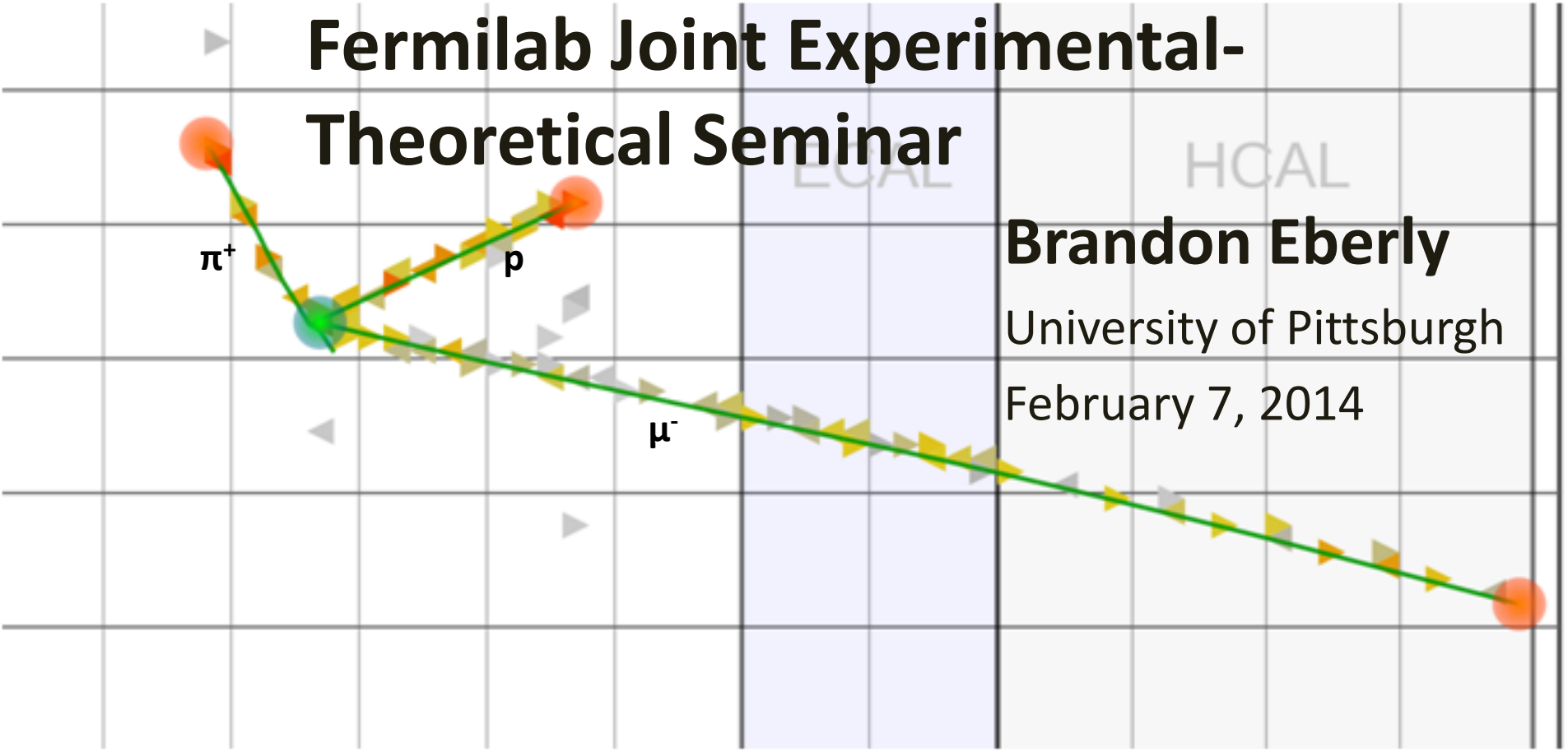
Probing Nuclear Physics with Neutrino Pion Production at MINERvA



Fermilab Joint Experimental-Theoretical Seminar

Brandon Eberly

University of Pittsburgh

February 7, 2014

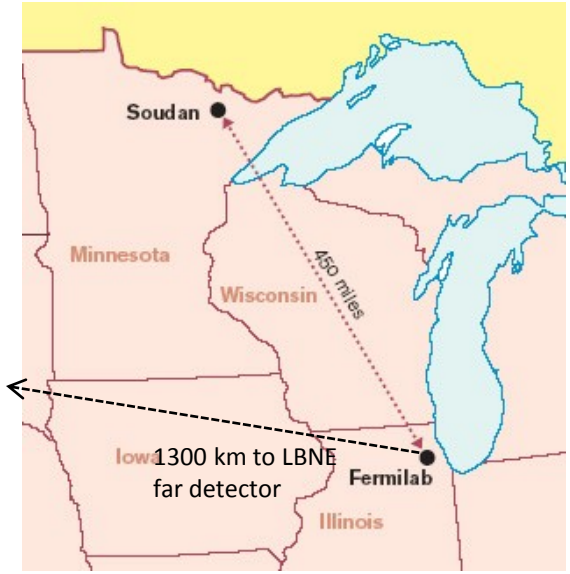
Outline

- Motivation and Introduction
  - Neutrino Oscillations
  - Pion Production in Nuclei
- MINERvA Detector
- MINERvA Reconstruction
- Charged Pion Analysis
- Future Prospects
- Conclusions

Motivation from Neutrino Oscillation Physics

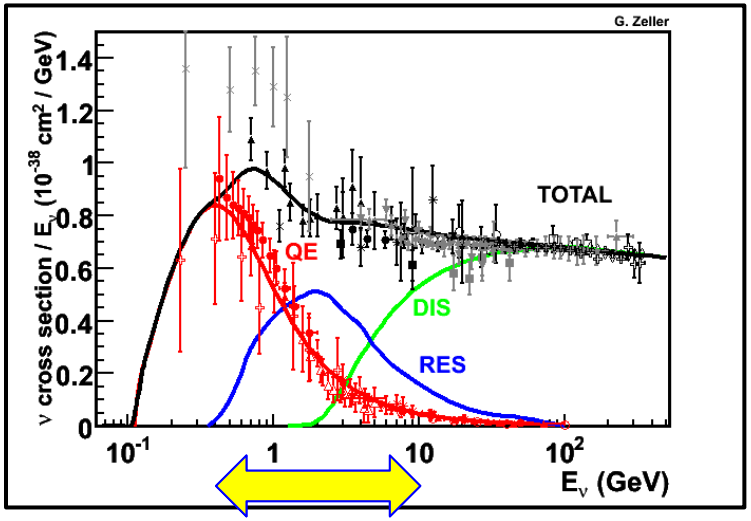
Long Baseline Oscillation Experiments

- Critical component of global effort to understand the nature of the neutrino
  - Measurements of neutrino mixing parameters
  - Will measure the neutrino mass hierarchy and CP-violation
- Ingredients:
  - Intense neutrino beam
  - **MASSIVE** detector composed of heavy nuclei (C, H_2O, Fe, Ar) **FAR** away from the beam source



Original image: Symmetry Magazine, May 2005

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



T2K LBNE

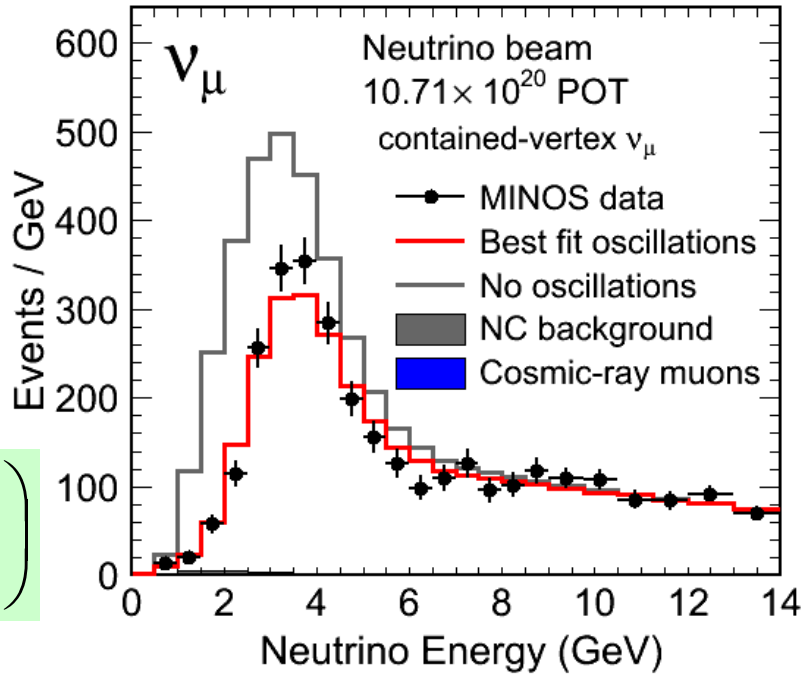
NOνA

Oscillation Parameter Measurement

- Measure the observed energy spectrum for a neutrino flavor at the far detector. Make a ratio with the expected spectrum

- Fit the ratio to the neutrino oscillation probability

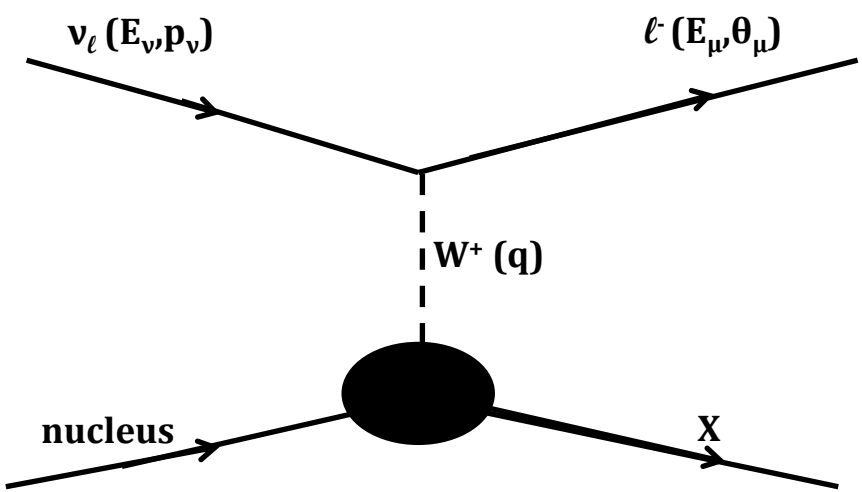
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(1.27 \Delta m^2_{23} \frac{L}{E}\right)$$



MINOS far detector neutrino energy spectrum – published in Phys. Rev. Lett. 110, 2518011
http://www-numi.fnal.gov/PublicInfo/plots/MINOS2013/minos2013_beam_atmos_spectra.png

Neutrino Energy Measurement

- Most experiments measure the neutrino energy by looking for charged current neutrino interactions



Error source	$\sin^2 2\theta_{13}$ = 0	0.1
Beam flux & ν int. (ND280 meas.)	8.5	5.0
ν int. (from other exp.)		
$x_{\text{CC other}}$	0.2	0.1
x_{SF}	3.3	5.7
p_F	0.3	0.0
$x^{\text{CC coh}}$	0.2	0.2
$x^{\text{NC coh}}$	2.0	0.6
$x^{\text{NC other}}$	2.6	0.8
x_{ν_e/ν_μ}	1.8	2.6
W_{eff}	1.9	0.8
$x_{\pi\text{-less}}$	0.5	3.2
$x_{1\pi E_\nu}$	2.4	2.0
Final state interactions	2.9	2.3
Far detector	6.8	3.0
Total	13.0	9.9

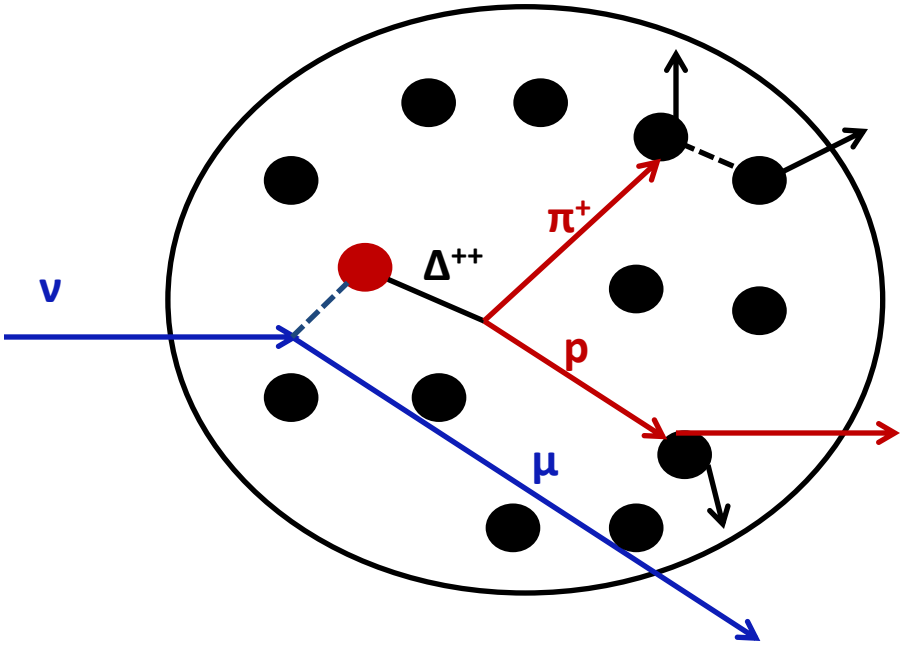
T2K ν_e appearance analysis event rate systematics:
Phys. Rev. D 88, 032002 (2013)

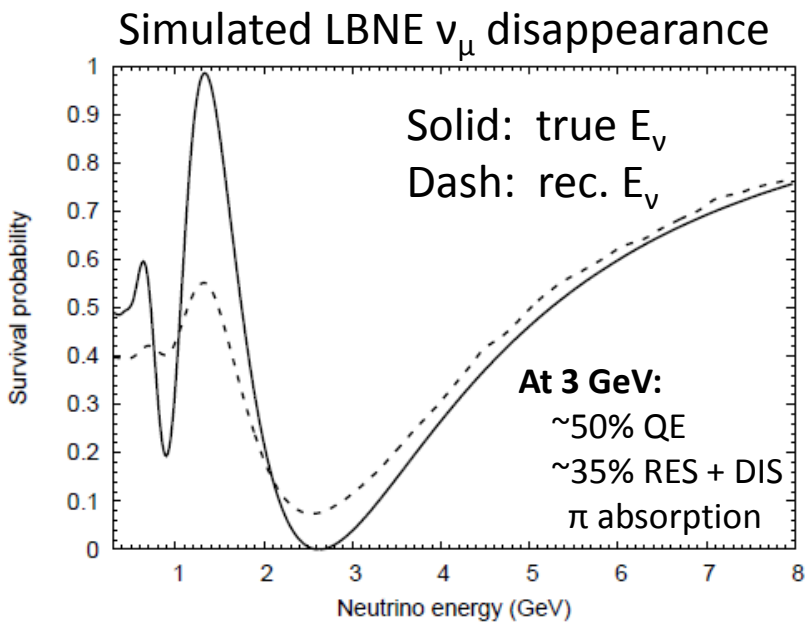
- Measure the lepton energy and do one of:
  - Measure the hadronic recoil energy calorimetrically (**MINOS**)
  - Restrict to a two body final state (QE) and use the lepton kinematics (**T2K**)

Nuclear Physics – Pion Absorption

- Particles can interact with nucleons before exiting the nucleus:
  Final State Interactions (FSI)

- Pions produced in the initial interaction can be absorbed
  ~25% of the time for π^+ from Δ decay!





Mosel *et al*: arxiv 1311.7288

Importance of Nuclear Physics

- Nuclear processes affect the final state content, and this needs to be modeled to correctly reconstruct the neutrino energy

- Need to understand nuclear physics to do neutrino physics!

If the current knowledge of neutrino-nucleus interactions does not improve, future experiments like LBNE will have added difficulty in meeting their physics goals!

(and I'm really looking forward to that CP violation measurement!)

Pion Production in Nuclei

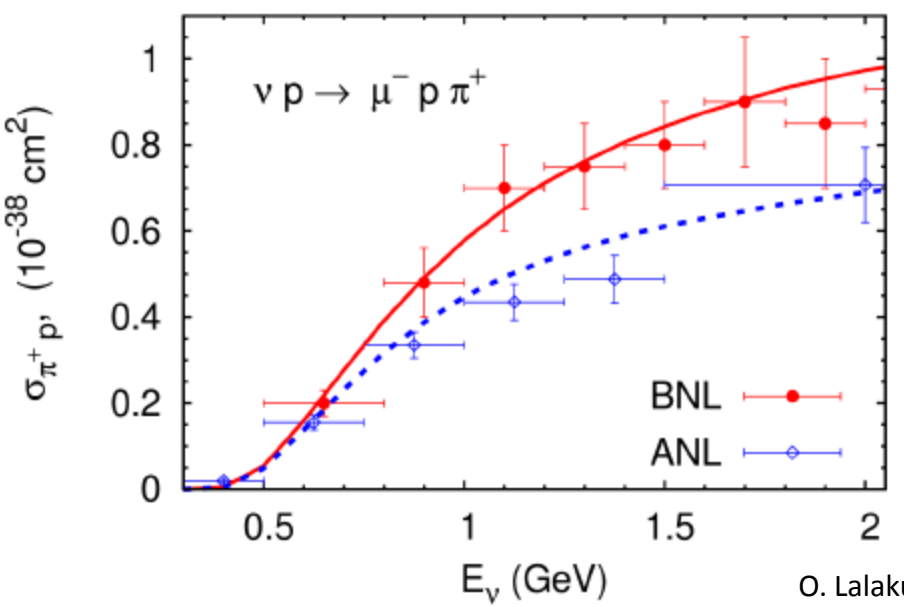
Recipe For a Pion Production Model

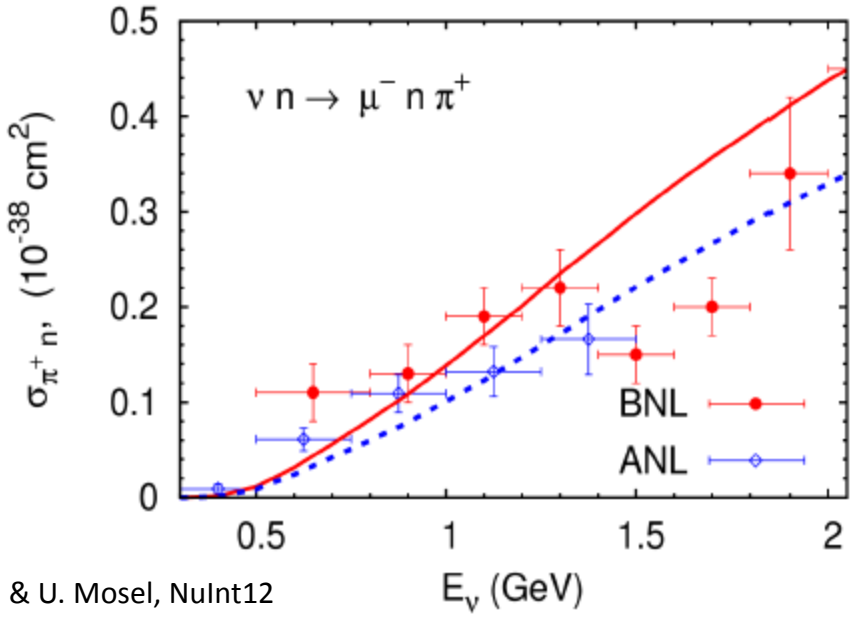
- Theoretical calculations are very difficult
  - Can't just write down the nuclear wave function
- Instead, build the model in pieces
  - Start with neutrino-nucleon and neutrino-quark interaction models
  - Add medium modifications of the initial interaction
    - Nuclear potential, modification of form factors and structure functions
    - Nucleon momentum and correlations
  - Install a final state interaction model
- Then check against data
  - Today, I will focus on final state interactions

Resonance Pion Production Model

- Most experiments use the Rein-Sehgal model for νN resonance production
  - More recent models by M. Athar, Salamanca-Valencia, M. Pascos

- Experimentalist's dilemma: Whichever model you use, it will be poorly constrained by νN data





O. Lalakulich & U. Mosel, NuInt12

Final State Interaction Models

- Neutrino oscillation experiments use neutrino event generators (Monte Carlo) to simulate neutrino-nucleus interactions
  - Need to be fast – produce millions of events

  - Example: GENIE event generator has two approaches
    1) (standard) Use p, π^+ interaction data on Fe, with $A^{2/3}$ scaling and isospin symmetry

    2) Simulate an intra-nuclear cascade with tree-level cross sections

- Theorists adopt more sophisticated techniques
  - Example: GiBUU FSI - solve the Boltzmann-Uehling-Uhlenbeck (BUU) equation
    - Coupled integro-differential equations – not as good for event generators

Neutrino-Nucleus Interaction Data

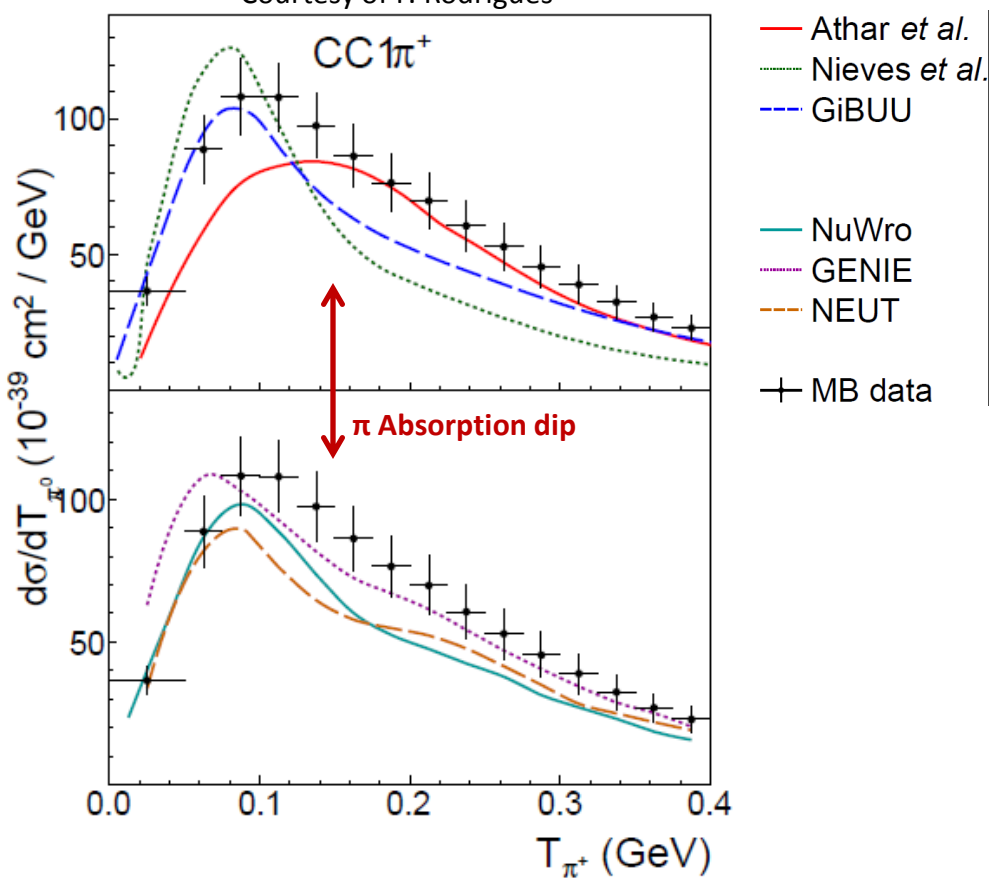
•The MiniBooNE experiment recently published a suite of cross sections for charged current pion production: **Phys.Rev.D83:052007,2011**

$$\nu_\mu CH_2 \rightarrow \mu^- \pi^+ X$$

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

•FSI model is responsible for the characteristic dip between 100-200 MeV

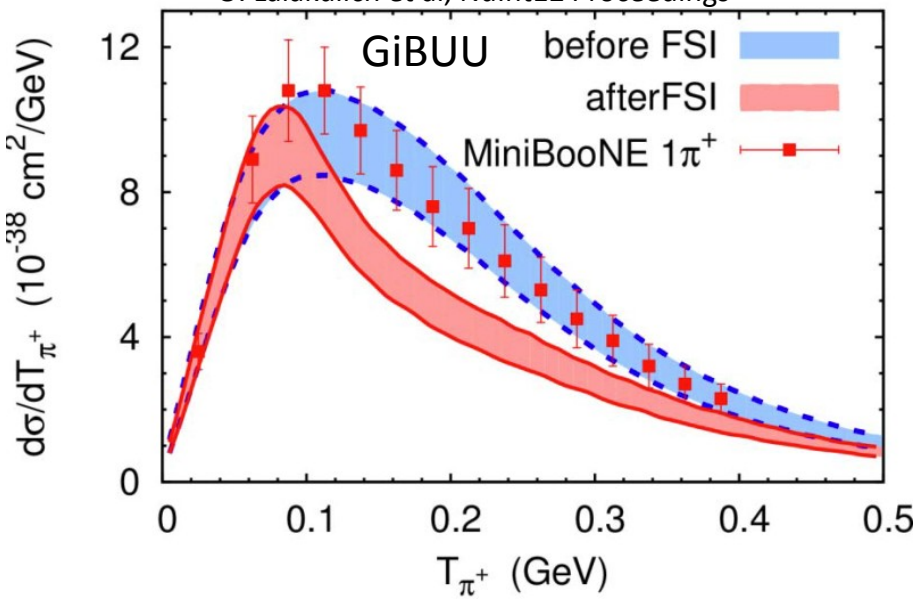
Courtesy of P. Rodrigues



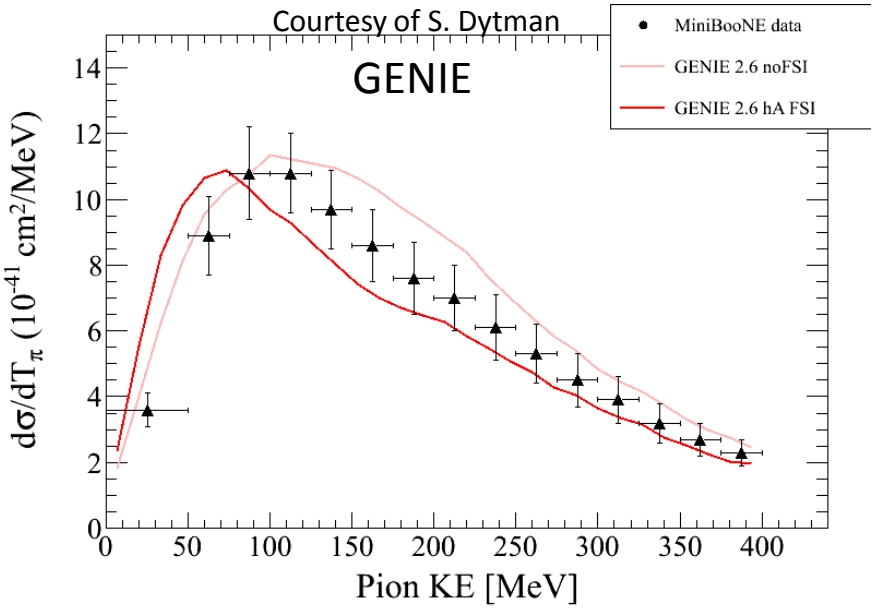
MiniBooNE and Final State Interactions

- Different calculations and event generators disagree in their disagreement

O. Lalakulich et al, NuInt12 Proceedings



Courtesy of S. Dytman



GiBUU: Strong FSI dip. MiniBooNE data is consistent with no final state interactions

GENIE: Weak FSI dip. MiniBooNE data is somewhere in between no FSI and full FSI

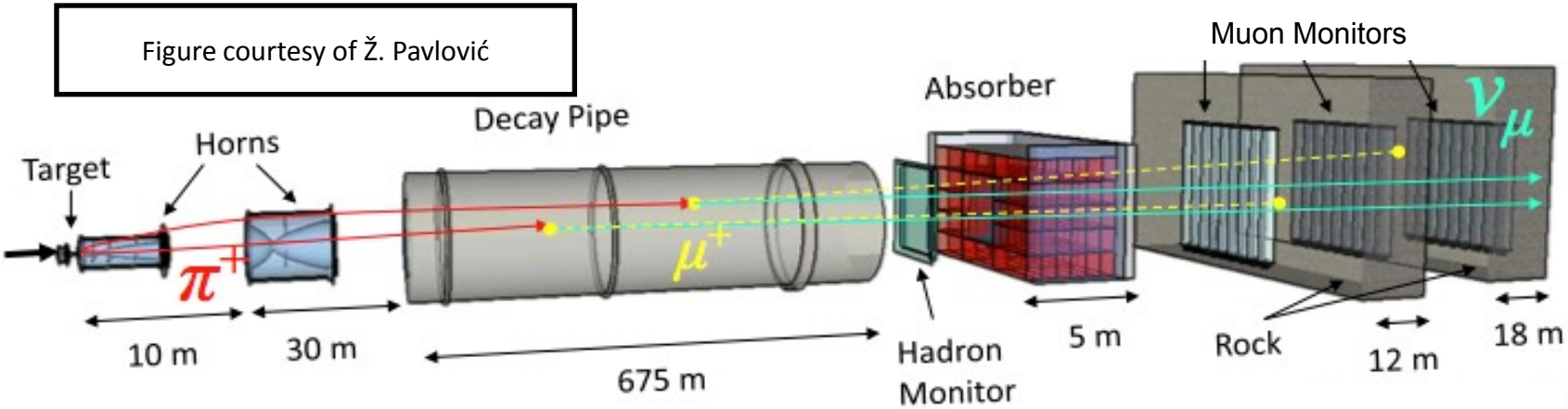
We need more data to help solve this puzzle!

The NuMI Beam and MINERvA Detector

NuMI Beam Line

- 120 GeV/c protons on C target
- Beam power: 300-350 kW (before NOvA upgrades)
- Magnetic horns can focus + or – particles -> neutrino or antineutrino beam
- Target can be moved relative to the horn to tune beam energy

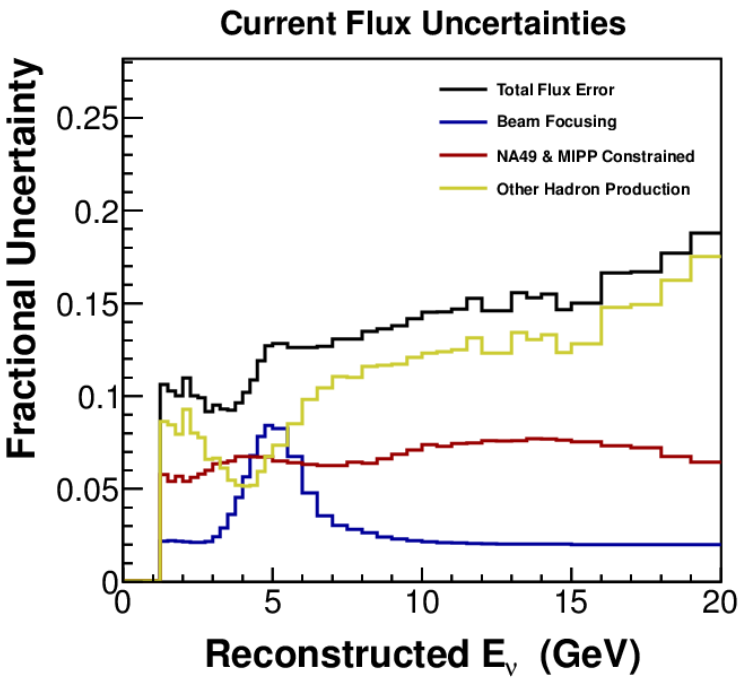
Figure courtesy of Ž. Pavlović

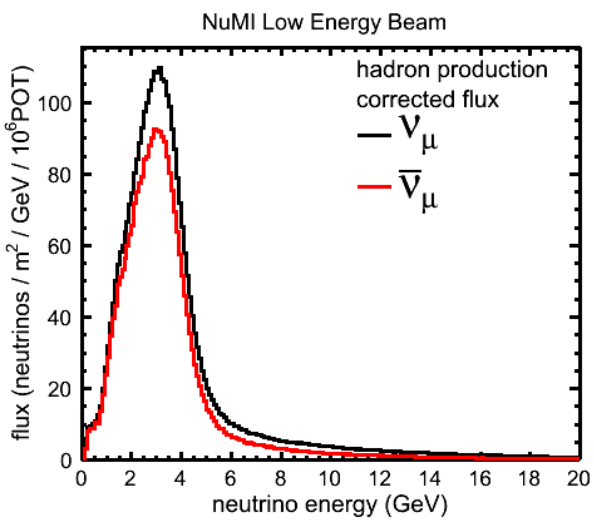


NuMI Flux Measurement

- Flux measurements are hard!
- MINERvA has a rich suite of measurements planned to improve flux estimate

The shape analysis presented in this talk is insensitive to the flux!





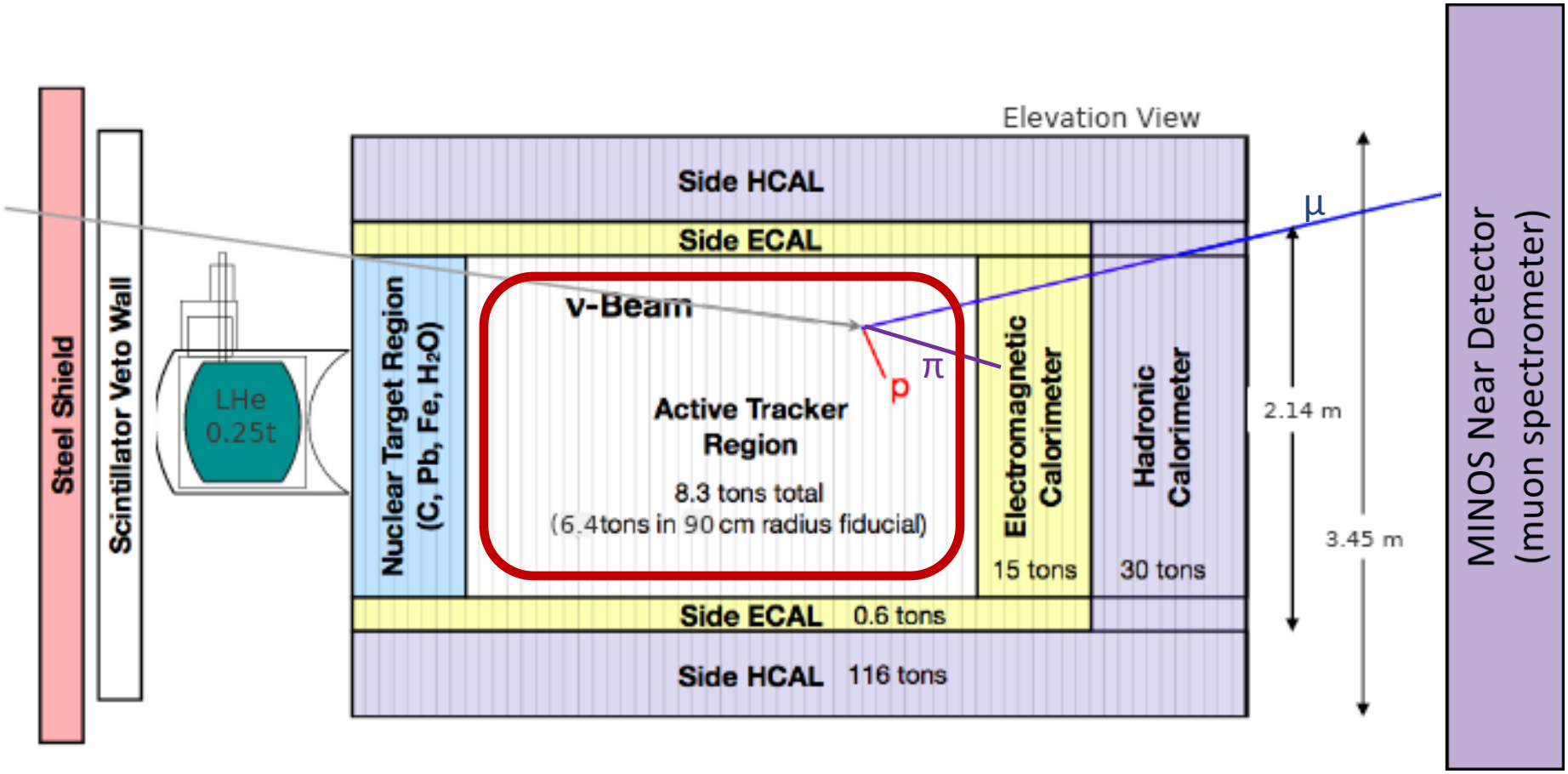
MINERvA Experiment

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
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

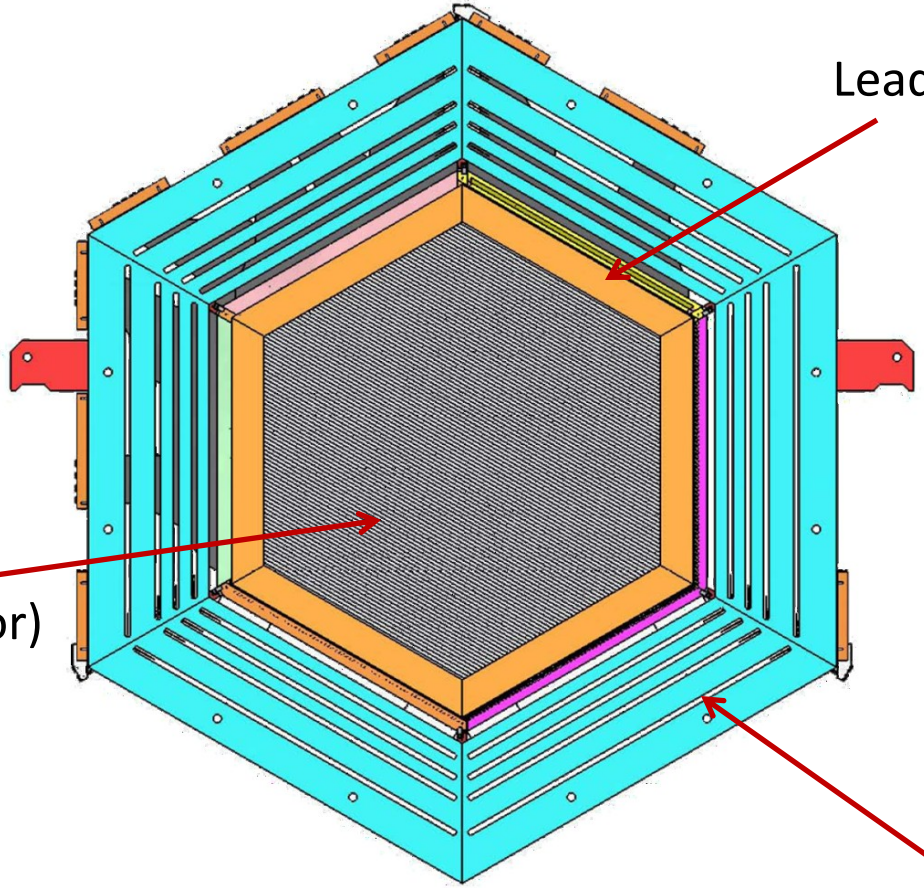
MINERvA Detector

- Fine-grained scintillator tracker surrounded by calorimeters
- MINOS near detector is the muon spectrometer (magnetized)

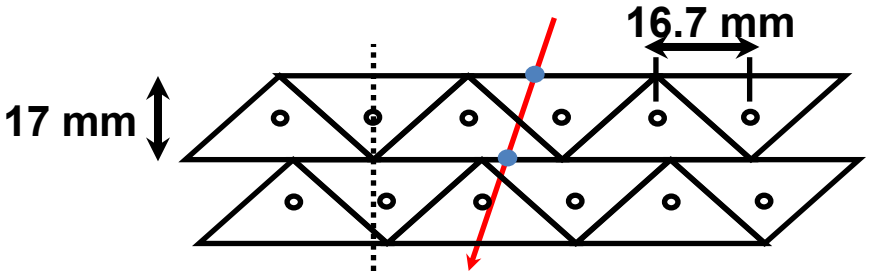


MINERvA Detector

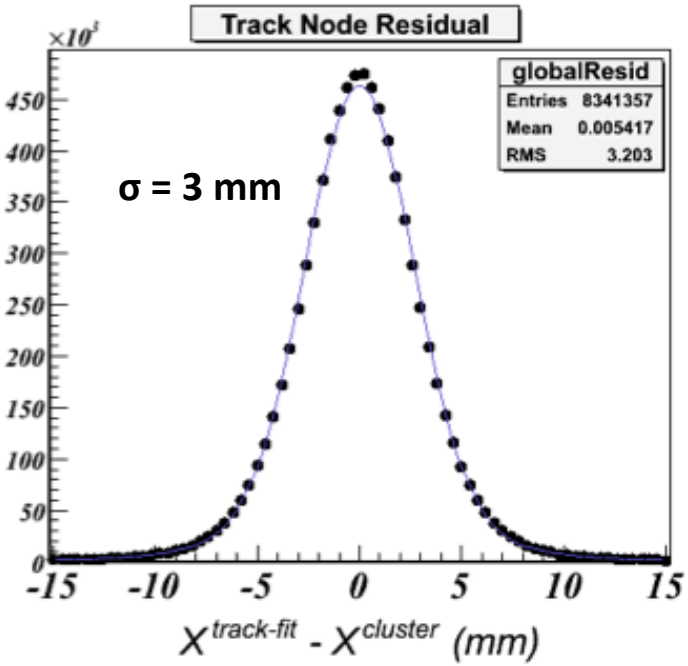
Front view of a tracker module

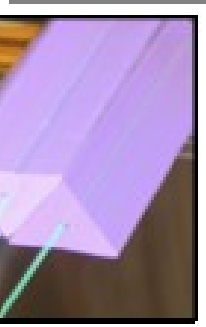


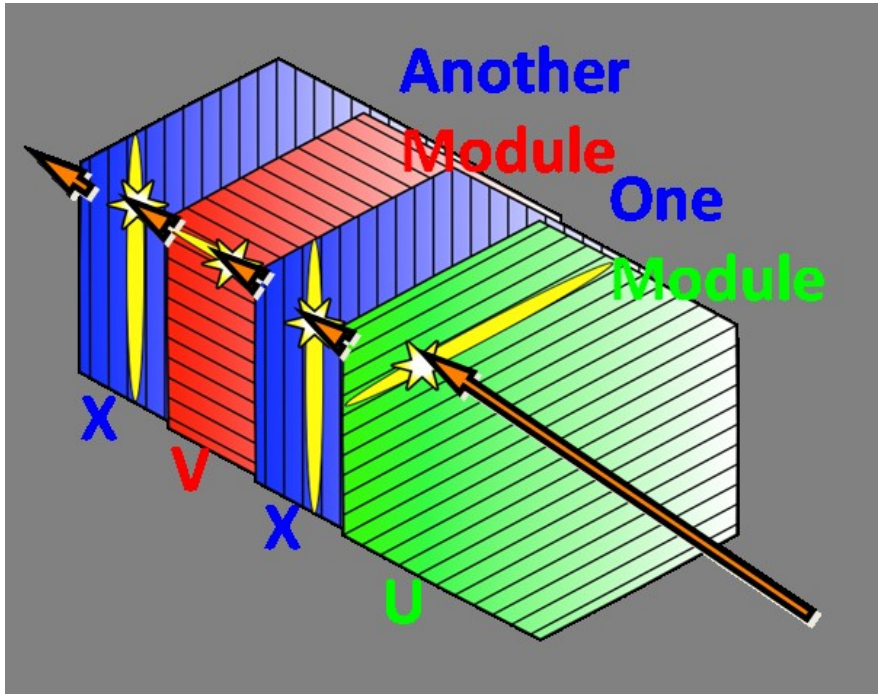
MINERvA Detector



Triangular scintillator strips allows charge-sharing for good position resolution (3 mm)







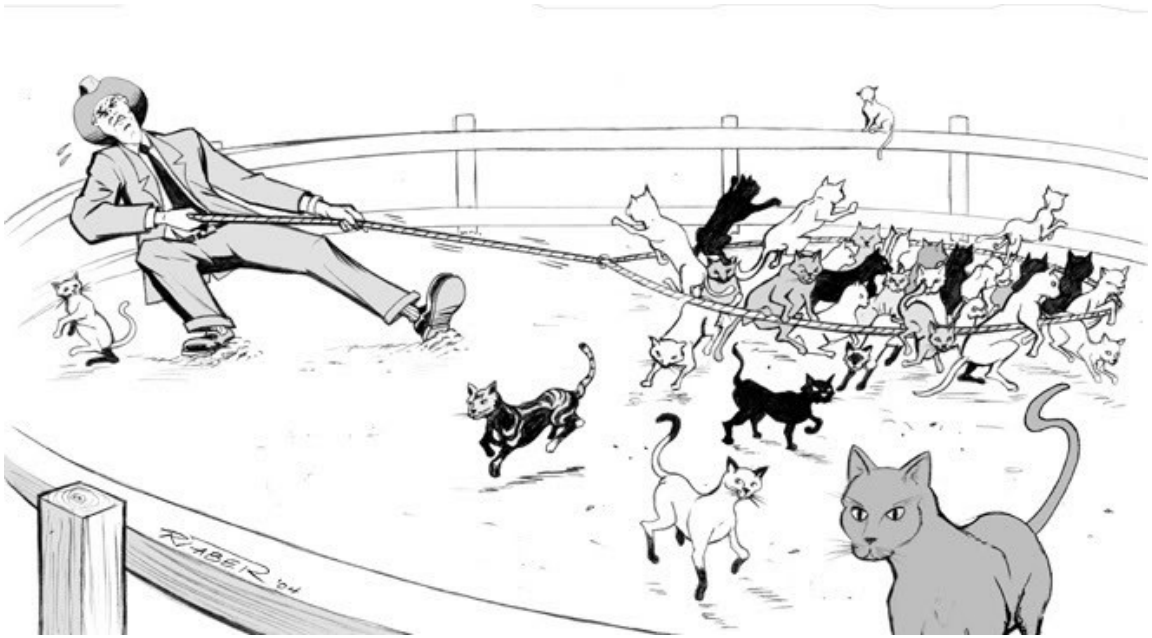
3 different rotated plane views to resolve high-multiplicity events

Pion and Event Reconstruction

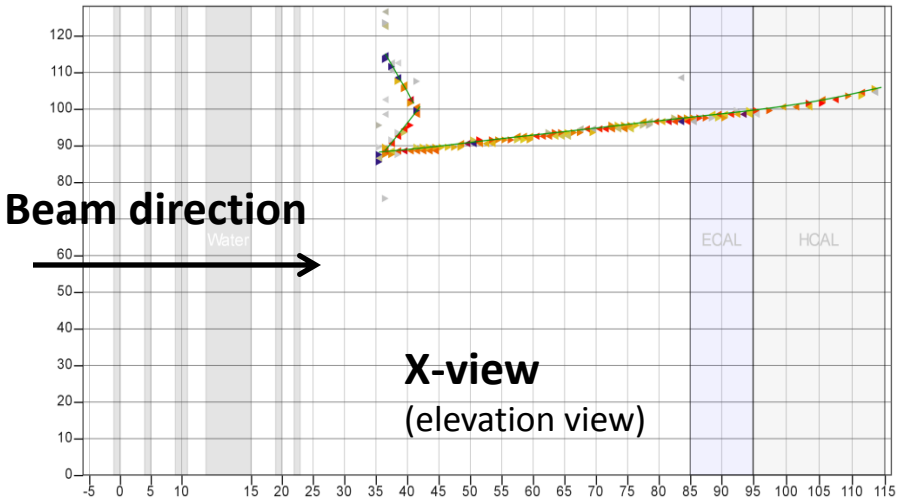
MINERvA Pion Reconstruction

- Want to leverage the scintillator tracker – find pion tracks

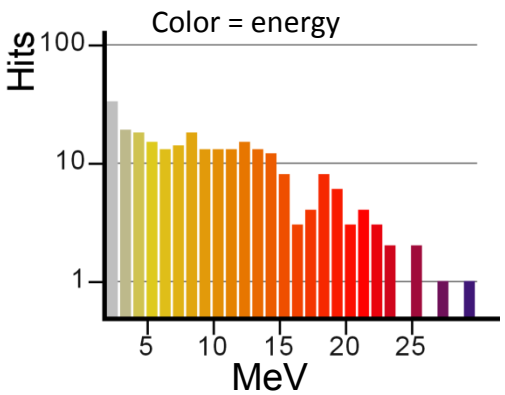
- Pions are not always cooperative!
  - Plastic scintillator is a dense tracker – pions can scatter, charge-exchange, or absorb

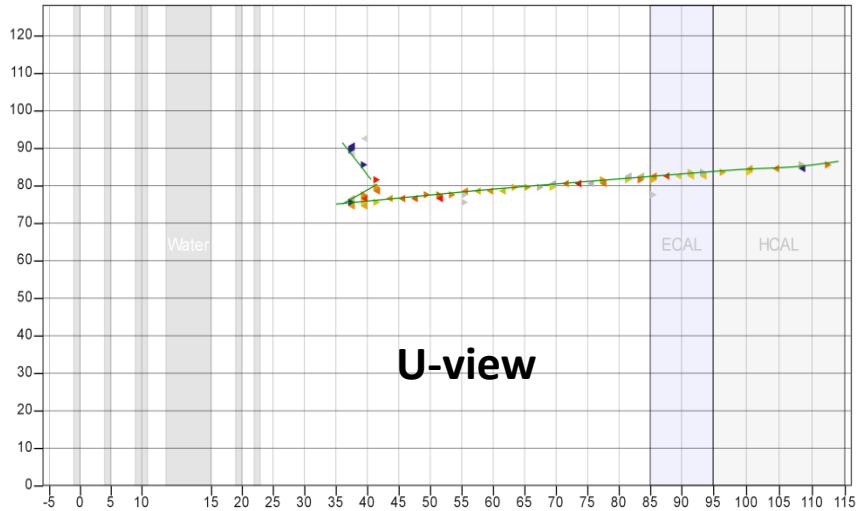


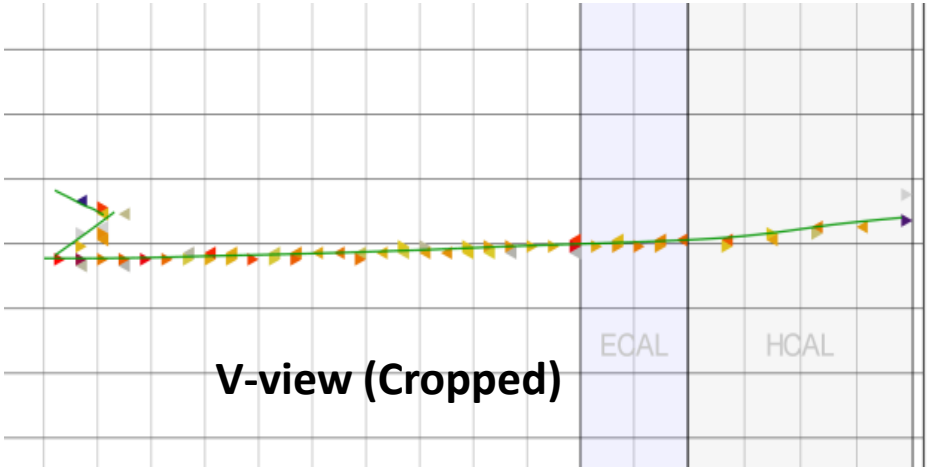
A Day in the Life of a MINERvA Pion



Data Candidate: Scattering π^+

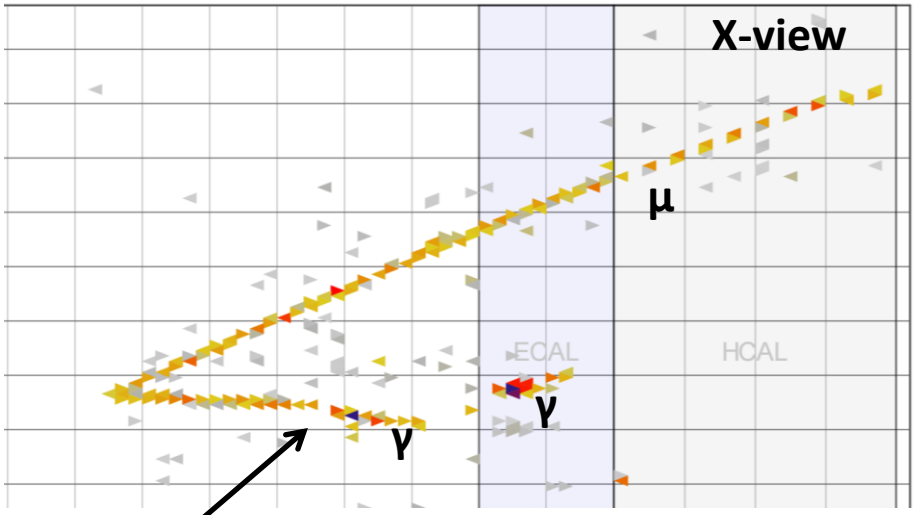






A Day in the Life of a MINERvA Pion

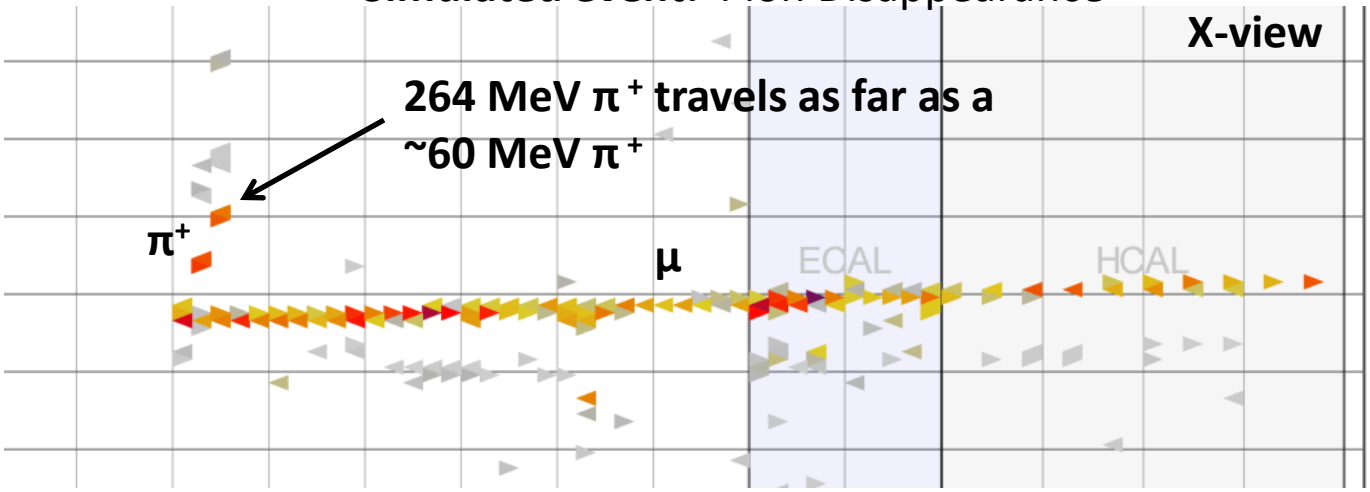
Simulated event: Pion Charge-Exchange



$\pi^+ \rightarrow \pi^0 \rightarrow \gamma\gamma$

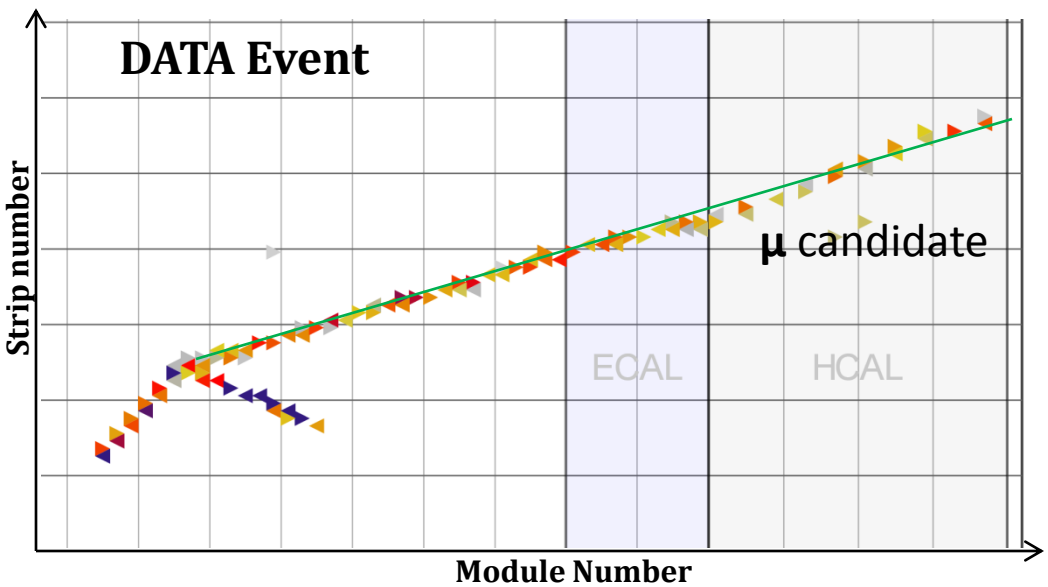
Analysis strategy: Avoid pions that interact in these ways

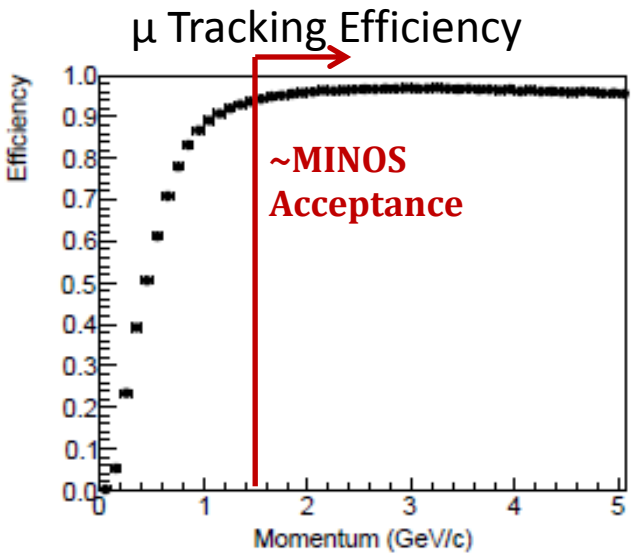
Simulated event: Pion Disappearance

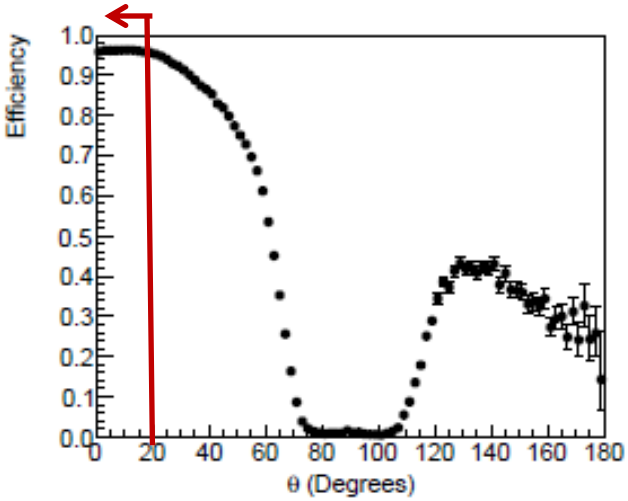


Track Reconstruction

- First search for a long, muon-like track.
- Use it to predict the interaction vertex location
- Employ a "cleaning" algorithm that removes overlapped hadronic energy from the muon

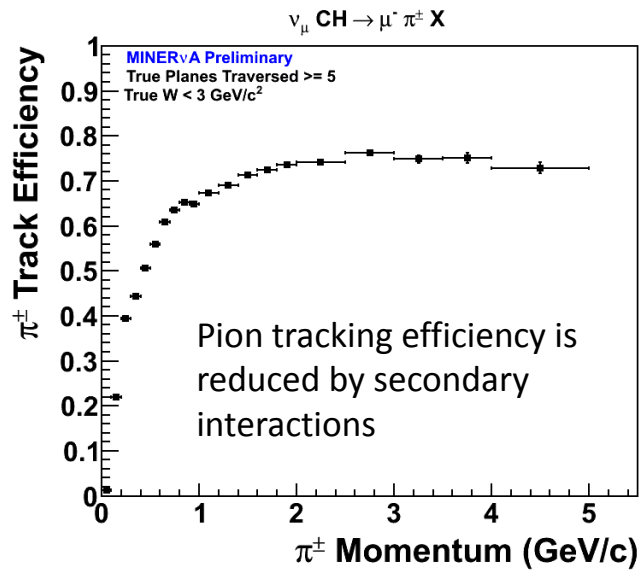


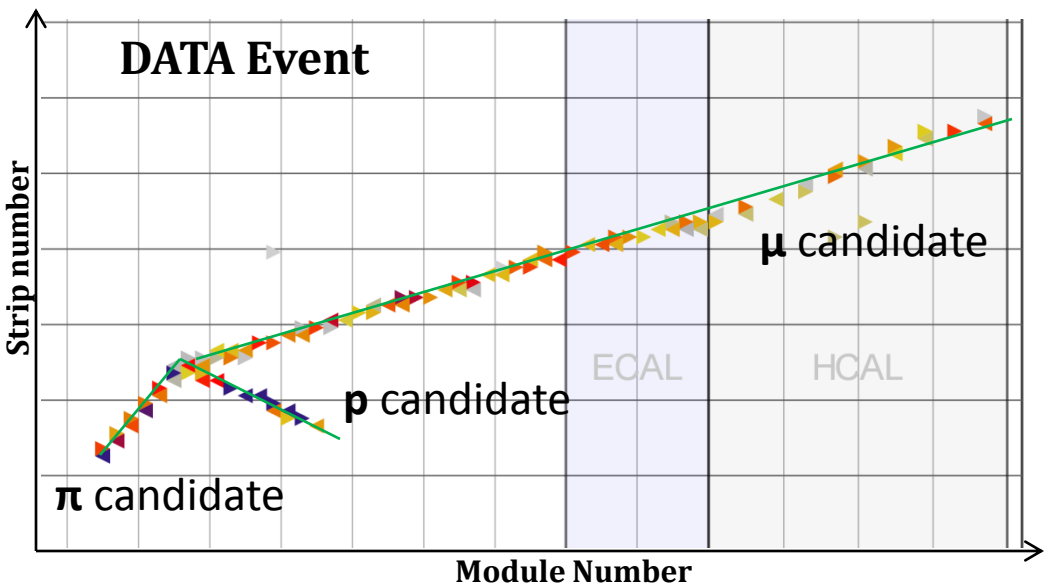




Track Reconstruction

- Next, look for additional tracks at the interaction vertex
- Fit for the interaction vertex using all available tracks





MINERvA Charged Current Charged Pion Analysis

Goal: Measure pion energy and angle distributions to determine strength and nature of FSI interactions

Data set: Entire MINERvA Low Energy neutrino data: 2.99e20 Protons on Target (P.O.T.)

Signal Definition

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

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

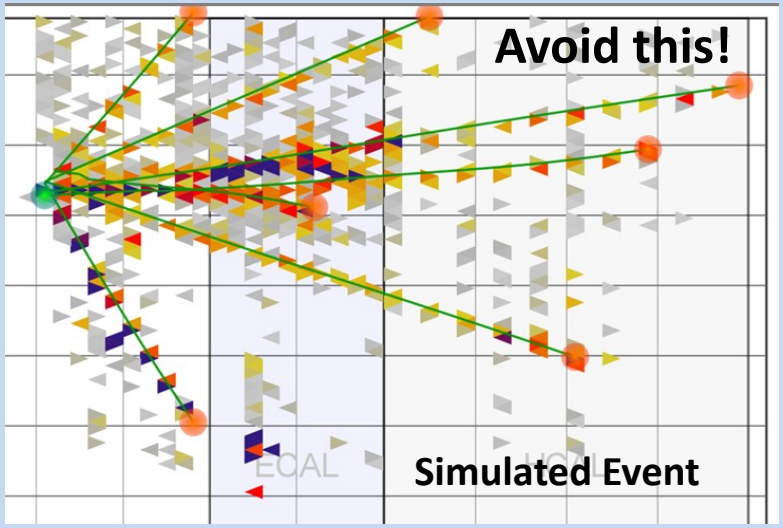
AND

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

- Coherent pion production: Struck nucleus is left in its ground state and a single π^+ is produced

- Other Requirements:
  - 1.5 GeV < E_ν < 10 GeV
  - Invariant hadronic mass (W – not the boson!) is less than 1.4 GeV

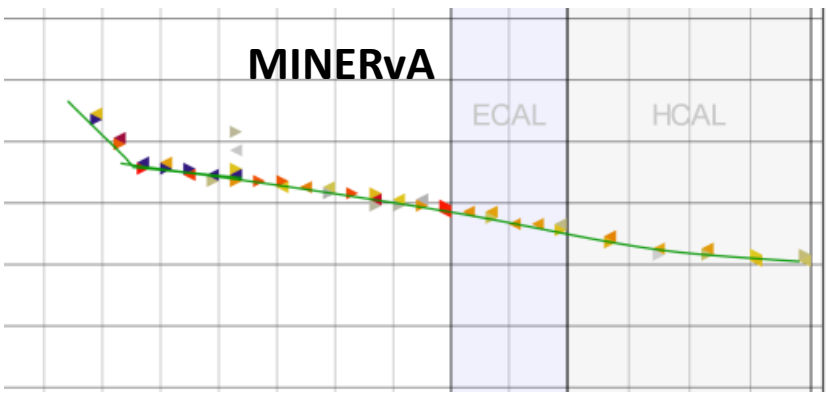
- Motivation:
  - Choose a MiniBooNE-like sample
  - Avoid high-multiplicity interactions

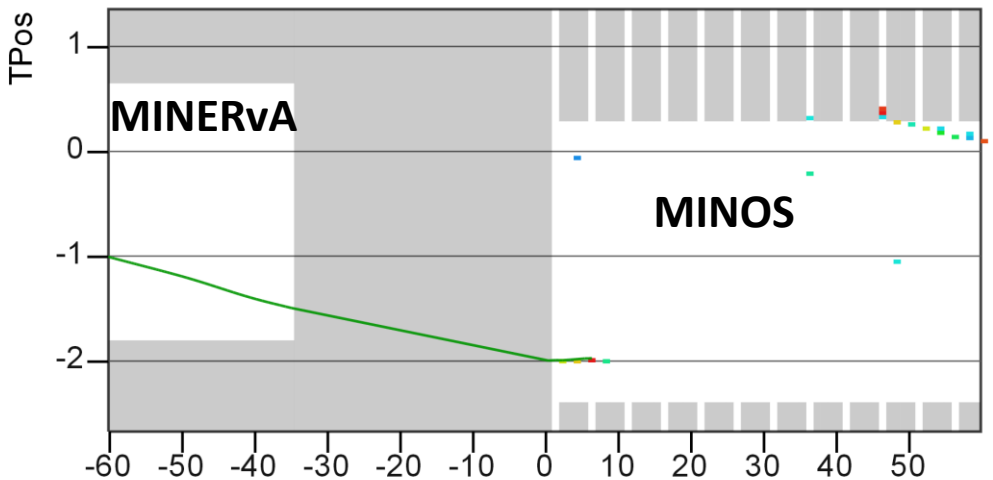


Event Selection – Muon

First, select charged current ν_μ events:

- Look for a MINERvA track that is matched to a track in MINOS
- Require that the reconstructed charge is negative





Event Selection – Kinematics

Limit the size of the hadronic recoil and neutrino energy

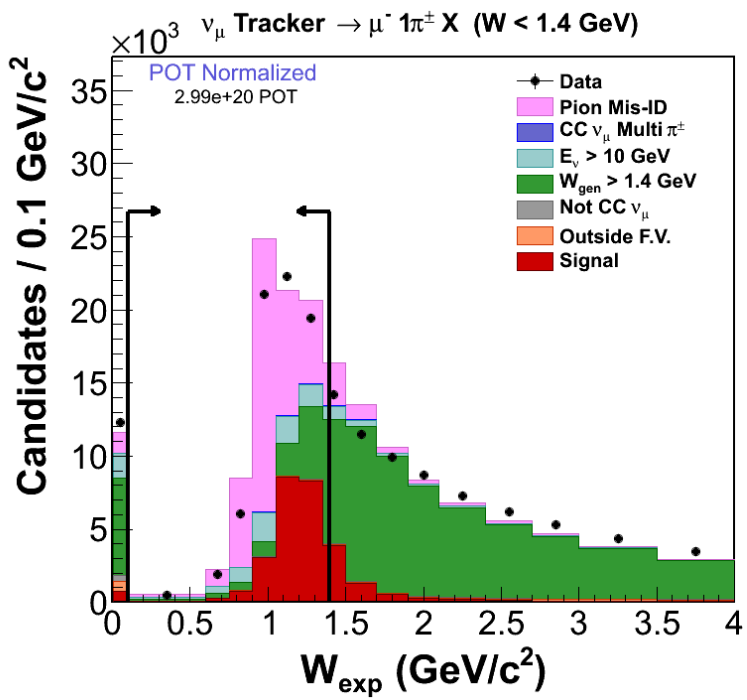
- Reconstruct hadronic recoil energy (E_H) calorimetrically
  - Sum non-muon energy, weighted by passive material constants
  - Apply additional scale, derived from MC, to tune to true E_H

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

Require:

$E_\nu < 10$ GeV

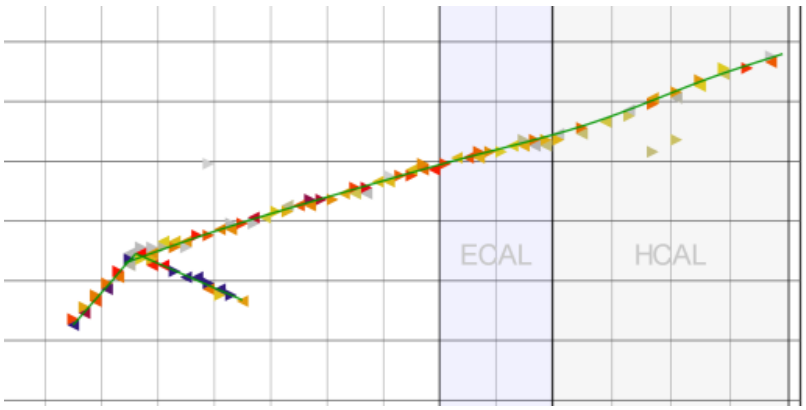
$W_{exp} < 1.4$ GeV

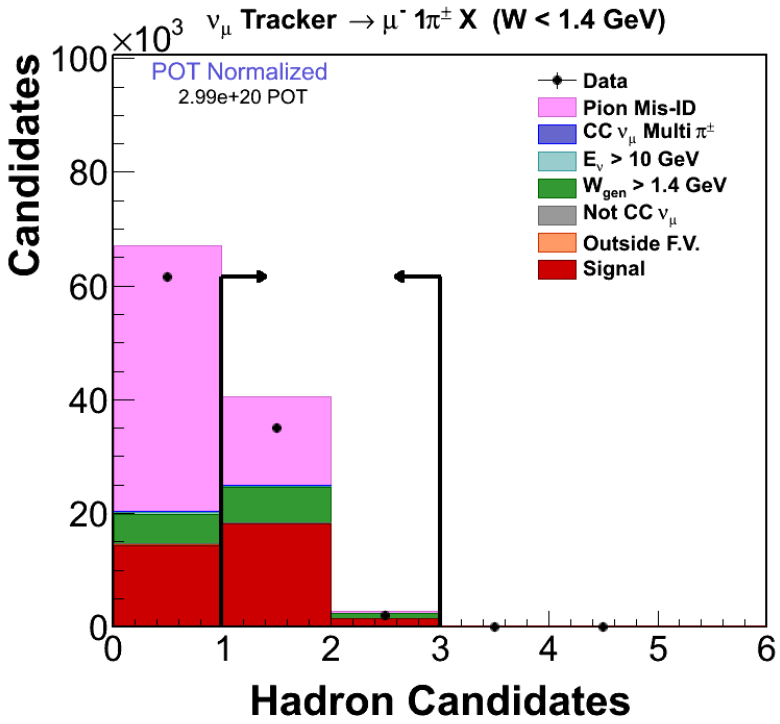


Event Selection - Pion

Find pion candidates:

•Require one or two hadron track candidates



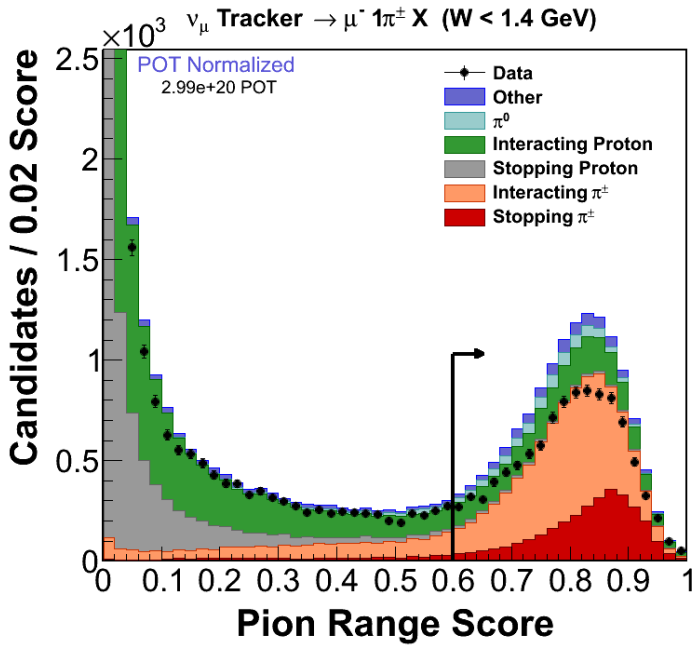


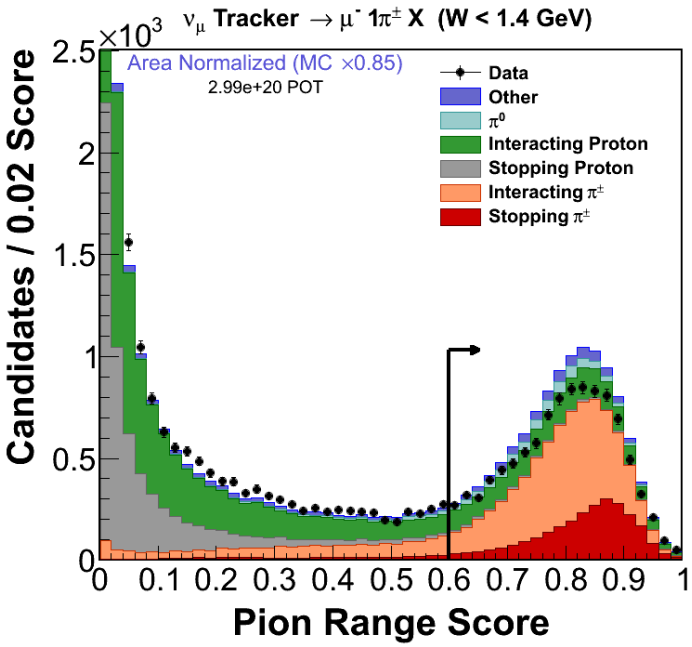
Event Selection – Pion ID

Select a pion (Particle ID):

•Use energy loss (dE/dx) profile of each hadron track to separate protons and pions

•Find the best fit momentum for a pion hypothesis: this is the ***reconstructed momentum***





Event Selection – Pion ID

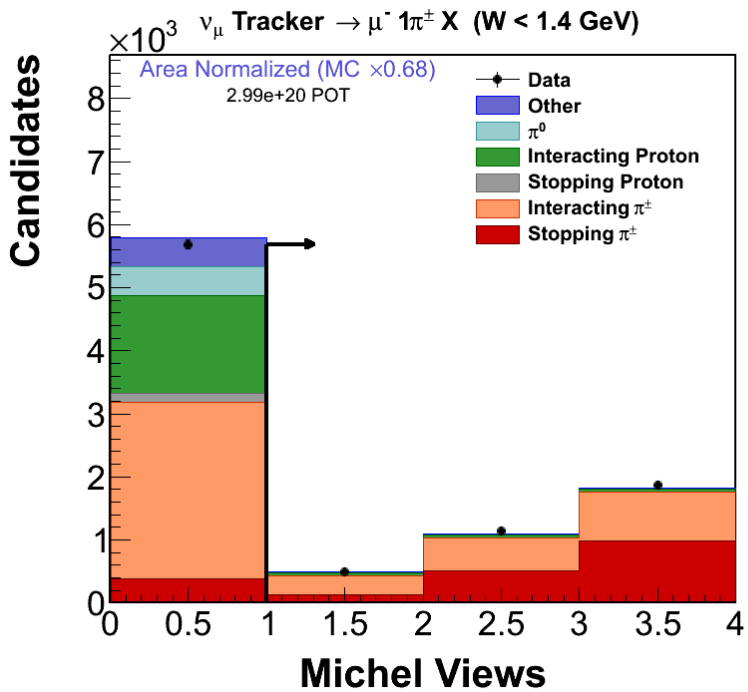
Select a pion (with good energy reconstruction):

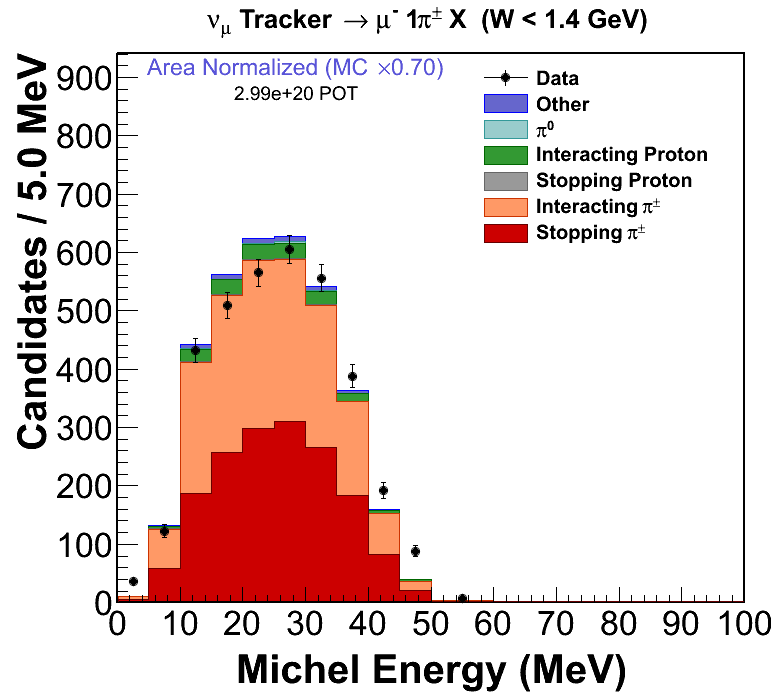
•Select pions that stop and decay in the detector by looking for a Michel electron at the end of the track

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

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

Shape Comparisons

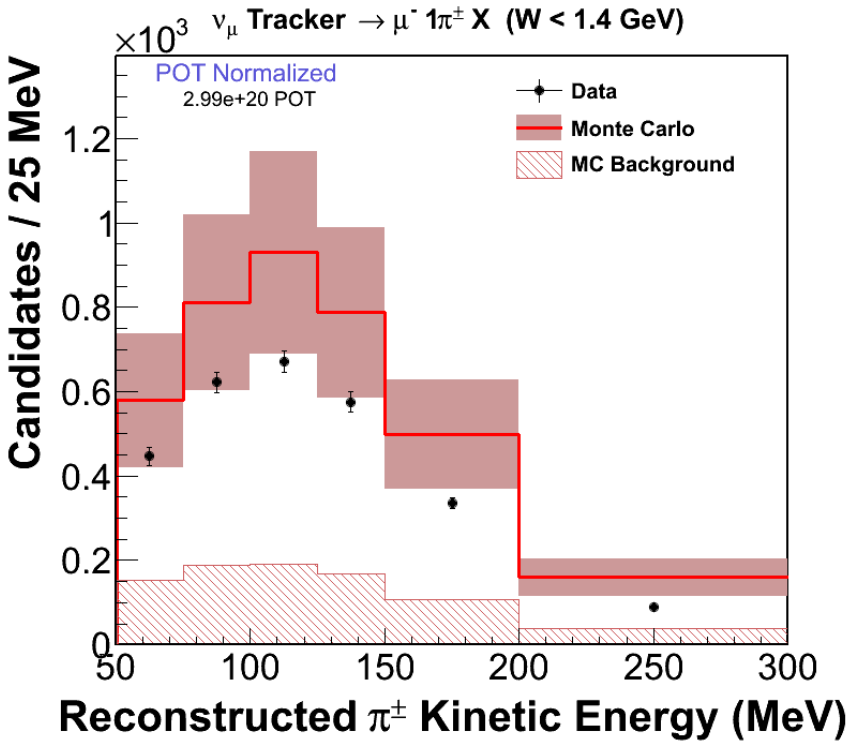


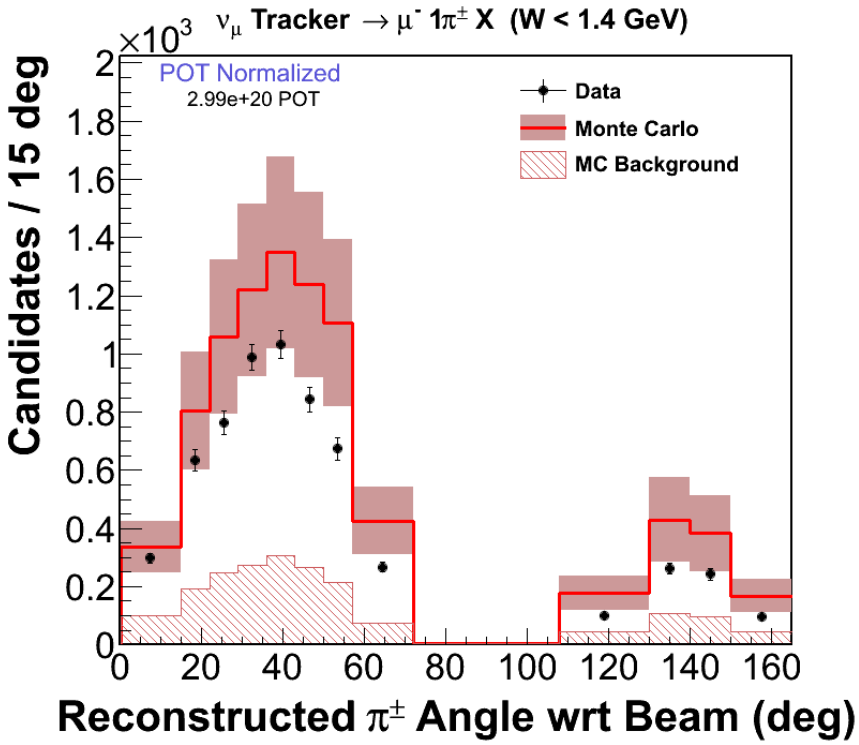


Reconstructed Pion Energy and Angle

Event selection yields **3474 pion candidates**

MC error bars include full systematic errors
Data errors are statistical only





Calculating a 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

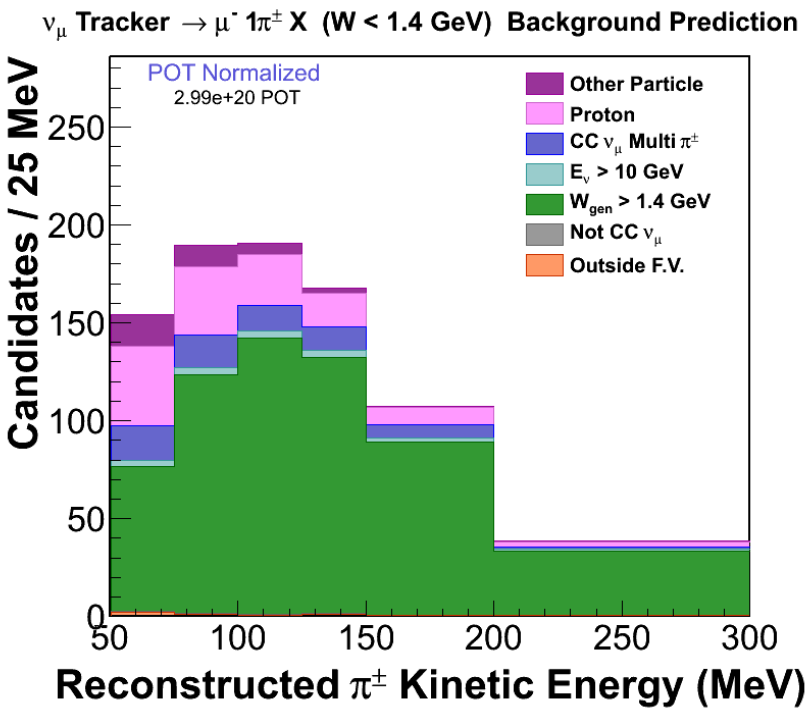
Selection efficiency and acceptance

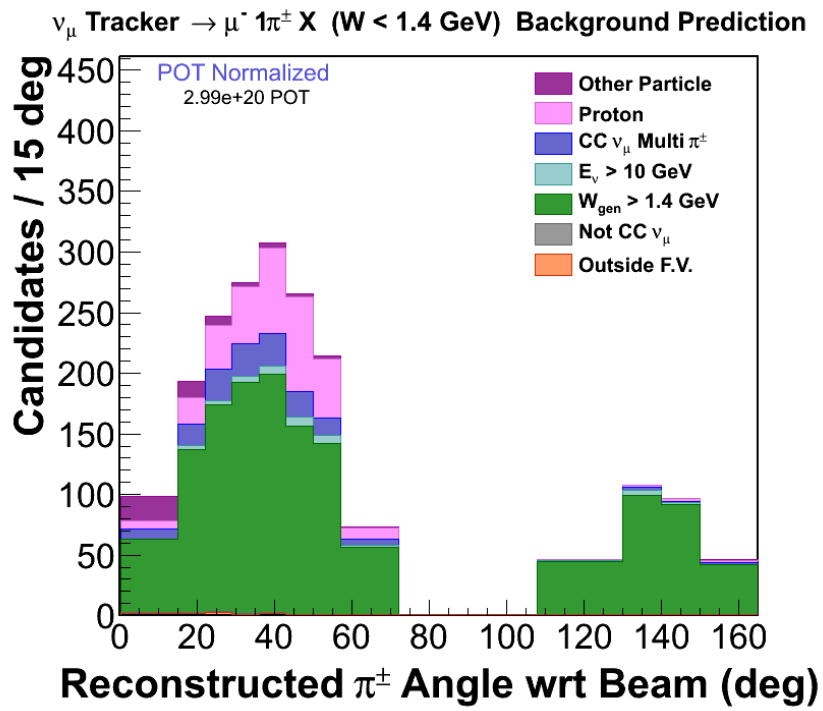
Background Summaries

Largest background: W > 1.4 GeV **~17%** of sample

PID backgrounds: Protons and other particles mis-ID as pion **~ 4%** of sample

All other backgrounds combined **~2%** of sample





Background Subtraction

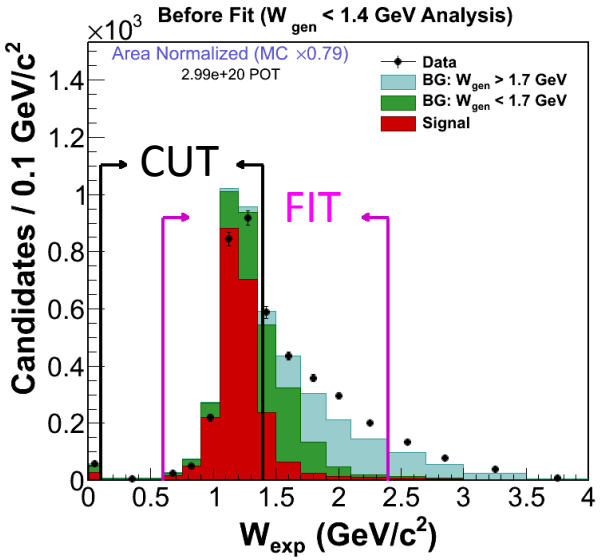
- Only significant background is feed down from large W. Concentrate on constraining this background with data

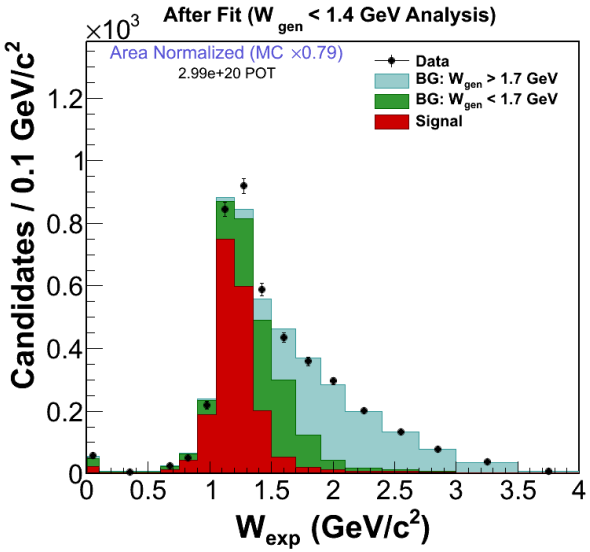
Procedure:

- Construct the W_{exp} distribution, applying all cuts except the W_{exp} cut

- Use the MC to create signal and background shape templates

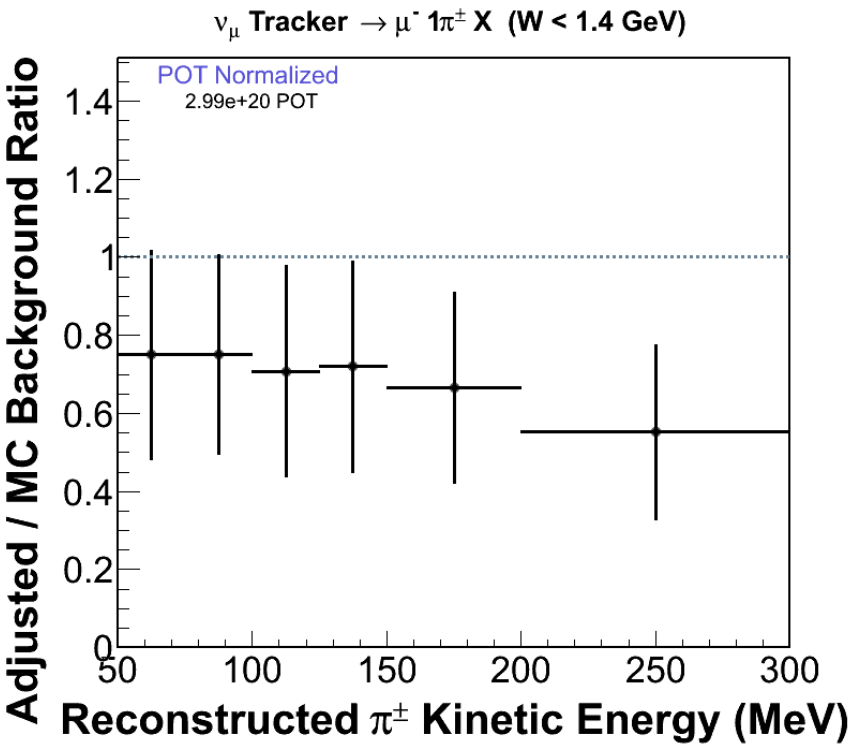
- Fit the data for the relative normalizations of the templates

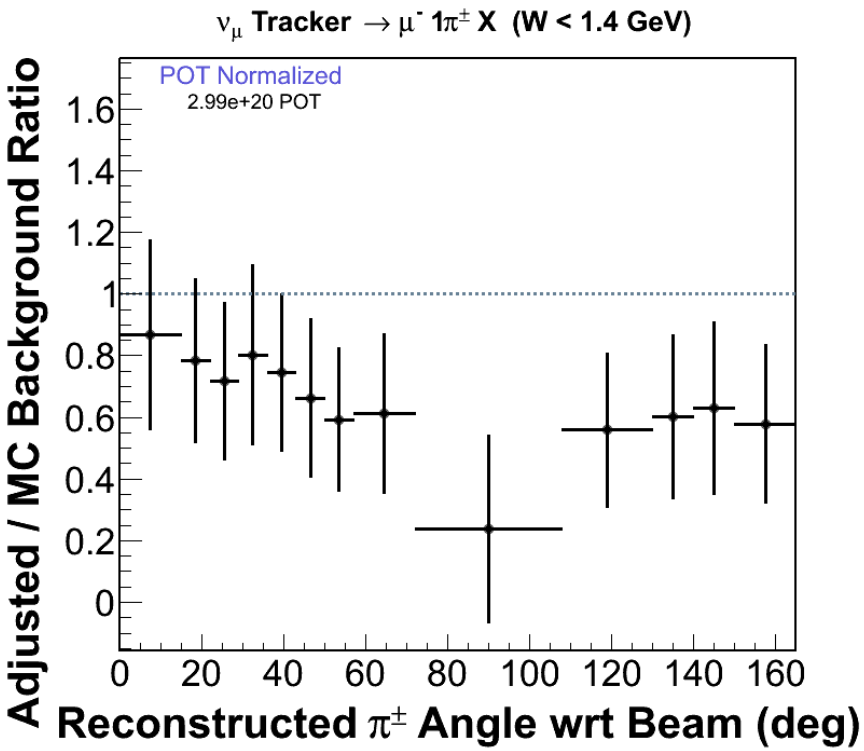




Background Scales

Ratio of adjusted to simulated background



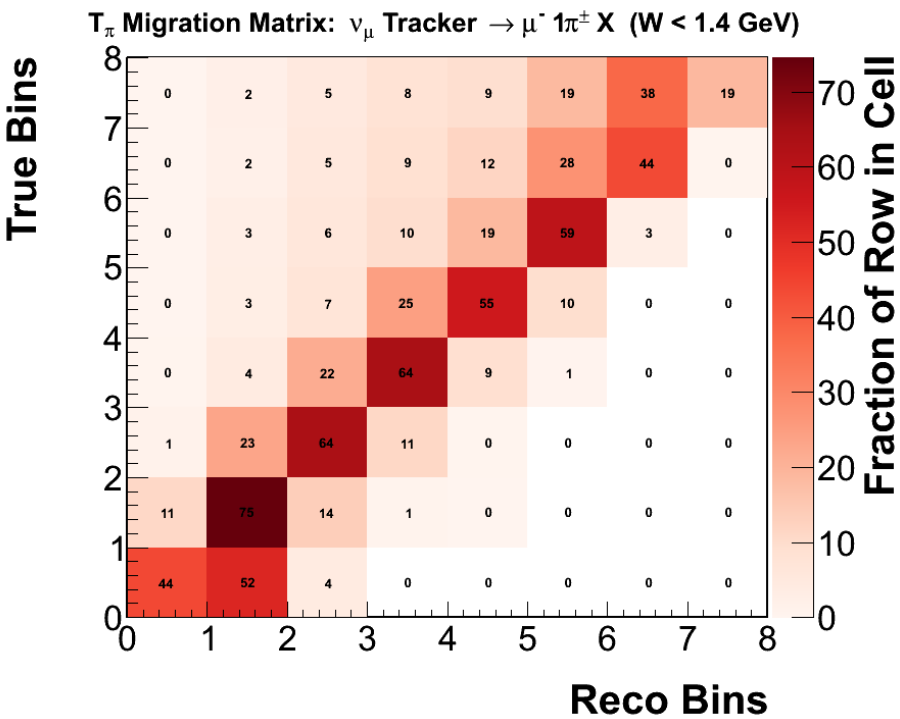


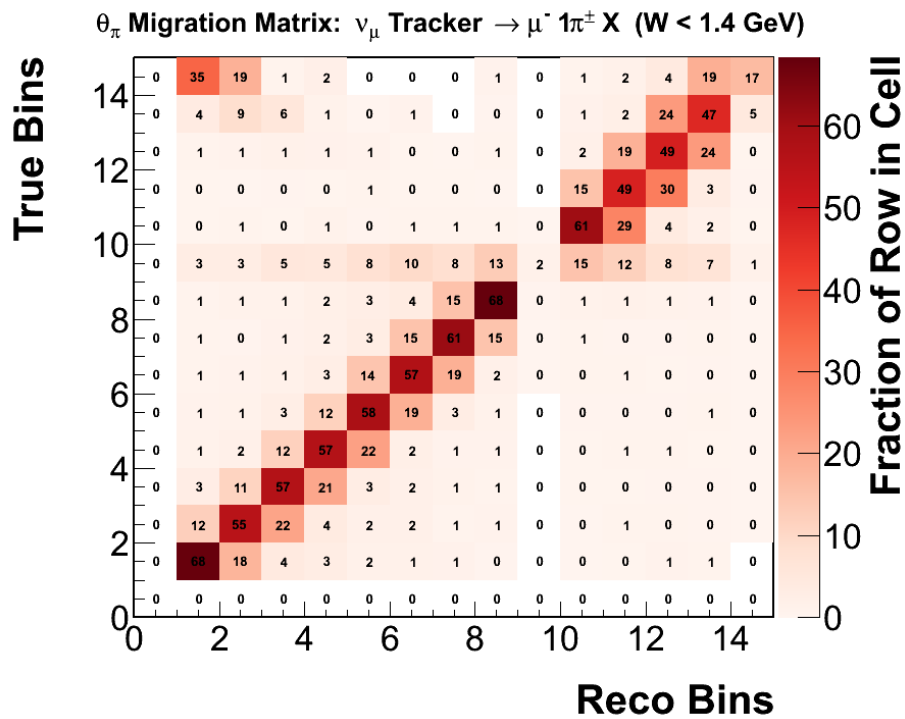
Dominate uncertainty on adjusted background is detector energy response

Unfolding

- Unfolding removes detector resolution effects:
  - transform to “true” variables

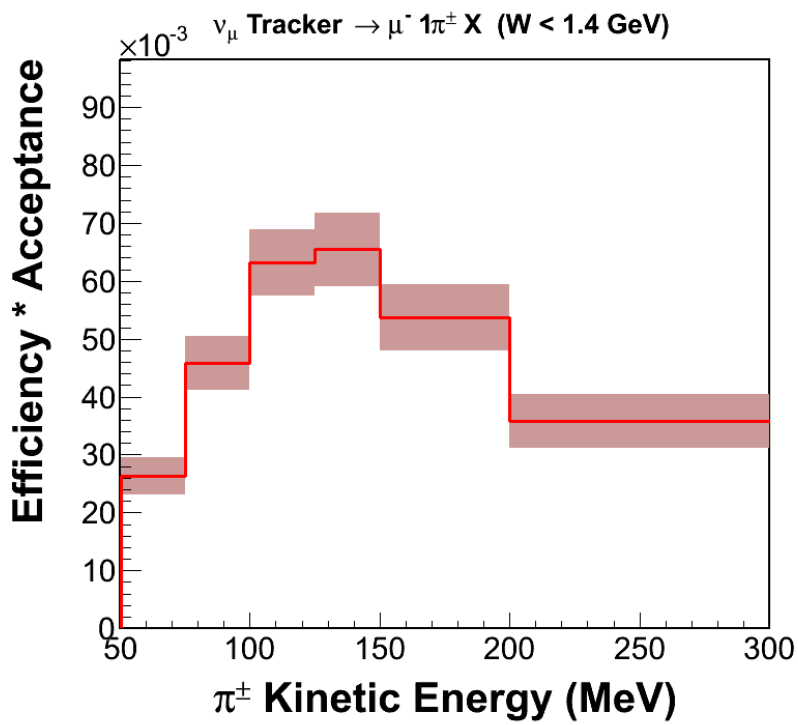
- Use an iterative Bayesian procedure: 4 iterations

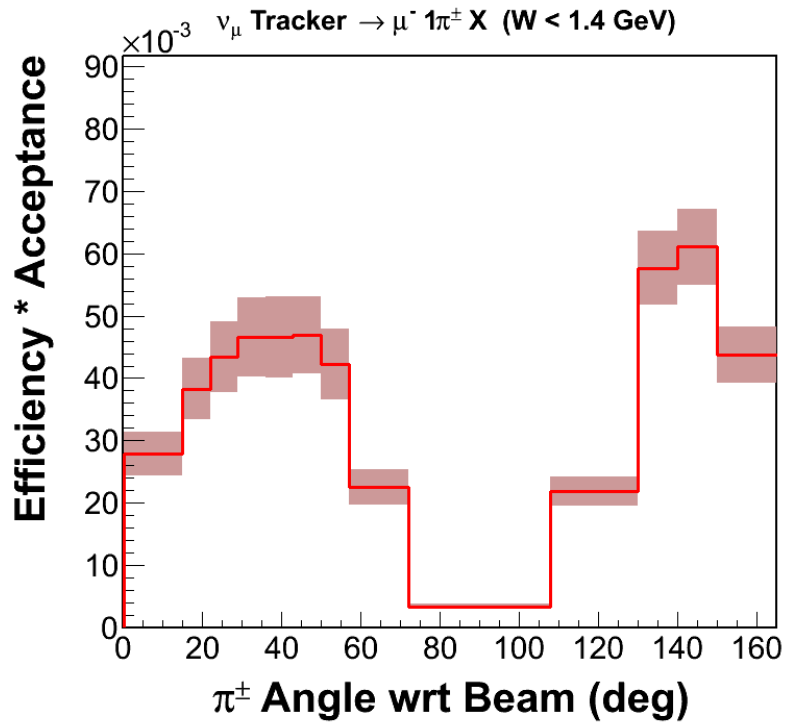




Efficiency Correction

Correct to the full range of muon energies and angles





Systematic Errors – Interaction Model

- Analysis uses GENIE 2.6.2 to simulate neutrino interactions in nuclei

- Cross section model uncertainties enter the analysis through the efficiency correction
  - ~10%, but negligible shape errors

- FSI uncertainties enter through background subtraction (change W_{exp})
  - ~3-4%, and < 2% shape errors

FSI model parameter	uncertainty
pion/nucleon mean path	±20%
pion/nucleon charge exchange	±50%
pion absorbtion	±30%
pion/nucleon inelastic cross-section	±40%
elastic cross sections	±10-30%

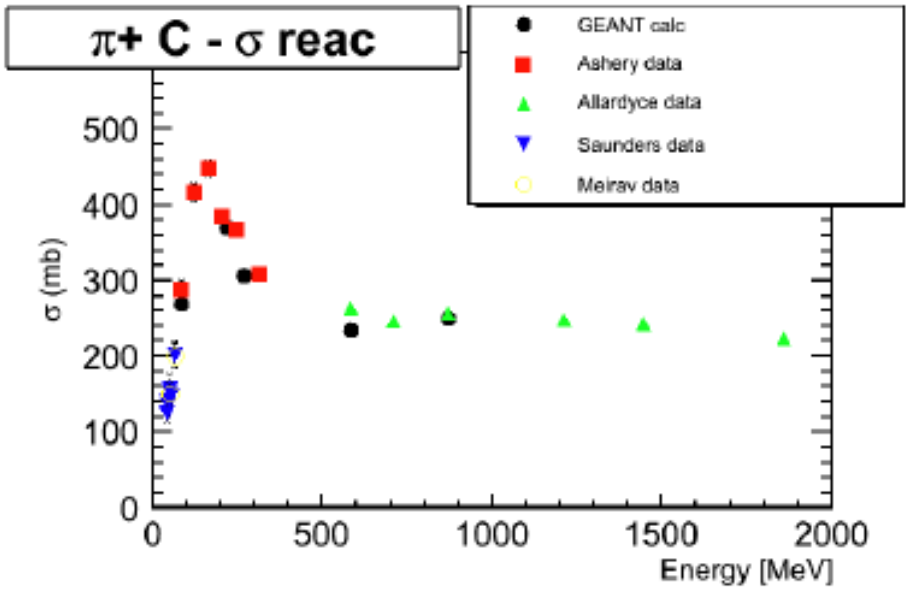
Systematic Errors – Detector Model

•Use Geant4 to simulate particle propagation in the detector

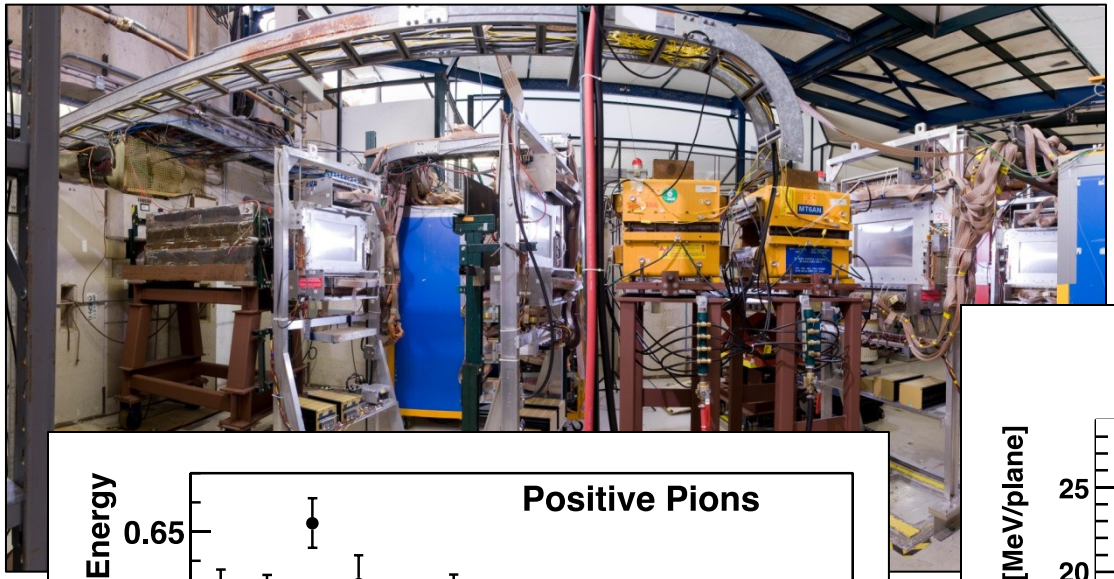
•Uncertainty on **inelastic pion** cross sections affects unfolding and efficiency correction. **Inelastic proton** cross section affects background estimate.

•Compare Geant4 predictions to external data to determine uncertainty on inelastic cross sections ~ 10%

•Leads to up to 7% errors in analysis (greatest at large pion KE)

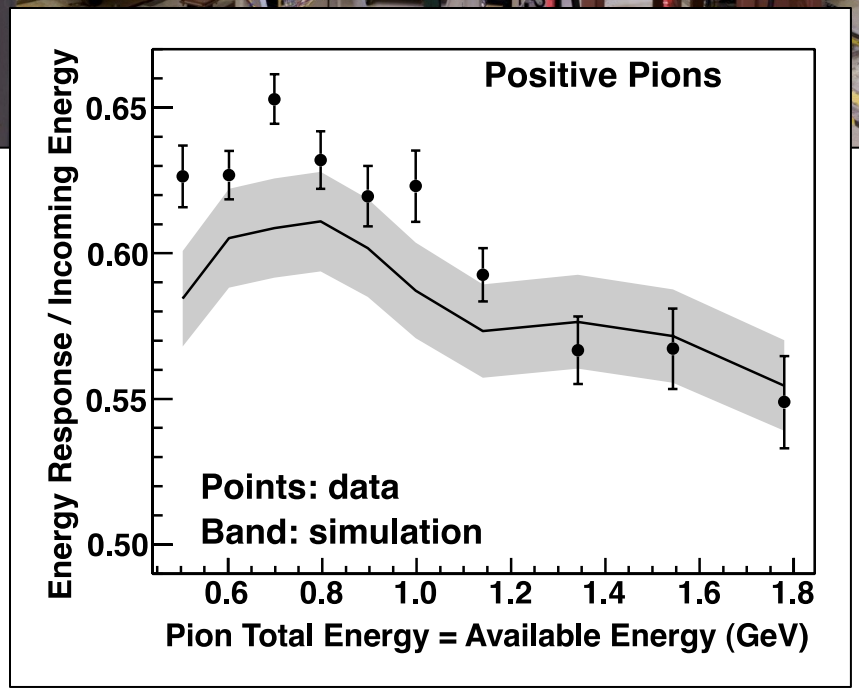


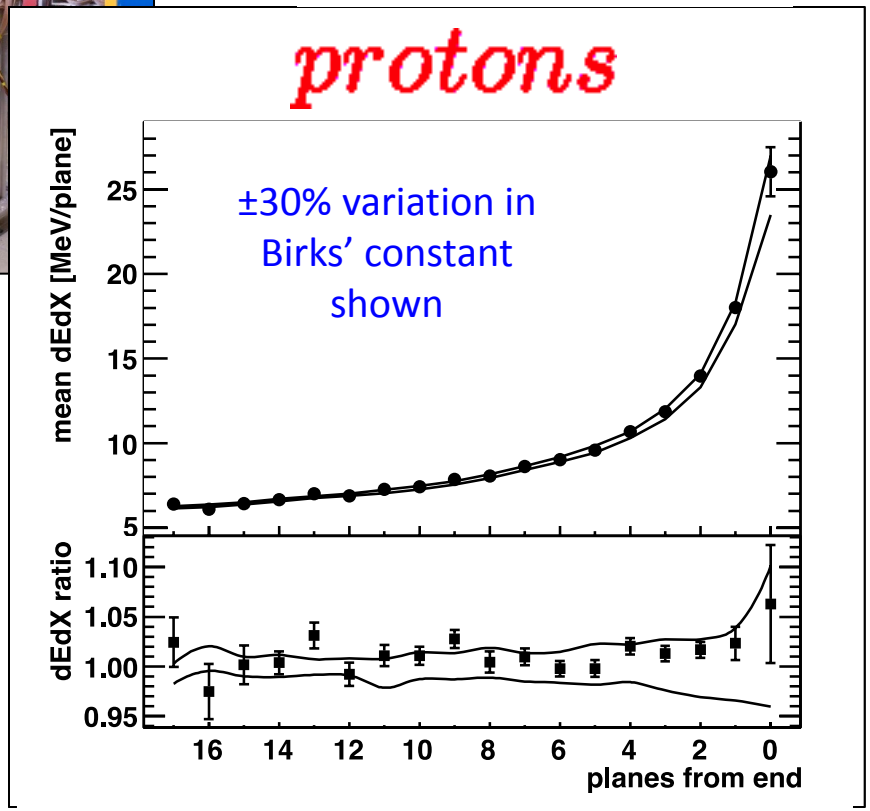
Systematic Errors – Hadron Response



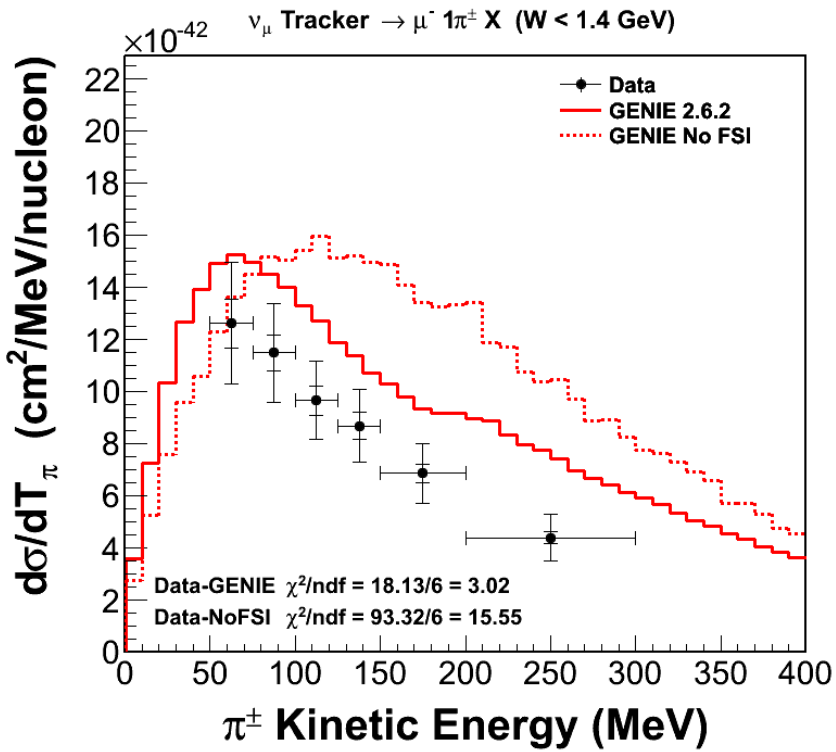
Thanks to AD and MTest!

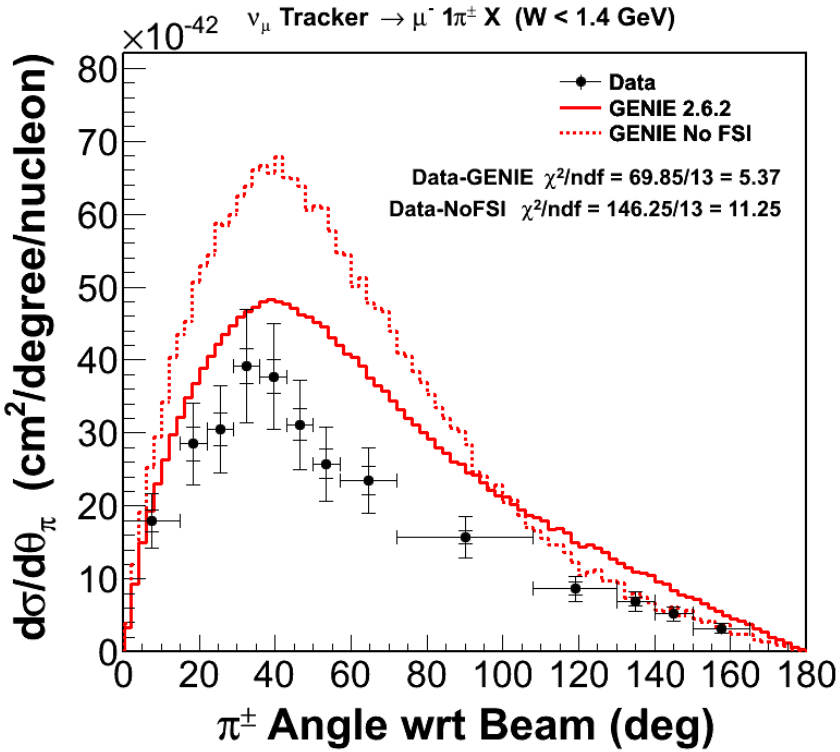
$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{\left(1 + k_B \frac{dE}{dx}\right)}$$





Results

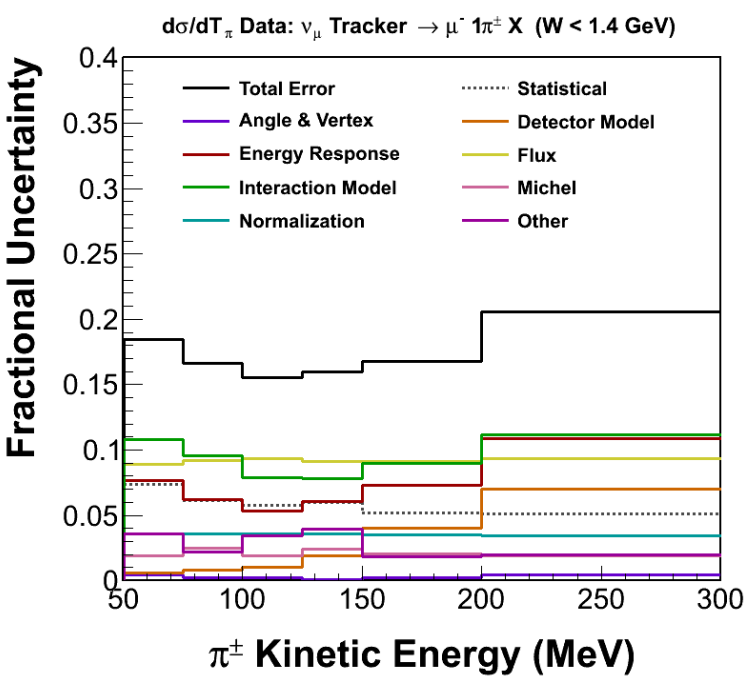




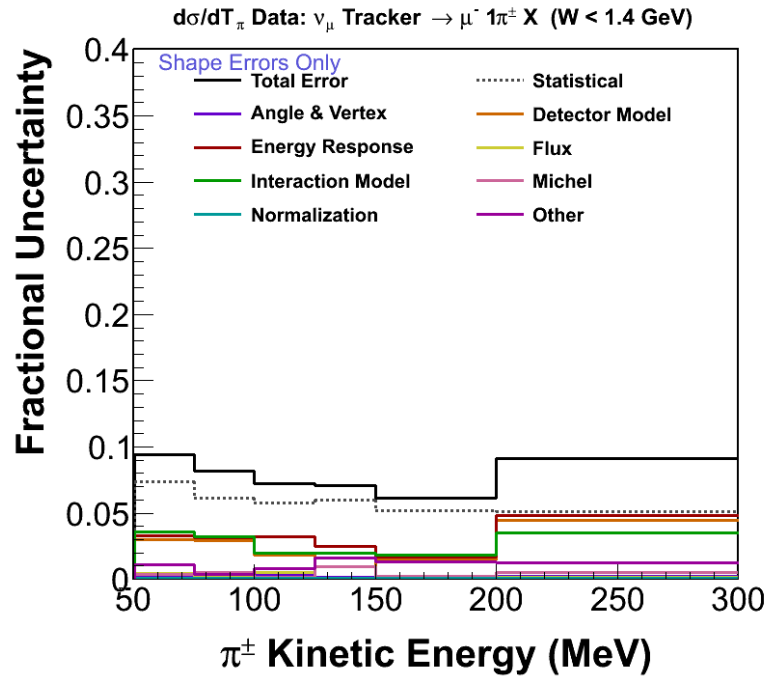
To interpret these results, focus on the shape of the cross sections.

- The data contain large but flat uncertainties on the pion production cross section model and flux

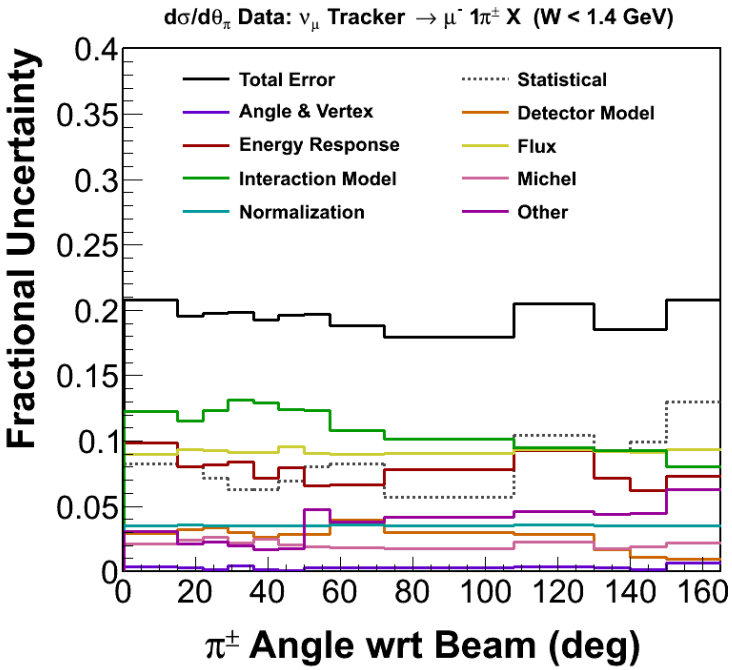
T_π Error Summary



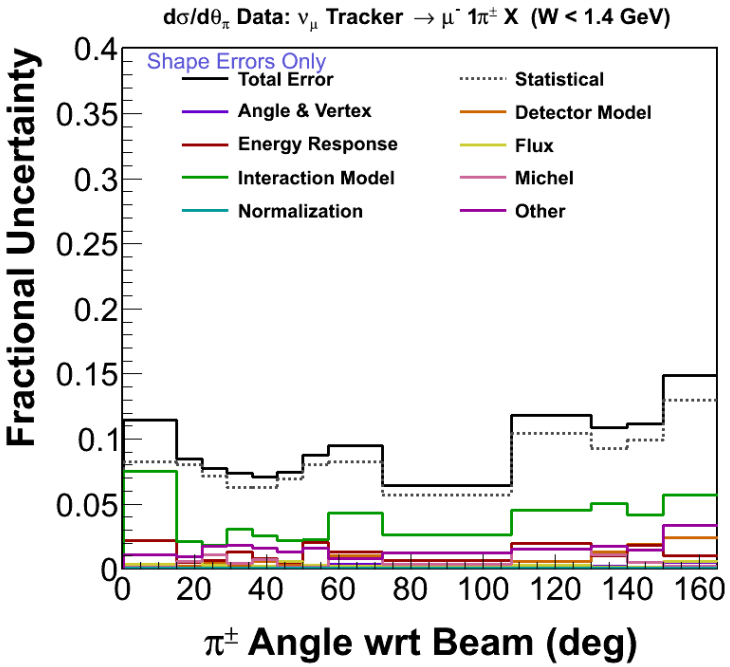
Shape Only



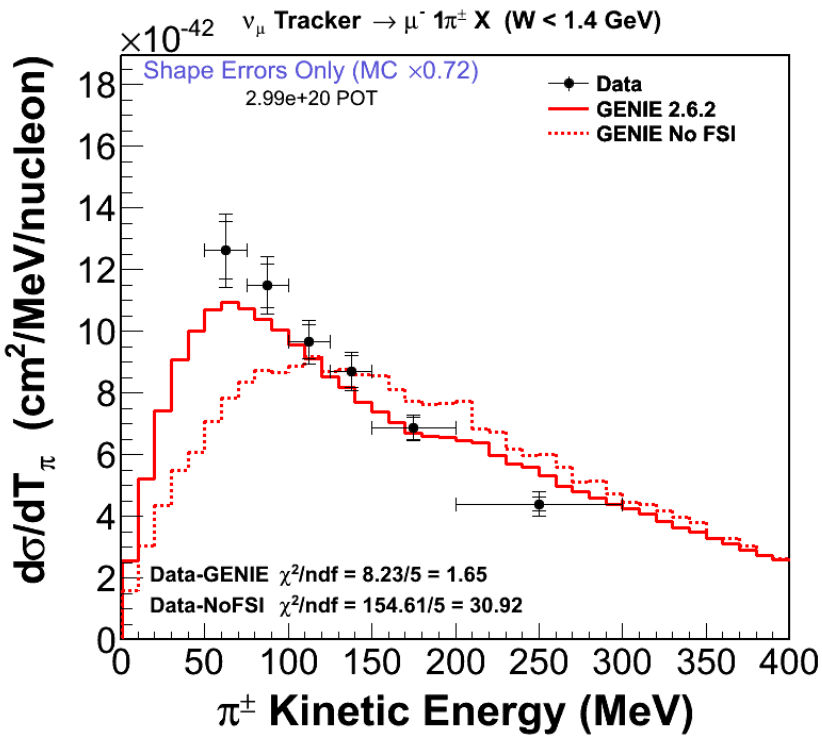
θ_π Error Summary

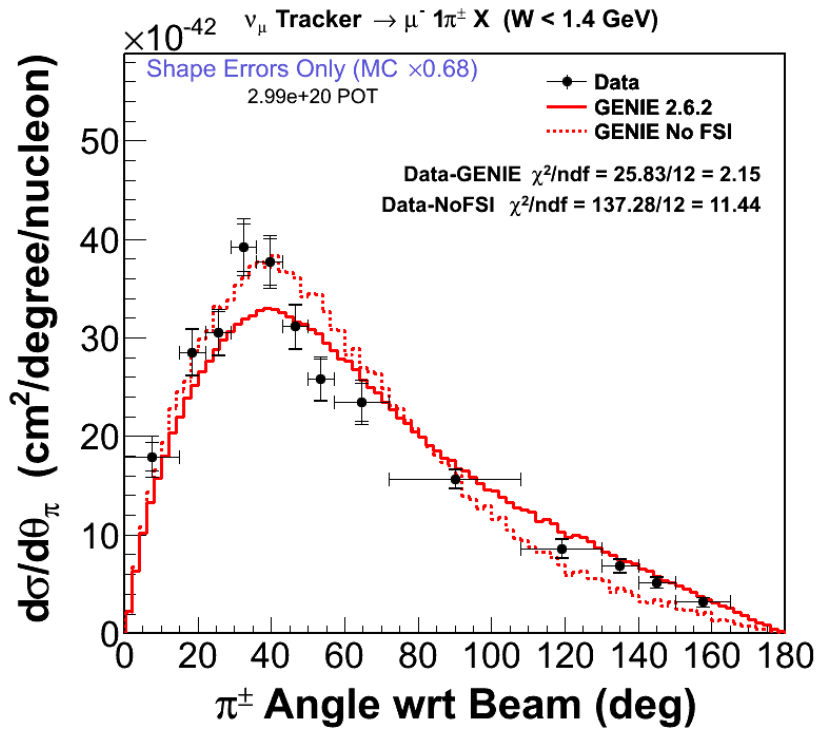


Shape Only



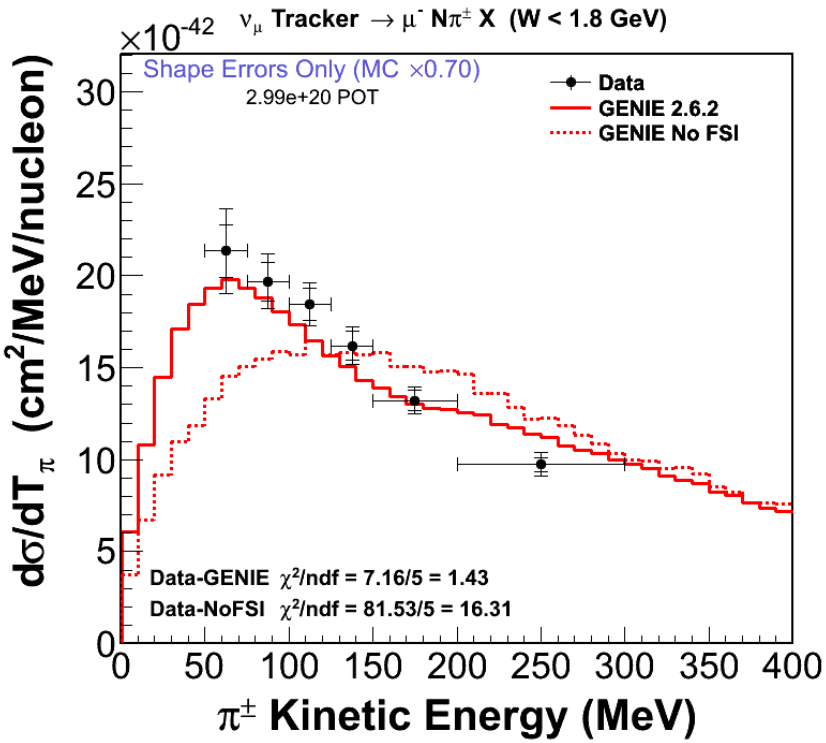
Shape Results

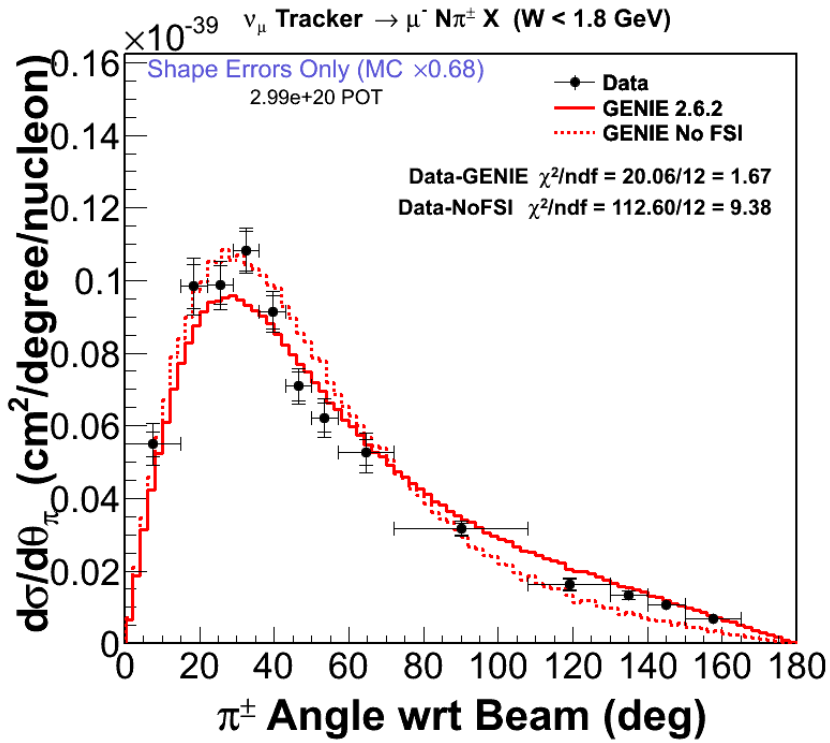




Conclusion: Data prefer GENIE with final state interactions

Shape Results, W < 1.8 GeV

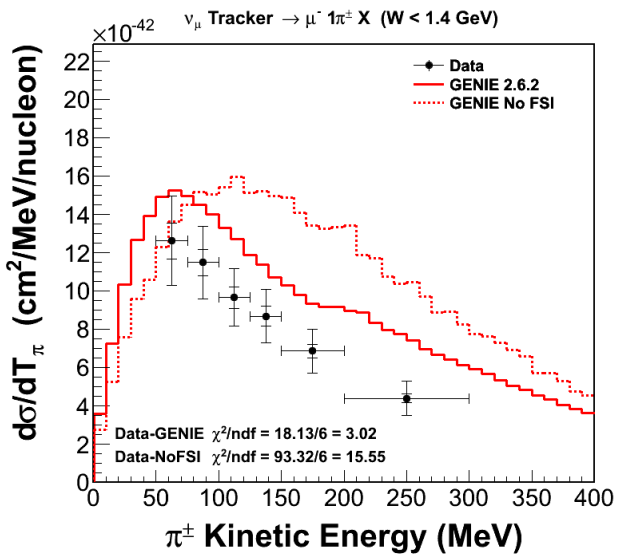


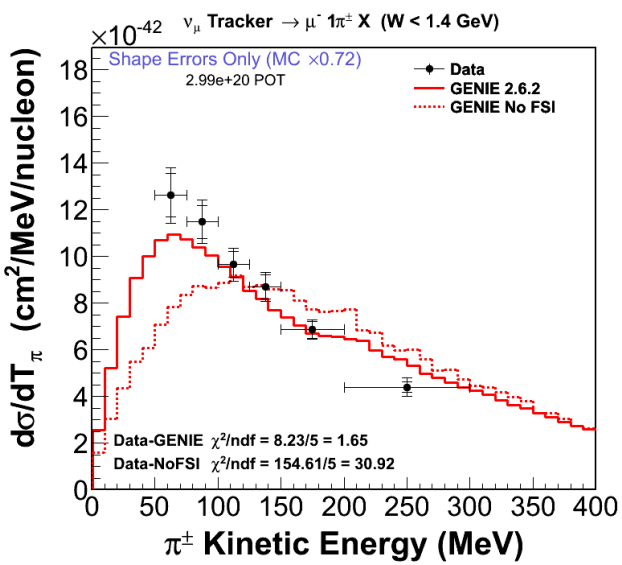


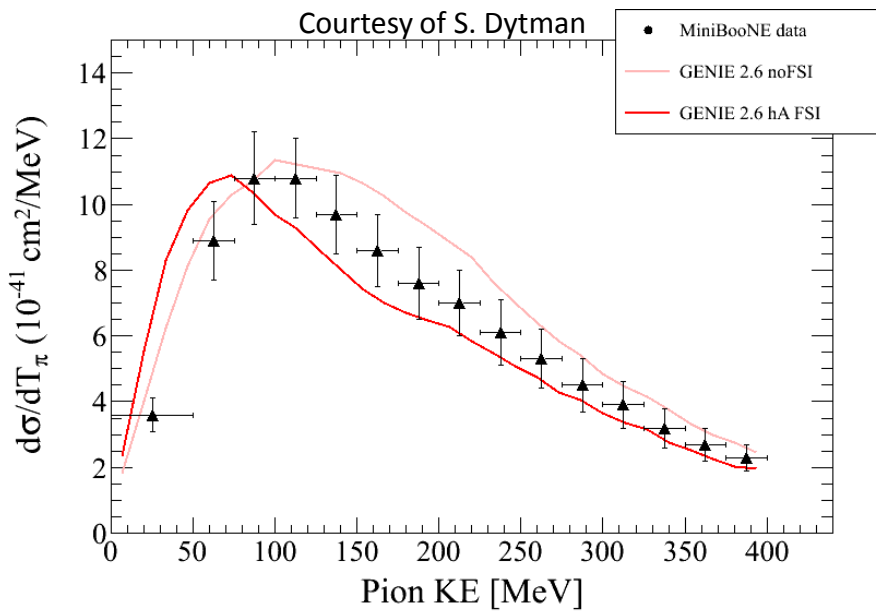
Another version of the analysis, allowing for multiple pions in the final state and higher order resonances: W < 1.8 GeV

An additional ~2000 pion candidates – shape is statistics limited

Results Compared to MiniBooNE



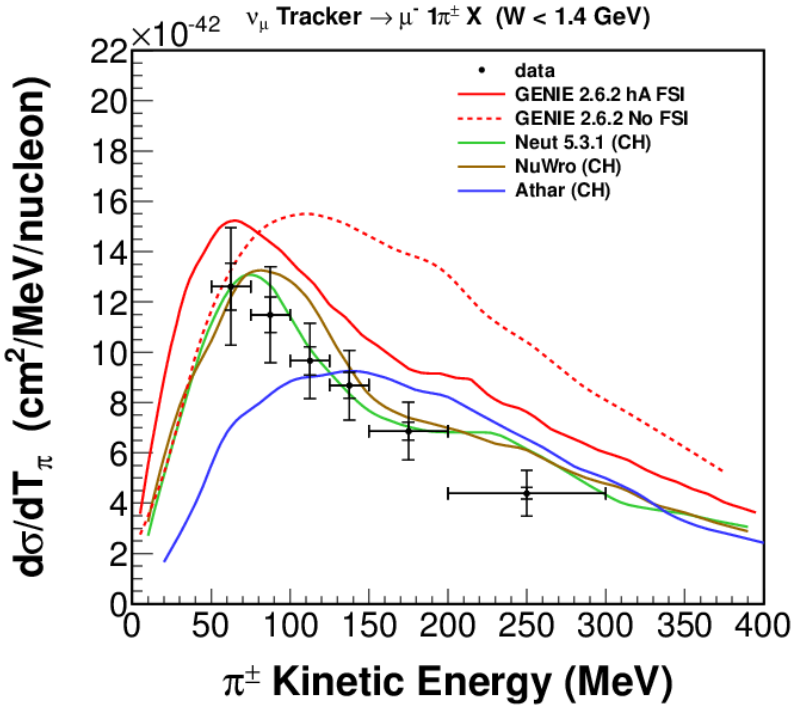


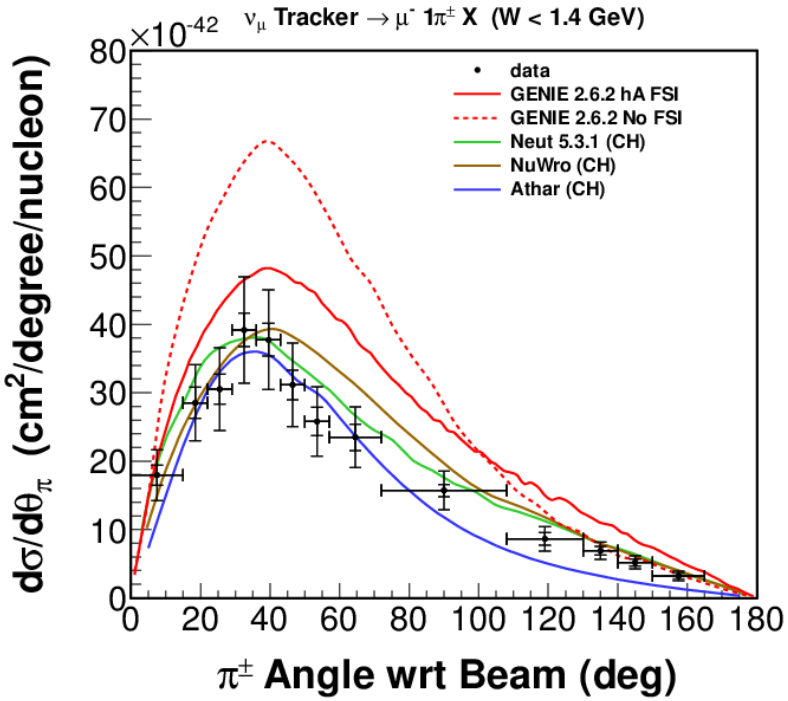


Conclusion: MINERvA data shape is consistent with the weaker absorption dip seen by MiniBooNE

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

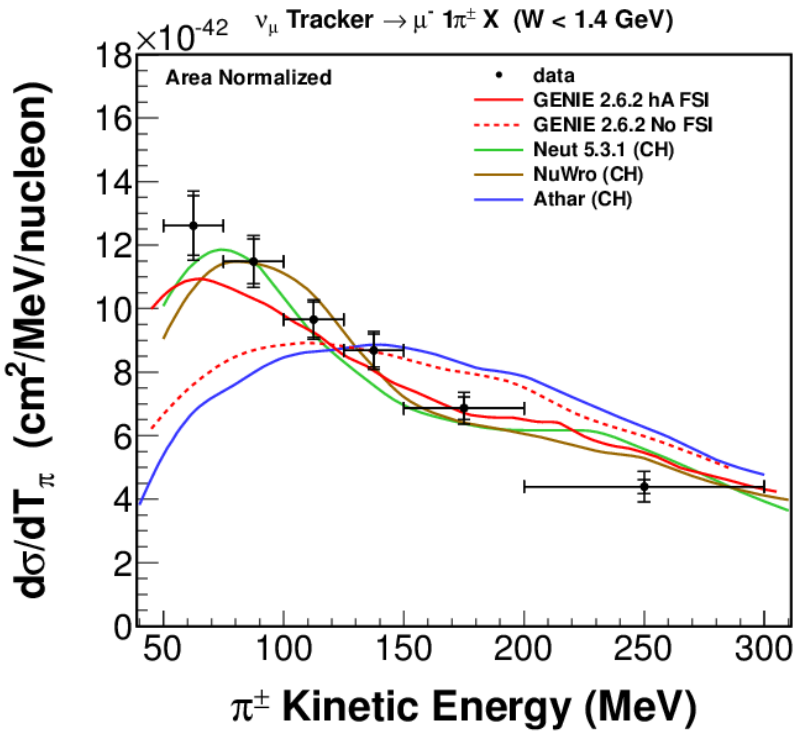
Results – Model Comparisons

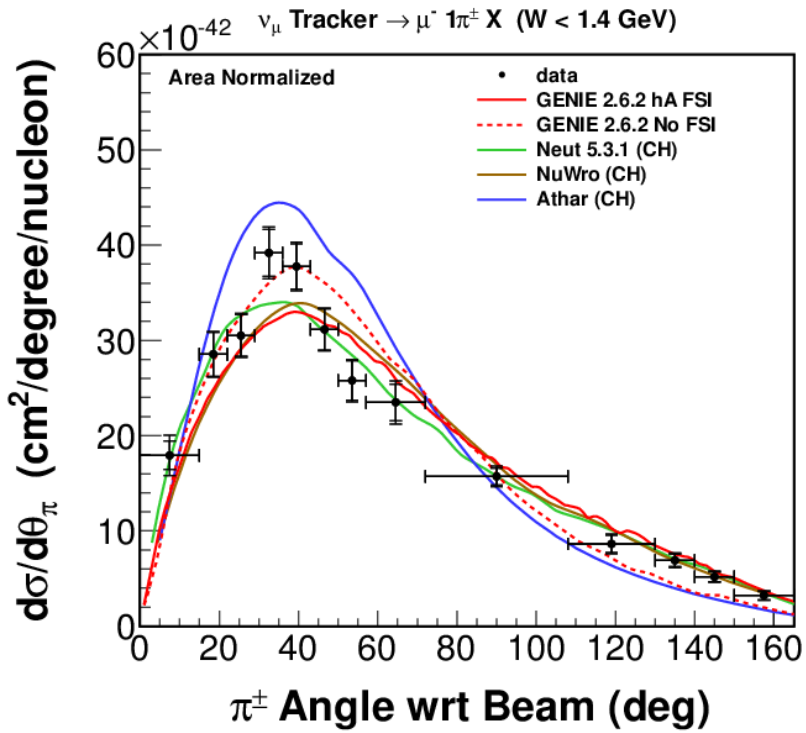




Conclusion: Neut and NuWro normalization agree the best with data. GENIE normalization is disfavored by a couple σ

Shape Results – Model Comparisons





Conclusion: NuWro, Neut, and GENIE all predict the data shape well

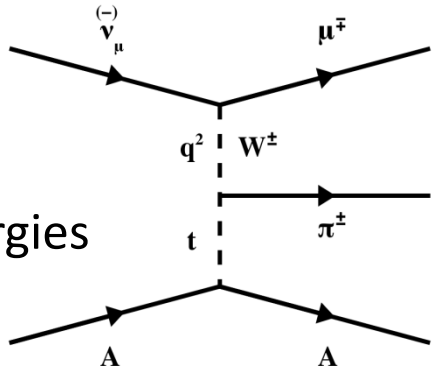
Conclusion: Data insensitive to the differences in pion absorption shape between GENIE, NuWro, and Neut

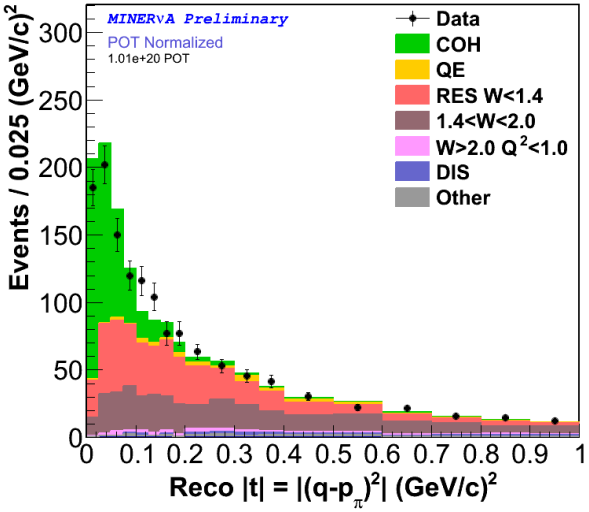
Conclusion: Athar, the sole theoretical calculation, does not agree with data. Likely due to an insufficient FSI model

Future Prospects and Conclusions

Future Pion Measurements in MINERvA

- Charged current coherent pion production
  - Has not been conclusively observed at ~few GeV energies

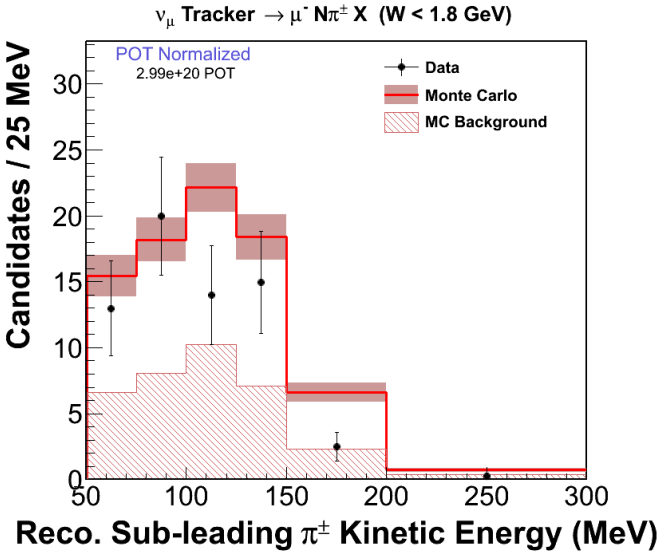




- Full suite of resonant pion 1D and 2D differential cross sections
  - Also for antineutrino and π^0

- Pion production (resonant and coherent) in the nuclear targets
  - A-dependence of cross sections, FSI

- Multi-pion events
  - Small sample, requires more statistics (ME beam) and/or better reconstruction (low energy pion reconstruction with Michels?)



Conclusions and Outlook

- **First neutrino pion production measurement from MINERvA:**
  - Measured delta resonance dominated differential cross sections with respect to pion energy and angle

- MINERvA data prefer the GENIE model with FSI
  - MiniBooNE data does not strongly prefer GENIE with or without FSI

- MINERvA data is also consistent in shape with NuWro and Neut event generators with FSI

- MINERvA and MiniBooNE data are inconsistent in normalization, relative to GENIE, Neut, and NuWro

- Promising extensions of analysis: nuclear targets and additional cross sections. We are also working on coherent pion production and π^0

Final Thought

- I showed you brand new results, and it is clear that more work is needed to fully understand them

- MINERvA includes GENIE, Neut, and NuWro developers

As such, we are both well-poised and eager to play a leading role in working towards understanding these results within the context of the MiniBooNE data, theoretical calculations, and event generator predictions.

Thank you!

Back Ups

Neutrino Oscillations

- Neutrino oscillations: Process by which neutrinos created in one flavor (e, μ, τ) are later measured to be another flavor

- Arise because neutrinos have mass:

$$\left|\begin{matrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{matrix}\right\rangle = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \left|\begin{matrix}\nu_1 \\ \nu_2 \\ \nu_3\end{matrix}\right\rangle$$

U is unitary: 6 independent parameters:
θ_{12} θ_{23} θ_{13} δ_{cp} α_1 α_2

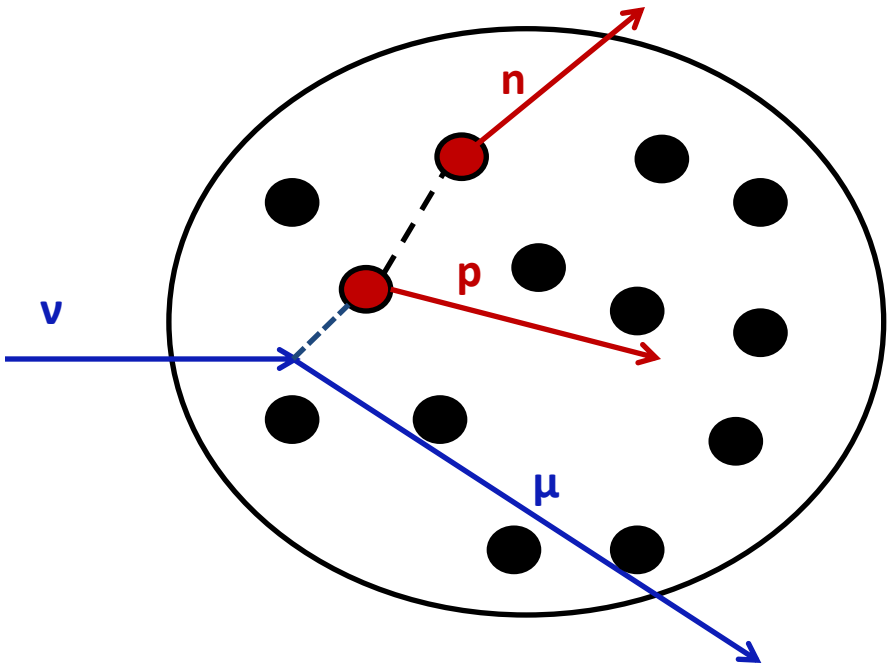
- Conclusive experimental discovery in 1998 provided a rich source of physics beyond the Standard Model

The Challenge of Neutrino Oscillations

- With neutrino mass comes many questions:
  - What are the three mixing angles?
    - Is θ_{23} maximal?
  - What are the values of the neutrino masses (m_1, m_2, m_3)?
    - We only know the mass-squared differences, and the ordering of one pair
  - What is the size of leptonic CP violation?
  - How do we put neutrinos into the standard model?
    - Are they Majorana or Dirac particles?
    - Why are neutrinos so much less massive than other particles?

Modification of Initial Interaction

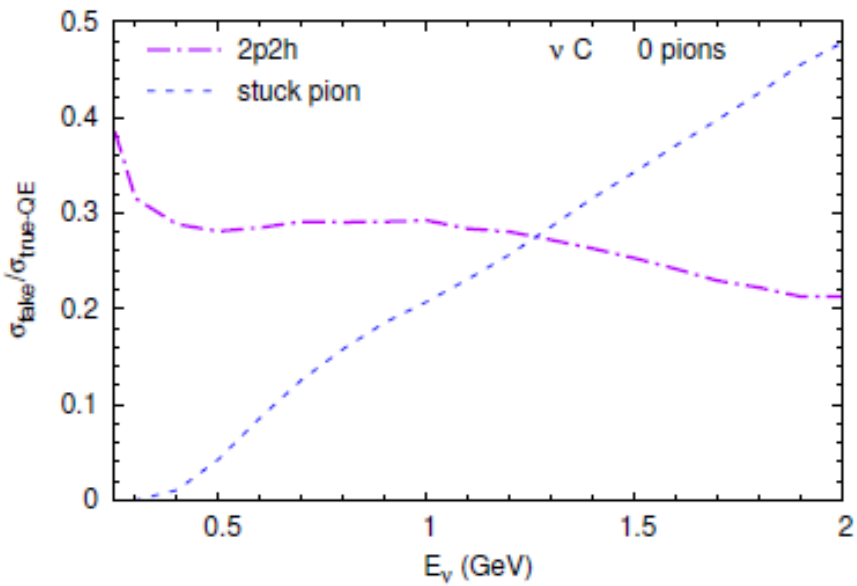
- Nuclear medium modifies the initial neutrino interaction
  - Binding energy: lower effective nucleon mass
  - Fermi motion: nucleons are not at rest
  - Q^2 dependence: interact with one nucleon or multiple nucleons?
  - Meson exchange currents: eject a correlated pair of nucleons



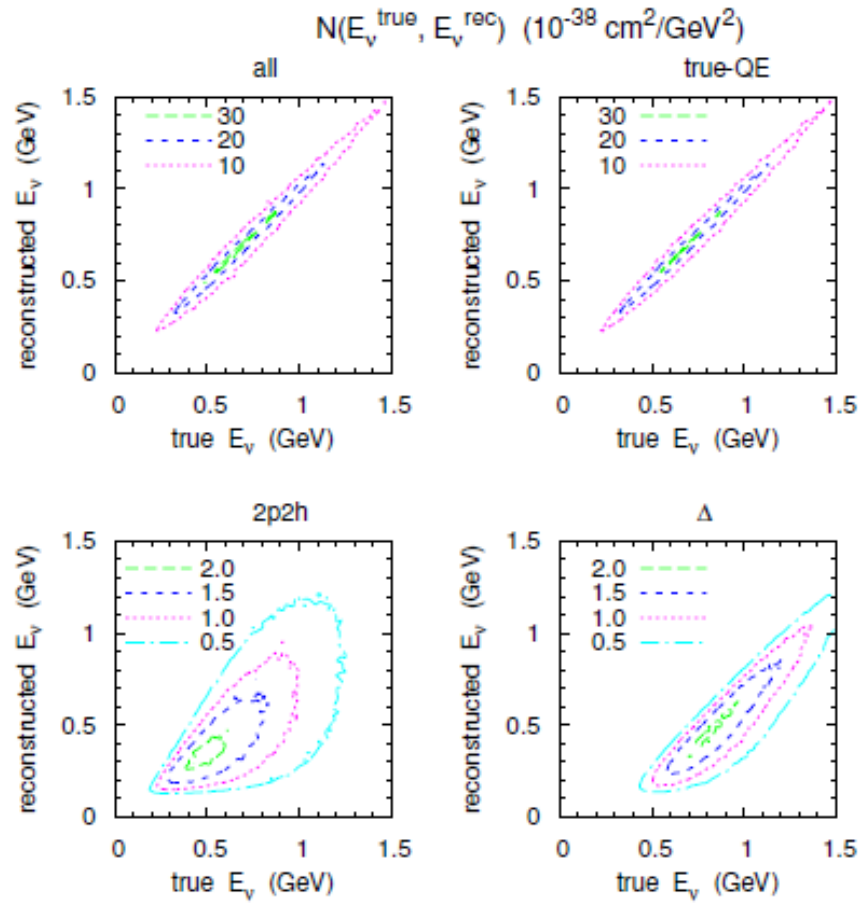
Oscillations and Energy Resolution

- Contribution of absorbed pion events to QE-like sample is significant at larger energies

- Pion absorption results in a systematically low reconstructed E_ν



Simulated MiniBooNE QE-like events

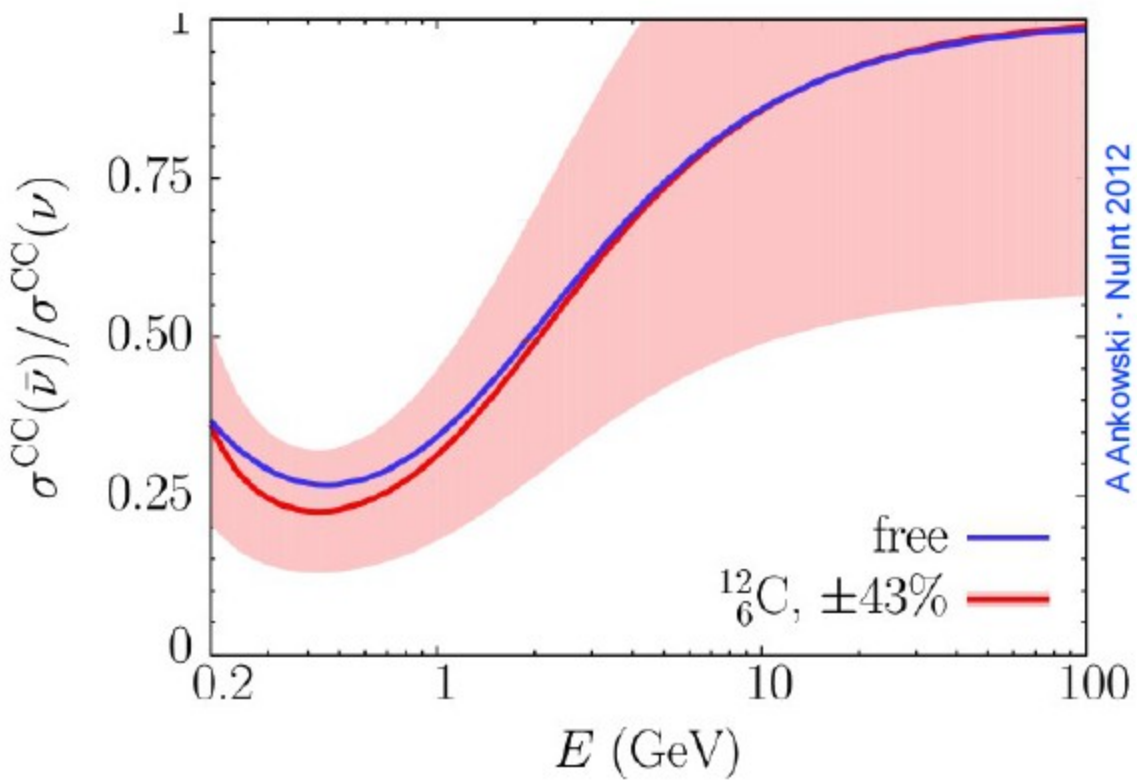


Lalakulich *et al*: arxiv 1208.3678v2

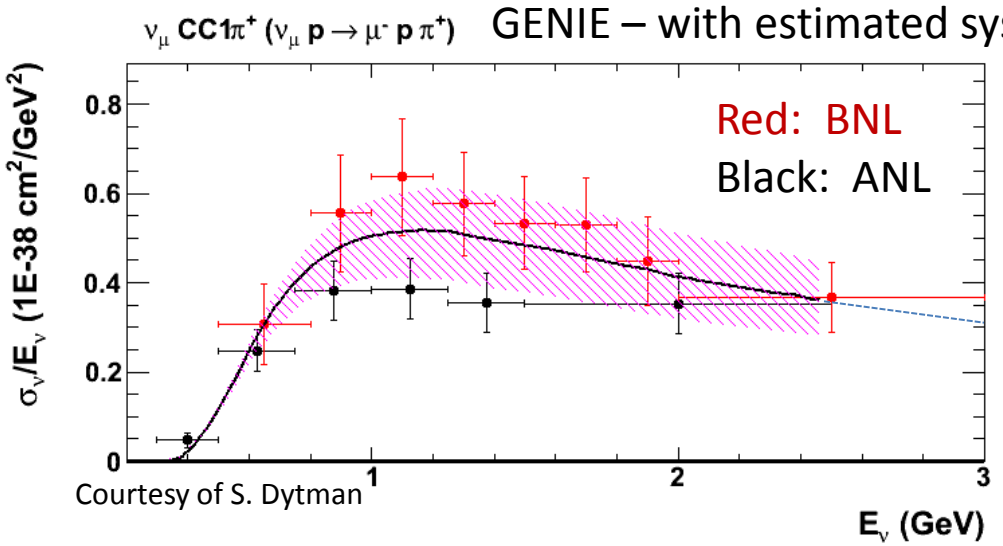
CP Violation

- CP violation measurement requires that we understand the difference between neutrinos and antineutrinos
  - Ratio understood to within ~40%

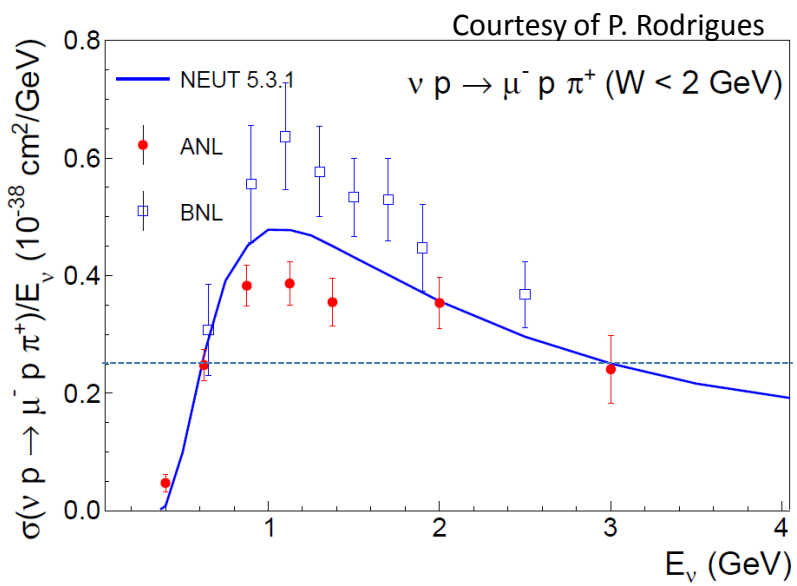
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$$



Pion Models & Deuterium Data



BNL: Kitagaki *et al*, Phys. Rev. D34 2554 (1986)
ANL: Radecky *et al*, Phys. Rev. D25 1161 (1982)

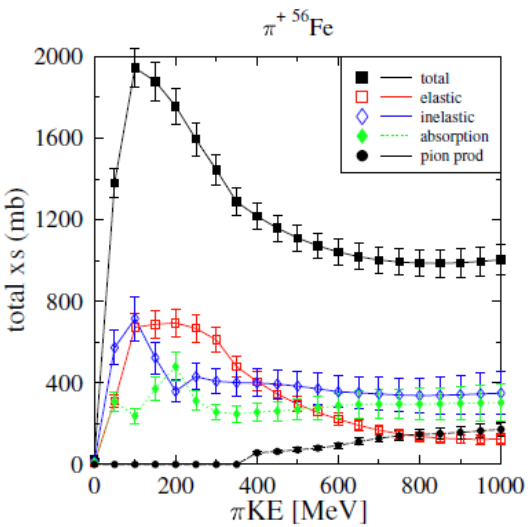


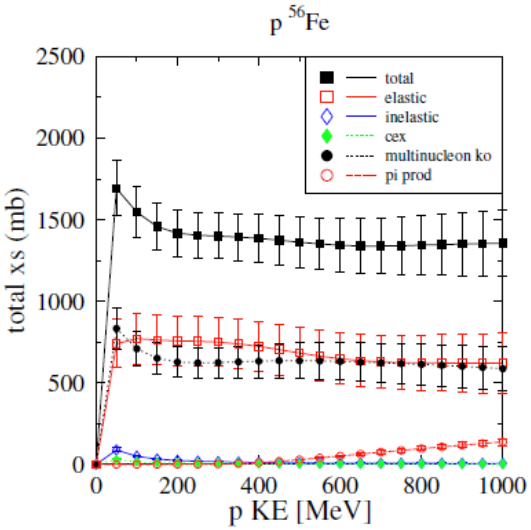
- GENIE and Neut are fairly consistent at lower energies, but appear to diverge by ~15% at MINERvA energies (~3 GeV)

Final State Interaction Models

- Neutrino oscillation experiments use neutrino event generators (Monte Carlo) to understand neutrino-nucleus interactions
  - Many current and future experiments use GENIE

- GENIE has two FSI models:
  - hA – use Fe reaction cross section data, isospin symmetry, and $A^{2/3}$ scaling to predict FSI reaction rates
  - Generate individual particle energy and angular distributions using data templates or sample from allowed phase space





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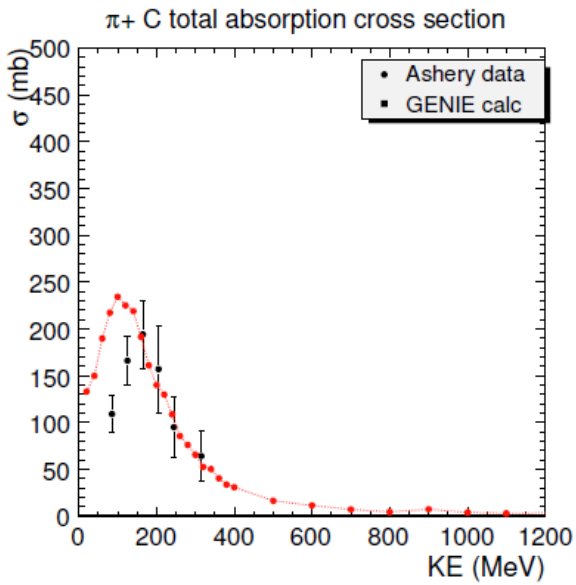
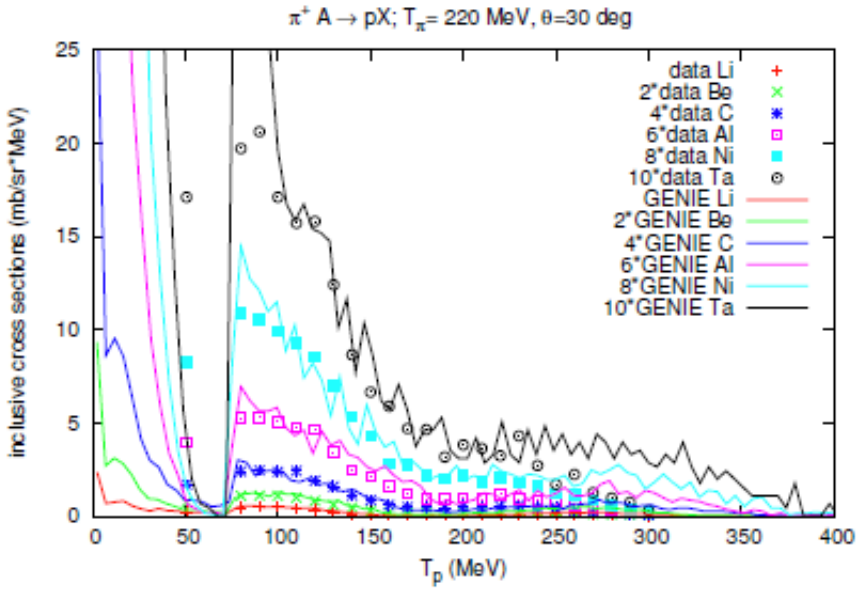
- Neutrino oscillation experiments use neutrino event generators (Monte Carlo) to understand neutrino-nucleus interactions
  - Many current and future experiments use GENIE

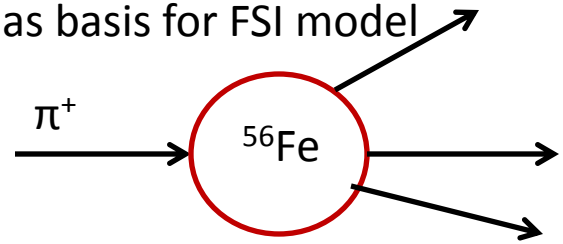
- GENIE has two FSI models:
  - hN – step final state particles through the nucleus and simulate full particle cascade using angular distributions as a function of energy



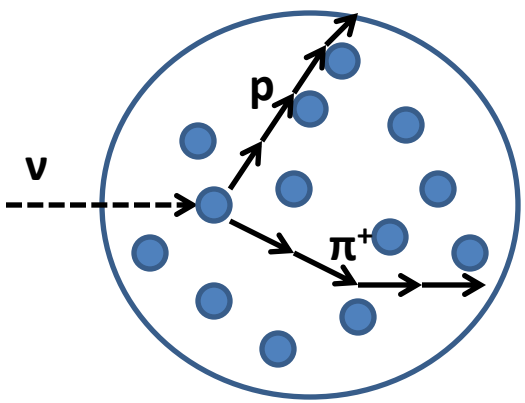


Pion Models & FSI

GENIE: Use p,π scattering on Fe data as basis for FSI model

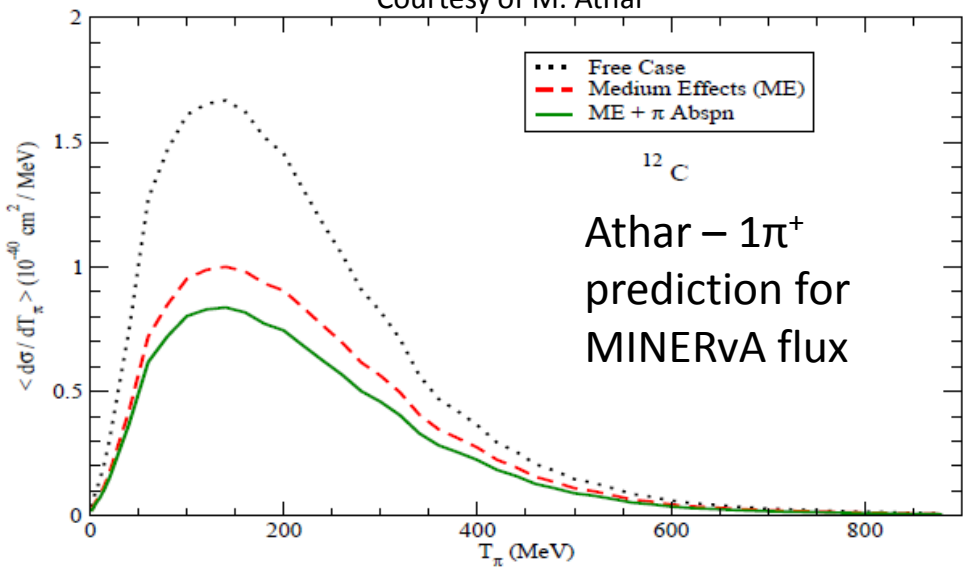


NuWro, Neut: Step interaction products through nucleus and use nucleon cross sections



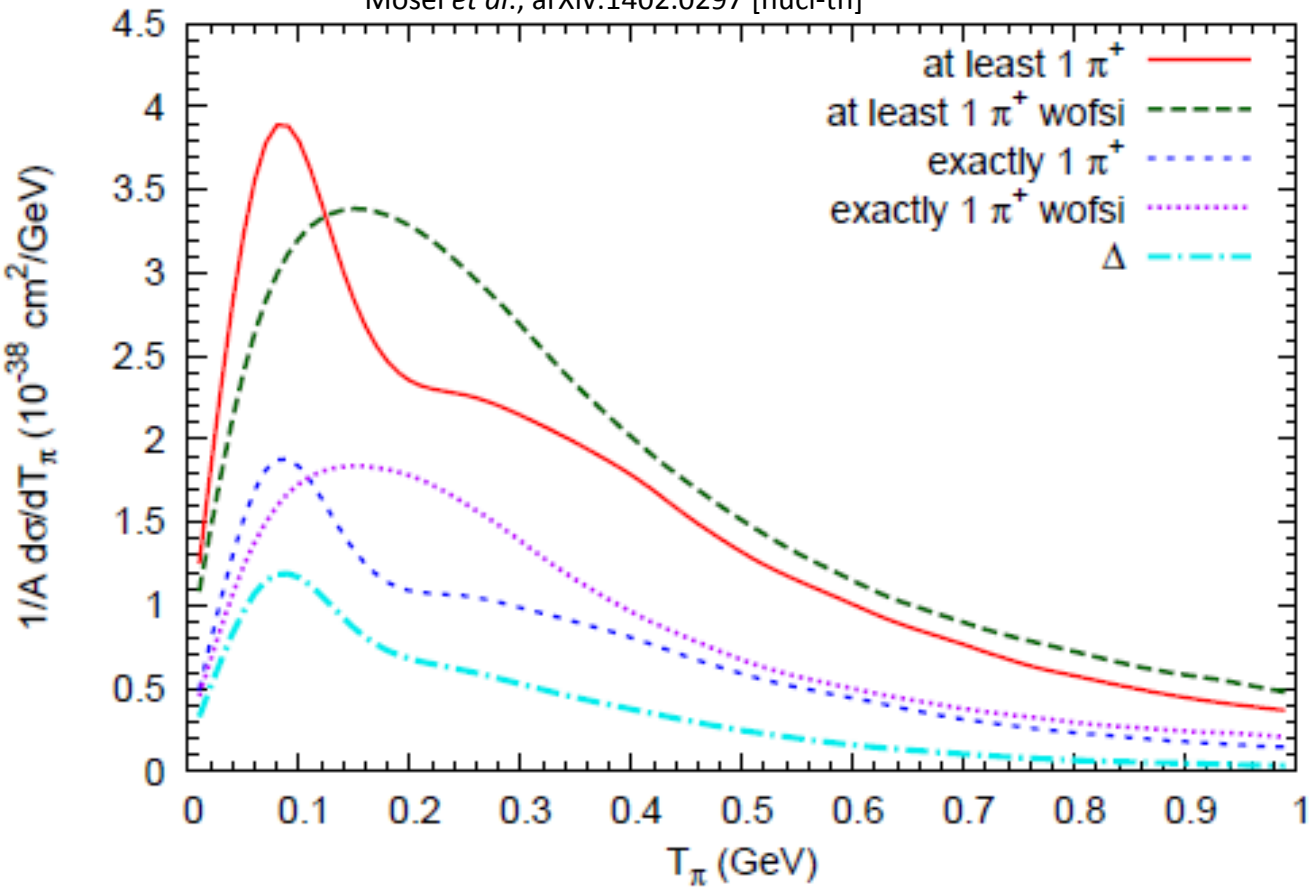
Athar: Use an Eiknonal approximation. Reduces observed pions, but does not significantly change T_π shape

Courtesy of M. Athar



GiBUU MINERvA Prediction

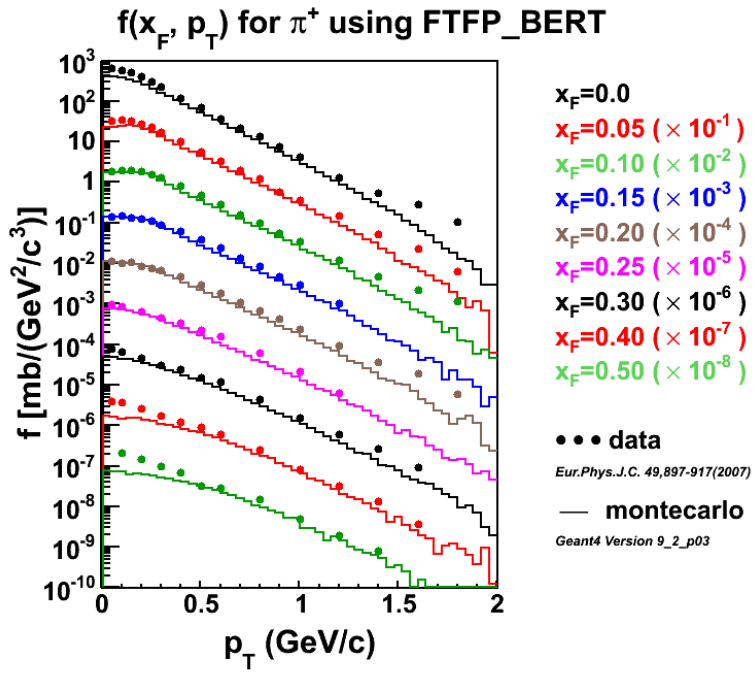
Mosel *et al.*, arXiv:1402.0297 [nucl-th]

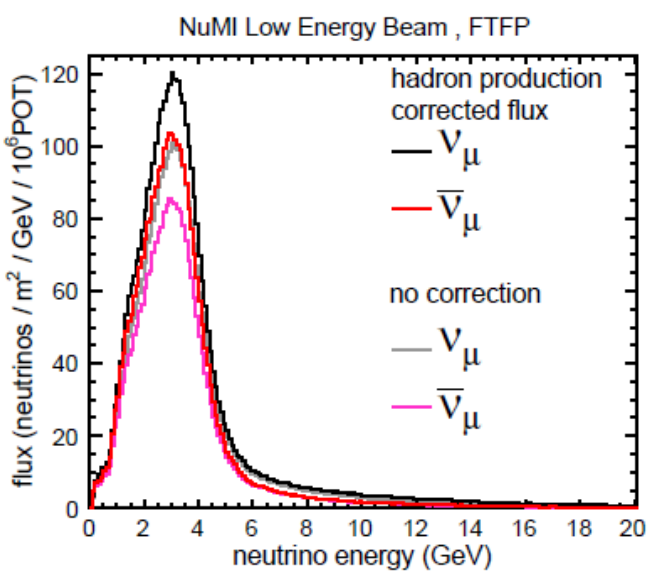


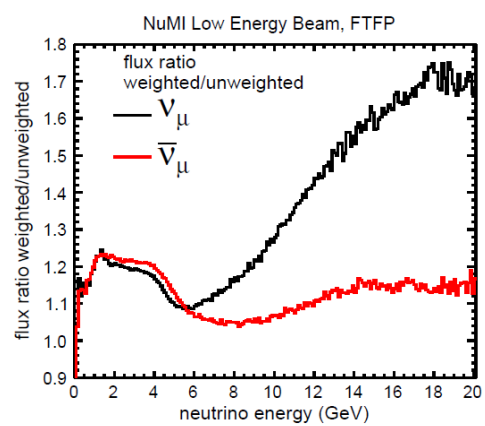
Does not contain a W cut. **1π, W < 1.4 GeV** lives between cyan and blue curves

NuMI Flux Measurement

- Flux measurements are hard!
- MINERvA flux is simulated by GEANT4 and reweighted to match hadron production data from NA49.





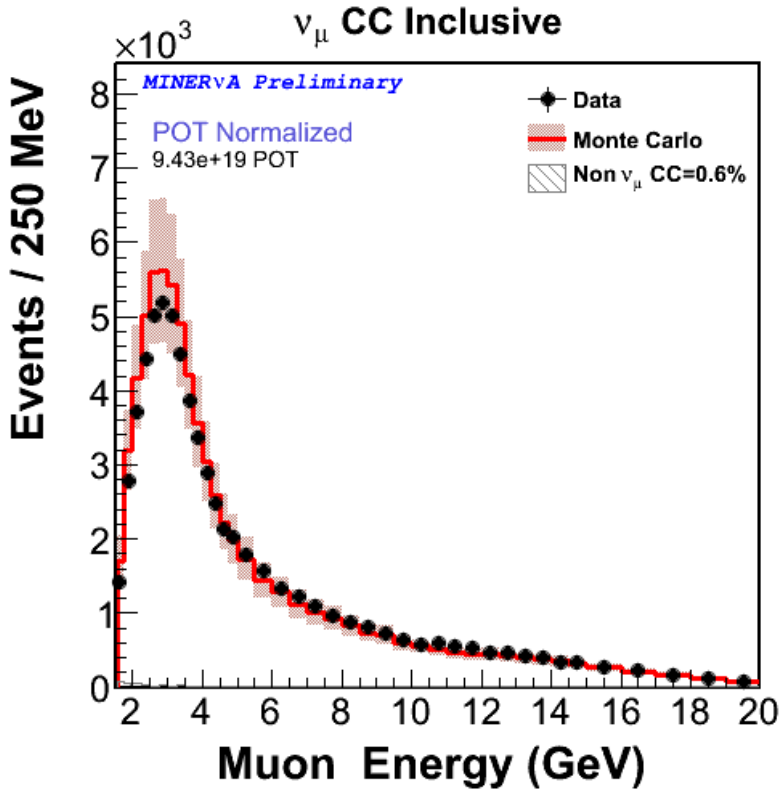


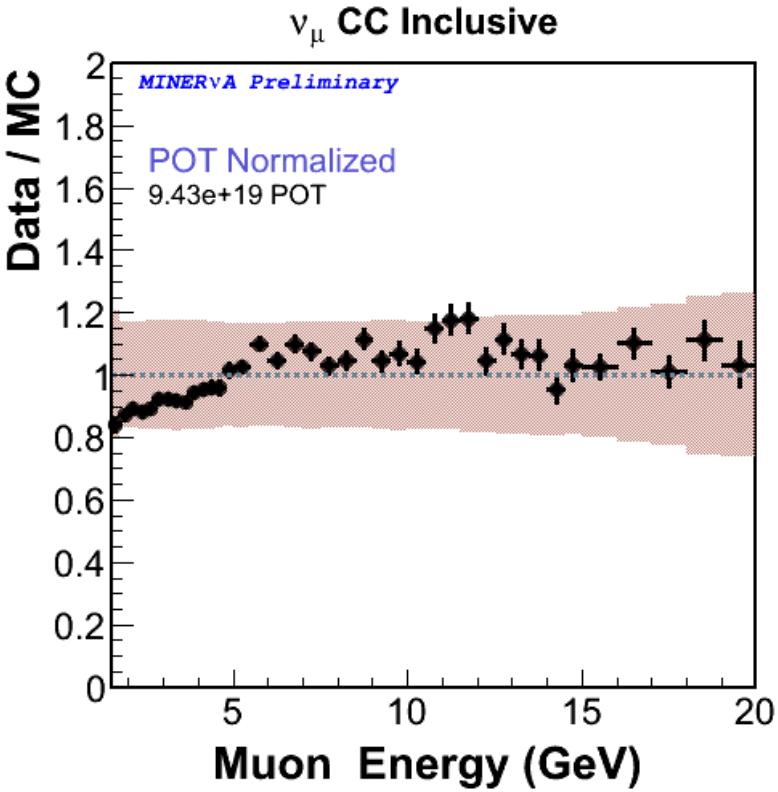
Future of NuMI Flux Measurement

- Future flux measurements will be improved by multi-pronged attack:
  - Data with different horn current and target position configurations
  - New NA61 hadron production data
  - Possible an in situ measurement with muon monitors

Meanwhile, MINERvA is focusing on measurements that are insensitive to flux!

CC Inclusive Muon Energy

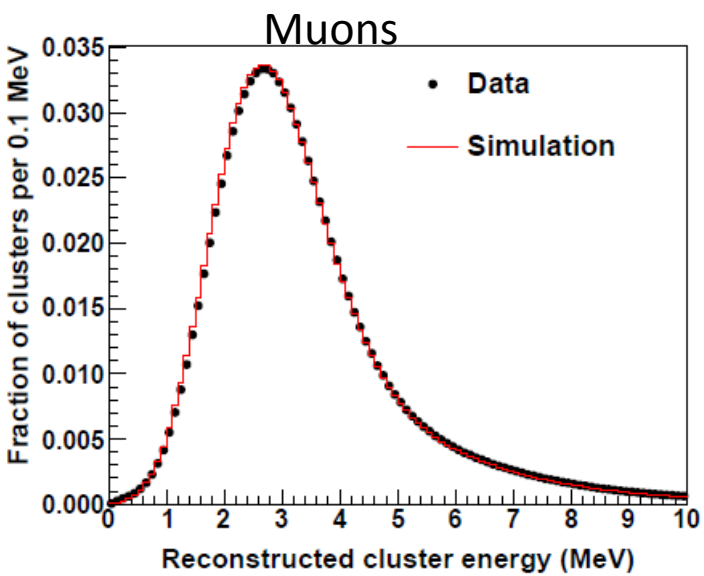




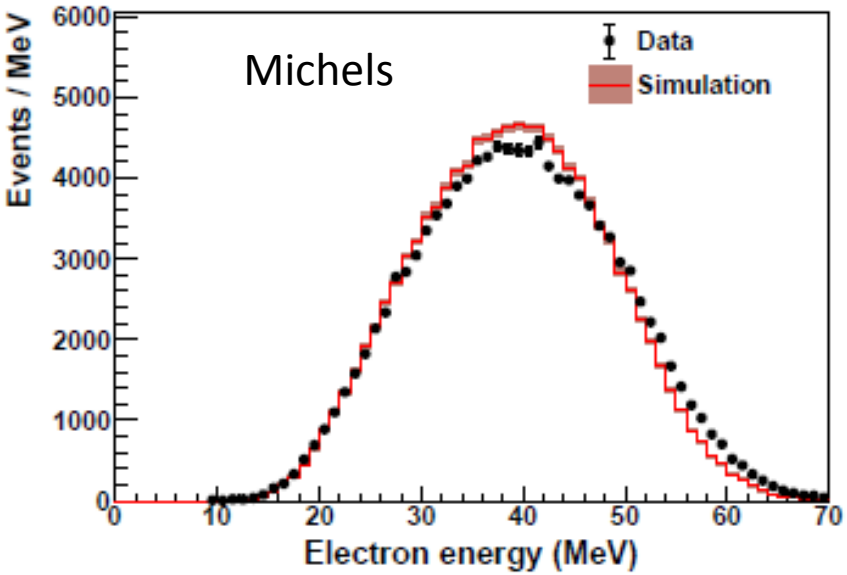
~10% normalization discrepancy between data and simulation in the peak region – dominated by GENIE uncertainties

Detector Calibration

- Muon calibration sample used to set absolute energy scale
  - 2% systematic error
  - Cross check with Michel electrons – agree within 3%

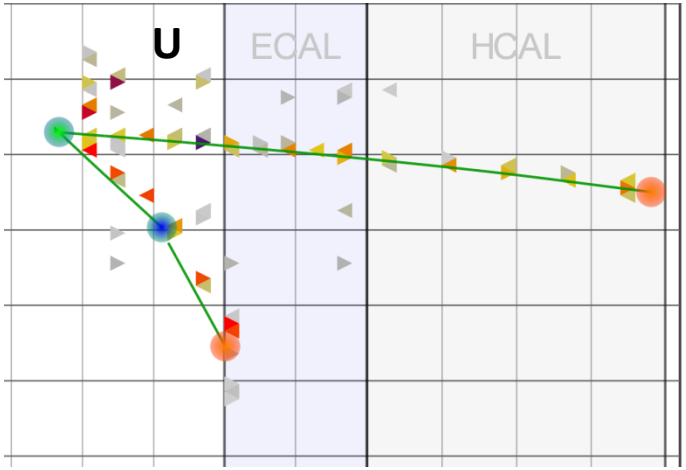


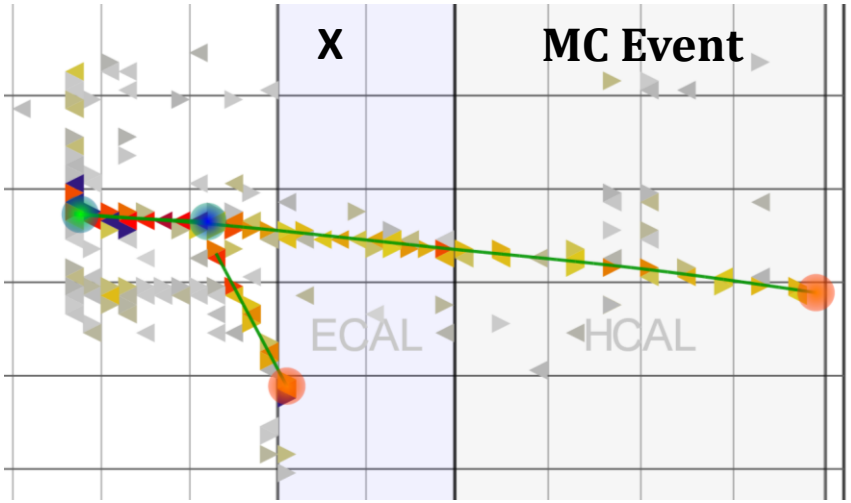
Michel electron: $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

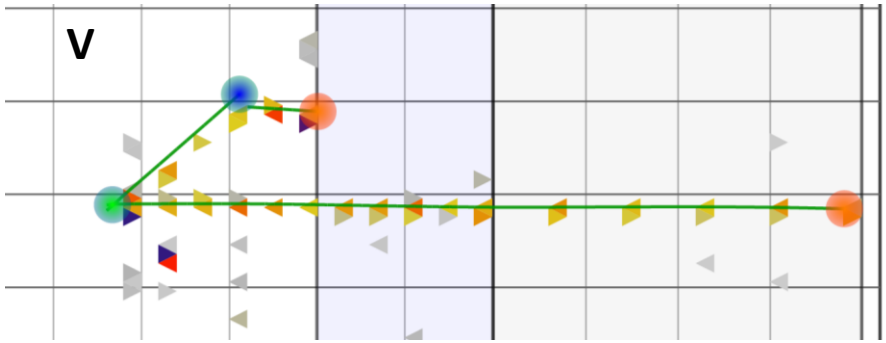


More Complicated Tracking Example

- Find "kinked" tracks by looking at the end of each track
- Overlap is handled correctly in the X view
- The pion appears "straight" in the U view and track is divided correctly

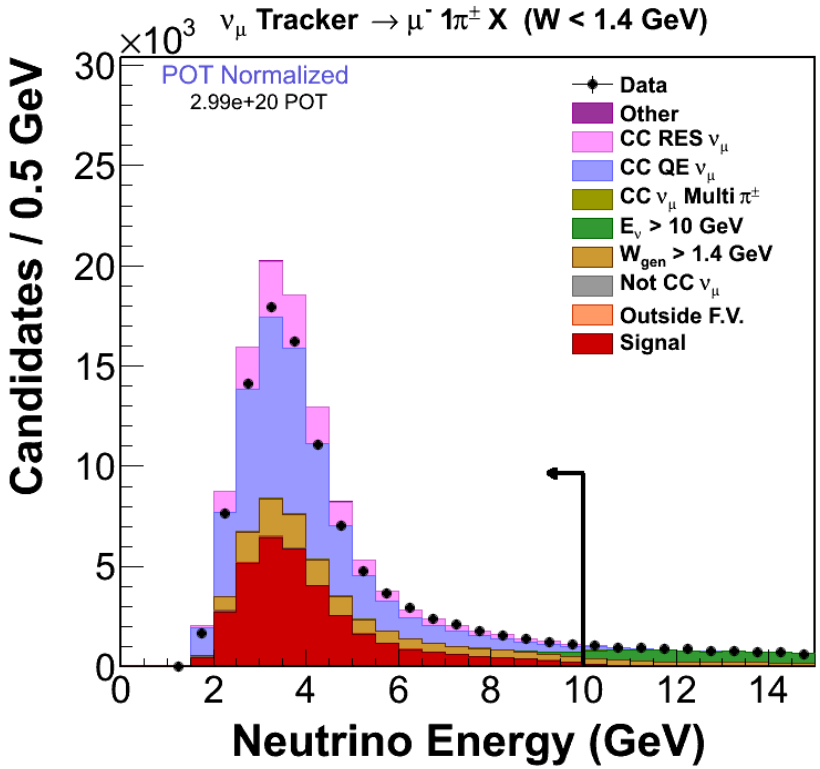






Event Selection – E_ν

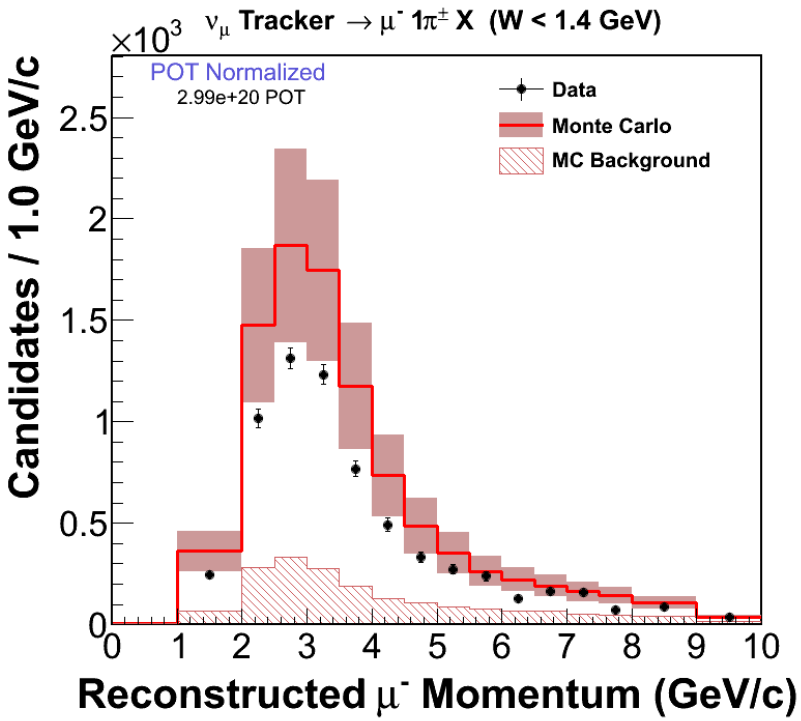
Limit the size of the hadronic recoil and neutrino energy

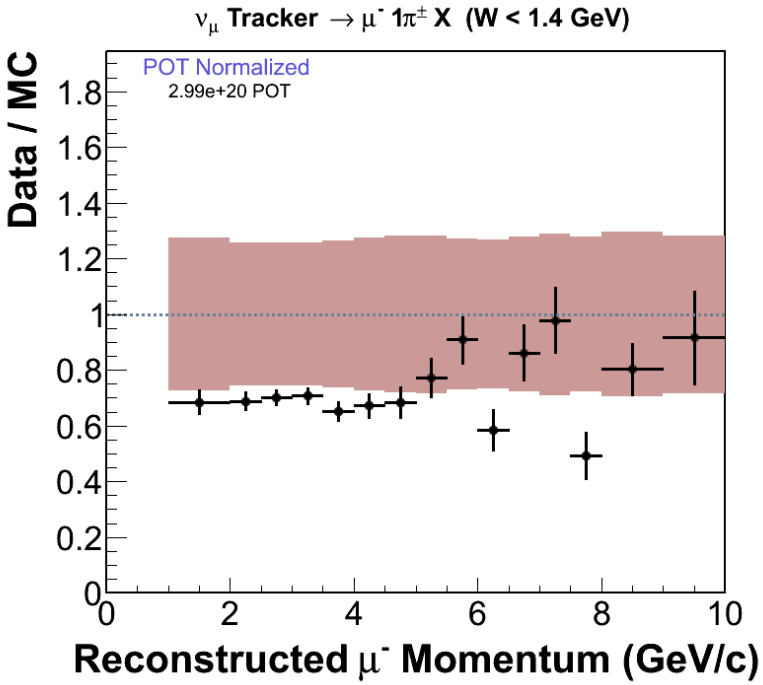


Reconstructed Muon P

- Large error bars on simulation from flux and signal model uncertainties

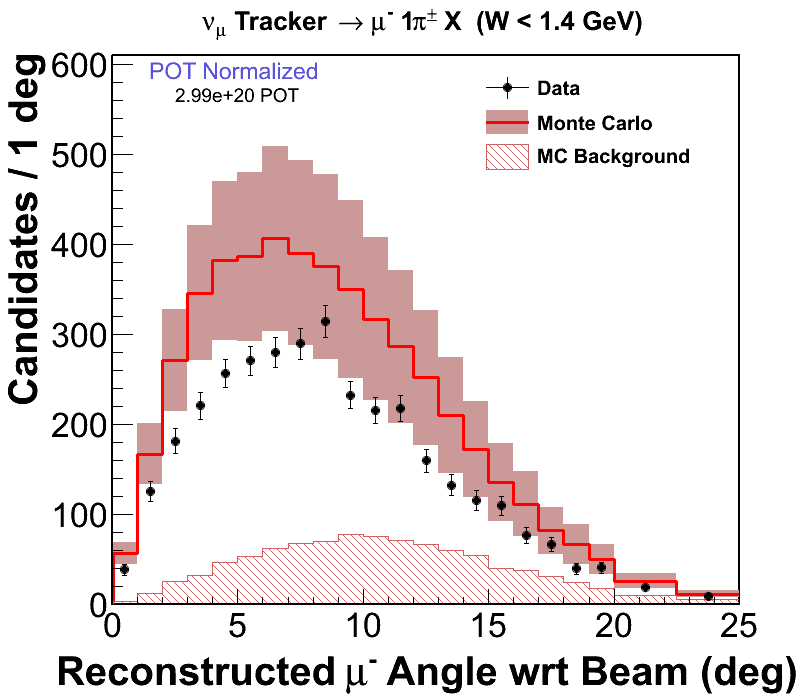
- We assign errors that effectively cover the disagreement with data

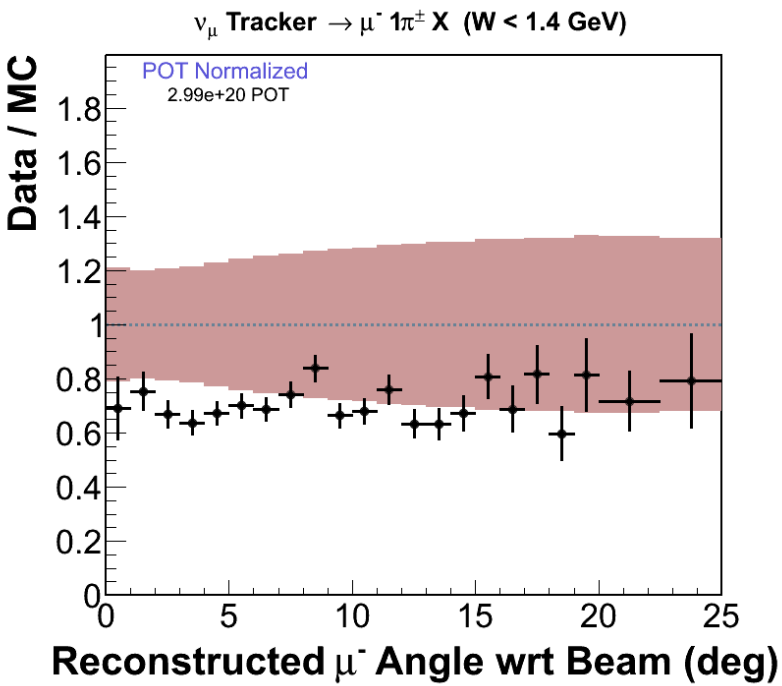




Reconstructed Muon θ

- Large error bars on simulation from flux and signal model uncertainties
- We assign errors that effectively cover the disagreement with data

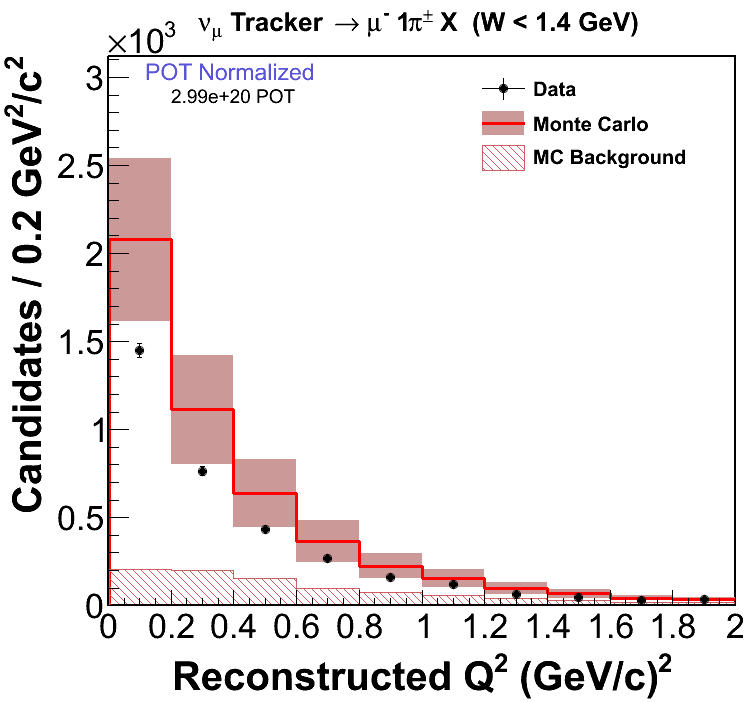


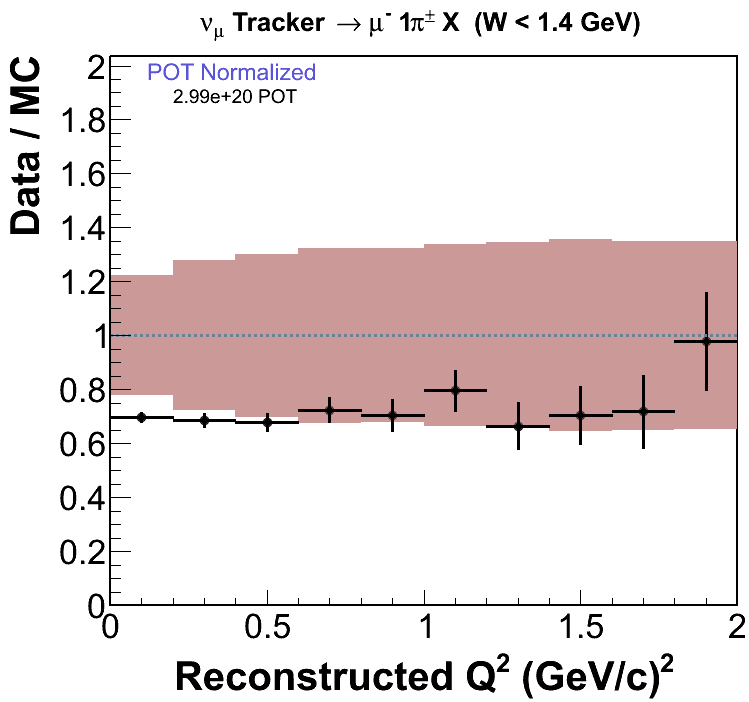


Reconstructed Q^2

- Large error bars on simulation from flux and signal model uncertainties

- We assign errors that effectively cover the disagreement with data



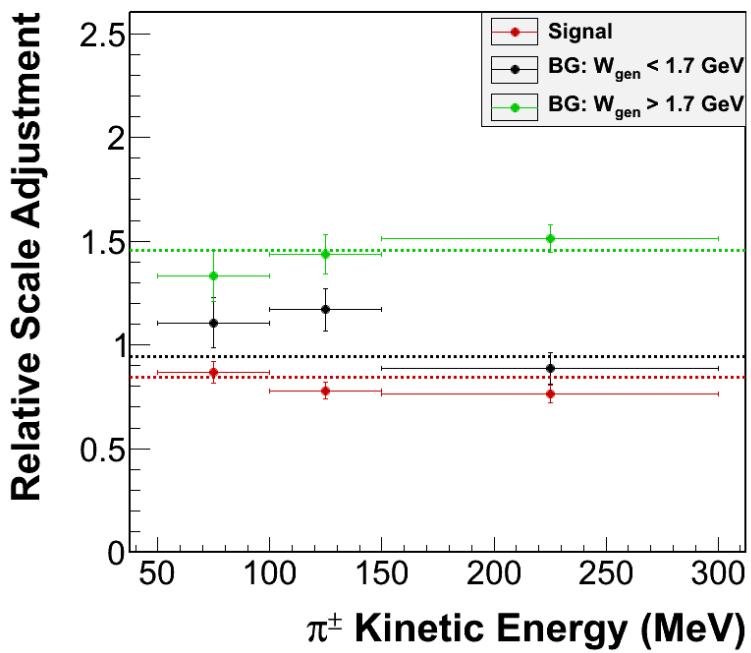


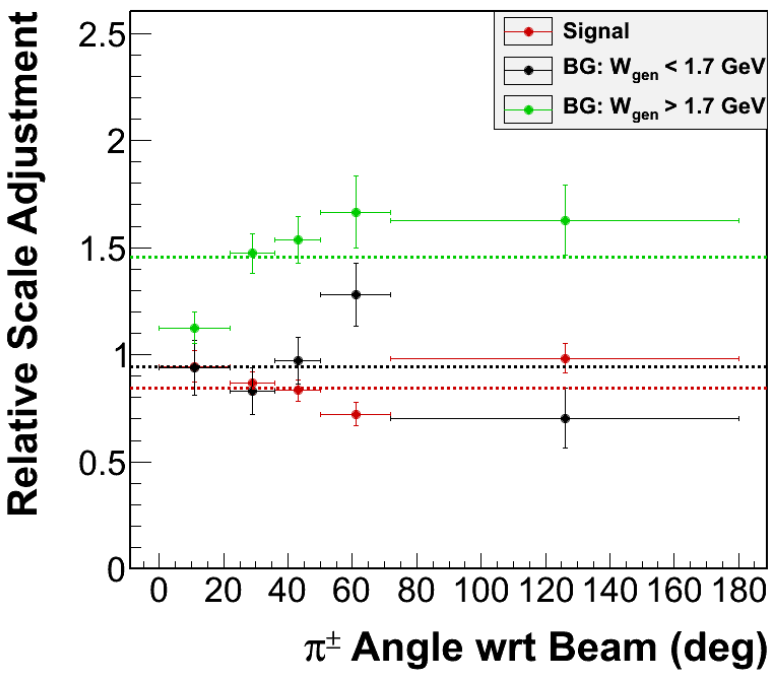
Background Subtraction

•For each background template: fit returns a scale $\mathbf{r_i}$ that adjusts the simulated prediction for the background fraction in bin i:

$$f_{bkg,i}^{adjusted} = r_i f_{bkg,i}^{simulated}$$

$$f_{bkg,i}^{simulated} = \frac{N_{bkg,i}^{simulated}}{N_{total,i}^{simulated}}$$





GENIE Uncertainties

Cross Section Model Uncertainties

Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% −15%
CCQE Normalization	+20% −15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production) 1.12 GeV	± 20%
M_V (Resonance Production)	± 10%
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
Modfiy Pauli blocking (CCQE) at low Q^2 (change PB momentum threshold)	± 30%

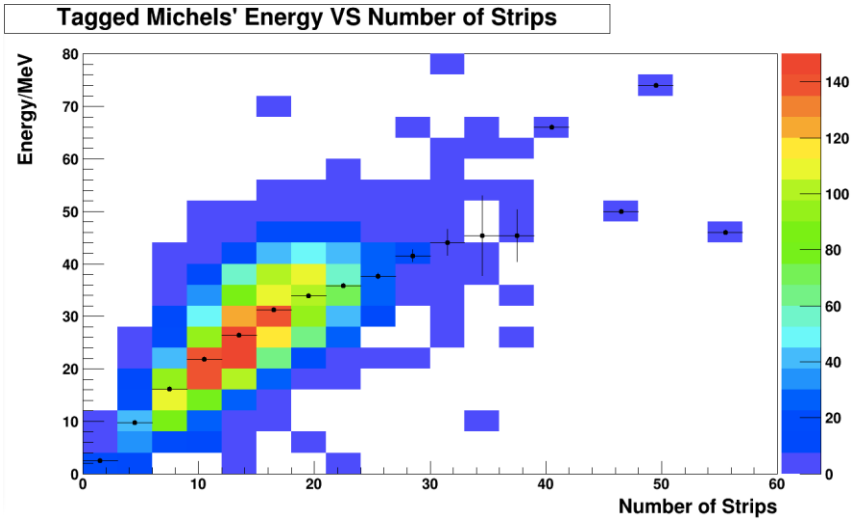
•*Intranuclear Rescattering Uncertainties*

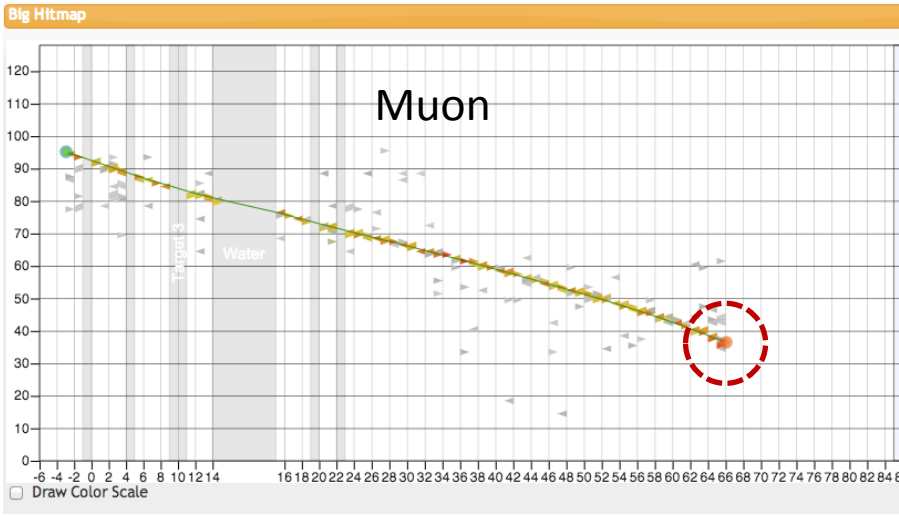
Uncertainty	1 σ
Pion mean free path	± 20%
Nucleon mean free path	± 20%
Pion fates – absorption	± 30%
Pion fates – charge exchange	± 50%
Pion fates – Elastic	± 10%
Pion fates – Inelastic	± 40%
Pion fates – pion production	± 20%
Nucleon fates – charge exchange	± 50%
Nucleon fates – Elastic	± 30%
Nucleon fates – Inelastic	± 40%
Nucleon fates – absorption	± 20%
Nucleon fates – pion production	± 20%
AGKY hadronization model – x_F distribution	± 20%
Delta decay angular distribution	On/off
Resonance decay branching ratio to photon	± 50%

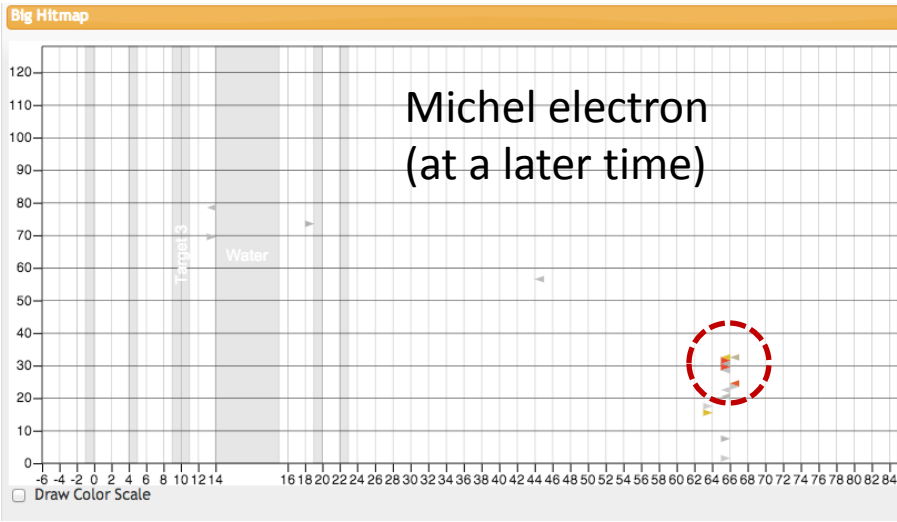
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

Systematic Errors – Michel Selection

- Select a sample of muons that stop in the tracker and compare the Michel selection efficiency between data and simulation:
  - Consistent within ~1%
- Background rate estimate – search in random locations for Michels.
  - Rate is low, ~4.8%, but under-predicted in simulation
- ~2% uncertainty in analysis





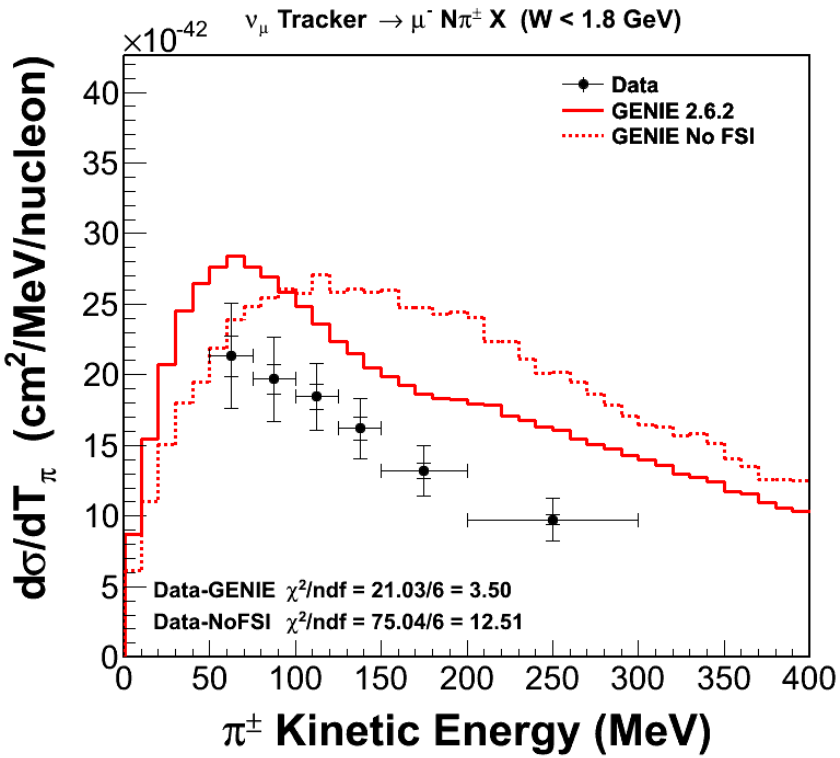


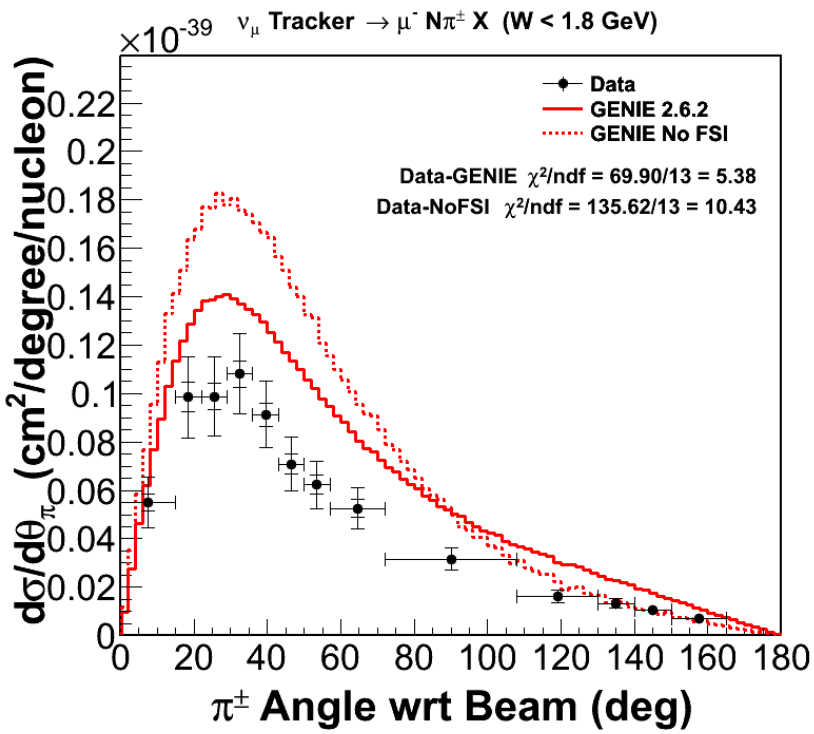
Shape Model Comparison Normalizations

Shape normalization of 1-Pion analysis distributions
(relative to GENIE in parentheses)

Model	T_π Normalization Factor	θ_π Normalization Factor
GENIE with FSI	0.72 (1)	0.68 (1)
GENIE no FSI	0.57 (0.79)	0.57 (0.84)
Neut	0.91 (1.26)	0.89 (1.31)
NuWro	0.87 (1.21)	0.86 (1.26)
Athar	0.96 (1.33)	1.23 (1.81)

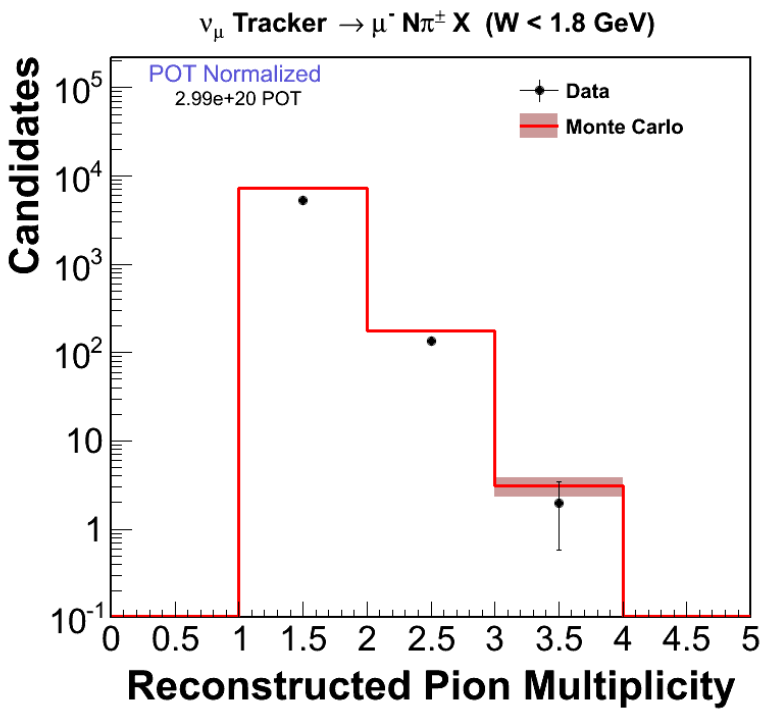
Results, W < 1.8 GeV

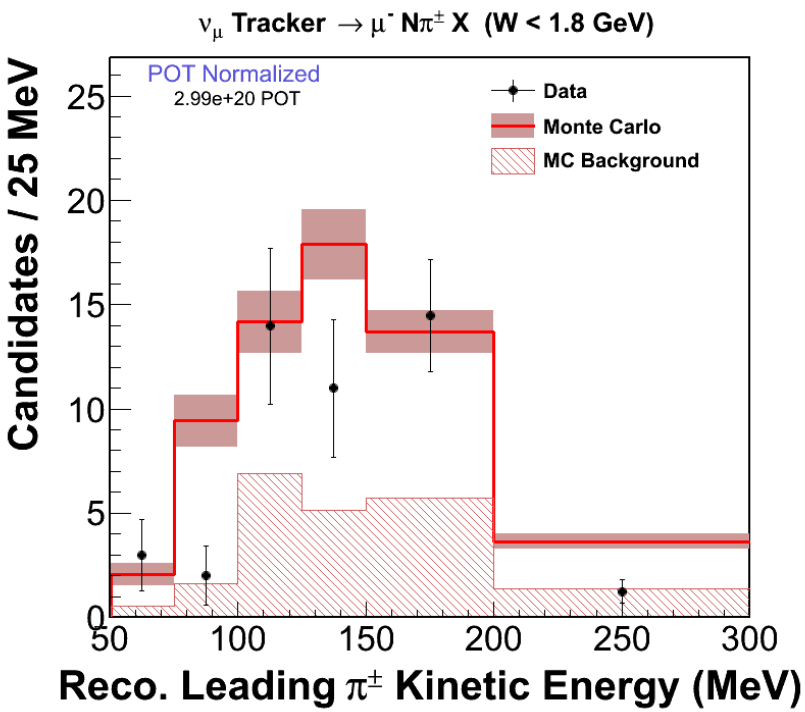
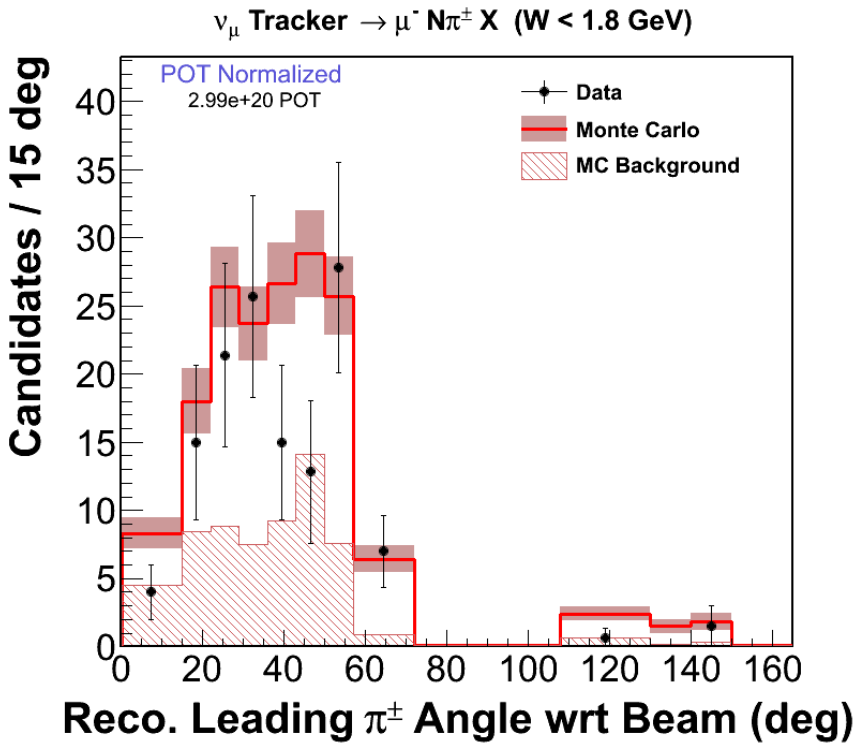
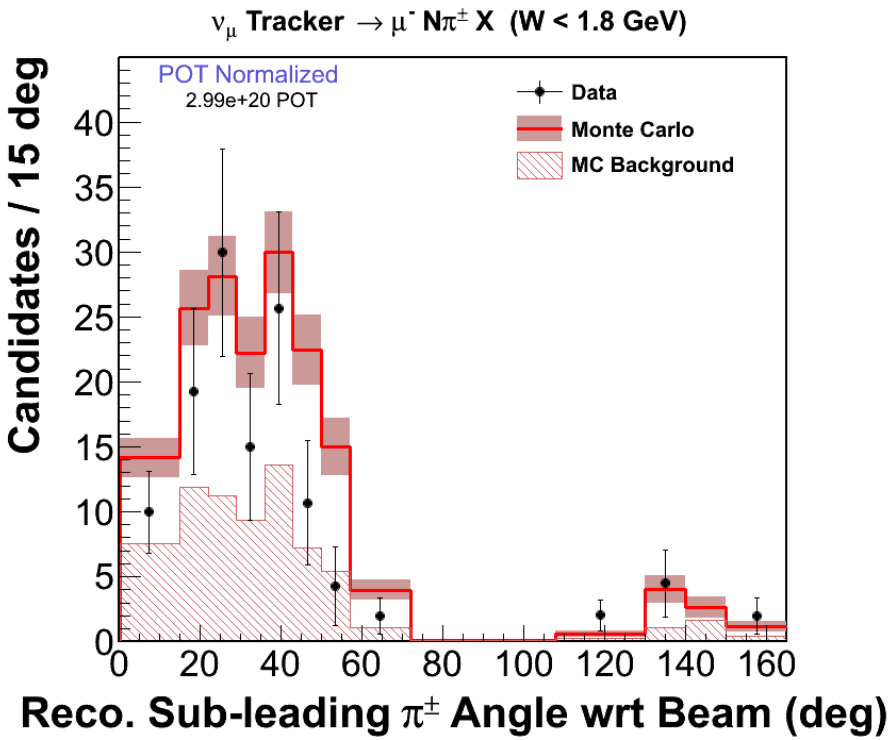




Another version of the analysis, allowing for multiple pions in the final state and higher order resonances: W < 1.8 GeV

Multi-Pion Distributions





Multi-Pion Distributions