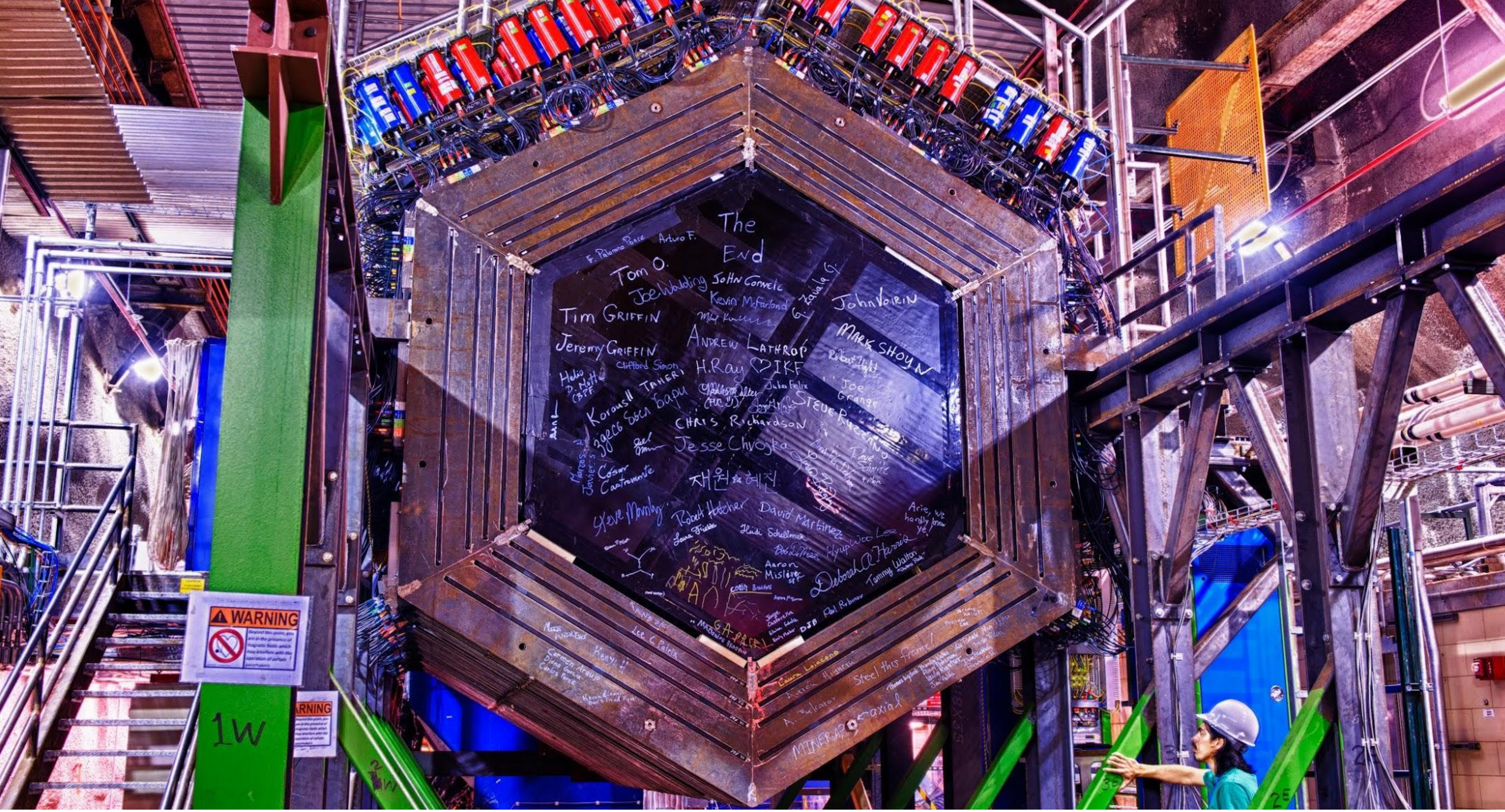


Neutrino Interactions on Nuclei at MINERvA

LaThuille 2015 - March 2nd

Mateus F. Carneiro - CBPF/Brazil

for the MINERvA Collaboration

CBPF
Centro Brasileiro de Pesquisas Físicas

Picture of how I broke both of my arms trying to learn how to ski in the first day, that will justify why I’m operating the pointer with my mouth

Introduction

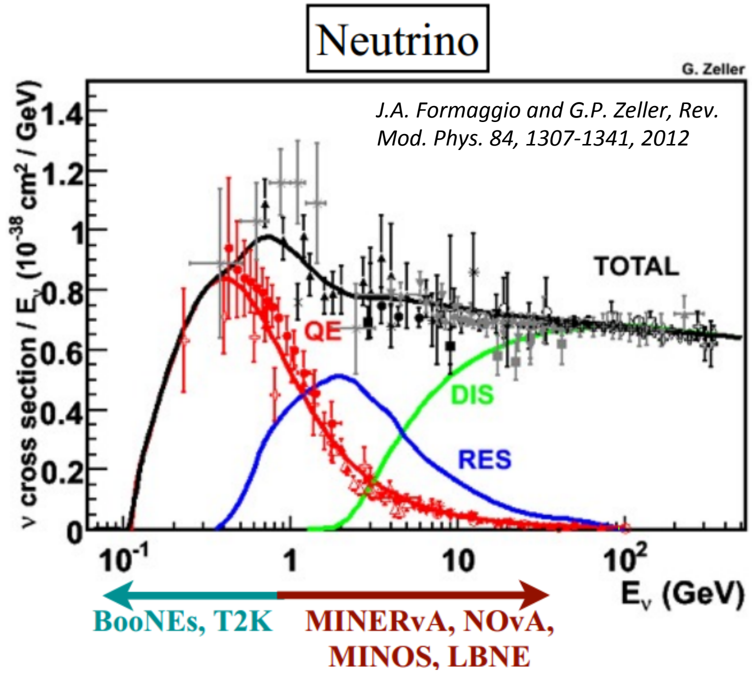
- MINERvA is a fully active, high resolution detector designed to study neutrino reactions in detail, situated in Fermilab’s NUMI beam along with MINOS and NOvA
- Precision neutrino measurements requires precise knowledge of cross sections, final states, and nuclear effects
- The MINERνA detector was designed to provide such data

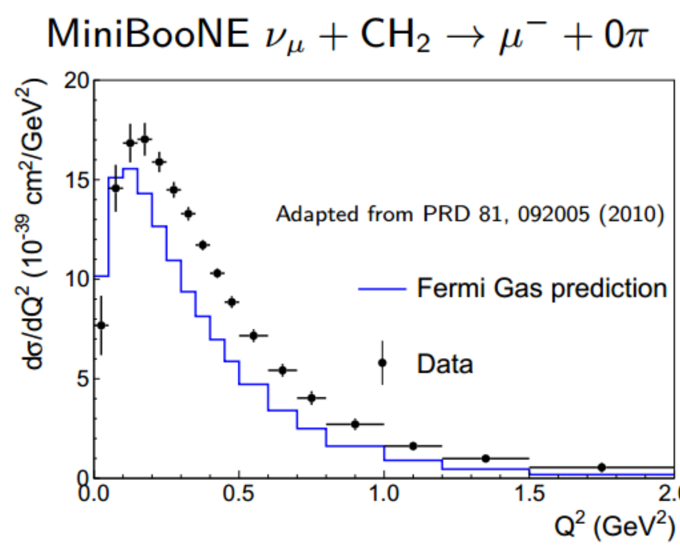
Motivation

- Measuring neutrino interaction cross sections facilitates high precision neutrino oscillation measurements
  - Signal, with quasielastic interactions
  - Backgrounds, such as pion production
  - How nuclear effects and Final State Interactions (FSI) affect observables
  - Nuclear mass dependence
  - Relationship between observed quantities and neutrino energy

- We need better models and high precision data to constrain those

- We're finding out is that the nucleus is more complicated than our current models can fully explain



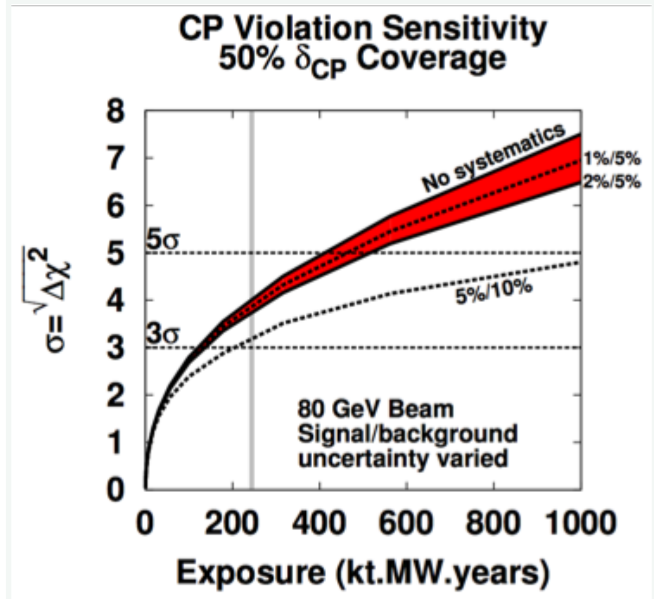


Why Cross Sections?

- Oscillation experiments compare event rates with predictions to determine parameters such as δ_{CP}

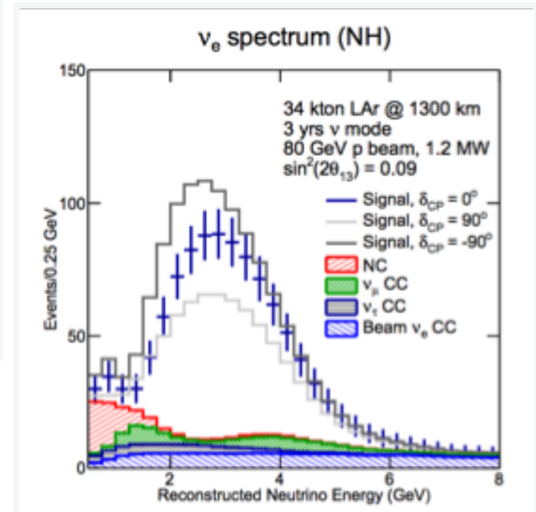
- To distinguish these parameters, they must reduce systematics. Cross section models are large contributors to the uncertainty

- Oscillation detectors are made of heavy materials, where nuclear effects complicate the cross-section distributions



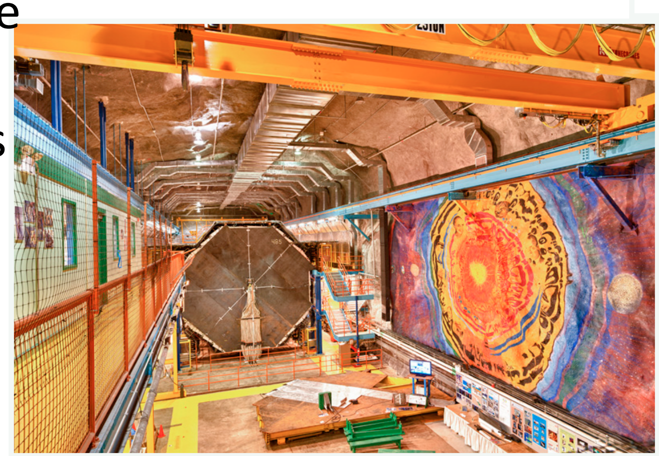
LBNE Sensitivity to δ_{CP} for different systematic uncertainties

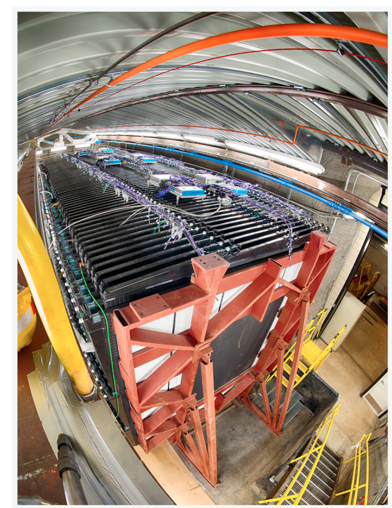
M. Bass, NuInt 2014



LBNE signal predictions arXiv 1307.7335

MINOS - steel





NOvA - liquid scintillator

not to scale

The NuMI beam

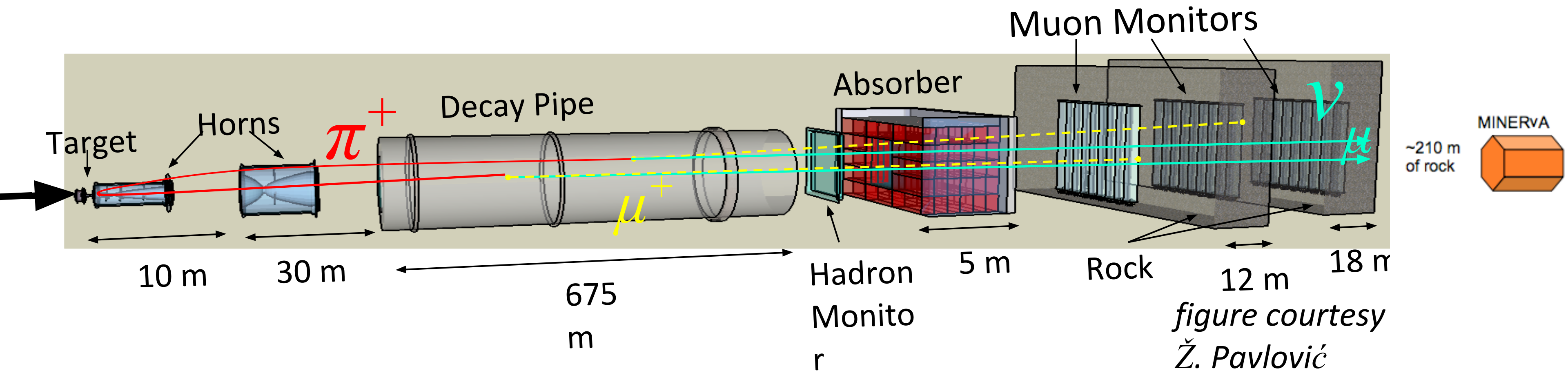
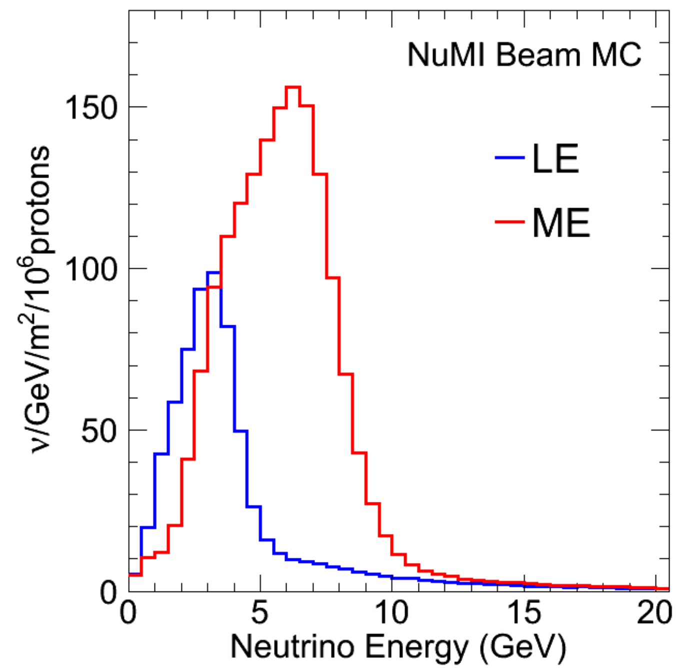


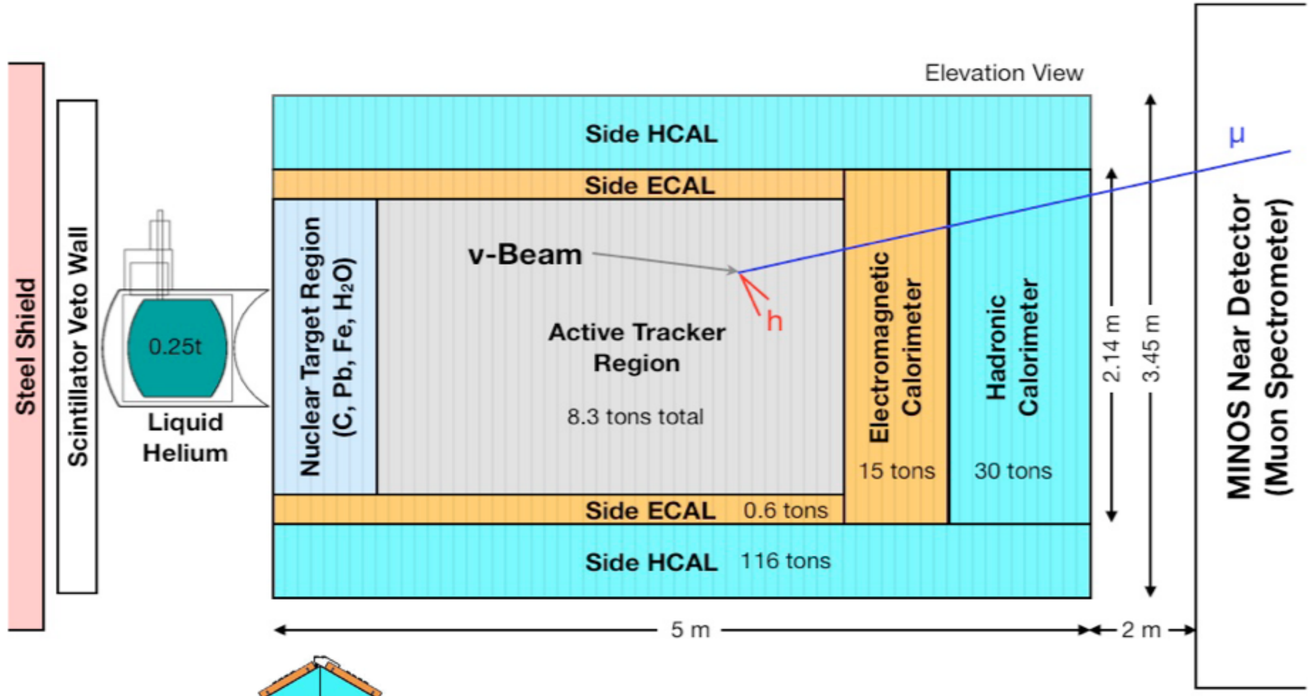
figure courtesy
Ž. Pavlović

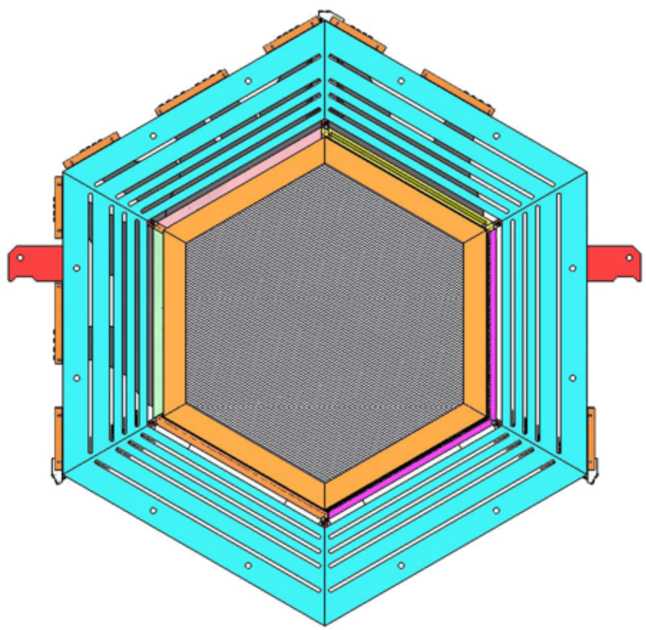
- 120 GeV/c protons on carbon target produce pions.
- Pions and kaons decay into muons and neutrinos.
- Horns focus positive or negative pions depending on their polarity
- Neutrino beam energy increased by moving target and one horn

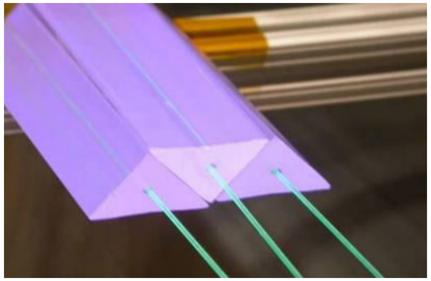


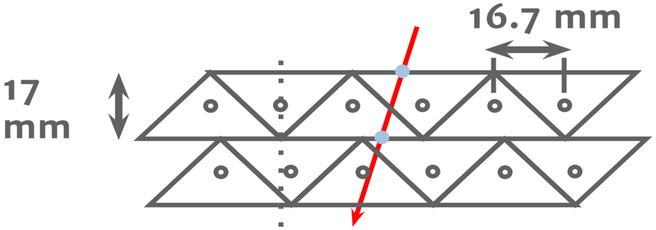
MINERvA Detector

- 120 modules stacked along the beam line in three orientations
- Fine-grained scintillator tracker surrounded by calorimeters
- Upstream nuclear targets to measure A-dependence
- MINOS near detector is the muon spectrometer (magnetized)





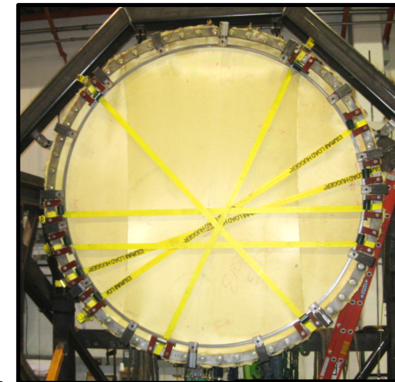


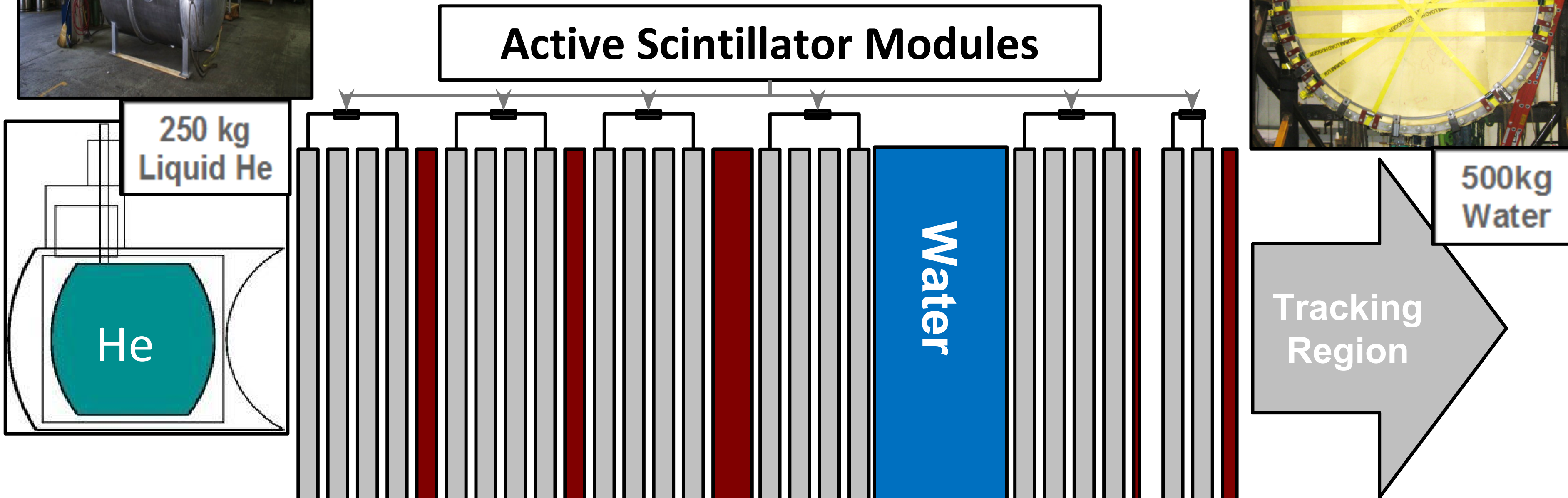


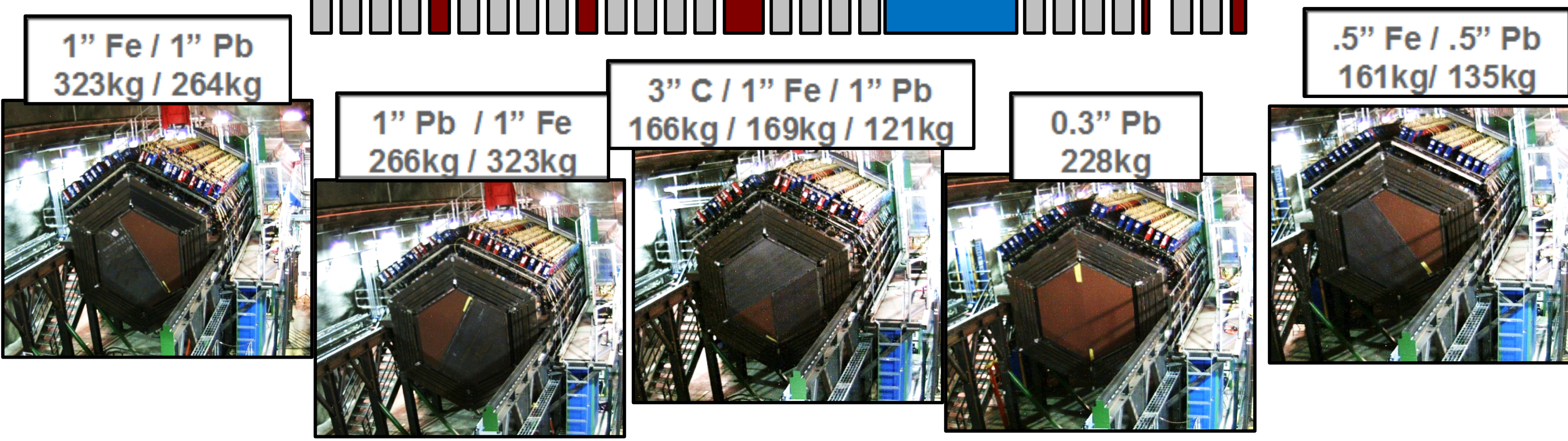
Charge sharing for improved position resolution (~3 mm) and alignment

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

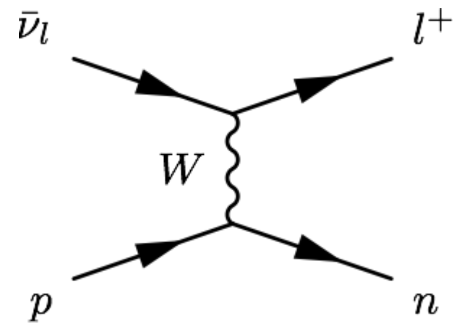
Nuclear Target Region

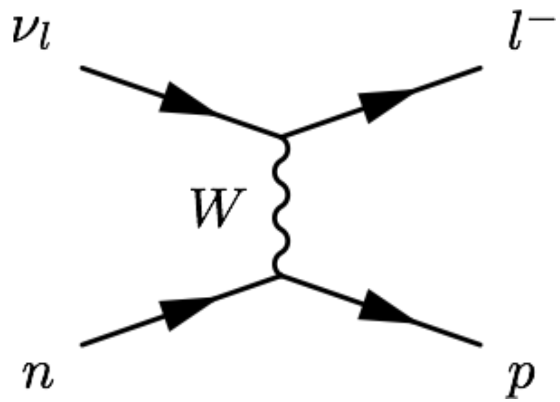






Charged-**C**urrent **Q**uasi**E**lastic scattering





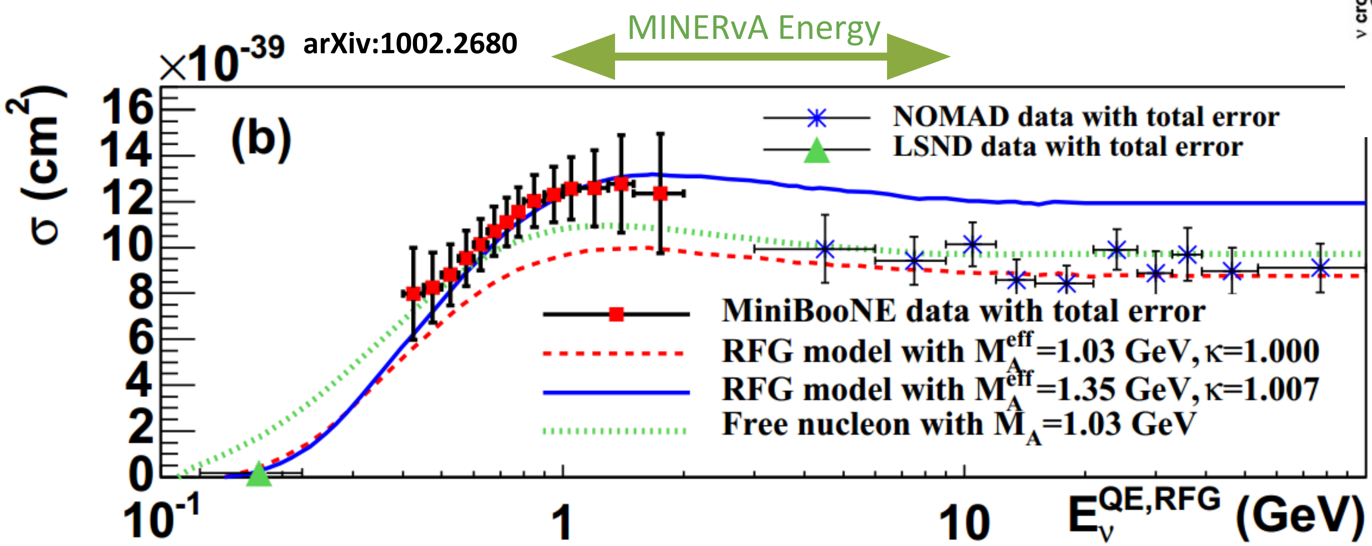
- Key signal channel for oscillation experiments
- Signature easy to identify
- Heavy nuclei complicate the picture

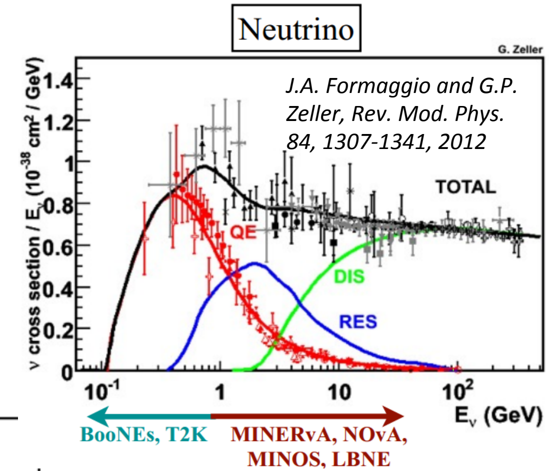
- We can reconstruct the neutrino energy and 4- momentum transfer Q^2 from just the muon kinematics, if we assume a stationary initial state nucleon

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

$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Charged-Current QuasiElastic scattering





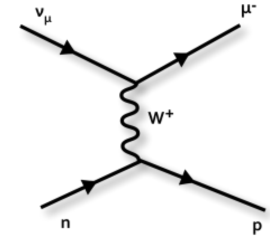
V. Lyubushkin et al., Eur. Phys. J. C 63, 355 (2009)

L. B. Auerbach et al., Phys. Rev. C 66, 015501 (2002)

Aguilar-Arevalo et al, PRD 81, 092005 (2010)

- This shows best fits of MiniBooNE, LSND and NOMAD cross-sections to the relativistic Fermi gas model for carbon
- We could be seeing additional nuclear effects beyond the Relativistic Fermi Gas model
- This is because we are using an incomplete model for the nucleus, and how the nucleons interact
- MINERvA energy range ideal to investigate this

CCQE lepton only event selection

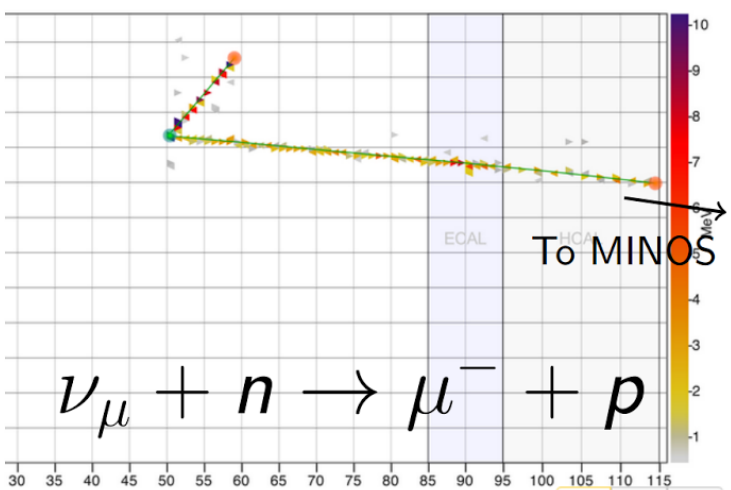


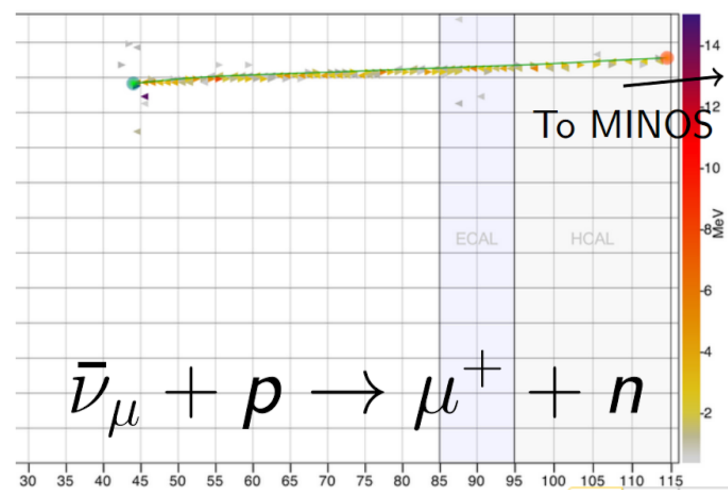
Neutrino mode:

- Muon track charge matched in MINOS as a μ^-
- No requirement on the number of additional tracks from the vertex
- The ejected proton may make a track, as in the example

Antineutrino mode:

- Muon track charge matched in MINOS as a $\mu+$
- No additional tracks from the vertex
- The ejected neutron may scatter, leaving an energy deposit, but it does not make a track from the vertex

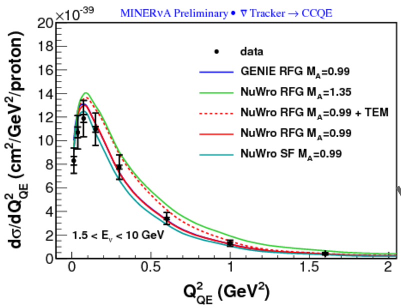


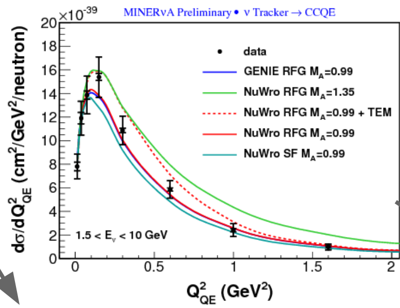


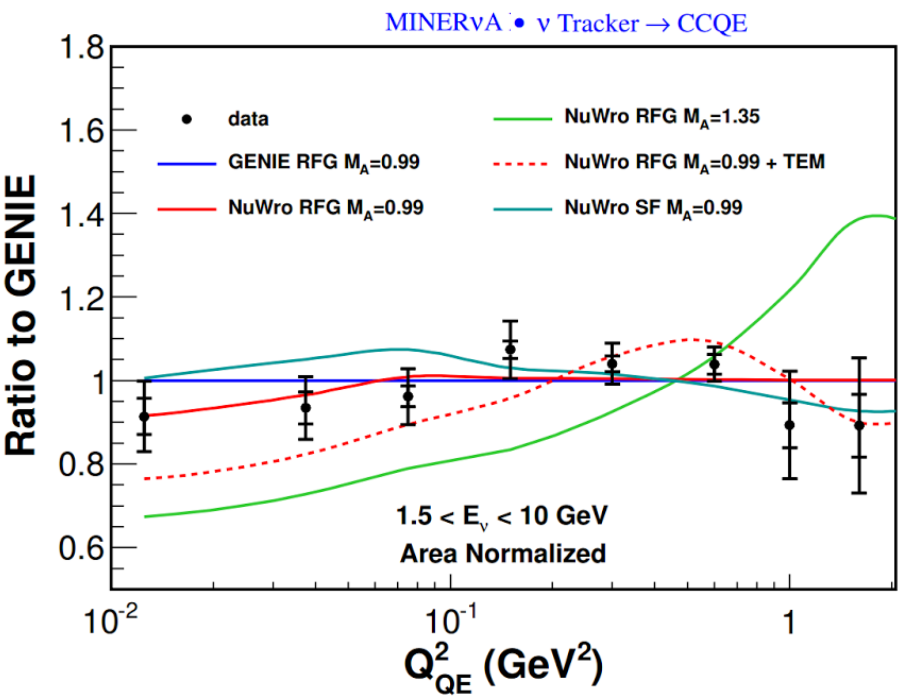
Measurement of anti-ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022501 (2013)
Measurement of ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022502 (2013)

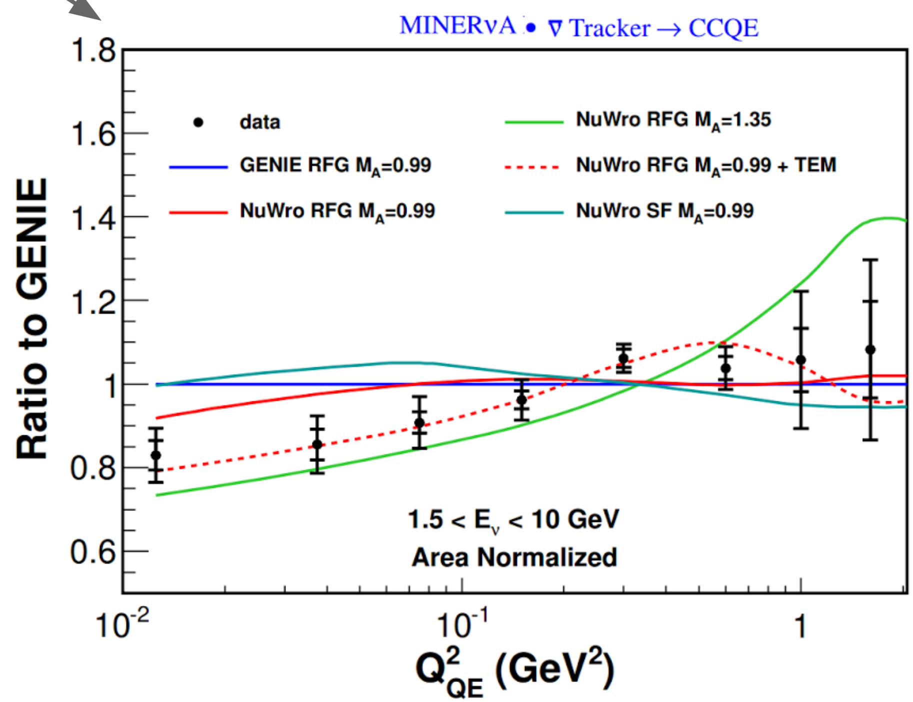
CCQE lepton only results

- Compare data to GENIE RFG (C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)) and NuWro (K. M. Graczyk and J. T. Sobczyk, Eur.Phys.J. C31, 177 (2003)) nuclear models
- Due to flux uncertainty, a shape-only fit is more valuable
- Both datasets favor the "Transverse Enhancement model" TEM model that parameterizes nucleon-nucleon correlations









Measurement of anti-ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022501 (2013)
Measurement of ν_μ Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022502 (2013)

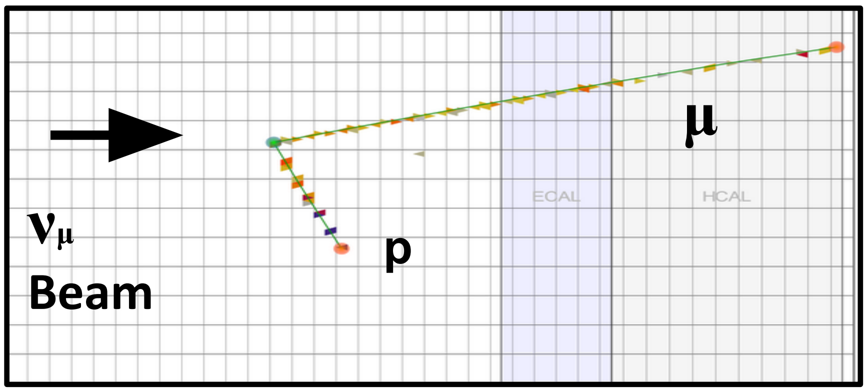
CCQE with Muon + N protons

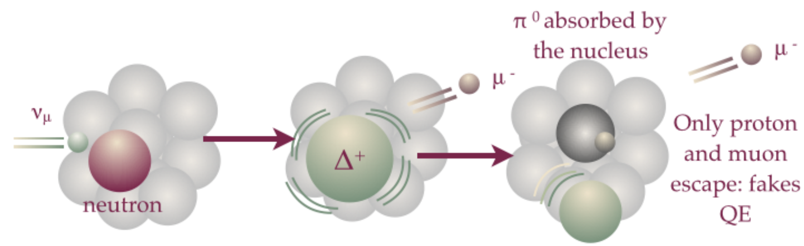
- Neutrino-neutron CCQE scattering produces a proton. Instead of using muon kinematics to reconstruct Q^2, we can use proton kinematics:

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

M' = Mn - Ebind
Ebind = binding energy
Tp = proton kinetic energy
Mn = mass of neutron
Mp = mass of proton

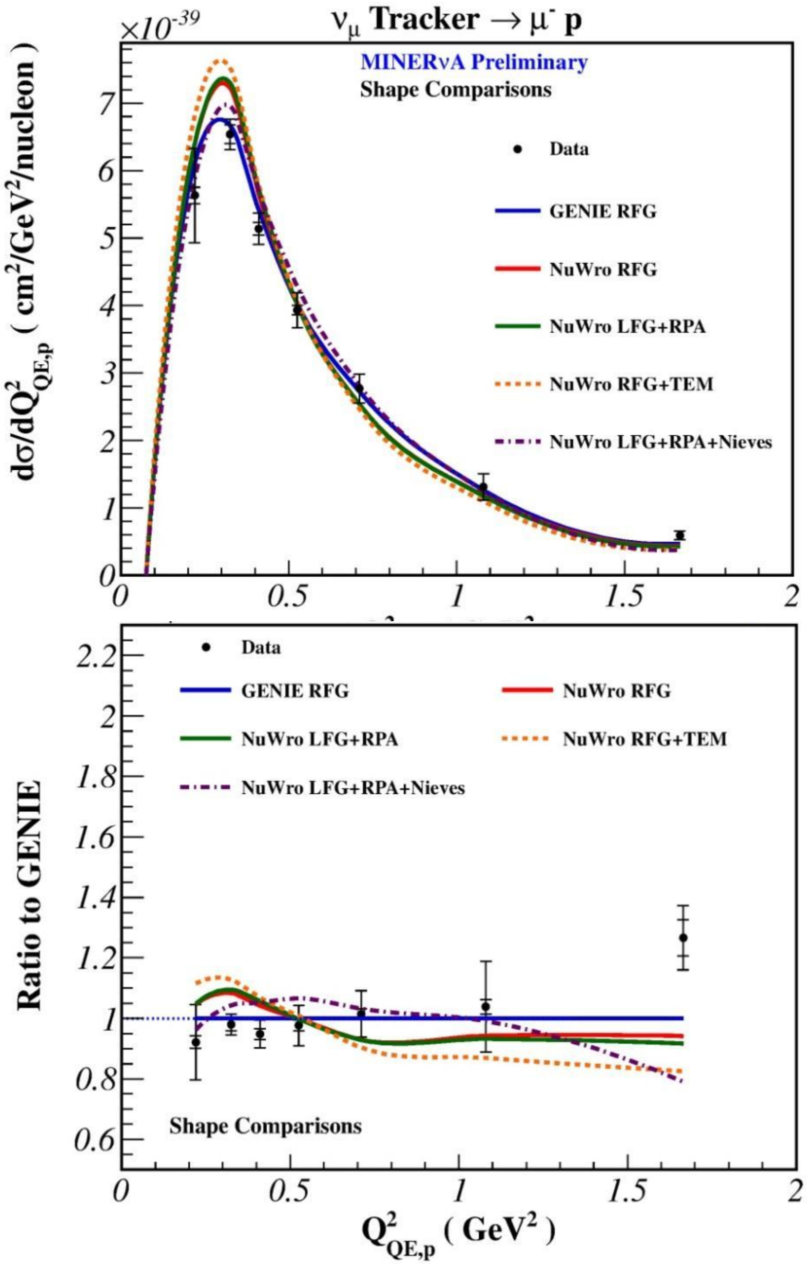
MINERvA Tracker Region:





- For this, we use a quasi-elastic-like signal definition - that is, a final state that mimics a CCQE
- We require a muon and at least one proton in the final state, but no pions or other mesons
- As well as quasi-elastic events, this includes resonant or DIS events that undergo final- state interactions, leaving only nucleons in the final state
- Quasi-elastics could produce more than one proton:
  - if the initial proton re-interacts in FSI and produces another
  - if we scatter from a correlated pair of nucleons

Muon + N Protons: Results

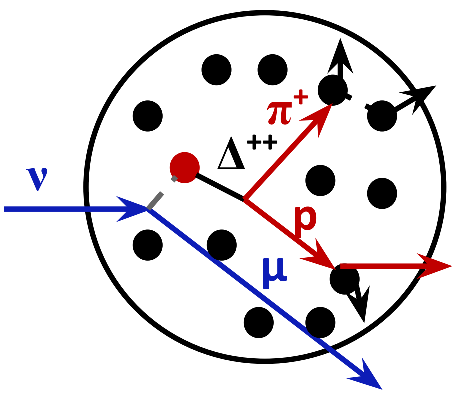


- Using proton kinematics, data favors standard Relativistic Fermi Gas (RFG), different from previous QE results
- As a check, muon kinematics were use to reproduce this, where the muon entered MINOS. Muon kinematics data favored RFG + TEM, similar to first QE results
- Models used by neutrino oscillation experiments must reproduce hadronic and leptonic kinematics, since both affect neutrino energy reconstruction
- No analogous method for antinu mode as neutron is hard to reconstruct

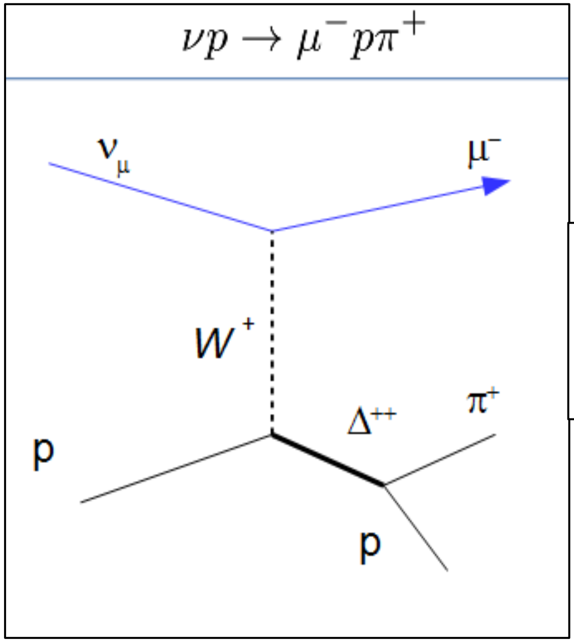
Measurement of μ plus p final states in ν_μ Interactions on Hydrocarbon at average E_ν of 4.2 GeV
arXiv:1409.4497

Pion analyses

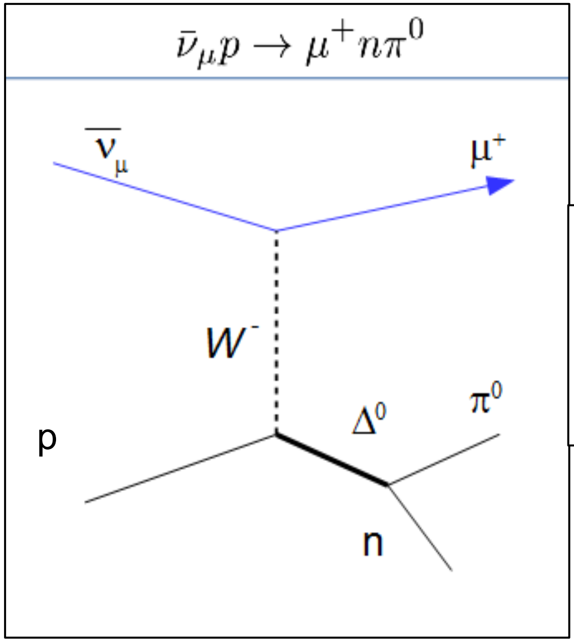
- Main method of pion production: delta resonance which decay to a pion and a nucleon.
- Final State Interactions can absorb the pion -> mimic QE signal
- Final State Interactions can produce pions -> contaminate QE signal



- To understand FSI is required to reduce oscillation experiment uncertainties



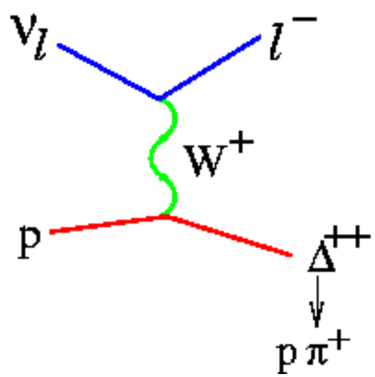
Charged-Current Single Charged Pion Production

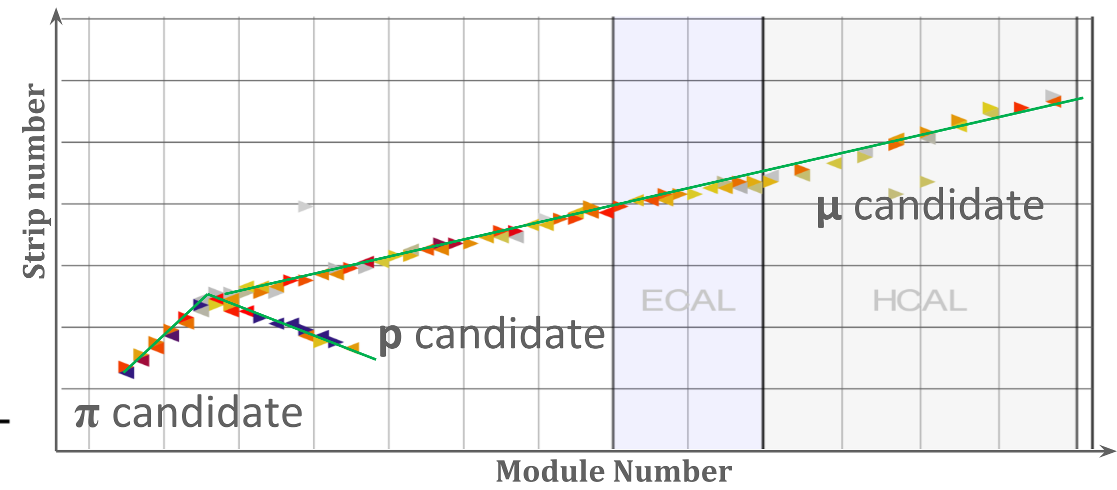


Charged-Current Single Neutral Pion Production by antinu

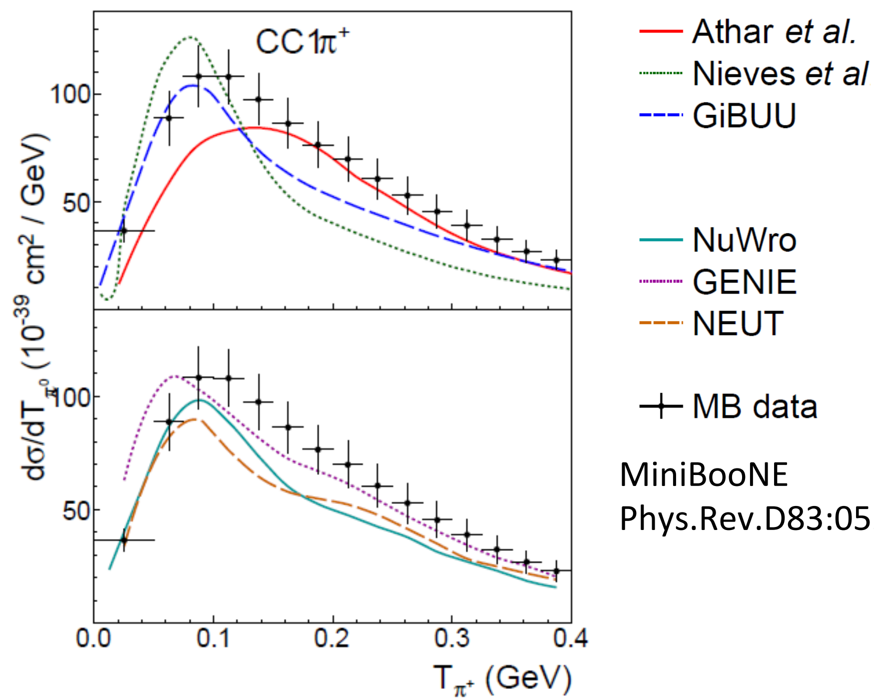
Charged Pion Production

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





- Events with a proton and a pion candidate selected
- Theoretical calculations and event generators are unable to reproduce recent pion KE differential cross section
- Goal: Determine strength and nature of FSI using pion kinematics

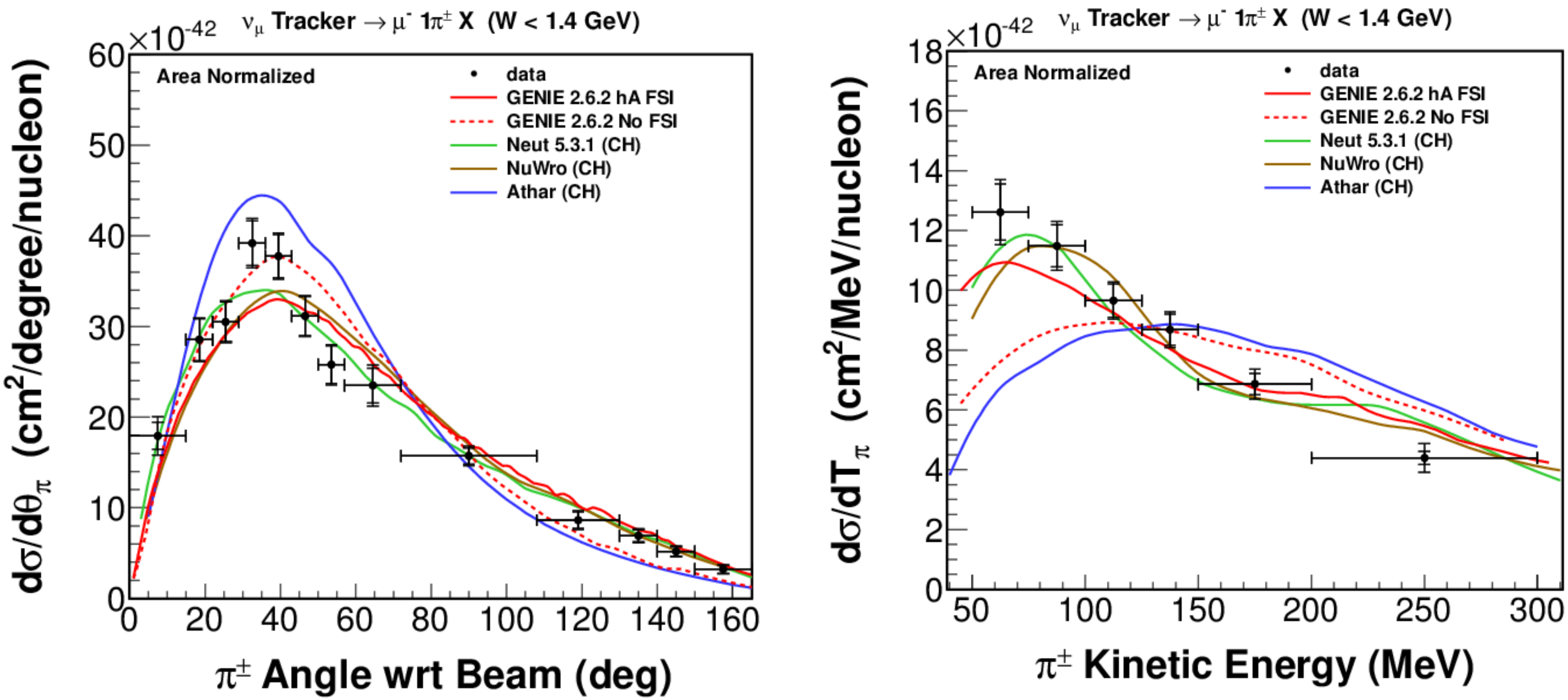


MiniBooNE
Phys.Rev.D83:052007

Charged Pion Production: Results

- Delta resonance dominated differential cross sections with respect to pion angle and pion energy
- Data prefers GENIE model with FSI
- Also consistent in shape with NuWro and Neut event generators with FSI

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

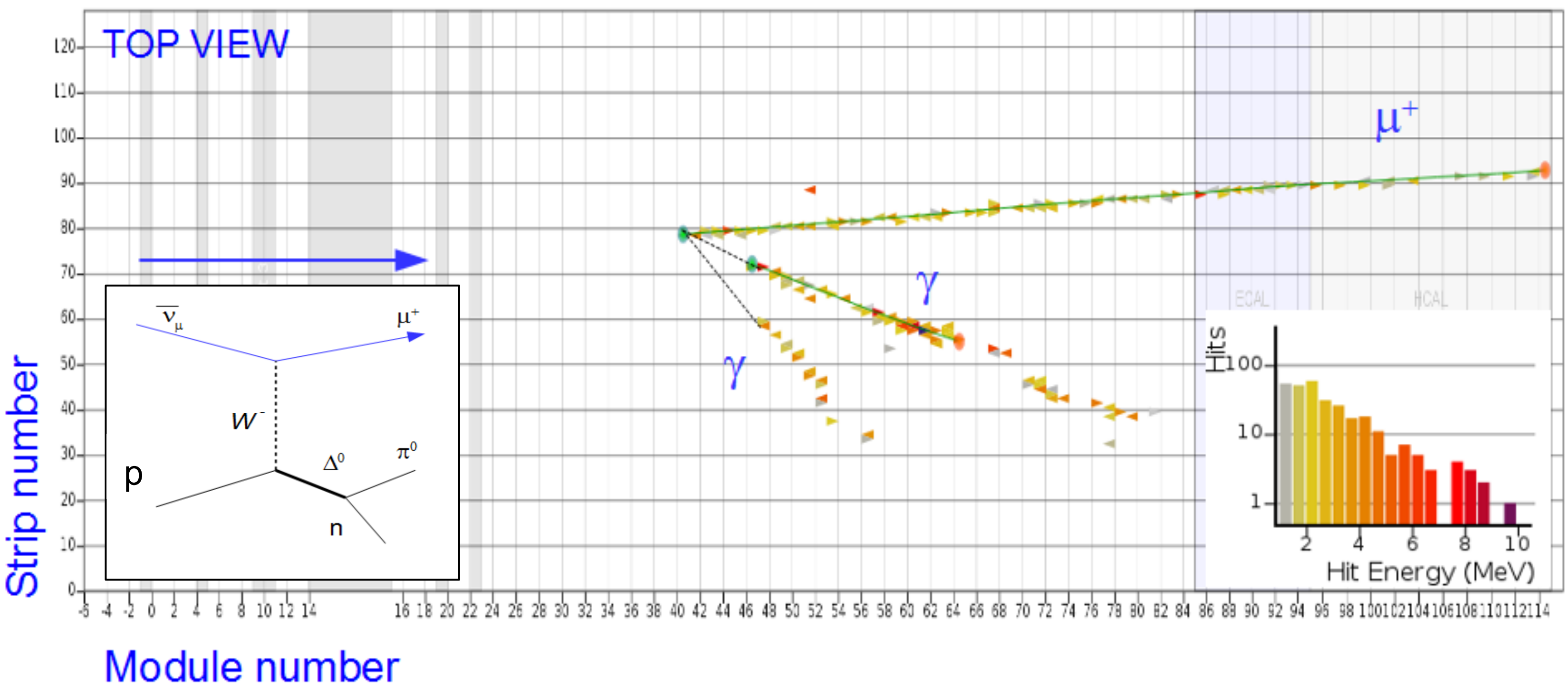


Neut (Rein-Segal + FSI): Hayato, Acta Phys.Polon. B40, 2477 (2009)
Athar – theoretical calculation with FSI: Athar, Chauhan, and Singh, Eur. Phys. J. A 43, 209 (2010)

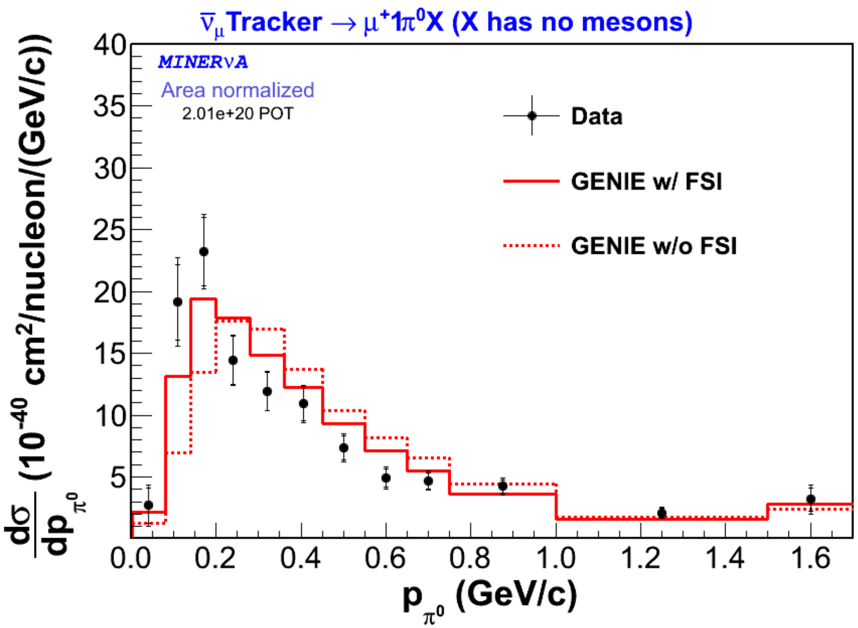
Charged-Current Single Neutral Pion Production by antinu

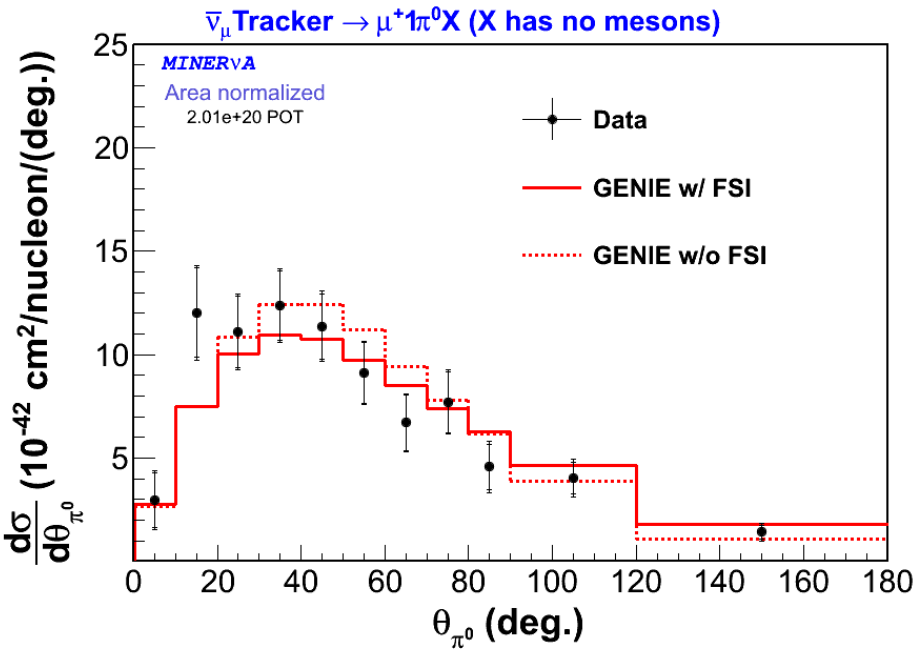
- Importance: background – can mimic electron neutrino signal as negative pion decays to 2 photons

$$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ \pi^0 X$$
$$\pi^0 \rightarrow \gamma\gamma$$



Single Neutral Pion Production Results



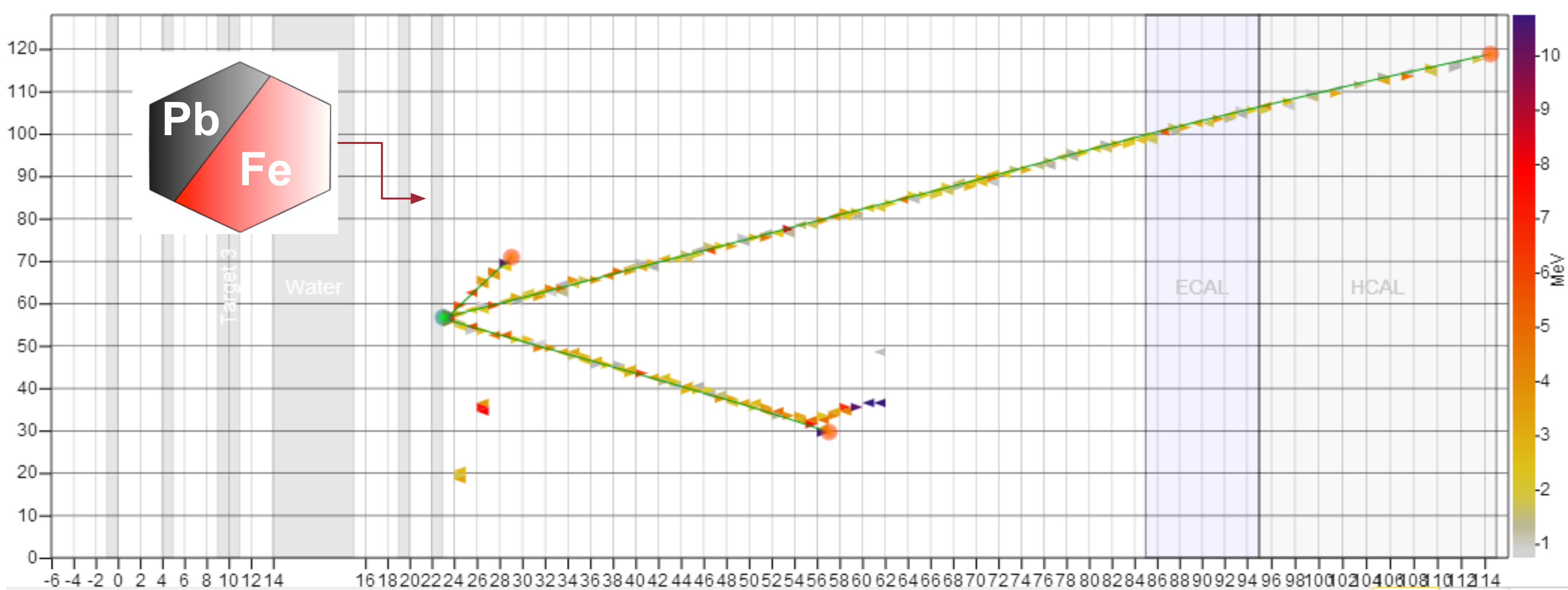


- Data are in better agreement when final state interactions are included
- First measurement of the differential cross sections vs p0 kinematics for this pion production channel
- These cross sections can be used as benchmark to evaluate neutrino generator performance in p0 production by anti-neutrinos for current and future oscillation experiments

Charged-Current Inclusive Ratios on Nuclear Targets

- Compares ratios of cross-sections for different materials/scintillator, flux uncertainty is largely cancelled
- Measure the nuclear dependence of neutrino cross sections directly
- **Inclusive** means a variety of events samples

Strip Number



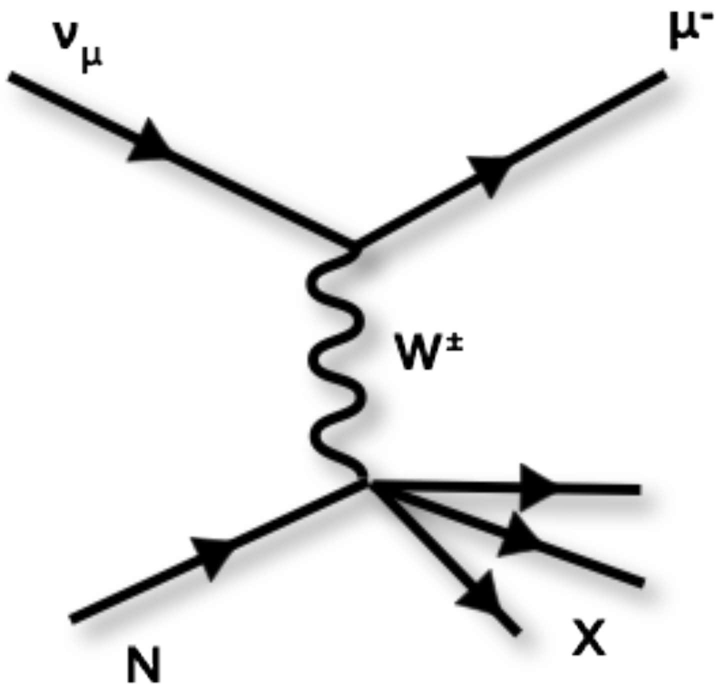
Module Number

Color = energy deposited

Charged-Current Inclusive Ratios on Nuclear Targets

- Inclusive charged current cross section ratios of a dimensionless scaling variable called "x"

$$Q^2 = 2E_\nu \left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)$$

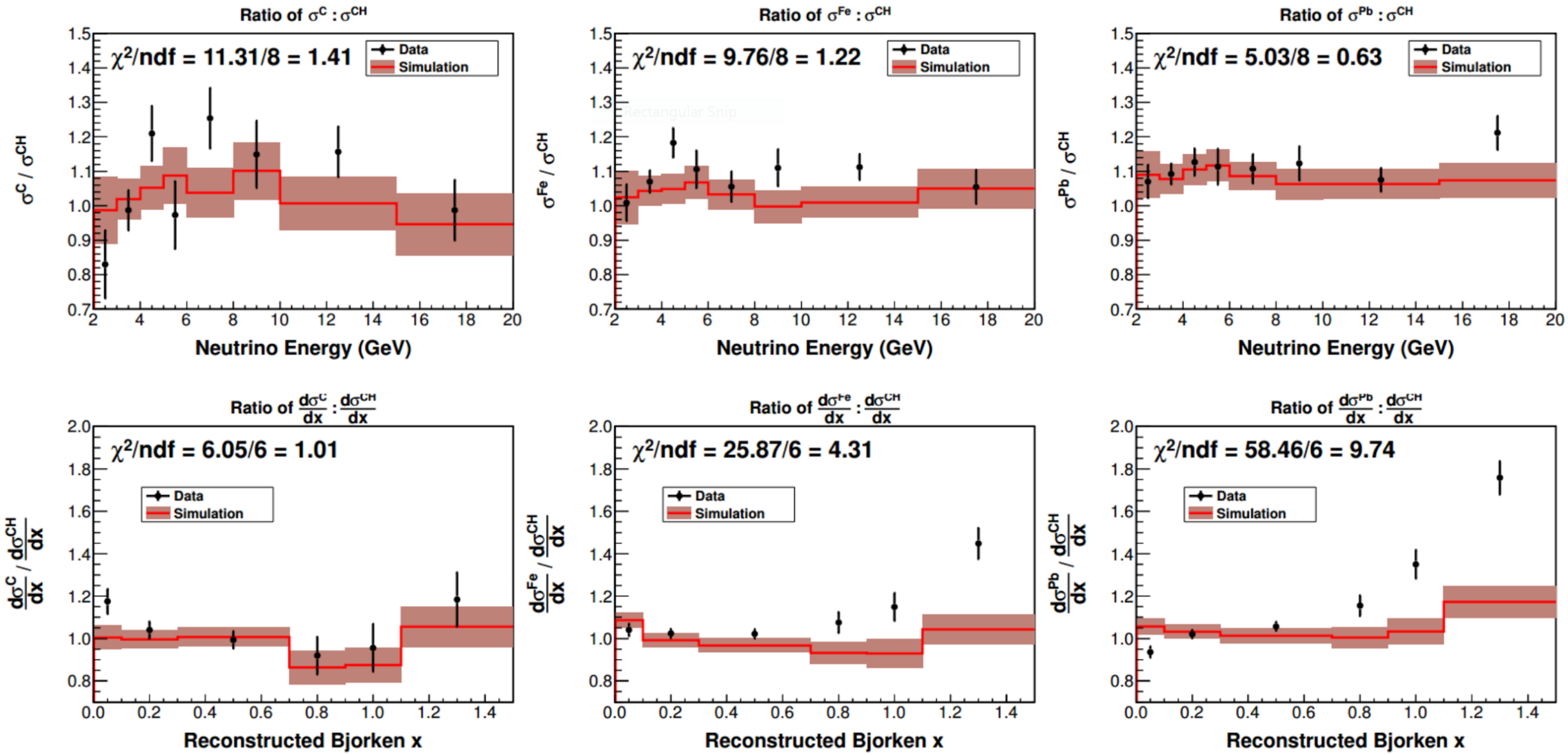


$$x = \frac{Q^2}{2M\nu}$$

- x corresponds to the fraction of the initial nucleon's momentum that is carried by the struck quark
- Large normalization uncertainties cancel in ratios

- If oscillation experiments are going to measure event rates, they know the cross sections on the materials their detector is made of. Especially if they aren't taking near/far detector ratios.

C/CH Fe/CH Pb/CH



Increasing $A \longrightarrow$

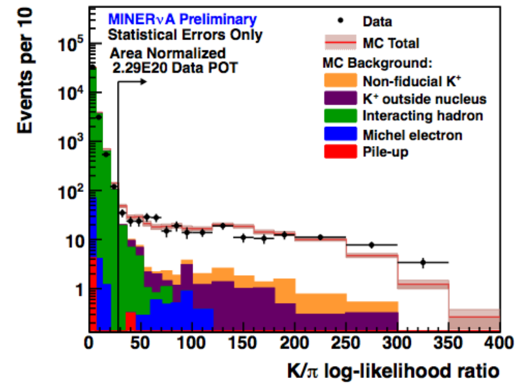
- No evidence of tension between our data and simulation in the Neutrino Energy comparison
- Ratios of inclusive cross sections C:CH, Fe:CH, Pb:CH
  - Excess at high x (elastic), deficit at low x (inelastic) → no theoretical explanation?
  - Analysis to be repeated with exclusive channels. DIS and QE analyses in progress
  - Medium energy beam provides millions of DIS events → A-dependent structure functions

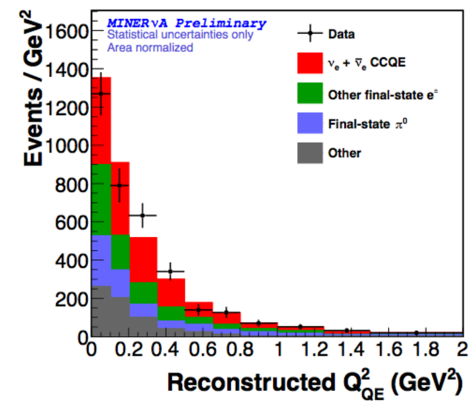
Phys. Rev. Lett. 112, 231801

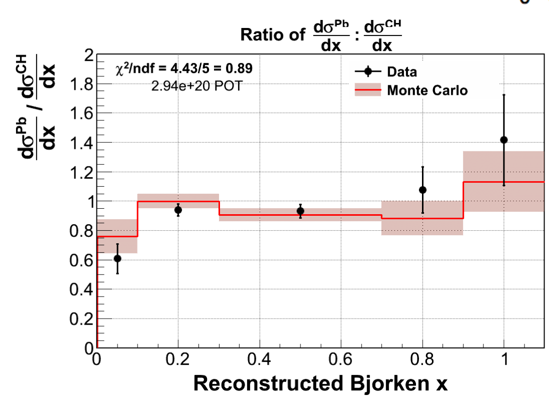
MINERvA Next Results

- MINERvA has lots of Low Energy Data for analysis
- Electron Neutrino CCQE
  - Important test of whether assumptions based on ν_μ scattering hold
- Kaon Production
  - Kaons can mimic proton decay signal
- Exclusive Nuclear Target ratios
- Double Differential CCQE Cross Section

… and more!





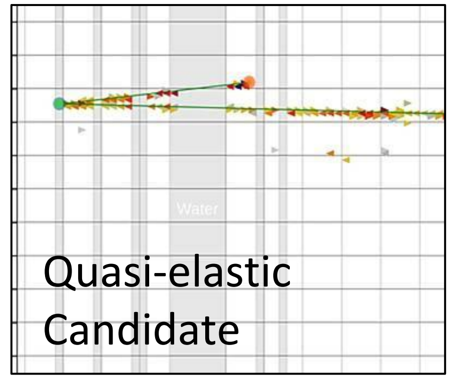


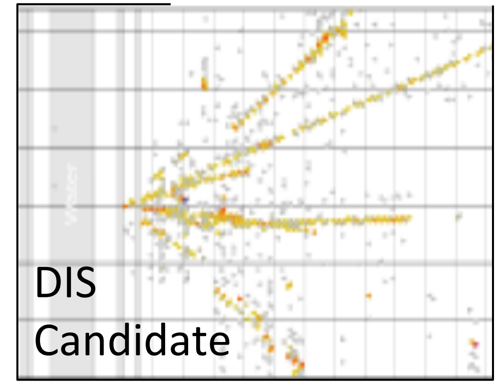
MINERvA Medium Energy Data

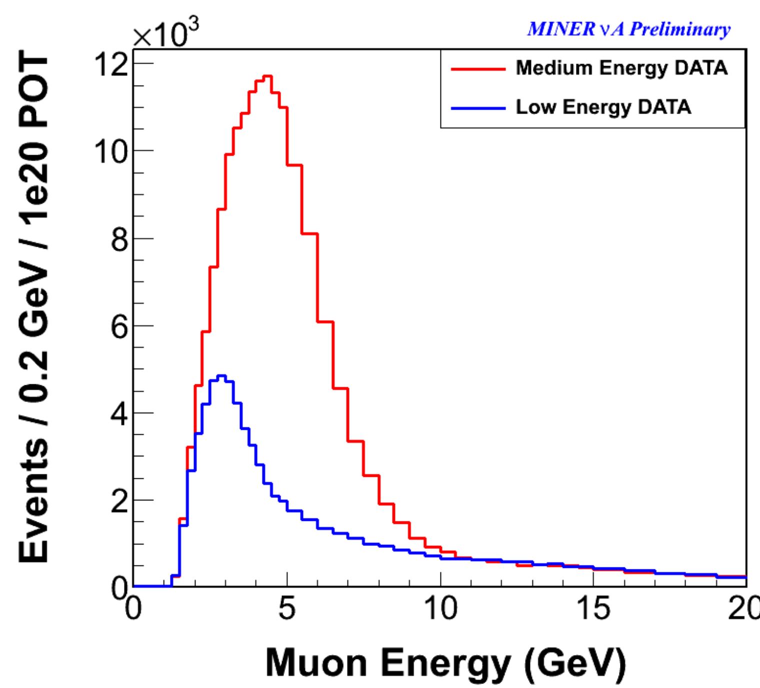
- Run started in 2013
  - First 3 months show more than a million neutrino events!

- Many more possibilities with high-statistics medium-energy beam
  - A higher energy range will allow us to probe the DIS region and nucleon structure functions
  - Increased statistics will let us study nuclear target ratios for individual interaction types

- Plus higher statistics overall will dramatically reduce uncertainties on all studies

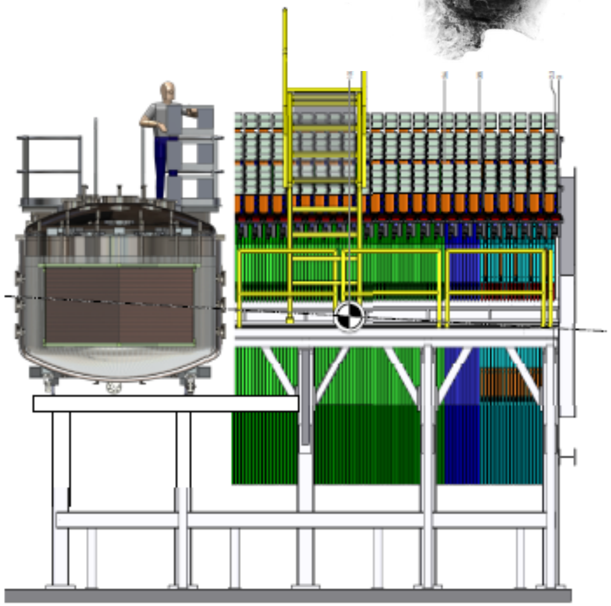




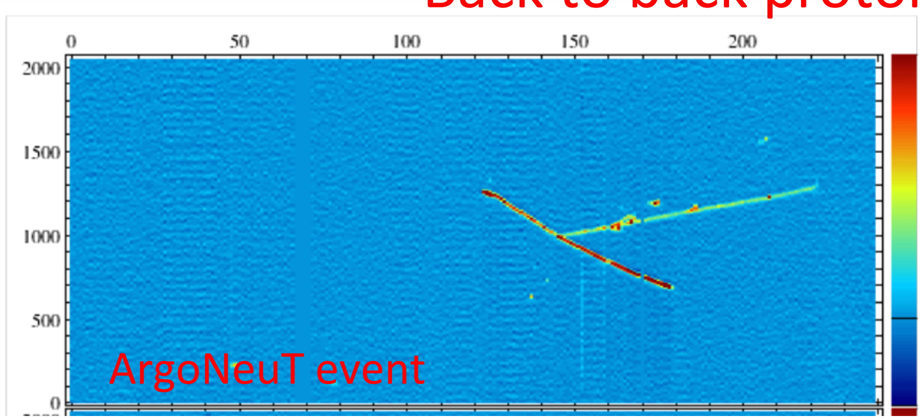


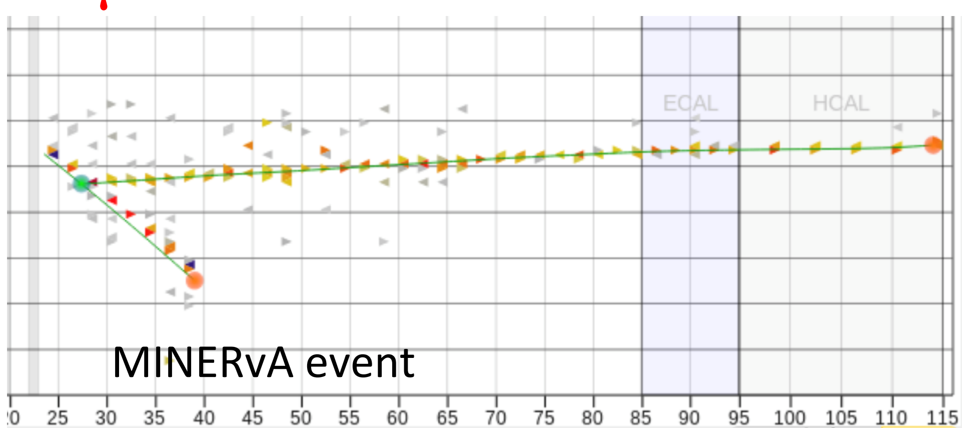
CAPTAIN-MINERvA

- Extend the physics reach of MINERvA by putting active LAr target upstream of scintillator
- High statistics measurements of Ar/CH ratios become available
- Direct probe of nuclear effects
- These will be used by ELBNF just like T2K is already making use of MINERvA data



Back to back protons + μ candidate events:





CAPTAIN-MINERvA letter of intent: http://minerva.fnal.gov

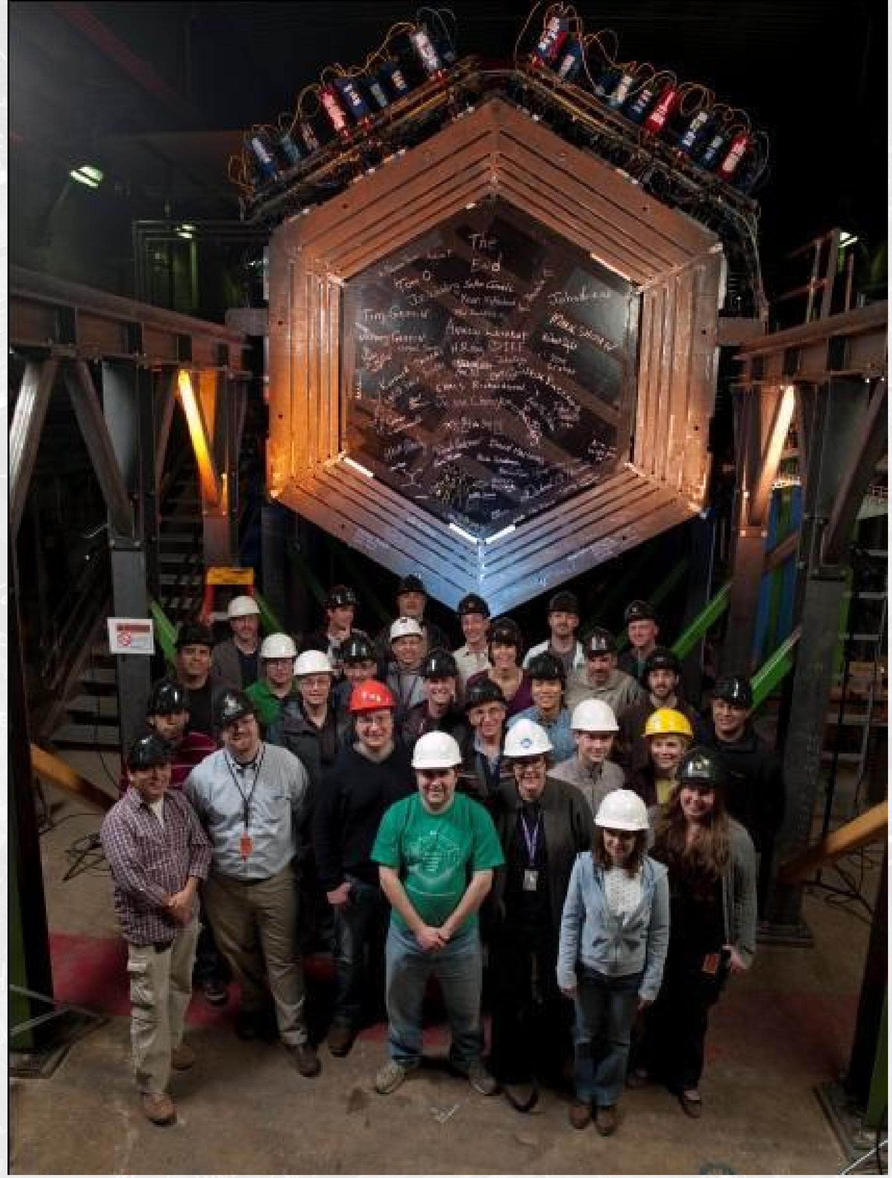
Summary

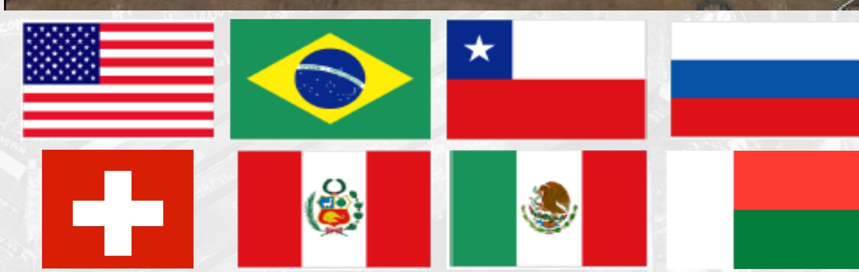
- For oscillation experiments, it is important that cross-sections be modeled as accurately as possible
  - CCQE for signal
  - Pion production etc as background
  - Also FSI needs to be understood as those two kind of interfere
- MINERvA shows that the models we currently have are not complete, and a more complicated model of the nucleus is needed in all ranges
- We see evidence of the important of final-state interactions and nucleon-nucleon correlations
- Many analyses underway to examine these in more detail, working closely with theorists

MINERvA Collaboration

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





BACKUPS

Inputs to $\nu_\mu \rightarrow \nu_e$ oscillation measurements

Observation fitted to prediction templates
to extract parameters (Δm^2, θ, δ)

$$N_{FD}(E_\nu) = \Phi_{\nu_\mu} \times P_{\nu_\mu \rightarrow \nu_e}(E_\nu) \times \boxed{\sigma_{\nu_e}(E_\nu)} \times \boldsymbol{R}(E_\nu, E_{visible}) + \boxed{N_{bg}}$$

flux prediction

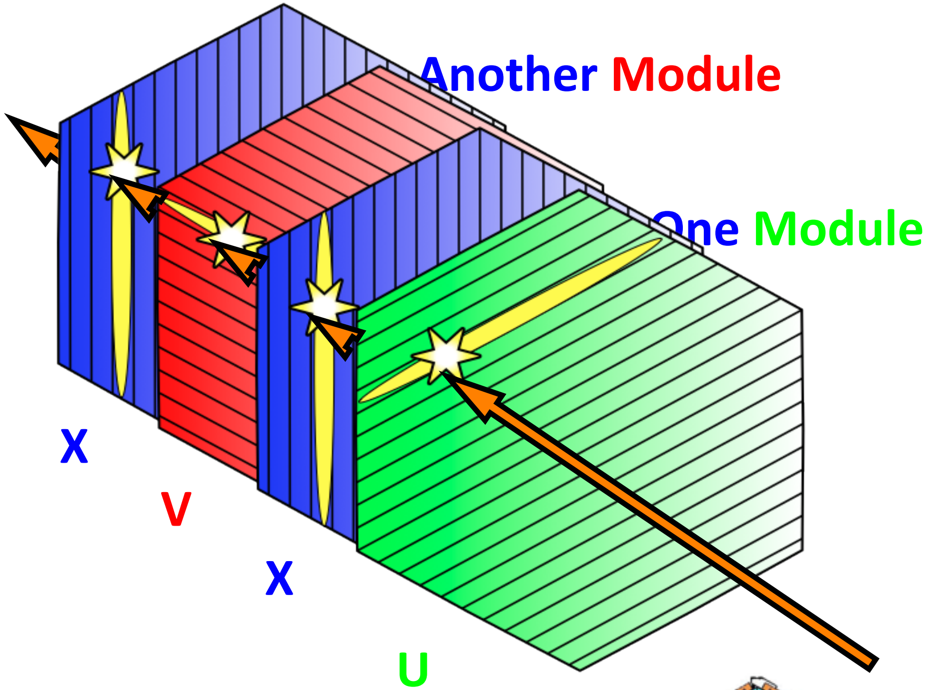
oscillation probability

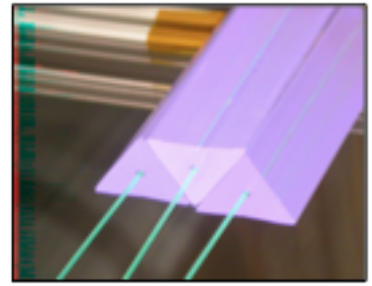
ν_e cross-section

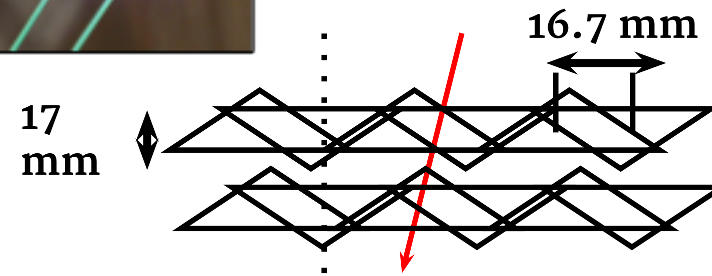
detector effects smearing matrix

accelerator ν_μ beams typically have an intrinsic ~1% ν_e contamination

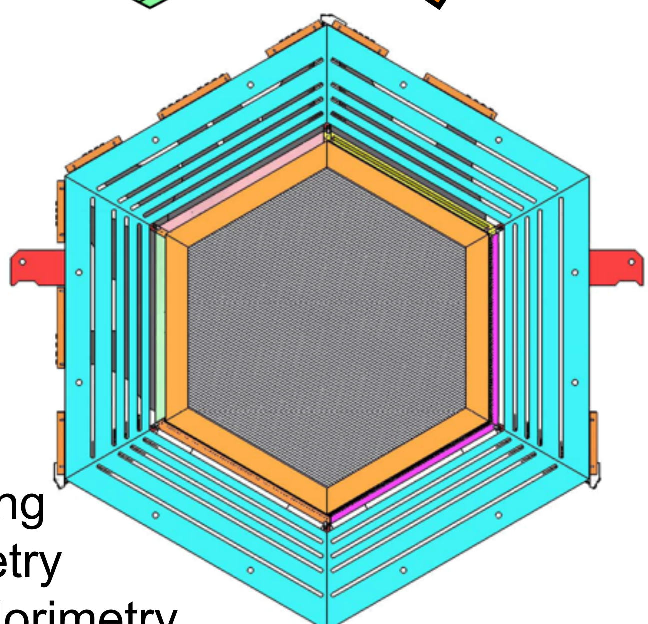
The ν_e cross-section enters *twice* in the prediction:
so a precision result necessitates a precision input.



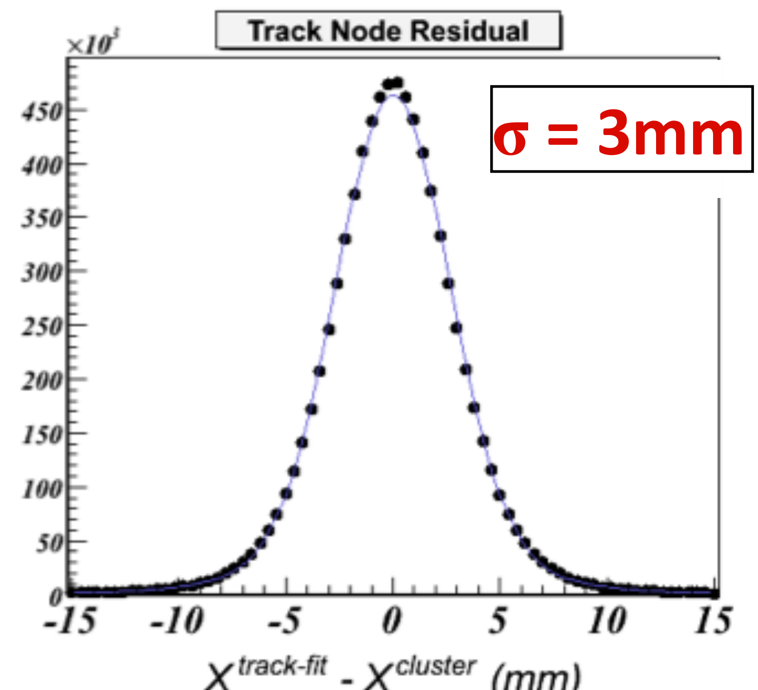




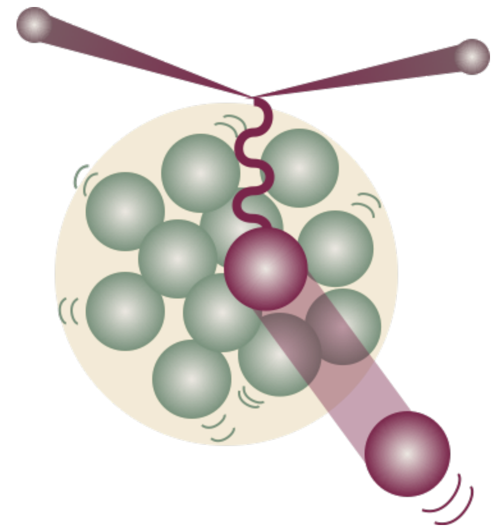
Charge sharing for improved position resolution (~3 mm) and alignment



Scintillator - tracking
Lead - EM calorimetry
Steel - hadronic calorimetry



Relativistic Fermi gas



- RFG is a frequently-used nuclear model
- Nucleons behave as if they are independent in the mean field of the nucleus
- Initial-state momenta are Fermi distributed
- Cross-sections can be modeled by a multiplier to the Llewellyn Smith cross-section for a free nucleon
- Its free parameters (form-factors) can be determined from electron scattering, except for the axial mass, MA, which must be measured in neutrino scattering

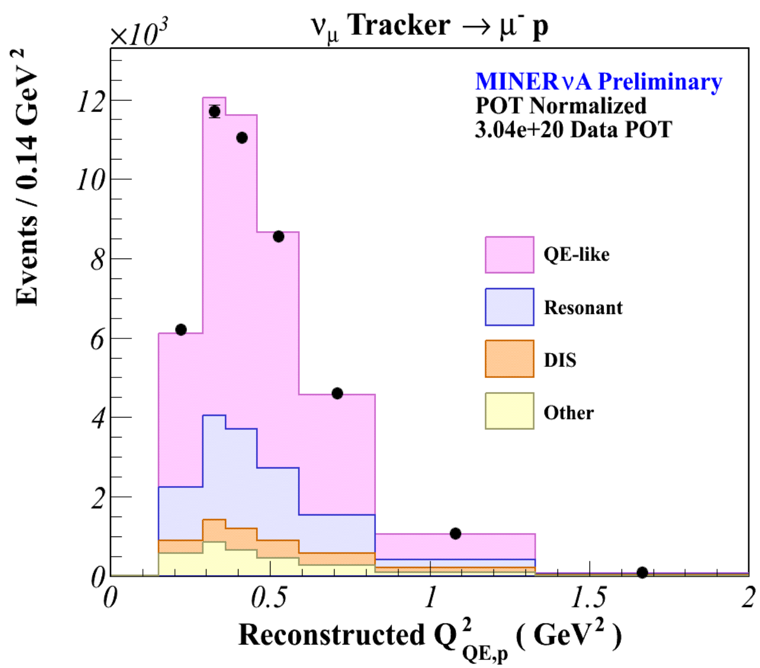
$$F_A(Q^2) = -\frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

Muon + N Protons: Analysis

- 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



Coherent Pion Production: Analysis

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

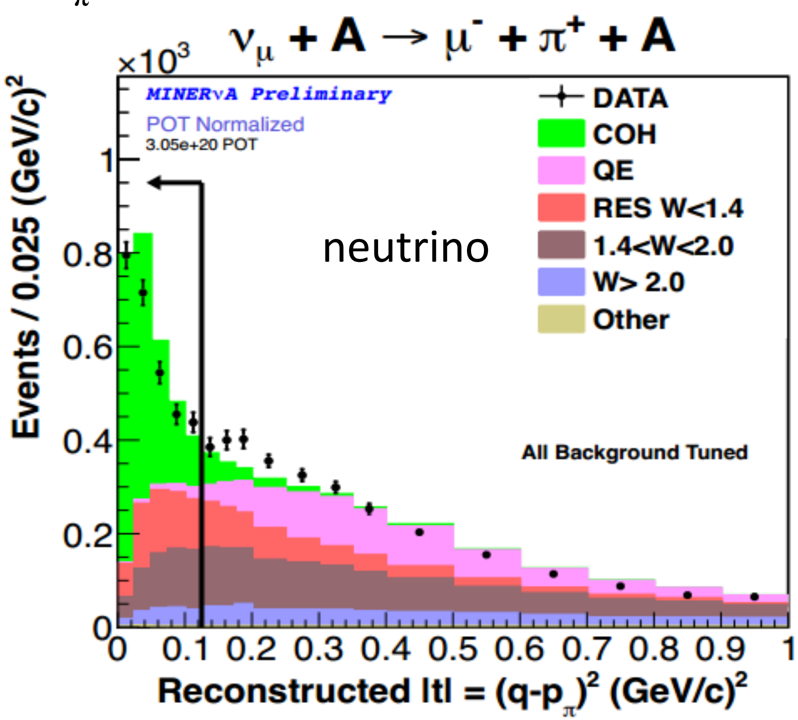
$$E_\nu = E_\mu + E_\pi$$

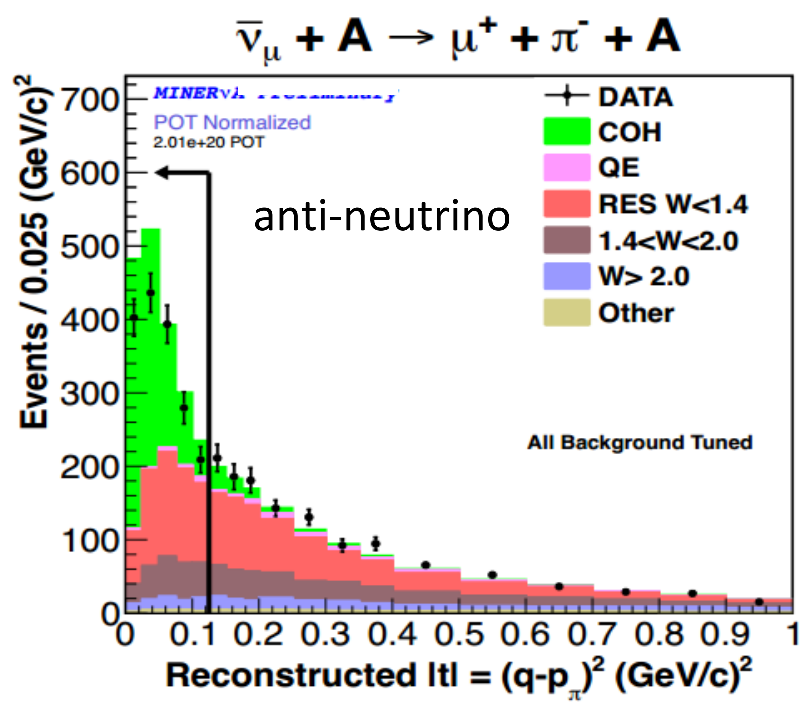
$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

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

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

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

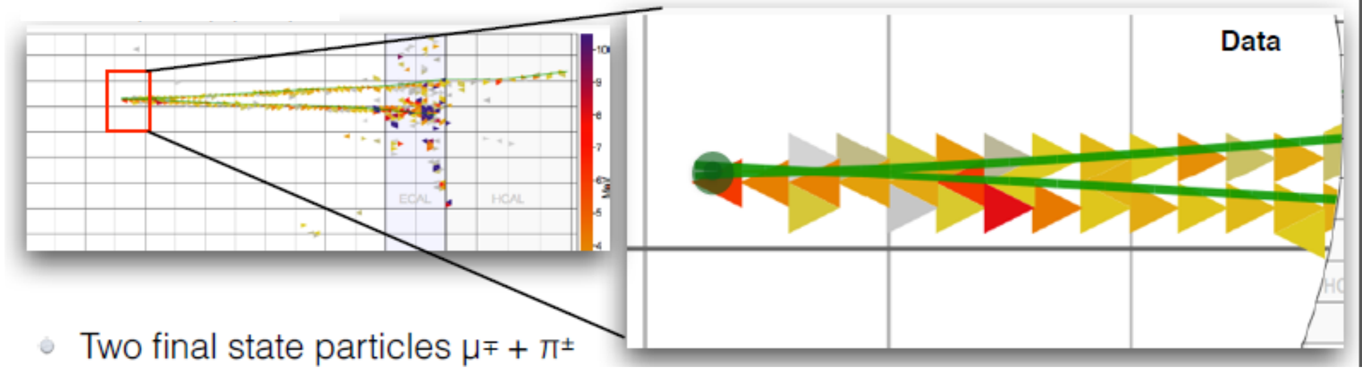




Coherent Charged Pion Production

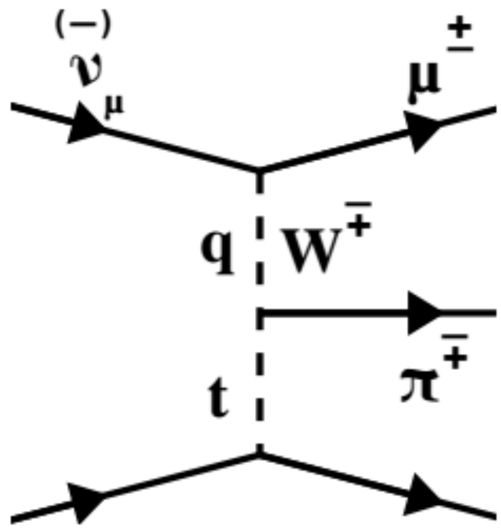
$\nu_\mu A \longrightarrow \mu^+ \pi^- A$

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



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

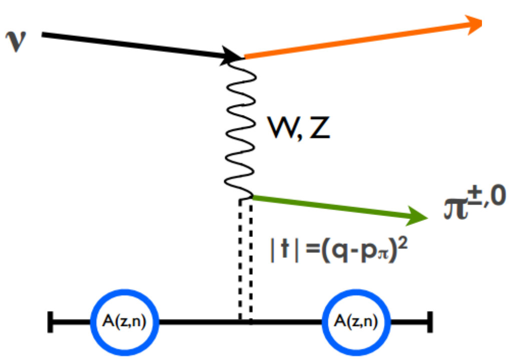
- Coherent pion production: Struck nucleus is left in its ground state and a single π^+ is produced
- Neutrino scatters off a ... on, and transfers low four momentum (|t|) to th... ntact
- Oscillation measureme... ing of these interactions
- SciBooNE and K2K hav... ction in the few GeV region to no avail



$= E_\mu + E_\pi$

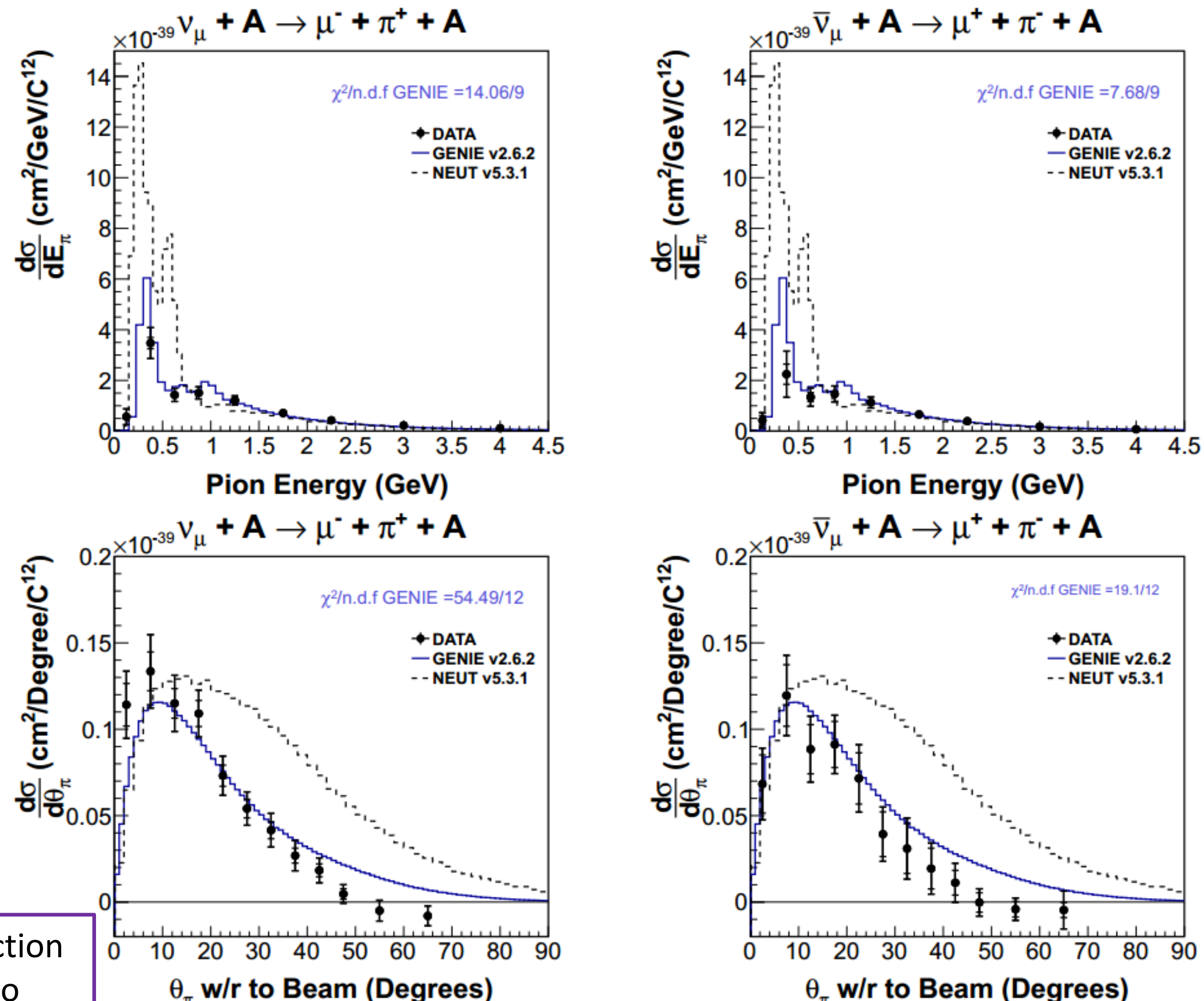
$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

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



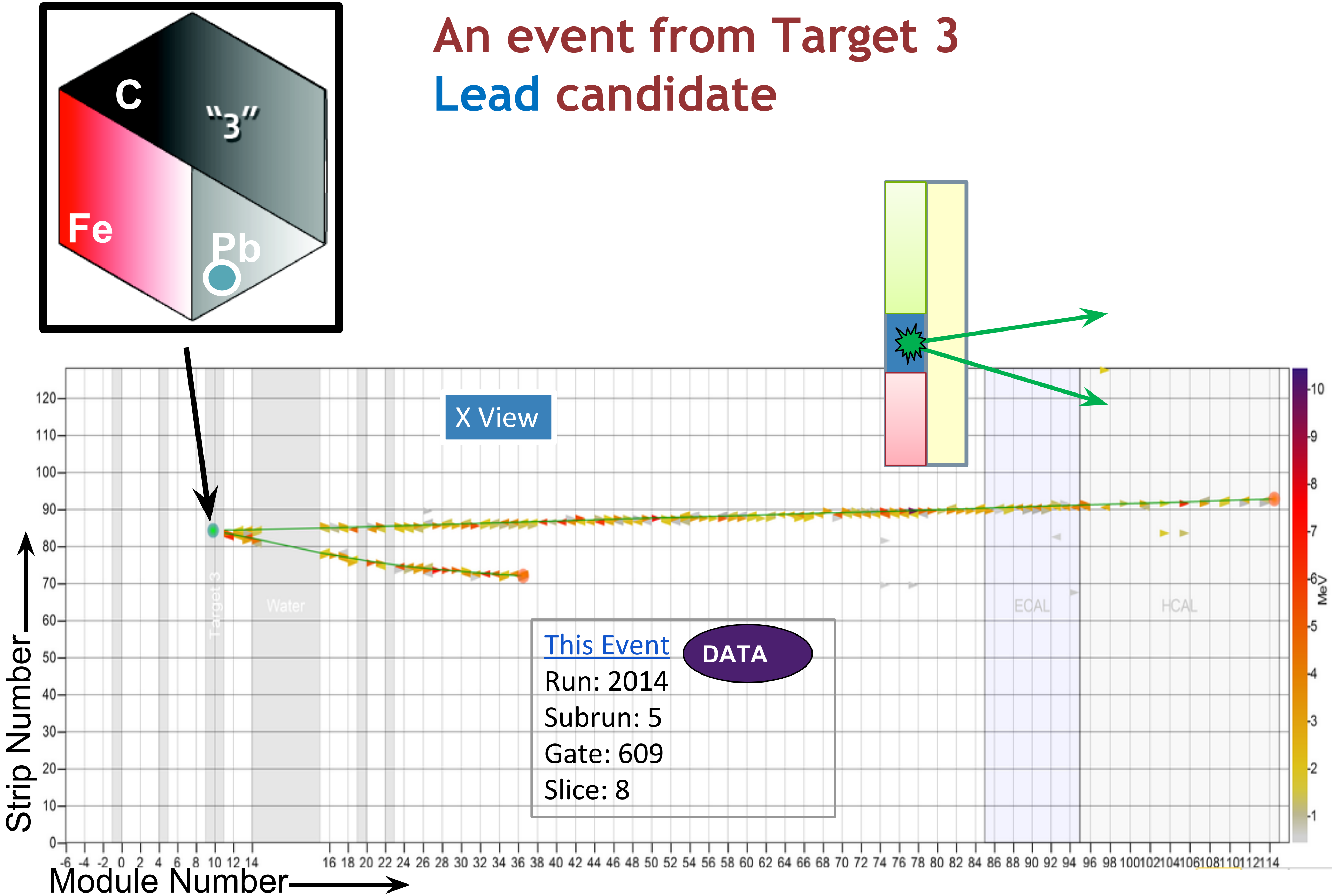
Coherent Pion Production: Results

- MINERvA sees coherent pion production! ~1.6K ν and ~900 anti-ν
- Differential cross sections as a function of pion energy and angle against GENIE and Neut (Rein-Segal)
- Disagreement at high θ_π is evident in both
- Data provides benchmark to 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)

An event from Target 3
Lead candidate



This Event

Run: 2014

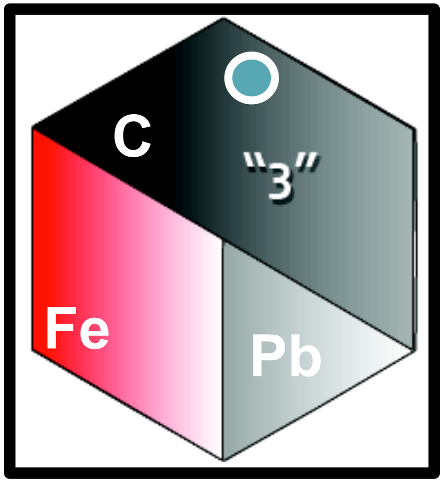
Subrun: 5

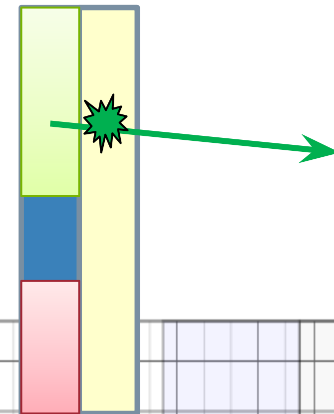
Gate: 609

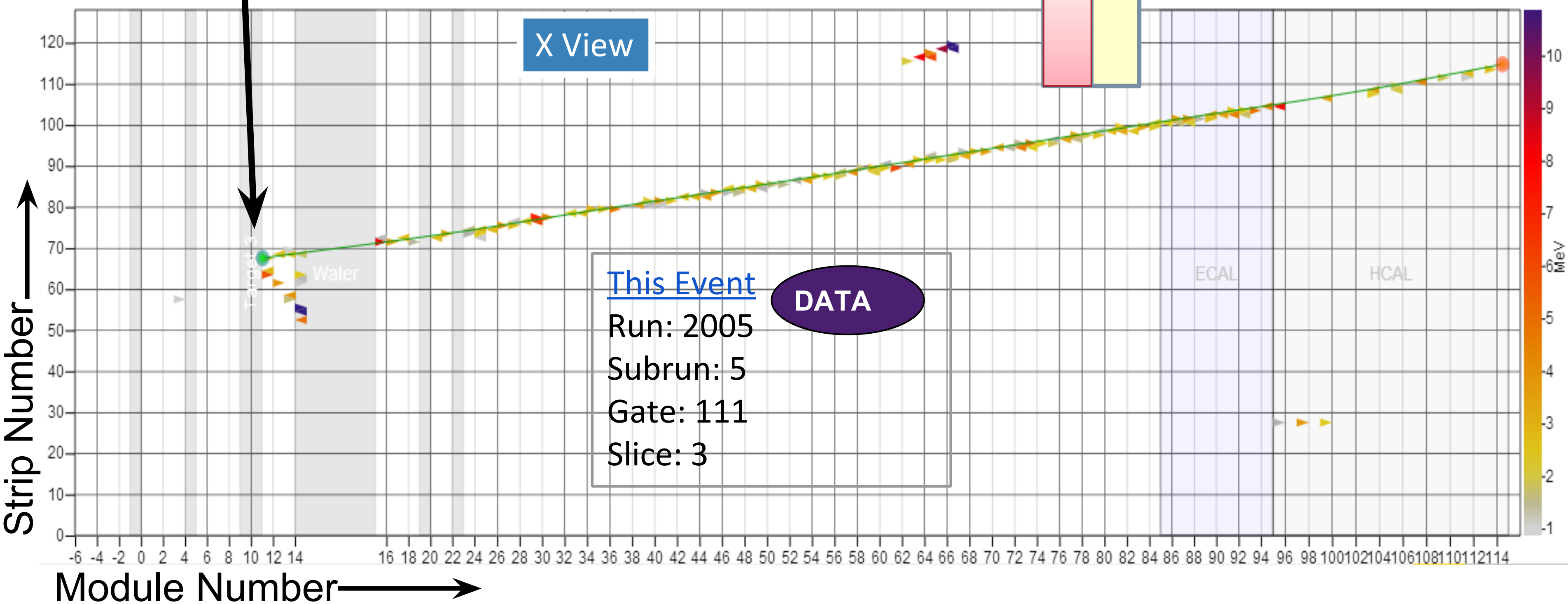
Slice: 8

DATA

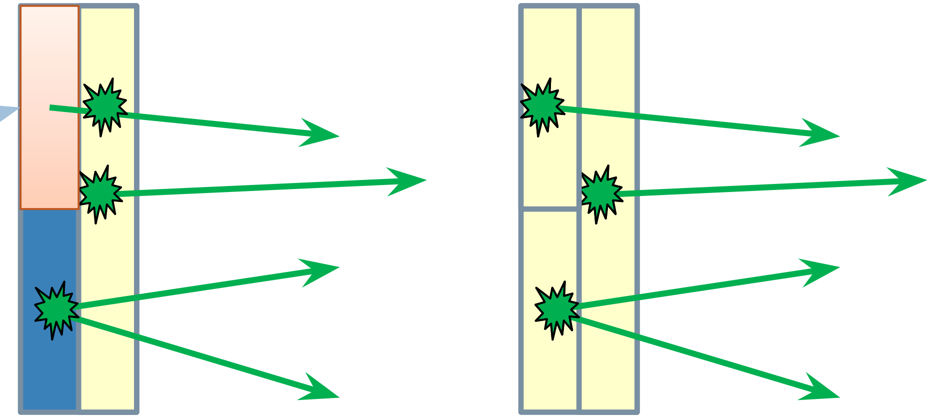
An event from Target 3
Carbon candidate

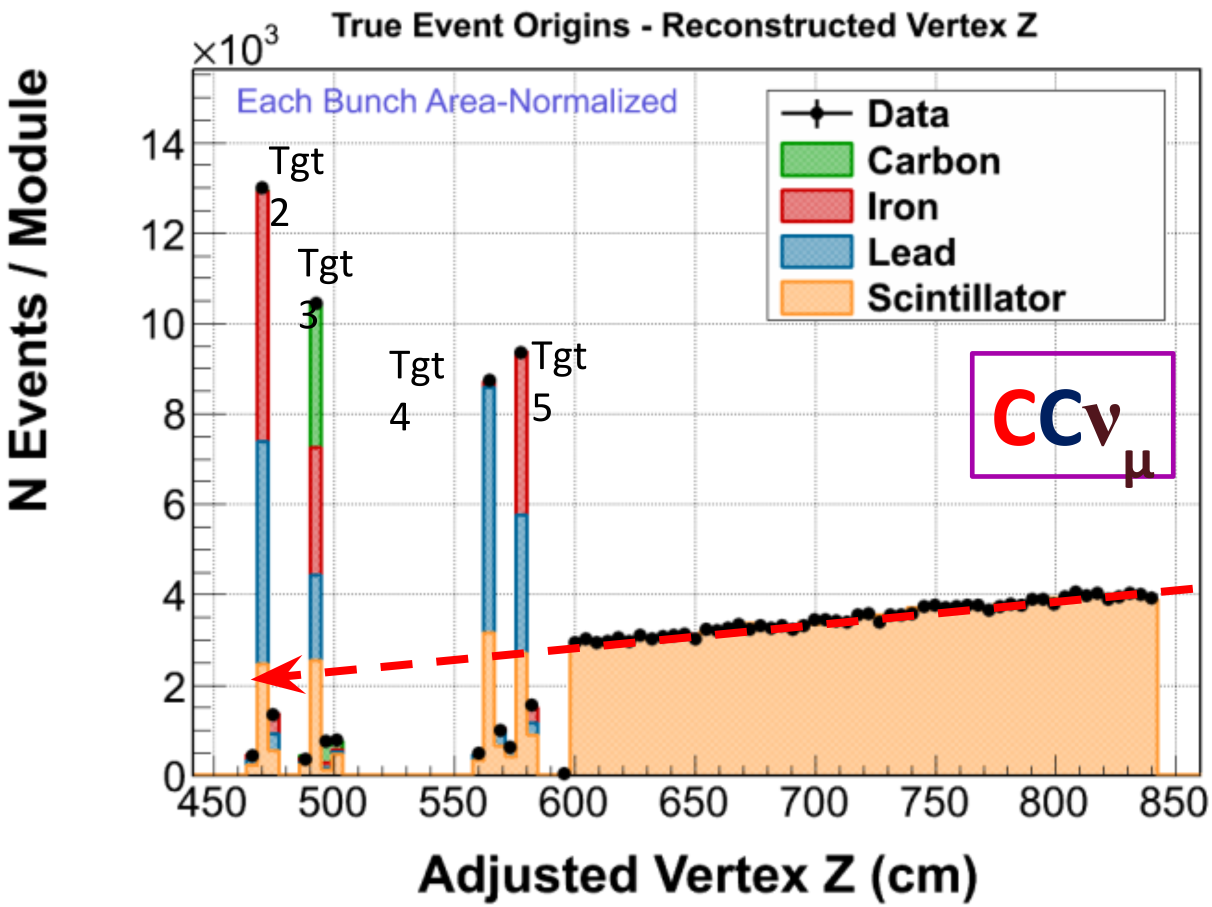






One track events from passive target have a vertex in the first plane downstream of the target.





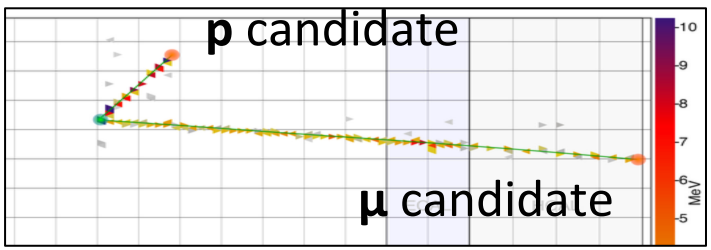
Tracking region used to estimate and subtract contamination from scintillator events.

MINERvA Results used by T2K

Key processes that cause mis-reconstruction of neutrino energy:

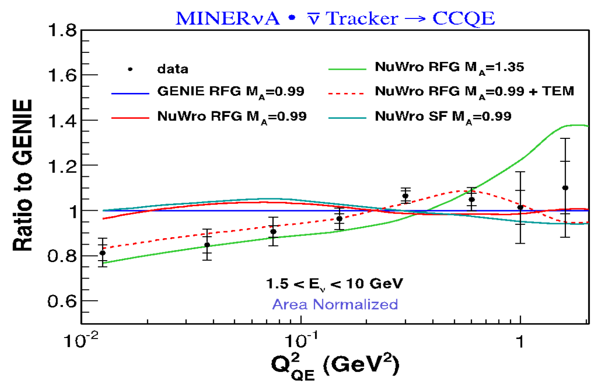
- Quasi-elastic scattering:

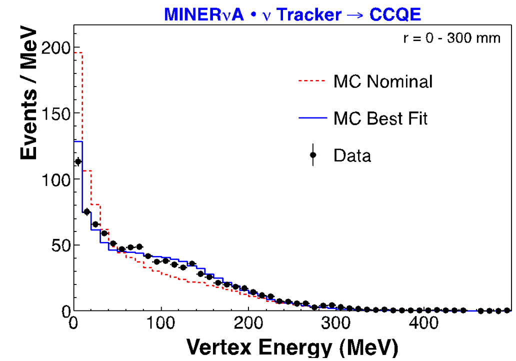
  Evidence for multi-nucleon effects in muon kinematics and additional soft protons near vertex



Module number

$$\nu_\mu + n \rightarrow \mu^- + p$$

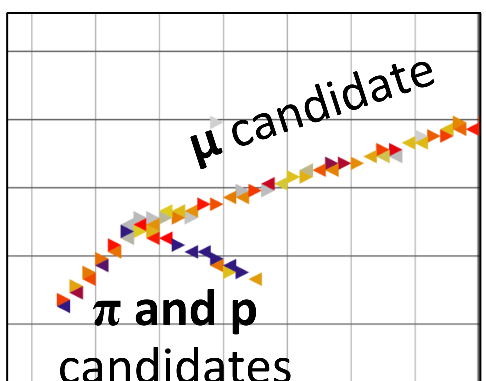


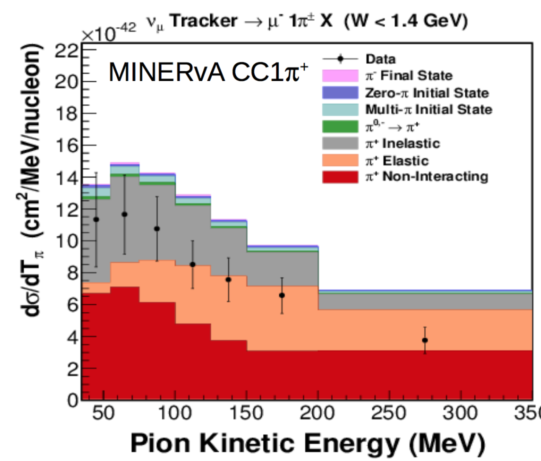


Phys. Rev. Lett. 111, 022501 (2013)

- Pion production:

  Kinematics of pions probe another effect of the nucleus





arXiv:1406.6415

MINERvA Physics Program in the NOvA Era

- Primary Goal: Measuring the most important processes for oscillation experiments
  - Comparing Pb, Fe, and C to CH interactions
  - Separate comparisons for Quasi-elastic & pion production
- Bonus: First demonstration of the role quark flavor plays in EMC effect (12x10^{20} POT in anti-ν mode)
- http://minerva.fnal.gov