New Perspectives 2024:
Anti neutrino inclusive analysis versus muon kinematics

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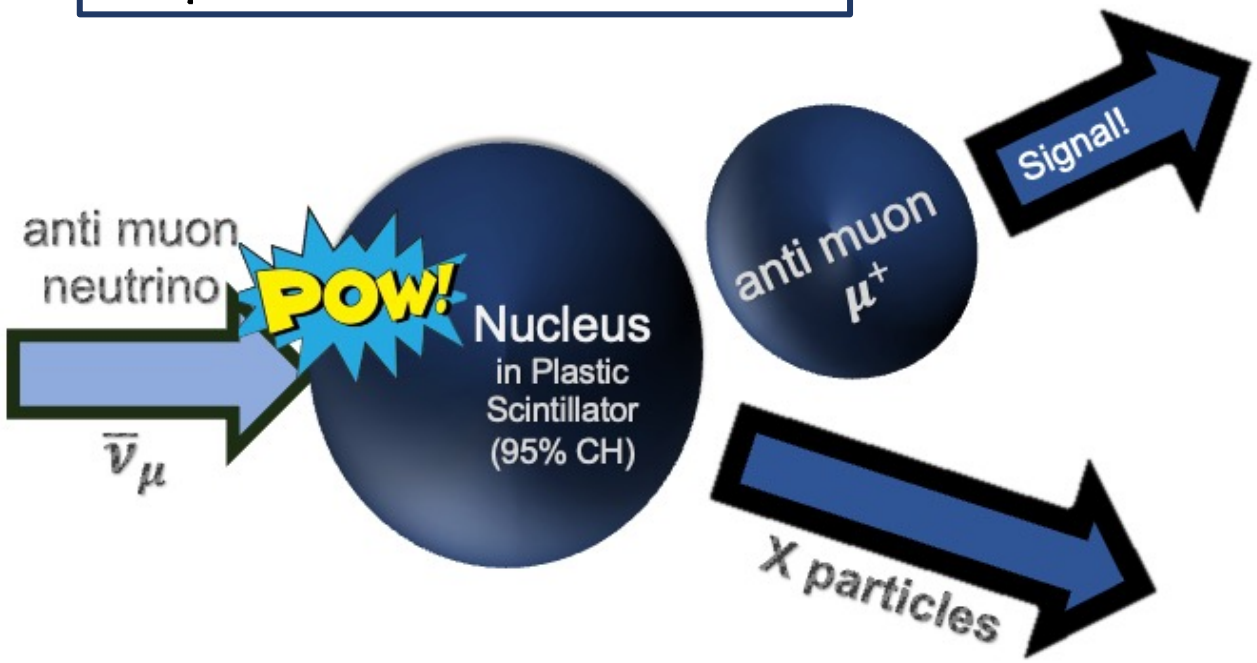
July 8, 2024

What's the Analysis?

- Goal: Extract a two-dimensional cross section on hydrocarbon in terms of muon pt and p||

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



Double Differential Cross Section in true bin α

$$\left(\frac{d^2\sigma}{dxdy}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{A_\alpha(\Phi T)(\Delta x)(\Delta y)}$$

j: reconstructed bin #
α: true bin #

Unfold

Subtract backgrounds

Acceptance-correct

Normalize by flux and target number

Bin width normalize

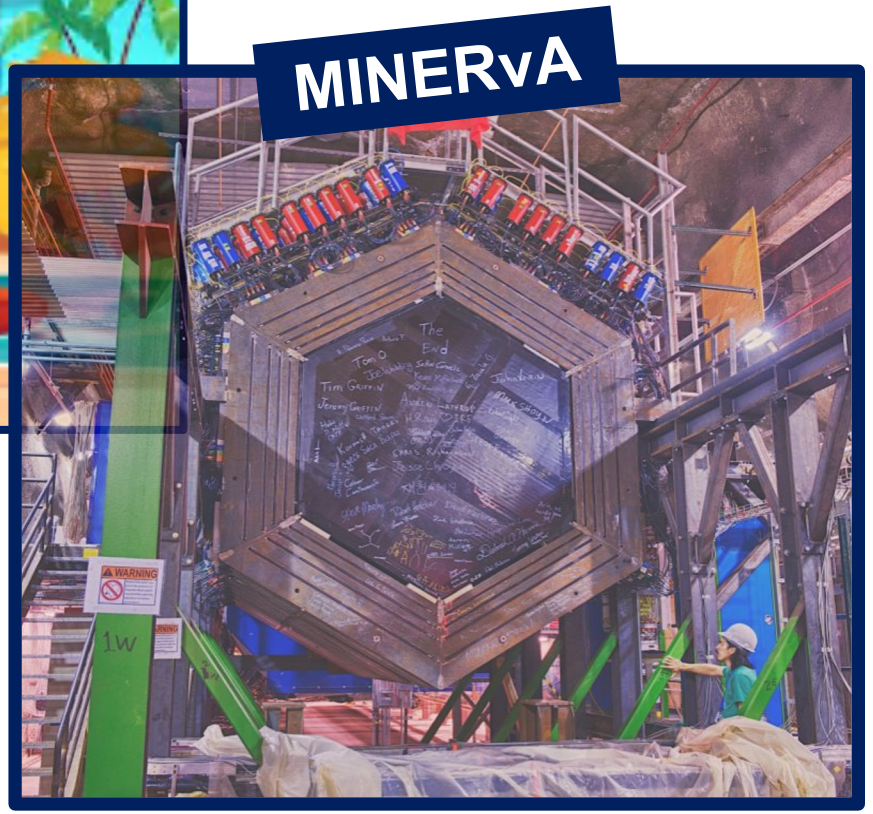
Analysis Overview

- Anti neutrino Inclusive 2D cross section in terms of muon kinematics on CH will be extracted

Goal: Take the **neutrino** to **anti neutrino** cross section ratio and do model comparisons for the ratio

- Neutrino Inclusive 2D cross section on CH in terms of muon kinematics has already been published
  - [PHYSICAL REVIEW D 104, 092007 (2021)]
- We will re extract the neutrino cross section with the newer flux constraint

Let's take a step back …



Kids that go to our waterpark

Let's take a step back …

Detector made of MATTER

Kids that go to our waterpark

Neutrinos

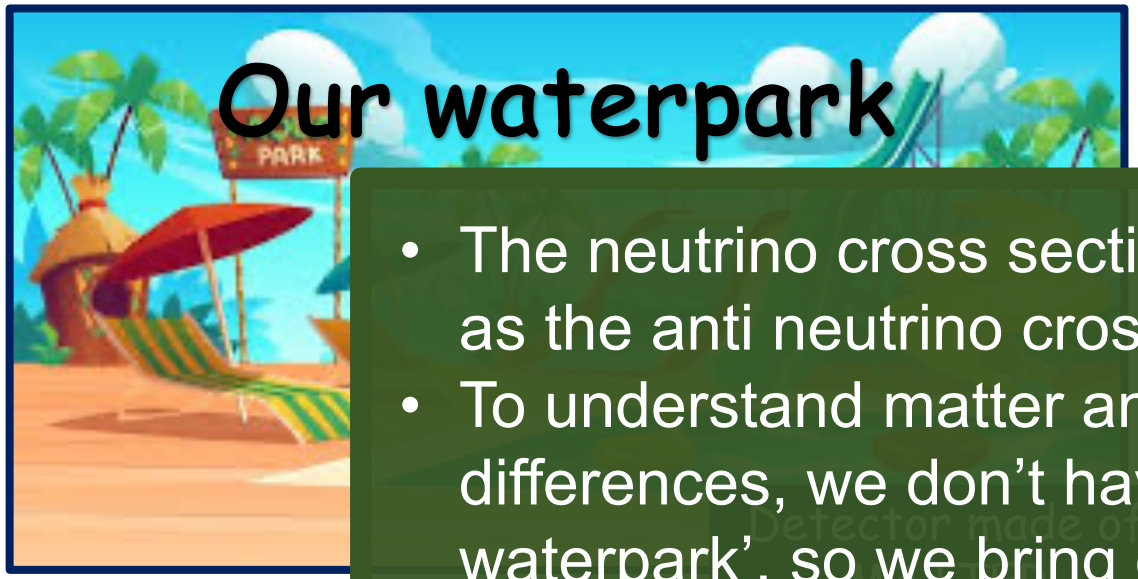
Hypothetical COUSIN Waterpark

Detector made of Anti MATTER

Cousin Kids that go to cousin waterpark

Anti Neutrinos

Let's take a step back …



- The neutrino cross section on matter is the same as the anti neutrino cross section on anti matter
- To understand matter and anti matter differences, we don't have access to the 'cousin waterpark', so we bring over the cousin kids to our waterpark
- We have anti neutrinos interacting on matter

Hypothetical

Detector made of Anti MATTER

Kids that go to our waterpark

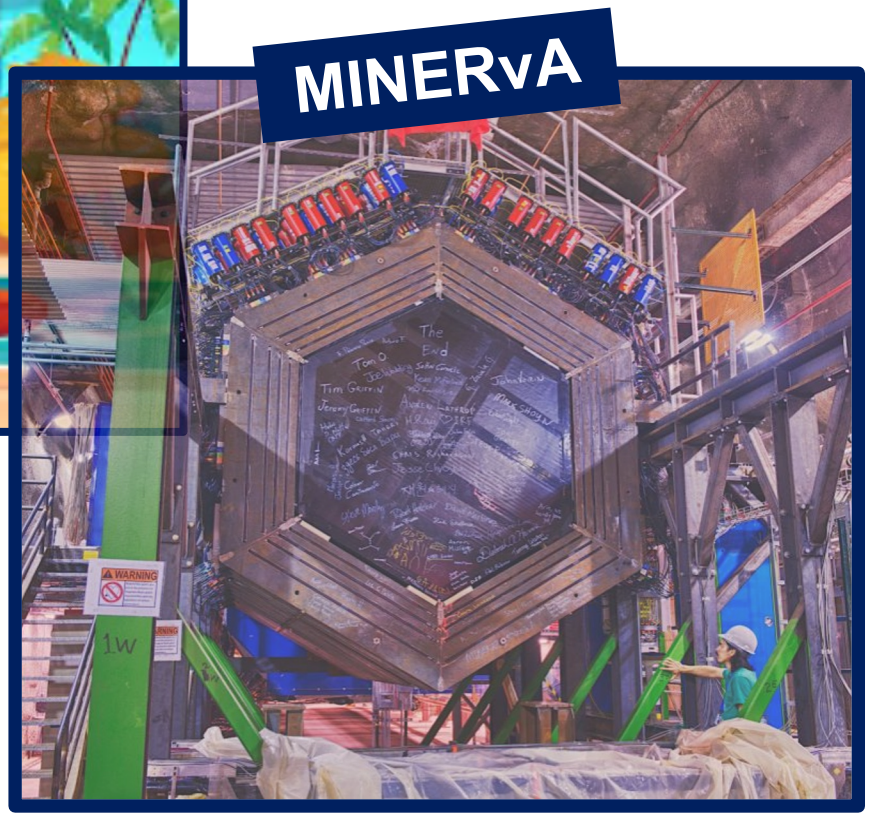
Neutrinos

Cousin Kids that go to cousin waterpark

Anti Neutrinos

Cousin kids (anti neutrinos) come to our waterpark

Caveat: There were some anti neutrinos already in the neutrino beam … will get to that soon



Kids that go to our waterpark

Neutrinos

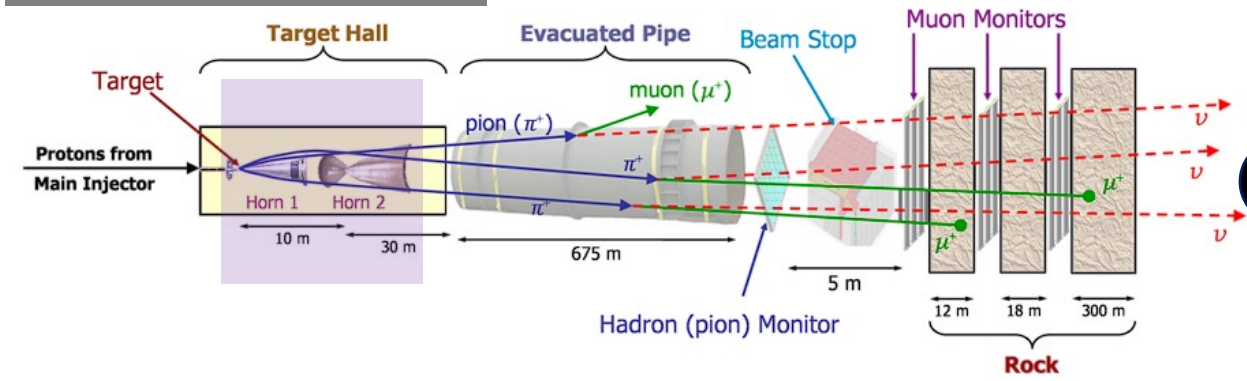
Cousin Kids

Anti Neutrinos

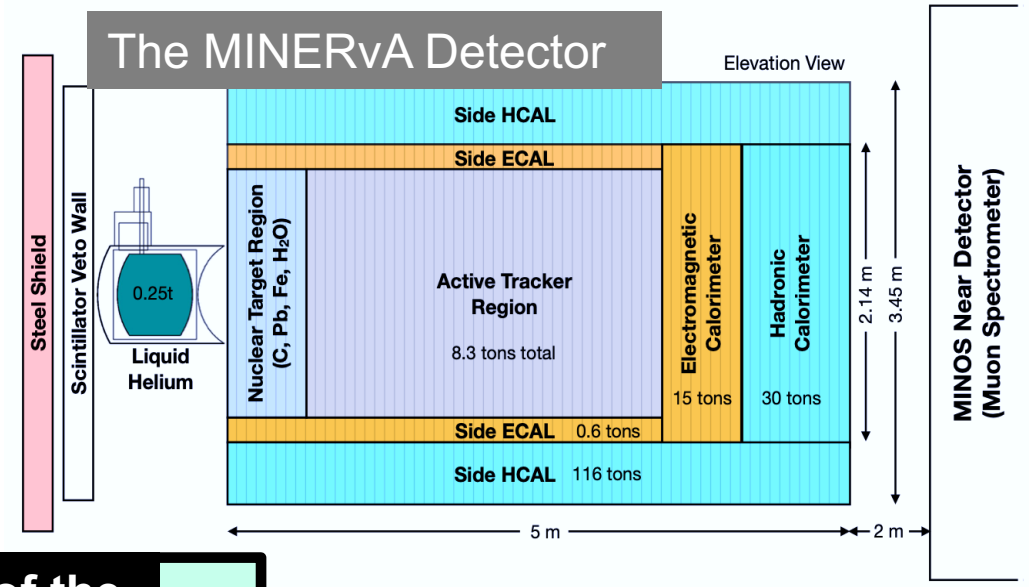
Analysis: Inclusive cross section measurement on CH

We're now at the entrance of the water park:

The NuMI Beamline



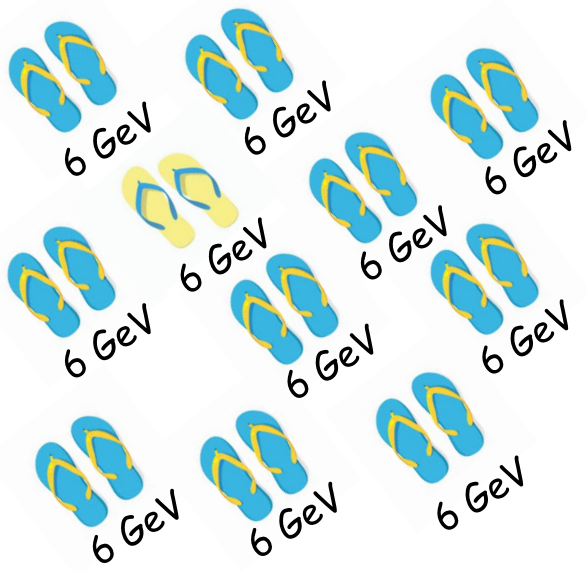
The MINERvA Detector

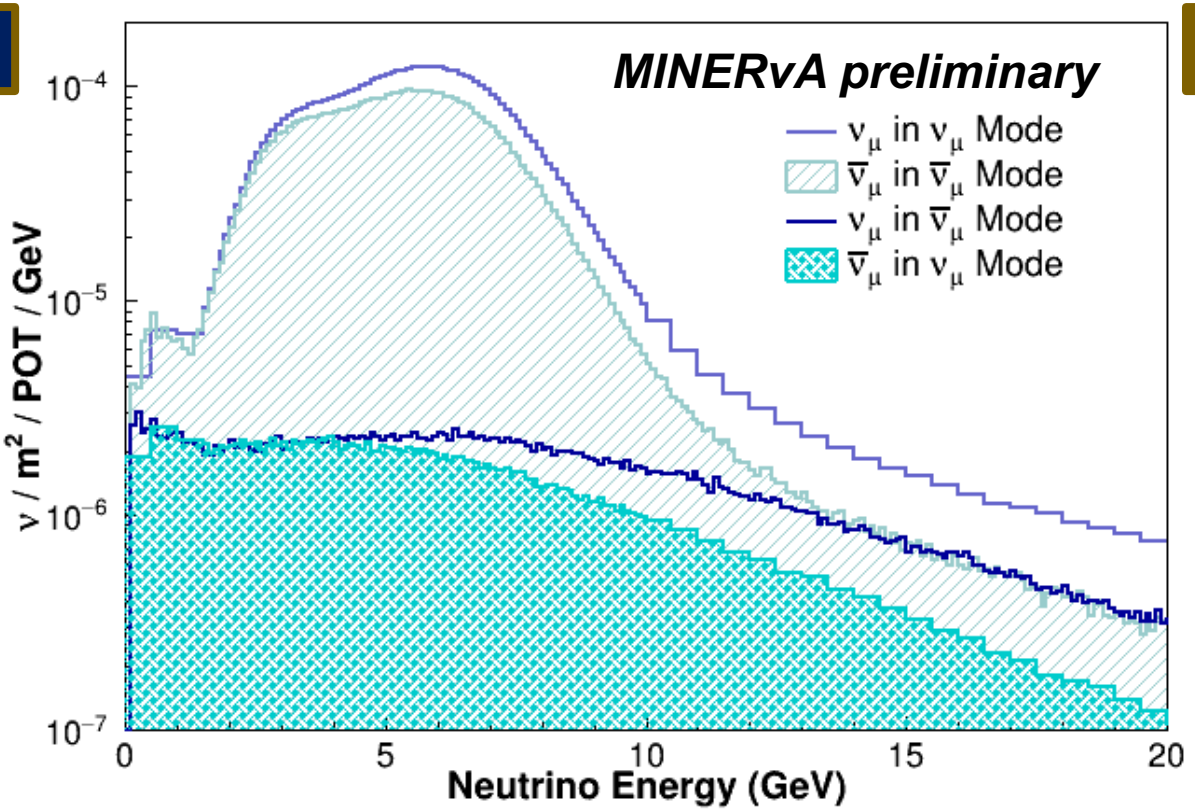


- Focusing horns in **Forward Horn Current** mode for neutrino beam
- Focusing horns in **Reverse Horn Current** Mode for the incident anti neutrino beam
- Results for both neutrino and anti neutrino mode will be presented side by side on the following slides

Assemble the group of kids to send in the water park

NEUTRINO MODE



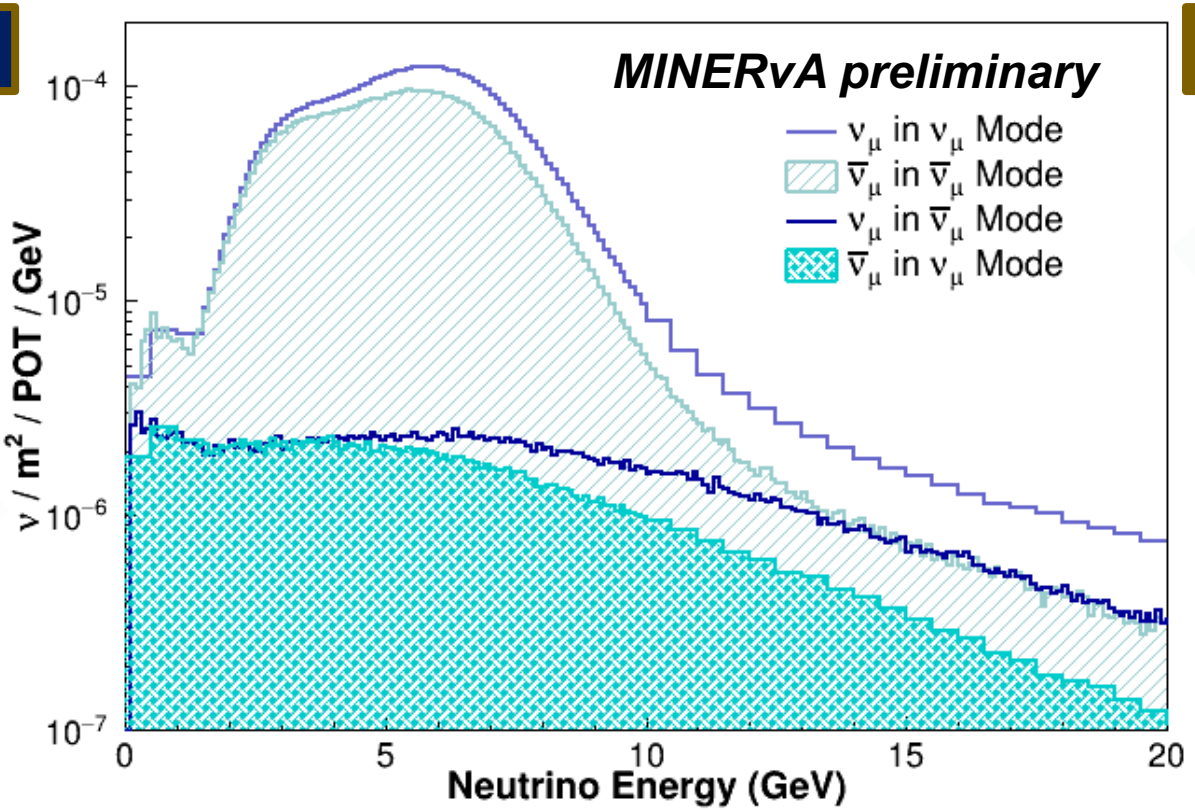


Anti NEUTRINO MODE

- Lower flux per proton on target in anti neutrino mode than in neutrino mode
  - *Fewer cousin kids going in at different neutrino energies*
- At lower energies, the wrong sign contamination around the same

Assemble the group of kids to send in the water park

NEUTRINO MODE



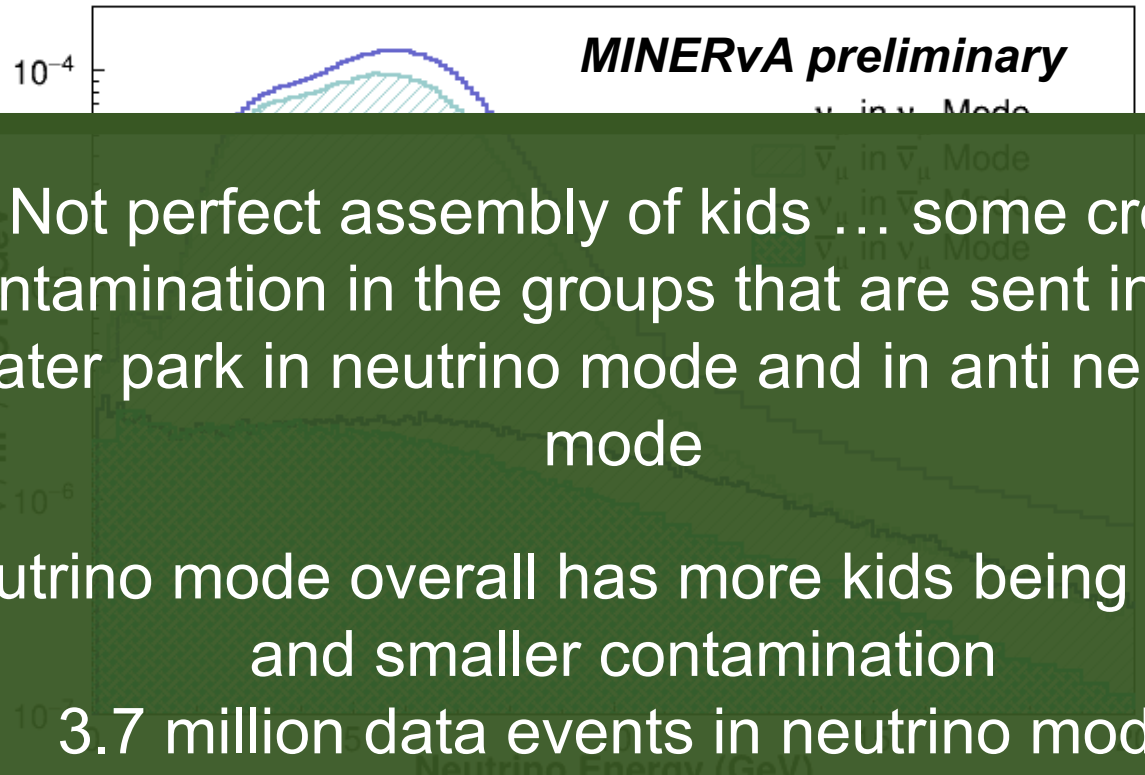
Anti NEUTRINO MODE

- Lower flux per proton on target in anti neutrino mode than in neutrino mode
  - *Fewer cousin kids going in at different neutrino energies*
- At higher energies, the wrong sign contamination around half in anti neutrino mode

Assemble the group of kids to send in the water park

NEUTRINO MODE

Anti NEUTRINO MODE



Not perfect assembly of kids … some cross contamination in the groups that are sent into the water park in neutrino mode and in anti neutrino mode

Neutrino mode overall has more kids being sent in and smaller contamination

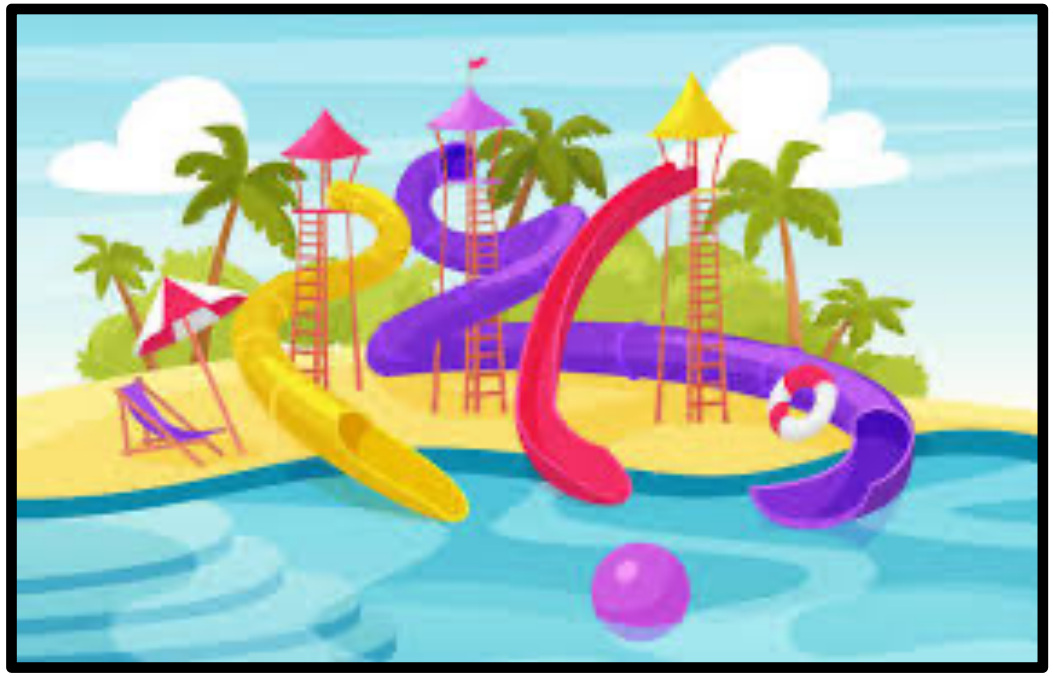
3.7 million data events in neutrino mode

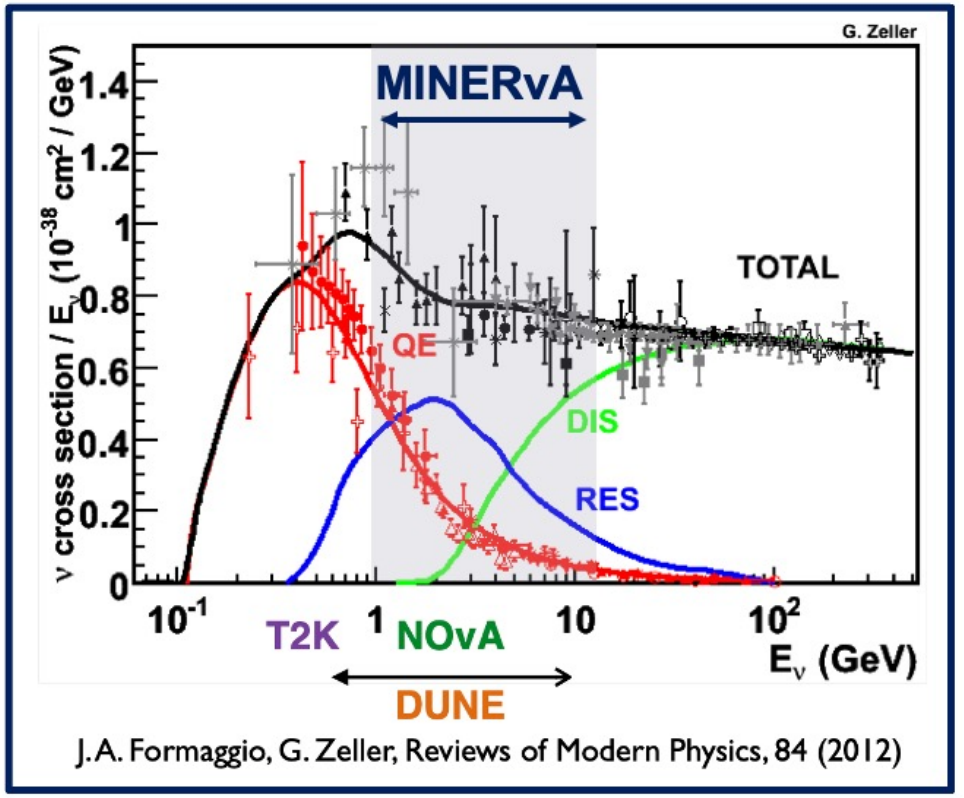
2.1 million data events in anti neutrino mode

- L… rino mode
  - *Fewer cousin kids going in at different neutrino energies*
- At higher energies, the wrong sign contamination around half in neutrino mode

Release the kids in the water park

The water park has **different kinds of slides** and **how energetic the kids are makes it more probable** for them to go on certain slides

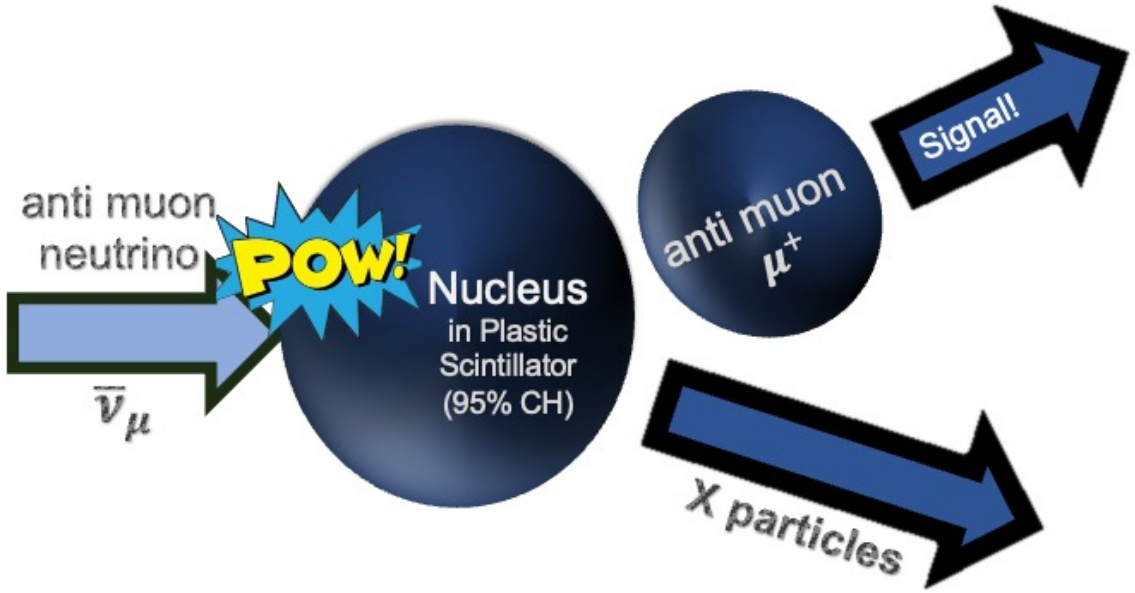


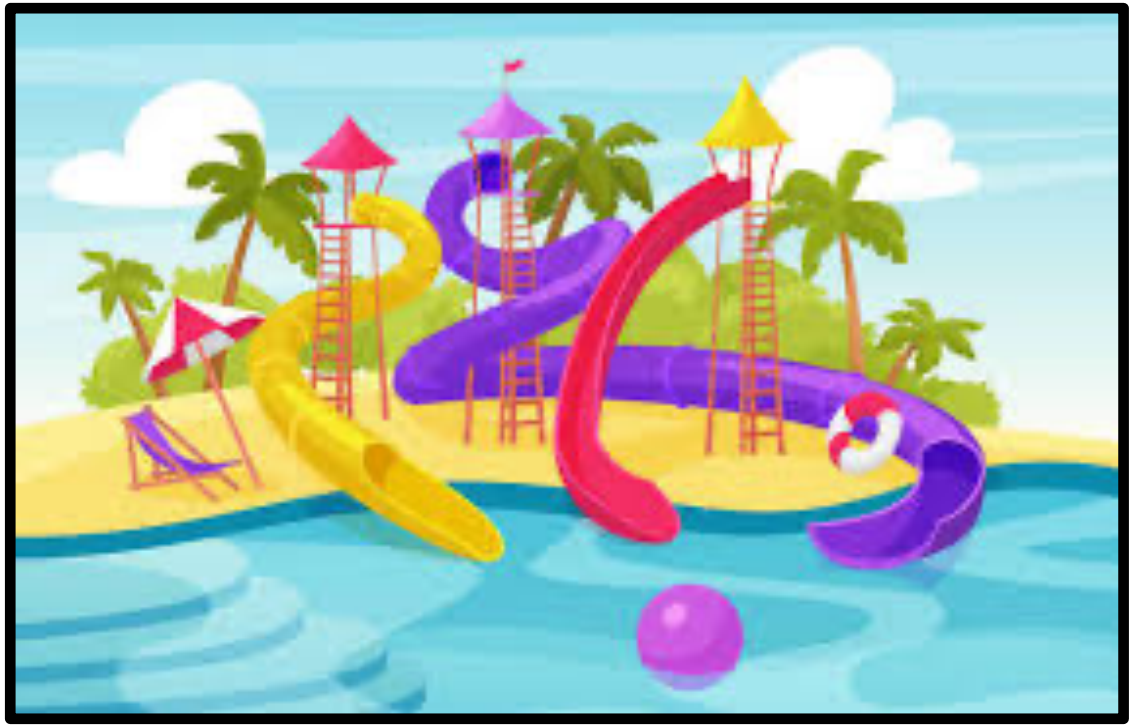


Different interaction channels more likely for different neutrino energies

Our Signal

- **Charged Current <u>Inclusive</u> Analysis:** Interested in looking at a bunch of slides together, all interactions that produce a muon in the final state are a signal process



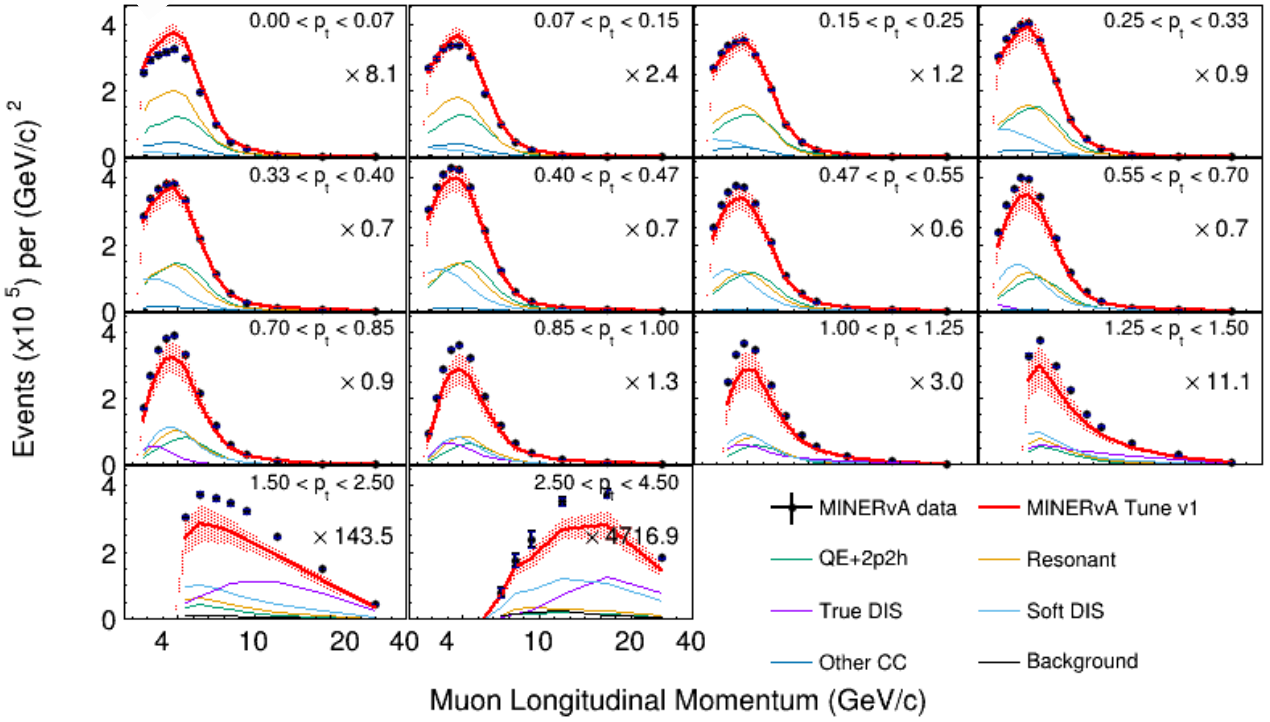


Reconstructed Event Samples

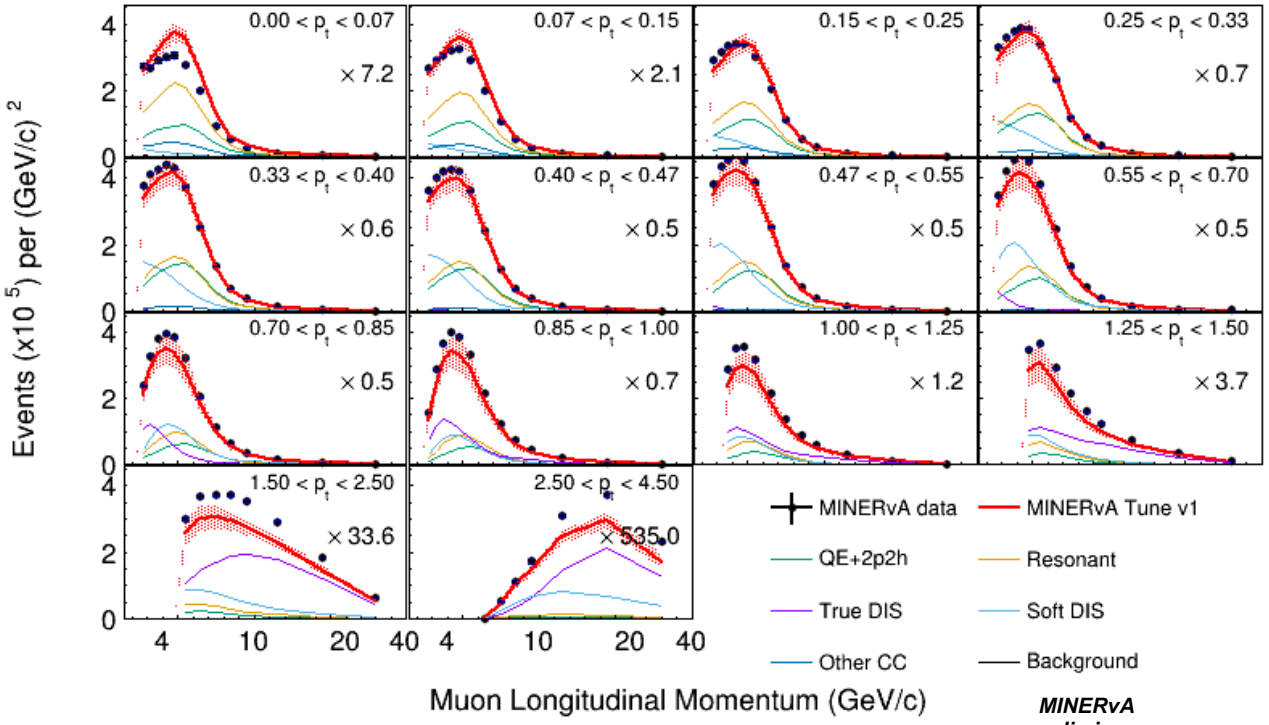
- The reconstructed event samples in both modes

Neutrinos in Neutrino Mode

MINERvA preliminary



Anti neutrinos in Anti Neutrino Mode



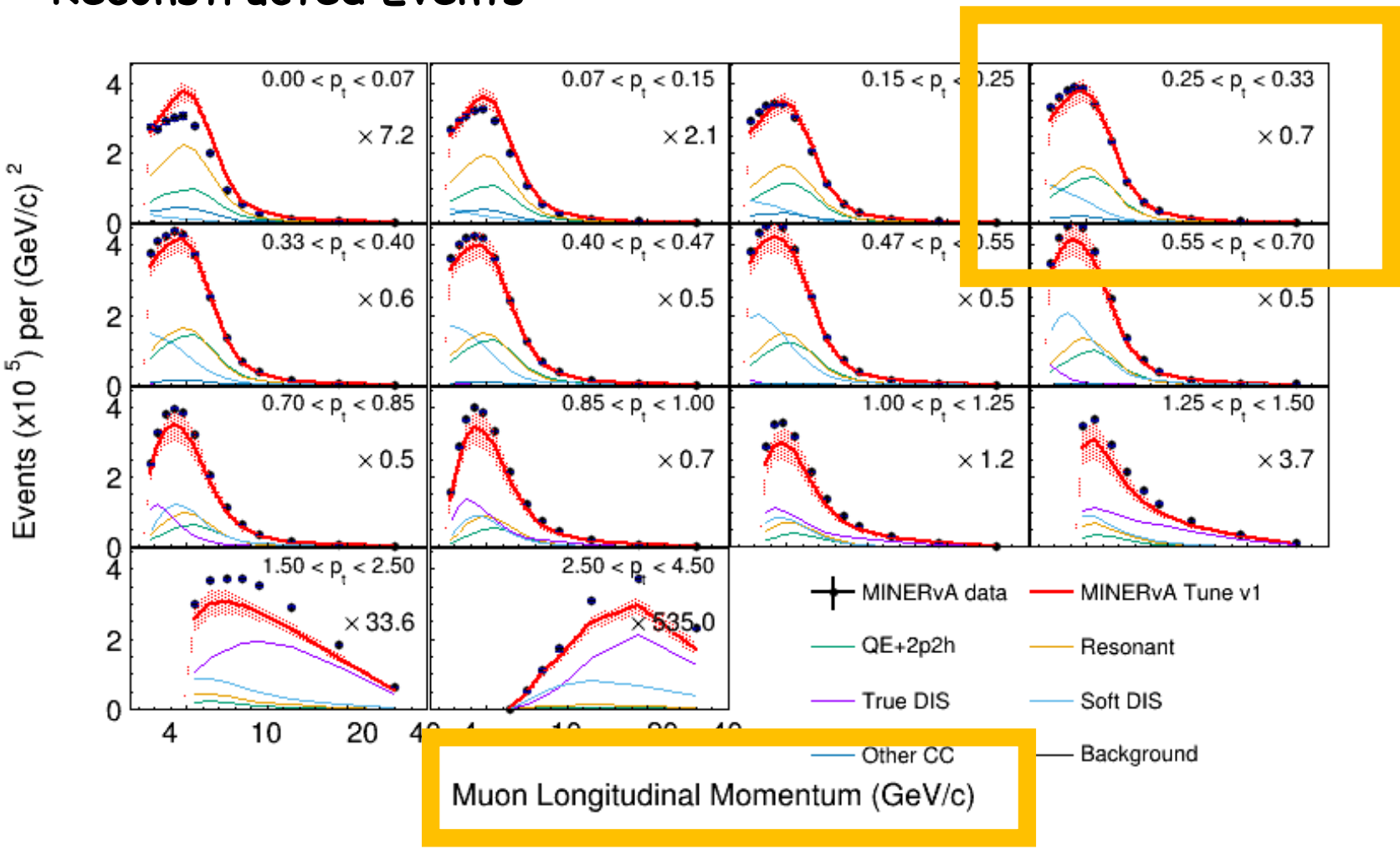
MINERvA preliminary

Analysis: Inclusive cross section measurement on CH

Event Distribution

$$\left(\frac{d^2\sigma}{dxdy}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)(\Delta y)}$$

- **Reconstructed Events**



Example of pt bin on the PANEL PLOT!

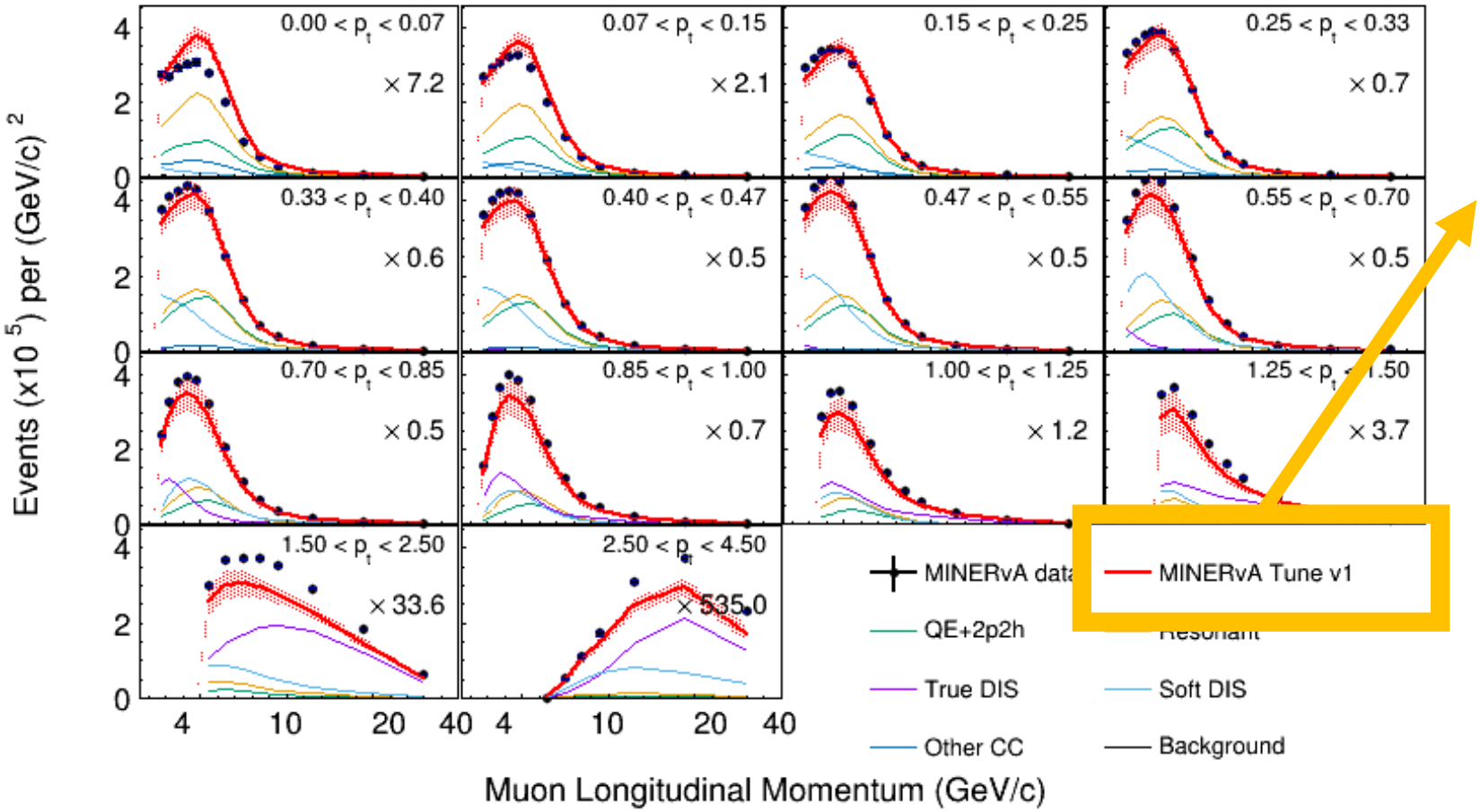
2D analysis in terms of transverse and longitudinal muon momenta

Event Distribution

$$\left(\frac{d^2\sigma}{dxdy}\right)_{\alpha} = \frac{\sum_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{A_{\alpha}(\Phi T)(\Delta x)(\Delta y)}$$

- Reconstructed Events

Red curve is the MC prediction with total error on it:



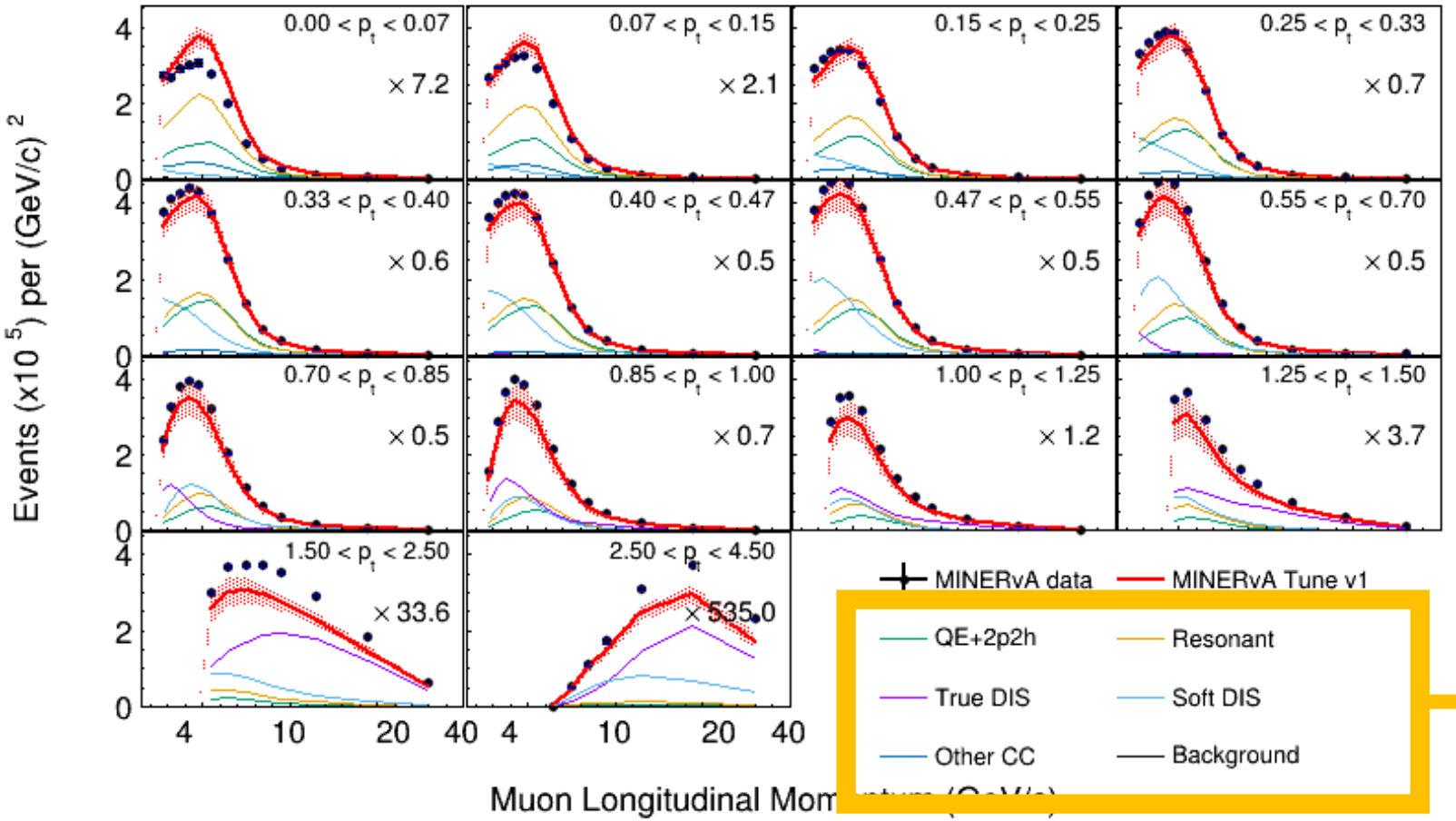
MINERvA Tune v1

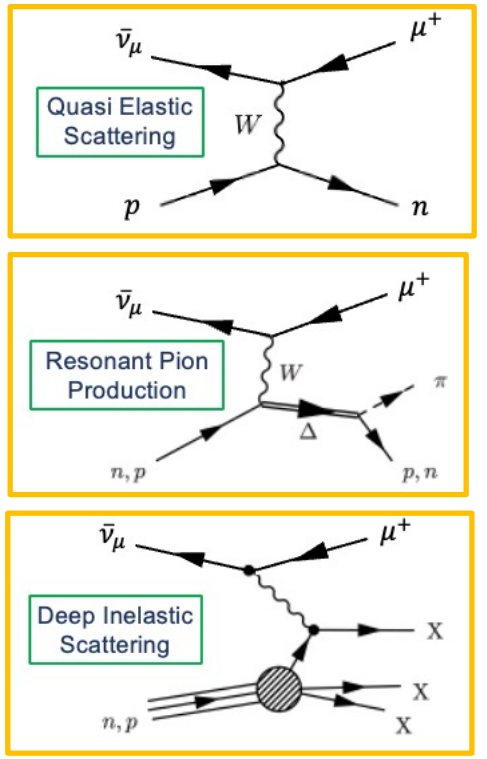
- GENIE version 2.12.6
- Valencia RPA applied to QE
- Non-resonant pion production reduction
- Low recoil fit (LE) applied to Valencia 2p2h

Event Distribution

$$\left(\frac{d^2\sigma}{dxdy}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)(\Delta y)}$$

- **Reconstructed Events**





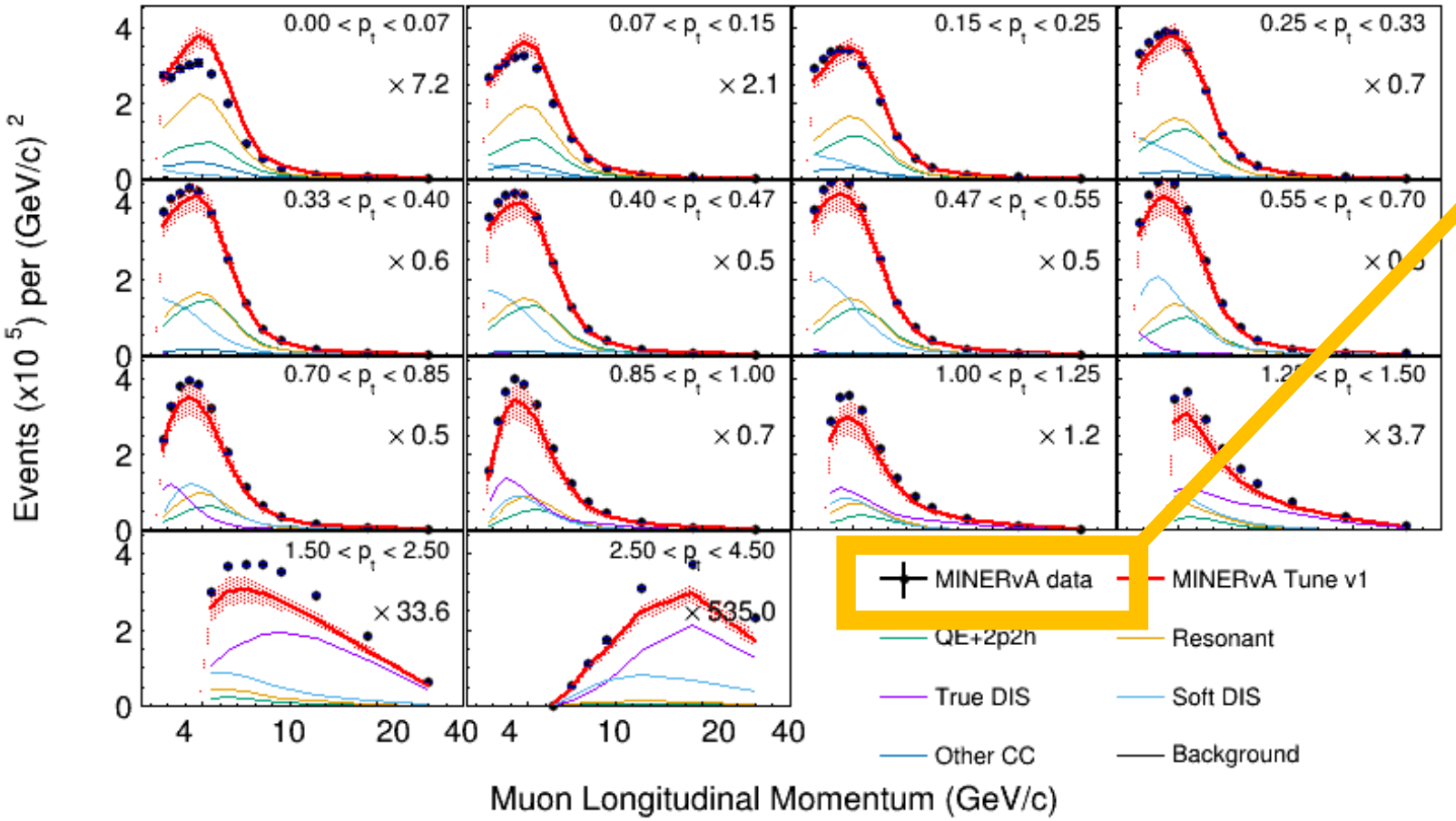
Inclusive analysis

Analysis: Inclusive cross section measurement on CH

Event Distribution

$$\left(\frac{d^2\sigma}{dxdy}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{A_\alpha(\Phi T)(\Delta x)(\Delta y)}$$

- **Reconstructed Events**



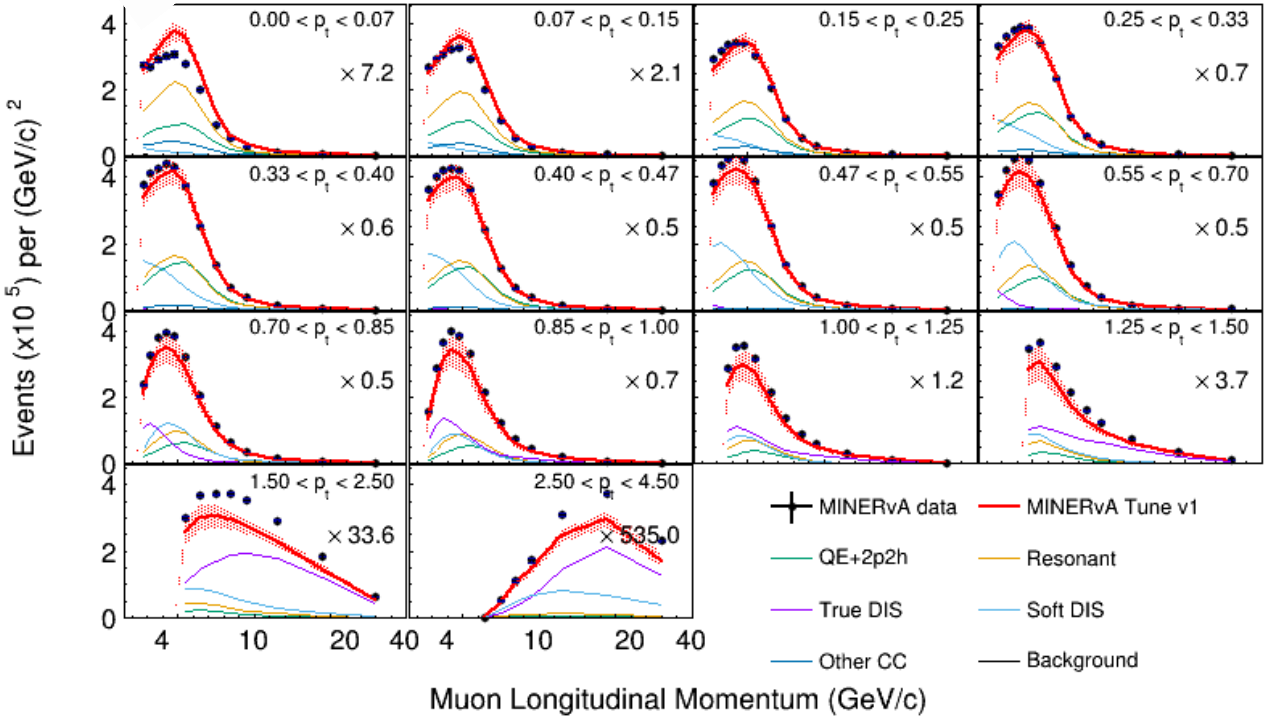
Data events reconstructed

Reconstructed Event Samples

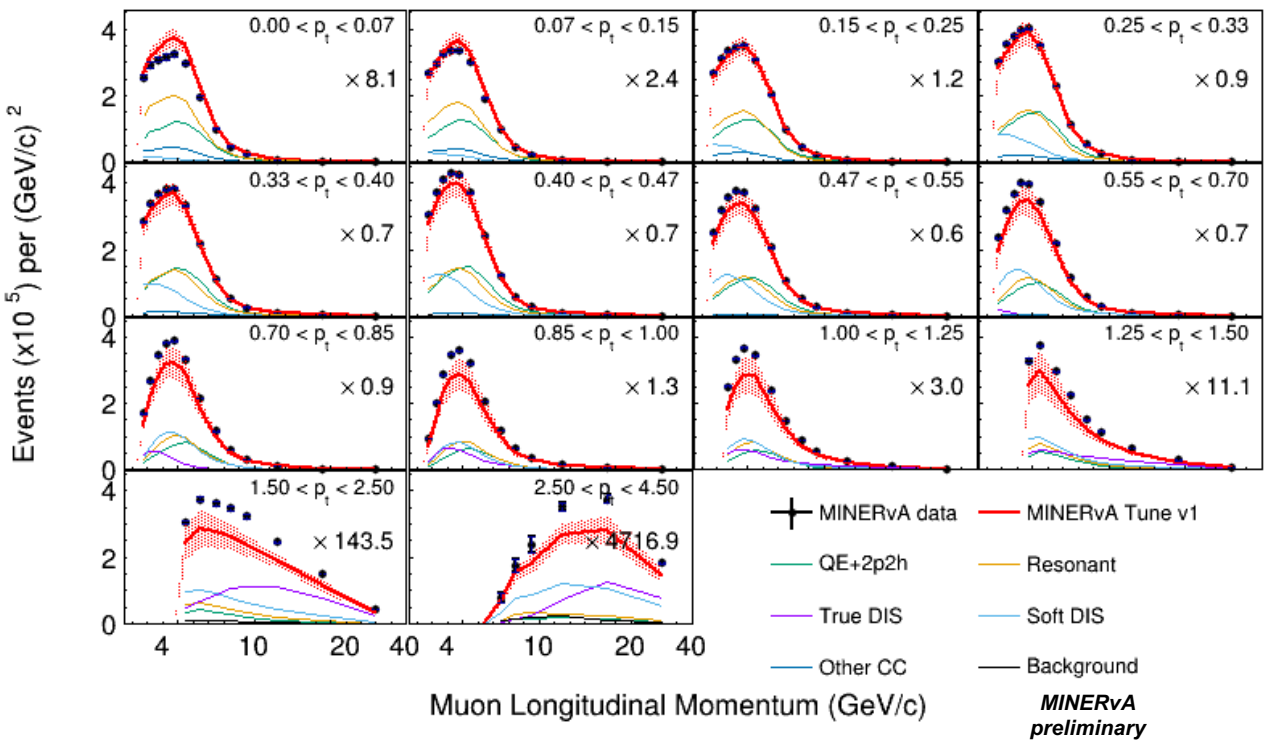
- The reconstructed event samples in both modes

Neutrinos in Neutrino Mode

MINERvA preliminary



Anti neutrinos in Anti Neutrino Mode



MINERvA preliminary

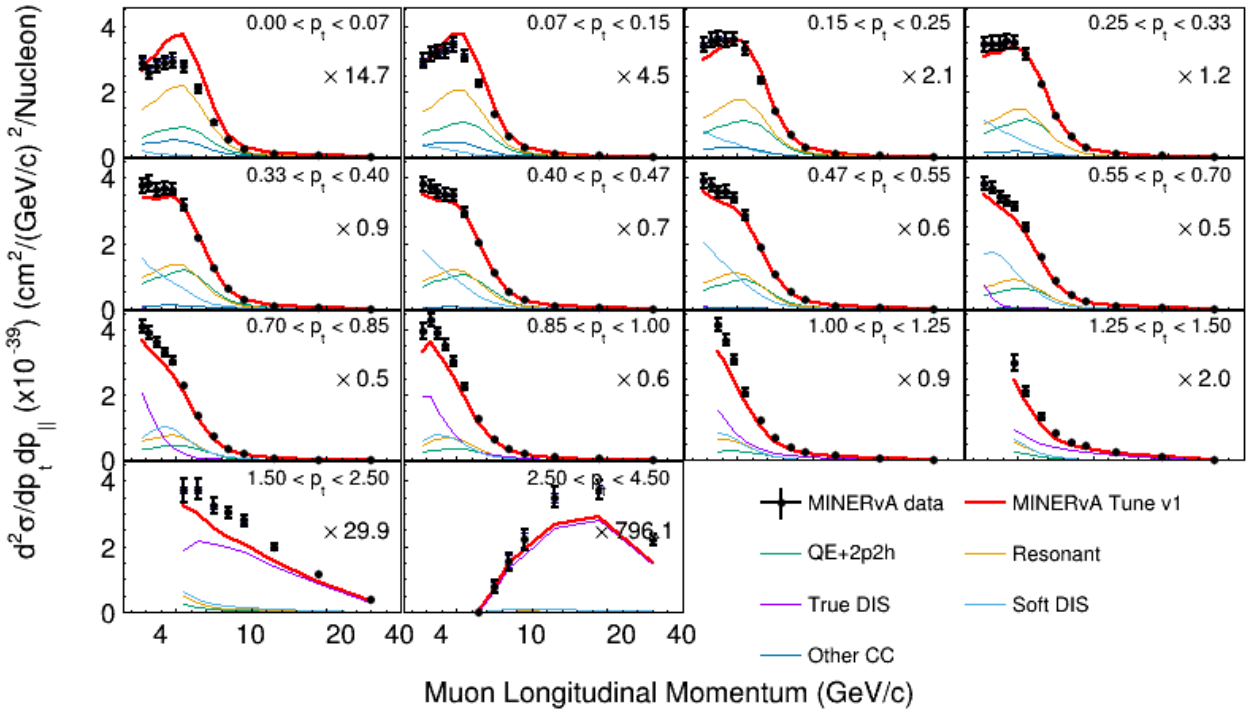
- Smaller backgrounds in neutrino mode

Analysis: Inclusive cross section measurement on CH

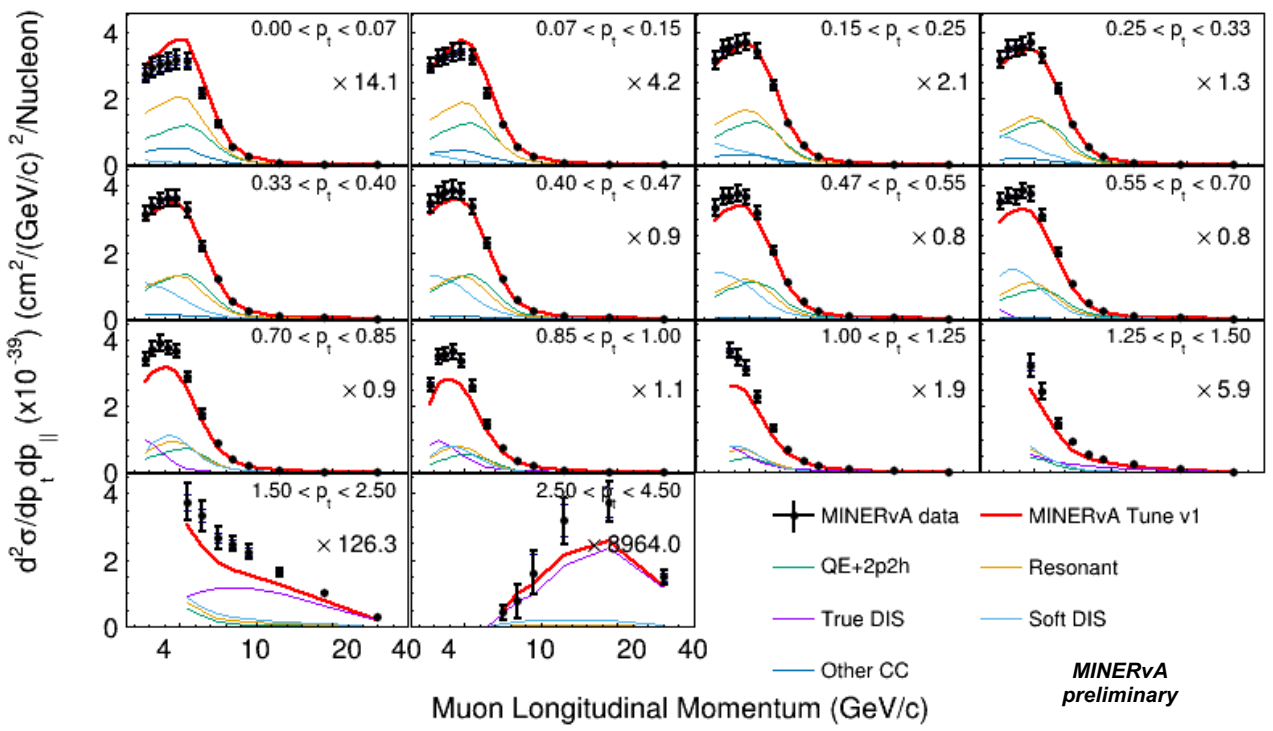
The results: Extracted Cross Section

Neutrinos in Neutrino Mode

MINERvA preliminary



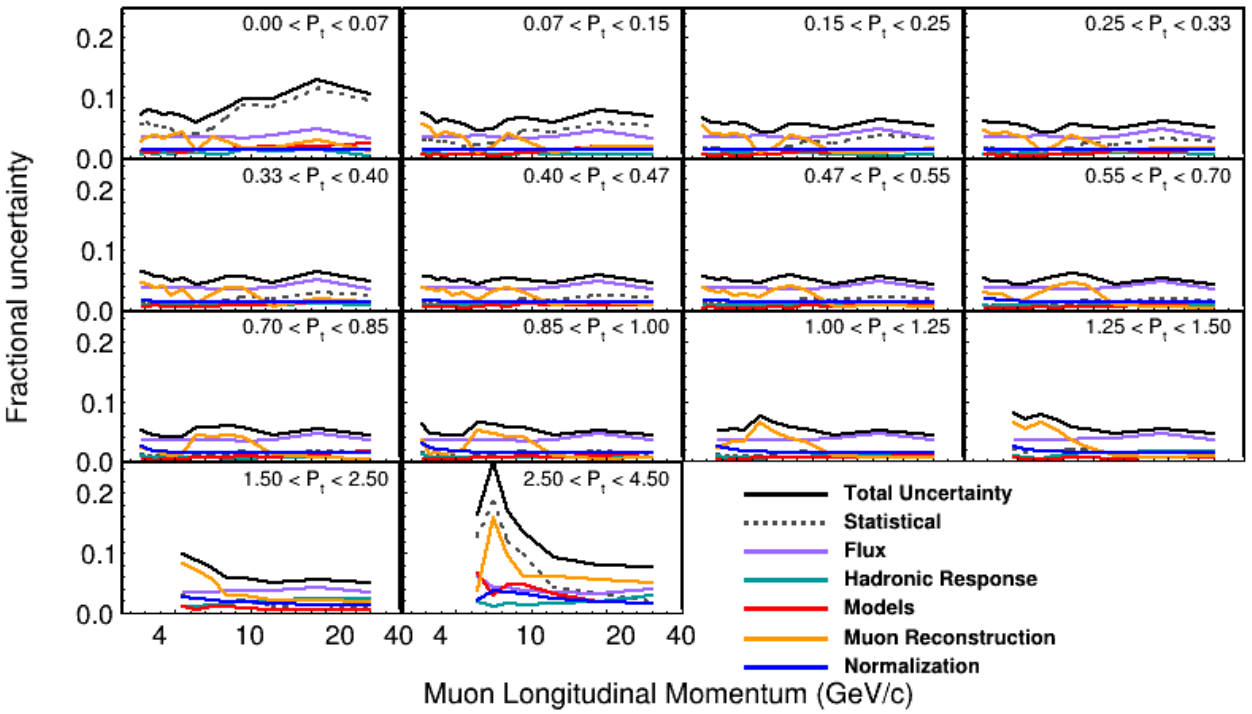
Anti neutrinos in Anti Neutrino Mode



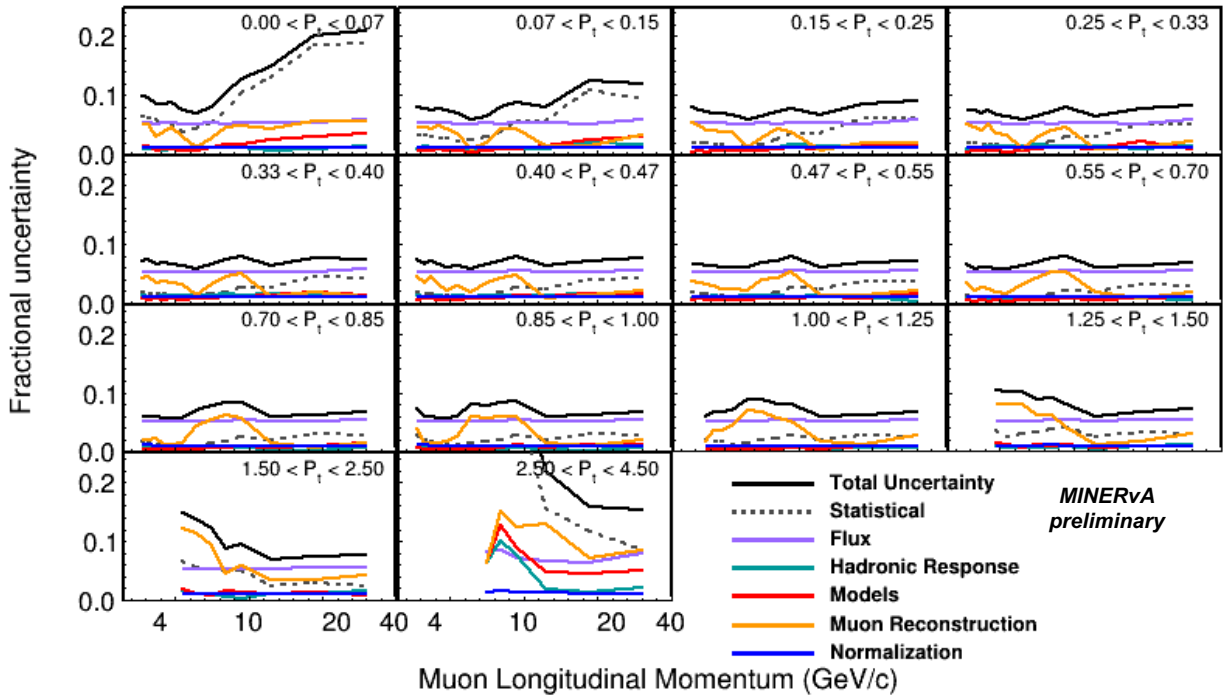
Breakdown of Uncertainties on Cross Section

Neutrinos in Neutrino Mode

MINERvA preliminary



Anti neutrinos in Anti Neutrino Mode

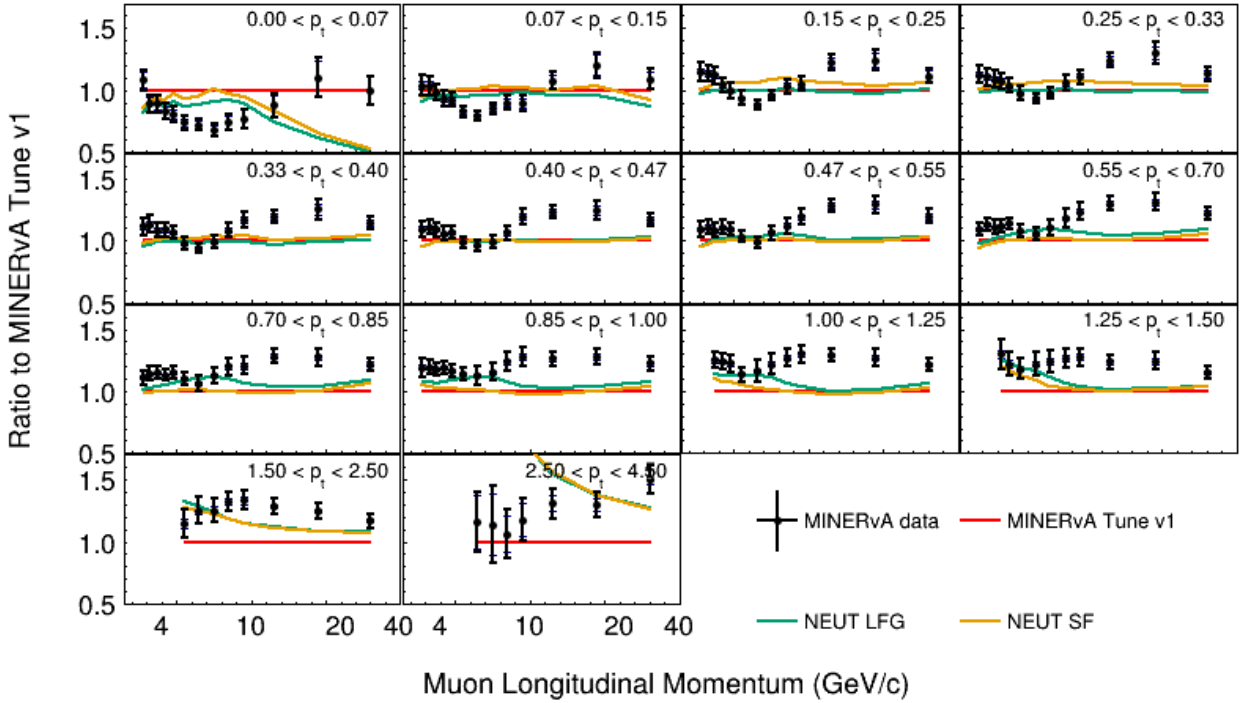


- Flux uncertainties lower in neutrino mode because stronger flux constraint used
- Muon reconstruction uncertainties similar because those don't depend on the charge of the muon getting reconstructed

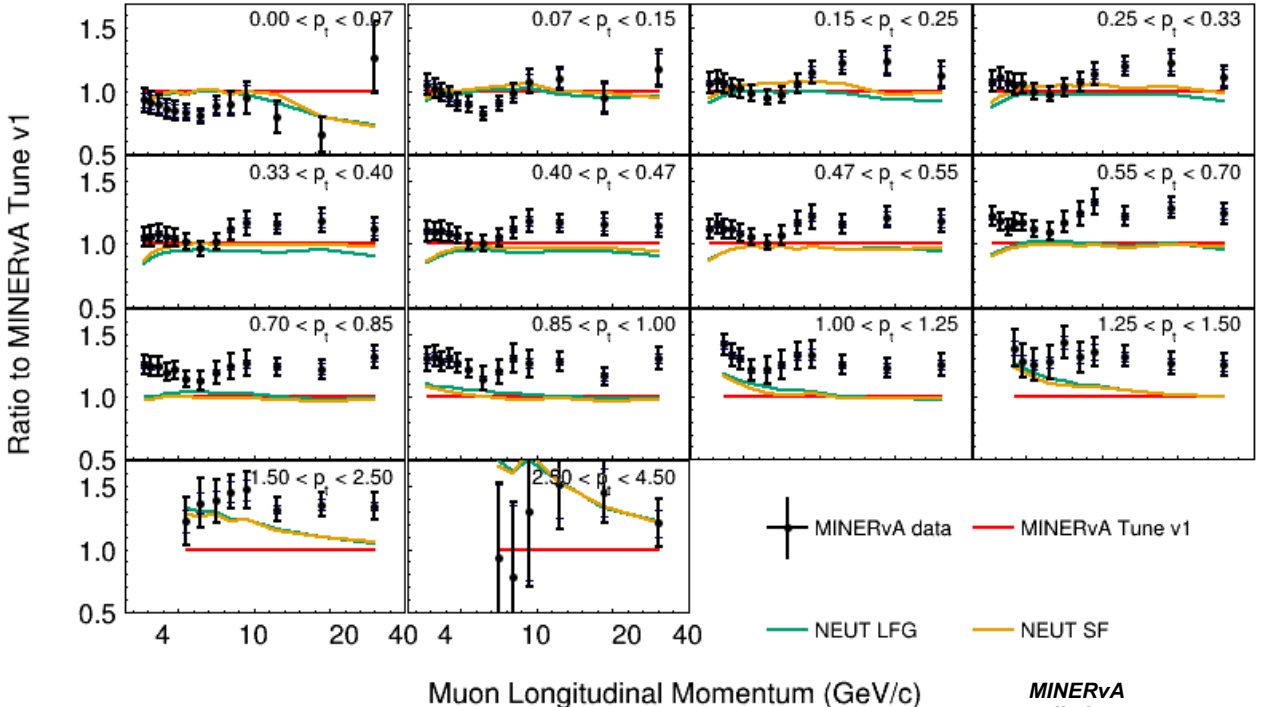
Model Comparisons: NEUT

Neutrinos in Neutrino Mode

MINERvA preliminary



Anti neutrinos in Anti Neutrino Mode

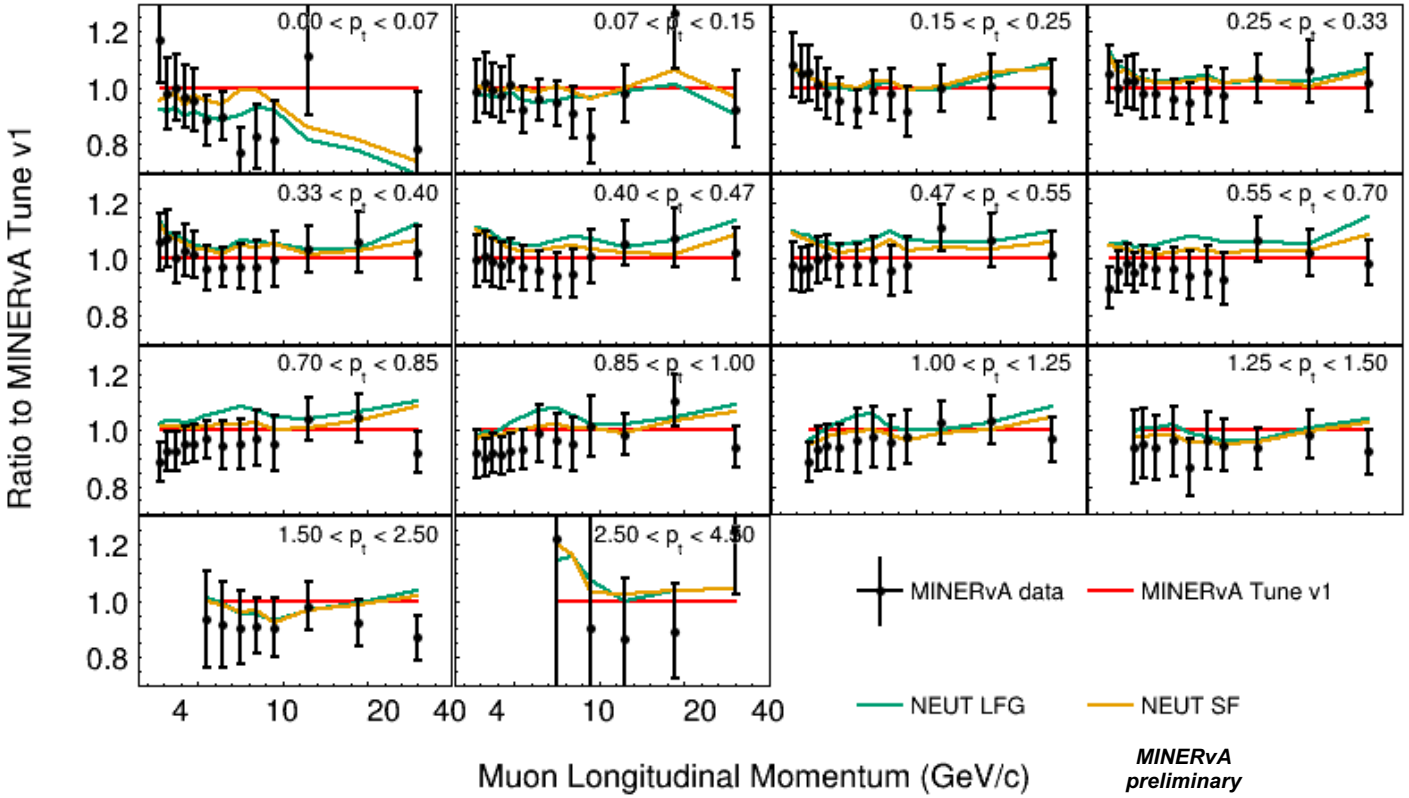


MINERvA preliminary

- Models need improvement in both modes

Model Comparisons: Neutrino to Anti neutrino cross section ratio

Neutrino to anti neutrino xsec ratio



- Models appear to be doing a **better job of capturing the neutrino to anti neutrino cross section ratio** than of capturing either cross section by itself

Conclusion

- We measured the double differential inclusive charged current cross section on hydrocarbon in both modes
- Will publish the neutrino to anti neutrino cross section ratio soon

Backup

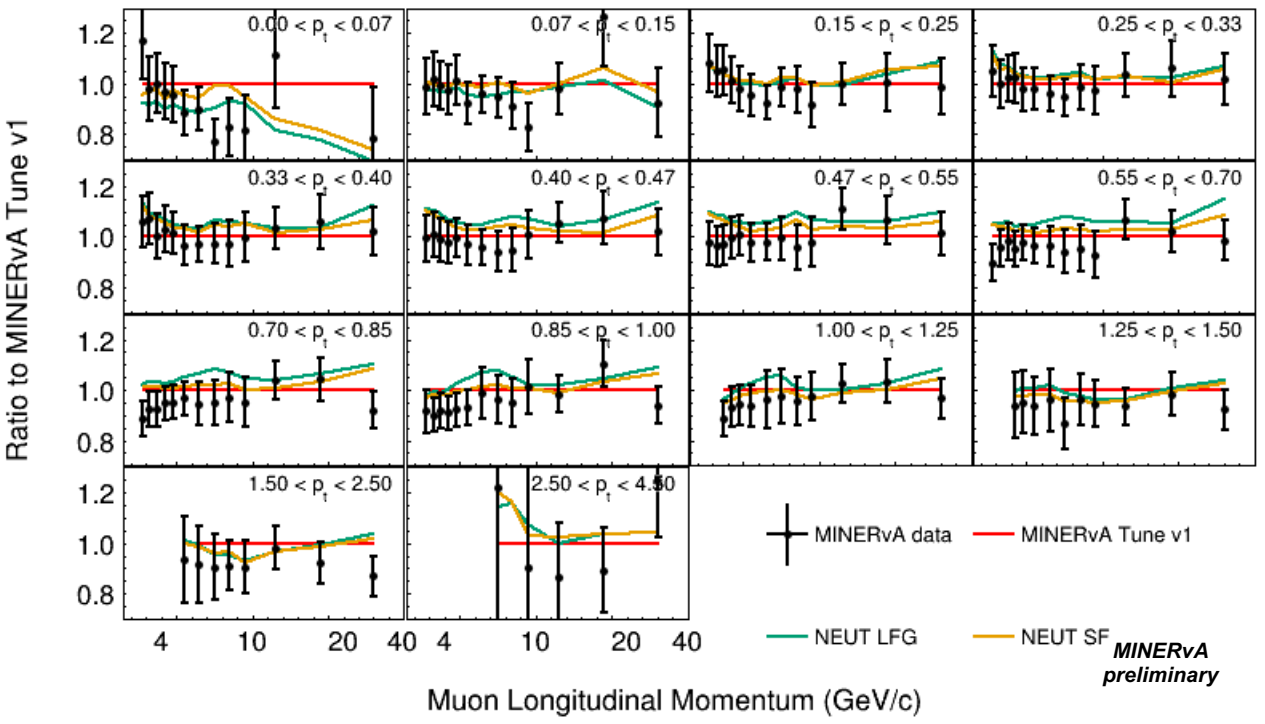
Comparison of Chi2

Process Variant	Chi2 for neutrino to anti neutrino ratio fit to the ratio predicted by other models	Chi2 for anti neutrino mode
NEUT LFG	2434.3	5835.8
NEUT SF	1418.6	6355.4
GENIE RFG hA	1400.8	1965.2
GENIE RFG hN	1392.5	1972.1
GENIE LFG hA	1364.8	2206.8
GENIE LFG hN	1358.4	2187.8
MINERvA Tune v1	705.6	2734.7

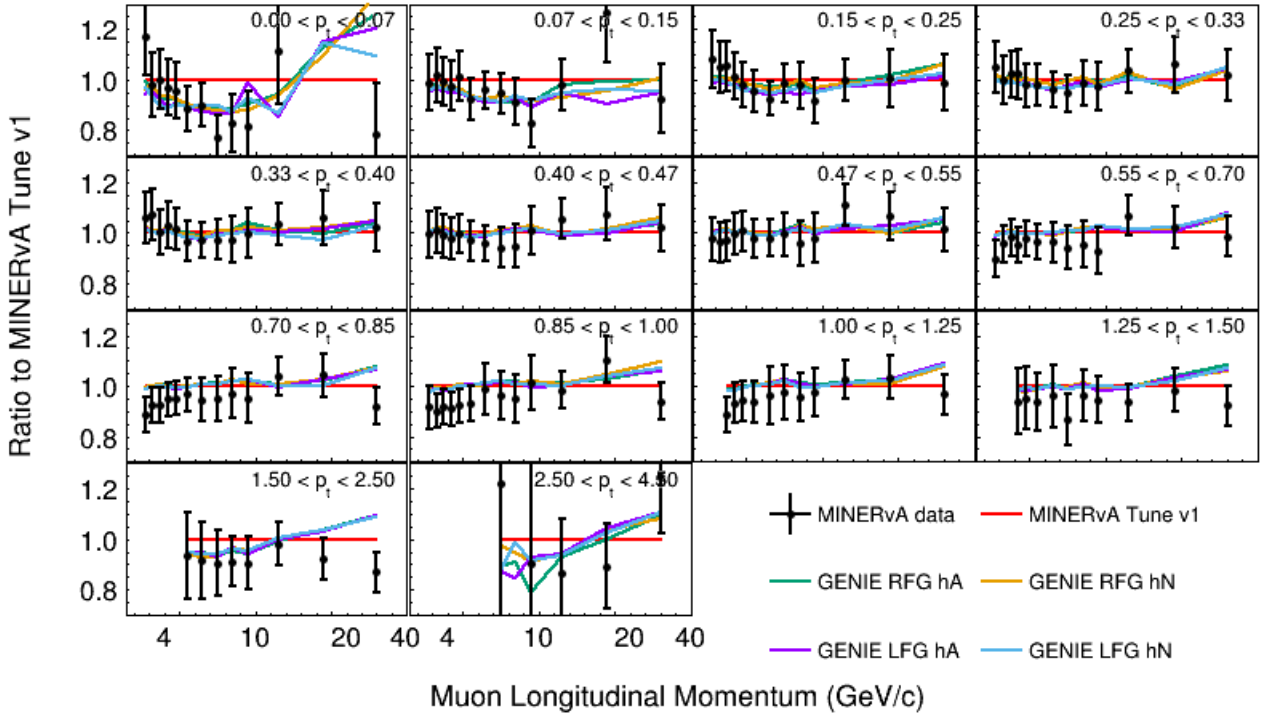
- NDF = 192
- Models appear to be doing a better job of capturing the neutrino to anti neutrino cross section ratio
- Out of these fits, MINERvA Tune v1 doing the best job

Model Comparisons: Neutrino to Anti neutrino cross section ratio

Neutrino to anti neutrino xsec ratio



Neutrino to anti neutrino xsec ratio



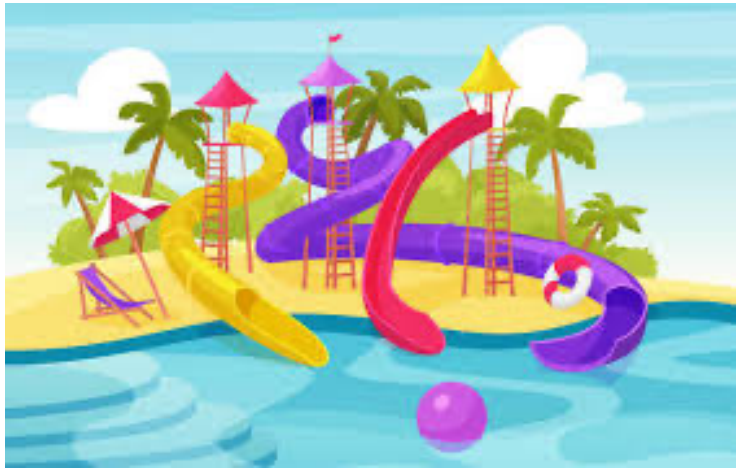
- Models appear to be doing a better job of capturing the neutrino to anti neutrino cross section ratio

Backgrounds

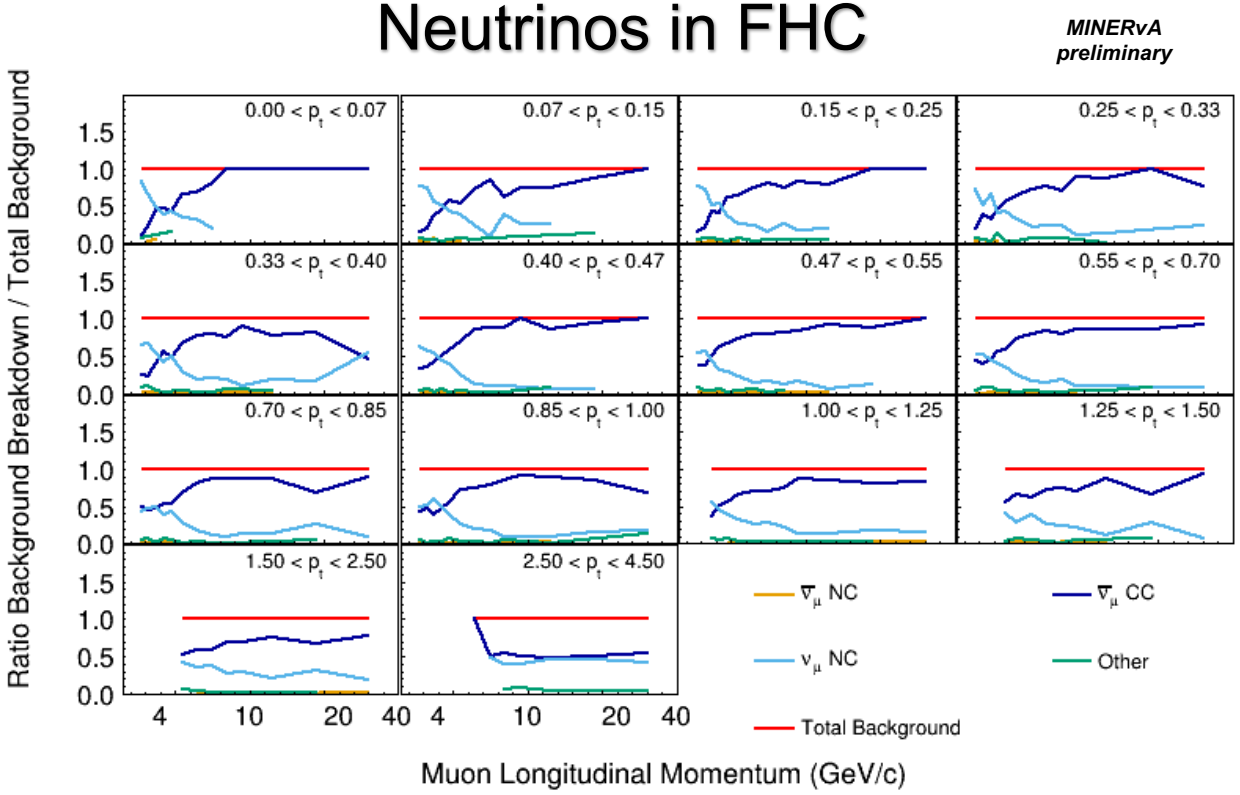
Backgrounds: Events that get reconstructed as signal but are not signal

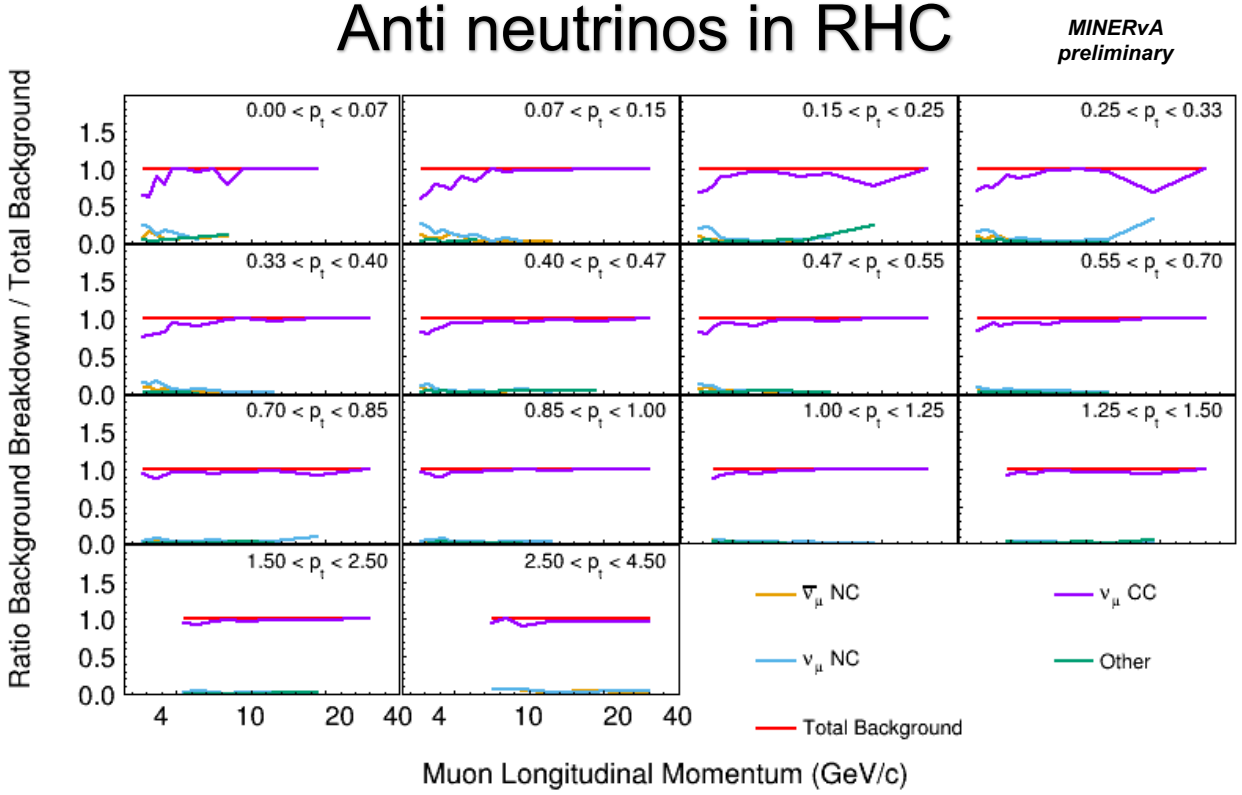
Stemming from 2 major sources:

- the wrong sign backgrounds are the contaminated kids that ARE MISMEASURED, most of the wrong sign neutrinos are really rejected by the helicity cut
- Neutral current backgrounds from events getting included in our sample that are not from the specific 'slides' (interaction channels) we were looking at



Let's look at the background breakdown in each mode





- Backgrounds in anti neutrino mode are mainly wrong sign because of the neutrino cross section being higher