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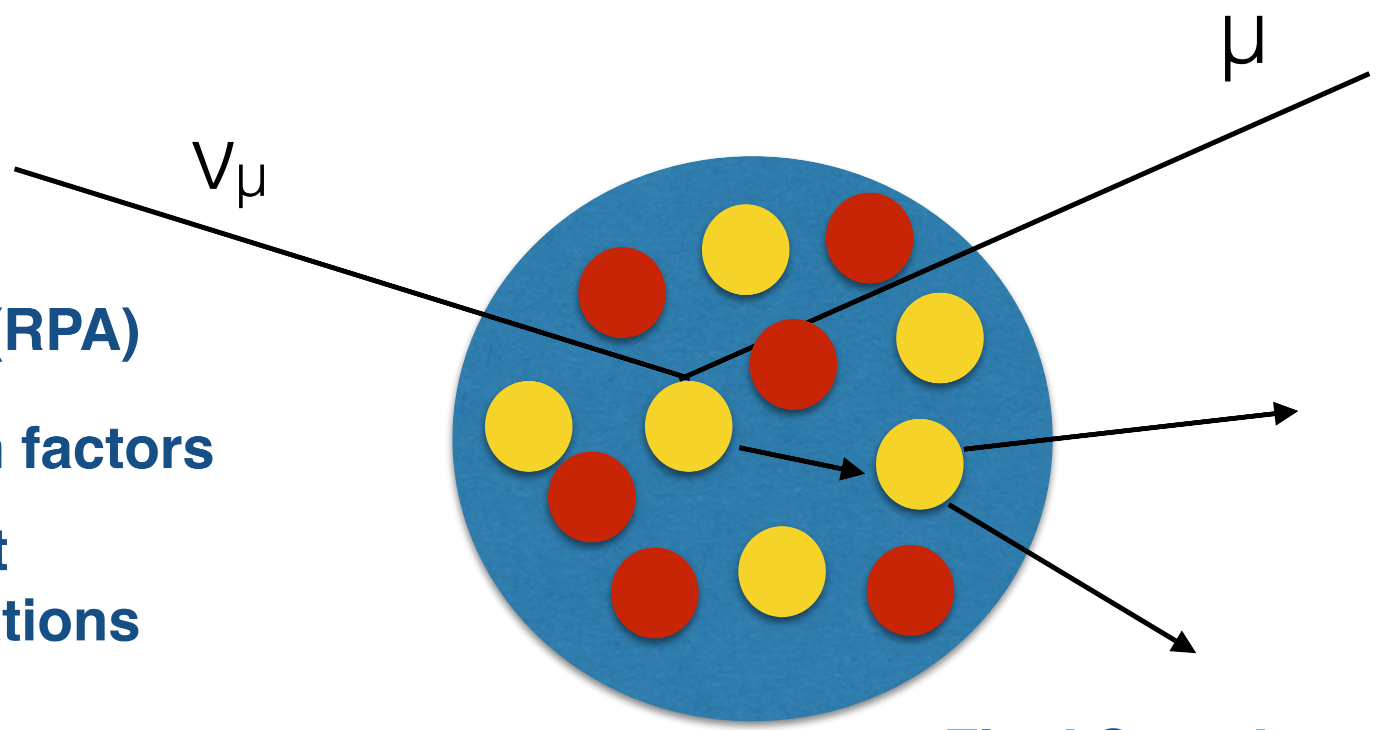
Newest Cross Section Results from MINERvA

Minerba Betancourt (Fermilab) on behalf of the MINERvA collaboration
18 September 2024

NuFact 2024

Introduction

- Understanding neutrino interactions is challenging
- Modeling the interactions and measuring them present different types of challenges



Nuclear long range correlations (RPA)

Nucleon form factors

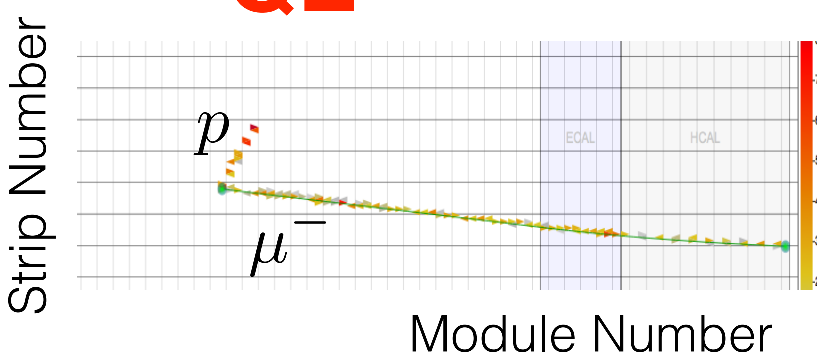
Nuclear short range correlations

Meson Exchange Currents (MEC=2p2h)

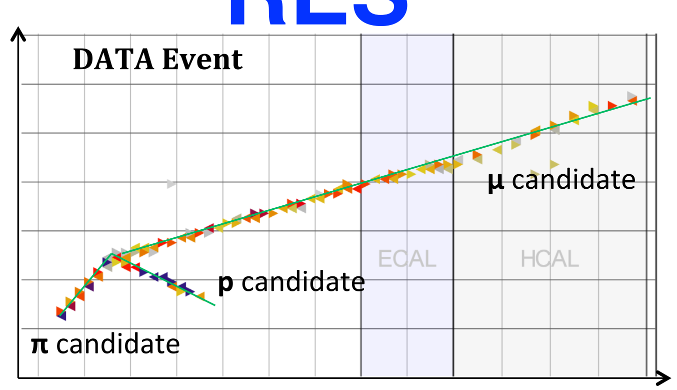
Fermi motion
Pauli blocking
Removal Energy

Final State Interactions

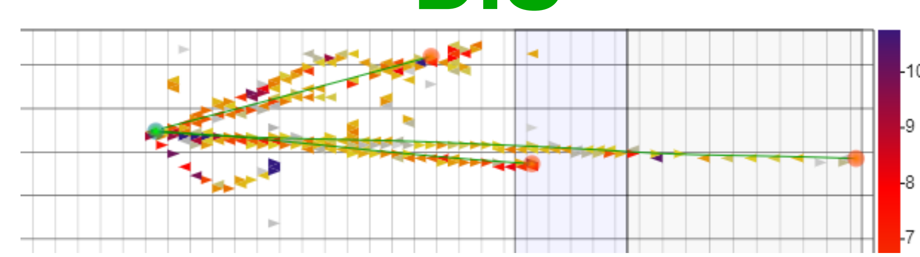
QE



RES



DIS



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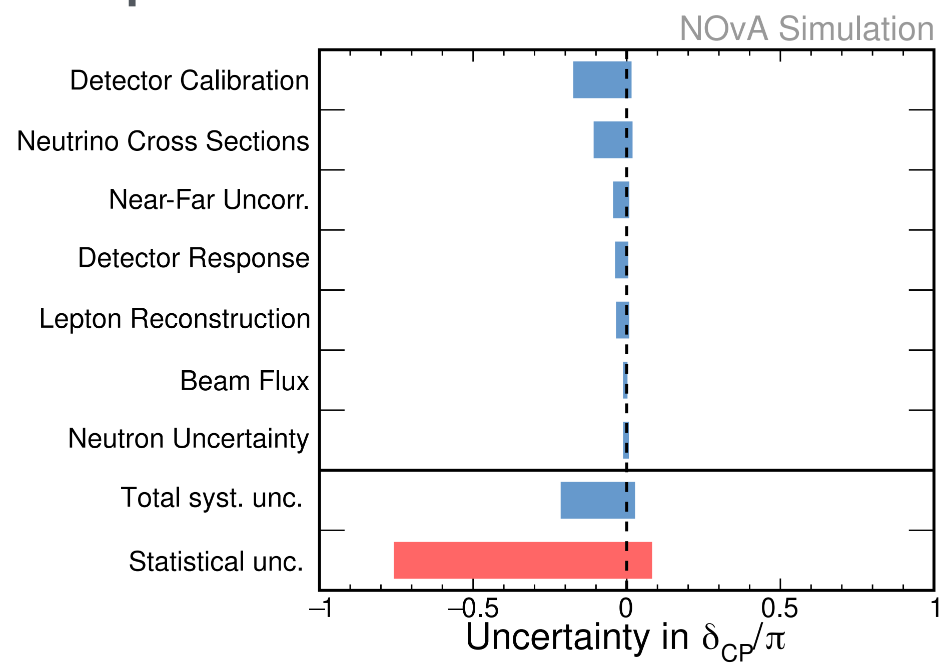
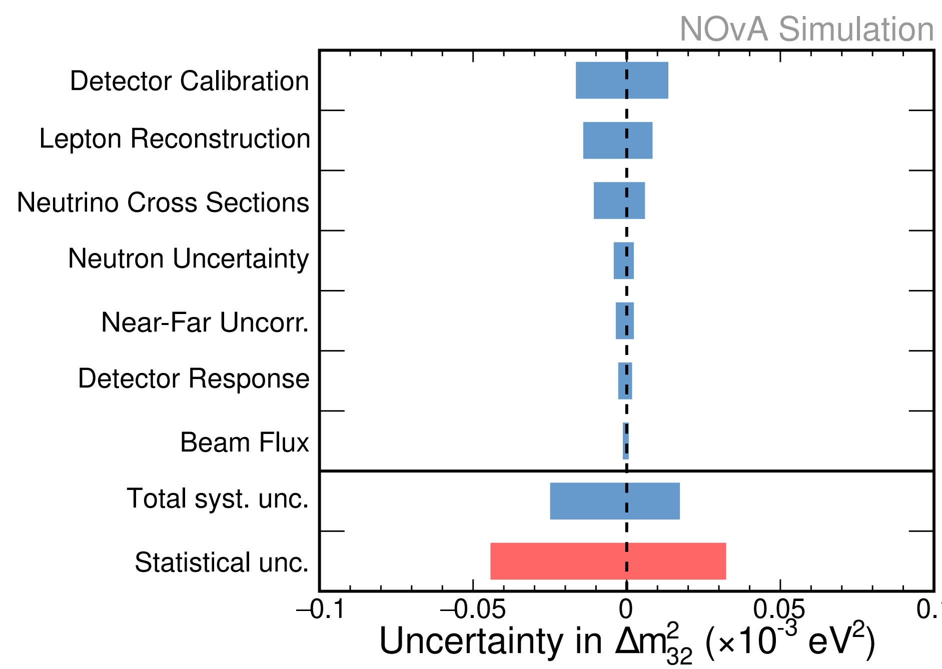
The State of Systematics for Oscillation Experiments

- Detailed understanding of neutrino interactions is critical for oscillation experiments





E. Catano, Fermilab JETP

Event counts at the Far Detector

Sample	T2K	NOvA	Hyper-Kamiokande	DUNE
N_μ^{rec} FHC	318	211	10000	7000
N_μ^{rec} RHC	137	105	14000	3500
N_e^{rec} FHC	108	82	3000	1500
N_e^{rec} RHC	16	33	3000	500

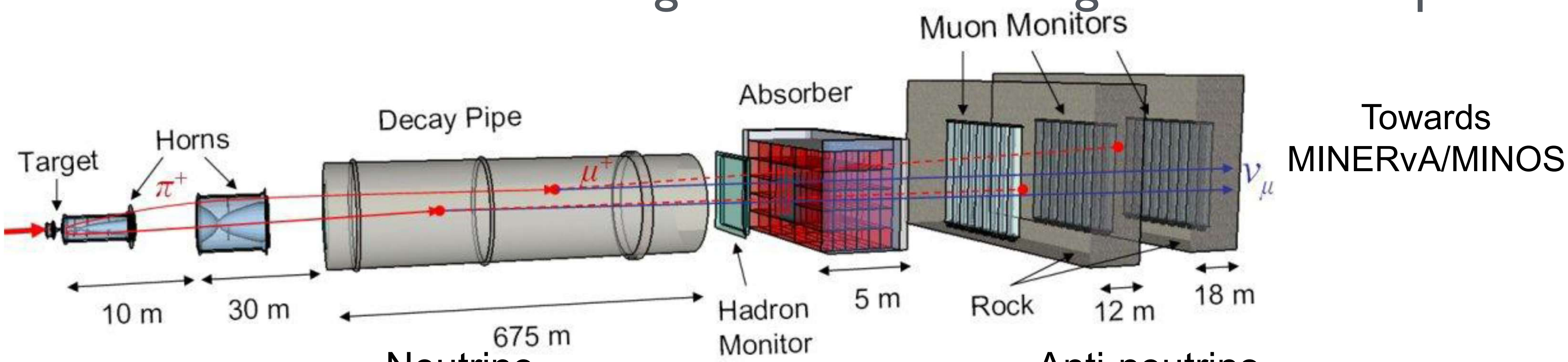
Clarence Wret, Nuint 2024

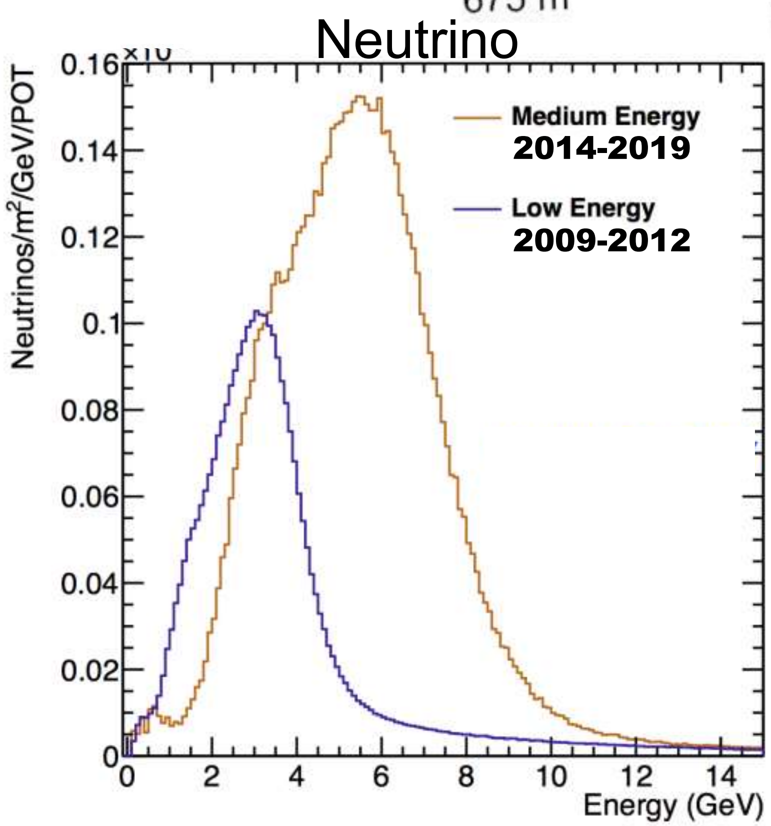
HK and DUNE will have enough events to be limited by cross section systematics

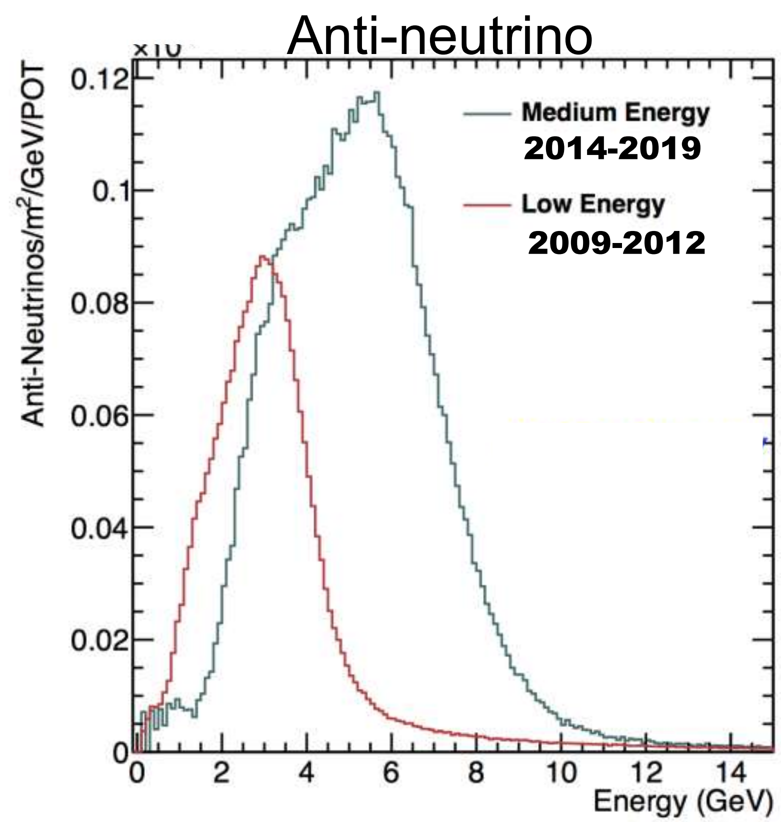
- Many measurements available, but we still have a lot to learn/understand from neutrino interactions: pions, transition between SIS and DIS, nuclear effects for Ar, neutrons…)

NuMI Beamline

- Several measurements including new ν-e scattering and low ν shape constraints



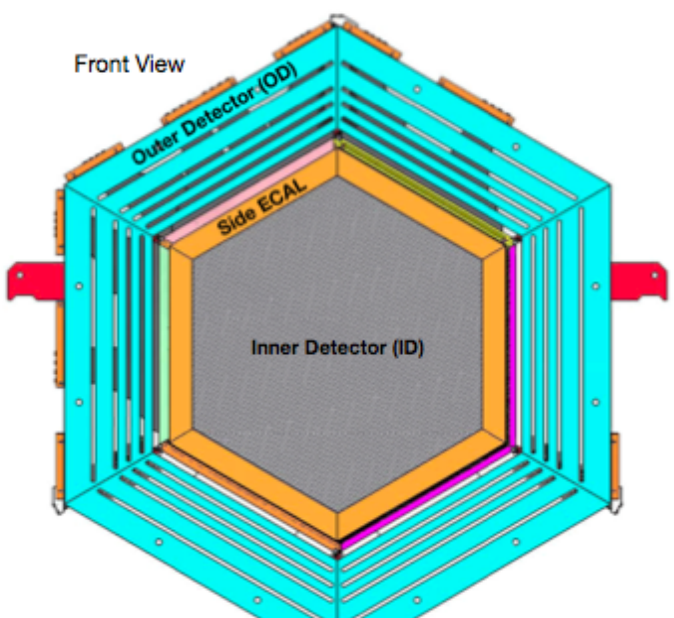


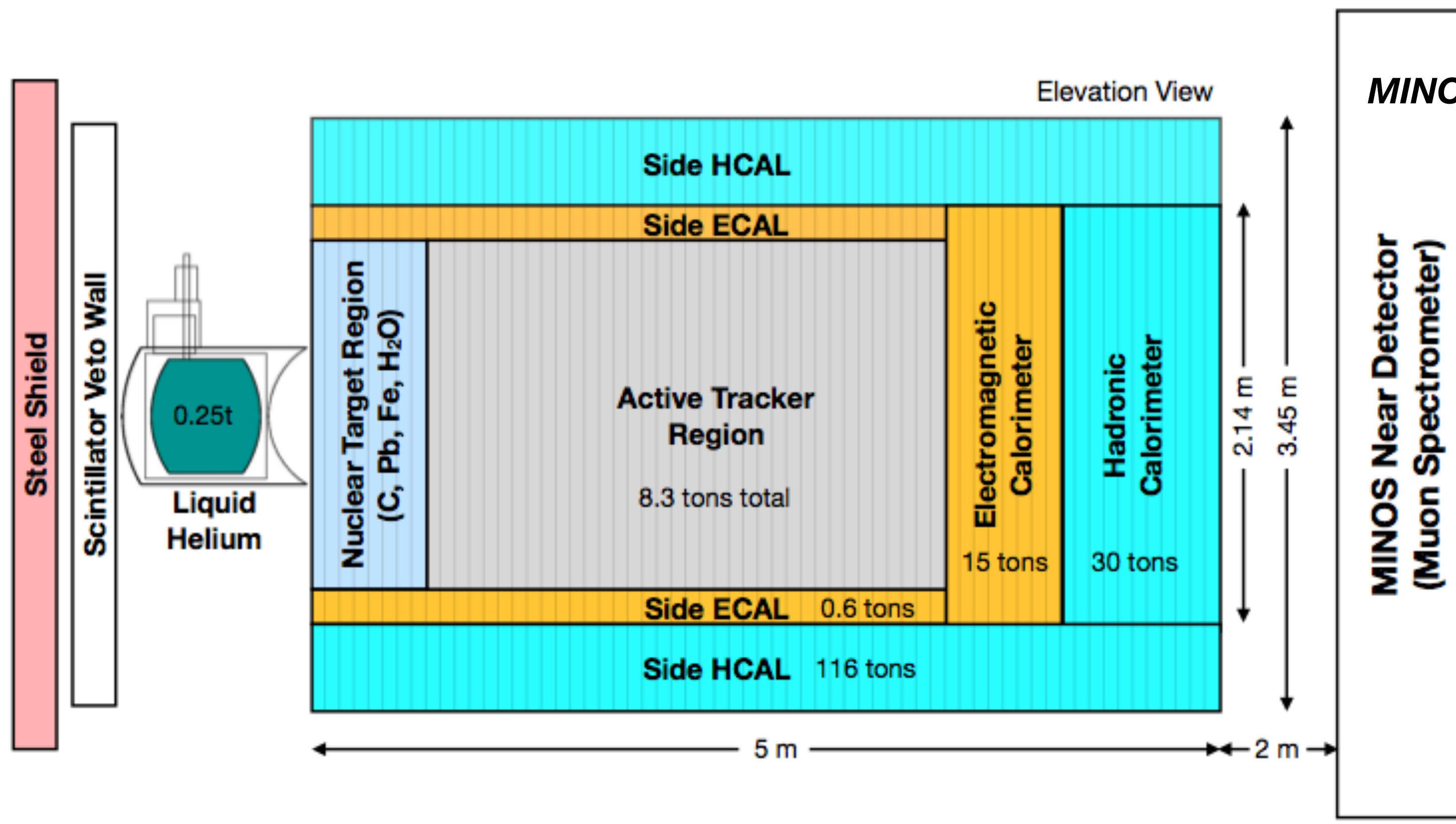


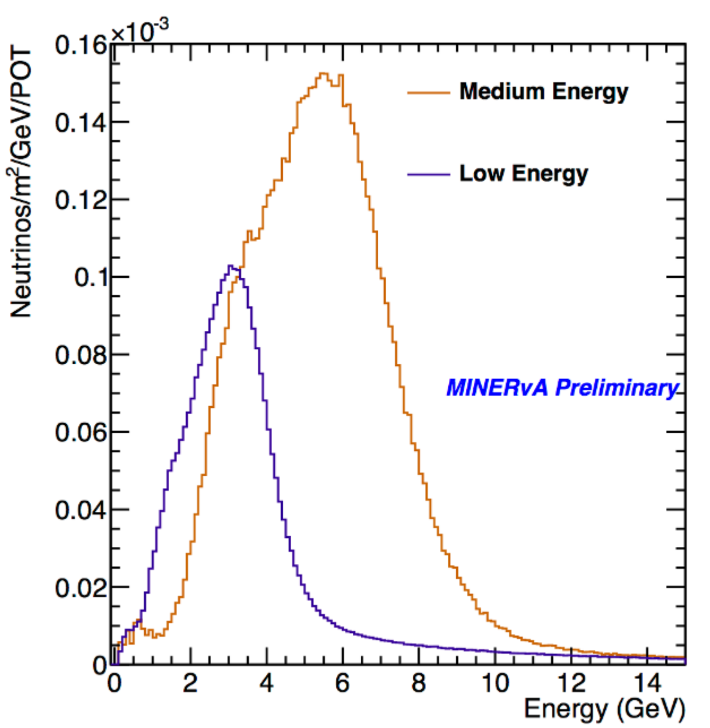
L. Zazueta et al., Phys.Rev.D 107 (2023) 1, 012001, D. Ruterbories et al., Phys.Rev.D 104 (2021) 9, 092010, A. Bashyal et al., JINST 16 (2021) P08068, E. Valencia et al., Phys. Rev. D 100, 092001 (2019). L. Aliaga, M. Kordosky, T. Golan et al, Phys. Rev. D 94, 092005

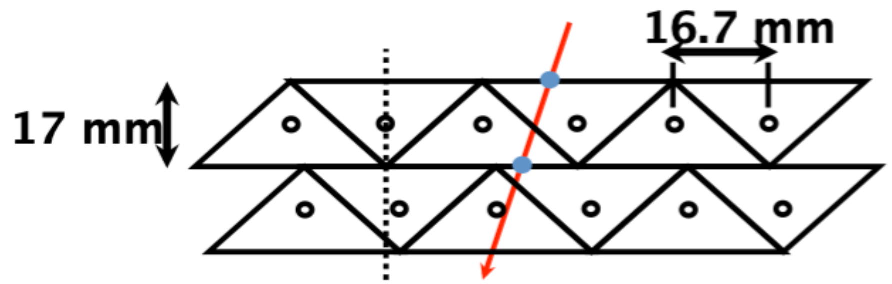
Studying Nuclear Effects in MINERvA

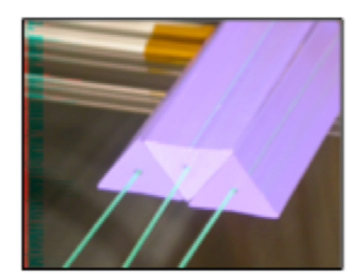
- Fine-grained scintillator tracker surrounded by calorimeters
- MINERvA has different nuclear targets iron, lead, carbon, helium, and water











Three views of scintillator bars give unambiguous 3D track reconstruction

Design, calibration, and performance of the MINERvA detector

Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

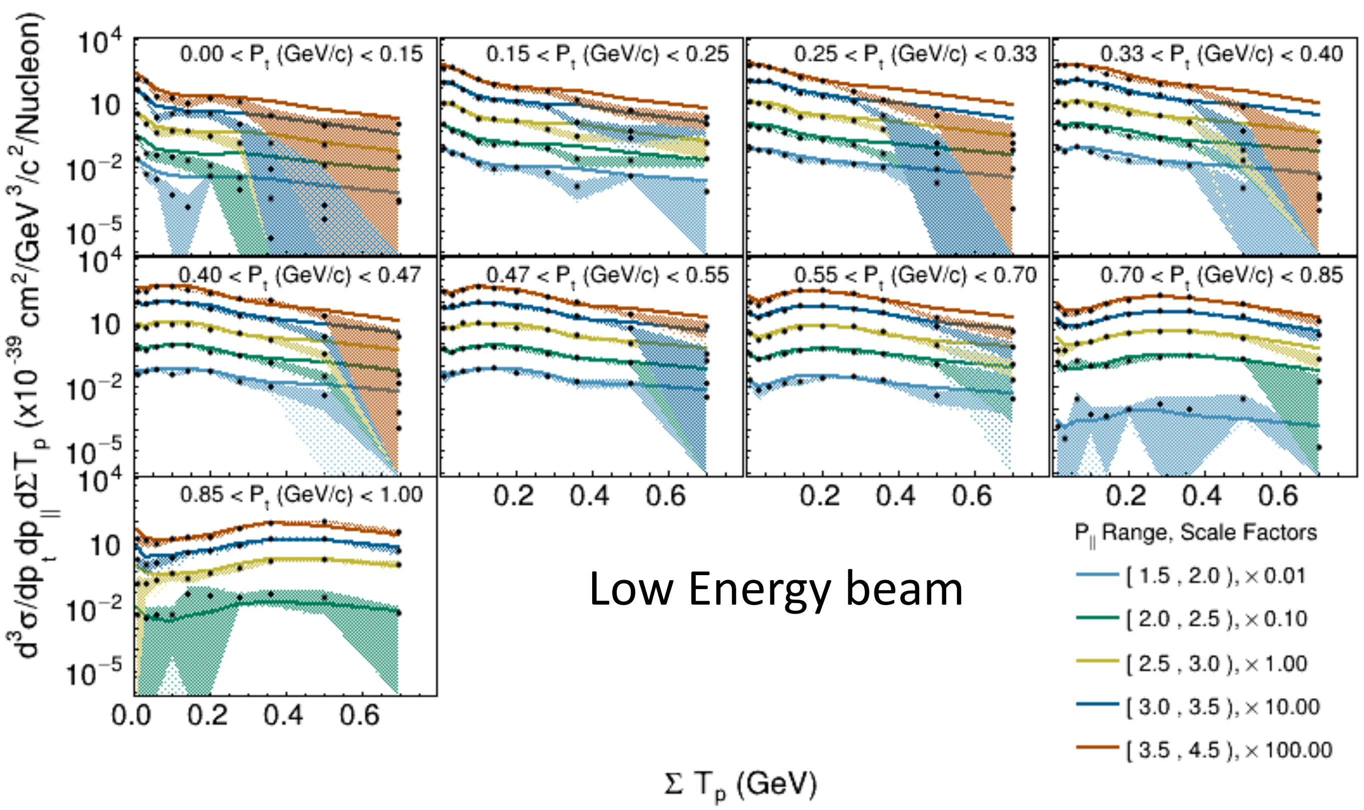
CC0π Muon Neutrino Measurements:

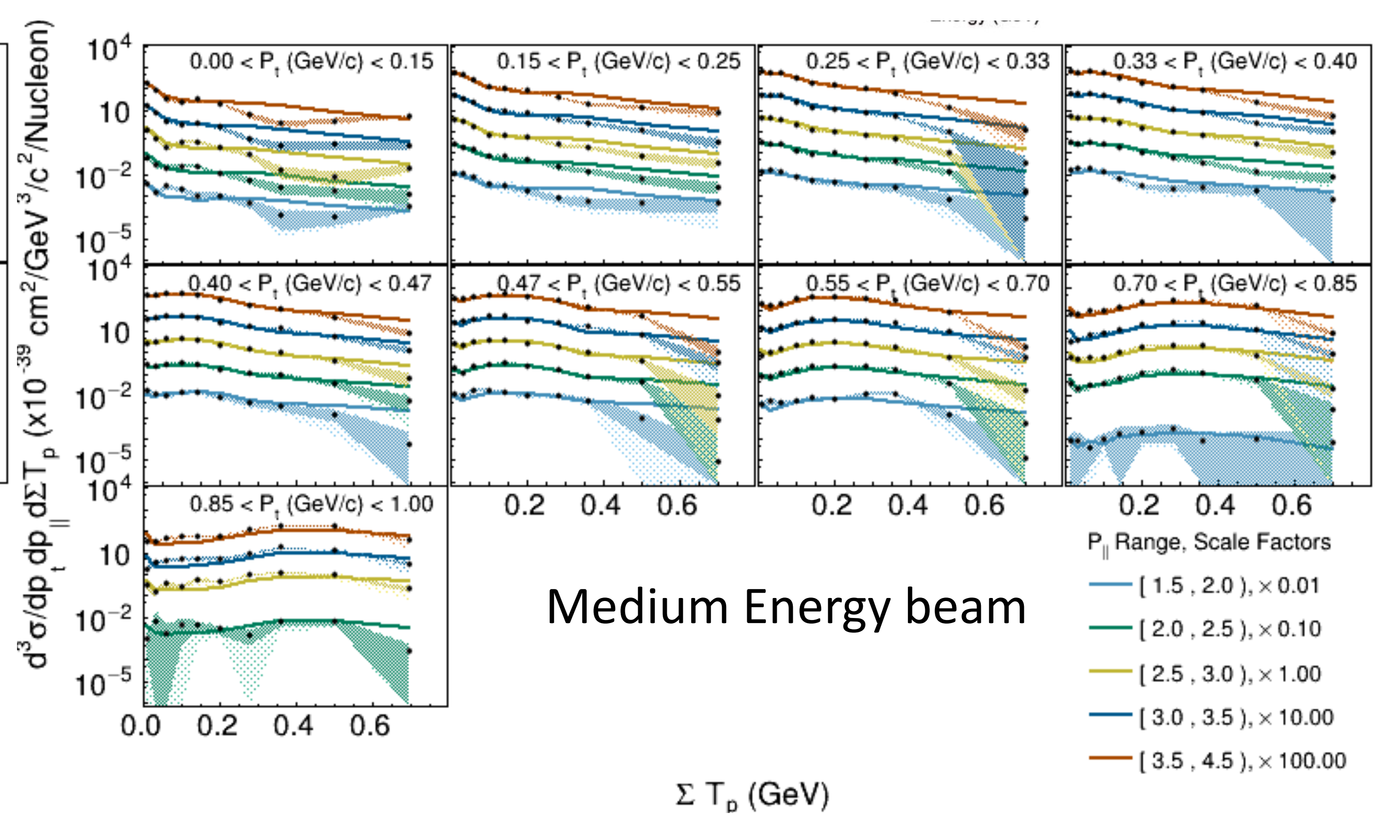
- Triple Differential cross section in Scintillator with Low and Medium energy
- Double differential cross section in the nuclear targets: water, CH, Carbon, Iron and Lead

Multi Neutrons Cross Section with Antineutrinos

Triple-Differential Cross Sections in both Low and Medium

- Quasielastic-like interactions, as function of muon transverse, longitudinal and hadronic energy
  - Alternative variables similar to those used in oscillation experiments get the neutrino energy
- Conclusions from these measurements:
  - Resonant pion production contributes a larger fraction of events at medium energy compared to low energy
  - There is a significant different in average recoil between the two datasets at the lowest Pt
  - At high Pt, low $\sum$Tp continue to observe MC-data differences. A region with large FSI effects
  - Low Tp has over prediction at higher $\sum$Tp



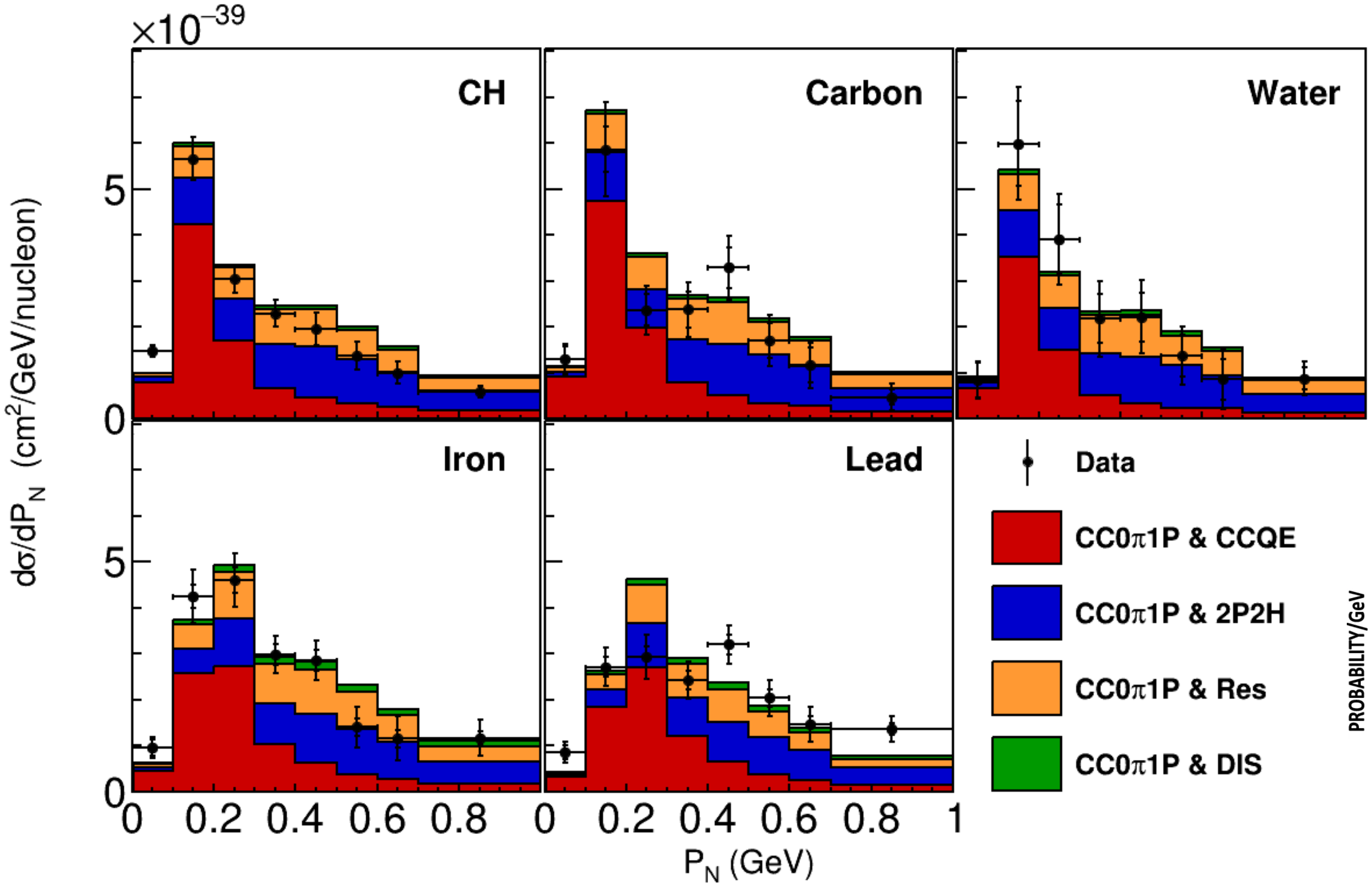


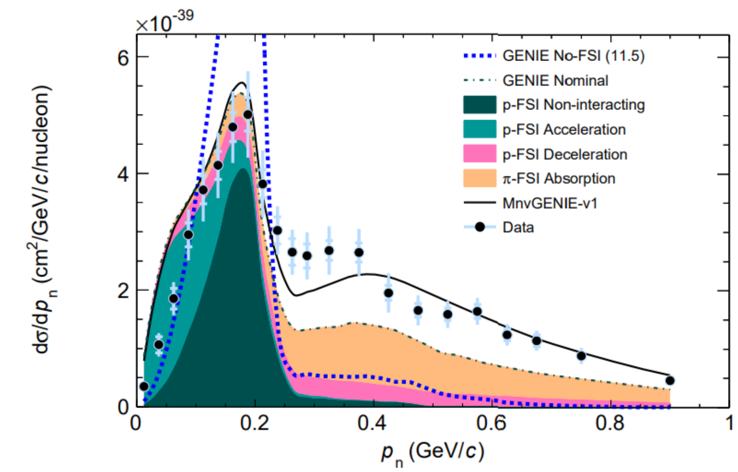
D. Ruterbories, NuINT 2024

Measurement of A-scaling of Nuclear Effects in Quasielastic-like

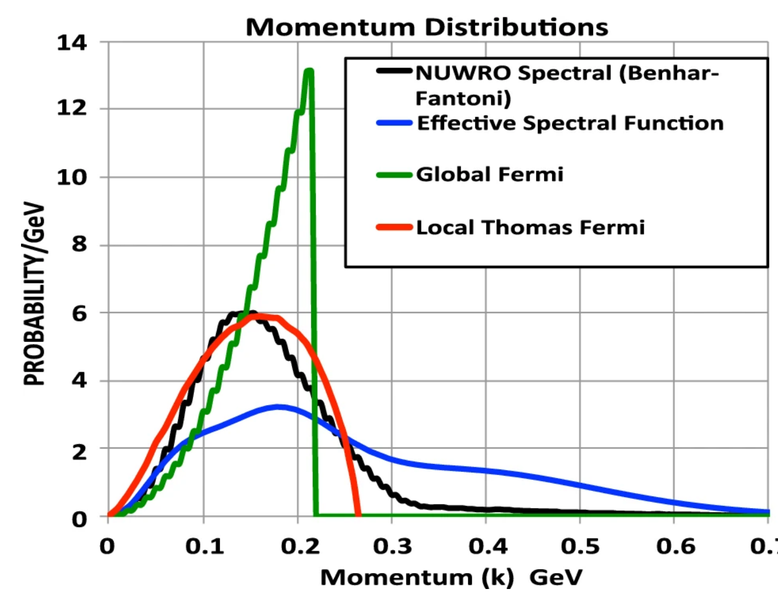
- New detailed measurements to study many nuclear processes: proton P loss, proton deflection, pion absorption, Fermi momentum, binding energy, final state interactions…

$$P_n \equiv \sqrt{\delta P_T{}^2 + \delta P_L{}^2}$$





Phys. Rev. Lett. 121, 022504 (2018)



Muon

- angle w.r.t. beam < 17 deg
- momentum between 2-20 GeV/c

Proton

- angle w.r.t. beam < 70 deg
- momentum between 500-1100 MeV/c

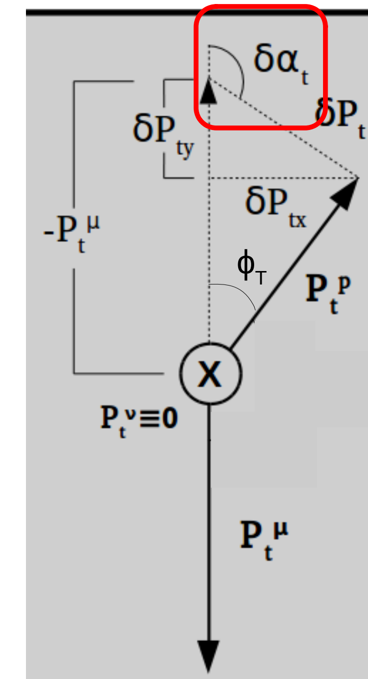
No mesons (pions)

Any number of nucleons

No heavy baryons

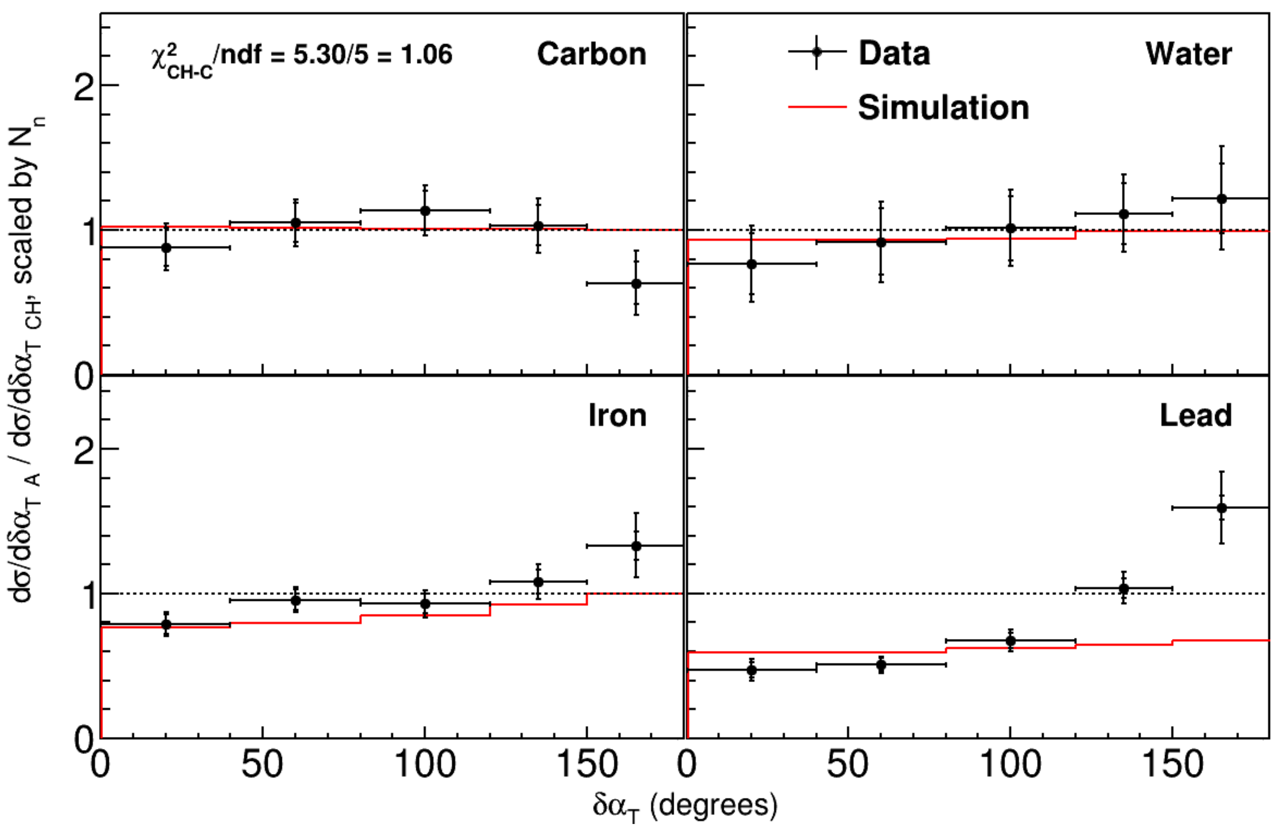
Jeffrey Kleykamp, Fermilab JETP

New CC-0pion Measurements in the Nuclear Targets

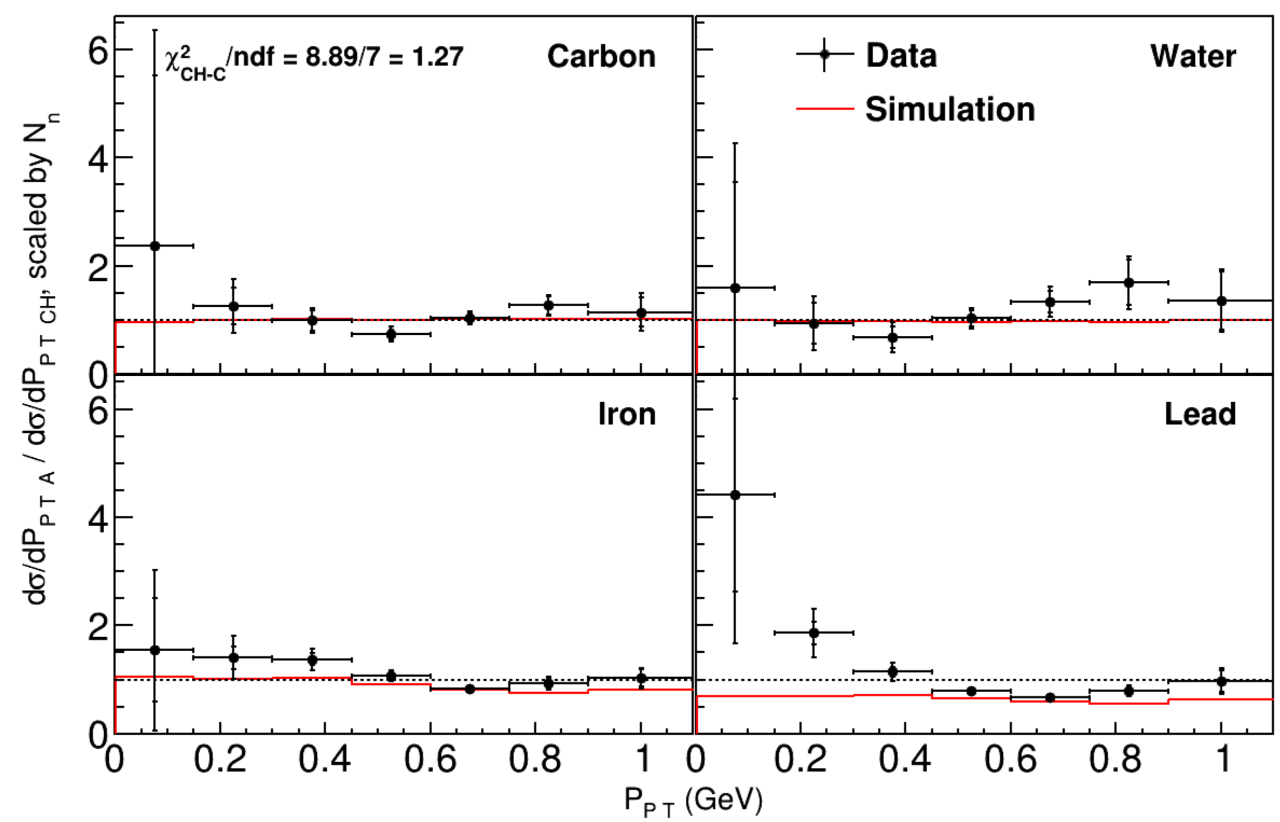


- Very rich dataset sharing same detector and flux, canceling out systematic uncertainties
- Several cross section measurements in print, seven transverse kinematic imbalance, three as a function of muon and proton kinematics across five nuclear targets (C, CH, iron, lead and water)

$\delta\alpha_T$



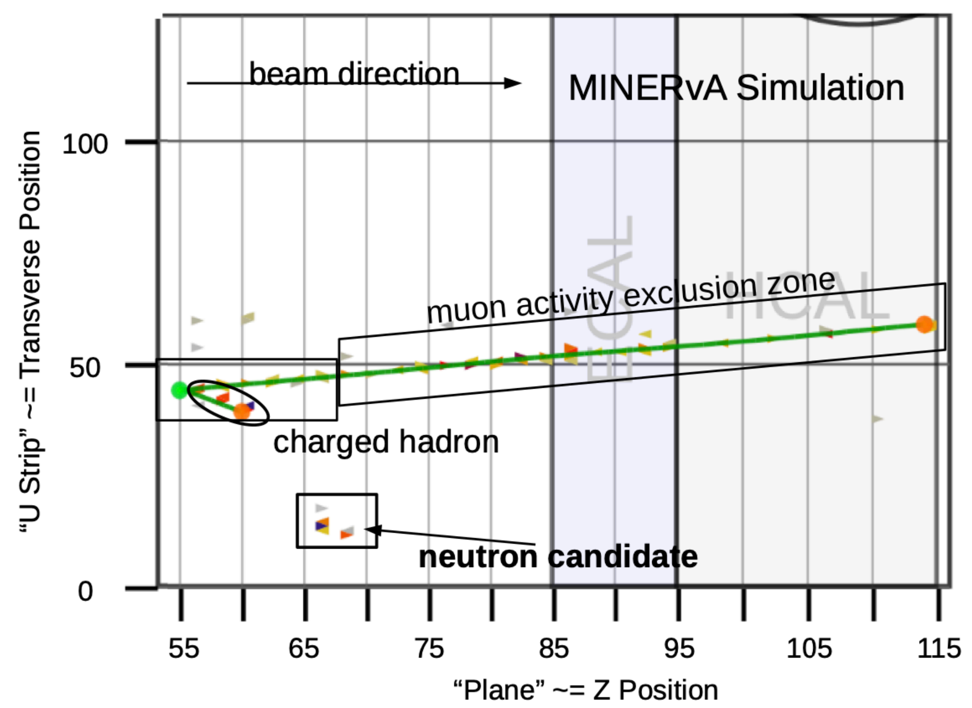
Proton Transverse Momentum

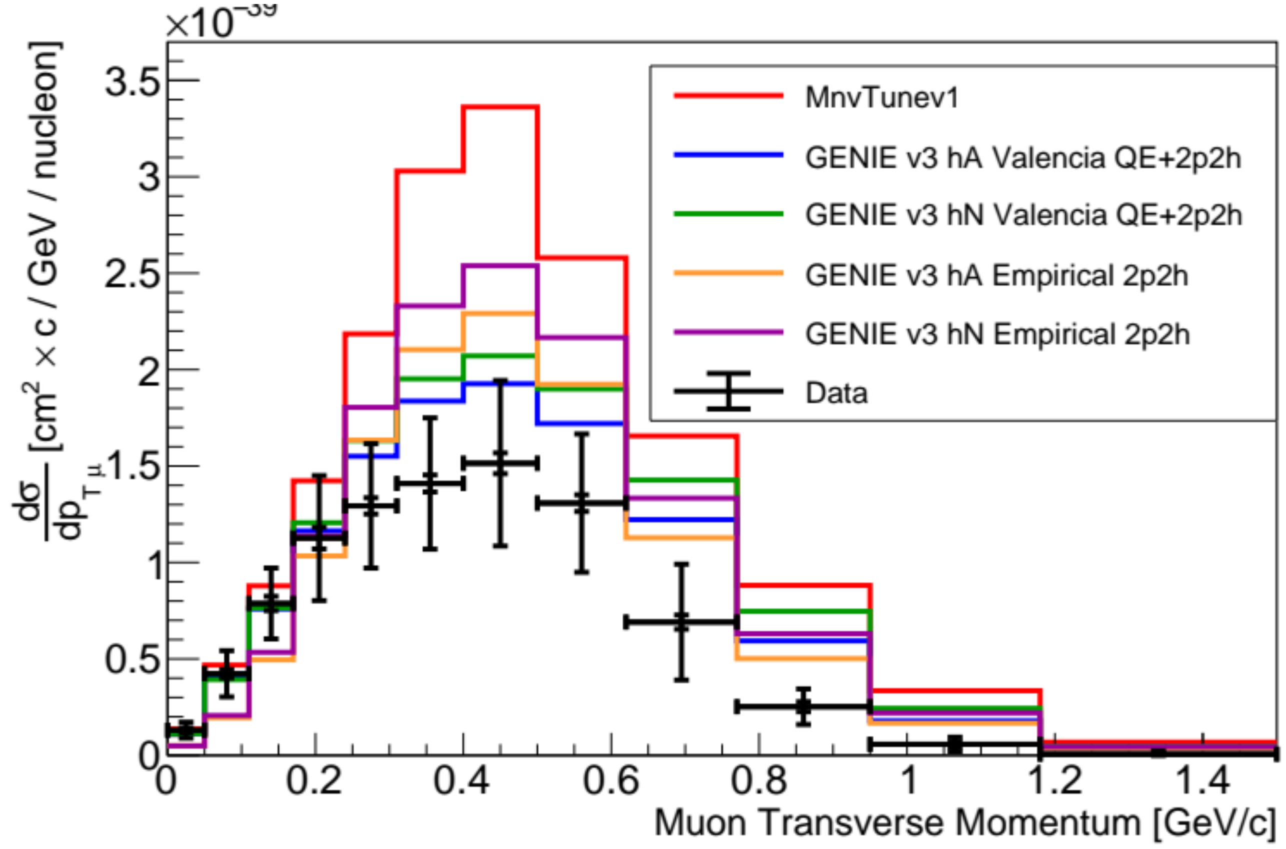


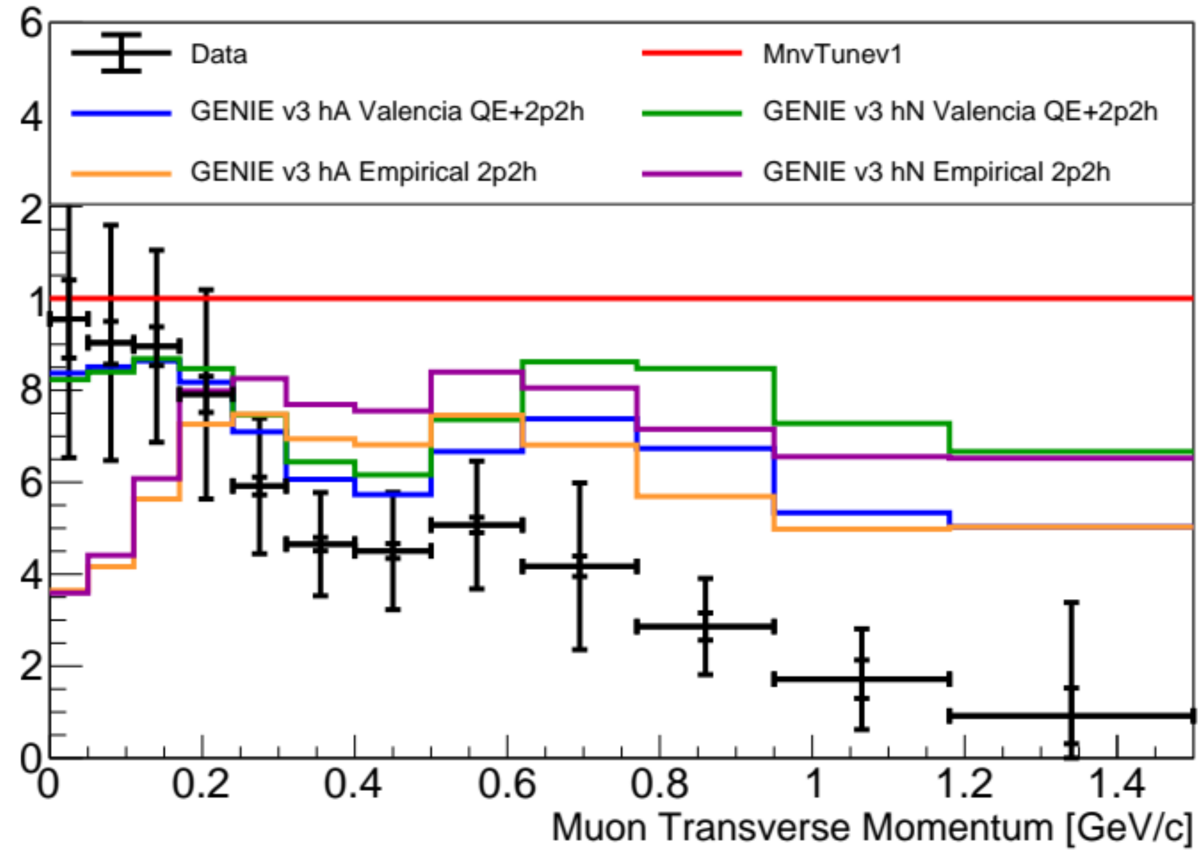
Jeffrey Kleykamp, Fermilab JETP

Multi-Neutron Cross section

- Neutrons are an important source of energy reconstruction bias for oscillation experiments
- MINERvA can detect neutrons efficiently
- Multi-neutron cross section for a sample dominated by 2p2h and FSI-rich







- Neutron production sensitive to 2p2h and FSI models
- Comparisons of two different 2p2h models and final state interaction models hA and hN
- Many leading models do not agree with data!

Phys. Rev. D 108 (2023) 11, 112010

Pion Cross section Measurements:

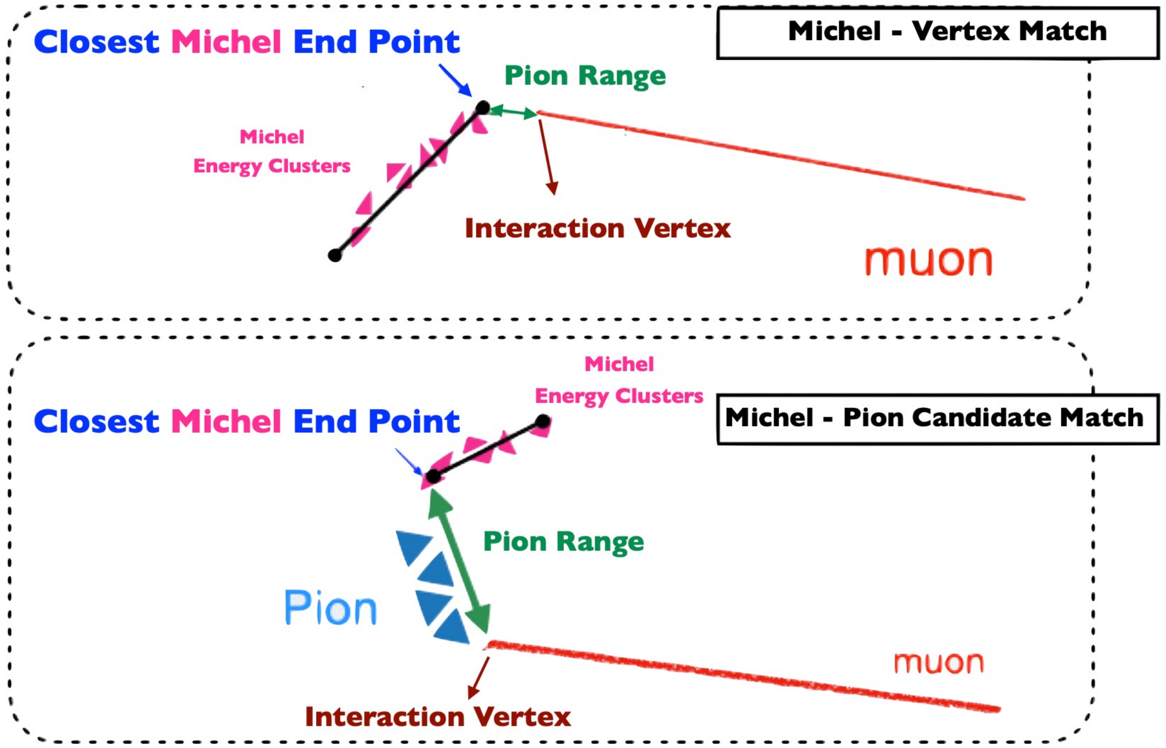
- New pion measurements with expanded π reach
- Single differential cross section in Scintillator
- Cross section in the nuclear targets

SIS Cross section Measurements:

- Neutrinos and Antineutrinos

Extending the π Reach

- DUNE will need to understand pion production, dominant processes (RES, DIS)
- New inclusive neutrino π+ production with extended π reached: added pions with a Michel tag
- If you determinate start of the Michel electron, and the muon vertex, you have an observable which is a function of kinetic energy of pion
- No tracking needed



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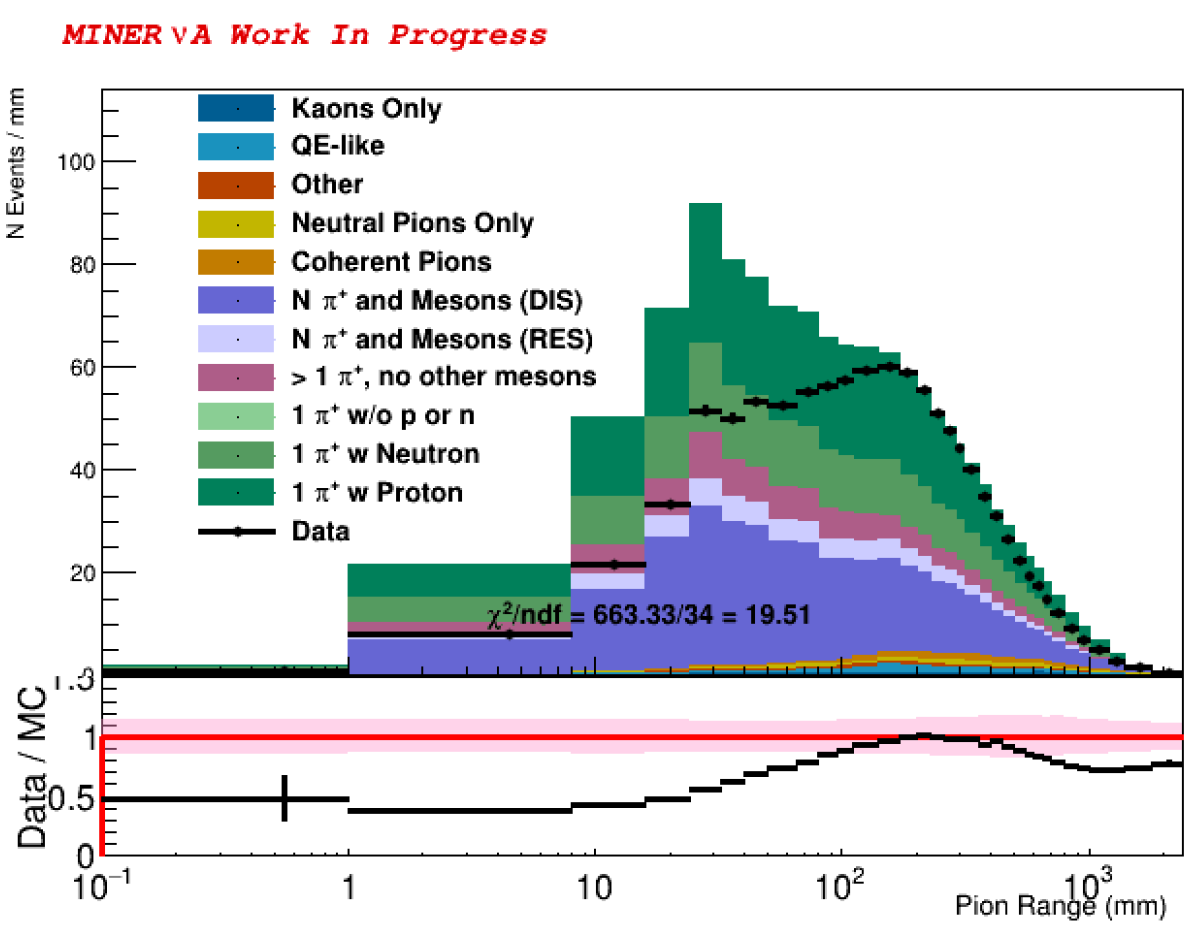
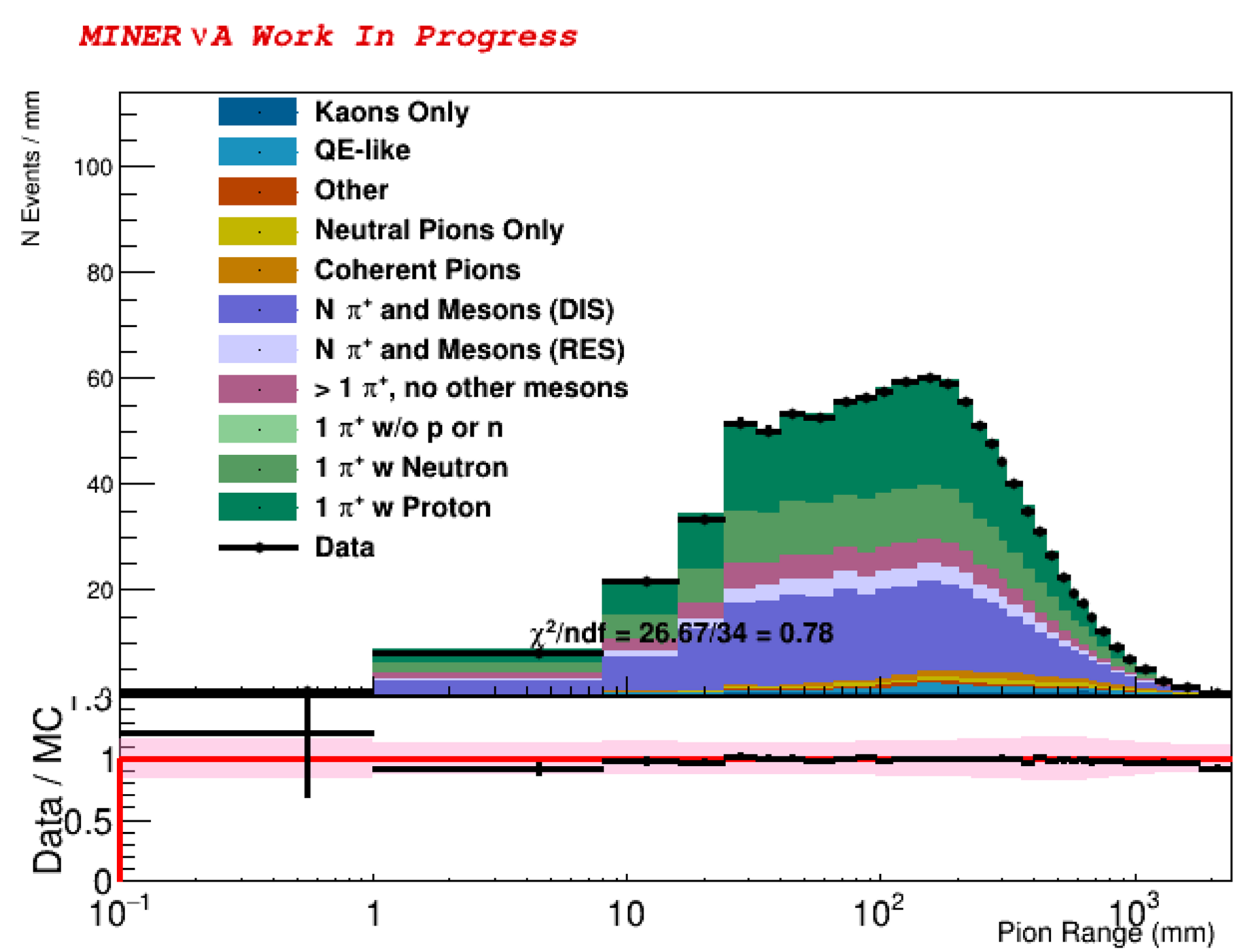
Studying the Pions at Low Energy

- This sample only has requirement of negatively charged muon, available energy < 1.5 GeV, where available energy is proton and $\pi^{\pm}$ KE plus other particles except neutrons, $1.5\text{GeV} < p_{\mu} < 20\text{GeV}$
- Agreement is poor: previous models unconstrained in this kinematics region
- What is missing? Nuclear effects or underlaying nucleon-level interaction!

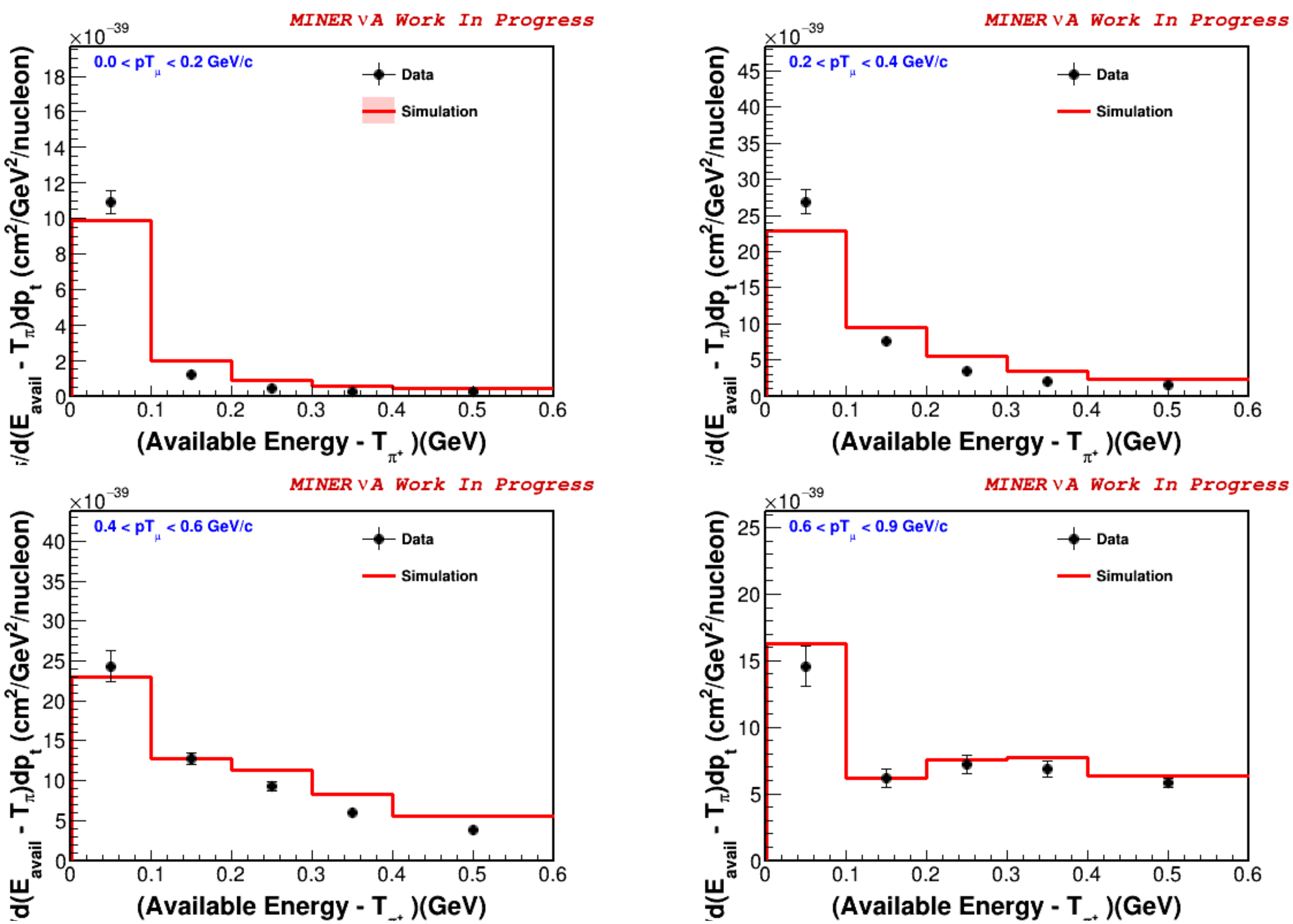




- Have to develop a reweight of simulation to correctly predict smearing

Pion Measurements

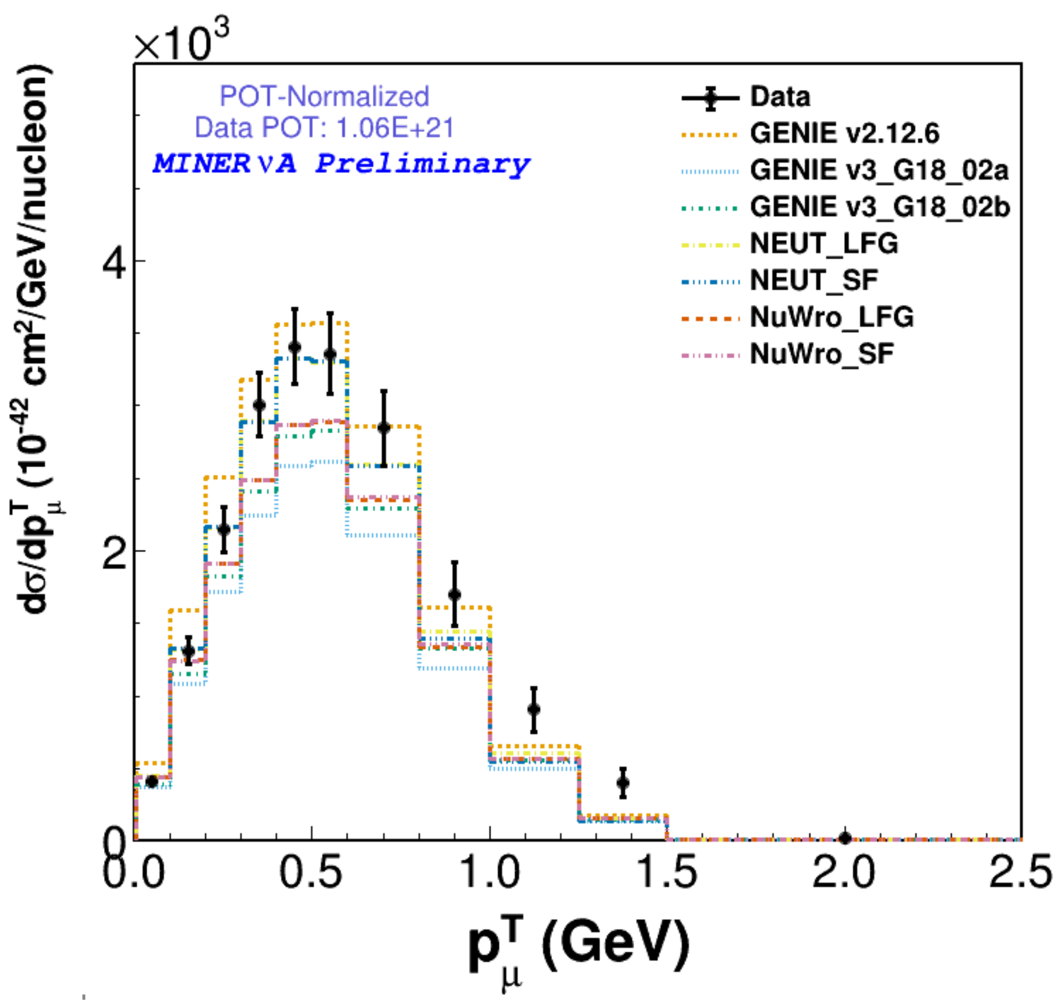
- Cross section versus available energy $T\pi$ and $p_{t\mu}$
- Agreement is not perfect but this point to the fact that the model is not predicting the pion spectrum correctly

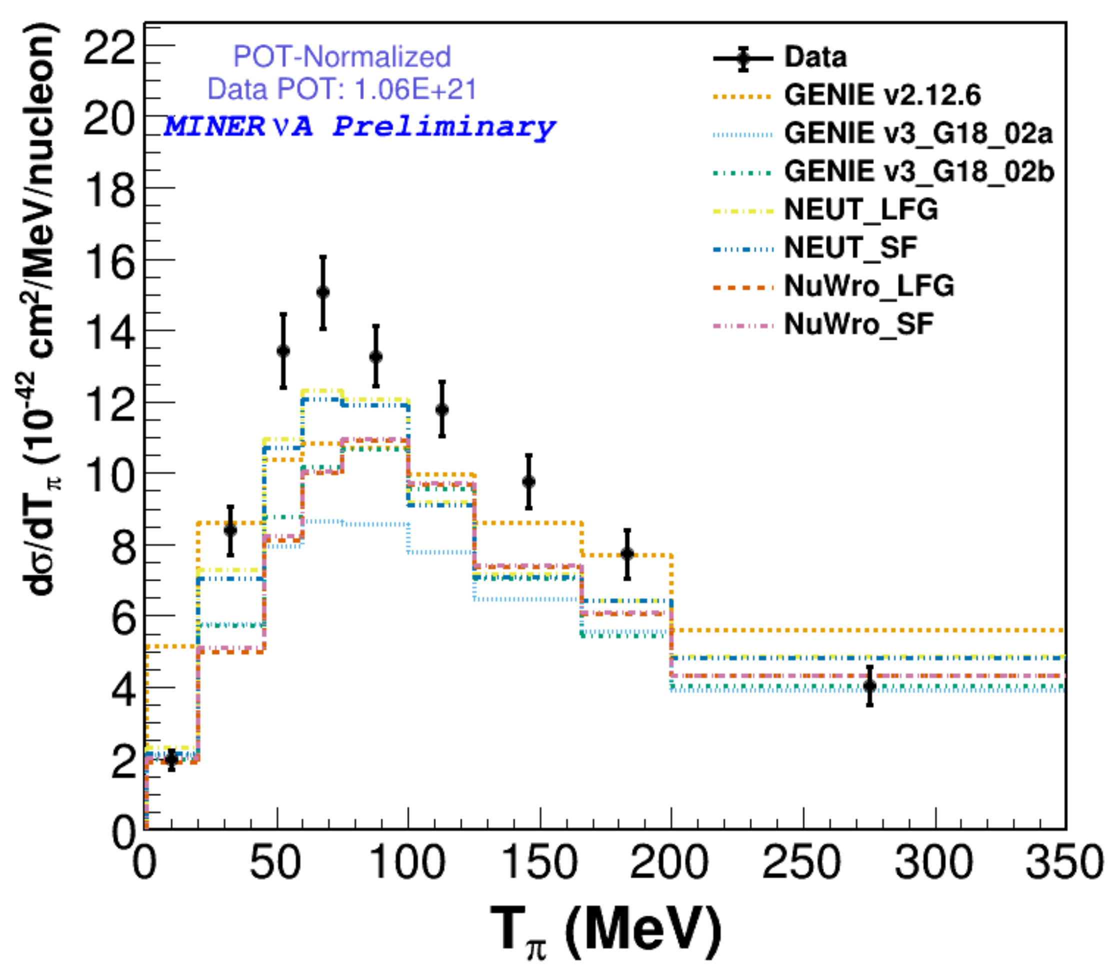


M. Sultana, Nuint 2024

New $1\pi^{+}$ Results in Scintillator

- Neutrino single π+ production with extended kinematic coverage in pion kinetic energy, removing Tpi<35 MeV cut from previous measurements
- First high statistics pion measurements, ~90K pion selected events



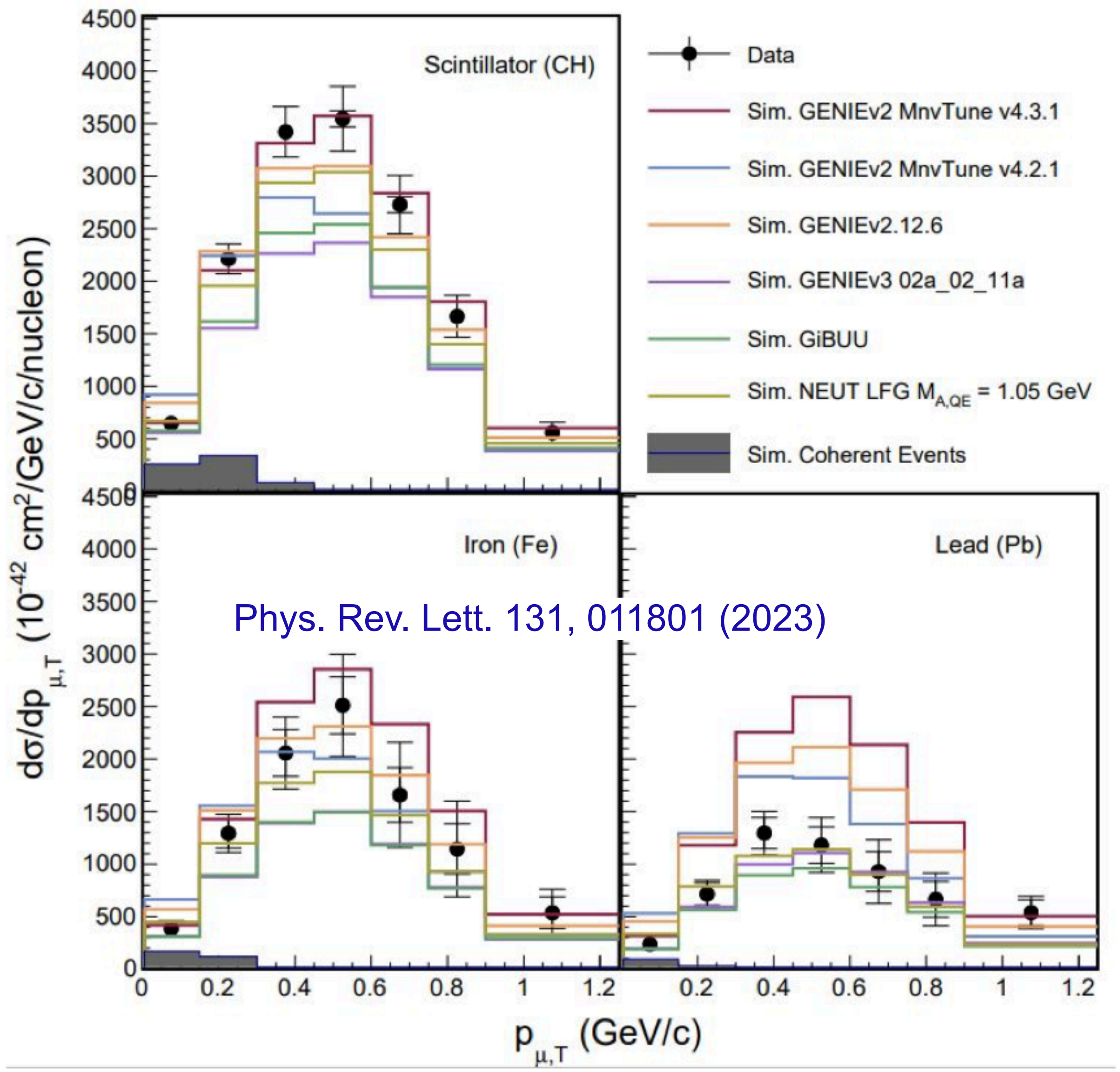


- Models get muon transverse dependence but miss kinematic energy dependence

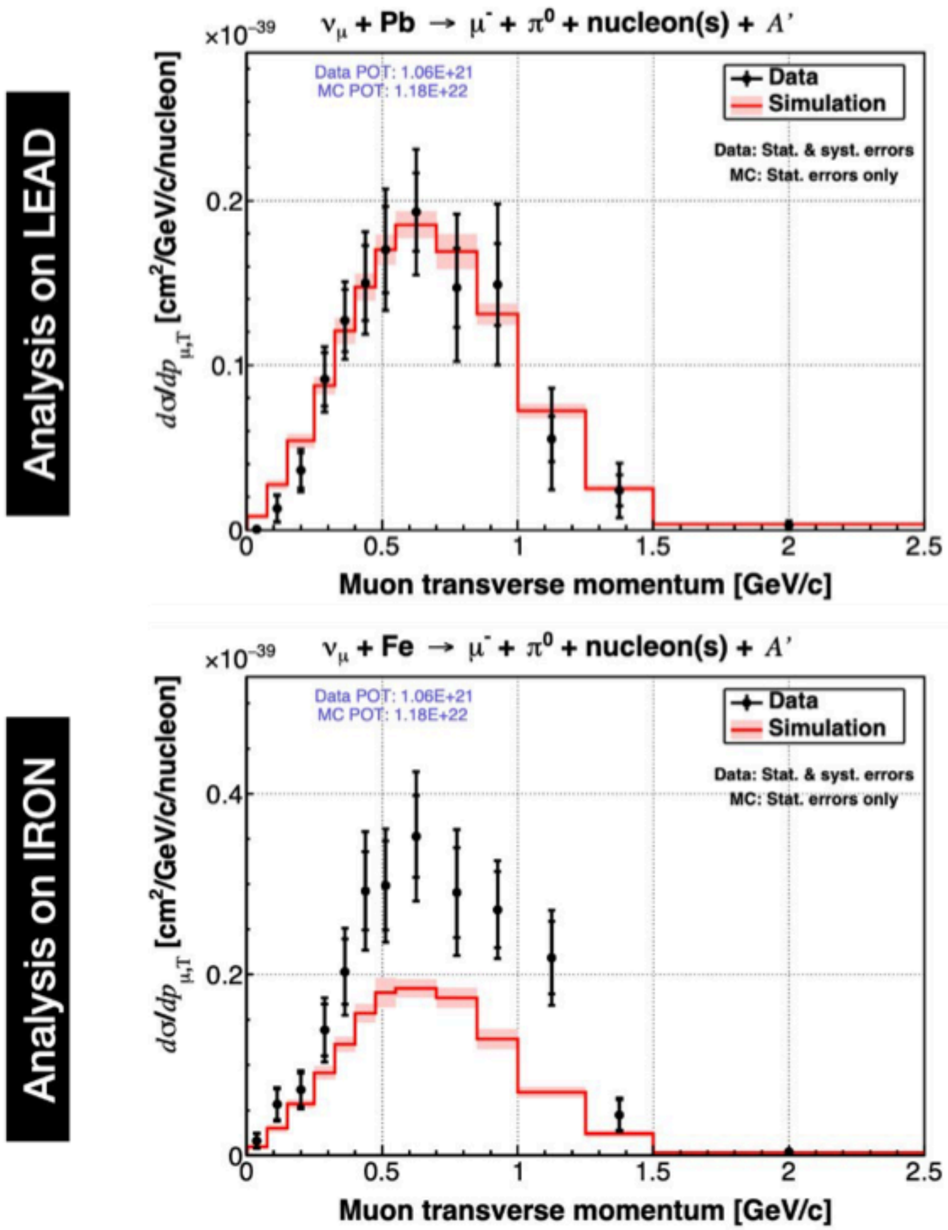
E. Granados and B. Messerly, Nuint 2024

Pion Measurements in the Nuclear Targets

- CC1π+ in carbon, iron, lead and scintillator and CC1π0 in iron and lead



The model variation (MnvTune v4.3.1) accurately model the cross section on lighter nuclei, but overpredicts the cross section on larger nuclei (Fe and Pb)

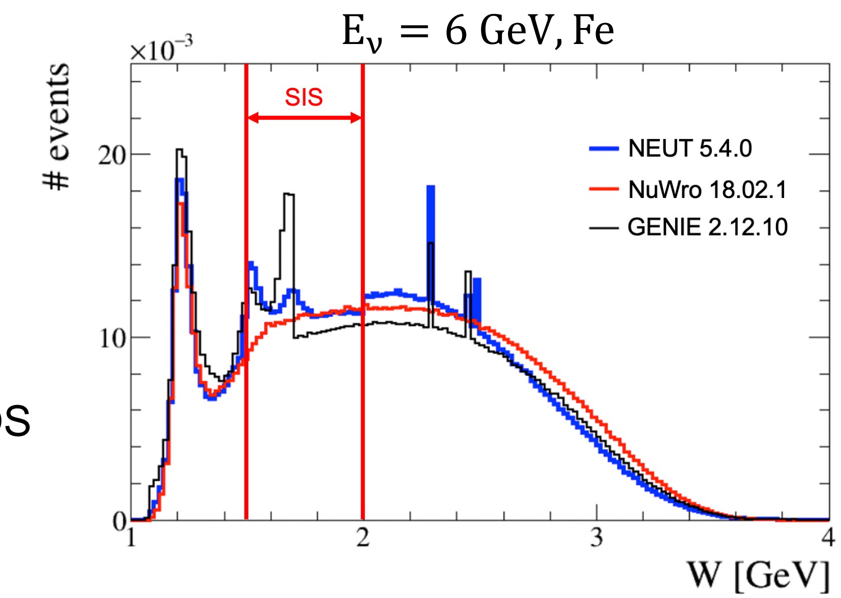


Disagreements between data and simulation in Iron

Aaron Bercellie and Gonzalo Diaz, Fermilab JETP

Shallow Inelastic Scattering

- Region between resonance and deep inelastic
- Significant fraction (~50%) of DUNE events are in SIS
- First measurements since bubble chambers



arXiv:1608.02716 (2016)

Signal Definition

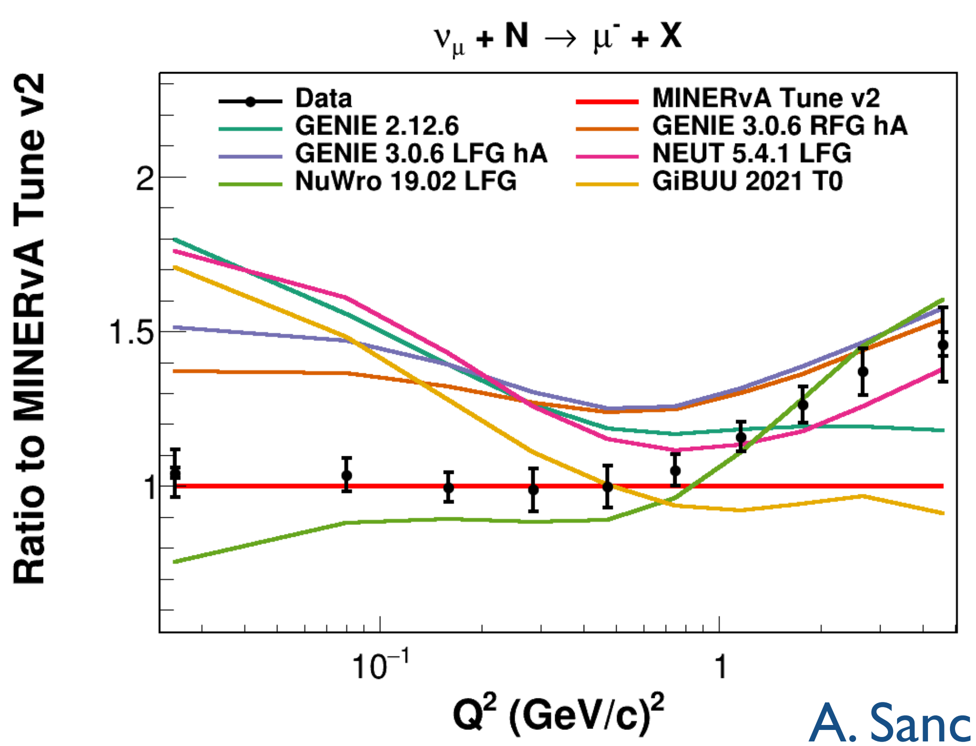
- $\nu_\mu(\bar{\nu}_\mu)$ CC
- 1.5 < W_{exp} < 2 GeV
- θ_μ < 20° wrt beam
- 2 < E_μ < 20 GeV

Event Selection

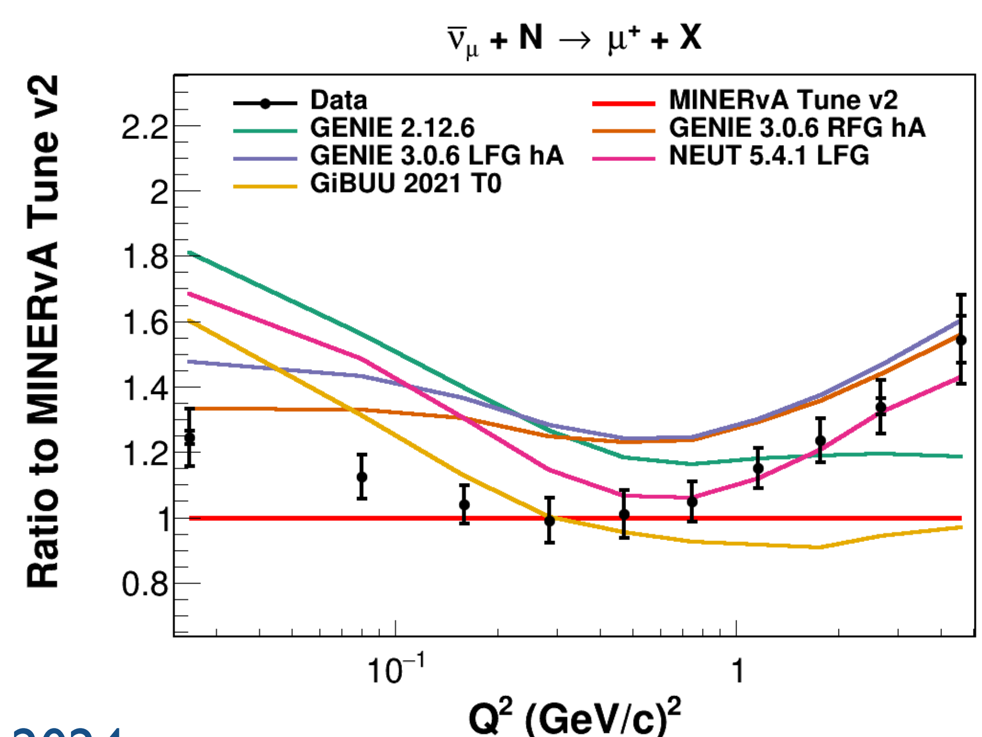
- Muon track in MINERvA that matches with a track in MINOS
- 1.5 < W_{exp} < 2 GeV
- Quality cuts

- None of the models describe the data across the full kinematic region for all considered variables, paper in preparation

Neutrinos



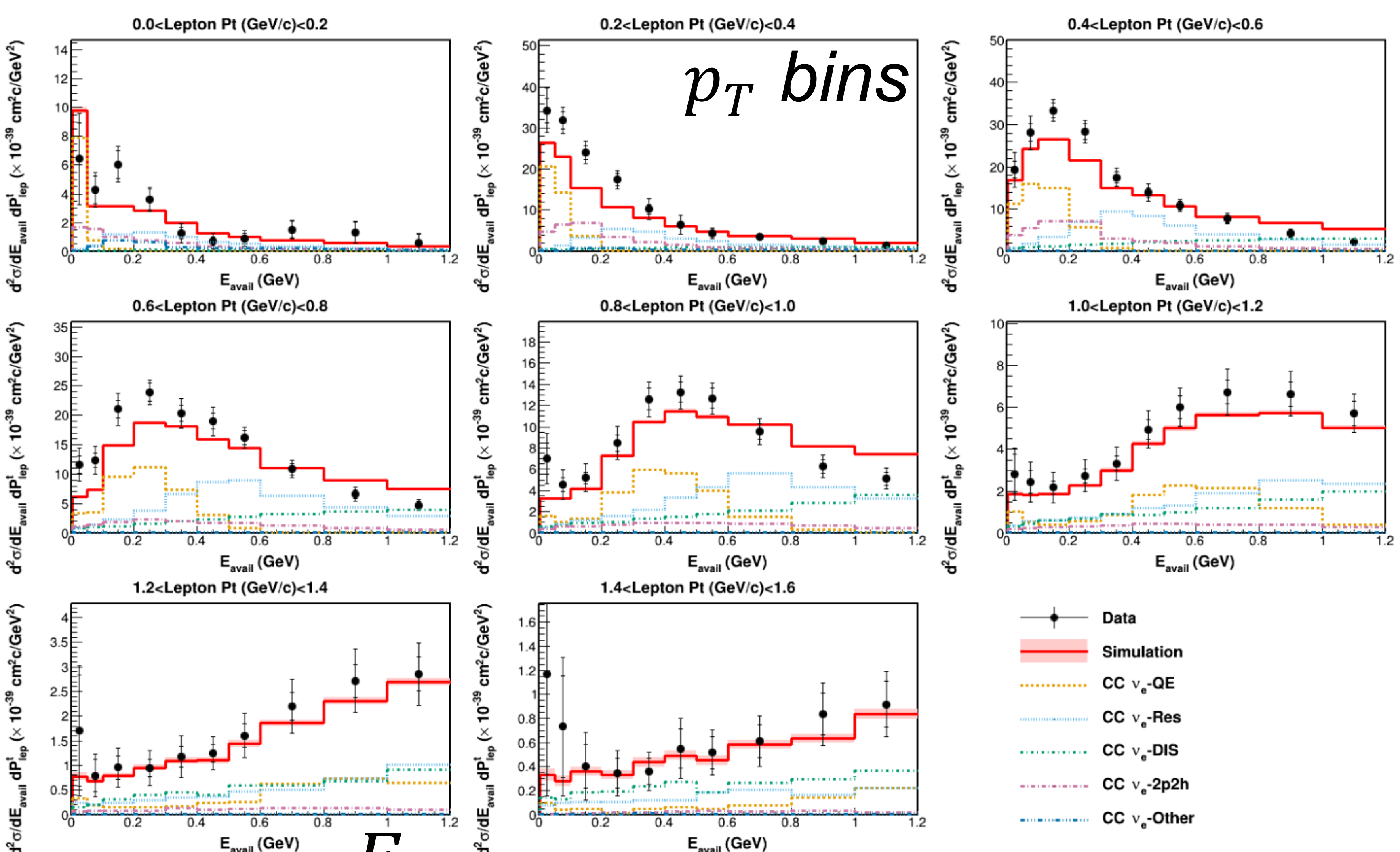
Antineutrinos



Electron Neutrinos and Ratios Electron to Muon

Double Differential Cross Section Electron Neutrinos

- Our ν_μ rich beams have few ν_e in them to allow us to study any difference between ν_μ and ν_e interactions
- Therefore, we infer ν_e interactions from studies of ν_μ
- But what we study cannot give us the whole picture, radiative corrections and nuclear effects might be different
- Double differential cross section as function of available energy



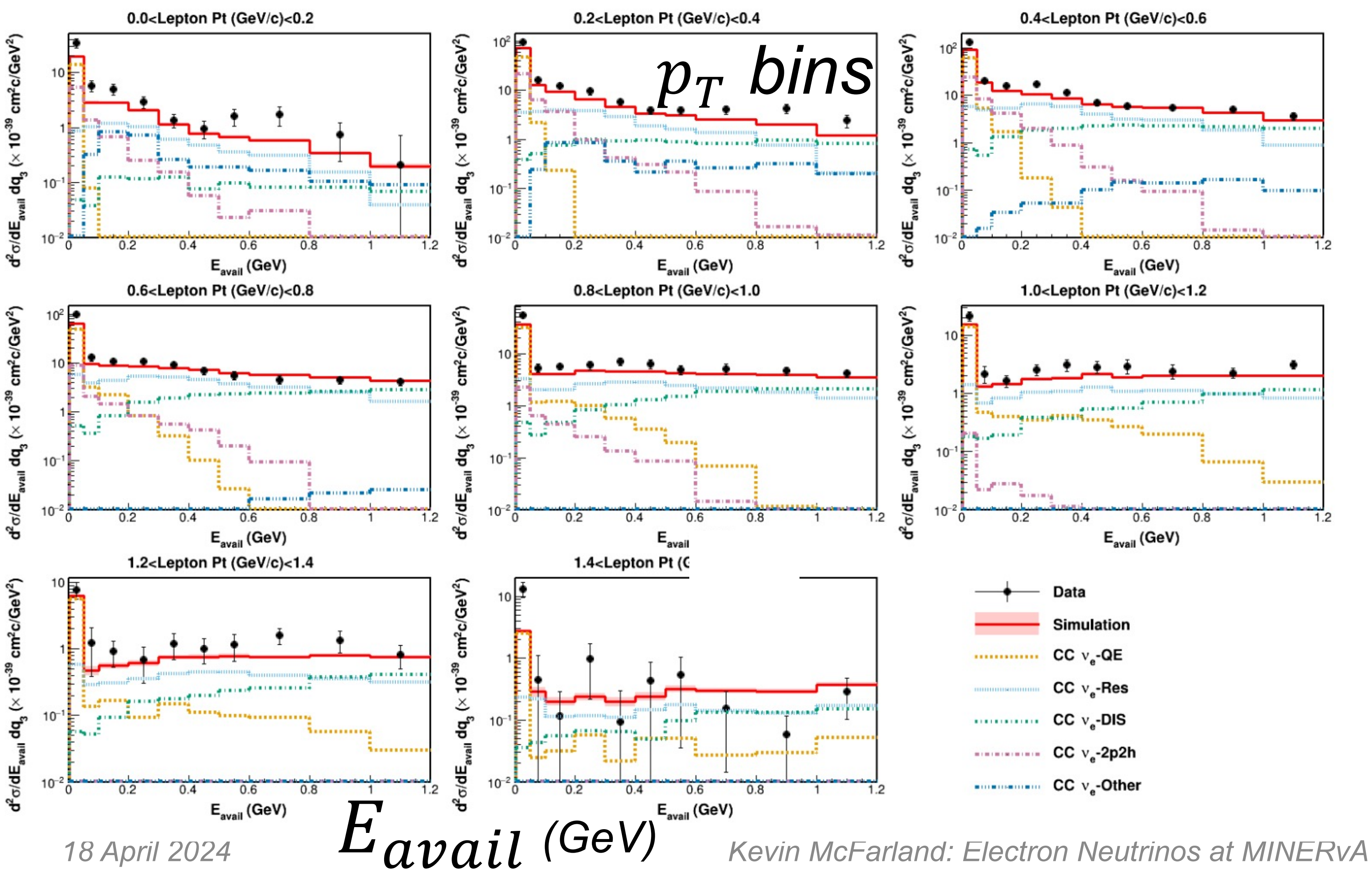
E_{avail} (GeV)

Eavail= proton and $\pi^{\pm}$ KE plus other particles except neutrons

Double Differential Cross Section Electron Antineutrinos

- Double differential cross sections for electron neutrinos/antineutrinos, first high statistics measurements with electrons

Antineutrinos

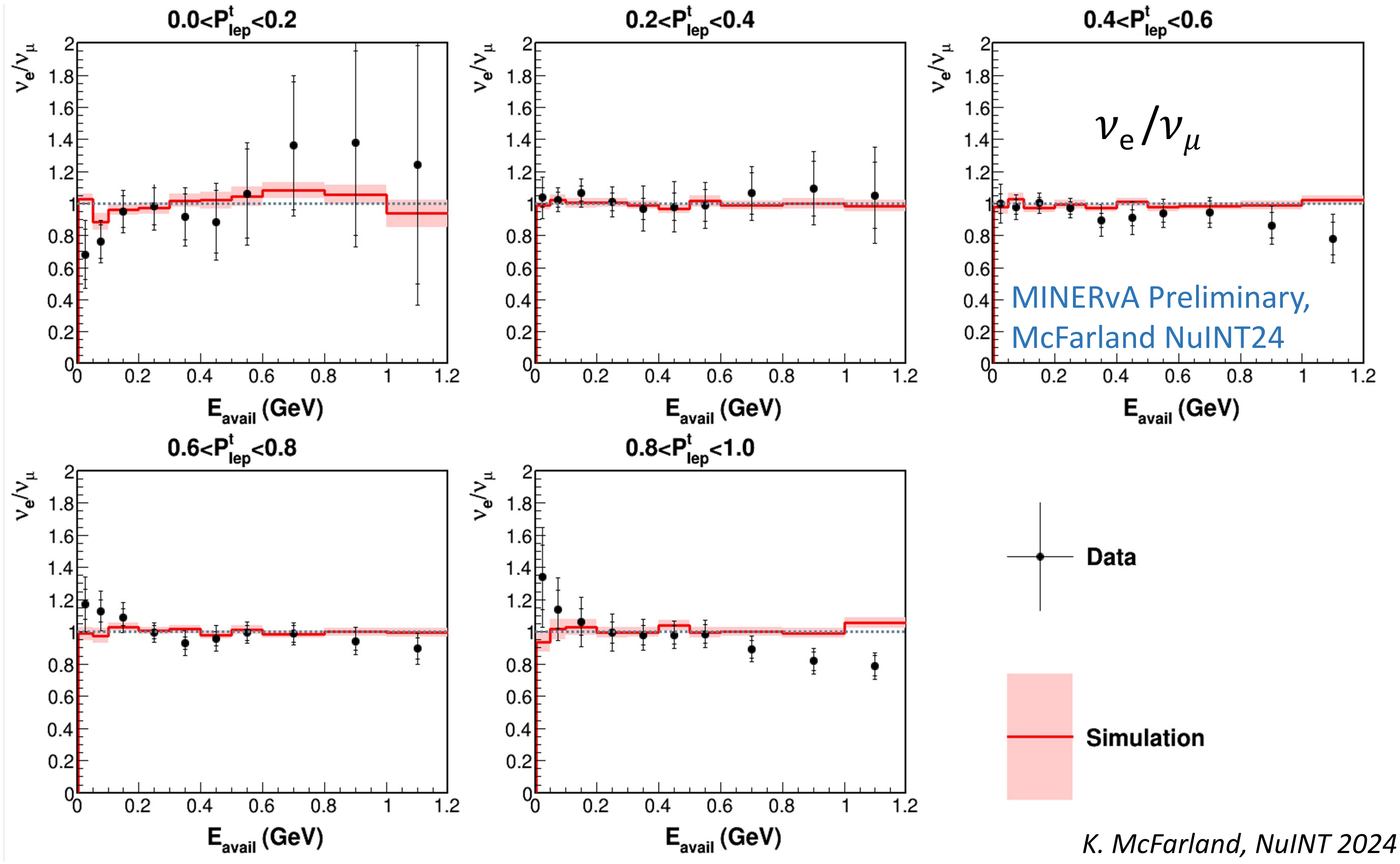


- Measured cross-section electron p_T bins (0.2 GeV/c with, from 0 to 1.6 GeV/c) of available calorimetric energy, Eavail= proton and $\pi^{\pm}$ KE plus other particles except neutrons

Phys. Rev. D 109, 092008, 2024

MINERvA ν_e/ν_μ Ratios

- Preliminary cross-sections in panels of p_T as a function of available energy

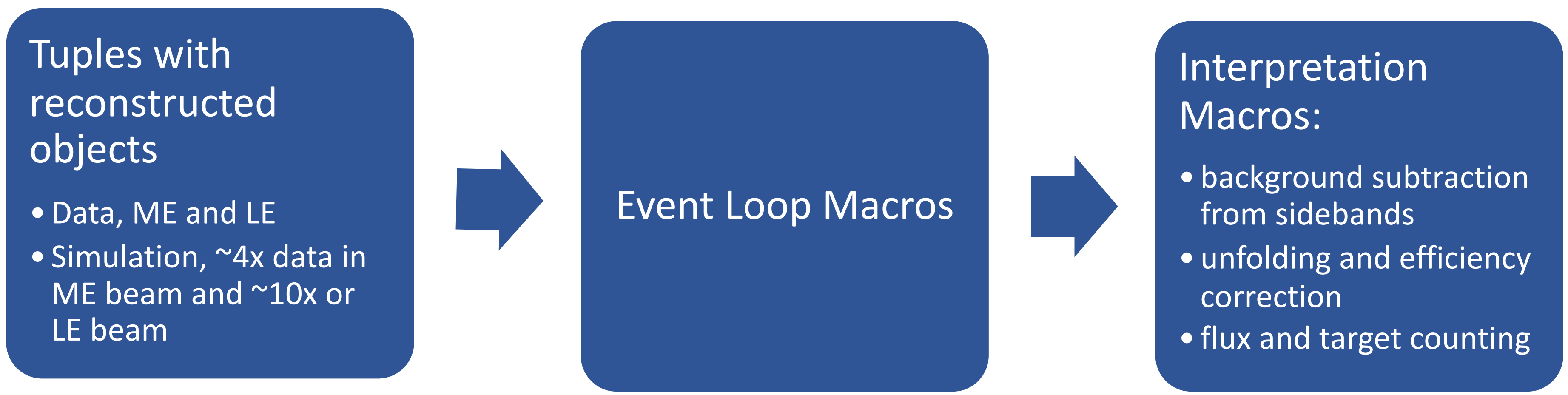


K. McFarland, NuINT 2024

- Simulation predicts a ratio very close to one dominated by statistical uncertainties
- ν_e/ν_μ uncertainty, dominant systematic for DUNE-CP violation measurements!

Keeping MINERvA data available

- MINERvA initiated a project to preserve its data to give the ability to go back and extract the cross section for all measurements
- In brief, it is a set of tuples of the results of our standard reconstructions for every event, and a set of macros to allow an analyzer to efficiently interpret that data, focused on the measurement of a cross-section

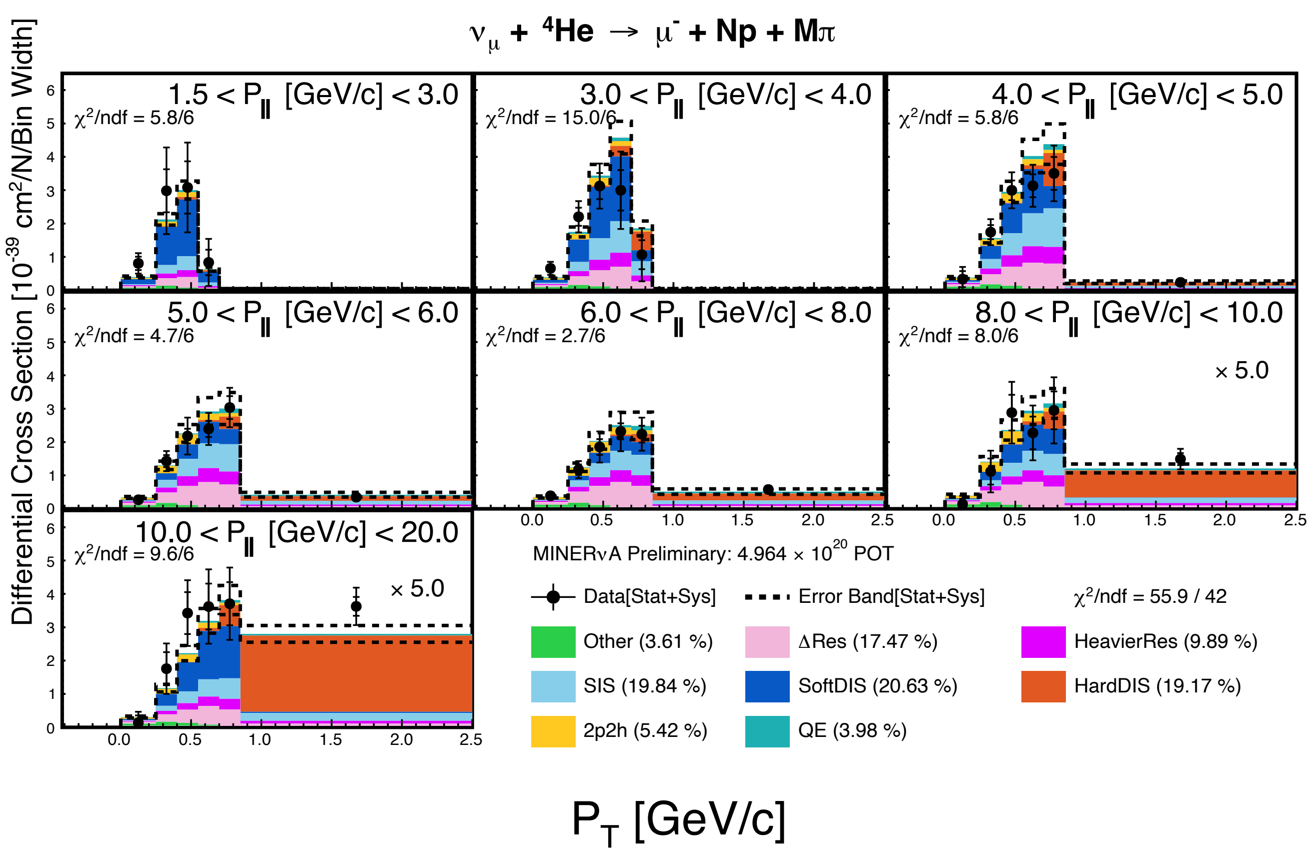


- All macros and analysis tools are public, and data will be available shortly
- Documentation with analysis examples
- May serve as a useful starting point for more experiments to do something similar

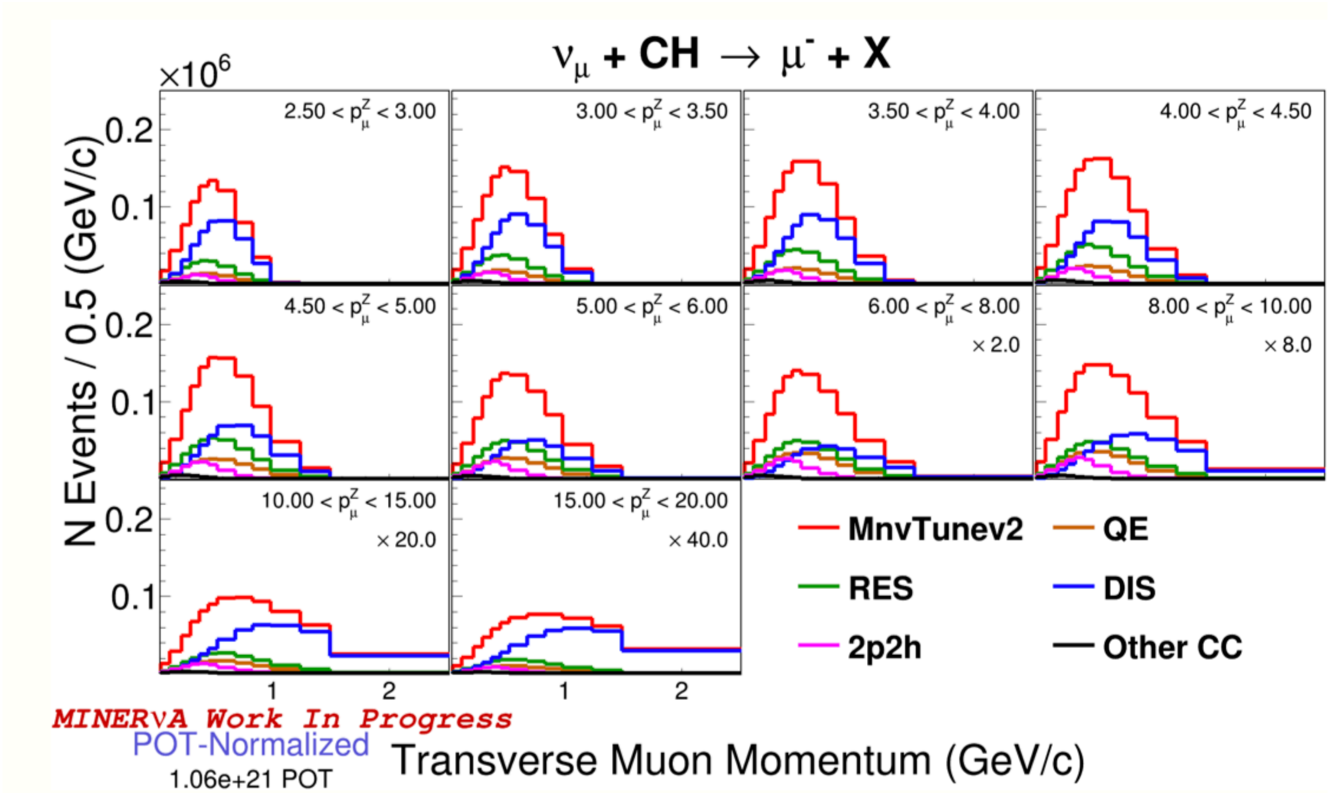
https://arxiv.org/abs/2103.08677, B. Messerly, R. Fine, A. Oliver et al, EPJ Web Conf. 251 (2021) 03046

Measurements in preparation

Helium cross section measurements



Double differential neutrino cross sections for Shadow Inelastic Scattering



See Christian Nguyen's poster

See Daniel Correia's poster

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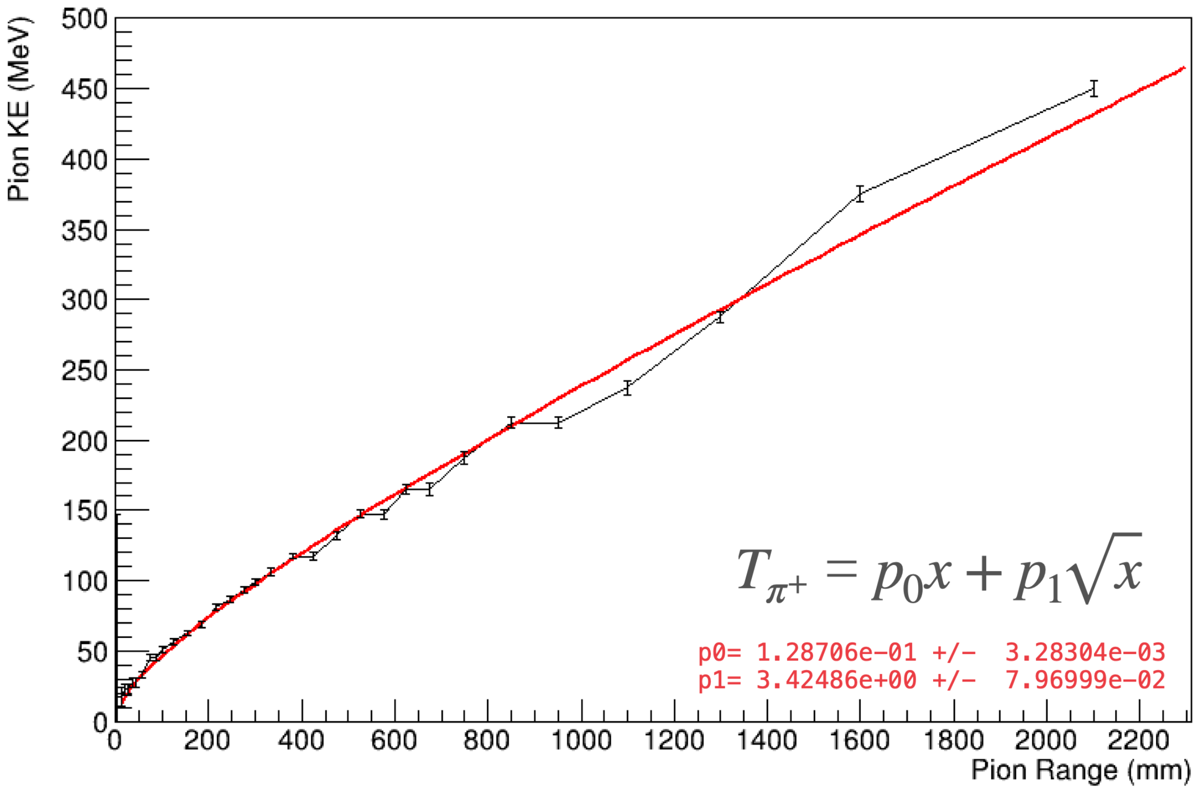
Summary

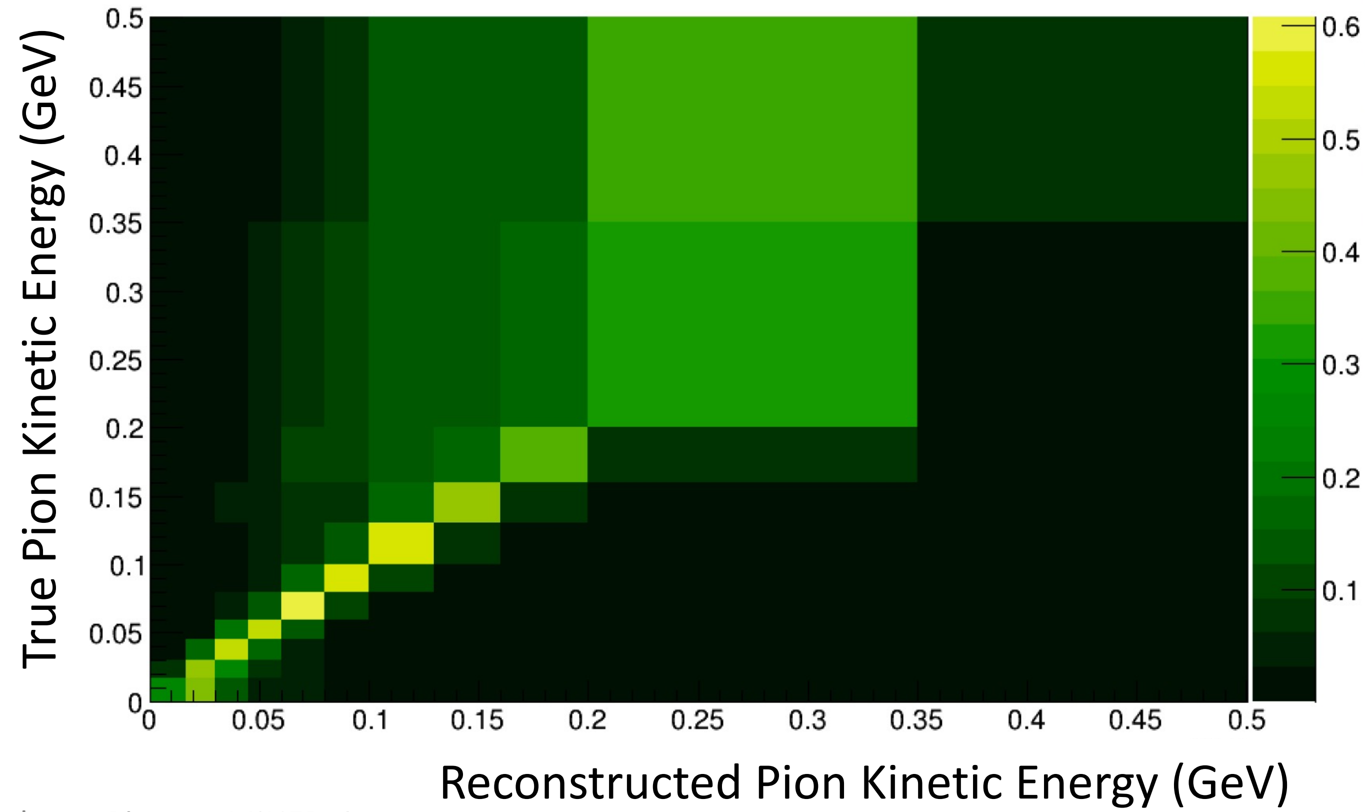
- Several challenges from the theoretical model side and experimental side to understanding neutrino interactions
  - Data-theoretical model disagreement across many measurements
- MINERvA is learning a lot from neutrino-nucleus interactions and building a rich set of cross section results for the oscillation experiments
- Latest MINERvA measurements:
  - Triple differential cross sections, comparing cross sections across different energy spectra
  - Double differential cross section for CC0pion
  - Measuring neutrons in antineutrino interactions
    - Cross section on hydrogen, by subtracting off carbon
    - Antineutrino interactions with two neutrons
  - Pion production cross section measurements
  - Shallow inelastic scattering cross section
  - Comparing electron to muon neutrino cross sections
- Data preservation effort for the neutrino community

Backup Slides

Relationship between KE and Distance

- Left plot: fit to the peak pion kinetic energy for each measured pion range in mm
- Note threshold well below tracking threshold of 35 MeV





18 April 2024 D. Harris for M. Sultana, Pions at MINERvA