Charged Current Pion Production in MINERvA

As Seen by the Muons

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June 26, 2015

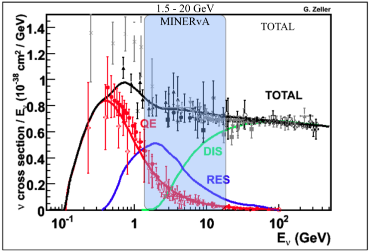
Outline

1. Motivation
   - Cross Section Importance
   - Final State Interactions and Nuclear Structure Effects
   - Previous Measurements
2. Beam and Detector
   - Neutrinos at the Main Injector
   - MINERvA
3. Event Reconstruction and Selection
   - Reconstruction
   - Background Subtraction
   - Detector Resolution Correction
4. Cross Section Results and Model Comparisons
   - Direct Muon Observables
   - Neutrino Energy and Q^2
5. Conclusion

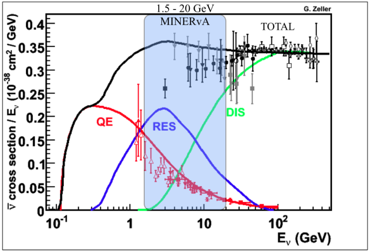
Why Do We Care?

- Cross sections between 0.1-20 GeV are not as well known, but important in the regime of oscillation experiments
  - Essential for experiments (NOvA, DUNE)
- Because DUNE will consist of LAr, we have to understand the effects of the nucleus
  - Large errors in cross section measurements and disagreements between experiments lead to systematic uncertainties in oscillation measurements

Neutrino



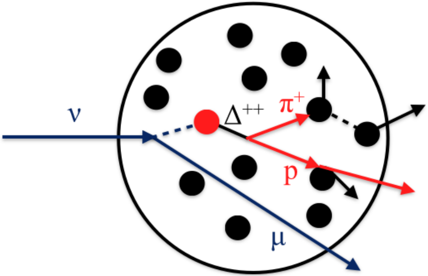
Antineutrino



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

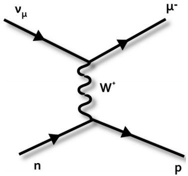
ν-Nucleus Interactions

- Complications of ν-nucleus interaction involve
  - ν-Nucleon amplitude or cross sections (from previous slide)
  - Nuclear structure (nucleon inside the nucleus interacts with its neighbors)
  - Final State Interactions (FSI) of outgoing hadrons
- This is a puzzle, all three effects must be disentangled!

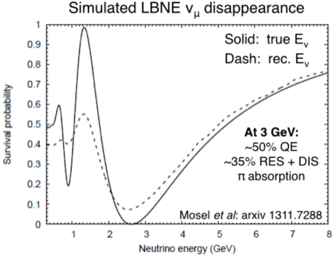


Final State Interactions

- Particles interact inside the nucleus before exiting
- Final state topology is therefore changed
- This can significantly change the measured neutrino energy spectrum
  - CCQE-hypothesis, based on muon kinematics, is often used to calculate the neutrino energy by using events without pions
  - Events with pion absorption can mimic CCQE topology : pions produced in the initial interaction can be absorbed on a pair of nucleons ($\sim$25% of the time for π from Δ decay)
- Figure shows resulting errors in neutrino energy calculation

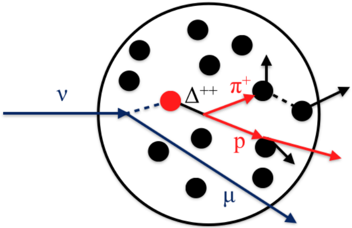


Charged Current Quasi-Elastic



What about the Muons?

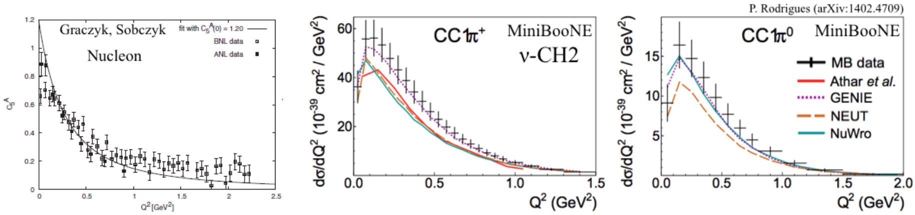
- Pion spectra (kinetic energy, angle) provides information about final state interactions
- Muons tell us about the interaction before FSI occurs
  - Sensitive to nuclear structure effects



- Dominant mechanism in CC pion production is Δ resonance
- For neutrinos and antineutrinos, we can measure the pion and muon's energy and angle
  - Can then reconstruct Q^2 (momentum transferred to the nucleus) and W (hadronic system's invariant mass)

Nuclear Effects

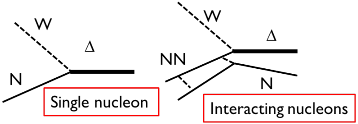
- Nuclear effects produce much slower fall off as compared to the free proton in Q^2 cross section
- Causes a turnover at $Q^2 \sim 0\ \mathrm{GeV}^2$ that is not seen in the proton distribution



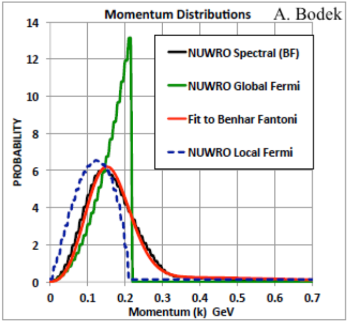
- Models differ mostly in magnitude, except at $Q^2 < 0.2\ \mathrm{GeV}^2$
  - Pauli blocking (outgoing nucleon momentum must be greater than Fermi momentum)
  - Long range NN correlations (RPA) (involves many nucleons)
  - Different models use different implementations of these nuclear effects

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

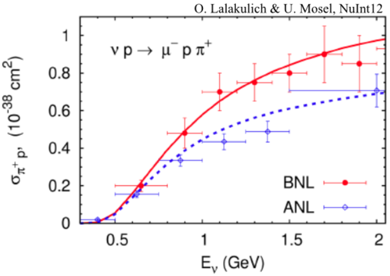


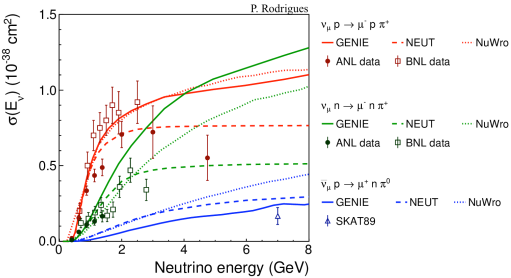
- Most models use Fermi Gas, but evolving to Local Fermi Gas and Spectral Function models



νN Cross Sections

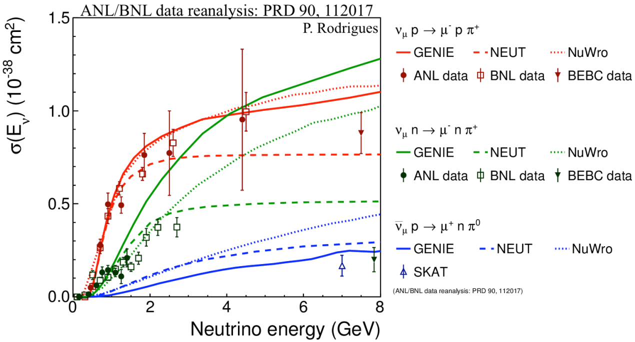
- All calculations must fit to old bubble chamber deuterium data
  - Many have trouble reconciling ANL/BNL data sets
  - Most authors split the difference (GENIE)
  - Recent reanalysis of deuterium data (Wilkinson *et al.*, 2014) finds consistency between ANL and BNL (NEUT)
- Very little data for $\bar{\nu}_\mu$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

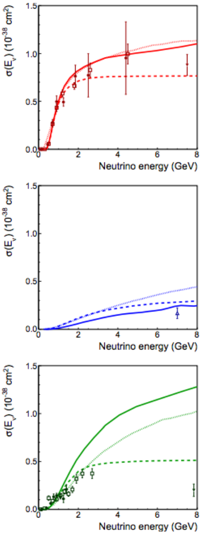




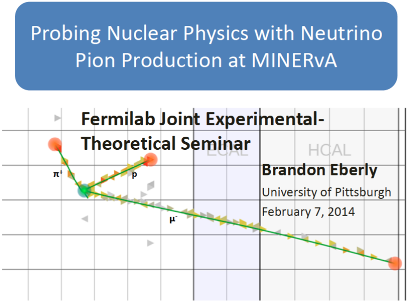
νN Cross Sections

- 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
- In antineutrino GENIE is low compared to NEUT and NuWro, while for neutrino GENIE is high

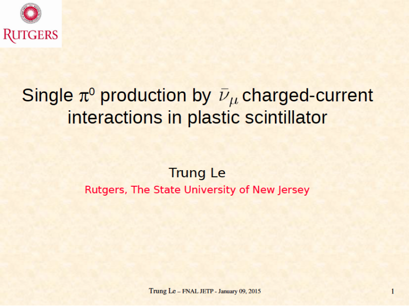




Recent Wine and Cheeses



Dr. Brandon Eberly
February 7th, 2014
(arXiv:1406.6415)



Dr. Trung Le
January 9th, 2015
(arXiv:1503.02107)

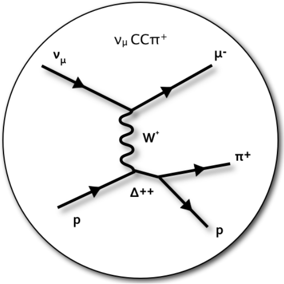
Signal Definitions

Neutrino

Single charged pion production

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

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

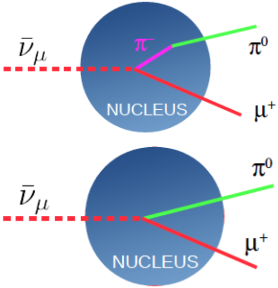


Antineutrino

Single neutral pion production

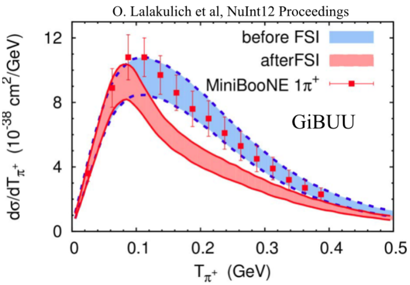
$$\bar{\nu}_\mu + CH \rightarrow \mu^+(1\pi^0)X$$

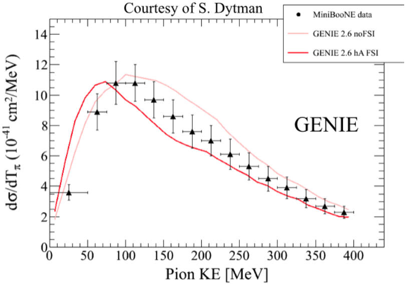
X contains no mesons



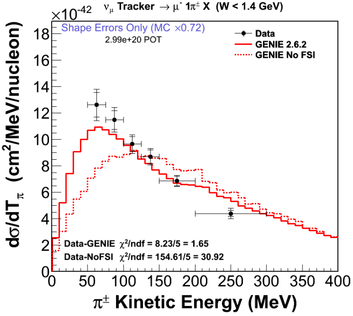
MiniBooNE and FSI

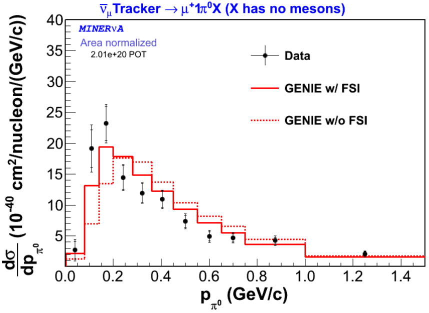
- Event generator disagreements...
  - GIBUU shows a strong FSI dip, MiniBooNE data is consistent with no FSI
  - GENIE has a weak FSI dip, MiniBooNE data falls in between





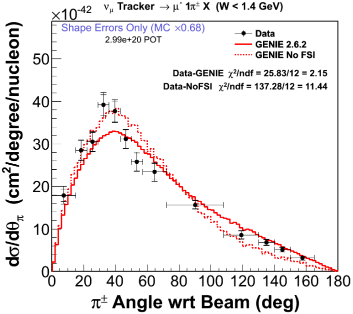
FSI Conclusions for Pion Energy (Shape Comparisons)

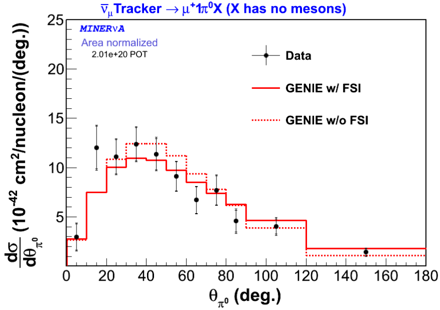




- Data prefer GENIE with FSI

FSI Conclusions for Pion Angle (Shape Comparisons)





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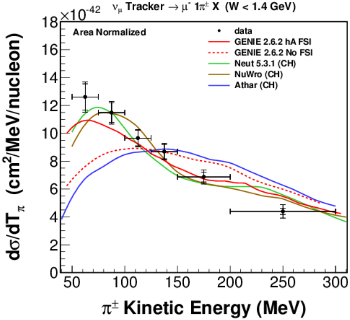
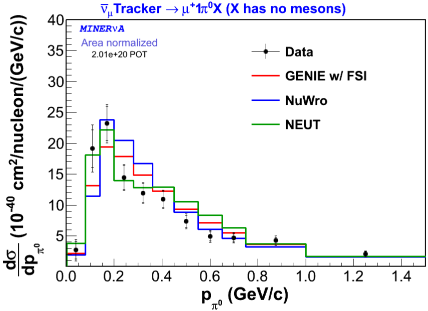
FSI Conclusions for Pion Energy (Shape Comparisons)



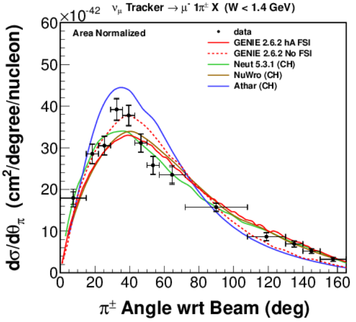


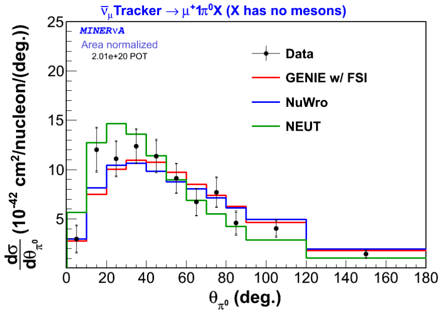
- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Data is unable to distinguish different FSI models

Prediction Models

- Event 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 - very good theoretical basis
    (T. Golan, C. Juszczak, and J.T. Sobczyk, *Phys. Rev. C* **86**, 015505 (2012))
- Theoretical work
  - Valencia - very good physics at low energies, coming to generators
  - GIBUU - very good physics at all energies
  - Athar, *et al.* - shown in plots, good nuclear model but poor FSI
- Good nuclear theory is moving from theorists to generators, but takes time.

FSI Conclusions for Pion Angle (Shape Comparisons)

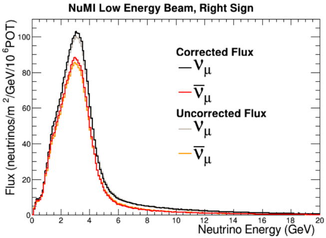




- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Again, data is unable to distinguish different FSI models

NuMI Beam

- 120 GeV protons from the Main Injector
- Average spill of 35x10^{12} Protons on Target (POT), with a beam power of 300-350 kW at $\sim$0.5 Hz
- Neutrino or antineutrino beam mode depending on horn current



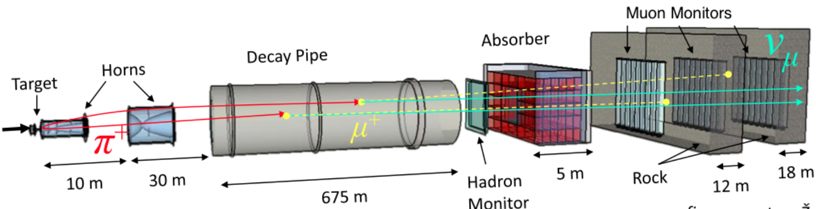
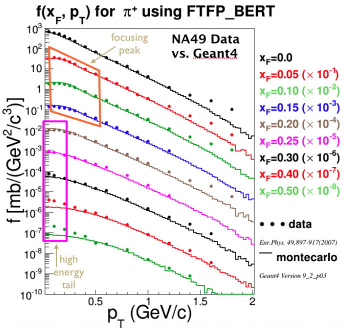
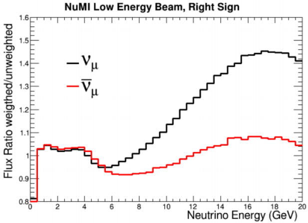


figure courtesy Ž. Pavlović

Low Energy Beam Flux

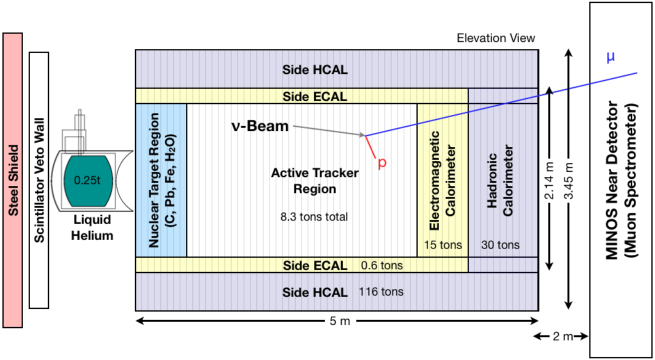
- Neutrino flux is estimated from hadron production
  - Monte Carlo (MC) is reweighted to match NA49 data
  - Flux is estimated using Geant4-based simulation, with the hadron production constrained by external data (NA49, MIPP)
  - Uncertainties due to the NA49 data and hadron production models are included as systematics



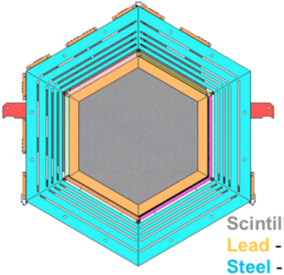


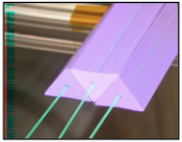
MINERvA Detector

- 120 “modules" perpendicular to the beam direction, containing $\sim$32k readout channels
- Finely-segmented scintillating central tracking region
- Nuclear targets, plastic (CH), EM and Hadronic calorimeters with additional lead and steel plates
- MINOS near detector doubles as a muon spectometer Thanks MINOS!

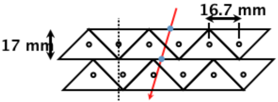


Minerva Detector (In More Detail)

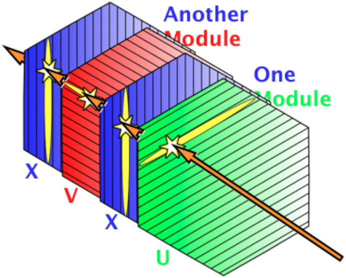




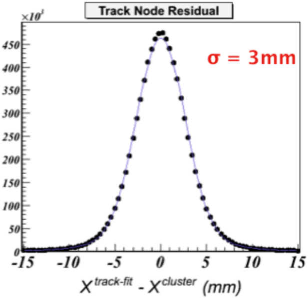
Extruded scintillator & wavelength shifting fibers.



Scintillator - tracking
Lead - EM calorimetry
Steel - hadronic calorimetry

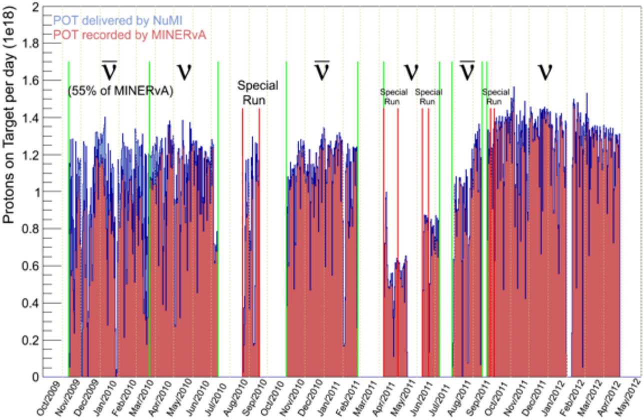


Charge sharing for improved position resolution (~3 mm) and alignment



Data Collected and Used

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



Thanks to the Accelerator Division for the beam!

New Event Selection Criteria

- Charged Pion Production (νCCNπ^+)
  - Negative muon
  - Require $1.5 < E_\nu < 10$ 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 ($\bar{\nu}$CC1π^0)
  - Positive muon
  - Photon conversion length greater than 15 cm
  - Di-photon invariant mass $75 < M_{\gamma\gamma} < 195\ \mathrm{MeV/c^2}$
  - Require $1.5 < E_\nu < 20$ Gev
  - Introduce W cut ($W < 1.8$ GeV)

Kinematic Equations

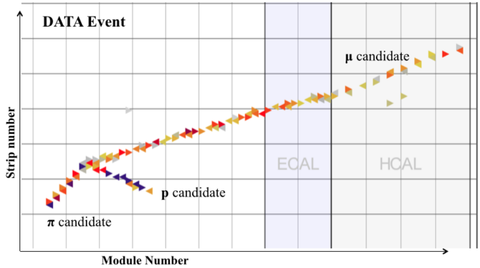
$$E_\nu = E_\mu + E_H \ (E_H \text{ determined calorimetrically})$$

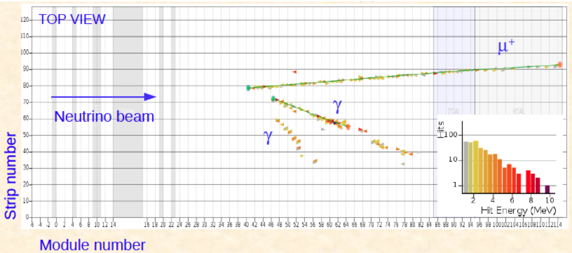
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_{\mu\nu})) - m_\mu^2$$

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

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

Event Displays



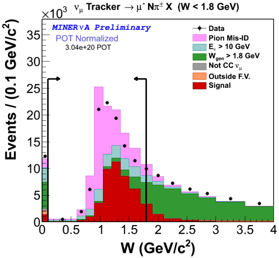


Charged Pion Event Reconstruction

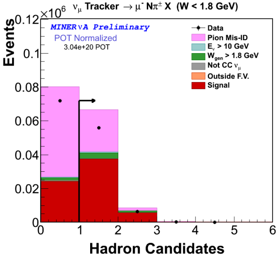
Hadronic invariant mass $W < 1.8$ GeV

$$W^2 = -Q^2 + m_N^2 + 2m_N E_H$$

- 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



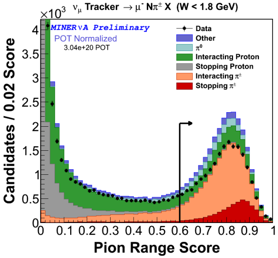
One or more hadron track candidates



Charged Pion Event Reconstruction Continued...

Pion identification

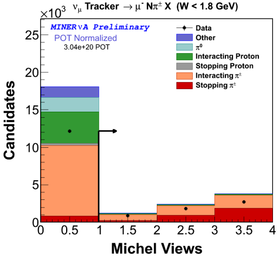
- Use energy loss (dE/dx) profile of each hadron track to separate pions from protons
- Find the best fit momentum for a pion hypothesis



Michel electron

$$\pi^+ \rightarrow \mu^+ \nu_\mu, \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

- Selects pions that decay in the detector

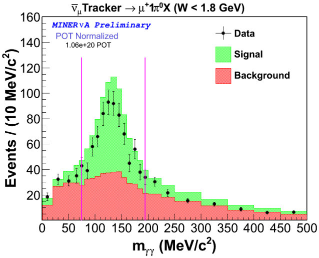


Neutral Pion Event Reconstruction

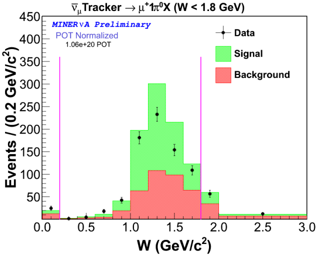
Di-photon Invariant Mass

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

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

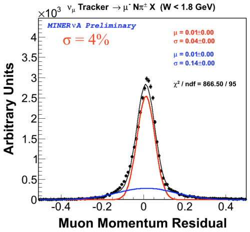


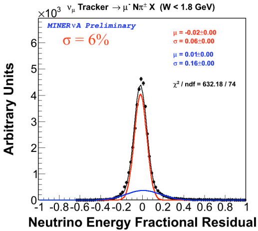
Hadronic invariant mass $W < 1.8$ GeV

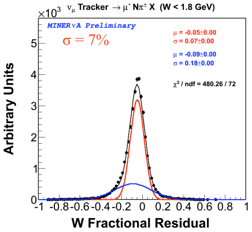


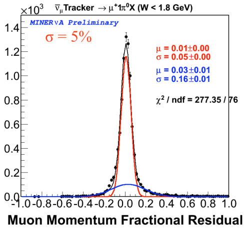
Resolution

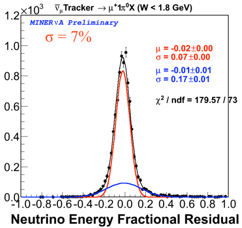
p_μ	E_ν	W

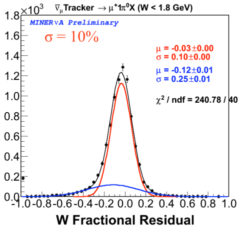






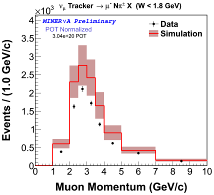


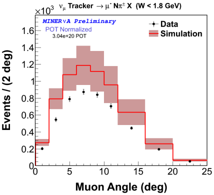


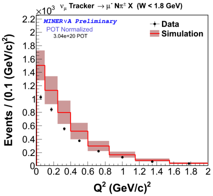


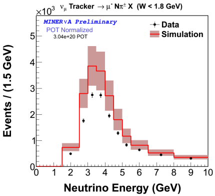
Charged Pion Reconstructed Distributions

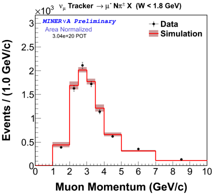
p_μ θ_μ Q^2 E_ν

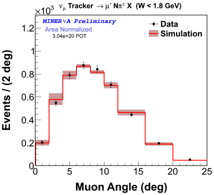


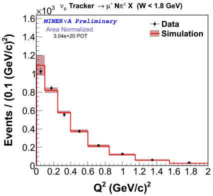








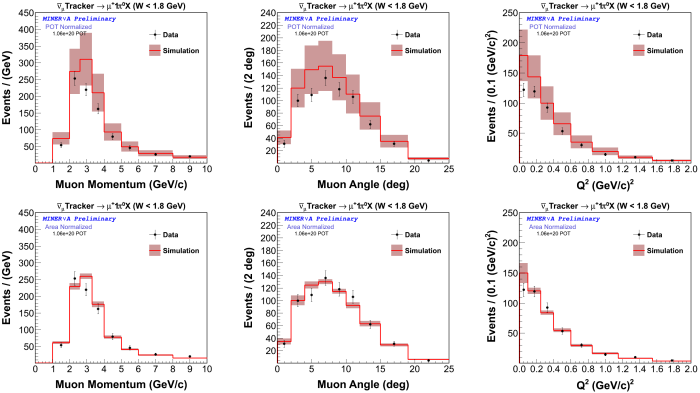




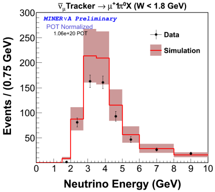
Absolute normalized distributions include uncertainty on the signal process

Neutral Pion Reconstructed Distributions

p_μ θ_μ Q^2



E_ν



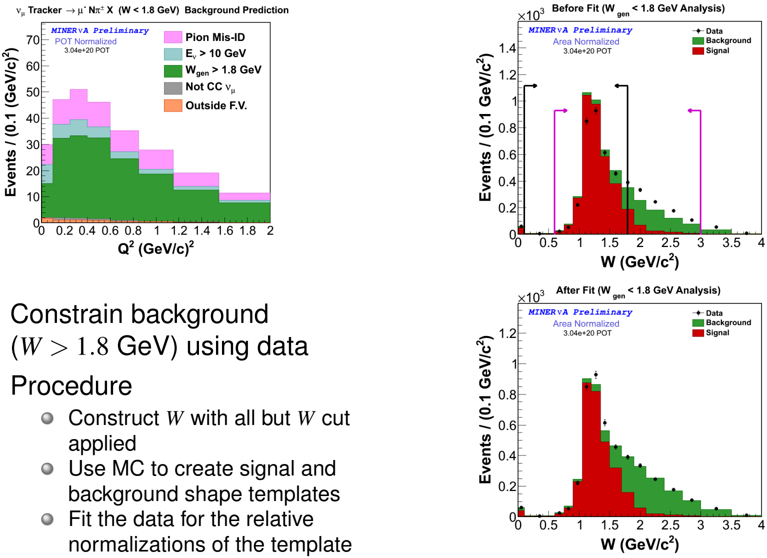
Absolute normalized distributions include uncertainty on the signal process

Differential Cross Section Equation

$$\left(\frac{d\sigma}{dQ^2}\right)_i = \frac{1}{\Phi T}\frac{1}{\Delta Q^2}\frac{\Sigma_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

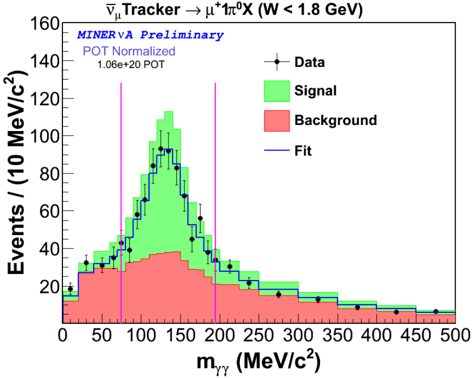
- Differential cross-section vs. Q^2 → $\left(\frac{d\sigma}{dQ^2}\right)_i$
- Integrated flux, targets → ΦT
- Bin size → ΔQ^2
- Unfolding function: convert from reconstructed Q^2 to true Q^2 → U_{ij}
- Backgrounds constrained by data → N_j^{bkg}
- Selection efficiency and acceptance → ϵ_i

Charged Pion Background Subtraction



- Constrain background ($W > 1.8$ GeV) using data
- Procedure
  - Construct W with all but W cut applied
  - Use MC to create signal and background shape templates
  - Fit the data for the relative normalizations of the template

Neutral Pion Background Constraint

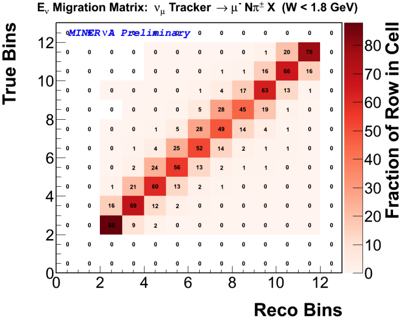


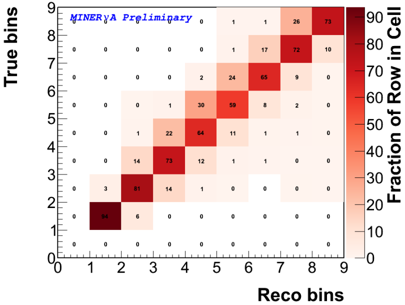
Background normalization constrained using data

- Signal and background shapes from the simulation
- These shapes are used to fit to the data
- Reduce the background normalization by 17%

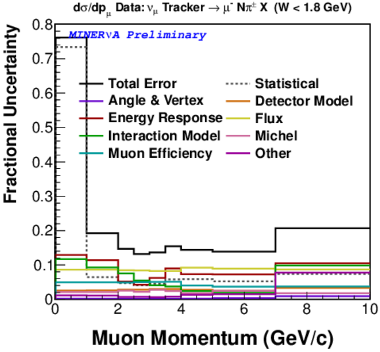
Detector Resolution Correction

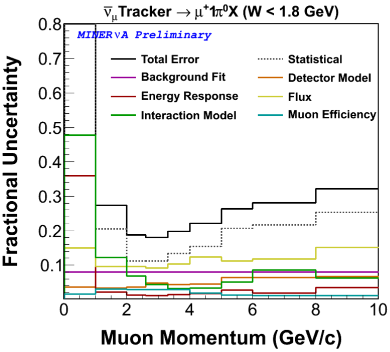
- Unfold data to remove detector resolution effects (transforms into “true" variables)
- Both analyses use an iterative Bayesian procedure
- Neutrino energy migration matrices used are shown





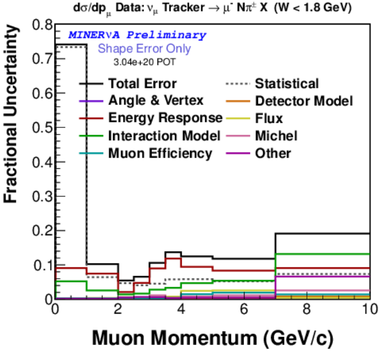
Muon Momentum Cross Section Uncertainties

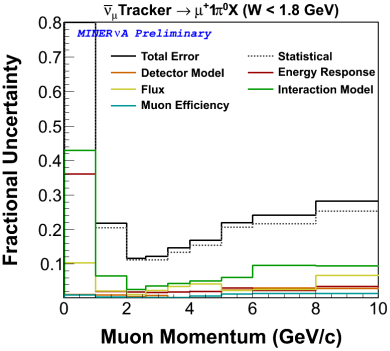




- Uncertainty driven by Flux, Energy Response, Interaction Model

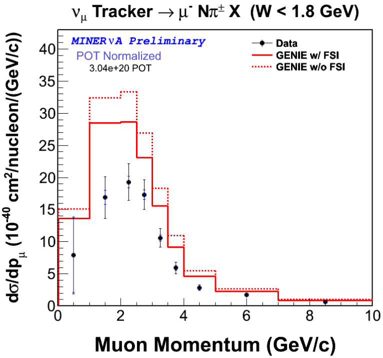
Muon Momentum Cross Section Uncertainties

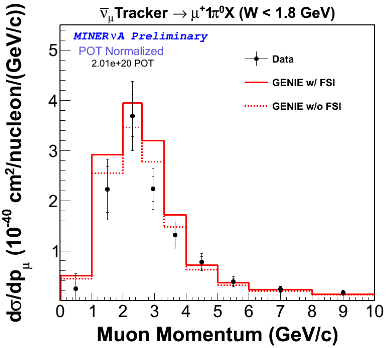




- Flux uncertainties become negligible

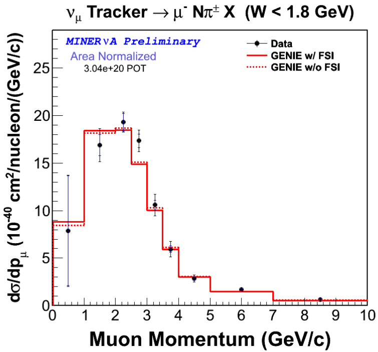
Cross Section as a Function of Muon Momentum

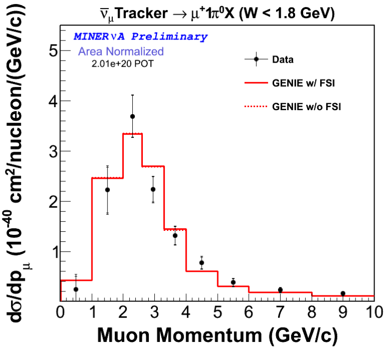




- In the charged pion analysis GENIE overestimates the normalization of the cross section
- GENIE no FSI in neutral pion analysis is less than with FSI prediction due to charge exchange from π^-

Shape Comparison for Muon Momentum





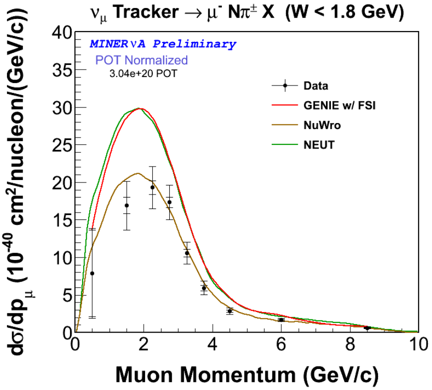
- GENIE shape agrees very well with the data
- Ratio of with FSI to no FSI is a constant factor

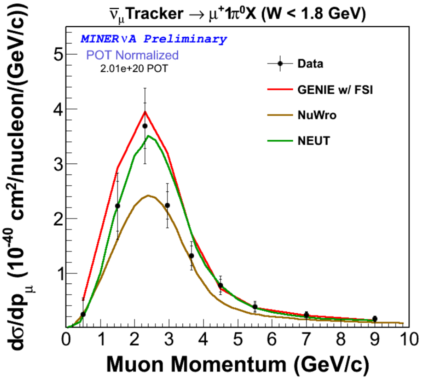
Comparison of Event Generators

	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

- Nuclear structure similar, Δ models are different

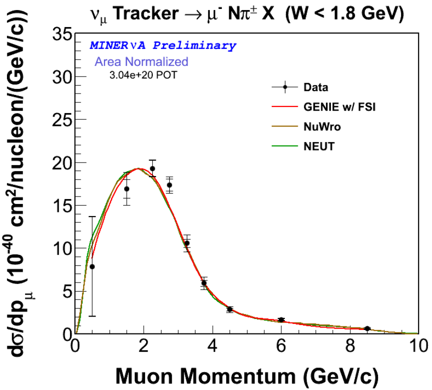
Cross Section as a Function of Muon Momentum

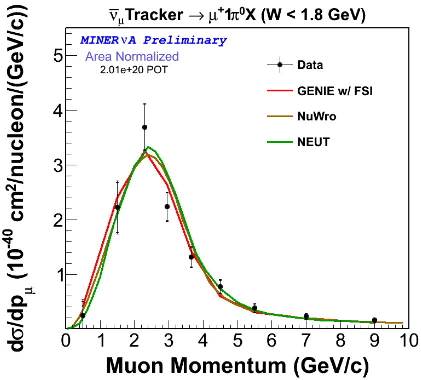




- In charged pion both GENIE and NEUT over estimate the cross section
- GENIE and NEUT predictions are similar and are higher than NuWro in both analyses

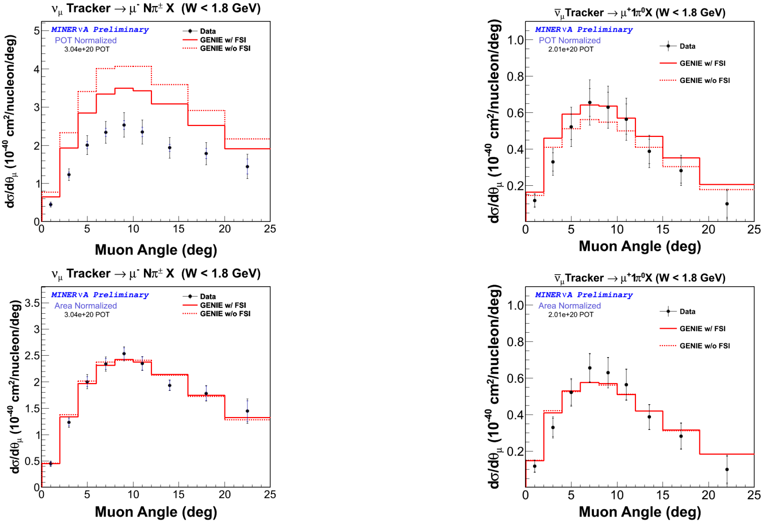
Shape Comparison for Muon Momentum





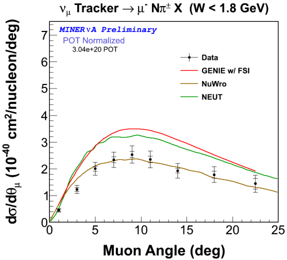
- But all three get the shape right

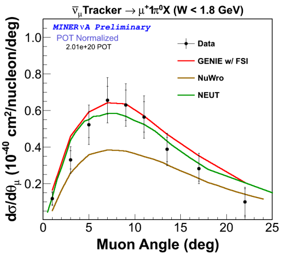
Cross Section and Model Comparison for Muon Angle

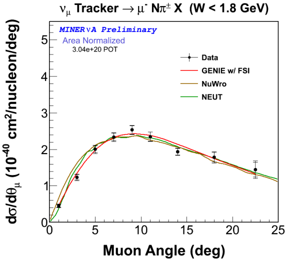


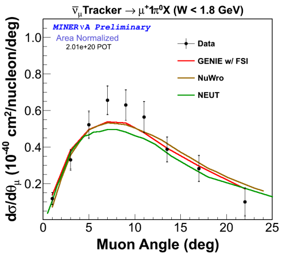
- See the same normalization and shape behavior as with muon momentum

Cross Section and Model Comparison for Muon Angle









- See the same normalization and shape behavior as with muon momentum

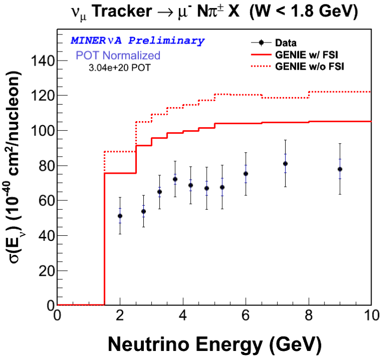
Remember...

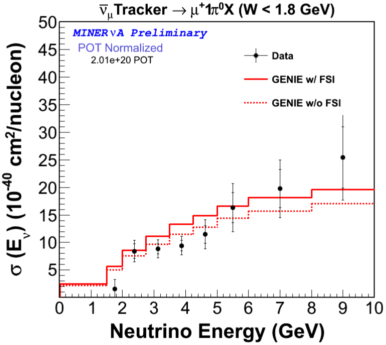
We use the following to reconstruct E_ν and Q^2

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

- Because muon momentum and angle shapes agree well, we expect this to be true in the derived observables

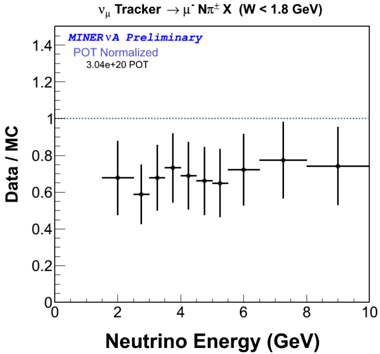
Cross Section as a Function of Neutrino Energy

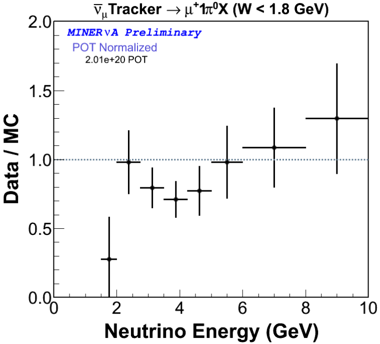




- The mix of models changes with increased energy (i.e. resonance to non-resonance) and it's not intuitive that the ratio should be the same
- GENIE successfully models the energy dependence

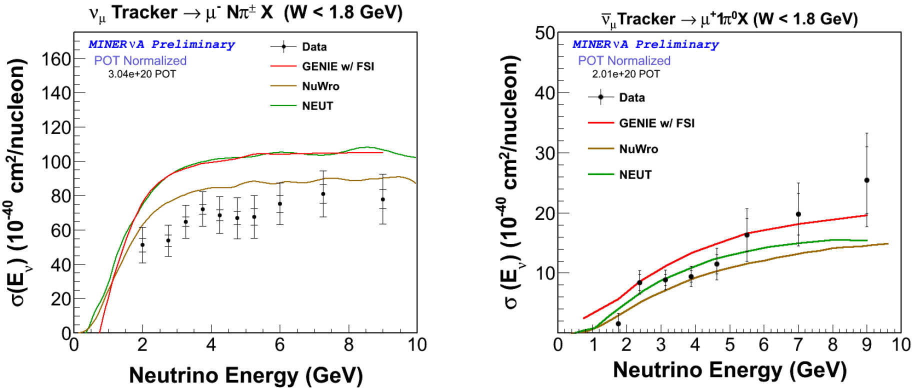
Cross Section as a Function of Neutrino Energy





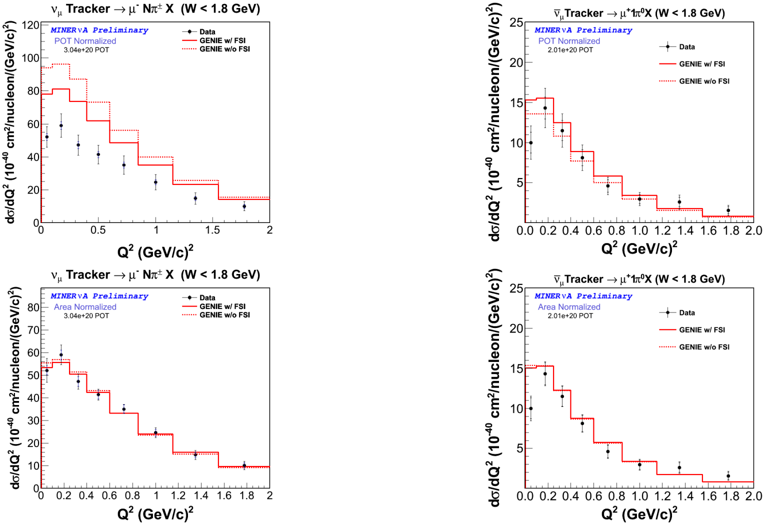
- Ratio between the absolute normalized data and MC
- This is interesting - neutrino and antineutrino interactions pick out different amounts of resonance and non-resonance contribution, so they don't need to agree

Cross Section as a Function of Neutrino Energy



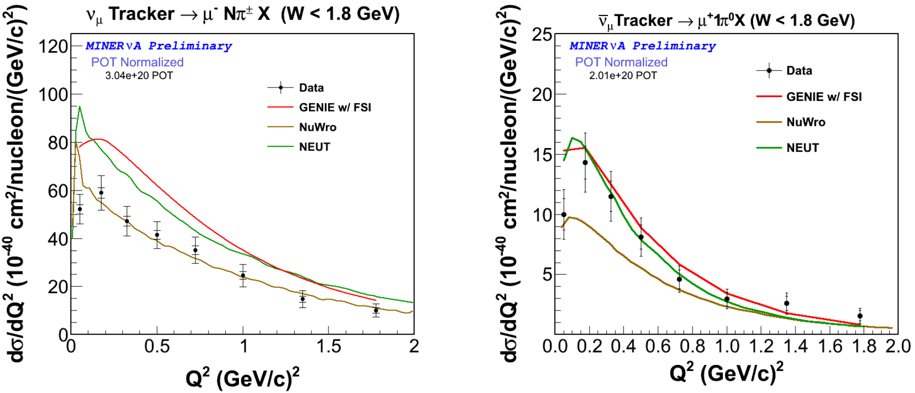
- With the charged pion analysis, we see the same behavior as with the muon observables, GENIE and NEUT predictions are similar and are higher than NuWro
- In the neutral pion analysis, there is less variation among the three predictions

Cross Section and Shape Comparison for Q^2



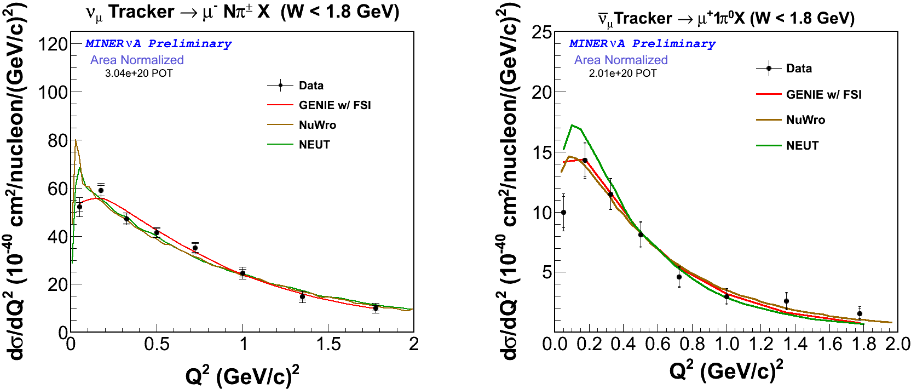
- Shapes agree very well with the data, except first bin in neutral pion analysis
- Pauli blocking and NN correlations are very important in that first bin, GENIE does not includes these effects

Cross Section as a Function of Q^2



- The shape difference is the most interesting feature

Shape Comparison for Q^2

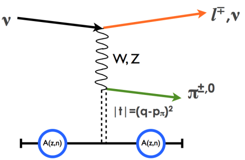


- GENIE shape agrees well except in the first bin for neutral pion production
- Since the nuclear models used in the three generators are very similar, agreement in the prediction is expected
- Should examine coherent production at low Q^2

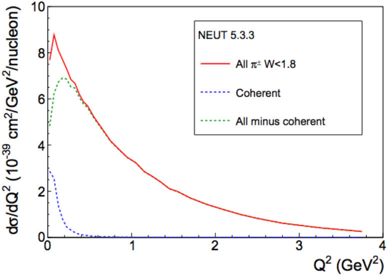
Q^2 Coherent Contribution

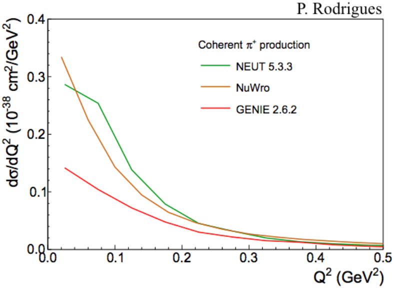
- Difference in shape between the three models at low Q^2 is largely due to coherent pion production
- No data on plots, not sure what is correct, but MINERvA does have coherent total cross section measurements

  (Phys. Rev. Lett. **113**, 261802 (2014))
  - Cross sections shows that GENIE agrees but NEUT overestimates the data

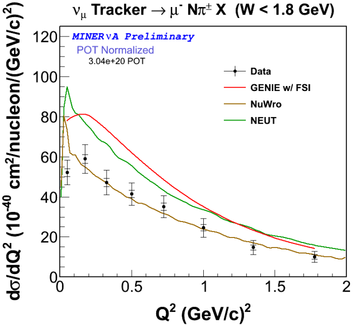


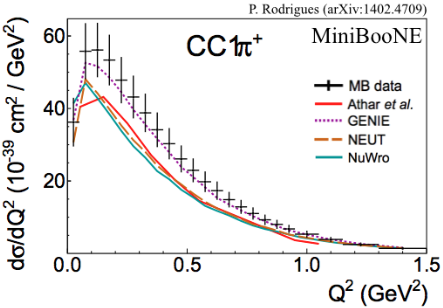
Coherent Pion Production





Q^2 and MiniBooNE

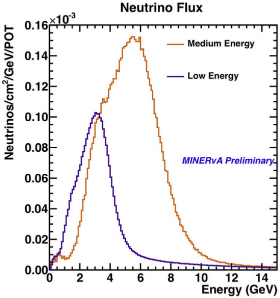




- MINERvA data falls off more slowly, consistent with higher beam energy
- Both analyses see a data turnover in the first two bins ($Q^2 < 0.2$ GeV^2)
- Nuclear structure contributions look to be similar between the two data sets

Future Work

- Publication of observables shown, plus additional muon variables (p_T^μ, p_z^μ)
- Neutrino charged current neutral pion production using low energy data $\rightarrow$ three channels to compare
- Repeat analyses using the medium energy data (E_ν peak around 6 GeV $\rightarrow$ much higher statistics)
  - Pion production in the nuclear targets region



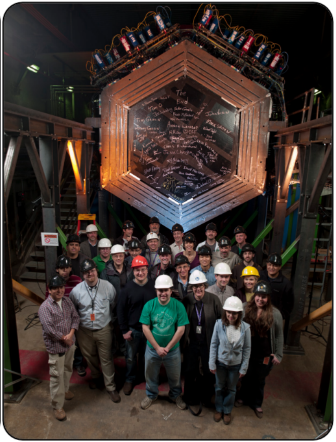
Conclusion

- Distributions of the muon observables $(p_\mu, \theta_\mu, E_\nu, Q^2)$ are sensitive to nuclear structure
- They are complementary to pion variables (T_π, θ_π), which are sensitive to FSI
- The Q^2 spectrum provides the most detail
  - The models agree better than expected given their simplicity
- Updates that include improved nuclear models are needed
- Disagreement between generators in charged pion production at low Q^2 is primarily due to differences in coherent production
- Higher statistics data sets from medium energy running are coming

MINERvA Collaboration

~65 collaborators from particle and nuclear physics

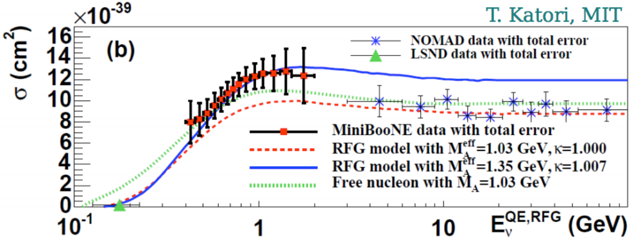
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Mass. Col. Lib. Arts
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
College of William and Mary



Backup Slides

Again, Why Do We Care?

- Working to understand the energy dependence in the CCQE cross section
  - MiniBooNE and SciBooNE disagree with the higher energy NOMAD data, MINERvA is in the energy range that can help resolve this discrepancy
  - Primary signal in the oscillation experiments

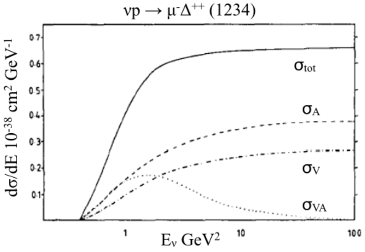


- Additionally, neutrinos make for a good weak-interaction probe of the nuclear structure (today's focus)

Comparison of Measurement

	νCCNπ^+	$\bar{\nu}$CC1π^0
Mechanism Model	Mostly Δ resonance	Mostly Δ resonance
Production	p,n	p only
νN cross section	ANL/BNL confusion	Poorly known
Flux	NUMI LE $+$ horns	NUMI LE $-$ horns

- Future measurements of the same final state with ν and $\bar{\nu}$ can be used to measure interference of vector and axial amplitudes
  - E.g., Rein-Sehgal (1981) for Δ production



Kinematic Equations and Definitions

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

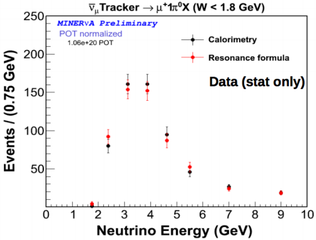
$$Q^2 = 2E_\nu (E_\mu - p_\mu \cos(\theta_{\mu\nu})) - m_\mu^2$$

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

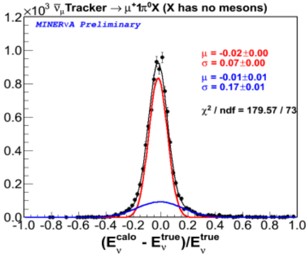
W_{gen} : W_{exp} w/o the assumption of a nucleon at rest

Calculating Neutral Pion Production Neutrino Energy

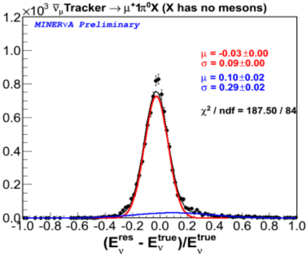
- Multiply the vertex and dispersed energies by calibration constants
- No assumptions on particle interactions



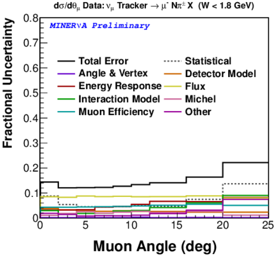
Calorimetry

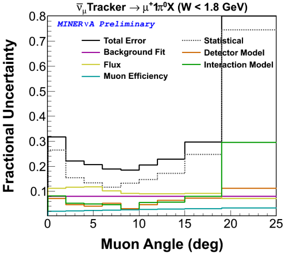


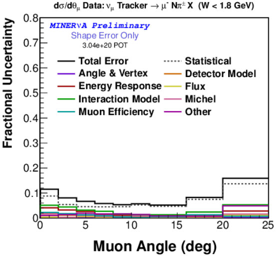
Resonance formula

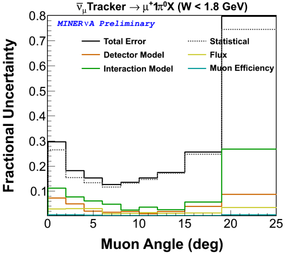


Muon Theta Cross Section Uncertainties

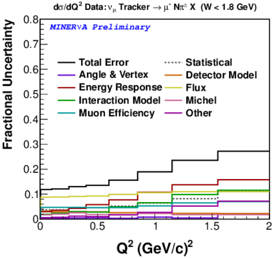


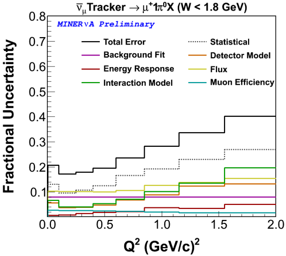


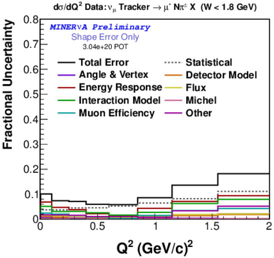


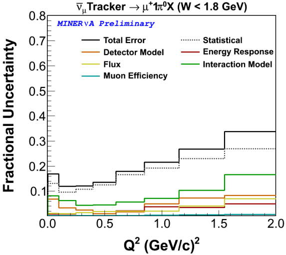


Q^2 Cross Section Uncertainties

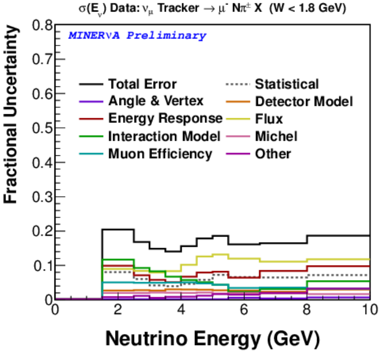


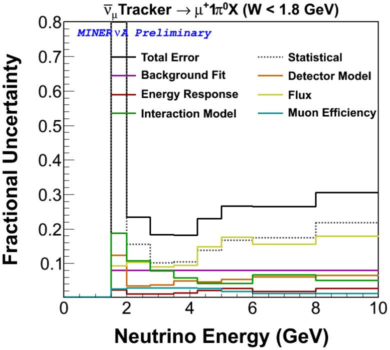






Neutrino Energy Cross Section Uncertainties





Q^2 Coherent Contribution

- Difference in shape between the three models at low Q^2 is largely due to coherent pion production
  - Nuclear models used in all three generators are similar
- No data on plots, so not sure what it correct, but MINERvA does have coherent total cross section measurements (Phys. Rev.Lett. 113, 261802 (2014))
  - Measurement shows that GENIE agrees but NEUT overestimates the data