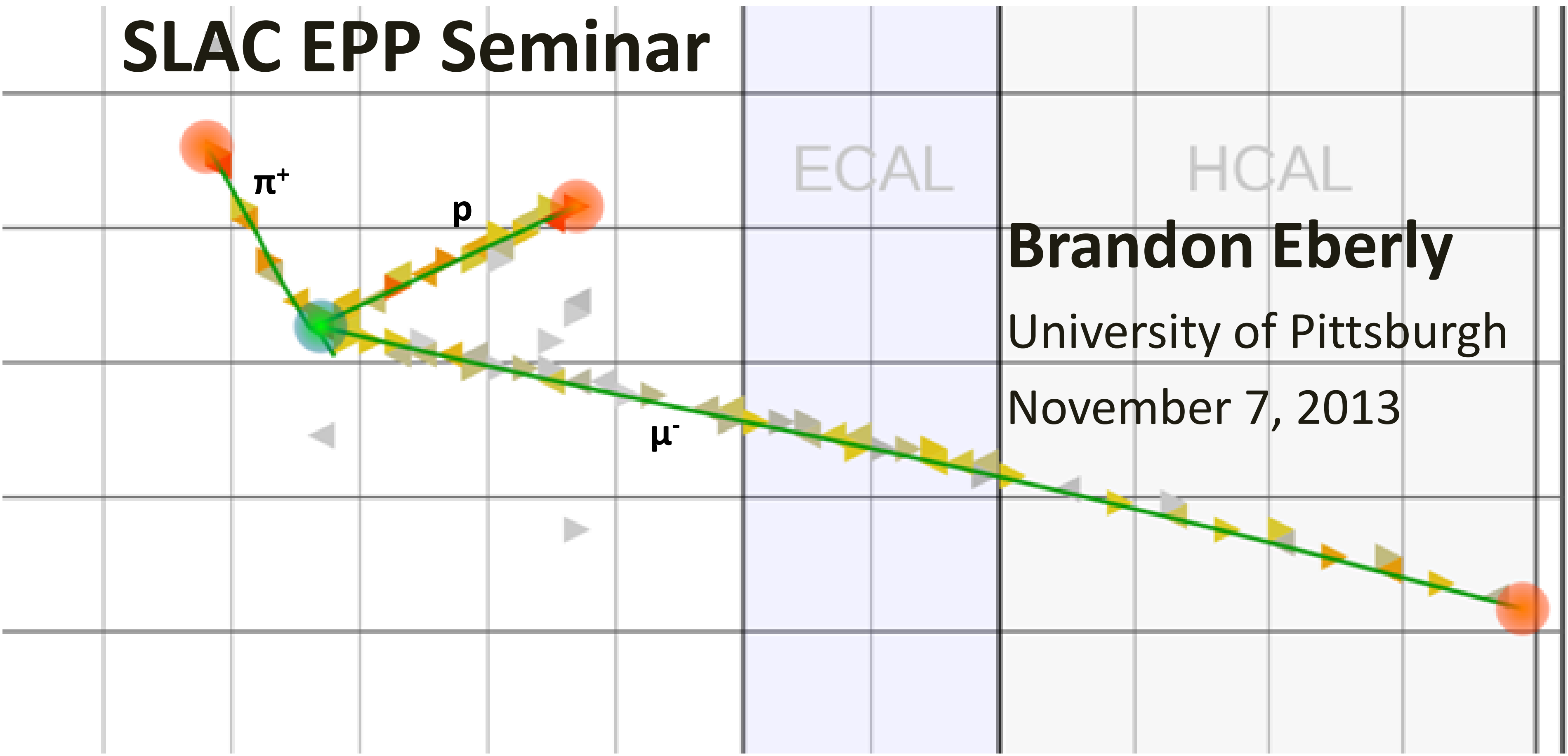
Probing Nuclear Physics with Neutrino Pion Production at MINERvA

SLAC EPP Seminar



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November 7, 2013

Outline

- Motivation – Neutrino Oscillations
- Nuclear Physics Overview
- MINERvA Detector
- MINERvA Reconstruction
- Charged Pion Analysis
- Conclusions

Motivation from Neutrino Oscillation Physics

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:

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

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

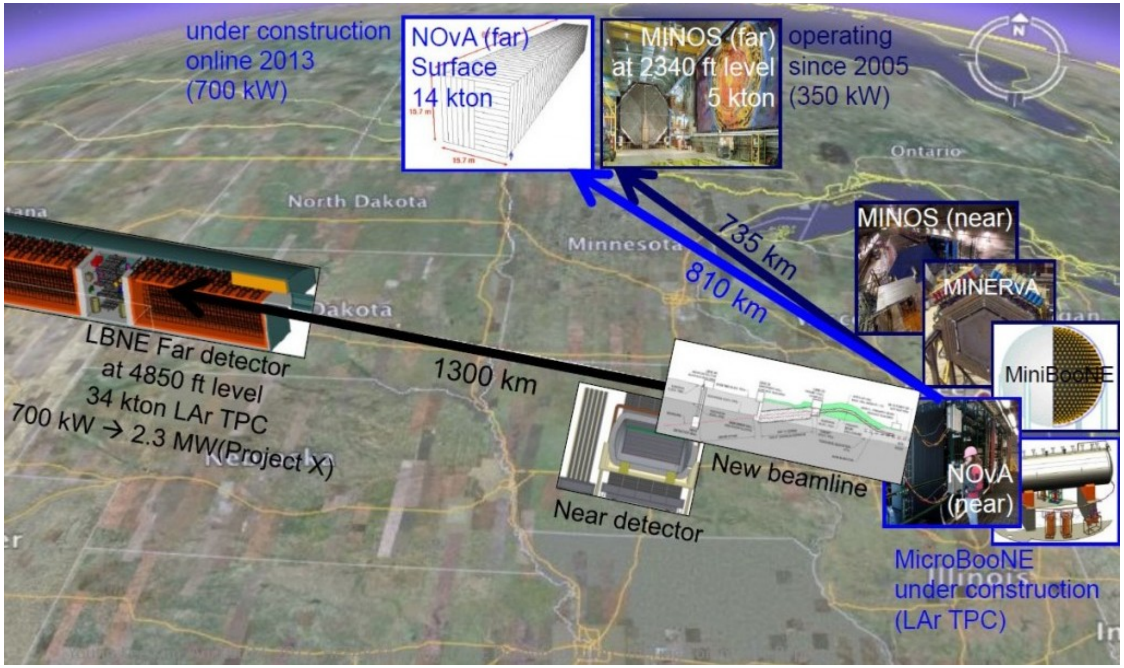
The Challenge of Neutrino Oscillations

- 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?

Long Baseline Oscillation Experiments

- Can measure the mixing angles, mass-squared differences, mass hierarchy, and CP violation with long baseline experiments

- Ingredients:
  - Intense neutrino beam
  - **MASSIVE** detector **FAR** away from the beam source

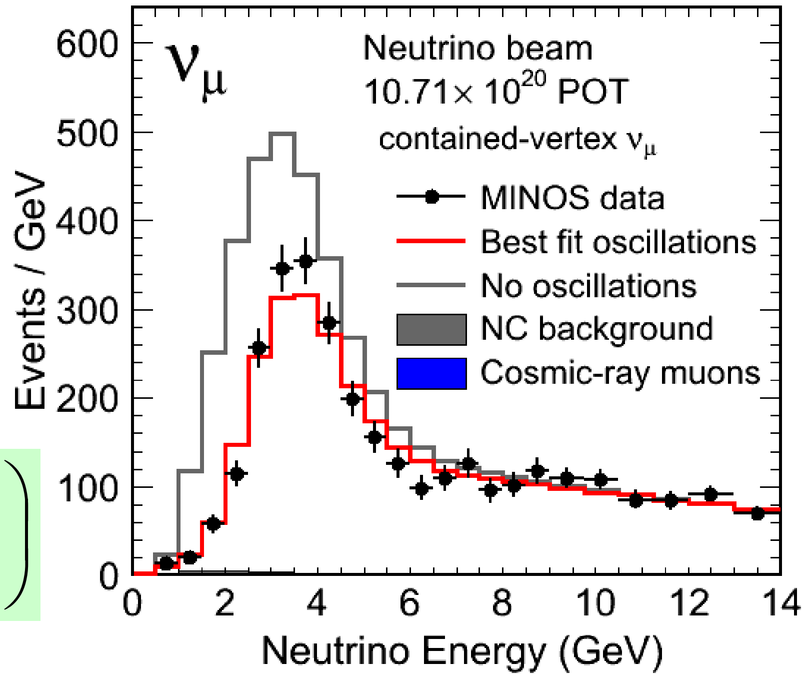


Long Baseline Oscillation Experiments

•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

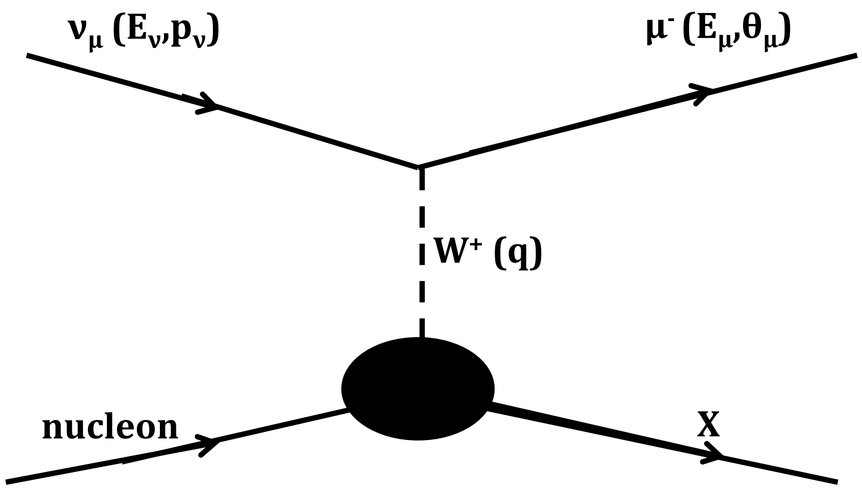
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m_{23}^2 \frac{L}{E}\right)$$



MINOS far detector neutrino energy spectrum:
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.)		
$x_{CCother}$	0.2	0.1
x_{SF}	3.3	5.7
p_F	0.3	0.0
x^{CCcoh}	0.2	0.2
x^{NCcoh}	2.0	0.6
$x^{NCother}$	2.6	0.8
x_{ν_e/ν_μ}	1.8	2.6
W_{eff}	1.9	0.8
$x_{\pi-less}$	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 muon energy and do one of:
  - Measure the hadronic recoil energy calorimetrically (MINOS)
  - Restrict to a two body final state and use the muon kinematics (T2K)

- But then systematics are evaluated…

The Influence of Nuclear Physics

•Listen to our friend Boromir!

•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!

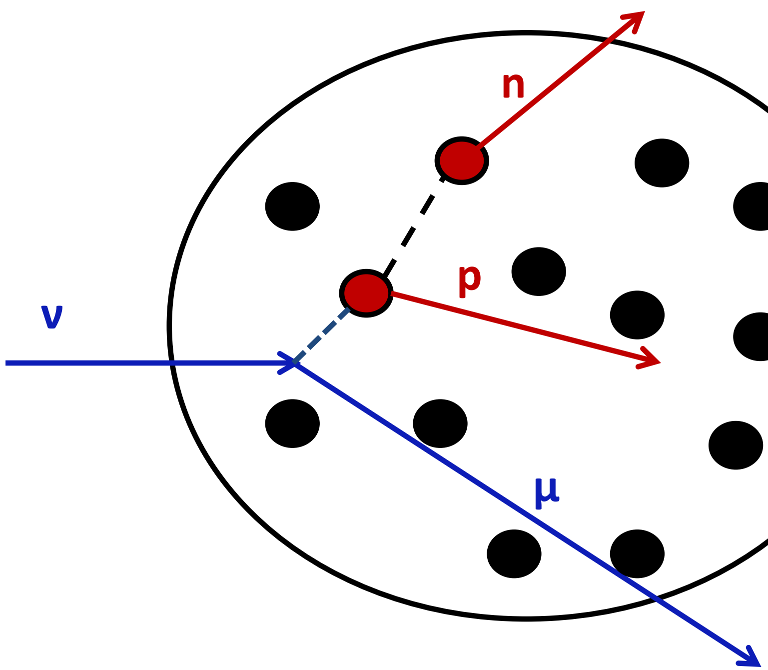
If the current knowledge of neutrino-nucleus interactions does not improve, future experiments like LBNE will have a difficult time meeting their physics goals!

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

Nuclear Physics Overview

Modification of Initial Interaction

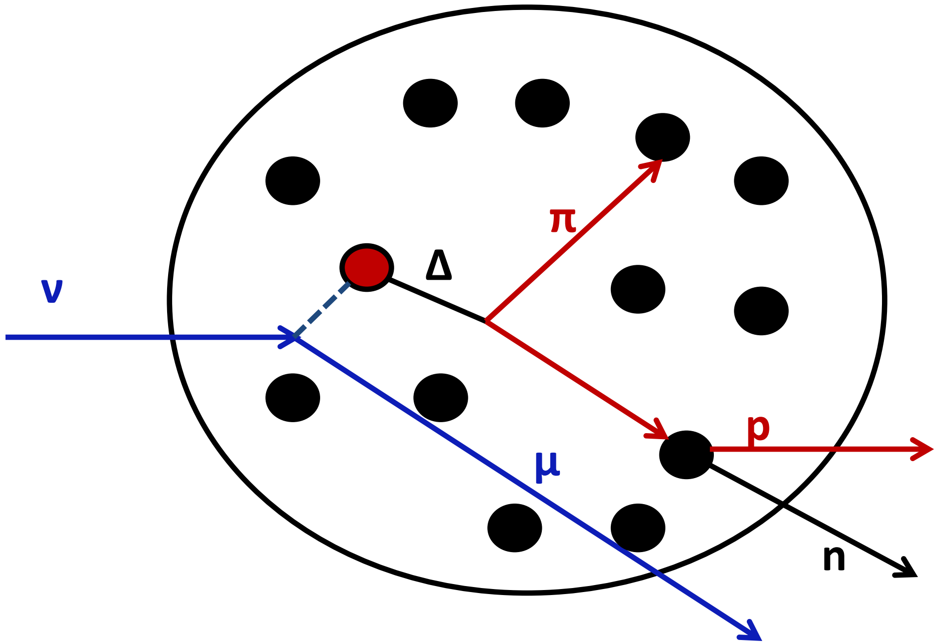
- Nuclear medium modifies the initial neutrino interaction
    - Binding energy: lower effective nucleon mass
    - Fermi motion: nucleons are not at rest
    - Q^2 dependence: interact with one nucleon or multiple nucleons?
    - Meson exchange currents: eject a correlated pair of nucleons



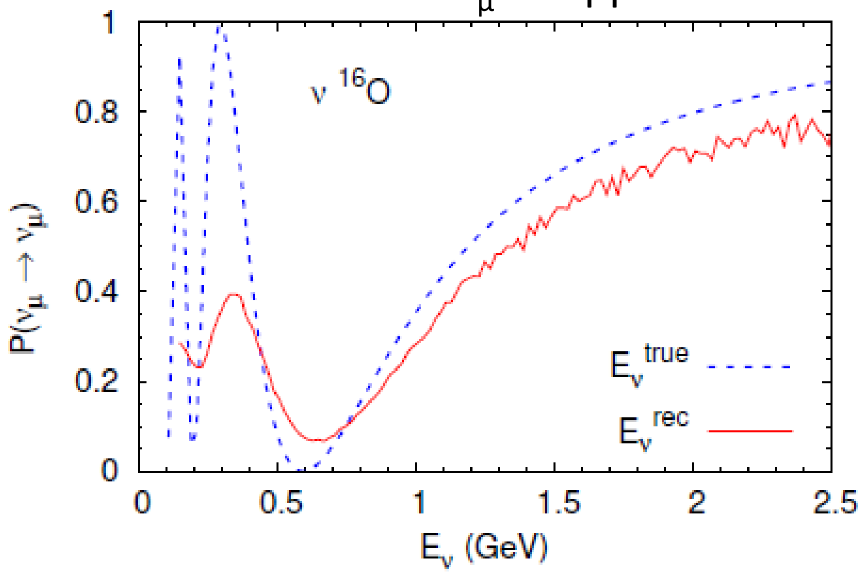
Final State Interactions

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

- Example:
  - Proton knocks out a neutron
  - Pion is absorbed (~25% of the time!)



Simulated T2K ν_μ disappearance



Lalakulich *et al*: arxiv 1208.3678v2

Final State Interaction Models

- Theoretical calculations are very difficult
  - Quantum mechanical models are basically impossible

- Neutrino oscillation experiments use neutrino event generators (computer simulations) to understand neutrino-nucleus interactions
  - Need to be fast – produce millions of events
  - Simulate an intra-nuclear cascade with tree-level cross sections

- Theorists can adopt more sophisticated, but still semi-classical approaches

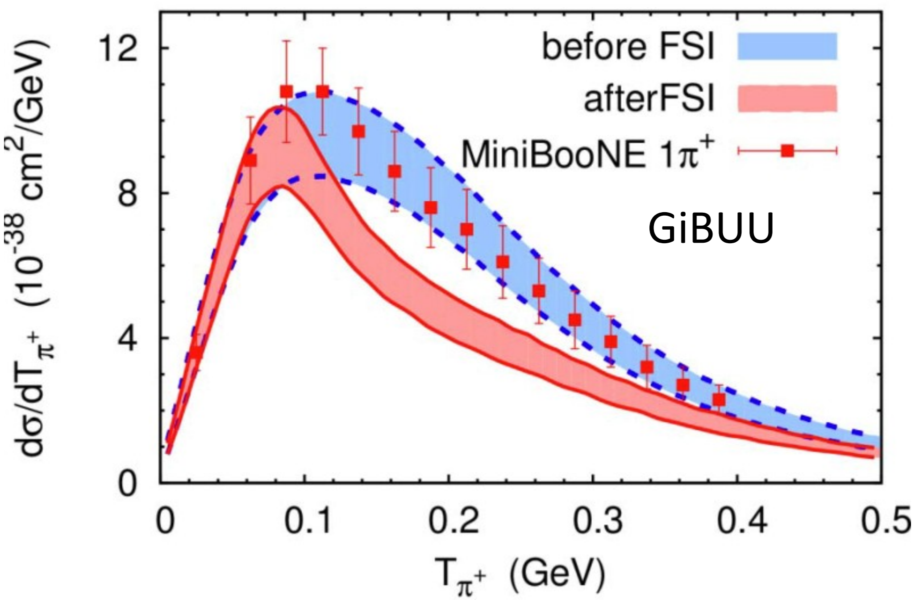
- Example: GiBUU FSI - solve the Boltzmann-Uehling-Uhlenbeck (BUU) equation
  - Coupled integro-differential equations – not good for event generators

Recent Discrepancies

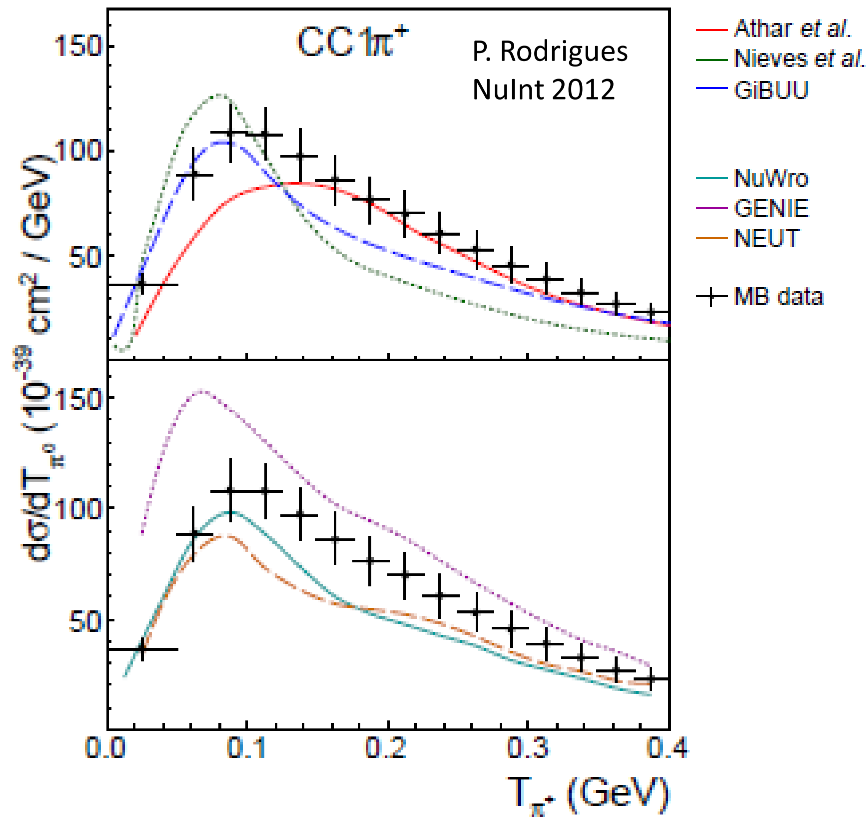
- The MiniBooNE experiment recently published a suite of cross sections for neutrino charged current charged single pion production on mineral oil:

$$\nu_\mu CH_2 \rightarrow \mu^- 1\pi^+ X$$

- Data prefer models with FSI turned off!



O. Lalakulich et al, NuInt12 Proceedings



Final State Interactions Summary

- Neutrino oscillation experiments need to understand final state interaction strength

- The shape and normalization of the pion energy differential cross section are powerful indicators of FSI strength

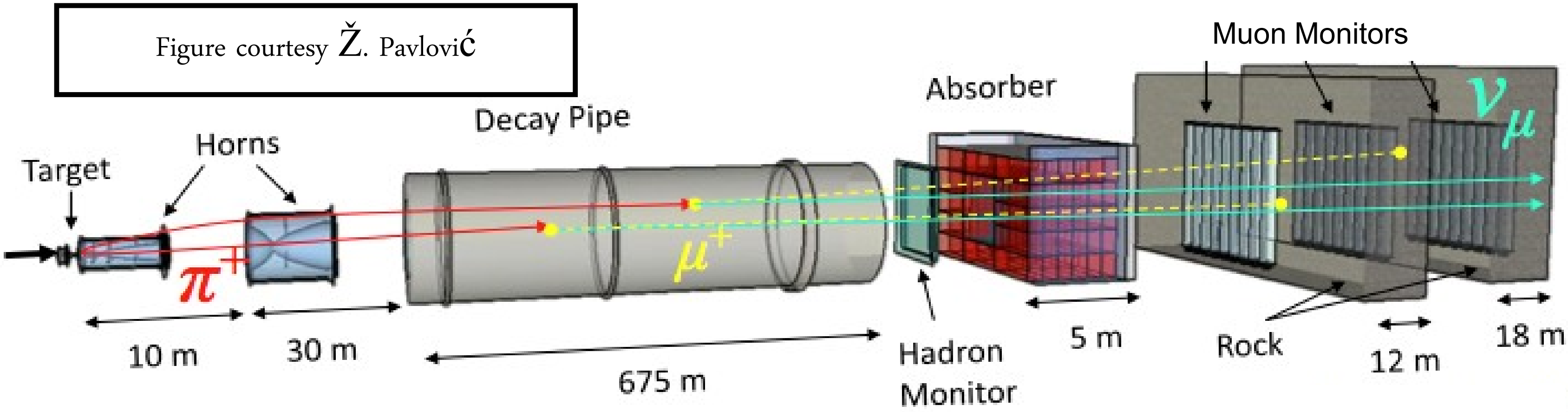
- MiniBooNE provides a suite of neutrino pion production cross section measurements, but the data is puzzling

- We need more neutrino pion production measurements to solve the puzzle!

The NuMI Beam and MINERvA Detector

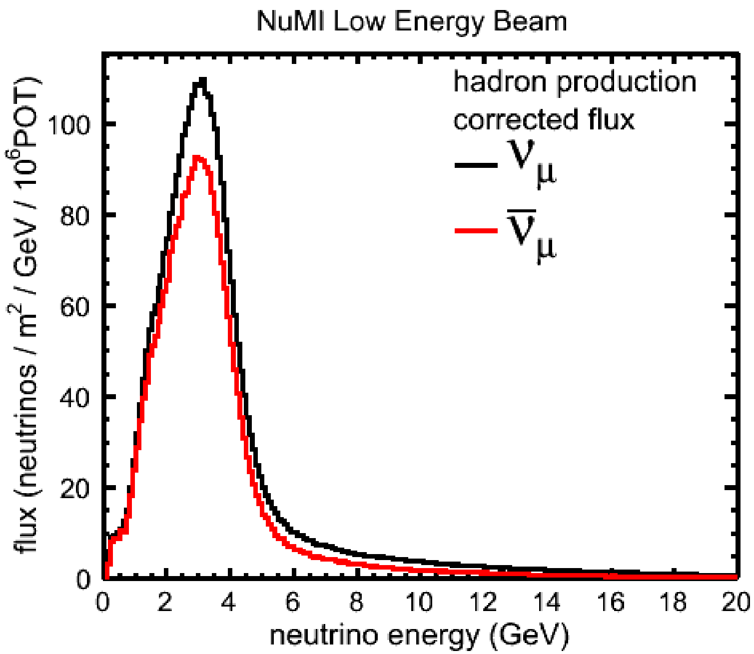
NuMI Beam Line

- 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



NuMI Flux Measurement

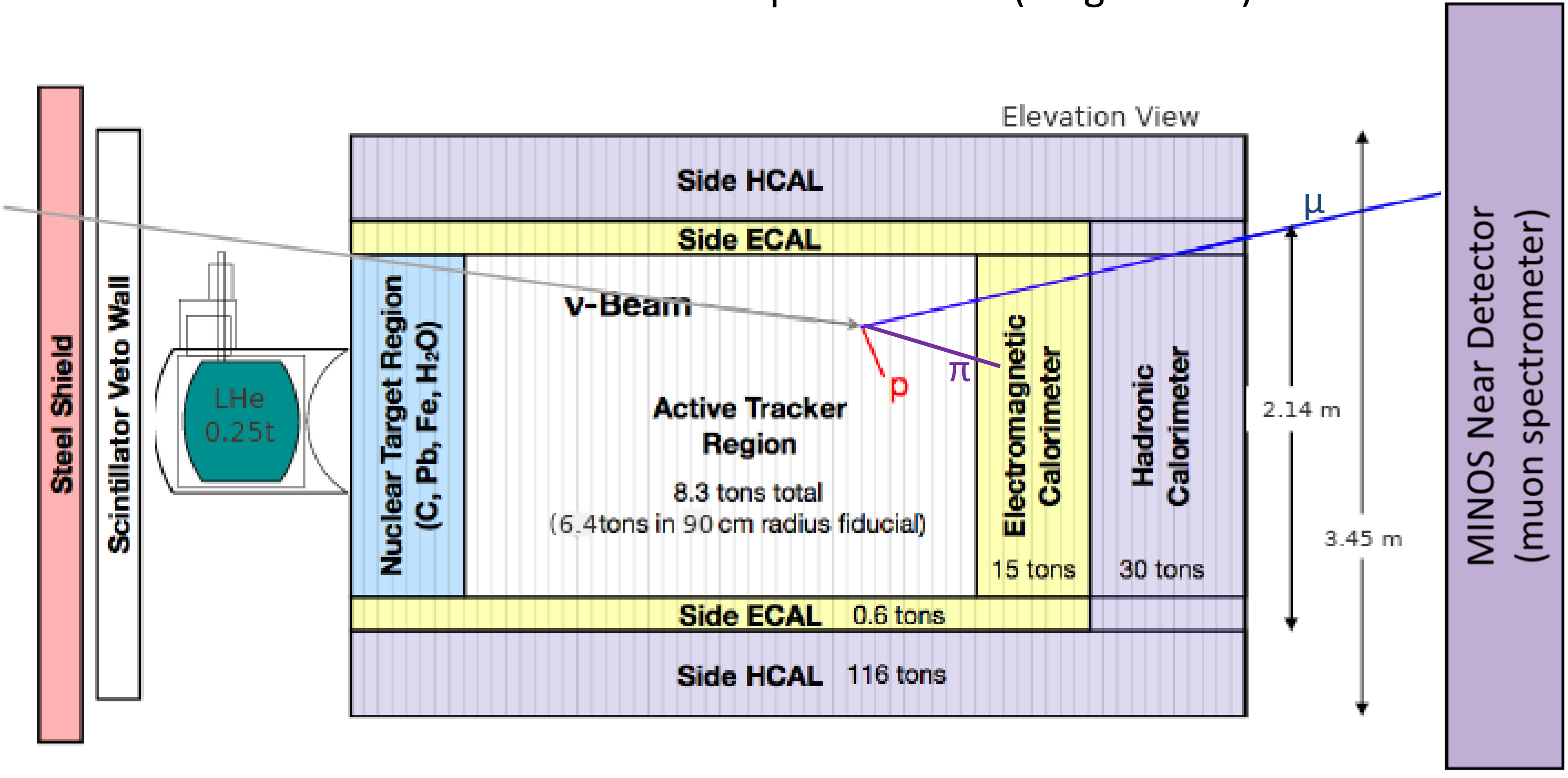
- Flux measurements are hard!
- MINERvA flux:
  - 7.5% statistical, 2-10% systematic uncertainties
- MINERvA has a rich suite of measurements planned to improve flux estimate



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

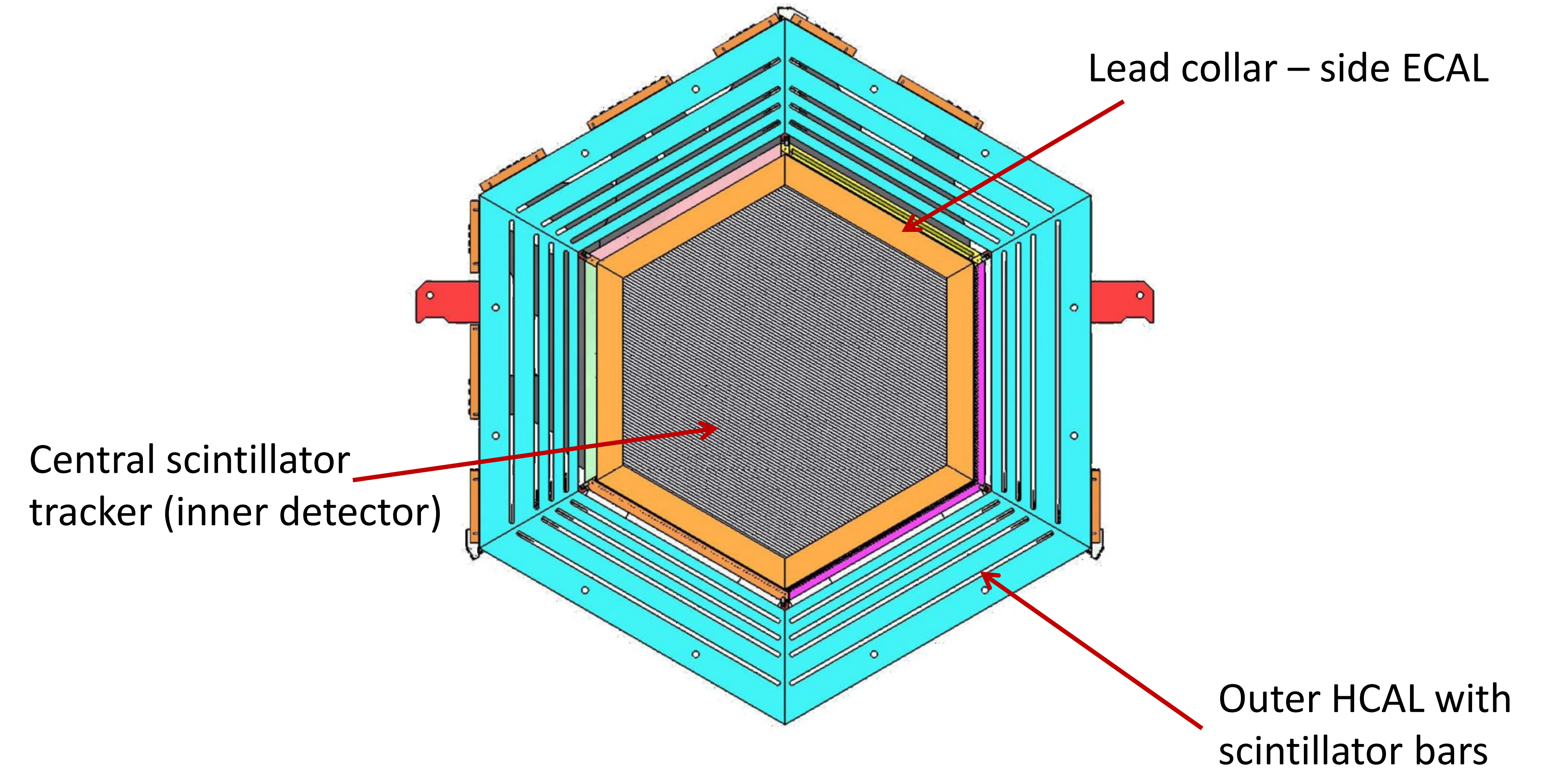
MINERvA Detector

- Fine-grained scintillator tracker surrounded by calorimeters
- Nuclear target region contains targets ranging from He to Pb
- MINOS near detector is the muon spectrometer (magnetized)

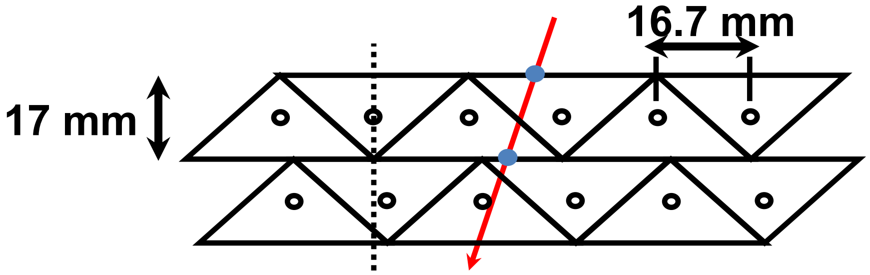


MINERvA Detector

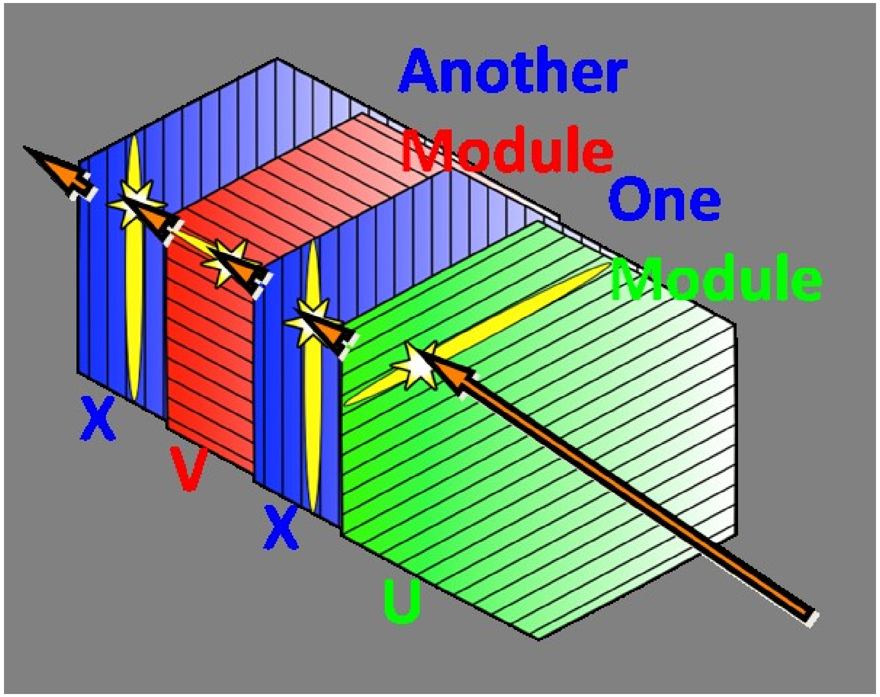
Front view of tracker module

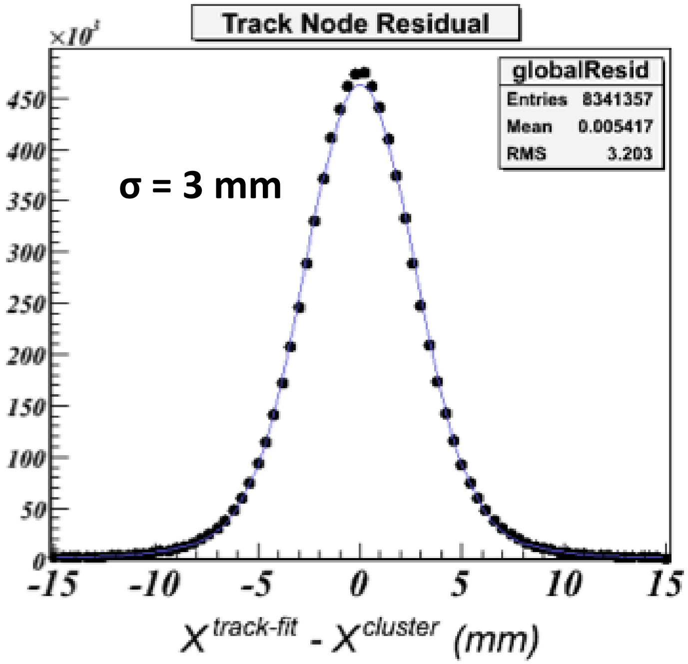


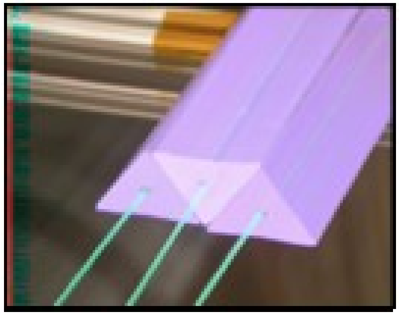
MINERvA Detector



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







3 different rotated plane views to resolve high-multiplicity events

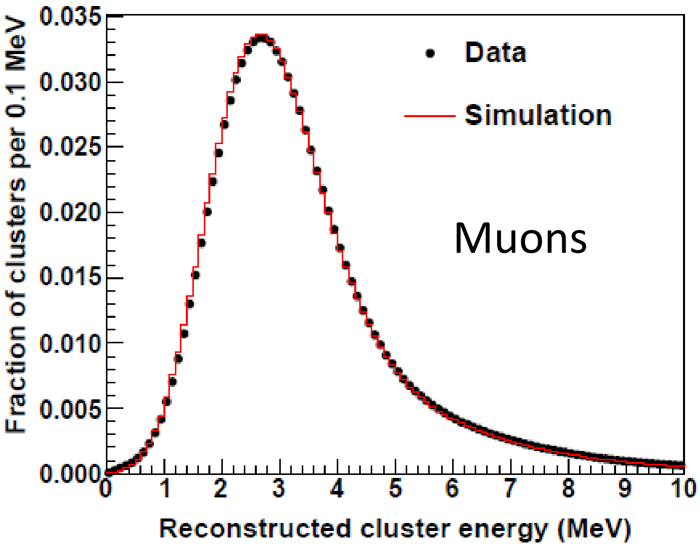
Detector Calibration

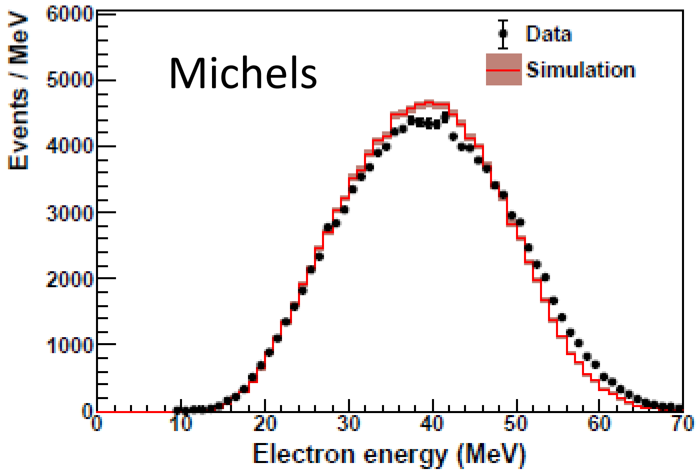
• Gains of ~32000 photomultiplier tube (PMT) measured daily to within ~5% with *in situ* calibration data

•Muon calibration sample used to remove remaining channel-to-channel differences and set absolute energy scale

- •2% systematic error!
- •Cross check with Michels – agree within 3%

•Electronic timing resolution: 3 ns

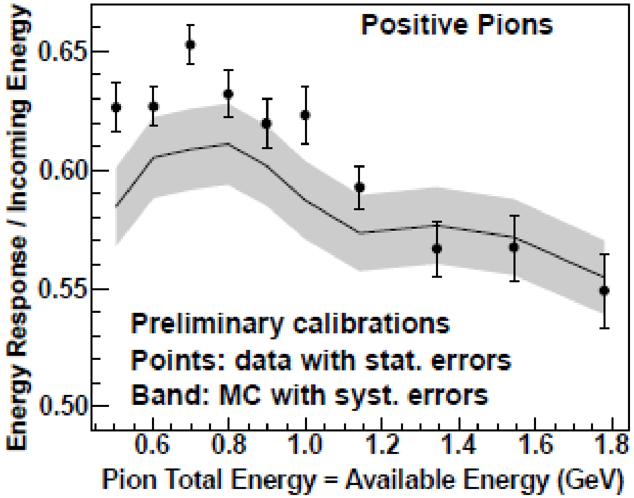




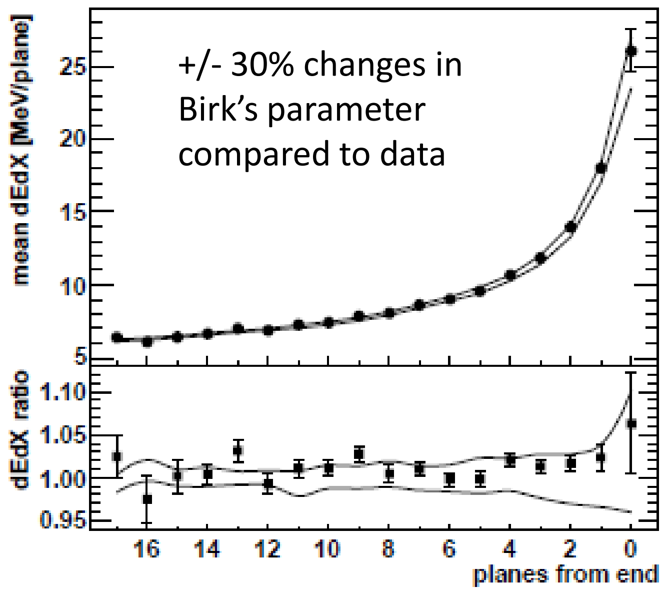
Detector Calorimetry

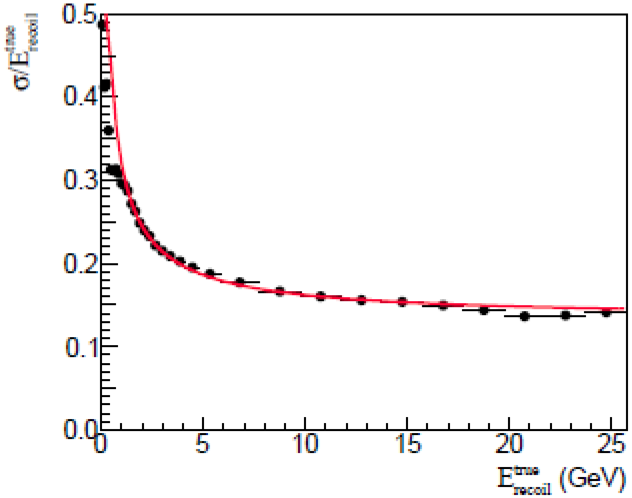
•Hadron response measured in a test beam detector:

•Agreement within for pions and protons



•Birks parameter constrained by energy loss profile of stopping protons in the test beam detector:



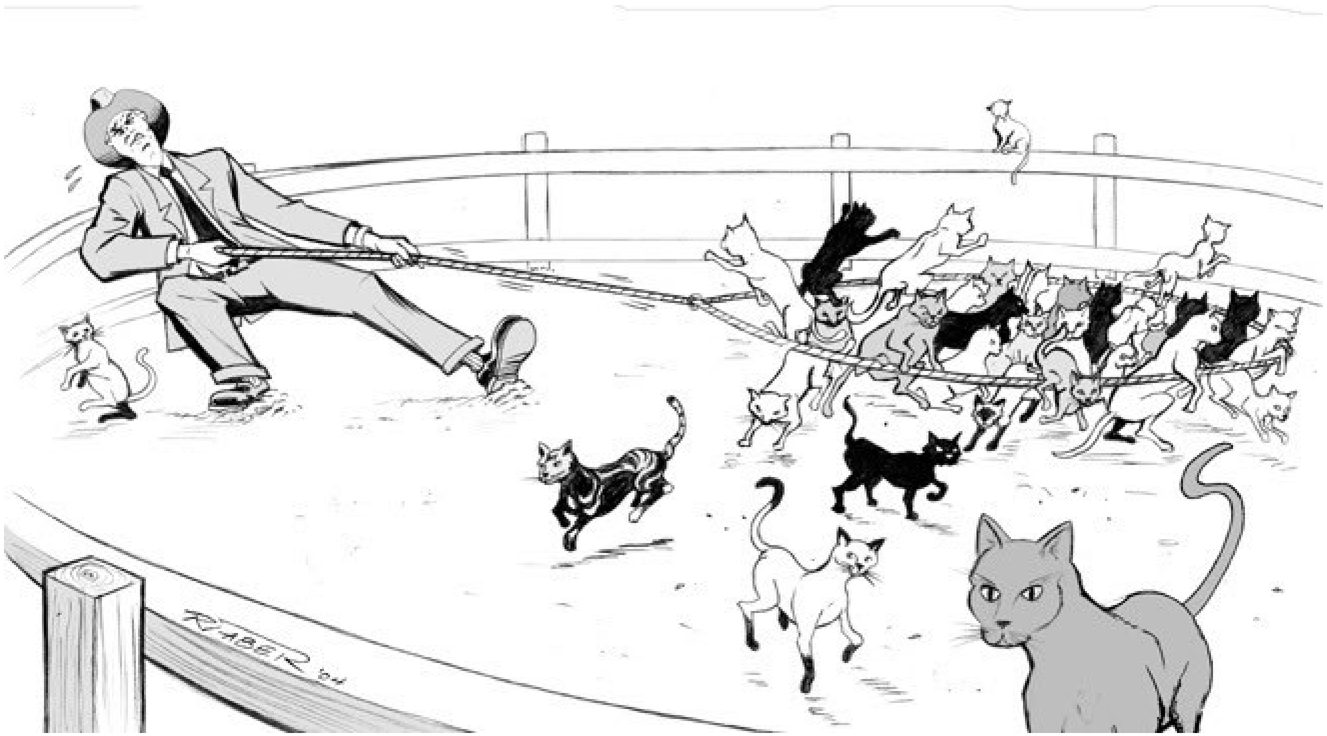


Pion and Event Reconstruction

A Day in the Life of a MINERvA Pion

- Want to leverage the scintillator tracker – find pion tracks

- Pions are not always cooperative!

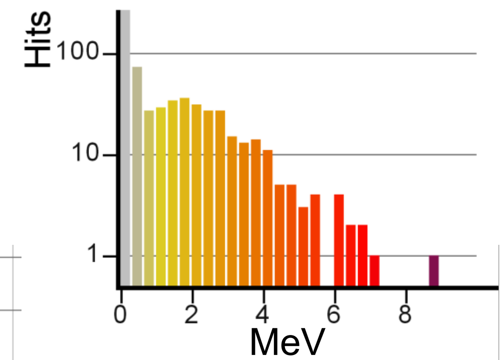


A Day in the Life of a MINERvA Pion

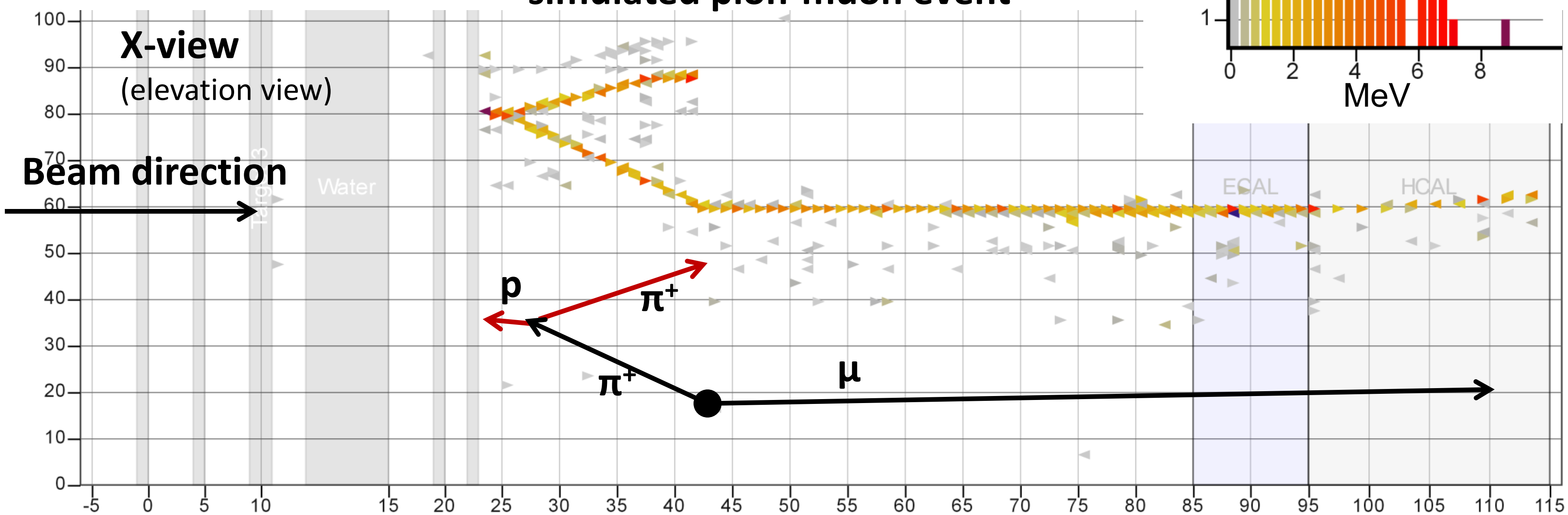
•Want to leverage the scintillator tracker – find pion tracks

•Pions are not always cooperative!

•They can scatter approximately elastically –
and this can happen close to the interaction vertex!

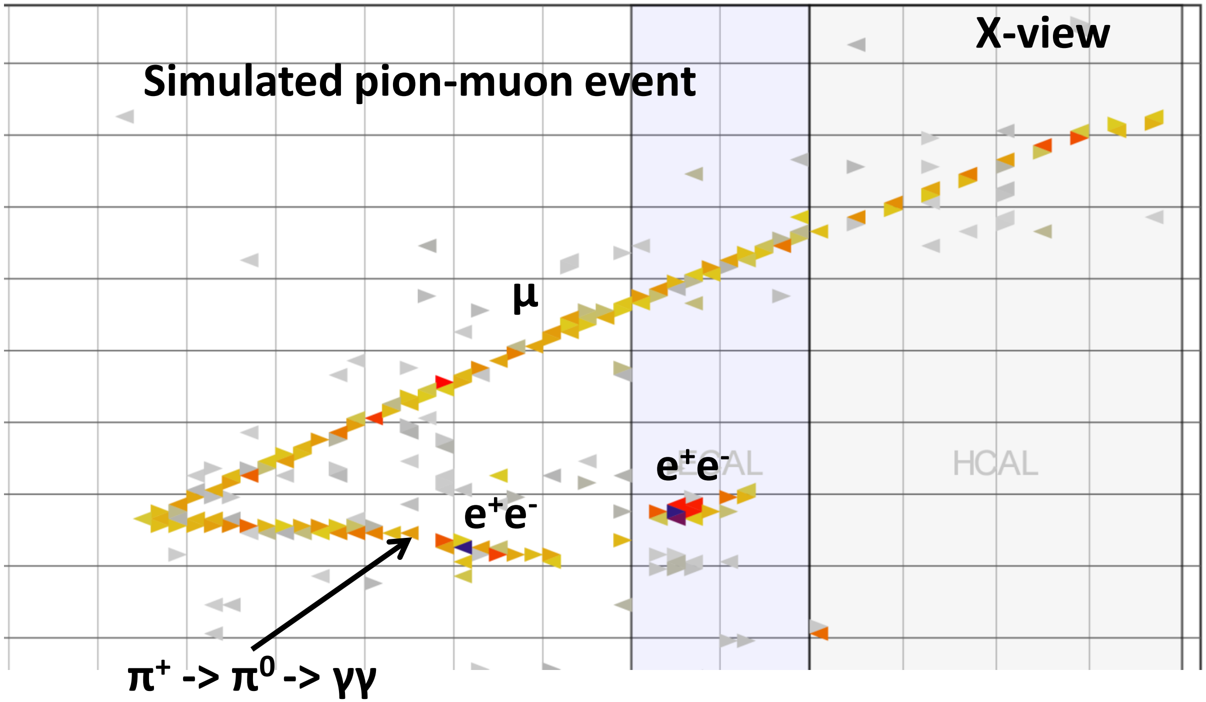


simulated pion-muon event



A Day in the Life of a MINERvA Pion

- Want to leverage the scintillator tracker – find pion tracks
- Pions are not always cooperative!
- They can charge exchange

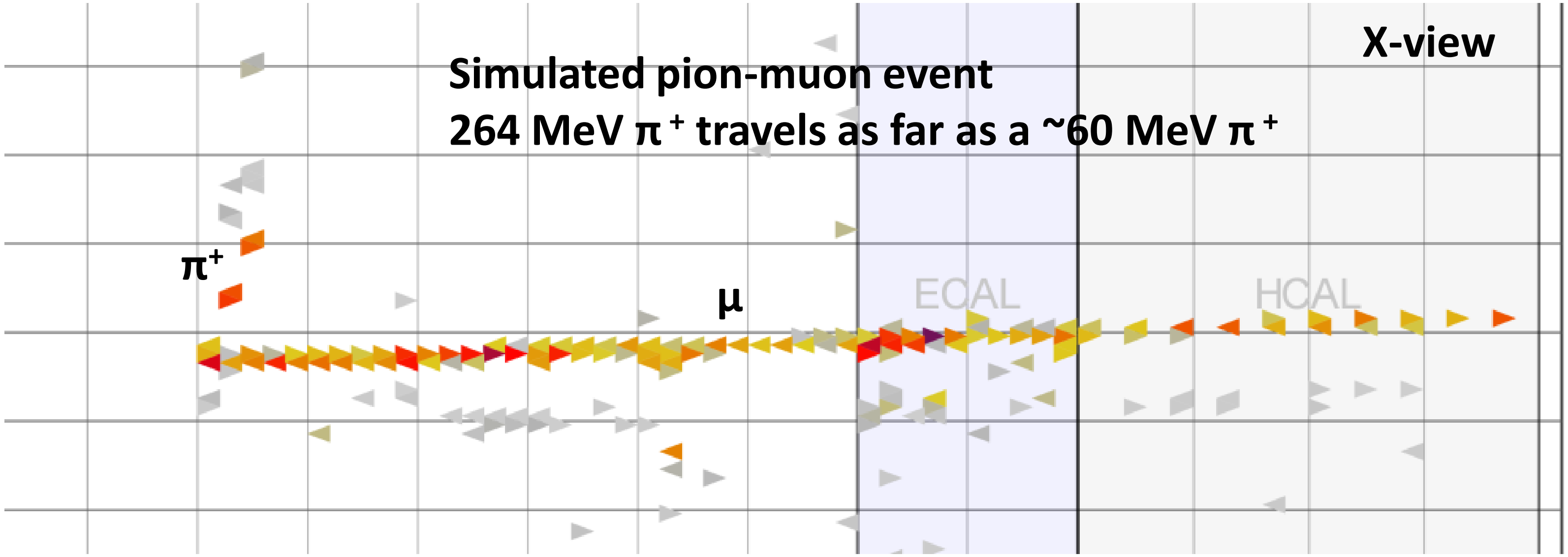


A Day in the Life of a MINERvA Pion

•Want to leverage the scintillator tracker – find pion tracks

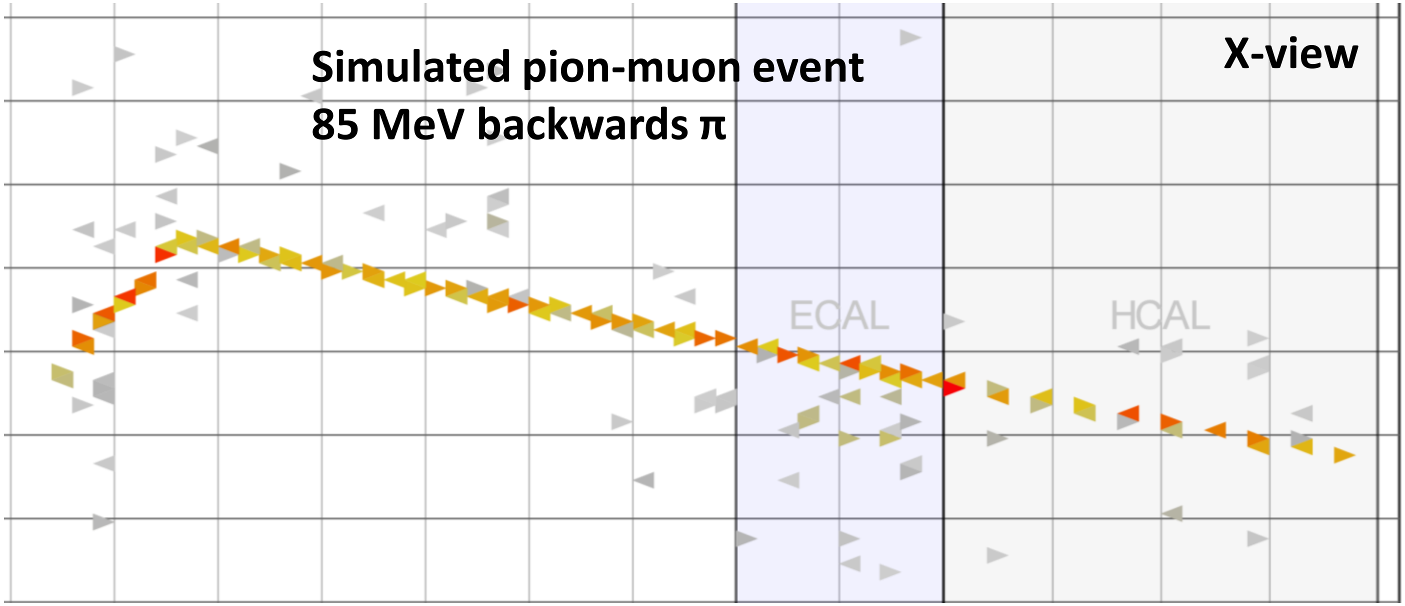
•Pions are not always cooperative!

•They can interact quickly without any hope of being tracked or good calorimetric reconstruction (20% of the time!)



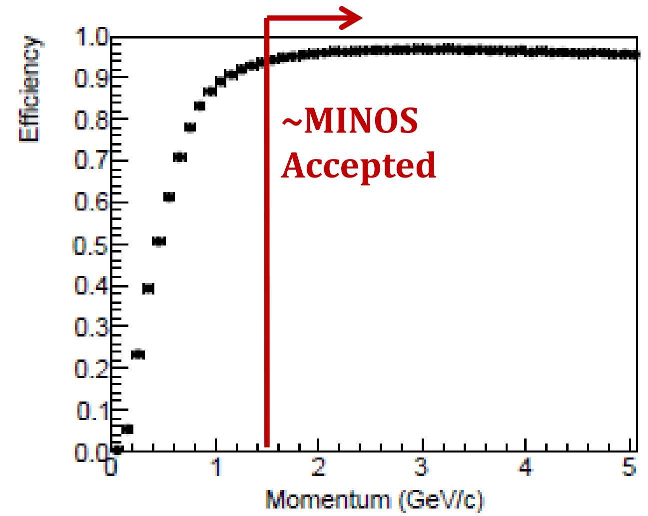
A Day in the Life of a MINERvA Pion

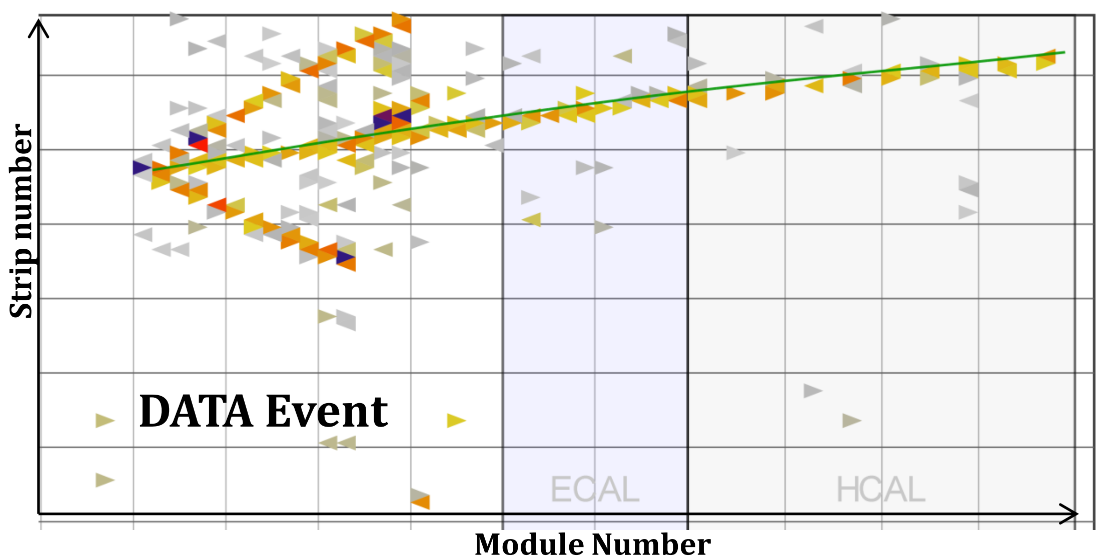
- Want to leverage the scintillator tracker – find pion tracks
- Pions are not always cooperative!
- And every so often, one will be nice and stop without a secondary interaction

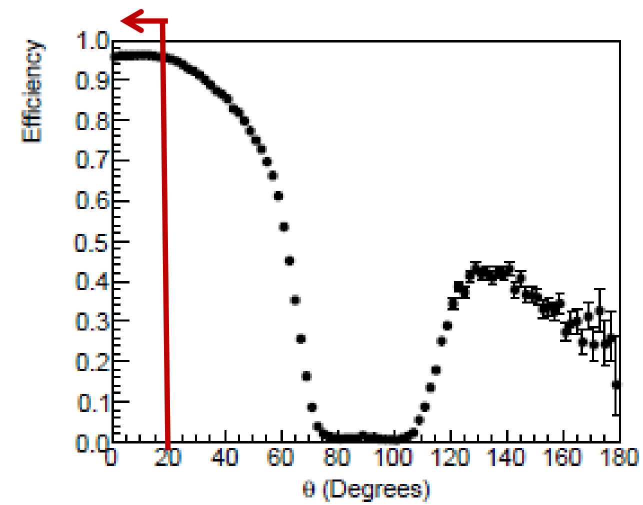


Event Reconstruction

- 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



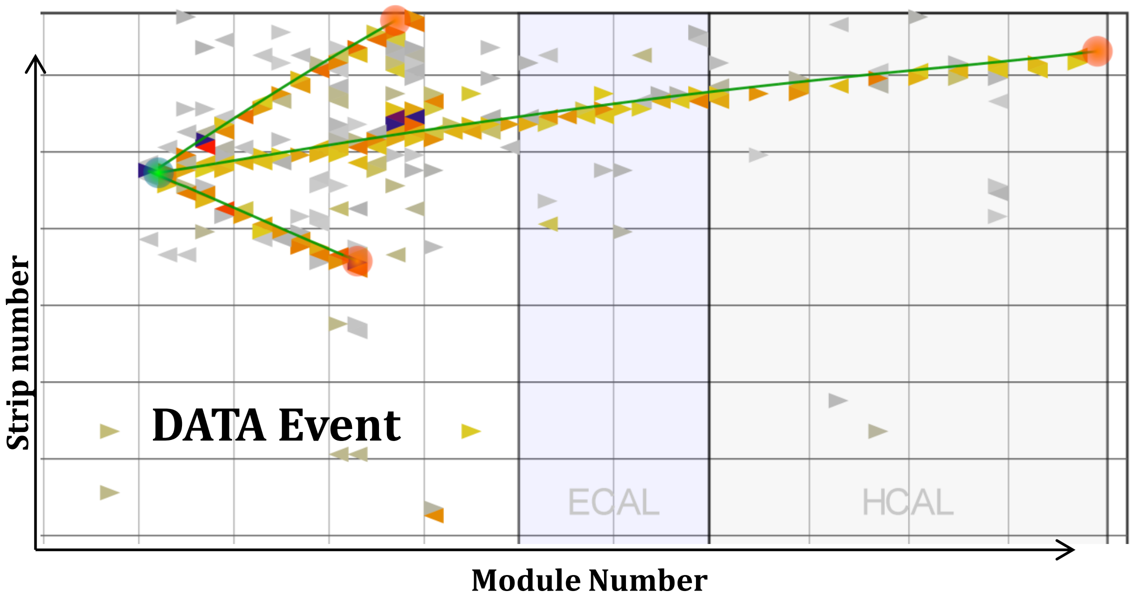


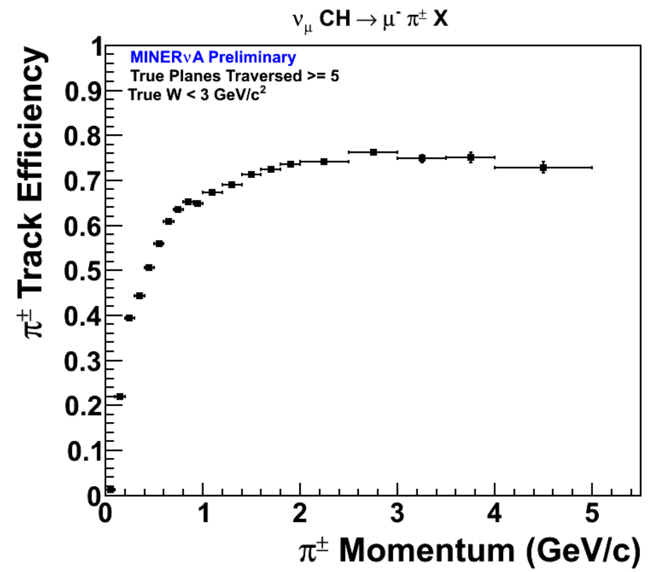


Event Reconstruction

•Next, look for additional tracks at the interaction vertex

•Fit for the interaction vertex using all available tracks



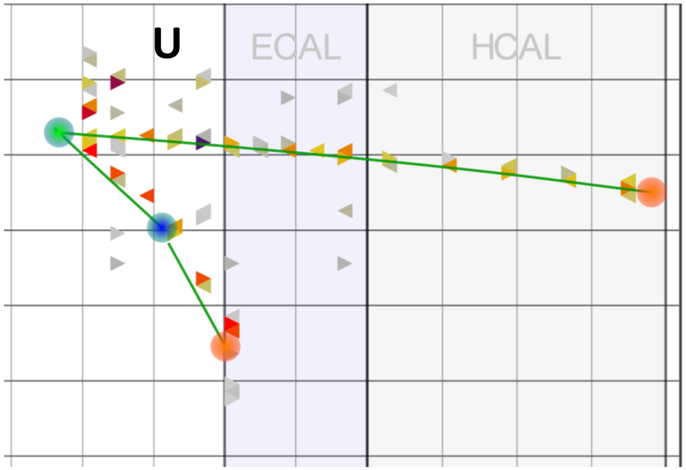


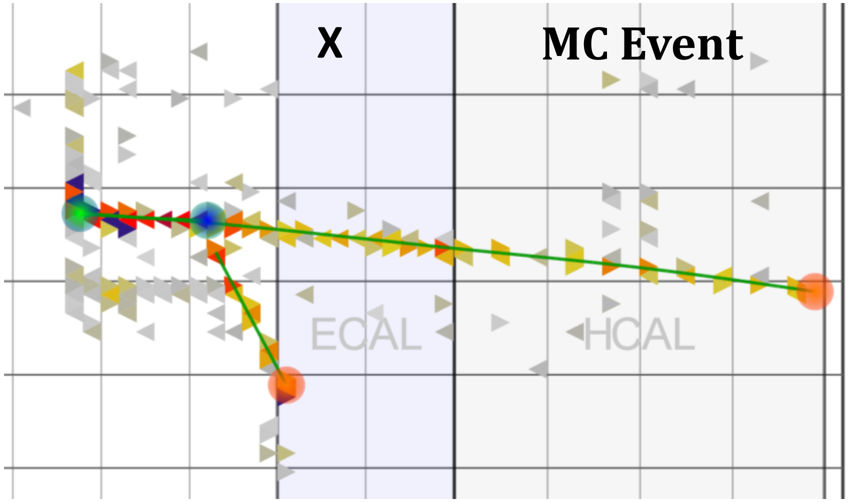
Event Reconstruction

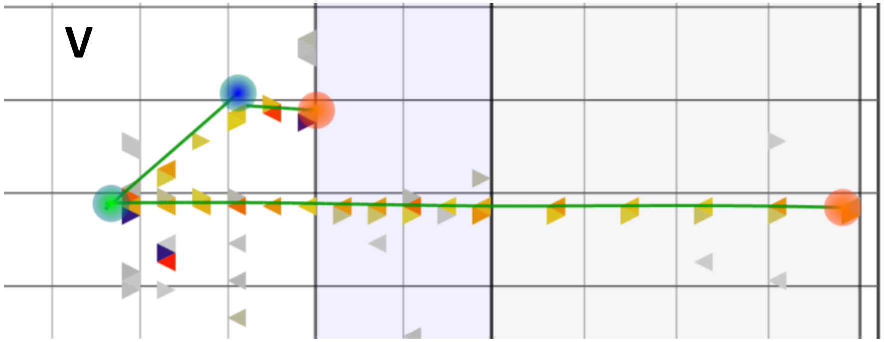
•Find "kinked" tracks by looking at the end of each track

•Overlap is handled correctly in the X view

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

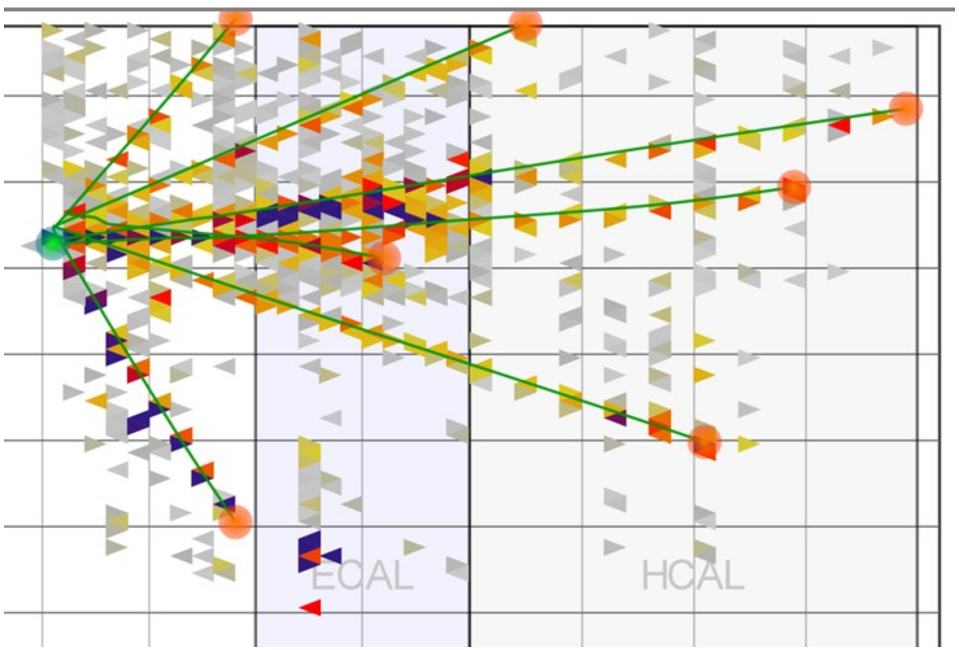






Event Reconstruction

•High multiplicity events are hard, but MINERvA has the reconstruction to handle quite a few of them:



•Keys:

- •Conservative line pattern recognition
- •Iterative vertex-anchored tracking procedure
- •Proper energy "cleaning" at the vertex

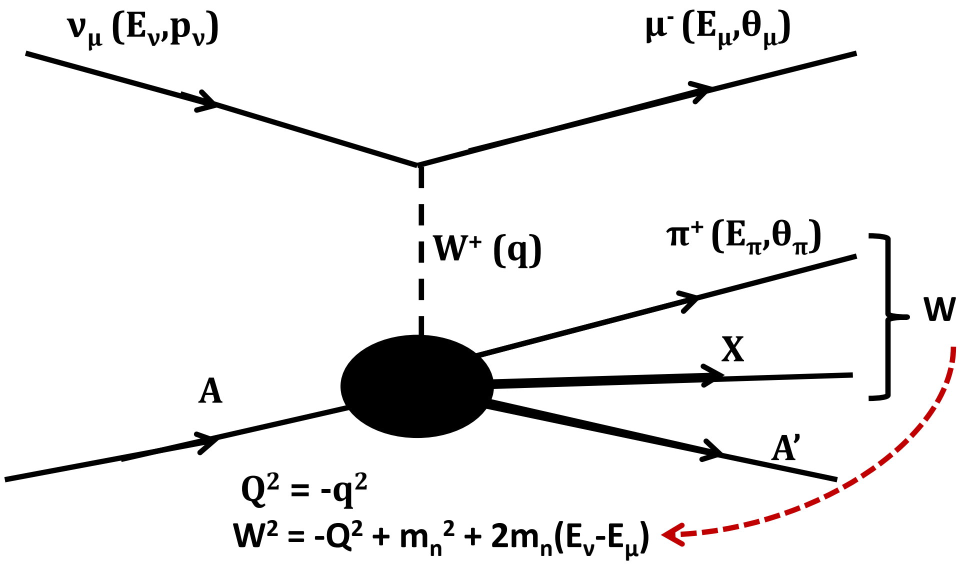
MINERvA Charged Current Charged Pion Analysis

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

Signal Definition

$\nu_\mu T \rightarrow \mu^- \pi^\pm X\ T'$

- T is a nucleus in the tracker
- T' is the recoil nucleus
- X includes any particles except charged pions



- Other Requirements:
    - Invariant hadronic mass (W) is less than 1.4 GeV
    - 1.5 GeV < E_ν < 10 GeV
- Motivation: Choose a MiniBooNE-like pion signal

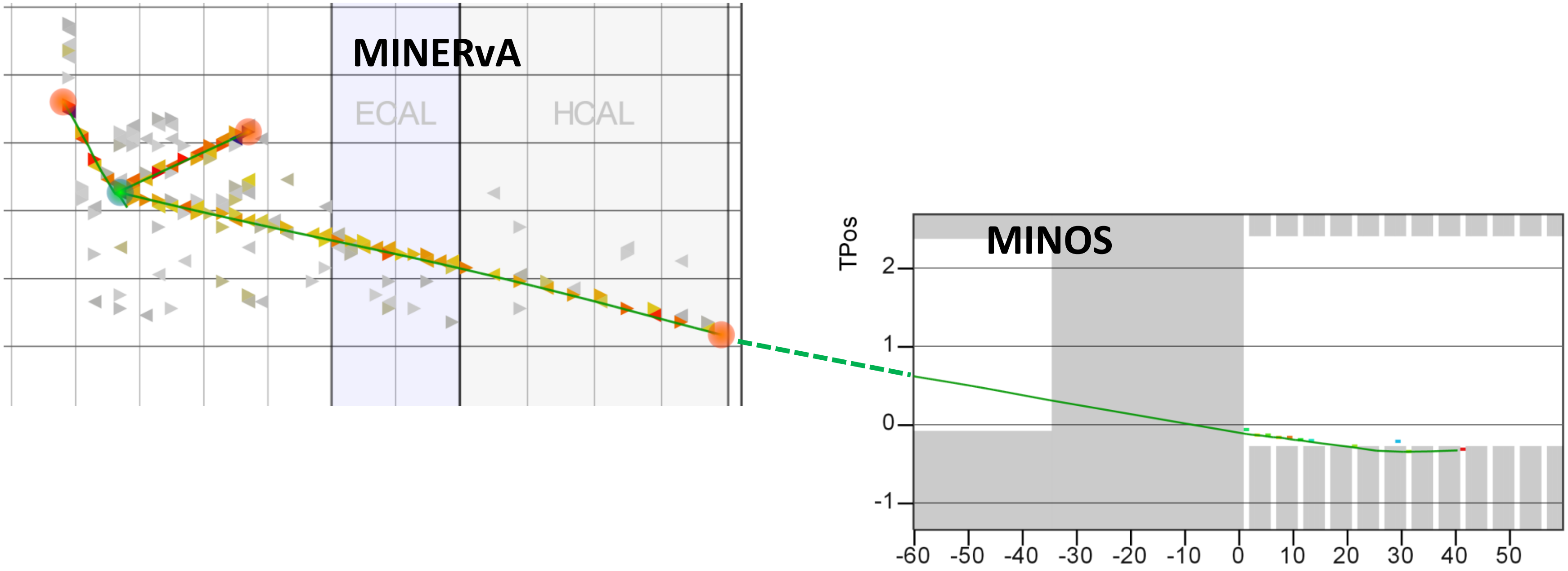
Event Selection

First, select charged current events:

•Look for a MINERvA track that is matched to a track in MINOS

•Require that the reconstructed charge is negative

•Employ data quality cut to remove "rock muon" background



Event Selection

Limit the size of the hadronic recoil and neutrino energy (MiniBooNE-like):

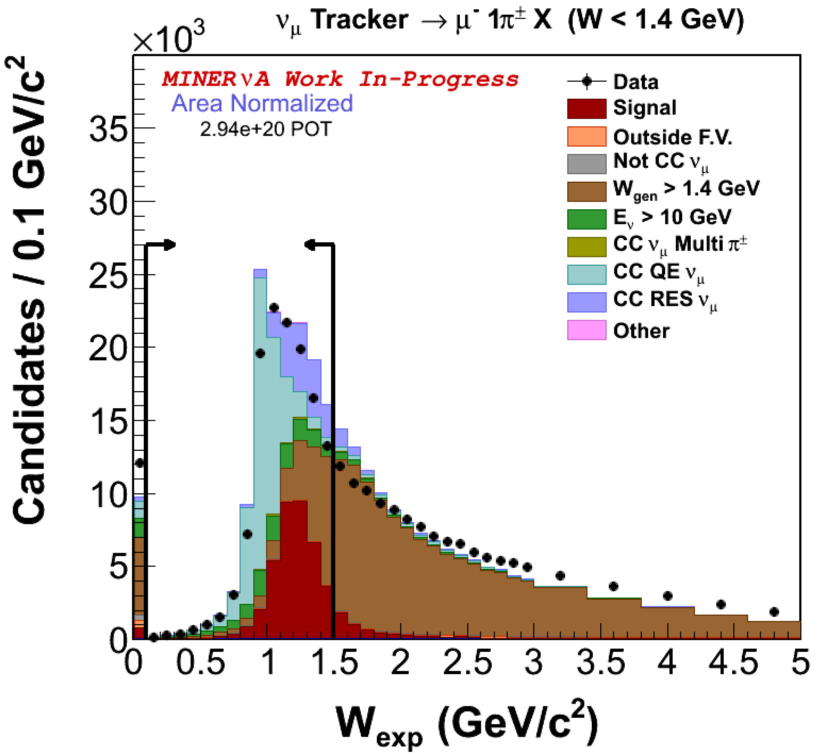
- Reconstruct hadronic recoil energy (E_H) calorimetrically
  - Sum non-muon energy, weighted by passive material constants
  - Apply additional scale, derived from MC, to tune to true E_H

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

Require:

$E_\nu < 10$ GeV

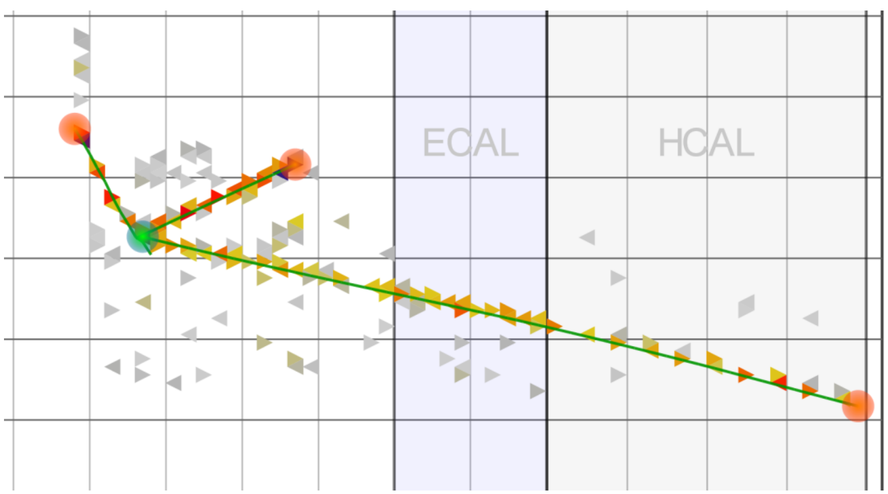
$W_{exp} < 1.5$ GeV

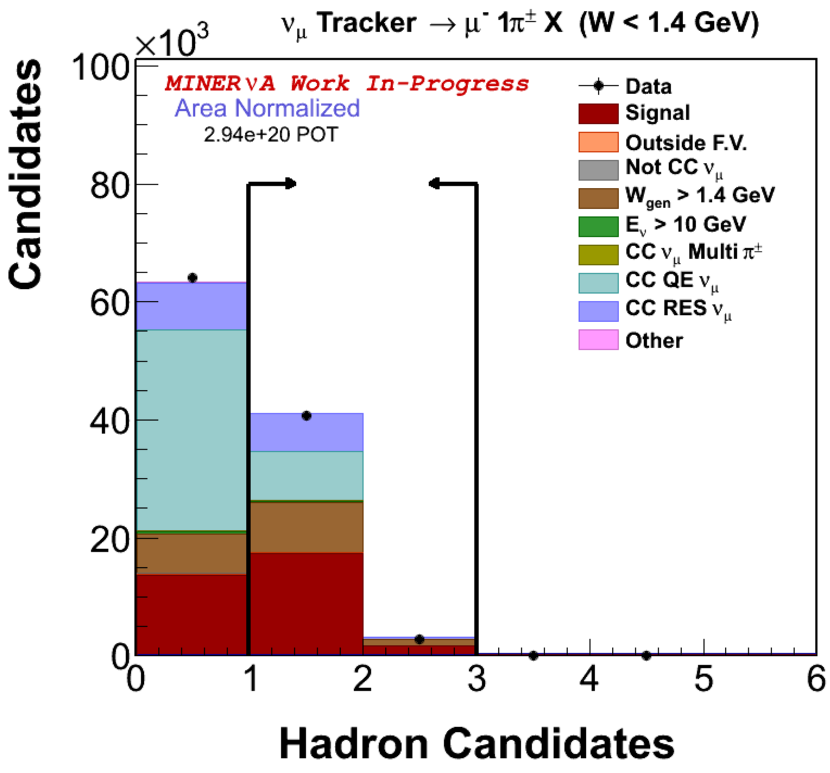


Event Selection

Find pion candidates:

•Require one or two hadron track candidates





Event Selection

Select a pion (Particle ID):

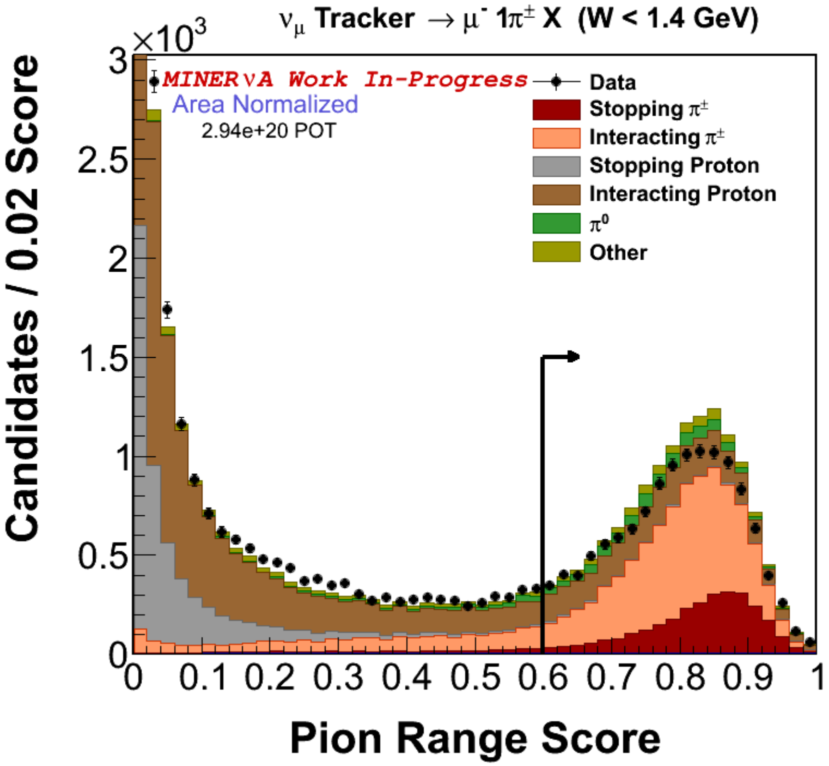
•Fit the energy loss profile of each hadron track to proton and pion hypotheses

•Find the best momentum for each hypothesis – this is the ***reconstructed momentum***

•Use an outlier removal procedure to remove vertex energy contamination from the fit

•Construct a score from the χ^2 of the best pion and proton fits

•Require particle containment



Event Selection

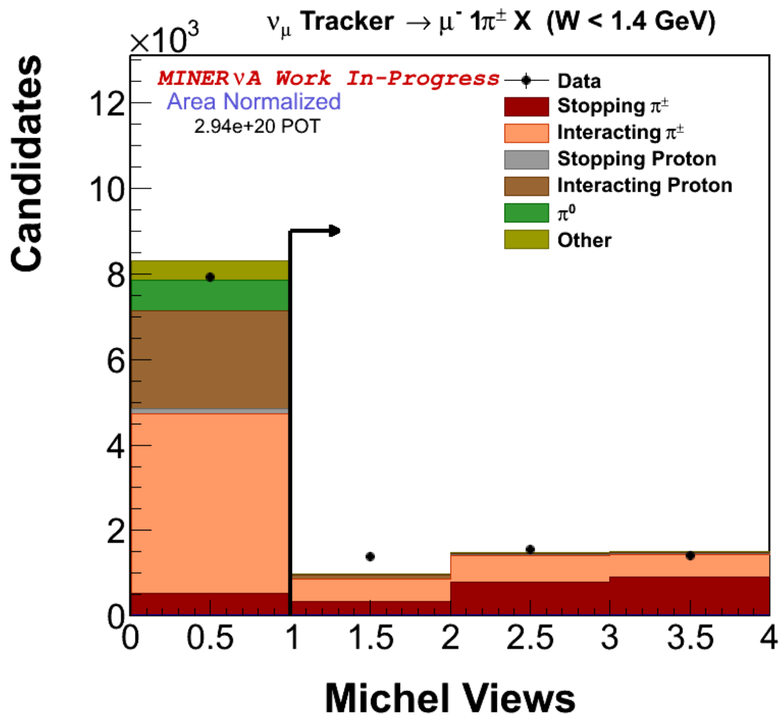
More Particle ID:

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

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

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

•Efforts to understand selection efficiency and data-MC disagreements are ongoing

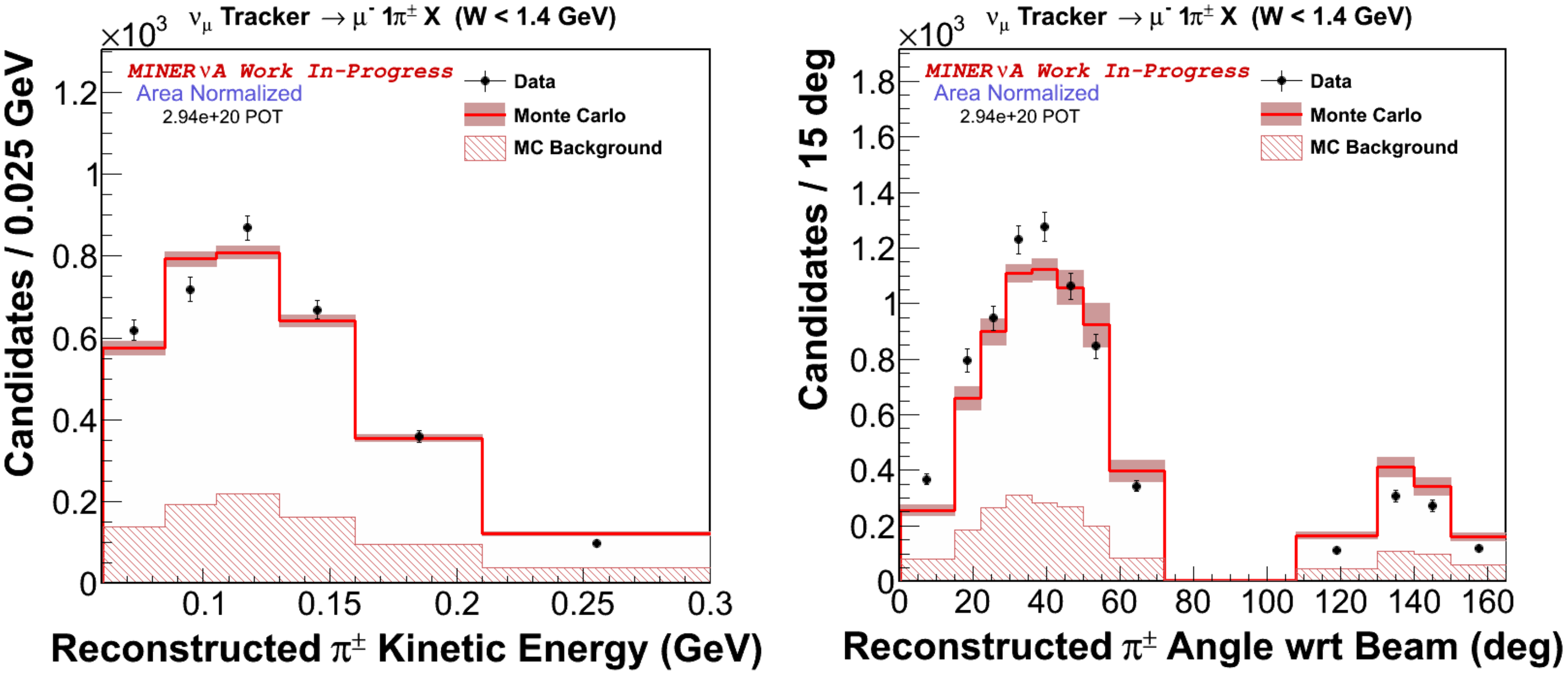


•Do not allow more than one track that meets the Particle ID criteria

-Final selection yields ~4000 pion candidates, ~94% pion purity

Reconstructed Pion Energy and Angle

MC error bars include GENIE and flux shape systematic errors
Data errors are statistical only

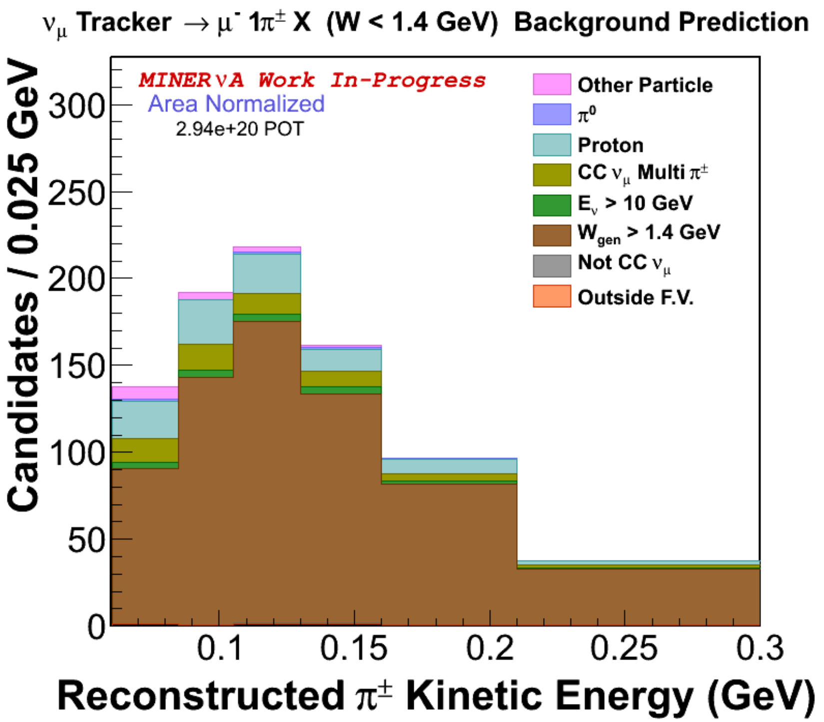


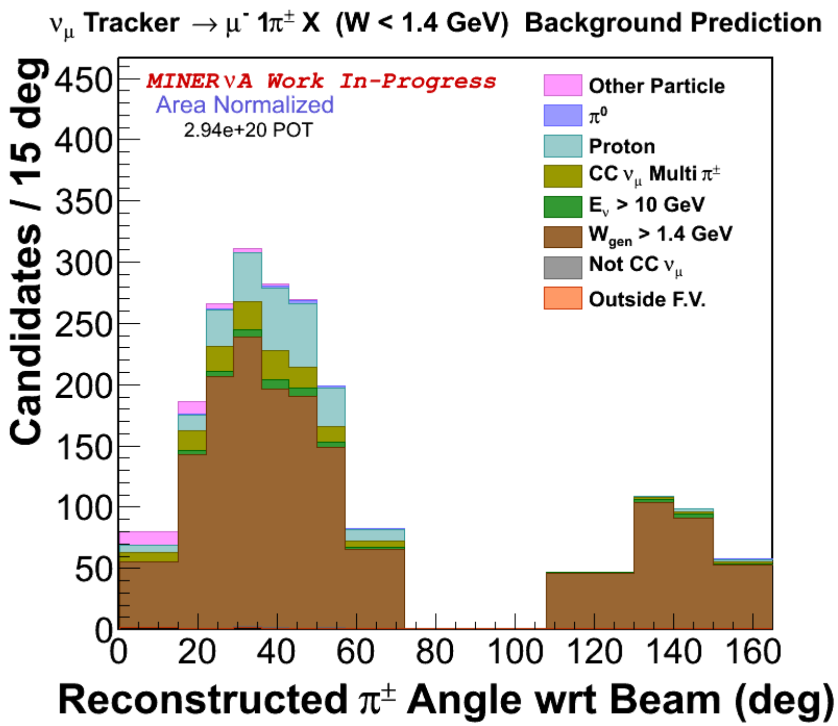
Background Summaries

Largest background: Large invariant hadronic mass (W > 1.4 GeV) **~20%** of sample

PID backgrounds: Protons and other particles mis-ID as pion **~ 3.5%** of sample

All other backgrounds combined **~2.5%** of sample



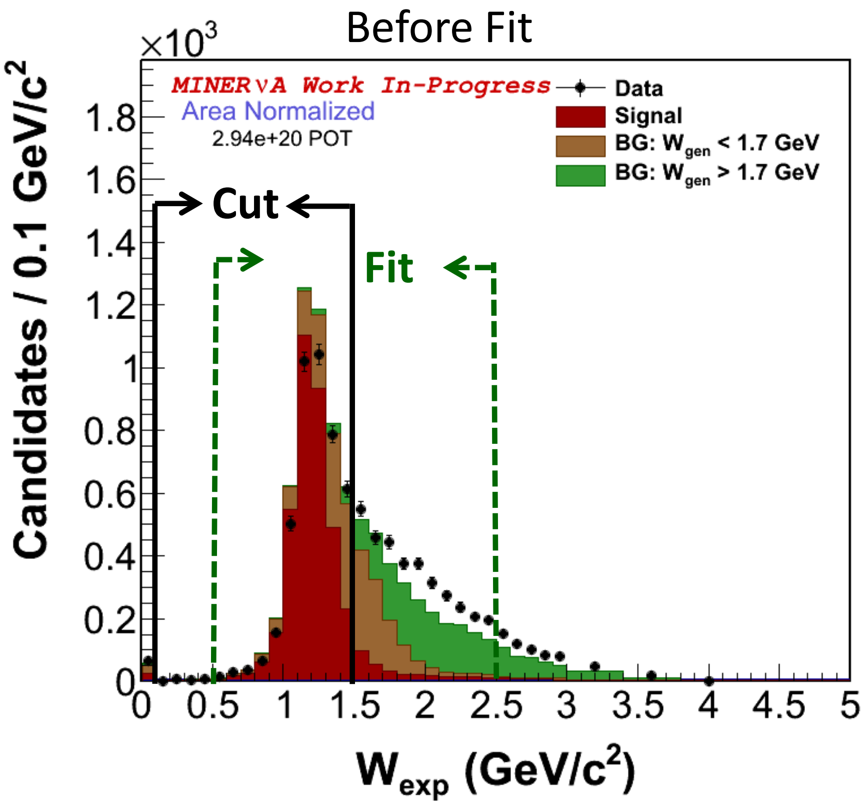


Background Subtraction

- Construct the reconstructed hadronic invariant mass (W) distribution with all cuts applied except the invariant mass cut

- Use the MC to create signal and background templates

- Hold template shapes constant and fit the data for the relative normalizations of the templates

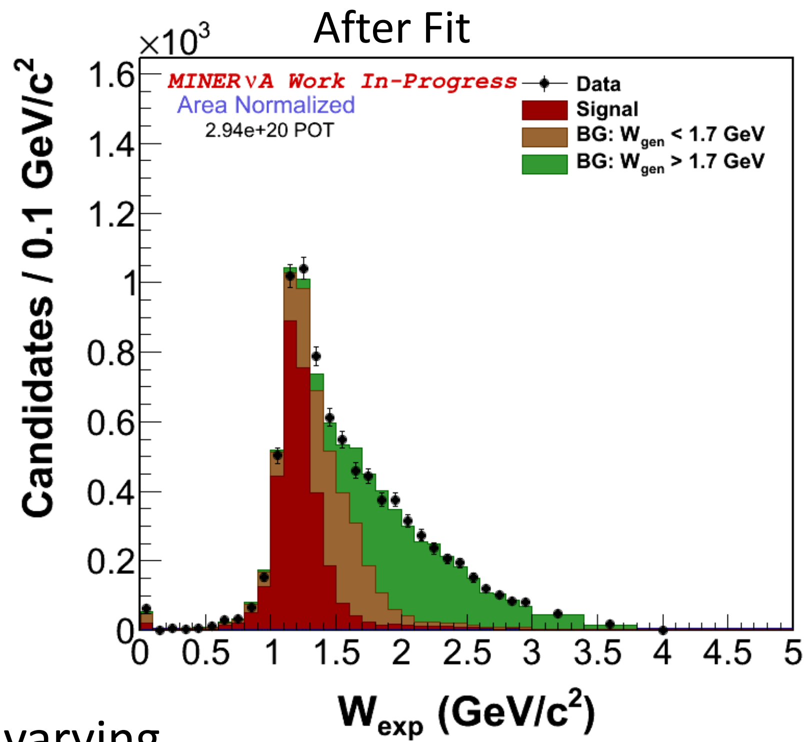


Background Subtraction

•Apply the new background scales to the MC background prediction and subtract from data

New Background Scales:
W < 1.7 GeV: 0.981 +/- 0.055 (stat)
W > 1.7 GeV: 1.47 +/- 0.05 (stat)

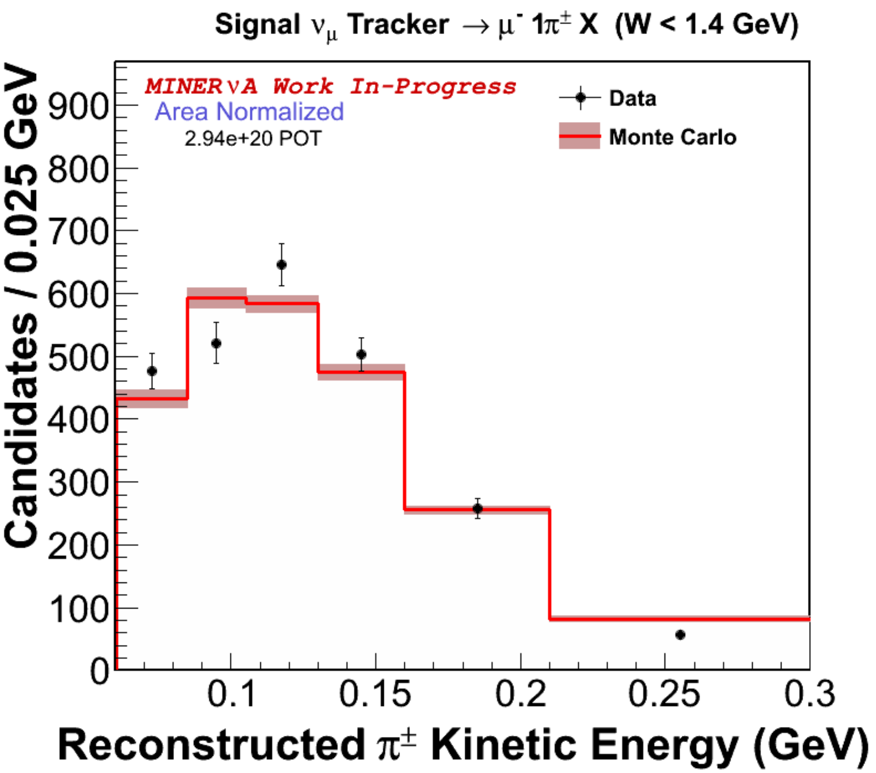
•The signal scale is only used for crosschecks

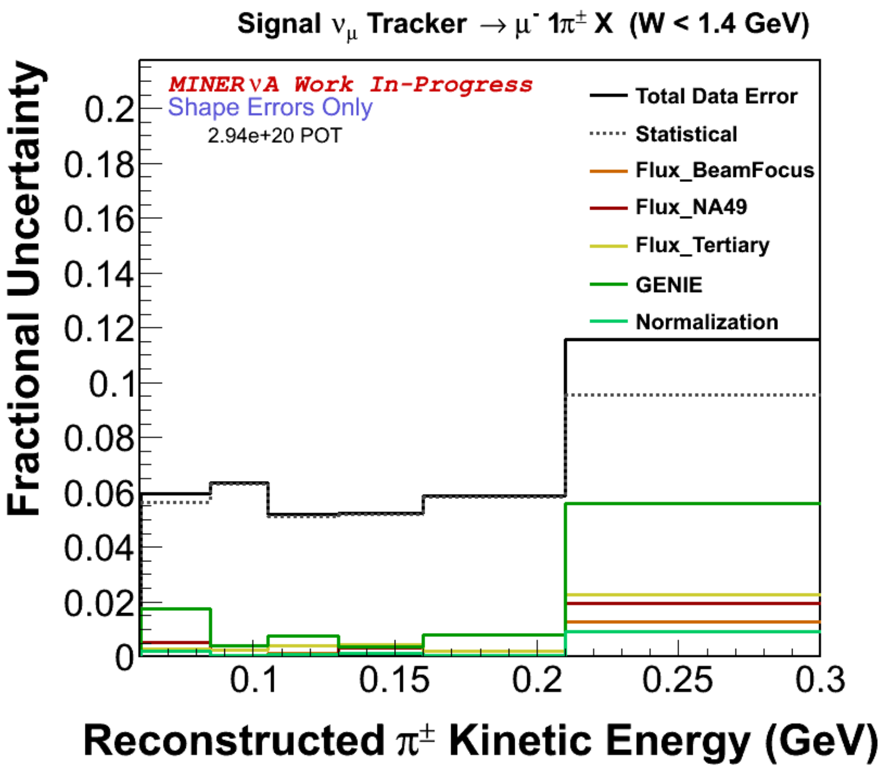


•Template shape systematics evaluated by varying GENIE parameters within errors

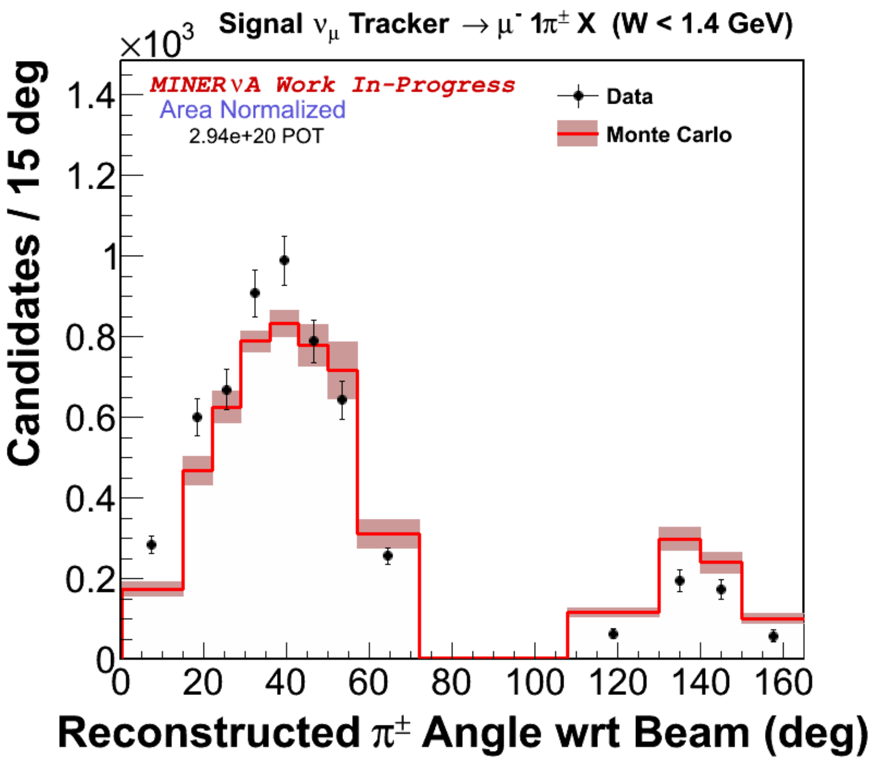
•Still to be done: Do the fit in bins of pion KE and angle to adjust the prediction of the MC background shape

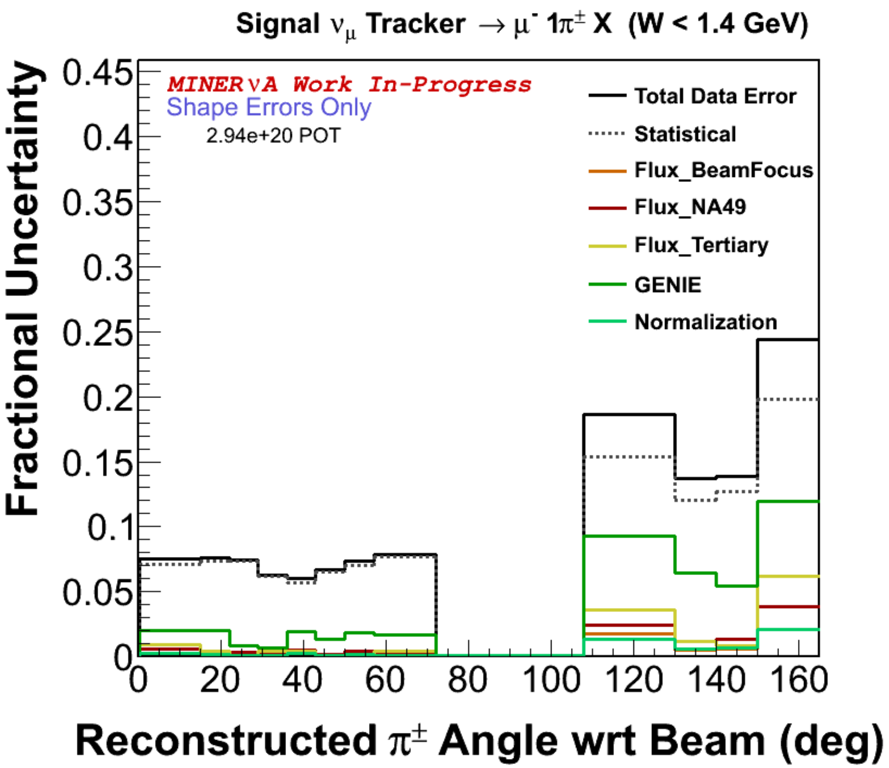
Background Subtracted Distributions





Background Subtracted Distributions

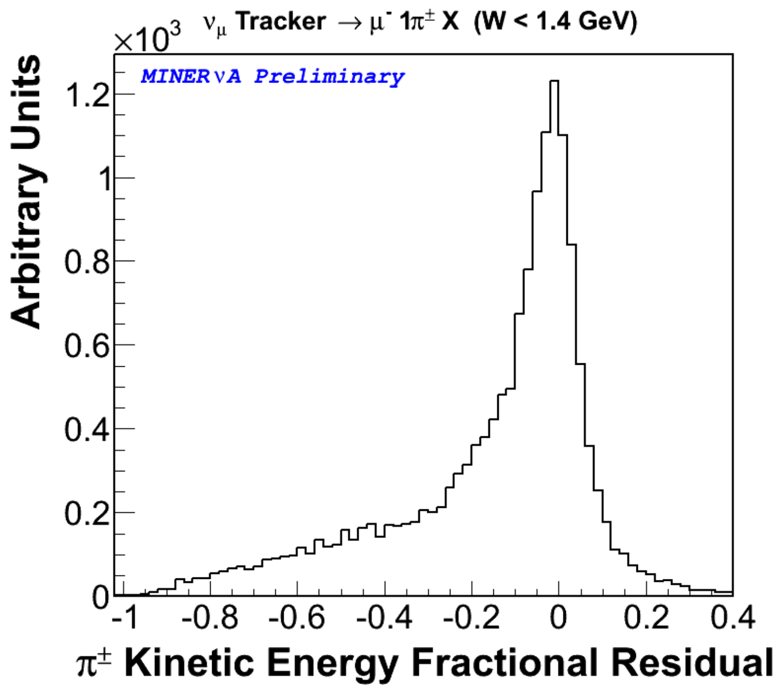


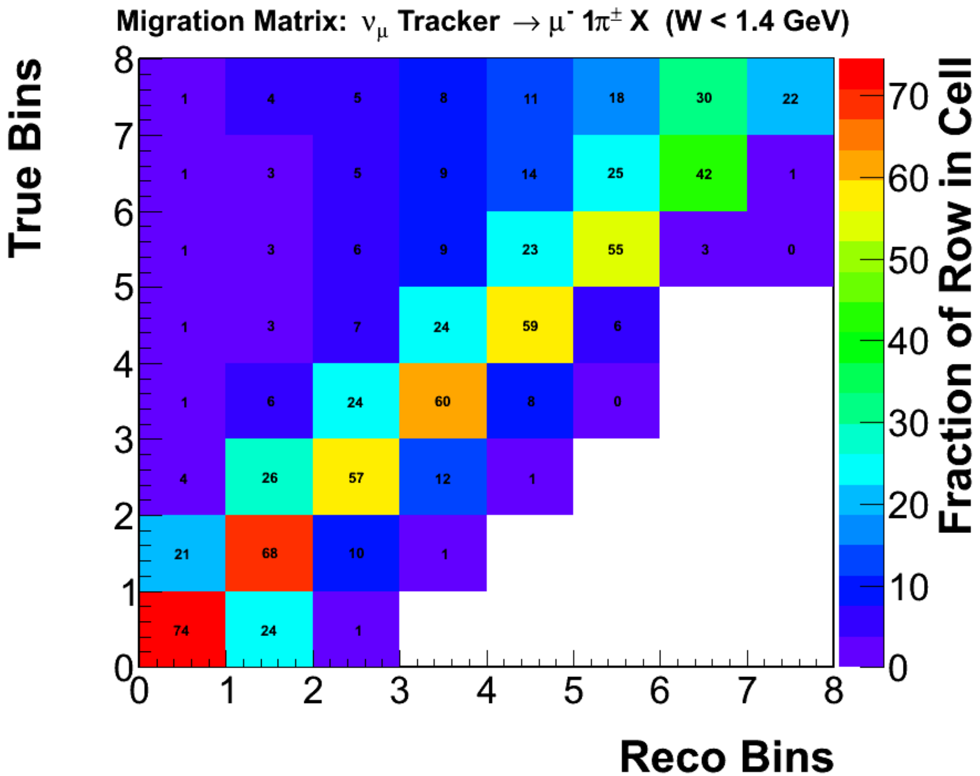


Unfolding

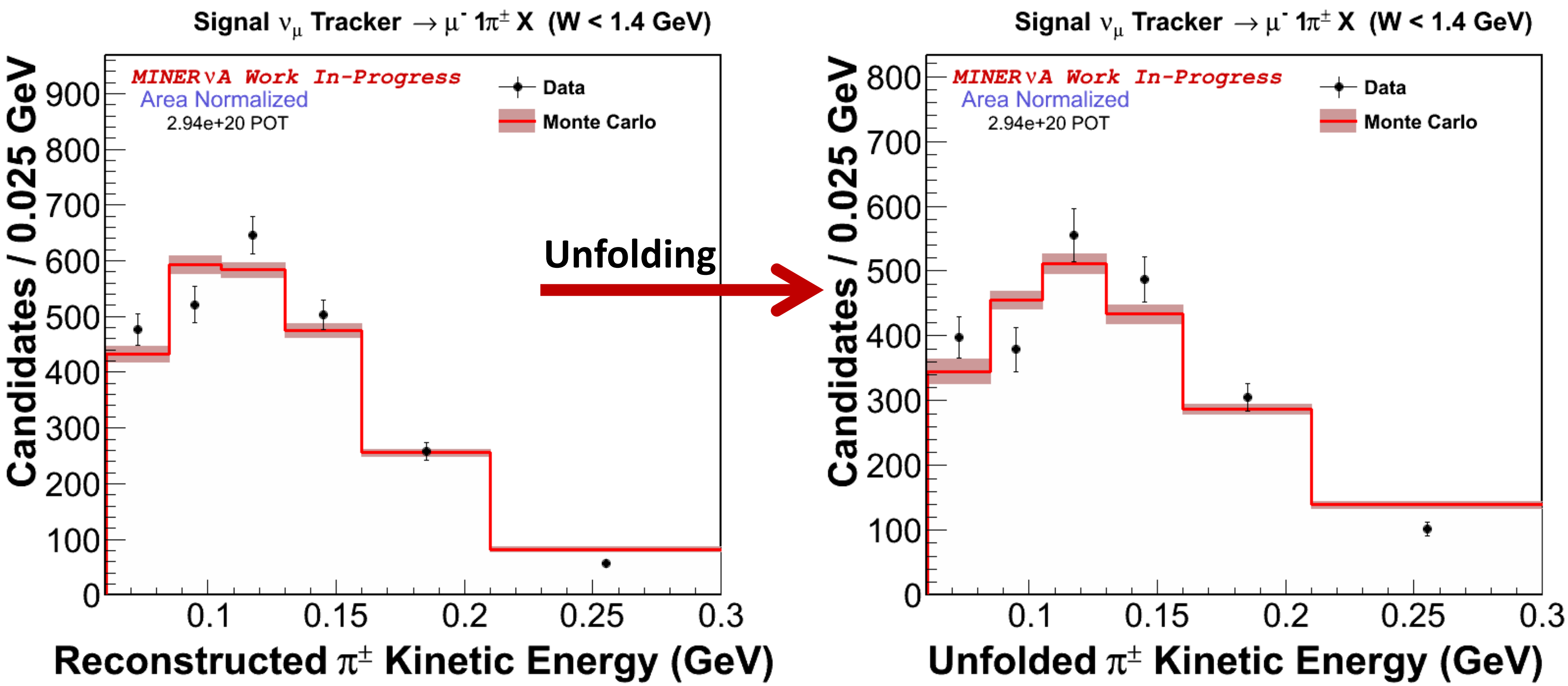
- Unfolding removes detector resolution effects:
  - transform to "true" variables

- Use an iterative Bayesian procedure: 4 iterations

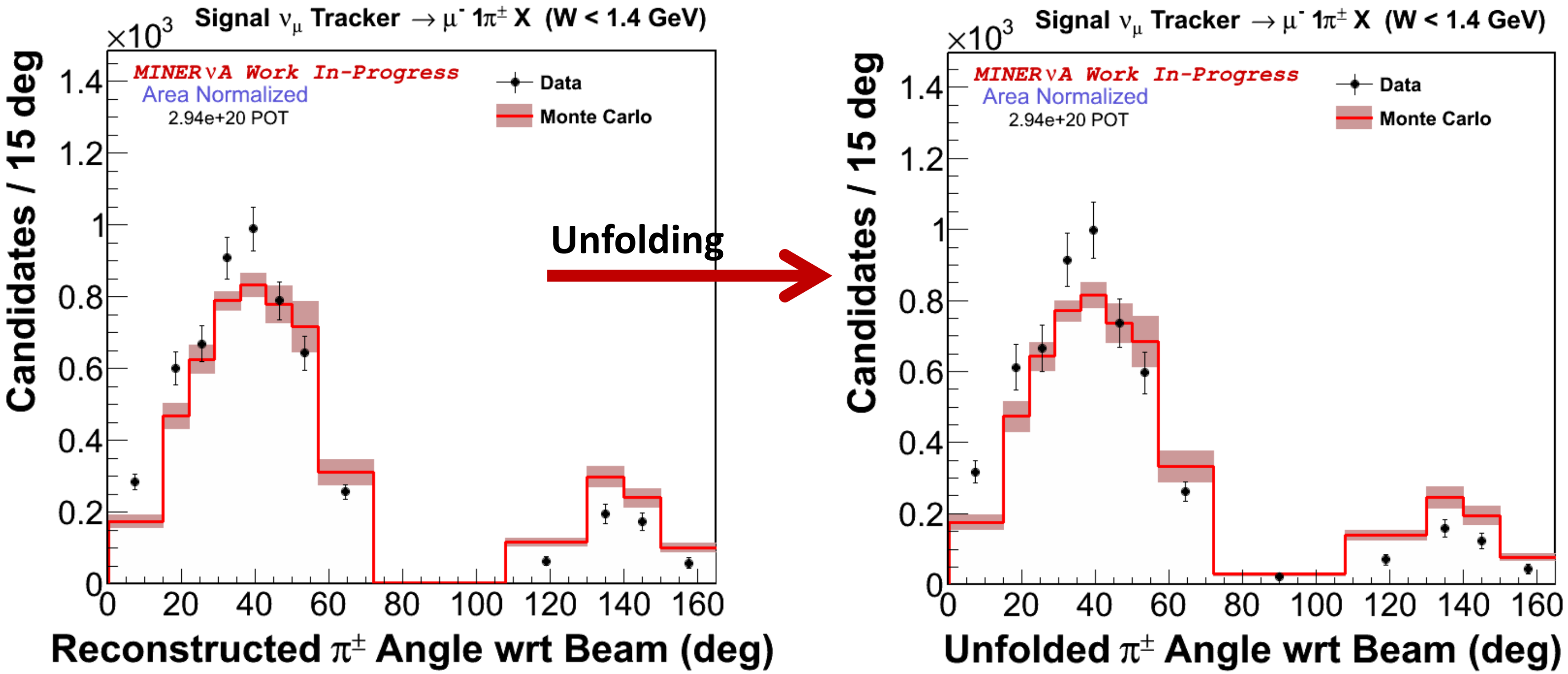




Unfolded Distributions

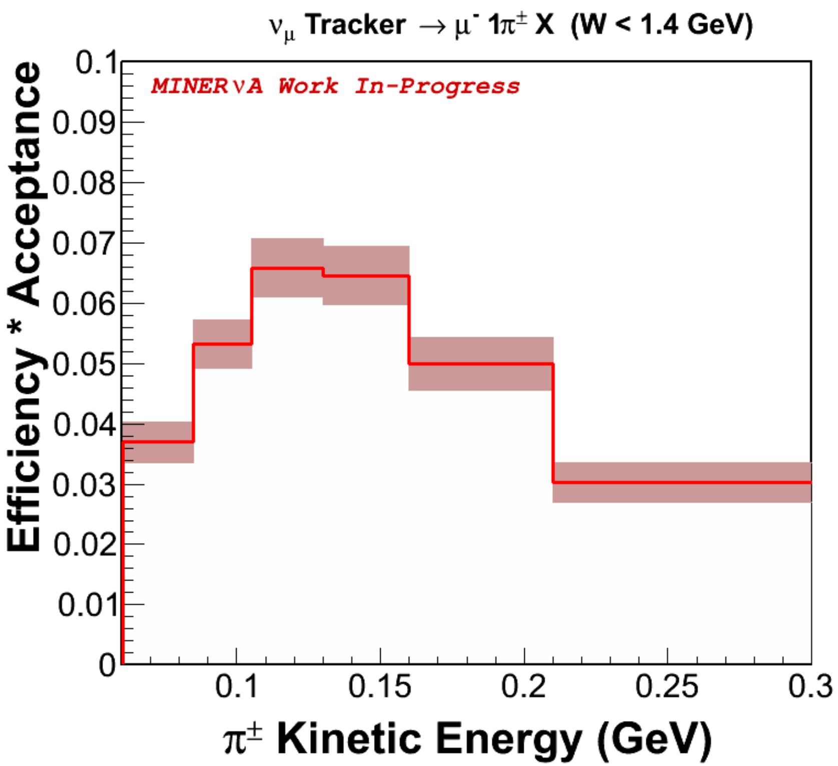


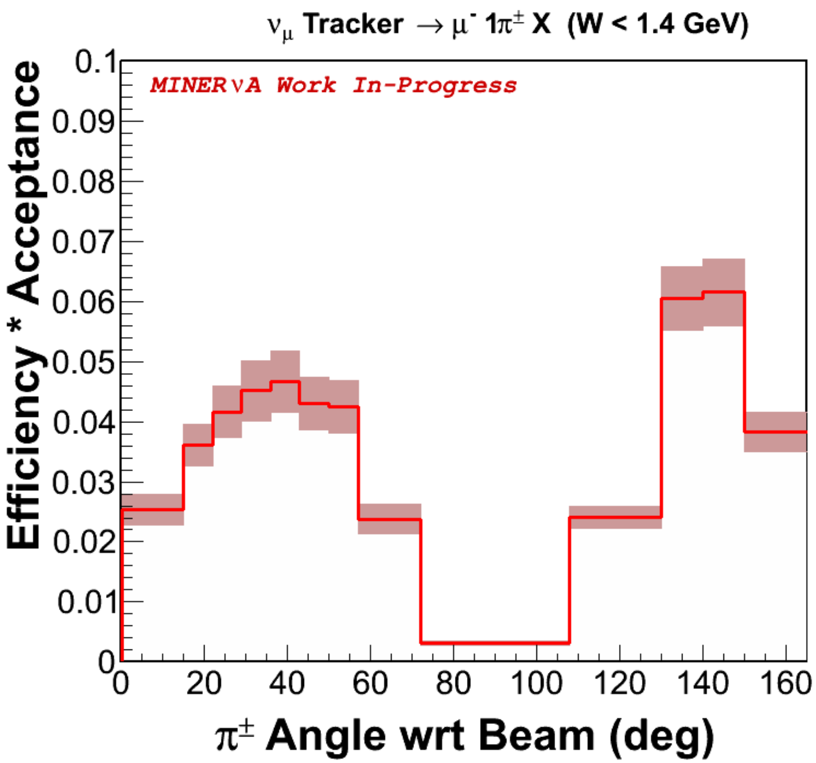
Unfolded Distributions



Efficiency Correction

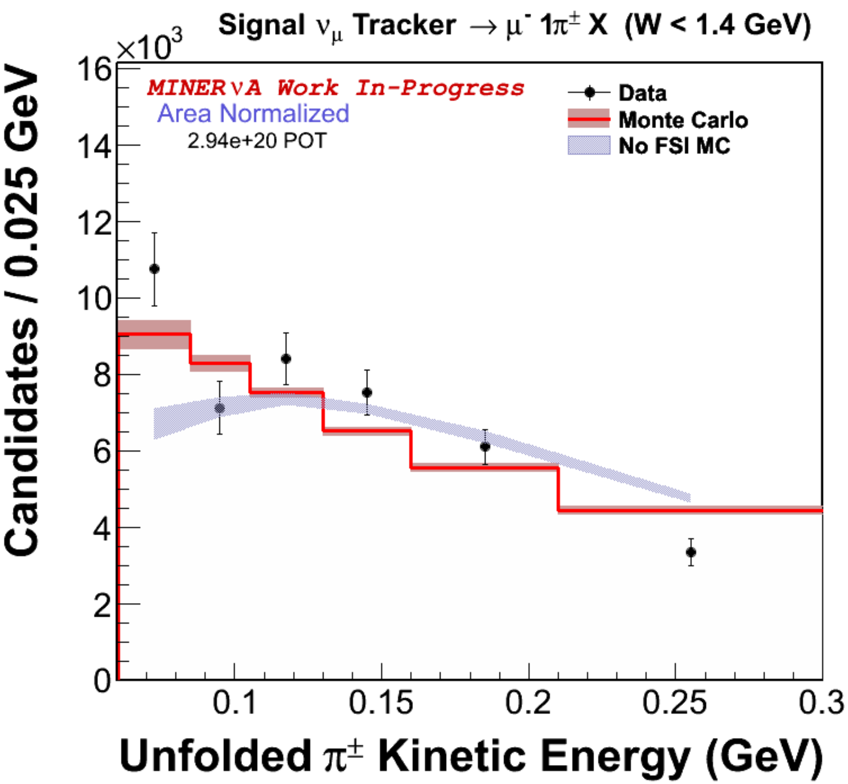
Error bars include flux and GENIE systematics

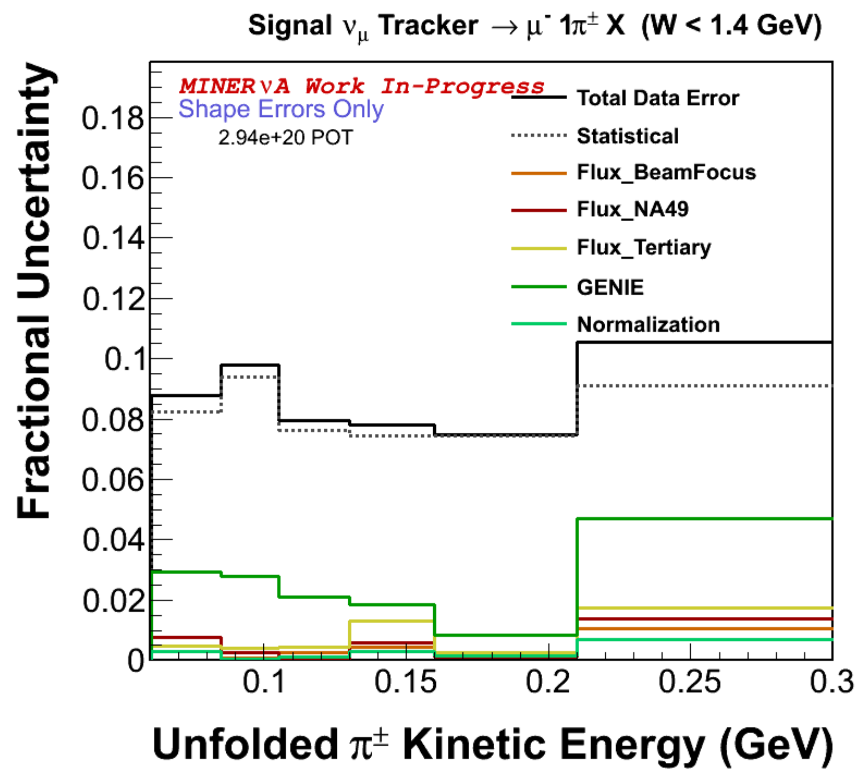




Efficiency-Corrected Distributions

No FSI MC errors include GENIE and flux shape systematics
– correlated with full MC errors





Efficiency-Corrected Distributions

No FSI MC errors include GENIE and flux shape systematics
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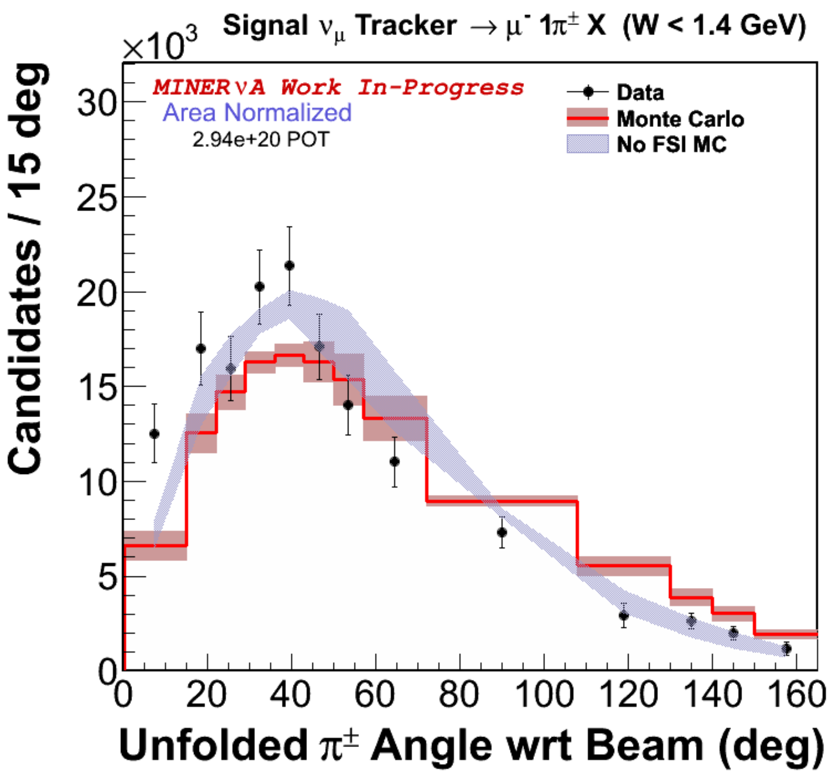
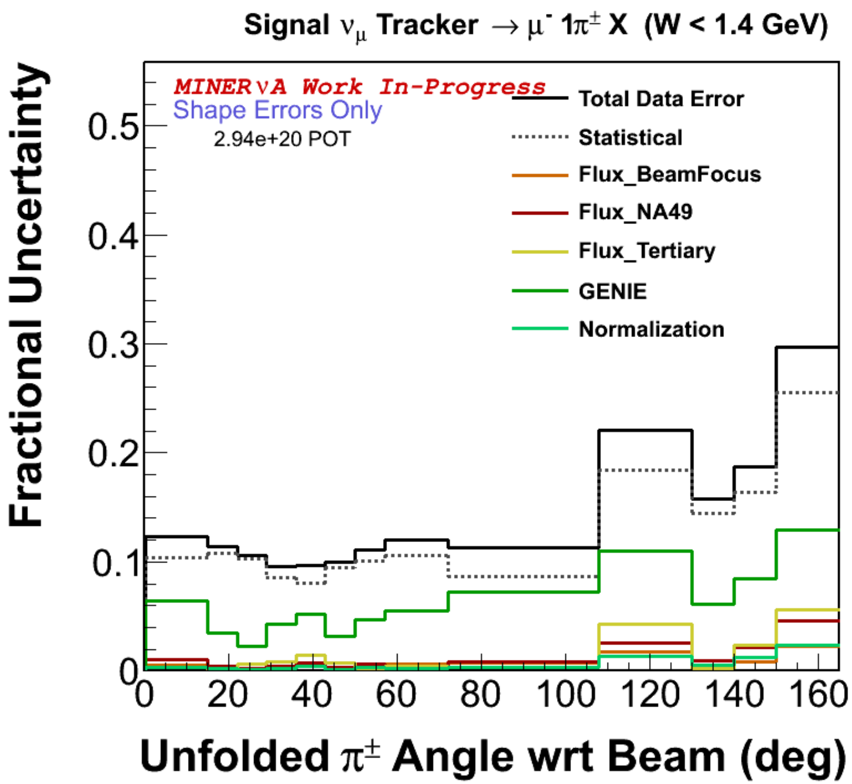




Conclusions and Outlook

- Current and future neutrino oscillation experiments need to better understand FSI and other nuclear effects

- MINERvA will contribute to understanding FSI through the kinematic distributions in the charged current single pion production analysis
    - 4000 pion candidates, very high purity

- Largest remaining tasks: evaluating pion secondary interaction and Michel systematics

- Ongoing discussions with nuclear theorists will be helpful for interpreting our results

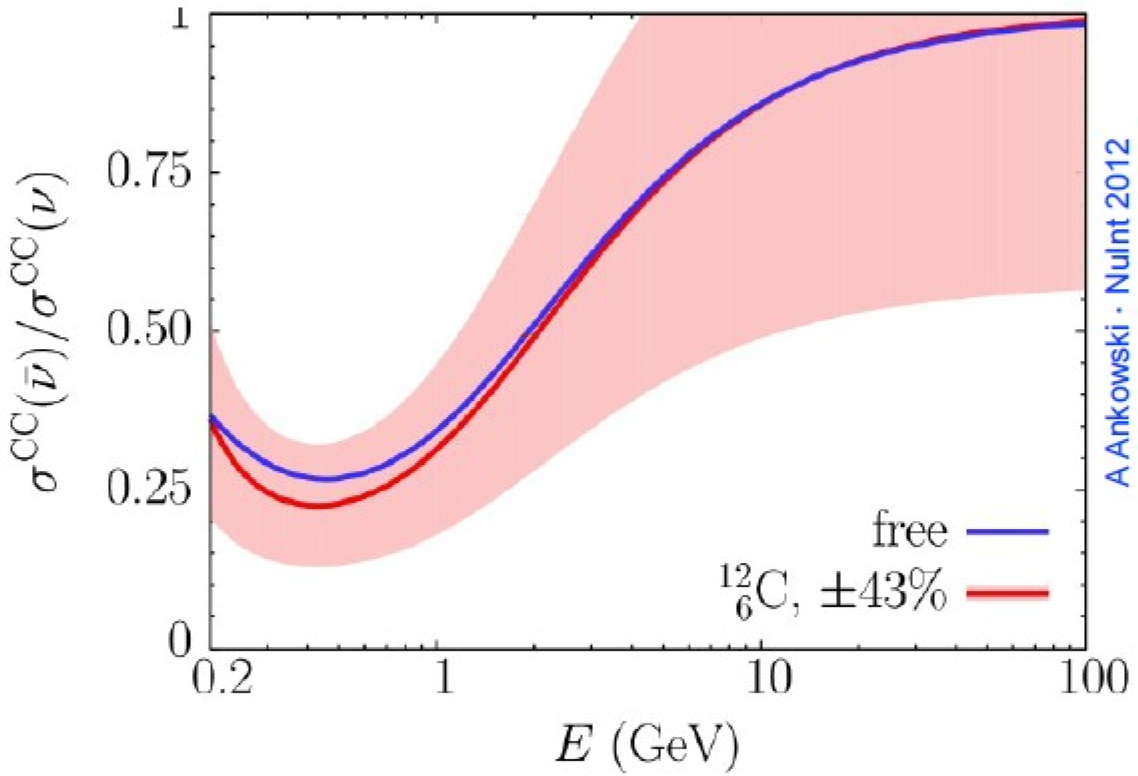
- Look for a final result in early 2014!

Thank you!

Back Ups

CP Violation

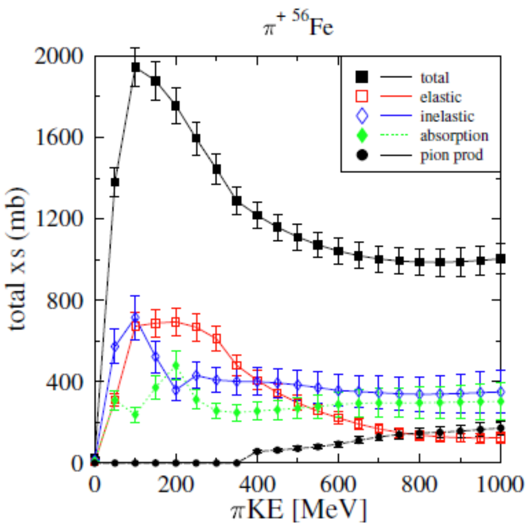
- CP violation measurement requires that we understand the difference between neutrinos and antineutrinos
    - Ratio understood to within ~40%

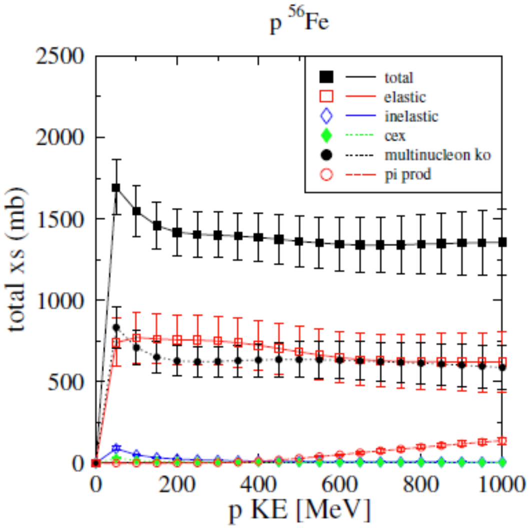


Final State Interaction Models

- Neutrino oscillation experiments use neutrino event generators (Monte Carlo) to understand neutrino-nucleus interactions
  - Most 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

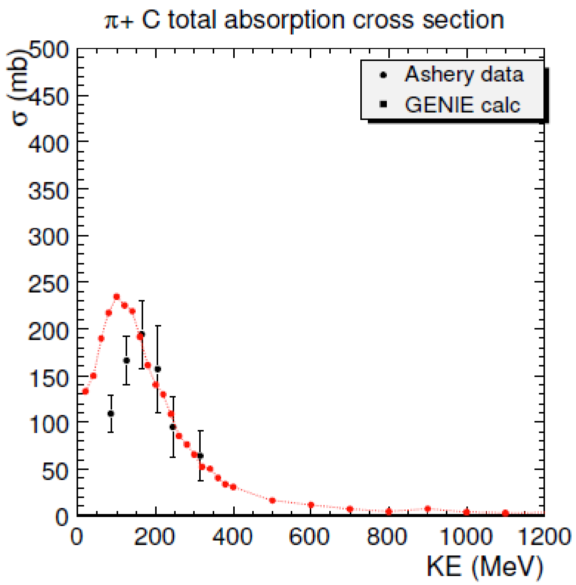


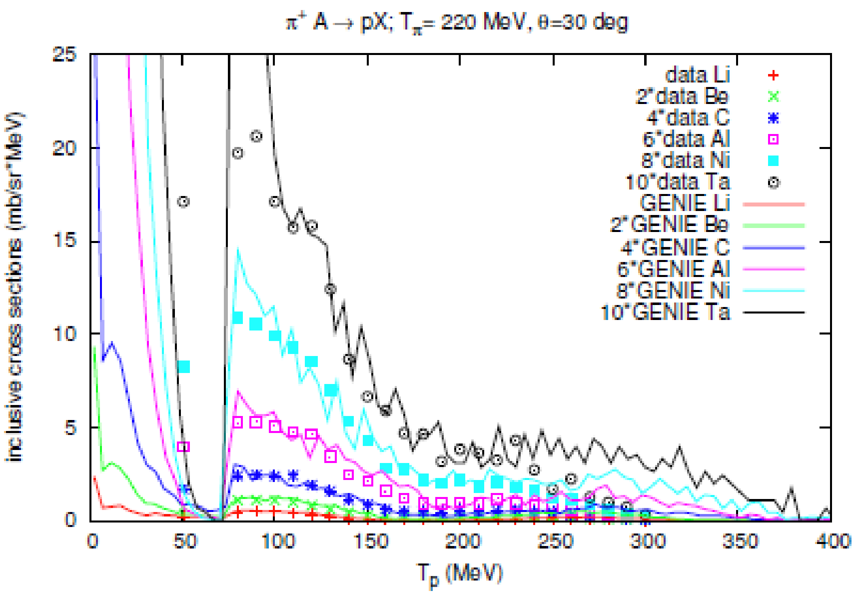


Final State Interaction Models

- Neutrino oscillation experiments use neutrino event generators (Monte Carlo) to understand neutrino-nucleus interactions
    - Most 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





Final State Interaction Models

- Theoretical calculations are very difficult
  - Quantum mechanical models are basically impossible

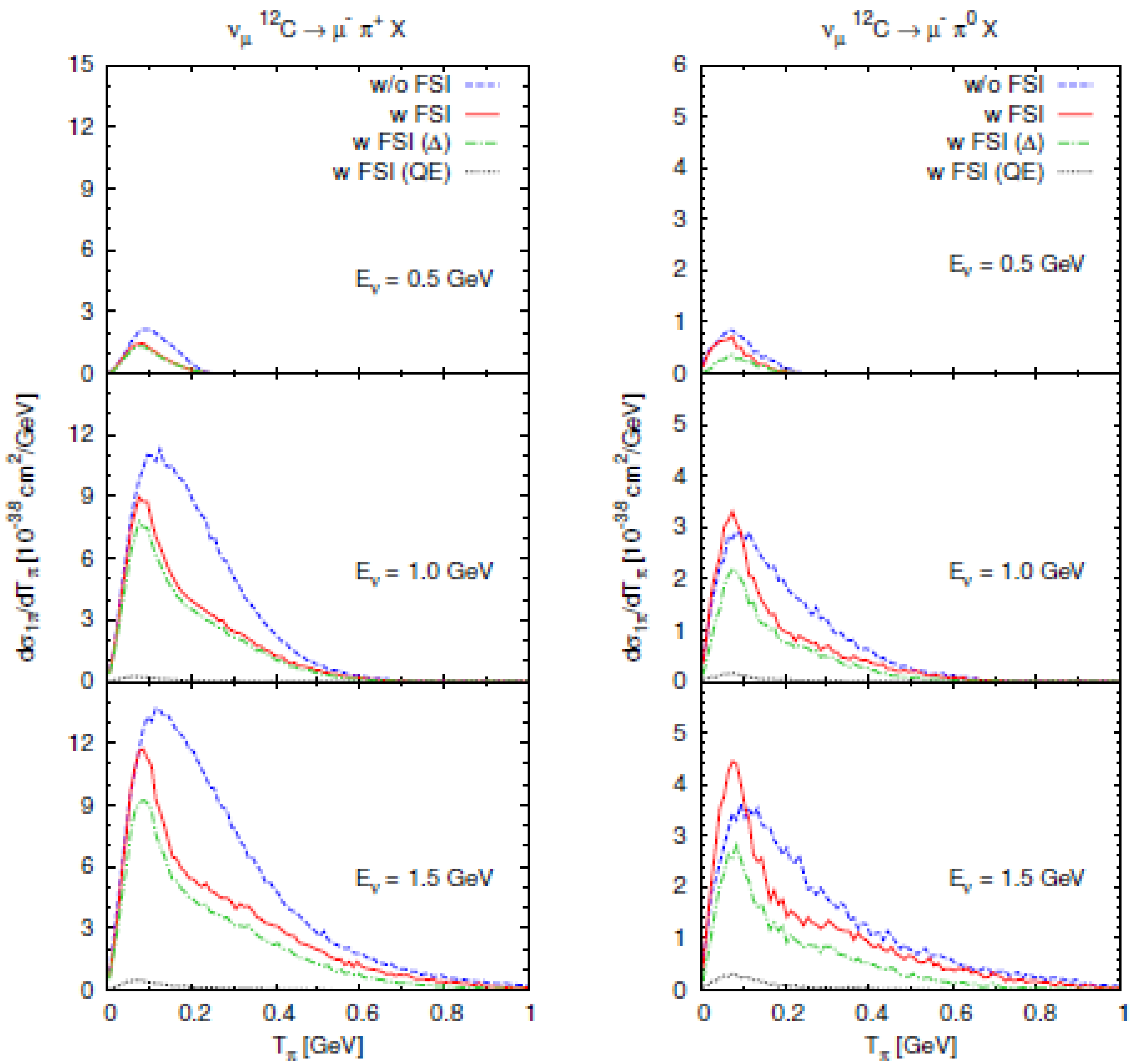
- Theorists use semi-classical models instead
  - GiBUU, a sophisticated theoretical calculator, is one example

- GiBUU FSI: solve the Boltzmann-Uehling-Uhlenbeck (BUU) equation
  - Describes the evolution of the phase space density for each particle through a nuclear mean field potential

  - Equations are coupled through the mean field and through contact terms – elastic and inelastic interactions, decays

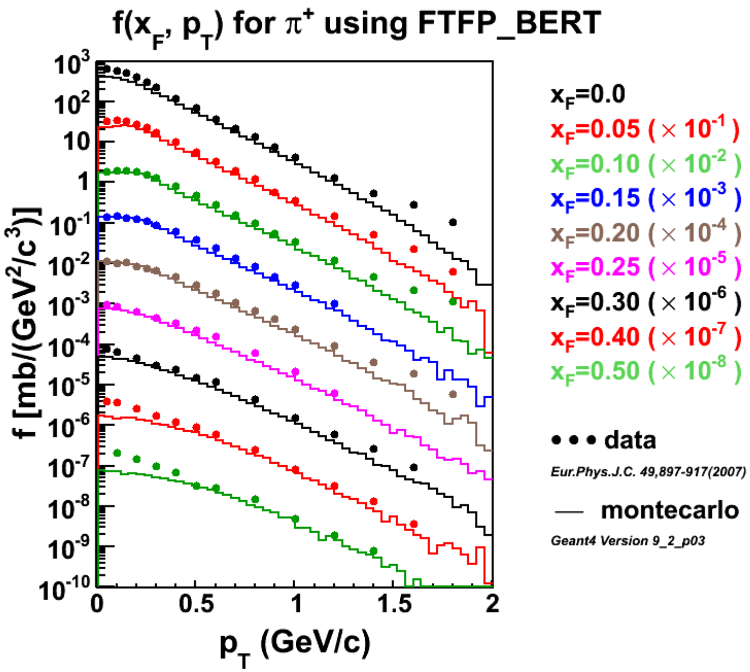
  - Solving these equations is computation-intensive – not a good event generator!

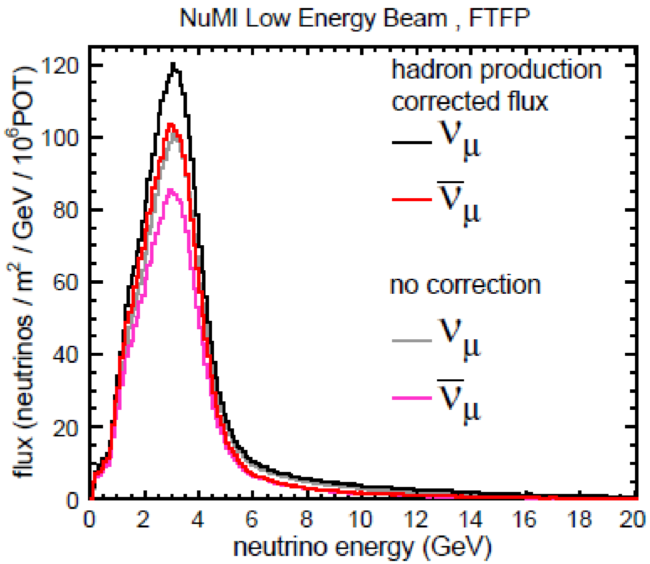
Example of GiBUU Predictions

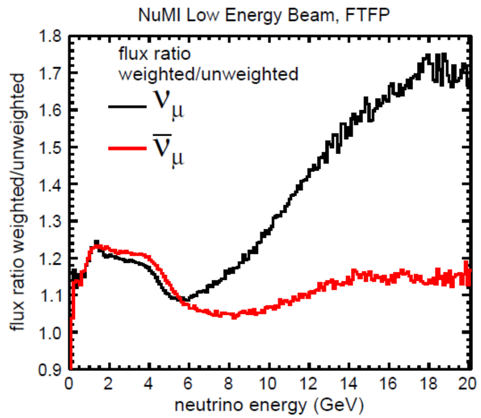


NuMI Flux Measurement

- Flux measurements are hard!
- MINERvA flux is simulated by GEANT4 and reweighted to match hadron production data from NA49.
  - 7.5% statistical, 2-10% systematic uncertainties







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

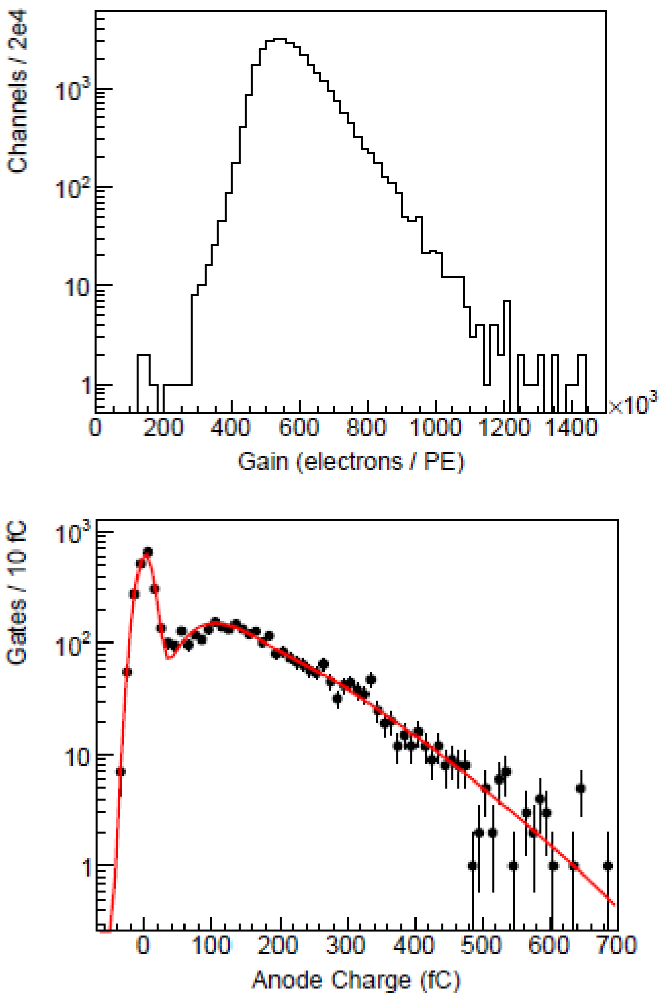
Meanwhile, MINERvA is focusing on measurements that are insensitive to flux!

Photomultiplier Tube Calibration

• Gains of ~32000 photomultiplier tube (PMT) measured daily to within ~5% with in situ calibration data

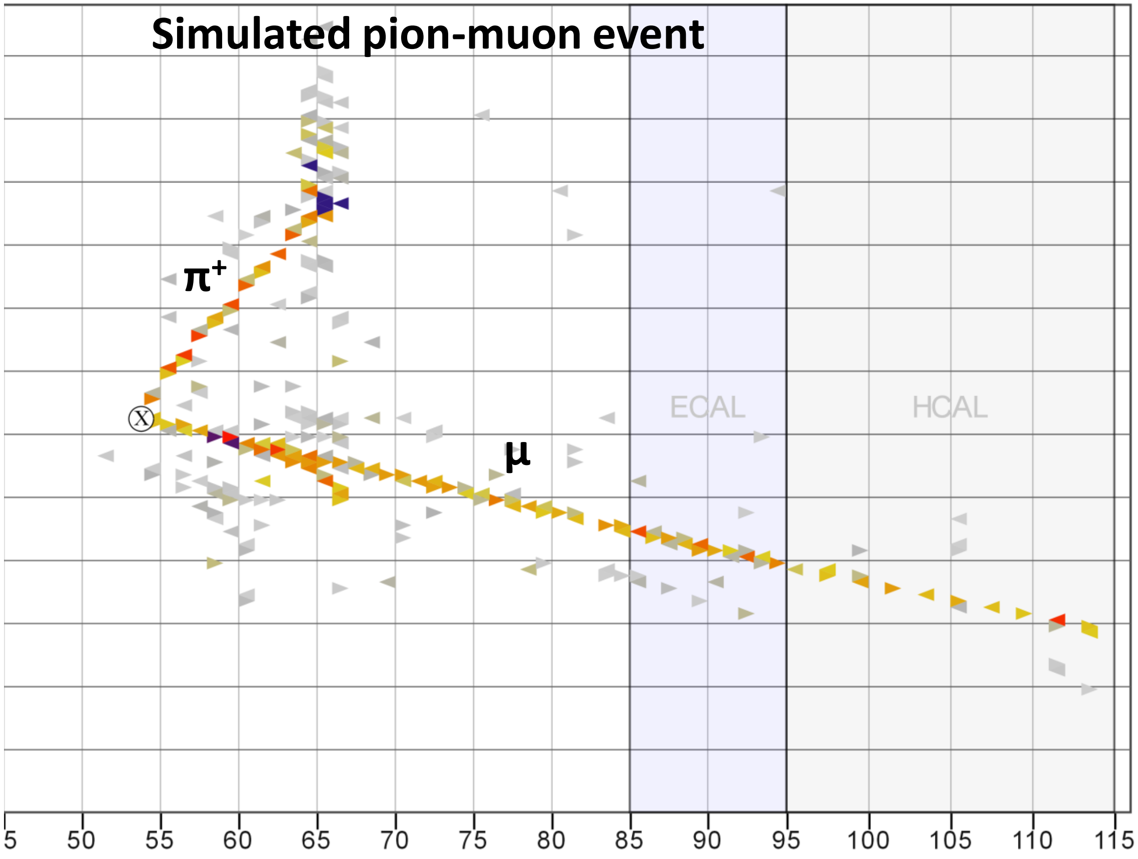
•Method validated with an independent single photon fitting procedure

•Results fed into development of PMT and detector optical model simulations



A Day in the Life of a MINERvA Pion

- Want to leverage the scintillator tracker – find pion tracks
- Pions are not always cooperative!
- They can shower or be absorbed



GENIE Uncertainties

Cross Section Model Uncertainties

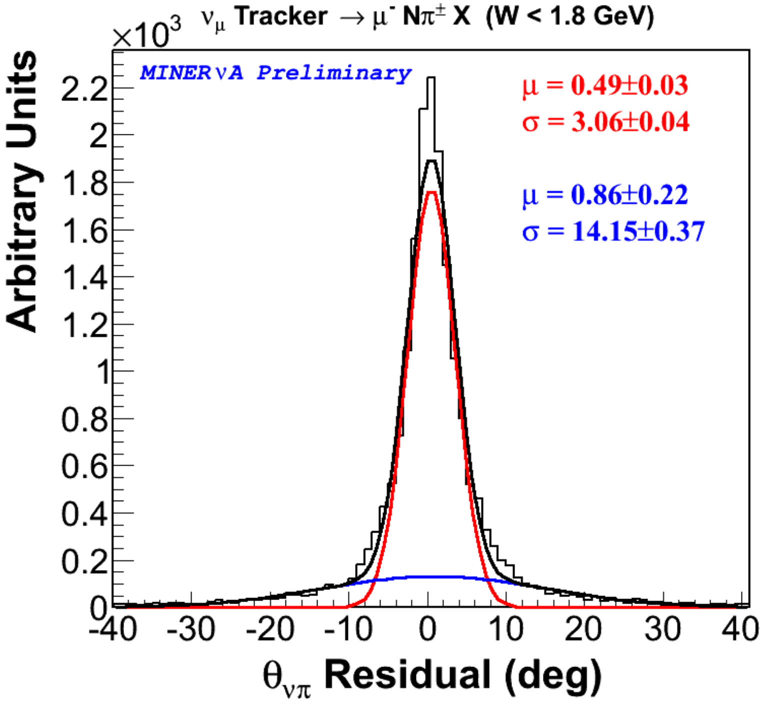
Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% −15%
CCQE Normalization	+20% −15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production)	± 20%
M_V (Resonance Production)	± 10%
1pi production from $\nu p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

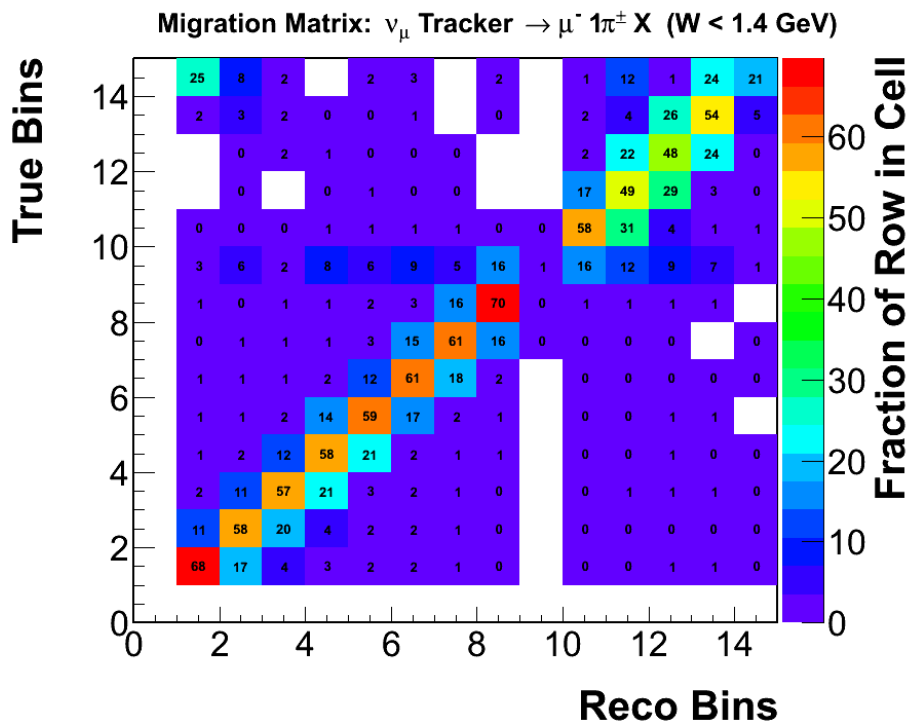
•*Intranuclear Rescattering Uncertainties*

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.

Pion Angle Unfolding





Efficiency-Corrected Ratios