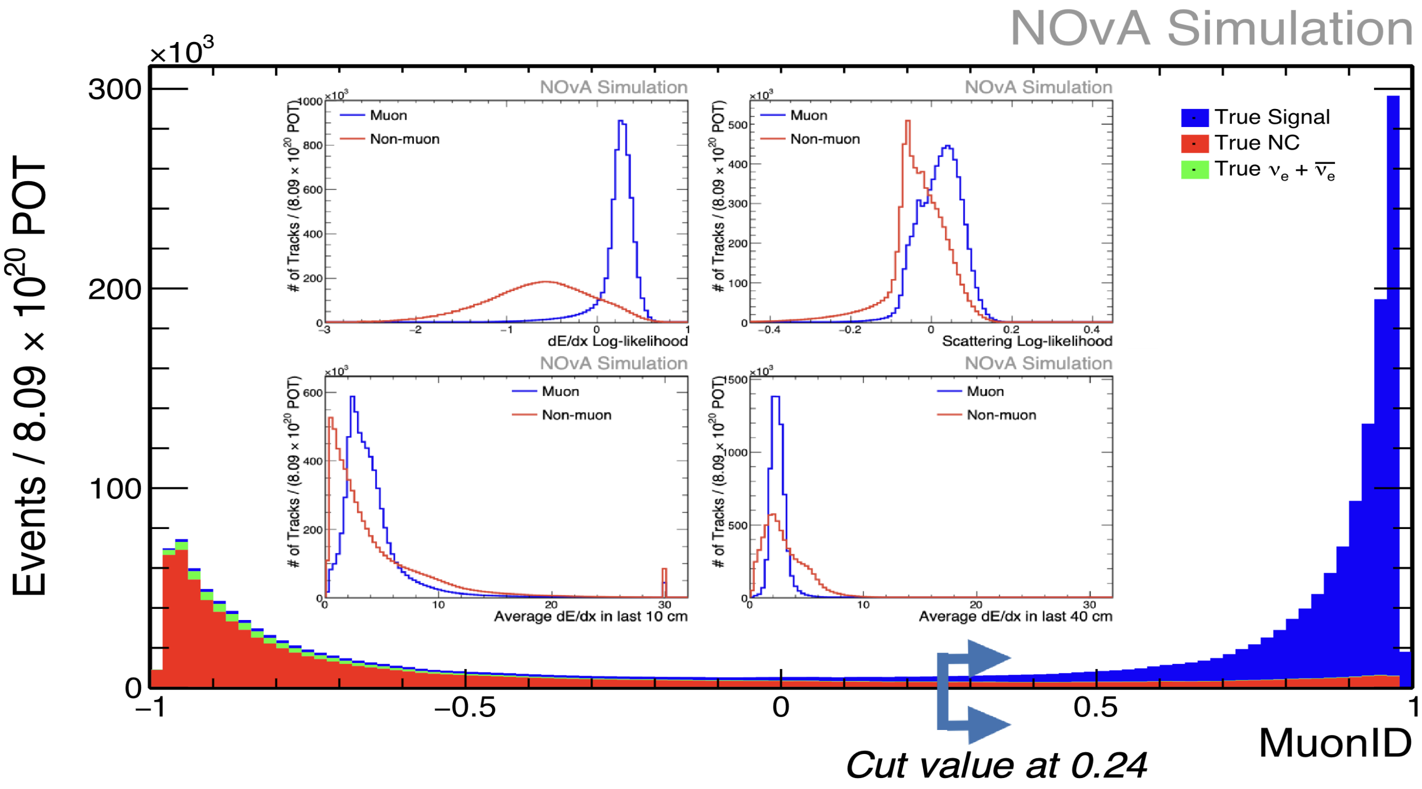
IS	QE	MEC	Res	DIS	FSI
LFG	Valencia, Z exp	Valencia	B-S	B-Y + Pythia	hN

Plus improvements in the tuning application

All analyses are constructed to be insensitive to the tuning

Muon Identification

- Developed within the **ν_μ CC inclusive analysis**
- Muon ID calculated with a **Boosted Decision Tree**
- Cut value is set to **minimize shape systematic uncertainty on cross-section** measurement
- Selected sample has **97% purity** and **98% efficiency** after pre selection (*containment*, data quality, fiducial volume)



Released Analysis:

ν_μ Charged Current with Low Hadronic Energy

Presented at the February 2nd, 2024 Fermilab
Wine & Cheese Seminar by Leo Aliaga

Released Analysis:
ν_μ Charged Current with Low Hadronic Energy

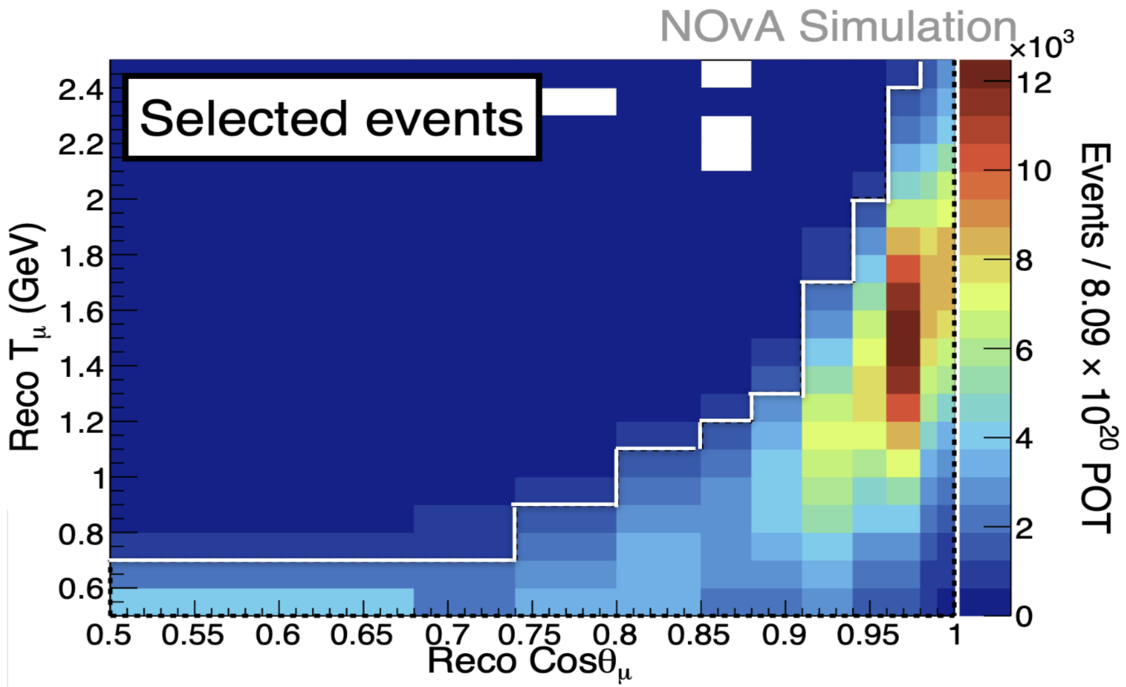
Signal Definition and Selection

- Aim to select sample enhanced in QE and 2p2h
- RES and DIS likely to produce multiple reconstructed particles

Selection:
*ν_μ CC with **one reconstructed particle (i.e. a muon)***

Scan proton and pion thresholds and minimize uncertainty in total cross section

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

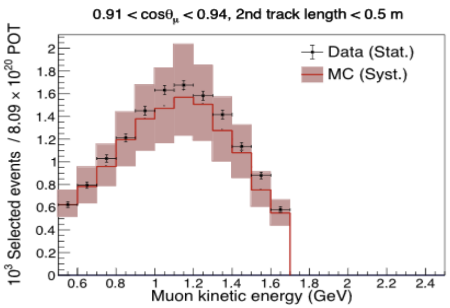


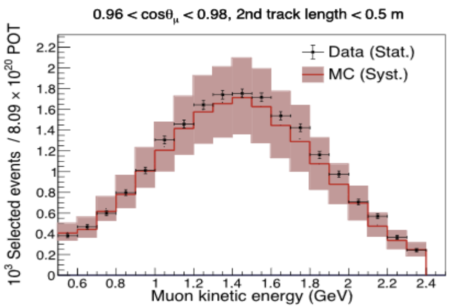
ν_μ Charged Current with Low Hadronic Energy

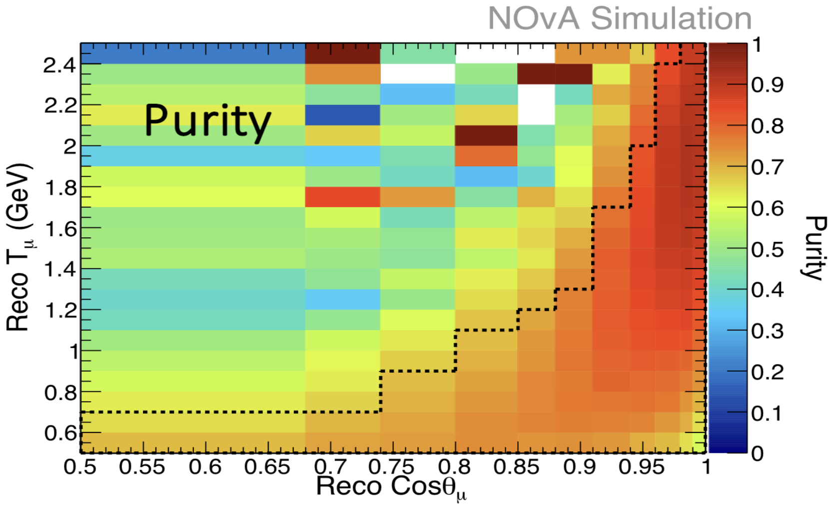
Analysis

- **Performed in 3D** (muon kinematics and E_{avail}), then projected on 2D
- Purity ranges from 60-90%
  - *Validation:* ***sideband*** *with an* ***additional, short reconstructed particle***:

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





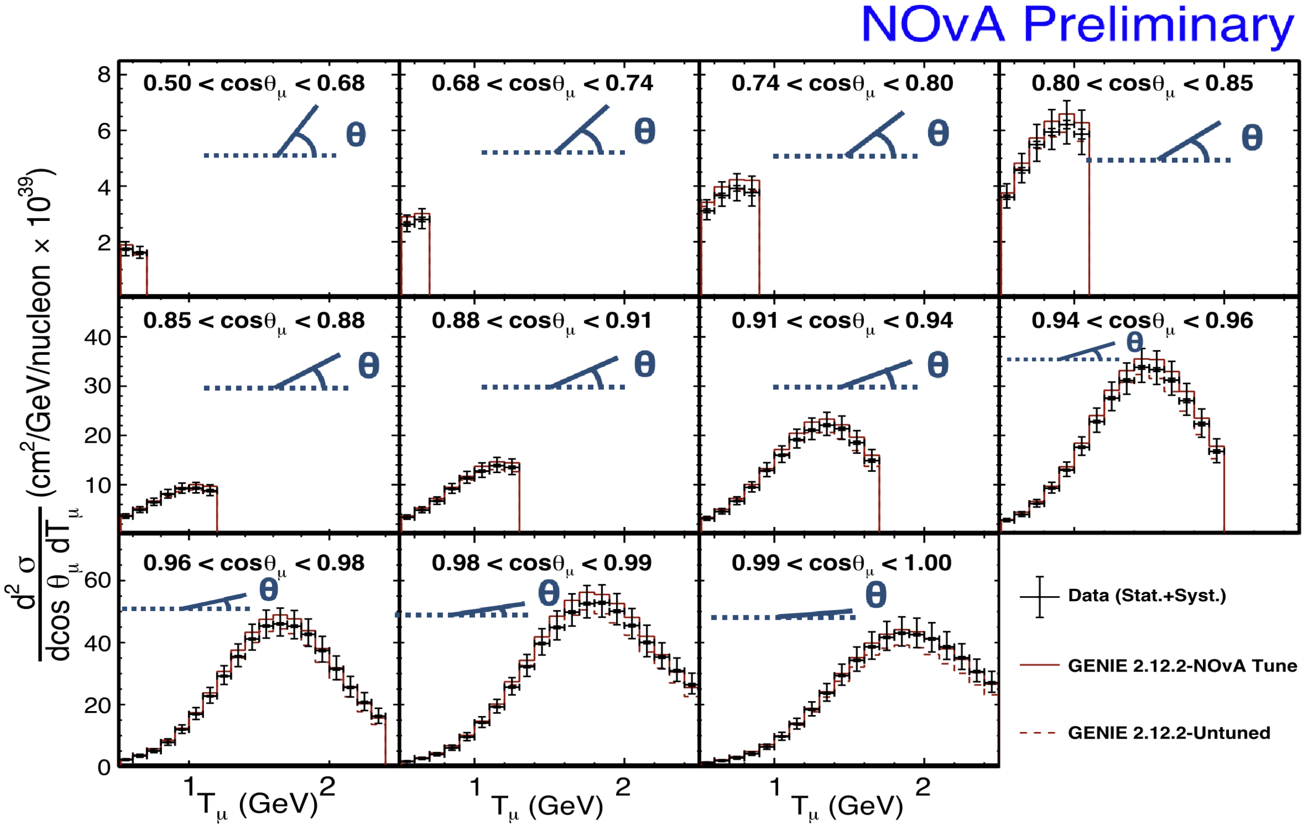


Released Analysis:

ν_μ Charged Current with Low Hadronic Energy

Results:

Muon Kinematics



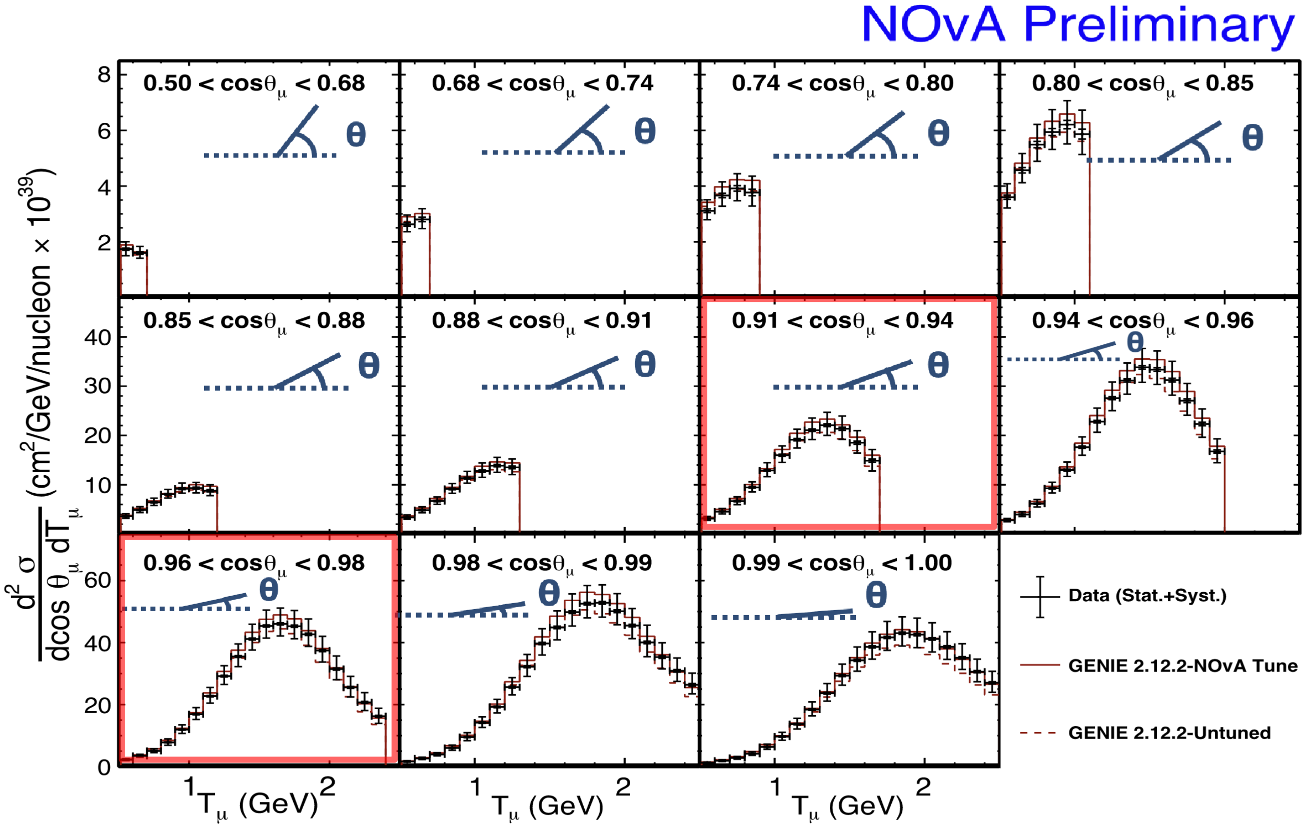
Released Analysis:

ν_μ Charged Current with Low Hadronic Energy

Results:

Muon Kinematics

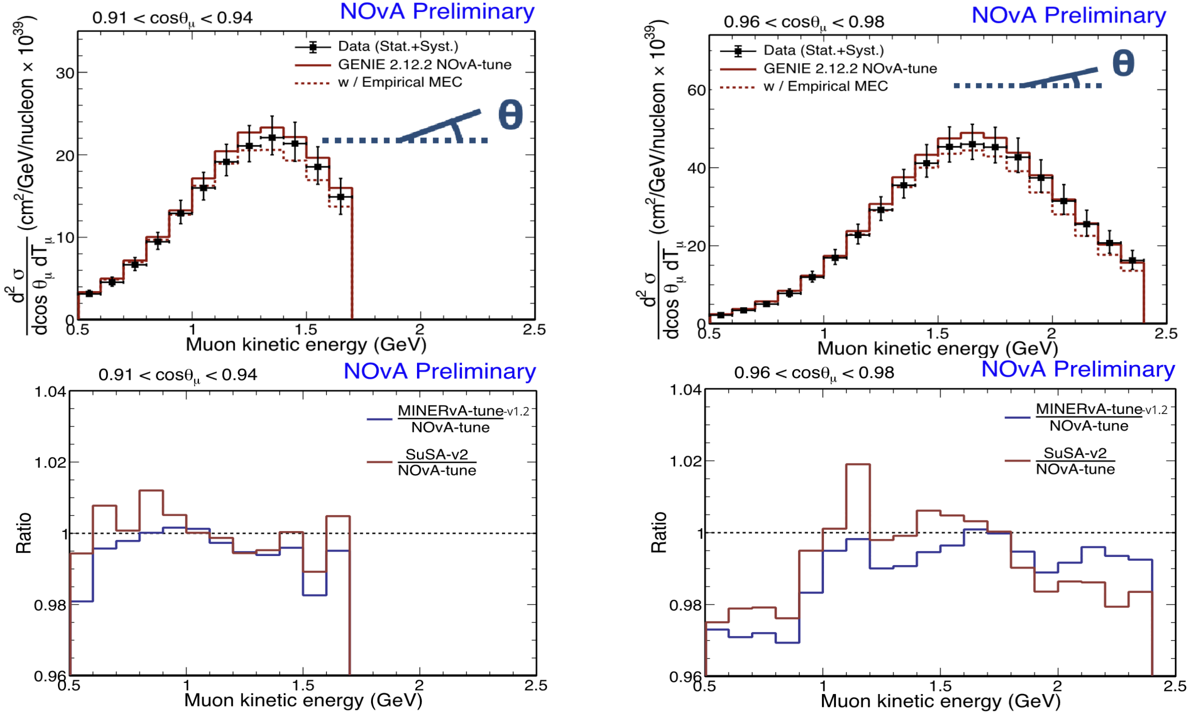
Let's take a closer look at two cosine bins…



Released Analysis:

ν_μ Charged Current with Low Hadronic Energy

Results: Muon Kinematics



2p2h uncertainties derived as the spread when **recalculating** the whole cross section using **SuSAv2 and MINERvA-tune-v1.2**

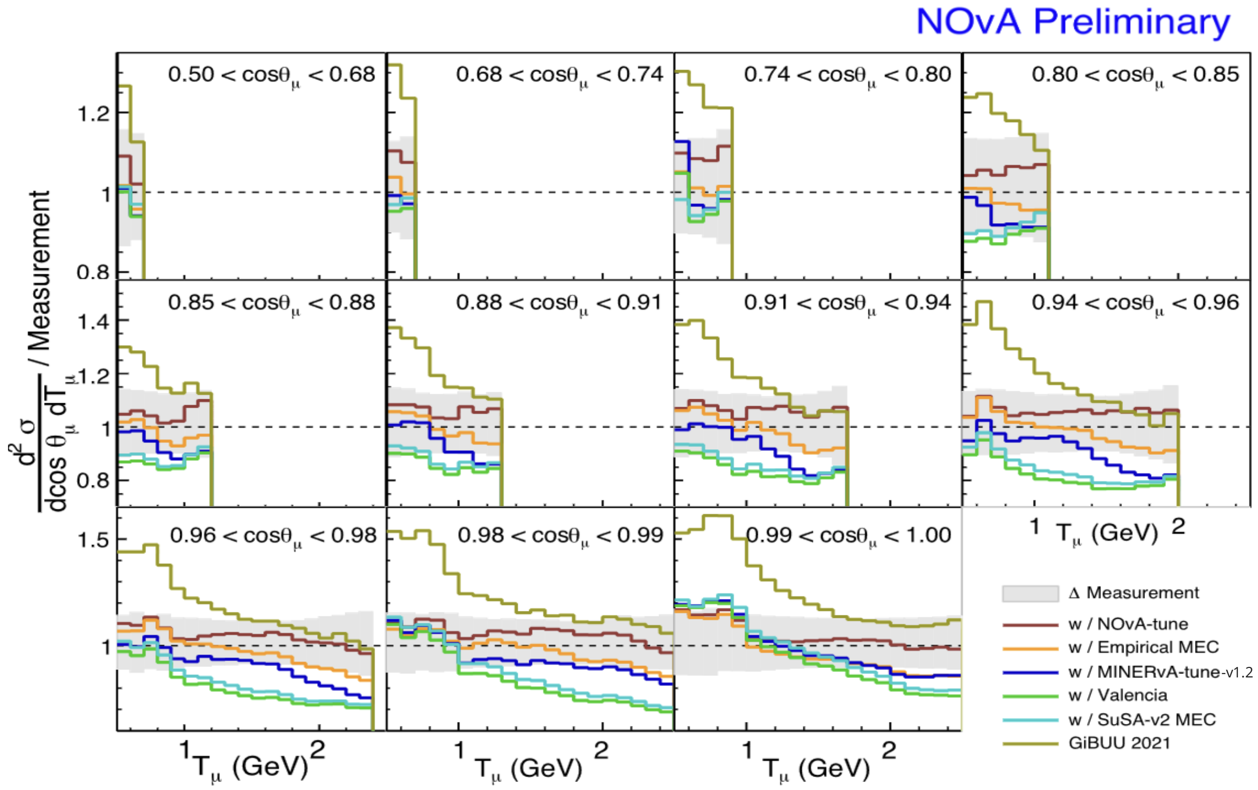
Released Analysis:

ν_μ Charged Current with Low Hadronic Energy

Results: Muon Kinematics

Comparison to 2p2h models:

- NOvA-tune overestimates most bins
- GiBUU overestimates most data
- Other models tend to predict lower values

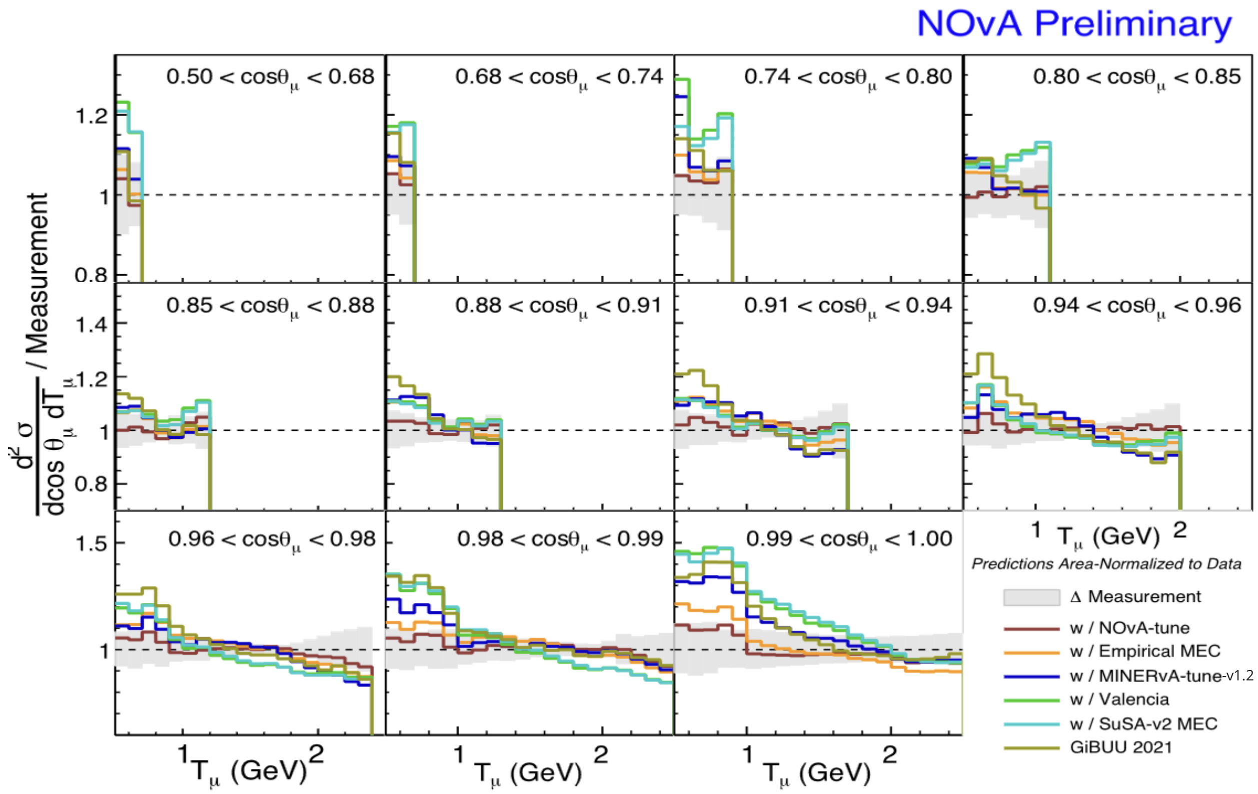


Released Analysis:
ν_μ Charged Current with Low Hadronic Energy

Results: Muon Kinematics

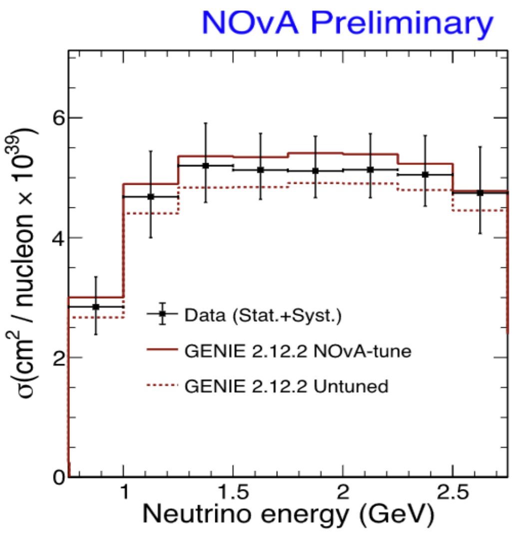
Comparison to 2p2h models:
Shape-only uncertainties

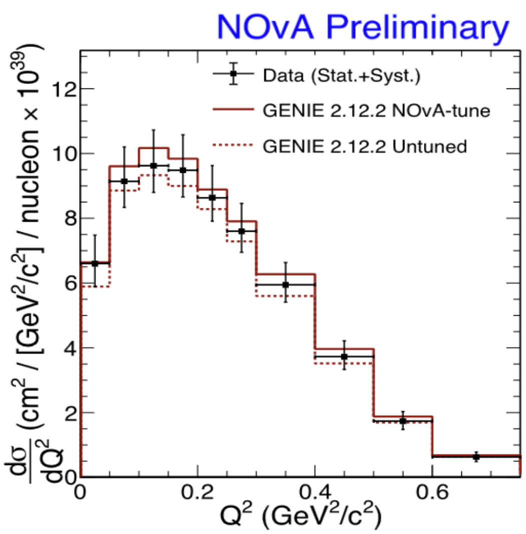
- Except NOvA-tune, models predict different cross section shapes



ν_μ Charged Current with Low Hadronic Energy

Results: E_ν and Q^2





- Limited to the phase space of the muon kinematics measurement
- Calculated as combinations of the reconstructed muon and remaining visible calorimetric energy

Released Analysis:

ν_μ Charged Current with Low Hadronic Energy

Comparison Summary:

χ^2 tests including bin-to-bin correlations

- Different levels of agreement w.r.t. the ratio plots coming from bin-to-bin correlations
- Empirical MEC has best performance modeling the data, followed by experiment-tuned models and then 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-v1.2	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)

In parentheses: shape only X^2

Released Analysis:

ν_μ Charged Current Inclusive and 2p2h estimation

Presented at the February 2nd, 2024 Fermilab
Wine & Cheese Seminar by Travis Olson

Released Analysis:

ν_μ Charged Current Inclusive and 2p2h estimation

Analysis variables:

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

4-momentum transfer squared:

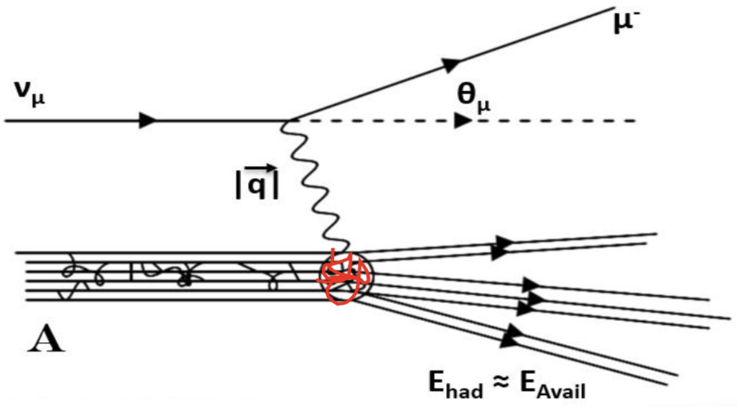
$$Q^2 = 2 * E_\upsilon * (E_\mu - P_\mu * \cos(\theta_\upsilon)) - m_\mu^2$$

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)



ν_μ Charged Current Inclusive and 2p2h estimation

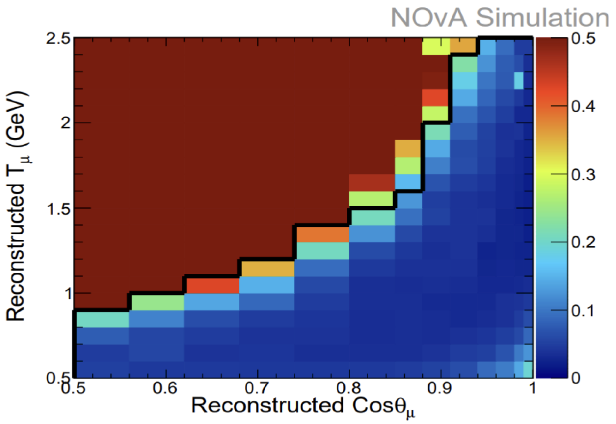
Signal Definition and Selection

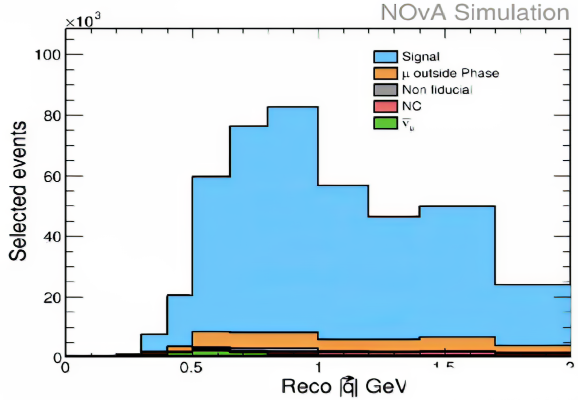
- **Signal:**

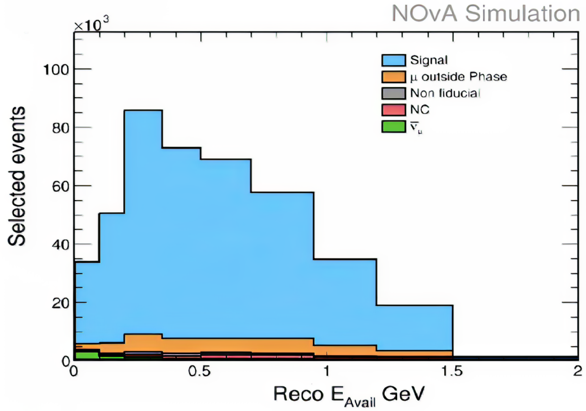
  1) *True ν_μ CC event in a fiducial volume*

  2) *Within muon phase space that enhances efficiency and purity (from inclusive analysis in muon kinematics)*

- **Selection:** MuonID > 0.24







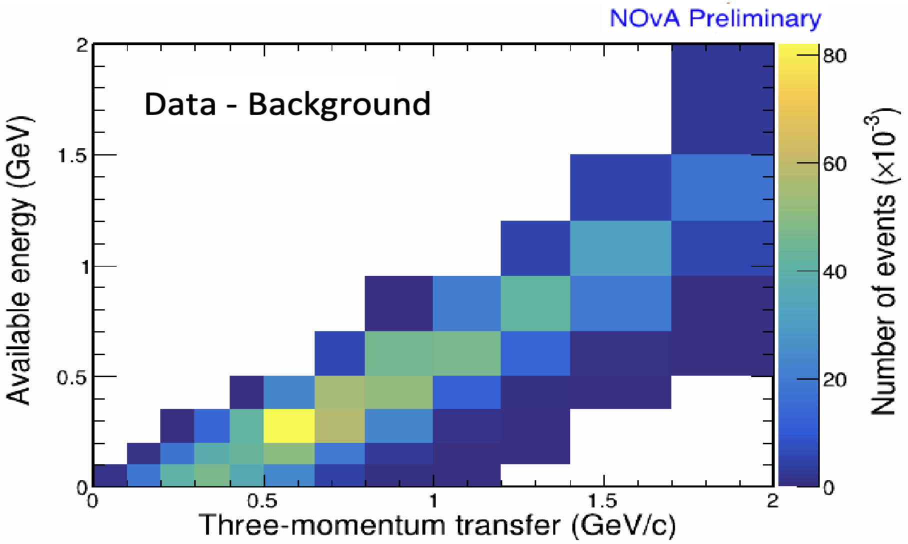
Released Analysis:
ν_μ Charged Current Inclusive and 2p2h estimation

Analysis

- **Background** estimated
- Overall purity is ~92%
- Background subtraction from simulation

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

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



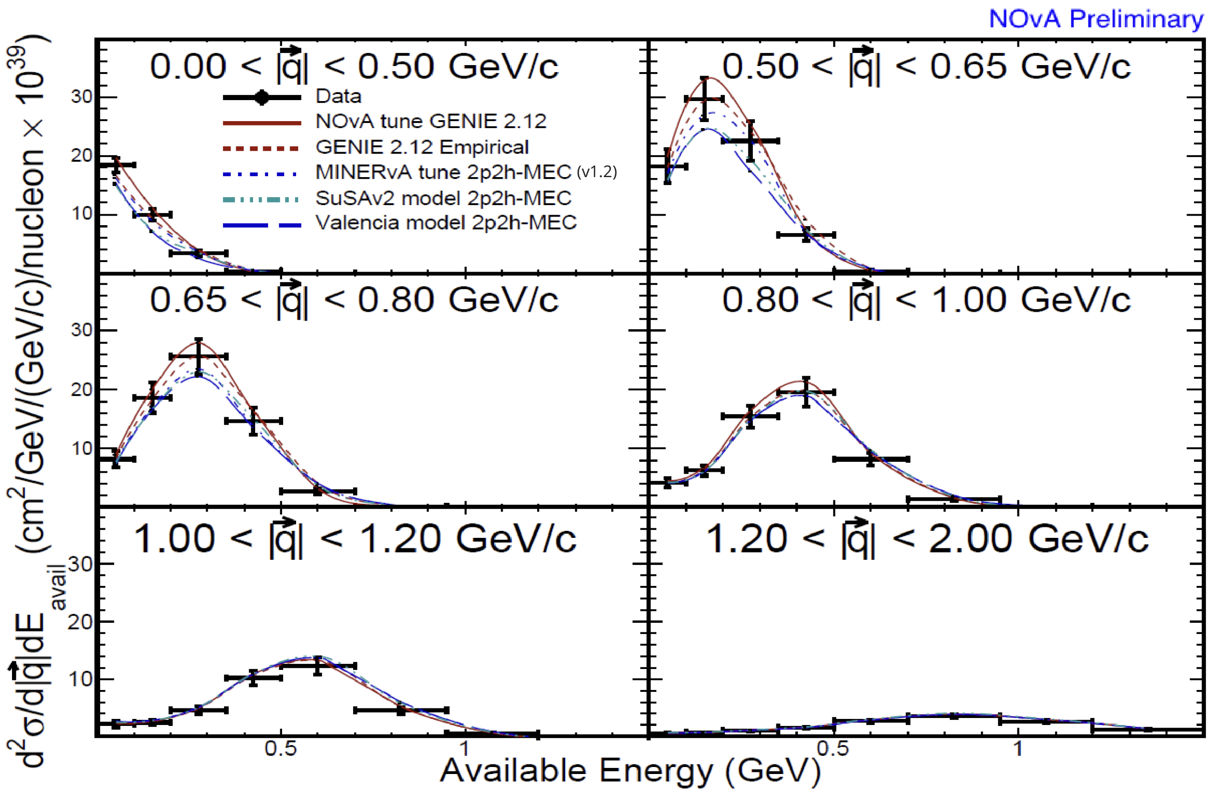
Released Analysis:
ν_μ Charged Current Inclusive and 2p2h estimation

Results: Inclusive Cross section

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

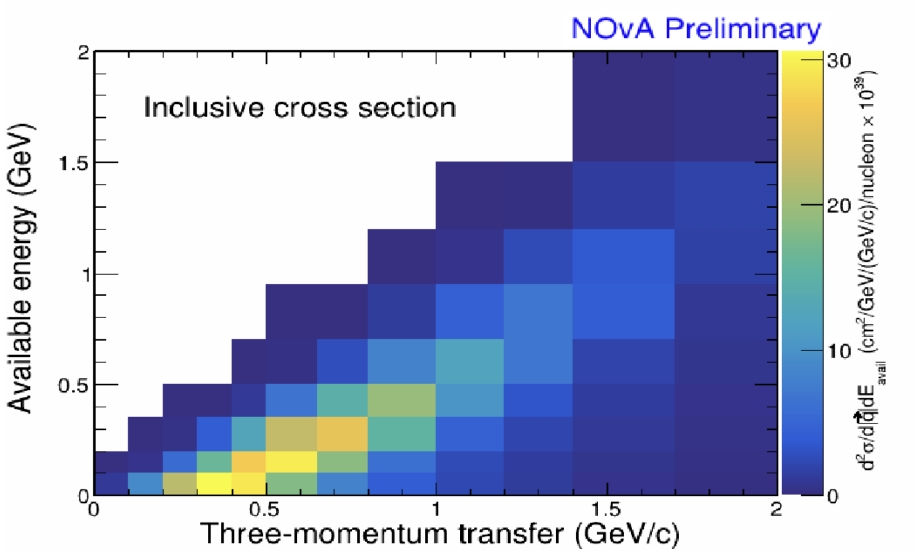
NOvA tune 2p2h gives best description of data.

SuSAv2 and Valencia models under-predict the data rate.



Released Analysis:
ν_μ Charged Current Inclusive and 2p2h estimation

Comparisons to 2p2h models



Model	χ^2 NDF: 61
NOvA tune	51 (50)
GENIE Empirical	514 (545)
MINERvA tune v1.2	1220 (1390)
SuSAv2 model	1610 (876)
Valencia model	2065 (2654)

The values in parentheses are the shape-only χ2 calculations

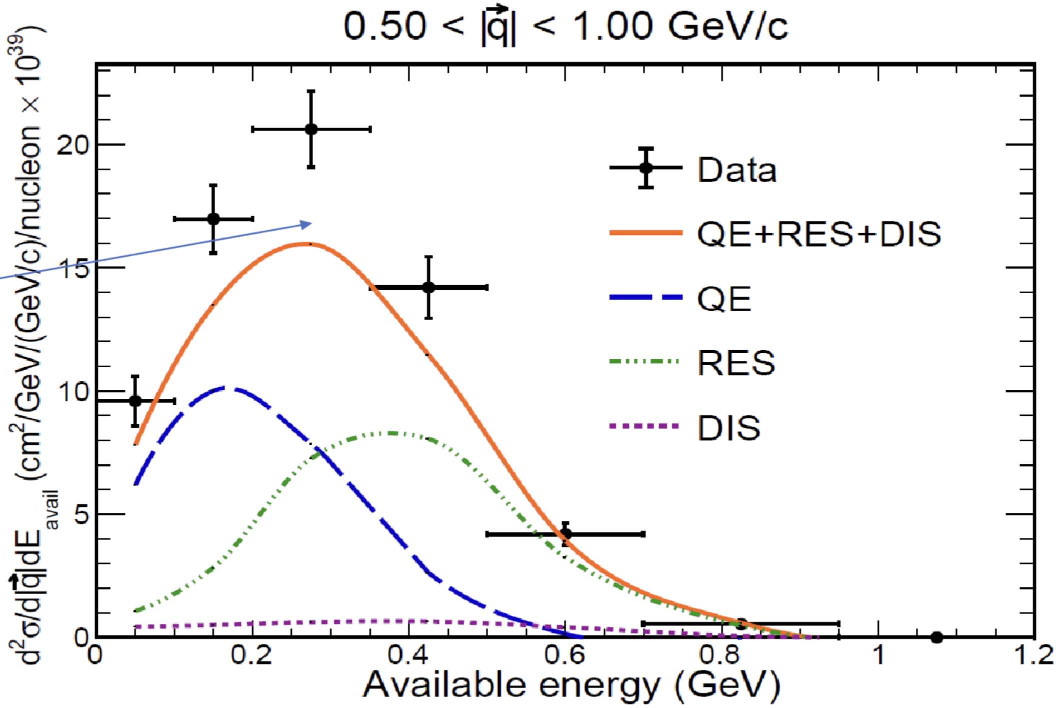
The NOvA tune and GENIE empirical 2p2h give better agreement with the data than the theory-based models or the MINERvA tune v1.2

Released Analysis:
ν_μ Charged Current Inclusive and 2p2h estimation

Results: Inclusive Cross section

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

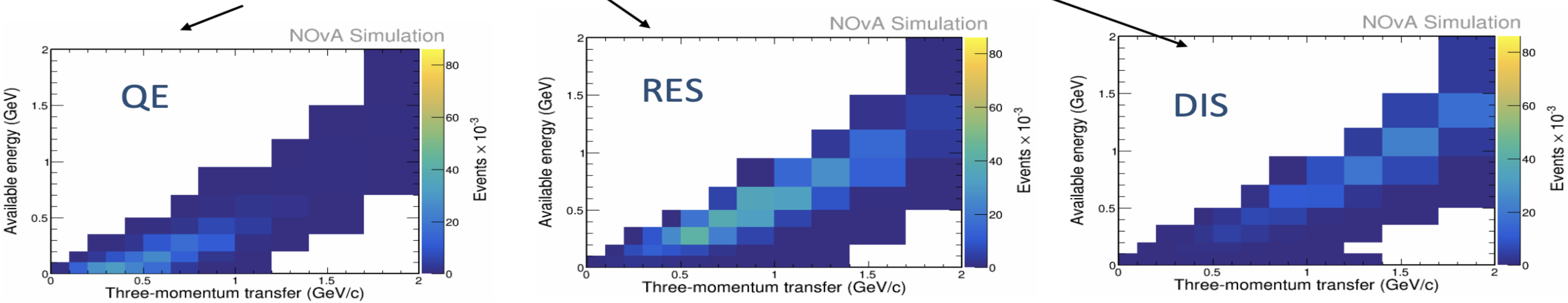
The data does indeed show an excess in that region above expectation for ν_μ CC single-nucleon scattering.



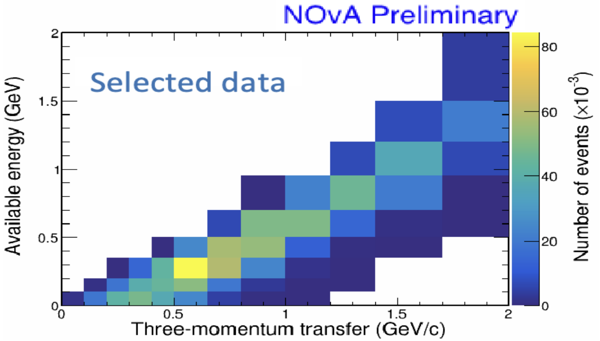
Released Analysis:
ν_μ Charged Current Inclusive and 2p2h estimation

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.

ν_μ Charged Current Inclusive and 2p2h estimation

Control sample: Has minimal QE and 2p2h, used to fit RES and DIS templates

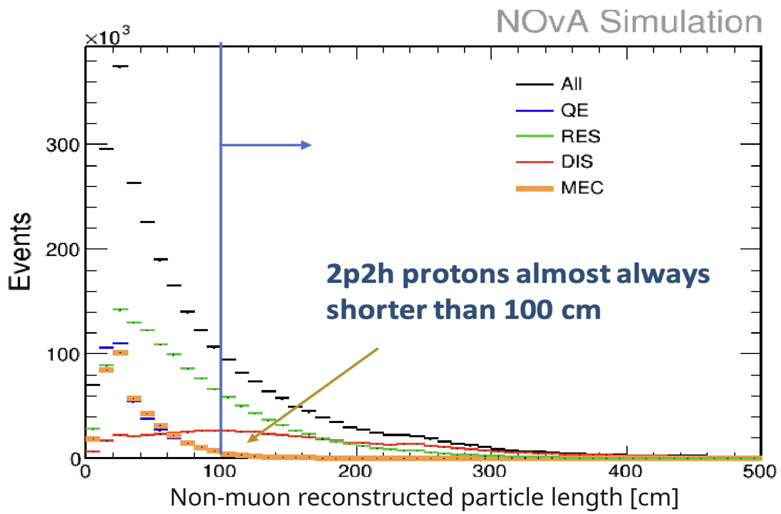
A non-muon reconstructed particle longer than 1 m

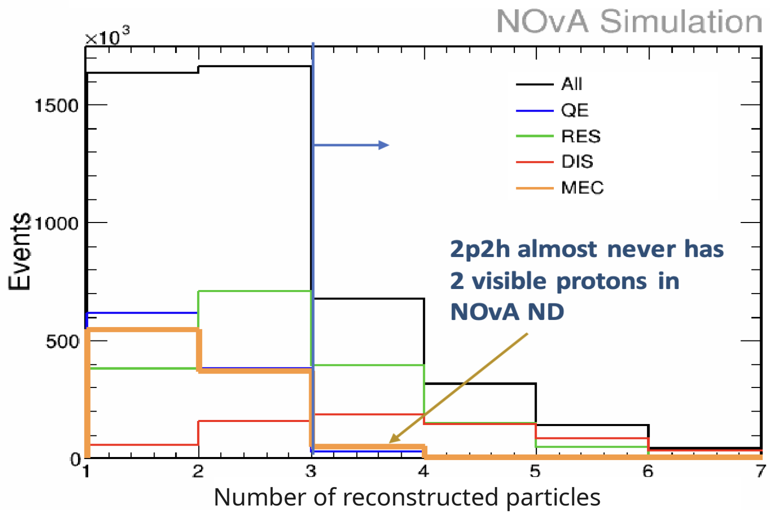
(very unlikely for protons from QE, 2p2h)

or

Three or more reconstructed particles or showers

(very unlikely for QE, 2p2h)

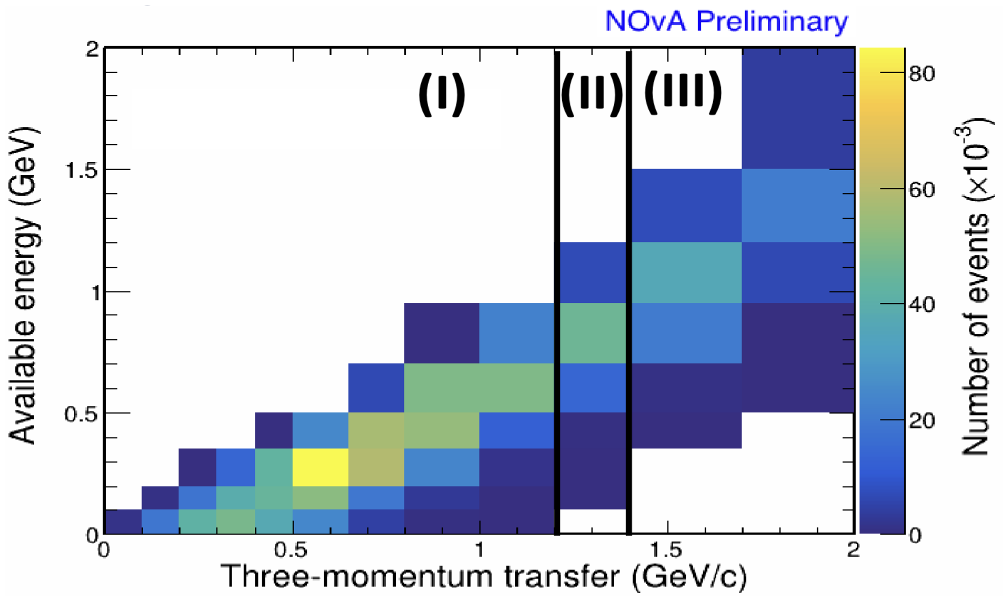




Released Analysis:
ν_μ Charged Current Inclusive and 2p2h estimation

Control Sample: Has minimal QE and 2p2h, used to fit RES and DIS templates

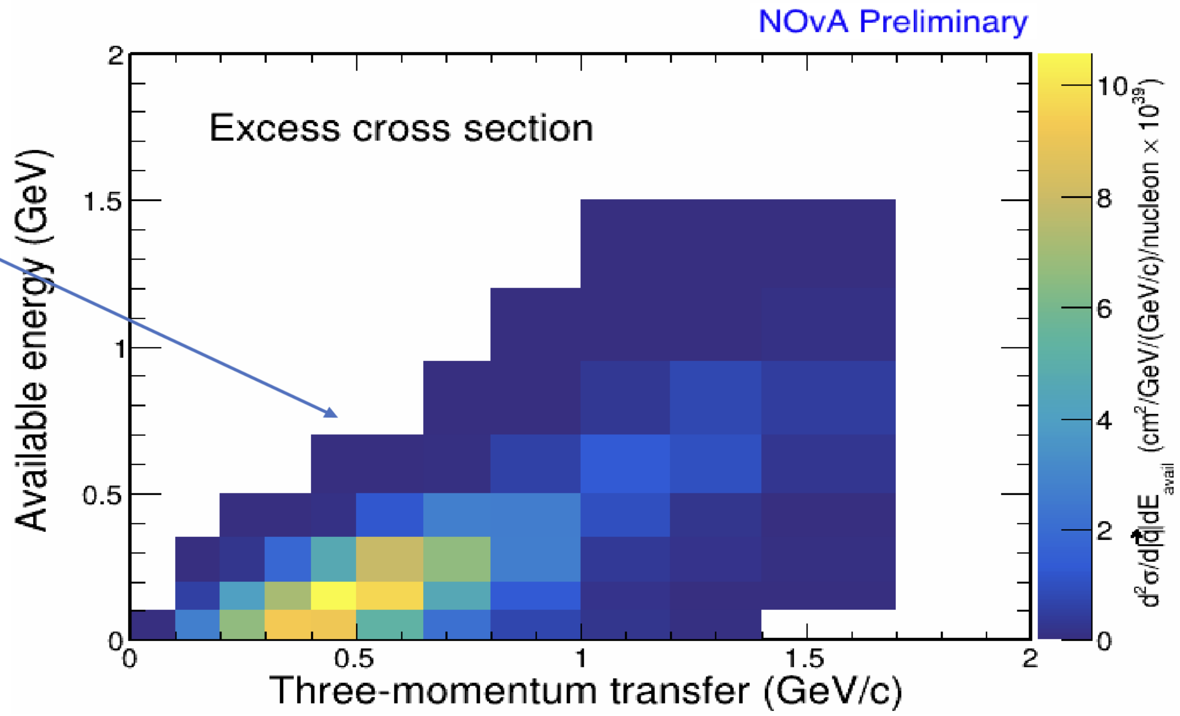
- Normalizations for **RES and DIS templates** are derived from **fits in the control sample**
- **Independent fits** in **region I** (RES-dominated) and **region III** (DIS-dominated)
- For **region II, average** normalizations from regions I and III
- **QE template** calculated using:
  - Llewellyn-Smith formalism
  - RFG nucleus with high momentum tail and RPA correction



Released Analysis:

ν_μ Charged Current Inclusive and 2p2h estimation

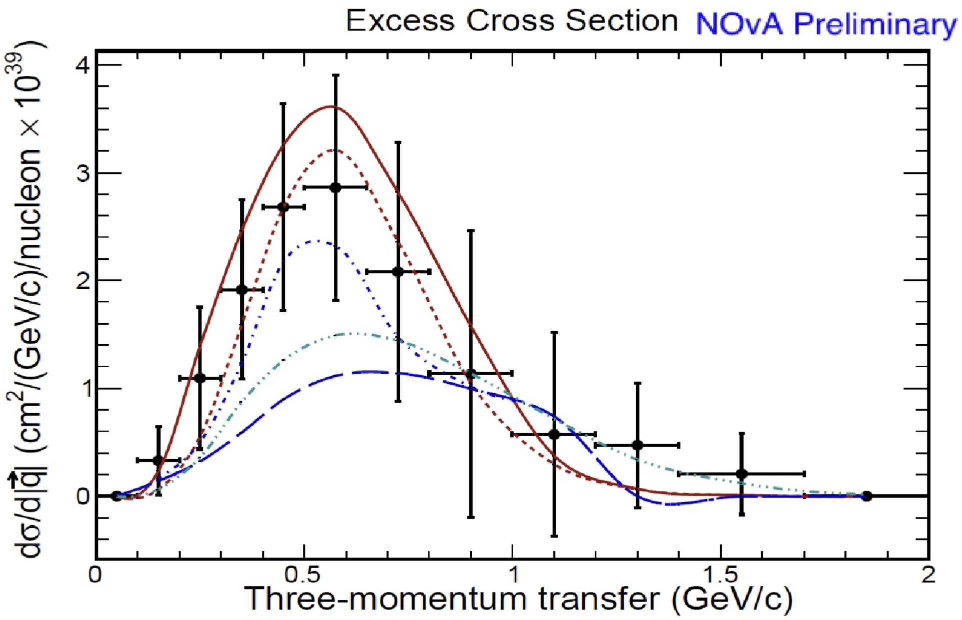
2p2h contribution is taken to be the data excess above the sum of the 1p1h templates.

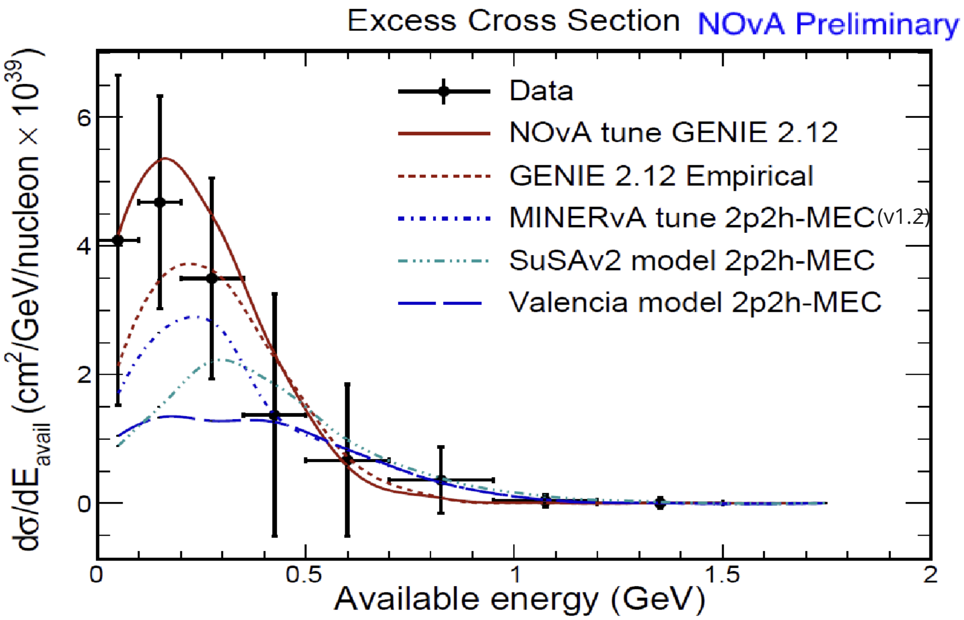


Released Analysis:

ν_μ Charged Current Inclusive and 2p2h estimation

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



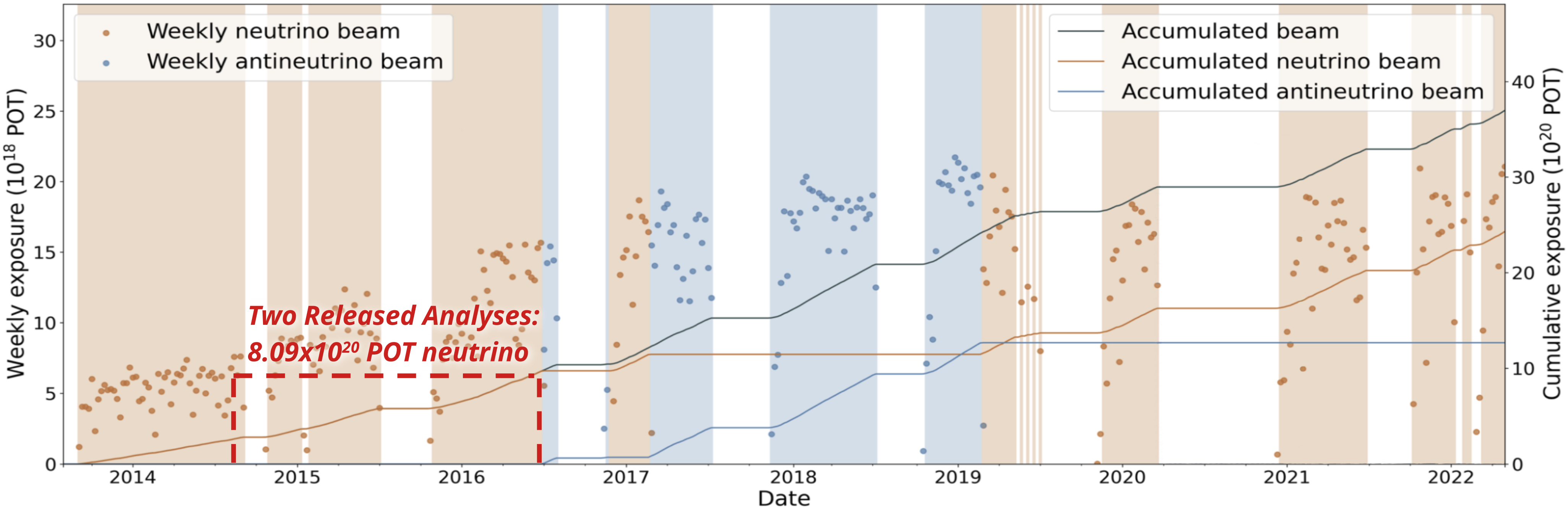


Upcoming Analyses

- Increased exposure
- Improved cross-section models and systematic uncertainties
- More detail on the final state

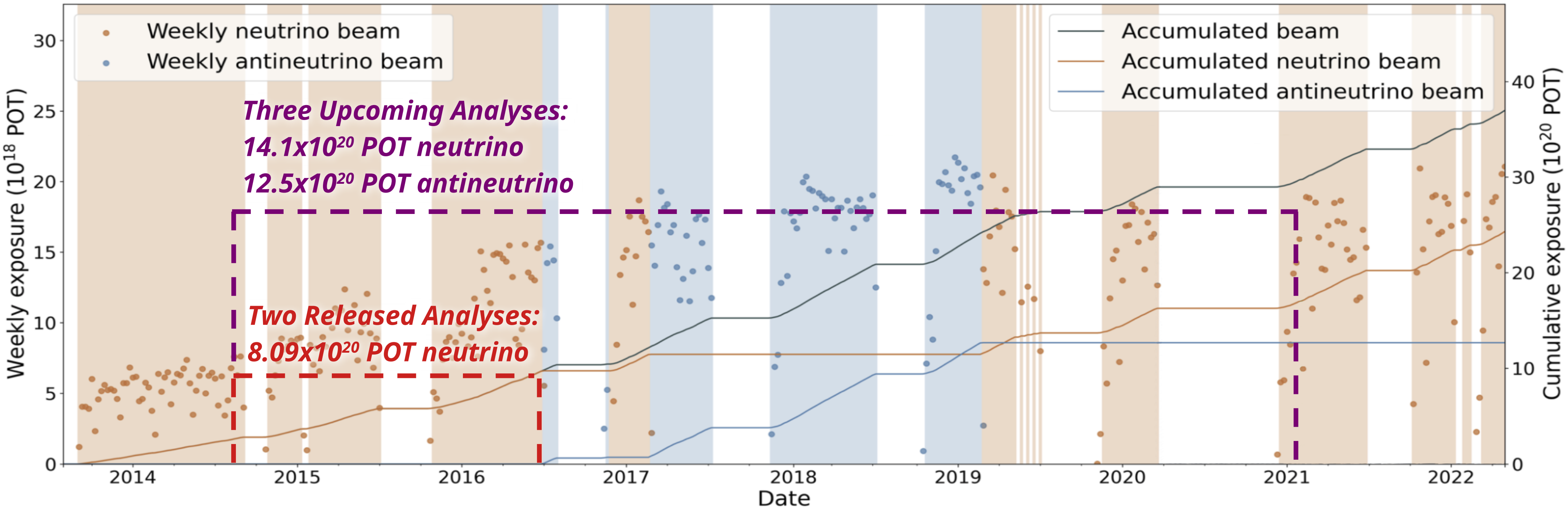
ZM/QE/2p2h-like

Neutrino Beam Exposures



Total exposures to date are 27.8x10^{20} POT neutrino and 12.8x10^{20} antineutrino

Neutrino Beam Exposures

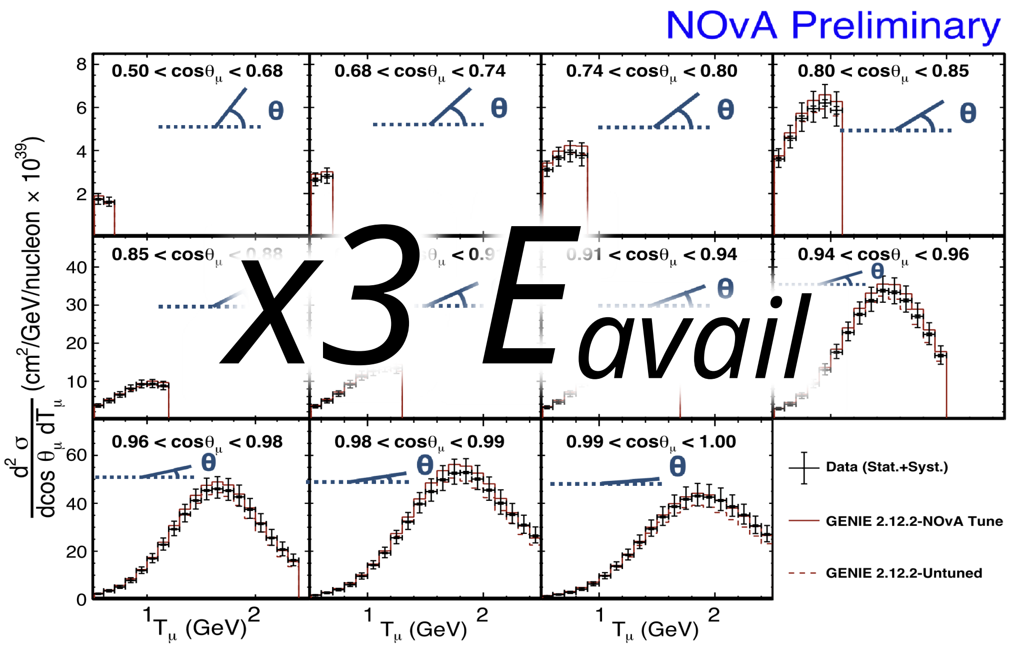


Total exposures to date are 27.8×10^{20} POT neutrino and 12.8×10^{20} antineutrino

Upcoming Analysis: *James Lesmeister*

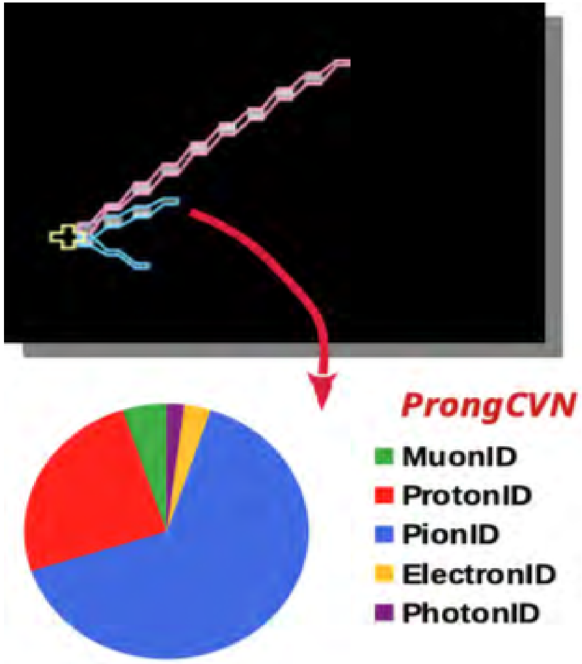
ν_μ Charged Current Low Hadronic E in 3D with E_{avail}

- **Inherits signal definition and event selection** of Released Low Hadronic analysis
  - Signal: ν_μ CC events with $T_p < 250$ MeV, $T_\pi < 175$ MeV in fiducial volume
  - Selection: Only one reconstructed particle
- **Extended Exposure**
- Delivering results in muon kinematics plus **three E_{avail} bins**



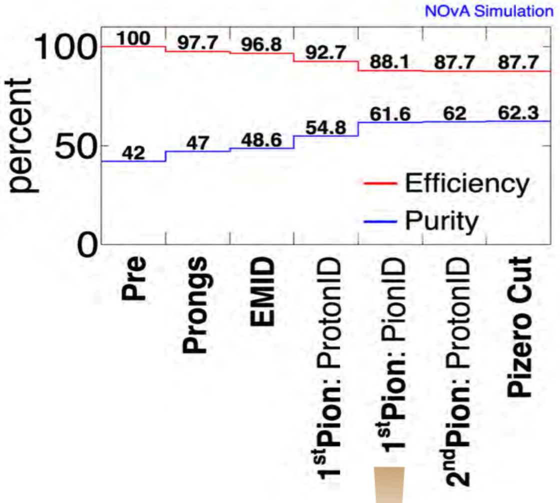
Upcoming Analysis: ν_μ Charged Current Zero Mesons

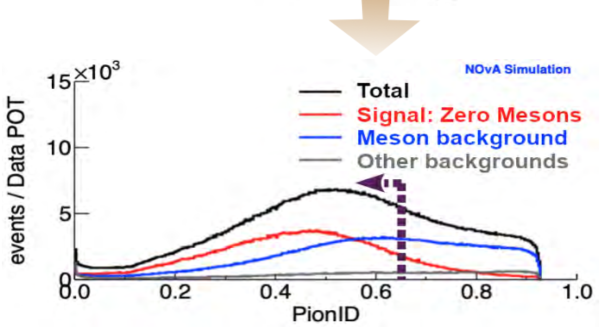
- **Inherits muon ID** and reconstruction
- Looser selection **allows for reconstructed nucleons** in the final state
- Signal: **ν_μ CC events with no Mesons** in the final state
- Event Selection Tool
  - **ProngCVN**: a convolutional neural network trained on single particles simulated in the Near Detector



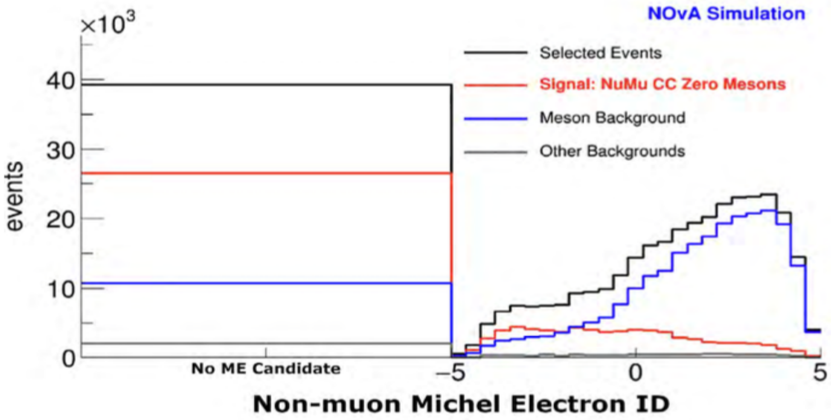
ν_μ Charged Current Zero Mesons

Optimized cuts on particle IDs targeted to **reject pion-like particles** while **preserving proton-like particles**





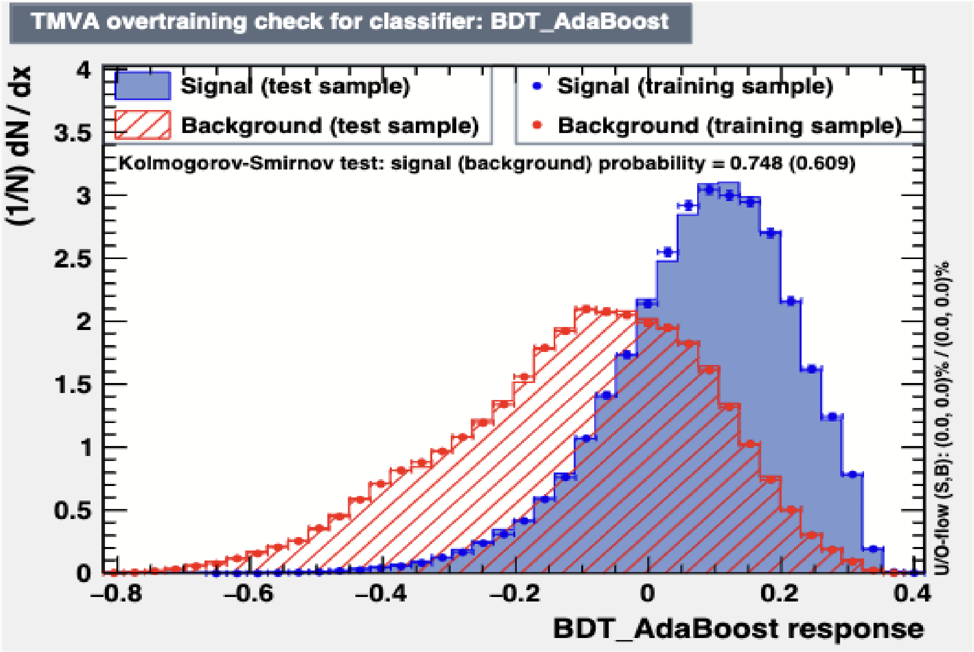
Template Fitting to **Michel Electron ID** to constrain the remaining charged pion background and extract signal events



Anti-ν_μ Charged Current Zero Mesons

Kevin Vockerodt

- Signal: **ν_μ CC events with no mesons** above 100 MeV
- Event Selection:
  - **MERMAID:** Custom BDT based on ProngCVN and Shower variables
- Exploring distributions in muon **longitudinal** and **transverse** muon momentum
- **Learn more from Kevin at the poster session!**



Summary

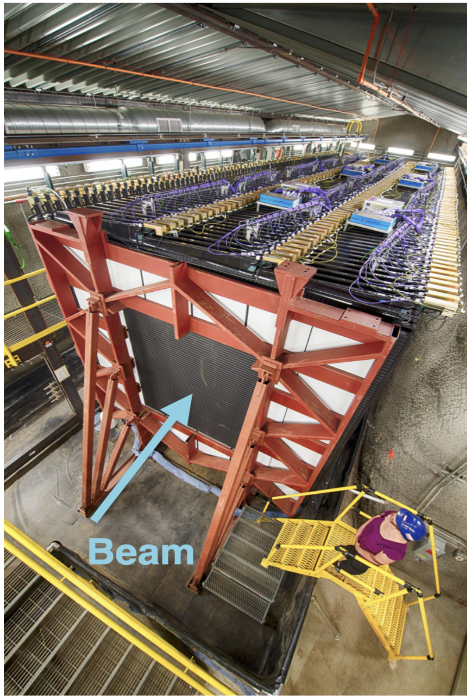
- **Two 2p2h-enhanced analyses released**
  - 2p2h shown to have a significant presence in both analyses
    - Under-prediction for forward, high energy muon; and also lower E_{avail}, and $|\vec{q}|$
  - **Estimated a 2p2h cross section** contribution in E_{avail}, and $|\vec{q}|$
  - Provide valuable input for model development and joint fits
- **Three upcoming analyses**
  - Almost **double the exposure** and more detail in final states
  - Stay tuned for more results!

Thank you!

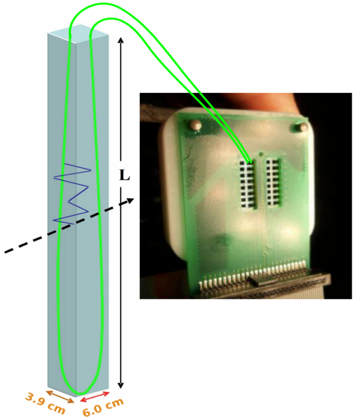
NOvA Collaboration at Illinois Institute of Technology, Wheaton, IL, Feb 2024

Backup

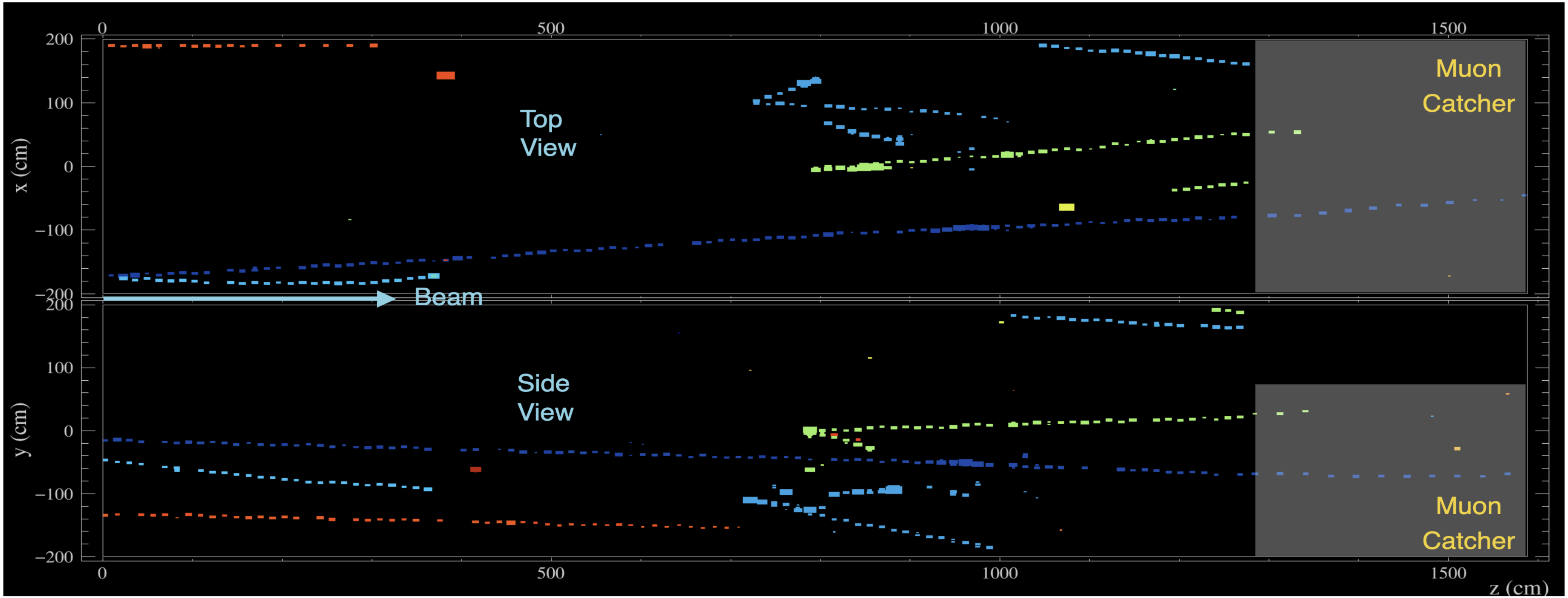
The NOvA Near Detector



- Fine-grained tracking calorimeter
- 14.6 mrad off-axis of the NuMI beam
- Layers of liquid scintillator-filled PVC cells in alternating orthogonal directions, providing a “top view” and “side view”
- 38 cm radiation length in tracker (0.07 X_0 per layer)
- Cells of cross section 3.9 × 6.6 cm^2 , 3.9m lon
- 300 ton, 63% by mass active material
- Muon catcher: scintillator layers are further interleaved with 10cm-thick steel, able to stop up to 2.5 GeV muons
- FD is roughly four times larger than ND with equal cell cross section



The NOvA Near Detector



NuMI Beam Composition Table

Predicted flux composition in absence of oscillations
Integrated in [1,5] GeV neutrino energy.

	ND, FHC %	ND, RHC %
ν_μ	93.765	6.602
$\bar{\nu}_\mu$	5.299	92.495
ν_e	0.814	0.170
$\bar{\nu}_e$	0.123	0.733

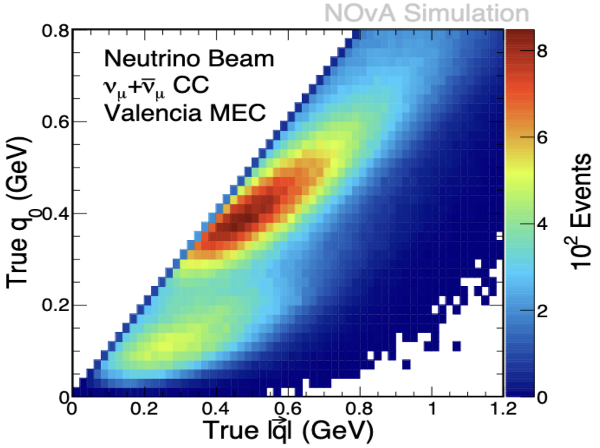
ZM/QE/2p2h-like
Cross Section Model

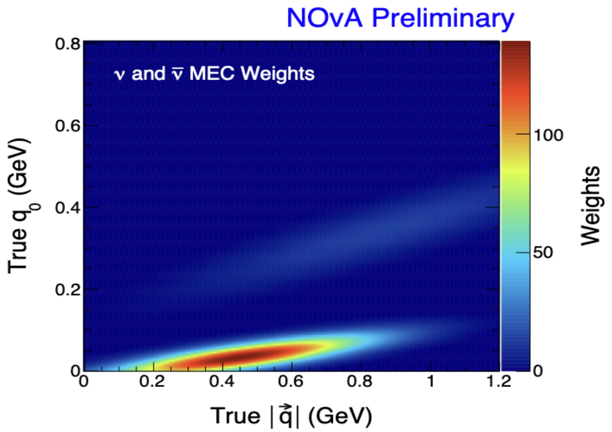
Upcoming Analyses: base model is **Genie 3.0.6**

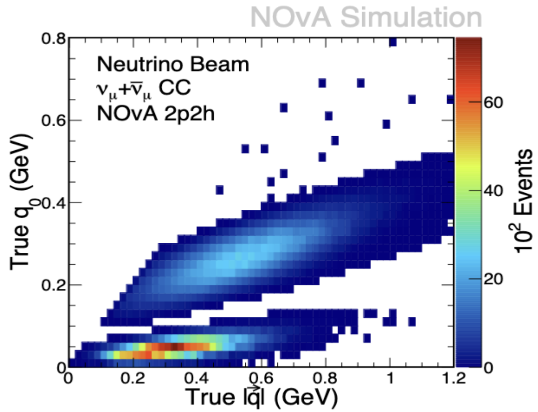
IS	QE	MEC	Res	DIS	FSI
LFG	Valencia, Z exp	Valencia	B-S	B-Y + Pythia	hN

Plus, further improvements in the tuning:

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

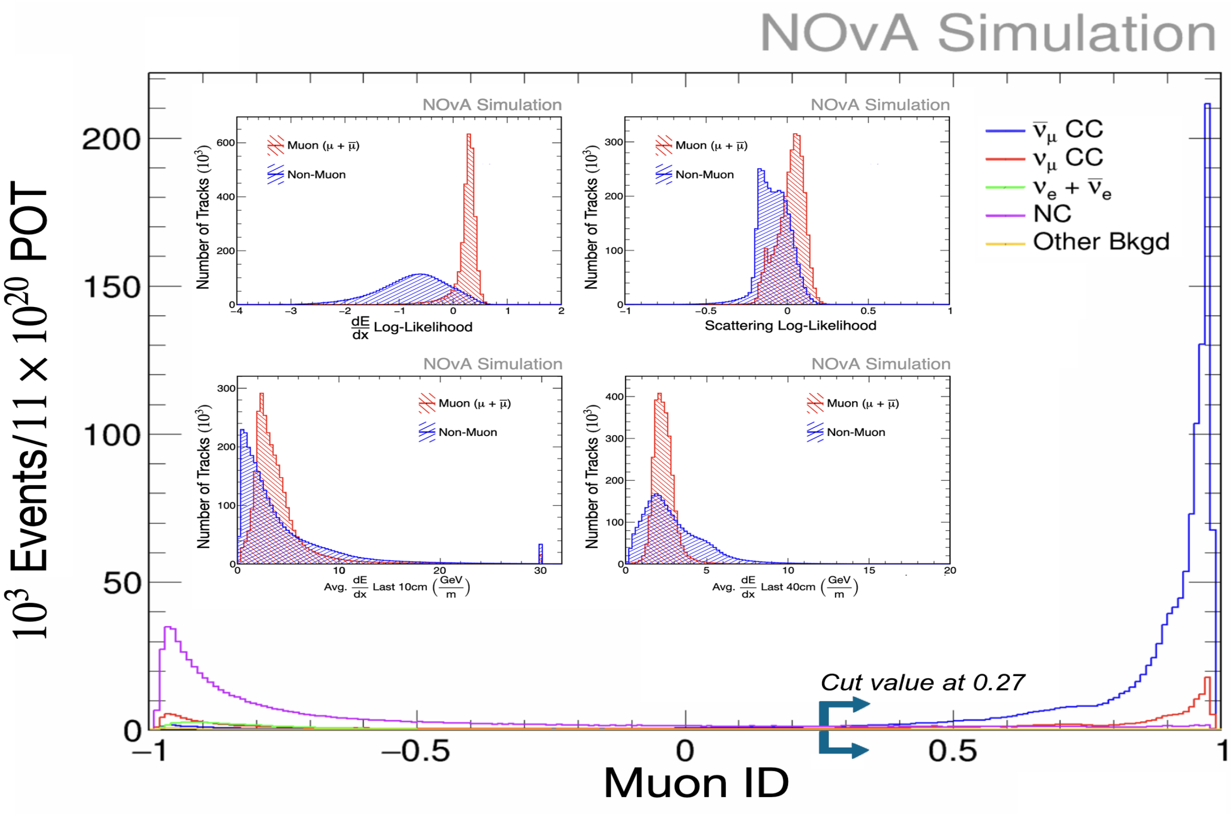




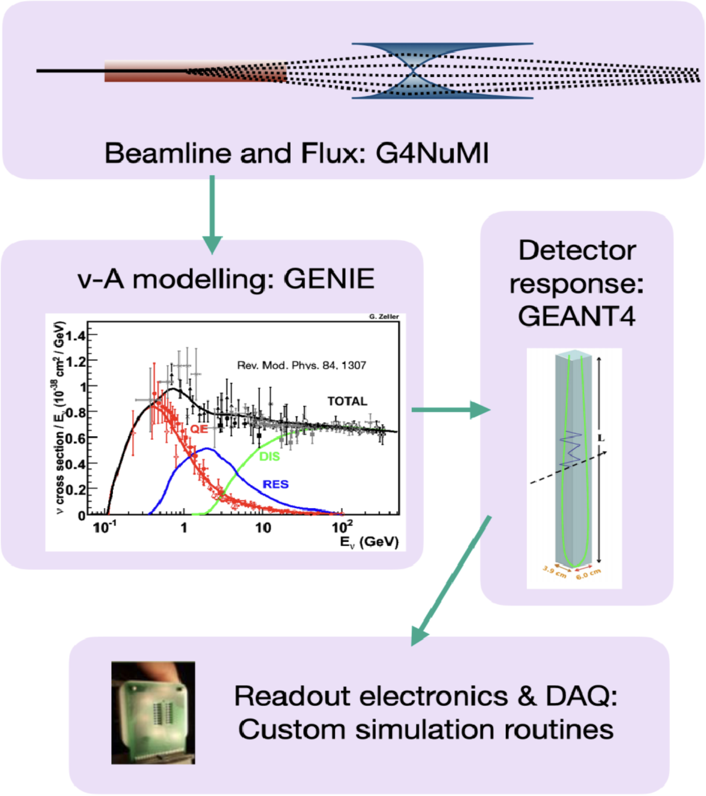


Muon Identification – Antineutrino mode

- Developed within the **Anti-ν_μ CC inclusive analysis**
- Muon ID calculated with a **Boosted Decision Tree**
- Cut value is set to **minimize shape systematic uncertainty on cross-section** measurement
- Sample has **90% purity** and **~32.9% efficiency** overall



Simulation

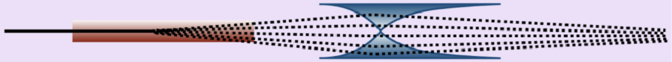

Beamline and Flux: G4NuMI
ν-A modelling: GENIE
G. Zeller
Rev. Mod. Phys. 84, 1307
TOTAL
QE
DIS
RES
E$_\nu$ (GeV)
Detector response: GEANT4
Readout electronics & DAQ: Custom simulation routines

ZM/QE/2p2h-like

Simulation => Systematic Uncertainties

Hadron Production

(PPFX multiverse weights)

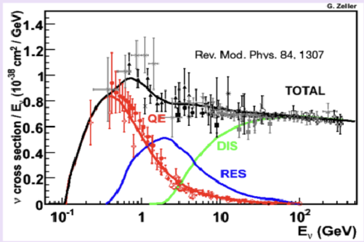


Beamline and Flux: G4NuMI

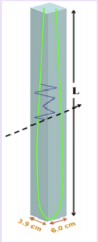
Beam Transport
(shifted samples)

Neutrino Interactions
(GENIE multiverse weights)

ν-A modelling: GENIE



Detector response: GEANT4



Particle Propagation
(Geant4 multiverse weights)

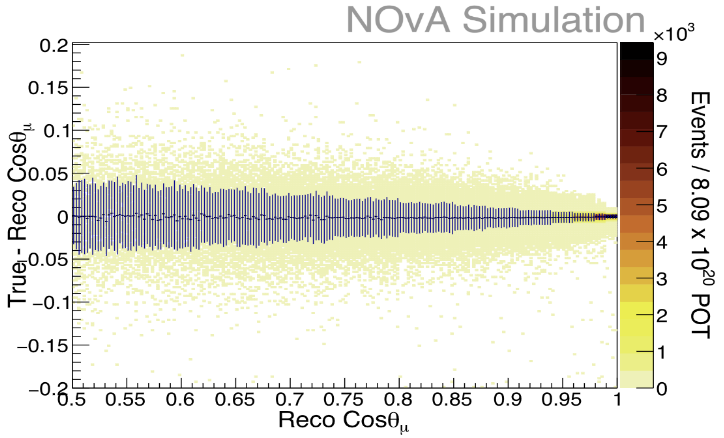
Neutrons
(shifted sample:
empirical => MENATE)

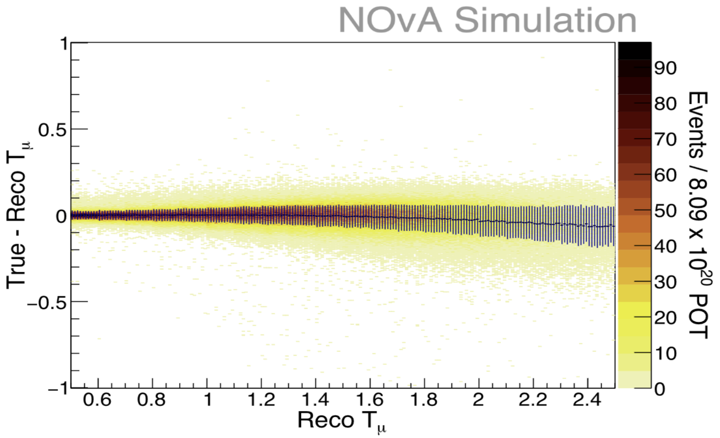
Detector Systematics
(shifted samples: calibration, light model, Cerenkov, aging)

Readout electronics & DAQ:
Custom simulation routines

Binning

Binning is determined considering resolution, statistical and systematic uncertainties



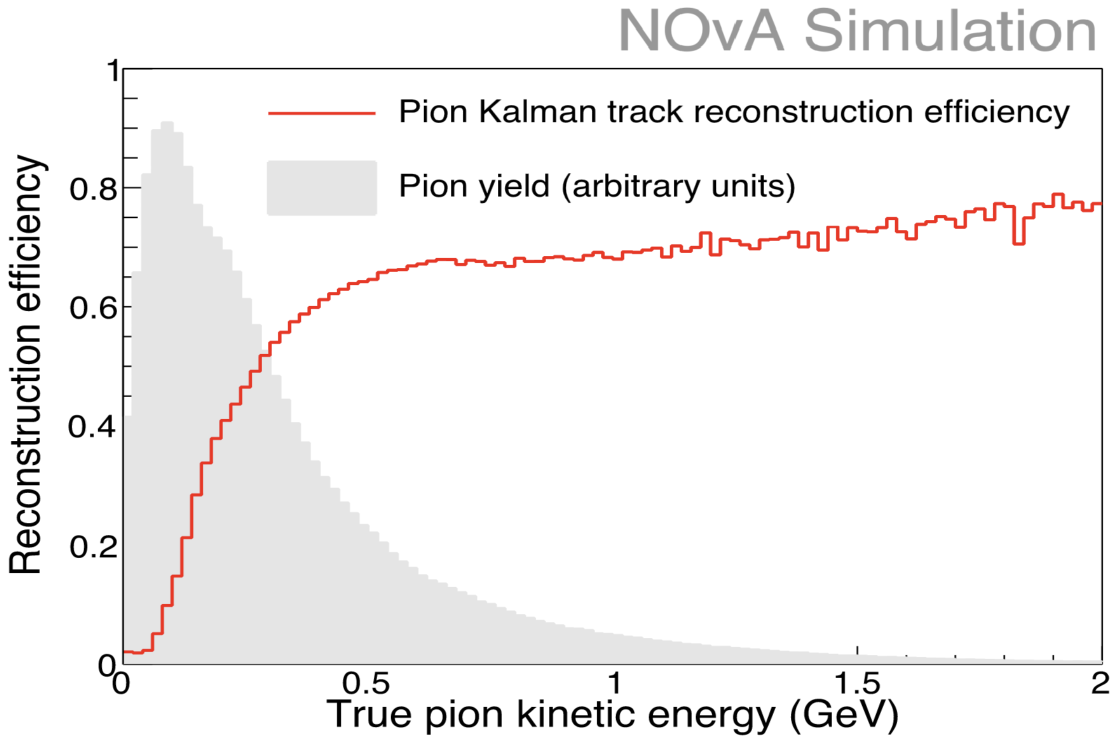


The muon energy is estimated by track length and has a resolution of approximately 4%

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

ν_μ Charged Current with Low Hadronic Energy

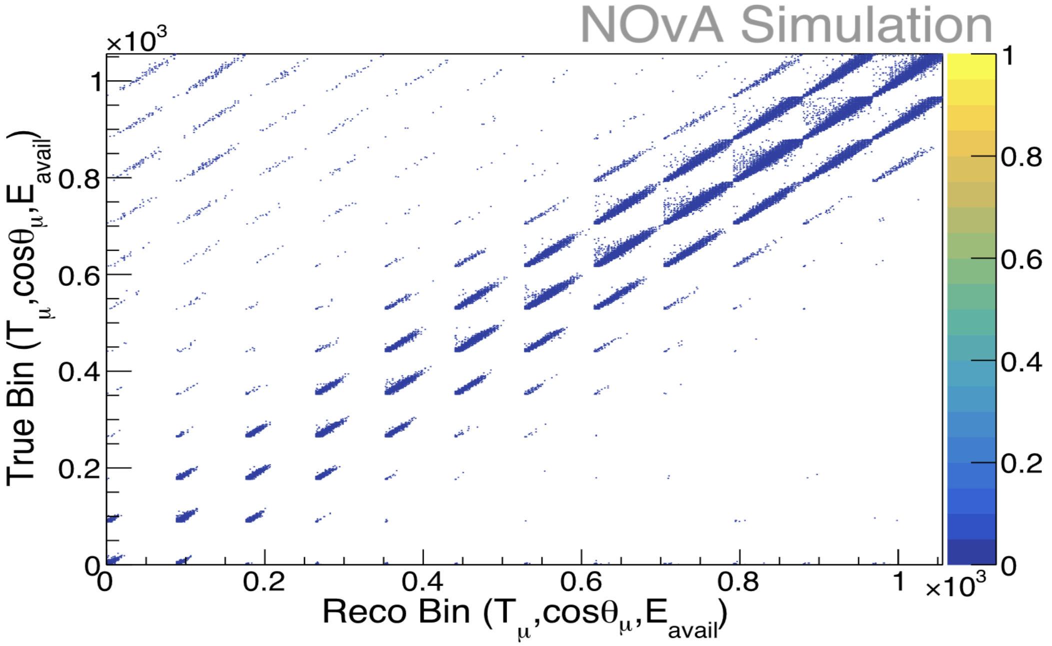
Pion reconstruction efficiency



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.



ν_μ Charged Current with Low Hadronic Energy

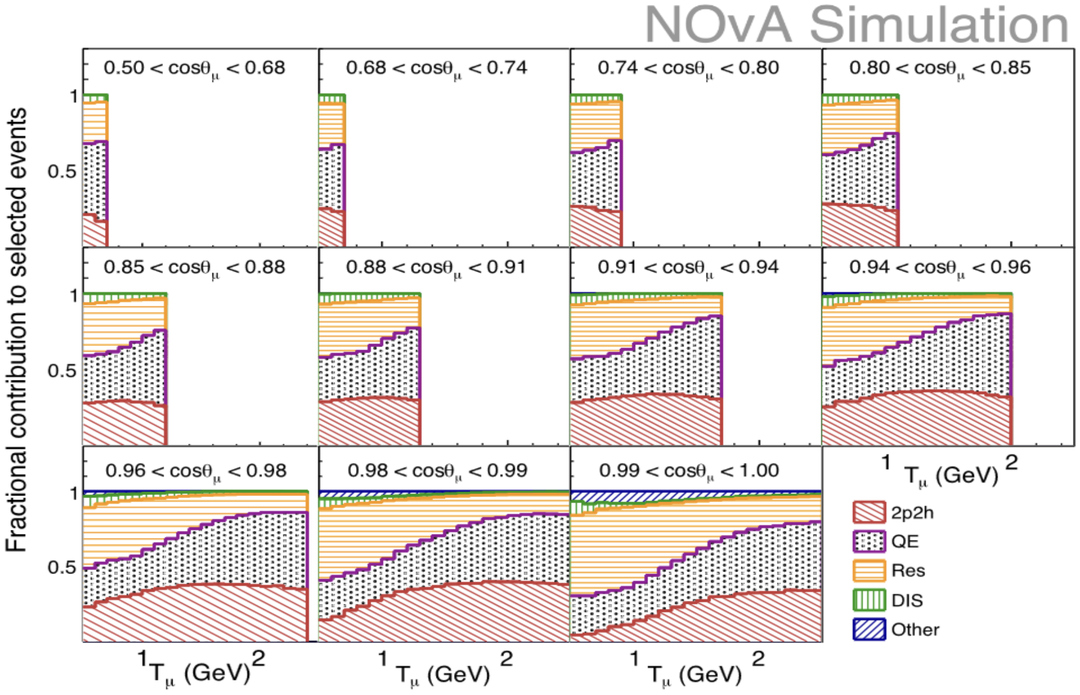
Selection by interaction modes

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%



Exploring 2p2h at NOvA (Leo Aliaga and Travis Olson) 28

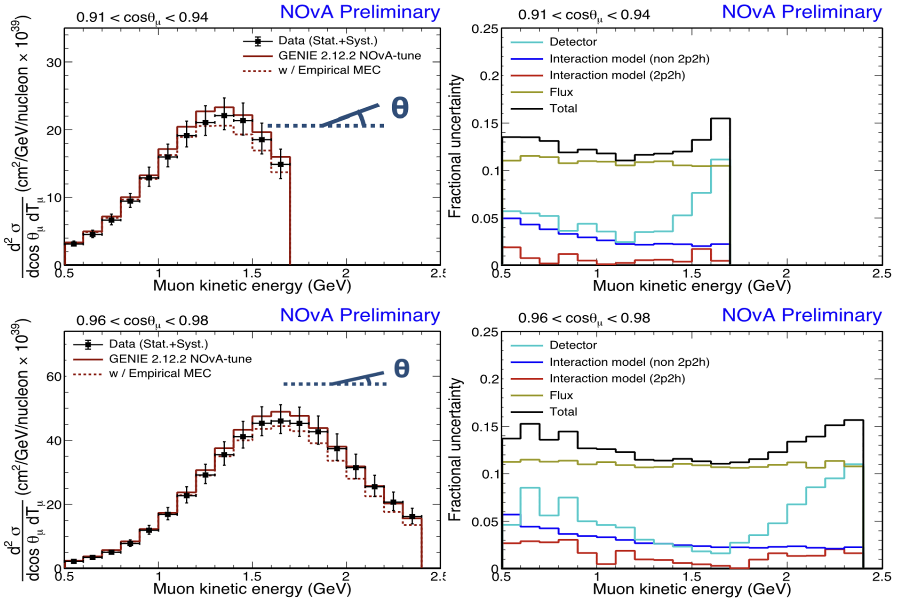
Public Analysis:

ν_μ Charged Current with Low Hadronic Energy

Leo Aliaga

Results: Muon Kinematics

2 cosine slice samples



Exploring 2p2h at NOvA (Leo Aliaga and Travis Olson) 38

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

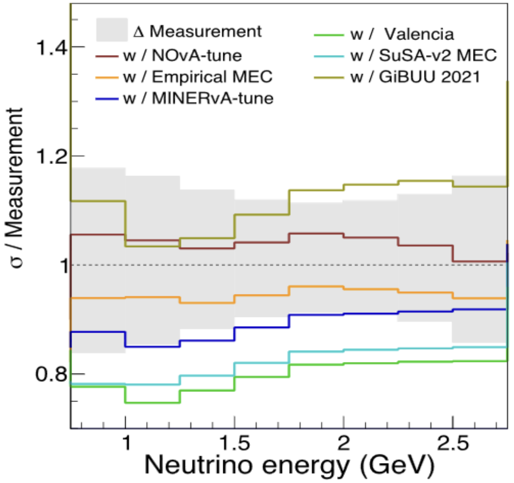
The **detector response** uncertainty comes from the calibration and the light model

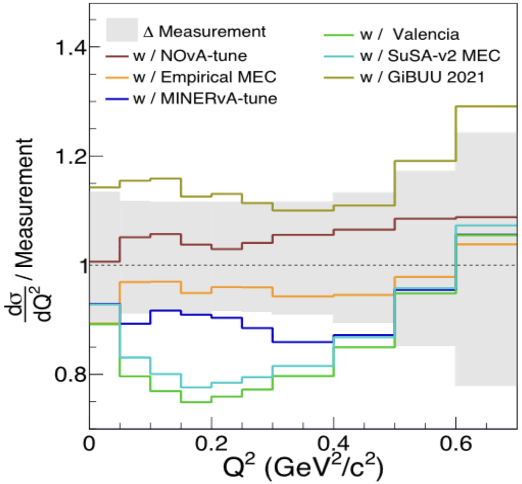
Results: E_ν and Q^2

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



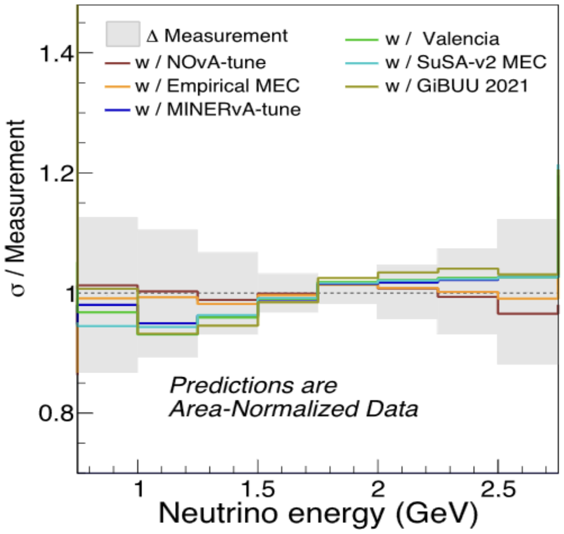


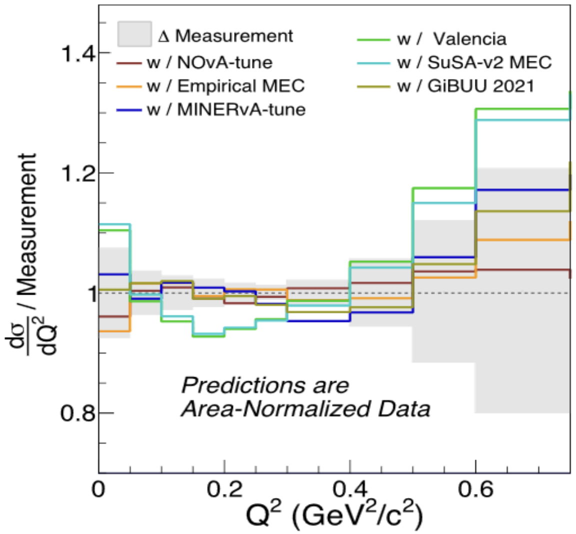
ν_μ Charged Current with Low Hadronic Energy

Leo Aliaga

Results: E_ν and Q^2

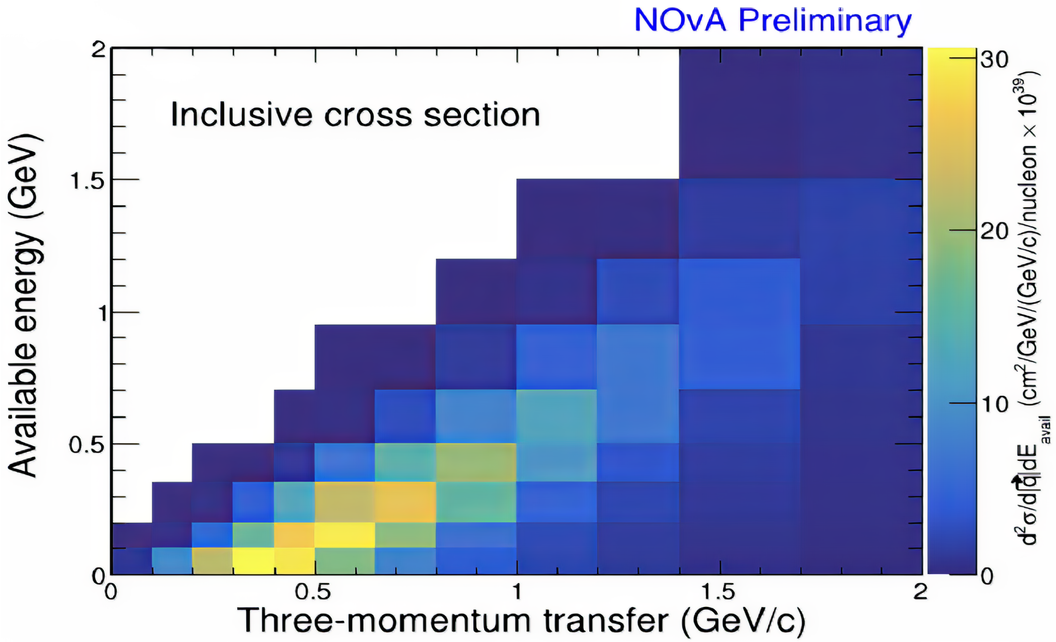
In the shape only comparison most of the models except Valencia and SuSAv2 follow the shape of our measurement





ν_μ Charged Current Inclusive and 2p2h estimation

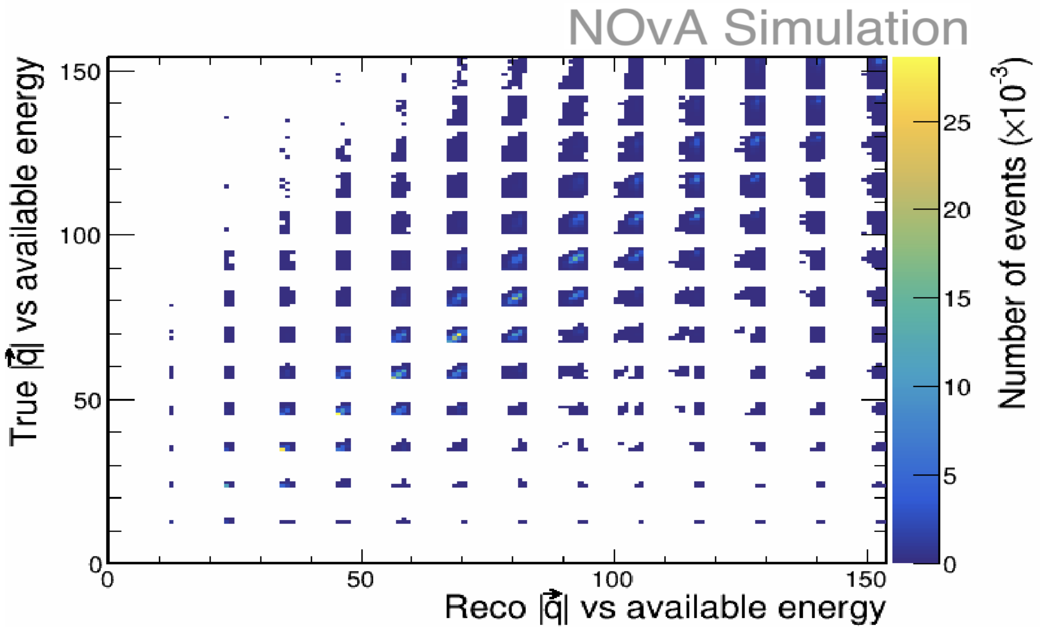
Results: Inclusive Cross section



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



Travis Olson

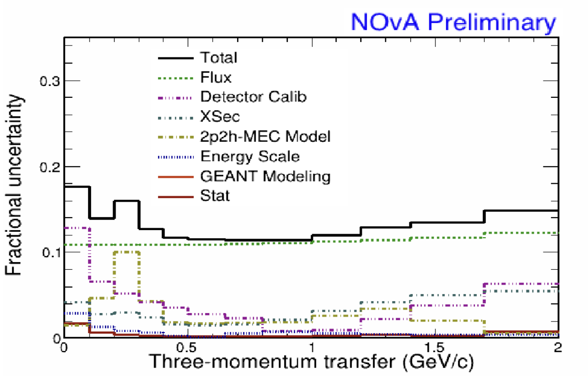
ν_μ Charged Current Inclusive and 2p2h estimation

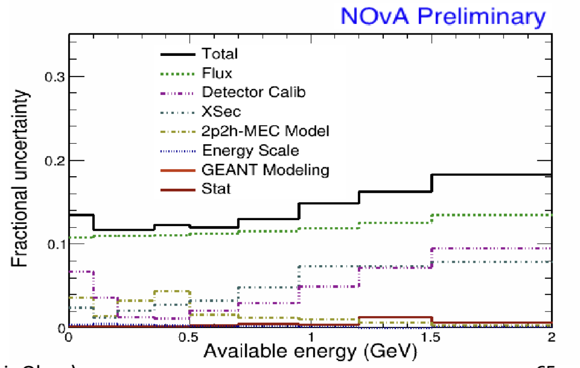
Cross-section Uncertainty:

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

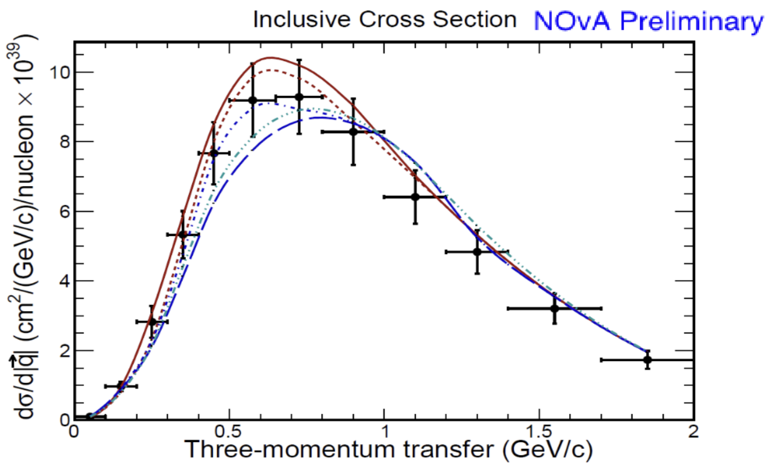


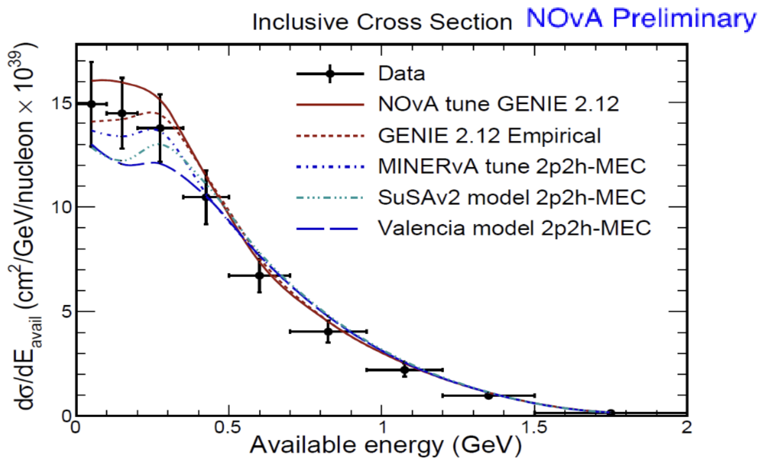


February 2, 2024 Exploring 2p2h at NOvA (Leo Aliaga and Travis Olson) 65

Results: Inclusive Cross Section

Data comparison with models:

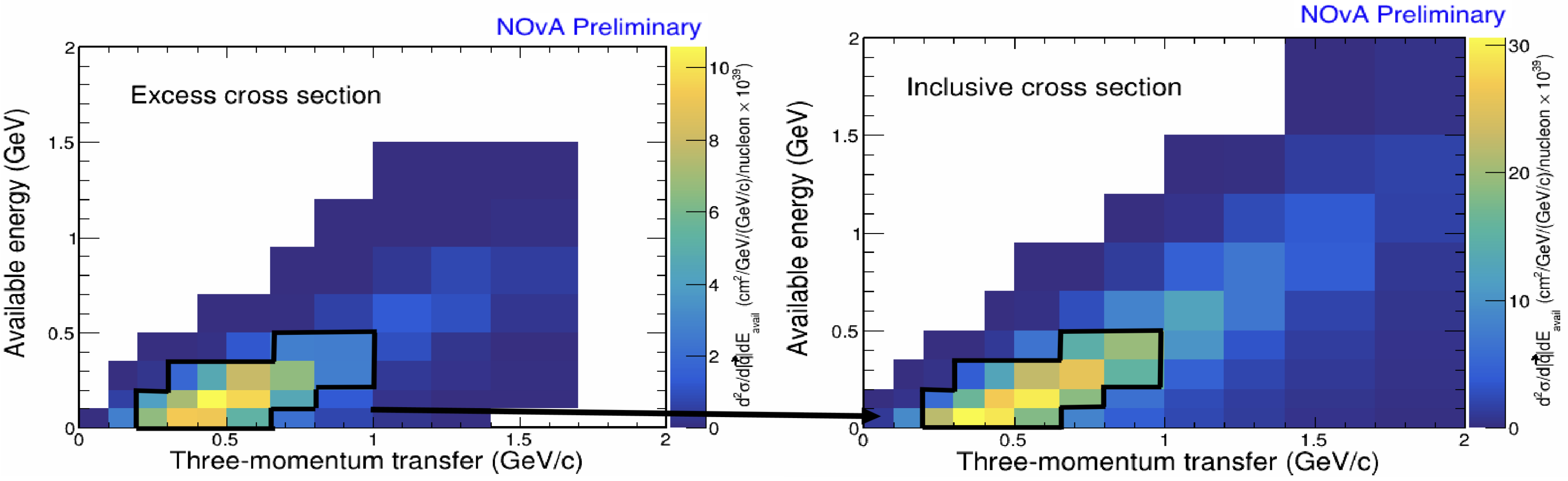




Better alignment with the data is obtained with NOvA tune and GENIE 2p2h than with theory-based models or the MINERvA tune.

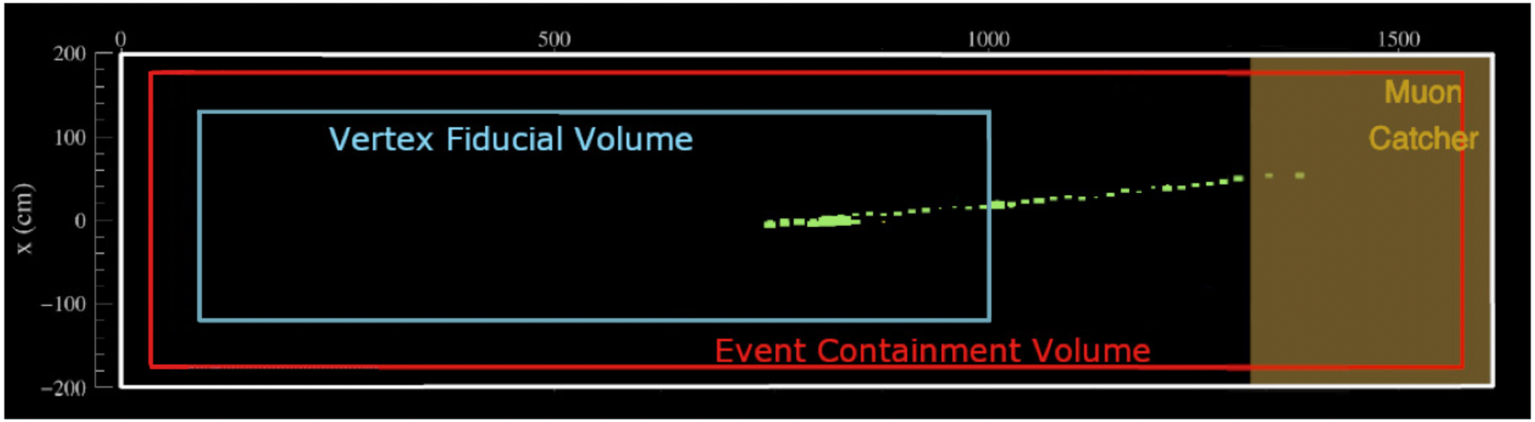
ν_μ Charged Current Inclusive and 2p2h estimation

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

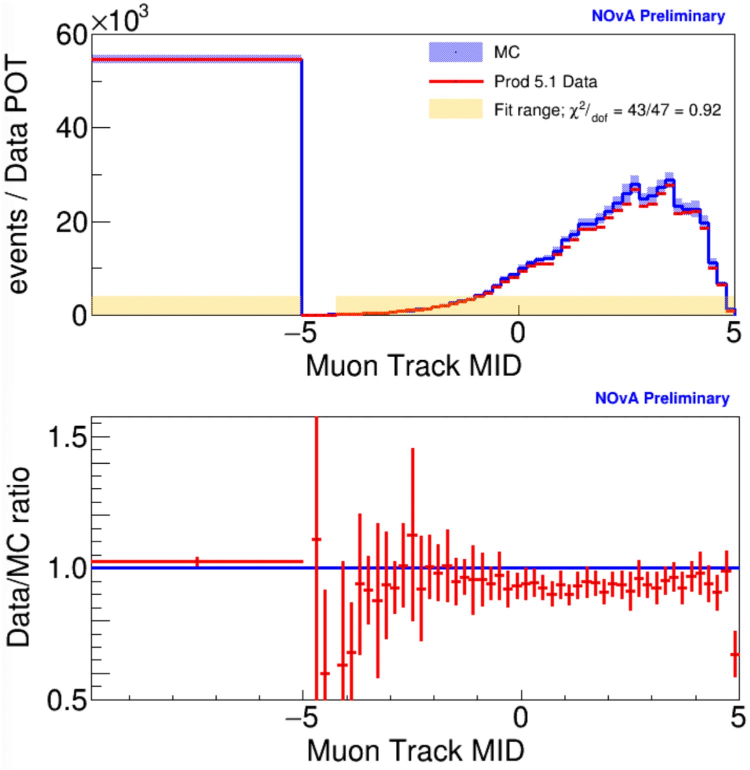


χ^2 now focuses on the 2p2h active region of the inclusive sample.

ν_μ CC Zero Mesons Selection: Containment



ν_μ CC Zero Mesons
Michel Electron ID (MID)



Validation of the ExMID simulation:

Data vs MC comparisons prod5.1

Selection: NuMu CC Inclusive selection

All histograms area-normalized (i.e. normalized to number of reco muons)

Shape-only (area normalized) covariance matrices used for the Chi square, considers Beam transport, Genie, PPFX, MENATE, Geant4 and Detector Systematics.

Bins with less than 100 entries excluded from fit