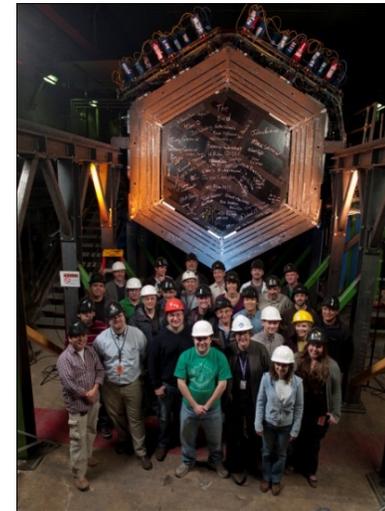
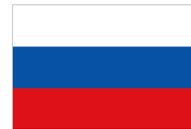


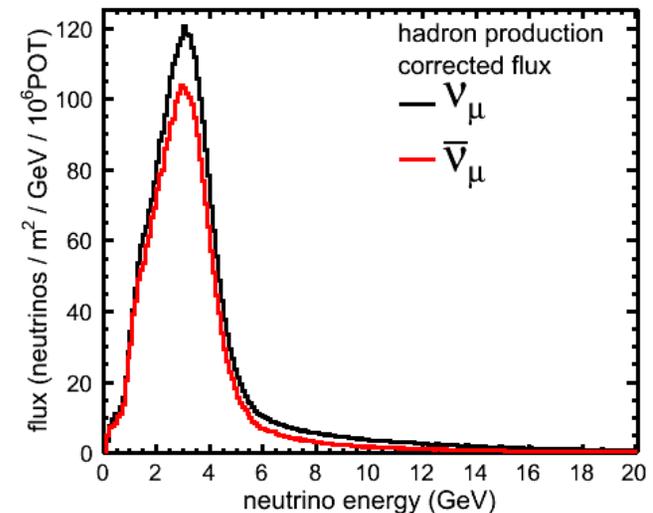
MINERvA Overview

- ◆ MINERvA 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 (NOvA) 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
- ◆ MINERvA detector provides
 - ▼ Reconstruction in different nuclei, broad range of final states

~65 Particle, nuclear and theoretical physicists from 20 institutions



NuMI “Low Energy” Beam Flux



MINERvA Collaboration



- ◆ University of California at Irvine
- ◆ Centro Brasileiro de Pesquisas Fisicas
- ◆ University of Chicago
- ◆ Fermilab
- ◆ University of Florida
- ◆ Universite de Geneve
- ◆ Universidad de Guanajuato
- ◆ Hampton University
- ◆ Inst. Nucl. Reas. Moscow
- ◆ Massachusetts College of Liberal Arts
- ◆ University of Minnesota at Duluth
- ◆ Universidad Nacional de Ingenieria
- ◆ Northwestern University
- ◆ Otterbein University
- ◆ Potificia Universidad Catolica del Peru
- ◆ University of Pittsburgh
- ◆ University of Rochester
- ◆ Rutgers, The State University of New Jersey
- ◆ Universidad Tecnica Federico Santa Maria
- ◆ Tufts University
- ◆ College of William and Mary

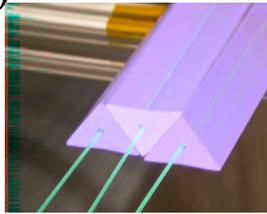


~65 **particle**, **nuclear** and **theoretical** physicists from 21 institutions

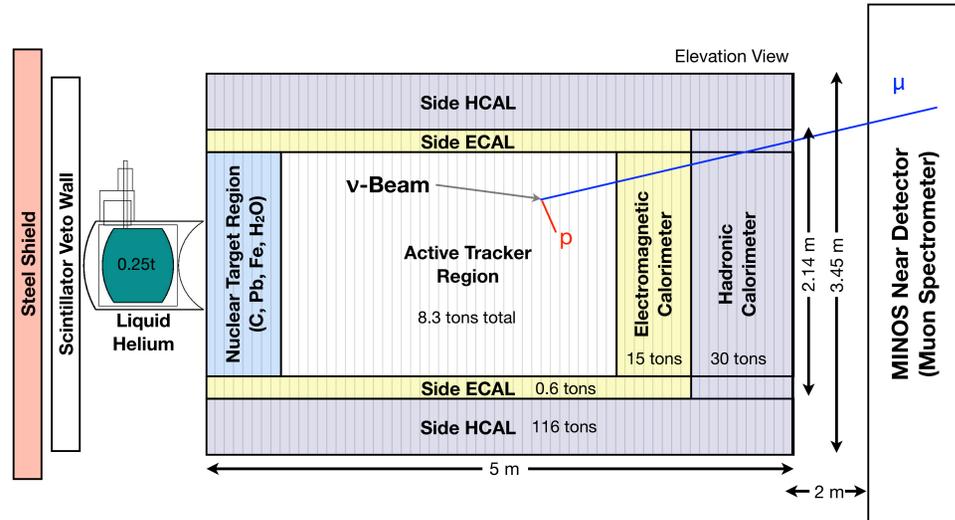
MINERvA's Detector



- ◆ Nuclear Targets
 - ▼ Allows side by side comparisons between different nuclei
 - ▼ Pure C, Fe, Pb, LHe, water
- ◆ Solid scintillator (CH) tracker
 - ▼ Tracking, particle ID, calorimetric 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



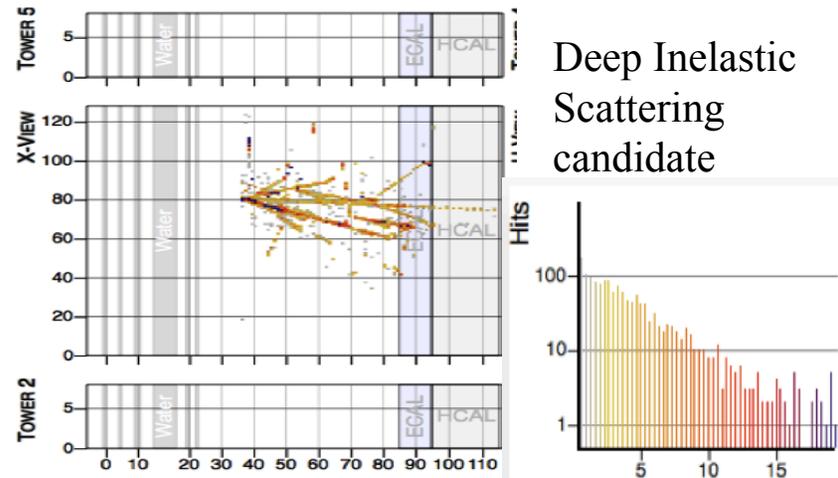
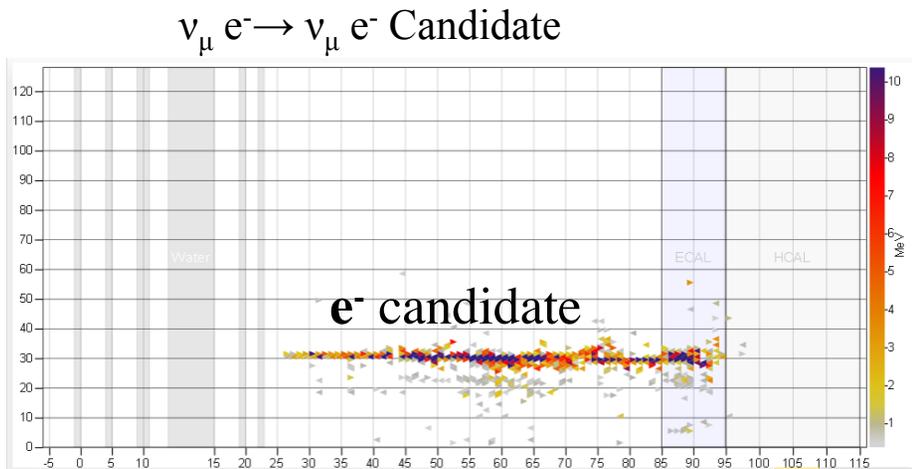
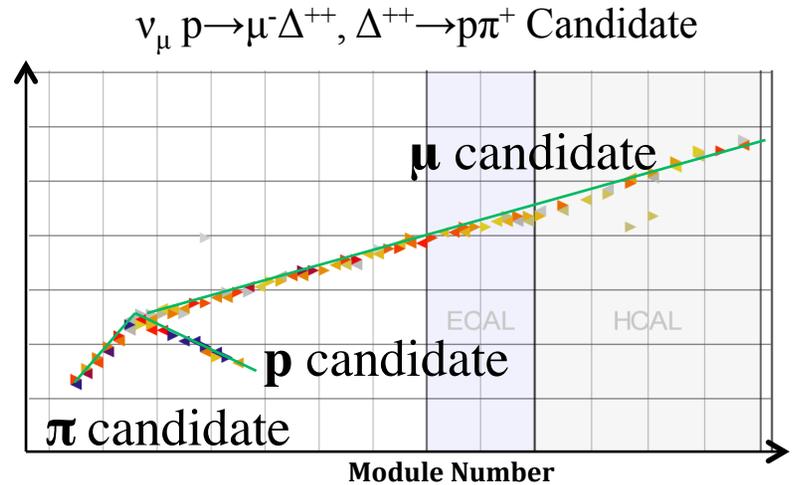
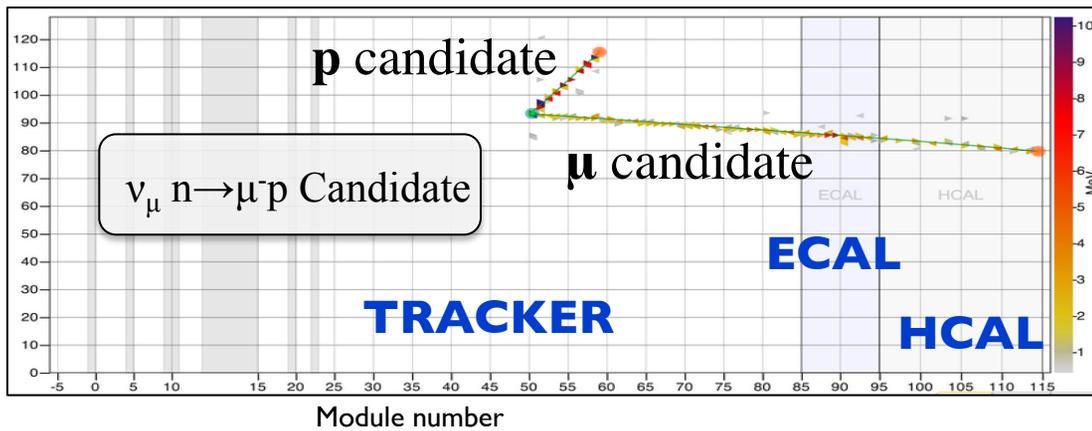
LHe cryotarget

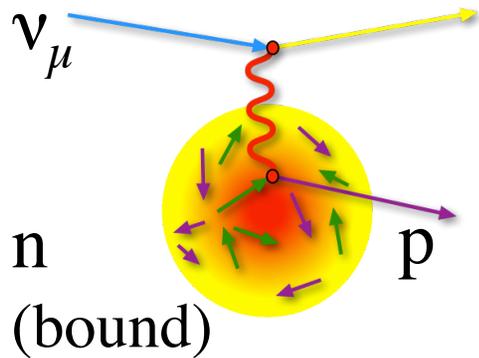


Events in MINERvA



One out of three views shown, color = energy





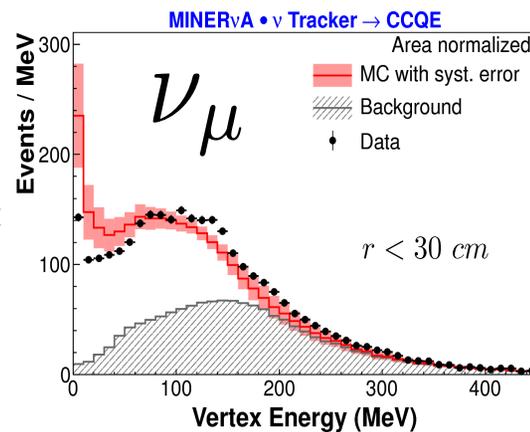
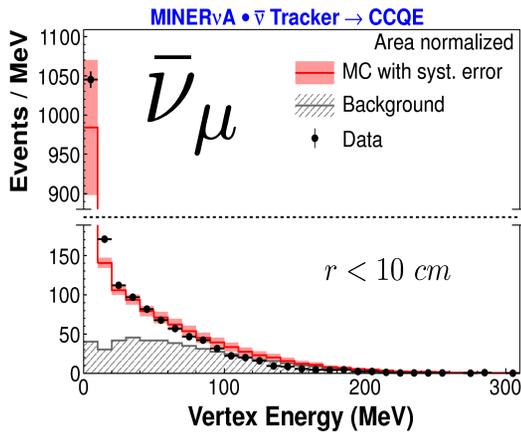
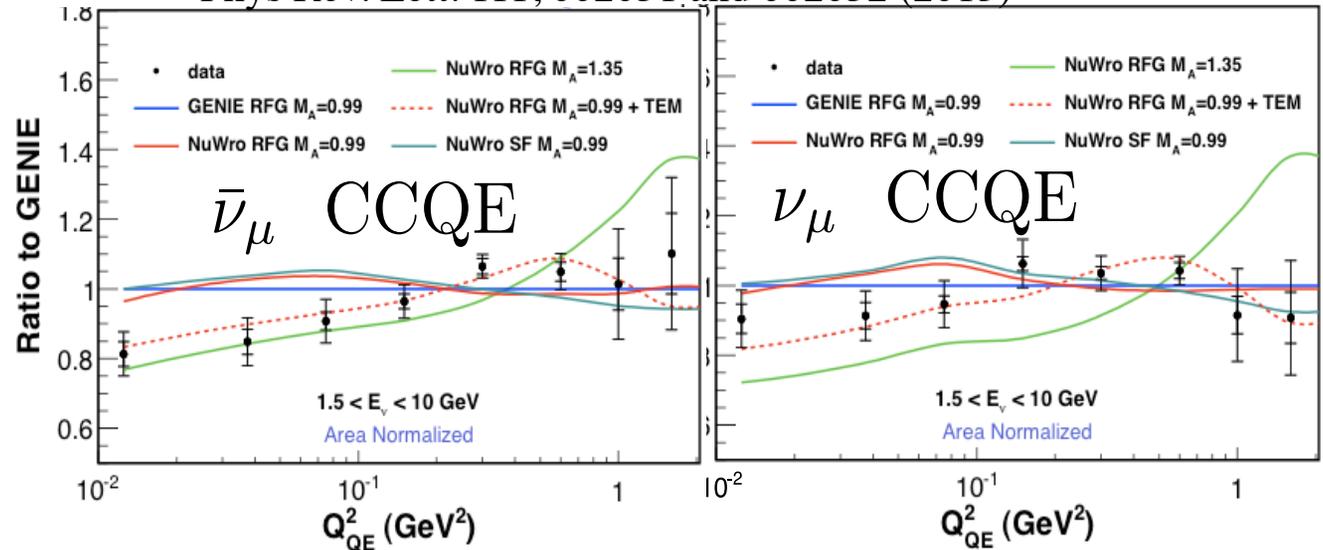
Neutrino & Anti-Neutrino Charged Current Quasielastic

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



What is effect of nucleus?

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

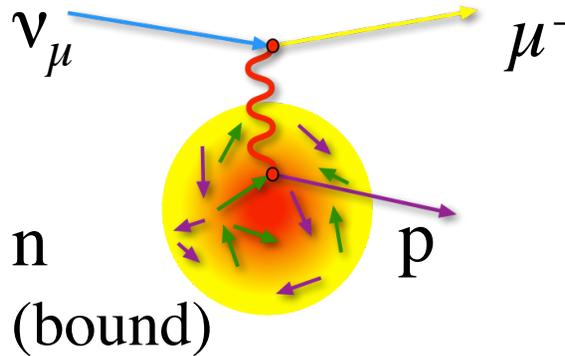


Look for energy near vertex consistent with extra nucleons
Data would prefer if $25 \pm 9\%$ of events ejected initial state np pairs (final state nn or pp)

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

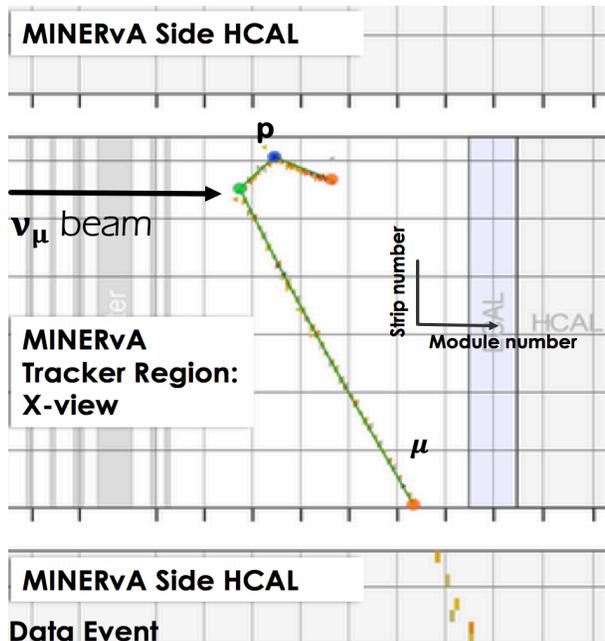
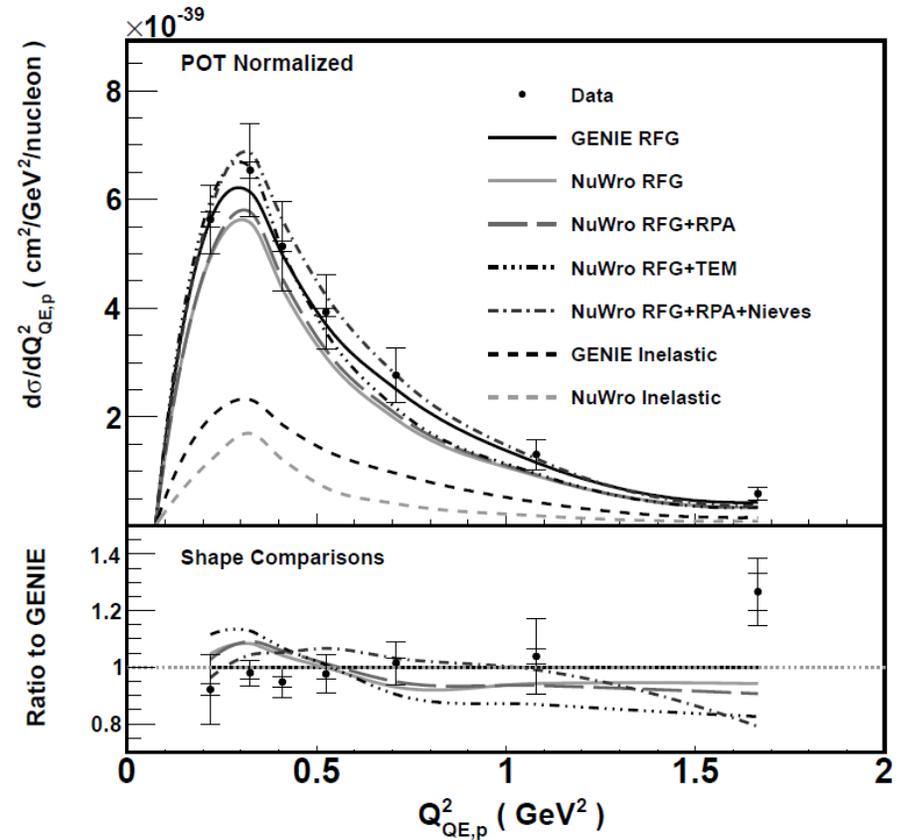


Quasielastic with Observed Proton Recoil



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

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

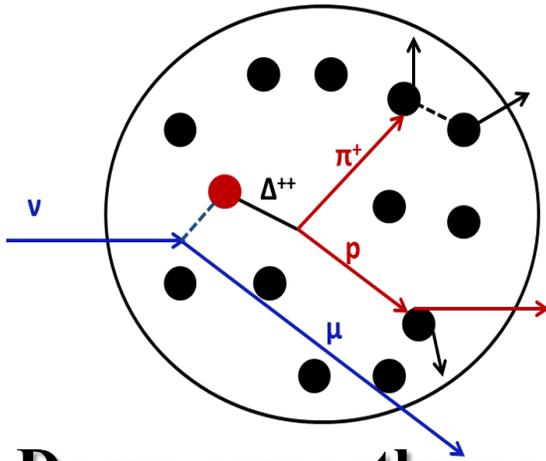


Best model for μ kinematics is not the same as the one that best describes the proton kinematics

hep-ex 1409.4497

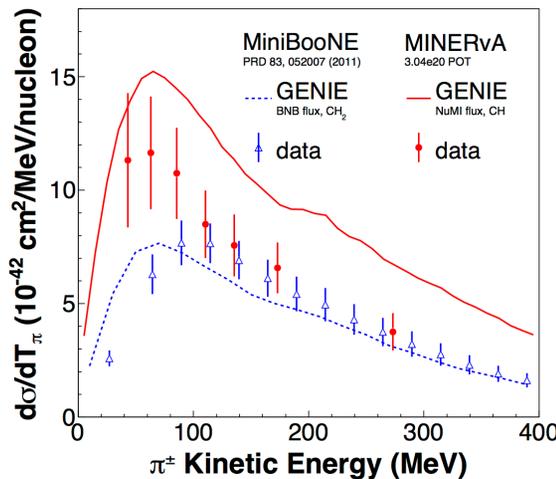
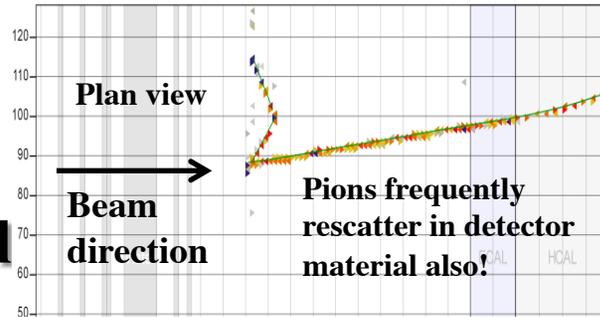


Charged Pion Production



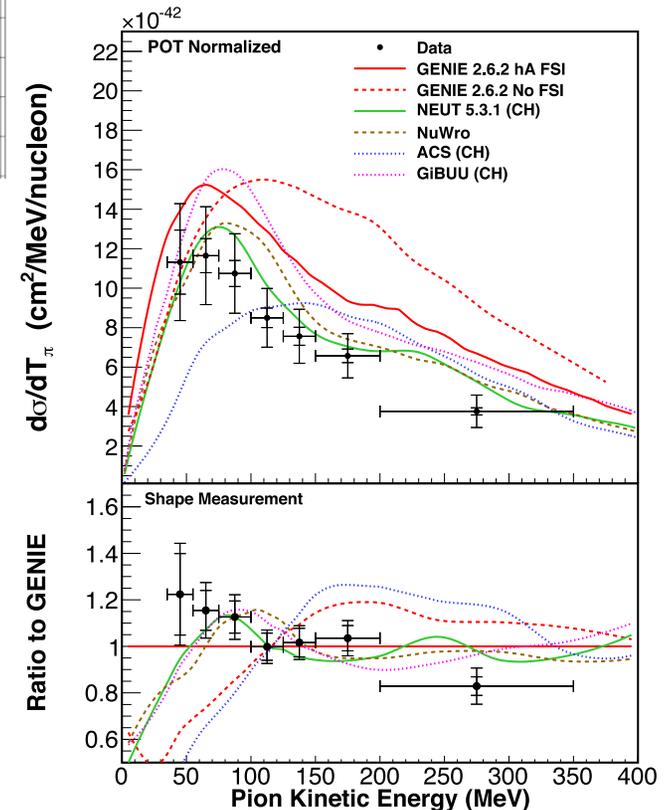
Do we correctly model nuclear rescattering, “final state interactions”?

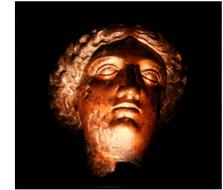
Our data on pion kinematics favors FSI models in generators (GENIE, NEUT, GiBUU)



MiniBooNE’s measurement of same reaction sees harder momenta, more events and suggest less FSI.

There is significant tension between the experiments.





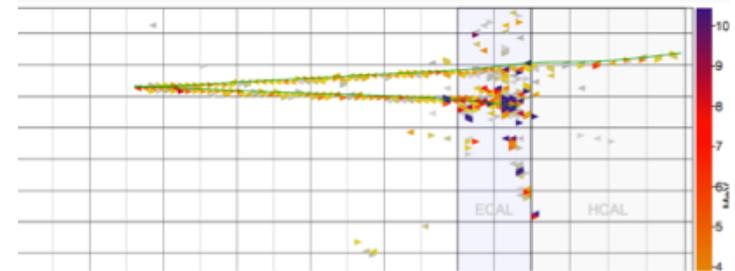
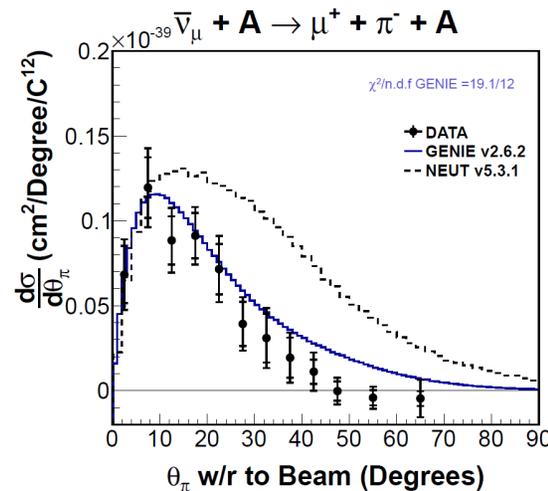
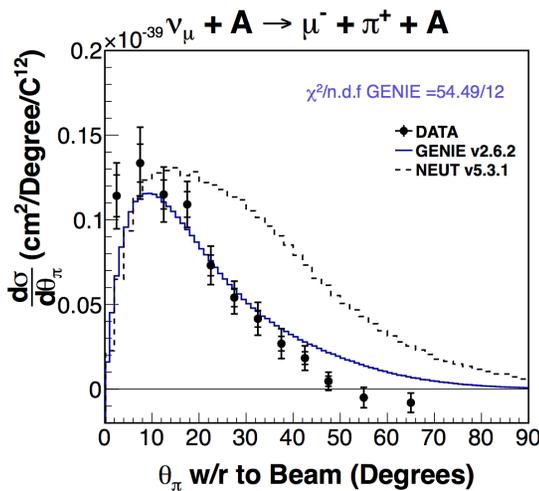
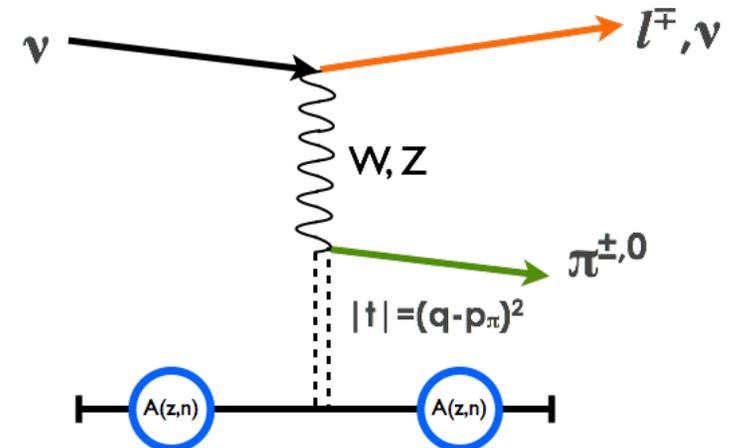
Coherent Pion Production

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



hep-ex 1409.3835

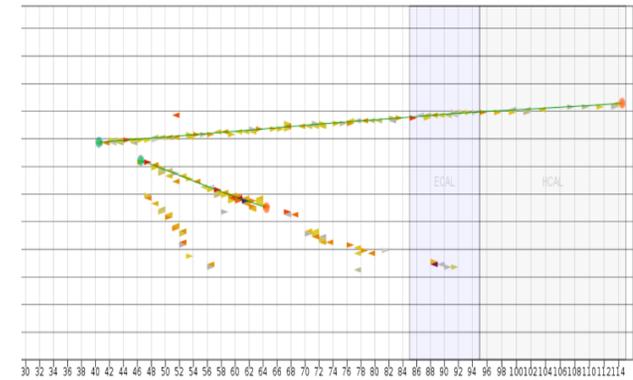
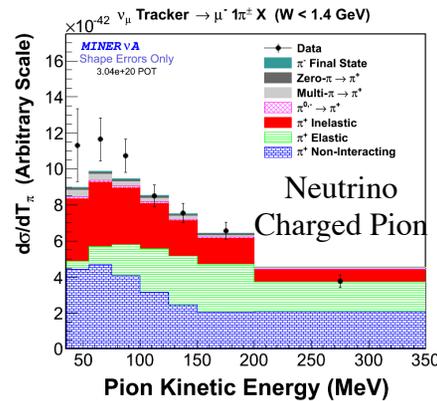
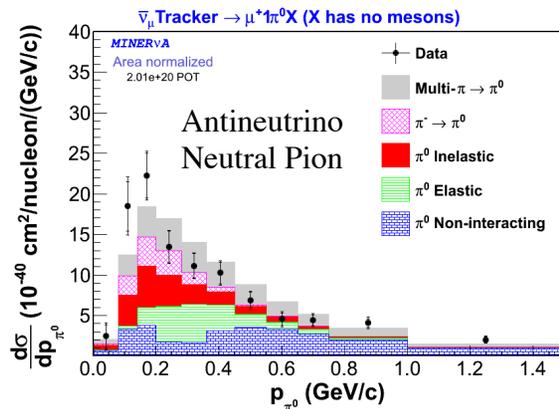
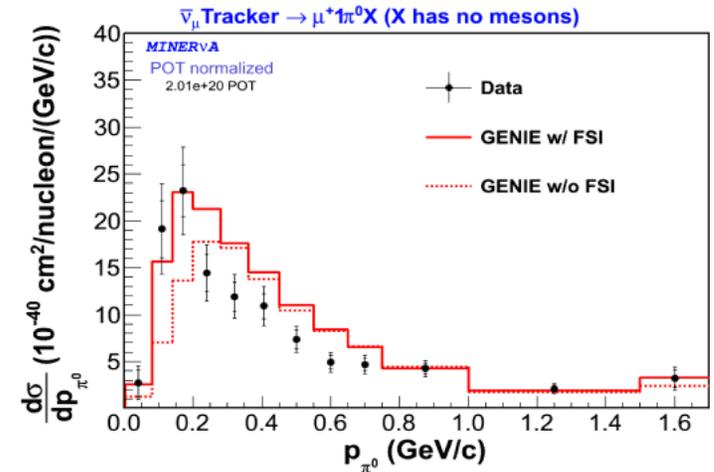
Current generators don't model process well at LBNF energies

Neutral Pion Production



Do we correctly model nuclear rescattering – complementary to charged pion production

Antineutrino cross section indicates good model agreement in kinematic regions where Final State Interactions (FSI) are minimal, but tension with models in FSI-dominated regions

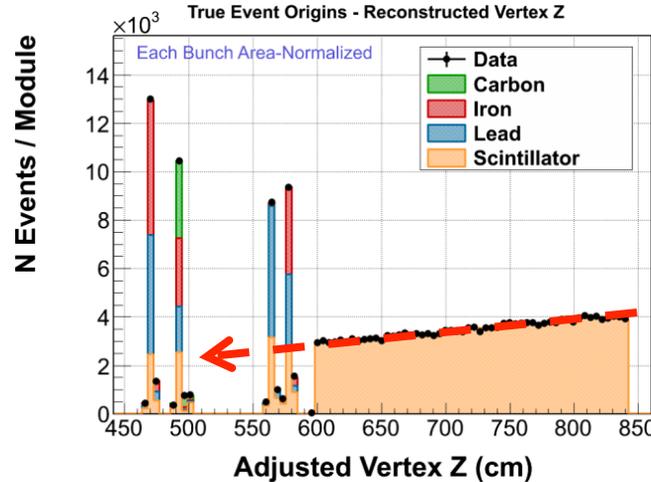
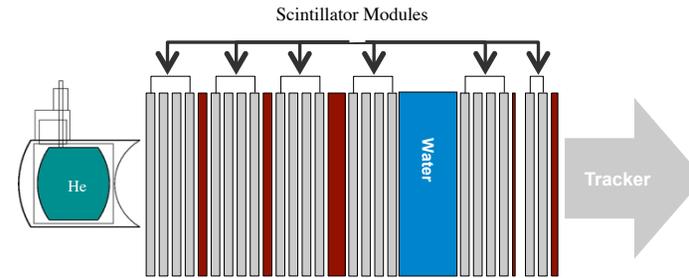
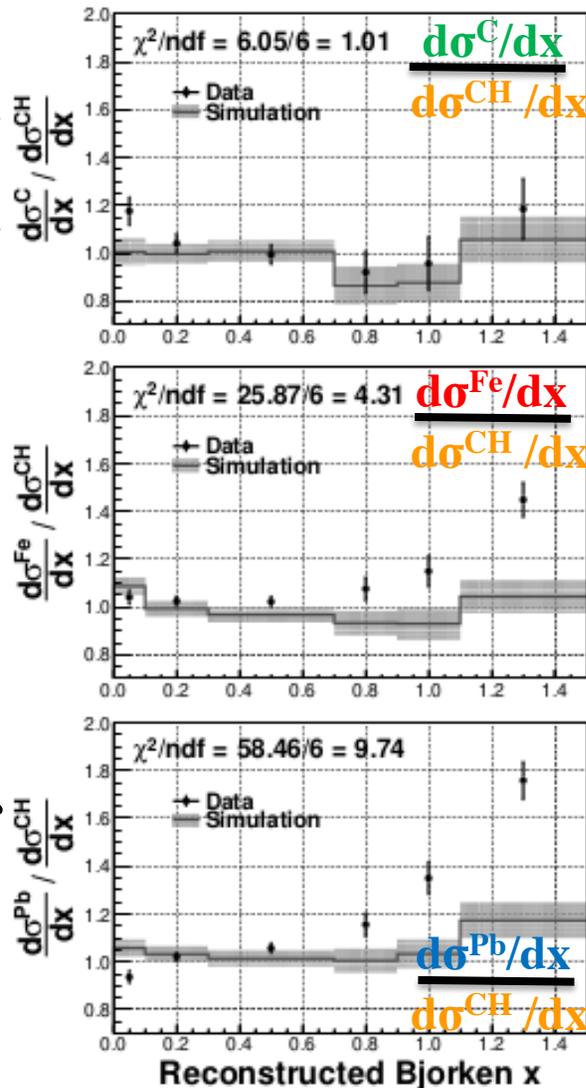


Trung Le FNAL W&C 9 Jan 2015

MINERvA's Pion measurements are powerful discriminators of FSI models 9

How are CC reactions modified by nucleus?

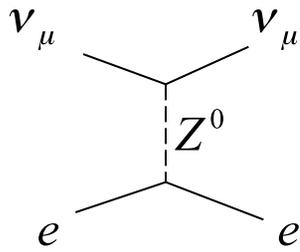
Ratios of Inclusive CC Reactions on Nuclei



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.*

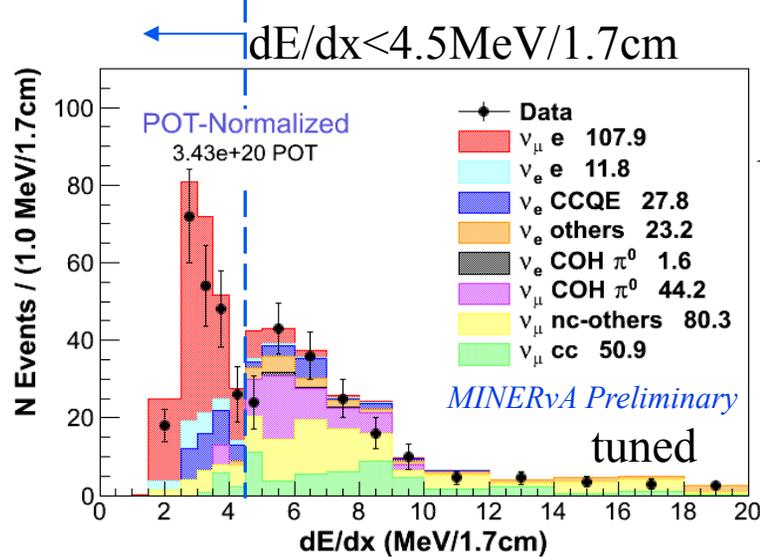
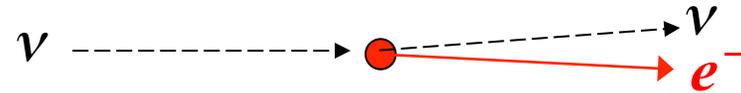


Neutrino-Electron Scattering

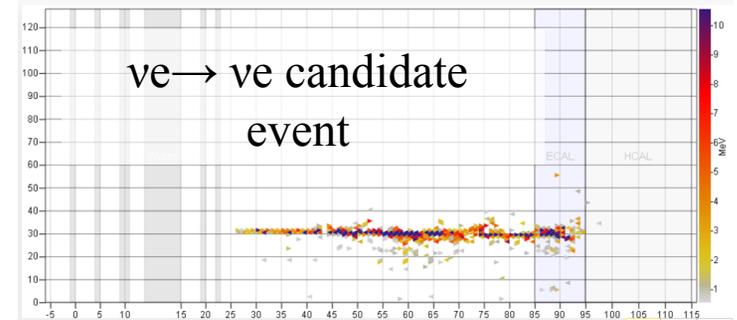


Can we isolate a sample of these well-predicted events to directly measure neutrino flux?

Very forward single electron final state

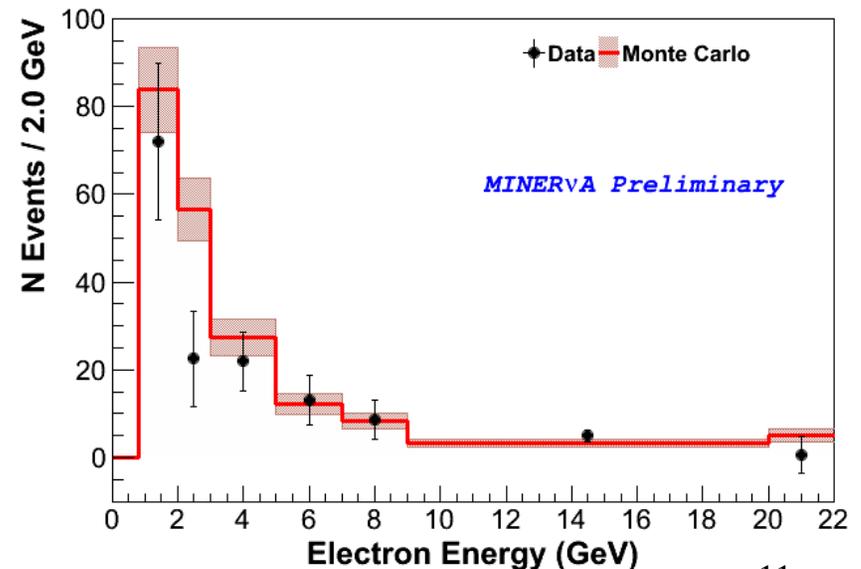


Use early ionization to reject photons and direction to reject interactions on nucleons



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
 - ▼ Electron Neutrino Cross Sections
 - ▼ Kaon Production
 - ▼ 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

