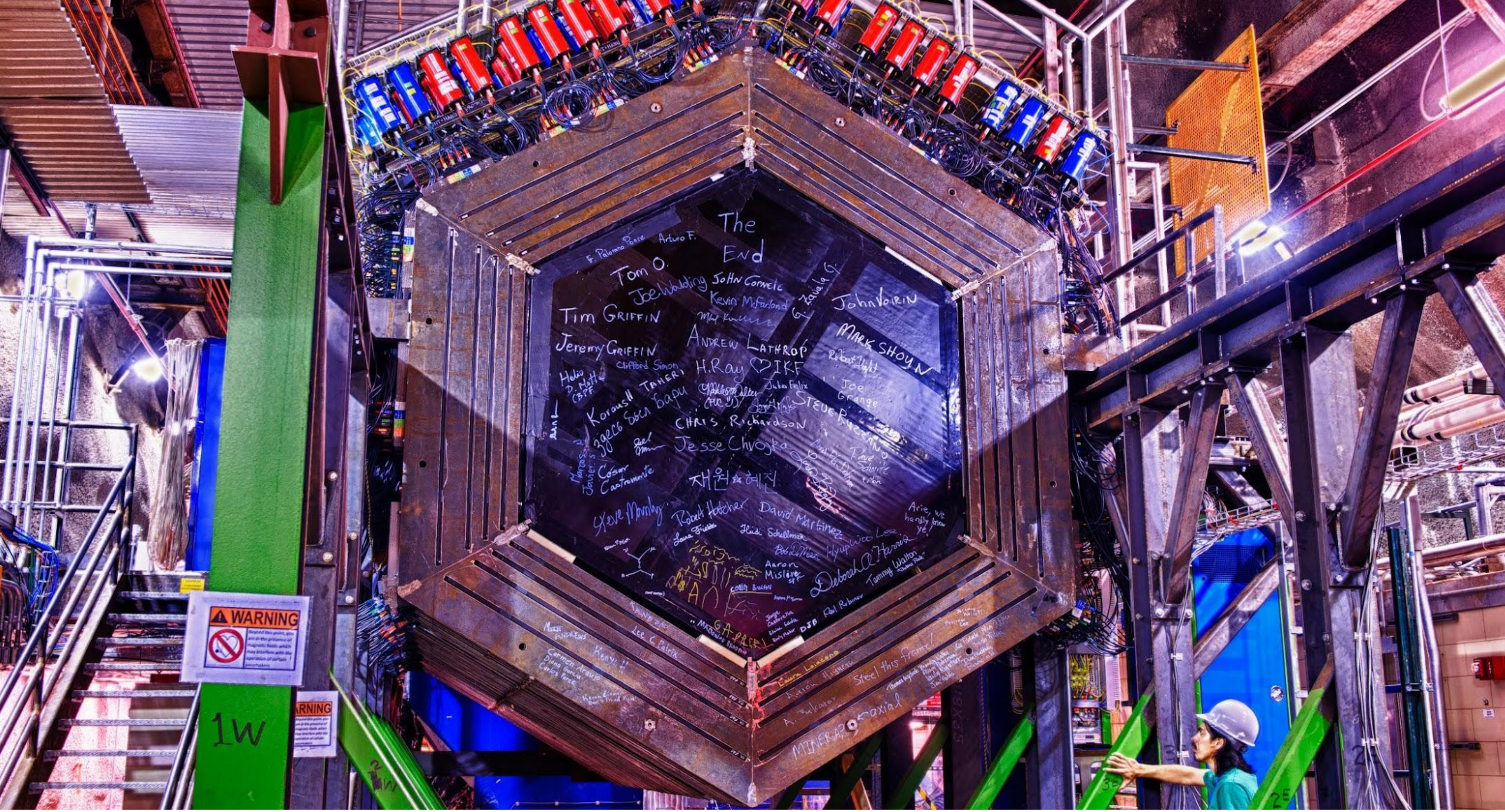


Pion and Kaon Production at MINERvA

NuFACT 2015 - August 12th

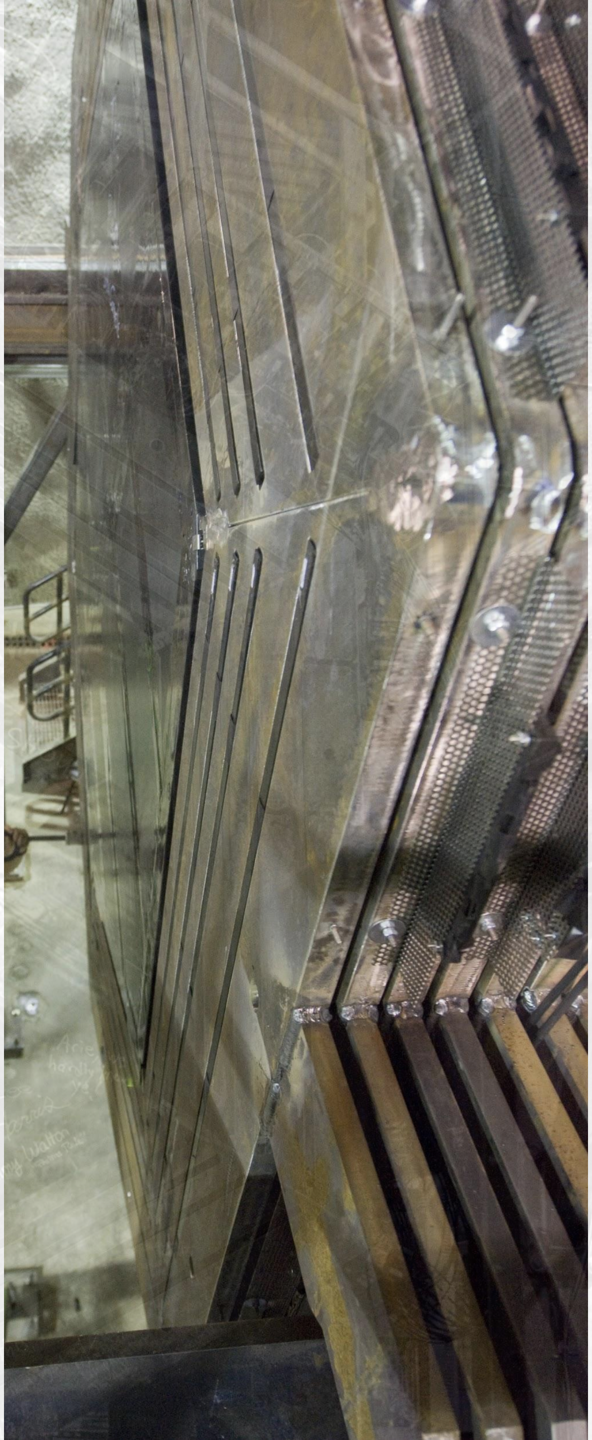
Mateus F. Carneiro - CBPF/Brazil

for the MINERvA Collaboration

CBPF
Centro Brasileiro de Pesquisas Físicas

Outline

- Introduction and Motivation
- Charged Current Pion Production
  - **Pion Production Analysis with muonic variables**
  - **Pion Production Analysis with hadronic variables**
  - **Coherent Pion Production**
- Kaon Production
  - **Neutral Current Kaon Production**
- Future Analysis and Summary



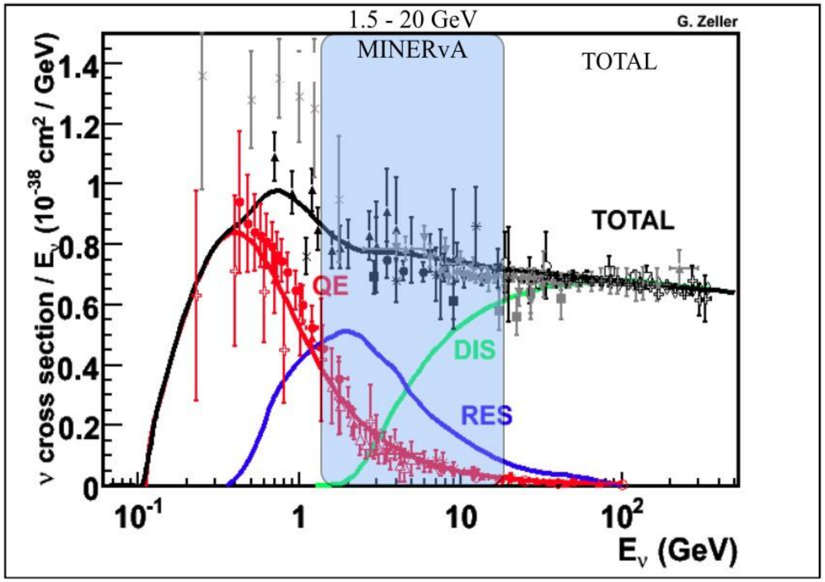
Introduction

- MINERvA is a fully active, high resolution detector designed to study neutrino reactions in detail, situated in Fermilab’s NUMI beam along with MINOS and NOvA
- Precision neutrino measurements requires precise knowledge of cross sections, final states, and nuclear effects
- The MINERνA detector was designed to provide such data

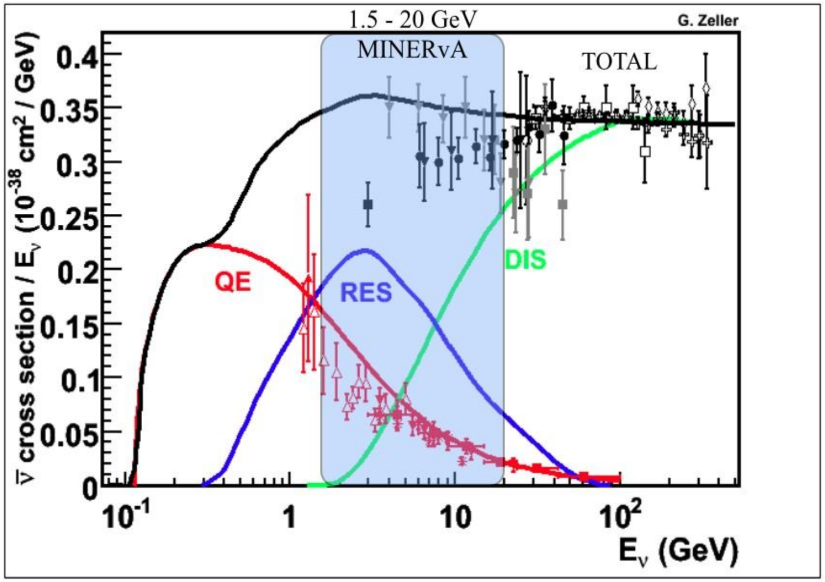
Motivation

- Measuring neutrino interaction cross sections facilitates high precision neutrino oscillation measurements
  - Quasielastic interactions
  - Delta resonance with pion production
  - Deep Inelastic Scattering
  - How nuclear effects and Final State Interactions (FSI) affect observables
  - Nuclear mass dependence
  - Relationship between observed quantities and neutrino energy
- We need better models and high precision data to constrain those
- We’re finding out is that the nucleus is more complicated than our current models can fully explain

Neutrino



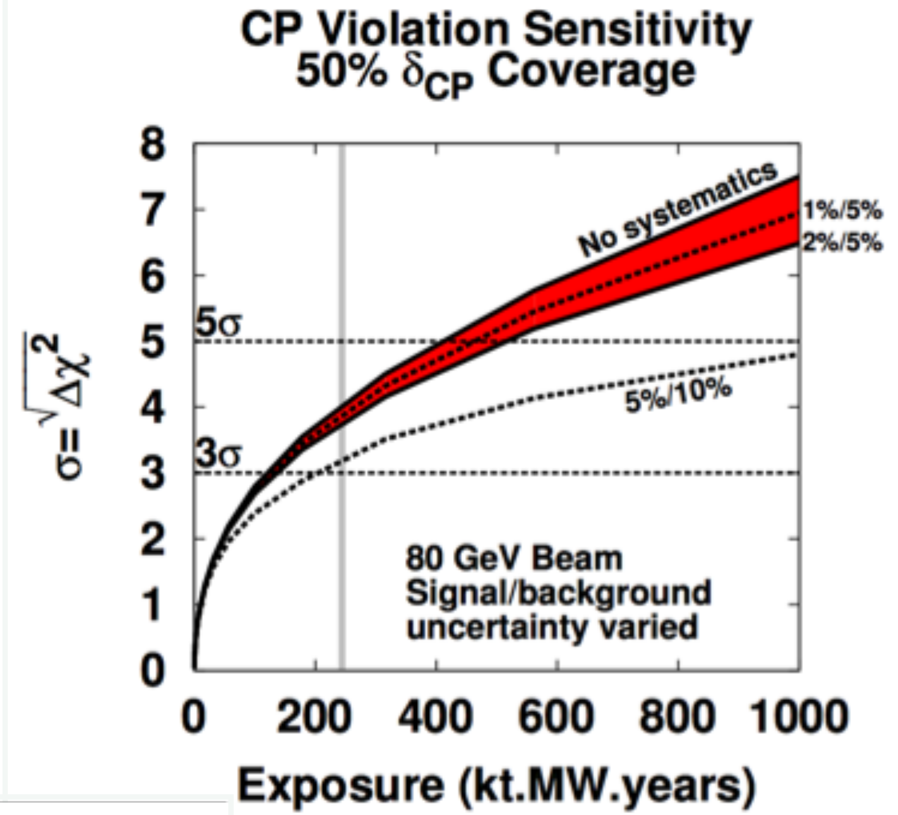
Antineutrino



G. Zeller and J. Formaggio,Rev. Mod. Phys. 84, 1307–1341 (2012)

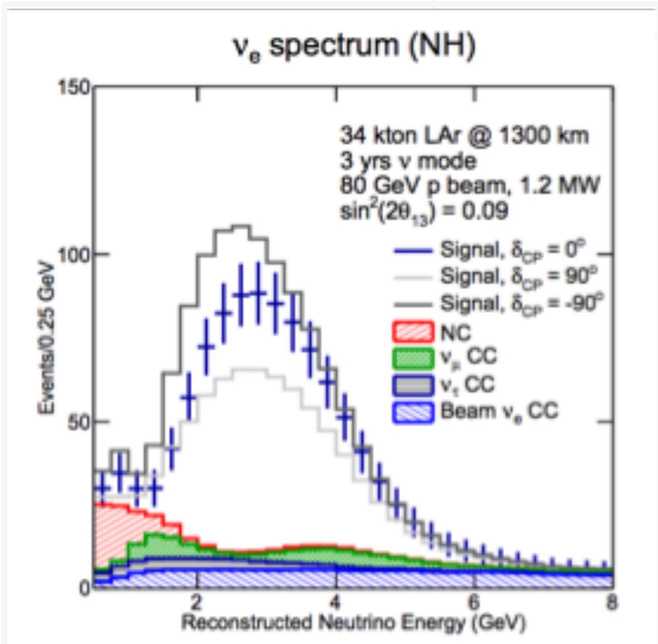
Why Cross Sections?

- Oscillation experiments compare event rates with predictions to determine parameters such as δ_{CP}
- To distinguish these parameters, they must reduce systematics. Cross section models are large contributors to the uncertainty
- Oscillation detectors are made of heavy materials, where nuclear effects complicate the cross-section distributions



LBNE Sensitivity to δ_{CP} for different systematic uncertainties

M. Bass, NuInt 2014



LBNE signal predictions arXiv 1307.7335

What are these Nuclear Effects in Neutrino Nucleus Interactions?

- Target **nucleon in motion** – classical Fermi gas model or spectral functions (Benhar et al.) or more sophisticated models.

- Certain **reactions prohibited** - Pauli suppression.

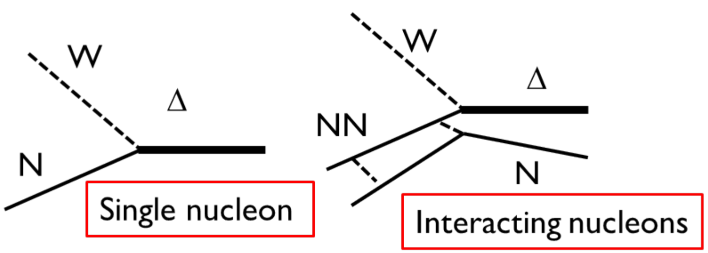
- **Nucleon-nucleon correlations** such as MEC and SRC and even RPA implying multi-nucleon initial states.

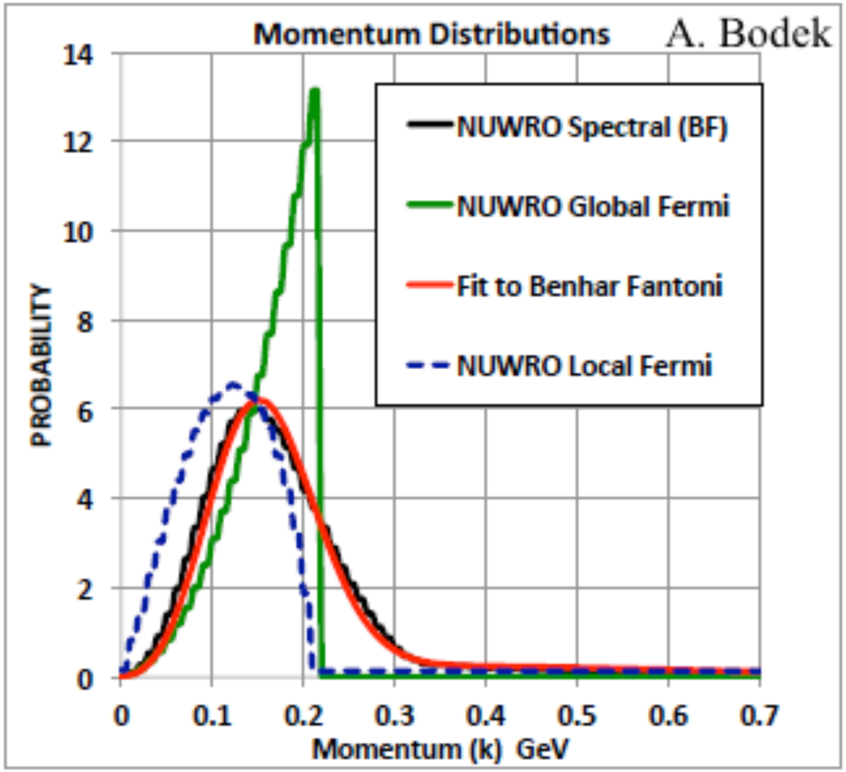
- Cross sections, form factors and structure functions are modified within the **nuclear environment and parton distribution functions** within a nucleus are different than in an isolated nucleon.

- Produced topologies are modified by **final-state interactions** modifying topologies and possibly reducing detected energy.

Nuclear Structure

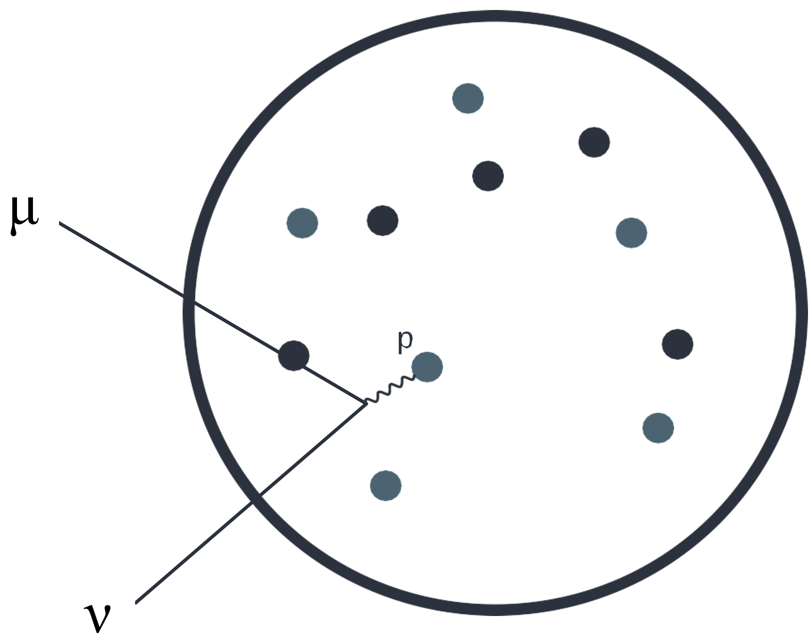
- Principal vertex properties (struck particle, W-boson exchanged) determine Q^2, which is largely influenced by nuclear structure
    - Momentum distribution
      Single nucleon or correlated nucleons





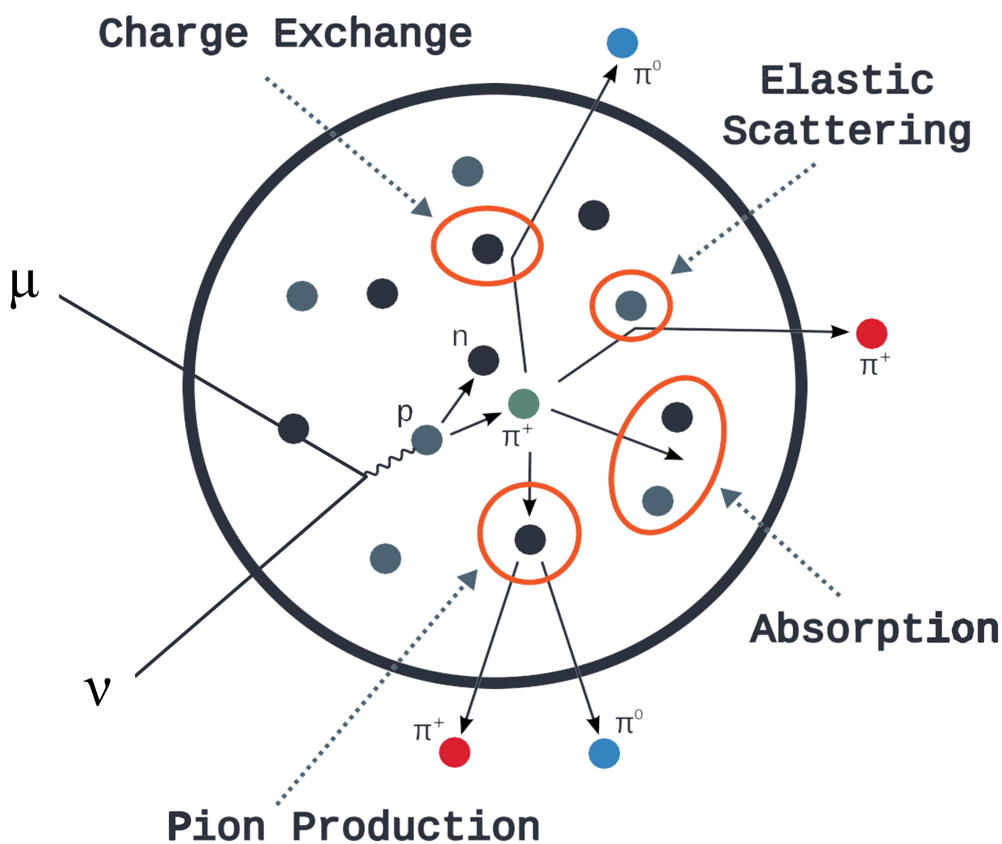
- Most models use Fermi Gas, but evolving to Local Fermi Gas and Spectral Function models

Final State Interactions (FSI)



- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy. Currently using mainly cascade models for FSI
- An initial pion can charge exchange or be absorbed on a pair of nucleons. The final state observed is $\mu + p$ that makes this a fine candidate for QE production
- We've probably also lost measurable energy

Final State Interactions (FSI)



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Putting it all together: The Nuclear Model

- The community models these last two terms in **event generators**:
  - Provide information on how signal and background events should **appear** in our detectors if the model is correct.
  - Provide means for estimating systematic errors on measurements.
  - One of the most important components in the analysis of neutrino experiments.

Generators

GENIE- used by almost all neutrino beam experiments
(C. Andreopoulos, *et al.*, *Nucl. Instrum. Meth.* **A614**, 87-104 (2010))

NEUT- used by T2K
(Y. Hayato, *Acta Phys. Polon.* **40**, 2477 (2009))

NuWro- solid theoretical basis
(T. Golan, C. Juszczak, and J.T. Sobczyk, *Phys. Rev. C* **86**, 015505 (2012))

GIBUU - abrange all neutrino energies
(O. Buss, *et al.,* Physics Reports, Volume 512, Issues 1–2, March 2012)

Theoretical work:

Valencia - efficient calculations at low energies, coming to generators
Athar, *et al.* - shown in plots, complex nuclear model but simple FSI

Putting it all together: The Nuclear Model

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  - Provide information on how signal and background events should **appear** in our detectors if the model is correct.
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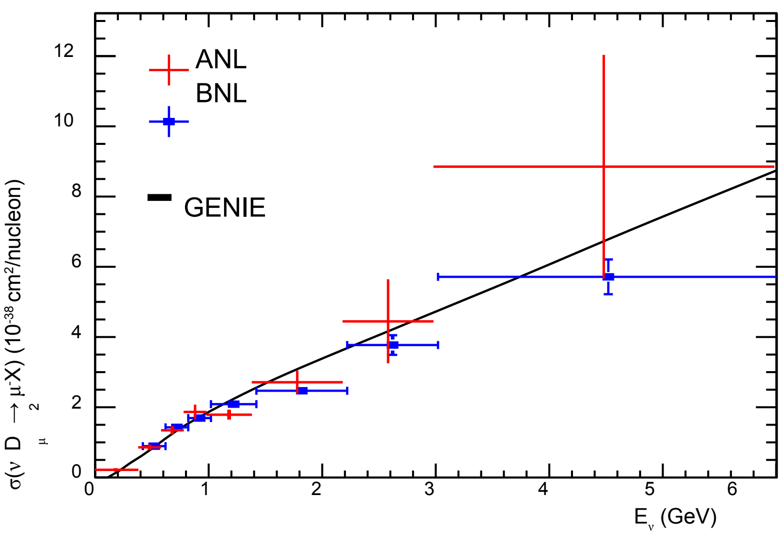
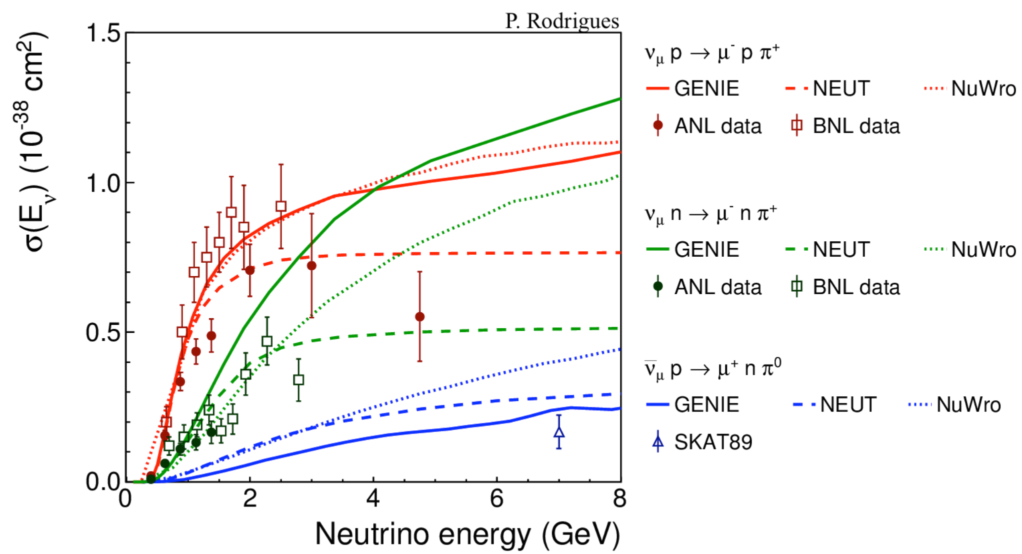
	GENIE	NEUT	NuWro
Δ Model	Modified Rein-Sehgal	Rein-Sehgal	Adler-Rarita-Schwinger
Non-Resonant	Scaled Bodek-Yang	Rein-Sehgal	Quark-parton model
Higher resonances	Modified Rein-Sehgal	Rein-Sehgal	Quark-parton model
Δ Form Factor	Dipole	Modified dipole	Modified dipole
Nuclear model	Rel. Fermi Gas	Rel. Fermi Gas	Rel. Fermi Gas
Pauli Blocking	None	None	Included

Neutrino Nucleon Scattering Data

- All calculations must fit to old bubble chamber deuterium data
  - Many have trouble reconciling ANL/BNL data sets Most authors split the difference (GENIE)
  - Recent reanalysis of deuterium data (Wilkinson *et al.*, 2014) finds consistency between ANL and BNL (NEUT)
- Very little data for π^0 production, authors tend to get it from isospin relations

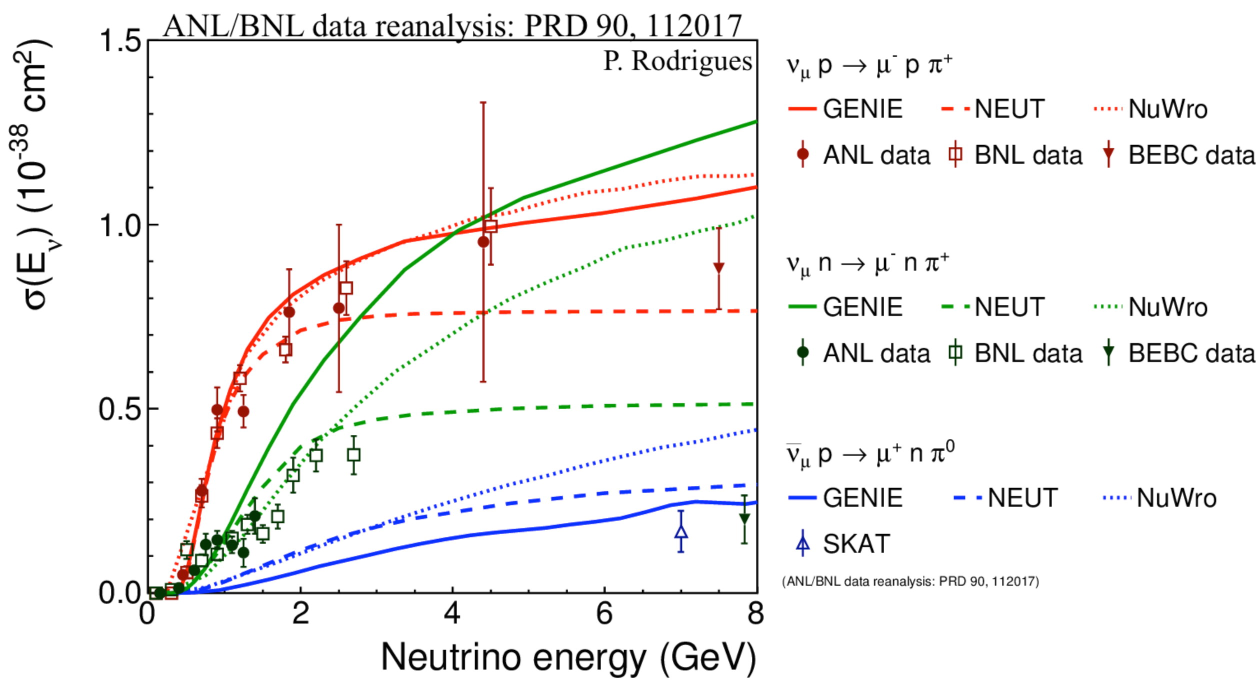


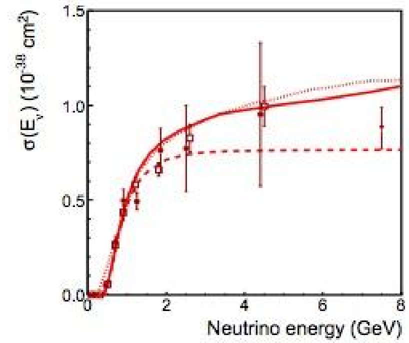


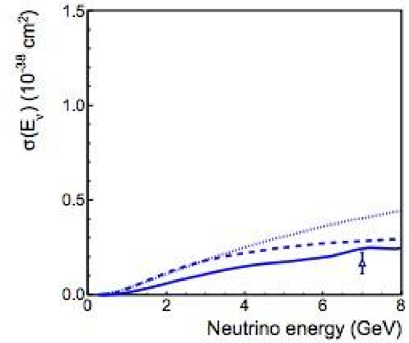
Wilkinson et al. – arXiv:1411.4482

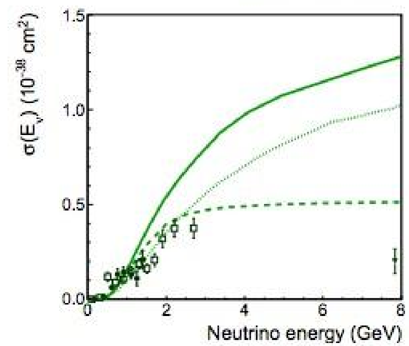
Neutrino Nucleon Scattering Data

- Shows the difference in generator choices
- Spread in data allows for a wide range of fits by the various generators
- These are the nucleon-level predictions that are relevant to the data presented later
- Limited statistics ANL and BNL bubble chamber data off D2 from the 80’s is what we have

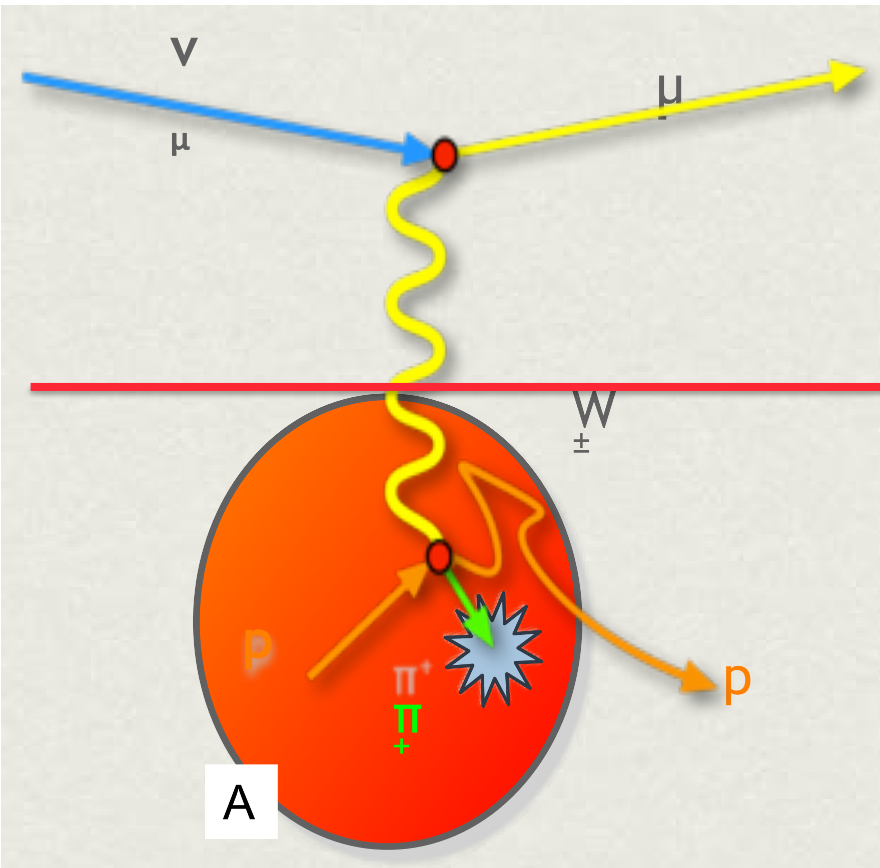








Understanding Effects of the Nucleus Leptonic vs Hadronic Clues



- **Lepton:**
- Provide information on initial interaction on nucleon within the nucleus.
- **Initial Nucleon State**
  - **Relativistic Fermi Gas Model**
  - **Local Fermi Gas Model**
  - **Spectral Functions**
  - **Correlated Nucleons (RPA, MEC, SRC..)**

- **Hadrons:**
- Provide information on Final State Interactions within the nucleus.
  - **Note that correlated nucleons (RPA, MEC, SRC..) also undergo final state interactions.**

The NuMI Beam and the MINERvA Detector

The NuMI beam

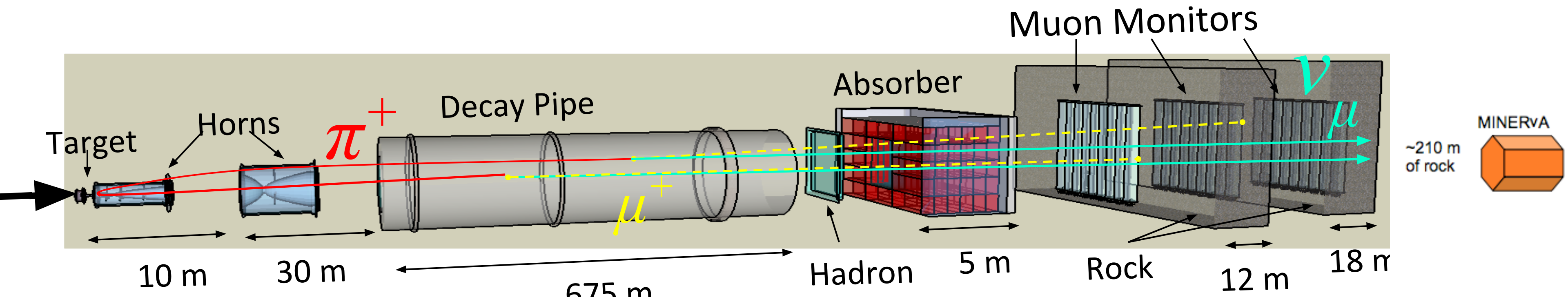
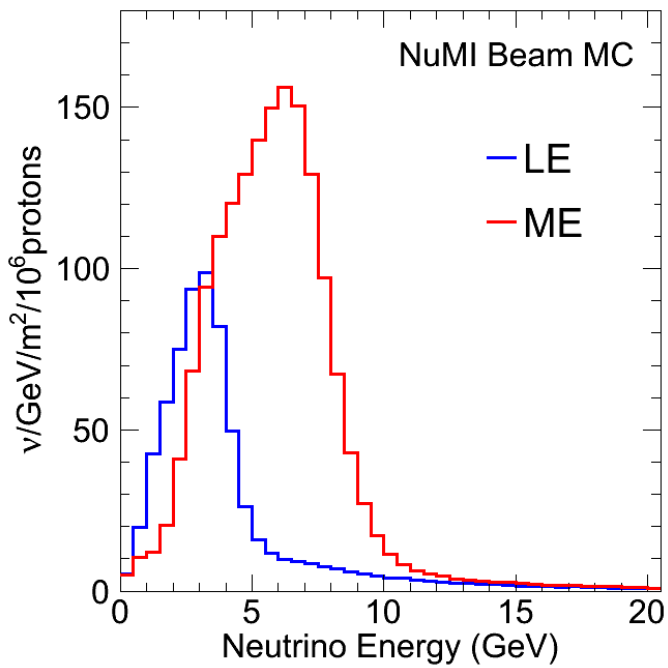


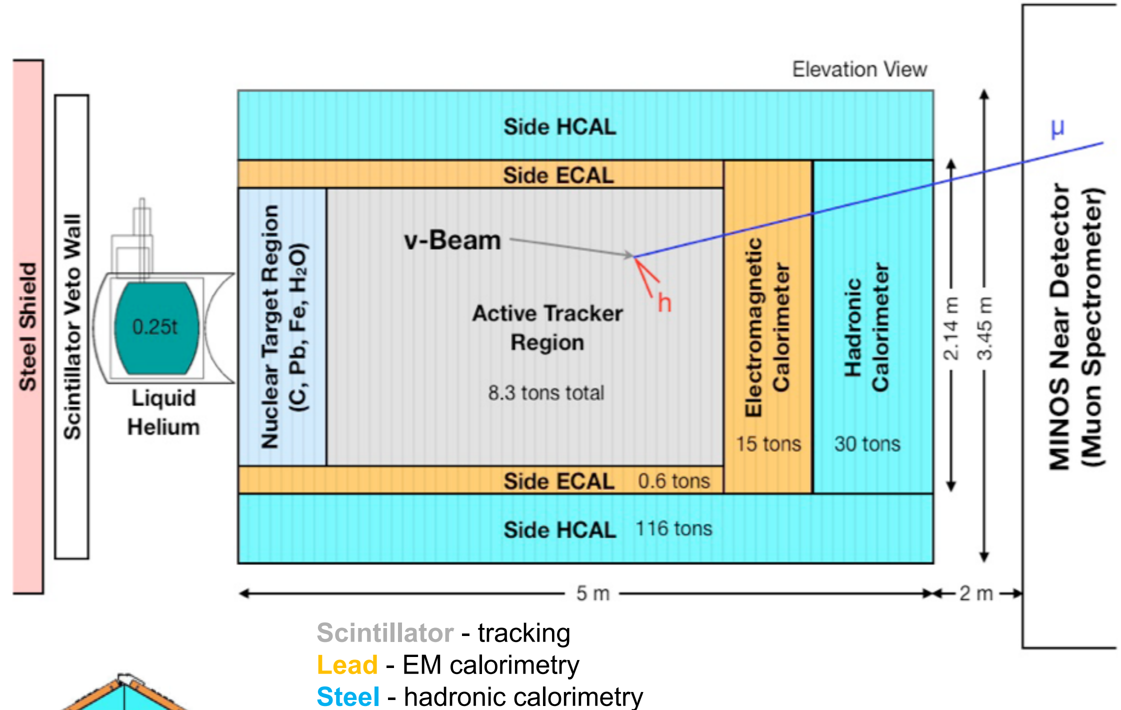
figure courtesy Ž. Pavlović

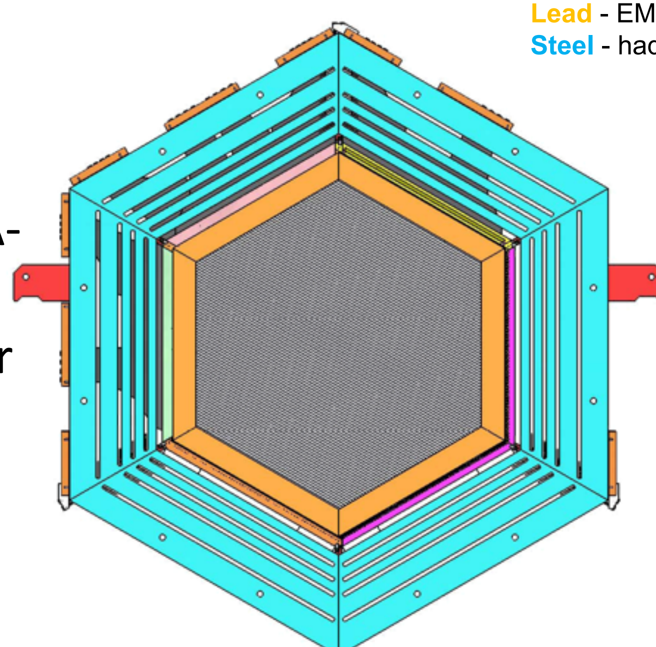
- 120 GeV/c protons on carbon target produce pions.
- Pions and kaons decay into muons and neutrinos.
- Horns focus positive or negative pions depending on their polarity
- Neutrino beam energy increased by moving target and one horn

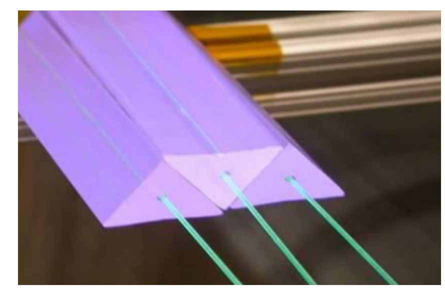


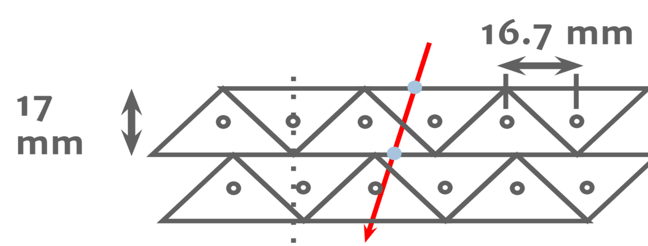
MINERvA Detector

- 120 modules stacked along the beam line in three orientations
- Fine-grained scintillator tracker surrounded by calorimeters
- Upstream nuclear targets to measure A-dependence
- MINOS near detector is the muon spectrometer (magnetized)







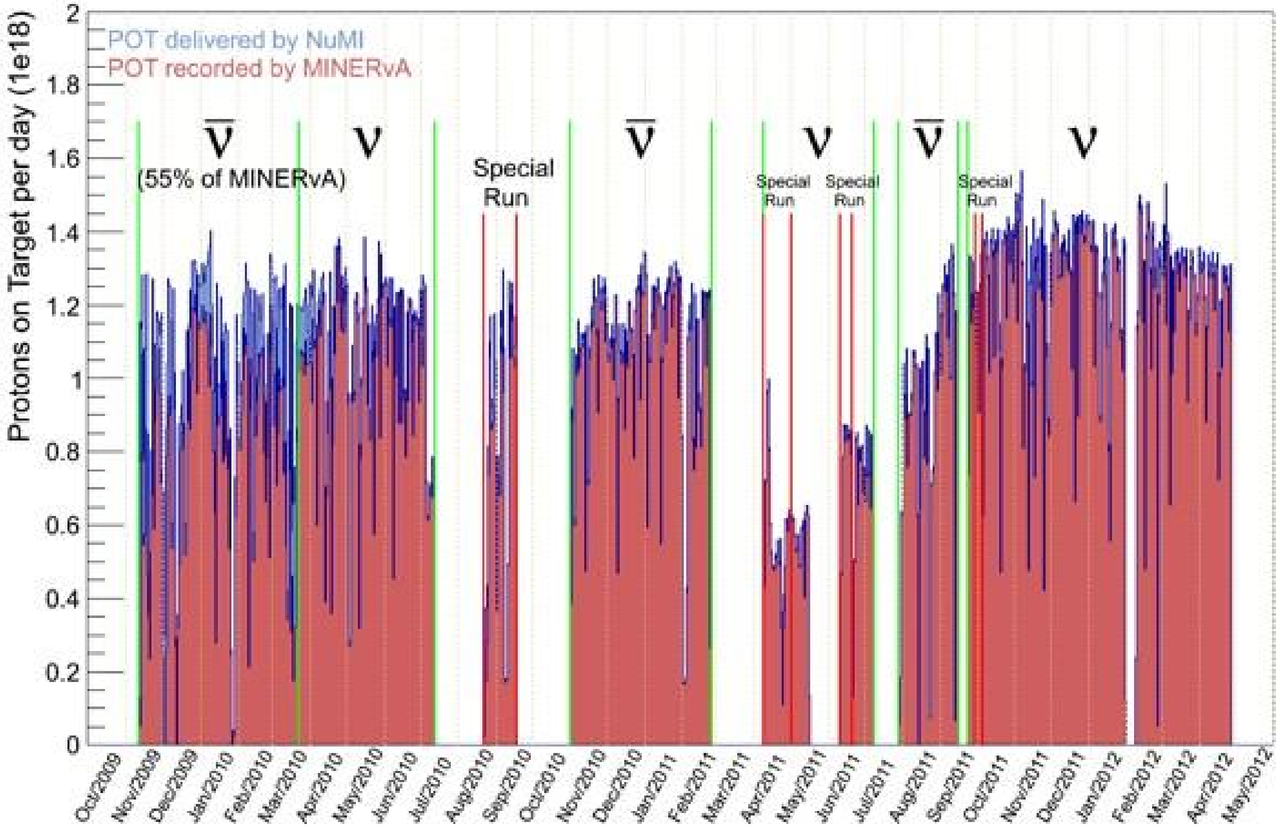


Charge sharing for improved position resolution (~3 mm) and alignment

Design, Calibration and Performance of the MINERvA Detector, NIM A743 (2014) 130

Data Collected and Used

- Neutrino charged pion production analysis uses 3.04e20
- POT Antineutrino neutral pion production analysis uses 2.01e20 POT

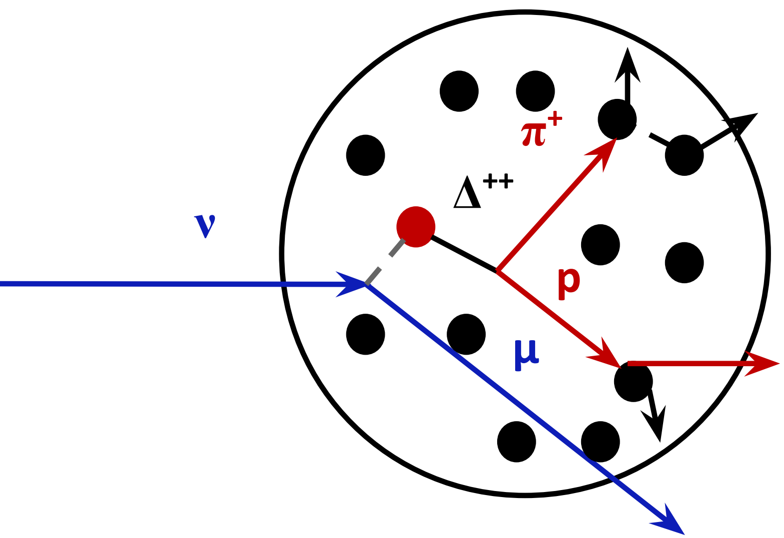


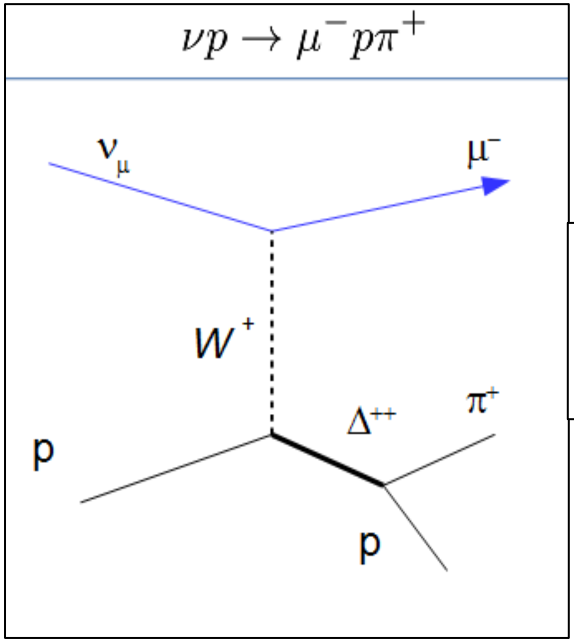
Charged Pion Production

MINERvA Event Selection

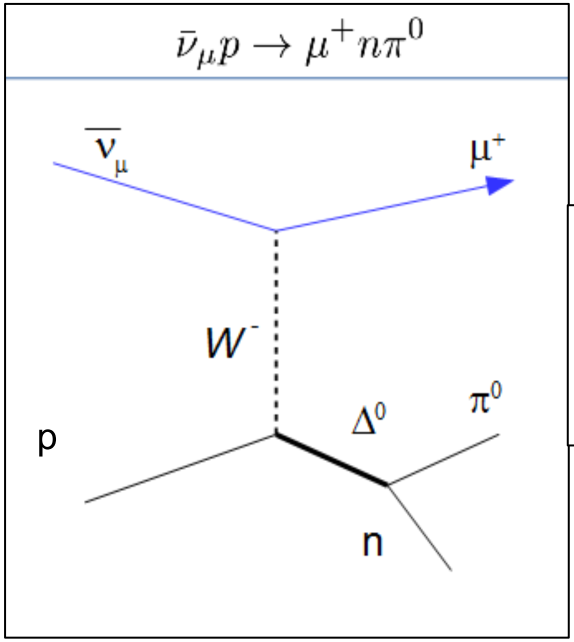
Pion Production

- Main method of pion production: delta resonance which decay to a pion and a nucleon.
- Final State Interactions can absorb the pion -> mimic QE signal
- Final State Interactions can produce pions -> contaminate QE signal





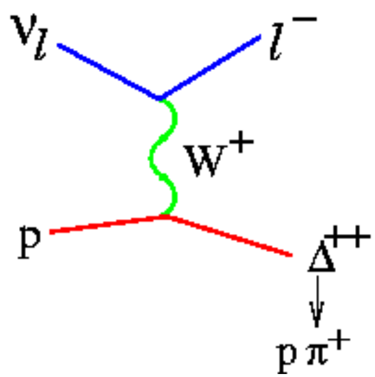
Charged-Current Single Charged Pion Production



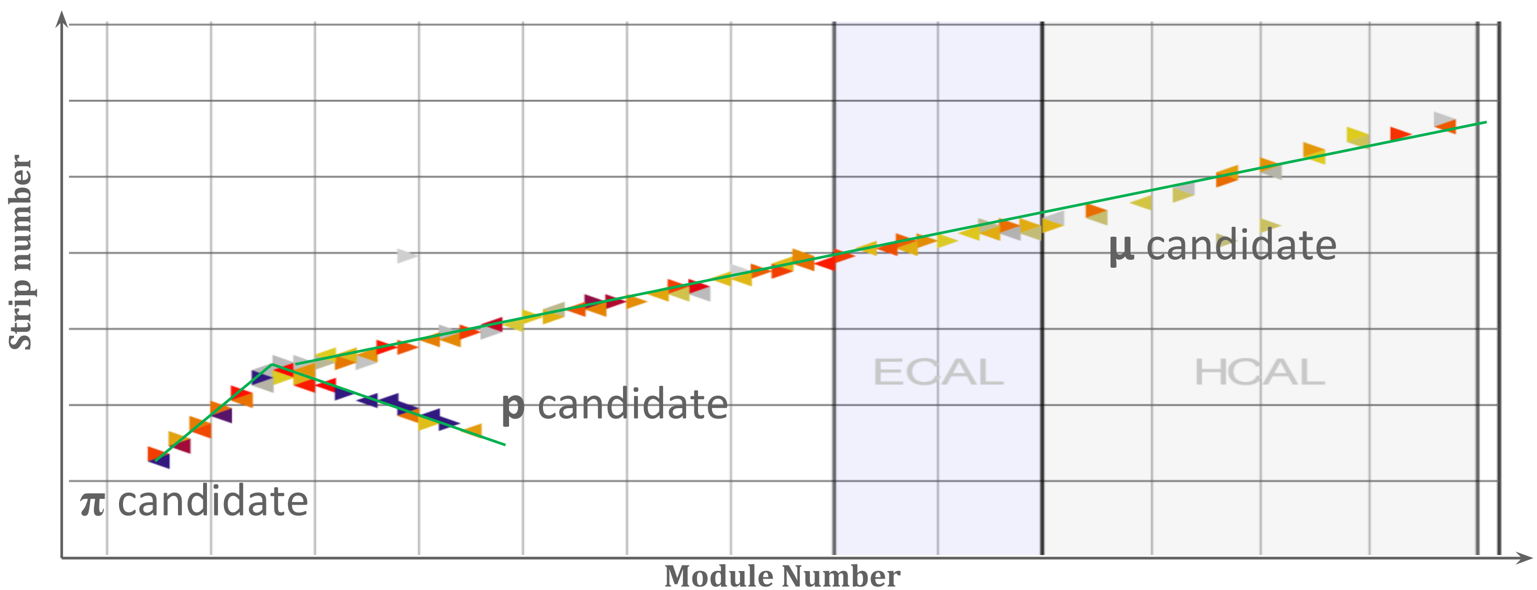
Charged-Current Single Neutral Pion Production by antinu

Charged Pion Production

$$\nu_\mu A \rightarrow \mu^- \pi^{\pm} X$$



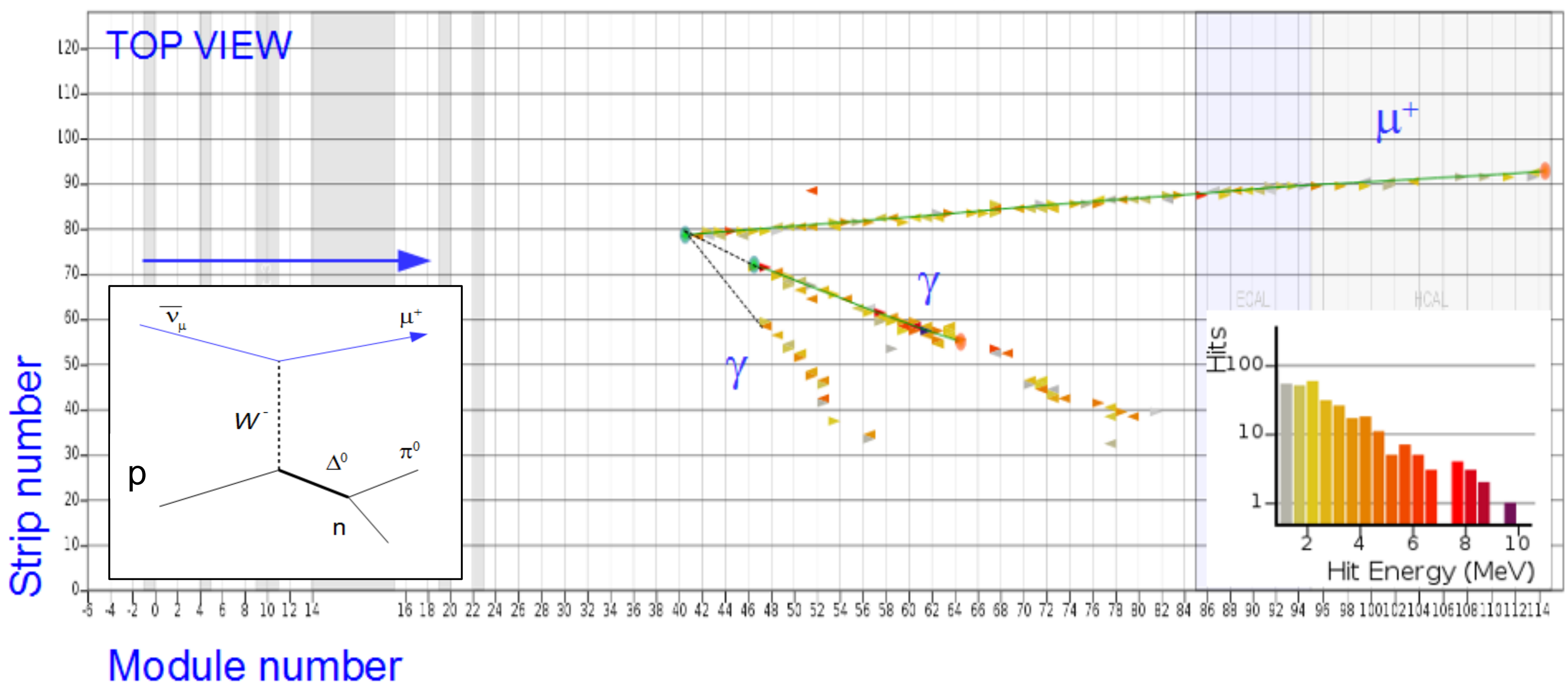
- Events with a proton and a pion candidate selected
- Theoretical calculations and event generators are unable to reproduce recent pion kinetic energy differential cross section
- Goal: Determine strength and nature of FSI using pion kinematics



Charged-Current Single Neutral Pion Production by antinu

- Importance: background – can mimic electron neutrino signal as negative pion decays to 2 photons

$$\bar{\nu}_\mu + \mathrm{CH} \to \mu^+ \underbrace{\pi^0}_{\to\gamma\gamma} X$$



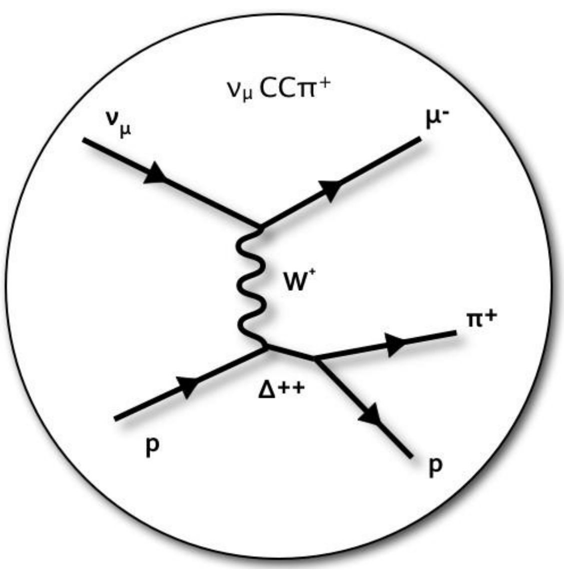
Signal Definitions

<u>Neutrino</u>

Single charged pion production

$$\nu_\mu + CH \rightarrow \mu^-(1\pi^\pm)X$$

X can contain any number of π^0s, no charged pions

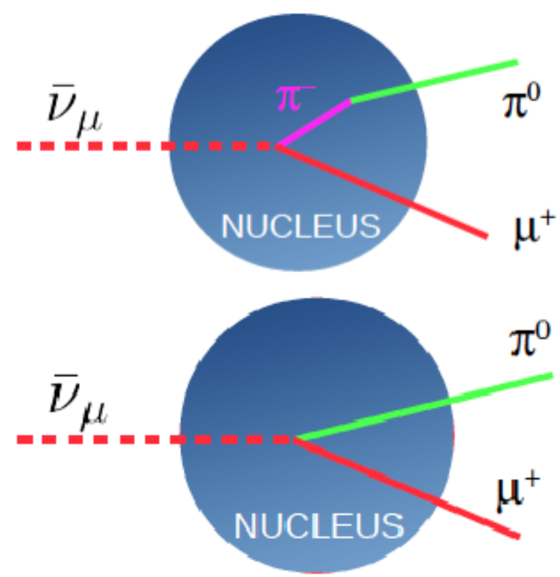


<u>Antineutrino</u>

Single neutral pion production

$$\nu_\mu + CH \rightarrow \mu^+(1\pi^0)X$$

X contains no mesons

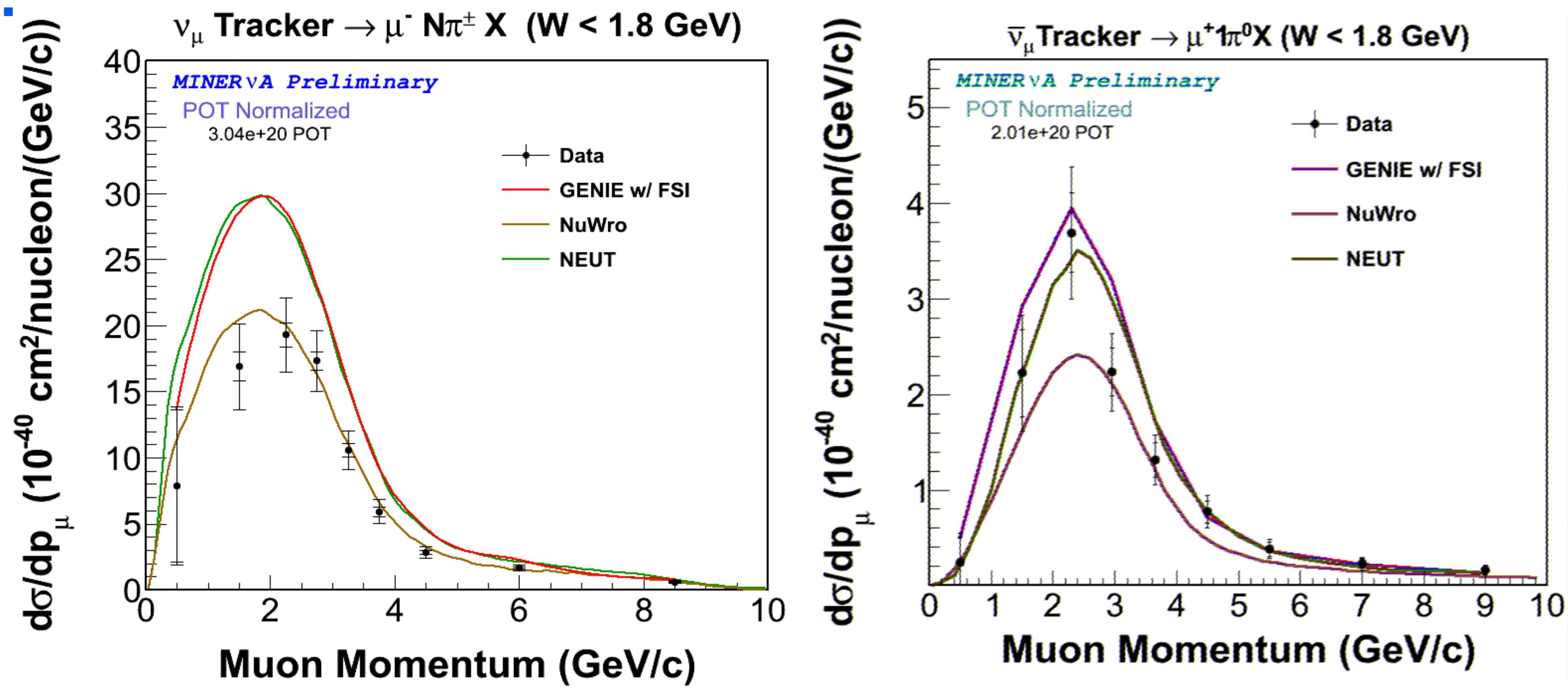


CC Pion Production Analysis with Muon variables

Neutrino
Single charged pion production

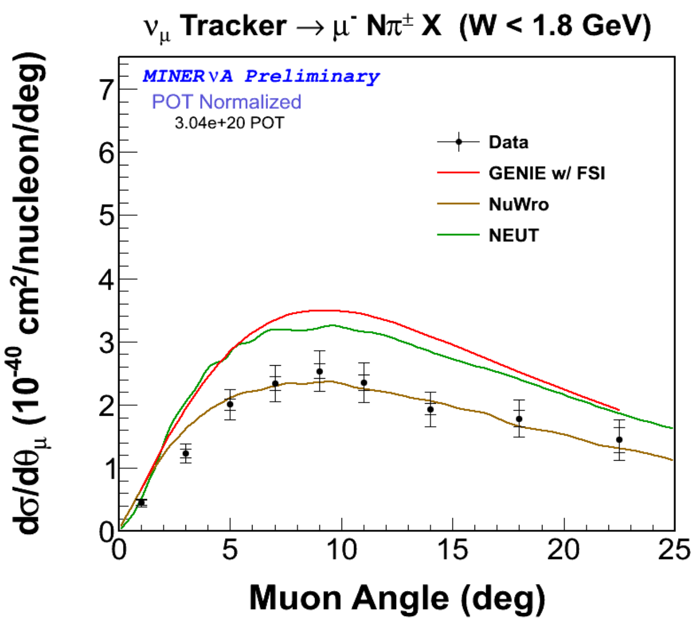
Antineutrino
Single neutral pion production

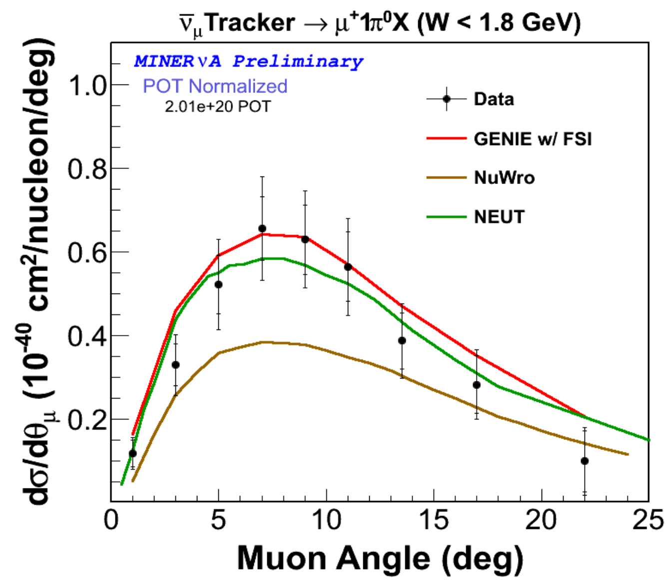
CCpion production from the lepton side: Cross section model comparisons for μ momentum



- In charged pion both GENIE and NEUT overestimate the cross section
- GENIE and NEUT predictions are similar and are higher than NuWro in both analyses

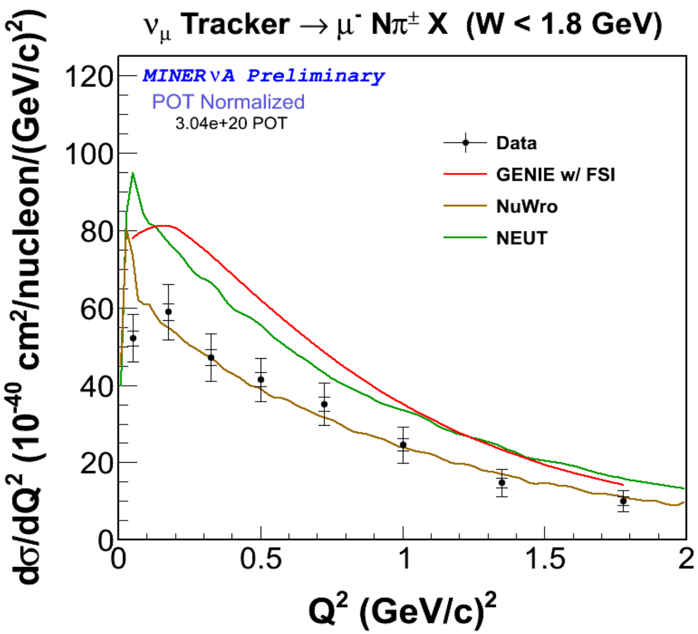
CCpion production from the lepton side: Cross section model comparisons for μ angle

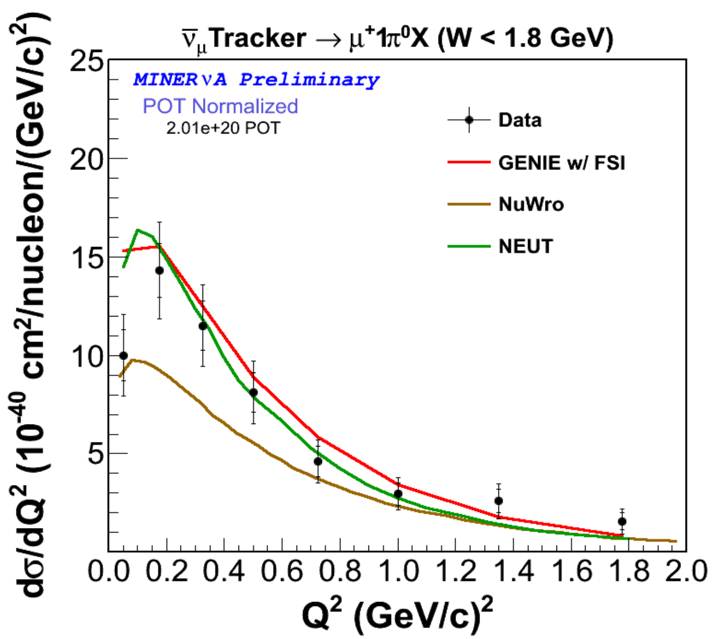




- The same normalization and shape behavior as with the μ momentum

CCpion production from the lepton side: Cross section model comparisons for Q^2





- In charged pion both GENIE and NEUT over estimate the cross section (as in the muon variables)
- In the shape analysis, GENIE agrees well with data except in lowest Q^2 bin of the neutral pions.
- In lowest Q^2 bin of the charged pions, coherent production in NuWro & NEUT

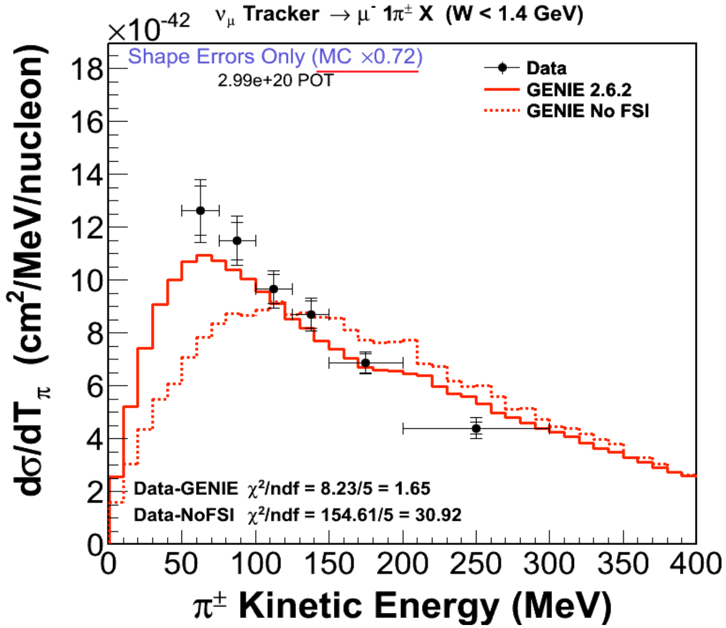
CC Pion Production

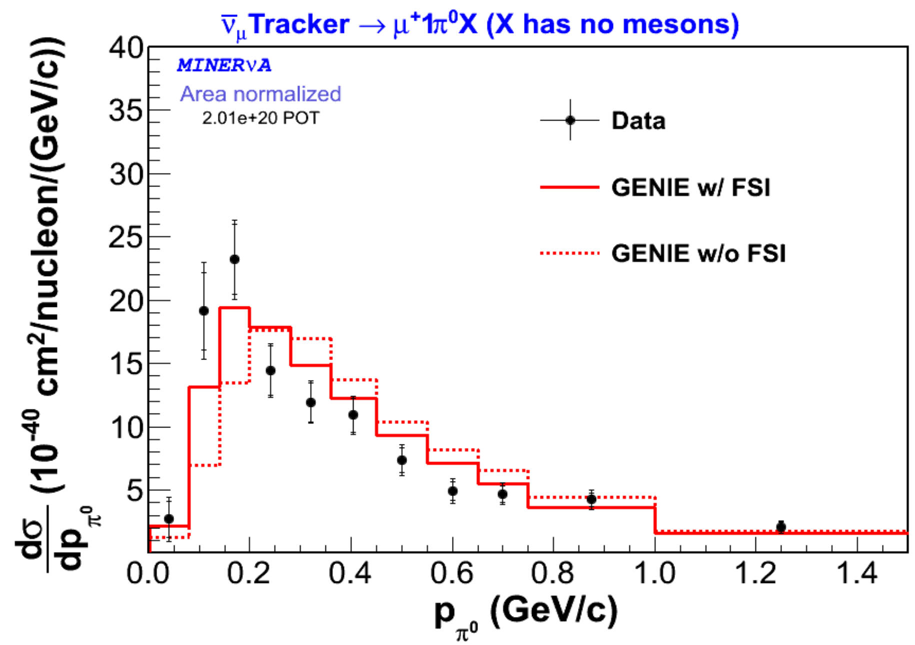
Neutrino - Nucleon Scattering (hadronic side)

Neutrino Single charged pion production	Antineutrino Single neutral pion production
B. Eberly et al.; arXiv:1406.6415	*T. Le et al., arXiv: 1503.02107 [hep-ex]*

FSI Conclusions for Pion Energy

(Shape Comparisons)

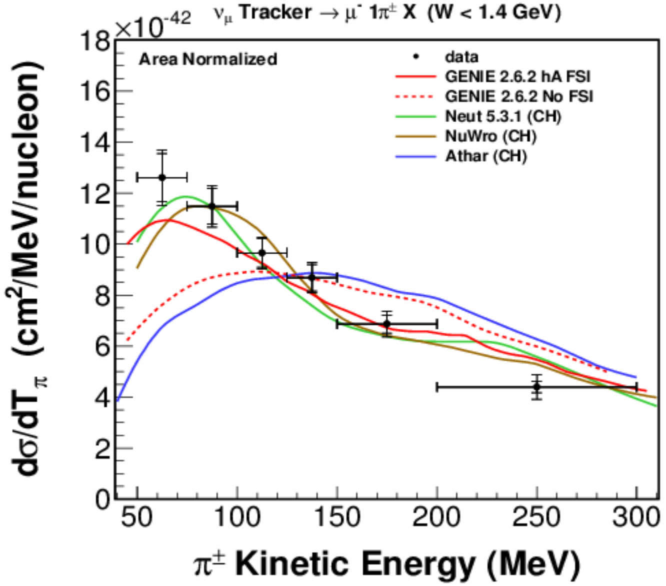


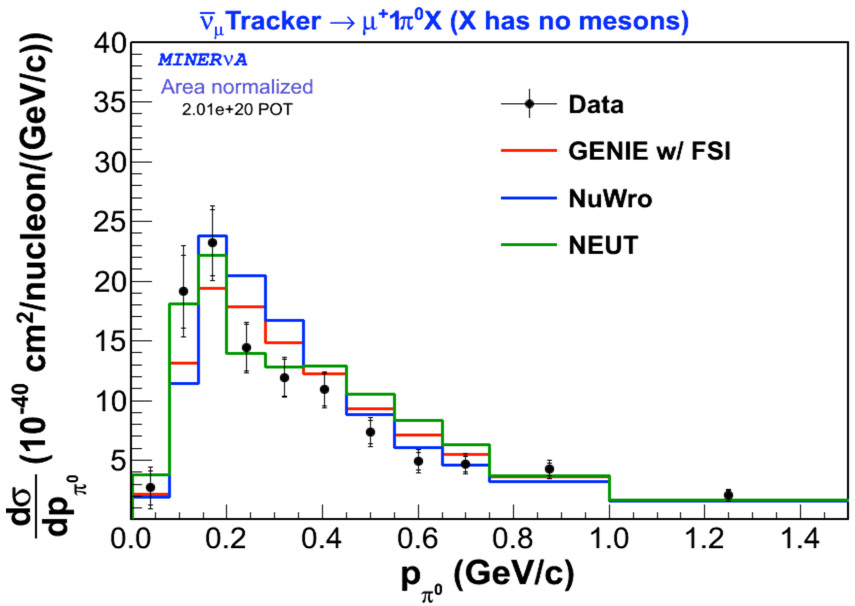


- Data prefer GENIE with FSI

FSI Conclusions for Pion Energy

(Multi model - Shape Comparisons)

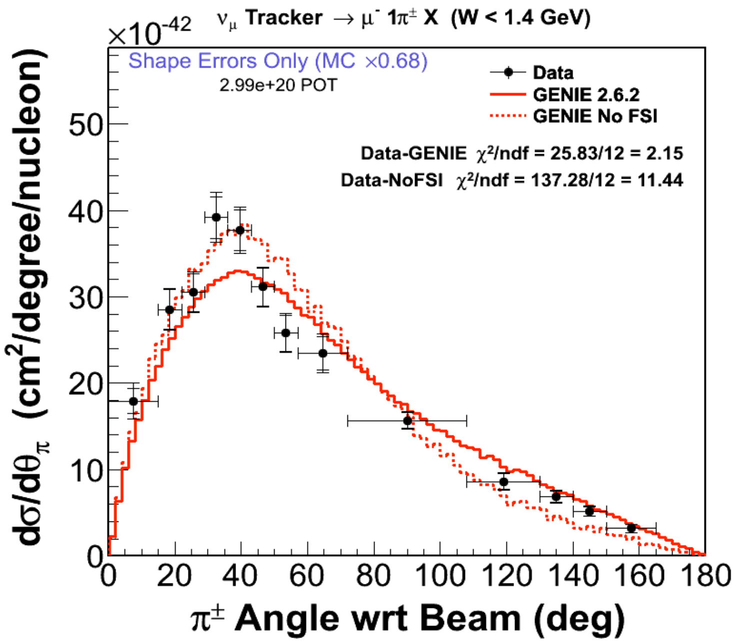


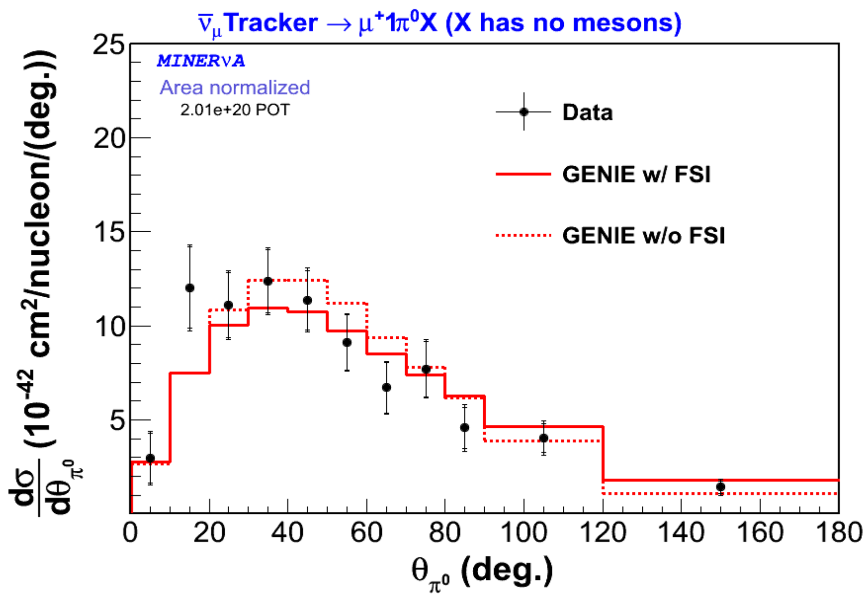


- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Data is unable to distinguish different FSI models

FSI Conclusions for Pion Angle

(Shape Comparisons)





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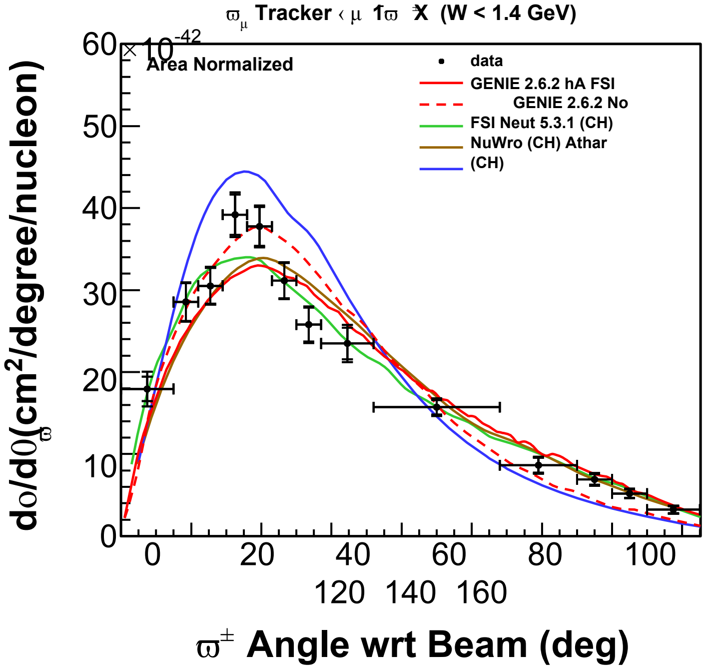
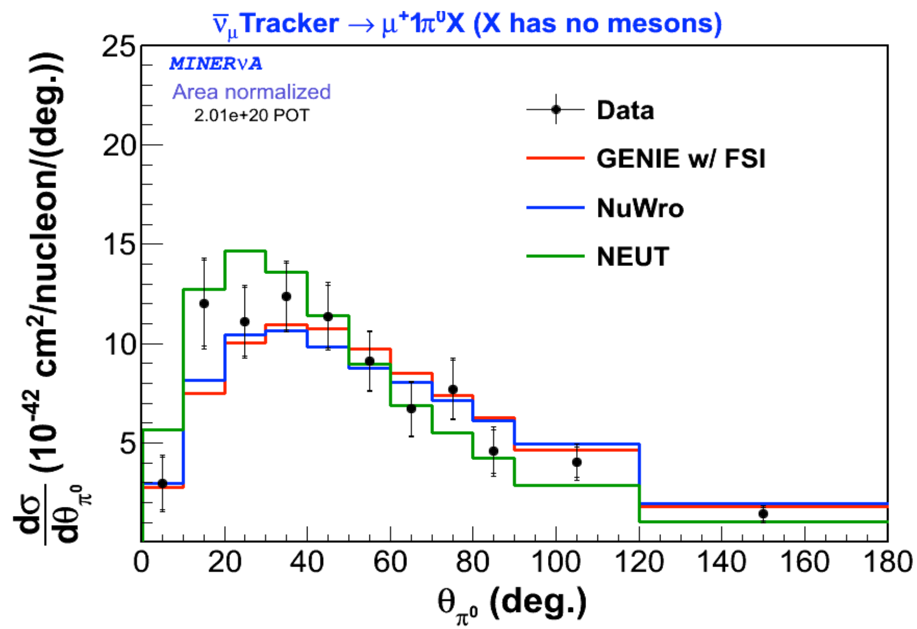
FSI Conclusions for Pion Angle

(Multi model - Shape Comparisons)





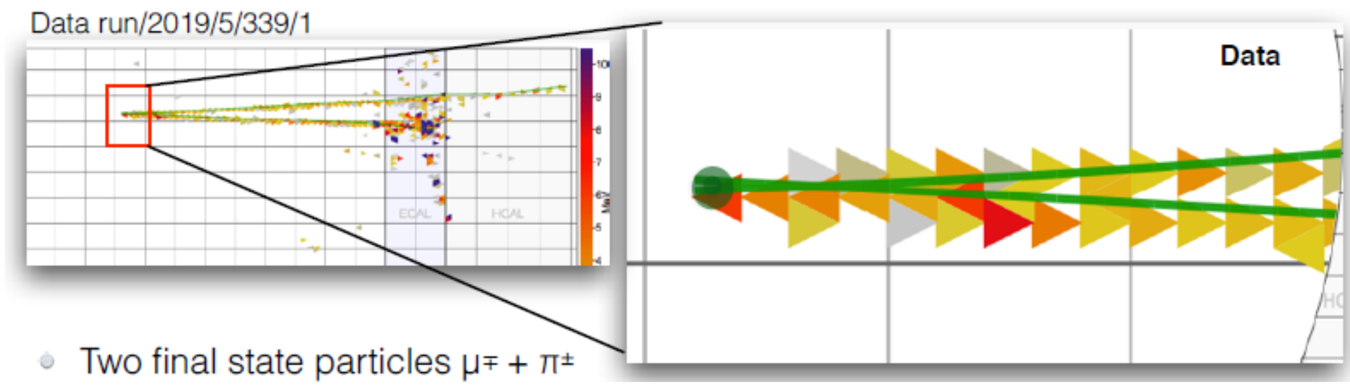
- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Again, data is unable to distinguish different FSI models

Coherent Charged Pion Production

Neutrino Nucleus Scattering

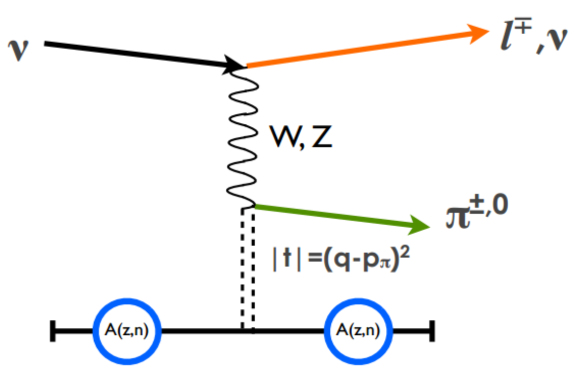
Coherent Charged Pion Production

$$\nu_\mu A \rightarrow \mu^+ \pi^- A$$
$$\bar{\nu}_\mu A \rightarrow \mu^- \pi^+ A$$



- Two final state particles $\mu^\mp + \pi^\pm$

- Coherent pion production: Struck nucleus is left in its ground state and a single π^+ is produced
- Neutrino scatters off a nucleus, produces a pion, and transfers low four momentum (|t|) to the nucleus, which stays intact
- Oscillation measurements require understanding of these interactions

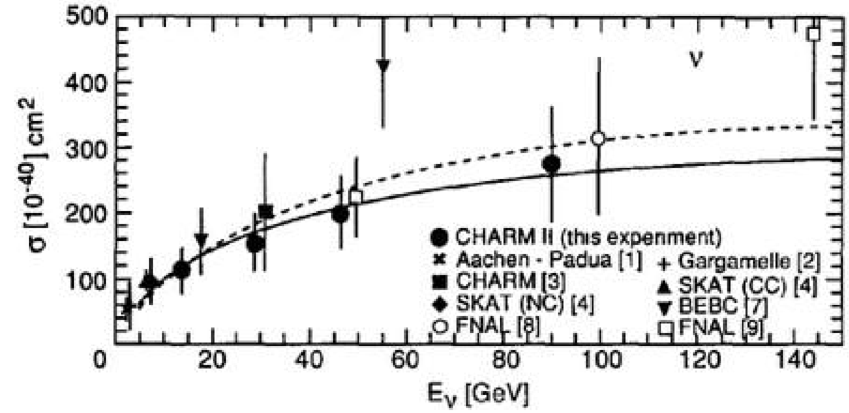


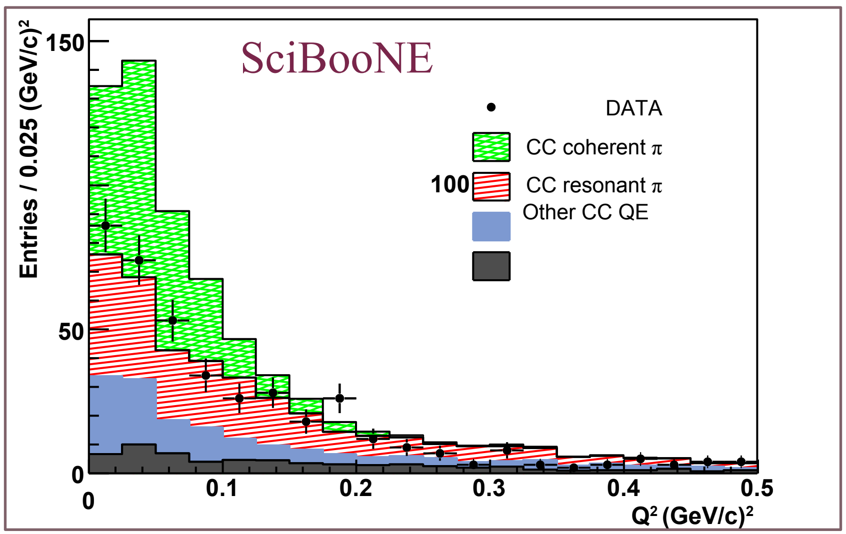
$$E_\nu = E_\mu + E_\pi$$
$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$

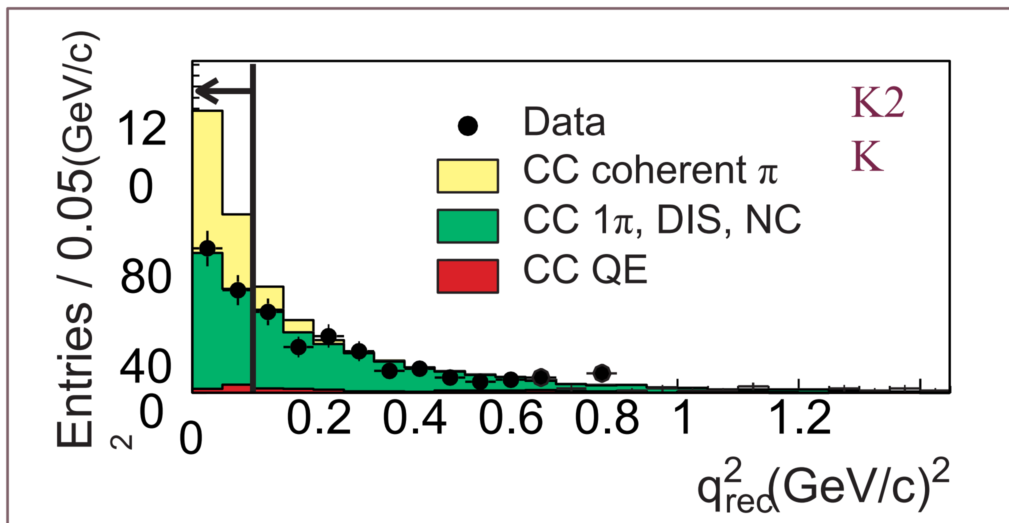
A Higuera, A Mislevic et al., Phys. Rev. Lett. 113, 261802 (2014)

Coherent pion production

- Early experiments at high energies see clear evidence of coherent pion production
- Lower energy experiments saw results consistent with NEUT's background predictions







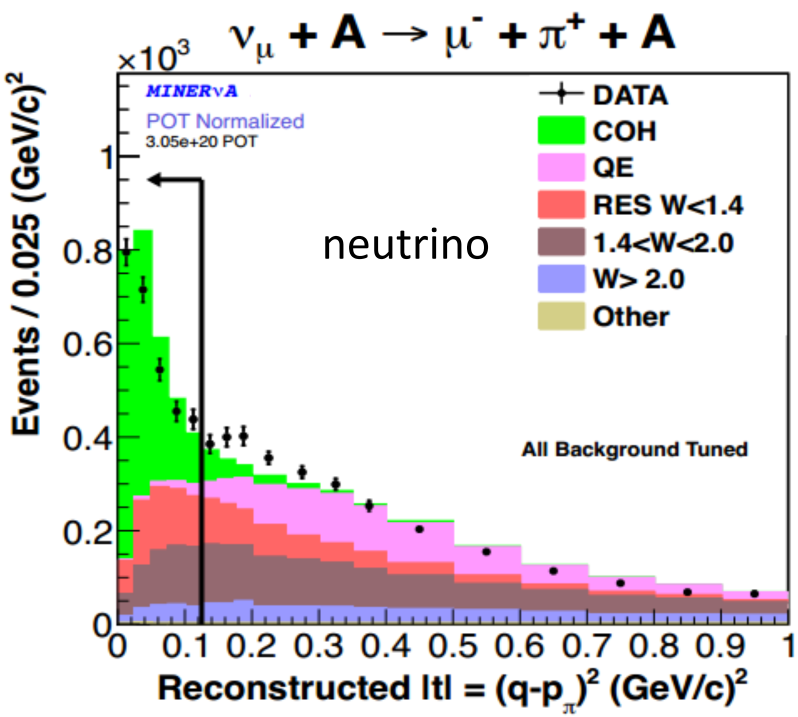
Coherent pion production

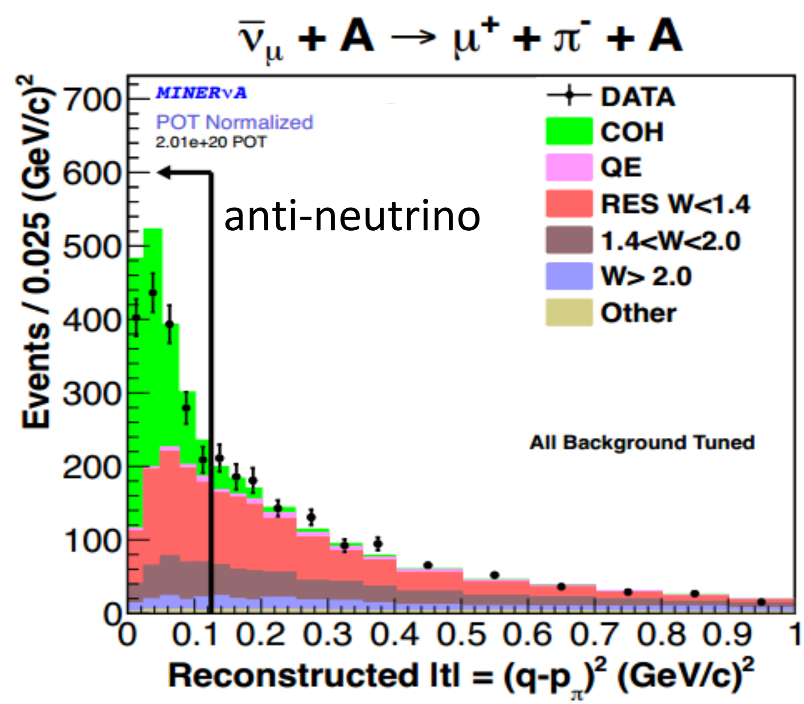
- Select event with $|t| < 0.125\ (\mathrm{GeV}/c)^2$, with defined as:

- Event Selection:
    - Require a muon which enters MINOS
    - Requires a pion
    - No extra visible energy near vertex
    - Cut on $|t|$
    - P_μ measured from reconstructed muon in MINOS
    - E_π is reconstructed calorimetrically

Coherent pion production

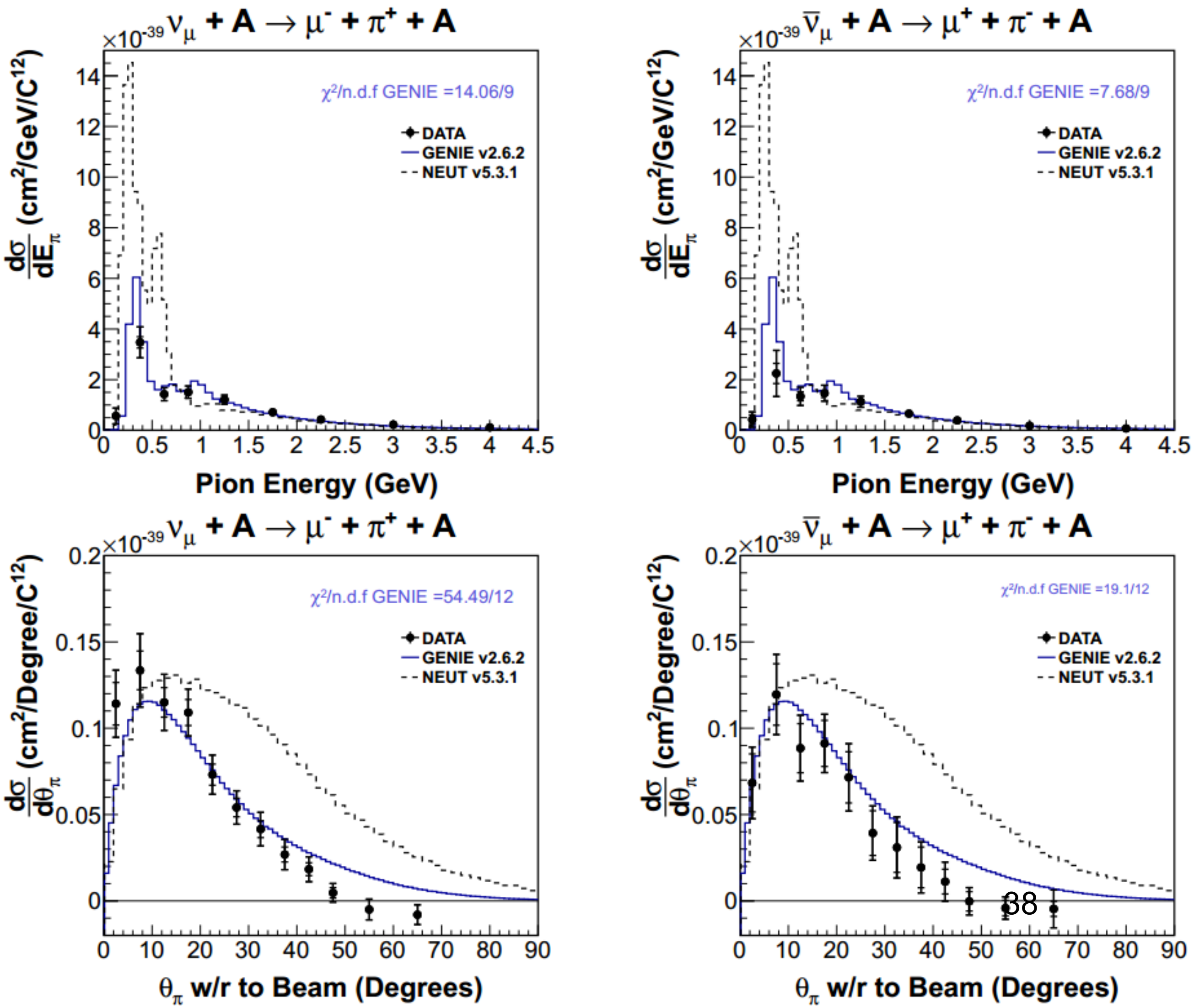
- MINERvA sees clear evidence of coherent scattering in the few-GeV energy region
- Our ability to measure the quantity |t| enables us to identify coherent candidates in a model-independent way
- The slope of the |t| distribution is related to the size of the target, so it is easy to distinguish scattering off a nucleus from a nucleon





Coherent Pion Production: Results

- MINERvA sees coherent pion production ~1.6K ν and ~900 anti-ν
- Differential cross sections as a function of pion energy and angle against GENIE and Neut (Rein-Segal)
- Disagreement at high θ_π is evident in both
- Data provides benchmark to test new PCAC and microscopic models



Measurement of Coherent Production of $\pi^\pm$ in Neutrino and Anti-Neutrino Beams on Carbon from E_ν of 1.5 to 20 GeV, PRL 113, 261802 (2014)

Kaon Production

Motivation

- SUSY GUT models predict $p \rightarrow K^+ \nu$ with lifetimes of (few) × 10^{34} years
- For water Cherenkov detector, K^+ is below detection threshold, so you see only μ^+ from K^+ decay
  - $\nu_\mu n \rightarrow \nu_\mu K^+ \Sigma^-$ where $\Sigma^- \rightarrow n \pi^-$ below threshold
- For a LAr detector, modeling K^+ FSI is important
  - What is the signal spectrum? Are there FSI processes that fake the kaon signal?
- Strangeness conservation prevents K^+ absorption, and processes like $\pi^+ n \rightarrow K^+ \Lambda$ inside the nucleus enhance cross section

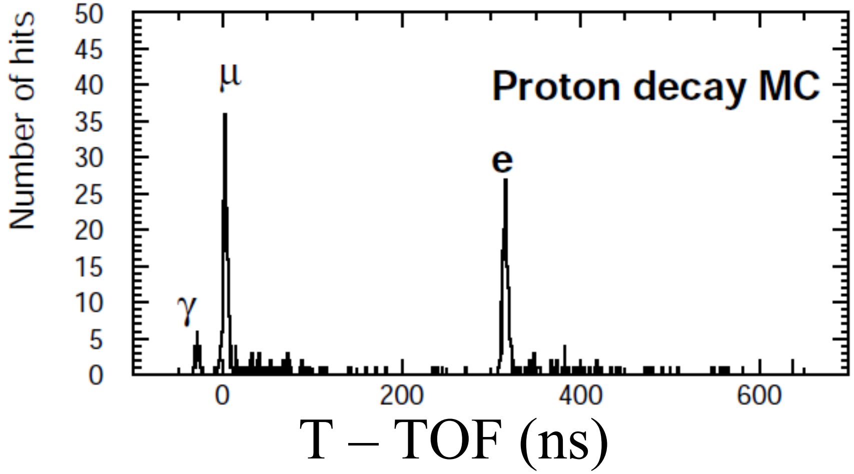
Why Neutral Current?

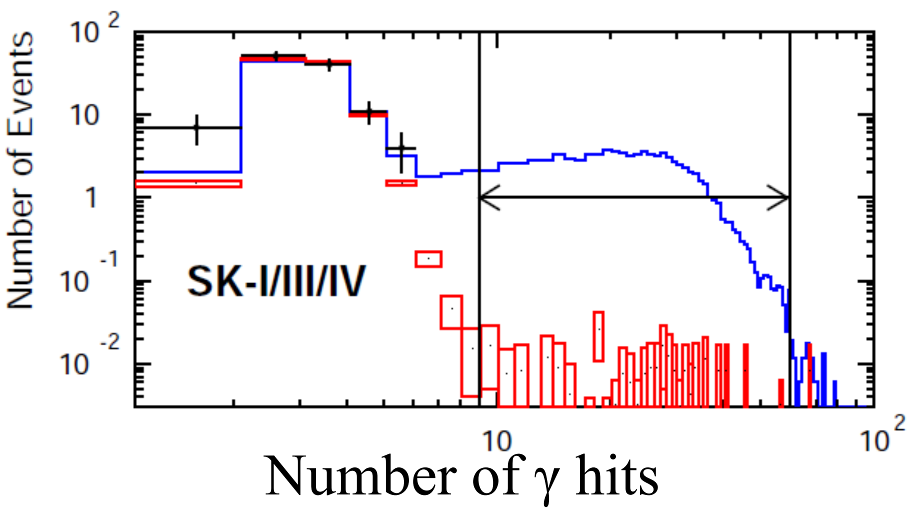
- Neutral-current reactions like
  - $\nu\, p \rightarrow \nu\, K^+ \Lambda$
  - $\nu\, n \rightarrow \nu\, K^+ \Sigma^-$

  are backgrounds in searches for $p \rightarrow K^+ \nu$
- Charged-current reactions are generally not backgrounds because they produce a detectable charged lepton

$p \to K^+\nu$ at Super-K

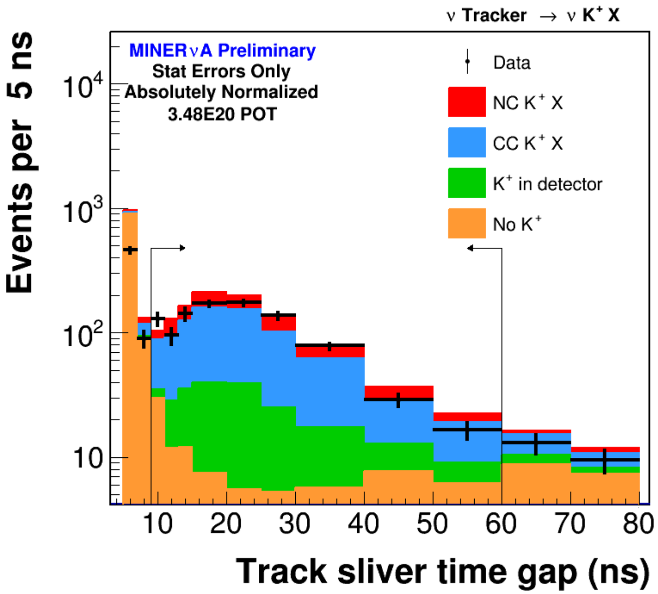
Phys. Rev. D 90, 072005 (2014)

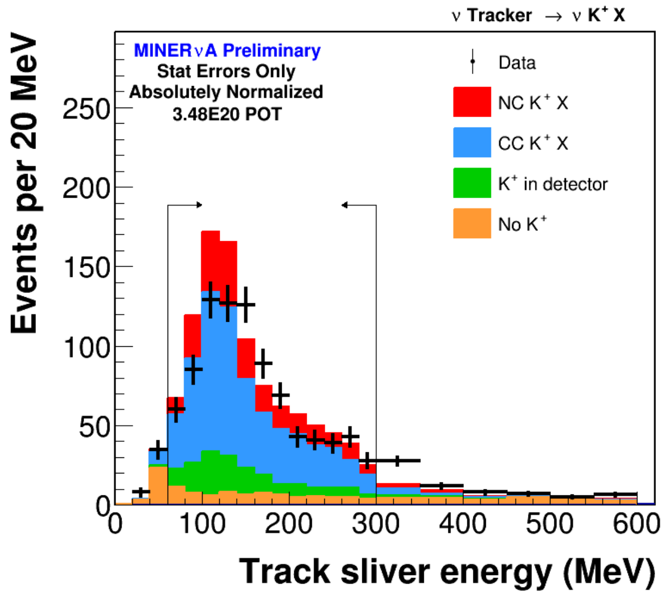




- K+ is below threshold
- Require prompt γ from ^{15}N de- excitation, delayed decay products from $K \to \mu \to e$
  $\nu\, p \to \nu\, K^+ \Lambda$ gives exactly the same signature – an irreducible background
- Expect ~3 of these in 5 years of Hyper-K

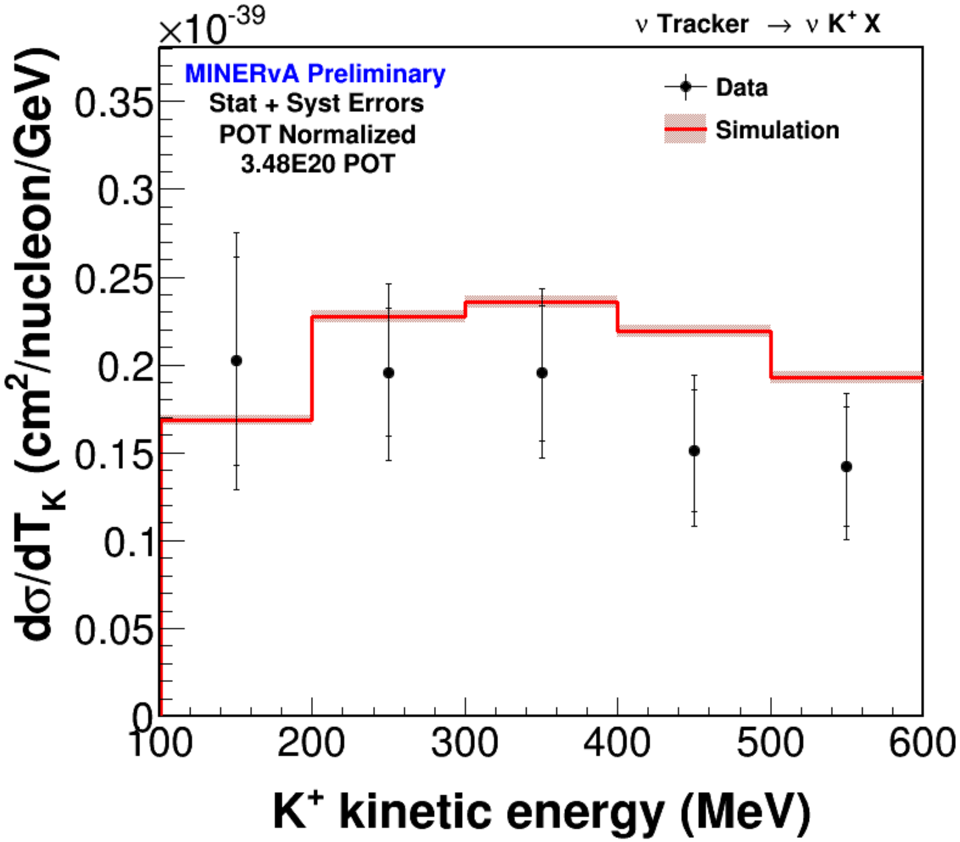
Selecting time sliver events

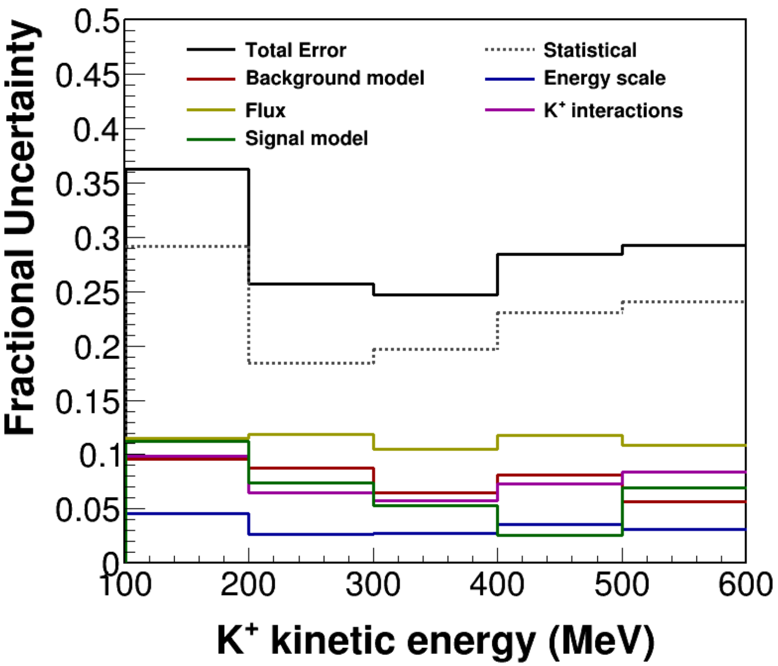




- $p/\pi \rightarrow p/\pi$ events have small time gap

Preliminary cross section





NC K^+ rate below water Cherenkov threshold is well modeled by GENIE

Summary

- Cross Section measurements are important and much needed
- Pion production analysis can test interaction models as well as FSI
- No model explain all data sets, we need more sophisticated models implemented into generators
- Kaon production analysis in the way, GENIE has a nice prediction for the NC cross section
- Many analyses underway to examine it all in more detail, working closely with theorists

MINERvA Collaboration

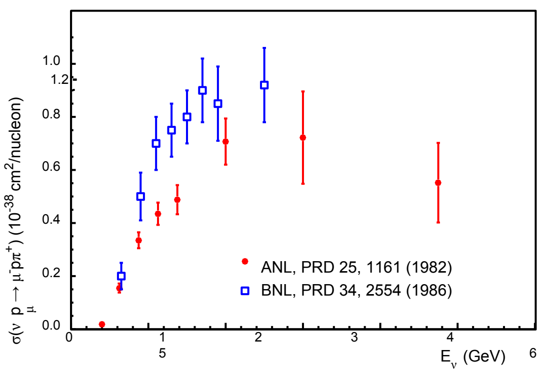
Collaboration of ~65 Nuclear and Particle Physicists

- University of California at Irvine
- Centro Brasileiro de Pesquisas Físicas
- University of Chicago
- Fermilab
- University of Florida
- Université de Genève
- Universidad de Guanajuato
- Hampton University
- Inst. Nucl. Reas. Moscow
- Massachusetts College of Liberal Arts
- University of Minnesota at Duluth
- Universidad Nacional de Ingeniería
- Northwestern University
- Oregon State University
- Otterbein University
- Pontificia Universidad Catolica del Peru
- University of Pittsburgh
- University of Rochester
- Rutgers, The State University of New Jersey
- Universidad Técnica Federico Santa María
- Tufts University
- William and Mary

BACKUPS

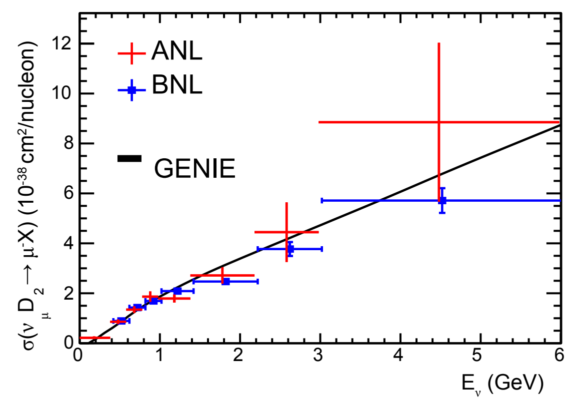
Neutrino Nucleus Scattering

- The events we observe in our detectors are convolutions of neutrino flux, cross section and nuclear effects.
- **The cross section** is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus.**



- **Limited statistics ANL and BNL bubble chamber data off D_2 from the 80's is what we have ie. 1 π production.**

- **Recent combined analyses of ANL and BNL data using ratios of σ_{QE} to σ_{Tot} have claimed to resolve flux issues and we now could have a much improved combined fit.**



Wilkinson et al. – arXiv:1411.4482

A Step-by-Step Two-Detector LBL Oscillation Analysis

1) Measure neutrino energy and event topology in the near detector.
2) Use the **nuclear model** to take the detected energy and topology back to the initial interaction energy and topology
3) Project this initial interaction distribution, perturbed via an oscillation hypothesis, to the far detector.
4) Use the **nuclear model** to take the incoming energy and topology to a detected energy and topology.
5) Compare with actual measurements in the far detector.

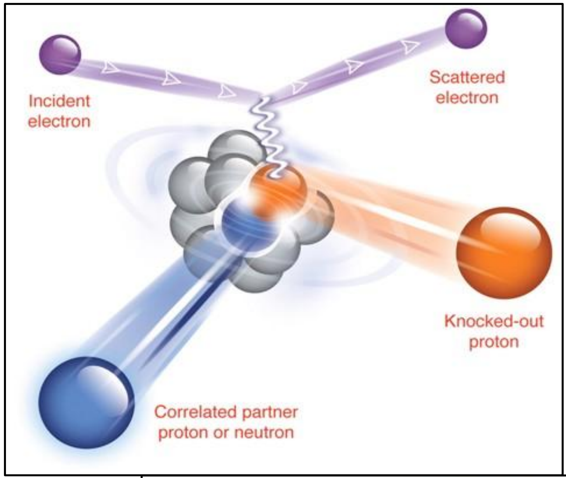
Critical dependence on the nuclear model <u>even with a near detector!</u>

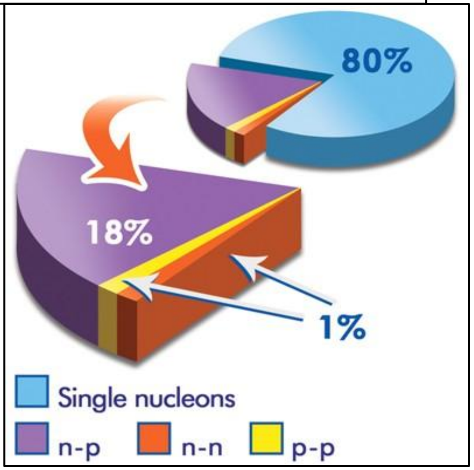
Independent Nucleons? Nucleon-Nucleon Correlations

- **Electron scattering**
  - Measurements on 12C indicate 20% correlated nucleons with mostly np pairs in the initial state

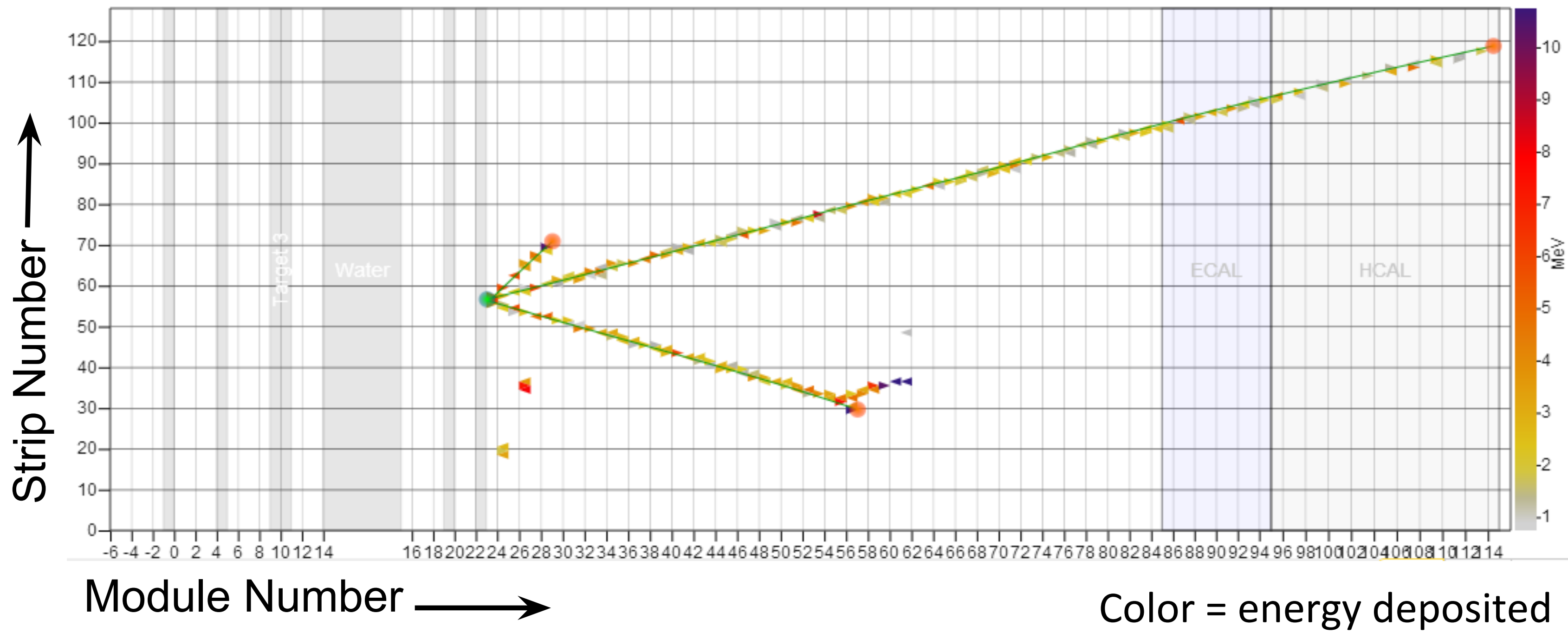
- **Neutrino scattering**
  - Implies initial produced state in neutrino scattering of nn in antineutrino and pp in neutrino CC scattering.
  - For other forms of correlation, final state depends on model.

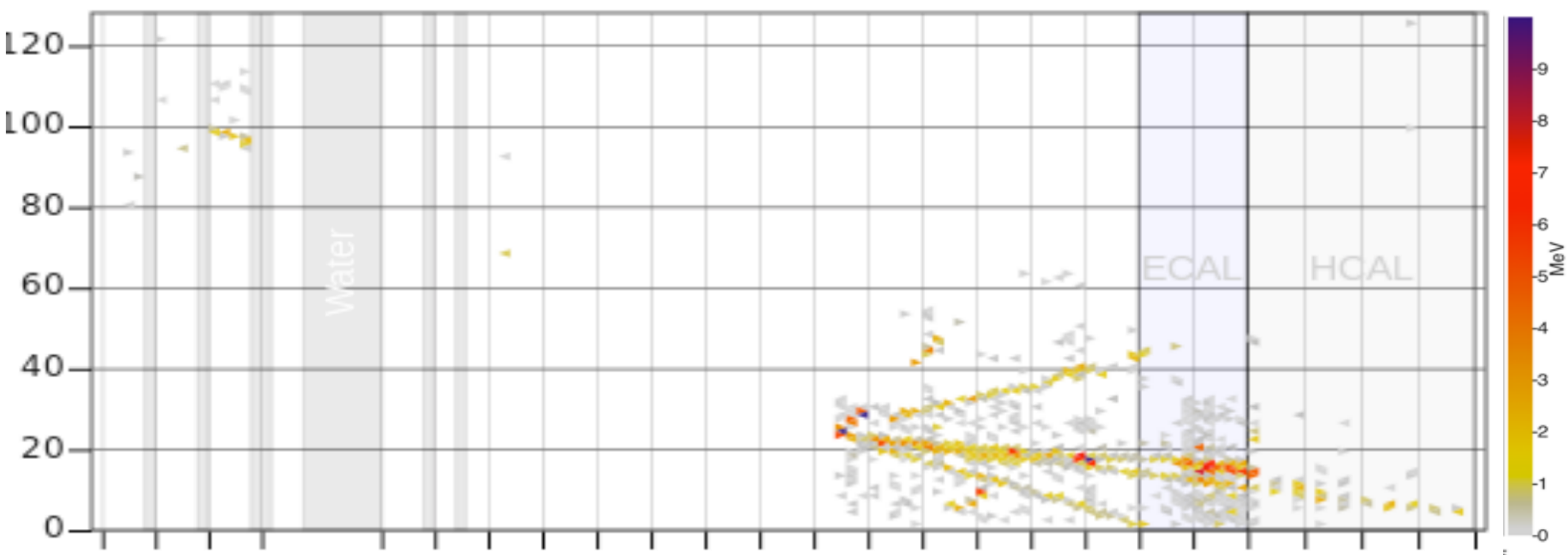
  - Of course, what we eventually detect can be modified by Final State Interactions when interpreting neutrino scattering data.





R. Subedi et al., Science 320, 1476 (2008)


Strip Number
Module Number
Color = energy deposited
Water
ECAL
HCAL
MeV


Water
ECAL
HCAL
MeV

CC Pion Production Event Selection (muonic variables)

Charged Pion Production ($\nu CCN\pi^+$)

- Negative muon
- Require 1.5 < Ev < 10 GeV
  Hadronic invariant mass W cut (W < 1.8 GeV)
- One or more hadron track candidates
- Pion identification
- Michel electron at endpoint

Neutral Pion Production (ν CC1π^0)

- Positive muon
- Photon conversion length greater than 15 cm
- Di-photon invariant mass 75 < Mγγ < 195 MeV/c2 Require 1.5 < Ev < 20 Gev Introduce W cut
- (W < 1.8 GeV)

Kinematic Equations

$$E_\nu = E_\mu + E_H \ (E_H \text{ determined calorimetrically})$$

$$Q^2 = 2E_\nu (E_\mu - p_\mu \cos(\theta_{\mu\nu})) - m_\mu^2$$

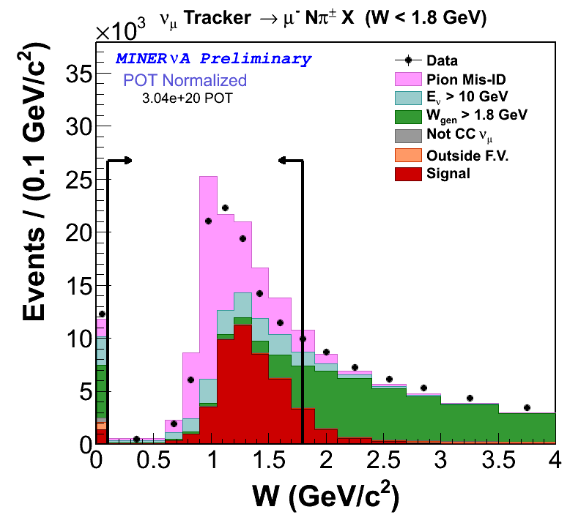
$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \ (m_N \text{ nucleon mass})$$

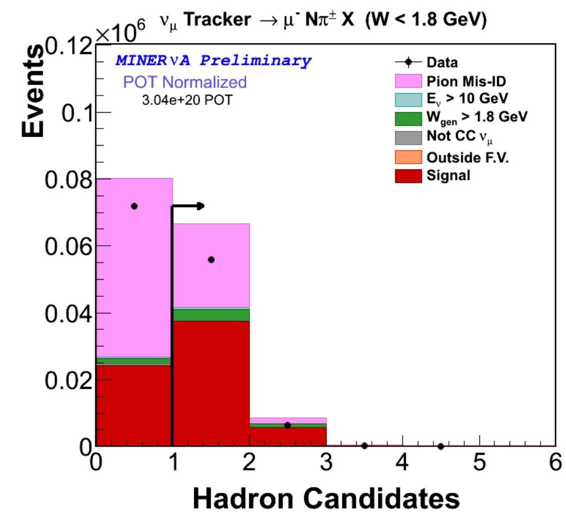
$$W_{gen} : W_{exp} \text{ w/o the assumption of a nucleon at rest}$$

Charged Pion Event Reconstruction

Hadronic invariant mass: $W^2 = -Q^2 + m_N^2 + 2m_N E_H$

- Reconstruct **hadronic recoil energy** (E_H) calorimetrically
    - Sum non-muon energy, weighted by passive material constants
    - Apply additional scale, derived from MC, to tune to true E_H
- One or more **hadron track** candidates
- Pion identification
    - Use energy loss (dE/dx) profile of each hadron track to separate pions from protons
    - Find the best fit momentum for a pion hypothesis
- Michel electron
    - $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
    - Selects pions that decay in the detector

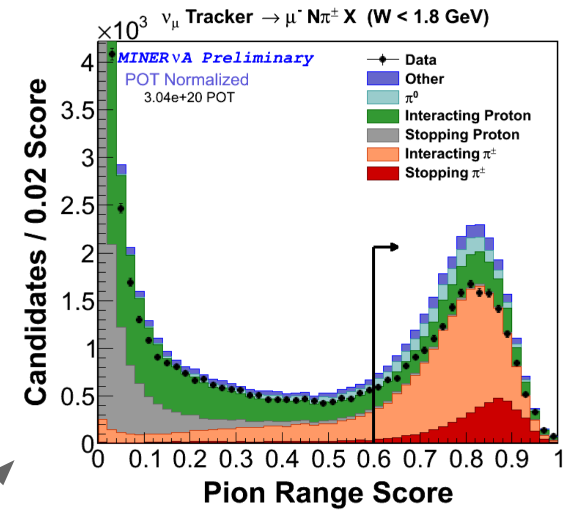


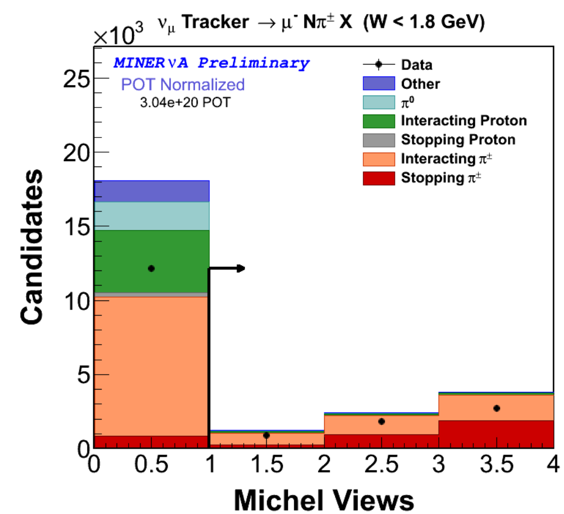


Charged Pion Event Reconstruction

Hadronic invariant mass: $W^2 = -Q^2 + m_N^2 + 2m_N E_H$

- Reconstruct hadronic recoil energy (E_H) calorimetrically
  - Sum non-muon energy, weighted by passive material constants
  - Apply additional scale, derived from MC, to tune to true E_H
- One or more hadron track candidates
- **Pion identification**
  - Use energy loss (**dE/dx**) profile of each hadron track to separate pions from protons
  - Find the best fit momentum for a pion hypothesis
- **Michel electron**
  - $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
  - Selects pions that decay in the detector

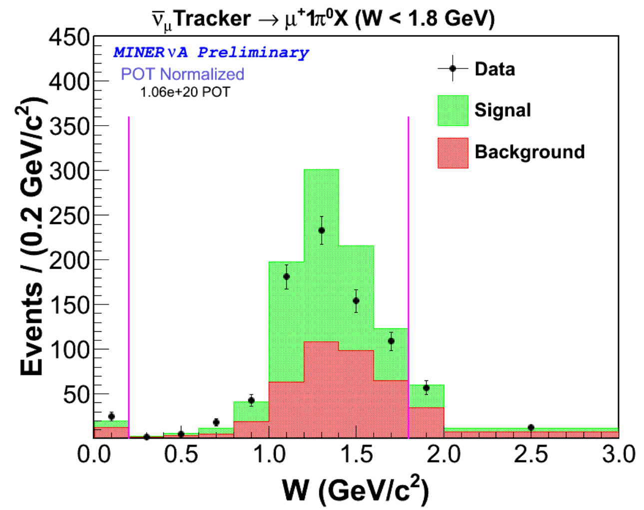




Neutral Pion Event Reconstruction

Hadronic invariant mass: $W^2 = -Q^2 + m_N^2 + 2m_N E_H$

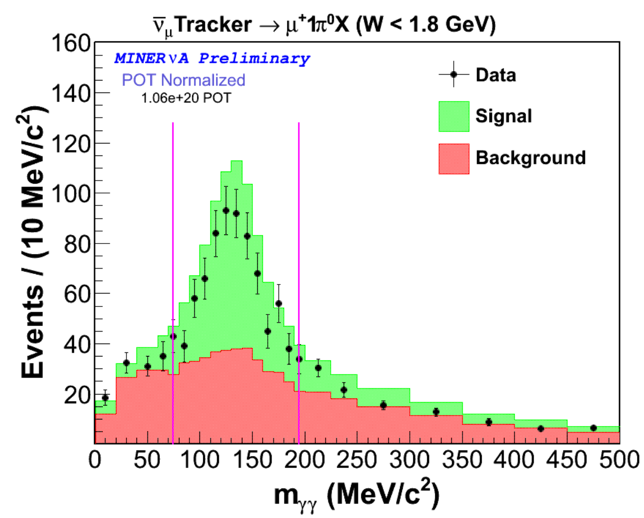
- Reconstruct hadronic recoil energy (E_H) calorimetrically
  - Sum non-muon energy, weighted by passive material constants
  - Apply additional scale, derived from MC, to tune to true E_H



Di-photon Invariant Mass

$$M_{\gamma\gamma} = 2E_1E_2(1 - \cos\theta_{\gamma\gamma})$$

Tail signal events are due to candidate photons reconstructed from neutron energy deposits



A pion Cross Section

Differential cross-section vs. ***Pion KE***

Unfolding function: convert from reconstructed KE to true KE

backgrounds constrained by data

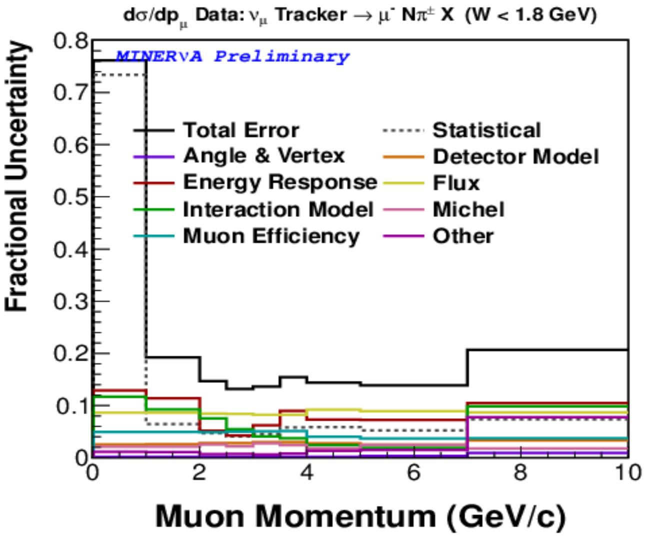
$$\left(\frac{d\sigma}{dT_\pi}\right)_i = \frac{1}{\Phi T}\frac{1}{\Delta T_\pi}\frac{\sum_j U_{ij}\left(N_{data,j} - N_{bg,j}\right)}{\varepsilon_i}$$

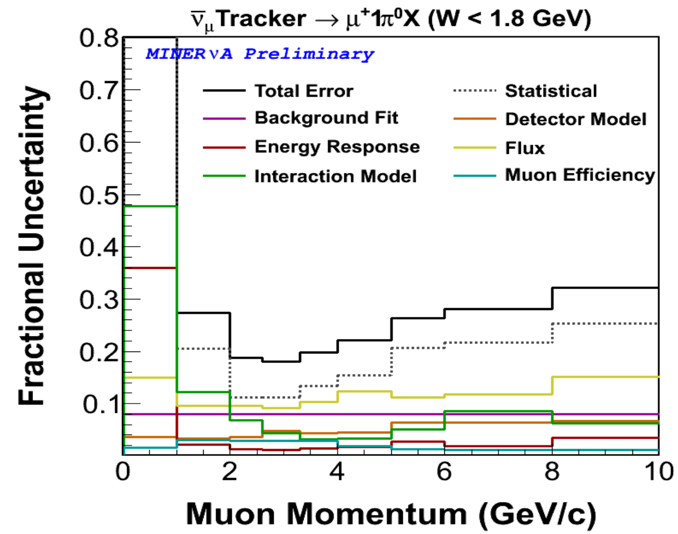
Integrated flux, targets

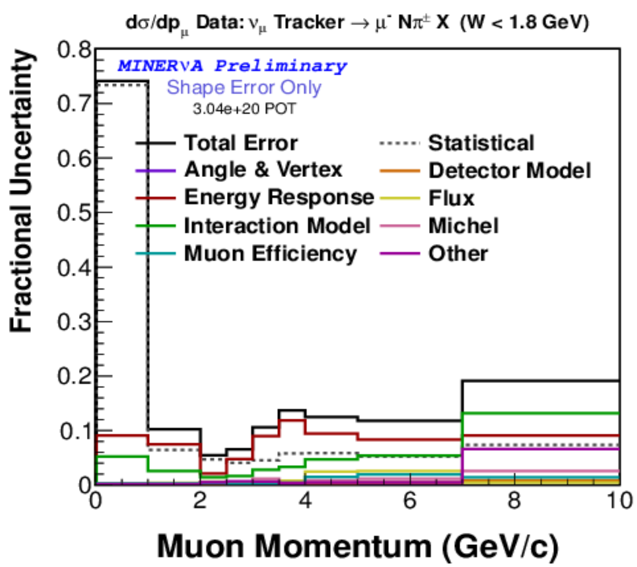
bin size

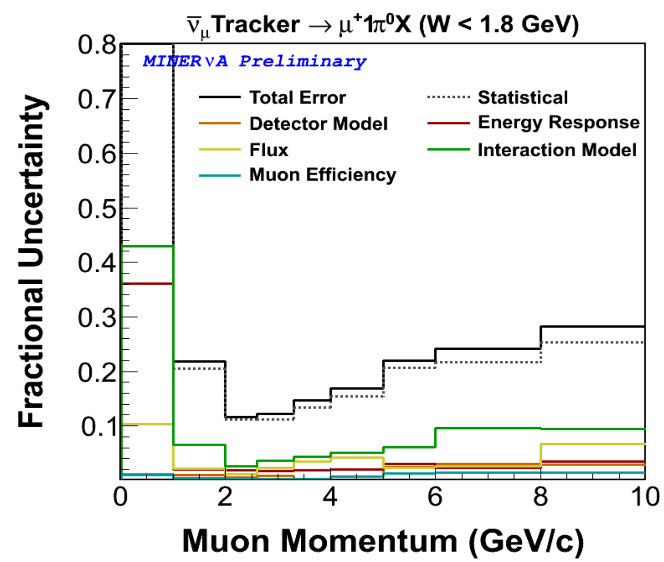
Selection efficiency and acceptance

Muon Momentum Cross Section Uncertainties



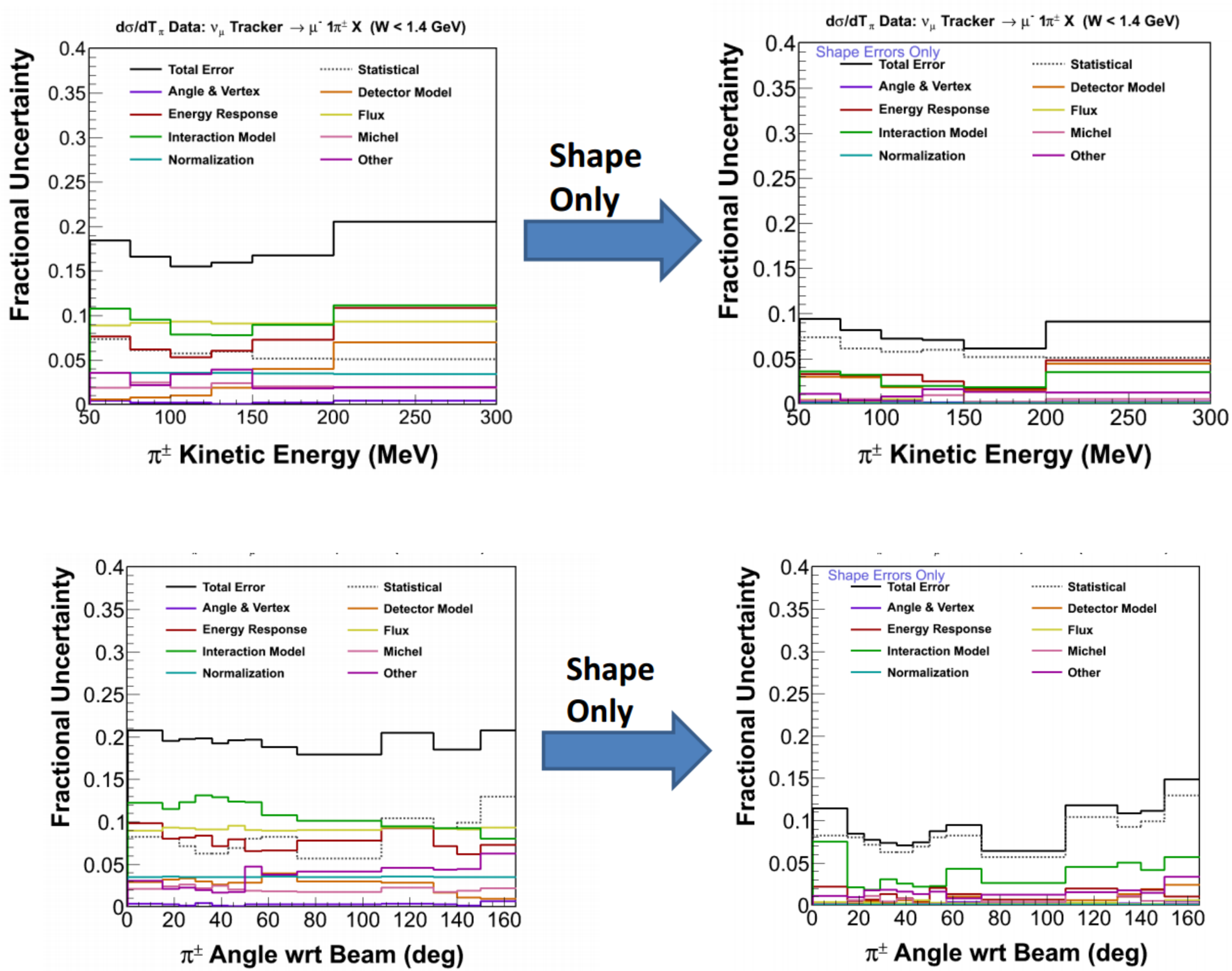






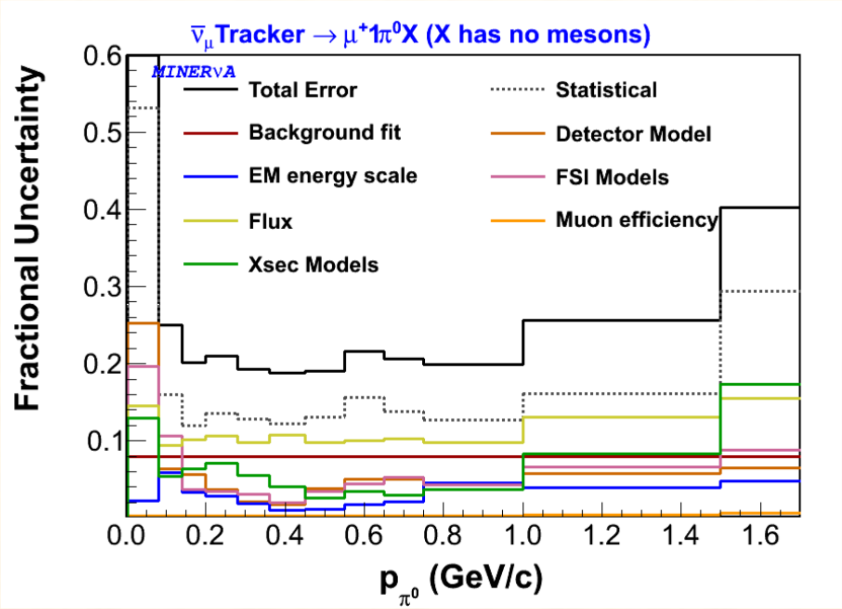
Uncertainty driven by Flux, Energy Response, Interaction Model

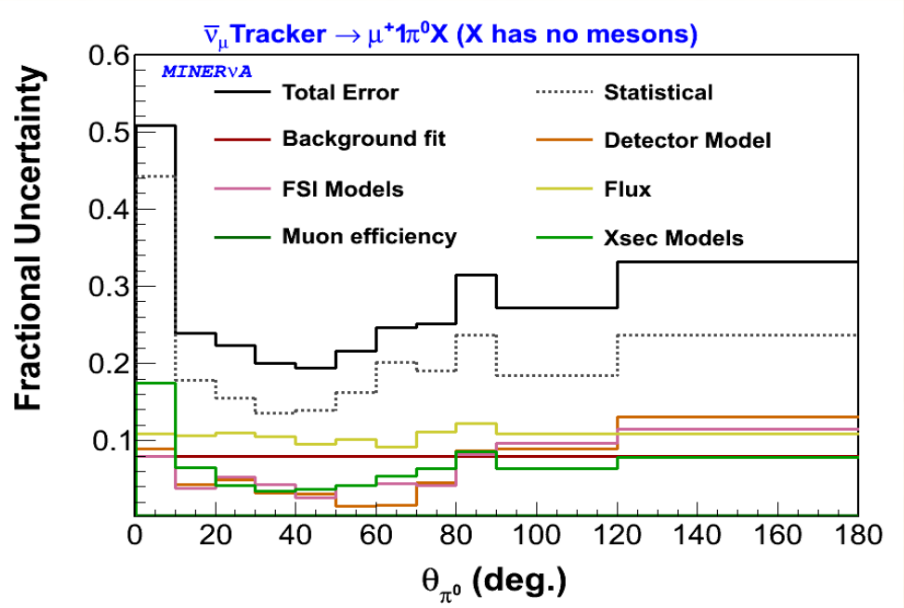
Charged Pion energy and angle X-Section Uncertainties



Neutral Pion energy and angle X-Section Uncertainties

Total uncertainties on the differential cross sections are about 20-30%





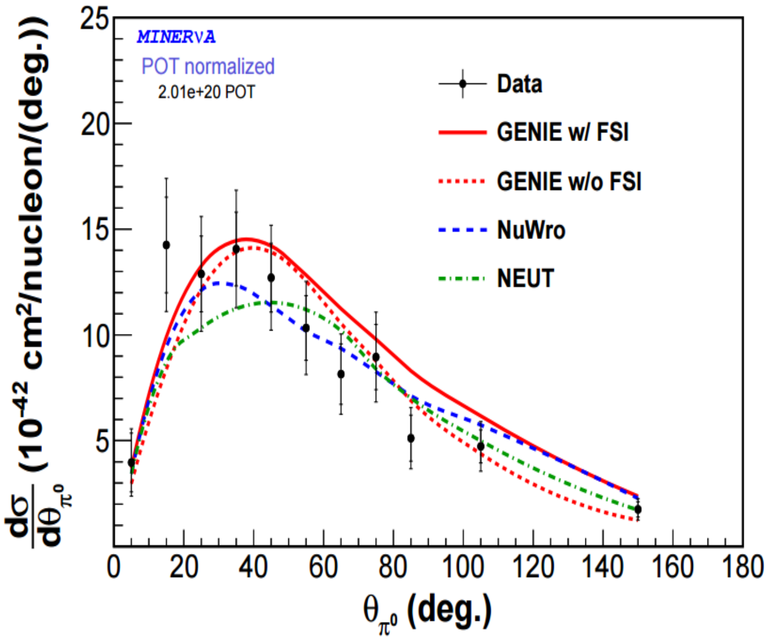


Figure 3: Differential cross section for $1\pi^0$ production as function of the π^0 polar angle. Data are shown as solid circles. The inner (outer) error bars correspond to statistical (total) uncertainties. The solid (dashed) histograms are GENIE prediction with (without) FSI, the long-dashed histogram is the prediction from the NuWro generator, and the dot-dashed histogram is the prediction from NEUT.

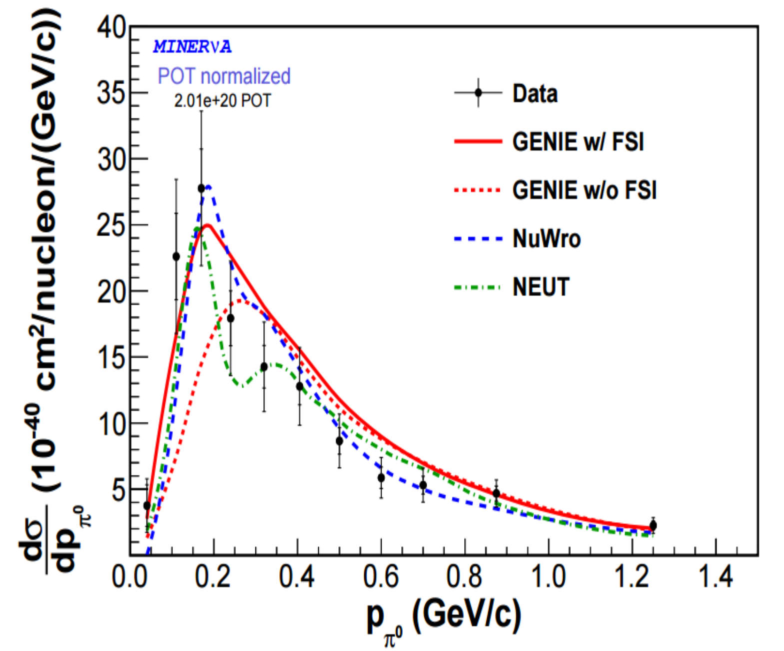


Figure 2: Differential cross section for $1\pi^0$ production as function of π^0 momentum. Data are shown as solid circles. The inner (outer) error bars correspond to statistical (total) uncertainties. The solid (dashed) histograms are GENIE prediction with (without) FSI, the long-dashed histogram is the prediction from the NuWro generator, and the dot-dashed histogram is the prediction from NEUT.

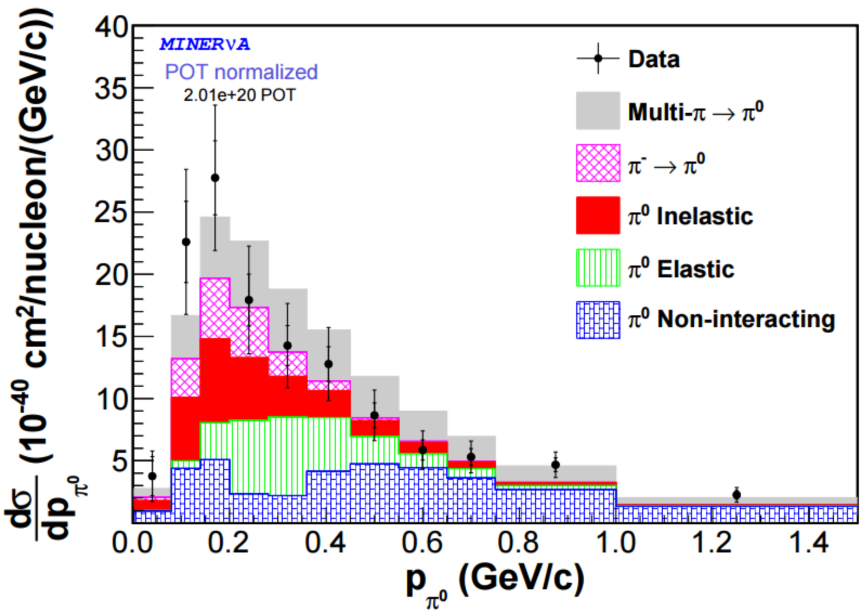


Figure 4: Same cross section data as Fig. 2. The stacked histograms show a decomposition of the $1\pi^0$ signal into different FSI channels as predicted by GENIE. Description of the FSI channels follows (from top to bottom): 1) Multi-$\pi \to \pi^0$: multi-pion produced by the primary interaction and all other pions are re-absorbed inside the nucleus, except a π^0, 2) $\pi^- \to \pi^0$: a π^- produced by the primary interaction, then charge exchanges inside the nucleus, 3) π^0 produced by the primary interaction and then undergoing inelastic scattering inside the nucleus, 4) π^0 produced by the primary interaction and then undergoing elastic scattering inside the nucleus, and 5) π^0 produced by the primary interaction and exiting the nucleus without interacting.

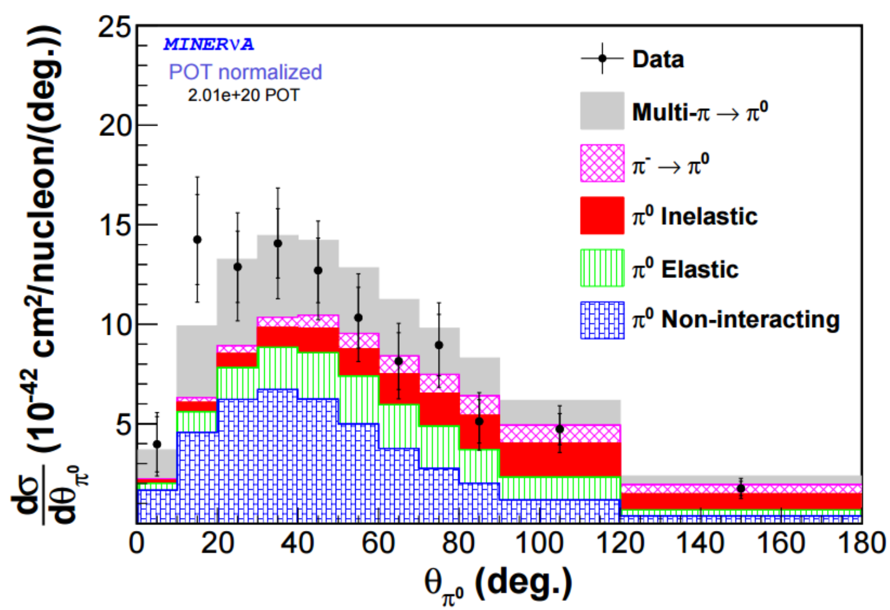


Figure 5: Same cross section data as Fig. 3 and same decomposition as with Fig. 4. The stacked histograms show a decomposition of the $1\pi^0$ signal into different FSI channels as predicted by GENIE.

$p \to K^+\nu$ at DUNE

"If it can be demonstrated that background processes mimicking this signature can be rejected at the appropriate level, a single $p \to K^+\nu$ candidate could constitute evidence for proton decay."

"...it is natural to ask to what extent simulations are capable of providing reliable estimates for such rare processes. What if the actual rate for single-kaon atmospheric-neutrino events is higher by a factor of ten or more? Is that even conceivable?"

DUNE/LBNE science document, Chapter 5