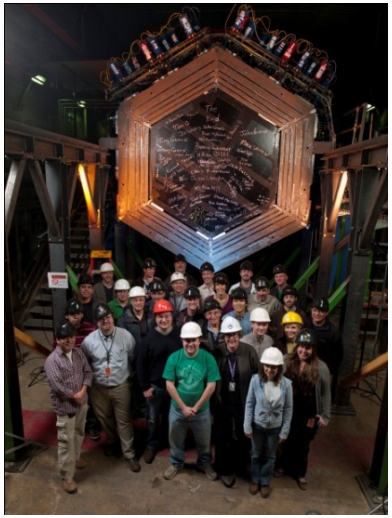
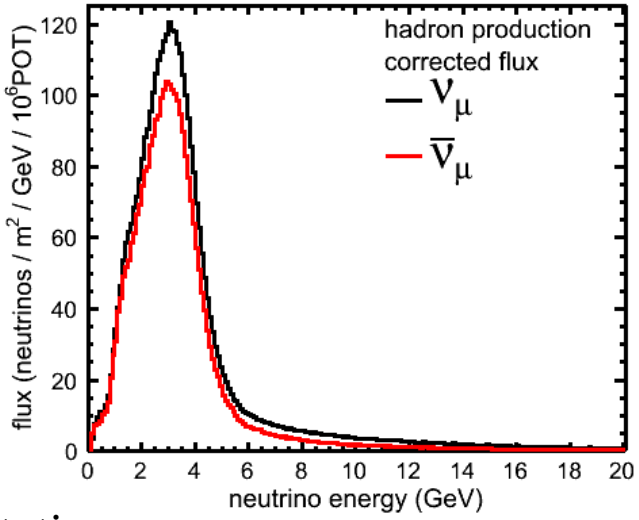
MINERνA Overview



- MINERνA is studying neutrino interactions in unprecedented detail on a variety of different nuclei
- Low Energy (LE) Beam Goals:
  - Study both signal and background reactions relevant to oscillation experiments (current and future)
  - Study nuclear effects in inclusive reactions
  - Measure nuclear effects on exclusive final states
    - » as a function of measured neutrino energy
    - » Study differences between neutrinos and anti-neutrinos
- Medium Energy (ME) Beam (NOνA) Goals:
  - Structure functions on various nuclei
  - Study high energy feed-down backgrounds to oscillation expt's
- NuMI Beamline provides
  - High intensity, wide range of available energies
- MINERνA detector provides
  - Reconstruction in different nuclei, broad range of final states

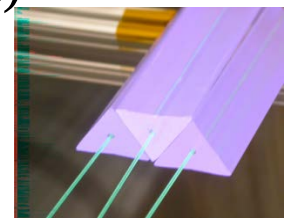
NuMI "Low Energy" Beam Flux

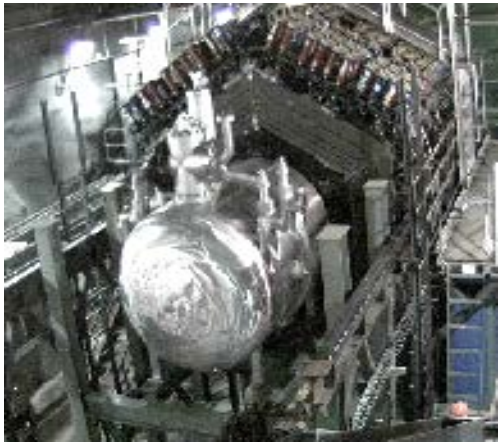


~65 Particle, nuclear and theoretical physicists from 20 institutions

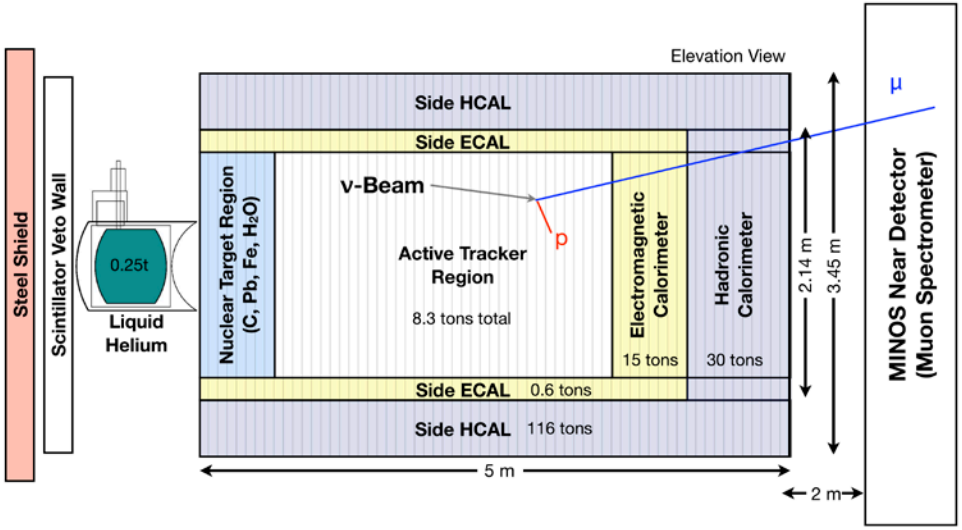
MINERνA's Detector

- Nuclear Targets
  - Allows side by side comparisons between different nuclei
  - Pure C, Fe, Pb, LHe, water
- Solid scintillator (CH) tracker
  - Tracking, particle ID, colorimetric energy measurements
  - Low visible energy thresholds
- Side and downstream electromagnetic and hadronic calorimetry
  - Allow for event energy containment
- MINOS Near Detector
  - Provides muon charge and momentum



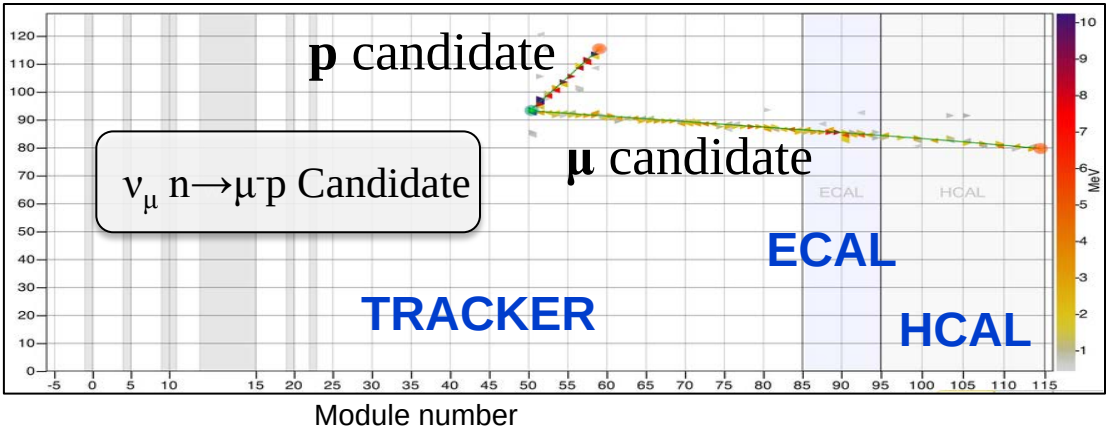


LHe cryotarget

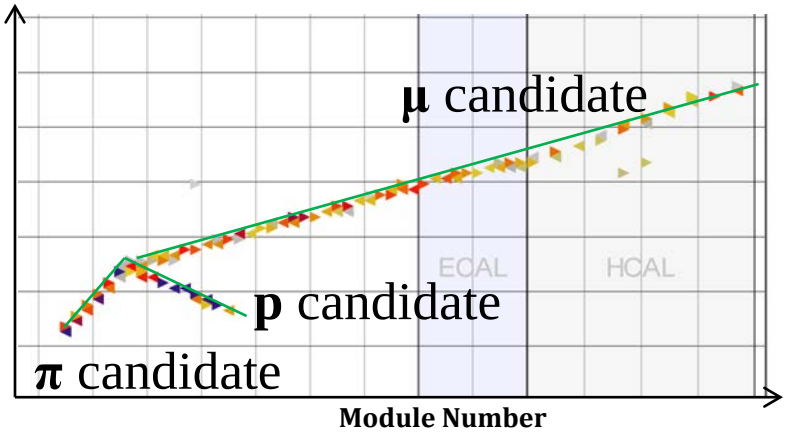


Events in MINERνA

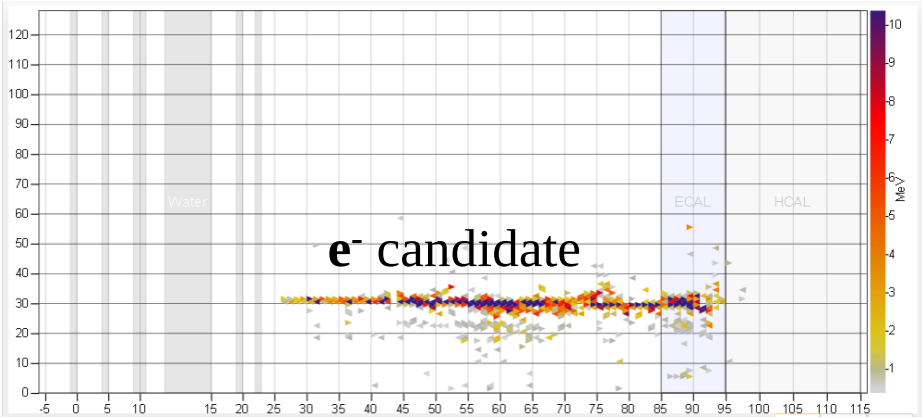
One out of three views shown, color = energy

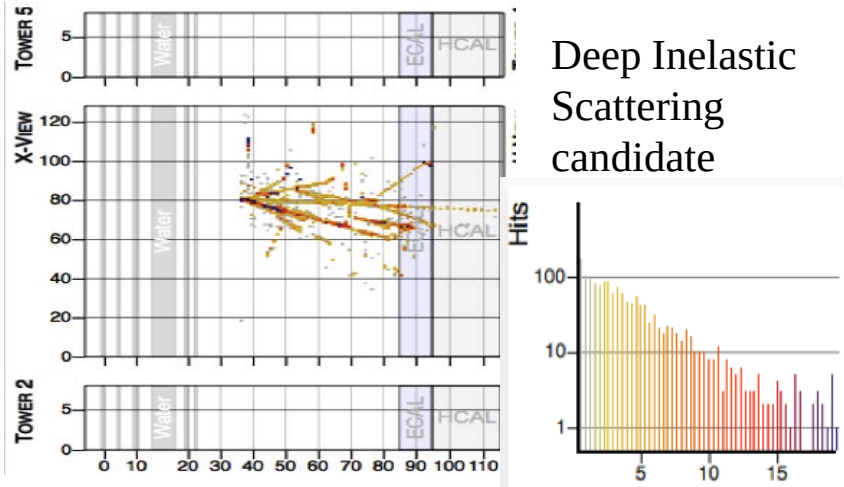


ν_μ p→$\mu^-\Delta^{++}$, Δ^{++}→pπ^+ Candidate



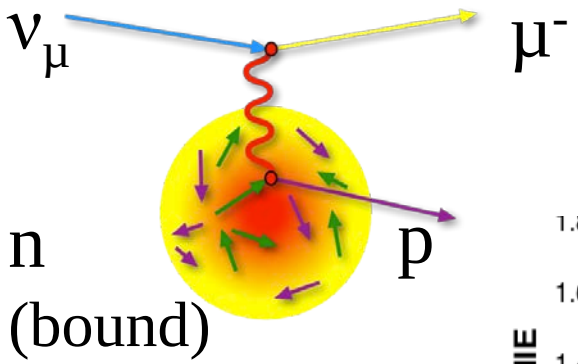
ν_μ e⁻→ ν_μ e⁻ Candidate



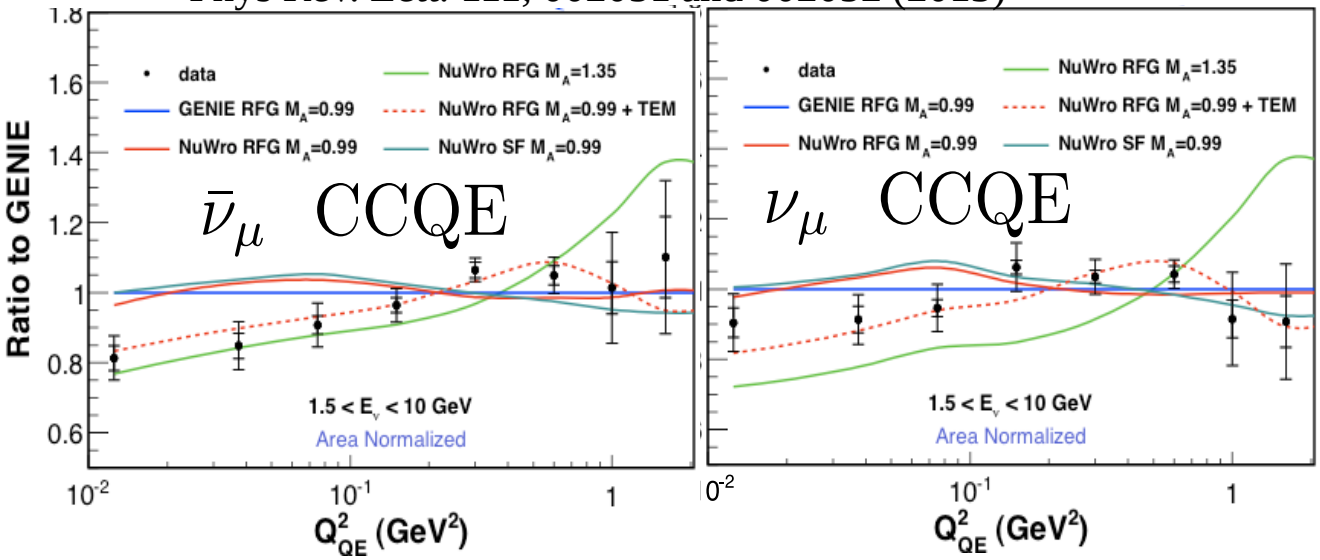


Deep Inelastic Scattering candidate

Neutrino & Anti-Neutrino Charged Current Quasielastic

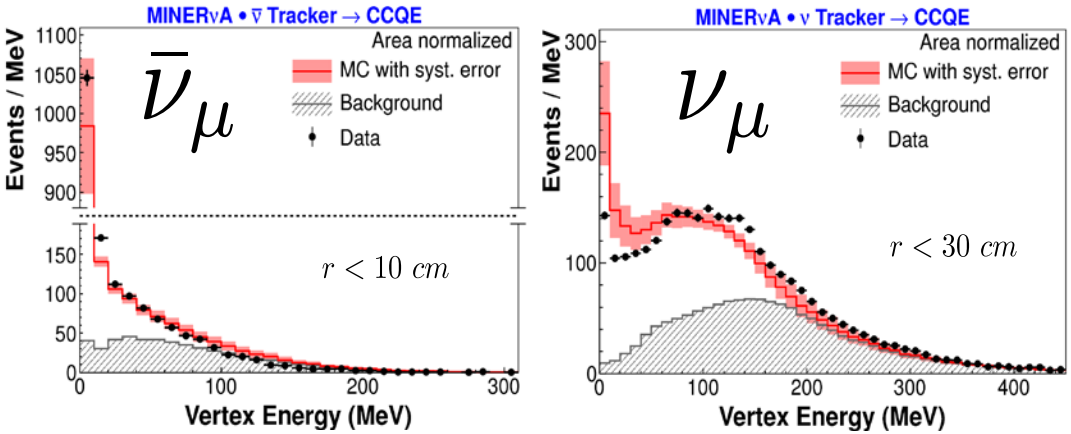


Phys Rev. Lett. 111, 002051 and 002052 (2013)



What is effect of nucleus?

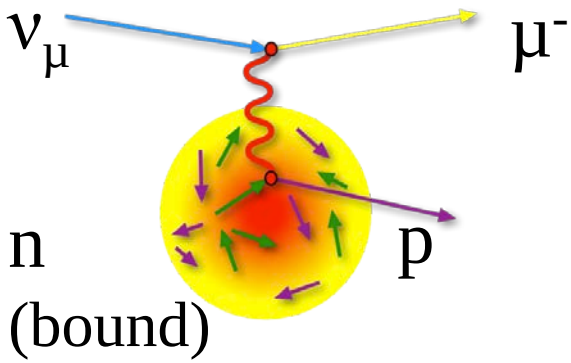
Compare shape of $d\sigma/dQ^2$ to models



Look for energy near vertex consistent with extra nucleons

Data would prefer if 25±9% of events ejected initial state np pairs (final state nn or pp)

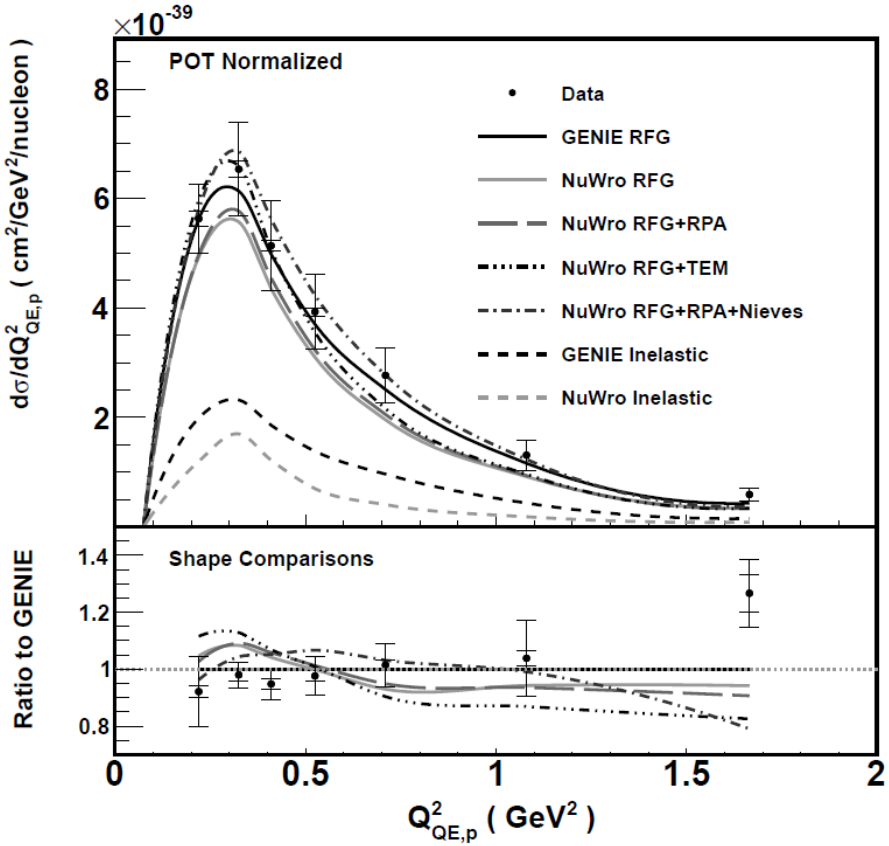
Cross-section vs Q^2 and vertex energy both consistent with multi-nucleon hypothesis

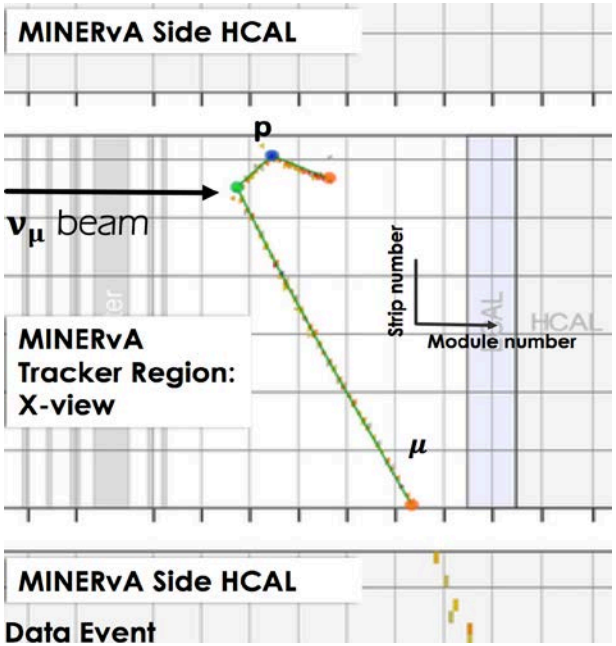


Quasielastic with Observed Proton Recoil

Is effect of nucleus the same as it is in inclusive CCQE?

Momentum transfer (Q^2) can also be measured from proton energy

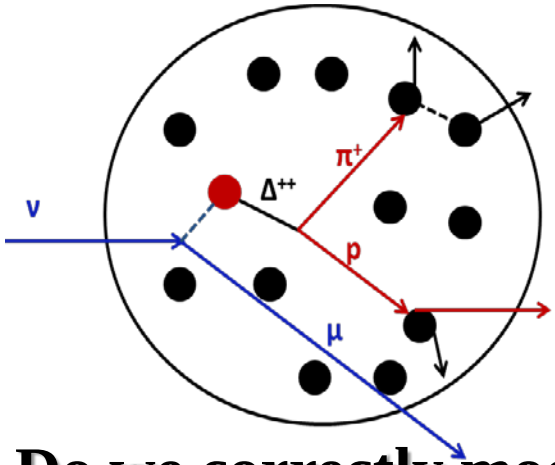


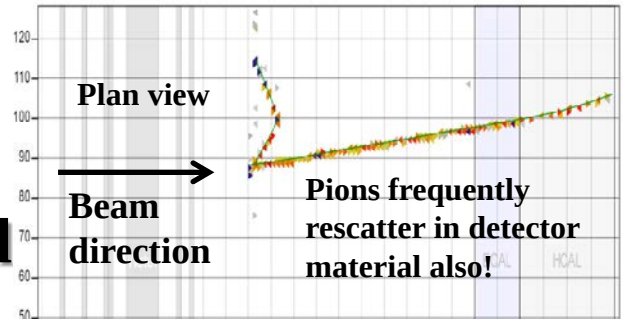


Best model for μ kinematics is not the same as the one that best describes the proton kinematics

hep-ex 1409.4497

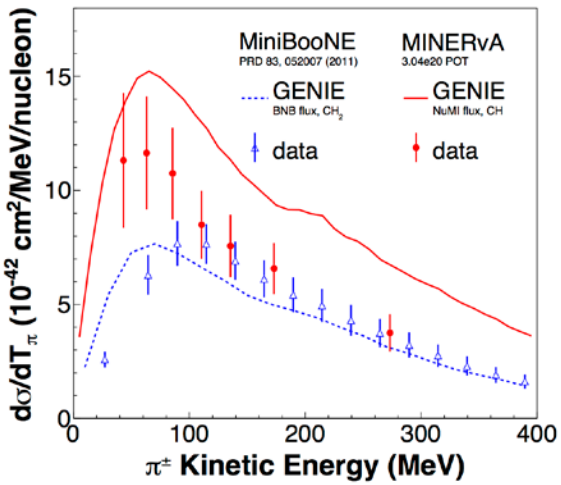
Charged Pion Production



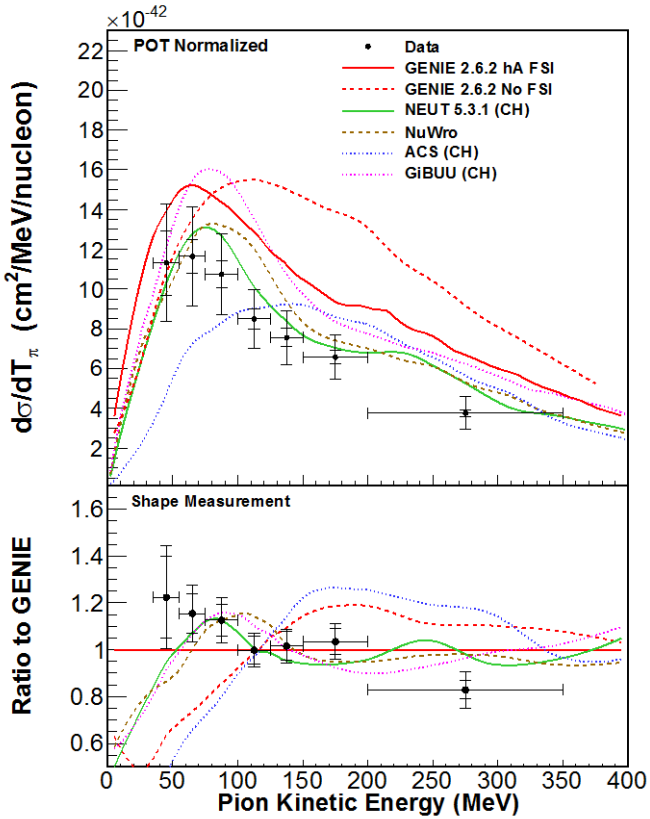


Do we correctly model nuclear rescattering, "final state interactions"?

Our data on pion kinematics favors FSI models in generators (GENIE, NEUT, GiBUU)



MiniBooNE's measurement of same reaction sees harder momenta, more events and suggest less FSI.
There is significant tension between the experiments.



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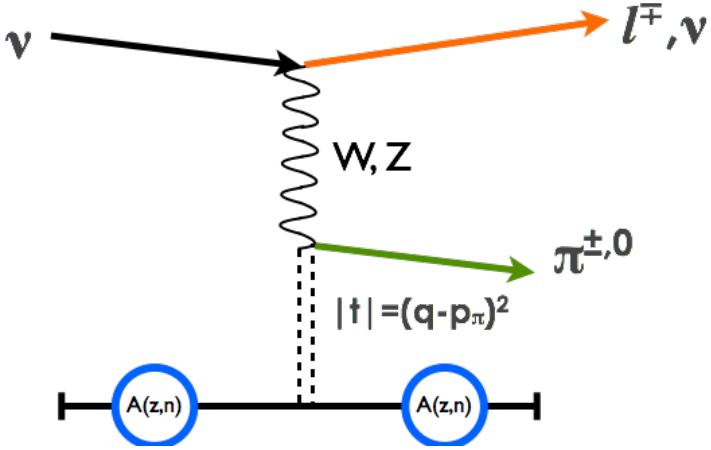
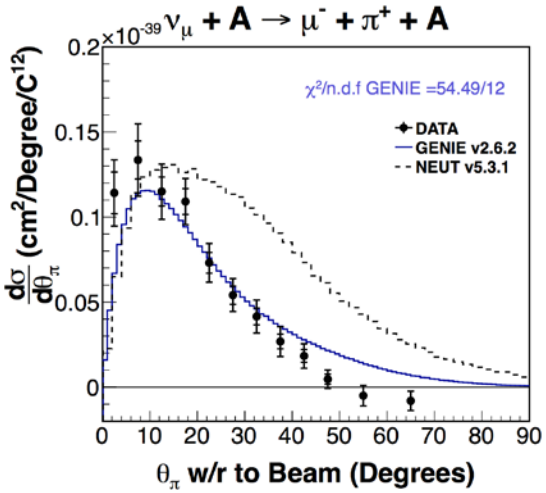
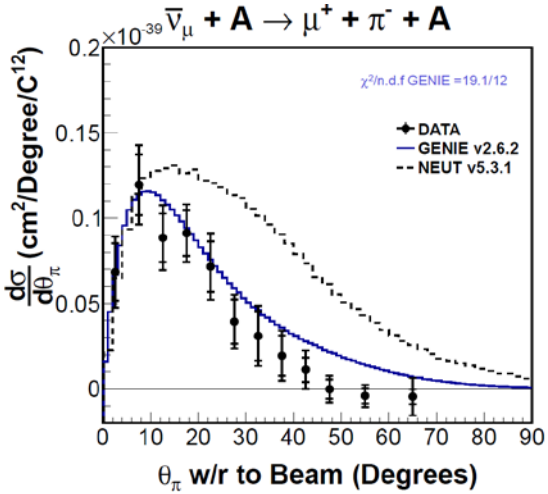
Coherent Pion Production

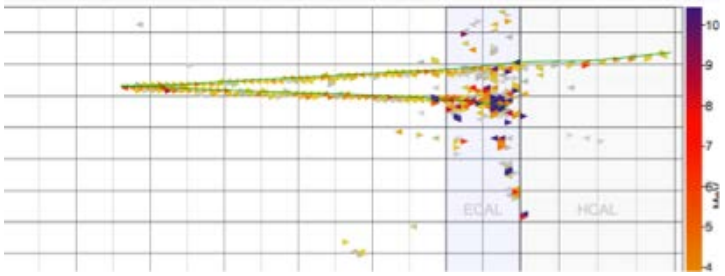
Can we resolve experimental puzzles on rate for this process?



- Low multiplicity process is a troublesome background for oscillation experiments and previous low energy data is confusing
- Model independent selection and high statistics allows test of pion kinematics
- 1628 (770) coherent neutrino (antineutrino) events







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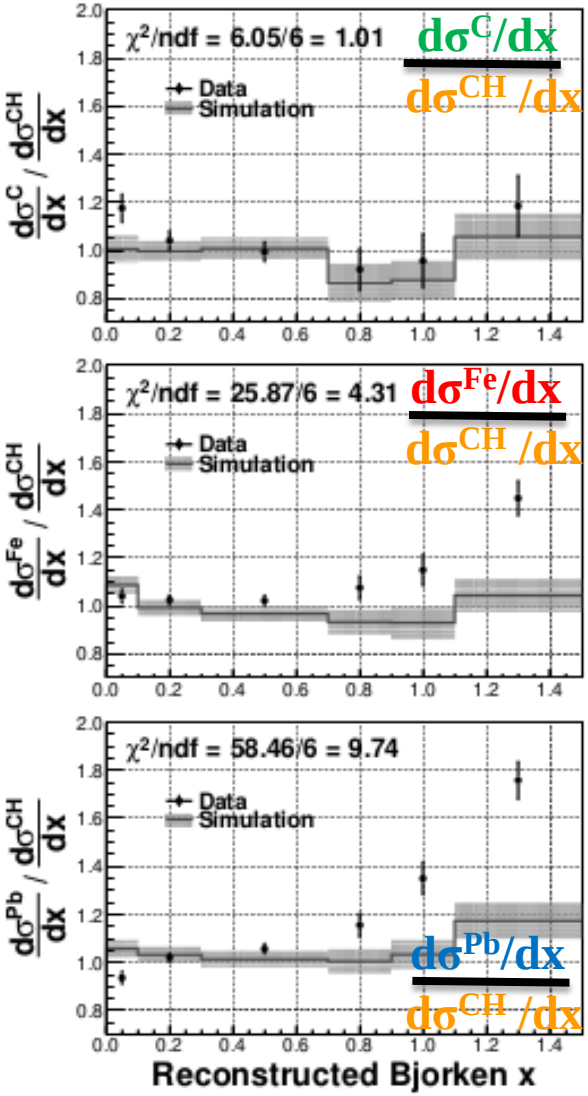
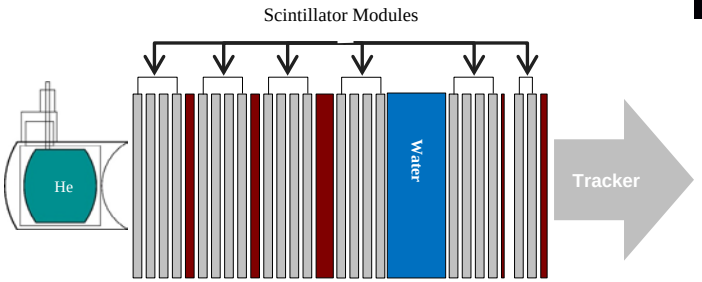
Current generators don't model process well at LBNF energies

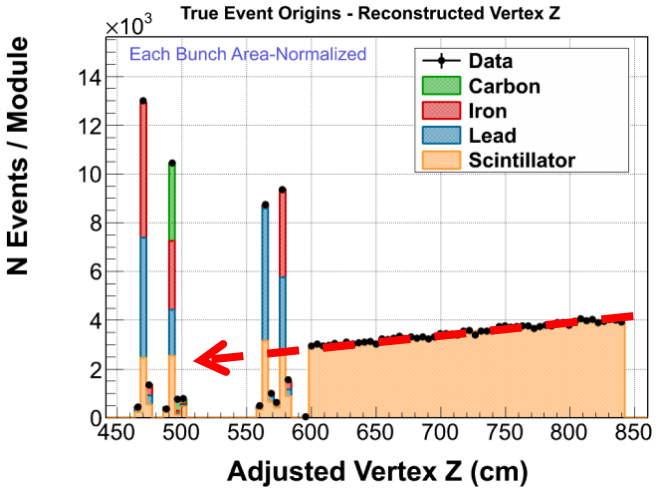
Ratios of Inclusive CC Reactions on Nuclei

How are CC reactions modified by nucleus?

Phys. Rev. Lett. 112, 231801 (2014)





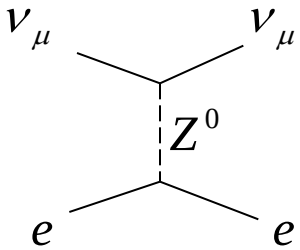


Targets are passive and there is contamination from nearby scintillator.

Use events in the tracker modules to estimate and subtract contamination from scintillator events.

1. *At low x*, we observe a *deficit* that increases with the size of the nucleus.
2. *At high x*, we observe an *excess* that increases with the size of the nucleus.

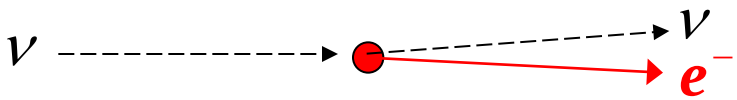
These effects are not reproduced by current neutrino interaction models.

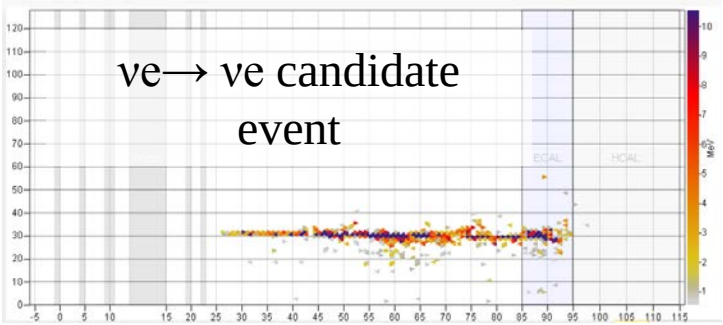


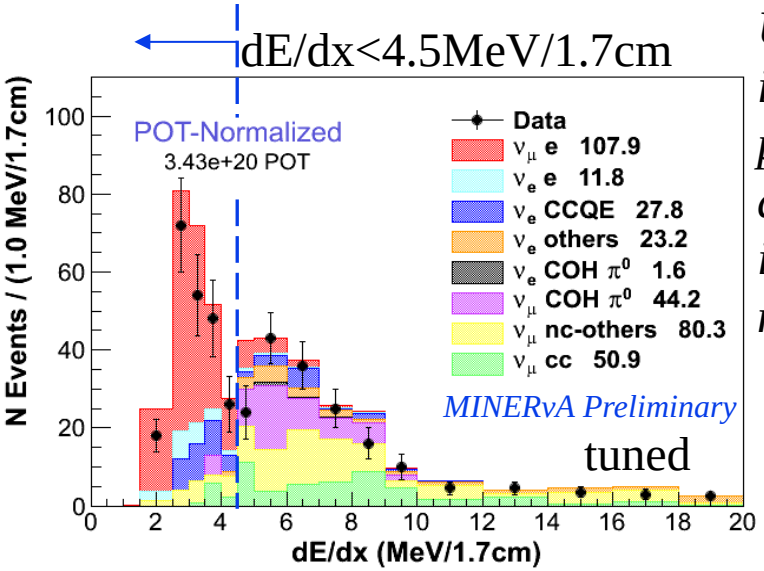
Neutrino-Electron Scattering

Can we isolate a sample of these well-predicted events to directly measure neutrino flux?

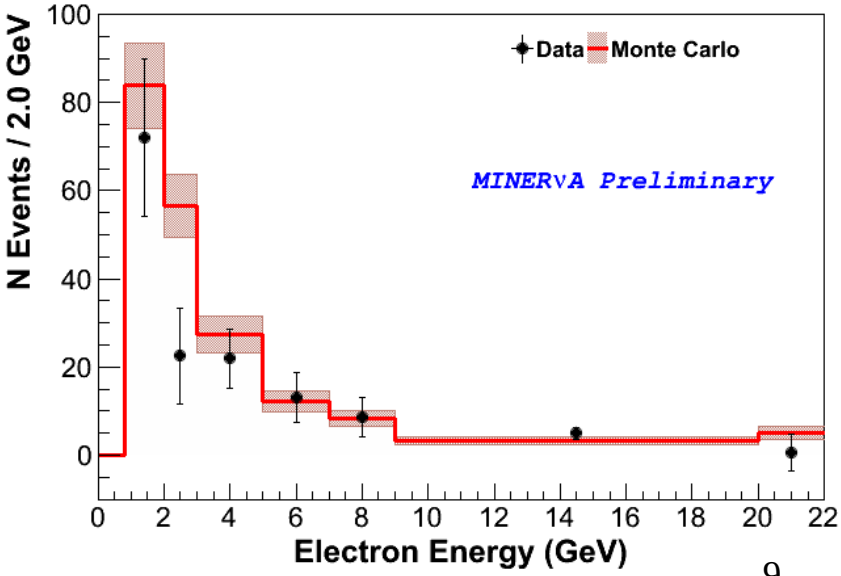
Very forward single electron final state





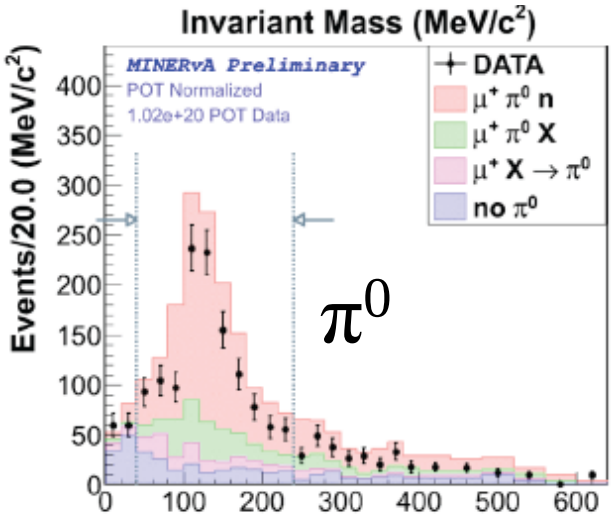
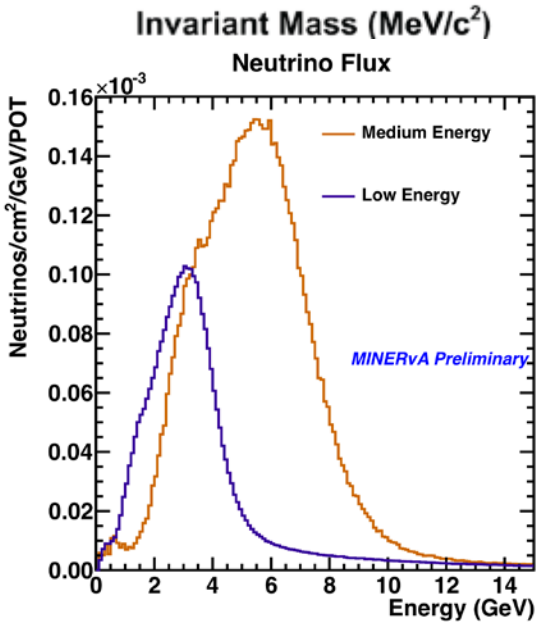


Use early ionization to reject photons and direction to reject interactions on nucleons



Measurement in LE NuMI beam constrains flux at precision similar to hadroproduction uncertainties

Technique will be even more powerful in NOvA era beam with higher energy and rate

MINERvA: Future Plans

- Still many interesting results to come out of the Low Energy dataset
  - Neutral Pion production
  - Electron Neutrino Cross Sections
  - More studies of Quasi-Elastic Interactions
    - » Double Differential cross sections, improved reconstruction
    - » Cross Section Ratios: Pb/CH, Fe/CH
- Currently taking Medium Energy data
  - Event rates much higher
  - Planning for 2 years anti-ν running + ν
  - Will be able to probe nuclear effects for several channels, especially DIS
- Results should continue to improve model descriptions used by both theory and oscillation experiments