# MINERvA

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FNAL PAC

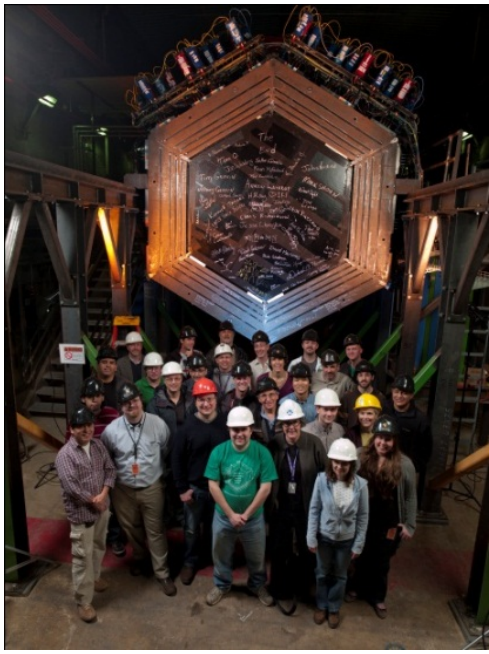
21 June 2016

# Topics for today's presentation

- Quick reminder of MINERvA's physics output and its impact so far
- Highlights of new work you can expect to see in near term and in next several years
- Our progress towards understanding the role of the medium energy (NOvA beam) data on our physics output
- The collaboration, the detector and operations program to complete our physics program with a high statistics antineutrino run

# MINERvA in One Slide

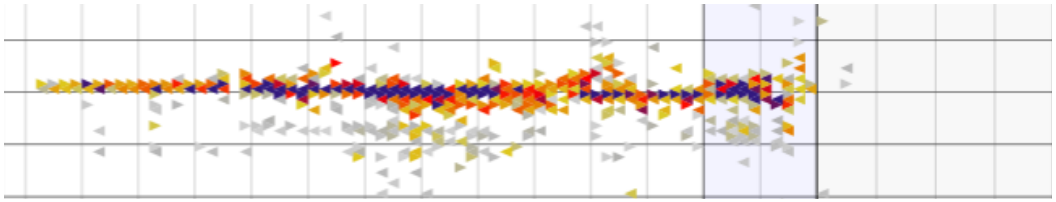
- MINERvA is studying neutrino interactions in unprecedented detail on nuclei – He, C, $CH_2$, $H_2O$,Fe,Pb
  - Unique information about nuclear effects
  - Measured in exclusive final states
    - As function of a measured neutrino energy
    - Study differences between $\nu$ and anti-$\nu$
- Low Energy (LE) Beam Goals:
  - Exclusive signal and background reactions relevant to oscillation experiments
- Medium Energy (ME) Beam Goals:
  - Structure Functions on nuclei (e.g., EMC effect, shadowing)
  - Exclusive reactions with expanded kinematics
  - First high statistics on nuclear targets, anti-neutrinos
- Collaborations with generator, flux and oscillation communities



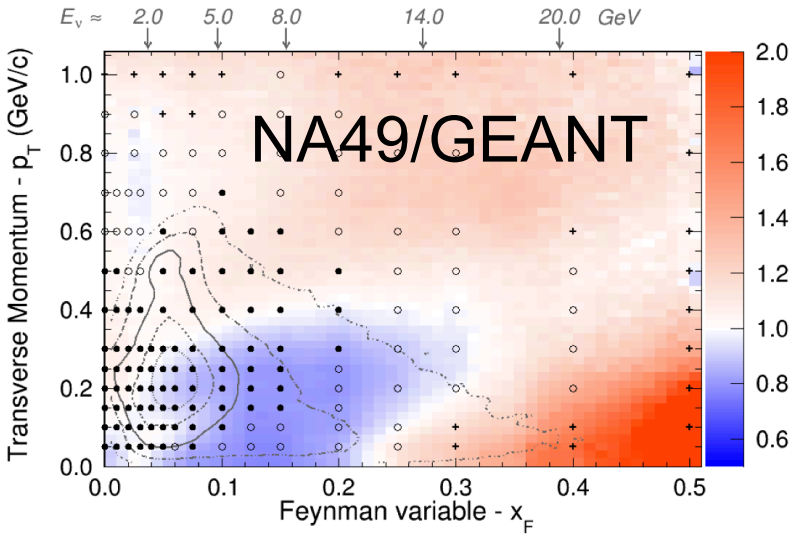
# Output is not limited to cross-sections

- We prototype ideas slated for DUNE

$\nu_\mu e^- \rightarrow \nu_\mu e^-$ candidate to constrain flux



- We code and tune models for GENIE (2p2h, kaons,…)
- We constrain flux for current and future experiments (NOvA, DUNE)




- Our collaborators work with current oscillation experiments (NOvA, T2K) to help them evaluate and reduce systematics

# CNN-style real time fact check

- We solicited letters from NOvA and T2K spokespersons.
- If we are doing what we say on this last point, then those letters to Nigel should reinforce what we say. (Full letters are available to PAC.)

Crucial to these investigations [of systematics] were, of course, our own high statistics near detector data, but we also relied on external measurements of quasi-elastic scattering, resonant production, and deep inelastic scattering by the MINERvA collaboration. Having those data available, and an engaged community of physicists who understood those data, enabled us to converge on a solution to the hadronic energy differences much faster that we would have otherwise….
At the Neutrino conference in July we expect to show updated results where the uncertainties in hadronic energy, neutrino energy, and electron neutrino selection efficiency uncertainties have been reduced to 5% (from 14%), 5% (from 7%), and ~2% (from 14%) …

M. Messier and P. Shanahan

T2K has its own near detectors, both on and off-axis. Even with these, the external cross-section data [from Fermilab] play a critical role in selecting neutrino scattering models for the oscillation analysis and in tuning/restricting parameters within those models. The fact that these measurements are made in neutrinos and antineutrinos, at energies and on nuclei beyond those used by T2K in its oscillation analysis sample, is actually a strength of the datasets, in that it helps to test models in ways that T2K cannot do by itself… Accordingly, T2K expects to benefit from more antineutrino results from MINERvA…
There is active feedback between MINERvA and T2K that has resulted in new analyses being completed on MINERvA which then are applied to the T2K oscillation analysis. The coherent pion and low recoil ("2p2h") analysis are good examples of this. The information provided by MINERvA has been important in not only formulating the systematic uncertainties for the oscillation results, but has also actively helped T2K reduce them to levels below what was foreseen in the original proposal.

T. Nakaya and M. Wascko

# Publications since Summer 2015 PAC update

- "Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering" , Phys. Rev. D 93, 112007 (2016)
- "Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA", Phys. Rev. D 93, 071101 (2016).
- "Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer", Phys. Rev. Lett. 116, 071802 (2016).
- "Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average $E_\nu$ of 3.6 GeV", Phys. Rev. Lett 116, 081802 (2016).
- "Single neutral pion production by charged-current anti-$\nu_\mu$ interactions on hydrocarbon at average $E_\nu$ of 3.6 GeV", Phys.Lett. B749 130-136 (2015).
- "Measurement of muon plus proton final states in $\nu_\mu$ Interactions on Hydrocarbon at average $E_\nu$ of 4.2 GeV" Phys. Rev. D91, 071301 (2015).
- "MINERvA neutrino detector response measured with test beam data", Nucl. Inst. Meth. A789, pp 28-42 (2015).

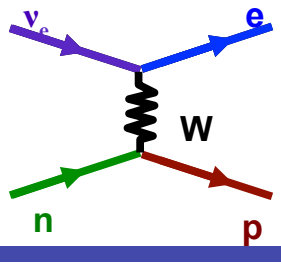
# ν Cross section Papers

(excluding proceedings)

| Published σ papers | PRL | PRD | PLB | Total |
|---|---|---|---|---|
| MINERvA | 6 | 4 | 1 | 11 |
| MiniBooNE | 2 | 8 | | 10 |
| T2K | 1 | 9 | | 10 |
| ArgoNEUT | 2 | 2 | | 4 |
| SciBooNE | | 4 | | 4 |
| MINOS | | 2 | | 2 |
| NOvA | | | | 0* |

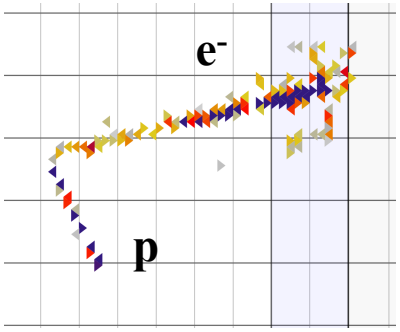
* NOvA is close to a $\nu_e$ cross-section paper, Welcome!

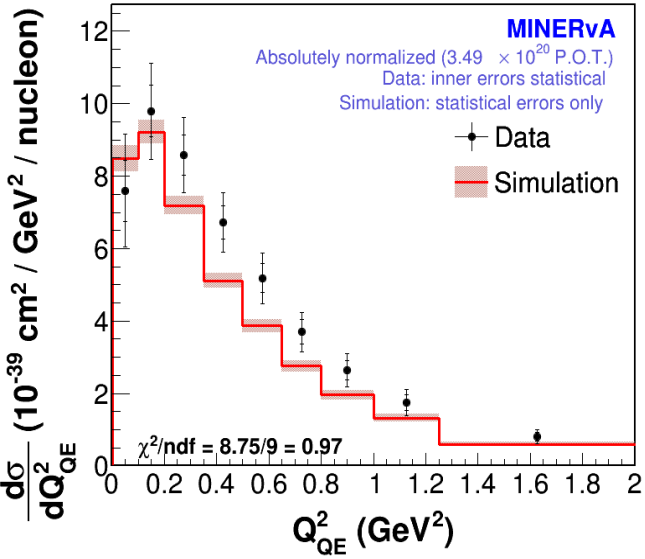
- We also have:
  - 2 PRL and 1 PRD in journal review (1 PRL and 1 PRD with positive initial feedback and 2nd PRL waiting initial feedback)
  - 3 PRDs in collaboration-wide review
  - 2 more PRDs in advanced draft stage




# In Detail: $\nu_e$ CCQE

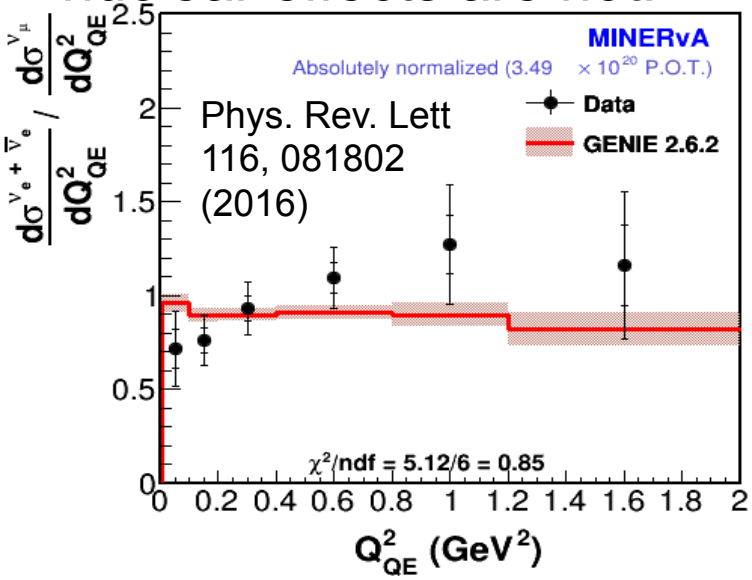
$\nu_e$ CCQE is oscillation signal, but almost no cross section data.




Measured cross sections and $\nu_e/\nu_\mu$ ratio consistent with GENIE model @ 1σ (~10-20% uncertainties) Absolute level is high

We all assume fundamental coupling is universal, but know nuclear effects are not!



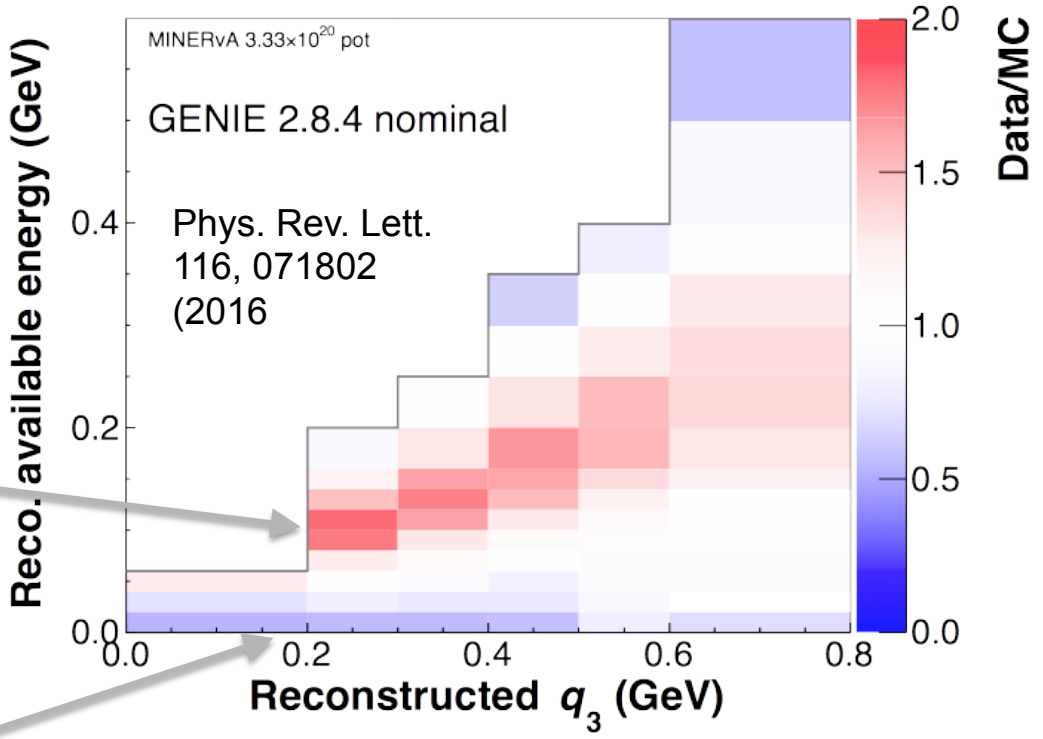

Also found an unsimulated background of photon like events, which we believe are due to diffractive production of $\pi^0$ from protons in scintillator.
(a 2nd PRL, arXiV:1604.01728, currently in journal review)

# In Detail: Low recoil “2p2h”

- Measure a cross section in momentum vs energy transfer space.
- Oscillation experiments depend on modeling this split correctly for energy reconstruction.

Data/MC large in region where neutrino scatters from two nucleons, “2p2h”

Data/MC small in region where scattering suppressed by long range correlations, “RPA”



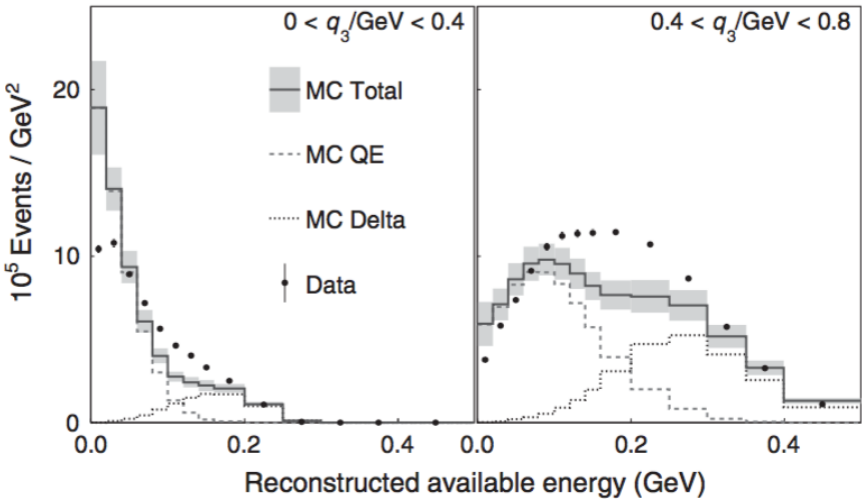

Overwhelming evidence for presence of these two effects, not in the standard GENIE (2.8.x, 2.10.x). *Coda: “2p2h” strength will not be well modeled in next GENIE 2.12.*

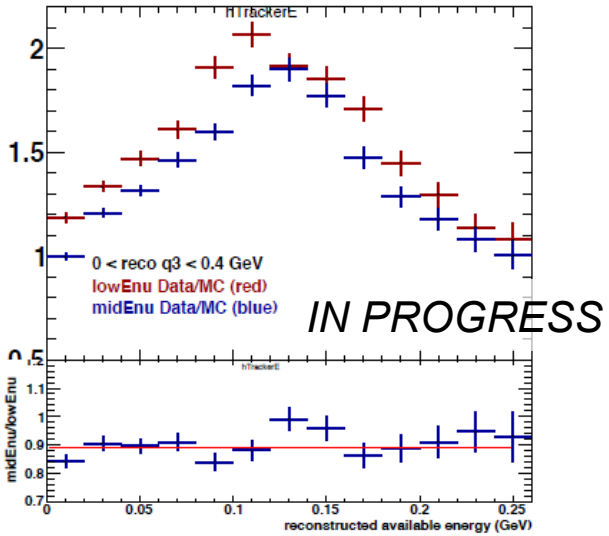
# What role does $E_\nu$ play?

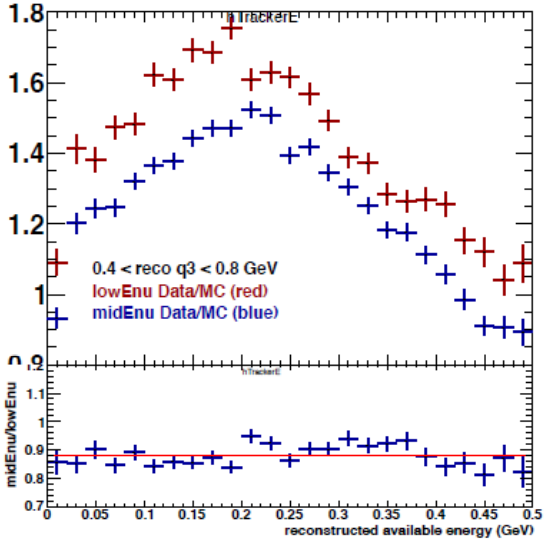
- MINERvA now runs at higher energies than DUNE. Is that good? Bad? Indifferent?
- Like most things with MINERvA, it's subtle
  - Higher neutrino energy gives access to a wider range of kinematics
  - It may also create more feed down backgrounds from high energies to exclusive processes
- What is always true is that at low energies, you never have access to kinematics you can reach at high energies.

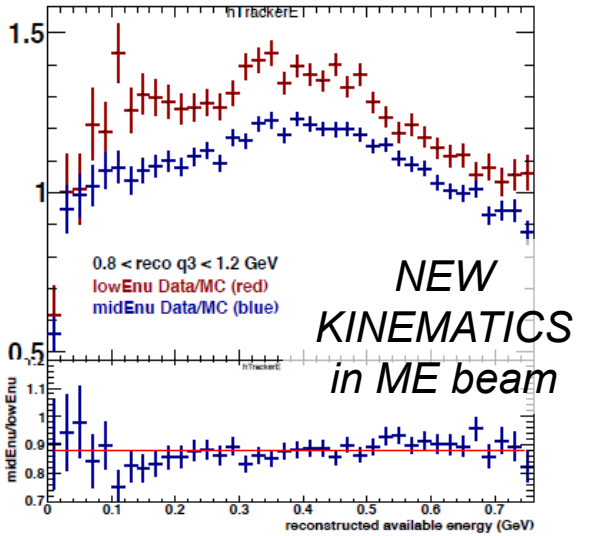
# $E_\nu$ and 2p2h

- At right is result from Phys. Rev. Lett. 116, 071802 (2016)
  - You saw 2D result earlier and NOvA's 1D equivalent before
  - Missing "dip region" → 2p2h
- Below ME data: high/low $E_\nu$ data/MC double ratio. Roughly independent of neutrino energy for same $q_0$-$|q_3|$



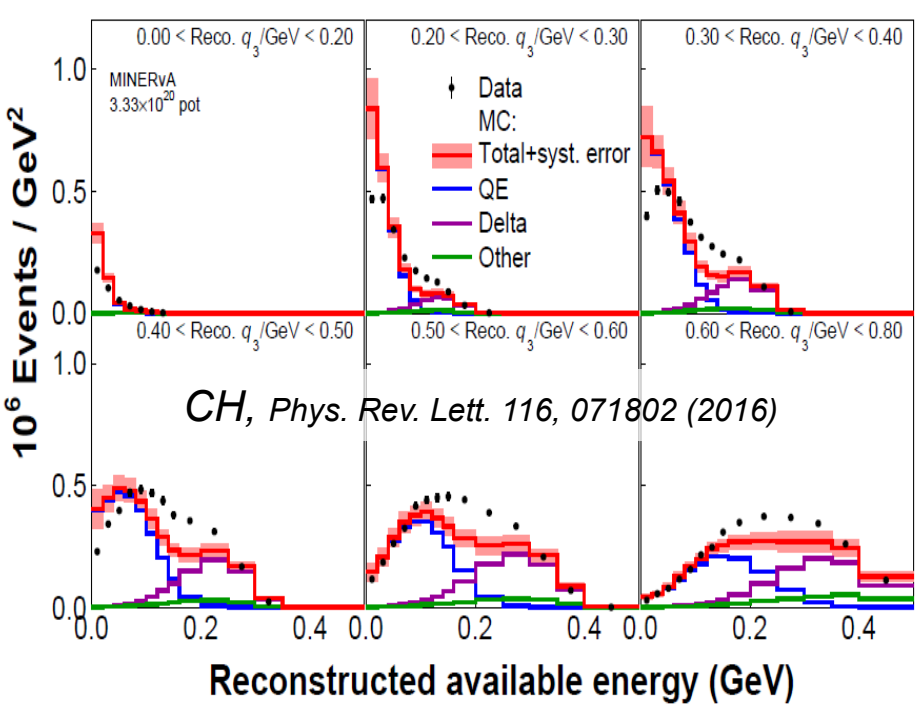



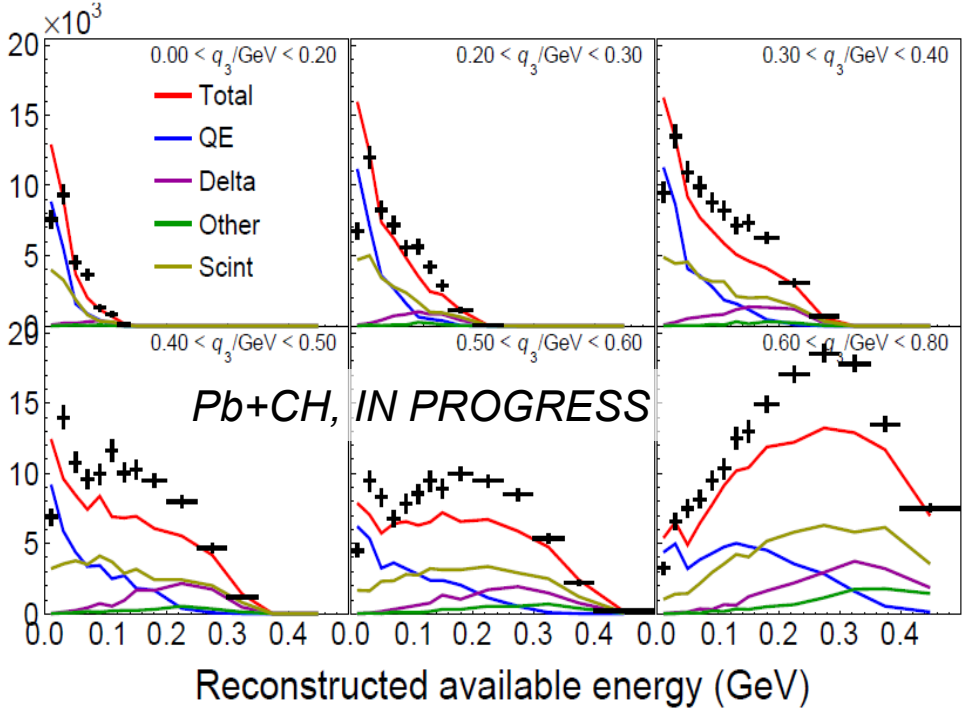



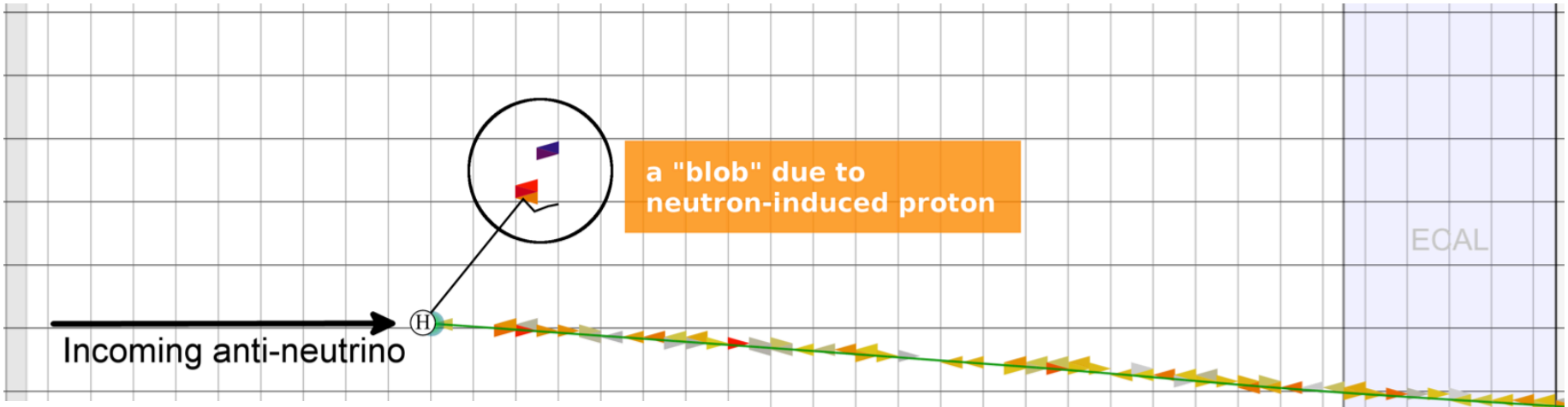
# Nuclear Targets: 2p2h

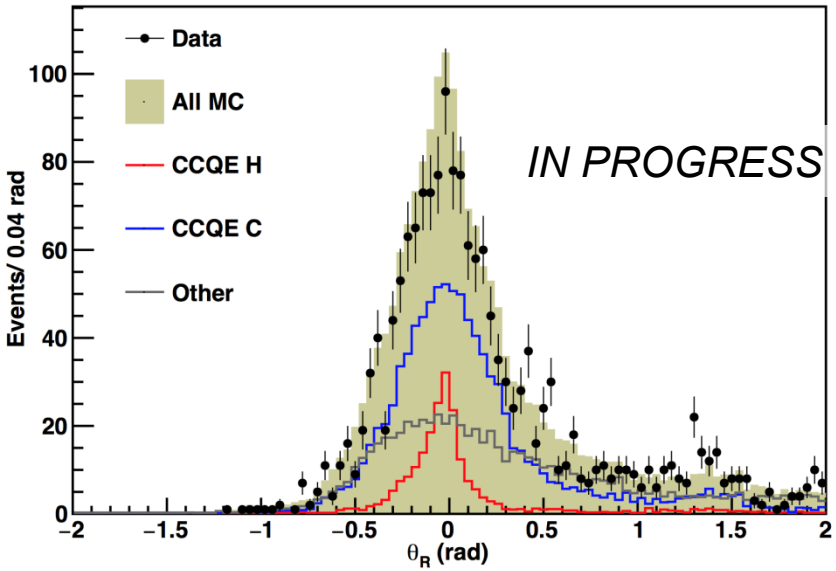
- MINERvA's plan to explore nuclear dependence is to compare scintillator (CH) to iron and lead
  - Without Ar data in the foreseeable future, plan is to test model dependence on other nuclei



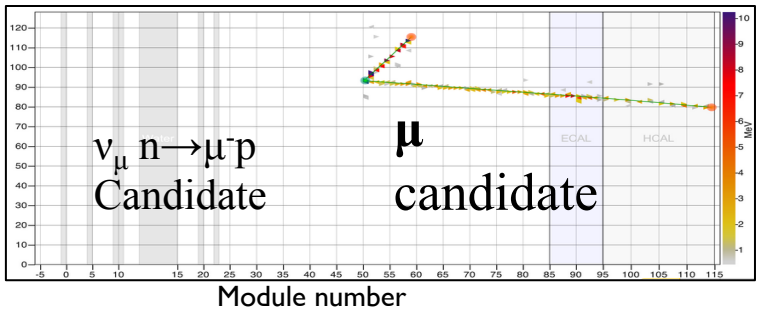
# New Directions: Neutron Tagging

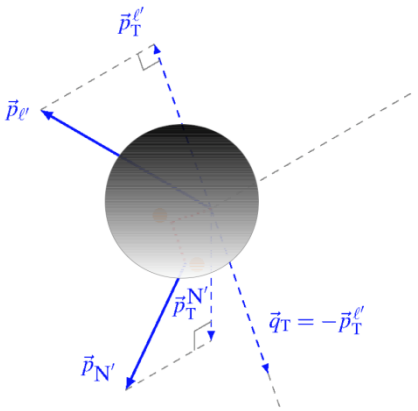


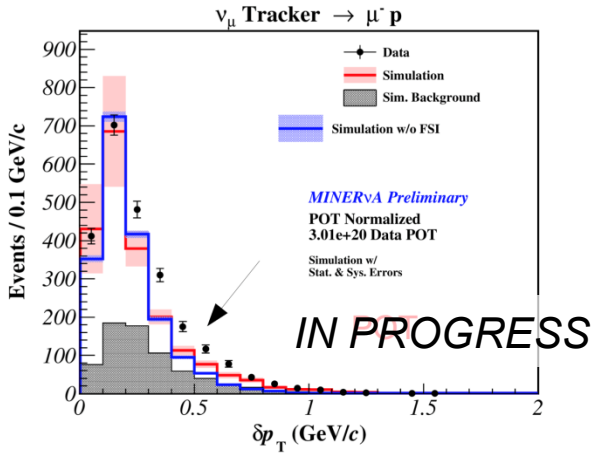




- Useful for estimating energy "lost" to neutrons
- Direction is precise enough to separate C and H due to Fermi motion (see left)
- Energy reconstruction is stochastic, as expected

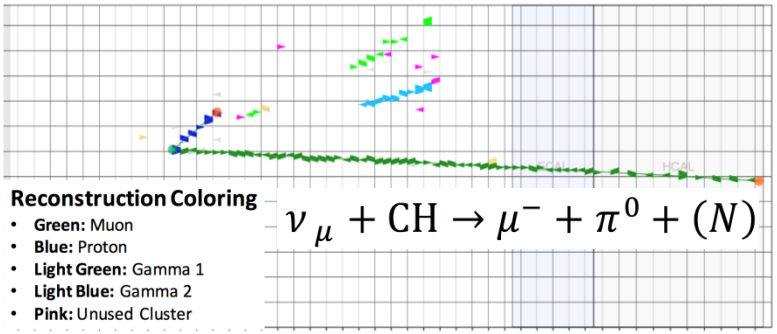
# New Directions: Multi-particle Correlations

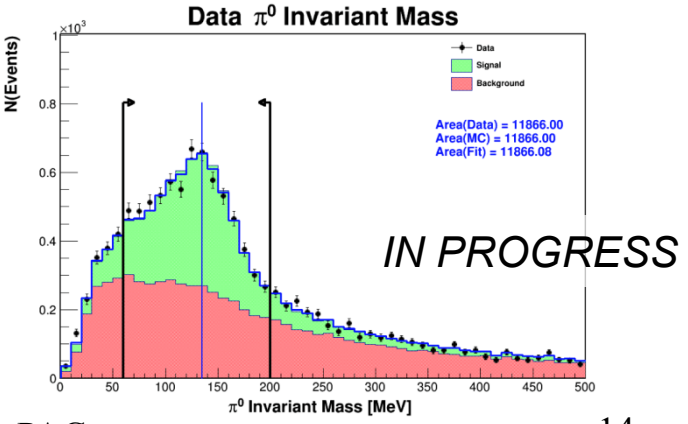


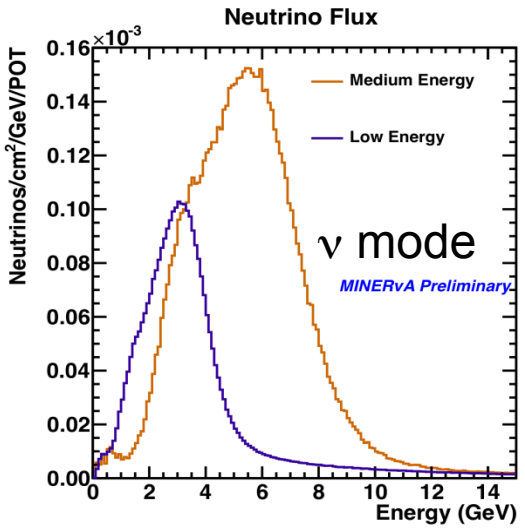

- Working to improve multi-particle reconstruction
- Also working on physics interpretation of correlations

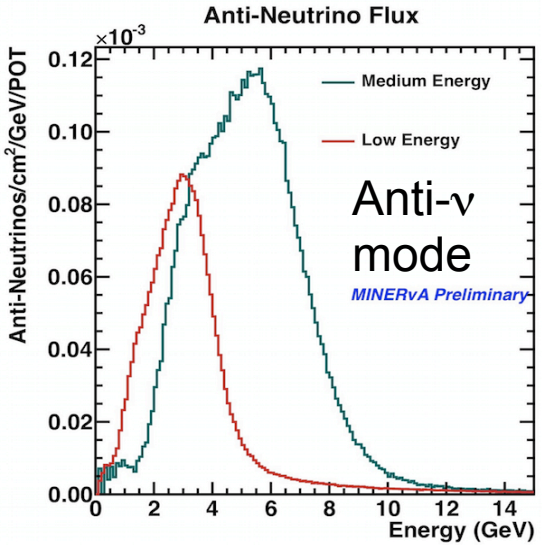


# What's different in the ME data analysis?

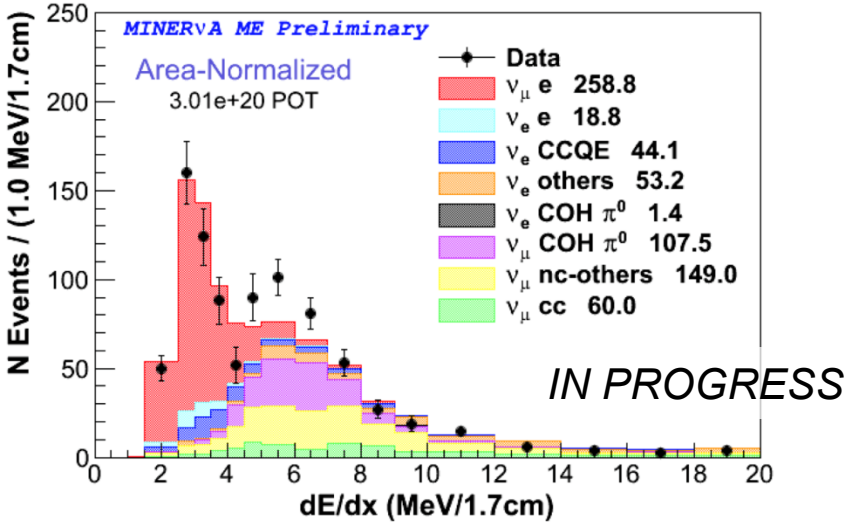
- νe→νe flux with <5% uncertainty
- Target ratio analyses will be less statistics limited
- Kinematic reach to higher $Q^2$, previously inaccessible with limited MINOS $\mu^{\pm}$ acceptance
- Pileup and deadtime in the detector are larger and require reassessment
  - Yes, loss of efficiency, but also higher backgrounds in Michel tagging, $K^+$ tagging, etc., even with few ns timing resolution

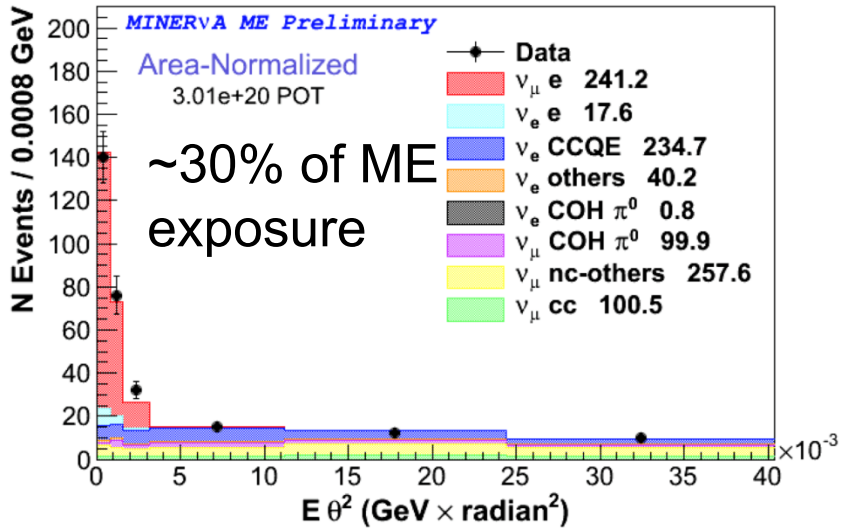


# Progress on ME Results: v-e

- Model independent flux constraint
  - Directly useful to NOvA
  - Technique planned by DUNE
  - MINERvA data also constrain hadron production for DUNE (120GeV protons on Carbon)
- LE data: 100 events measured
- ME data looks as expected
  - Expect 1000 events in $\nu$ mode
  - We should meet goal of 5% flux constraint from v-e

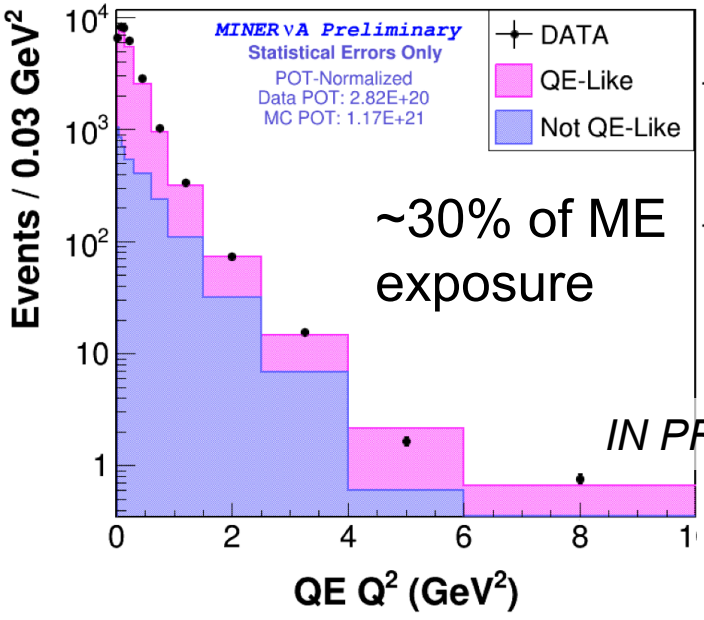


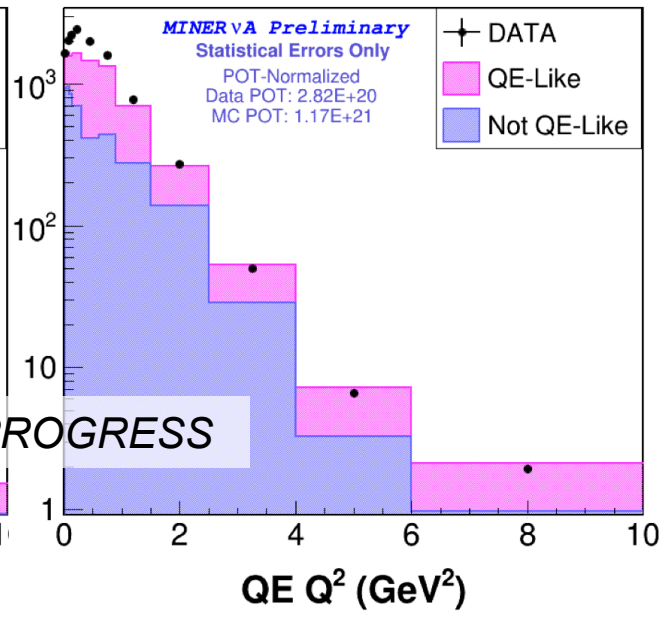
# Progress on ME Results: CCQE

- Reach to higher momentum transfer
- 10-fold increase in statistics over LE sample

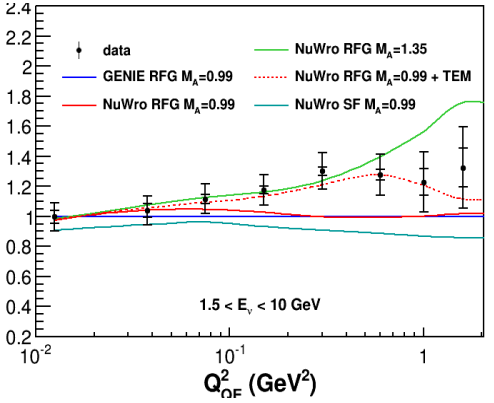
1 track




2 tracks



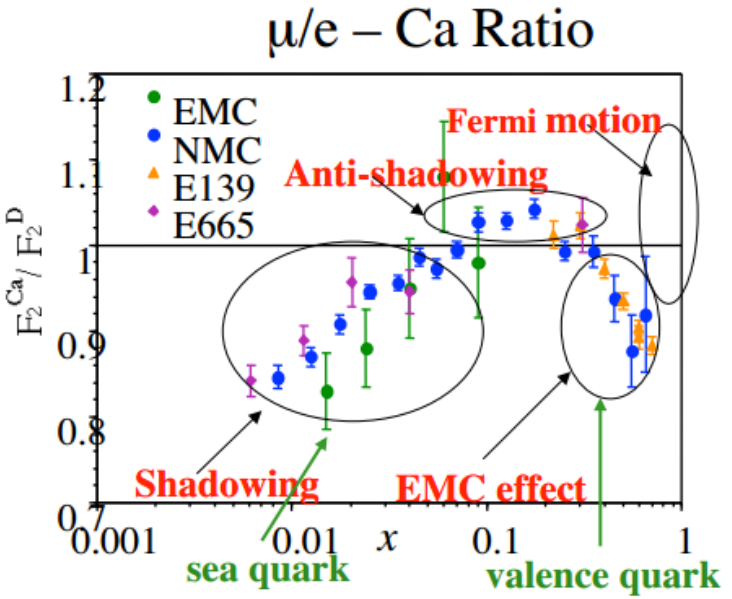

c.f., LE result that ends at 2 GeV²




*Parenthetically, we note that the last two results are from Mexican and Brazilian students. We help the lab attract more Latin American collaborators.*

# Another Science Goal: Nuclear Effects in DIS

- In Deep Inelastic kinematic regime, there are a variety of effects observed in charged lepton scattering: shadowing at low x, Fermi Motion at high x and the "EMC effect"
- Viable models exist for the former two and related phenomena are observed
- The "EMC effect" region has one data set, charged lepton DIS, on a variety of nuclei.
- Difficult to distinguish models: the "Every Model's Cool" problem
- No neutrino data on these ratios prior to MINERvA




CERN COURIER

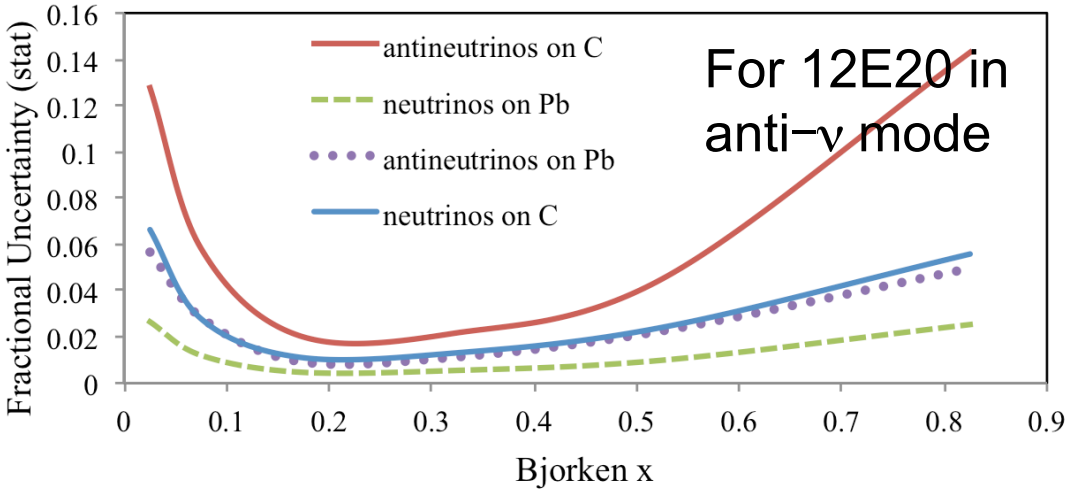
Apr 26, 2013

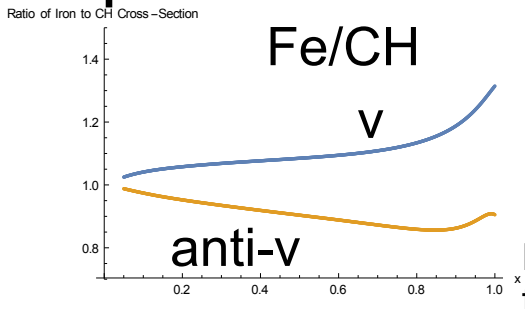
**The EMC effect still puzzles after 30 years**

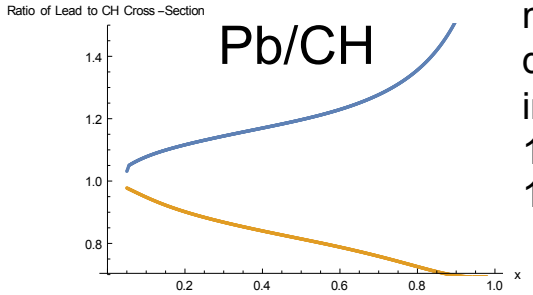
**Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.**

# Reminder: Antineutrino Run

- We expect ~10E20 POT in ν by NOvA switch
- Have requested 12E20 POT in anti-ν running (2 years at 700kW)
- This allows "ν-EMC" ratio measurement vs. quark momentum fraction at ~5% precision for Fe and Pb



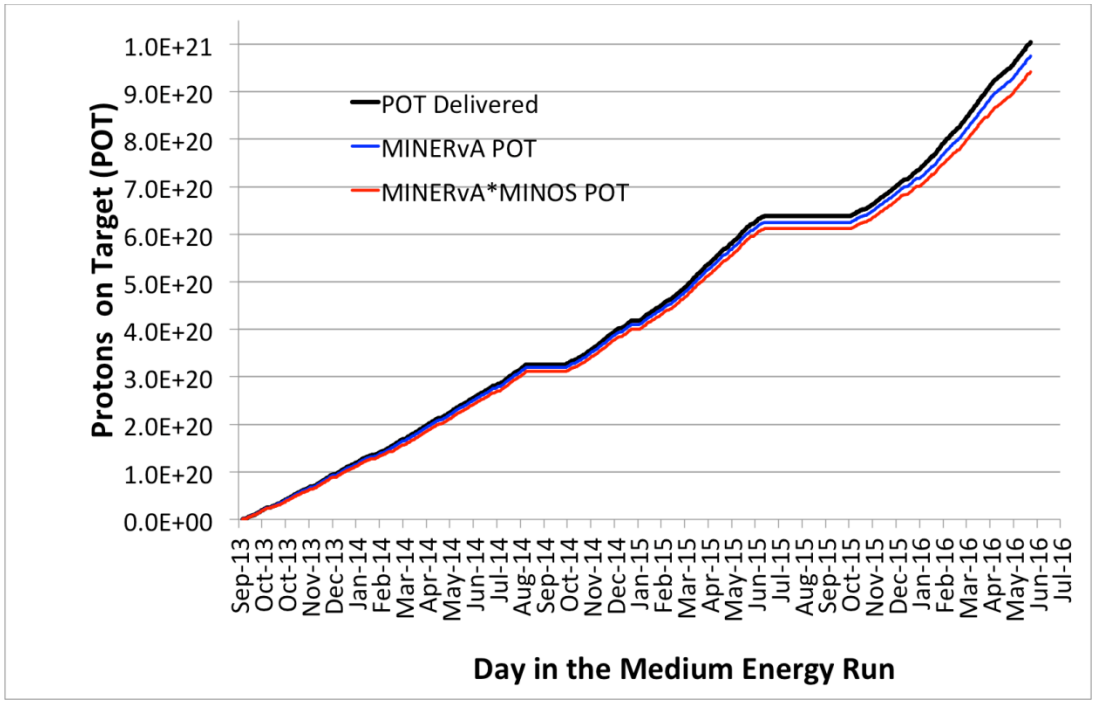

Prediction from Cloët model described in PRL 109, 182301

# Health of Collaboration

- The decision by the lab not to proceed with CAPTAIN-MINERvA was a blow
- Collaboration nevertheless remains healthy and committed to MINERvA
  - Broad realization that absent high energy interactions on Argon for DUNE, then the MINERvA program of C-Fe-Pb comparisons becomes more important
  - New postdocs and students are typically performing a MINERvA analysis and working on hardware for other experiments that are part of the global program
- We have successfully integrated a new “limited” author institution for data mining on two topics (Oxford)
- At least one CAPTAIN institution and a generator institution (NuWro) plan to join by fall

# Medium Energy Operations

- MINERvA and MINOS Detectors are running well.
- Strong partnership between collaboration and lab support staff.
- Some modest DAQ upgrades to be completed this summer.




- Expertise for significant parts of the MINOS ND and MINERvA operations resides with lab staff.
- Strengthened collaboration with SCD in the past few years has been very valuable for our processing effort.

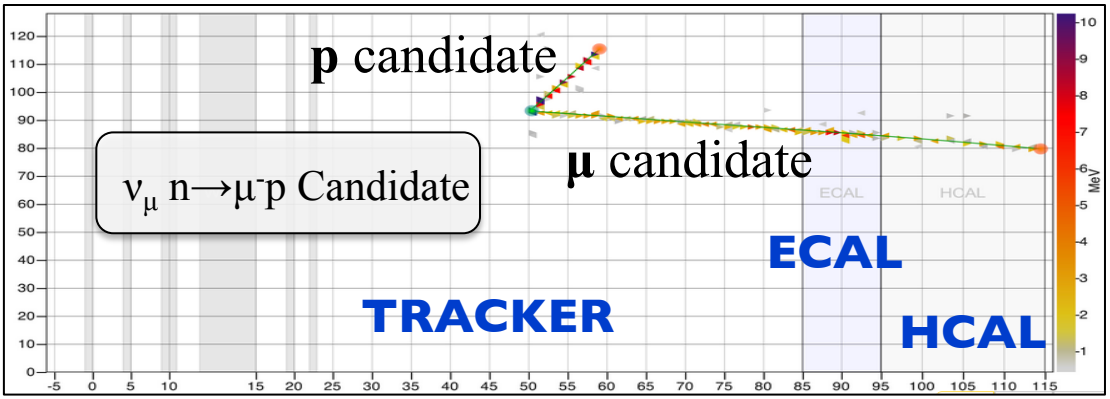
# Summary

- If Fermilab has no room for even modest augmentation of its physics program (e.g., CAPTAIN-MINERvA), it is critical to complete the MINERvA program
- Program has proven its ability to improve oscillation experiments. Will continue to do so with new data.
- Collaboration is healthy and maintaining strength. Our students and postdocs will continue to produce quality science while working on technology for future experiments.

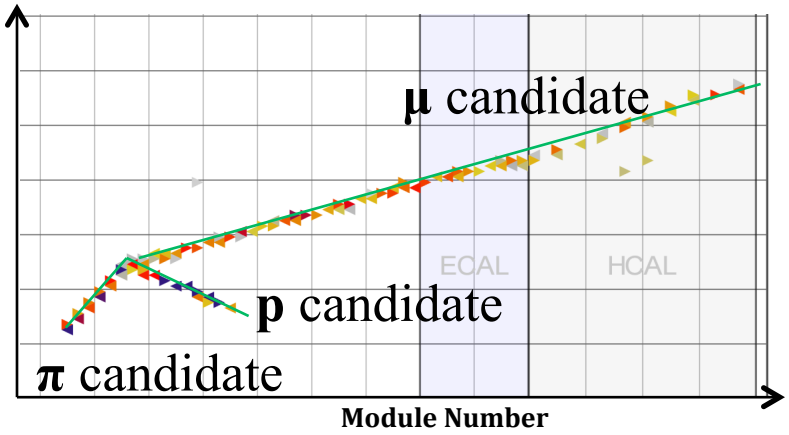
# Backup

# Events in MINERvA

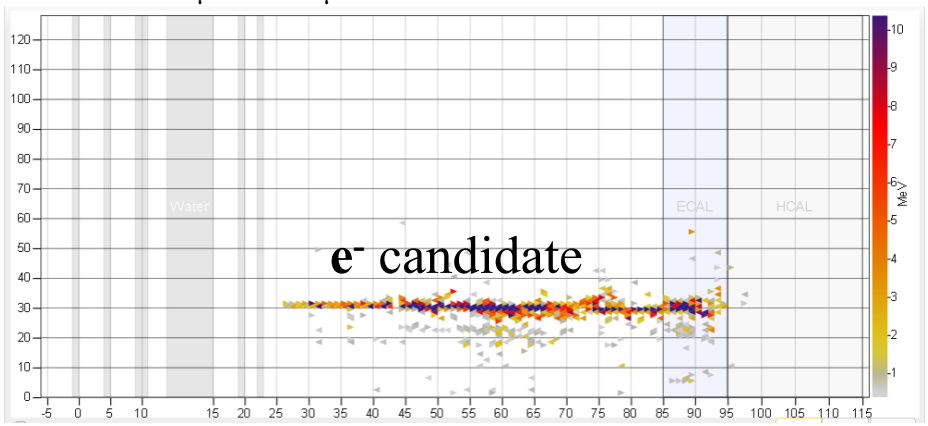
One out of three views shown, color = energy

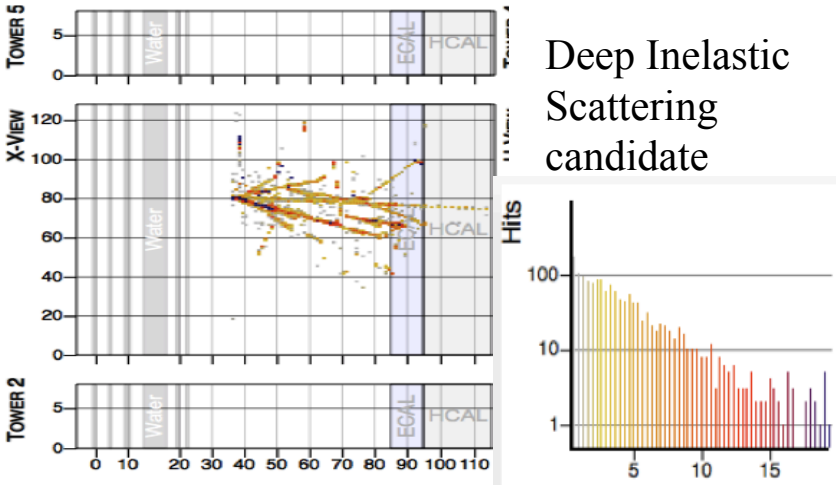



$\nu_\mu p \rightarrow \mu^- \Delta^{++}$, $\Delta^{++} \rightarrow p\pi^+$ Candidate




$\nu_\mu e^- \rightarrow \nu_\mu e^-$ Candidate

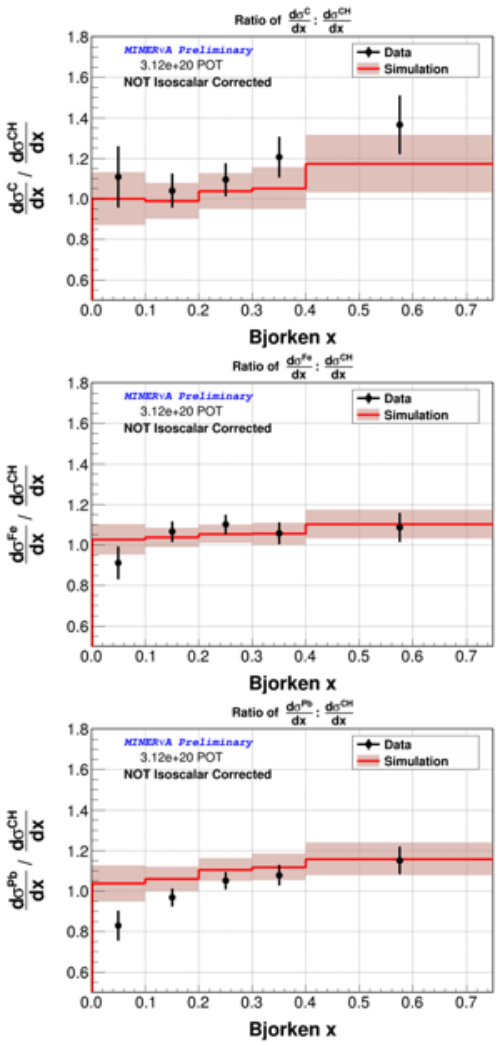



Deep Inelastic Scattering candidate

# LE Ratios of CC Deep Inelastic Scattering on Nuclei

J. Mousseau. JTEP 8 May 2015

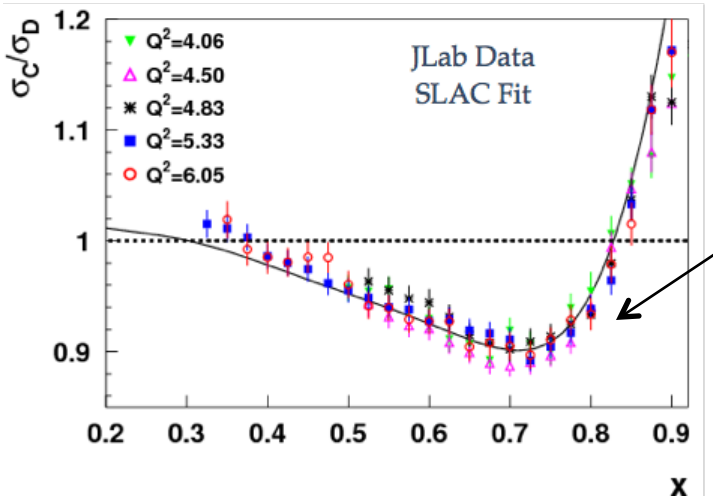



$\frac{d\sigma^C/dx}{d\sigma^{CH}/dx}$

$\frac{d\sigma^{Fe}/dx}{d\sigma^{CH}/dx}$

$\frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$

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

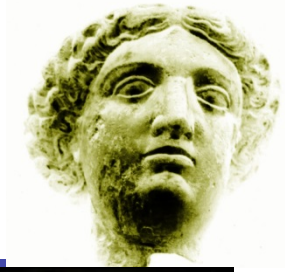



EMC Effect: dip in heavy/light nucleus cross section ratio at moderate x

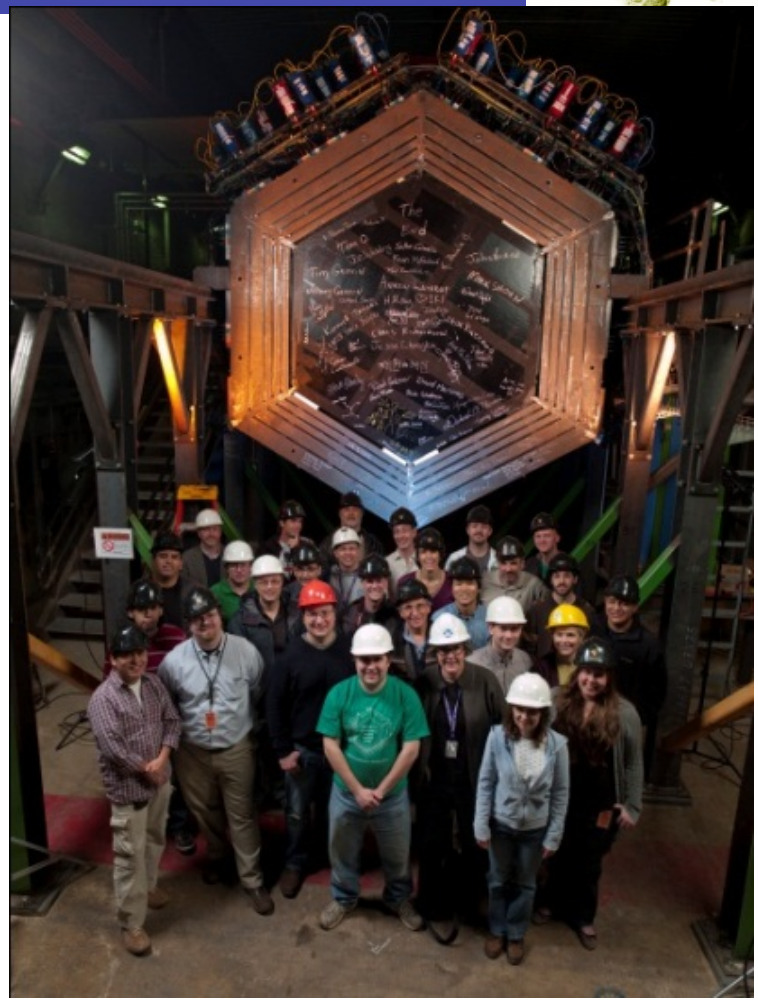
MINERvA is the first experiment to look for the "EMC Effect" in neutrino scattering

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

# MINERvA Collaboration

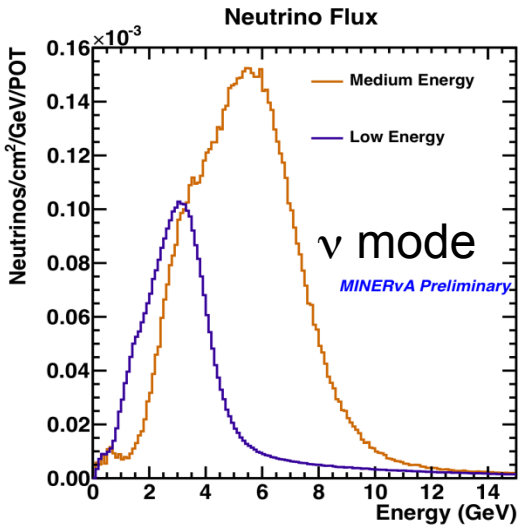


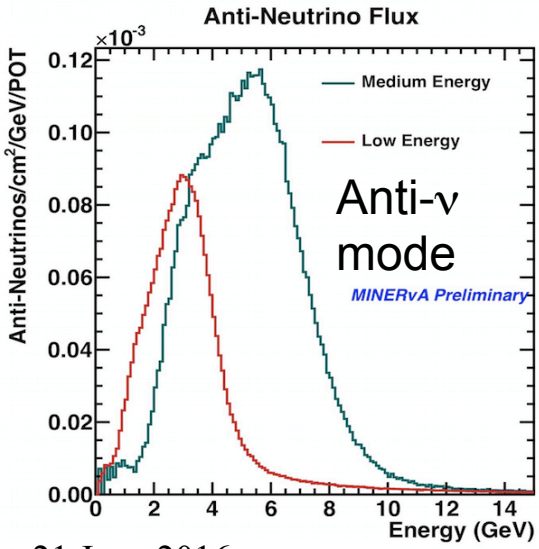
- Centro Brasileiro de Pesquisas Fisicas
- Fermilab
- University of Florida
- Universite de Geneve
- Universidad de Guanajuato
- Hampton University
- Massachusetts College of Liberal Arts
- University of Minnesota at Duluth
- Universidad Nacional de Ingenieria
- Oregon State University
- Otterbein University
- Oxford University
- Potificia Universidad Catolica del Peru
- University of Mississippi
- 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

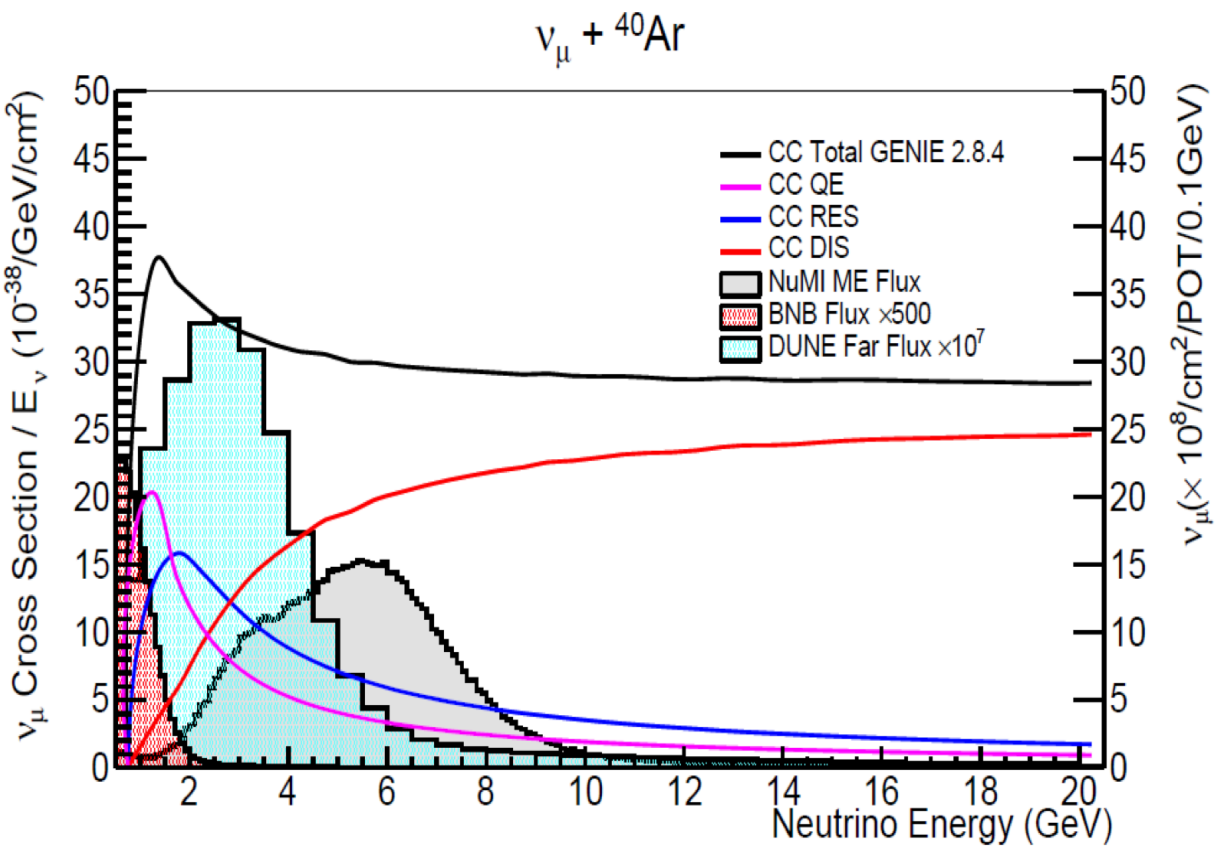


~66 particle, nuclear and theoretical physicists from 20 institutions

# Fluxes

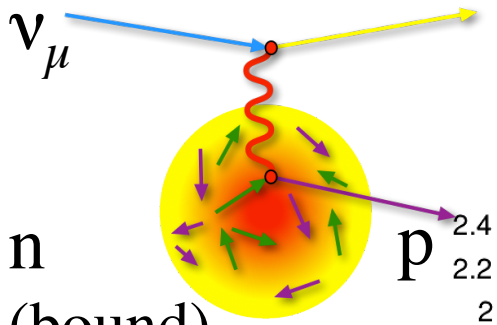

Neutrino Flux
Neutrinos/cm²/GeV/POT
×10⁻³
Medium Energy
Low Energy
ν mode
MINERvA Preliminary
Energy (GeV)


Anti-Neutrino Flux
Anti-Neutrinos/cm²/GeV/POT
×10⁻³
Medium Energy
Low Energy
Anti-ν mode
MINERvA Preliminary
Energy (GeV)


νμ + 40Ar
νμ Cross Section / Eν (10⁻³⁸/GeV/cm²)
νμ(× 10⁸/cm²/POT/0.1GeV)
CC Total GENIE 2.8.4
CC QE
CC RES
CC DIS
NuMI ME Flux
BNB Flux ×500
DUNE Far Flux ×10⁷
Neutrino Energy (GeV)

# MINERvA analysis summaries

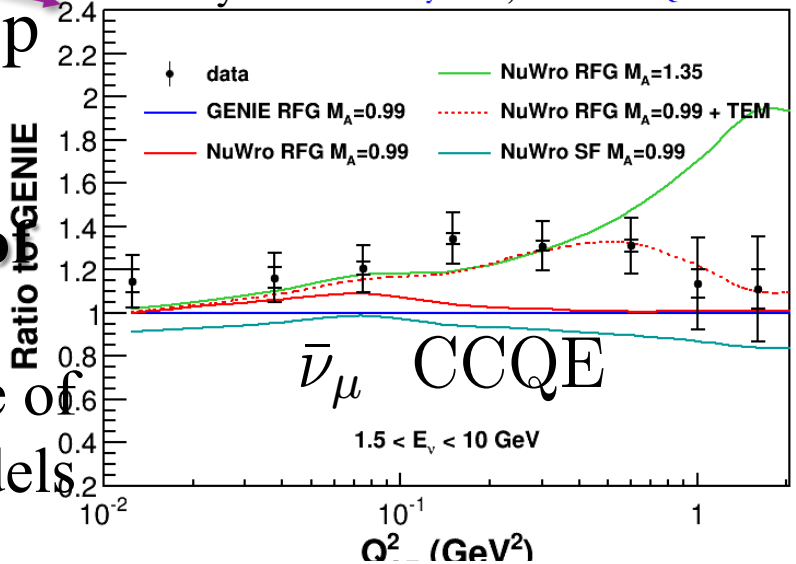
# $\nu_\mu$ and $\bar{\nu}_\mu$ Charged Current Quasielastic

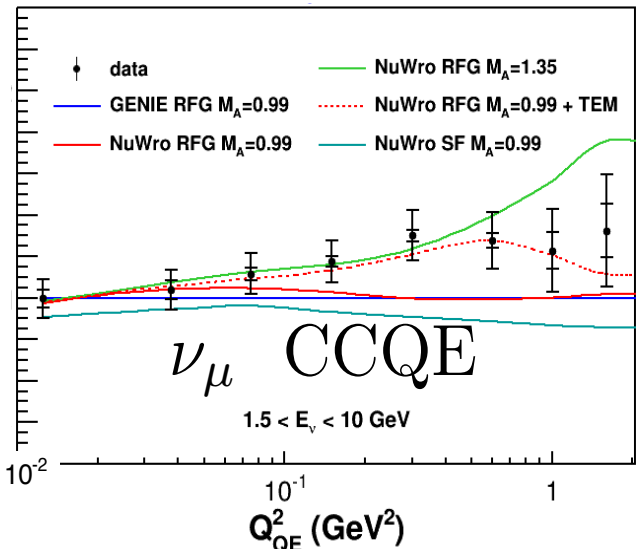


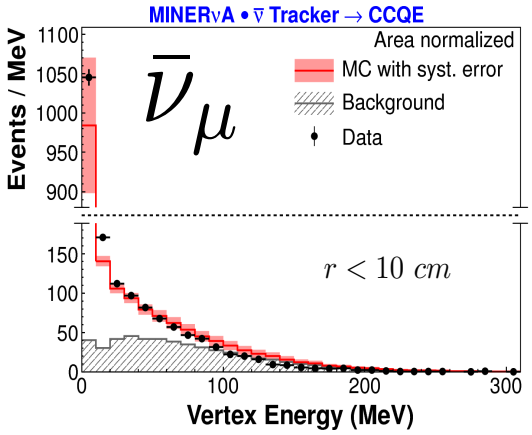

Phys Rev. Lett. 111, 002051 and 002052 (2013), updated to 2015 flux

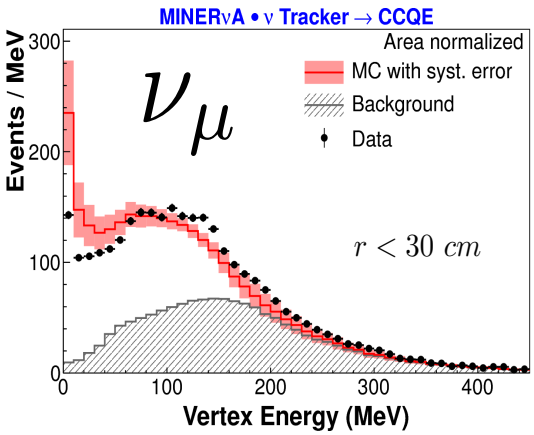
**What is effect of nucleus?**

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



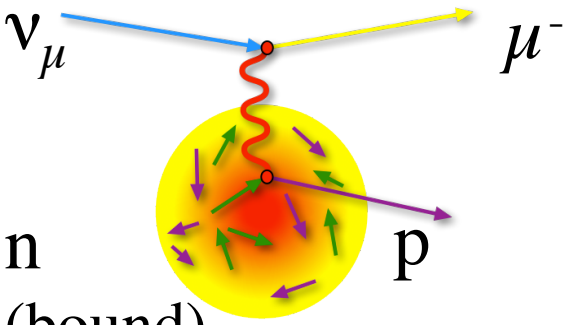




Look for energy near vertex consistent with extra nucleons

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

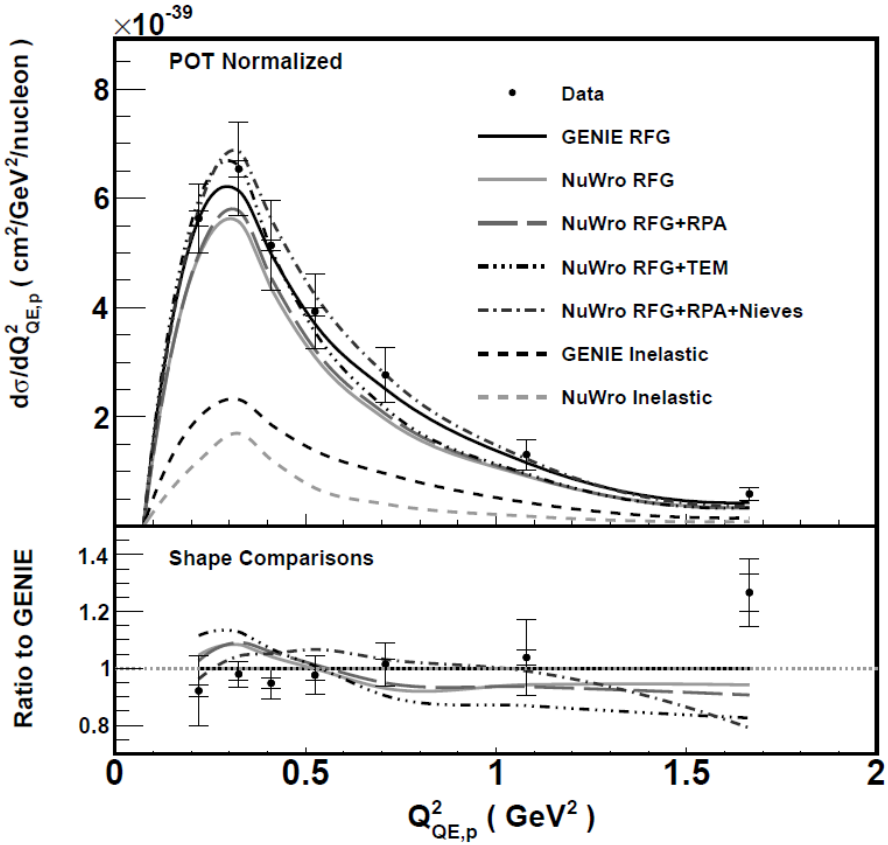
Cross-section vs $Q^2$ and vertex energy both consistent with multi-nucleon hypothesis

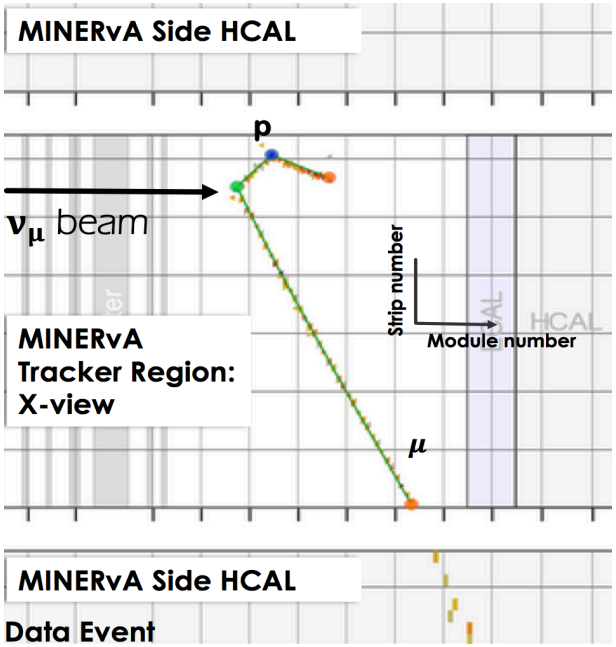



# $\nu_\mu$ Quasielastic with Observed Proton Recoil

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

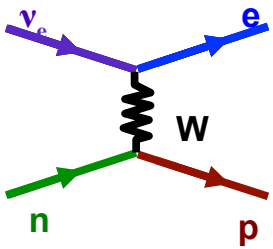
Momentum transfer ($Q^2$) can also be measured from proton energy




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

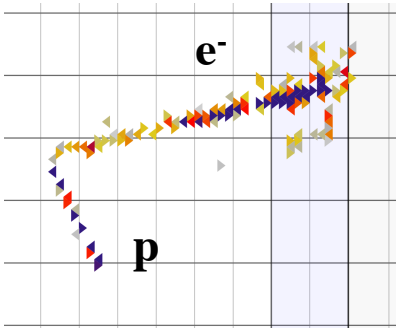
Phys. Rev. D 91, 071301 (2015)

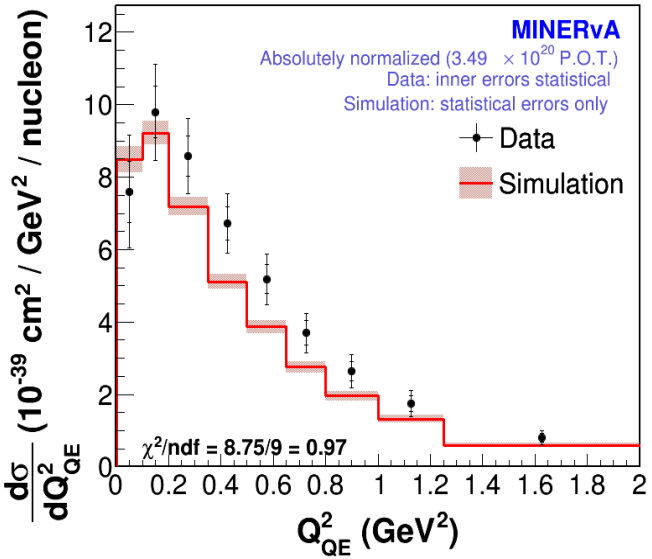



# Electron neutrino CCQE

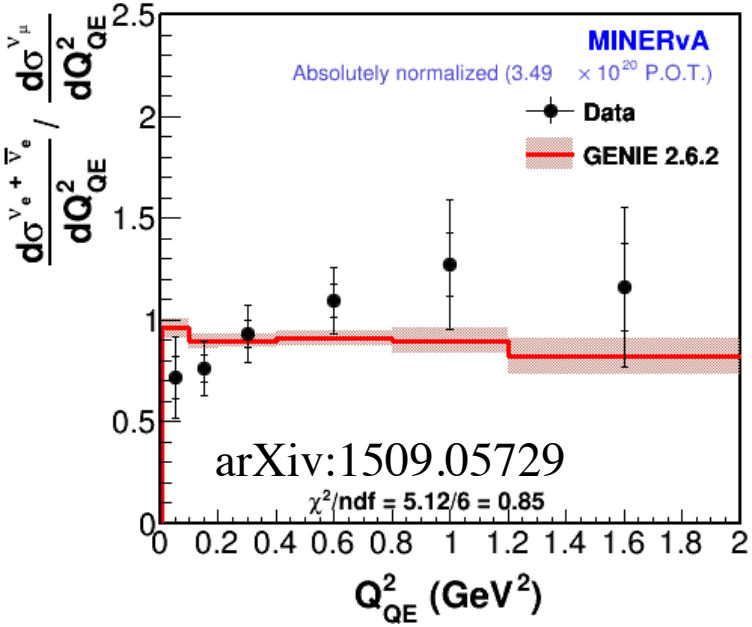
$\nu_e$ CCQE is oscillation signal, but almost no cross section data.

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



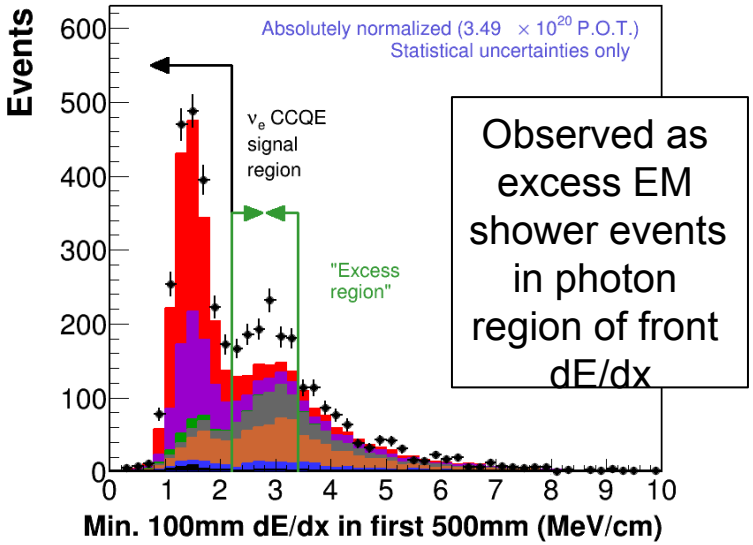




Measured cross sections consistent with GENIE model (assumes charged lepton mass only difference between XS) at 1σ (~15-20% uncertainties)

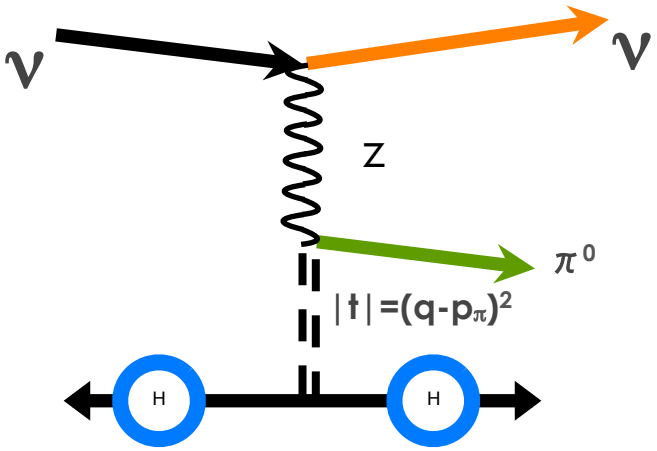



$\nu_e/\nu_\mu$ difference not significant (~1σ). Good enough for current expts. but shape may need further investigation for future high-precision oscillation results

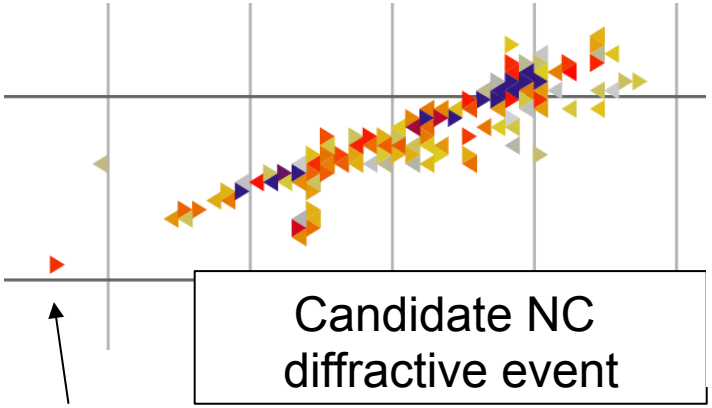
# NC diffractive scattering from H




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

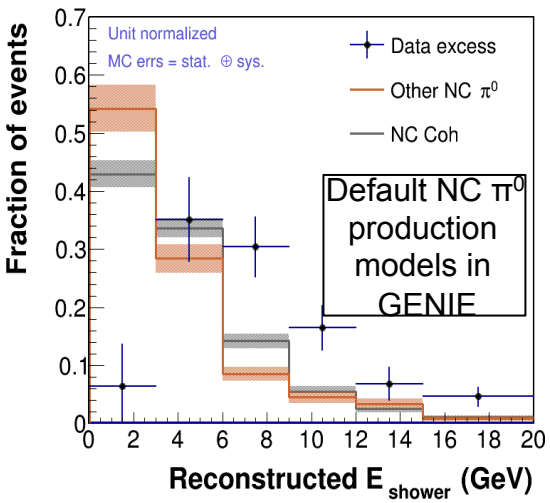


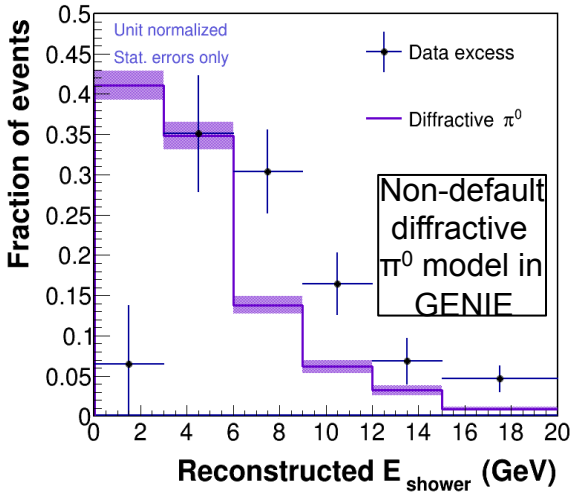

Analogous to NC coherent production. Potential background for $\nu_e$ appearance. Not in default generator models.



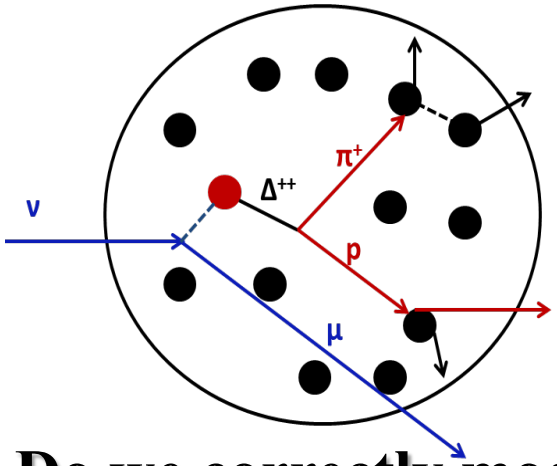
Candidate NC diffractive event

Probable recoil from proton

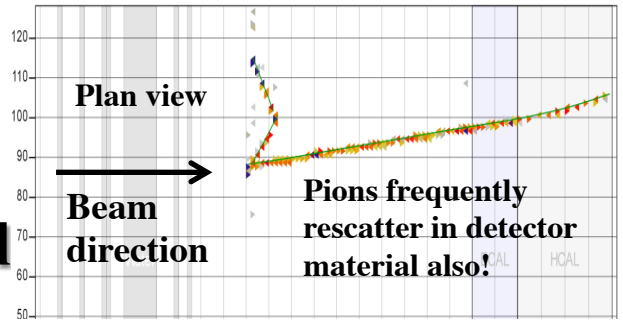



**Observed energy behavior is very different from any other NC $\pi^0$ production models**

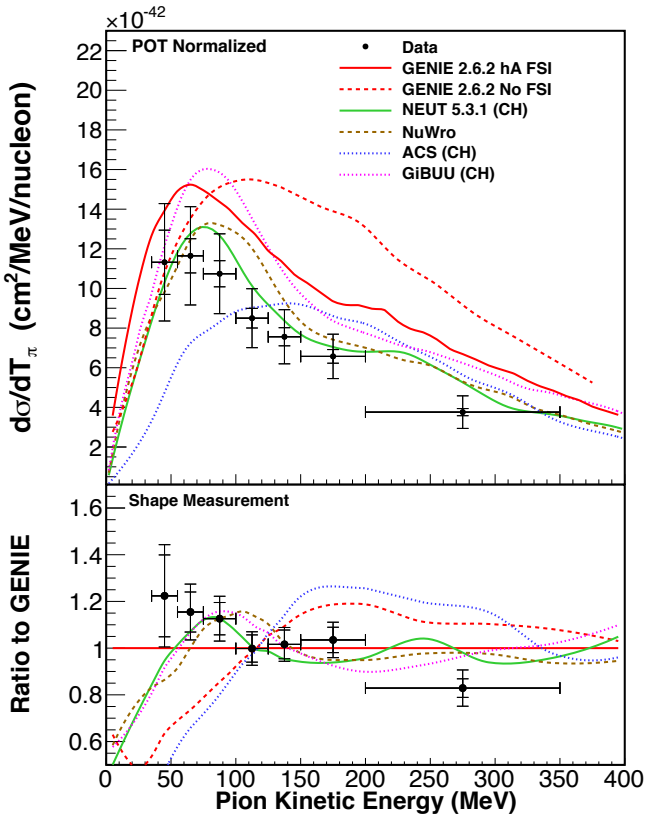


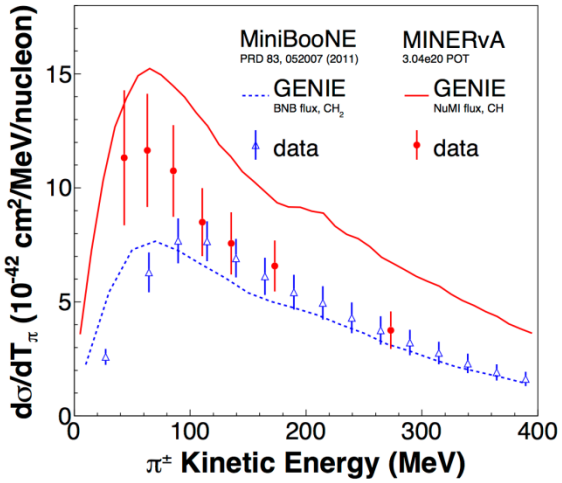

# Charged Pion Production




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

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

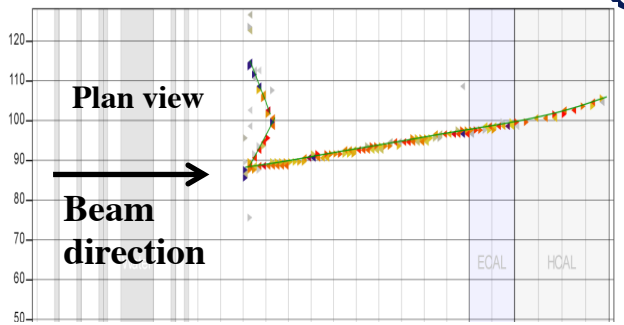


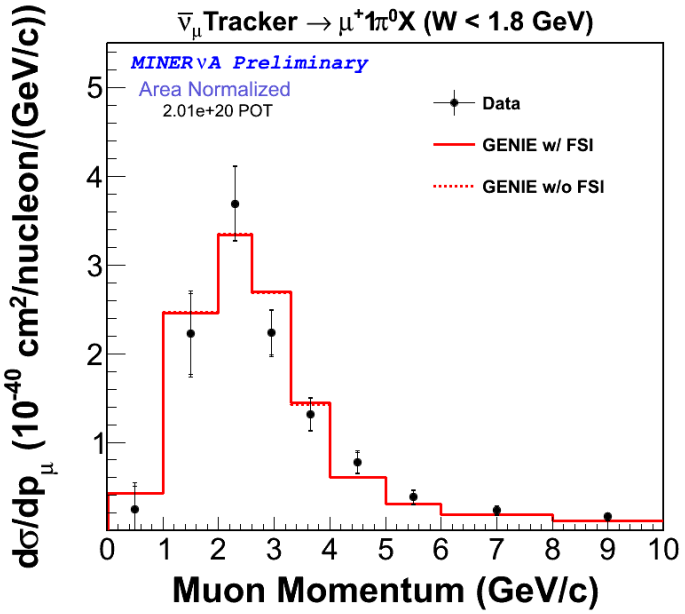

MiniBooNE's measurement of same reaction sees harder momenta, more events and suggest less FSI.
*There is significant tension between the experiments.*

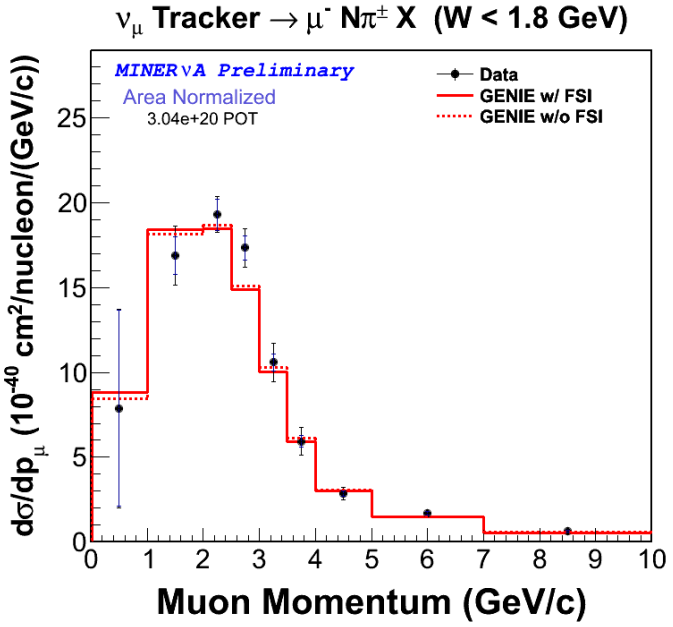
hep-ex 1406.6415

# 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

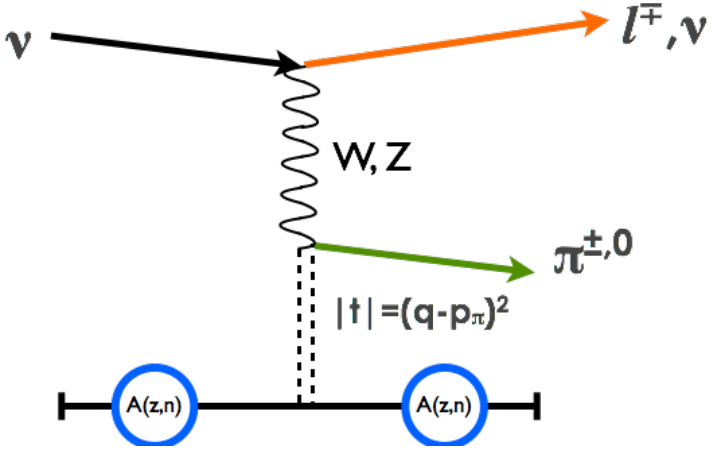
# Coherent Pion Production

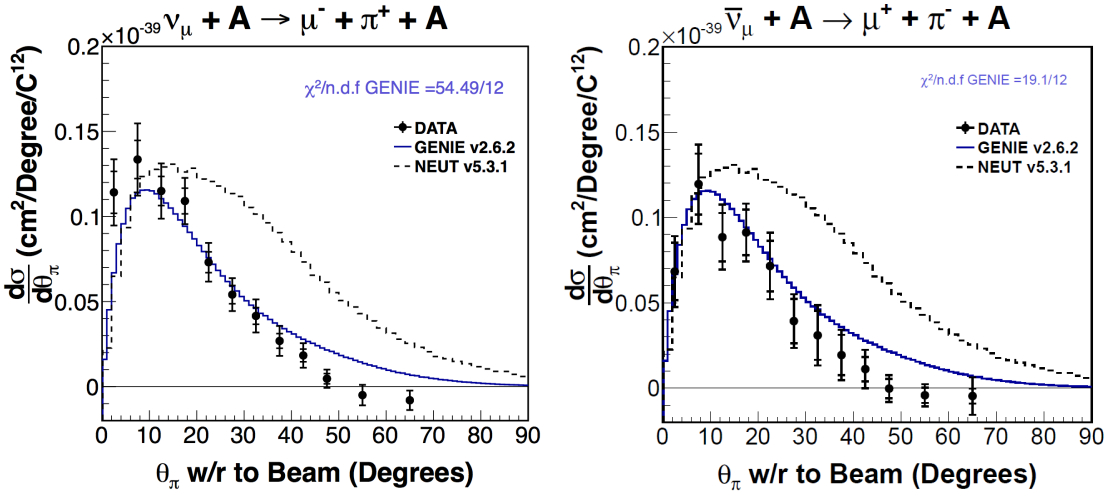
**Can we resolve experimental puzzles on rate for this process?**

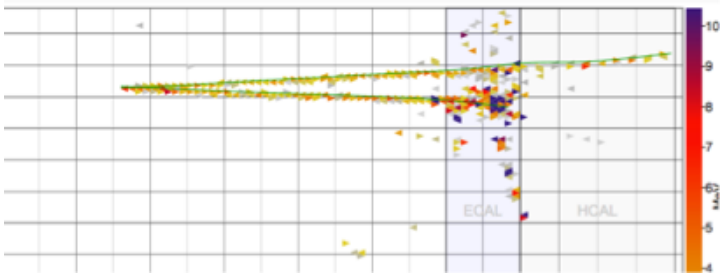
Low multiplicity process is a troublesome background for oscillation experiments and previous low energy data is confusing

Model independent selection and high statistics allows test of pion kinematics

1628 (770) coherent neutrino (antineutrino) events



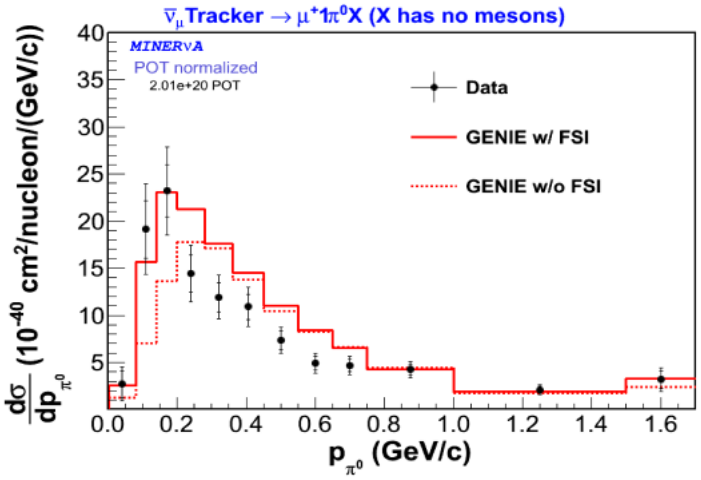

hep-ex 1409.3835

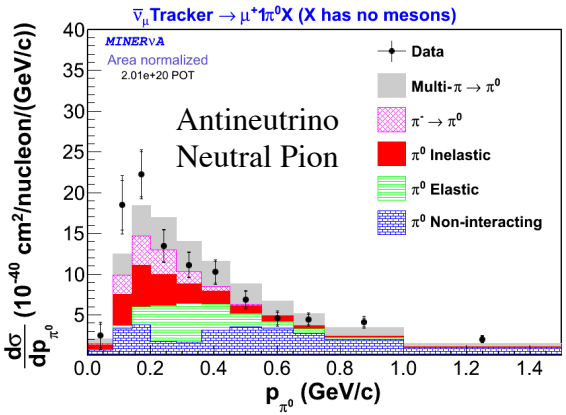
*Current generators don't model process well at LBNF energies*

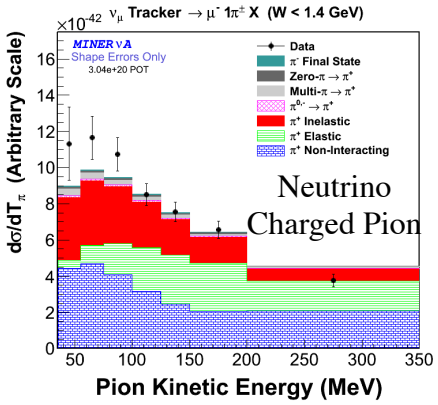
# Neutral Pion Production

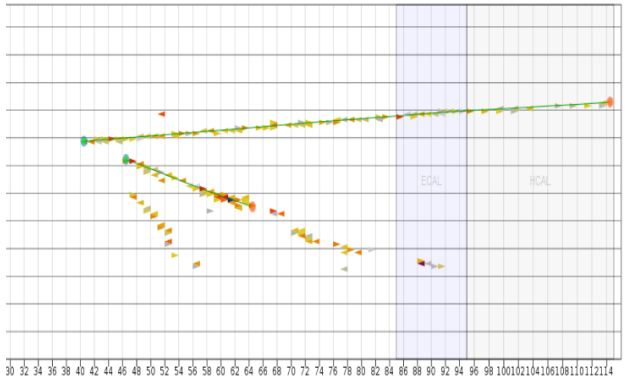
**Do we correctly model nuclear rescattering – complementary to charged pion production**

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

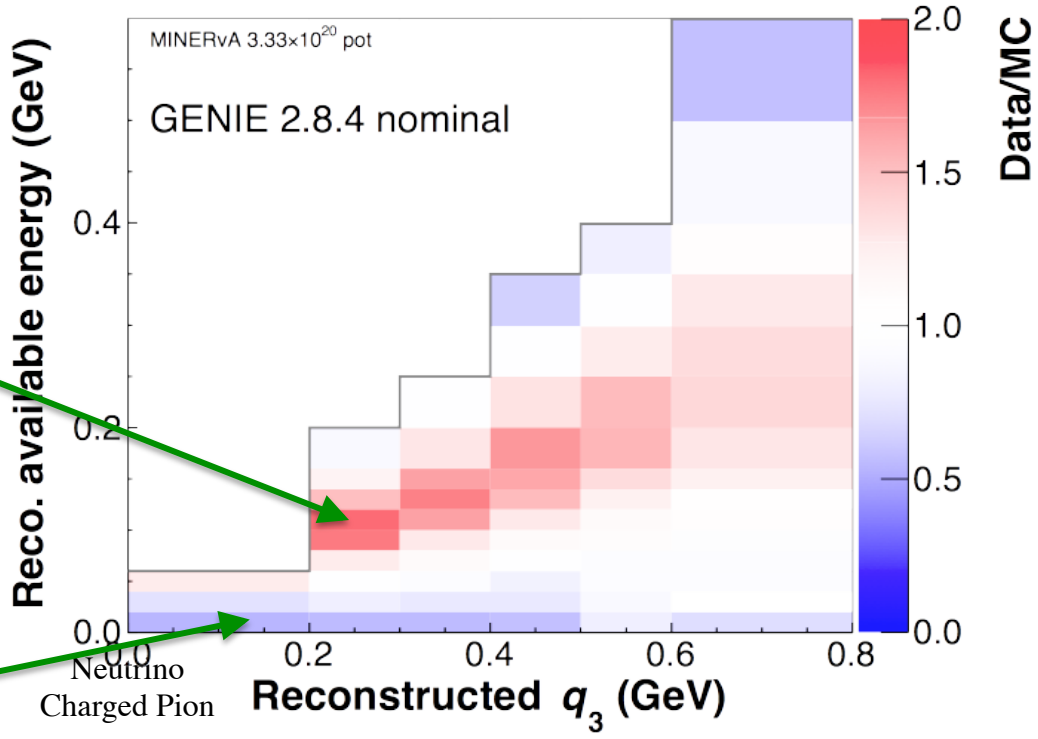
*MINERvA's Pion measurements are powerful discriminators of FSI models*

# $\nu_\mu$ 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

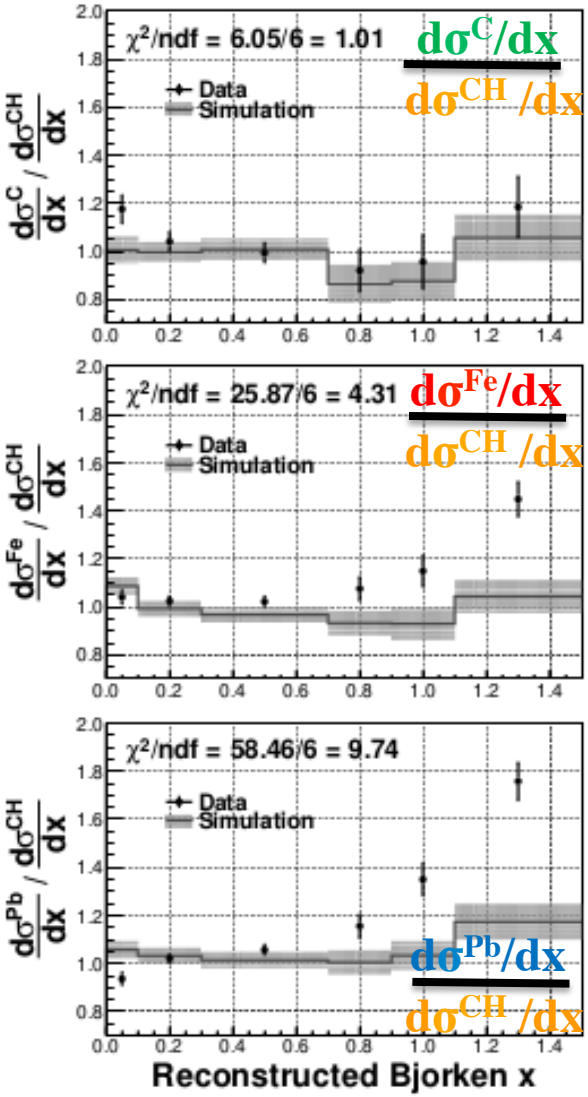


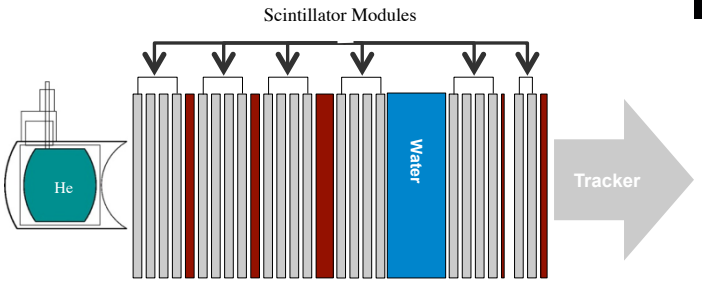

*Strong evidence for two nuclear effects not in our standard prediction*

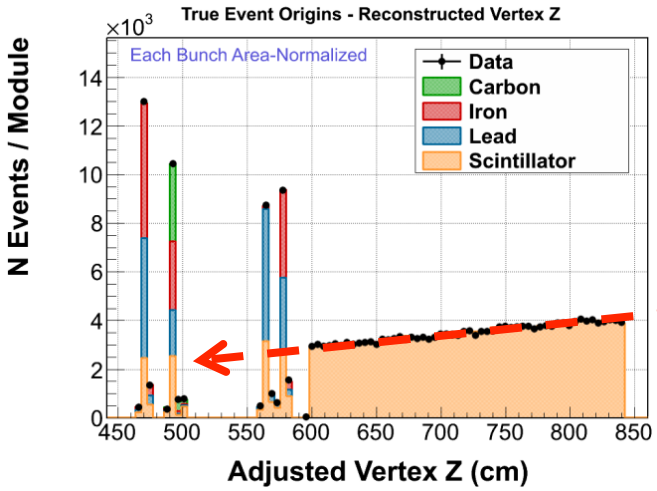
# Ratios of Inclusive CC Reactions on Nuclei

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

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




Targets are passive and there is contamination from nearby scintillator.

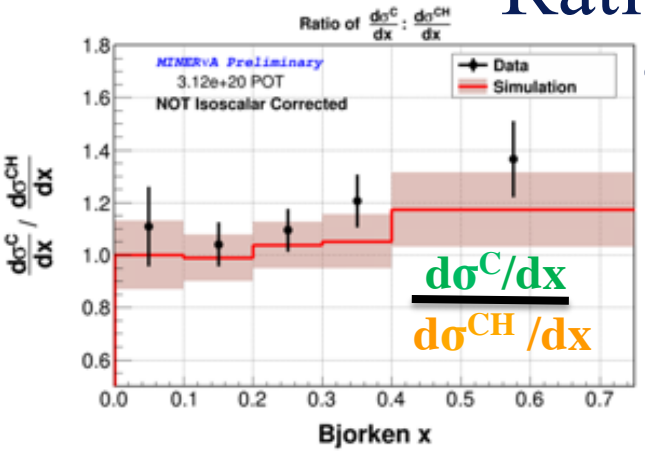
*Use events in the tracker modules to estimate and subtract contamination from scintillator events.*

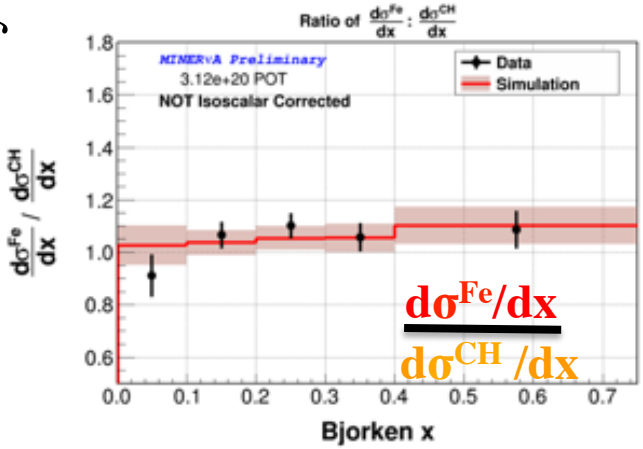
1. *At low x*, we observe a *deficit* that increases with the size of the nucleus.
2. *At high x*, we observe an *excess* that increases with the size of the nucleus.

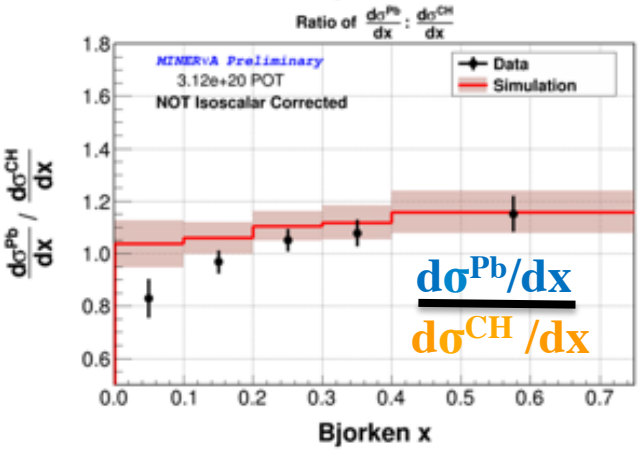
*These effects are not reproduced by current neutrino interaction models.*

# Ratios of CC Deep Inelastic Scattering on Nuclei

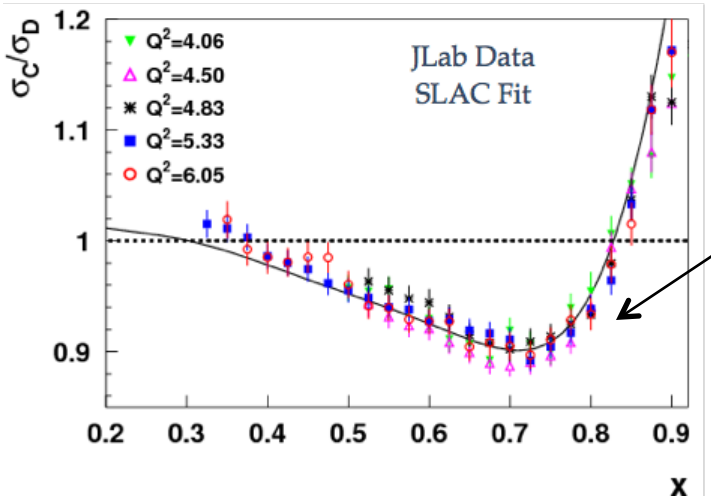
J. Mousseau. JTEP 8 May 2015



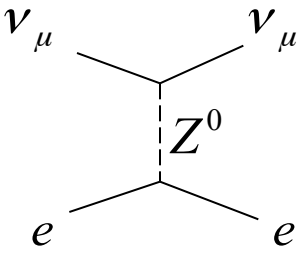

Seely, J. et al. Phys.Rev.Lett. 103 (2009) 202301 arXiv:0904.4448




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

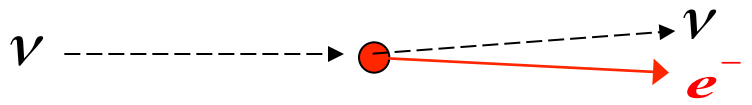
*No evidence of discrepancy with model (which does not include EMC effect). Currently statistically limited. Much higher stats analysis underway*

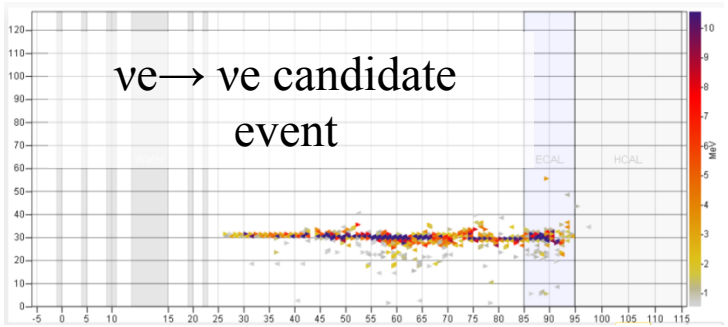


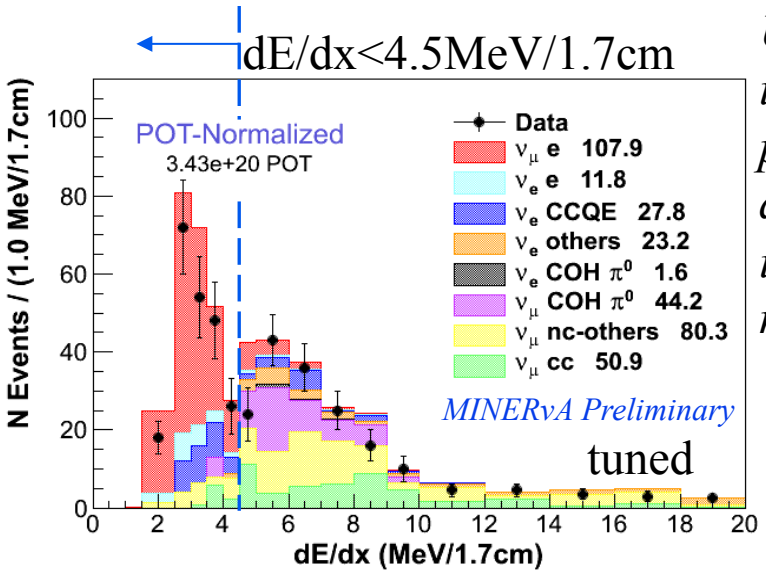

# Neutrino-Electron Scattering

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

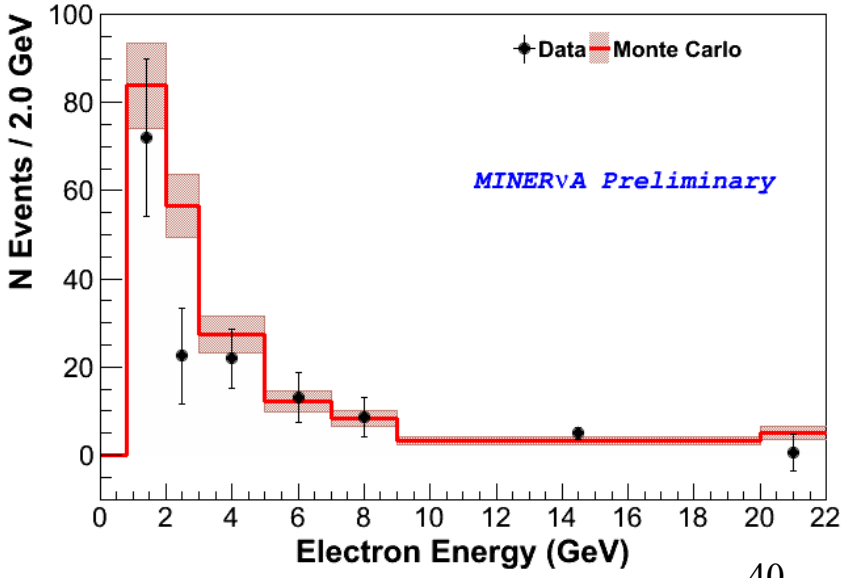
Very forward single electron final state




*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*