Recent Results from the MINERvA Experiment

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MCLA
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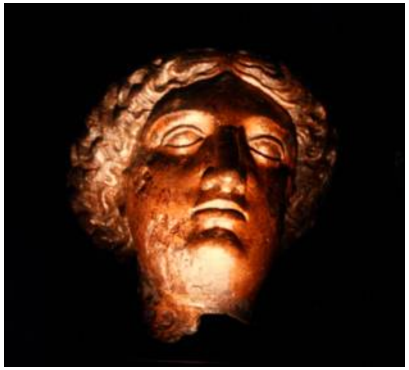
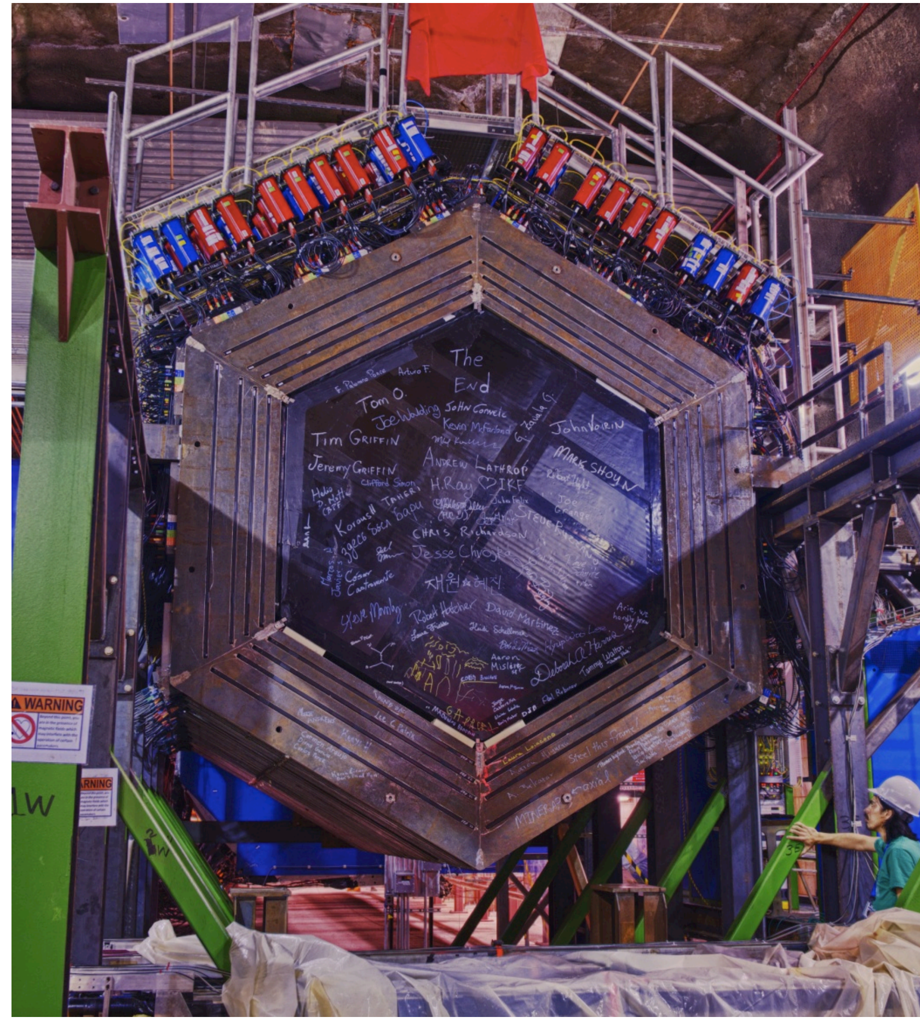


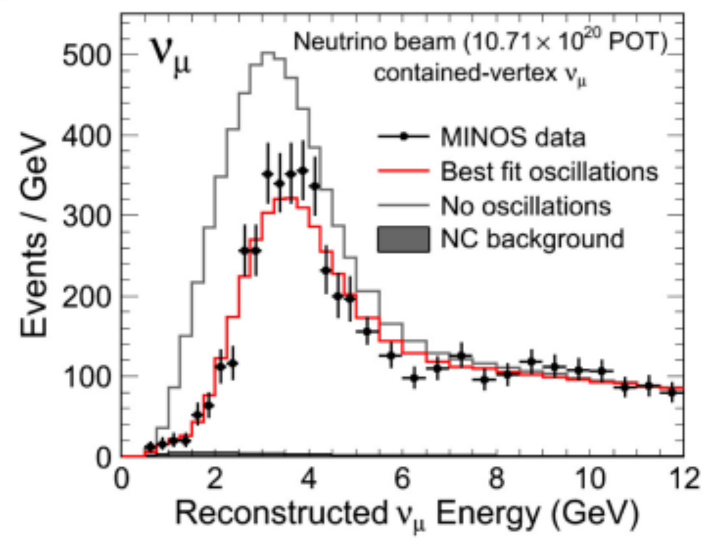
Outline

- Motivation
- MINERvA & Detector
- Previous Results
- Three New Results
  - Muon + N proton(s) (QE-like analysis)
  - Charged Pion Production
  - Coherent Charged Pion Production
- Conclusions



Motivation: Neutrino Oscillations!

- Long baseline neutrino oscillation experiment:
  - Send neutrinos through two detectors – near and far
  - Count neutrinos in the near detector
  - Predicted expected number of neutrinos in far detector
  - Count neutrinos in far detector
- Expected number of neutrino interactions in far detector depends on
  - Flux
  - Probability of oscillation (E_ν)
  - Cross section of neutrinos (E_ν)
  - Model predictions to compare to data



Phys. Rev. Lett. 110, 251801 (2013)

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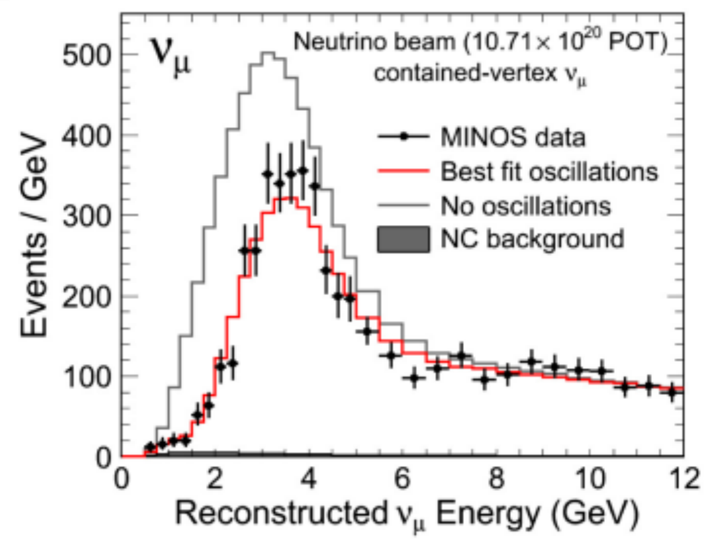
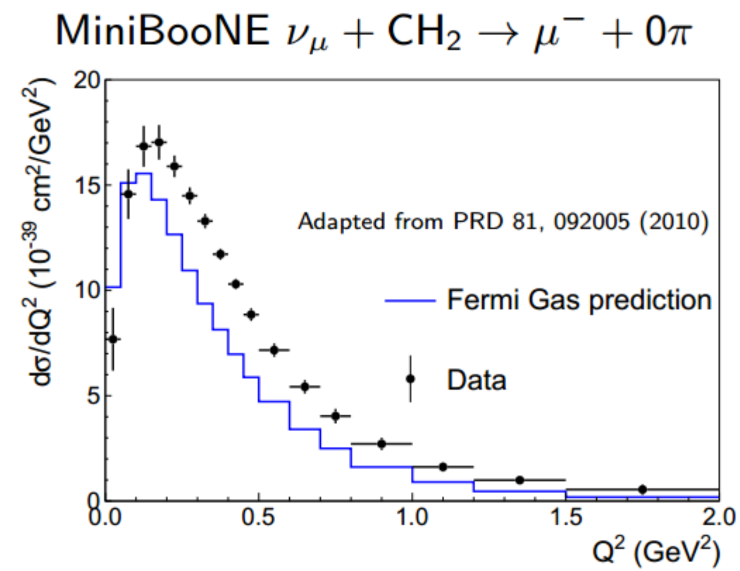
  - **Cross section of neutrinos (E_ν)**
  - **Model predictions to compare to data**

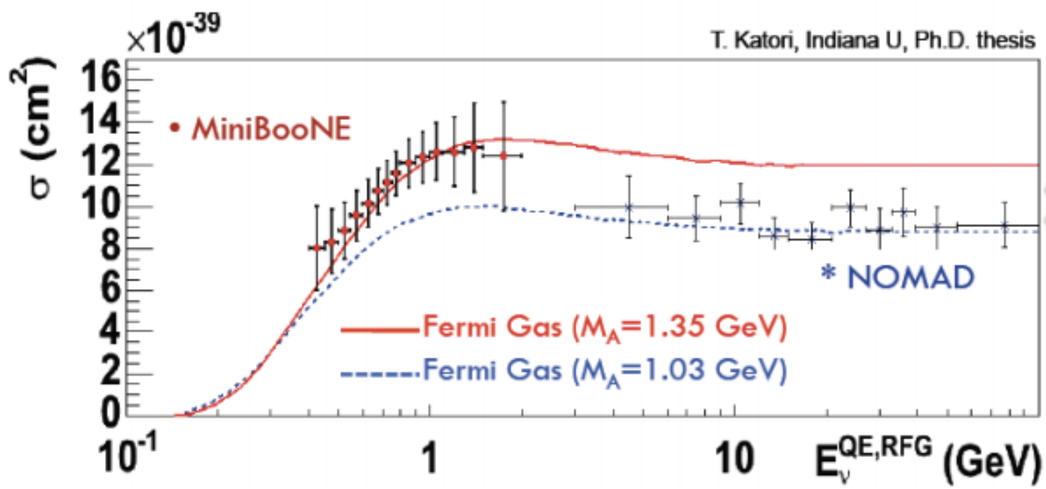


Phys. Rev. Lett. 110, 251801 (2013)

Motivation: Models in Neutrino Physics

- Most neutrino experiments use the same model: Impulse Approximation with Relativistic Fermi Gas (RFG)
  - Cannot explain recent cross section data
  - Open questions
  - MINERvA will provide data to help answer these questions



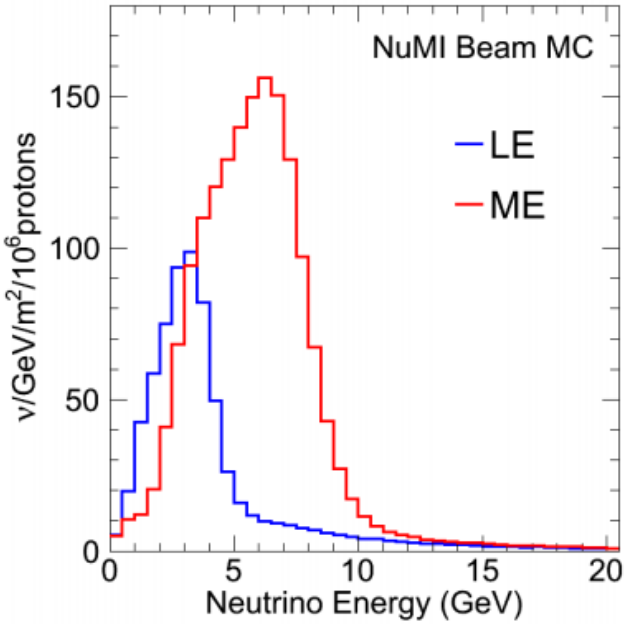


MINERvA

- Neutrino-nucleus cross section experiment in the NuMI beam at Fermilab

- Low energy data set complete with ν: ~3e20 POT, and anti-ν: ~2e20 POT

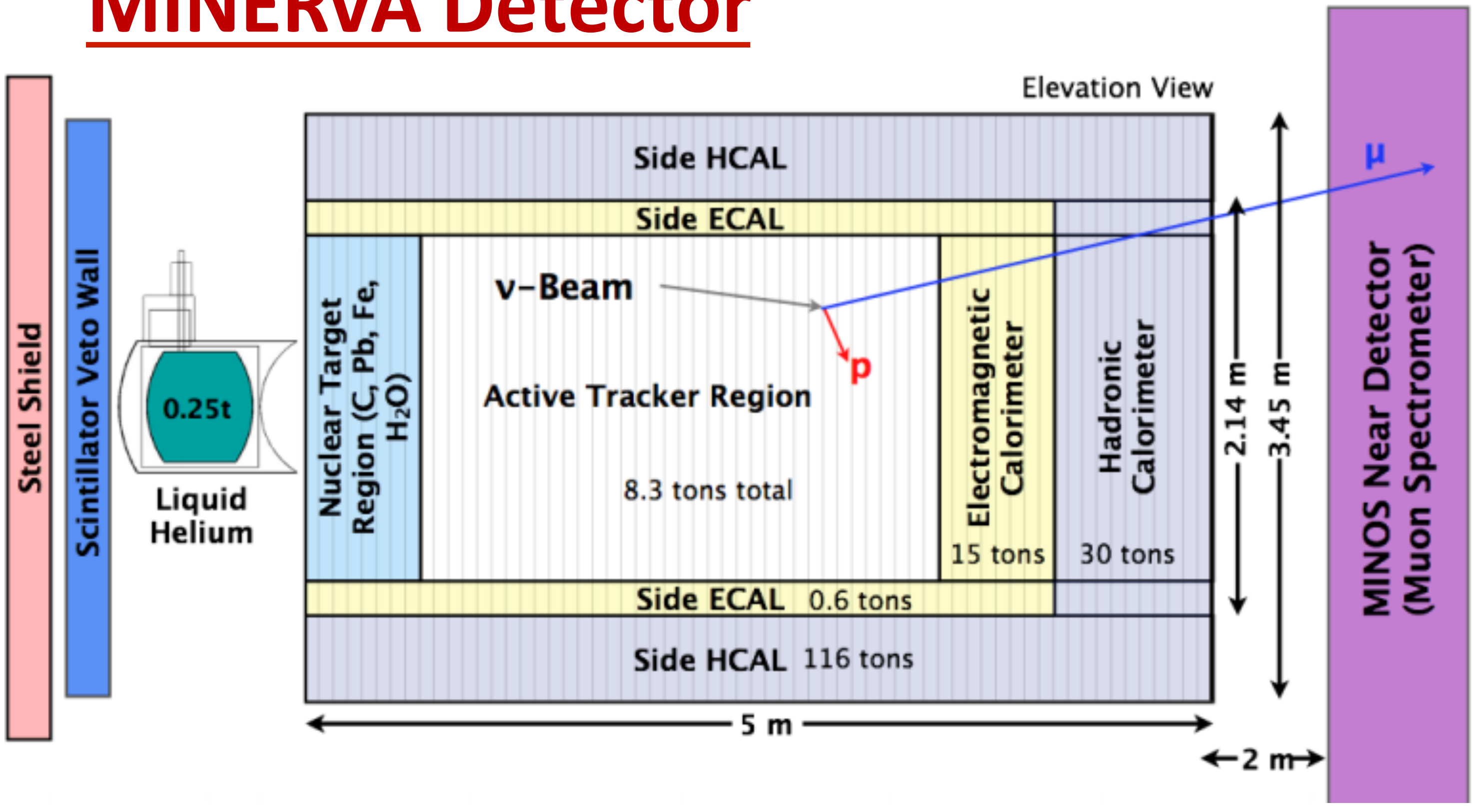
- Currently taking medium energy data



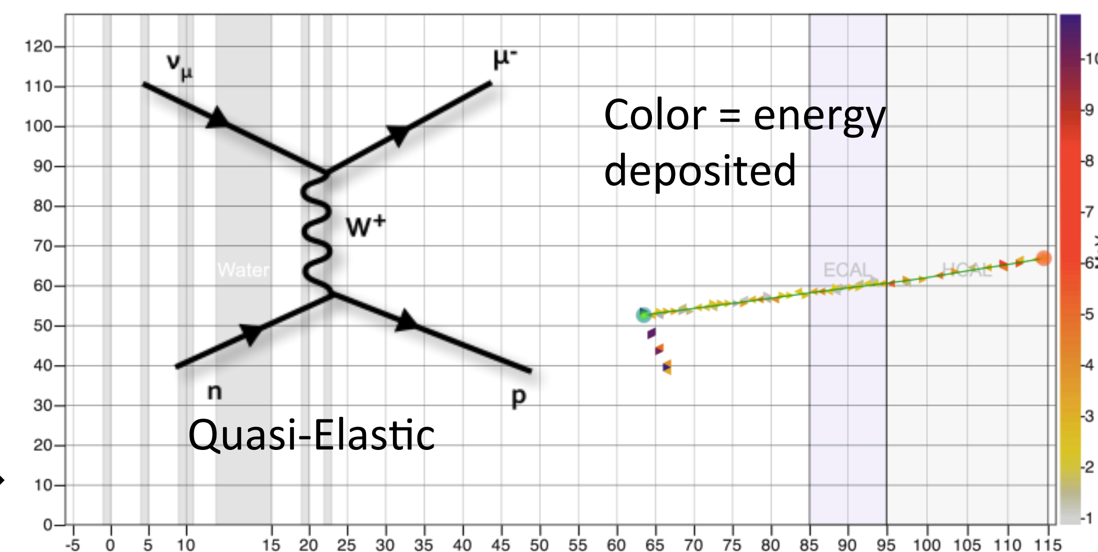
MINERvA Goals

- Measure precision **ν cross section** in few-GeV region
  - Quasi-elastic cross sections
  - Pion cross sections (backgrounds to oscillation signal)
  - + many more
- Study nuclear dynamics and their effects on ν-Nucleus scattering
  - A-dependence
  - Nuclear effects
  - Final state interactions
  - Effects on **reconstructed neutrino energy**
- Produce data to **test models**

MINERvA Detector

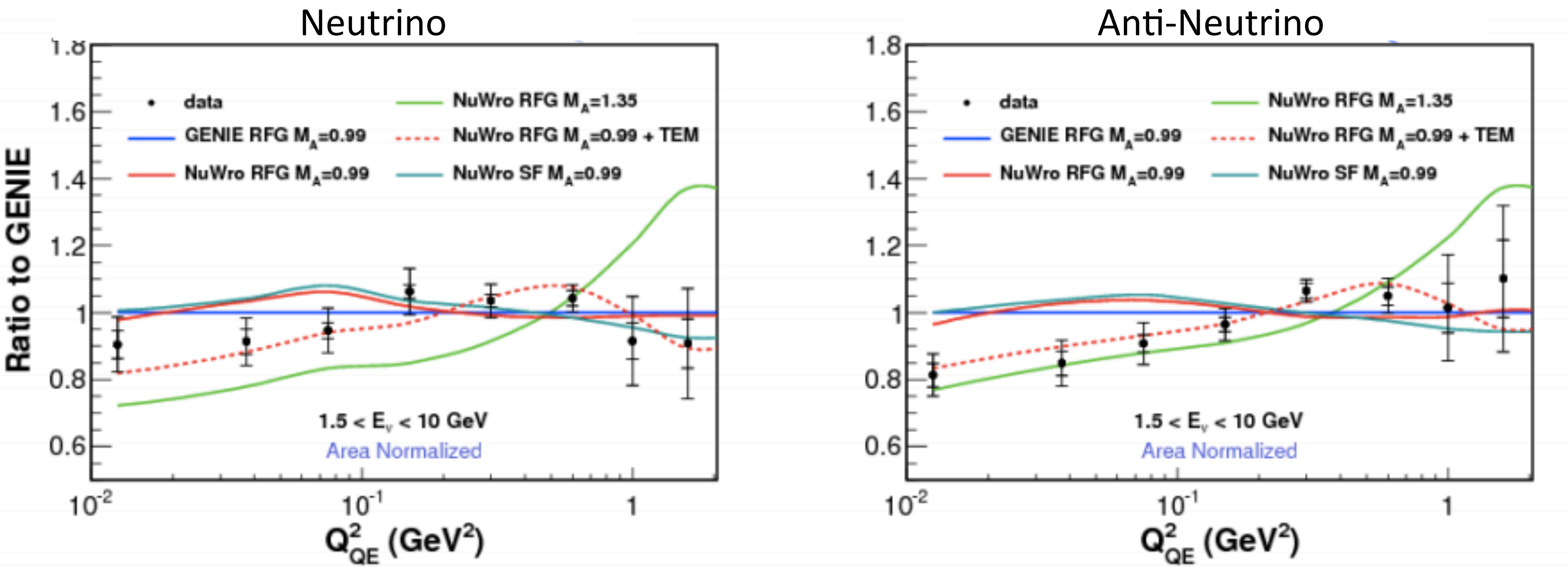


Design, Calibration and Performance of the MINERvA Detector, NIM A743 (2014) 130



Z-direction →

Previous Results: ν_μ and $\overline{\nu}_\mu$ Charged Current Quasi-Elastic Cross Sections

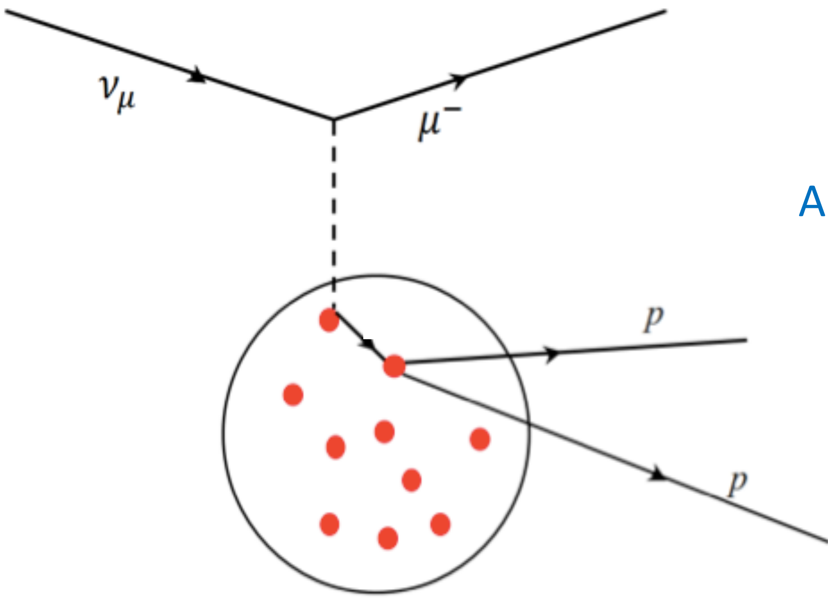


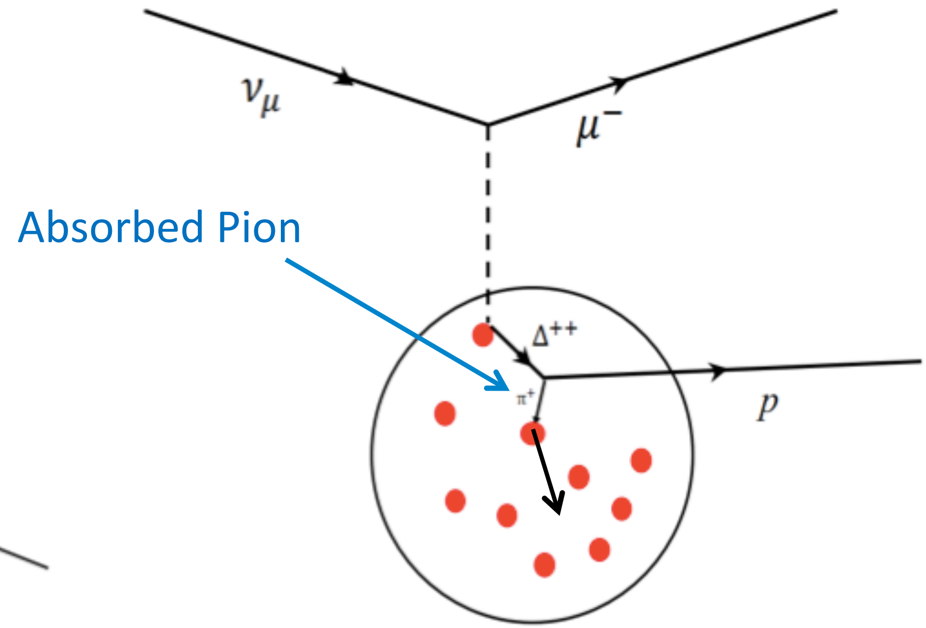
- First results disfavor standard RFG model
- Favor RFG + TEM (neutrino interacts with a pair of nucleons instead of just one!)
- Analysis used muon kinematics

Measurement of anti-ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022501
Measurement of ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022502

Result 1: Muon + N Proton(s)

- Non-QE processes that appear to be QE directly affect the **reconstructed neutrino energy**

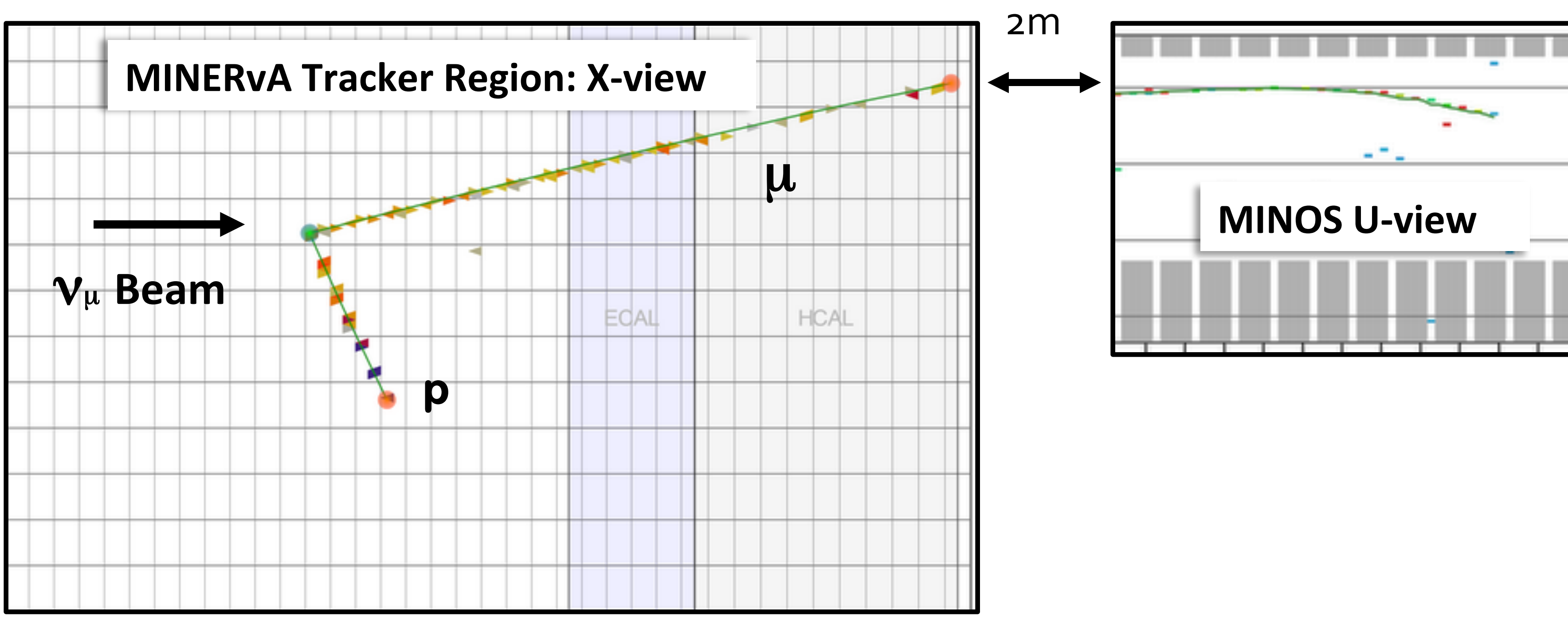




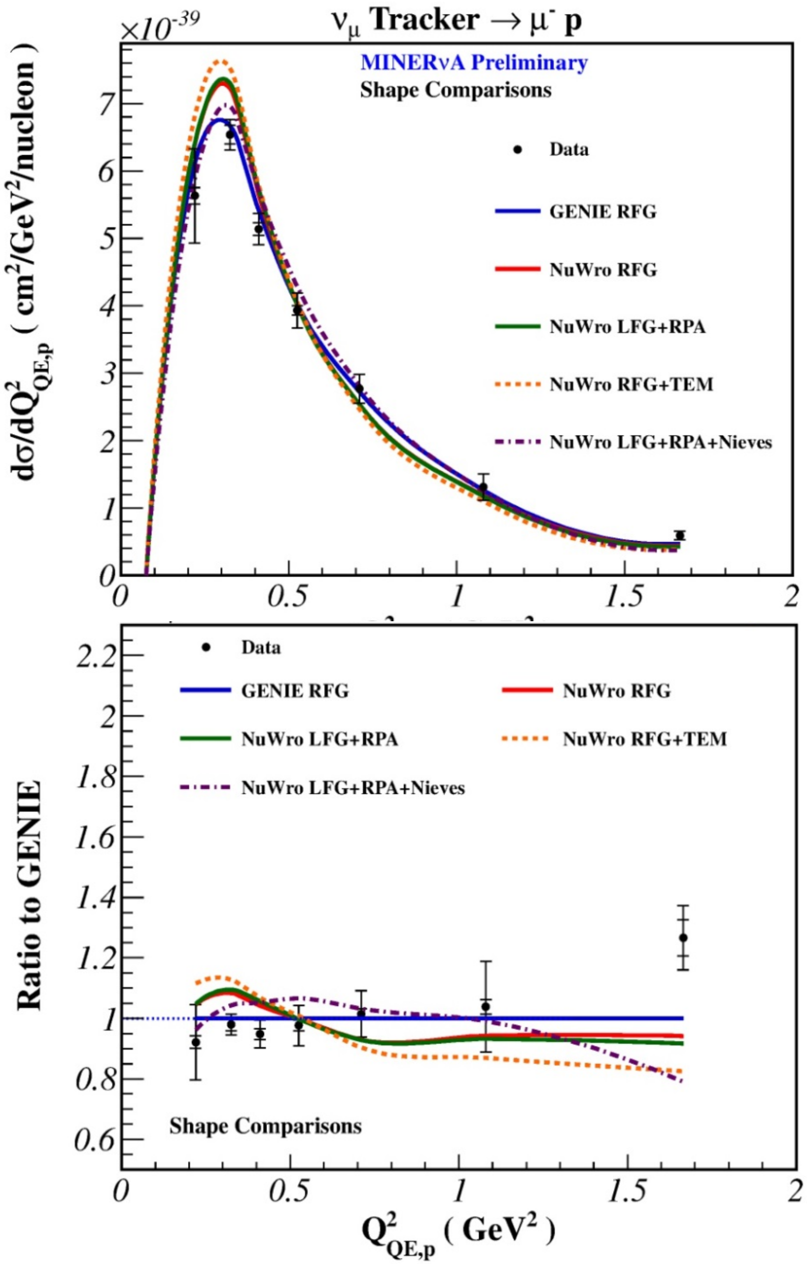
- Use the muon and proton kinematics to study the nuclear effects and final state interactions

Muon + N Protons: Event Selection

- Event Selection:
  - Final state consist of proton(s) a μ and no π
  - Muon must exit detector
  - dE/dx differentiates protons and pions
  - Cut on extra energy not associated with the tracks or vertex
  - Michel electrons used as filter



Muon + N Protons: Results

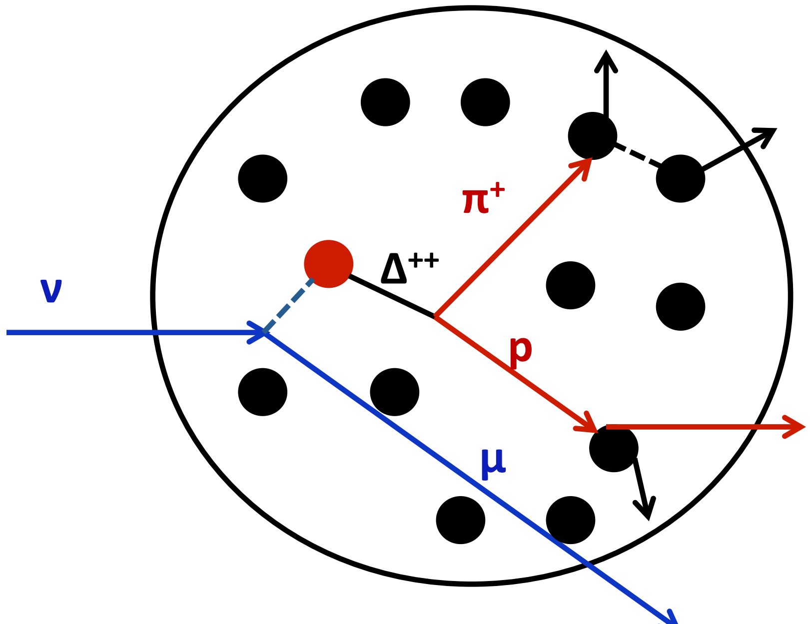


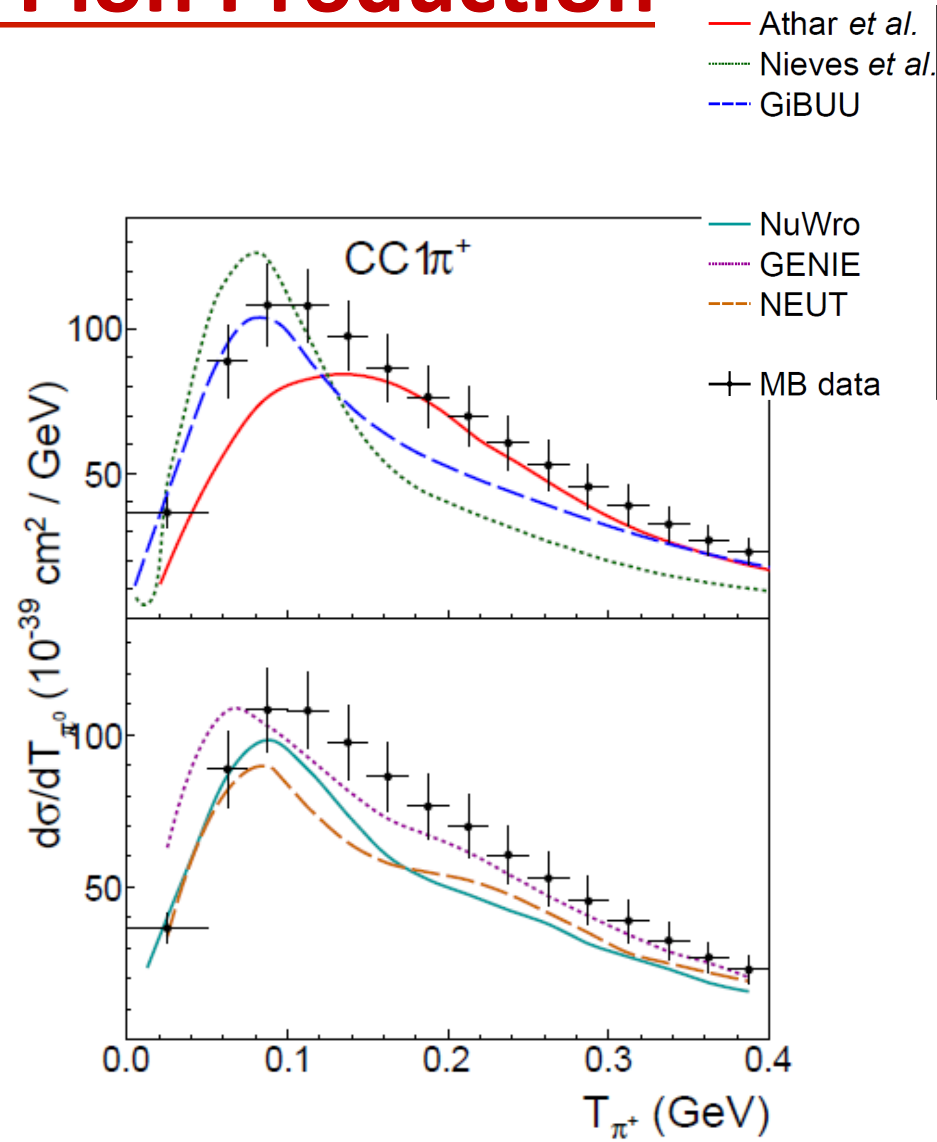
- Proton kinematics favor standard RFG model
- Muon kinematics favor RFG + TEM (neutrinos interacting with pairs of nucleons)
- Neutrinos oscillation experiments should use models that reproduce hadronic and leptonic kinematics, since both affect **neutrino energy reconstruction**

Measurement of μ plus p final states in ν_μ Interactions on Hydrocarbon at average E_ν of 4.2 GeV arXiv:1409.4497

Result 2: Charged Pion Production

- Theoretical calculations and models cannot reproduce recent pion cross section
- **Pion events are backgrounds to oscillation signal**
- Determine strength and nature of final state interactions (FSI) using pion kinematics





MiniBooNE
Phys.Rev.D83:052007

Charged Pion Production: Event Selection

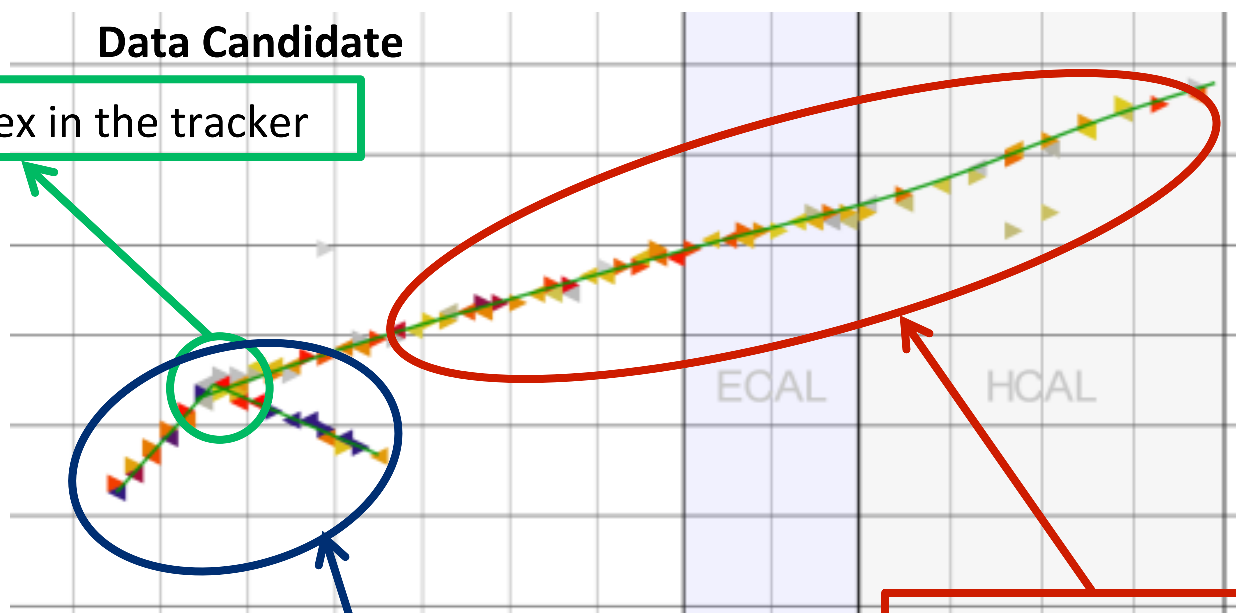
$\nu_\mu A \rightarrow \mu^- \pi^\pm X$

A = nucleus in the tracker

X = recoil nucleus + any particles except charged pions

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

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



Selection: Vertex in the tracker

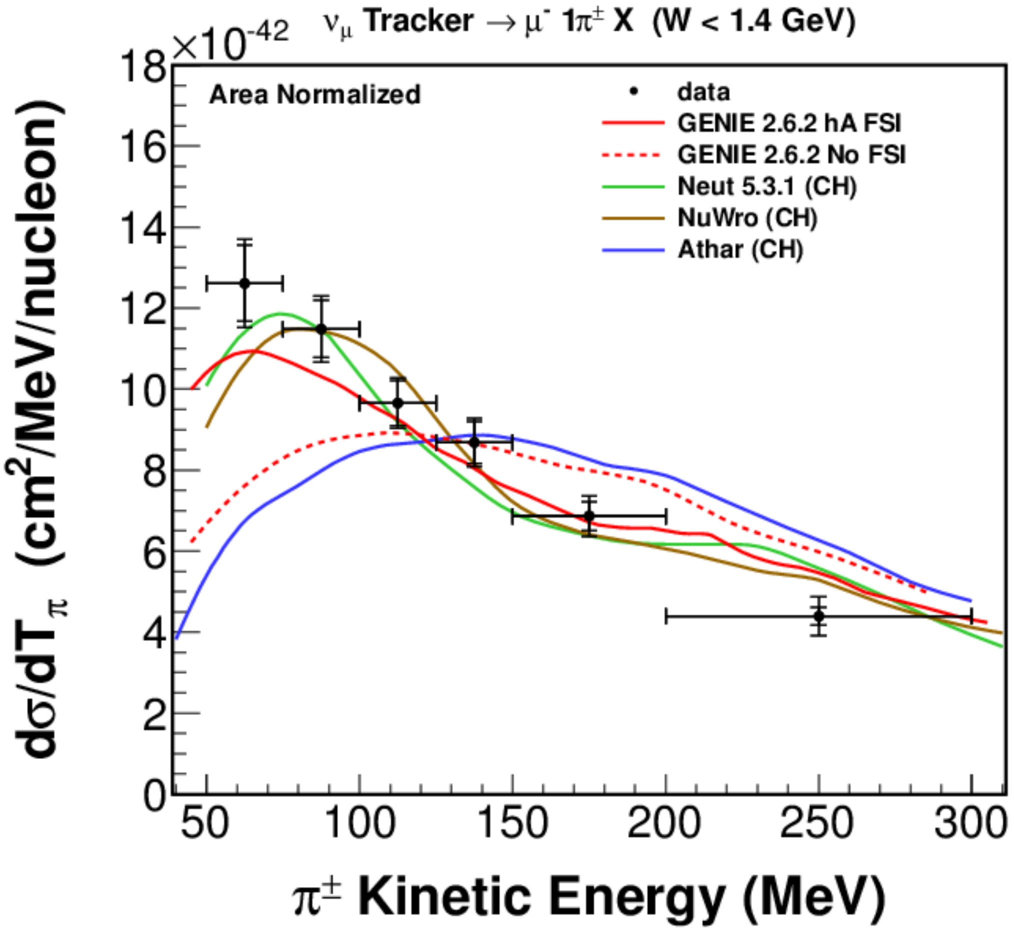
Selection: 1-2 non-muon tracks at the primary vertex, but only 1 π

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

Avoid high multiplicity by requiring the invariant hadronic mass , W <1.4 GeV

Charged Pion Production: Results

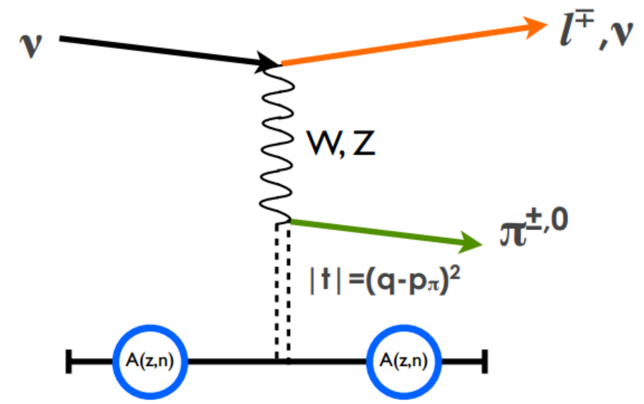
- **Data strongly prefers models with final state interactions**
- Useful in understanding **backgrounds in oscillation experiments**



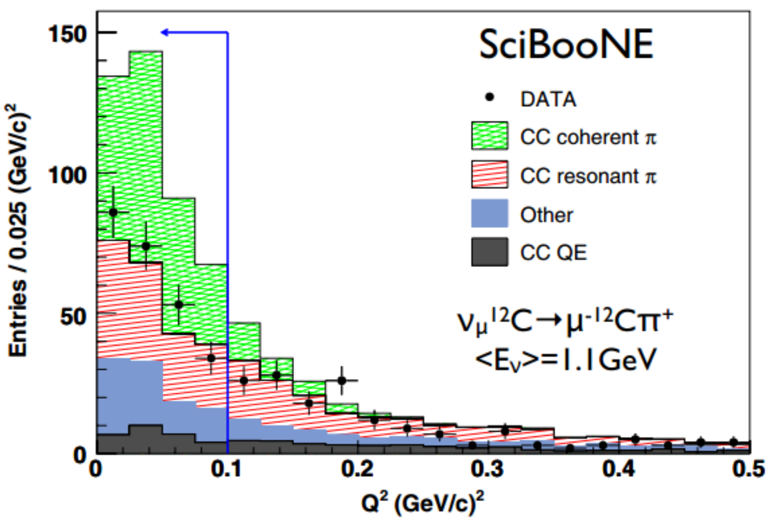
Charged Pion Production in ν_μ Interactions on Hydrocarbon at average E_ν of 4.0 GeV: arXiv:1406.6415

Result 3: Coherent Charged Pion Production

- Neutrino scatters off a nucleus, produces a pion, and transfers $|t|$ to the nucleus, which stays intact
- **Oscillation measurements require understanding of these interactions**
- SciBooNE and K2K have looked in the few GeV region but found nothing
- Select low $|t|$ events
- Produce model-independent measurements – **can use to test models**



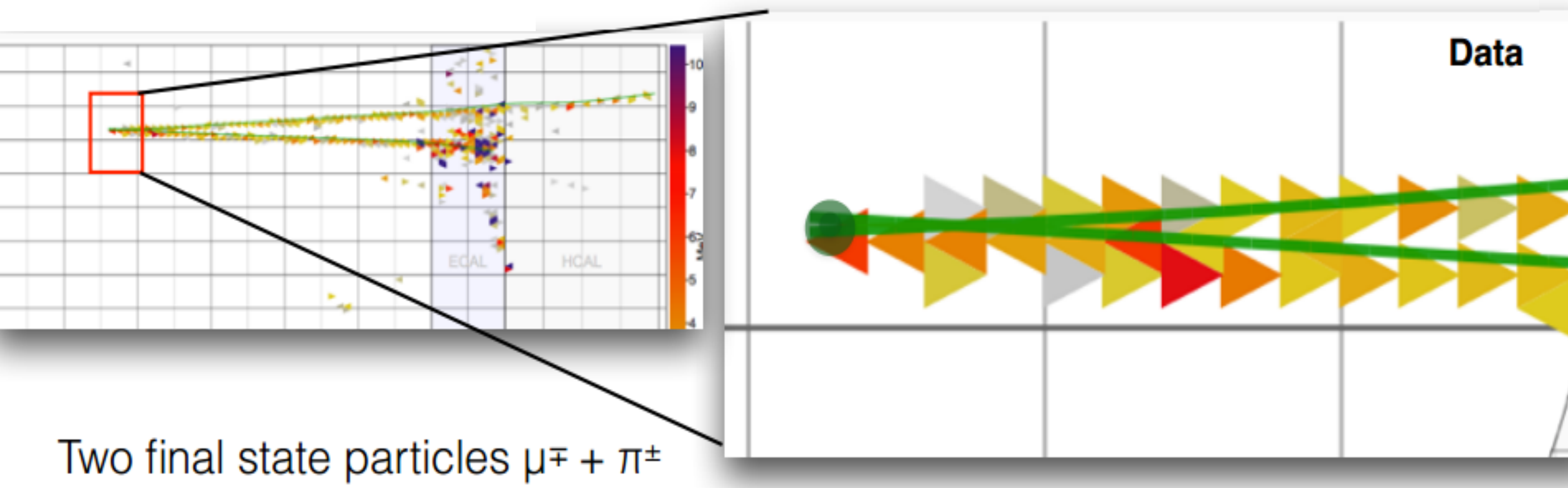
Phys. Rev. D 78, 112004 (2008)



Coherent Pion Production: Event Selection

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

- Event Selection:
  - Require a muon which enters MINOS
  - Requires a pion
  - No extra visible energy near vertex
  - Cut on $|t|$



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

Coherent Pion Production: Analysis

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

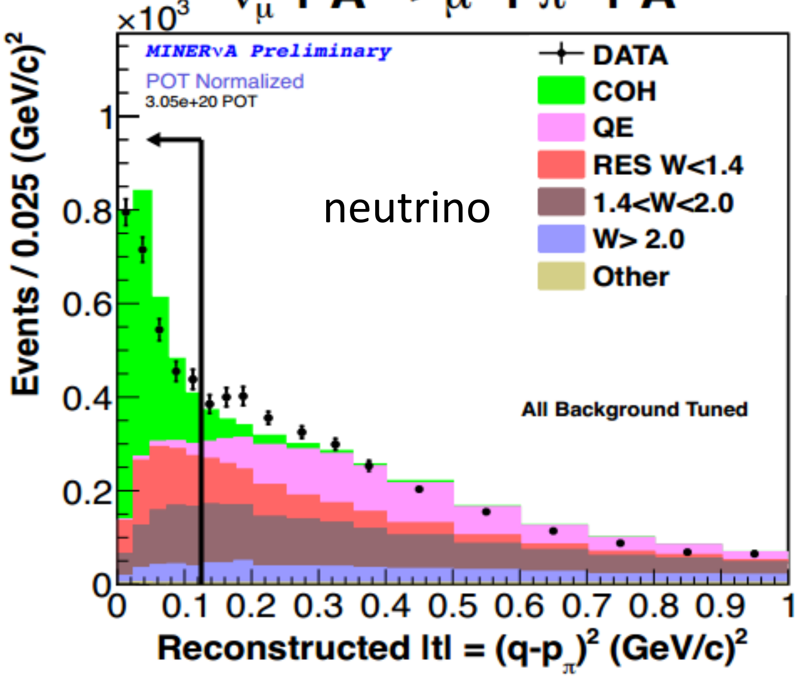
$$E_\nu = E_\mu + E_\pi$$

$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

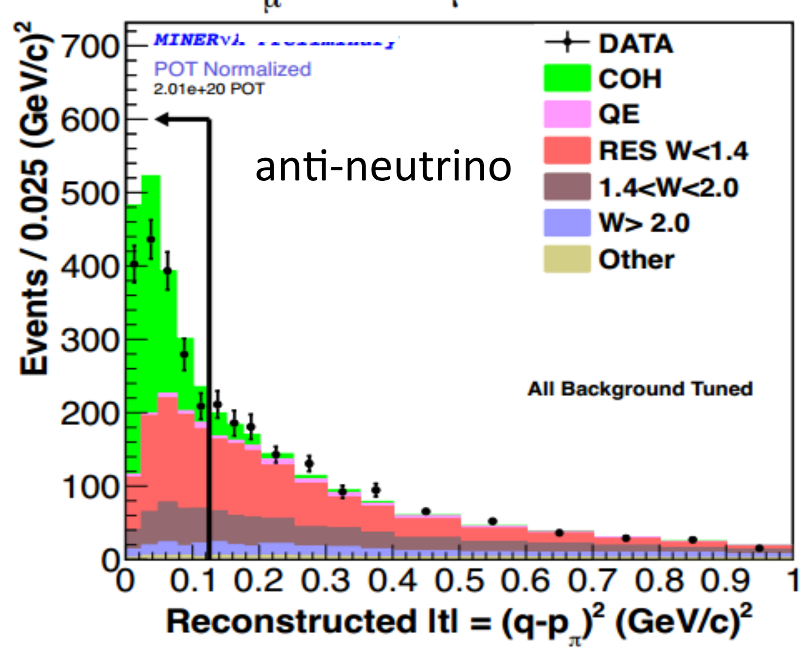
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$

- P_μ measured from reconstructed muon in MINOS
- E_π is reconstructed calorimetrically

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

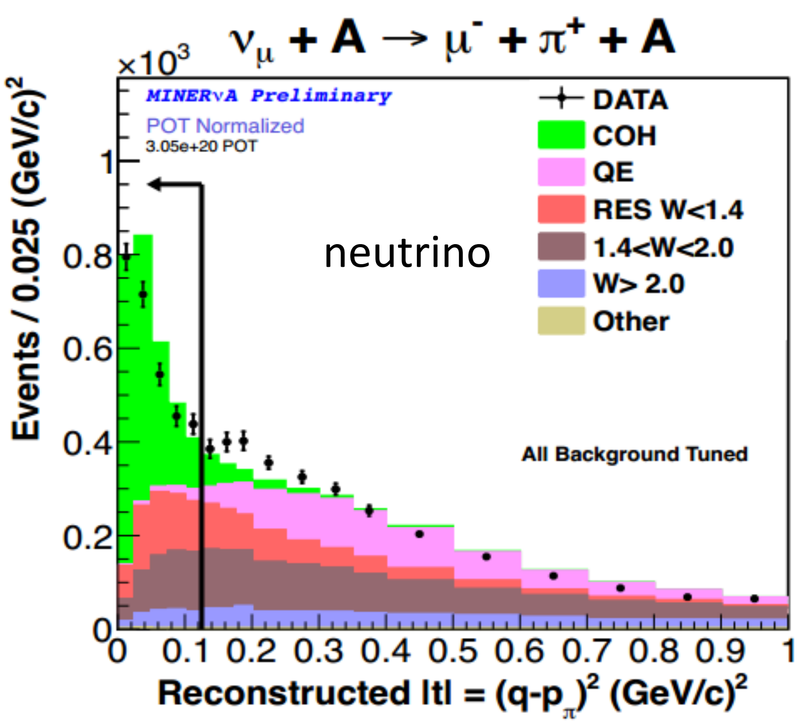


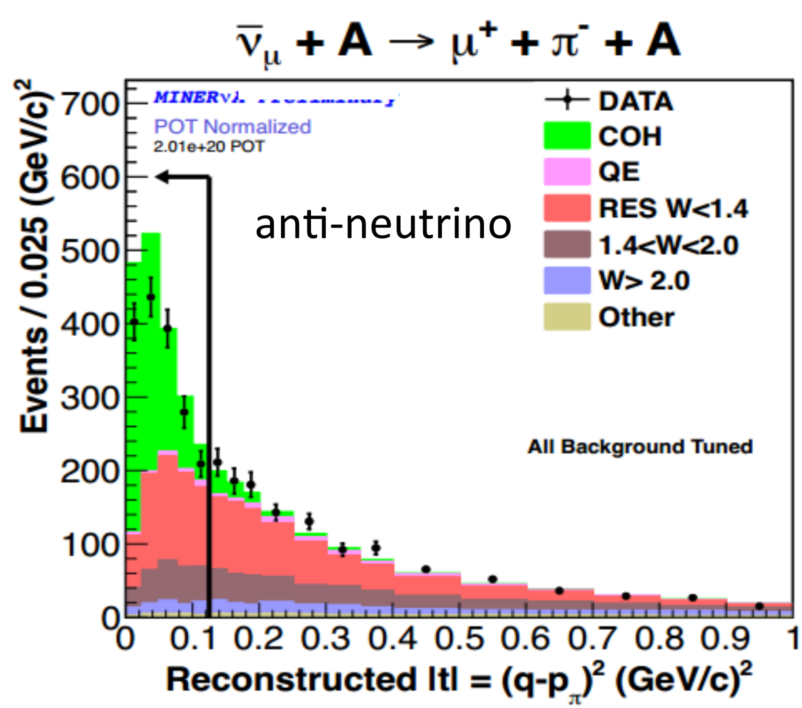
$\bar{\nu}_\mu + A \rightarrow \mu^+ + \pi^- + A$



Coherent Pion Production: Analysis

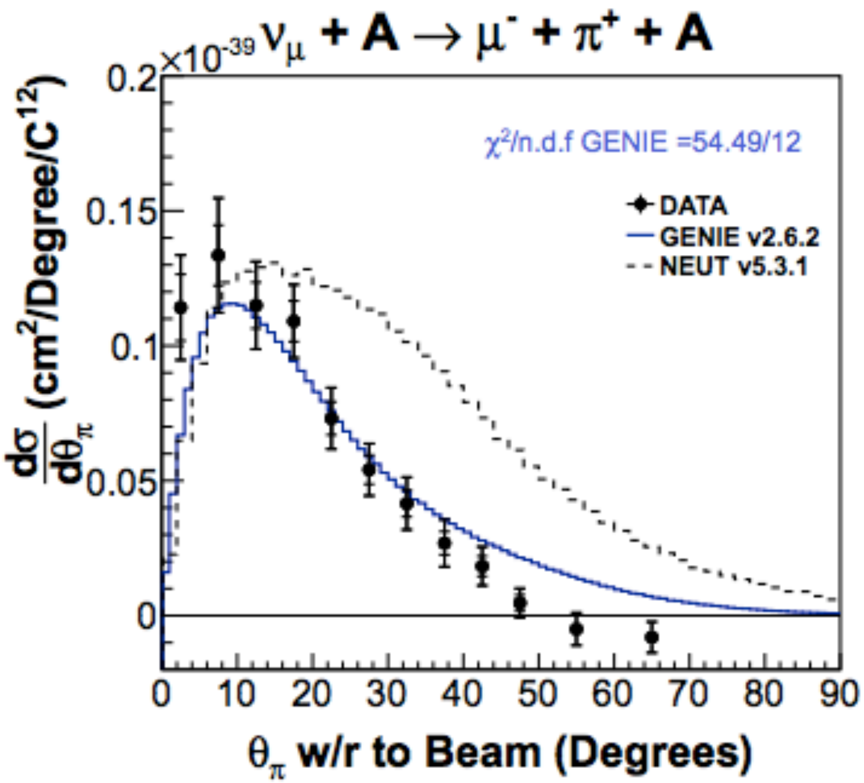
Significant Signal Observed!!!

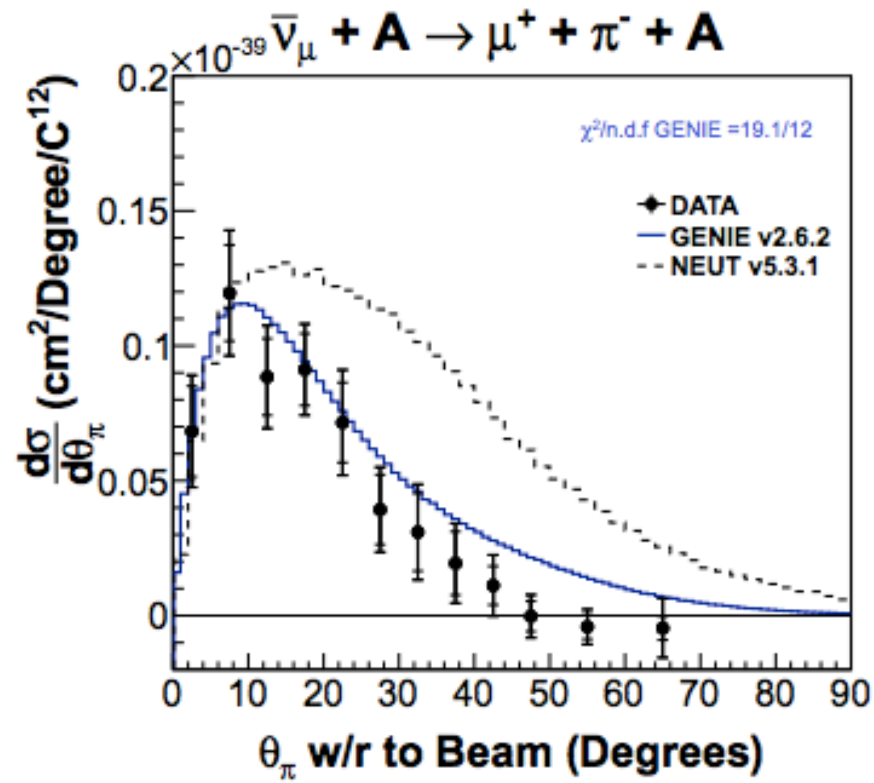




Coherent Pion Production: Results

- Differential cross sections as a function of pion angle
- Disagreement at high θ_π is evident in both
- **Data can test new PCAC and microscopic models**





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

Conclusions

- MINERvA is measuring **cross sections** needed for oscillation experiments
- Determining importance of nuclear effects and final state interactions on **neutrino energy reconstruction**
  - Our muon + N proton(s) and charged pion production analyses
- MINERvA is producing results that will help **guide models**
  - Coherent charged pion production
- Expect more low energy results in the near future and, later, medium energy results!
  - π^0 production
  - ν_e CCQE cross section
  - CCQE double differential cross section ($d^2\sigma/dp_z dp_t$)
  - Kaon production
  - Deep inelastic scattering

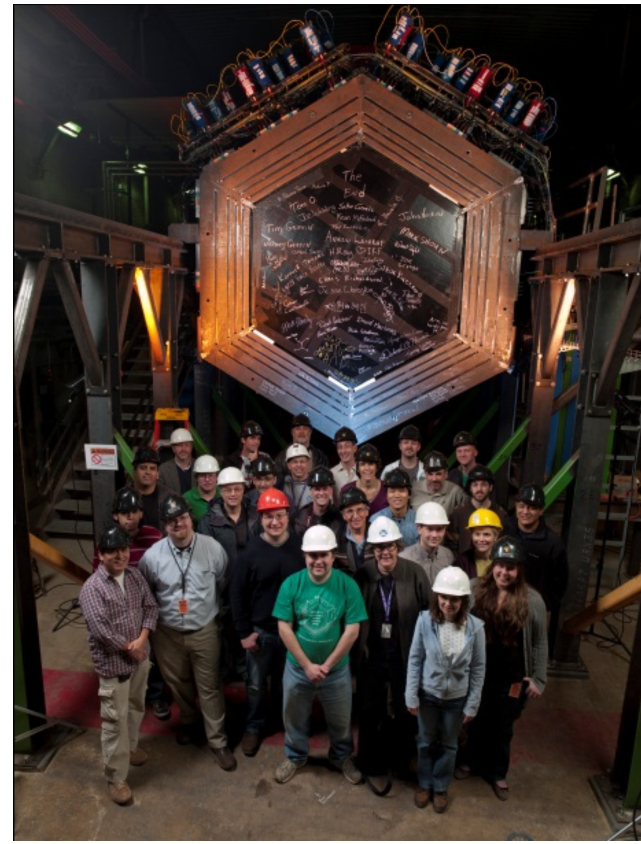
Thank you for Listening!

Questions?

The MINERvA collaboration consists 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

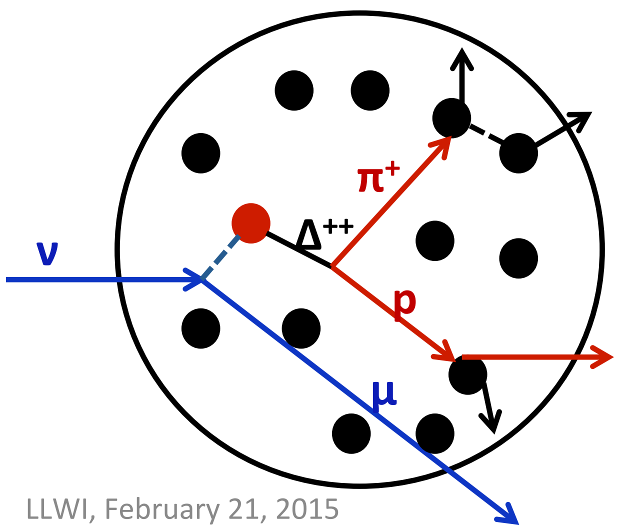
Universidad Nacional de Ingeniería
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers, The State University of New Jersey
Universidad Técnica Federico Santa María
Tufts University
William and Mary

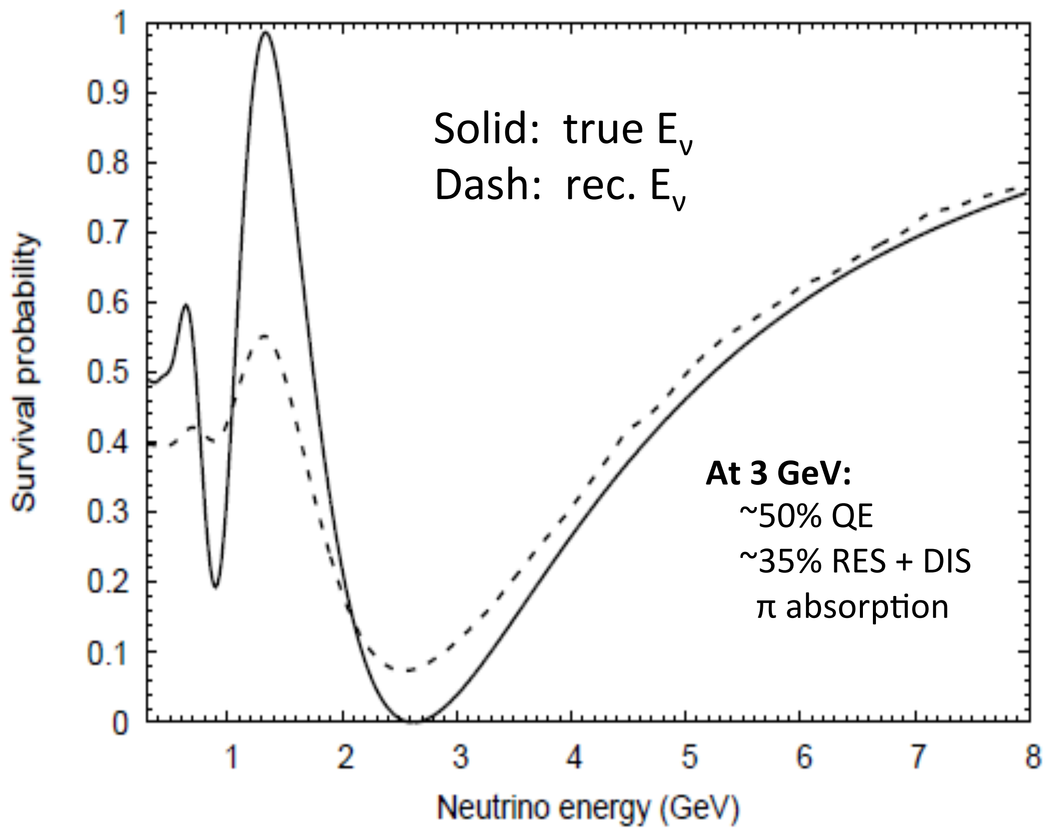


Backup Slides

More Motivation: Neutrino Energy with and without Final State Interactions

Simulated LBNE ν_μ disappearance



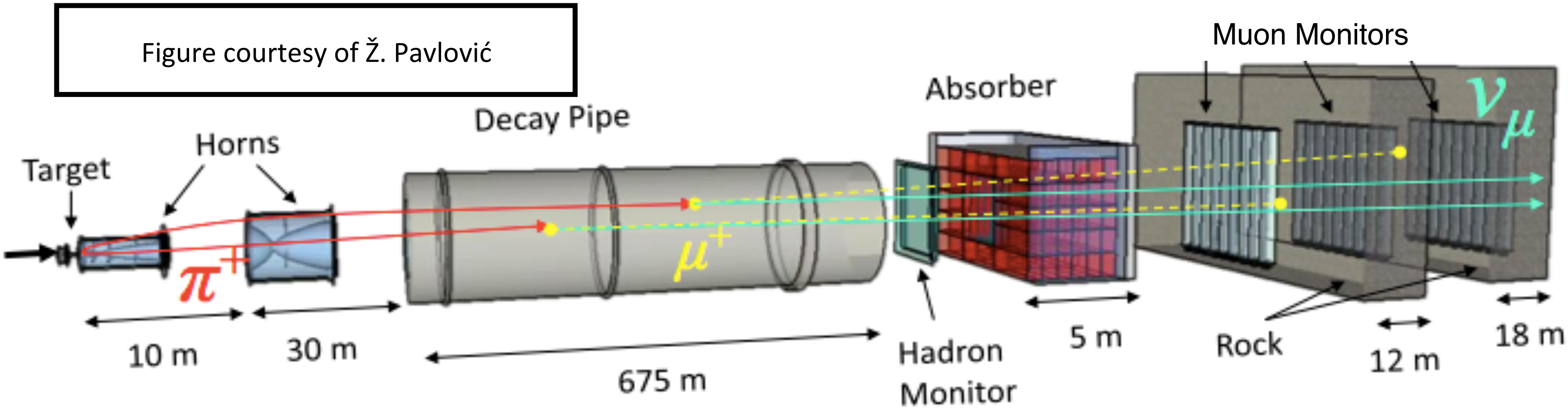


Mosel *et al*: arxiv 1311.7288

NuMI Beamline

- 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

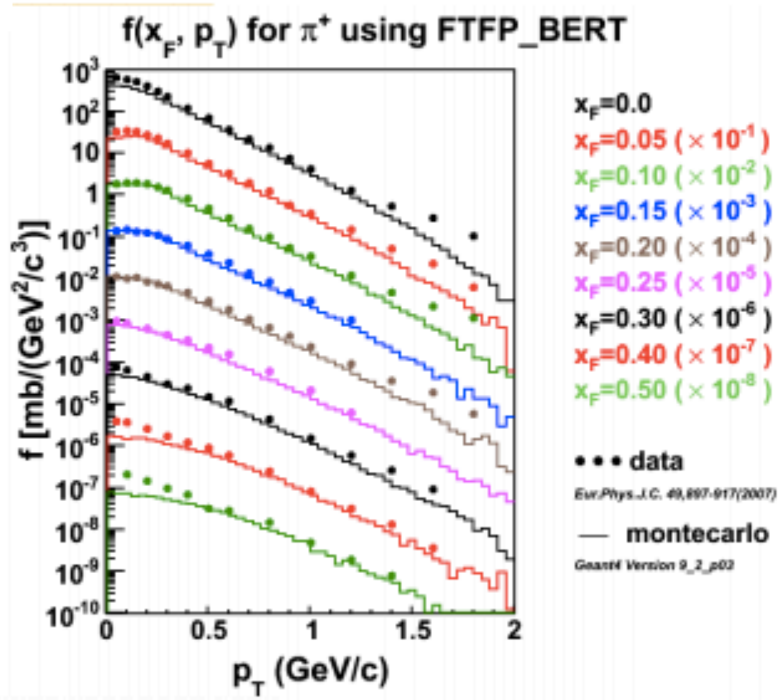
Figure courtesy of Ž. Pavlović

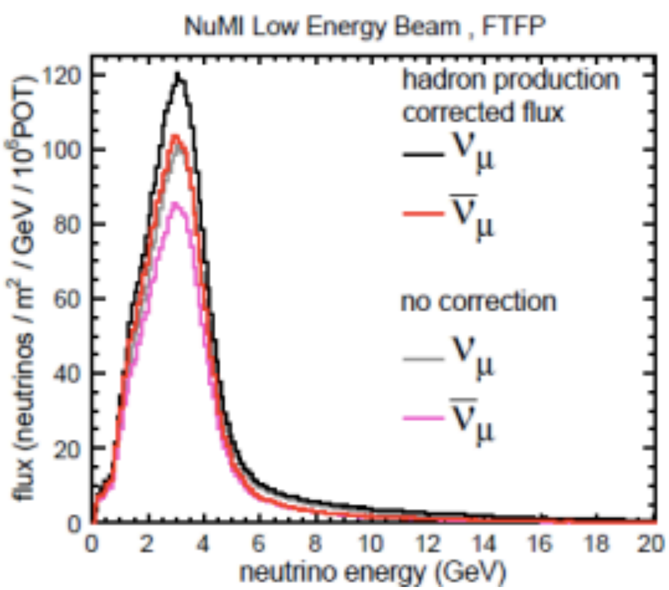


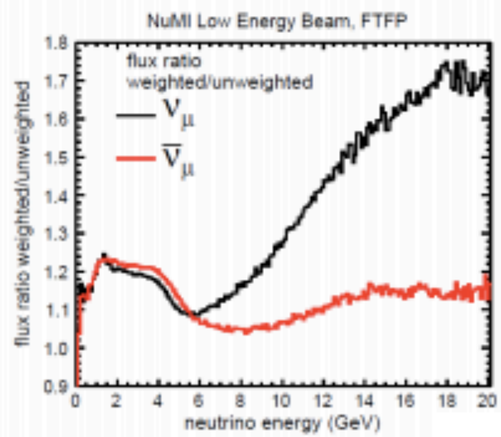
Flux

- Flux measurements are hard!

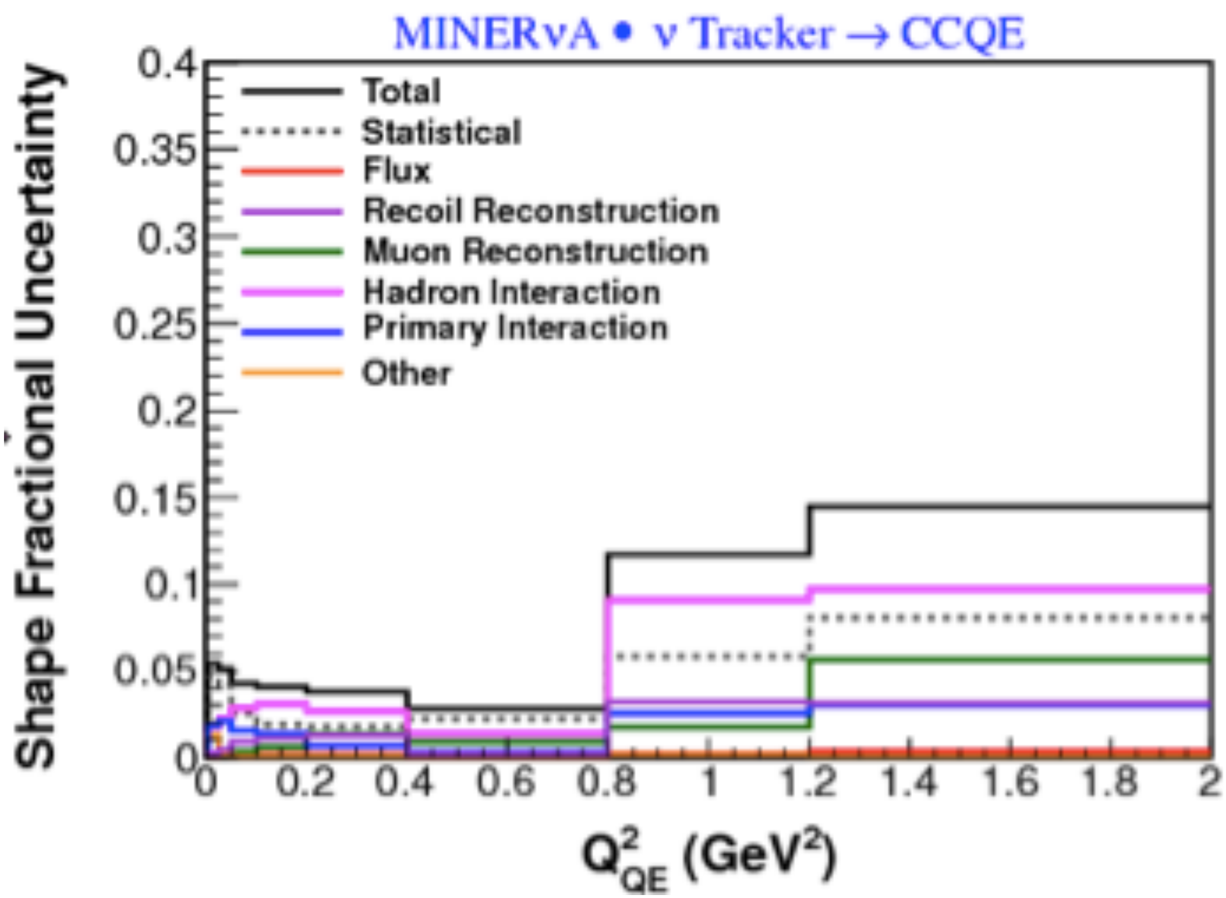
- MINERvA flux is simulated by GEANT4 and reweighted to match hadron production data from NA49. Recent MIPP publication will help a lot.





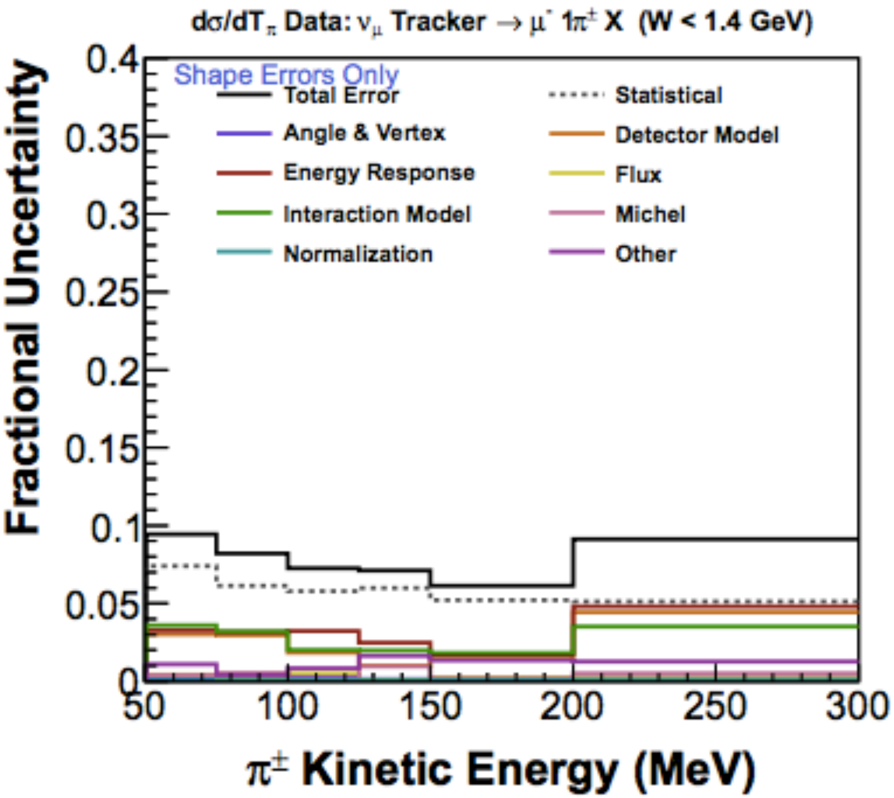


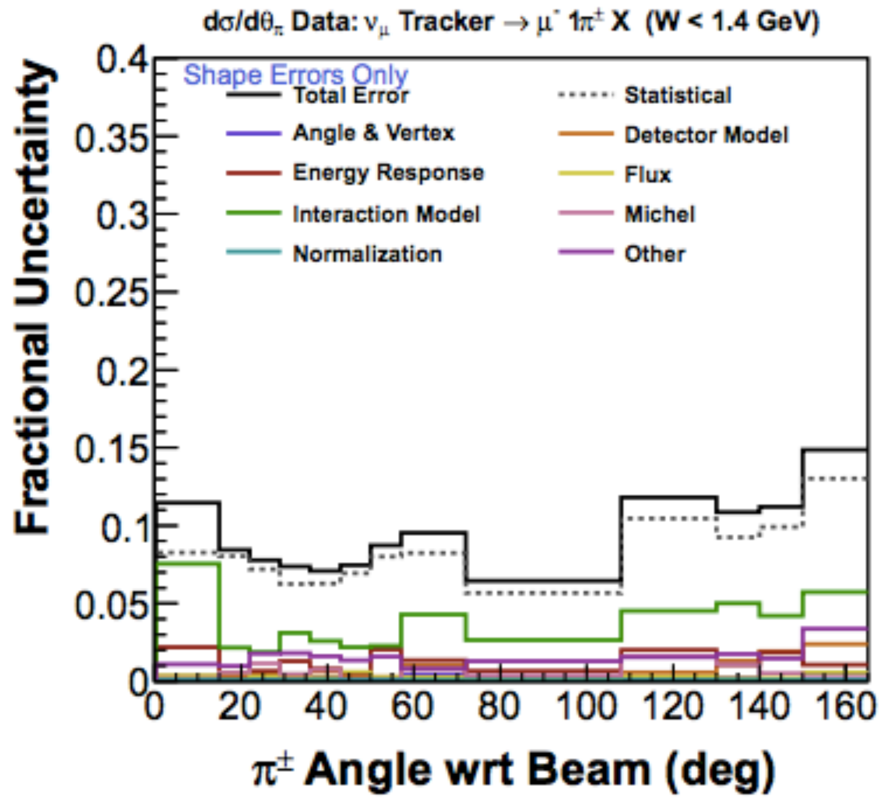
Systematic Errors – Muon + N Proton(s)



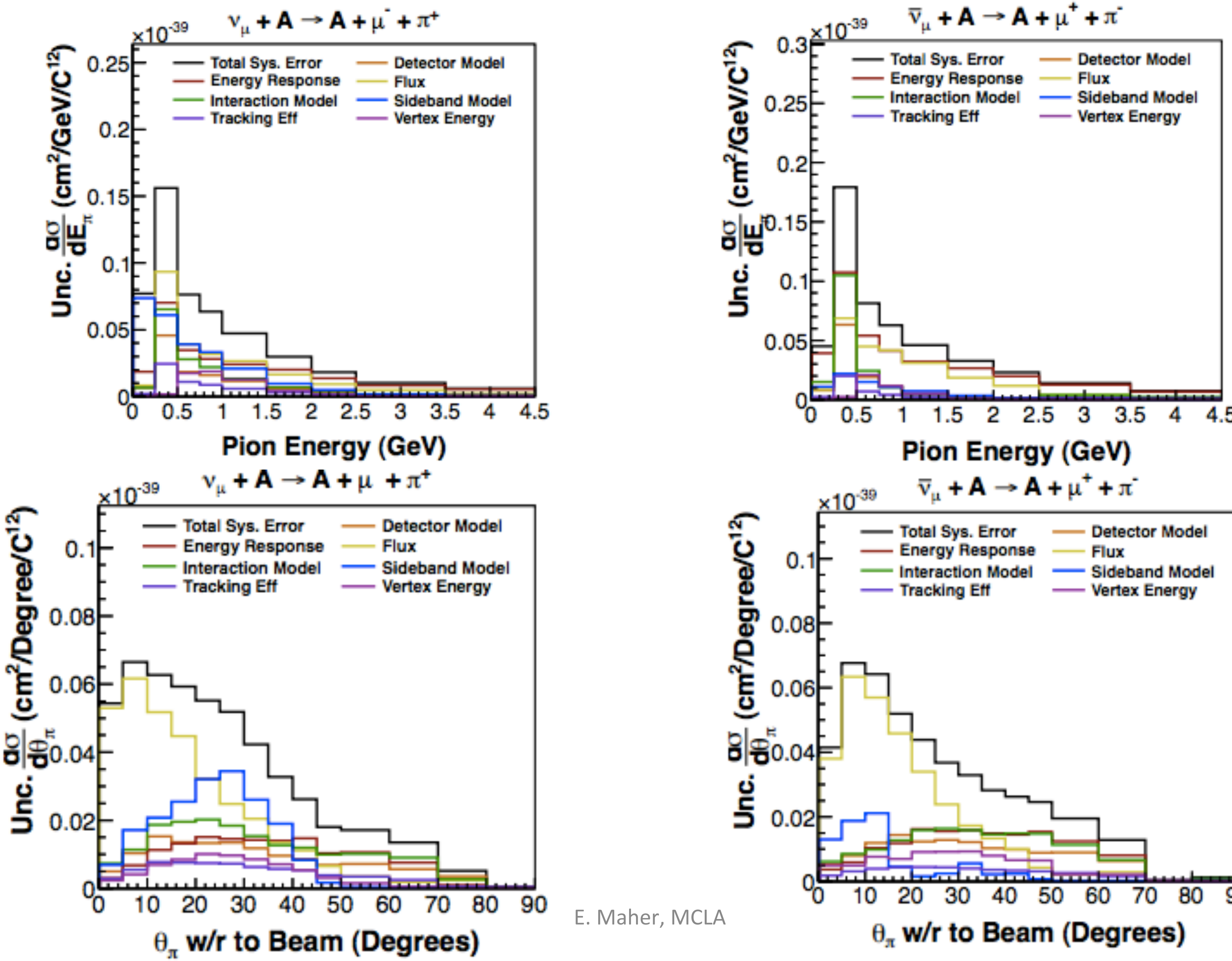
Systematic Errors - Charged Pion Production

Shape-only errors





Systematic Errors - Coherent Pion Production

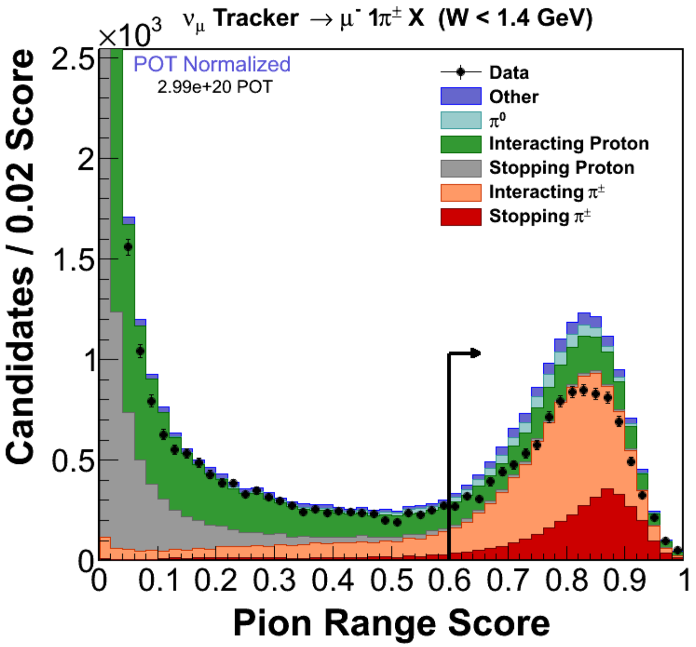


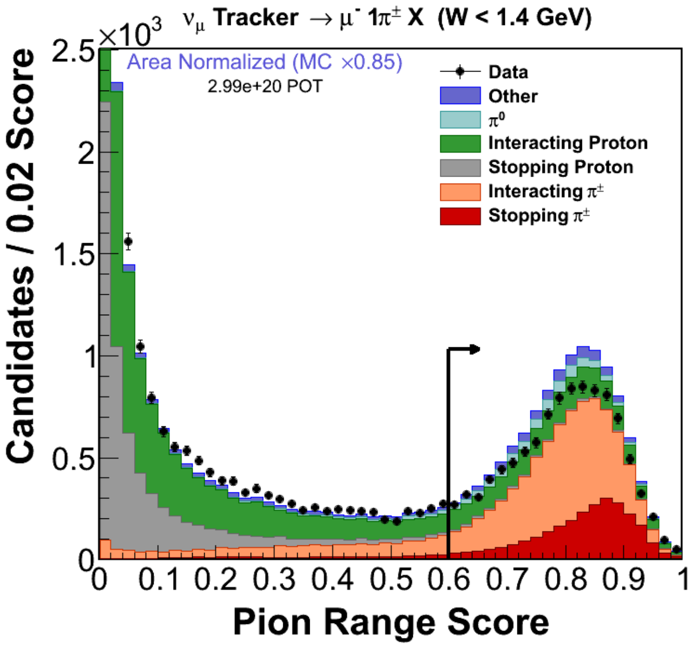
dE/dx for Pions vs. Protons

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***



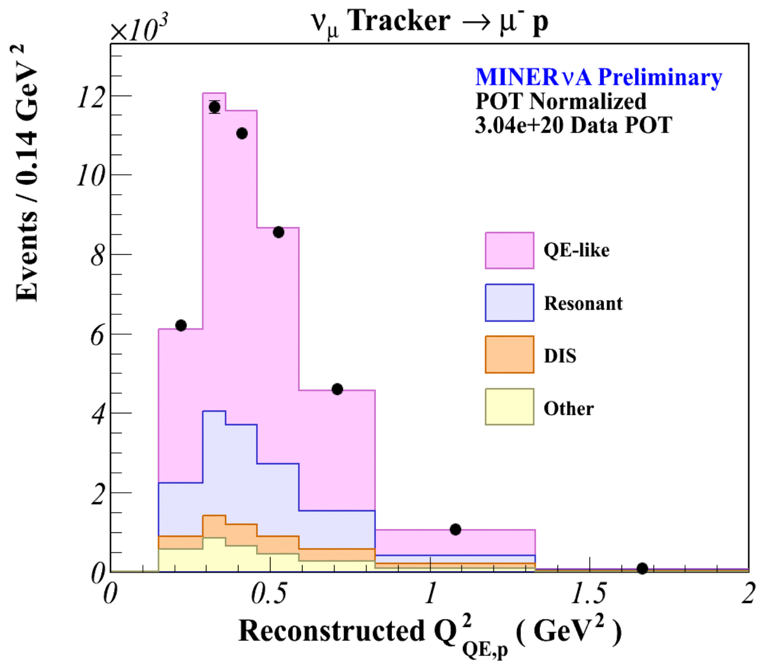


Muon + N Protons: Analysis Details

- Reconstruct Q^2 using kinetic energy of leading proton and QE hypothesis
- Assume scattering from free nucleon at rest

$$Q^2_{QE,p} = (M')^2 - M_p^2$$
$$+2M'(T_p + M_p - M')$$

$M' = M_n - E_{bind}$
E_{bind} = binding energy
T_p = proton kinetic energy
M_n = mass of neutron
M_p = mass of proton



Pion Production: Hadronic Mass Cut W < 1.4 GeV

Limit the size of the hadronic recoil and neutrino energy

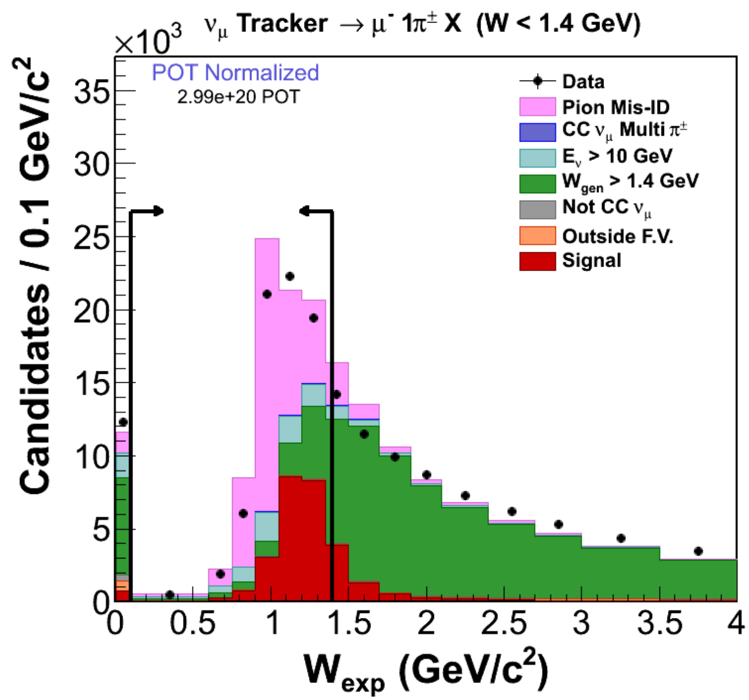
- Reconstruct hadronic recoil energy (E_H) calorimetrically
  - Sum non-muon energy, weighted by passive material constants
  - Apply additional scale, derived from MC, to tune to true E_H

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

Require:

$E_\nu < 10$ GeV

$W_{exp} < 1.4$ GeV



Generators and Models

- Generators – frameworks to implement models
  - GENIE: C. Andreopoulos et. al., NIM A614:87-104
  - NuWro: NuWro: Golal, Jusczak, Sobczyk arXiv:1202.4197
  - NEUT: Neut (Rein-Segal + FSI): Hayato, Acta Phys.Polon. B40, 2477 (2009)
    - D. Rein,
- Models
  - Relativistic Fermi Gas (RFG): Nucleons move "freely" in nuclear potential wells, standard model used in neutrino physics
  - Transverse Enhancement Model (TEM): empirical model tuned to eA scattering
    - Bodek, Budd, Christy Eur. Phys. J. C(2011) 71:1726
  - Nuclear Spectral Function (SF) - more realistic model of the nucleon momentum
    - Benhar, Fabrocini, Fantoni, and Sick, Nucl.Phys. A579, 493 (1994)
  - Athar - theoretical calculation with FSI
    - Athar, Chauhan, and Singh, Eur. Phys. J. A 43, 209 (2010)
  - Local Fermi Gas (LFG) + Random Phase Approximation (RPA)
  - Nieves (TEM + Meson Exchance Currents (MEC)
    - Nieves, Amaro, and Valverde, Phys. Rev. C 70, 055503 (2004)
    - MEC – multi-nucleon ejection: Phys. Rev. C 49, 2650 (1994)

Previous Results: Nuclear Ratios (A-dependence)

- Ratios of differential cross sections reduce normalization error
- Cross section ratios of Bjorken x (fraction of the initial nucleon's momentum that is carried by the struck quark) show
  - Current models do not predict the excess at large x
  - The larger the nucleus, the more disagreement

Measurement of ratios of ν_μ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2–20 GeV, Phys. Rev. Lett. 112, 231801 (2014)