Measurement of Inclusive Antineutrino Cross-sections in 3.5 GeV and 6 GeV Antineutrino Beams and Neutrino Counterparts in Neutrino Beams

Maria Mehmood on behalf of the MINERvA Collaboration

June 2026

On the Horizon …

The next generation of long-baseline neutrino oscillation experiments:

- **Require a high precision understanding of <u>neutrino-nucleus interactions</u>**

On the Horizon …

The next generation of long-baseline neutrino oscillation experiments:

- **Require a high precision understanding of <u>neutrino-nucleus interactions</u>**

- The MINERvA experiment at Fermilab was designed to provide this by making **<u>cross-section measurements</u>** → Used to tune cross-section models

On the Horizon …

The next generation of long-baseline neutrino oscillation experiments:

- **Require a high precision understanding of <u>neutrino-nucleus interactions</u>**

- The MINERvA experiment at Fermilab was designed to provide this by making **<u>cross-section measurements</u>** → Used to tune cross-section models

- **Cross section:** A measure of the probability of an interaction occurring

  # of Interactions = Cross-section * Flux * # of Targets

The Incident Neutrino Flux

The next generation of long-baseline neutrino oscillation experiments:

- **Will be sensitive to different fluxes (one oscillated and one not)**

The Incident Neutrino Flux

The next generation of long-baseline neutrino oscillation experiments:

- **Will be sensitive to different fluxes (one oscillated and one not)**
- **Cross-section models must be robust at modeling interactions for different fluxes**

A benchmark for tuning cross-section models:

The Incident Neutrino Flux

The next generation of long-baseline neutrino oscillation experiments:

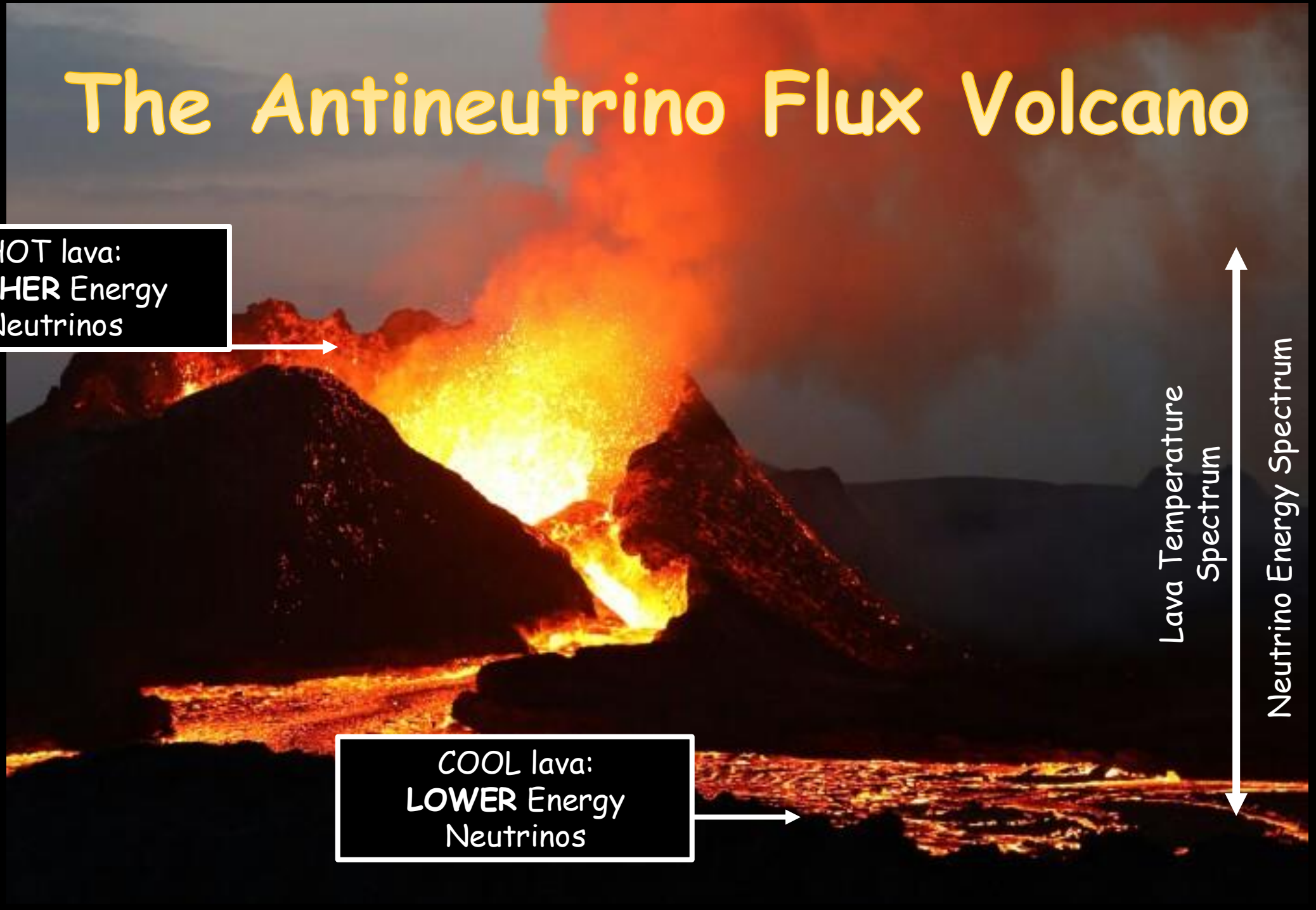
- **Will be sensitive to different fluxes (one oscillated and one not)**
- **Cross-section models must be robust at modeling interactions for different fluxes**

A benchmark for tuning cross-section models:

- Use **IDENTICAL** detector technology, simulation, and measurement extraction procedures while the **flux varies** to extract the cross-section measurement

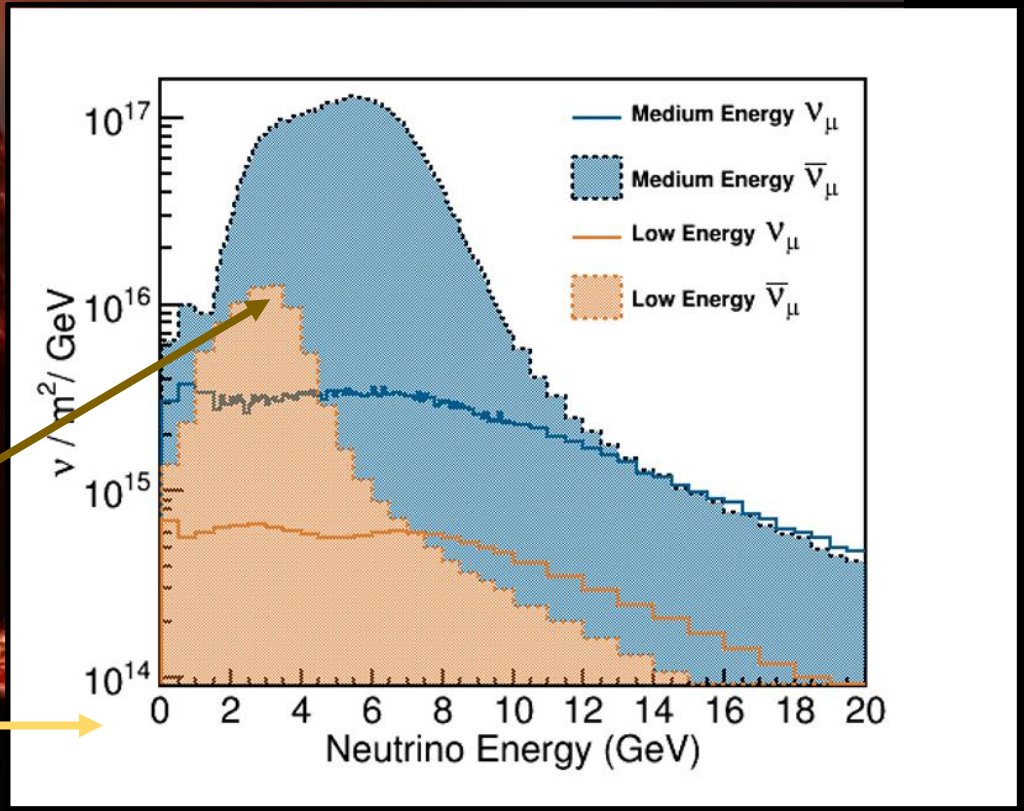
The Incident Flux: The NuMI Beamline at Fermilab

The Antineutrino Flux Volcano



The Antineutrino Flux Volcano

HOT lava:
HIGHER Energy
Neutrinos



MINERvA's
Low Energy Flux
Peaks at 3.5 GeV

COOL lava:
LOWER Energy
Neutrinos

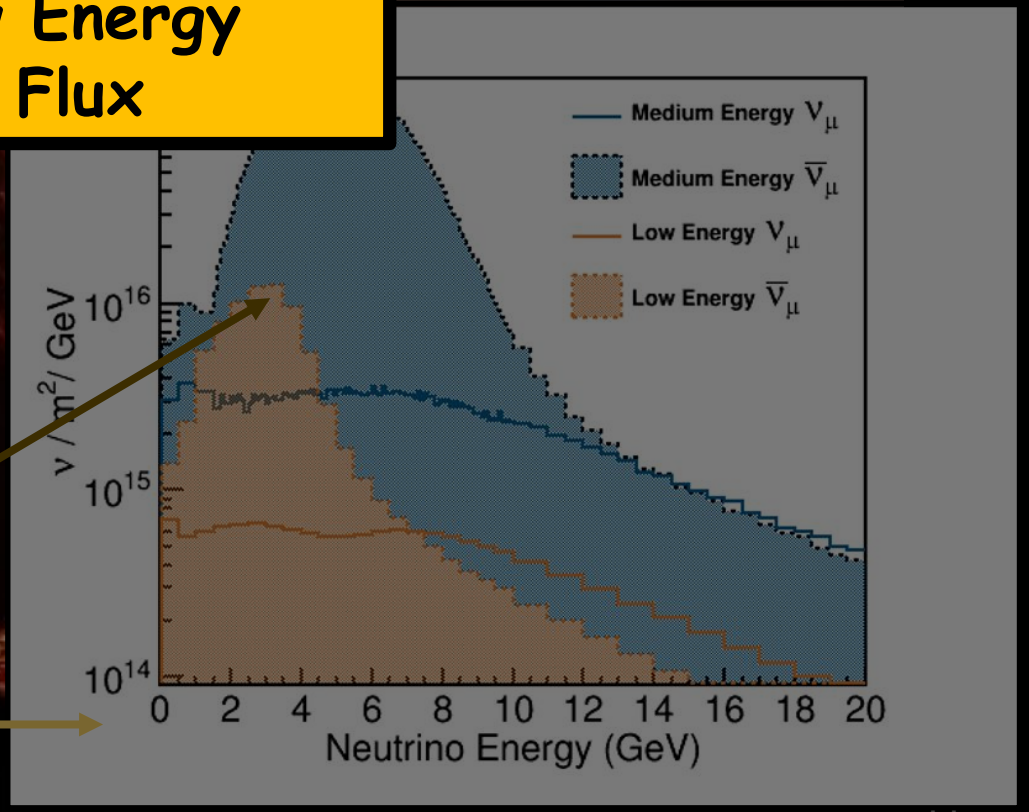
The Antineutrino Flux Volcano

HOT lava:
HIGHER Energy
Neutrinos

Goal: Measure the antineutrino inclusive cross section using **MINERvA's Low Energy Antineutrino Flux**

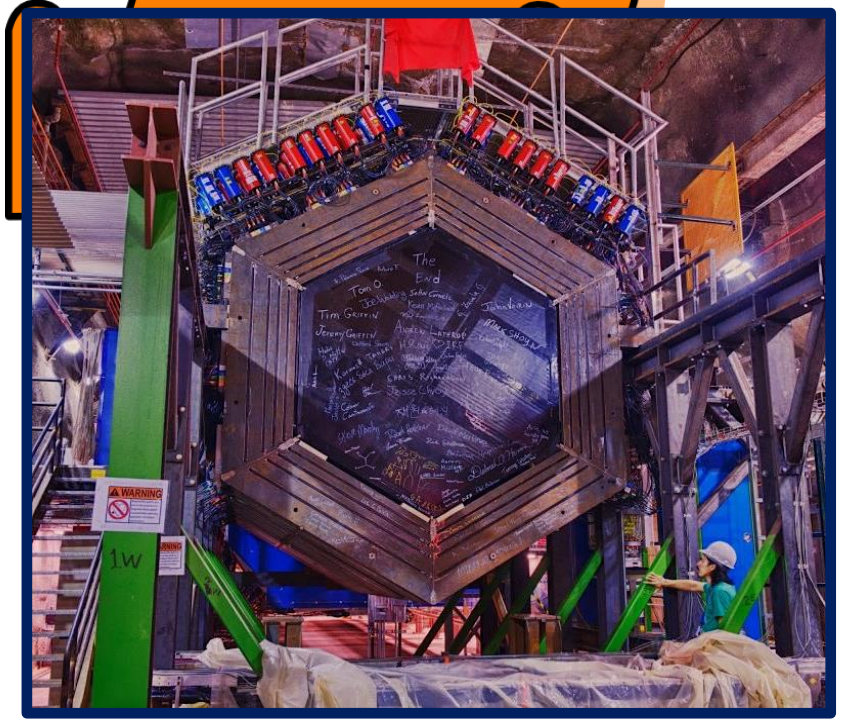
MINERvA's
Low Energy Flux
Peaks at 3.5 GeV

COOL lava:
LOWER Energy
Neutrinos



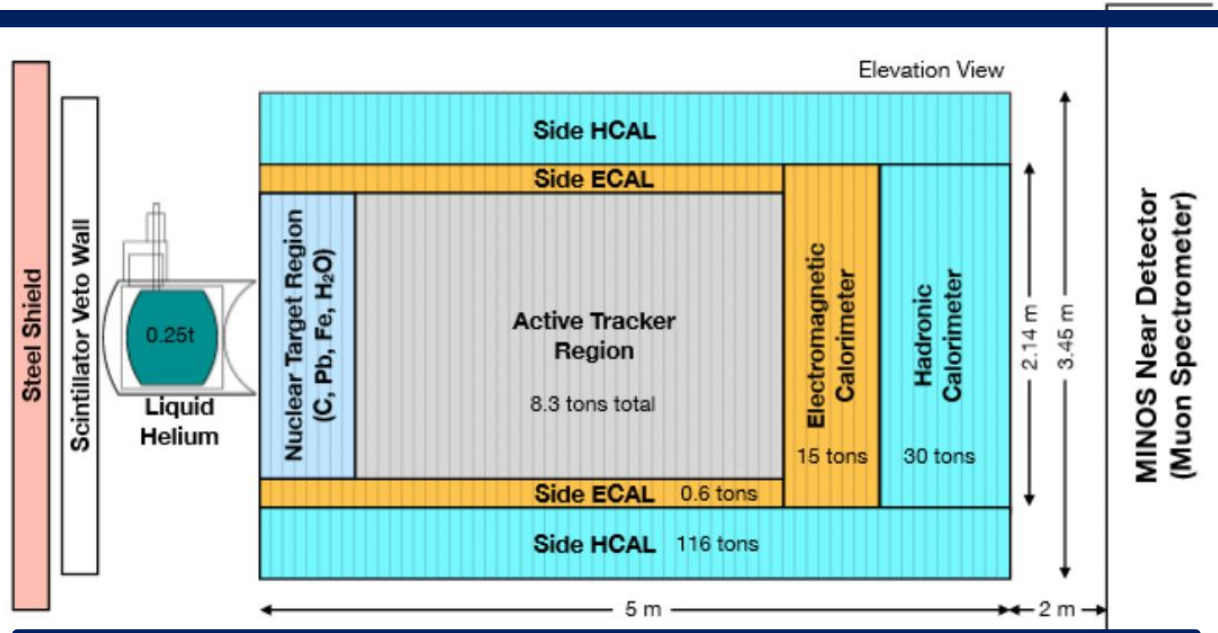
1. Antineutrinos and the MINERvA Experiment

Place the MINERvA Detector in the beamline

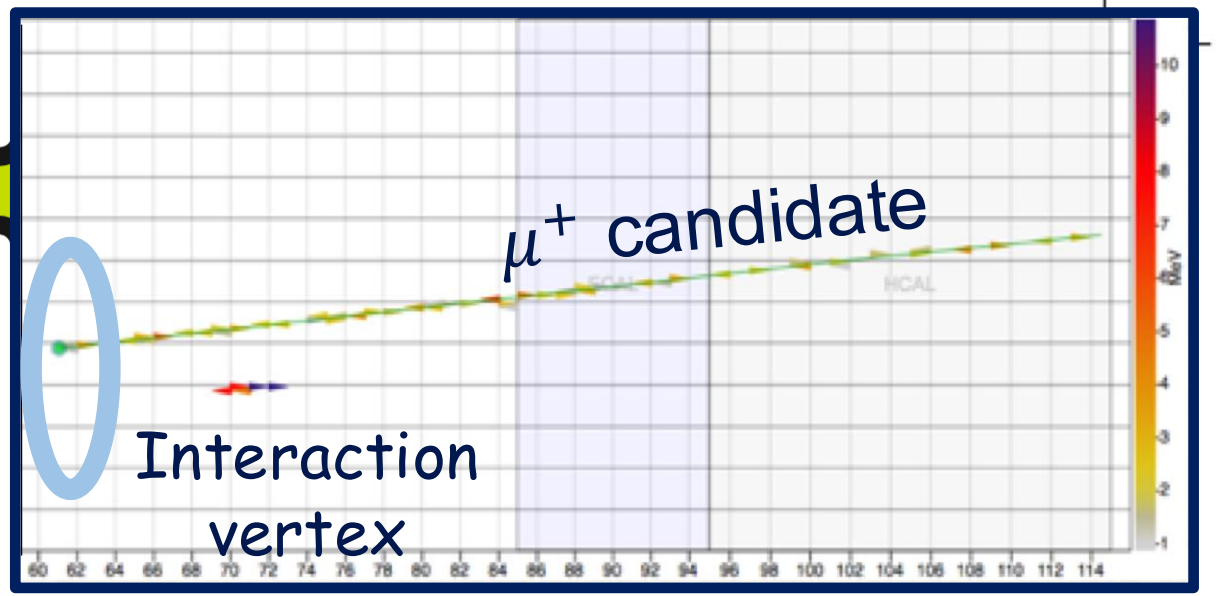


The MINERvA Detector, front face view of module

The MINERvA detector sideview. Segmented with target planes and interspersed with scintillator planes



Use energy deposits in the detector to reconstruct events

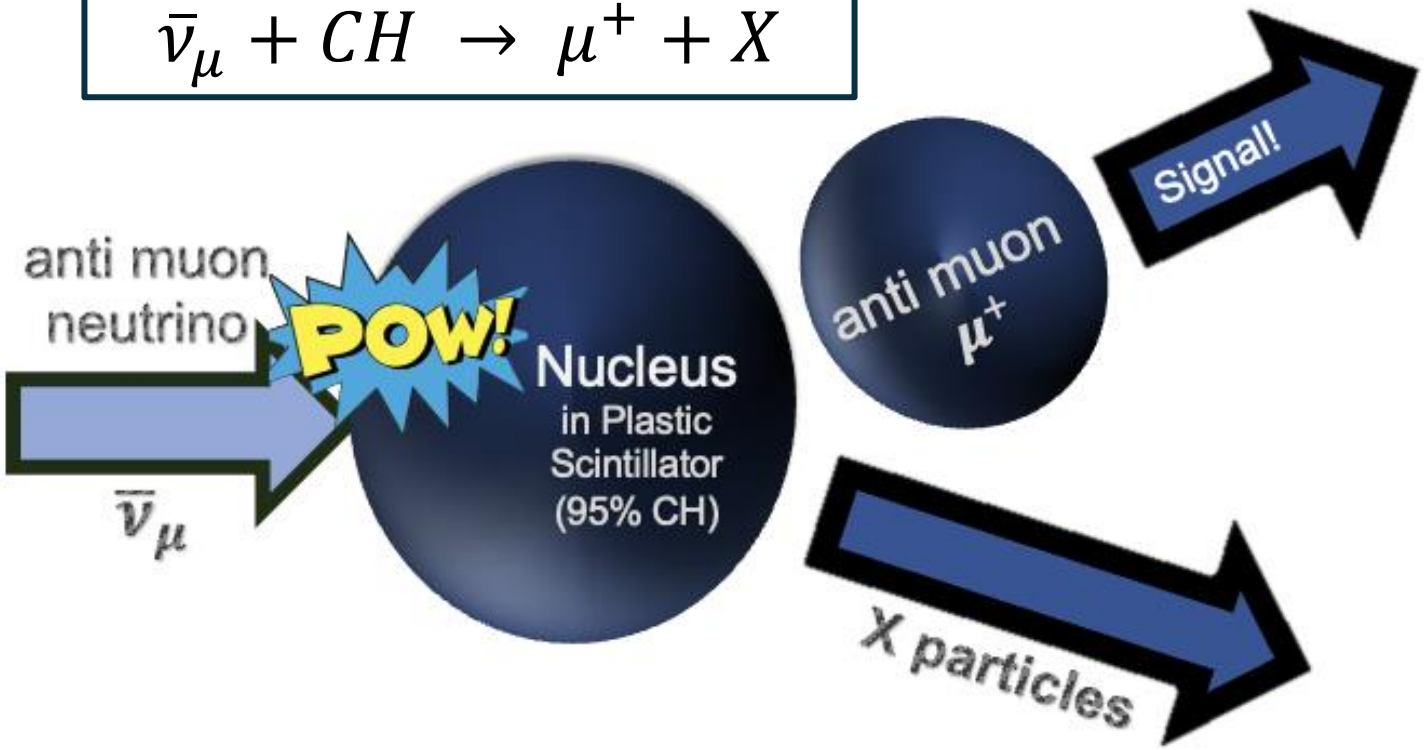


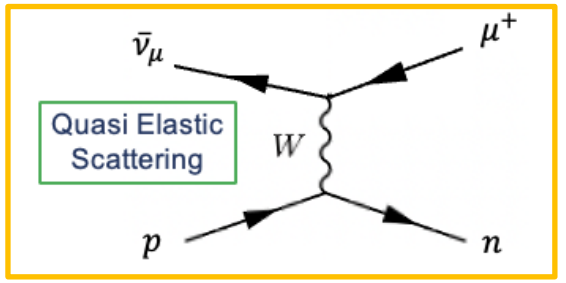
Maria Mehmood, YorkU

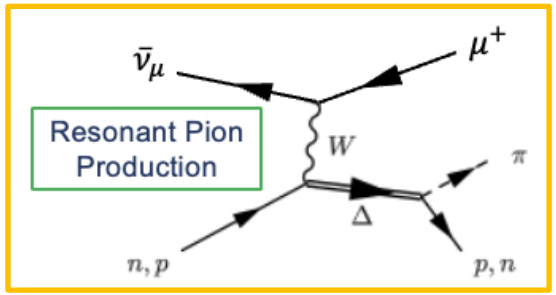
2. What is this analysis about?

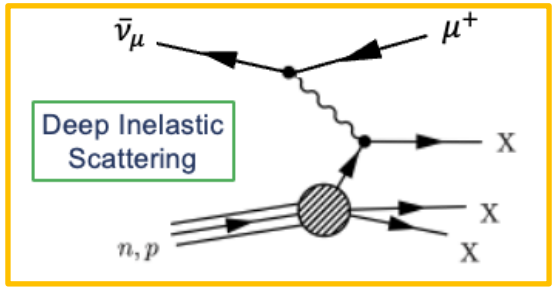
- **Goal:** Extract antineutrino (and neutrino) two-dimensional **cross sections** in the tracker in terms of muon transverse and longitudinal momenta
- Antineutrino inclusive cross section:

$$\bar{\nu}_\mu + CH \rightarrow \mu^+ + X$$







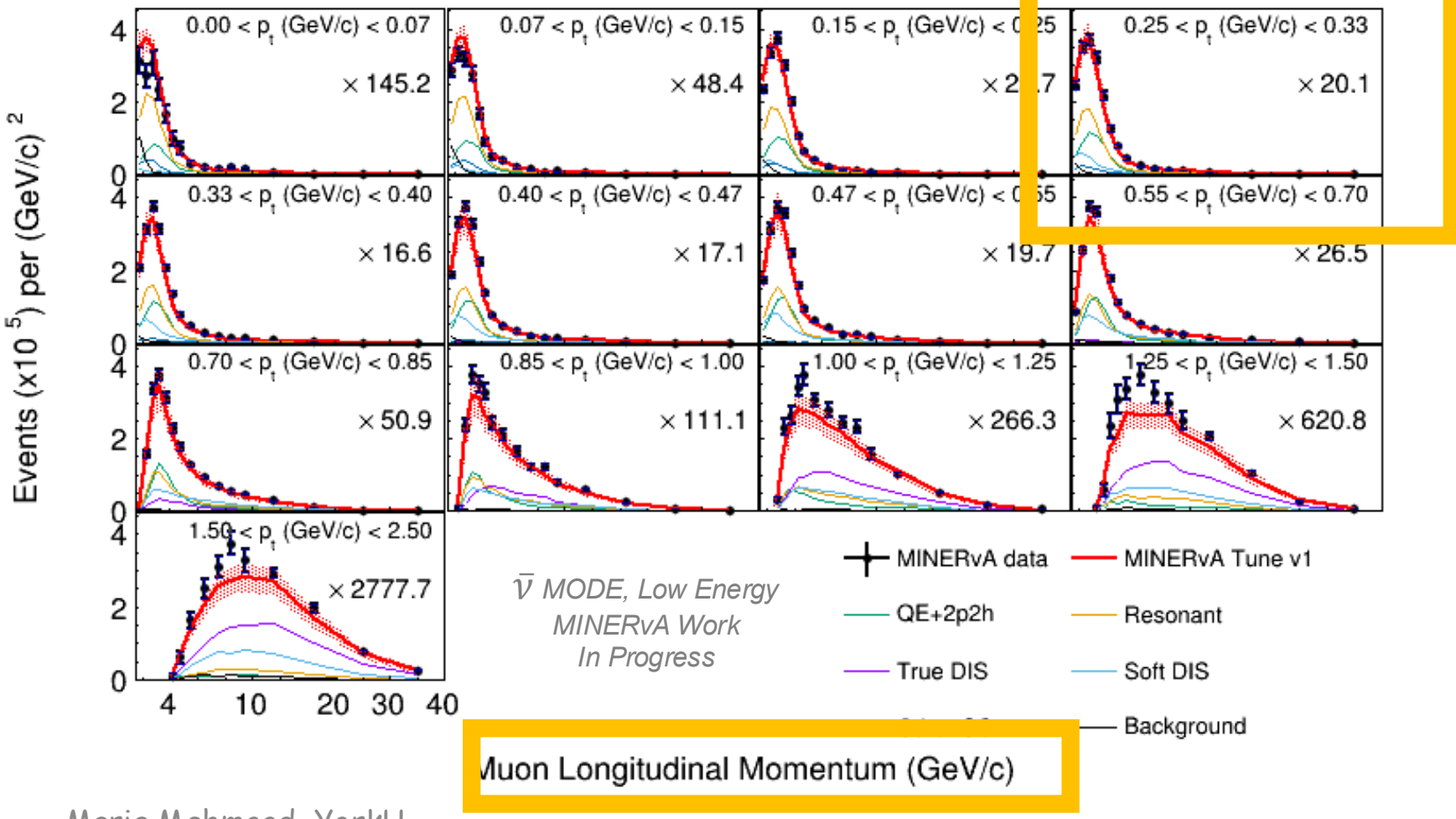


Different amounts of energy and momentum transferred to nucleus.

All interactions that **produce an anti muon** are **considered signal!**

2. What is this analysis about?

- **Reconstructed Events**



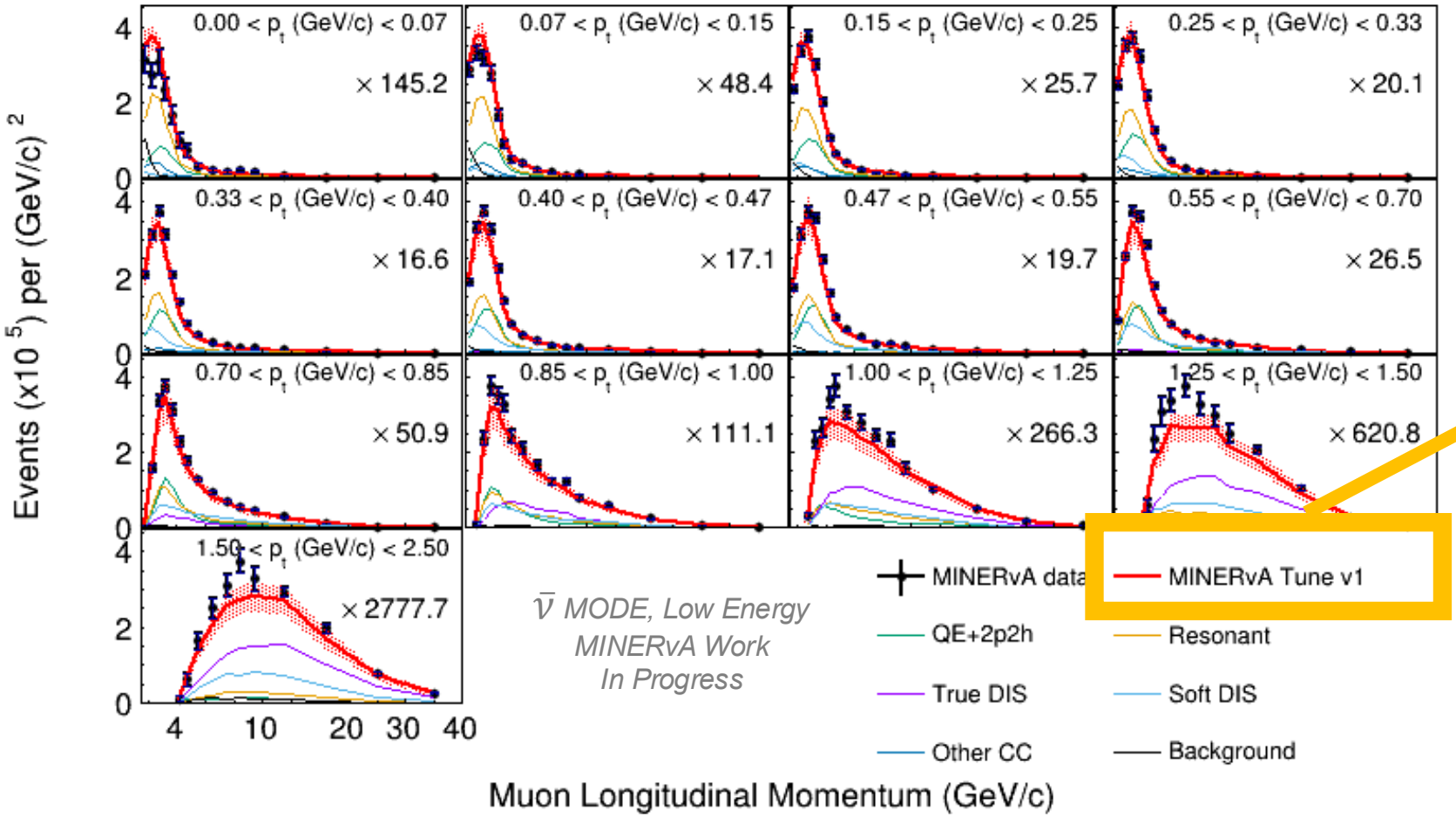
Example of muon transverse momentum bin on the PANEL PLOT!

Two-dimensional analysis in terms of transverse and longitudinal muon momenta

Muon kinematics proxy for neutrino energy and momentum transferred
→ Good resolution + Less Model dependence

2. What is this analysis about?

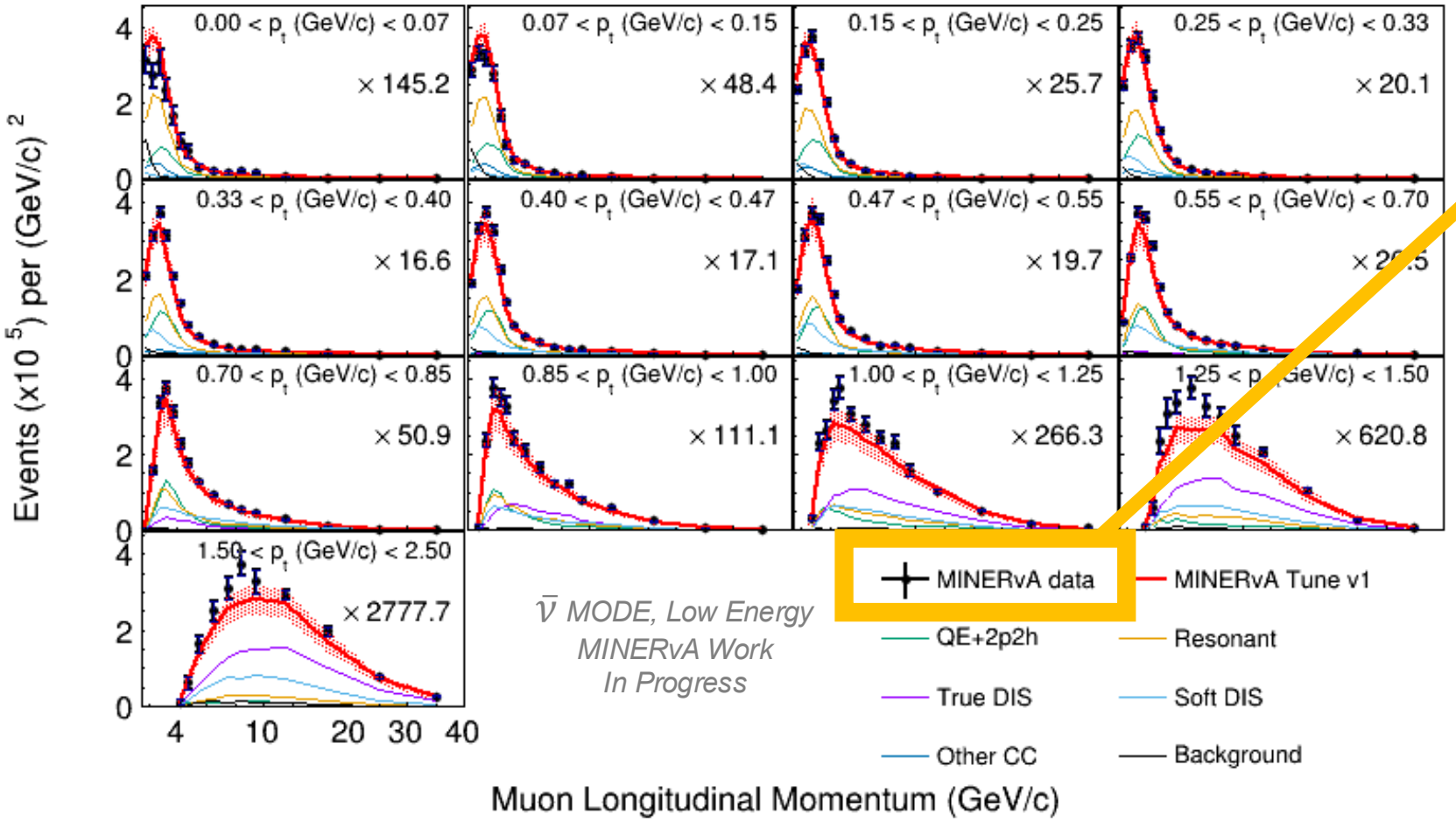
- **Reconstructed Events**



Collection of models used to generate events, same models will be used to predict the cross section

2. What is this analysis about?

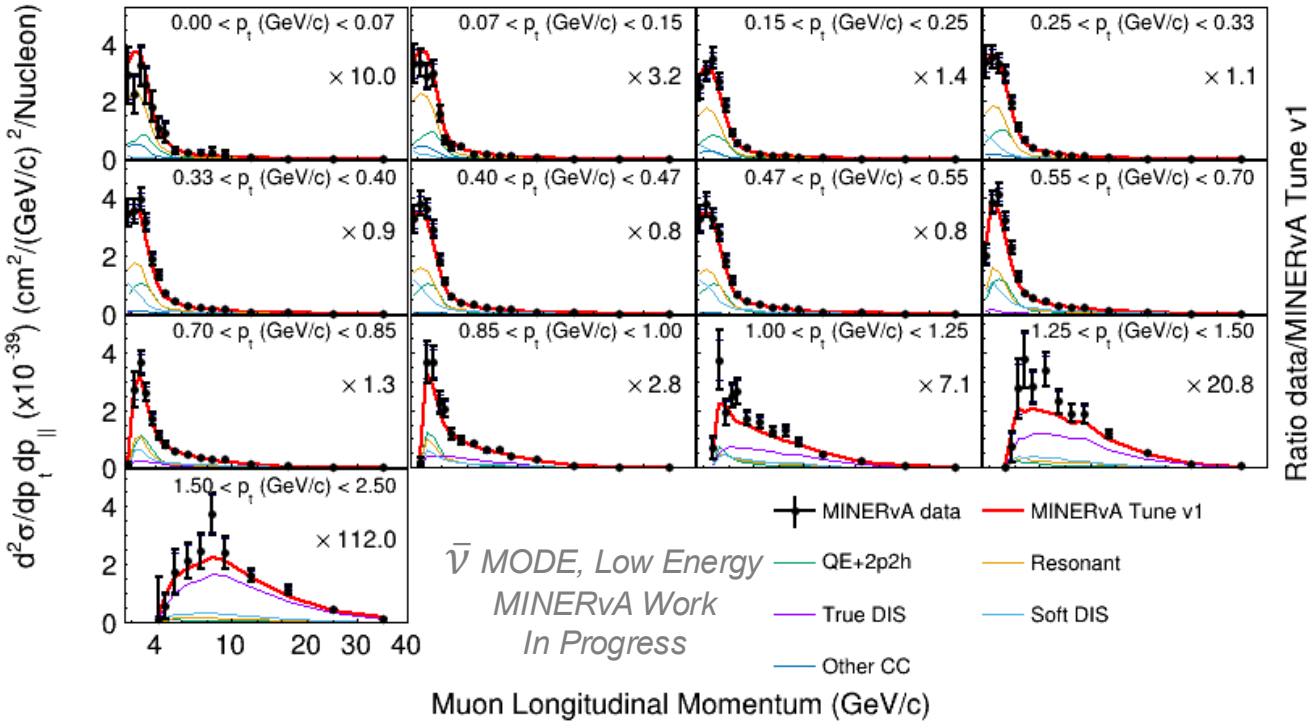
- **Reconstructed Events**

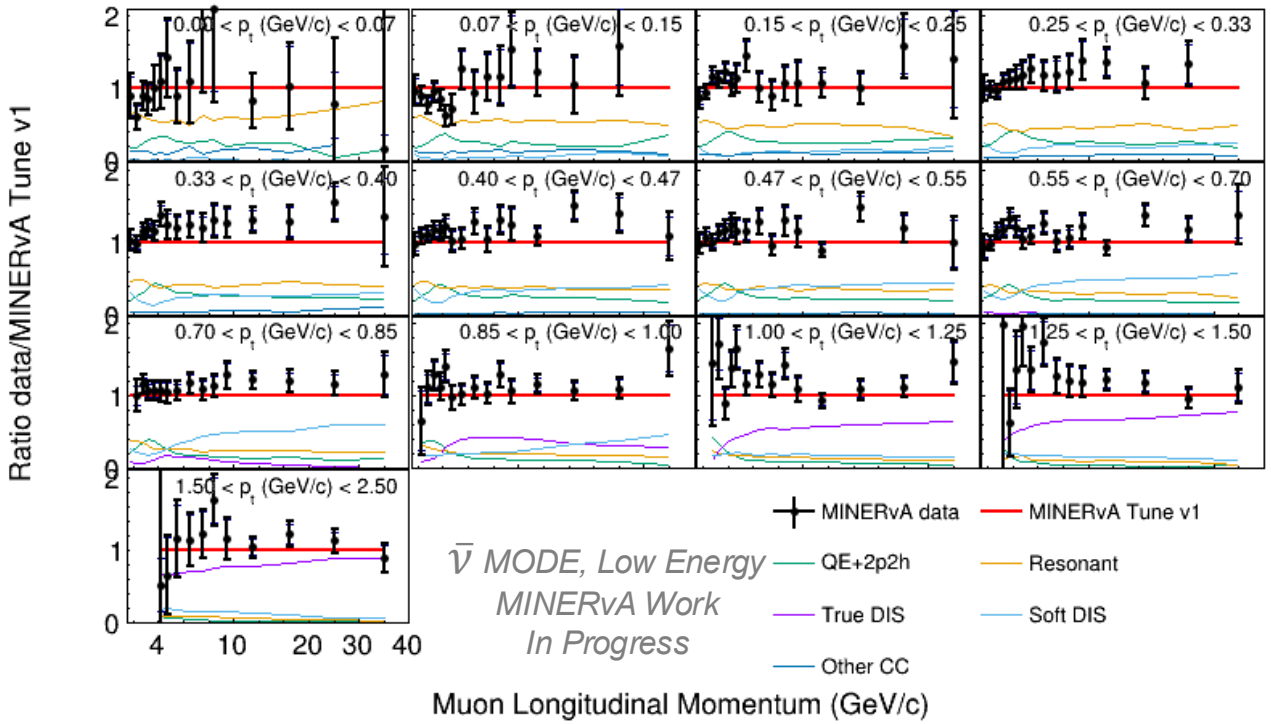


41 961
data events reconstructed

Antineutrino Cross Section Measurement

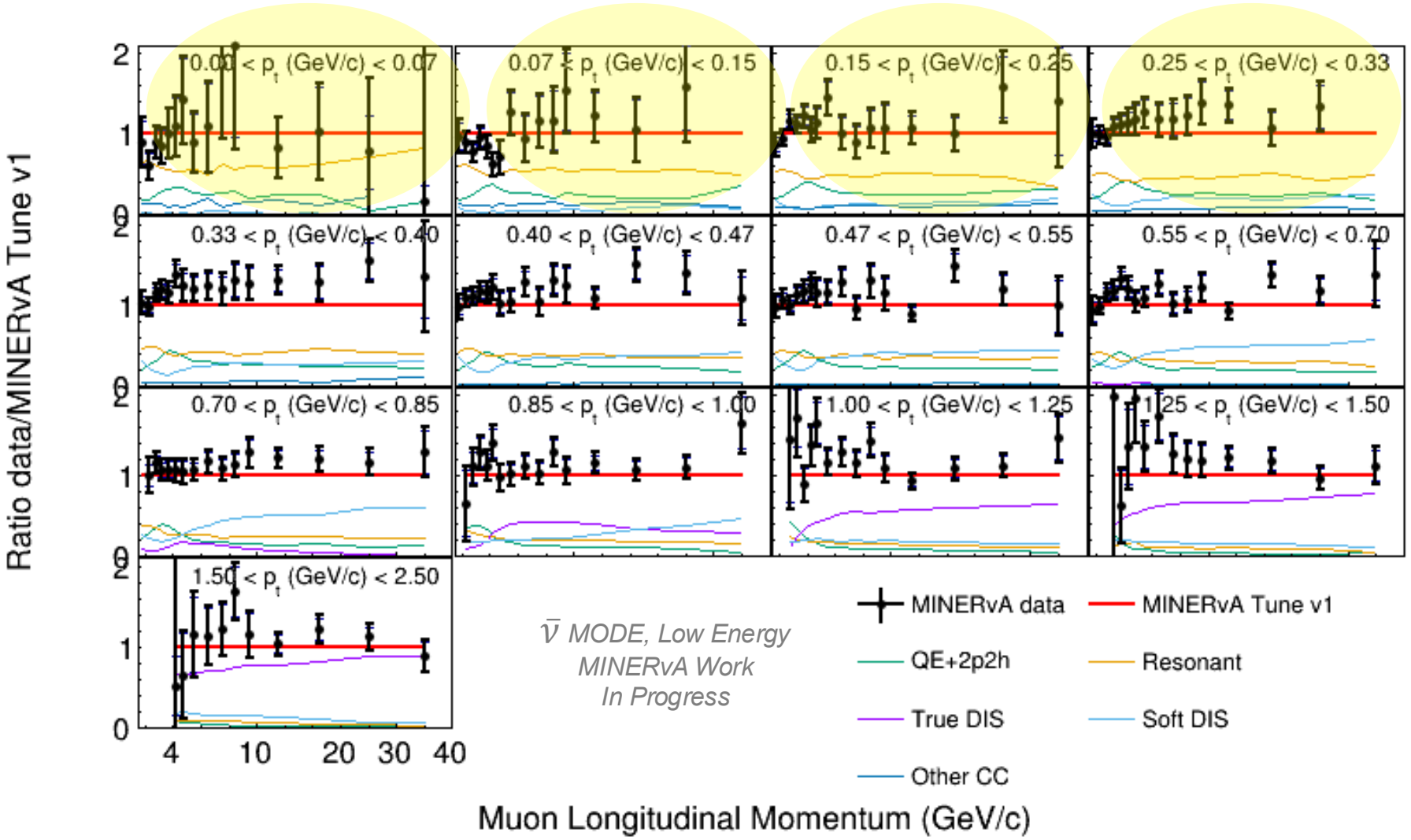
- Low Energy Beam (flux peaks at 3.5 GeV)
- Inclusive cross section shown with predicted breakdown by interaction channel





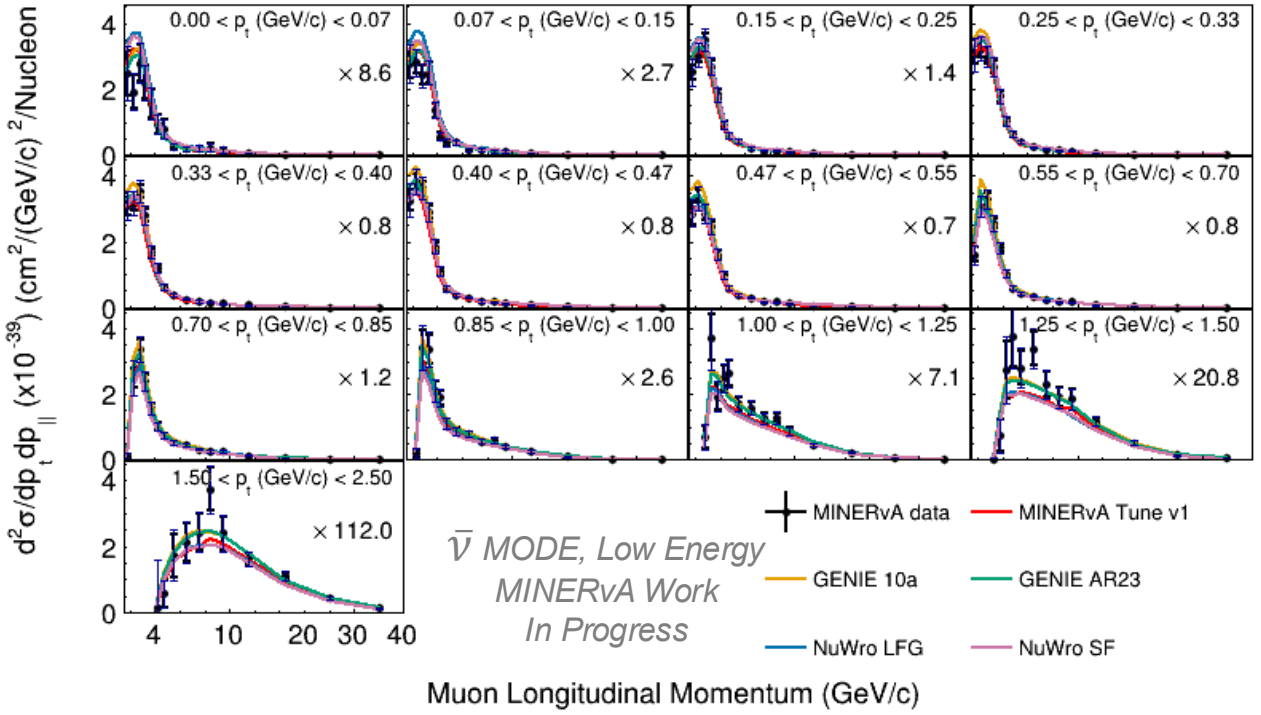
Antineutrino Cross Section Measurement

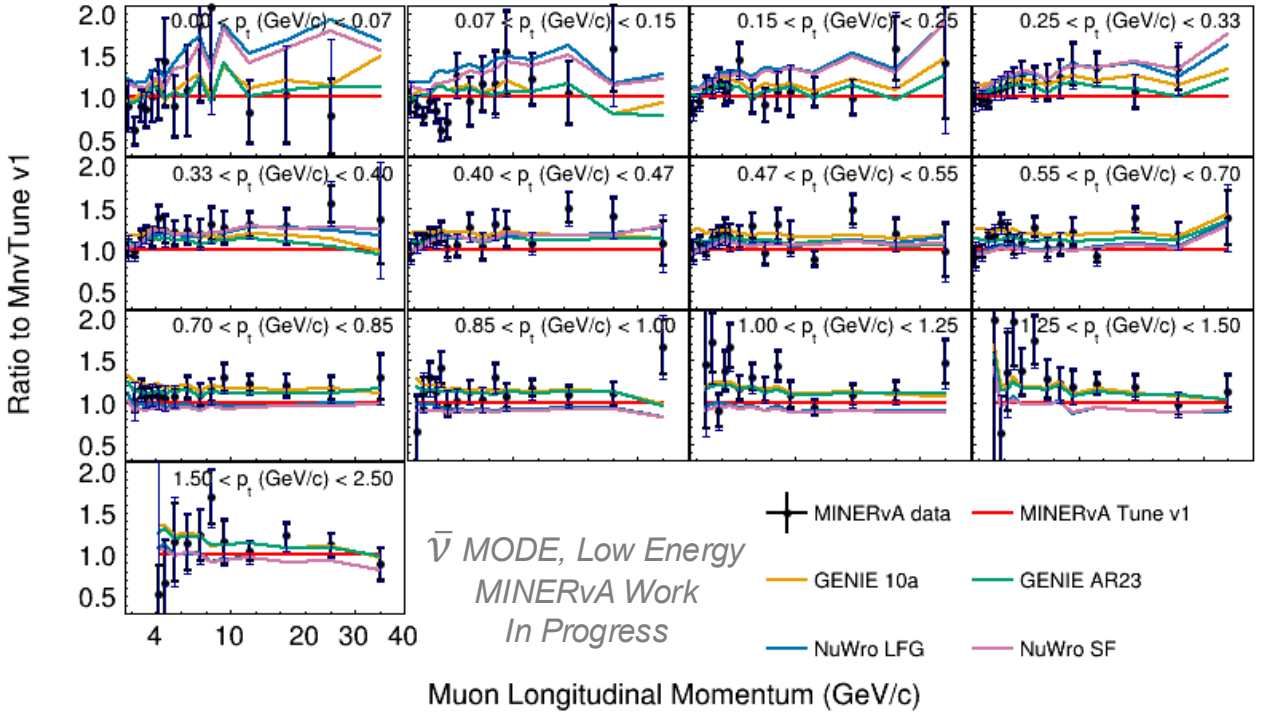
- Low Energy Beam (flux peaks at 3.5 GeV)
- In lowest pt bins, resonant and QE+2p2h dominate → Motivation for improving modeling of those interaction channels



Antineutrino Cross Section Measurement

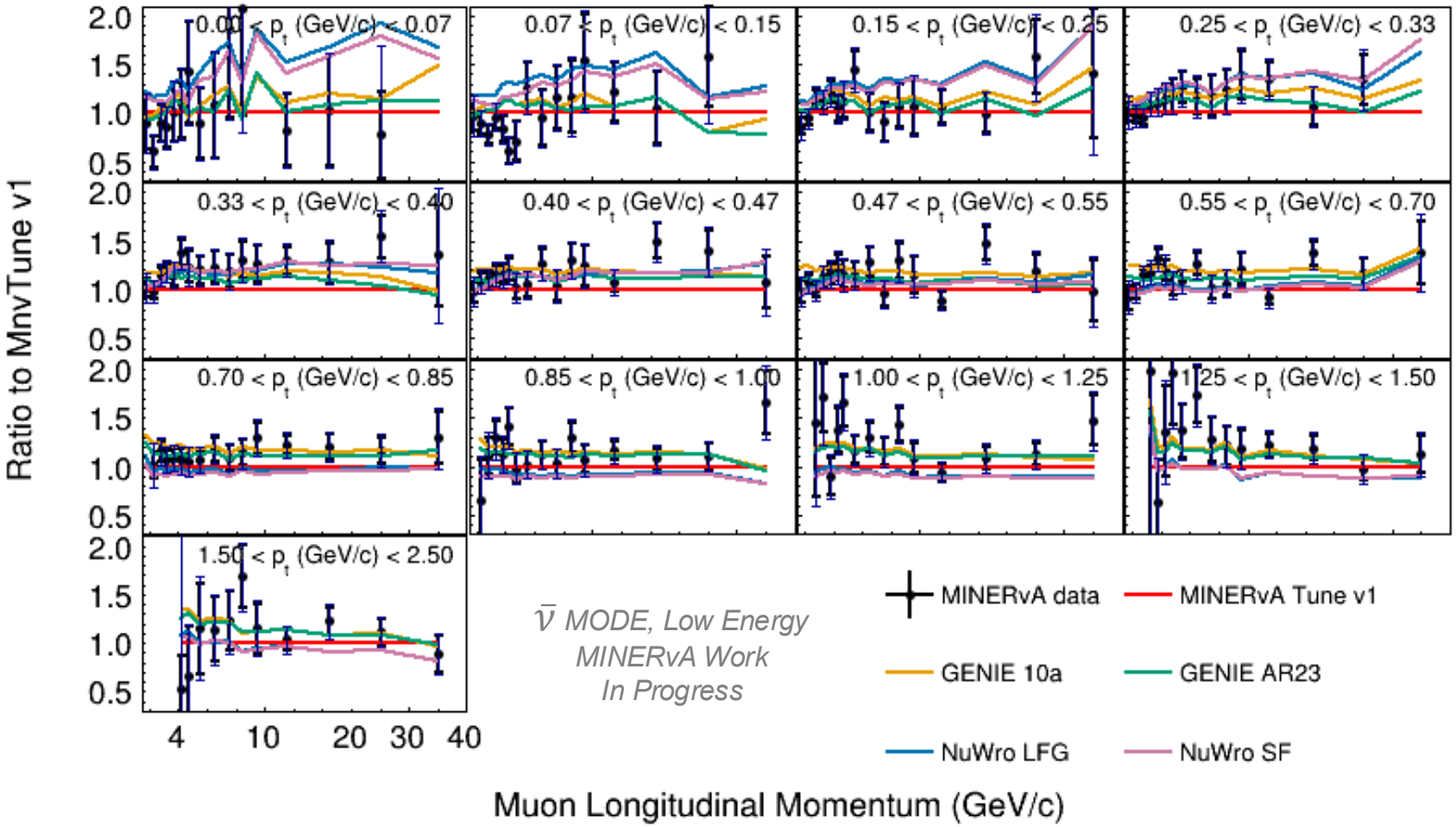
- Low Energy Beam (flux peaks at 3.5 GeV)
- Inclusive cross section shown with model predictions from various event generators





Antineutrino Cross Section Measurement

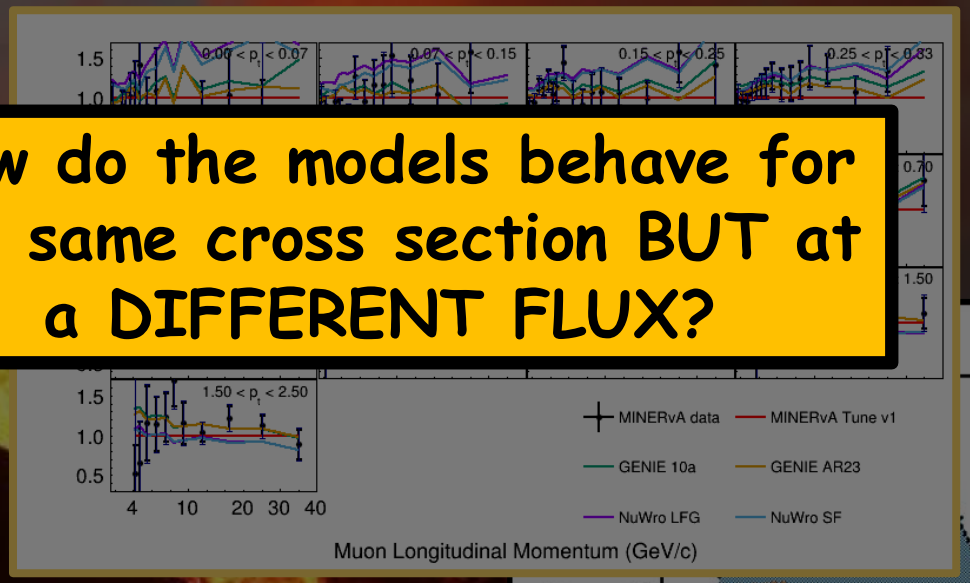
- Low Energy Beam (flux peaks at 3.5 GeV)
- Greater spread in the models at low muon pt which is sensitive to resonant interactions

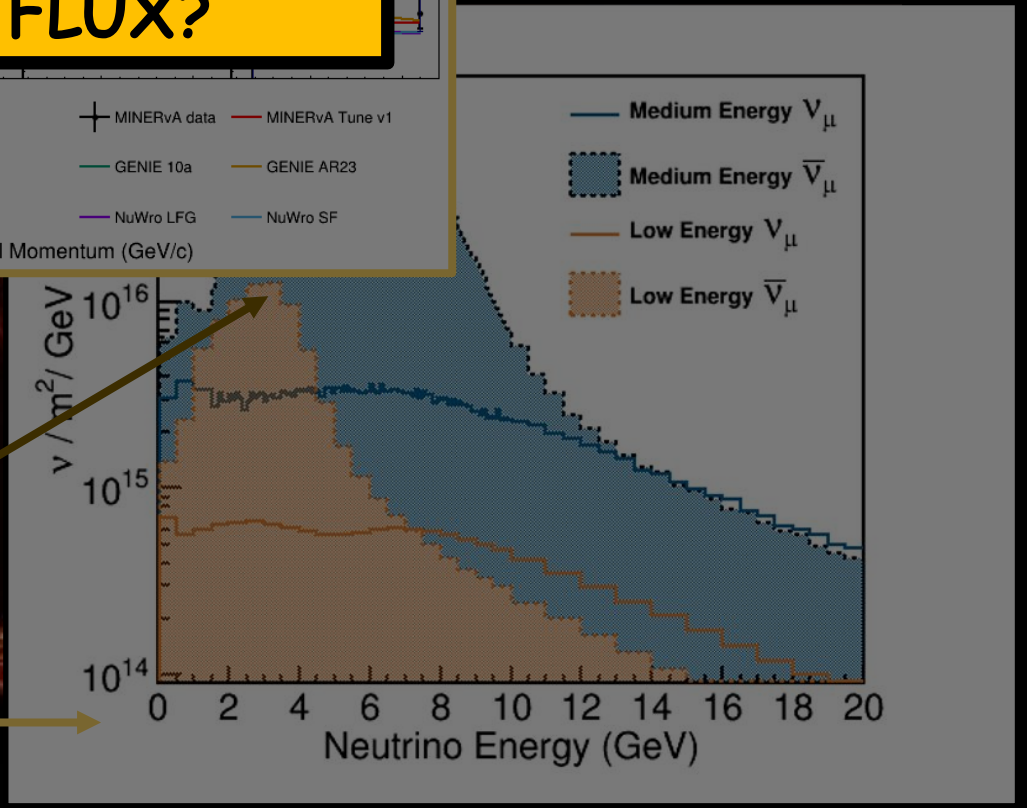


The Antineutrino Flux Volcano

HOT lava:
HIGHER Energy
Neutrinos

How do the models behave for the same cross section BUT at a DIFFERENT FLUX?



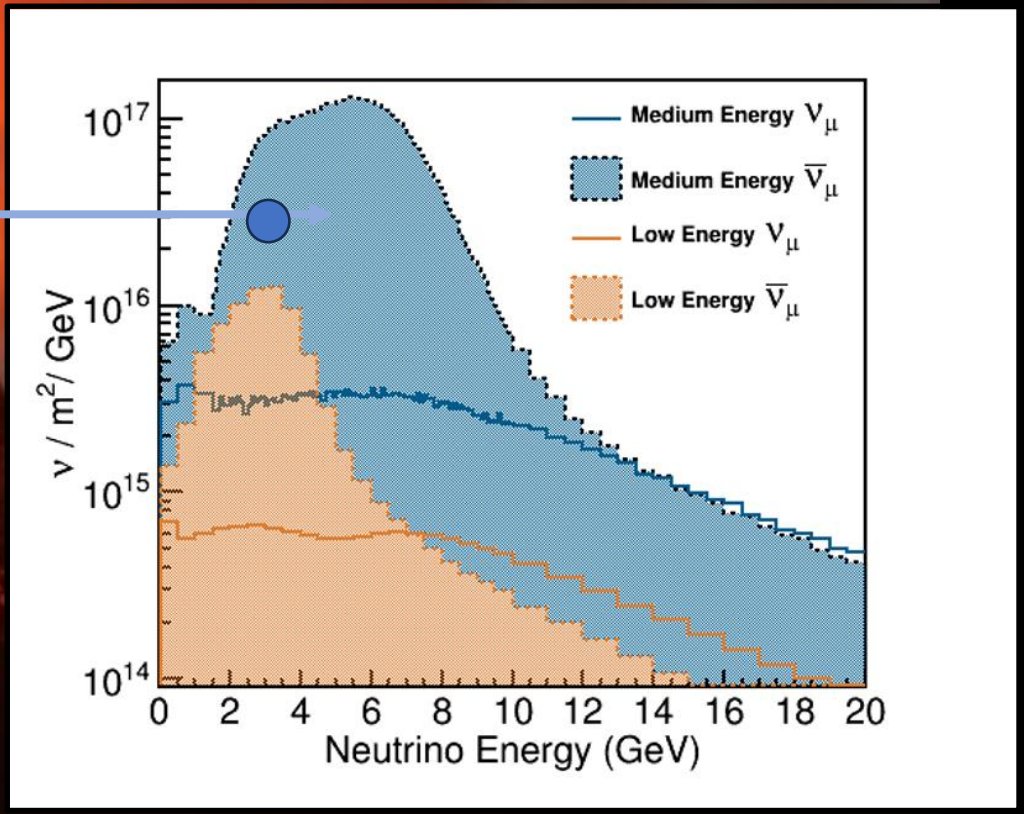


MINERvA's
Low Energy Flux
Peaks at 3.5 GeV

COOL lava:
LOWER Energy
Neutrinos

The Antineutrino Flux Volcano

HOT lava:
HIGHER Energy
Neutrinos



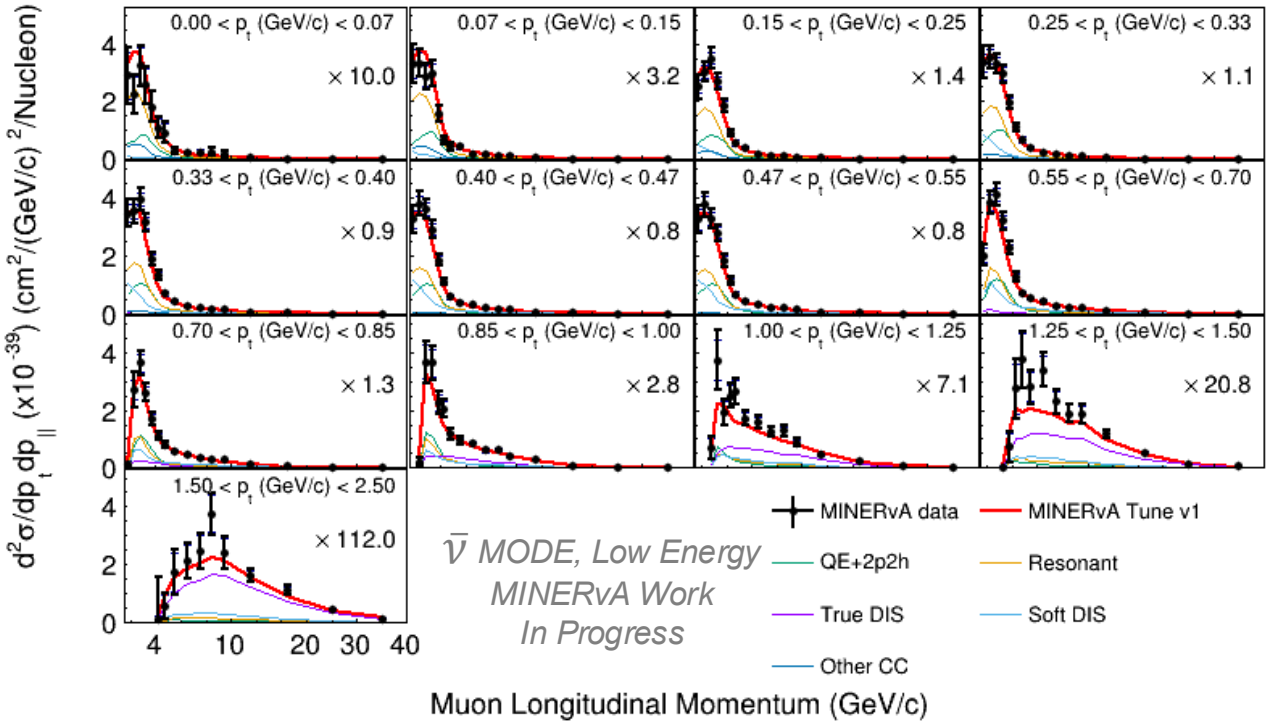
MINERvA's
Medium Energy Flux
Peaks at 6 GeV

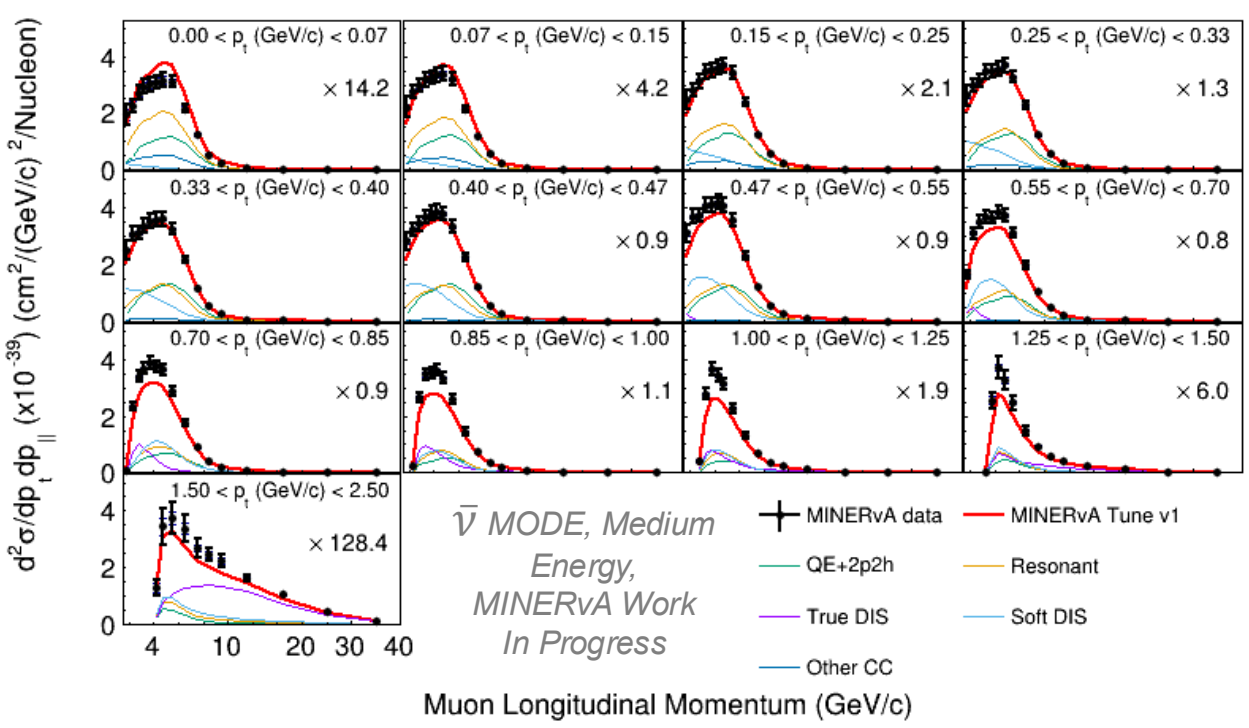
MINERvA's
Low Energy Flux
Peaks at 3.5 GeV

COOL lava:
LOWER Energy
Neutrinos

Data Cross Section

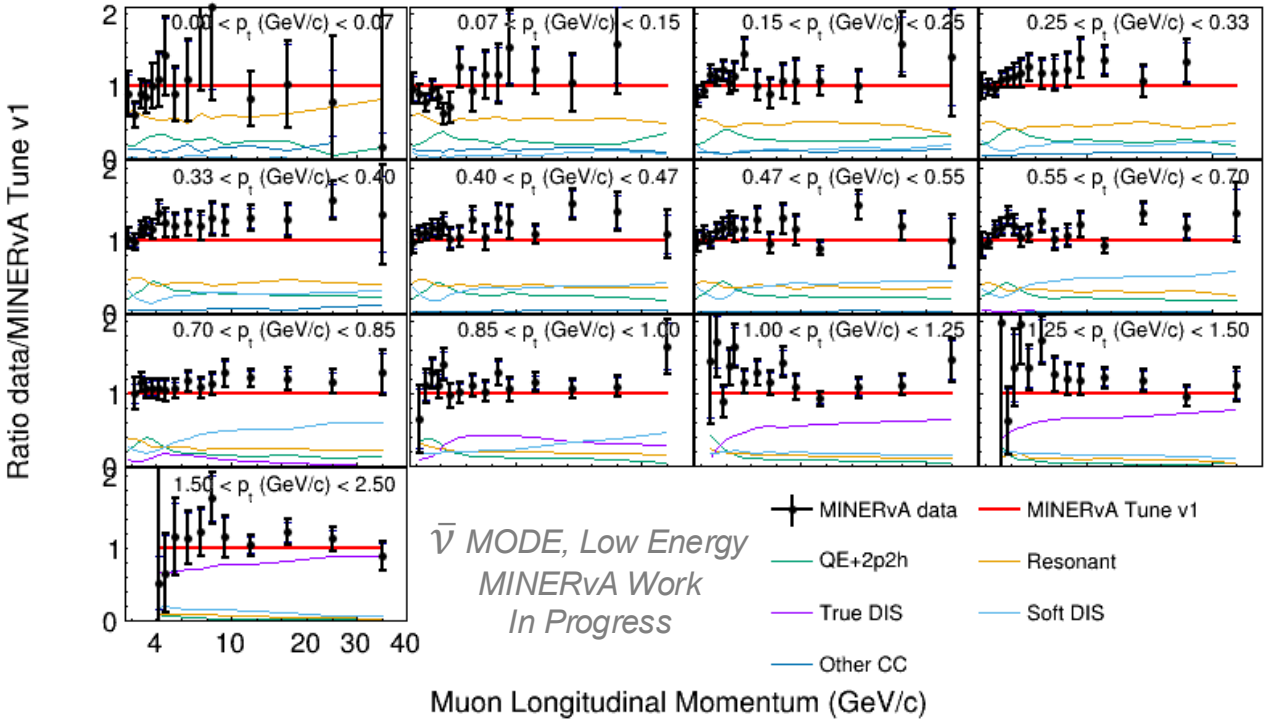
- **Antineutrinos:** Low Energy Flux on Left, Medium Energy Flux on Right

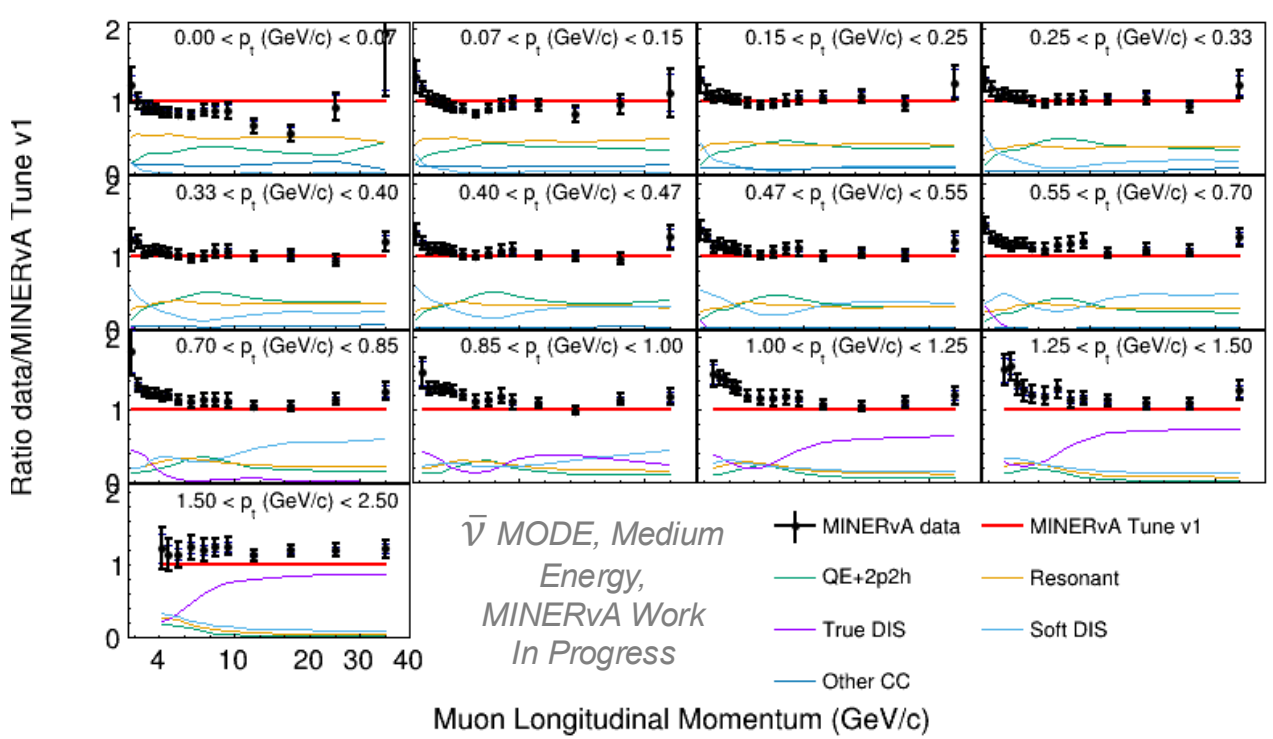




Data Cross Section – Breakdown by Interaction Type

- **Antineutrinos:** Low Energy Flux on Left, Medium Energy Flux on Right

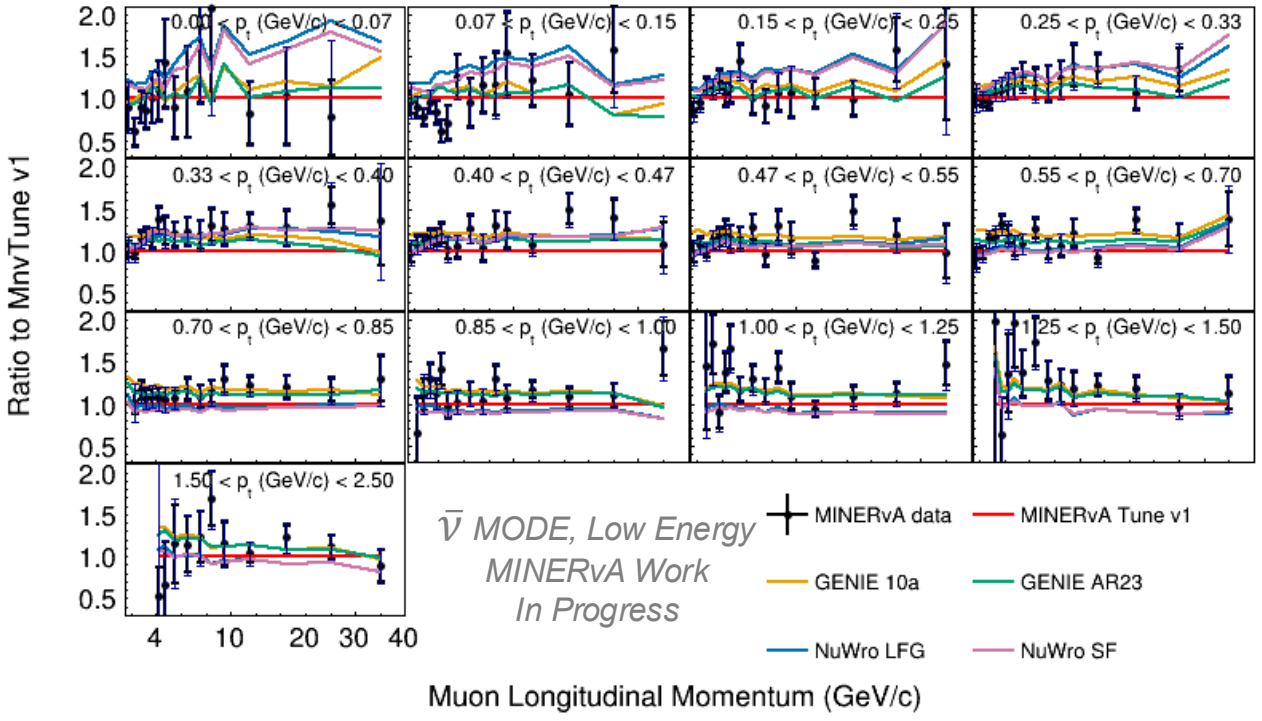


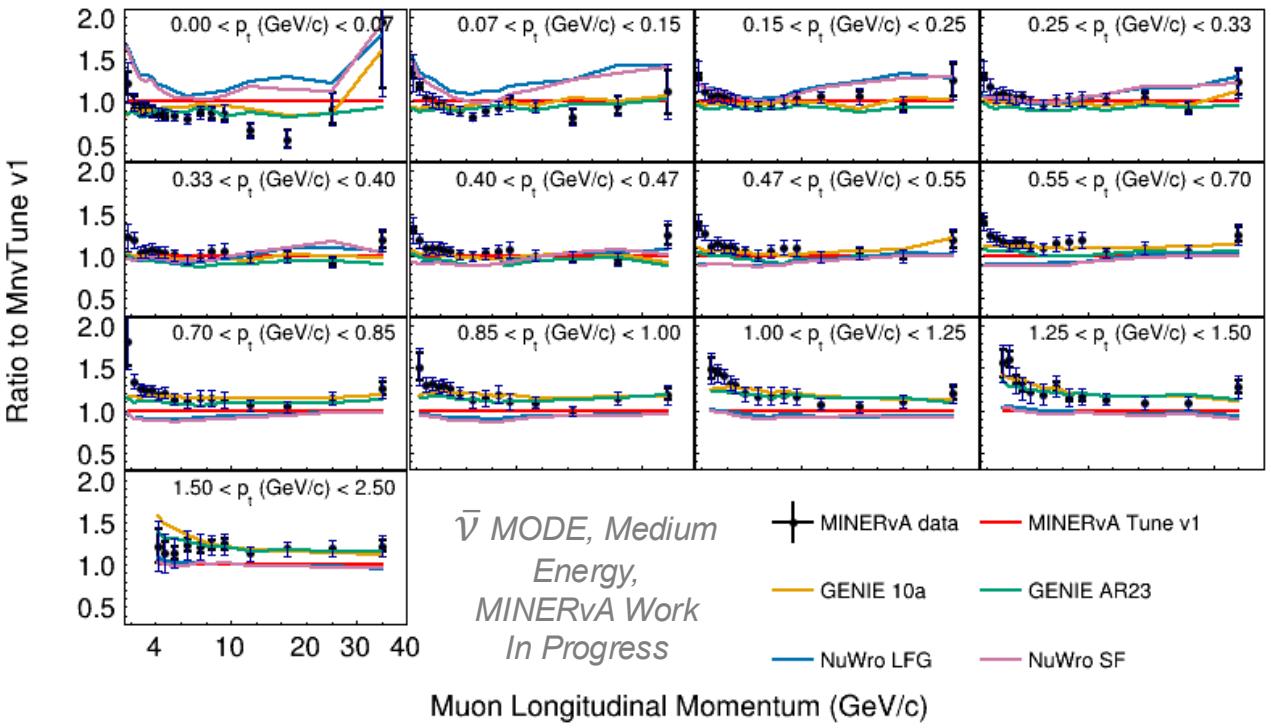


- Event rate changes as the incident flux changes
- **Composition of interaction channels changes as the incoming flux changes even with the same detector**

Model Comparisons

- **Antineutrinos:** Low Energy Flux on Left, Medium Energy Flux on Right

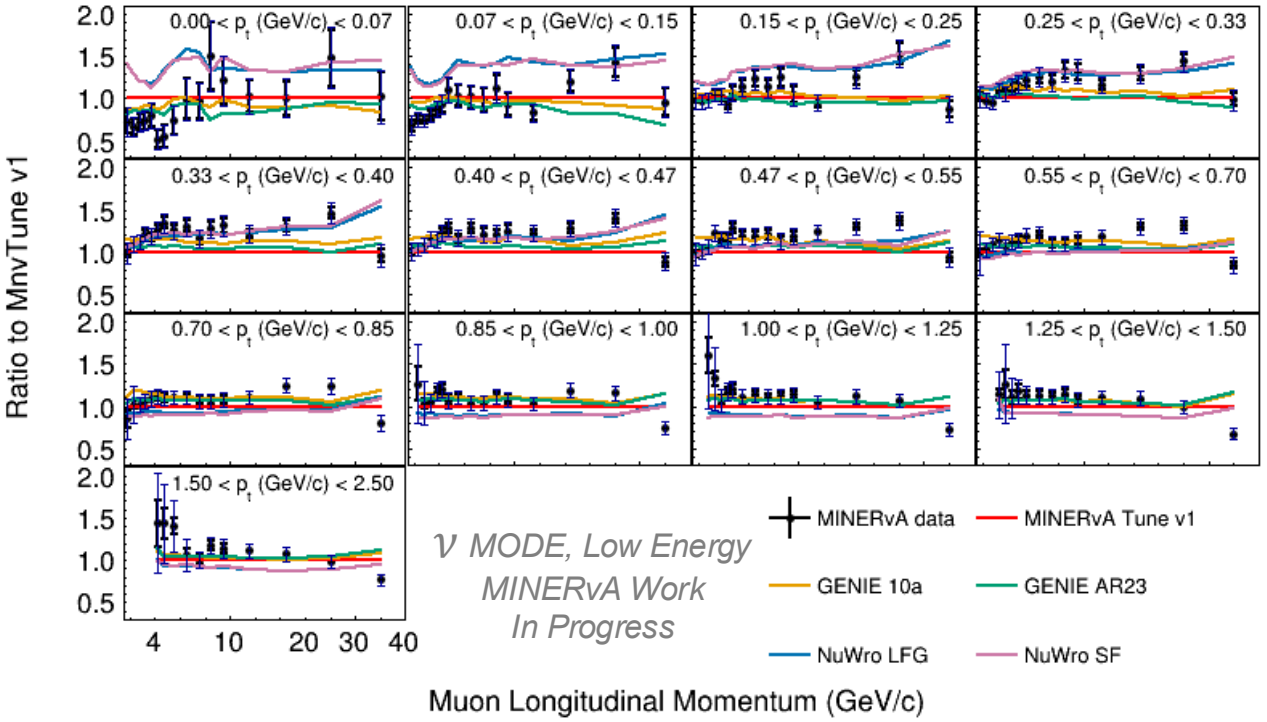


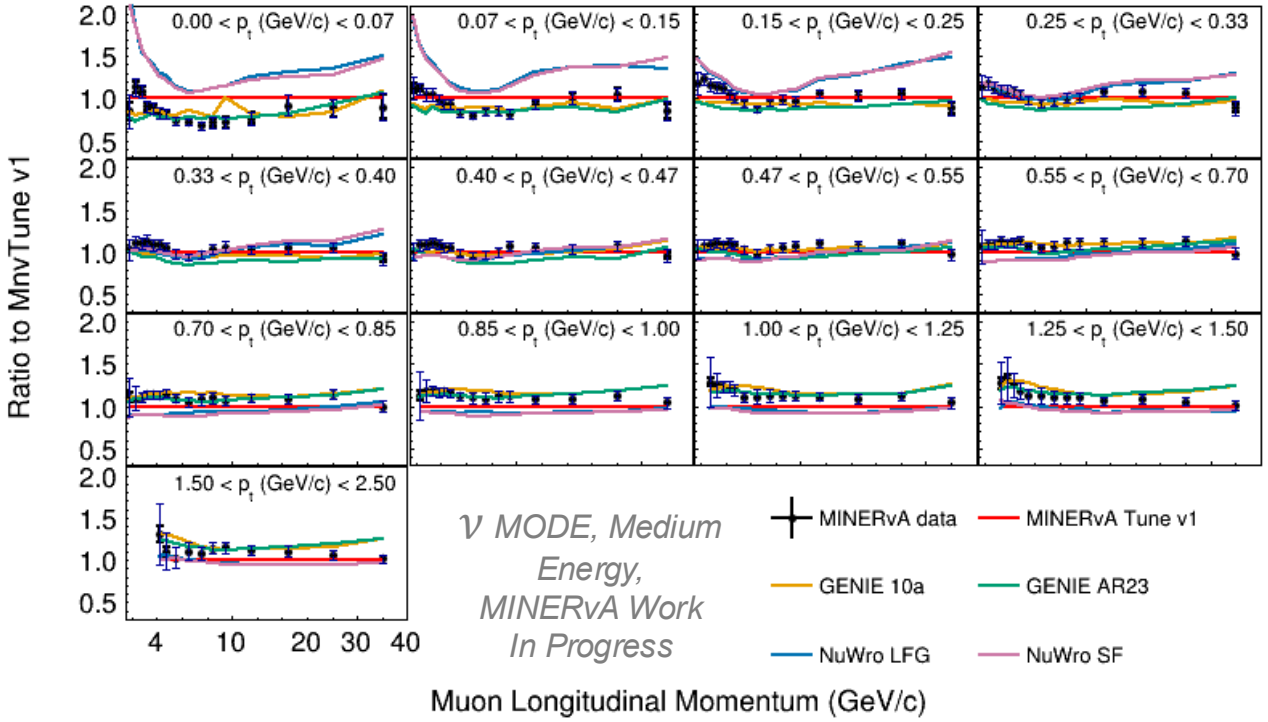


- Nuclear effect modeling is one of the dominant sources of generator variation across beam configurations

Model Comparisons - NEUTRINO MODE

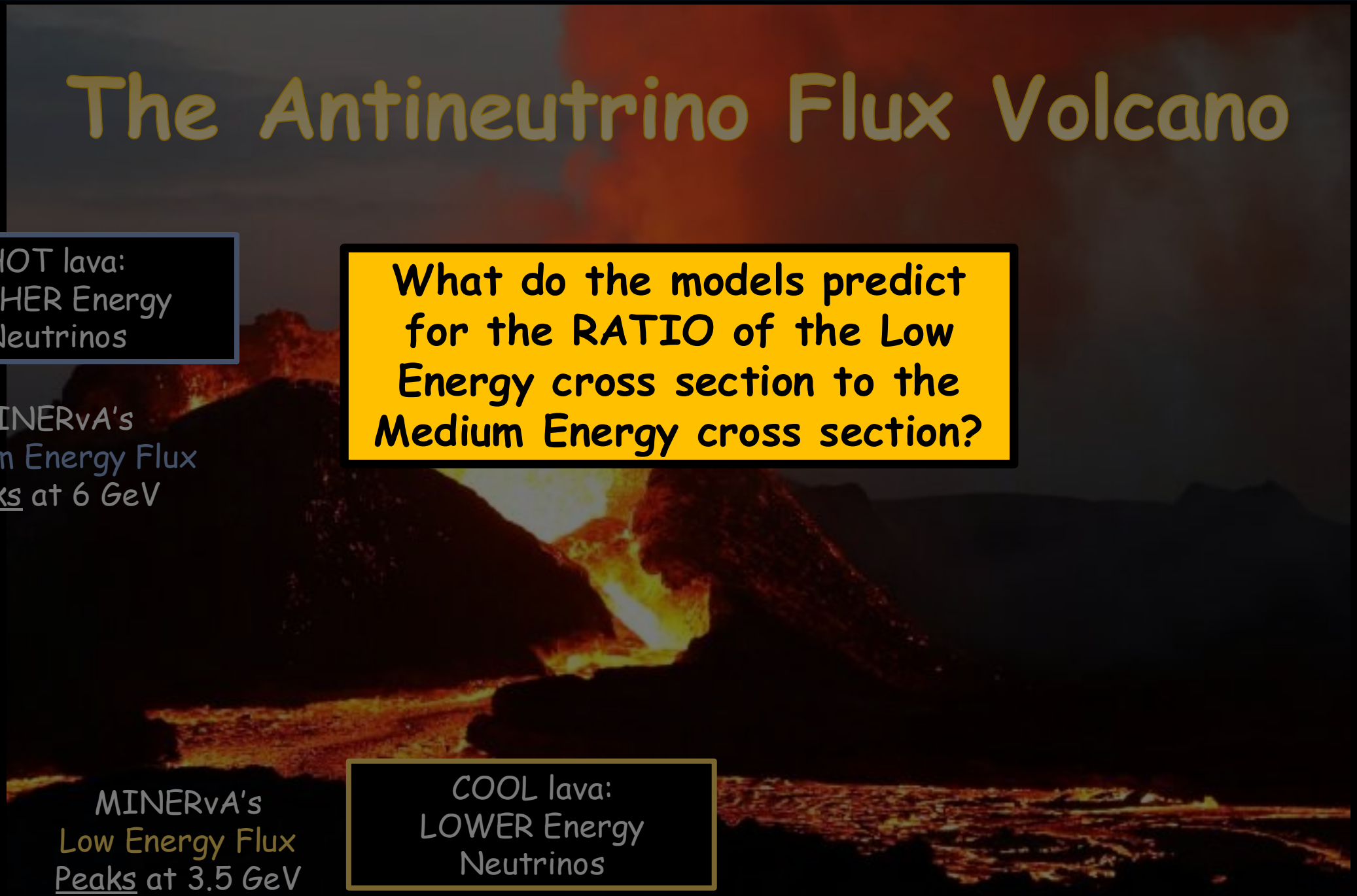
- **Neutrinos:** Low Energy Flux on Left, Medium Energy Flux on Right





- Similar behaviour of the models for antineutrino mode and neutrino mode

The Antineutrino Flux Volcano



HOT lava:
HIGHER Energy
Neutrinos

MINERvA's
Medium Energy Flux
Peaks at 6 GeV

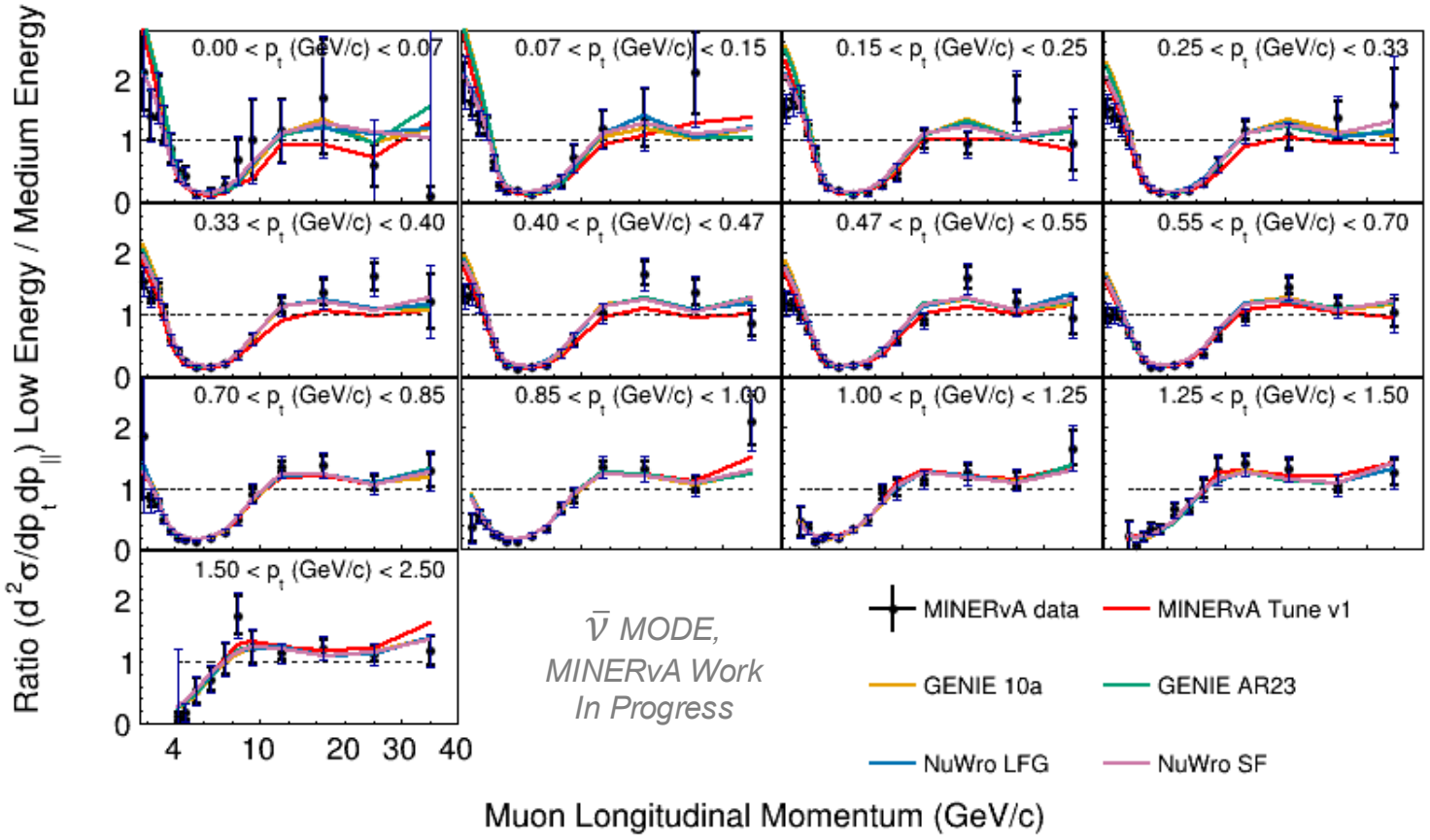
What do the models predict for the RATIO of the Low Energy cross section to the Medium Energy cross section?

MINERvA's
Low Energy Flux
Peaks at 3.5 GeV

COOL lava:
LOWER Energy
Neutrinos

Low Energy to Medium Energy Ratio

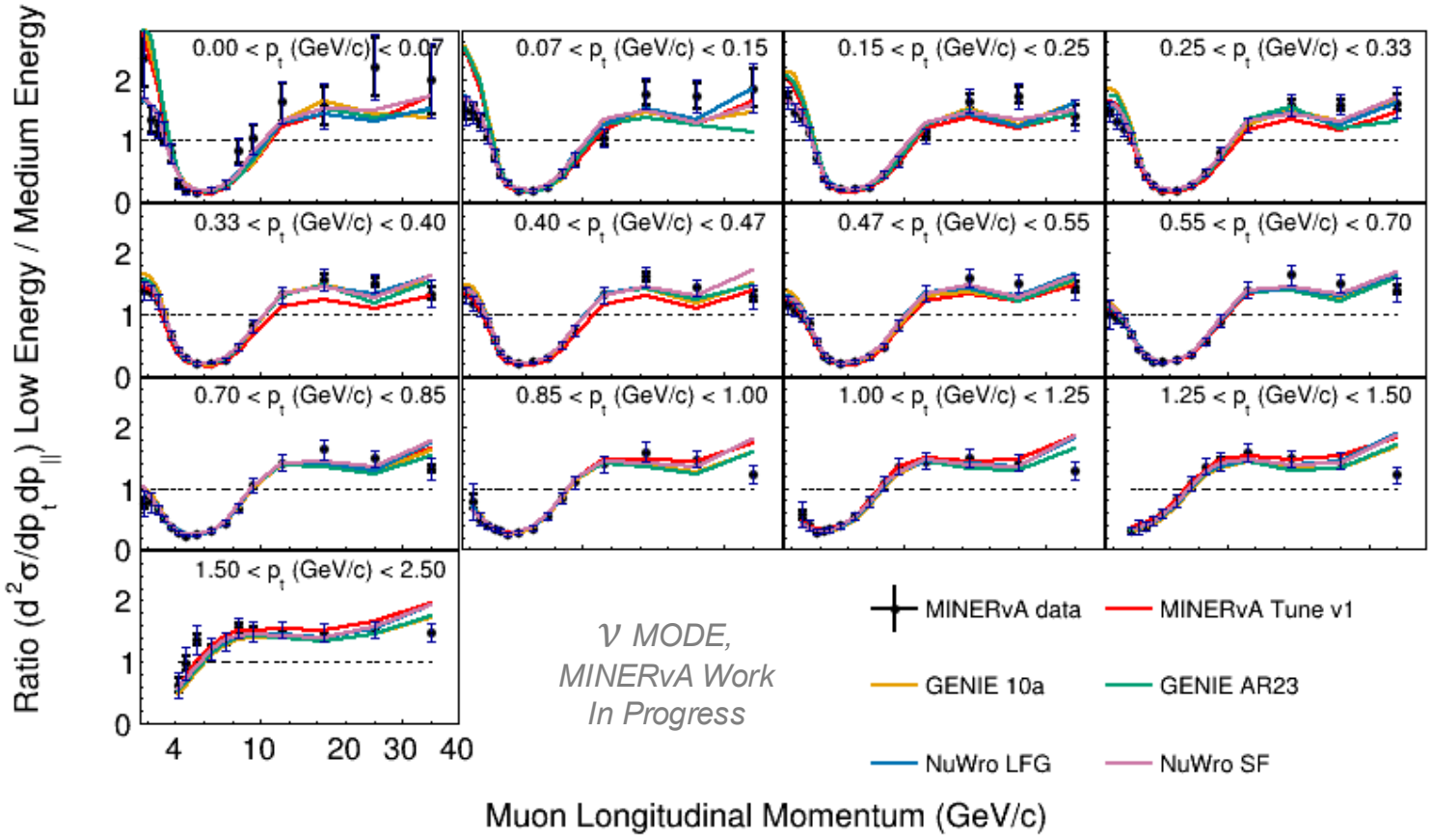
- Ratio of **antineutrino cross section** for low energy flux / cross section for medium energy flux



- The dip shape is showing the ratio of low energy flux to medium energy flux, if instead of flux integrated cross sections, we were doing total cross sections at each energy it would be flat at 1
- Models closer to data for the ratio
- Less spread in models when predicting the ratio

Low Energy to Medium Energy Ratio

- Ratio of **neutrino cross section** for low energy flux / cross section for medium energy flux



- The dip shape is showing the ratio of low energy flux to medium energy flux, if instead of flux integrated cross sections, we were doing total cross sections at each energy it would be flat at 1
- Models closer to data for the ratio
- Similar behaviour for antineutrino mode and neutrino mode

Conclusion

- Antineutrino and neutrino cross sections measured in two different beams
- The **models show similar behaviour** across the modes and beam configurations
- **No model performs the best** across both modes and beam configurations
- Greater spread of models at low muon momentum bins
  - Model variation dependent on nuclear modeling
- Modeling of low energy to medium energy cross section ratio has small model spread and improved agreement with the data ratio

Backup

Model Comparisons: Chi2 Values

- Chi2 values for various model predictions
- 208 degrees of freedom

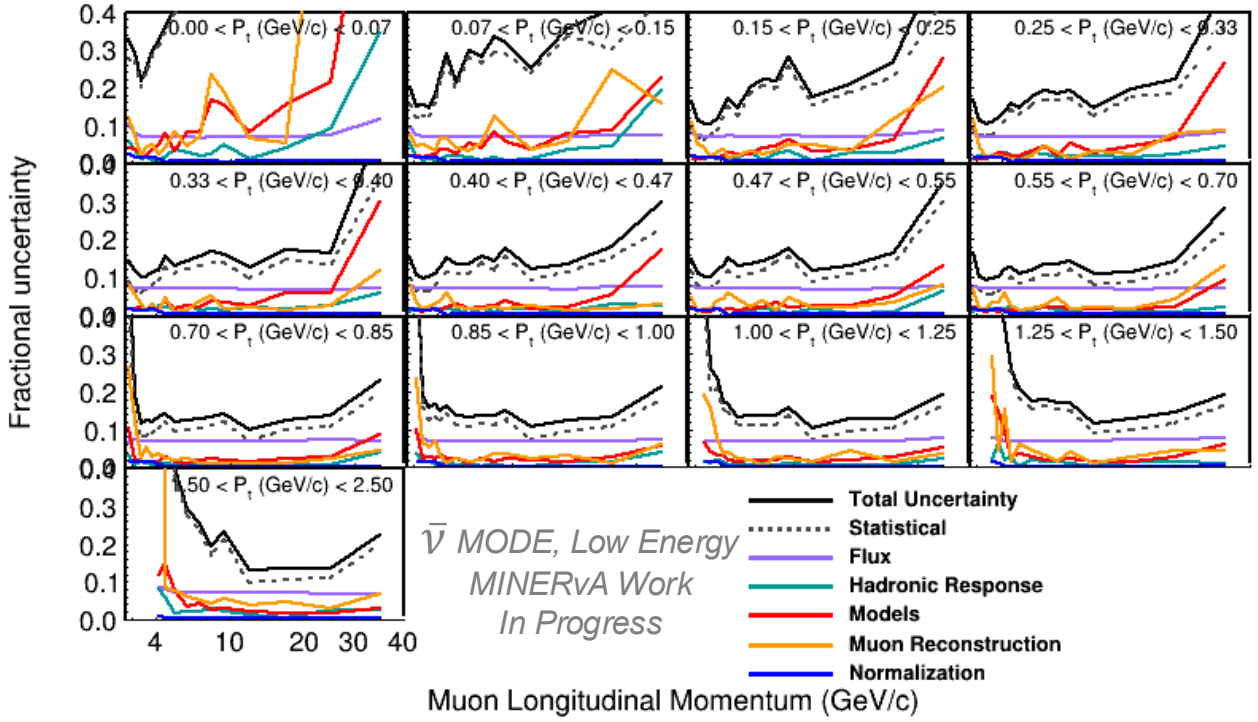
	GENIE 10a	MnvTune v1	GENIE AR23
Neutrinos Medium Energy	2052	3913	1883
Neutrinos Low Energy	704	610	679
Antineutrinos Medium Energy	1154	2746	1201
Antineutrinos Low Energy	314	215	258

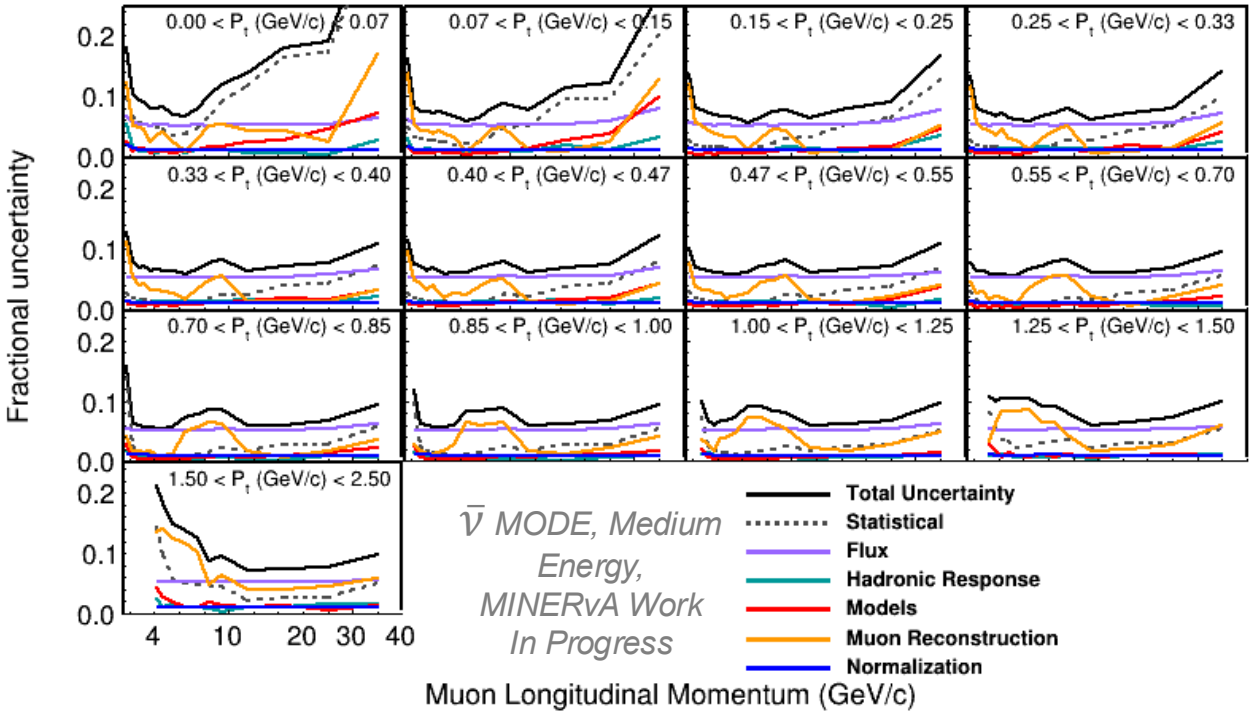
- No model performs the best across both modes and beam configurations
- MnvTunev1 performs well for low energy and GENIE AR23 performs well for medium energy with GENIE 10a a close candidate as well

Fractional Uncertainty on Cross Section

- **Antineutrinos RHC:** Low Energy on Left, Medium Energy on Right

MINERvA Work In Progress





Fractional Uncertainty on Cross Section

- **Neutrinos FHC:** Low Energy on Left, Medium Energy on Right

MINERvA Work In Progress