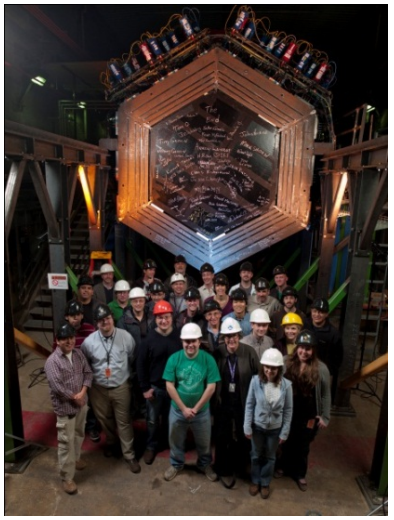
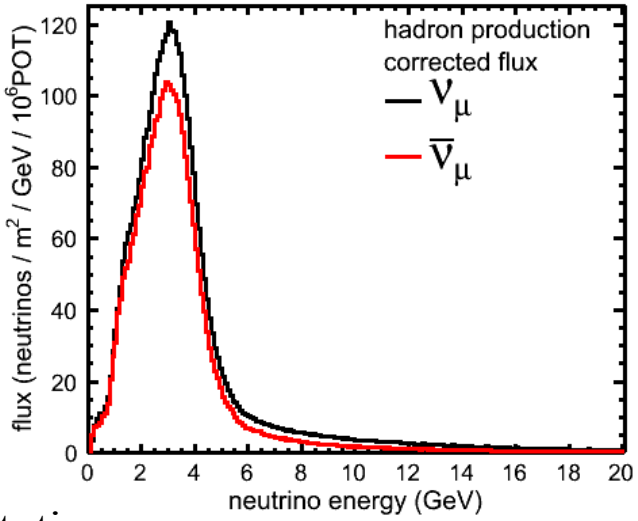
# MINERvA Overview

- 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



NuMI "Low Energy" Beam Flux

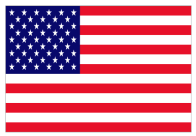



~65 Particle, nuclear and theoretical physicists from 20 institutions



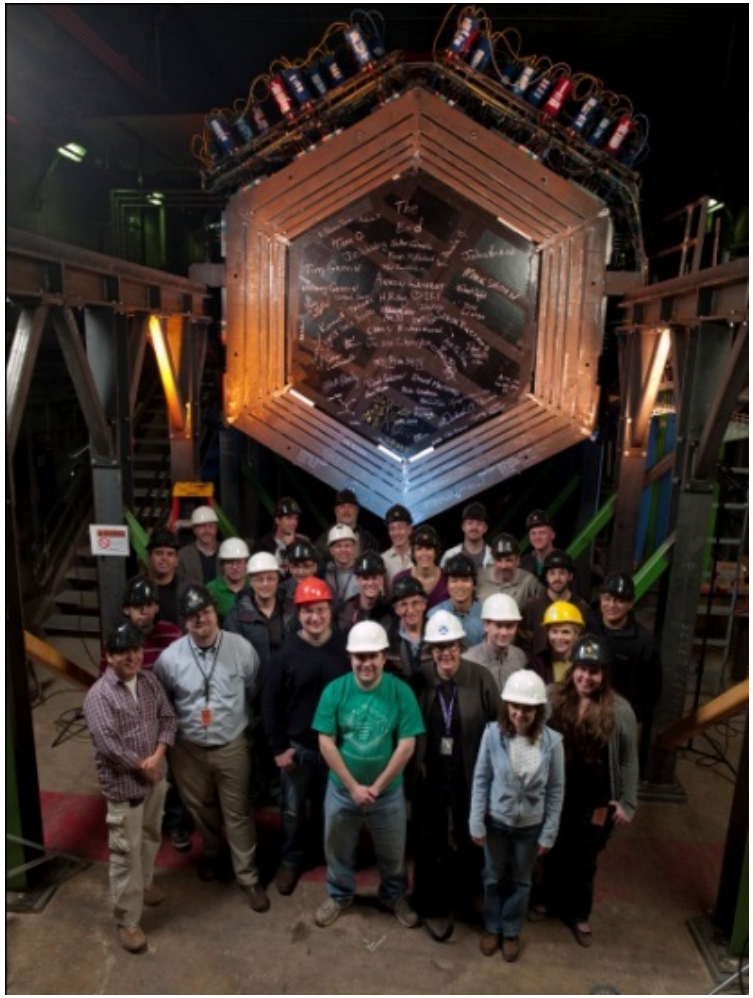






# MINERvA Collaboration

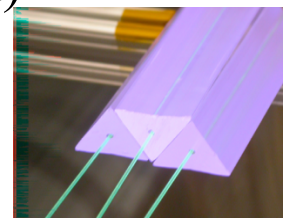
- University of California at Irvine
- Centro Brasileiro de Pesquisas Fisicas
- University of Chicago
- Fermilab
- University of Florida
- Universite de Geneve
- Universidad de Guanajuato
- Hampton University
- Inst. Nucl. Reas. Moscow
- Massachusetts College of Liberal Arts
- University of Minnesota 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

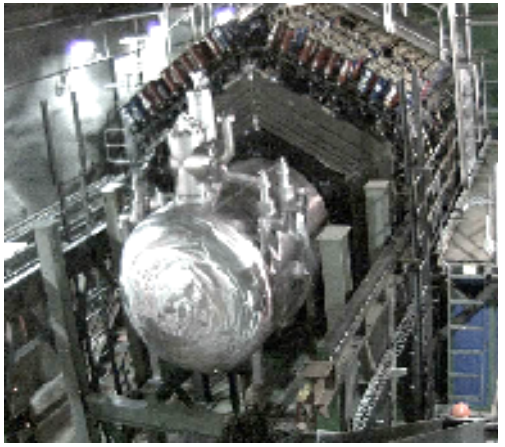


~65 particle, nuclear and theoretical physicists from 21 institutions

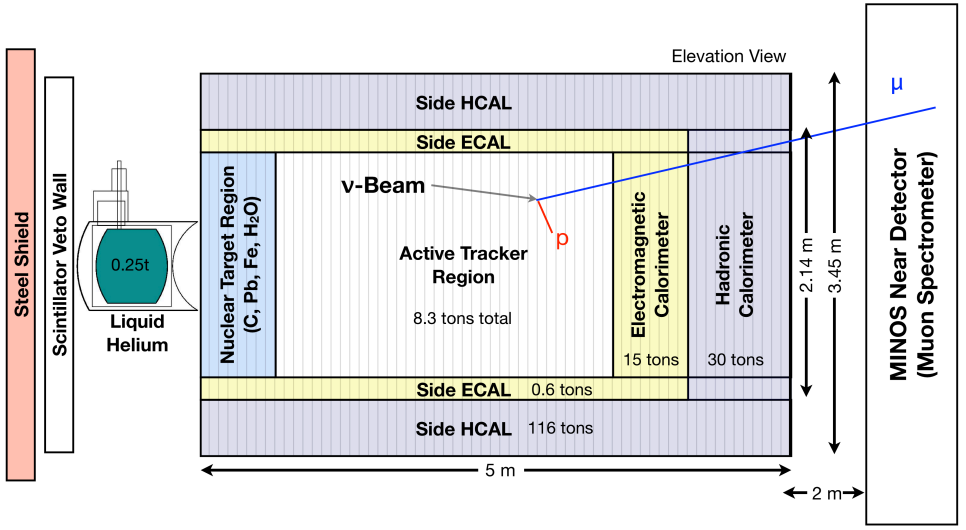
# MINERvA Detector

- 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



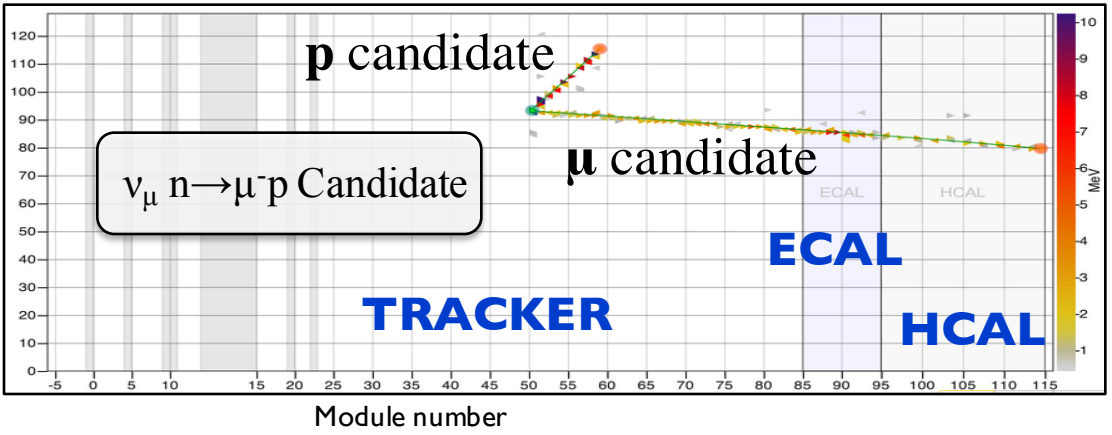


LHe cryotarget

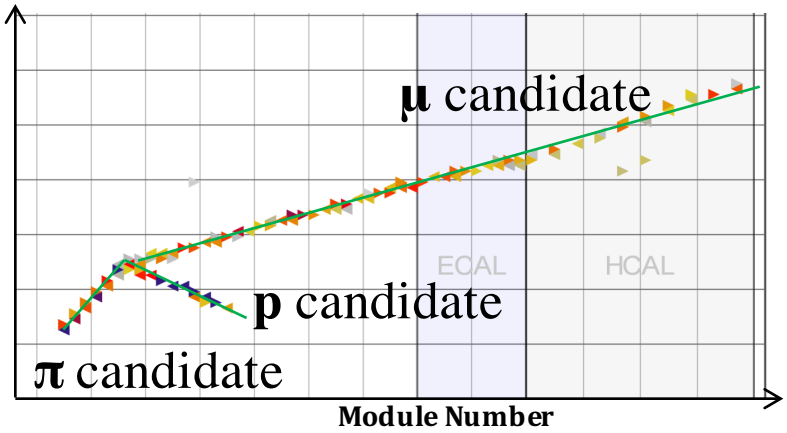


# Events in MINERvA

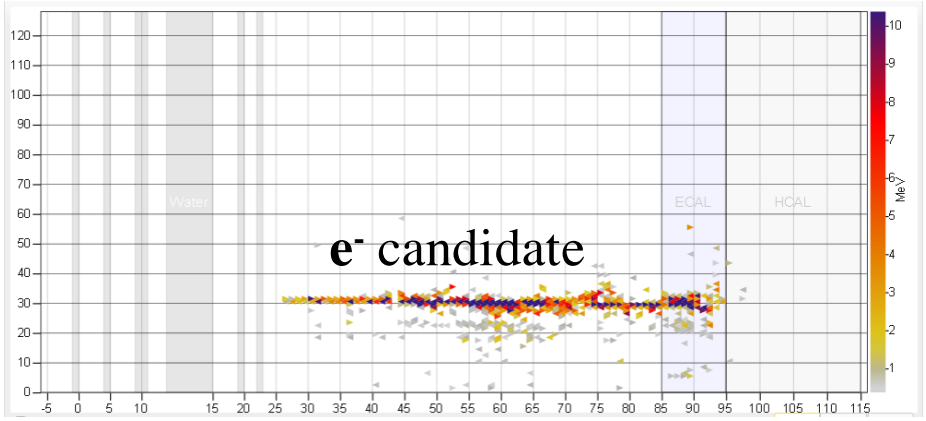
One out of three views shown, color = energy

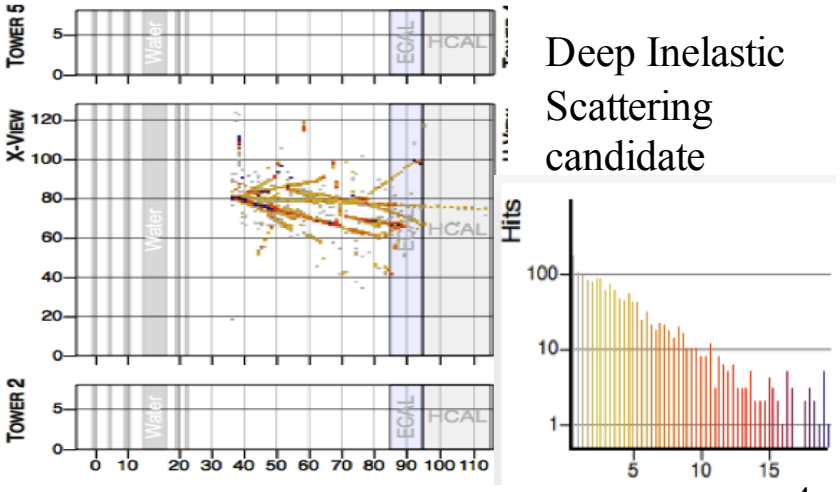



νμ p→μ⁻Δ⁺⁺, Δ⁺⁺→pπ⁺ Candidate

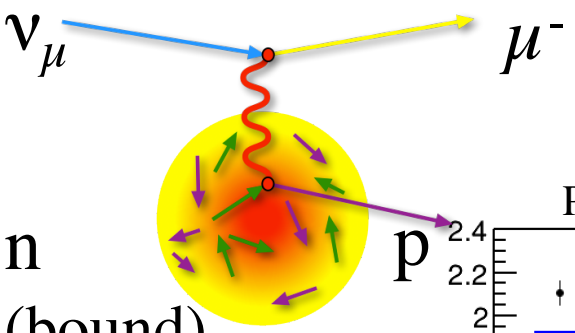



νμ e⁻→ νμ e⁻ Candidate




Deep Inelastic Scattering candidate

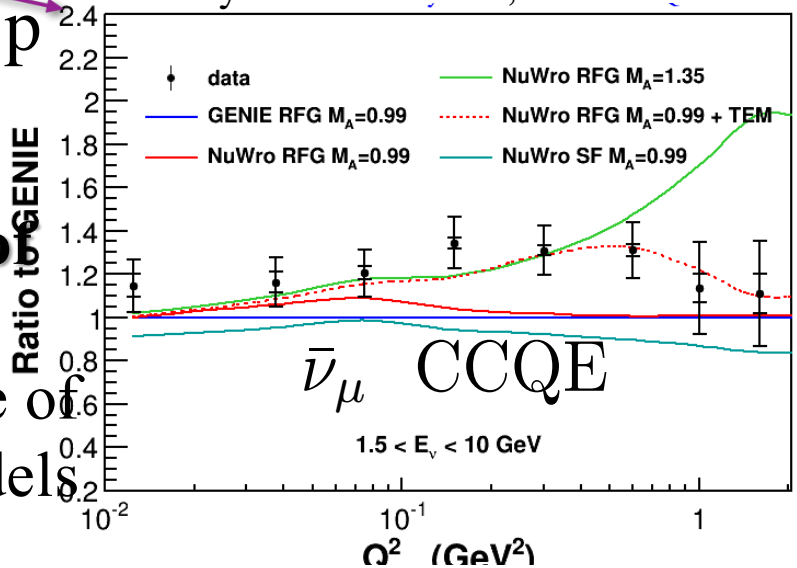


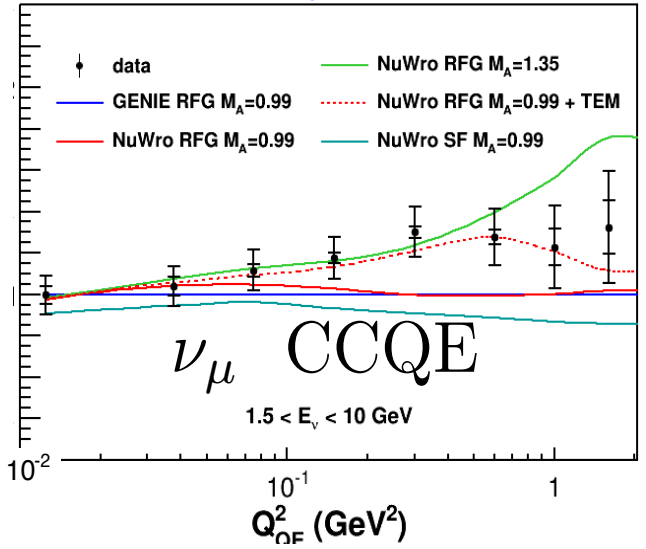

# $\nu_\mu$ and $\bar{\nu}_\mu$ Charged Current Quasielastic

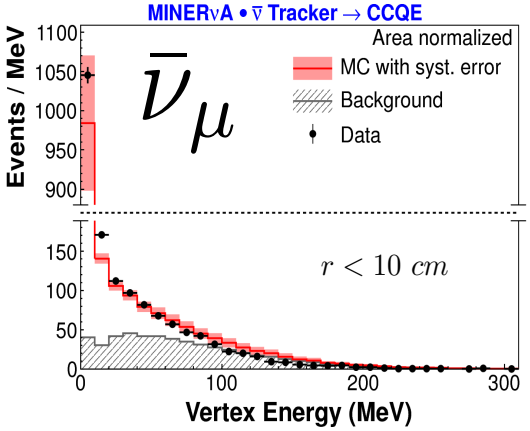
Phys Rev. Lett. 111, 002051 and 002052 (2013), updated to 2015 flux

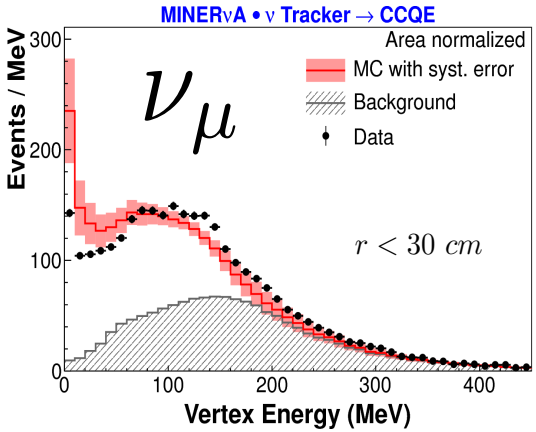
**What is effect of nucleus?**

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



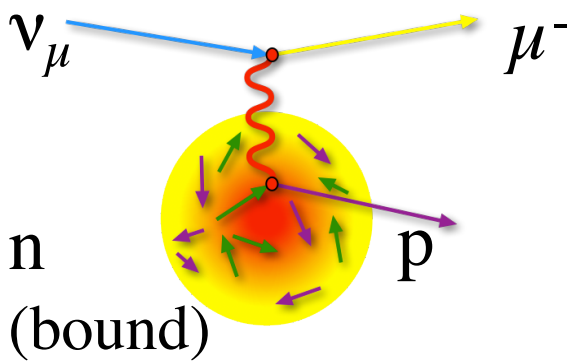




Look for energy near vertex consistent with extra nucleons

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

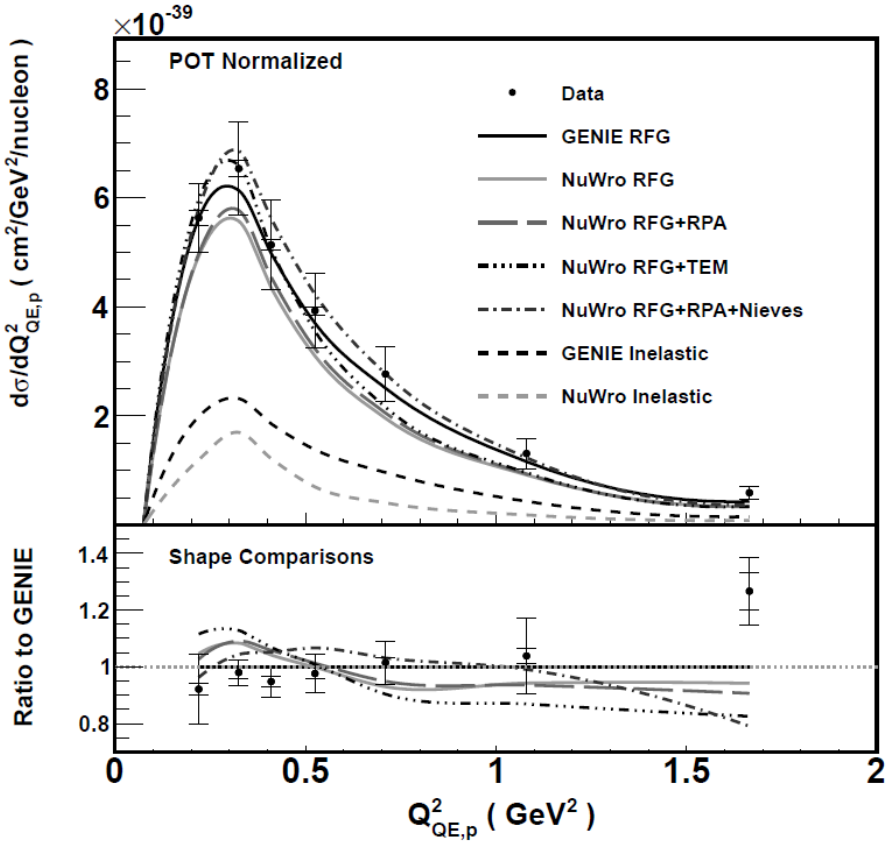
Cross-section vs $Q^2$ and vertex energy both consistent with multi-nucleon hypothesis

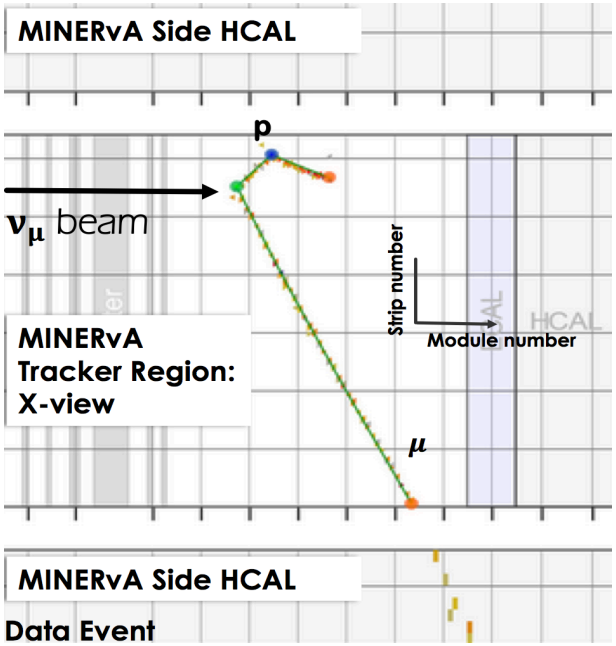



# $\nu_\mu$ Quasielastic with Observed Proton Recoil

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

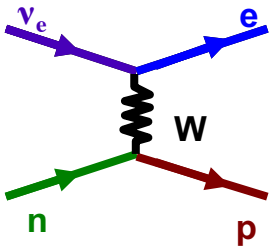
Momentum transfer ($Q^2$) can also be measured from proton energy




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

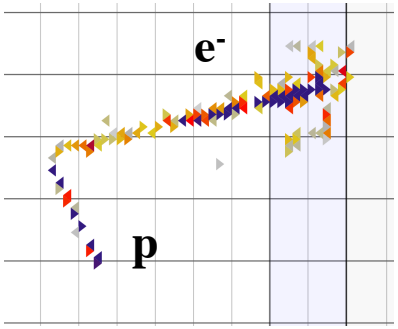
Phys. Rev. D 91, 071301 (2015)

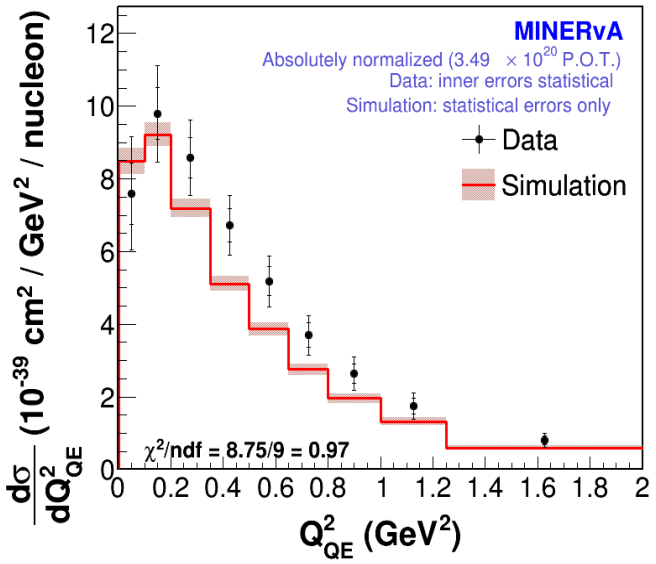



# Electron neutrino CCQE

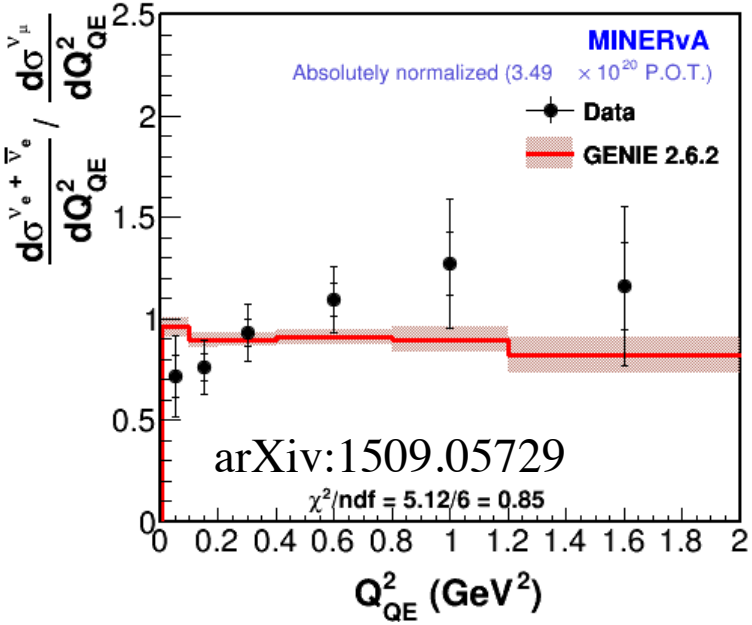
$\nu_e$ CCQE is oscillation signal, but almost no cross section data.

Can we trust $\nu_\mu \rightarrow \nu_e$ cross section universality in complex nuclei?



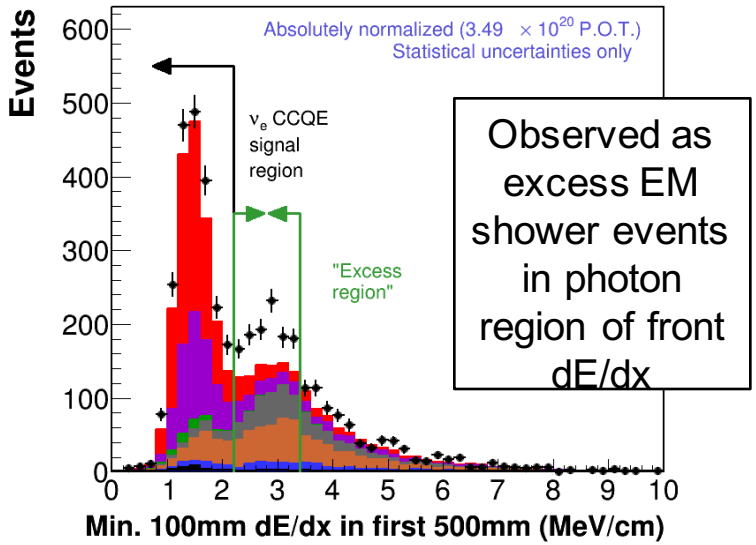




Measured cross sections consistent with GENIE model (assumes charged lepton mass only difference between XS) at 1σ (~15-20% uncertainties)

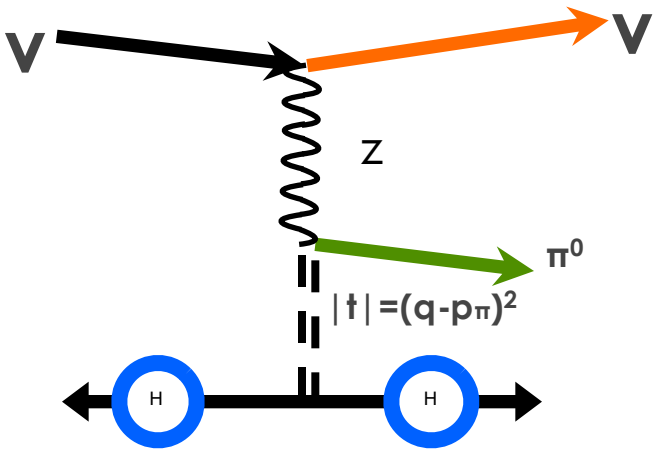



$\nu_e/\nu_\mu$ difference not significant (~1σ). Good enough for current expts. but shape may need further investigation for future high-precision oscillation results

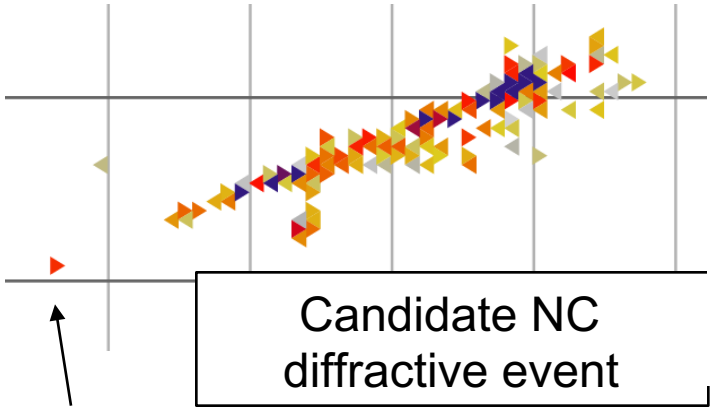
# NC diffractive scattering from H




Observed as excess EM shower events in photon region of front dE/dx

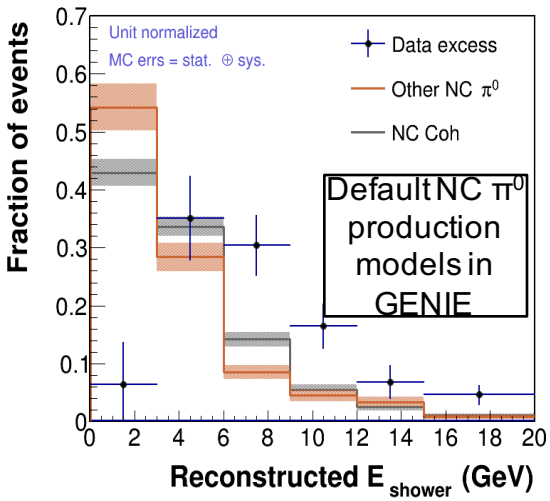


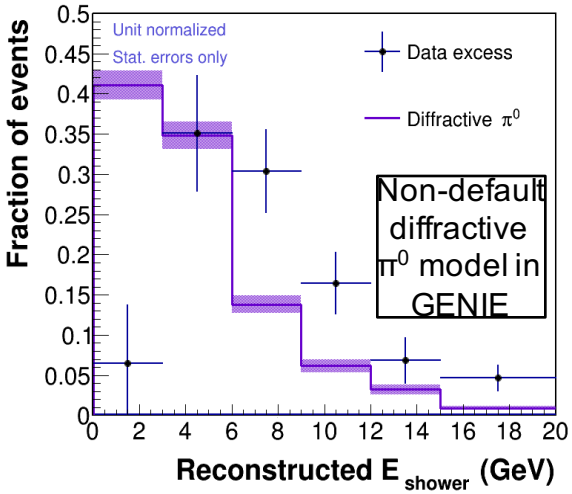

Analogous to NC coherent production. Potential background for $\nu_e$ appearance. Not in default generator models.



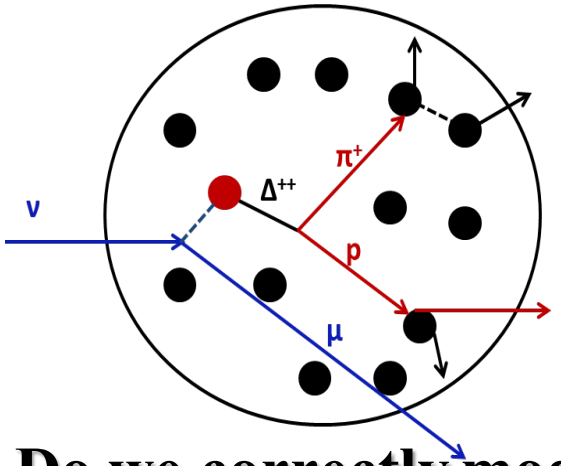
Candidate NC diffractive event

Probable recoil from proton

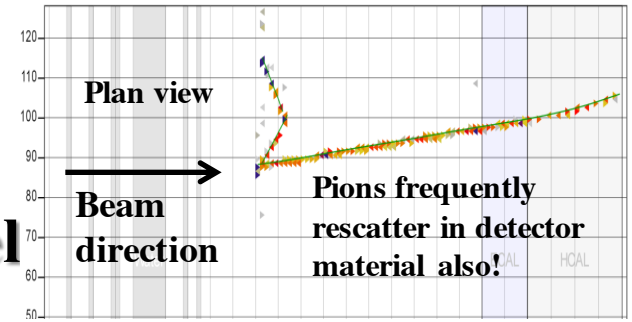



**Observed energy behavior is very different from any other NC $\pi^0$ production models**

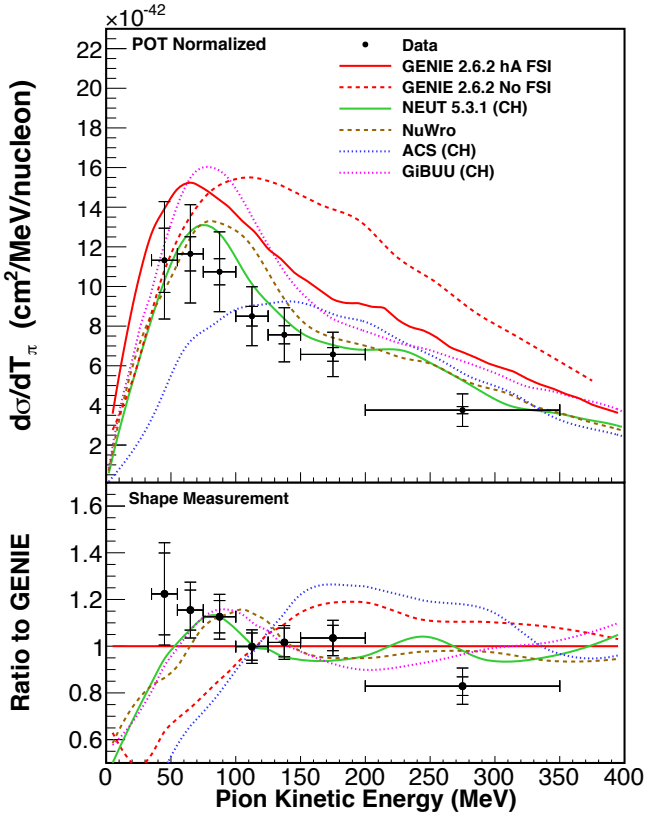


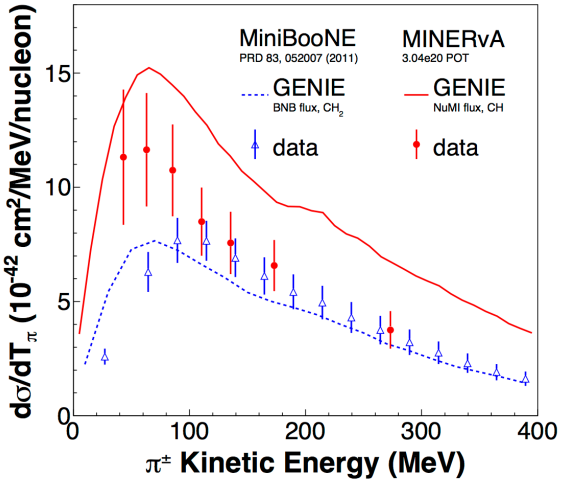

# Charged Pion Production




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

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



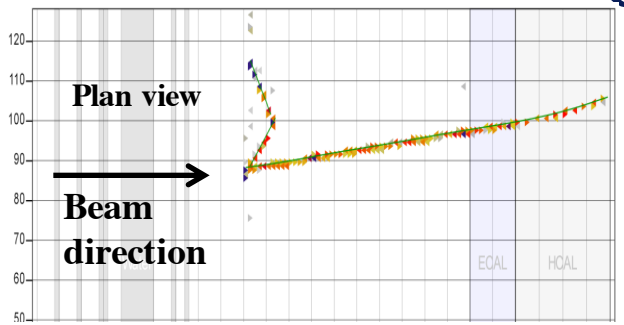




MiniBooNE's measurement of same reaction sees harder momenta, more events and suggest less FSI.

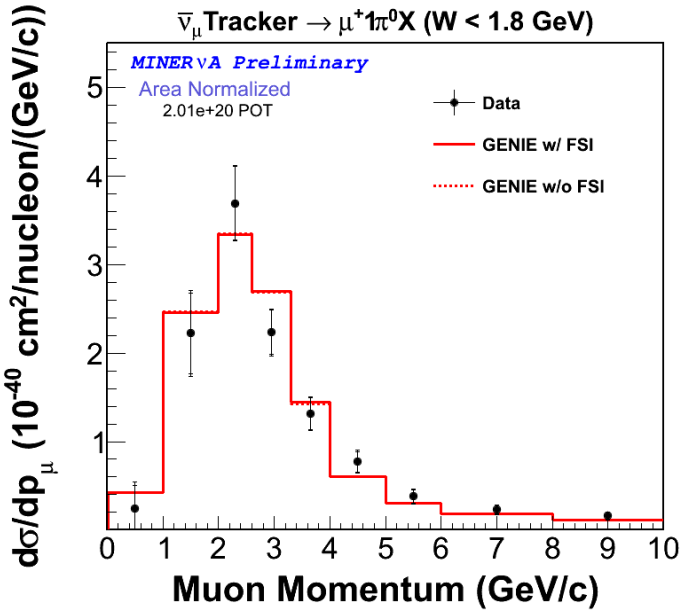
*There is significant tension between the experiments.*

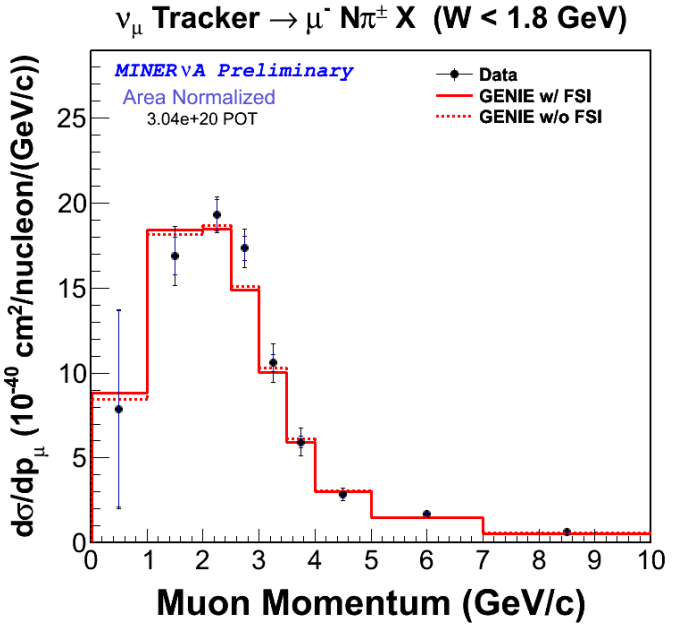
hep-ex 1406.6415

# Charged Pion Production Muon Variables




Shape of cross section versus **muon kinematics** is independent of FSI model. GENIE agrees well with MINERvA's data here, indicating that the disagreement in pion variables is likely due to problems with FSI models




hep-ex 1406.6415

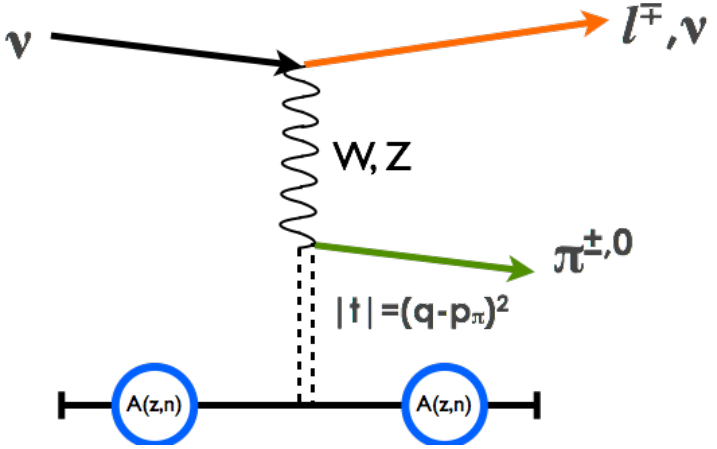
# Coherent Pion Production

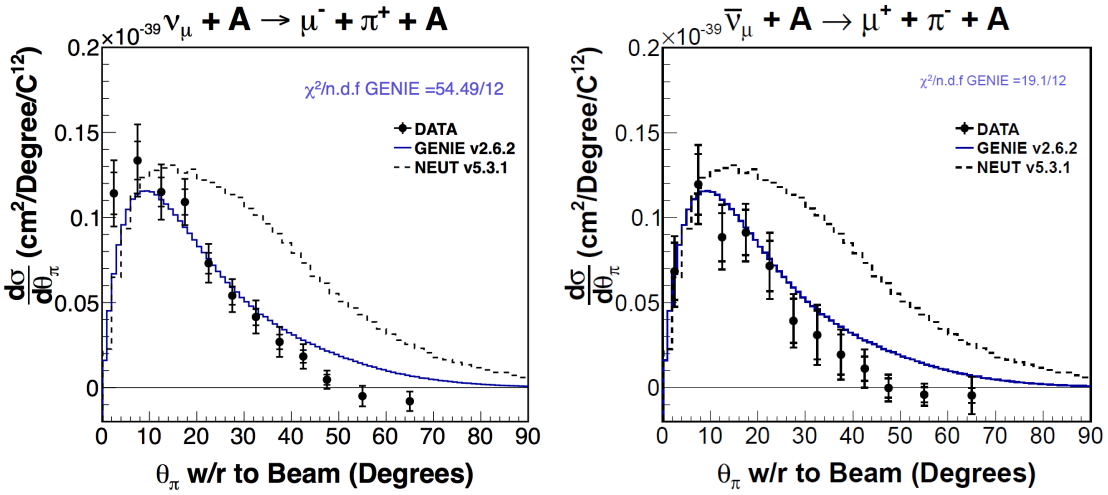
**Can we resolve experimental puzzles on rate for this process?**

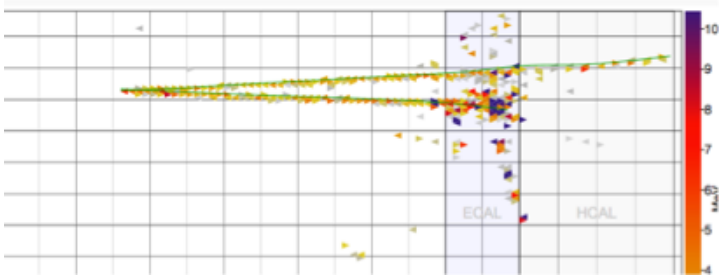
Low multiplicity process is a troublesome background for oscillation experiments and previous low energy data is confusing

Model independent selection and high statistics allows test of pion kinematics

1628 (770) coherent neutrino (antineutrino) events

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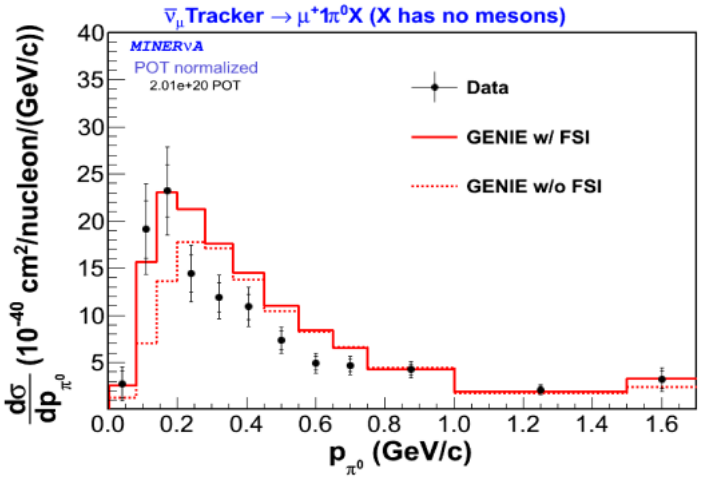
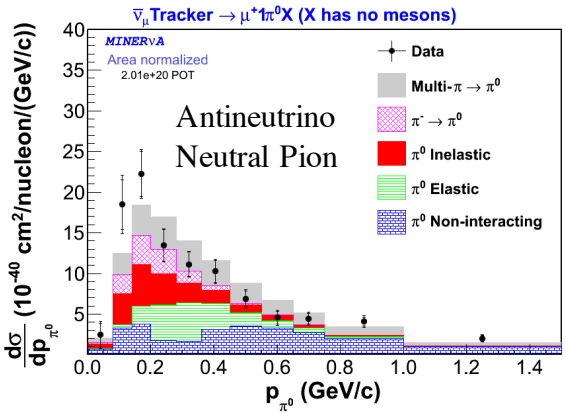
*Current generators don't model process well at LBNF energies*

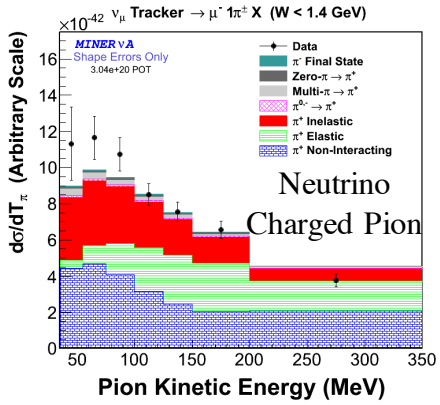
# Neutral Pion Production

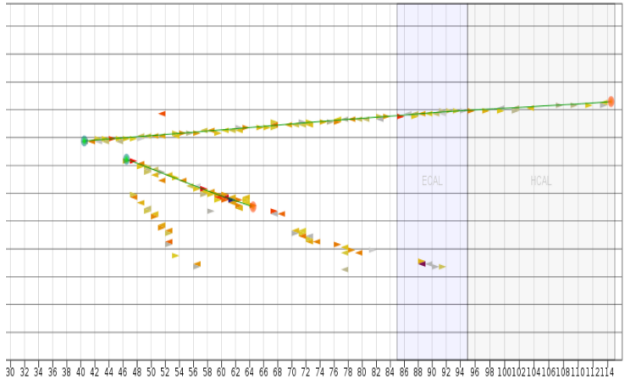
**Do we correctly model nuclear rescattering – complementary to charged pion production**

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

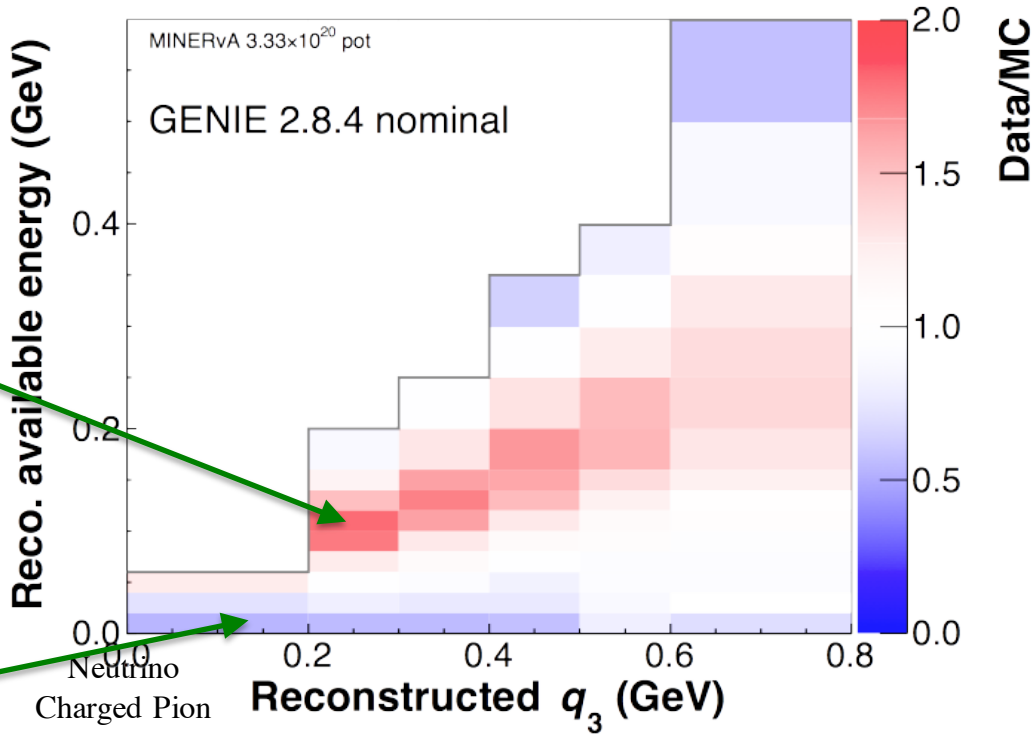
*MINERvA's Pion measurements are powerful discriminators of FSI models*

# $\nu_\mu$ CC Inclusive Double Differential

- Measure a cross section in two variables that show how the neutrino's energy is split between the outgoing muon and outgoing hadrons.
- Oscillation experiments depend on modeling this split correctly!

Data higher than model in region where neutrino scatters off two nucleons

Data lower than model in region where neutrino sees combined effect of the nucleus as a whole

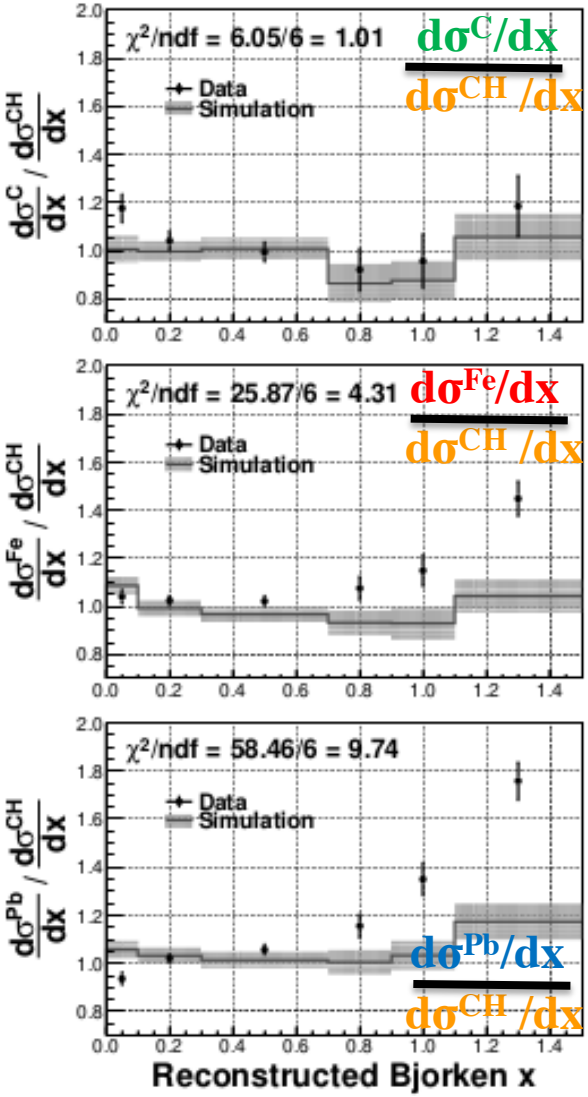


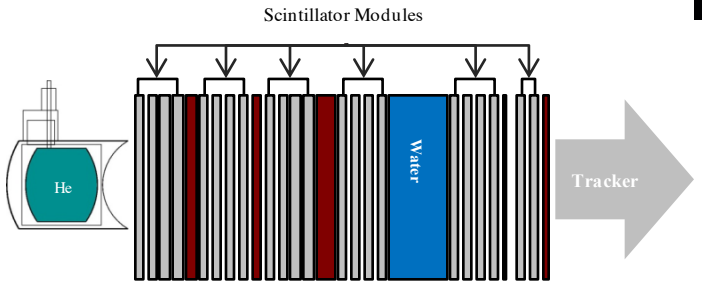

*Strong evidence for two nuclear effects not in our standard prediction*

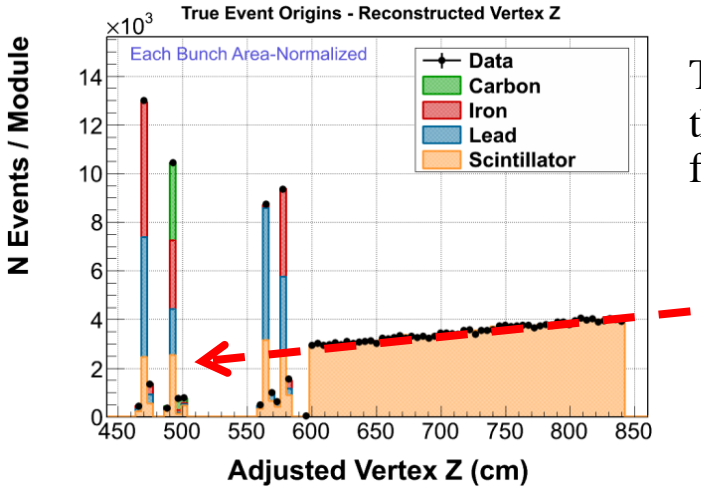
# Ratios of Inclusive CC Reactions on Nuclei

**How are CC reactions modified by nucleus?**

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




Targets are passive and there is contamination from nearby scintillator.

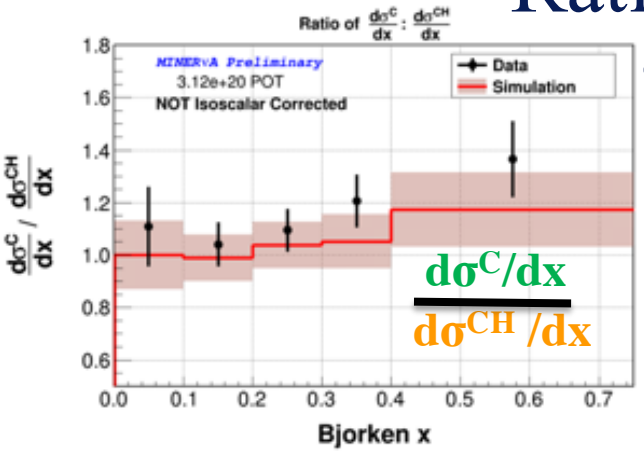
*Use events in the tracker modules to estimate and subtract contamination from scintillator events.*

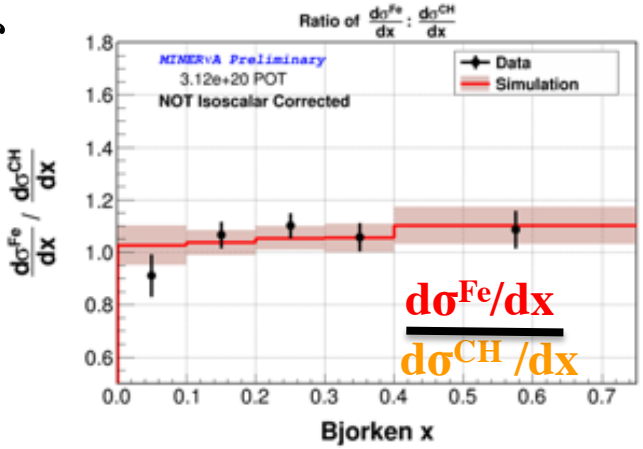
1. *At low x*, we observe a *deficit* that increases with the size of the nucleus.
2. *At high x*, we observe an *excess* that increases with the size of the nucleus.

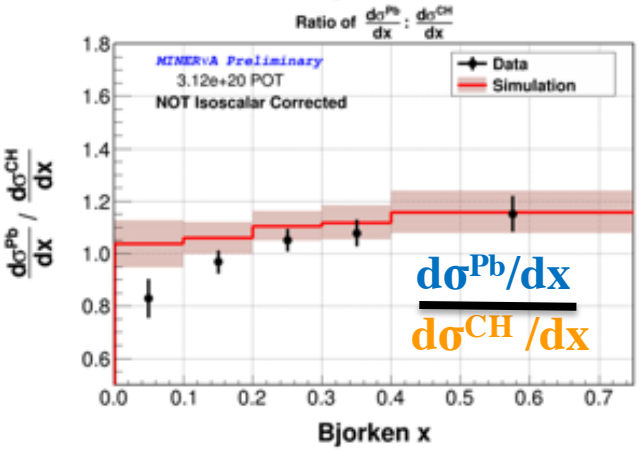
*These effects are not reproduced by current neutrino interaction models.*

# Ratios of CC Deep Inelastic Scattering on Nuclei

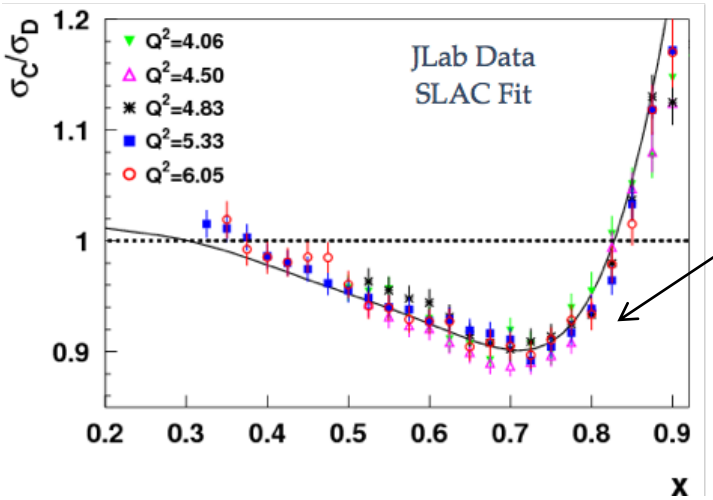
J. Mousseau. JTEP 8 May 2015



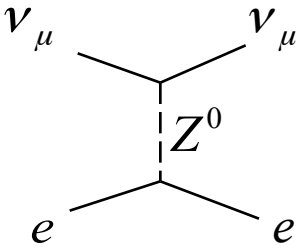

Seely, J. et al. Phys.Rev.Lett. 103 (2009) 202301 arXiv:0904.4448




EMC Effect: dip in heavy/light nucleus cross section ratio at moderate x

MINERvA is the first experiment to look for the "EMC Effect" in neutrino scattering

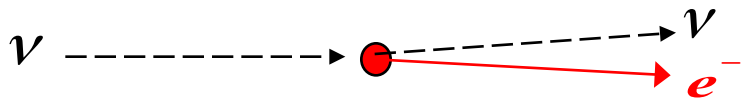
*No evidence of discrepancy with model (which does not include EMC effect). Currently statistically limited. Much higher stats analysis underway*

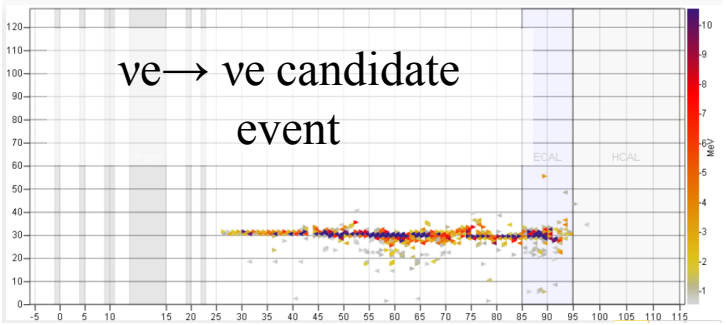


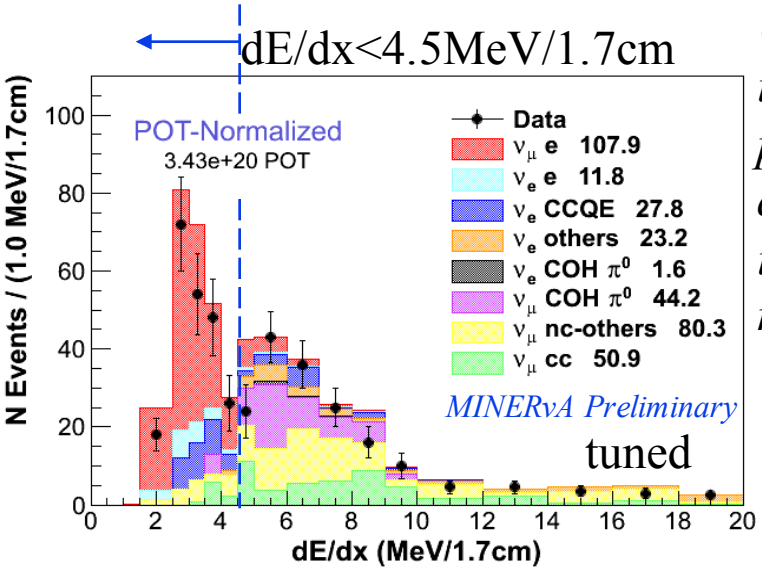

# Neutrino-Electron Scattering

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

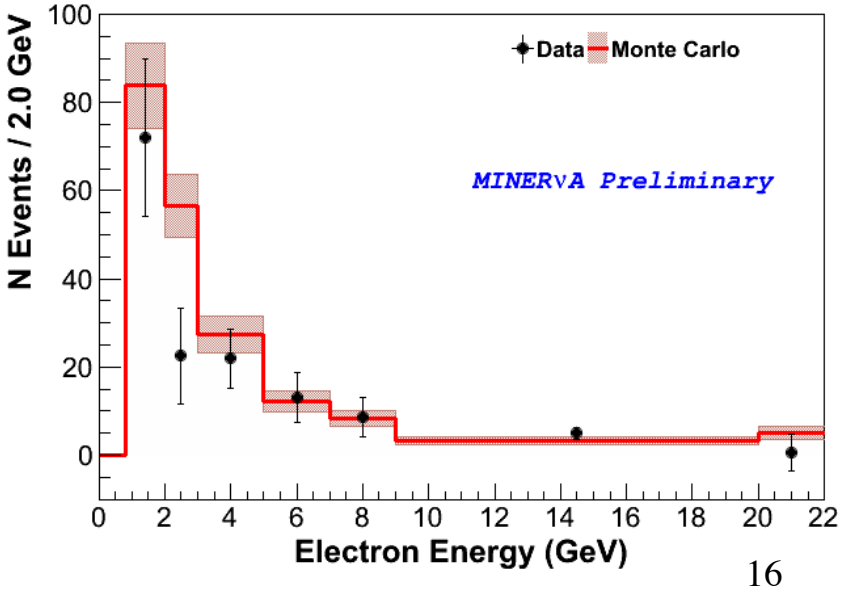
Very forward single electron final state




*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
  - 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