Charged Pion Production in MINERνA

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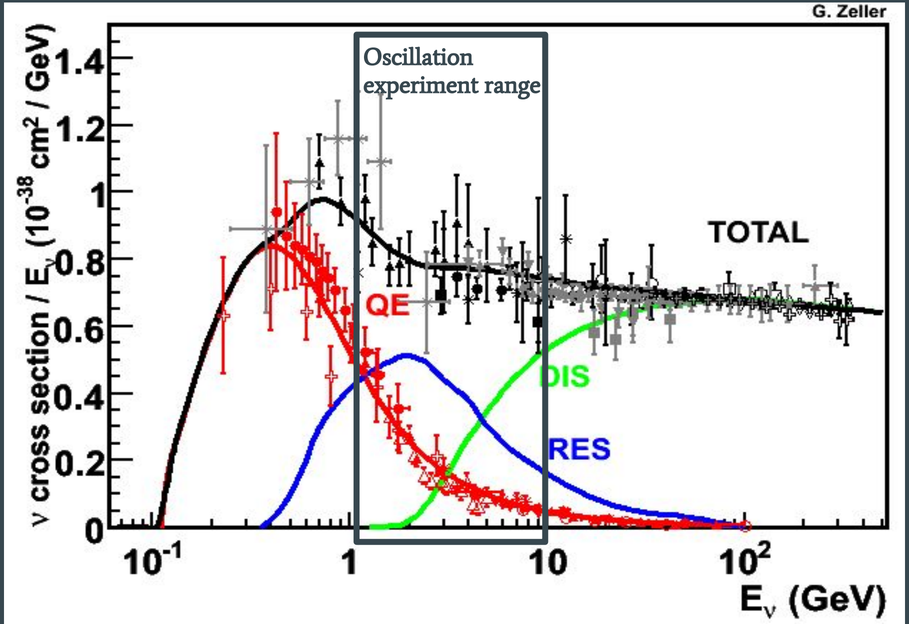
On behalf of the MINERνA Collaboration

New Perspectives 2016 - Fermilab

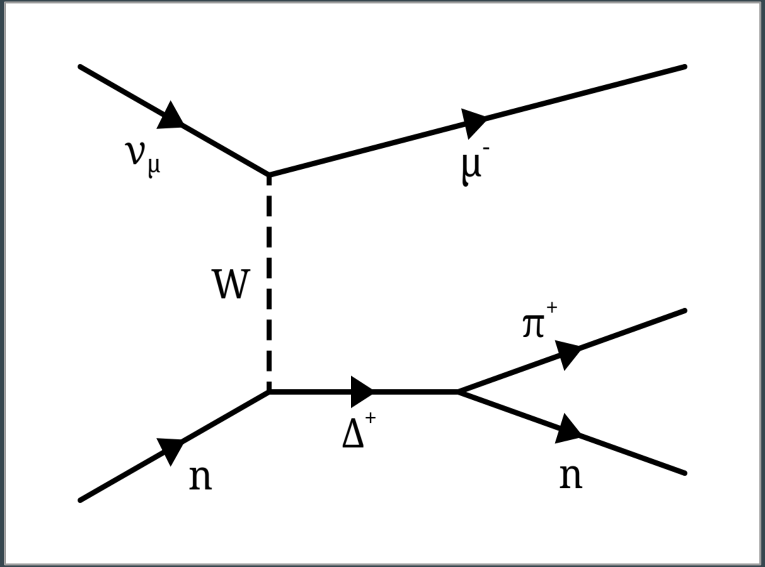
Motivations for Pion Production Measurements

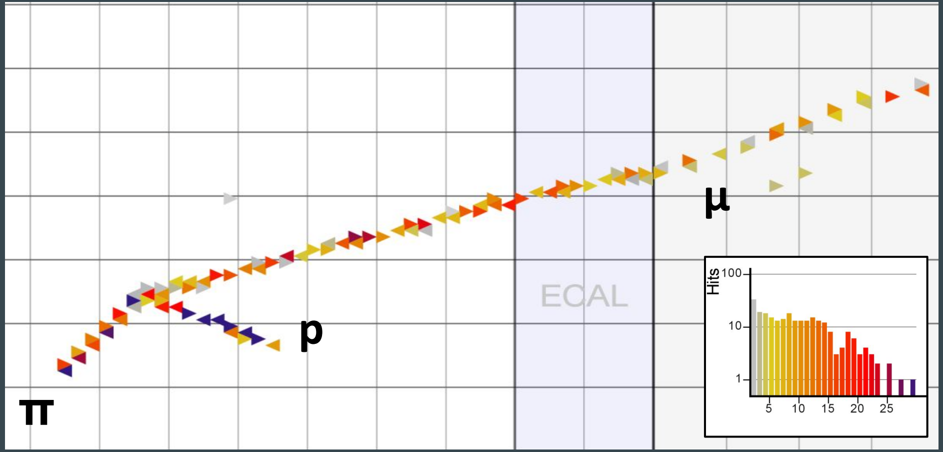


See: J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

Resonant pion production is a dominant interaction channel in the energies of oscillation experiments

Resonance Pion Production

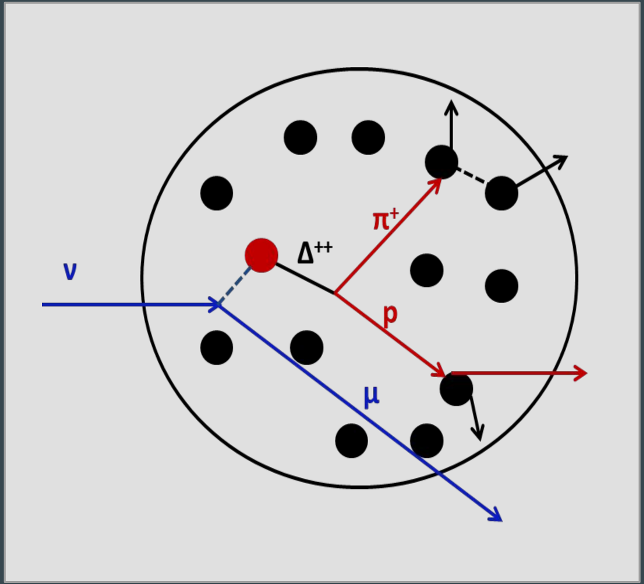




Simple? NO:

- Pions can fake protons (and muons)!
- $\gtrsim$ 25% of resonant pions re-scatter or absorb before they leave the nucleus, thus undergoing "Final State Interactions".

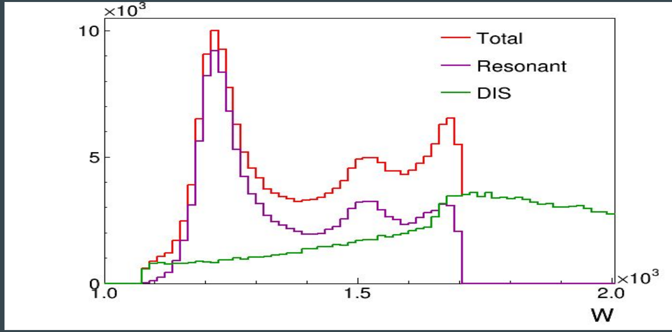
Final State Interactions (FSI's), Nuclear models



Final state interactions (FSI) can ruin the measurement of neutrino energy and the identification of the interaction channel

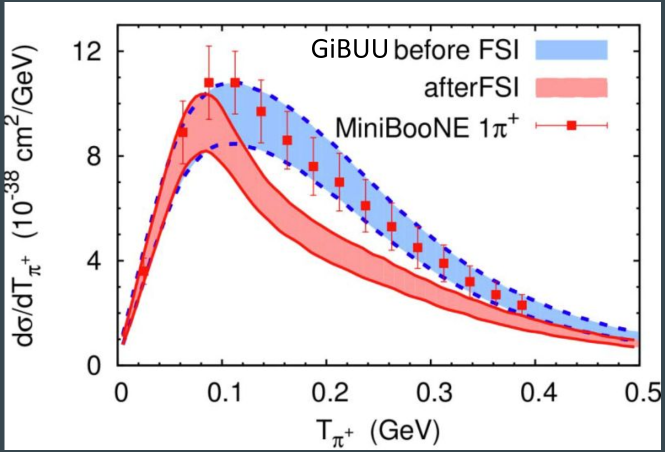
- Modeling FSI's is hard and verifying the models is even harder
- Physics simulations are ~~slow~~ careful in adopting new models
- Experiments must often work with discontinuous models that don't agree with data.

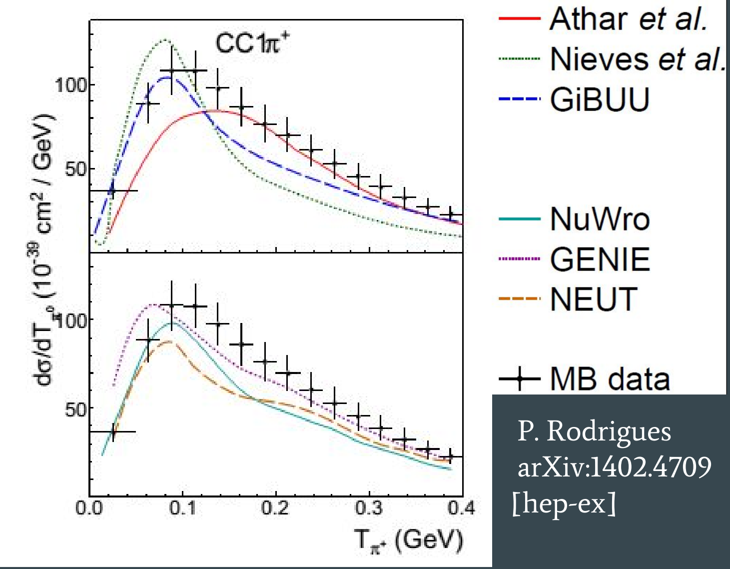
Example Pion Production in GENIE
(Courtesy of P. Rodrigues)



FSI Models vs Results

Theoretical calculations and event generators are unable to reproduce the π KE differential cross section.





P. Rodrigues
arXiv:1402.4709
[hep-ex]

GiBUU: O. Lalakulich and U. Mosel, PRC 87, 014602 (2013)
NuWro: T. Golan, C. Juszczak, J. Sobczyk Phys Rev C80, 15505 (2012)
Nieves: E. Hernanadez, J. Nieves, M.Vicente Vacas, Phys Rev D87, 113009 (2013)

MINERνA can help!

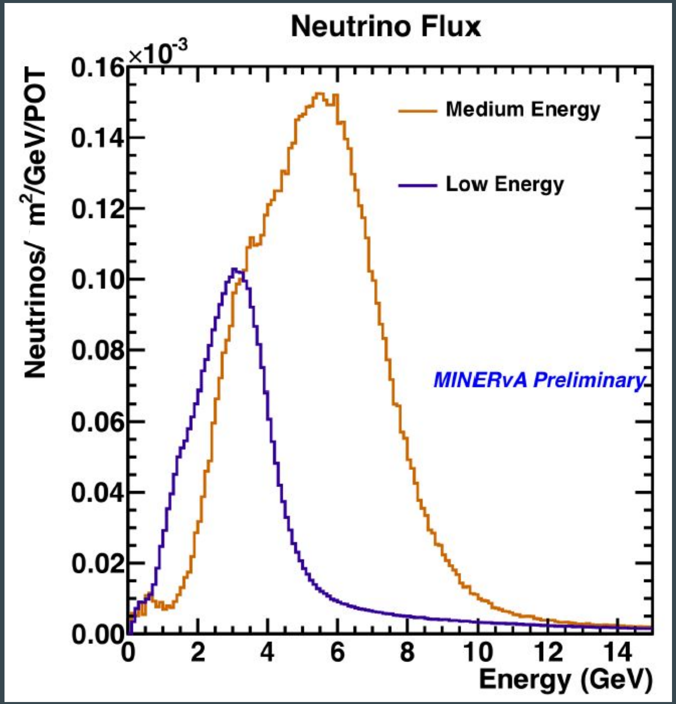
MINERνA Charged Current Charged Pion Production

- **Goal:** Measure pion and muon kinematic distributions to determine strength and nature of FSI interactions

- MINERνA has measured π production in the low energy NuMI beam – Phys. Rev. D 92, 092008 (2015)

The NuMI Beam – π production in the medium energy

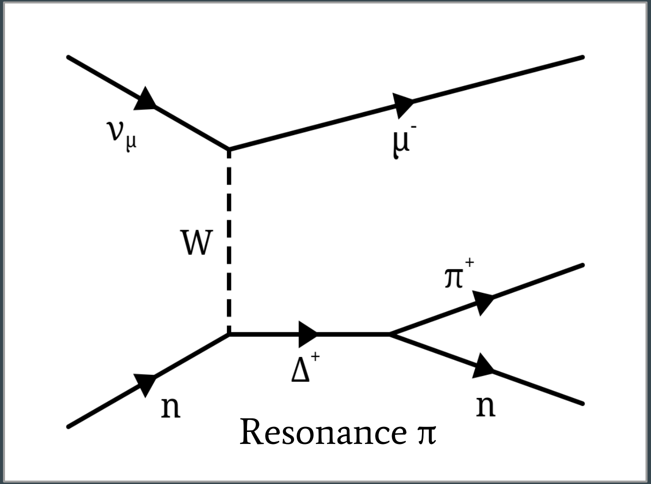
- 3.18×10^{20} POT in the low energy
- Already have 9×10^{20} POT in the medium energy and still running.
- A medium energy measurement of π's:
    - reduced statistical (and systematic) uncertainties
    - wider pion kinematic range
    - nuclear targets
    - double differential cross sections



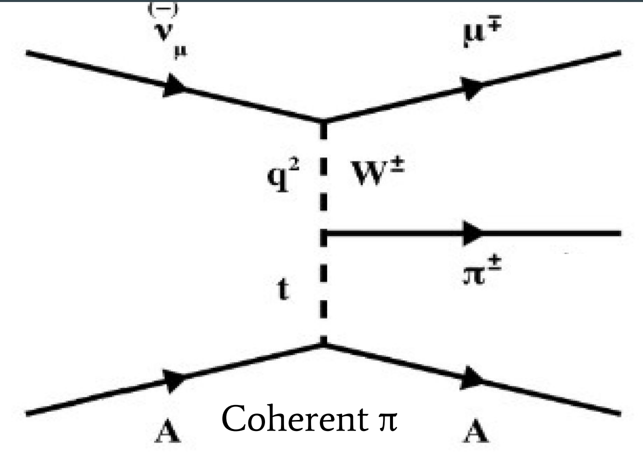
Signal Definition

Signal: $\nu_\mu A \rightarrow \mu^- \pi^\pm X$

- A is a nucleus in the tracker
- X includes the recoil nucleus and any particles except charged pions



- Mostly see π^+ but allow π^-
- Mostly *resonance* pions, but allow *coherent* pion
  - See Alejandro Ramírez Delgado User's Meeting Poster!



Signal Definition

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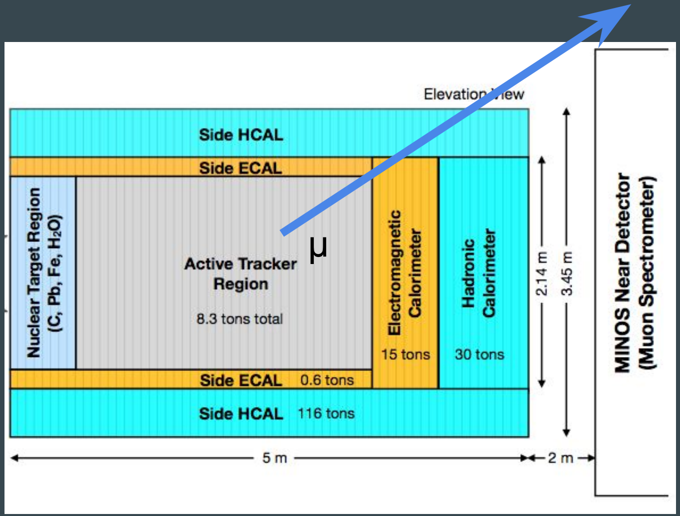
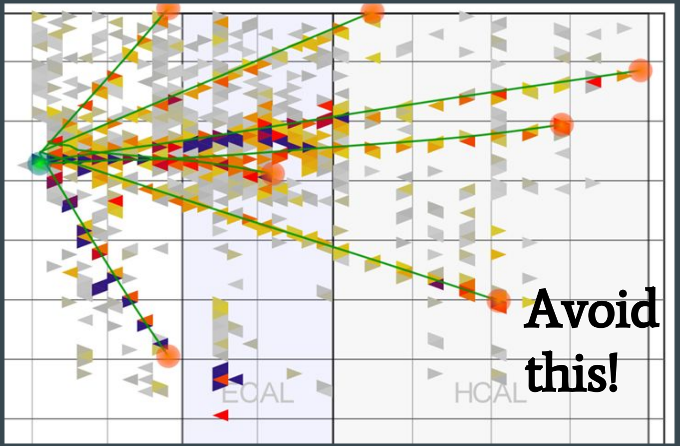
Additional Signal Restrictions:

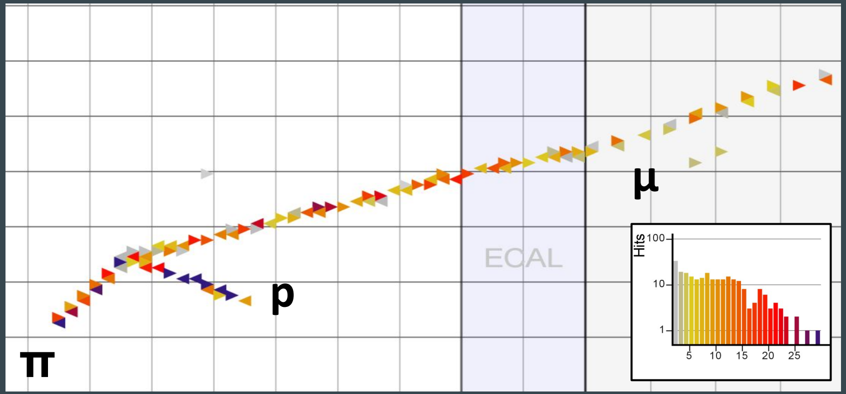
1. 1.5 GeV $< E_\nu <$ 10 GeV
    - Poor muon reconstruction at low energies and high flux errors above $E_\nu = 10$ GeV
2. Reconstructed invariant hadronic mass, W < 1.4 GeV (for single pion events)
    - Physics-wise, selects a MiniBooNE-like, resonance dominated sample (M_Δ = 1232 GeV)
    - Avoid high multiplicity events





How to Find Pions: Particle Identification (PID) Methods

- Particles deposit an energy loss (dE/dx) signature in the detector, theoretically defined by a Bethe-Bloch curve.
- A track's energy loss in MINERνA can be fit to a B-B curve, and the particle can be scored according to a prior particle hypothesis.
- Pions and protons can be hard to distinguish.



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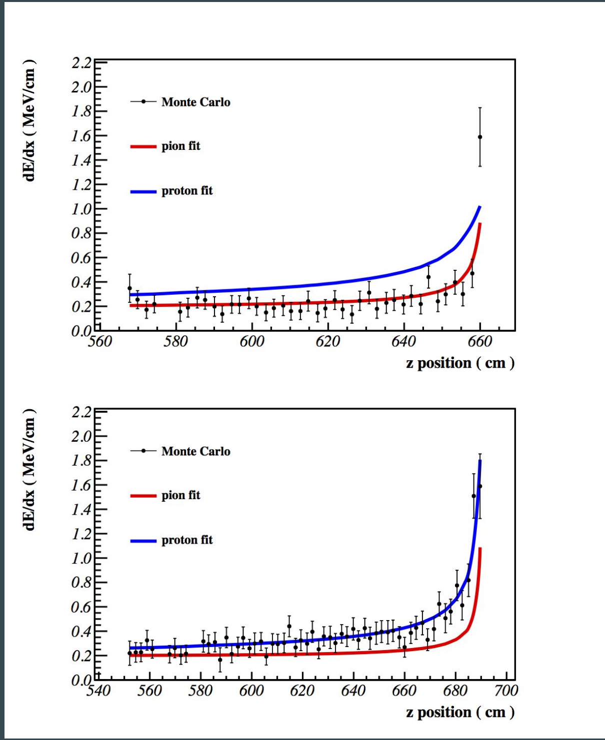


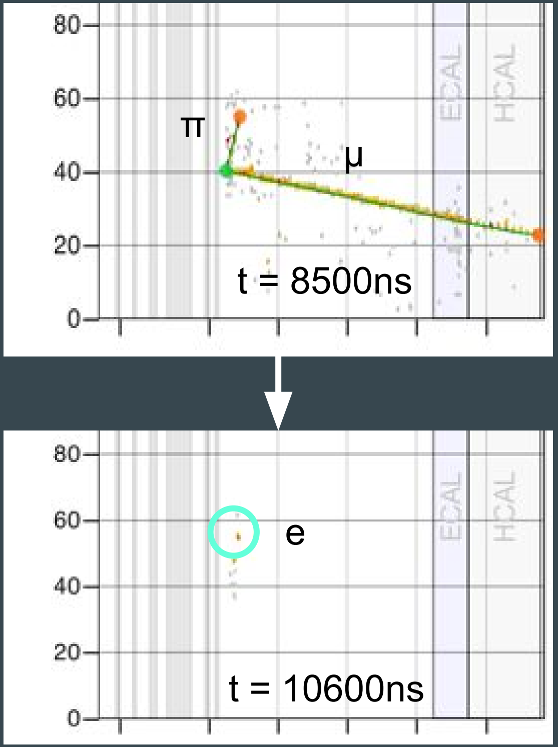
Nucl. Inst. and Meth. A743 (2014) 130.

How to Find Pions: Michel Electron Selection

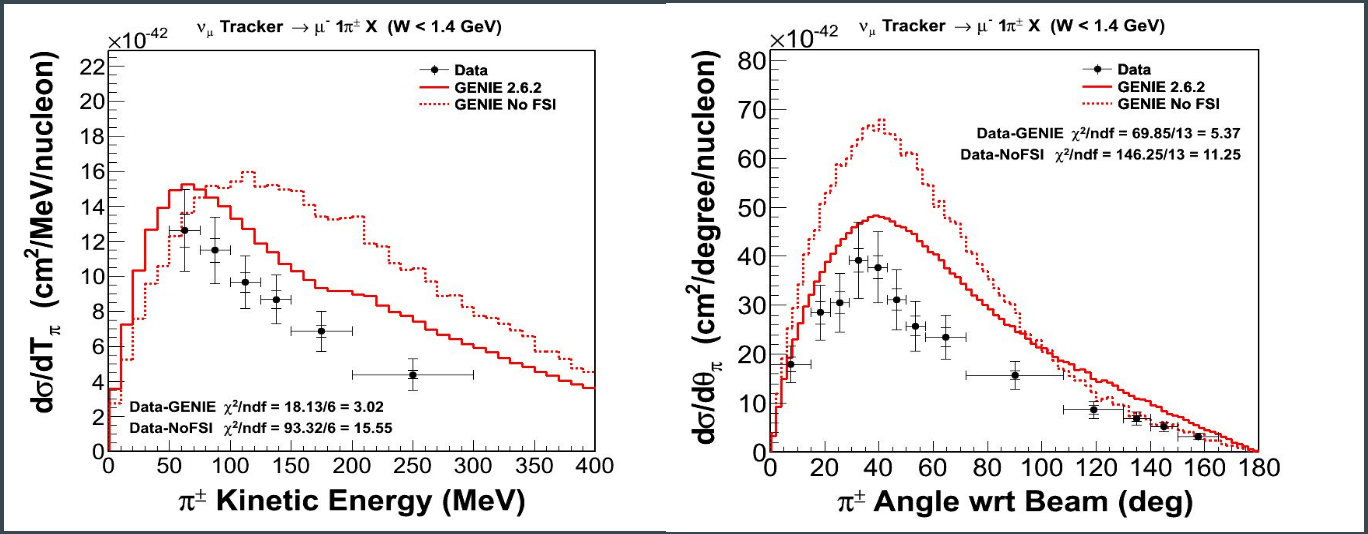
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$$

- This analysis requires that a "Michel electron" is found.
- Employ algorithm that searches for energy deposits near the end of a pion candidate track.



Low Energy Results & Conclusions

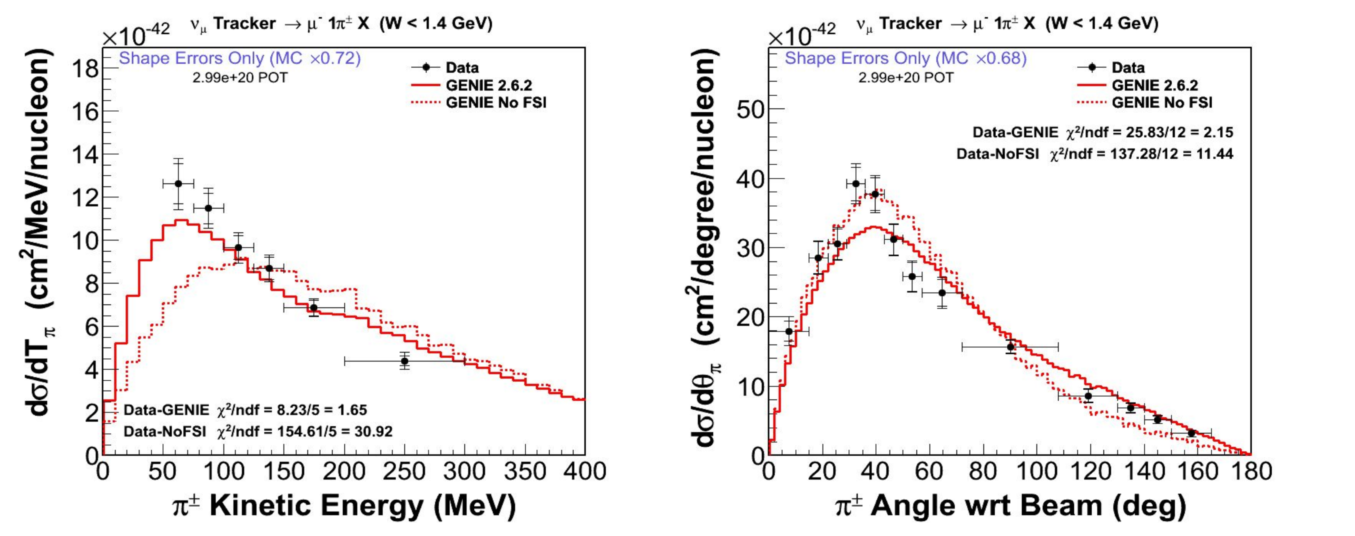


Phys. Rev. D 92, 092008 (2015)

Probing Nuclear Physics with Neutrino Pion Production at MINERvA Date: 02/07/2014

- To interpret these results, focus on the **shape** of the cross sections
  - The data contain large but flat uncertainties on the pion production cross section model and flux
- Muon distributions also measured for an upcoming publication

Low Energy Results & Conclusions

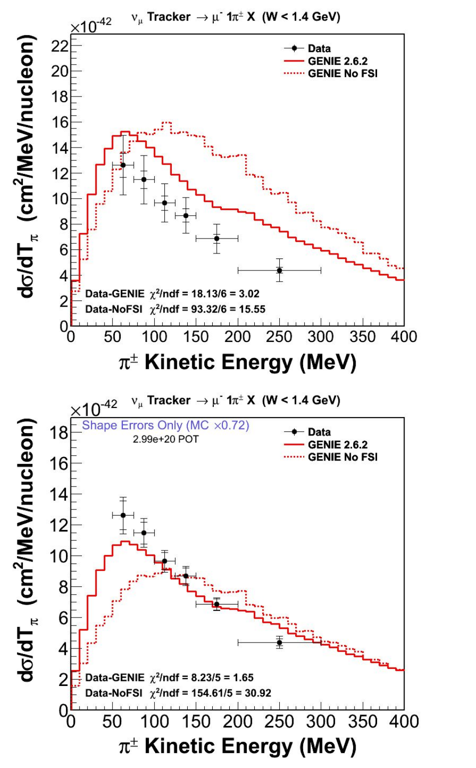


Phys. Rev. D 92, 092008 (2015)

Probing Nuclear Physics with Neutrino Pion Production at MINERvA Date: 02/07/2014

Conclusion: Data prefer GENIE with final state interactions

Results & Conclusions



Phys. Rev. D 92, 092008 (2015);
[Probing Nuclear Physics with Neutrino Pion Production at MINERvA]
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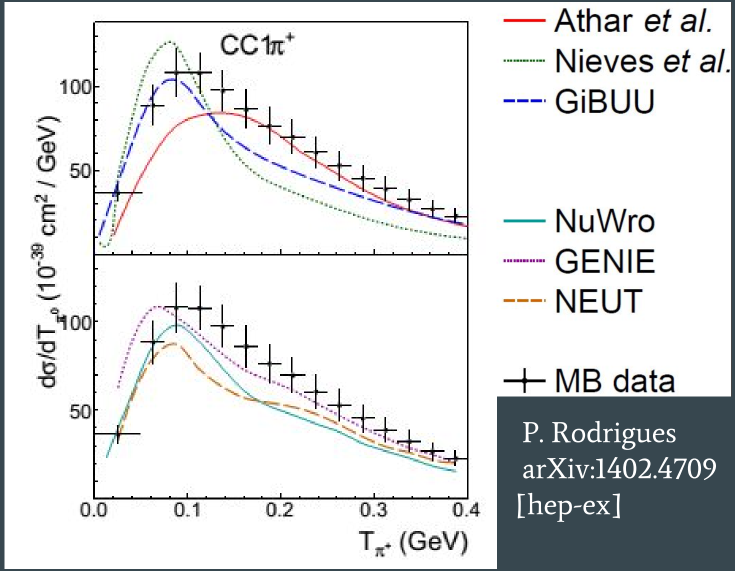

P. Rodrigues arXiv:1402.4709 [hep-ex]

Conclusion: MINERvA data shape is consistent with the weaker “absorption dip” seen by MiniBooNE

Conclusion: GENIE agrees better in shape with MINERvA, but better in normalization with MiniBooNE.

Looking Ahead

- Medium energy will provide higher statistics, but also higher multiplicity, more complicated events
- Systematic uncertainties must be reduced, and there are many avenues for improvement:
  - Pion selection method (Advanced PID methods, michel selection, both/neither)
  - Flux
  - Improved reconstruction and calorimetry methods