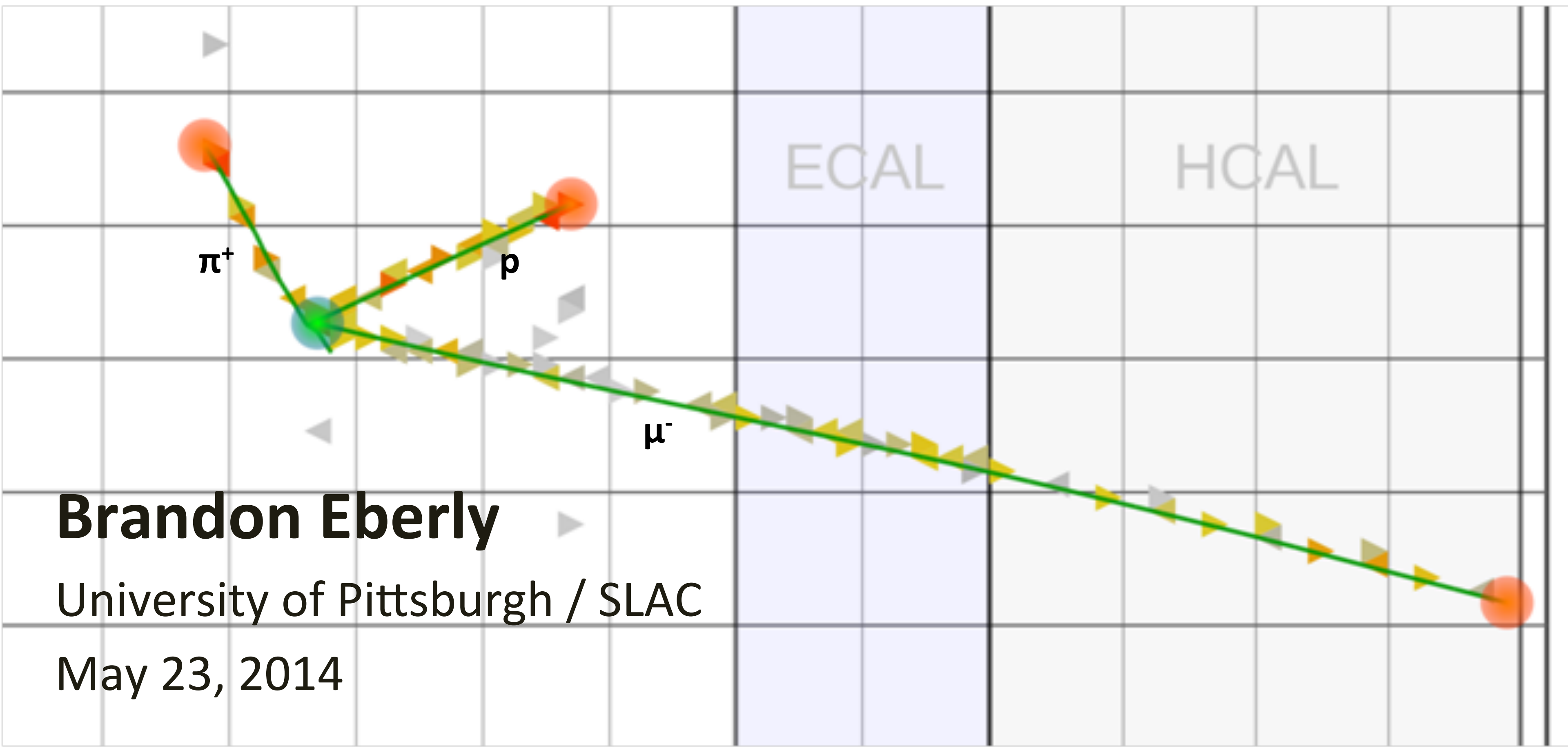
Charged Current Single Pion Production at MINERvA



Brandon Eberly

University of Pittsburgh / SLAC

May 23, 2014

Outline

- Motivation and Introduction
- MINERvA Detector
- Charged Pion Analysis
- Future Prospects
- Conclusions

At NuInt '12

Physicists enjoy a challenge!

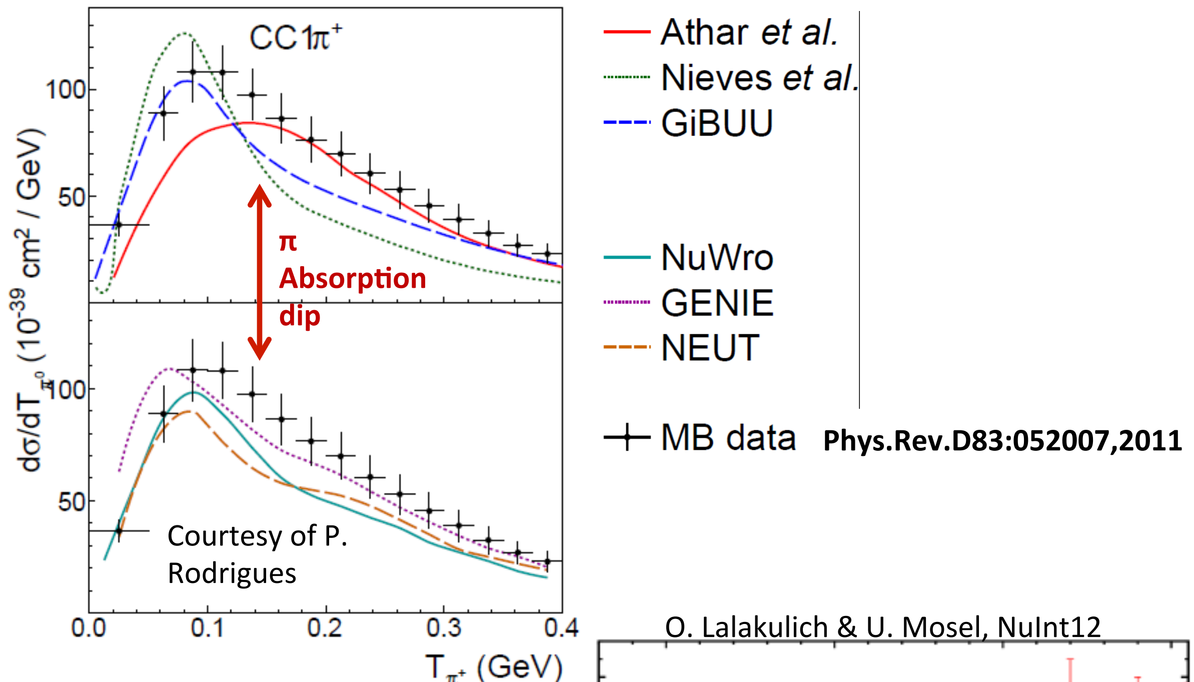
Photo credit: J. Grange

"We have an afternoon off? Let's hike up a mountain in the sweltering heat of the rain forest!"

At NuInt '12

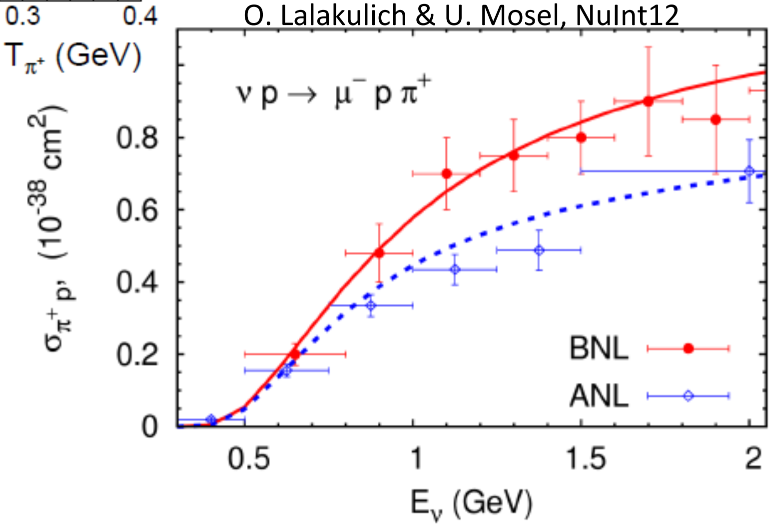
Physicists enjoy a challenge!

Photo credit: J. Grange



"We have an afternoon off? Let's hike up a mountain in the sweltering heat of the rain forest!"

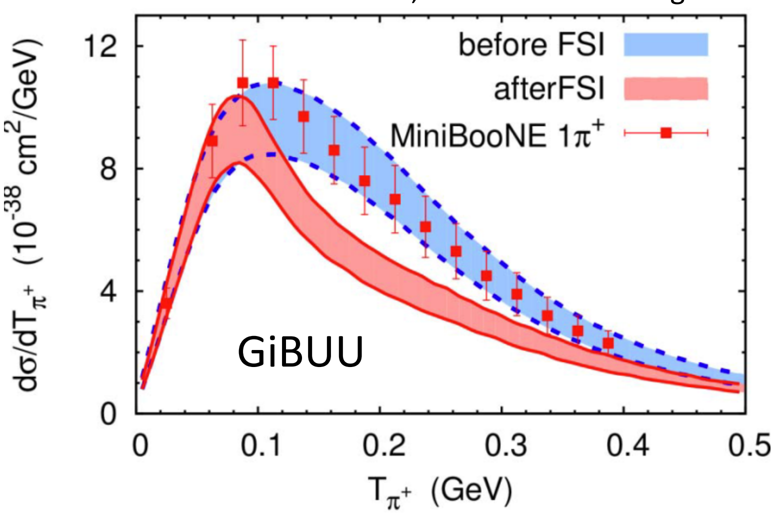
O. Lalakulich & U. Mosel, NuInt12



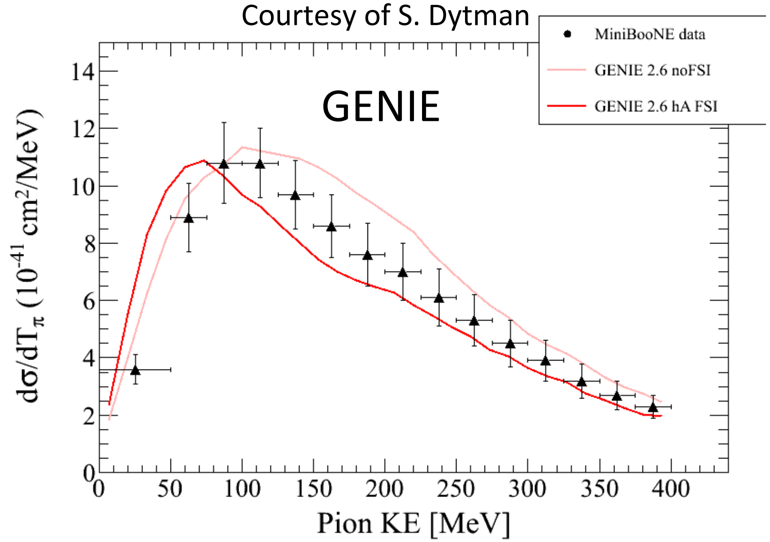
And there were physics challenges too!

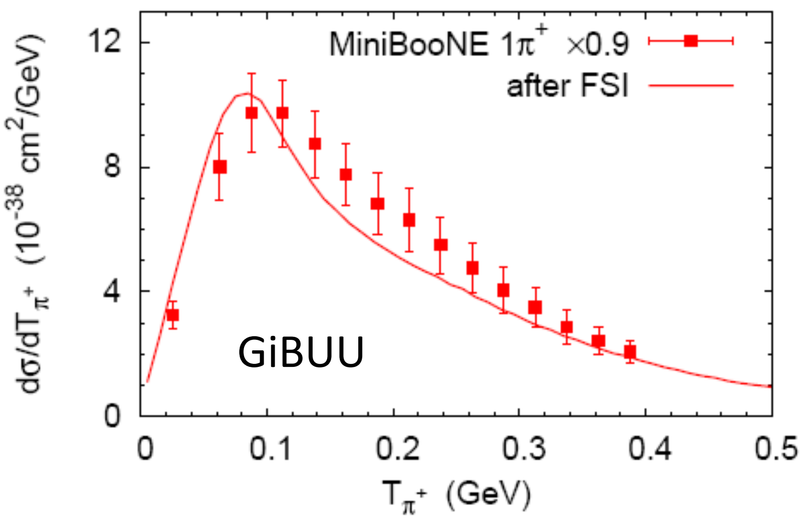
MiniBooNE and Final State Interactions

O. Lalakulich et al, NuInt12 Proceedings



Courtesy of S. Dytman





GiBUU (after normalization adjustment) and GENIE predict slightly stronger absorption, softer spectrum than data

The NuMI Beam and MINERvA Detector

NuMI Beam and Flux Measurement

<E_ν> ~ 3.5 GeV

- Flux measurements are hard!
- Large uncertainties result in large normalization errors

Analysis Strategy: Measure shape – mitigate normalization uncertainties!

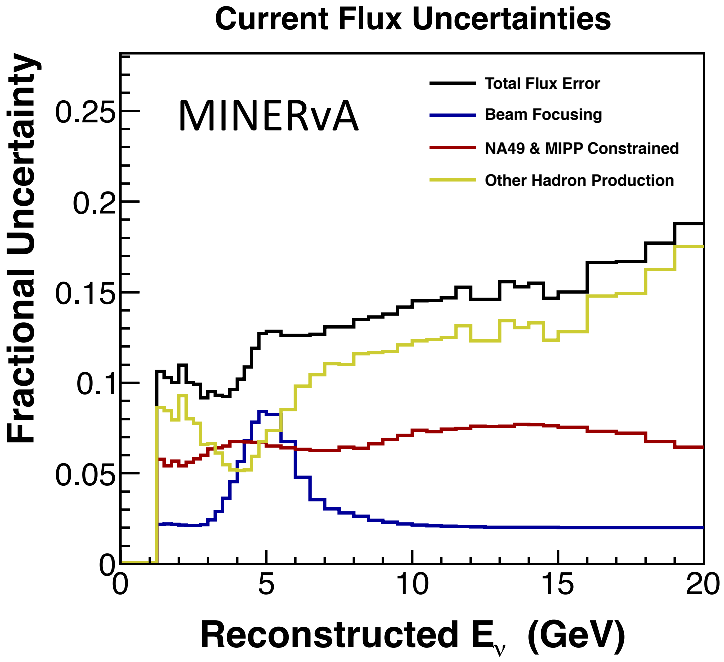
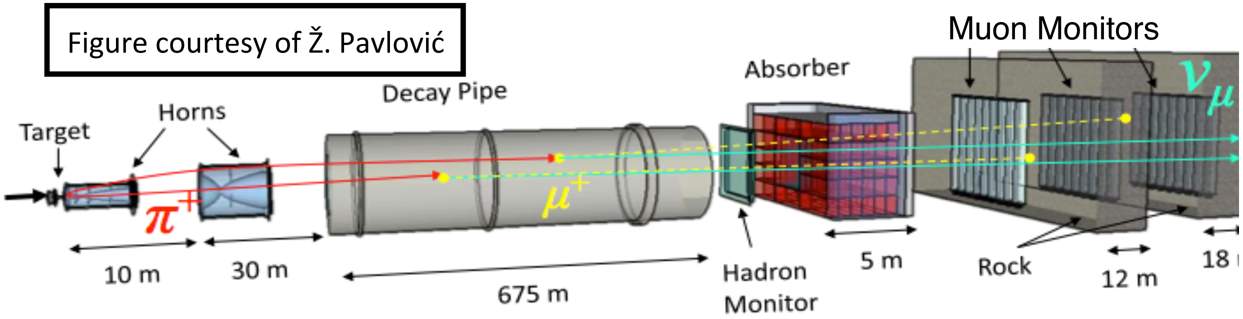
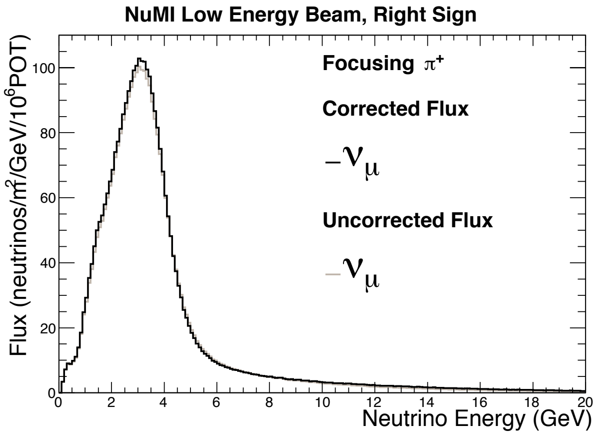


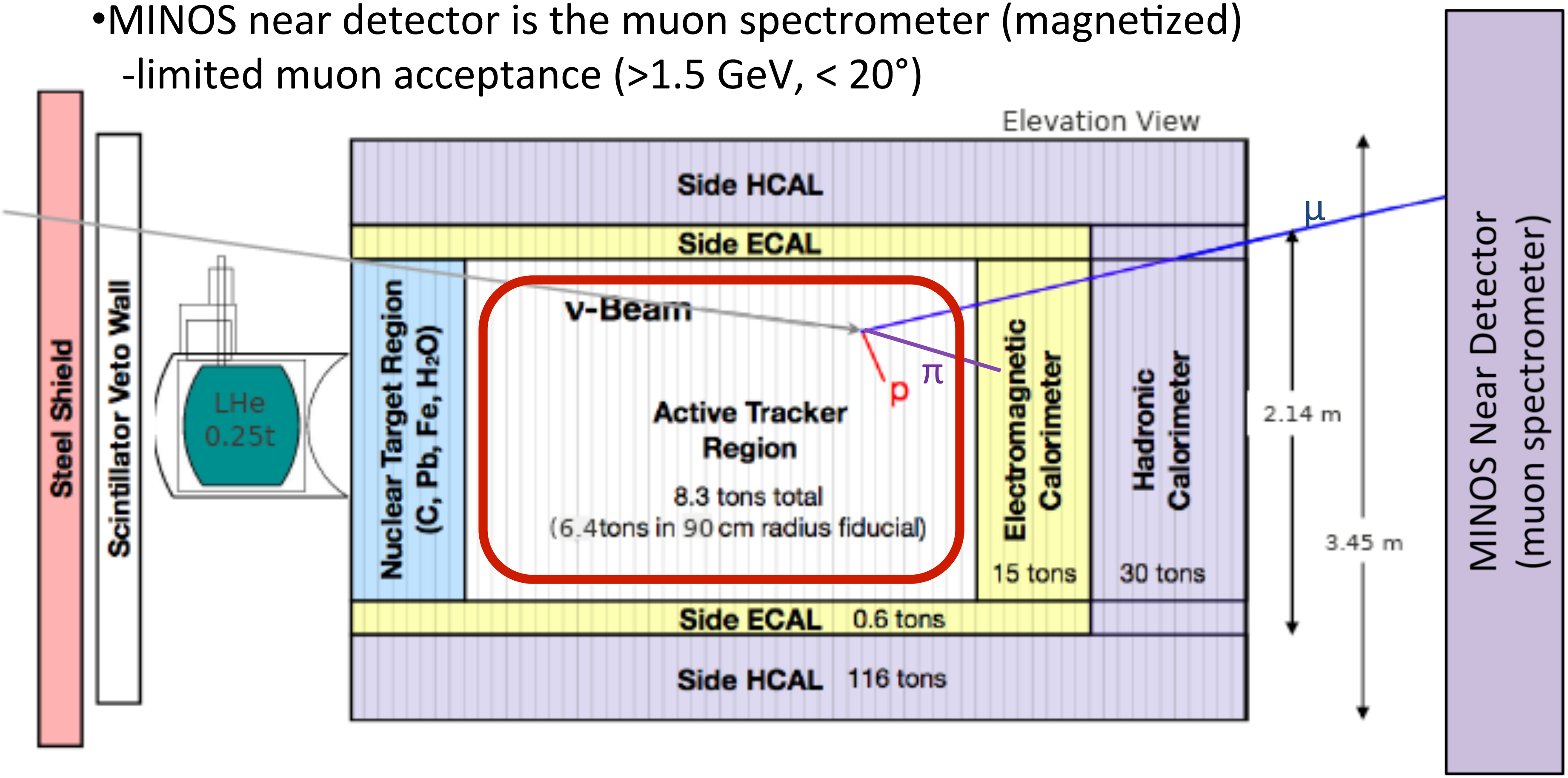
Figure courtesy of Ž. Pavlović





MINERvA Detector

- Fine-grained scintillator tracker surrounded by calorimeters
  - -search for pion tracks!
  - -beware of secondary pion interactions
- MINOS near detector is the muon spectrometer (magnetized)
  - -limited muon acceptance (>1.5 GeV, < 20°)



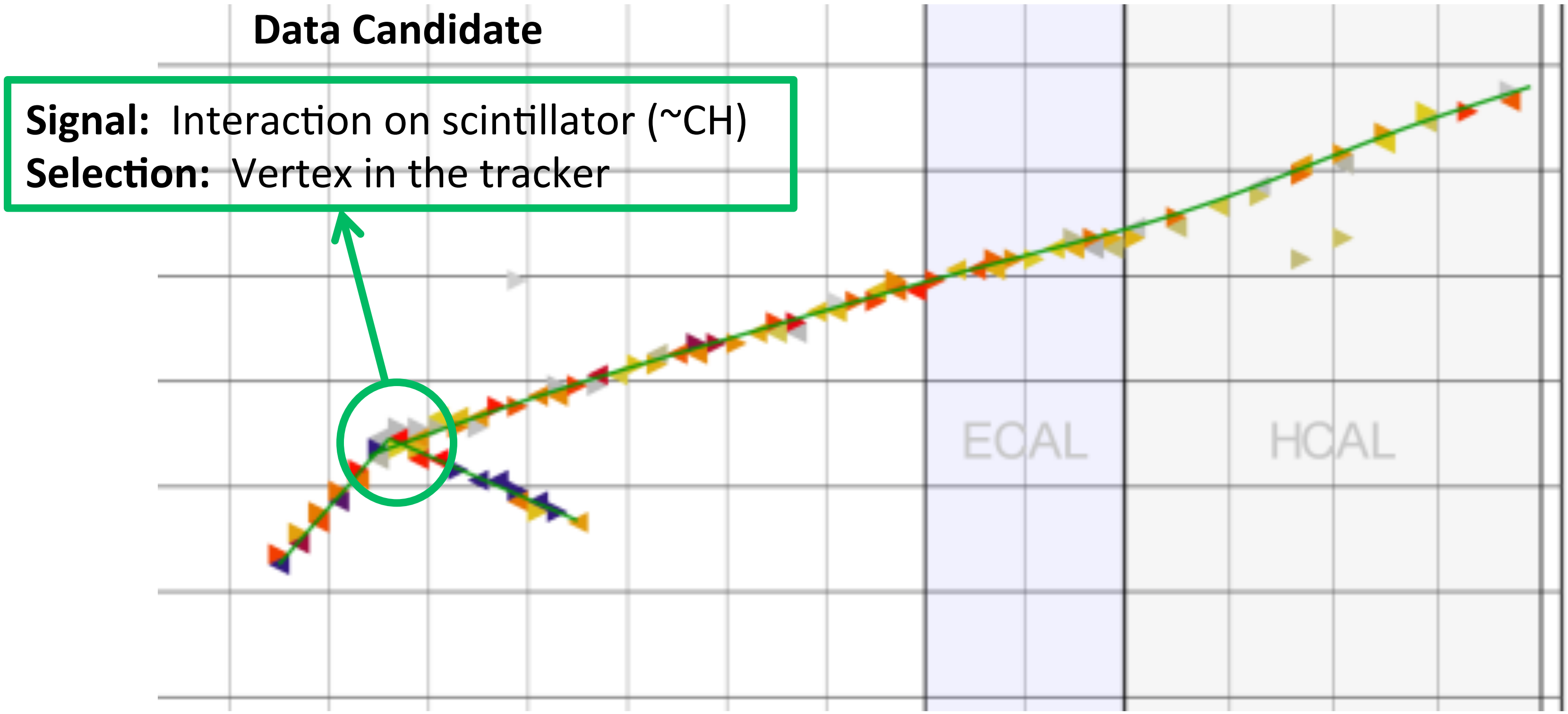
MINERvA Charged Current Charged Pion Analysis

1.5 GeV < E_ν < 10 GeV

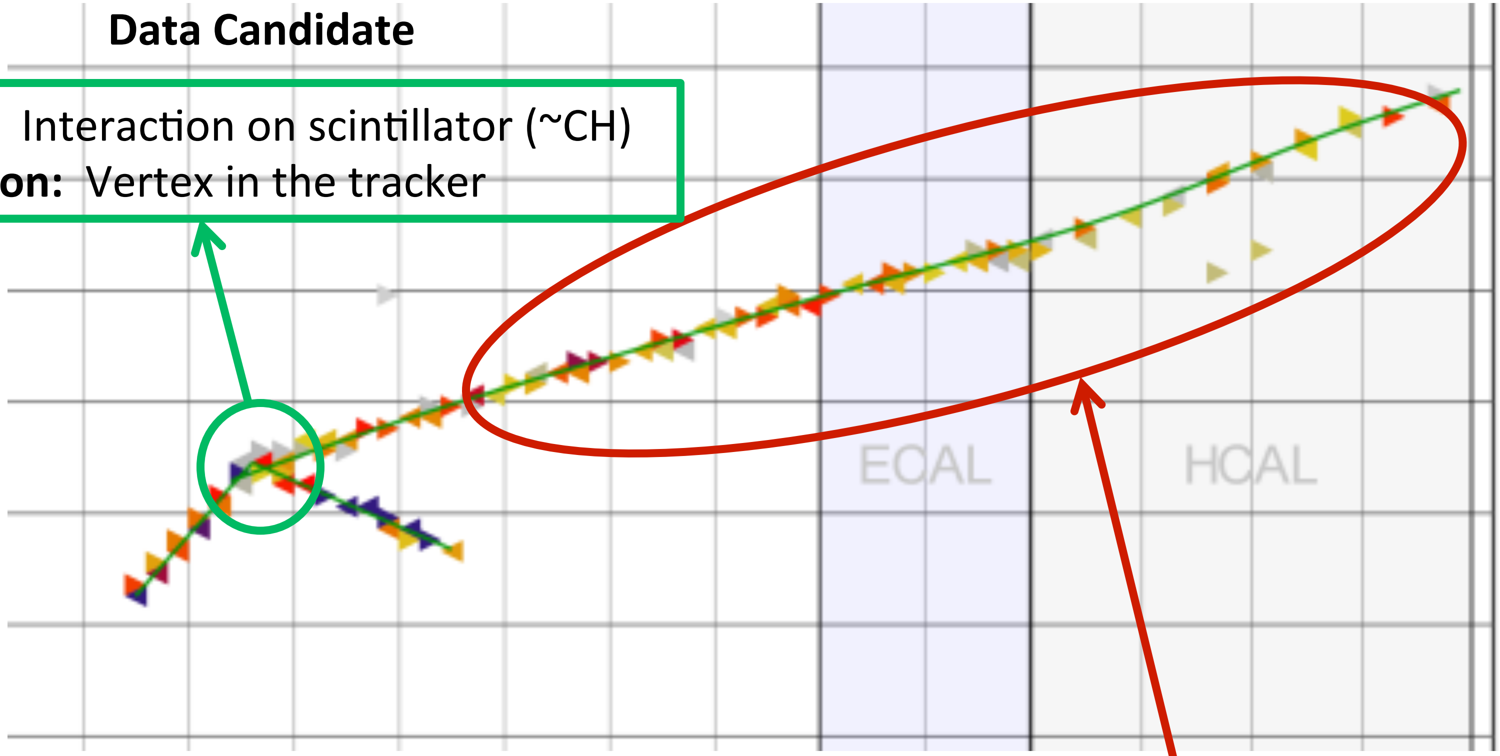
Goal: Measure **pion energy and angle** distributions to determine strength and nature of FSI interactions

Data set: Entire MINERvA (with MINOS) Low Energy neutrino data: 3.04e20 Protons on Target (P.O.T.)

Signal Definition & Event Selection



Signal Definition & Event Selection

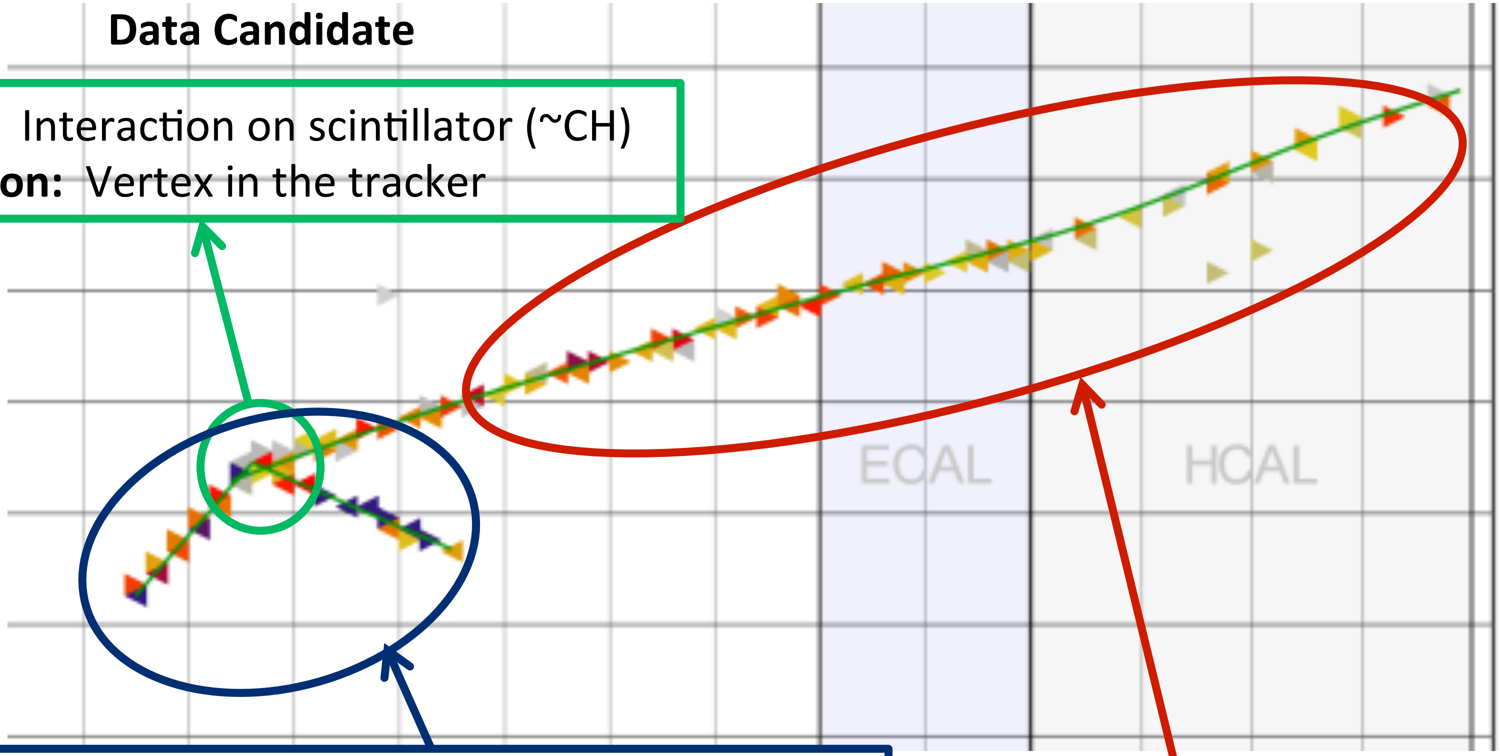


Signal: Interaction on scintillator (~CH)
Selection: Vertex in the tracker

Signal: CC muon neutrino interaction

Selection: Muon track that is matched with the correct charge sign in MINOS

Signal Definition & Event Selection



Signal: Interaction on scintillator (~CH)
Selection: Vertex in the tracker

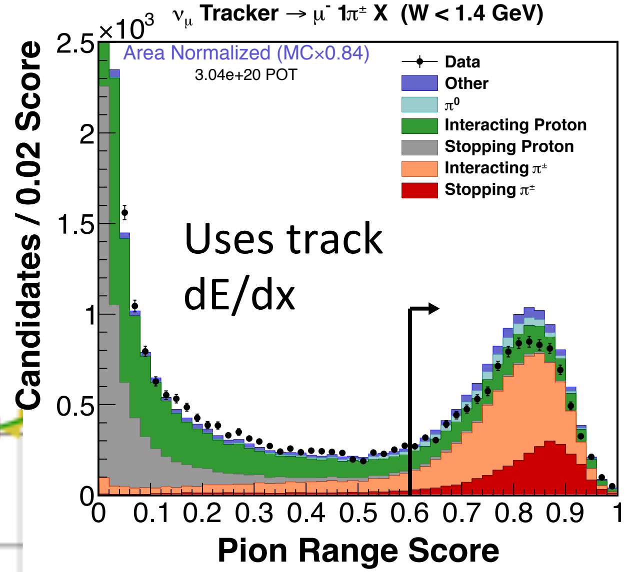
Signal: Exactly one charged pion in the final state

Selection: 1-2 non-muon tracks at the primary vertex

Signal: CC muon neutrino interaction

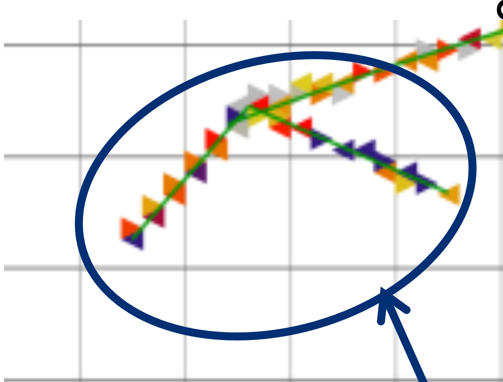
Selection: Muon track that is matched with the correct charge sign in MINOS

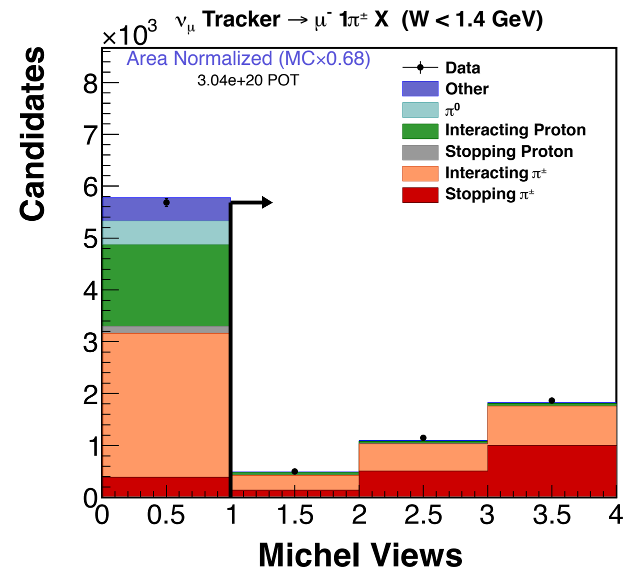
Signal Definition & Event Selection



$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$





Signal: Exactly one charged pion in the final state

Selection: 1-2 non-muon tracks at the primary vertex

1 reconstructed pion candidate

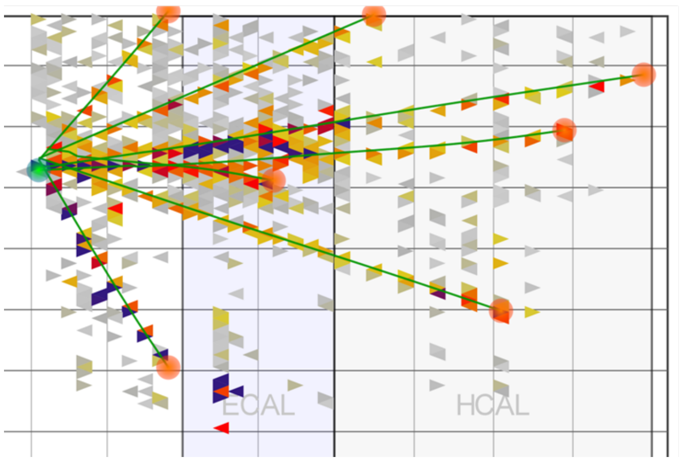
Signal Definition & Event Selection

And one more: Hadronic invariant mass (W) < 1.4 GeV

Signal Definition & Event Selection

And one more: Hadronic invariant mass (W) < 1.4 GeV

Why?



Do not want to treat high-activity events as *signal*

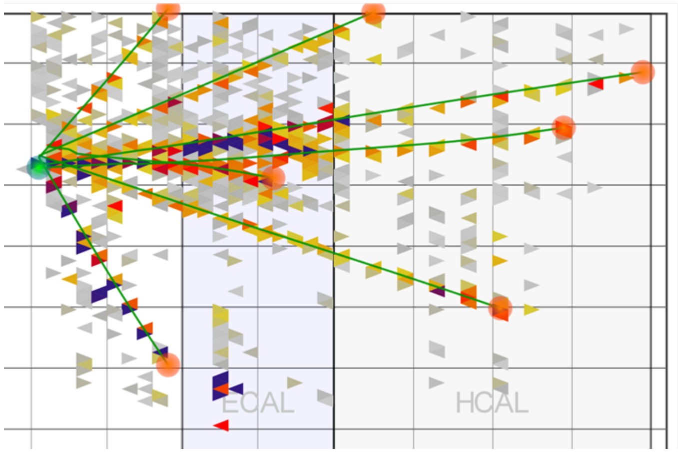
Choose W because it's simple, intuitive

…except in multi-nucleon interactions (more on this later)

Signal Definition & Event Selection

And one more: Hadronic invariant mass (W) < 1.4 GeV

Why?

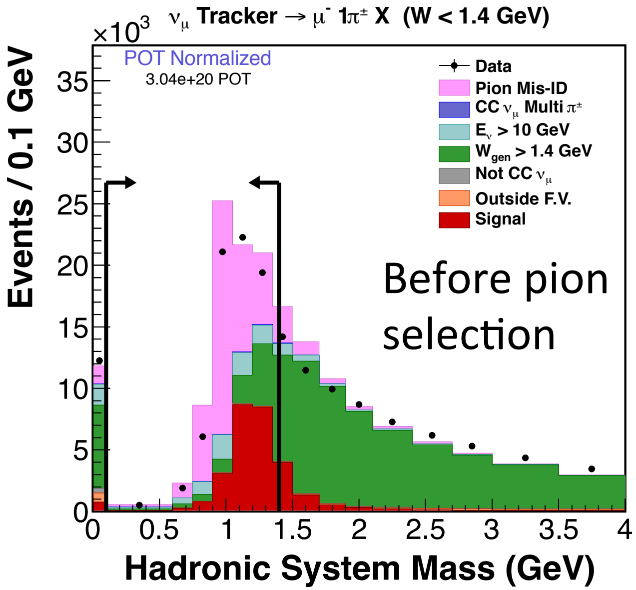


Do not want to treat high-activity events as *signal*

Choose W because it's simple, intuitive

…except in multi-nucleon interactions (more on this later)

How?

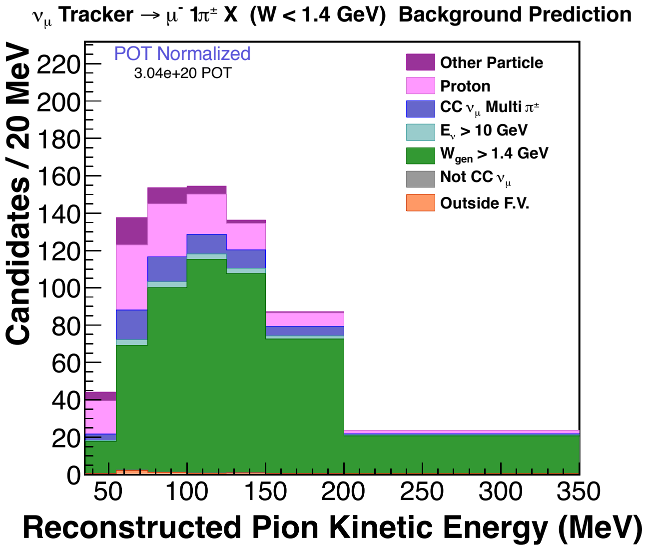


Reconstruct hadronic recoil energy calorimetrically and cut on W_{exp}

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

Introduces model dependence (FSI, nucleon momentum) - small

Background Constraint

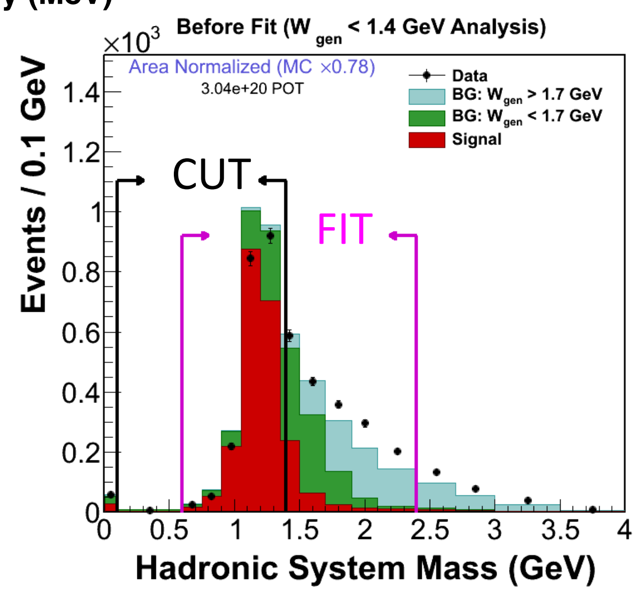


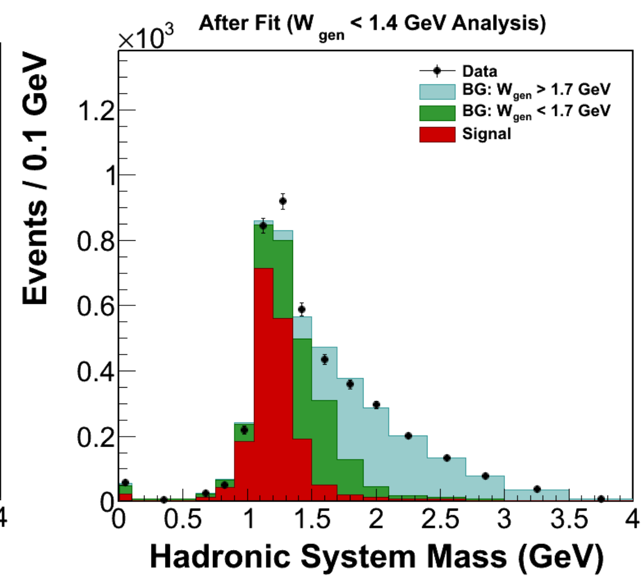
Purity: 77%

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

Fit the shape of the data W_{exp} distribution to signal and background templates.

Use the fit results to adjust the background prediction. Reduces model-dependence!





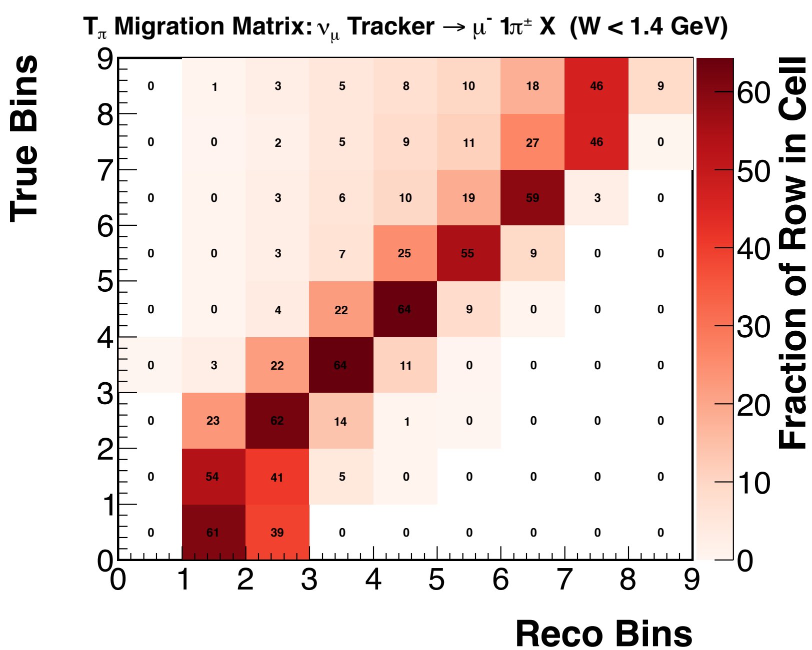
Making a Cross Section

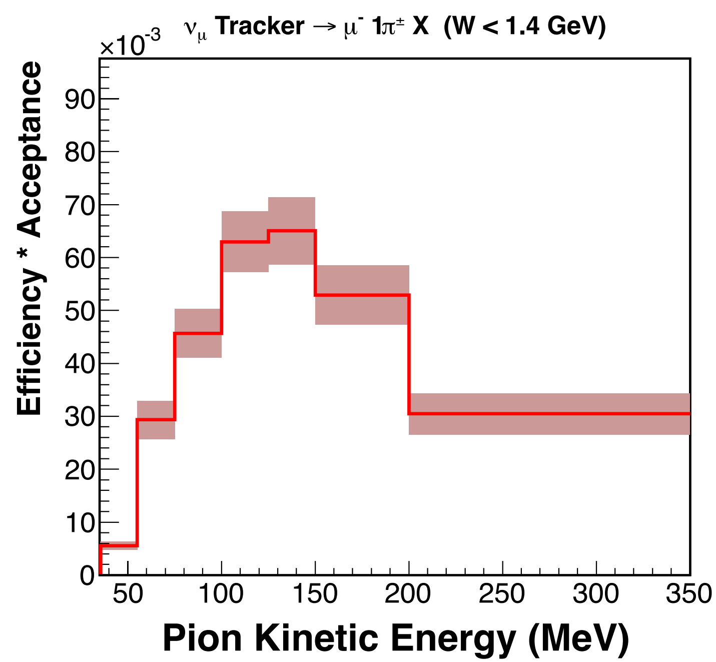
Iterative Bayesian unfolding

Efficiency correction partially constrained by data

- Correct for all muon phase space – including muons not seen by MINOS
- (introduces a Q^2 model dependence from $M_{A,RES}$, $M_{V,RES}$ – very small effect on cross section shape in the measured variables)

Make flux-integrated (1.5-10 GeV) cross sections per nucleon



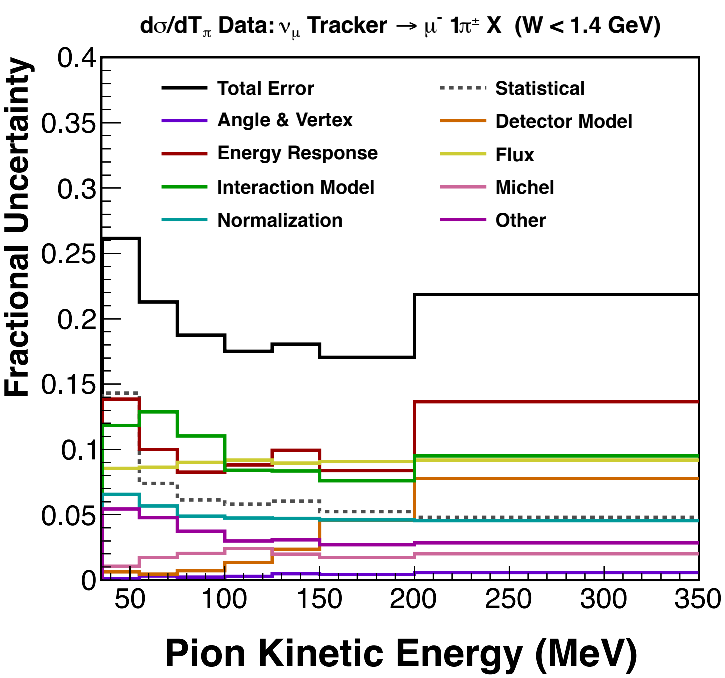


Systematic Errors

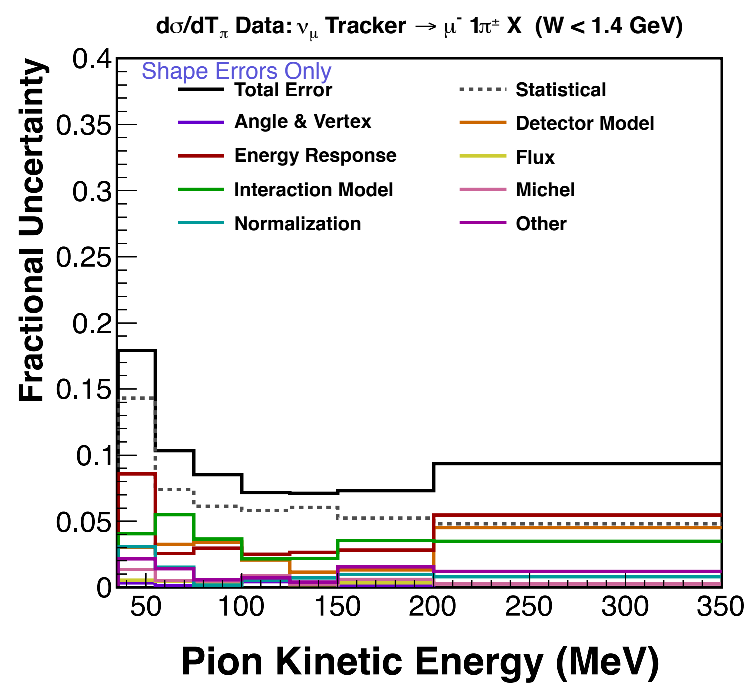
Largest systematic errors are from flux and GENIE cross section model parameters

Other important systematics: GEANT4 interaction model, hadron tracking and PID efficiency, and detector energy response and calorimetry

Shape measurement is **statistics limited** in most bins

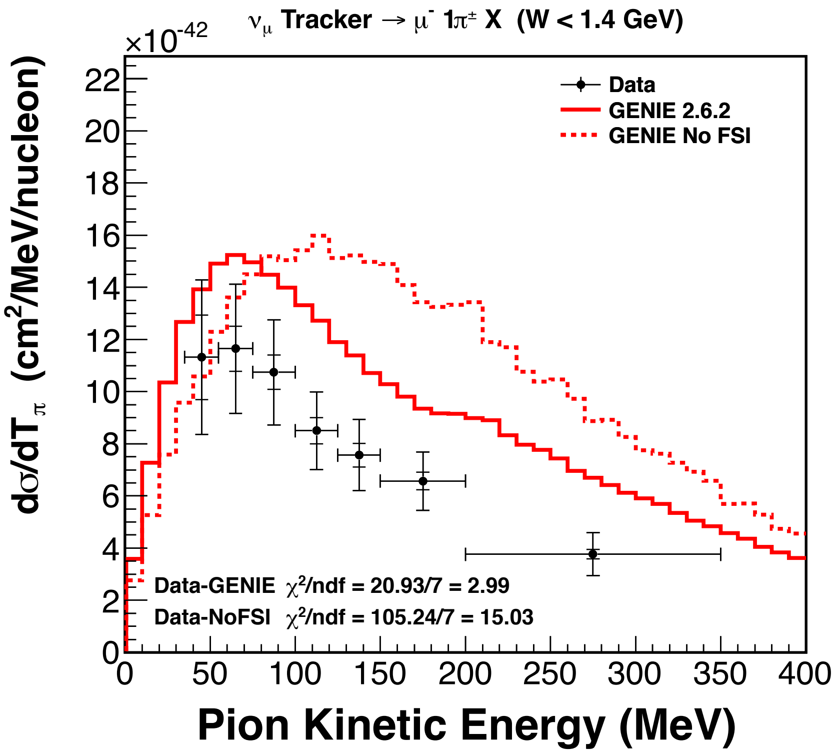


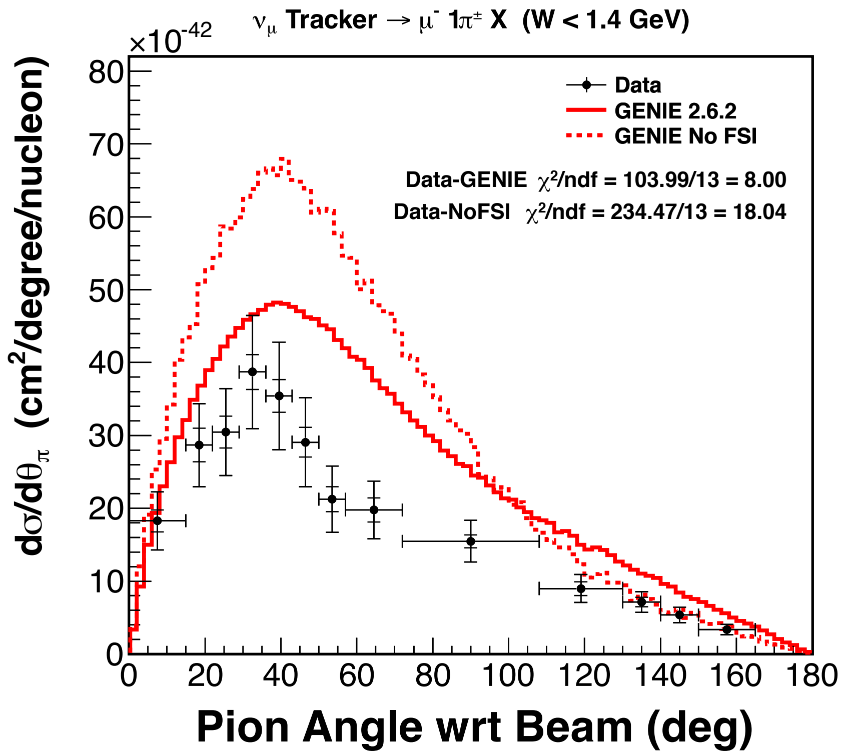
Shape Only



Results

PRELIMINARY

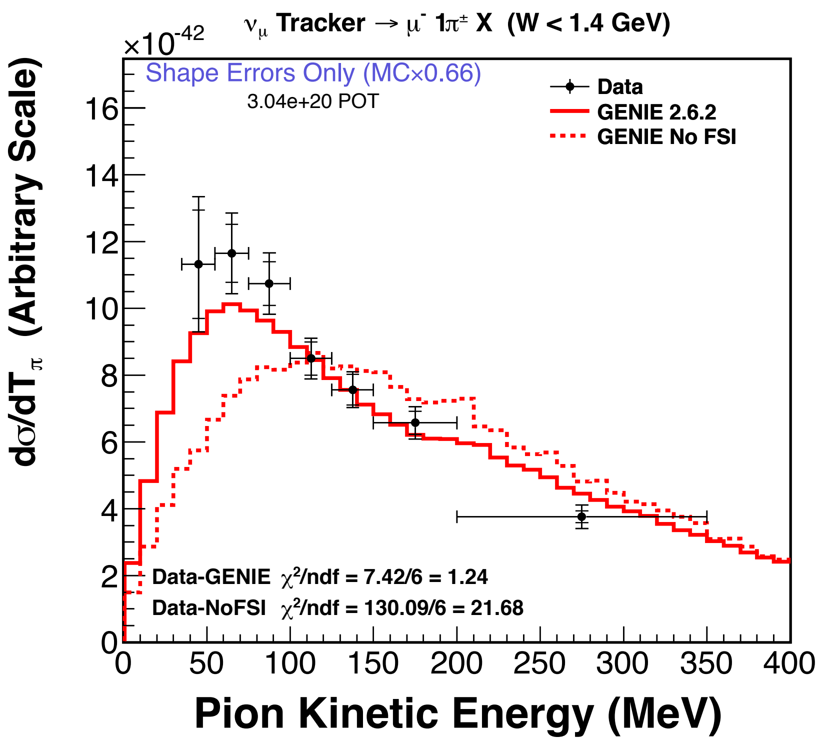


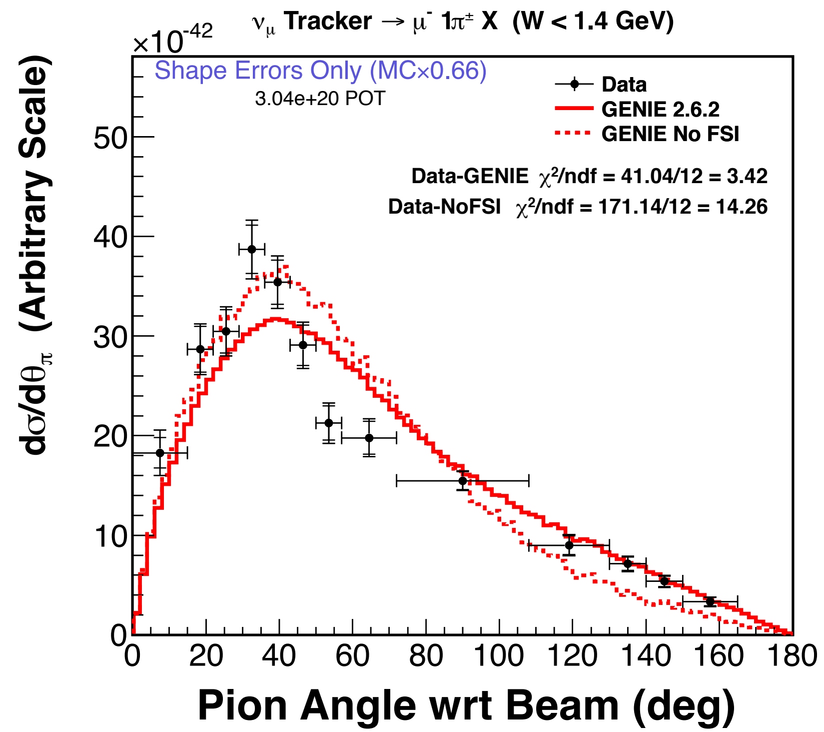


- GENIE prediction is much higher than data (flux, νN cross sections?)

Shape Results

PRELIMINARY





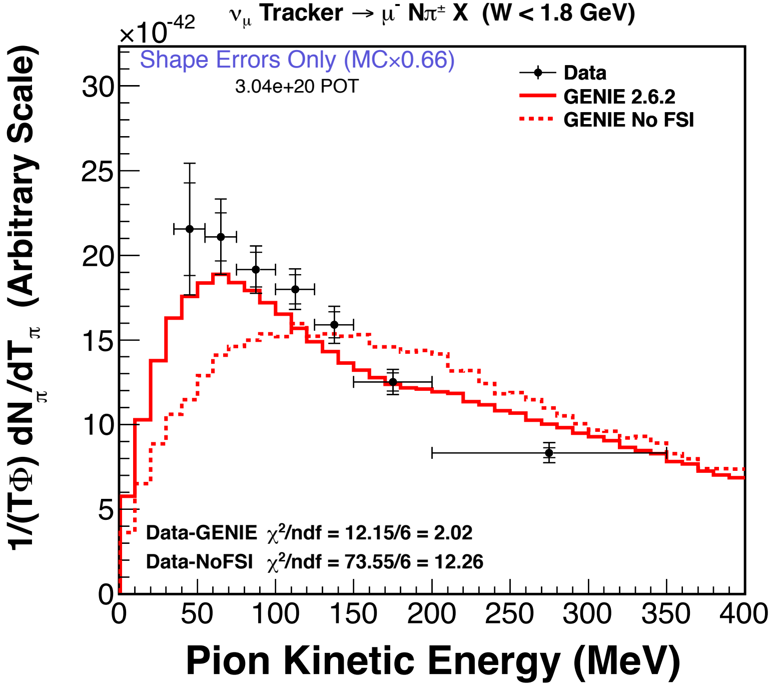
MC is normalized to match the integral of the data

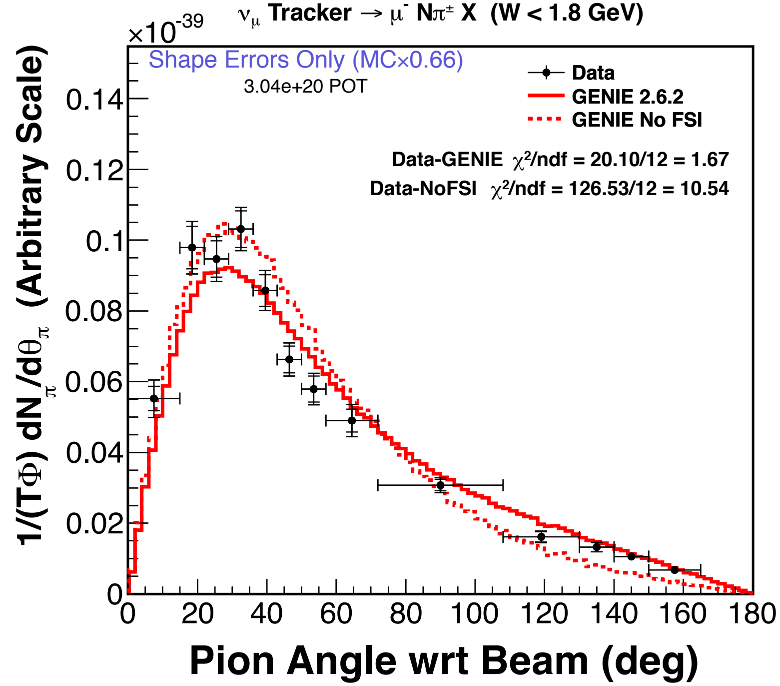
Conclusion: Data prefer GENIE with final state interactions

Comment: GENIE has difficulty reproducing the shape of the angular distribution

Shape Results, W < 1.8 GeV

PRELIMINARY

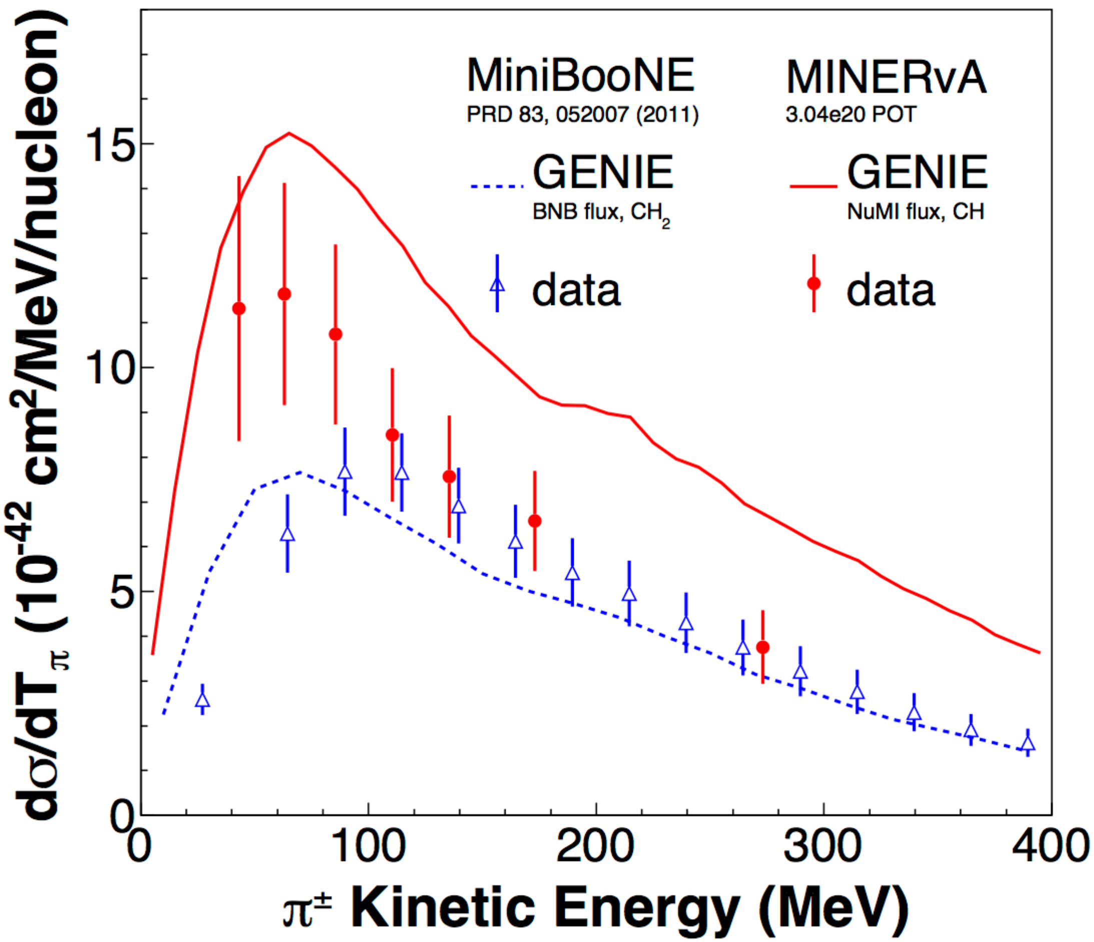




- Another version of the analysis, allowing for multiple pions in the final state and higher order resonances: W < 1.8 GeV
- At higher W, GENIE better matches the angular shape.
- Consistency with W < 1.4 results provides reassurance that the analysis is robust against choice of W cut, multi-nucleon correlations

Results Compared to MiniBooNE

PRELIMINARY



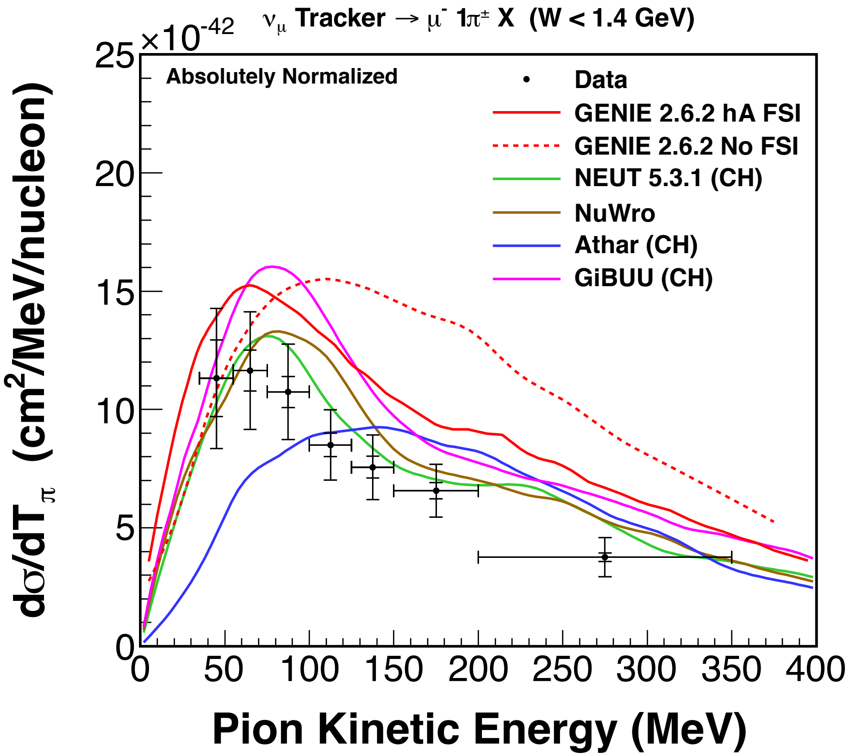
Within the context of the GENIE model:

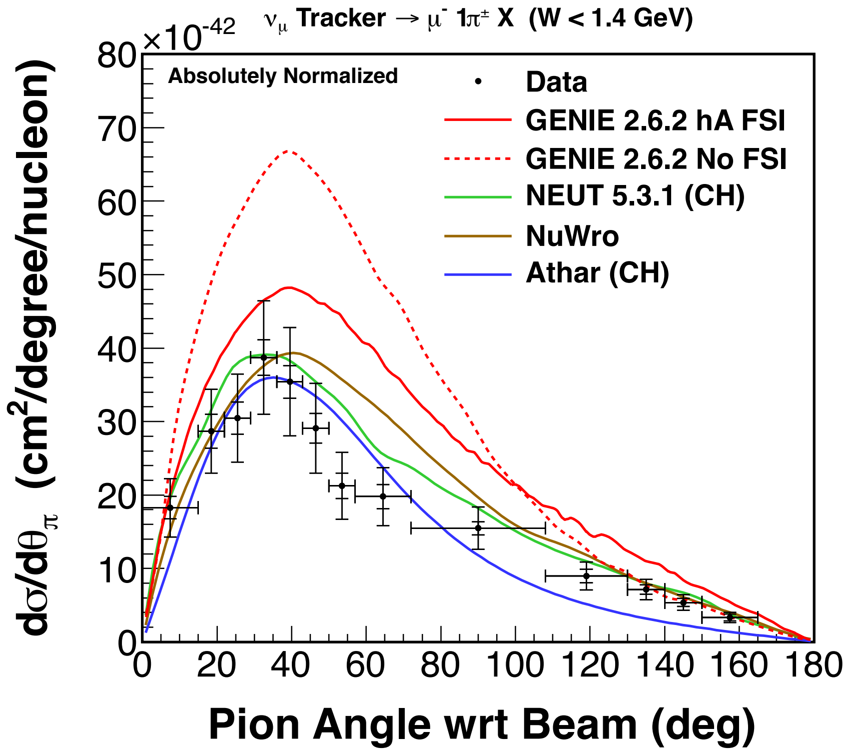
MINERvA and MiniBooNE appear to have inconsistent peaks

MINERvA and MiniBooNE normalization disagree at the level of a couple sigma

Results – Model Comparisons

PRELIMINARY

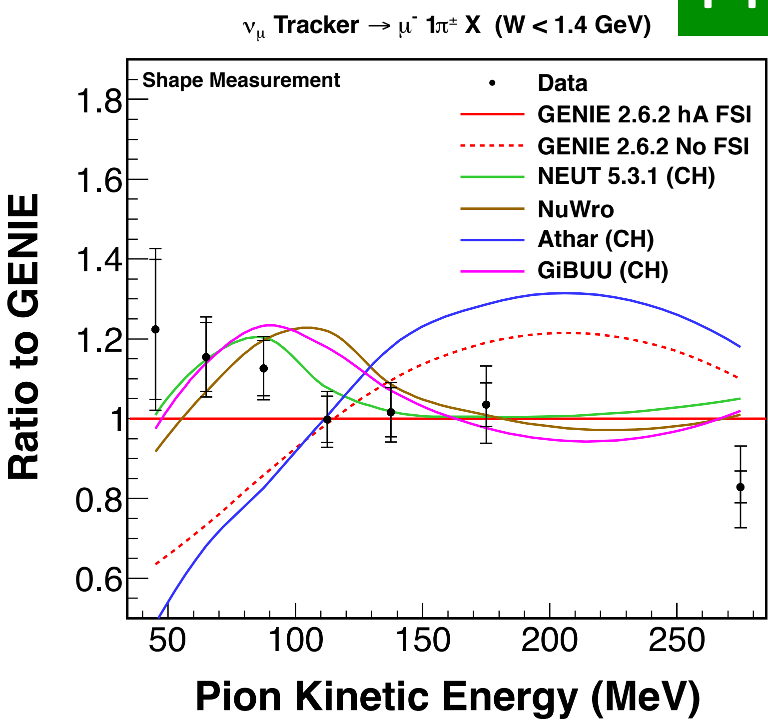


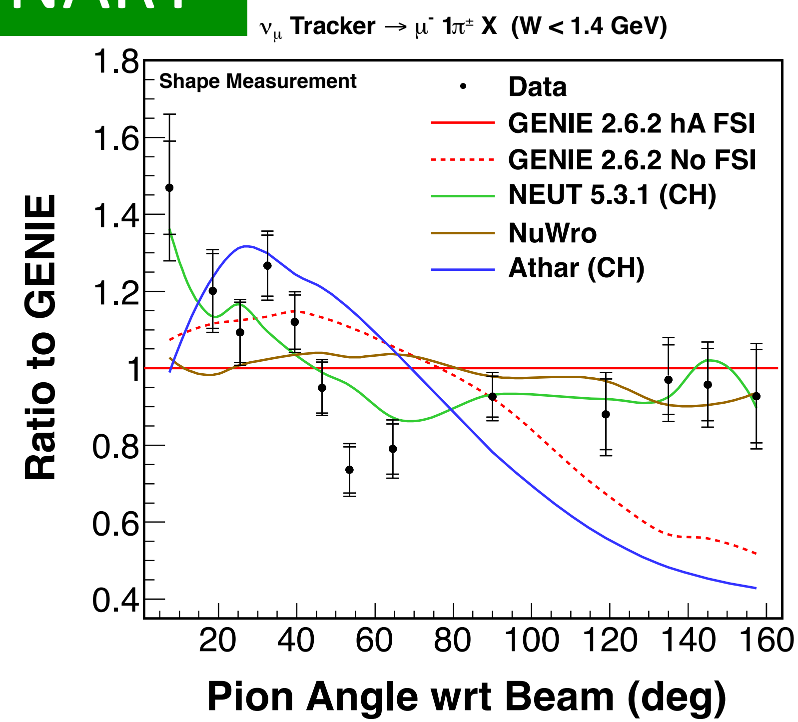


Conclusion: Neut and NuWro normalization agree the best with data.

Shape Results – Model Comparisons

PRELIMINARY





Normalize all models to integral of data, then divide by GENIE prediction

Conclusion: NuWro, Neut, GiBUU and GENIE all predict the KE shape well. GENIE seems to do best with the peak

Conclusion: All models have some trouble with the angle shape – by eye, NEUT does the best job

Antineutrino CC π^0 Production

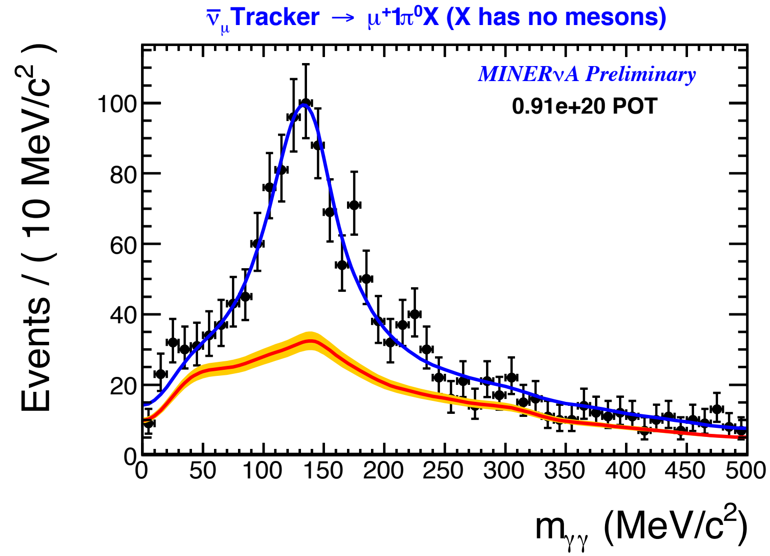
Signal definition:

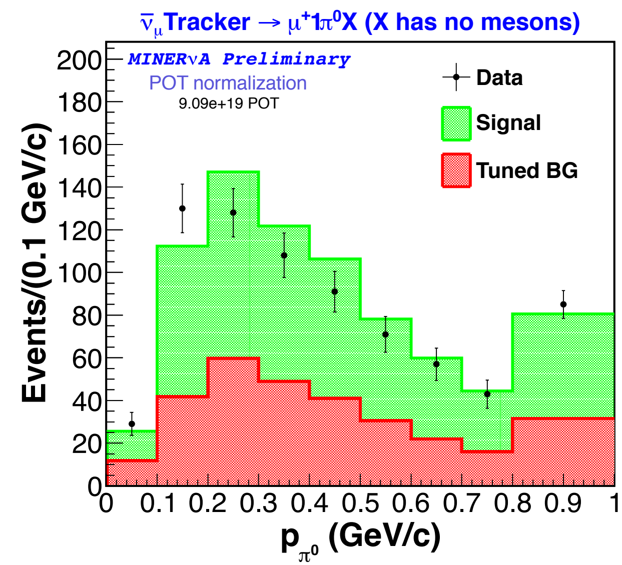
- Muon antineutrino CC interaction
- 1 π^0 in the final state
- 0 charged pions and other mesons

Event selection: 6% efficiency, 55% purity

- MINOS matched muon
- 1 track vertices
- Bounds on visible energy in detector
- 2 reconstructed photons consistent with π^0 mass

Background normalization constrained with extended maximum likelihood fit to 2-photon invariant mass





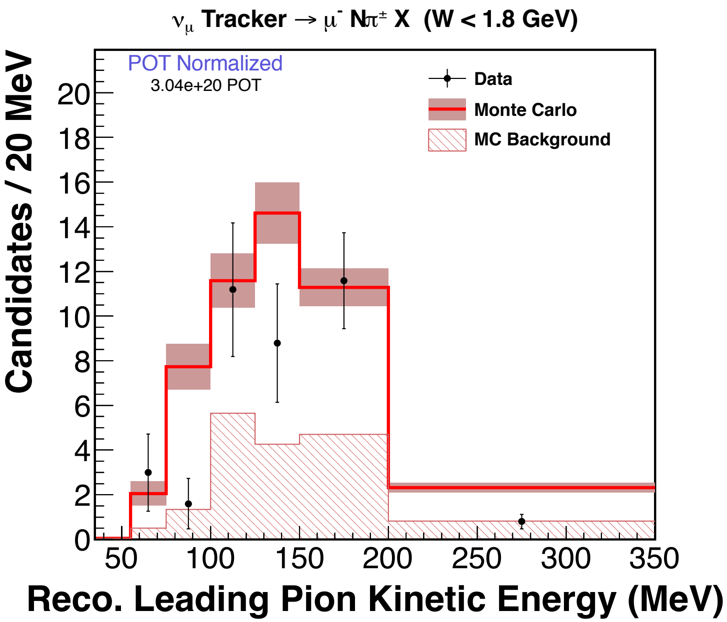
Future Pion Measurements in MINERvA

- See Aaron Mislivec's talk on coherent pion production!

- Full suite of (anti)neutrino resonant pion 1D and 2D differential cross sections
  - As statistics allow

- Pion production 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

- **First neutrino pion production measurement from MINERvA:**
  - Measured delta resonance dominated differential cross sections with respect to pion energy and angle
  - Paper is in preparation and we hope to submit soon

- MINERvA data prefer the GENIE model with FSI

- MINERvA and MiniBooNE data are inconsistent when compared using the GENIE model

- Most models do a good job of reproducing the shape of the MINERvA KE distribution, though have some trouble with the location of the peak

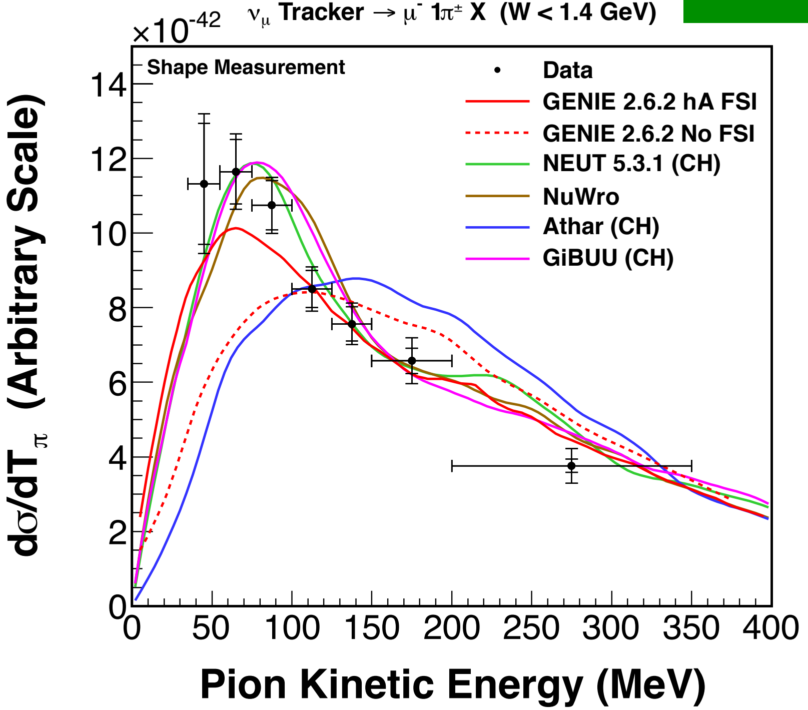
- Modeling the MINERvA angle distribution at $W < 1.4$ GeV is a bit more difficult

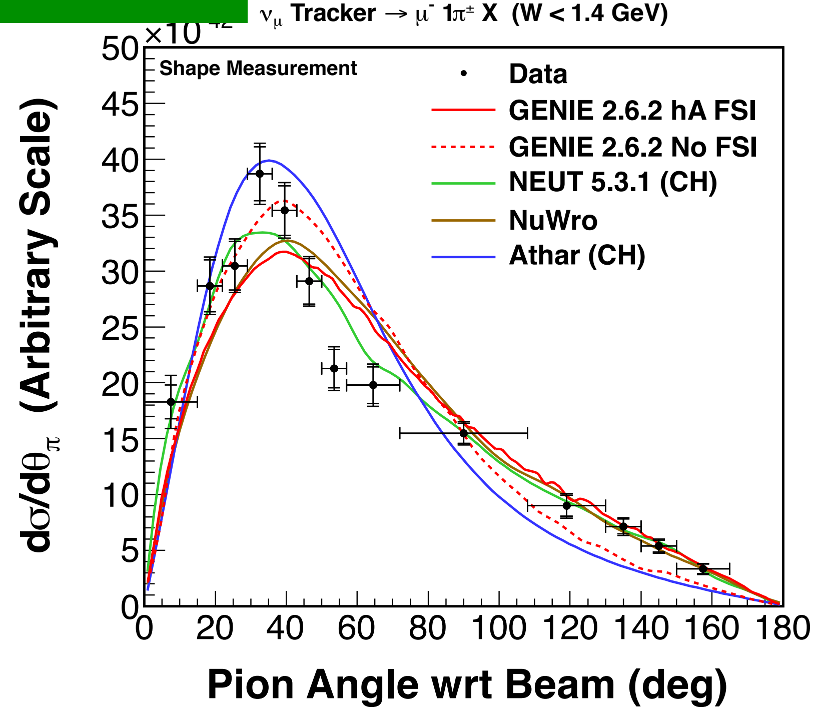
- More MINERvA pion measurements are underway and coming soon!

Back Ups

Shape Results – Model Comparisons

PRELIMINARY

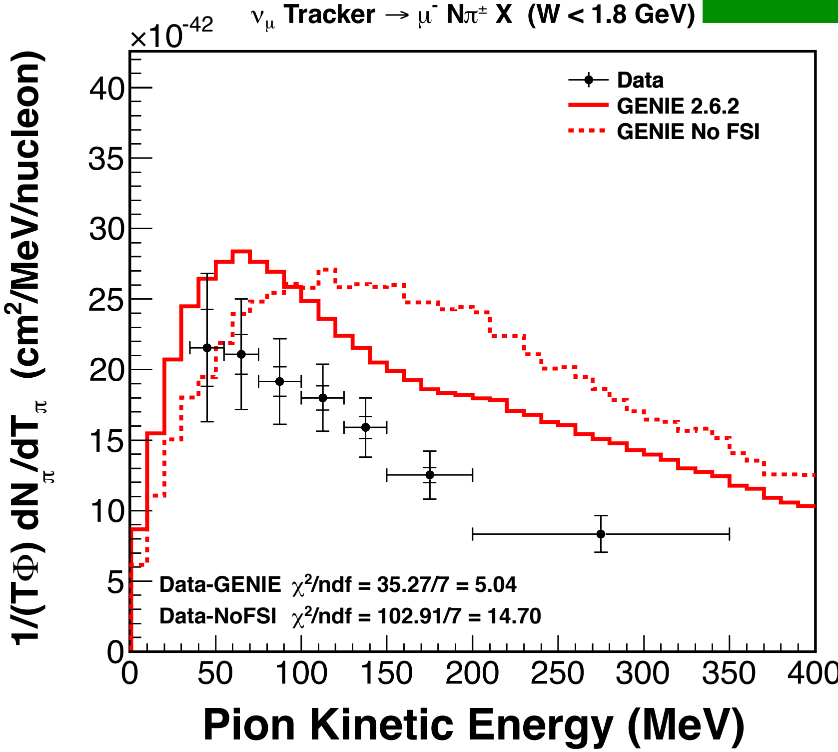


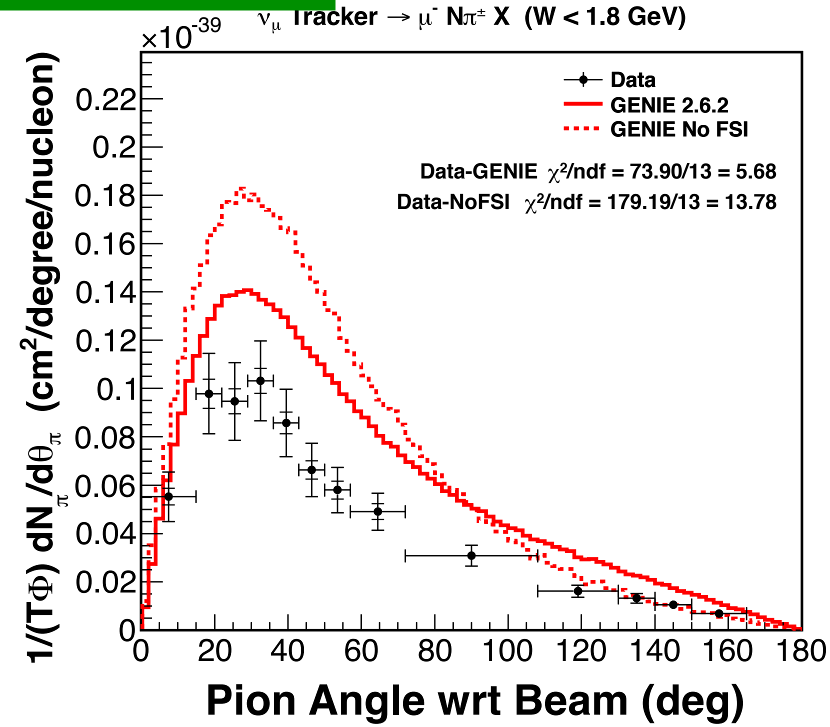


Normalize all models to integral of data

Results, W < 1.8 GeV

PRELIMINARY

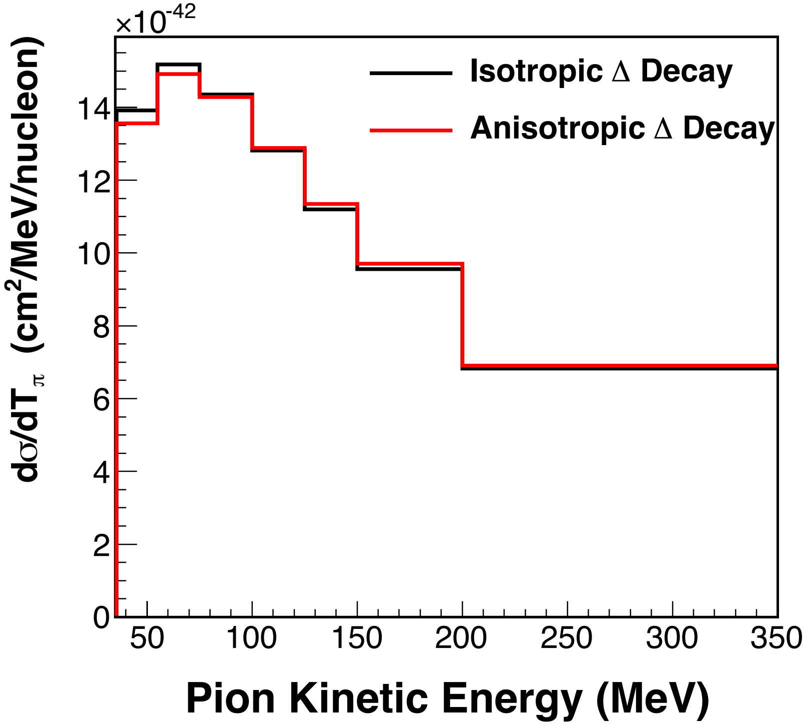


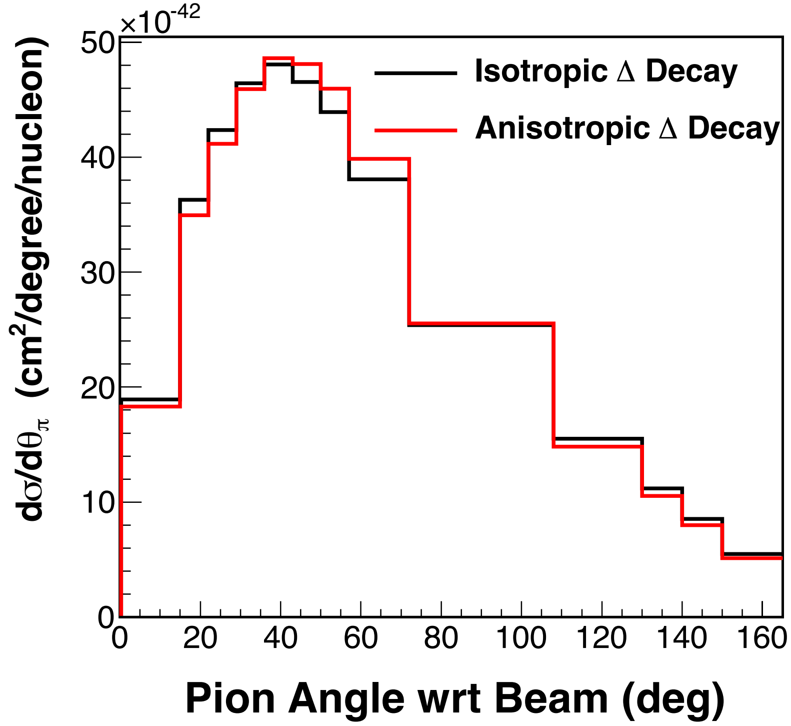


Another version of the analysis, allowing for multiple pions in the final state and higher order resonances: W < 1.8 GeV

Delta Decay Model

Compare GENIE default model (isotropic) to an anisotropic model



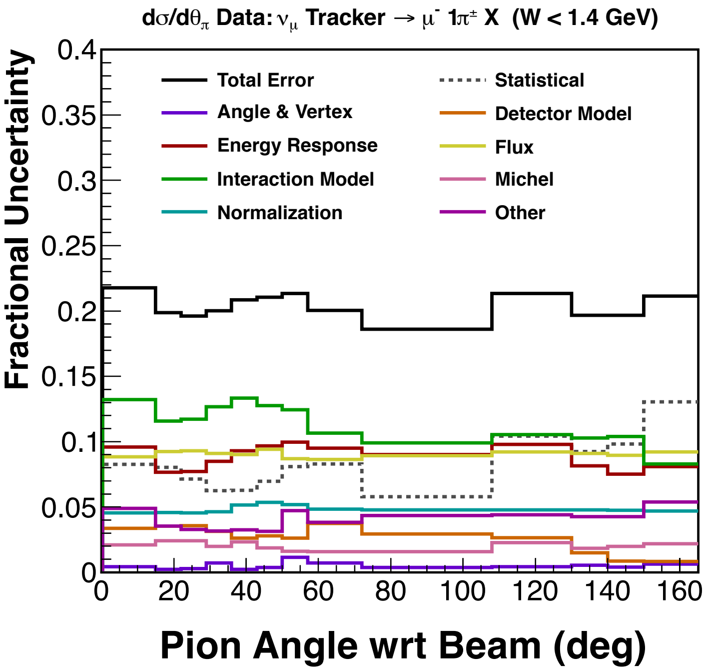


Shape Model Comparison Normalizations

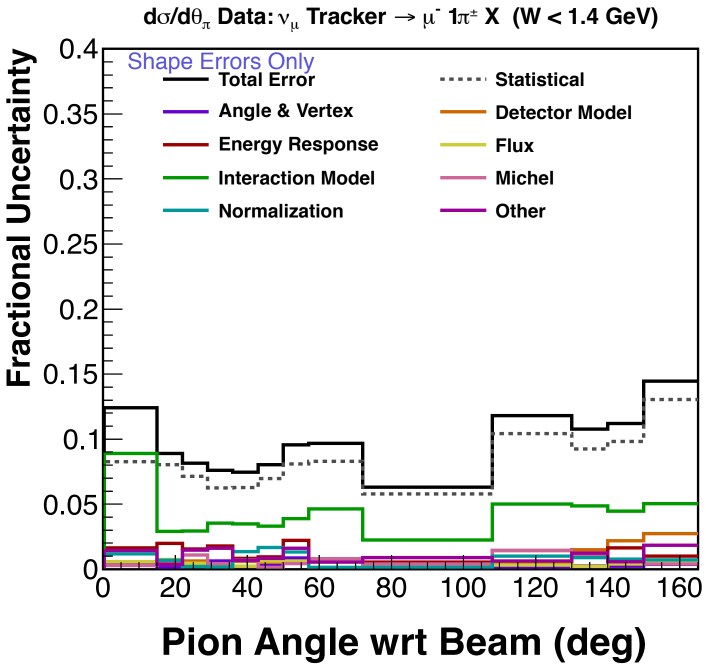
Shape normalization of 1-Pion analysis distributions
(relative to GENIE in parentheses)

Model	T_π Normalization Factor	θ_π Normalization Factor
GENIE with FSI	0.66 (1)	0.66 (1)
GENIE no FSI	0.54 (0.82)	0.54 (0.82)
Neut	0.91 (1.38)	0.86 (1.3)
NuWro	0.86 (1.30)	0.83 (1.26)
Athar	0.95 (1.44)	1.11 (1.68)
GiBUU	0.74 (1.12)	N/A

θ_π Error Summary



Shape Only

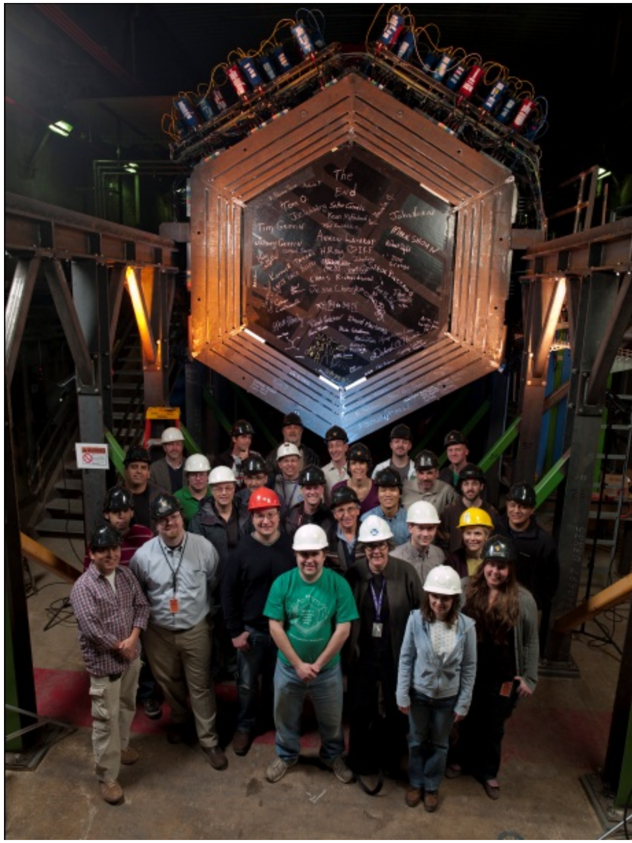


MINERvA Experiment

Collaboration of ~65 Nuclear and Particle Physicists

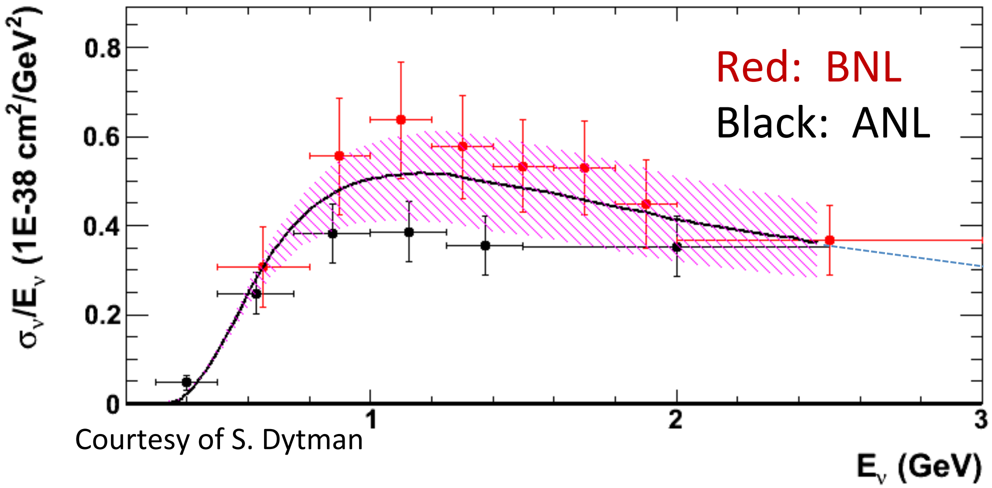
University of California at Irvine
Centro Brasileiro de Pesquisas Físicas
University of Chicago
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Massachusetts College of Liberal Arts
University of Minnesota at Duluth

Universidad Nacional de Ingeniería
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh / SLAC
University of Rochester
Rutgers, The State University of New Jersey
Universidad Técnica Federico Santa María
Tufts University
William and Mary



Pion Models & Deuterium Data

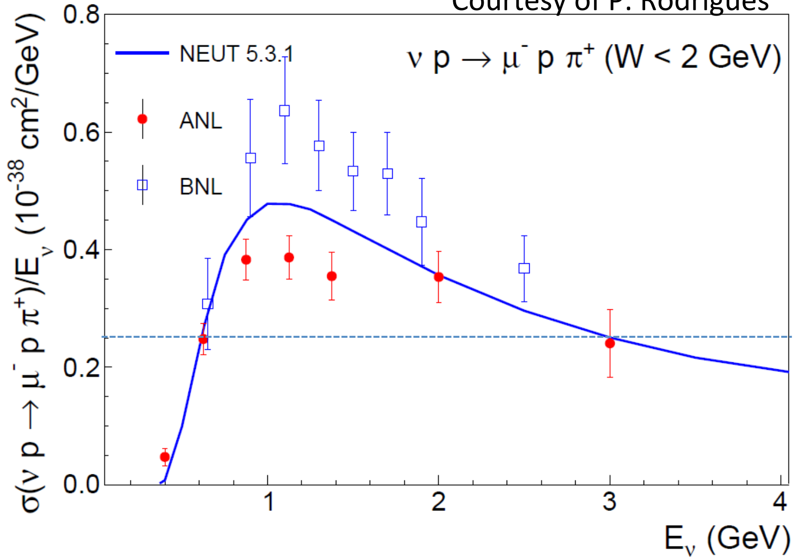
ν_μ CC1π^+ ($\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$) GENIE – with estimated systematic error



Courtesy of S. Dytman

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

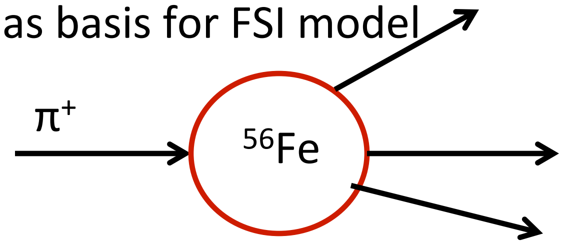
Courtesy of P. Rodrigues



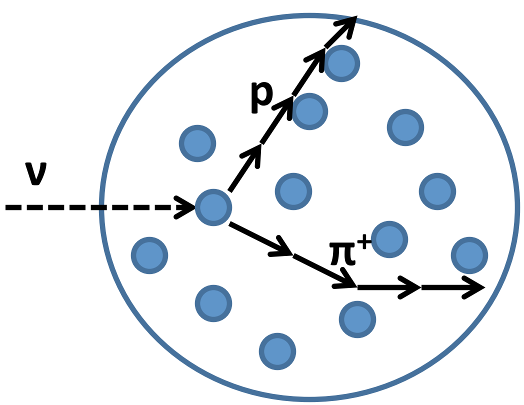
- GENIE and Neut are fairly consistent at lower energies, but appear to diverge by ~20% at MINERvA energies (~3 GeV)

Pion Models & FSI

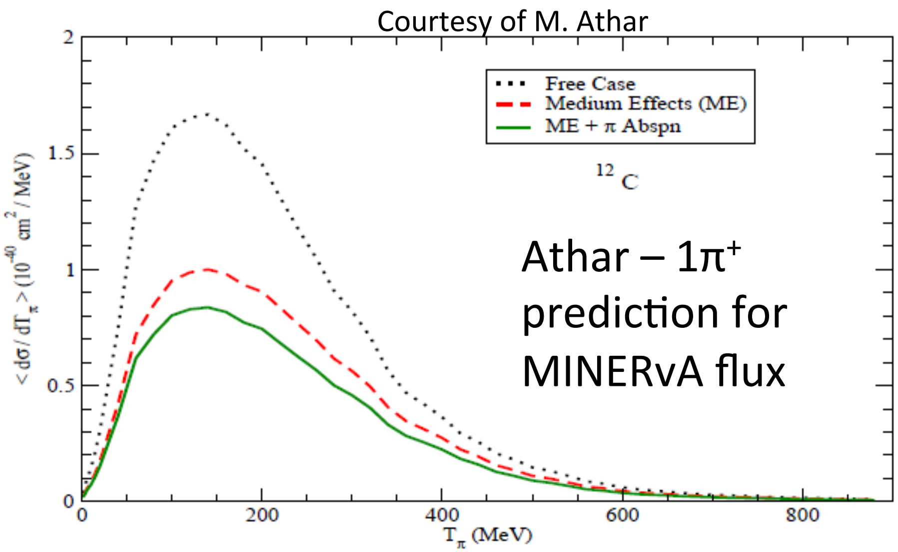
GENIE: Use p,π scattering on Fe data as basis for FSI model



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

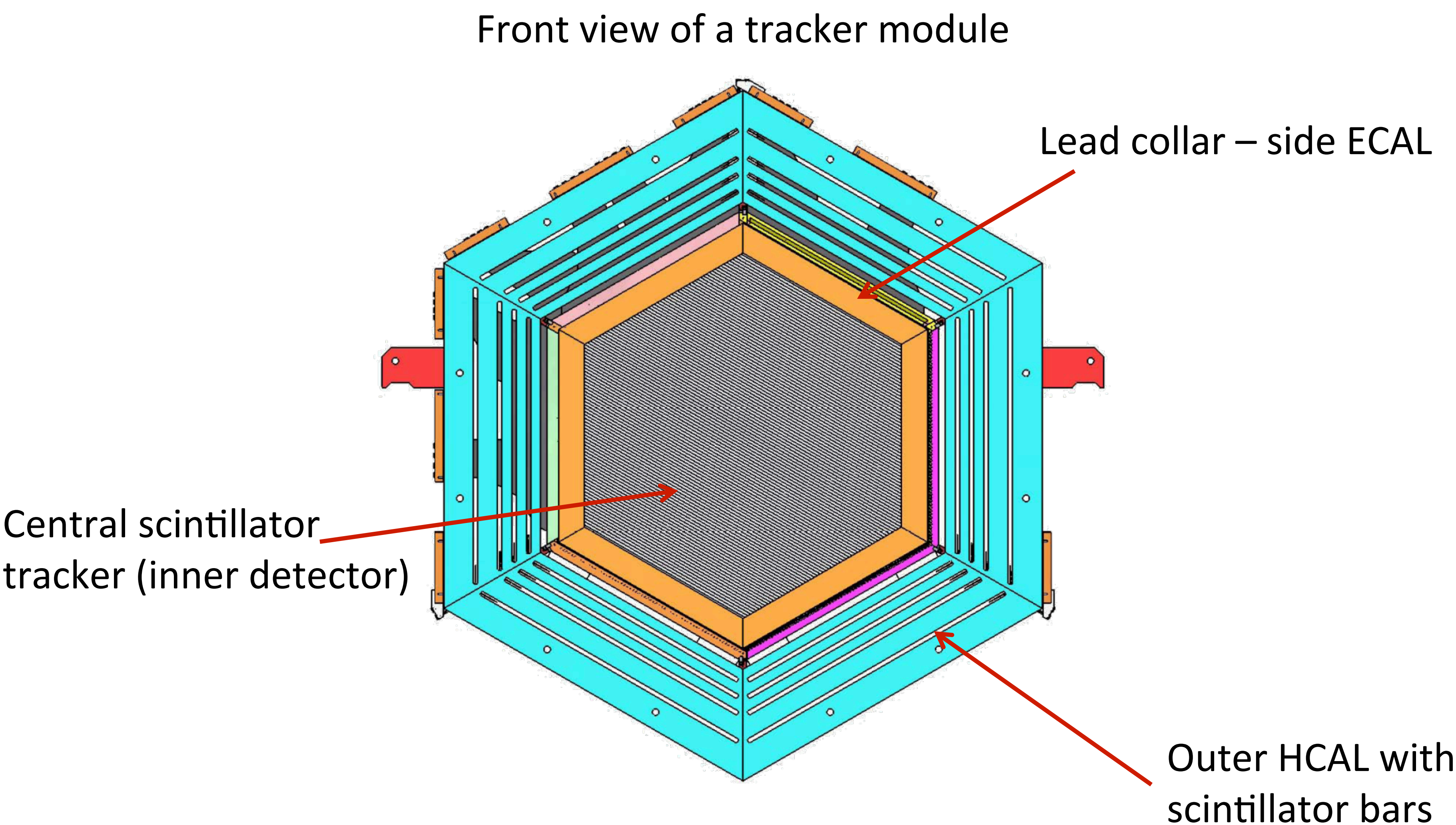


Athar: Use an Eiknonal approximation. Reduces observed pions, but does not significantly change T_π shape

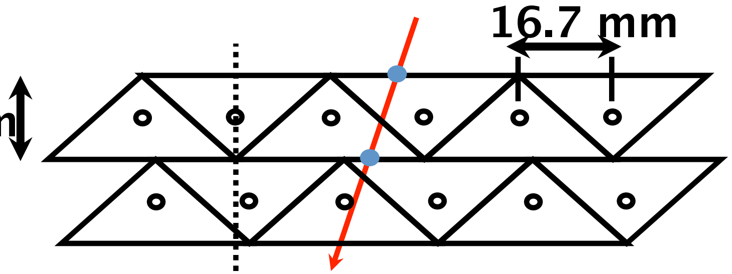


GiBUU: Solve the BUU equation

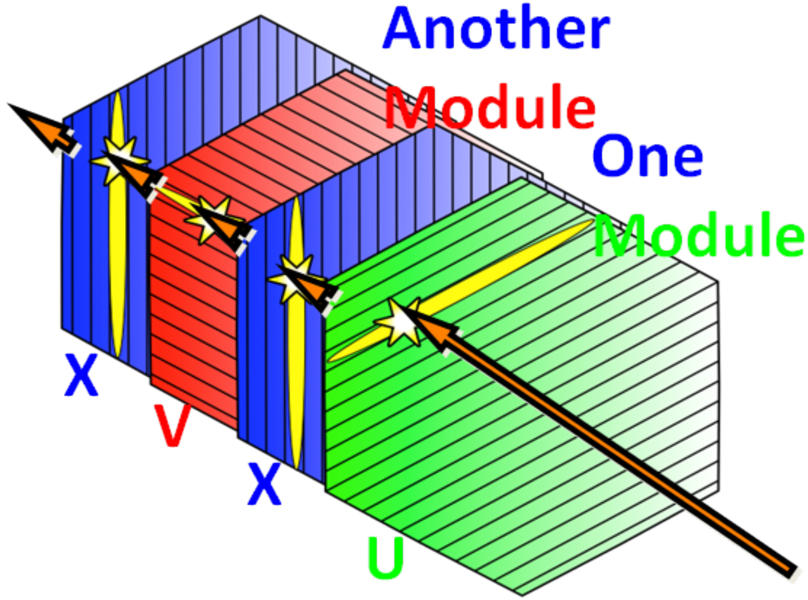
MINERvA Detector

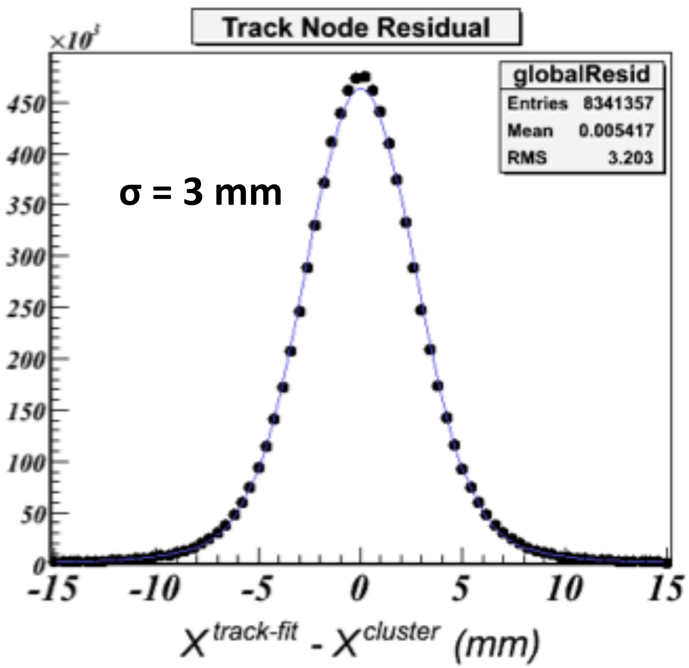


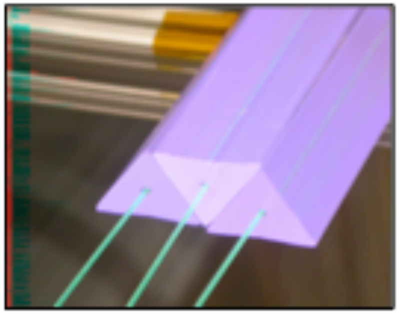
MINERvA Detector



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

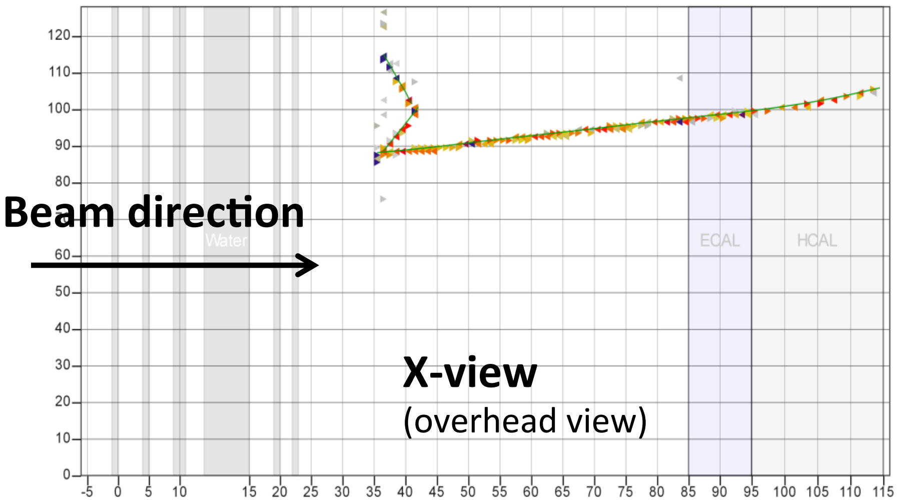




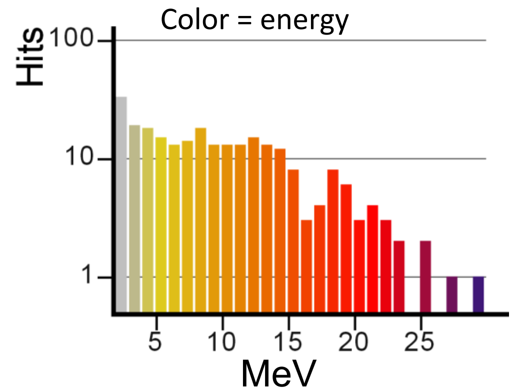


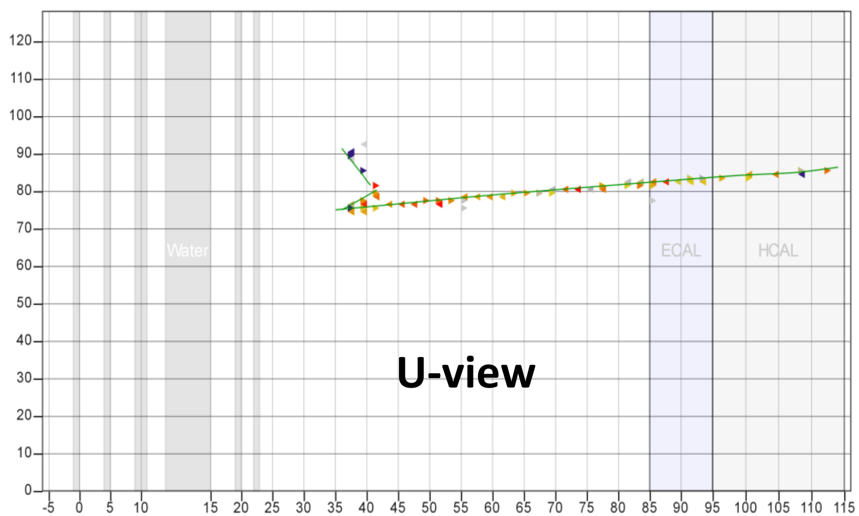
3 different rotated plane views to resolve high-multiplicity events

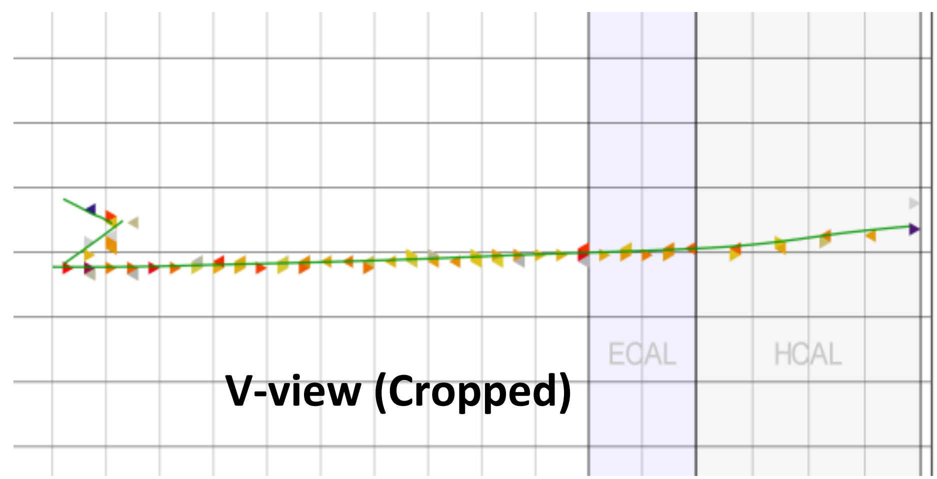
A Day in the Life of a MINERvA Pion



Data Candidate: Scattering π^+

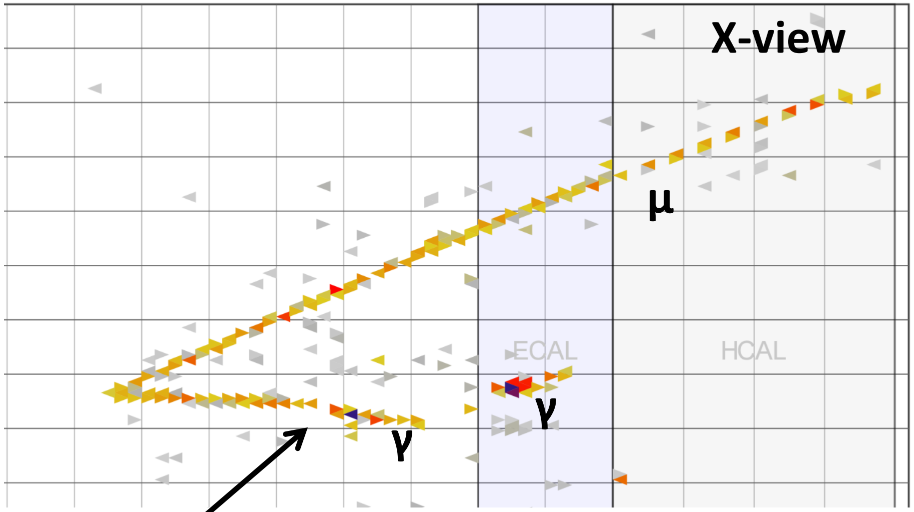






A Day in the Life of a MINERvA Pion

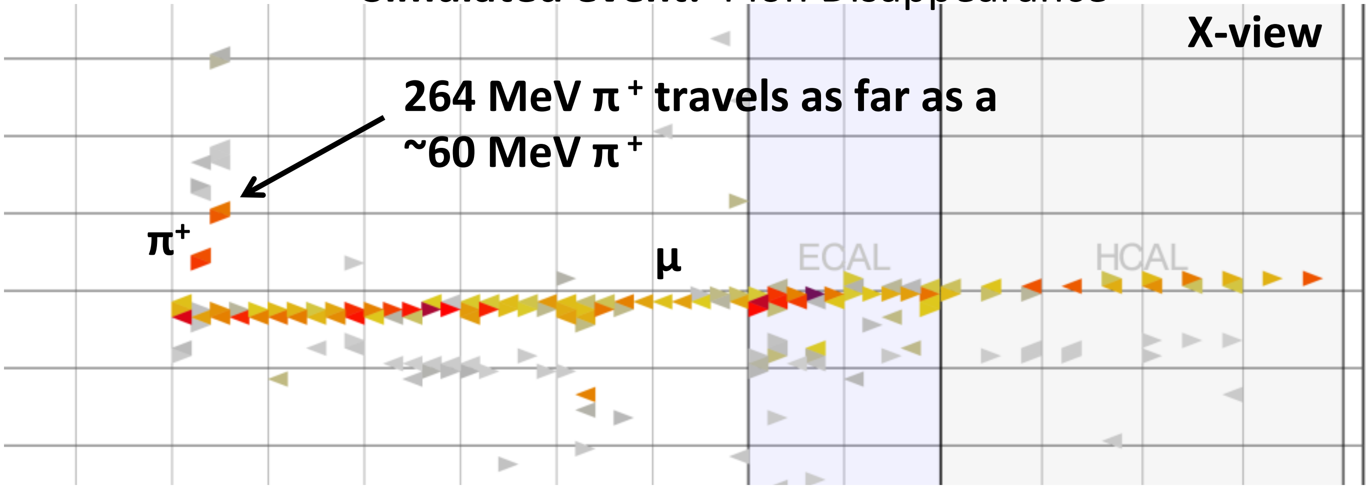
Simulated event: Pion Charge-Exchange



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

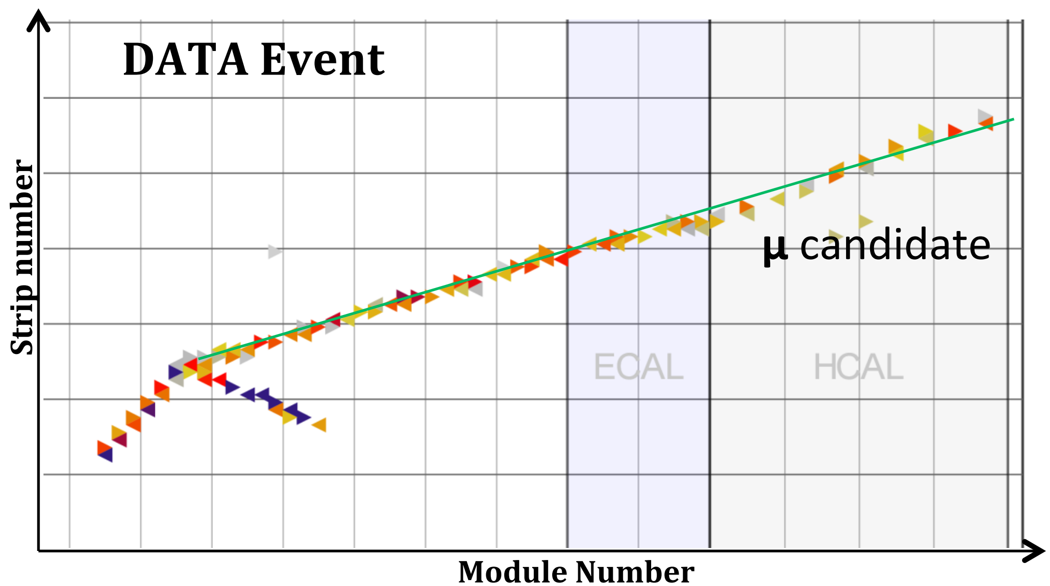
Analysis strategy: Avoid pions that interact in these ways

Simulated event: Pion Disappearance

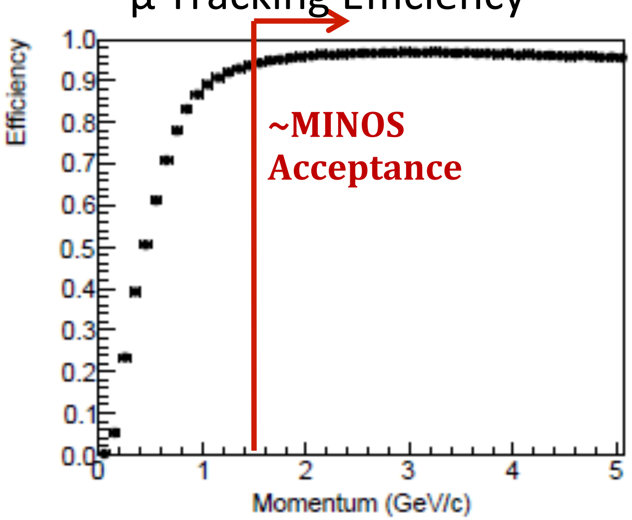


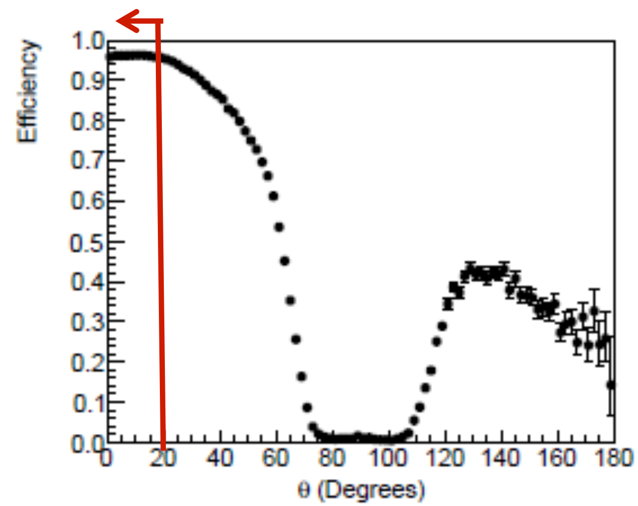
Track Reconstruction

- 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



μ Tracking Efficiency

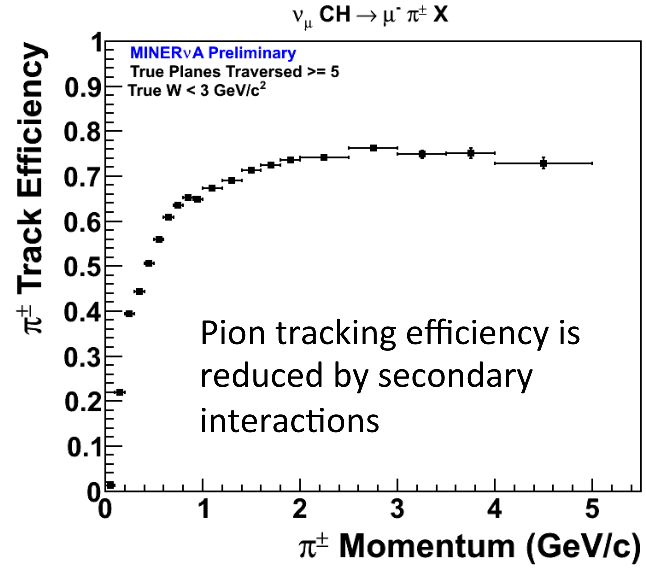


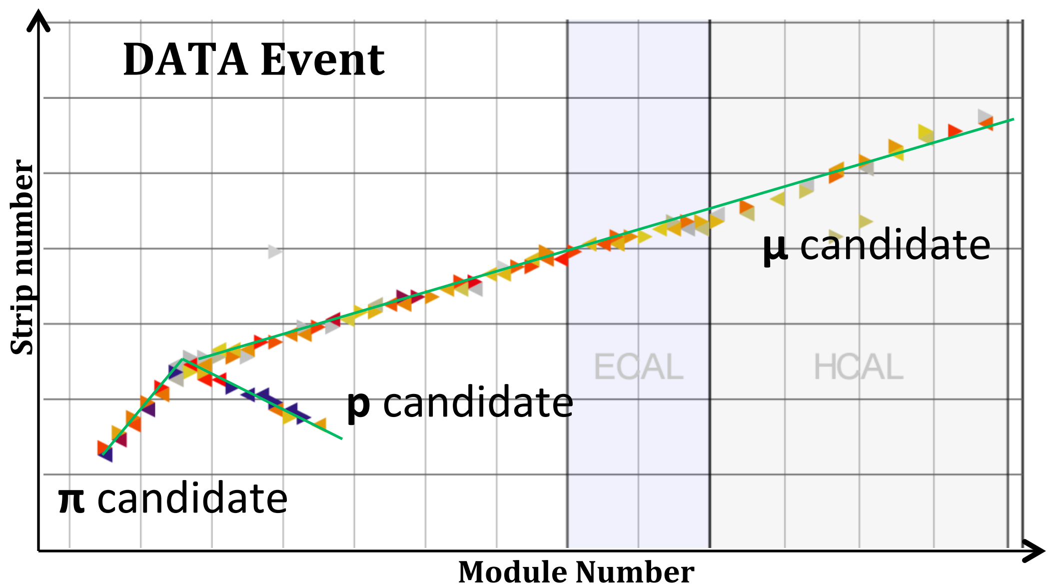


Track Reconstruction

•Next, look for additional tracks at the interaction vertex

•Fit for the interaction vertex using all available tracks



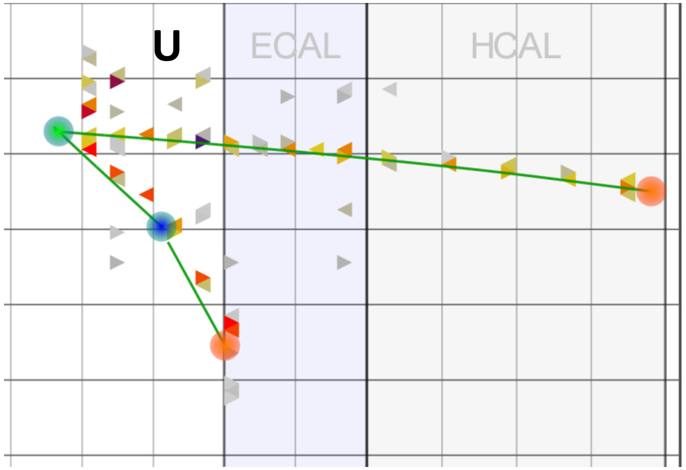


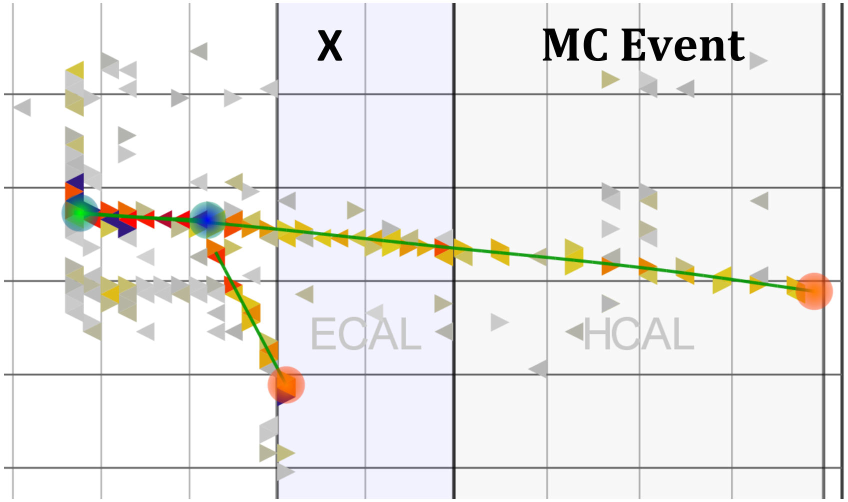
More Complicated Tracking Example

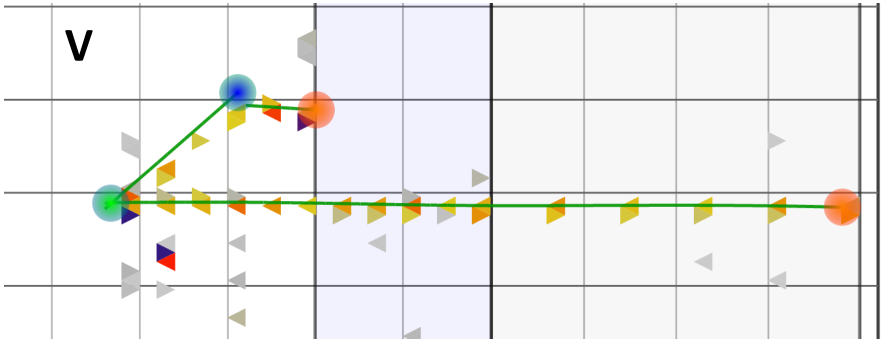
- Find "kinked" tracks by looking at the end of each track

- Overlap is handled correctly in the X view

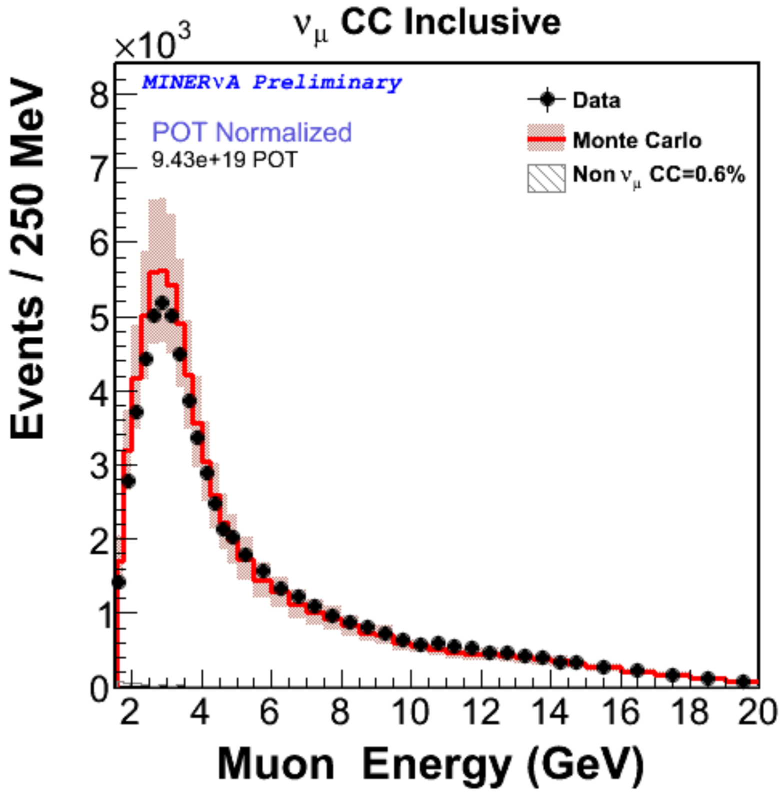
- The pion appears "straight" in the U view and track is divided correctly

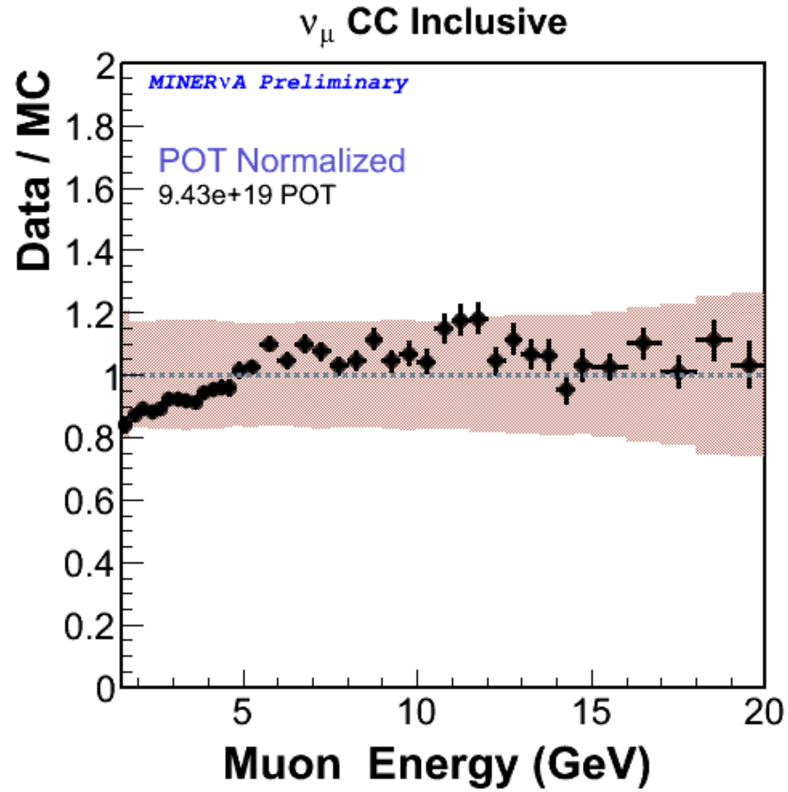






CC Inclusive Muon Energy



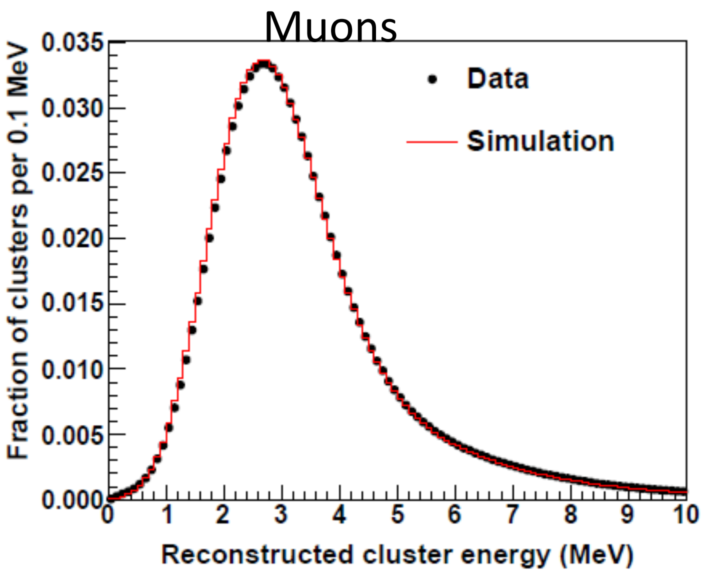


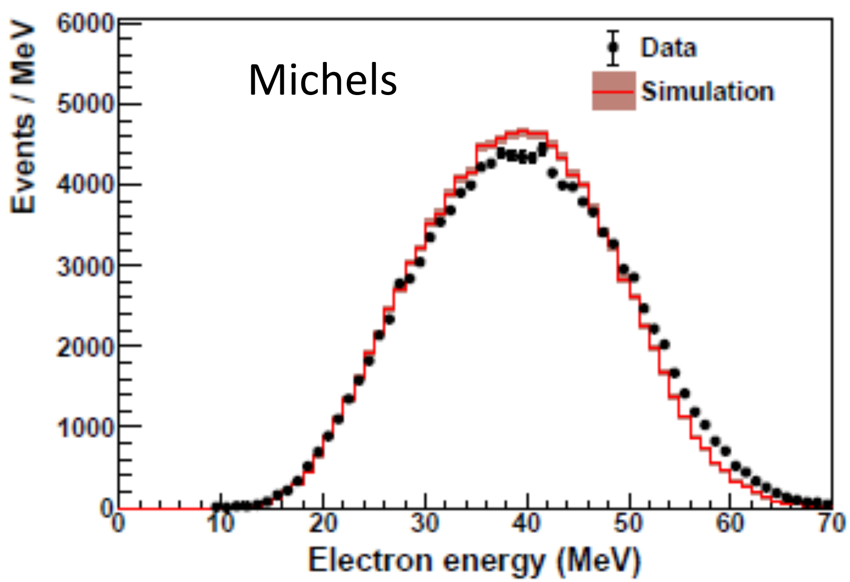
~10% normalization discrepancy between data and simulation in the peak region – dominated by GENIE uncertainties

Detector Calibration

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

Michel electron: $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$

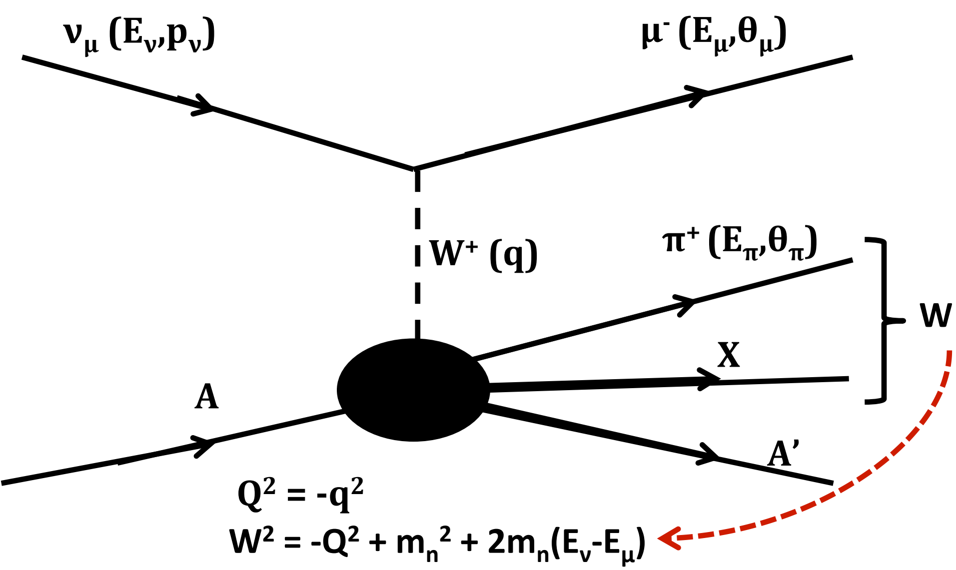




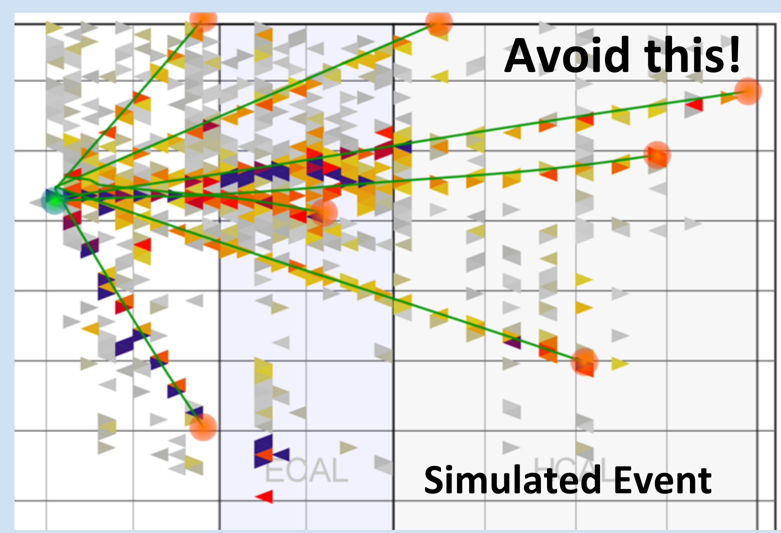
Signal Definition & Event Selection

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

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



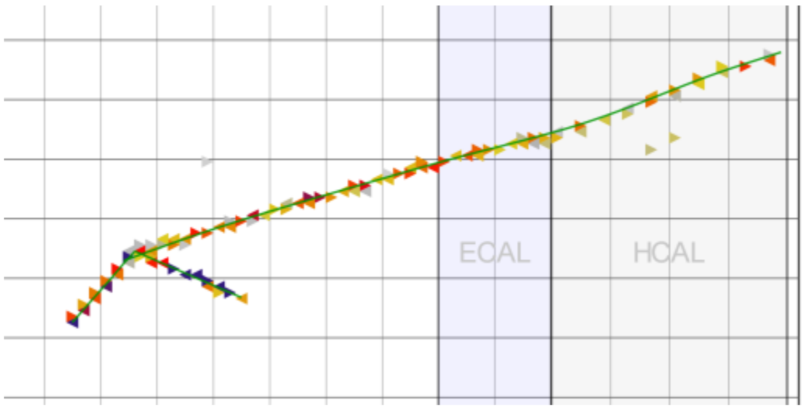
- Other Requirements:
  - 1.5 GeV < E_ν < 10 GeV
  - Invariant hadronic mass (W – not the boson!) is less than 1.4 GeV
- Motivation:
  - Choose a MiniBooNE-like sample
  - Avoid high-multiplicity interactions

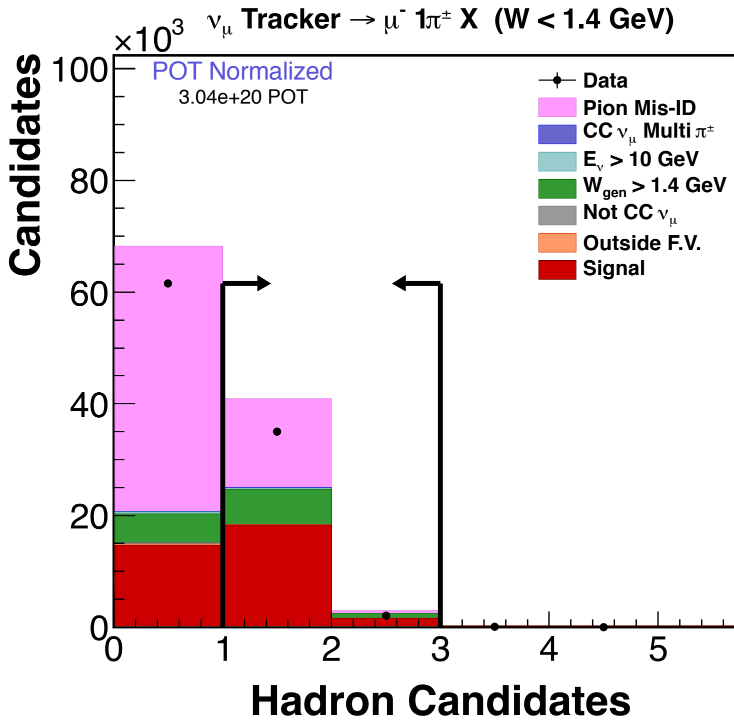


Event Selection - Pion

Find pion candidates:

- Require one or two hadron track candidates



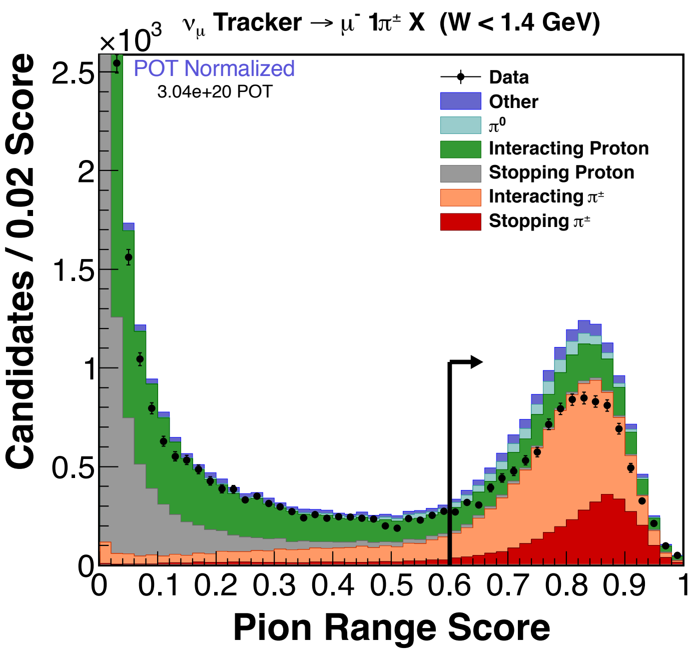


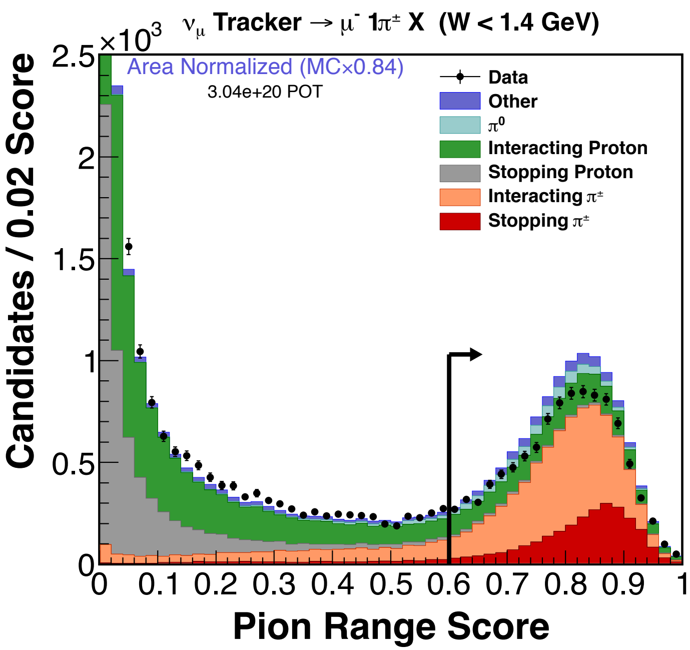
Event Selection – Pion ID

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

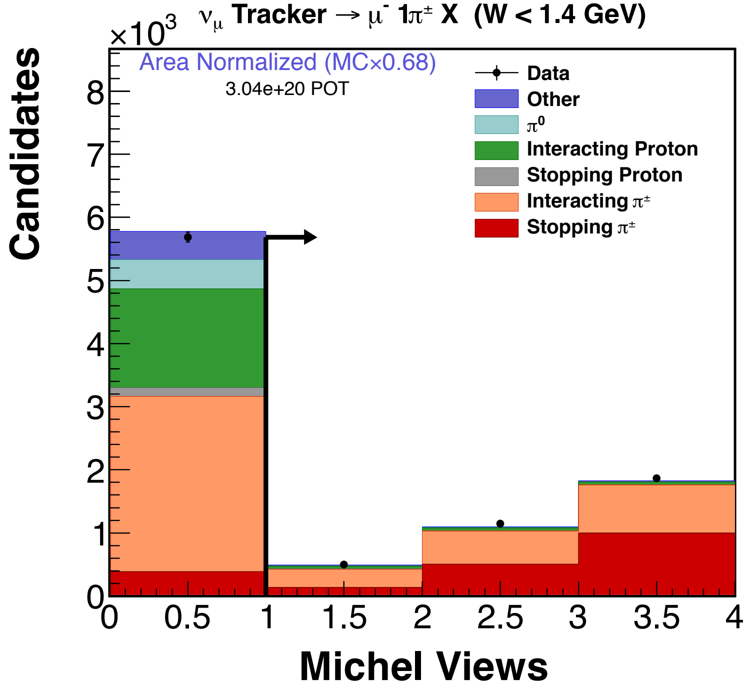
Select a pion (with good energy reconstruction):

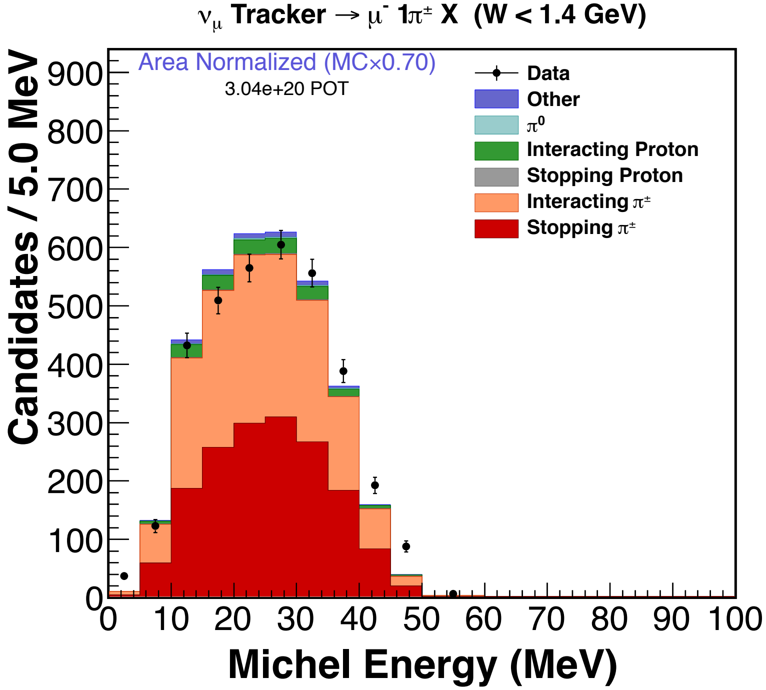
•Select pions that stop and decay in the detector by looking for a Michel electron at the end of the track

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

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

Shape Comparisons

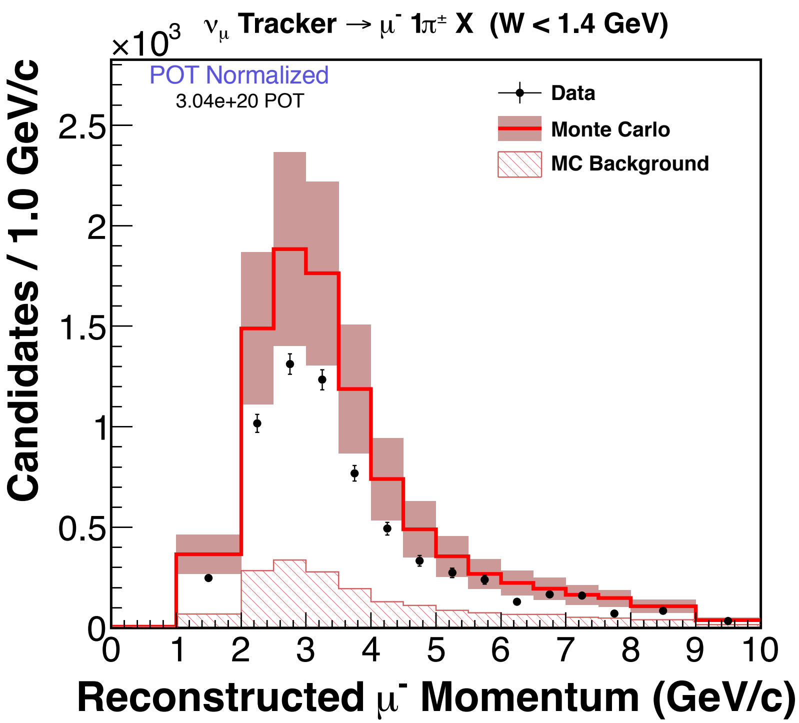


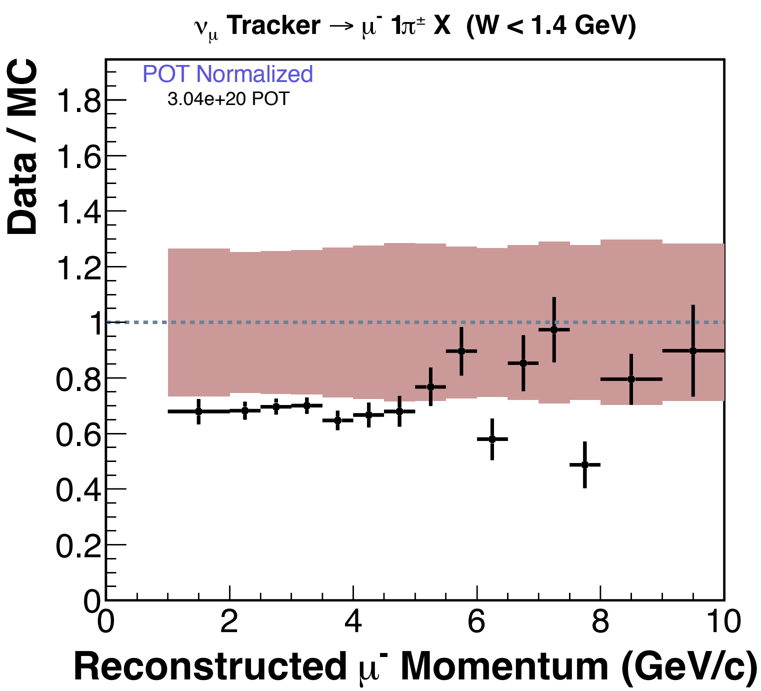


Reconstructed Muon P

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

- We assign errors that effectively cover the disagreement with data

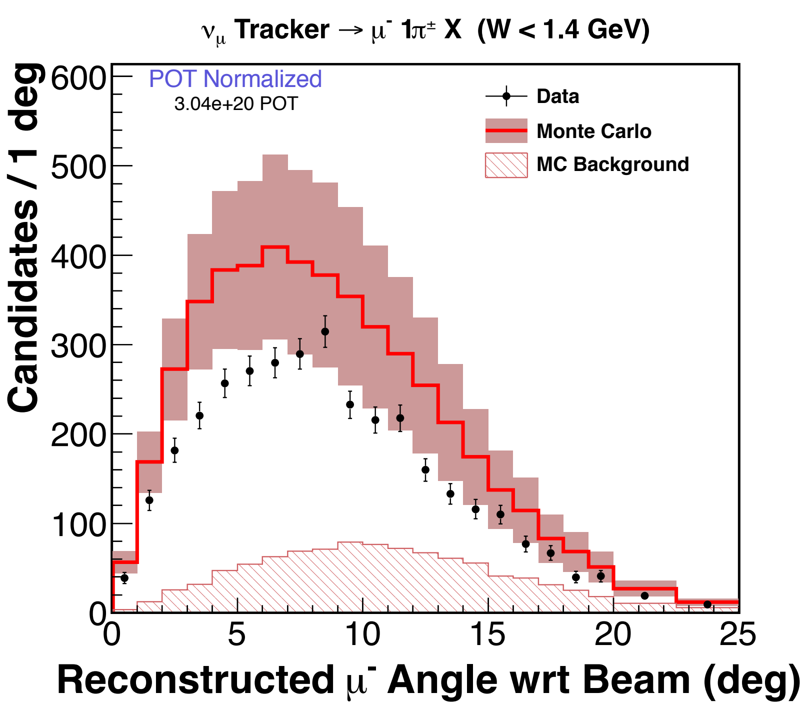


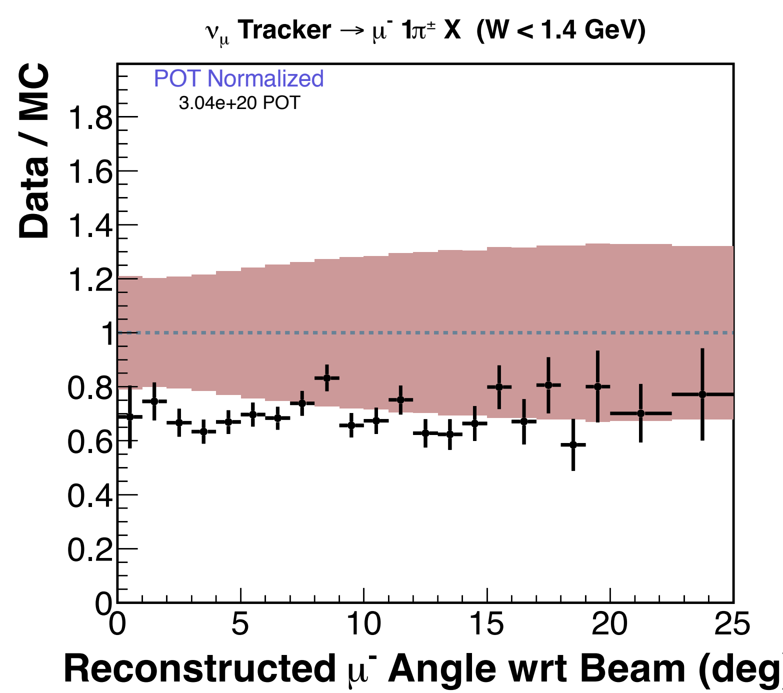


Reconstructed Muon θ

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

- We assign errors that effectively cover the disagreement with data

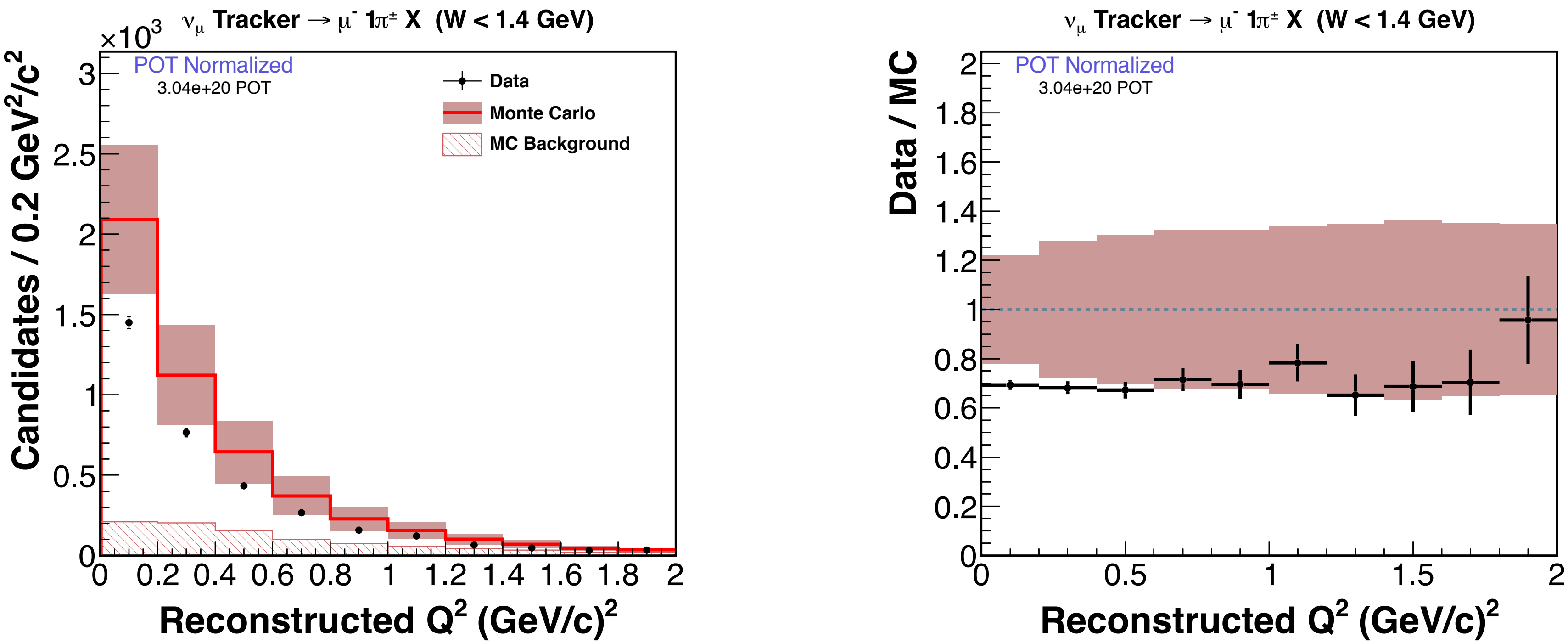




Reconstructed Q^2

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

- We assign errors that effectively cover the disagreement with data



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, targ bin size

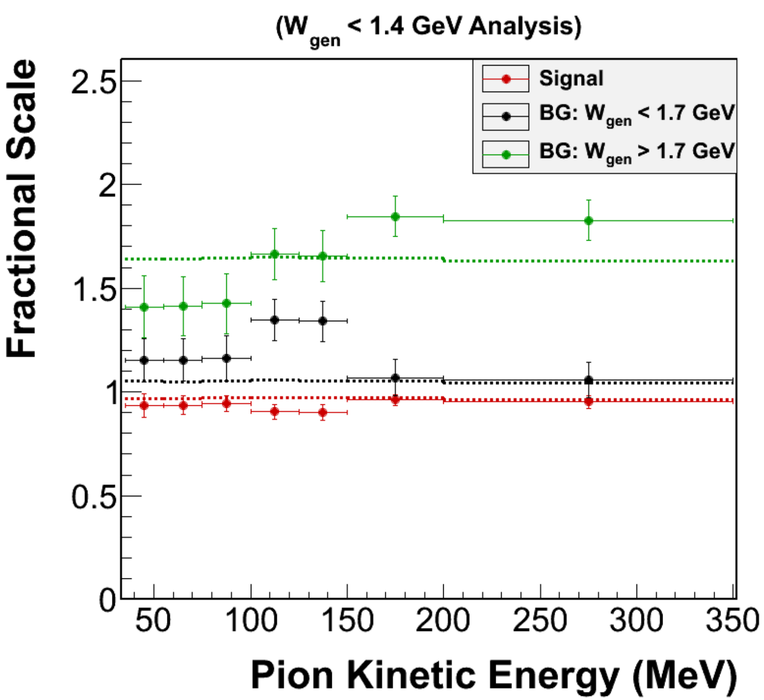
Selection efficiency and acceptance

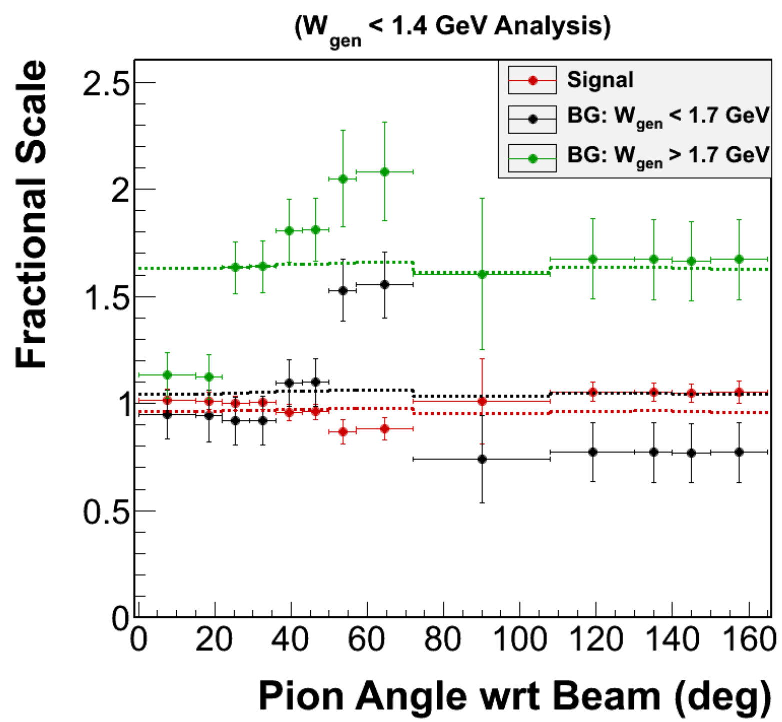
Background Subtraction

•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

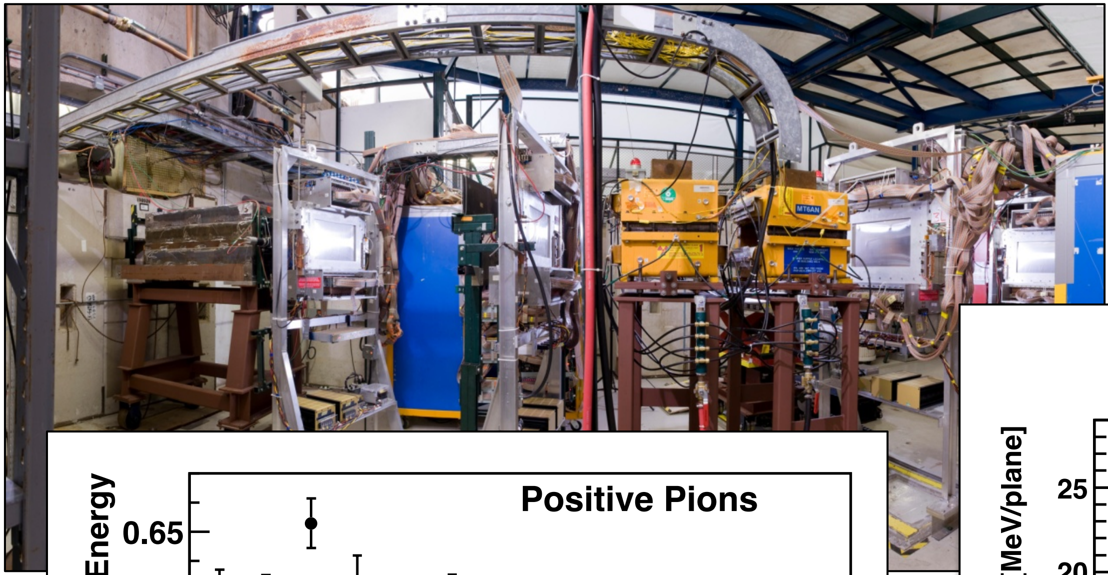
Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% −15%
CCQE Normalization	+20% −15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production) 1.12 GeV	± 20%
M_V (Resonance Production)	± 10%
1pi production from νp / $\bar{\nu} n$ non-resonant interactions	± 50%
1pi production from νn / $\bar{\nu} p$ non-resonant interactions	± 50%
2pi production from νp / $\bar{\nu} n$ non-resonant interactions	± 50%
2pi production from νn / $\bar{\nu} p$ 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%

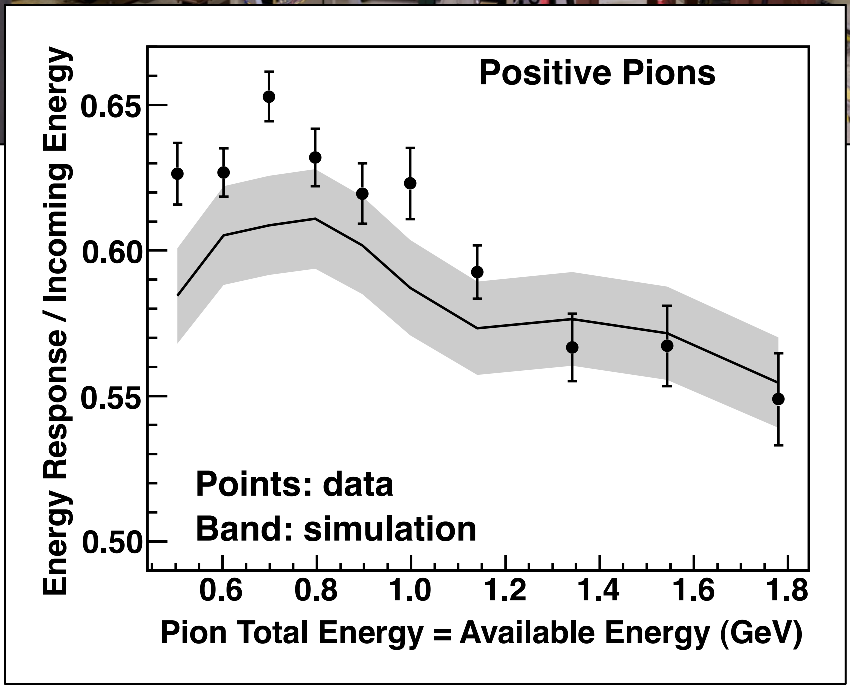
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

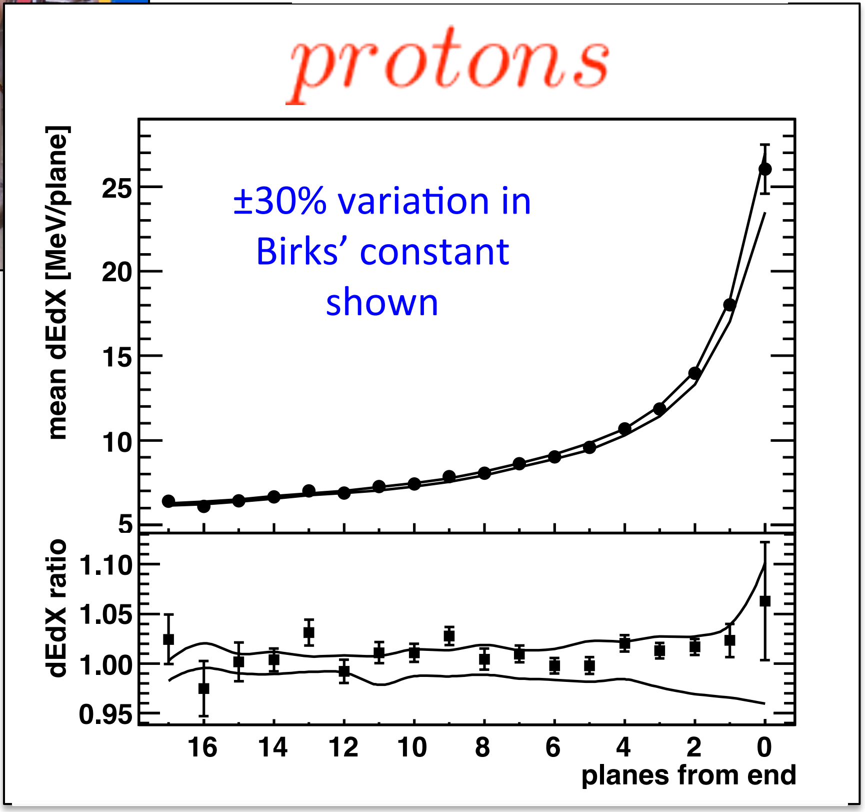
Systematic Errors – Hadron Response



Thanks to AD and MTest!

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





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