When Neutrinos Encounter Nuclei

What happens when the mini-mass Neutrino encounters a very massive Nucleus?

Neutrinos in Nuclear Physics: 29-31 July, 2016

Jorge G. Morfín
Fermilab

Why Renewed Interest in ν − nucleus interactions?

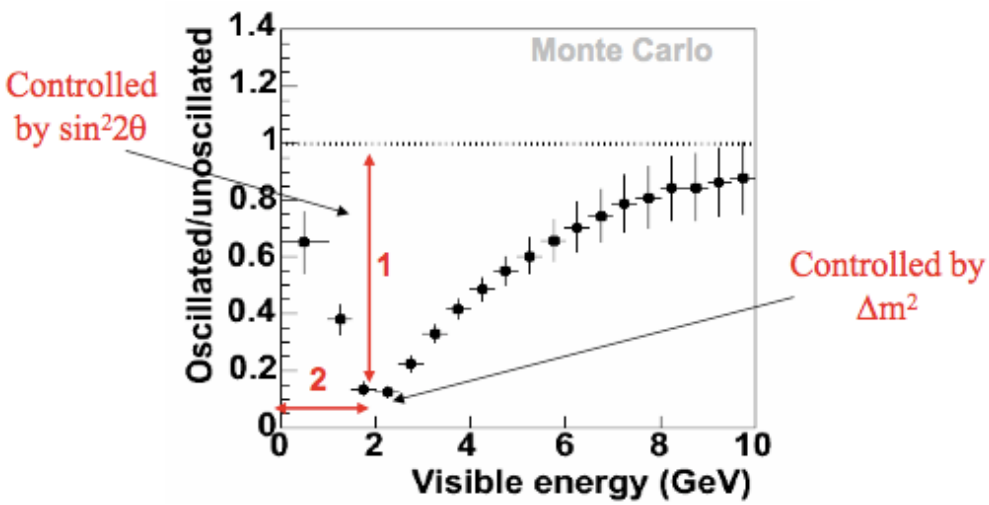
Neutrino Oscillations Experiments

Particularly those that want 1% systematics!

- HOWEVER also understanding axial-vector nucleus interactions!!
- The precision with which we measure neutrino oscillation parameters limited by our **knowledge of ν − nucleus interactions**.

$$P(\nu_1 \rightarrow \nu_{1'}) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right]$$

with $\Delta m^2 \equiv M_2^2 - M_1^2$



In a two-detector experiment, use observed neutrino energy spectra in ND to predict spectra in FD.

Significant challenges from ν − nucleus interactions to do this!!

Knowledge of ν-Nucleus Interactions

How do these interactions manifest themselves in our detectors constructed of heavy nuclei?

$Y_{c\text{-like}}(E_d)$: Yield in our detectors is dependent on

$\phi(E' \geq E_d)$ Neutrino Flux

⊗

$\sigma_{c,d,e..}(E' \geq E_d)$ Neutrino Cross Section

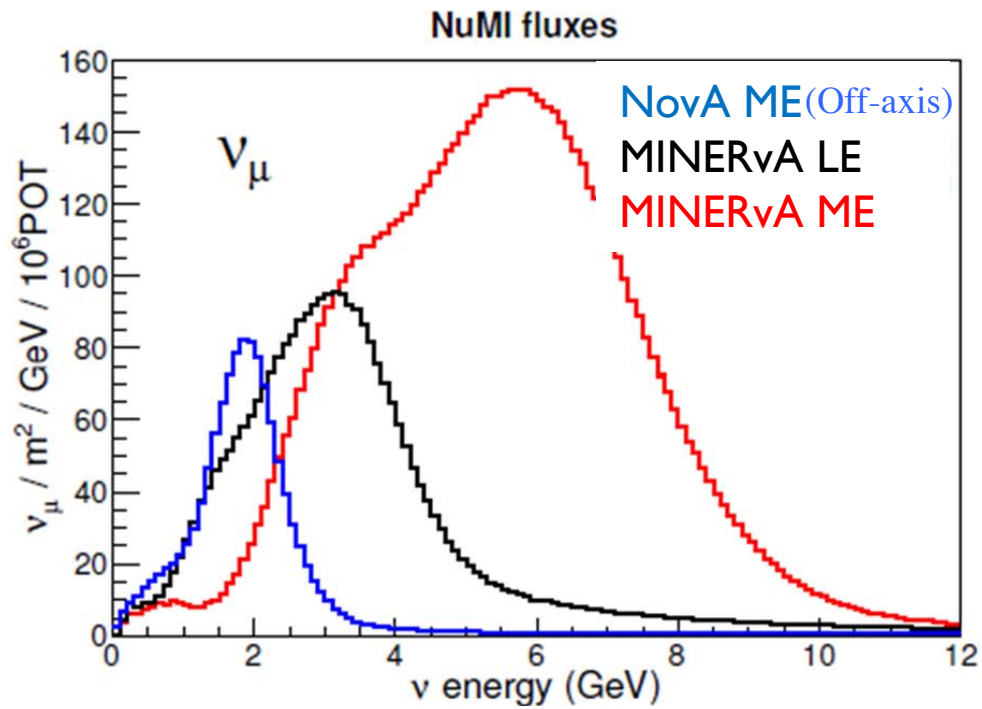
⊗

$Nuc_{c,d,e..}(E' \geq E_d)$ Neutrino Nuclear Effects

$Y_{c\text{-like}}(E_d)$: What we find in our detectors **is not necessarily** what was produced at the interaction. The physics we are after depends on what was produced!

What are the challenges
$\phi(E)$ – The Neutrino Flux

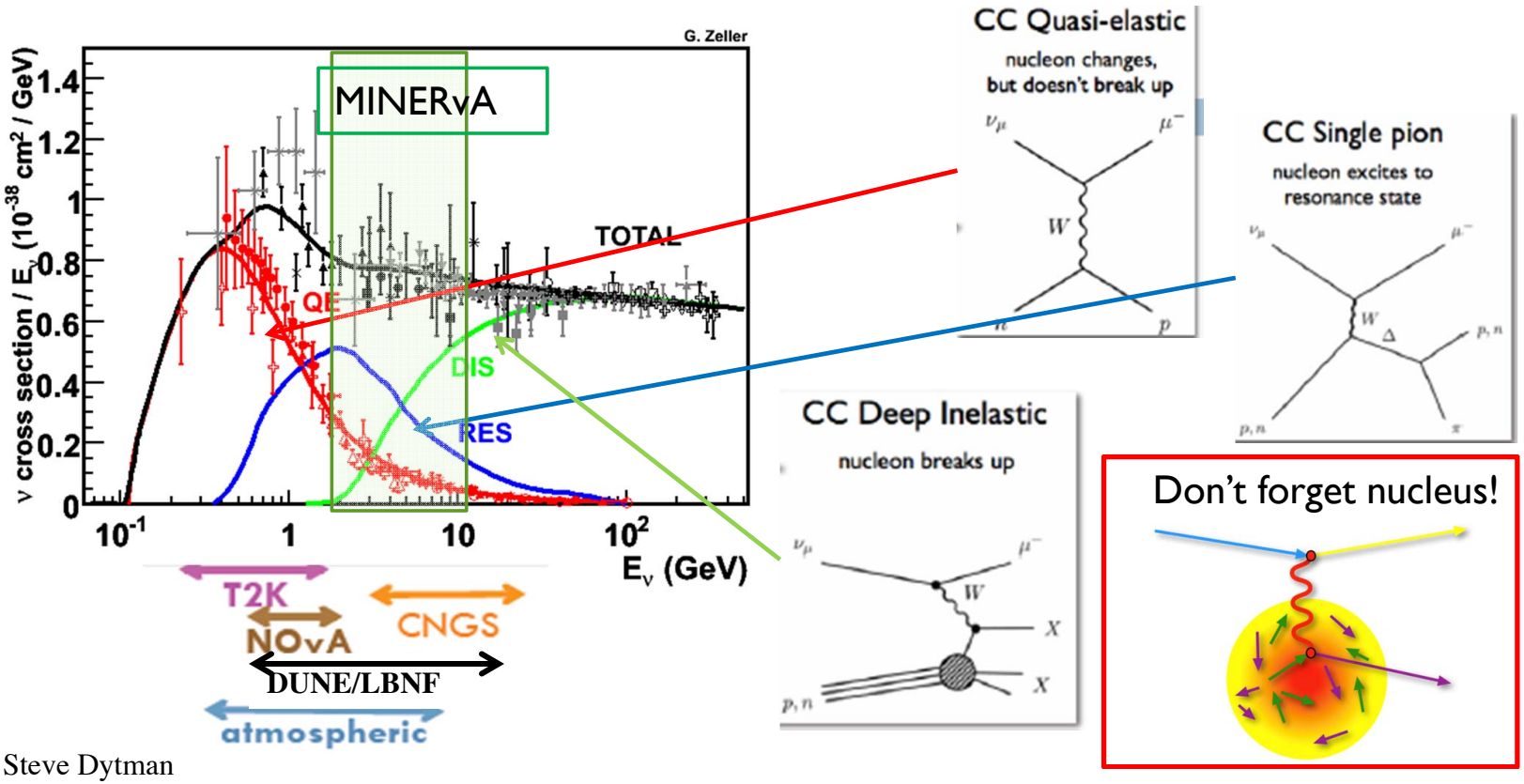
- Wide energy spread of incoming neutrinos.
- We do not know a priori the energy of the interacting neutrino.
- We measure the energy by what we observe in our detectors.
- The energy we measure is not necessarily the energy of the incoming neutrino.



What are the challenges?

GeV Neutrino experiments see a mix of cross-sections

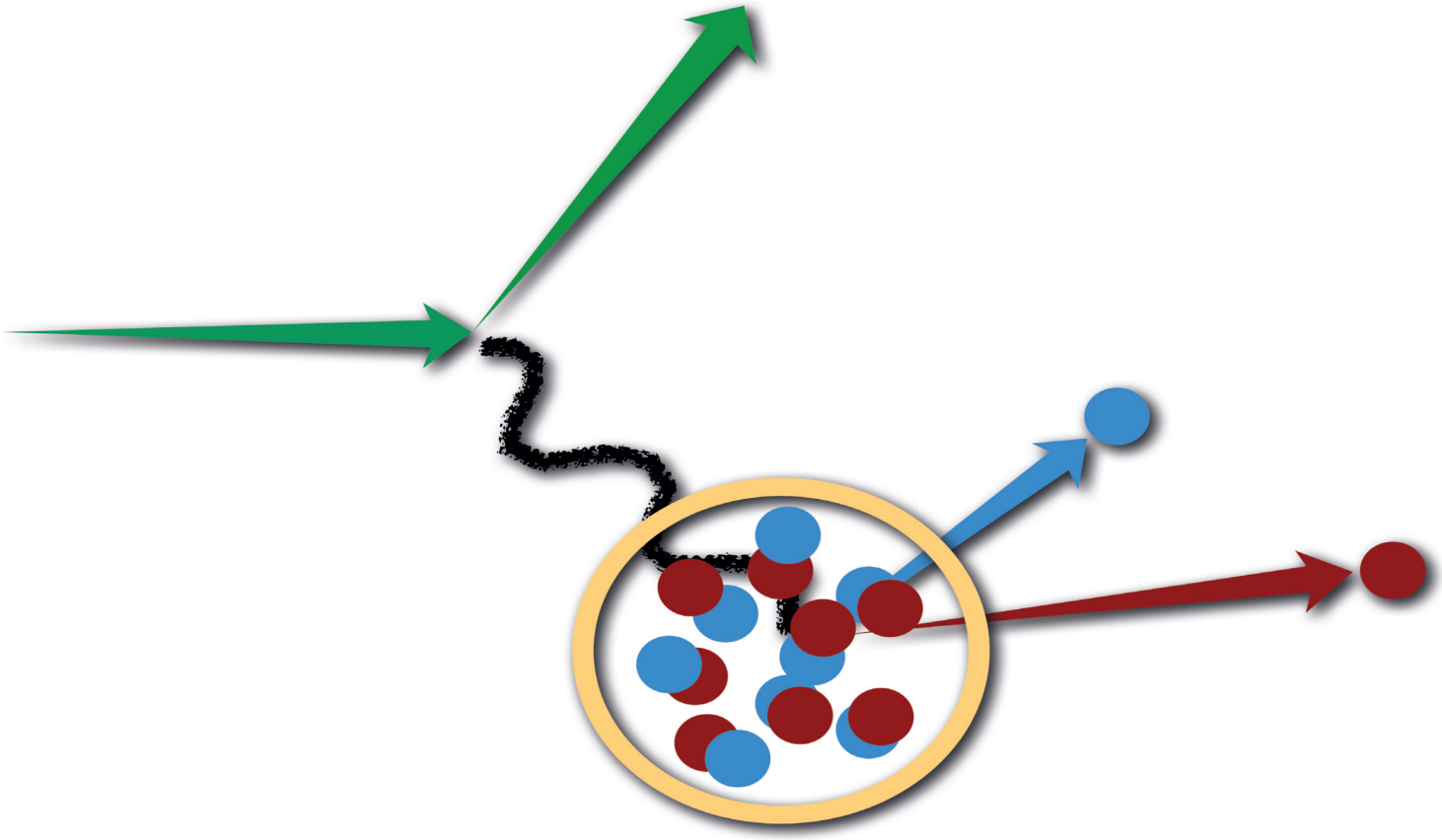
- Most nucleon data from **bubble chambers** (low statistics)
- All present-day ν experiments beams with energies 0.5-20 GeV



Thanks to Steve Dytman

DON'T FORGET THE NUCLEUS!

Most present-day ν experiments use CH, H_2O, Ar targets



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⊗

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⊗

$Nuc_{c,d,e..}$ c $(E' \geq E_d)$ Neutrino Nuclear Effects

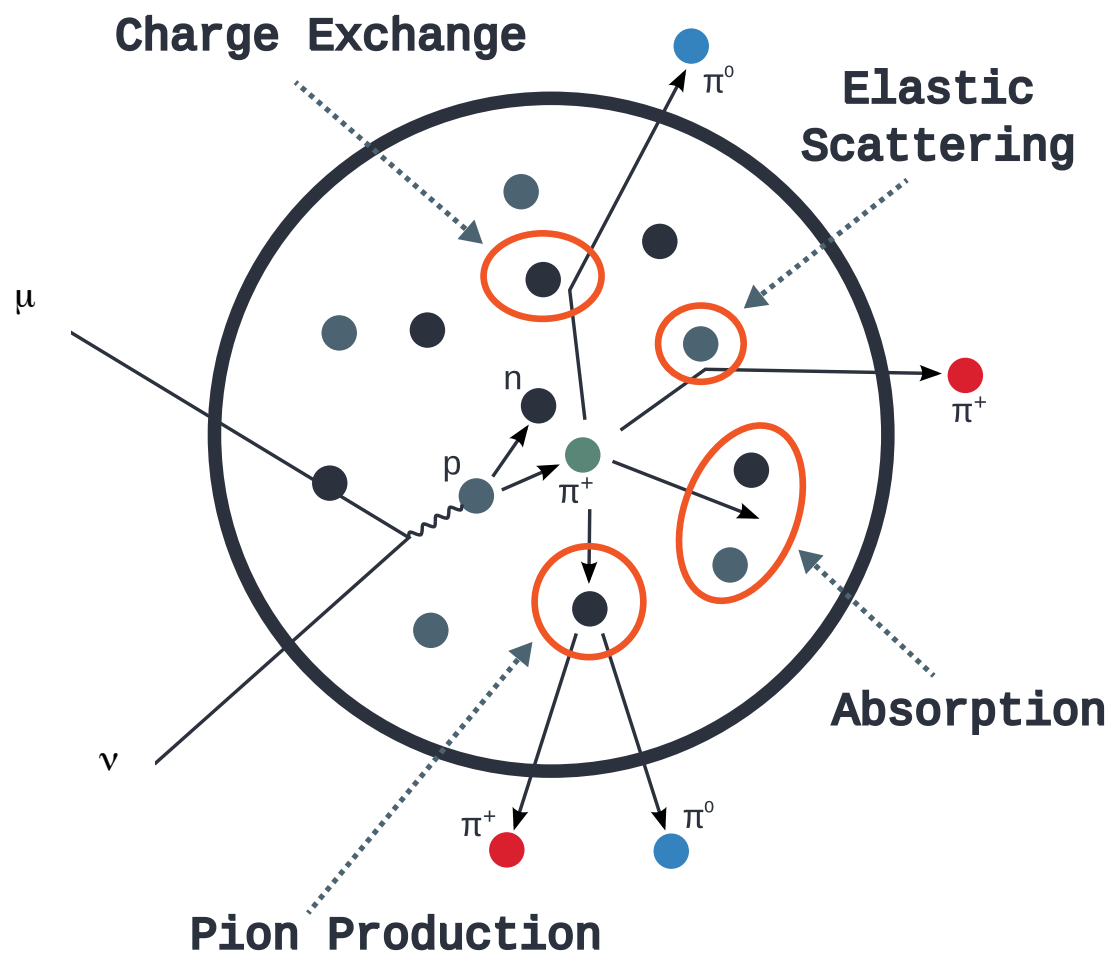
The Supreme Mixer / The Grand Deceiver – where neutrino physics meets nuclear physics - a migration that mixes produced channel and energy to detected channel and energy. **How do we move backwards through the nucleus?**

What are these Nuclear Effects $\mathbf{Nuc_{c,d,e..}}$ [illegible] $\mathbf{c}$ $\mathbf{(E' \geq E)}$ in Neutrino Nucleus Interactions?

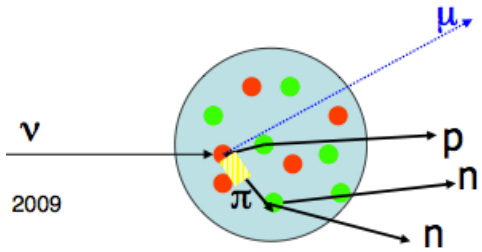
Improving the sophistication of our nuclear model

- Target nucleon in motion – classical Fermi gas model or spectral functions (Benhar et al.) ----> more sophisticated models.
- Certain reactions prohibited - Pauli suppression.
- Cross sections, form factors and structure functions are modified within the nuclear environment and parton distribution functions of bound nucleon are different than in an isolated nucleon.
- **Produced topologies are modified by final-state interactions modifying topologies and possibly reducing detected energy.
  - Convolution of $\sigma(n\pi)$ ⊗ formation zone model ⊗ π-charge-exchange/ absorption.
- **Nucleon-nucleon correlations such as MEC and SRC and even RPA implying multi-nucleon initial states.
- Ab initio Green's Function MC techniques - limited to inclusive, non-relativistic $\leq$ C. Need exclusive, relativistic on A $\geq$ Ar.

Final State Interactions (FSI)



The Nucleus: Final State Interactions (FSI)

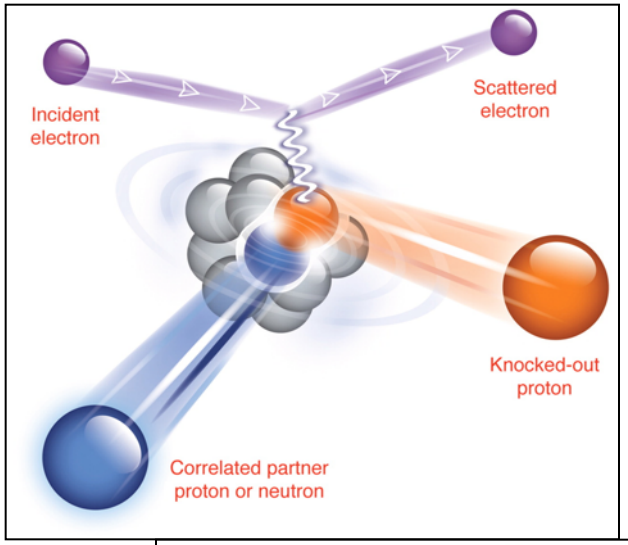


- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy. Currently using mainly **cascade models for FSI**.
- For example, an initial pion can charge exchange or be absorbed on a pair of nucleons.
- Final state observed is μ + p that makes this a fine candidate for QE production. We've probably also lost measurable energy.

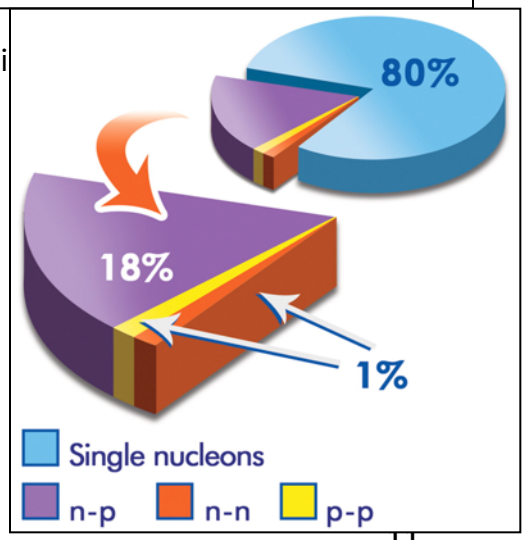
Example numbers	**Final μ p**	**Final μ p π**
Initial μ p	90%	10%
Initial μ p π	25%	75%

Independent Nucleons?
The Nucleus: Nucleon-Nucleon Correlations -npnh

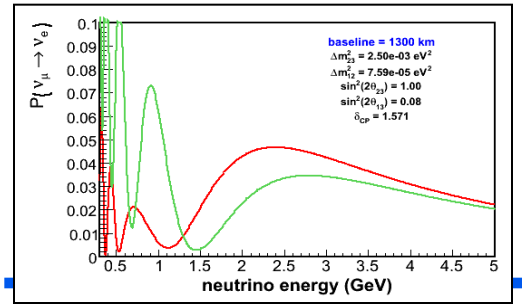
- Electron scattering
  - Measurements on ^{12}C indicate 20% correlated nucleons with mostly **np** pairs in the initial state.
- Neutrino scattering
  - Implies initial produced state in neutrino scattering of **nn in antineutrino** and **pp in neutrino** CC scattering.
  - Do not forget the **axial-vector** component!
  - **Of course, what we eventually detect can be modified by Final State Interactions when interpreting neutrino scattering data.**



R. Subedi et al., Sci 320, 1476 (2008)



Physics of GeV ν-nucleus Interactions – **Nuclear Effects**



E_ν^{Incoming}

E^{Detected}

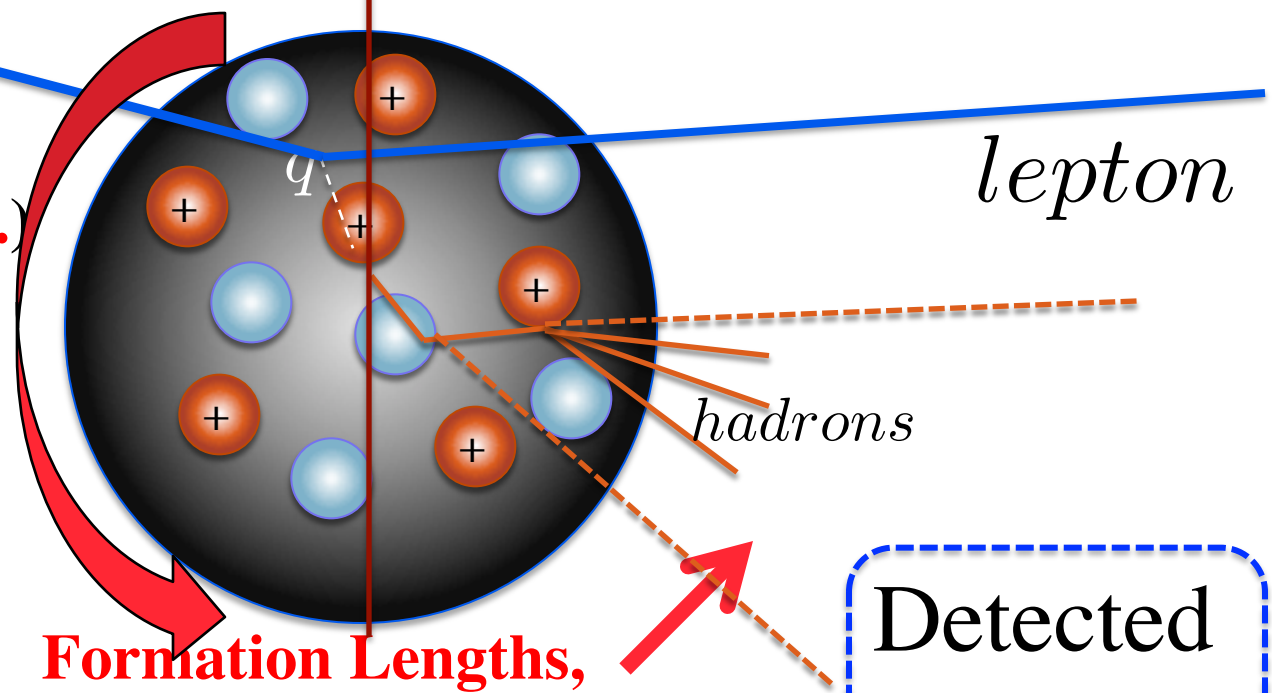
What we want! – What we get!

ν

Initial Nucleon State (RFG, SF, MEC, SRC..)

Cross Sections

Produced Channel



Formation Lengths, Final-State Interaction Nuclear Parton Distributions

Detected Topology

Putting it all together: The Nuclear Model
The Nuclear Environment used in Experiments

- The events we observe in our detectors are convolutions of:

effective $\sigma_{c\text{-like}}^{A}(E)$

$$Y_{c\text{-like}}(E_d) \;\alpha\; \phi_\nu(E' \geq E_d) \;\otimes\; \sigma_{c,d,e..}(E' \geq E_d) \;\otimes\; \mathbf{Nuc}_{c,d,e..\to c}(E' \geq E_d)$$

- These last two terms are the **nuclear model** in **event generators (simulators)**:
  - Provide information on how signal and background events should **appear** in our detectors if the model is correct.
  - Provide means for estimating systematic errors on measurements.
  - One of the most important components in the analysis of experimental data.

- Current Generators used by experimental community – **each with its own model of the nuclear environment!**
  - ***GENIE*** – ArgoNeut, MicroBooNE, MINOS, MINERvA, NOvA, T2K, DUNE
  - **NEUT** – SuperKamiokande, K2K, SciBooNE, T2K
  - **NuWRO** – K2K, MINERvA as check of other generators

- **GiBUU** – Nuclear Transport Model: compare to generators

It turns out where we are depends on which nuclear model / generator we use!

Where are we?

Map at Great Wall

Outline of A Step-by-Step Two-Detector LBL Oscillation Analysis

Importance of the Nuclear Model

1) Measure detected E_d and event topology in the near detector.
2) Use the **nuclear model** to take the detected E_d and topology back to the initial interaction energy E_ν and topology.
3) Project this initial interaction E_ν distribution, perturbed via an oscillation hypothesis that **changes ϕ_ν** at the far detector.
4) Following the initial interaction in far detector, use the **nuclear model** to take the initial E_ν and topology to a detected E_d and topology.
5) Compare with actual measurements in the far detector.

Critical dependence on the nuclear model <u>even with a near detector – SYSTEMATICS DO NOT CANCEL!</u>

How do we improve the nuclear model?!?

How do we Improve the Nuclear Model?

- Perfecting the nuclear model is non-trivial— A single measurement off a nucleus is sensitive to many different effects

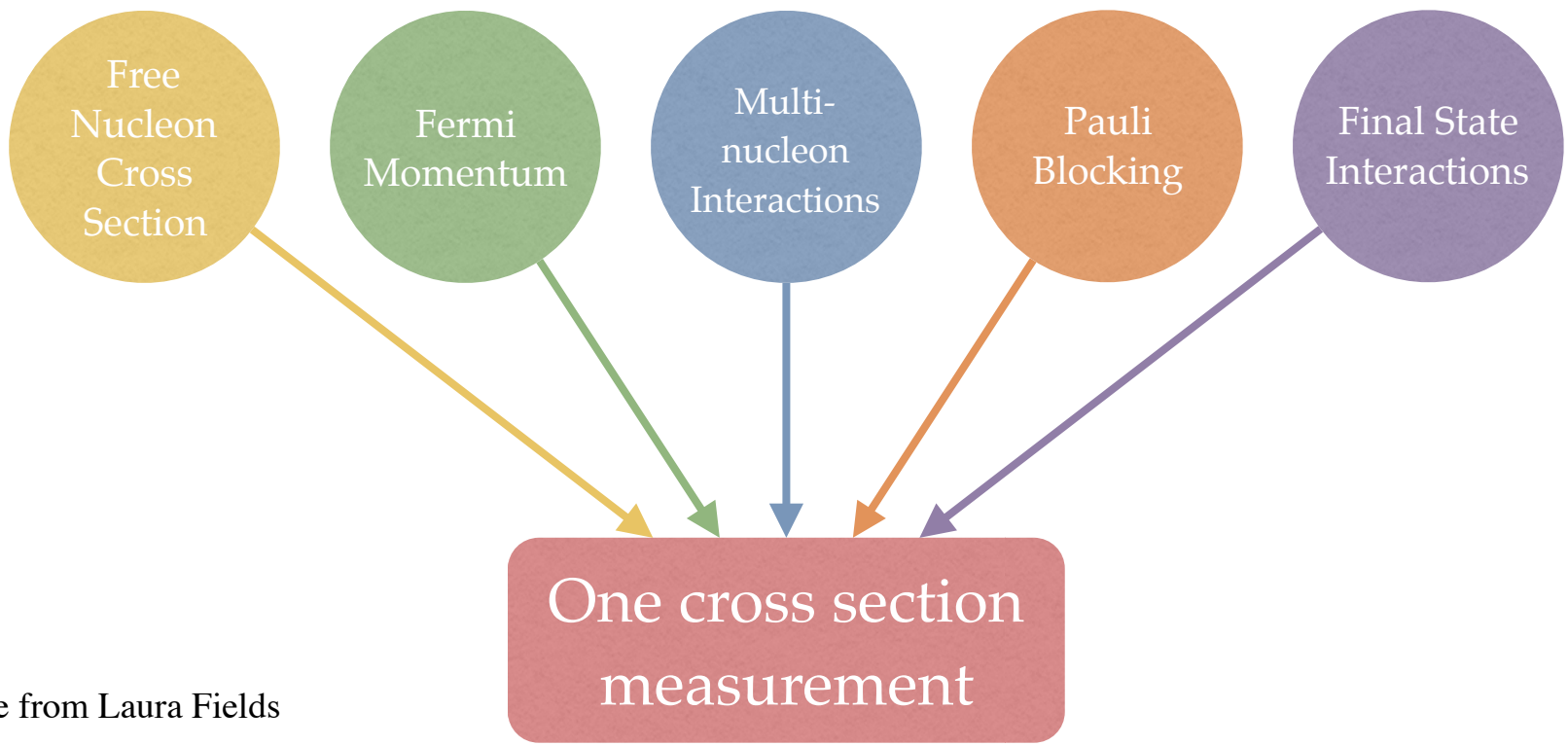


Figure from Laura Fields

How do we Improve the Nuclear Model?

- We need to have many different measurements sensitive to the same effects to have any hope of separating and defining the effects.

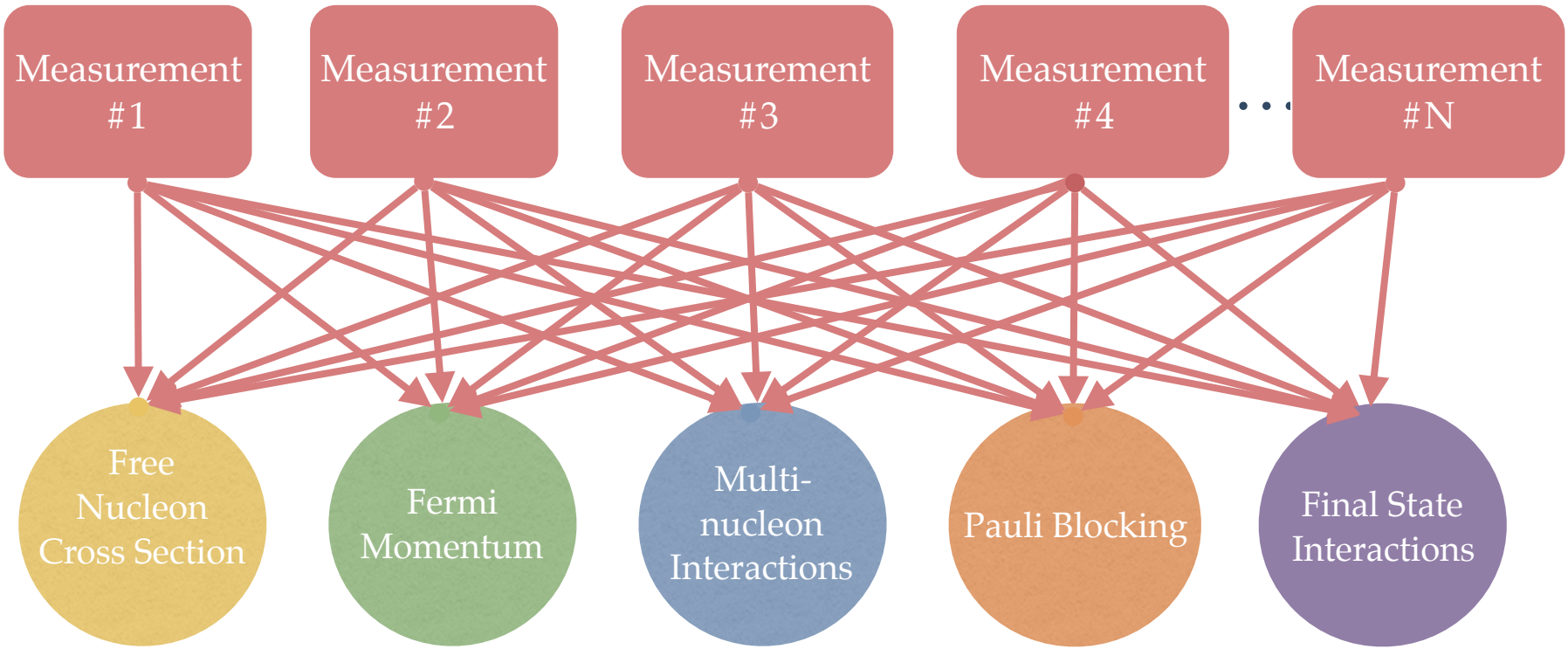
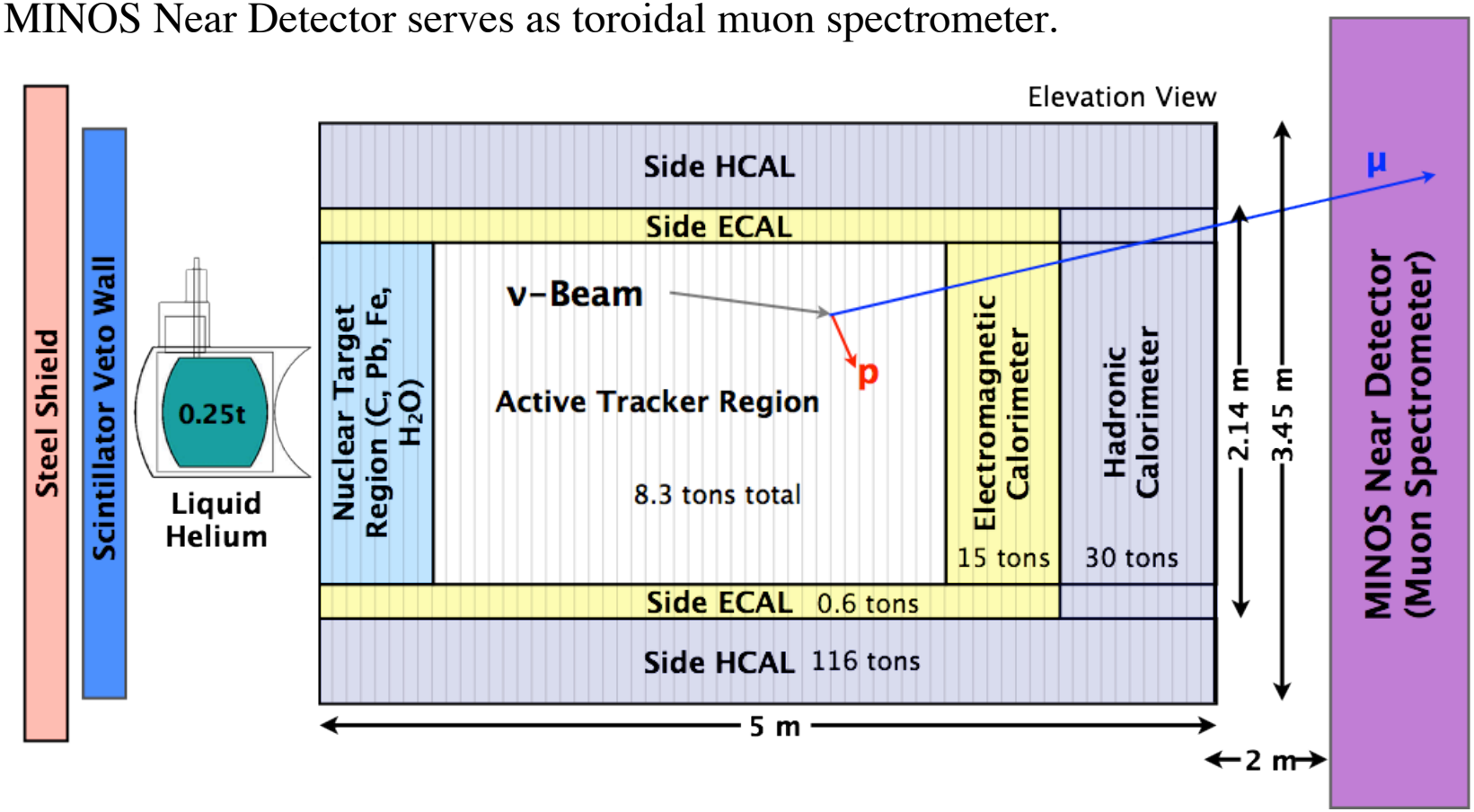


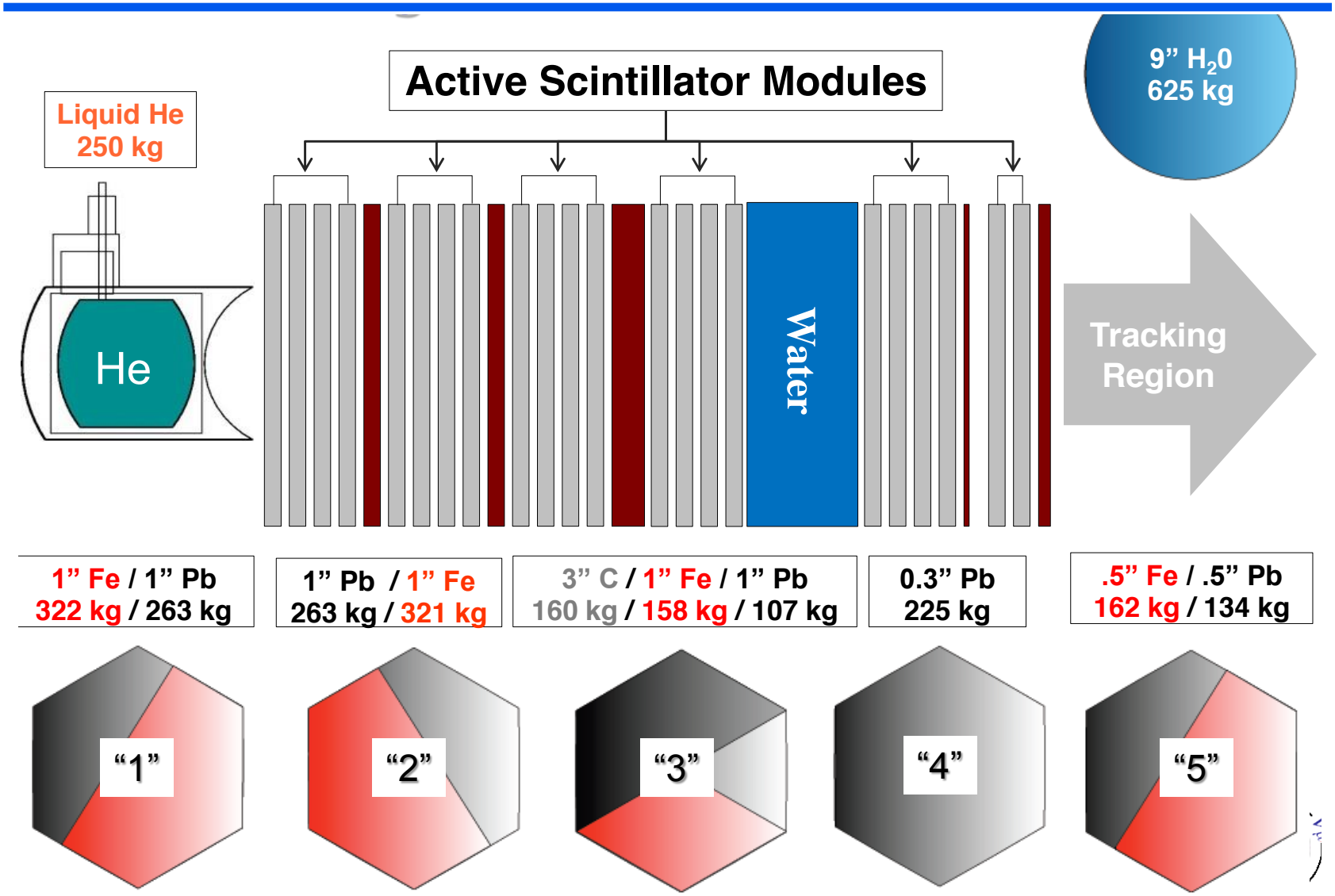
Figure from Laura Fields

Refining the Nuclear Model
The MINERνA Experiment - Detector

- 120 plastic scintillator modules for tracking and calorimetry (~32k readout channels).
- Construction completed Spring 2010. He and Water added in 2011.
- MINOS Near Detector serves as toroidal muon spectrometer.



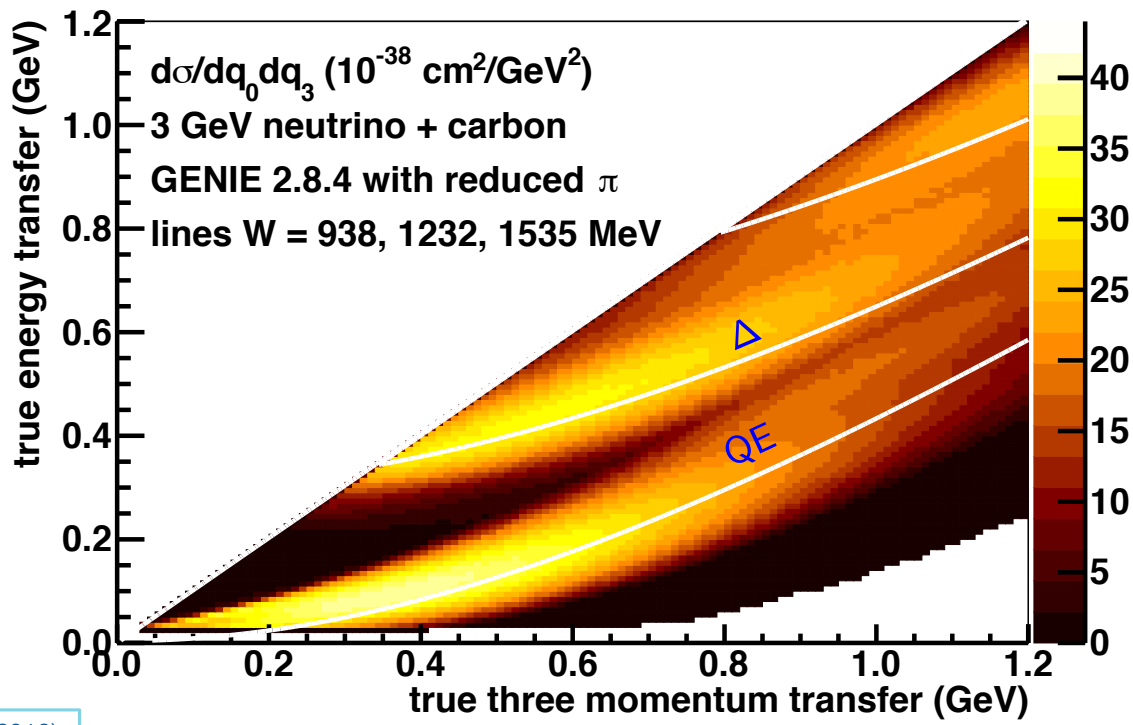
Nuclear Targets



Correlated Nucleon Pairs

Muon Neutrino CC Inclusive w/ Low Recoil

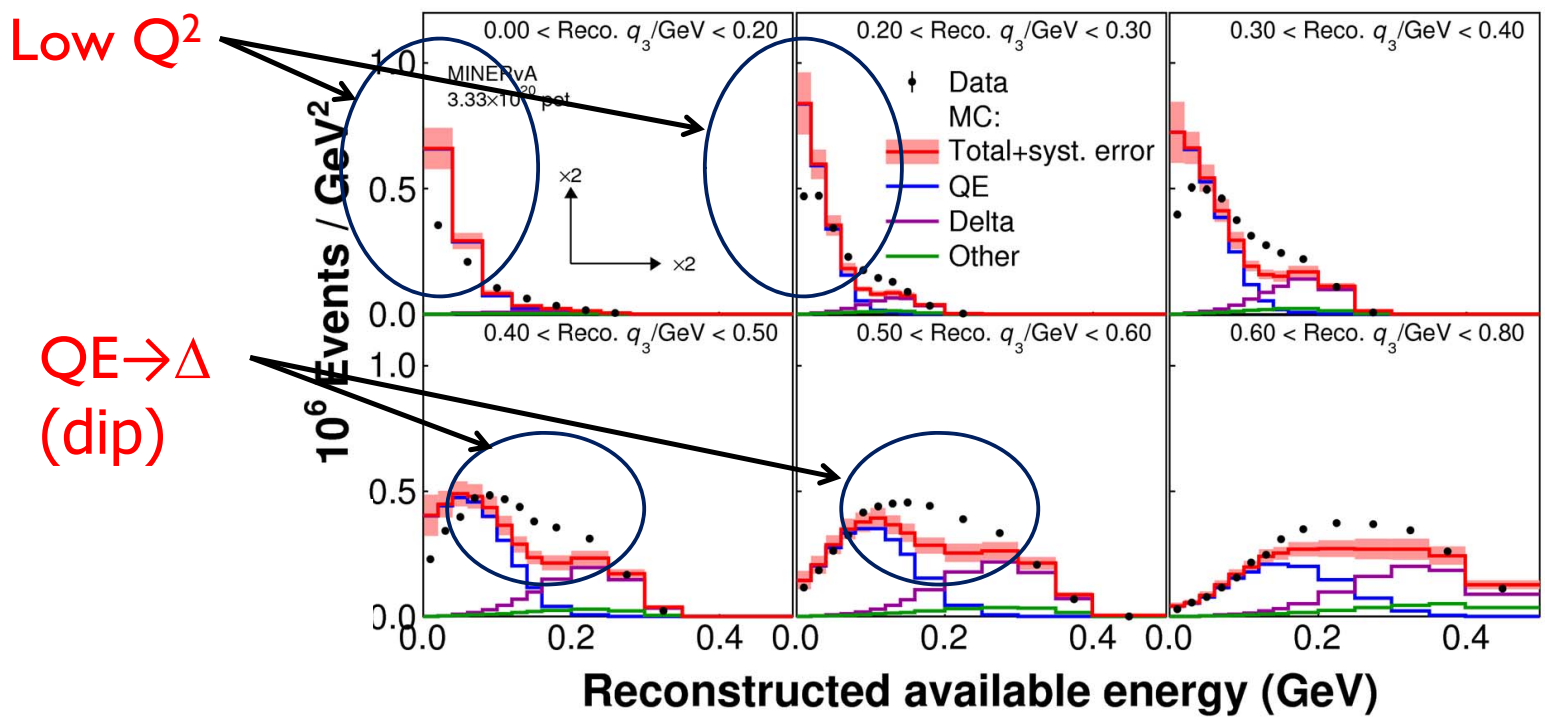
- A tactic is to borrow a page from electron scattering and not make a cut, but to look at an inclusive sample bridging QE and Δ.
- Reconstructing energy and momentum transfer allows us to isolate channels in a fashion (somewhat) analogous to electron scattering



Phys. Rev. Lett. 116, 071802 (2016)

First look at what's missing…

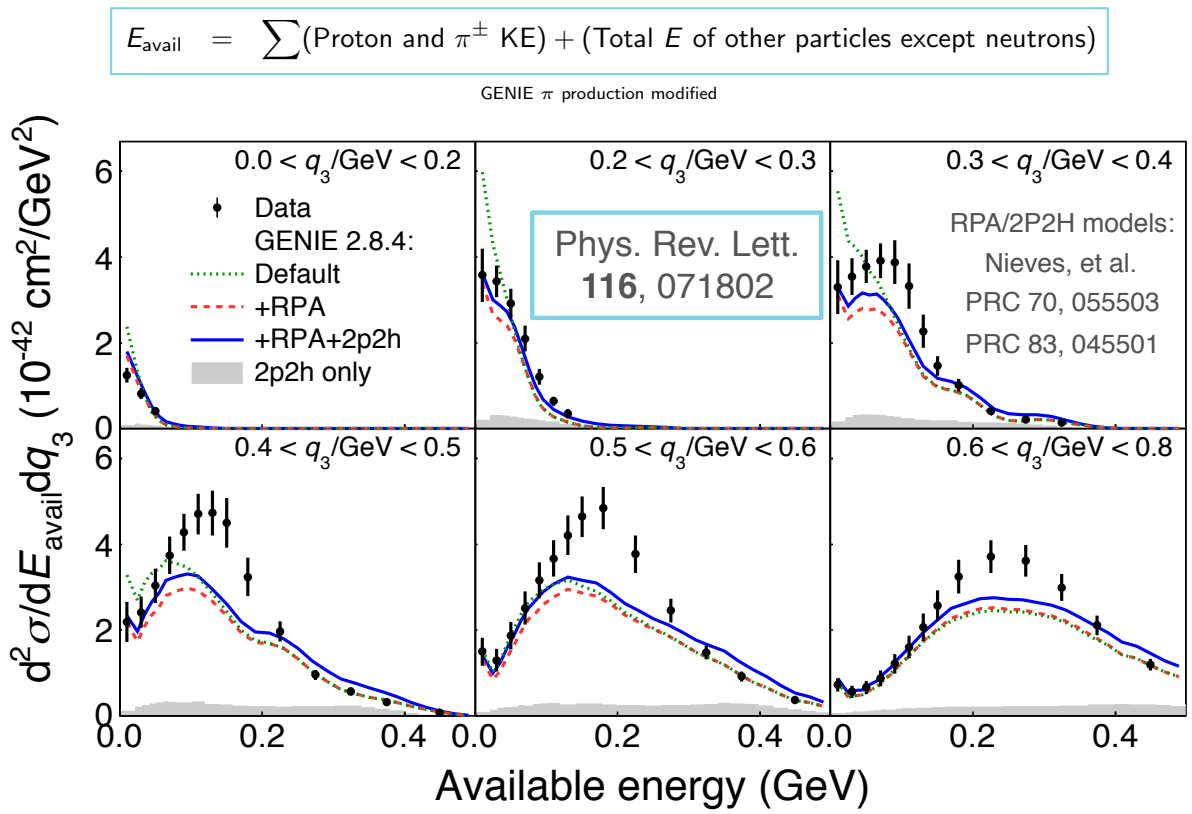
- Compare the MINERvA measurements to the default GENIE event simulator (no RPA and no 2p2h contributions)
- The default nuclear model has difficulty describing the data.
- Clearly problems at low q and n between QE and Delta peaks



Valencia Model for Low E_H Inclusive Scattering

Juan Nieves - **Springer Proc.Phys. 182 (2016) 3-54**

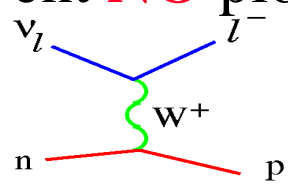
- Introduce RPA and 2p2h correlations to the neutrino community via the Valencia model !
- This improves agreement but obviously needs more work! Is the axial vector contribution larger than modeled?



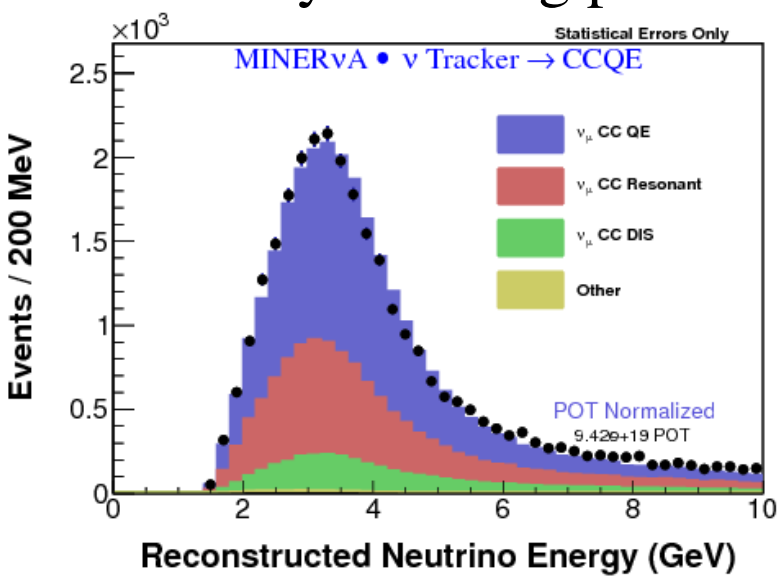
Phys. Rev. Lett. **116**, 071802

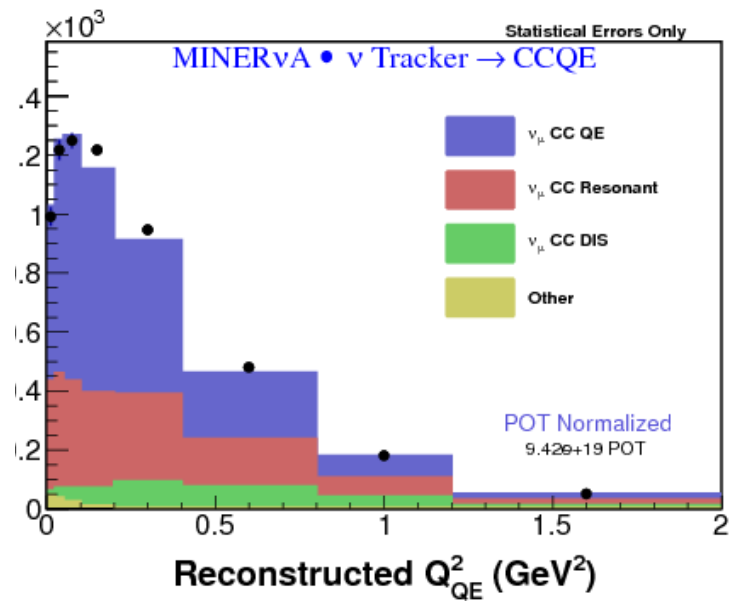
MINERvA: Single Muon QE-like Analysis

- Demand that the measured topology in the detector is consistent with a Quasi-elastic (QE) event **NO** pion in the observed state:



- Less then ½ of the events meeting this requirement are actually QE events. The rest are resonance and even DIS events at production but have only 1 exiting proton in the final state!

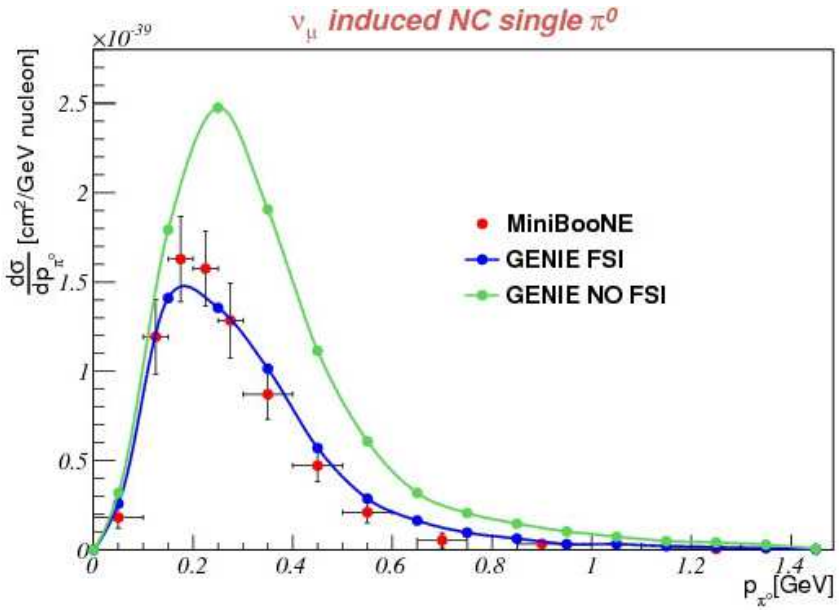


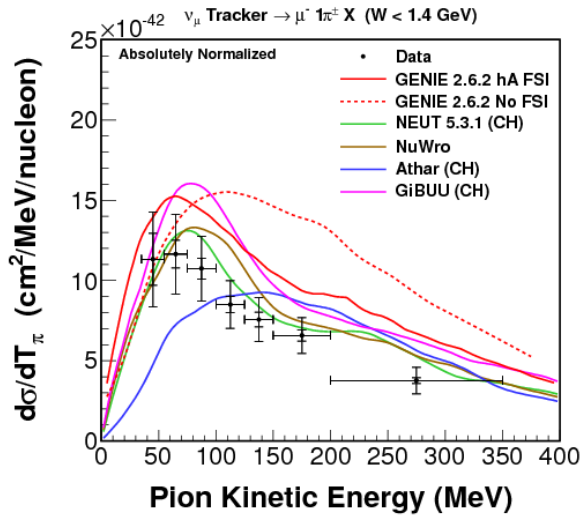


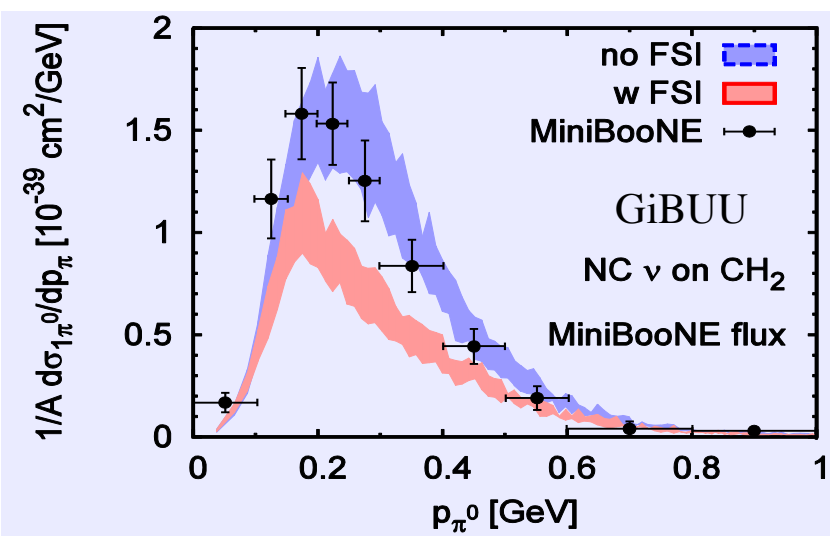
Conclusions: QE-like Scattering off a Nucleus

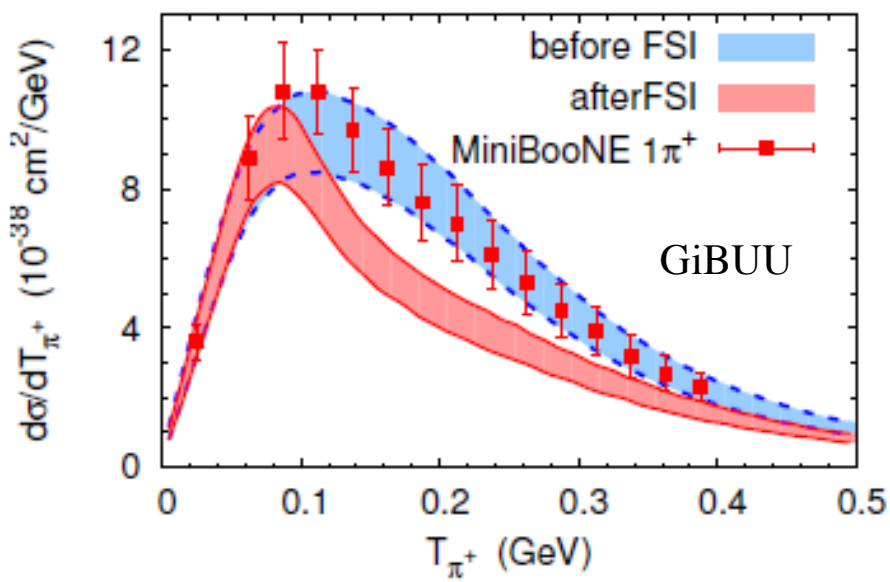
- Compare QE-like (no pion) with only single muon to QE-like (no pion) events with a single muon + 1 proton with K.E. > 110 MeV.
- Best model fitting single μ QE-like events is NOT best for μ + p ! Problem with FSI model?
- **No single model fits MINERVA single μ and μ + p data. Not to mention other experiment's QE results**
- The QE-like channel contributes more evidence for necessity of considering nucleon-nucleon correlations from multiple experiments.

A step up in W to pion production
Comparison of π^0 and $\pi^{\pm}$ Models with Data



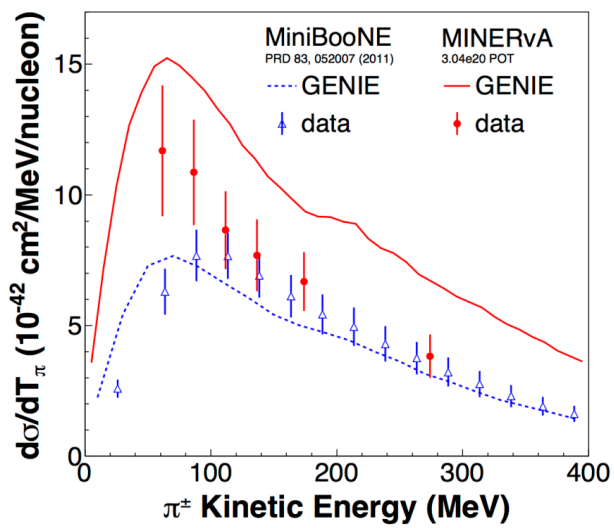






Summary for 1-π Analysis

- MiniBooNE - E_ν~1 GeV
  - Best theory models (GiBUU, Valencia) strongly disagree in shape
  - Event generators have shape right, but problems in detail
- MINERvA - $\langle E_\nu \rangle$ = 4 GeV
  - Dominantly Δ resonance formation, decay in nucleus, very similar to MiniBooNE)
  - Event generators have shape but not magnitude
  - Event generators show the absolute need for FSI
  - GiBUU has shape right, but wrong magnitude

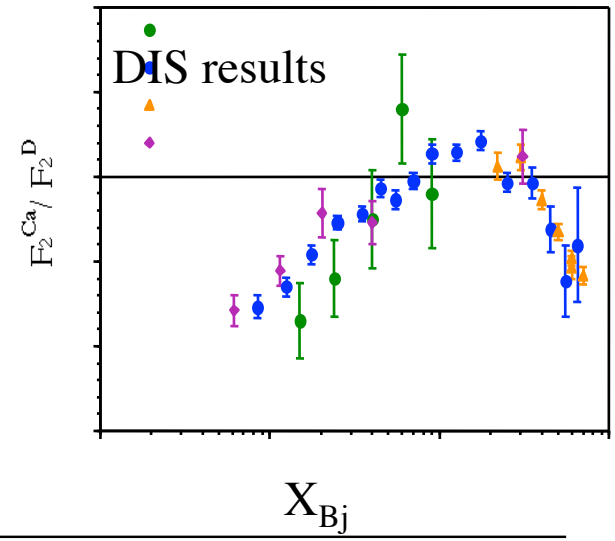


- **No models describes all data sets well!**
  - Theory based calculations have better physics (nuclear corrections), but don't describe data better than simpler event generator codes.

Inclusive Nuclear Target Cross section Ratios

Minimal contribution from DIS

- MINERvA nuclear targets of C (166 Kg), Fe (653 kg) and Pb (750 Kg)
- We are used to seeing ratios like at right that has been measured for **DIS events.**
- **This data includes QE and Resonance!**



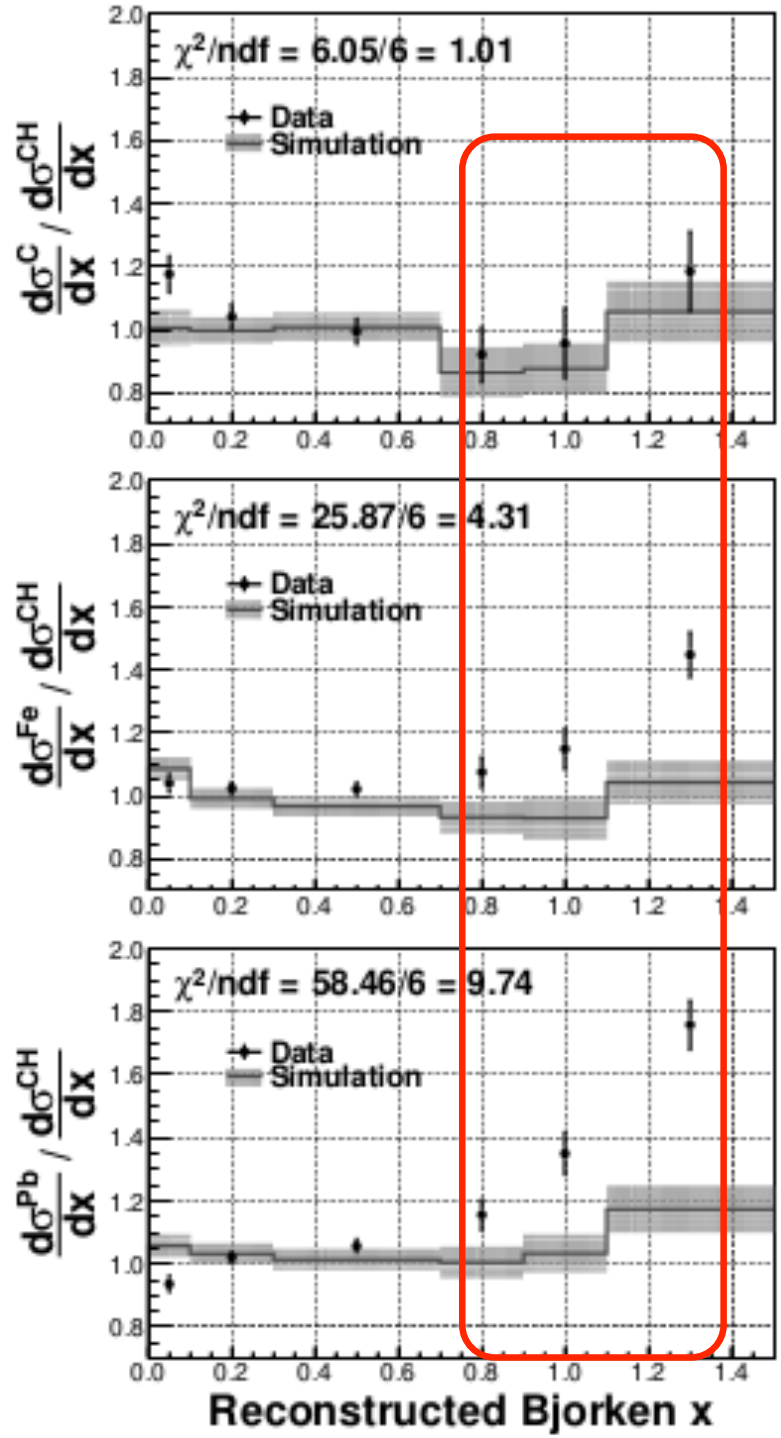
Reconstructed x MINERvA	QE (%)	Res (%)	DIS (%)	lowQ DIS (%)	Con (%)	Mean Generated Q^2 (GeV^2)
0.0–0.1	11.3	42.5	5.9	19.2	15.7	0.23
0.1–0.3	13.6	36.4	16.7	9.1	23.0	0.70
0.3–0.7	32.7	32.8	11.8	1.4	21.1	1.00
0.7–0.9	55.1	25.4	4.3	0.5	14.6	0.95
0.9–1.1	62.7	21.6	2.8	0.5	12.3	0.90
1.1–1.5	69.6	18.1	1.9	0.4	9.9	0.82
> 1.5	79.1	12.8	0.6	0.3	7.1	0.86

High x summary
INCLUSIVE RATIOS

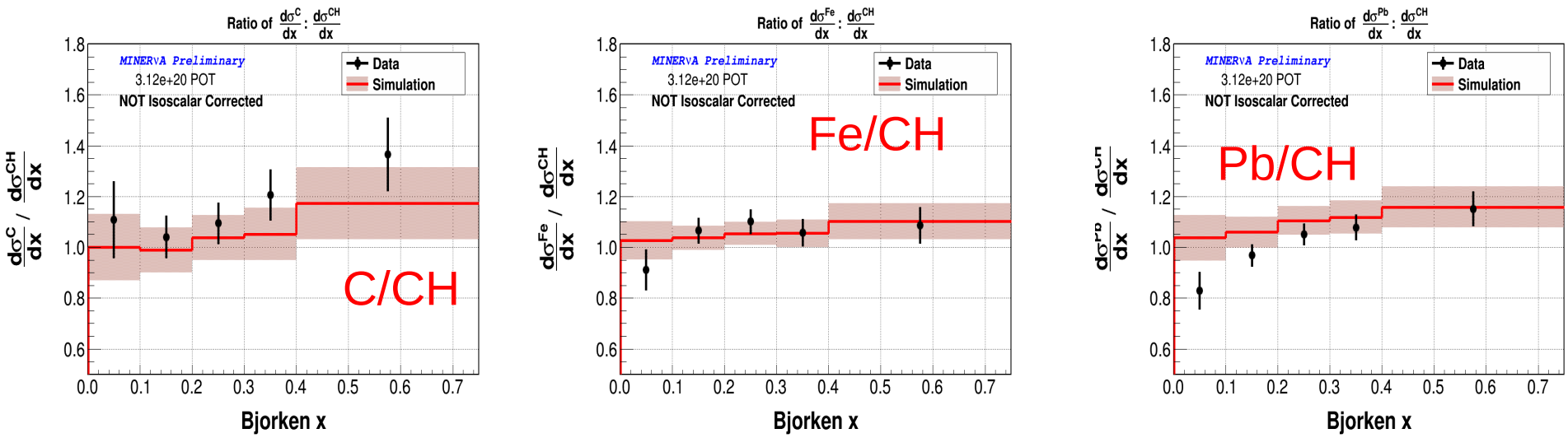
- At x = [0.7,1.1], we observe an **excess** that grows with the size of the nucleus
- This effect is not modeled in the GENIE simulation.
- **Do we not understand the A-dependence of QE and Resonance production??**

x_{bj}	QE	DIS	OTHER
0.0 – 0.1	11.3%	5.9%	77.4%
0.1 – 0.3	13.6%	16.7%	68.5%
0.3 – 0.7	32.7%	11.8%	55.3%
0.7 – 0.9	55.1%	4.3%	40.5%
0.9 – 1.1	62.7%	2.8%	34.4%
1.1 – 1.5	69.9%	1.9%	28.4%
> 1.5	79.1%	0.6%	20.2%

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



MINERvA Nuclear DIS Cross Section Ratios



- Our data suggest additional nuclear shadowing in the lowest x bin ($0 < x < 0.1$) than predicted in lead with a hint also in iron.
- Lowest x bin is at $\langle x \rangle \sim 0.07$ and $\langle Q^2 \rangle \sim 2.0\ (\mathrm{GeV}/c)^2$
- At this x and Q^2, shadowing is not expected in Pb with the vector current.

In Summary: Nuclear Physics Meets Neutrino Physics

No single nuclear model can fit all of the accumulated data.

However, it is not a knockout – we are simply "on the ropes" and need collaboration with the nuclear physics community.

First Conclusions

- Need to move away from the simple IA models of the nucleus used in most event generators.
- Need to develop a model of neutrino nucleus interactions that is not a patchwork of individual thoughts that are difficult/impossible to combine in a smooth continuous and correct whole.
- The model has to work for nuclei from C to Ar to Fe and for energies from sub-to-multi-GeV. **NP-HEP Collaborations!**
- Need highly accurate neutrino nucleus scattering measurements to constrain the nuclear model. **NP-HEP Collaborations!**

NuSTEC?

Neutrino Scattering Theory Experimental Collaboration

- NuSTEC promotes the collaboration and coordinates efforts between:
  - Theorists (mainly NP) – studying neutrino nucleon/nucleus interactions.
  - Experimentalists – primarily those actively engaged in neutrino nucleus scattering experiments as well as those trying to understand oscillation experiment systematics. e-A experimentalists are certainly welcome.
  - Generator builders – actively developing/modifying the model of the nucleus as well as the behavior of particles in/out of the nucleus within generators
- The main goal is to improve our understanding of neutrino interactions with nucleons and nuclei and, practically, get that understanding in our event generators.
  - The impact of our main goal will be widespread in both hadron and nuclear physics and directly effect oscillation physics.
- Along the way we want to expand support for theorists and encourage a growing theoretical community.

NuSTEC

A Collaboration of HEP and Nuclear Experimentalists and Theorists Studying Low-energy Neutrino Nucleus Scattering **Physics**

- **Workshops**: Coordinate and Organize Community-wide Workshops when needed
  - Main Conference: The NuInt Neutrino Interaction Workshop (next, June 2017, Toronto)
  - **Do we need a modern neutrino-deuterium/hydrogen experiment?**
- **Schools/Training Programs**: Organize and run training programs in:
  - Neutrino Scattering Event Generators: 30 students University of Liverpool last May
  - Theory-oriented Neutrino-nucleus Scattering physics: 85 students Fermilab October 2014.
  - **Next such extended School to be held at Fermilab in Oct/Nov 2017.**
- **Global Fits**: Combine results from multiple experiments to compare with and then, if necessary, modify a theory/model framework.
- **Current Project White Paper/Review Publication – State of Neutrino Nucleus Scattering Physics.**

The NuSTEC Board

One Experimentalist from every ν-A experiment and one theorist from every ν-A nuclear theory "school"

Theorists (9)

- Luis Alvarez Ruso (co-spokesperson)
- Sajjad Athar
- Maria Barbaro
- Omar Benhar
- Natalie Jachowicz
- Marco Martini
- Toru Sato
- Rocco Schiavilla
- Jan Sobczyk (nuWRO)

Experimentalists (16)

- Steve Brice
- Dan Cherdack
- Steve Dytman (GENIE)
- Rik Gran
- Yoshinari Hayato (NEUT)
- Teppei Katori
- Kendall Mahn
- Camillo Mariani
- Mark Messier
- Jorge G. Morfín (co-spokesperson)
- Ornella Palamara
- Roberto Petti
- Gabe Perdue (GENIE)
- Makoto Sakuda
- Federico Sanchez
- Sam Zeller

NuSTEC White Paper / Review

- **Executive Summary.**
- **Overview of the Current Challenges in the Theory of Neutrino Nucleon/ Nucleus Interaction Physics.**
  - Initial Interaction Dynamics
  - Final State Interaction Models
  - Radiative and Coulomb Corrections
- **The Impact of Neutrino Nucleus Interaction Physics on Oscillation Physics Analyses**
  - How the cross section model couples to oscillation parameters
  - Description and current systematics of T2K, NOvA
  - Description and projected systematics of SBN / MicroBooNE
  - Description and projected requirements of DUNE, HK
- **Neutrino Event Generators**
- **e-A Scattering Input to ν-A:**

NuSTEC White Paper / Review

- **Quasi-elastic, Quasi-elastic-like Scattering**
  - QE on the nucleon
  - 1p1h, including Axial form factors for CCQE (non dipole, second class currents)
  - 2p2h, initial state and extensions to higher energy transfer, artificiality of separation into 1p1h/ 2p2h, double counting considerations, interference
  - Collective effects (RPA)
  - Experimental situation: MINERvA, MiniBooNE, T2K
  - Generator status
  - Open questions
- **Resonance Model**
  - Particle (meson, photon) production on the nucleon
    - » Resonant contribution: Delta(1232) and higher states
    - » Non-resonant backgrounds
    - » Model comparison
  - Particle production on nuclei: in-medium modifications
  - Final State Interactions and Generator Status
  - Experimental situation: MINERvA, MiniBooNE, T2K,...
  - Open questions

NuSTEC White Paper / Review

- **Coherent and Diffractive Meson Production**
  - Theoretical status
  - Experimental situation: K2K, SciBooNE, MINERvA, T2K
  - Generator status
  - Open questions
- **Shallow Inelastic Scattering and Deep Inelastic Scattering**
  - Low-Q kinematic and dynamic higher twist
  - Nuclear effects
  - Hadronization model
  - Experimental status
  - Generator status
  - Open questions

Current NuSTEC Style Collaboration

HEP Proposal: Nuclear Theory for Neutrino-Nucleus Interactions

Introduce extended ab initio GFMC techniques into GENIE

S.J. Brice , J.G. Morfin, G.N. Perdue, and G.P. Zeller
Fermi National Accelerator Laboratory

S.A. Dytman
Department of Physics and Astronomy, University of Pittsburgh

H. Gallagher
Tufts University

R. Schiavilla and J.W. Van Orden
Old Dominion University

A. Lovato, S.C. Pieper, and R.B. Wiringa
Argonne National Laboratory

J. Carlson and S. Gandolfi
Los Alamos National Laboratory

T.W. Donnelly
Massachusetts Institute of Technology

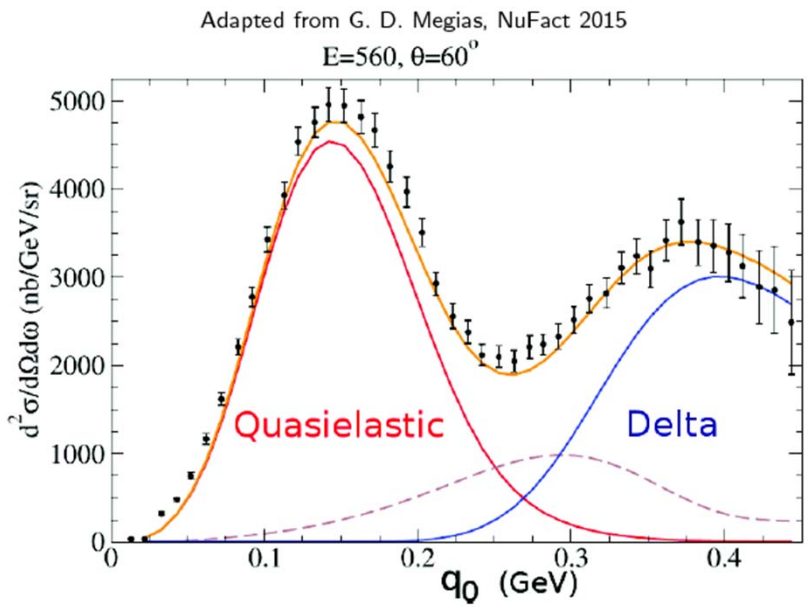
Conclusions

- Our knowledge of the nuclear environment has improved considerably in the last 10 years.
- This has been due to the concerted effort of nuclear theorists and HEP experimentalists often guided by the event generator physicists.
- We have come a long way but there are still O 10% uncertainties in almost all descriptions of **ν** nucleus interactions. The situation with **$\bar{\nu}$ is much worse!** We are still **a long way** from having a model that will enable us to project ND observables to FD predictions at the O few % level required by DUNE.
- NuSTEC is a significant step toward combining the talents of the NP and HEP communities to develop the necessary physics and produce the corresponding model for our experiments.
- The affected experiments and corresponding funding agencies need to acknowledge the absolute importance of this effort by earmarking funds for the personnel necessary to ensure success.

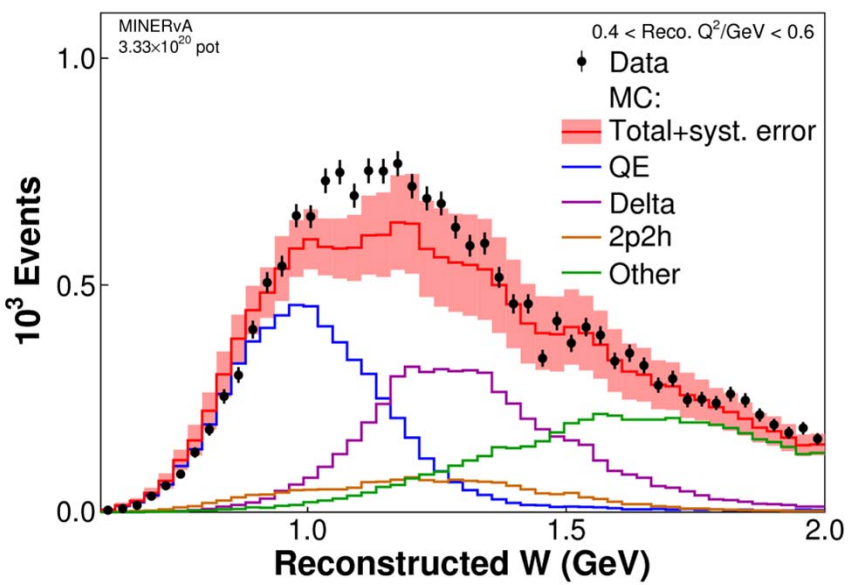
Backup Slides

Inclusive scattering with (e,e') and (ν_μ,μ)

- Electron scattering uses well-monitored high intensity beams with well-known initial and final lepton energy.
- Neutrino scattering uses high intensity but weakly interacting beams with a priori unknown energy. Energy is determined by sum measured event energy.



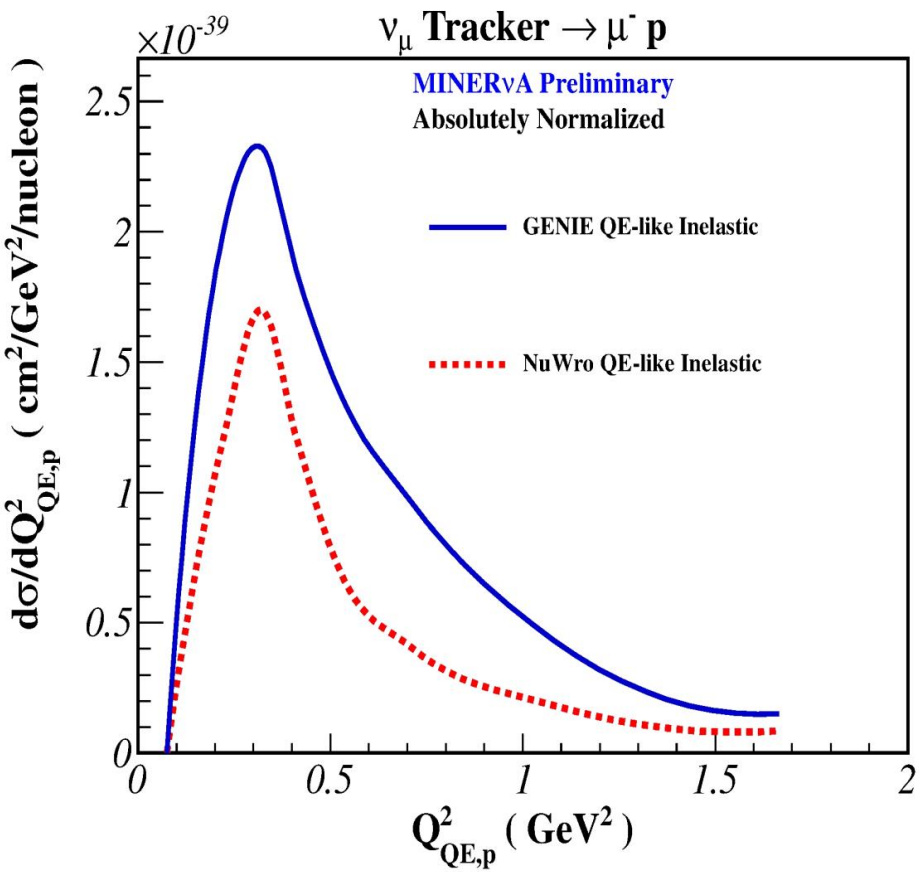
$\nu = q_0 = E_e - E_{e'}$



Nuclear Structure in the GENIE Event Generator

- Relativistic Fermi gas (RFG) – basic model in most generators
- Local Fermi gas (LFG) - depends on mass density
- Spectral function – simplified solution to many-body calculation
  - Great success in (e,e'), suggested for many years
  - Effective SF alternate model now
  - Full calculation in next major release of GENIE
- Greens' Function MC (GFMC) calculation (many-body)
  - Done by Carlson, Wiringa, Schiavilla, Pieper over many years
  - Proposal now being finished to submit to HEP-theory
  - Proposal includes working with GENIE experts to insert nuclear theory into the generator.

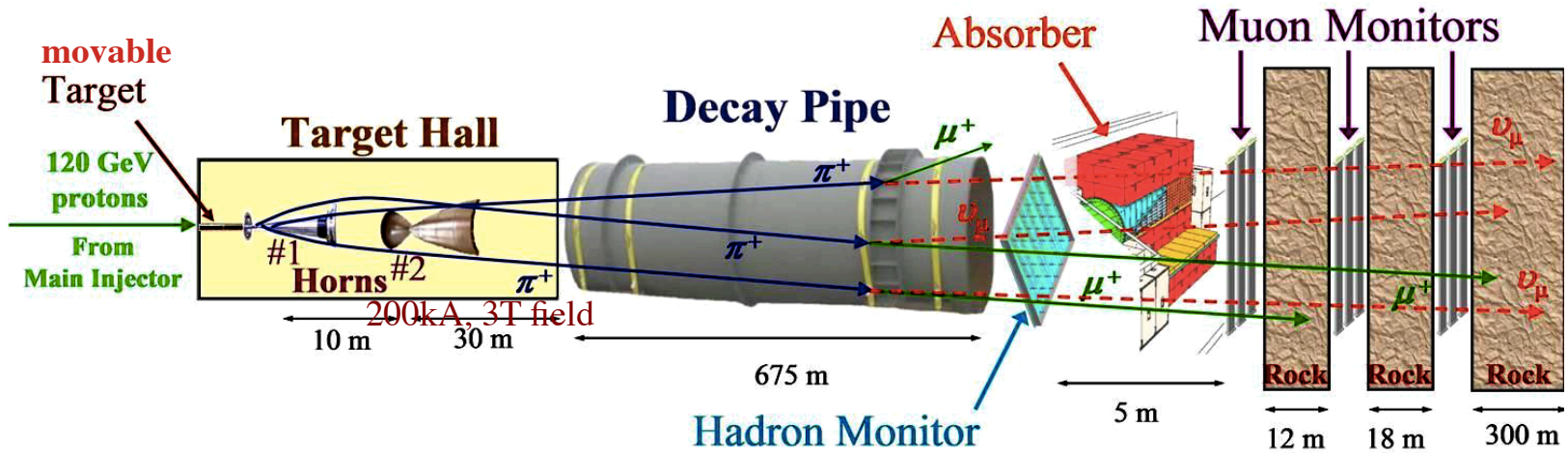
QE-like background

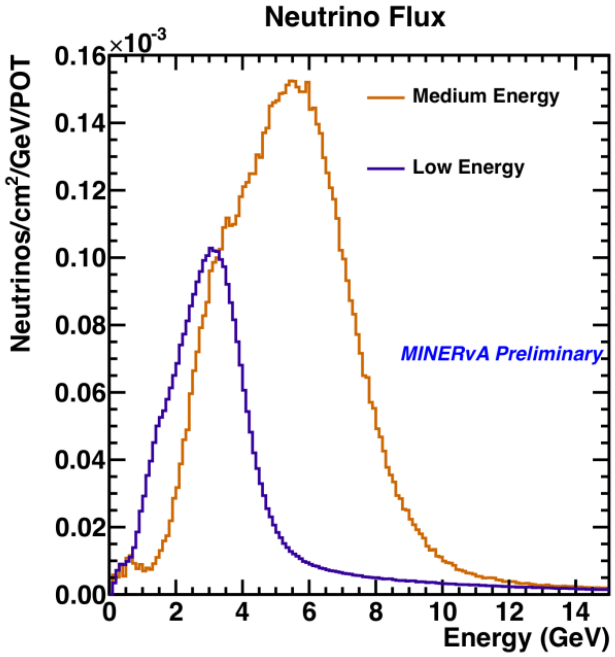


- The major background to true QE events comes from ineleastic produced events detected as QE-like.
- Observe the difference in this inelastic contribution from the NuWro vs GENIE nuclear models!
- Difference in both magnitude and shape coming from modeling of the production cross sections and final state interactions!
- **Reduce GENIE resonance production by 30%!**
- **Big differences expected between ν and $\bar{\nu}$!!**

How do we **Measure** these Oscillation Parameters?

Develop an extremely Intense and Versatile Neutrino Beam





The MINERνA Experiment

Studying Neutrino-Nucleus Cross Sections & Nuclear Effects:

The MINERνA Experiment: Five Latin American Groups

Collaboration of 65 nuclear and particle physicists.

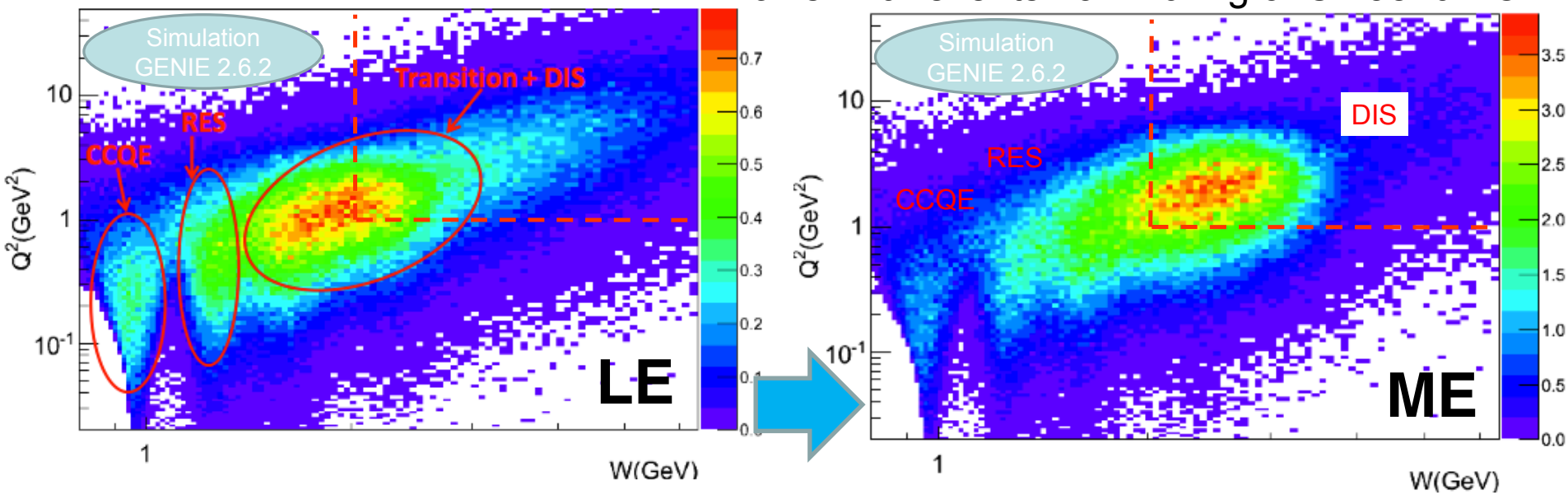
Centro Brasileiro de Pesquisas Físicas. Brasil
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato, Mexico
Hampton University
Mass. Col. Lib. Arts
Northwestern University
Otterbein University

Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of Minnesota at Duluth
Universidad Nacional de Ingeniería, Peru
Universidad Técnica Federico Santa María, Chile
William and Mary

Now Taking MUCH HIGHER Statistics in the ME Beam

W – Q^2 Kinematical Region in LE and ME

z axis : 10^3 events / 3 x 10^3 kg of C / 5e20 POT



Many more neutrino interactions in DIS regime

→ higher beam energy

→ increased statistics (beam intensity, energy)

→ improve on systematical uncertainties

→ structure function measurements on different nuclei

→ probe quark flavor dependence of nuclear effects

Energy Reconstruction

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

$$E_\nu = E_\nu(E_\mu, \theta_\mu)$$

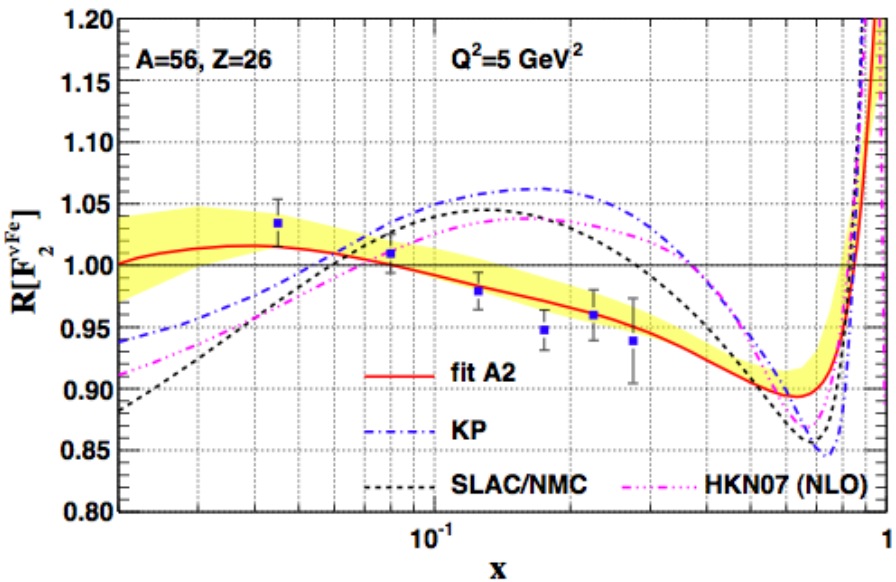
- Kinematic: Assume 2-body final state and calculate En
- Advantages: do not have to deal with the complicated hadron shower
- Disadvantages: Energy is wrong if the initial interaction is incorrect

$$\nu_\mu + N \rightarrow \mu^- + X$$

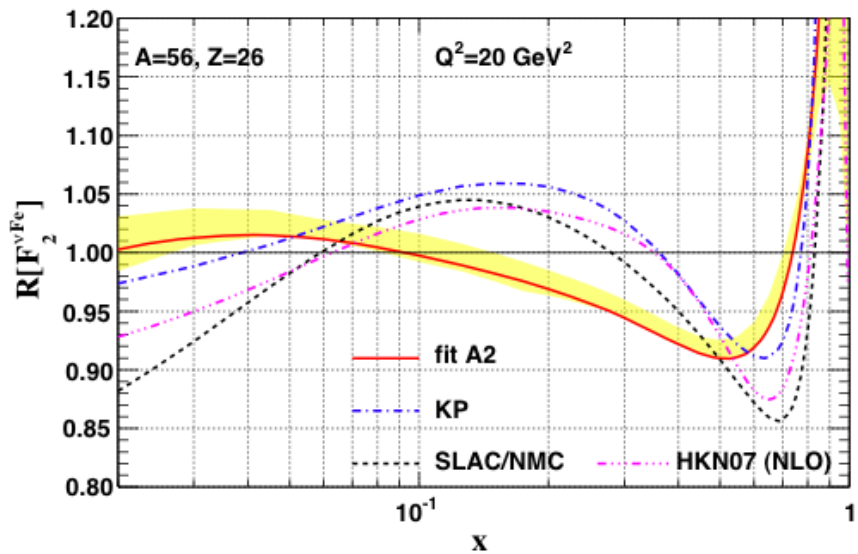
$$E_\nu = E_\mu + E_X$$

- Calorimetric: Add the energy of the muon and hadronic shower
- Advantages: does not rely on a particular initial state
- Disadvantages: relies on reconstruction of hadronic energy

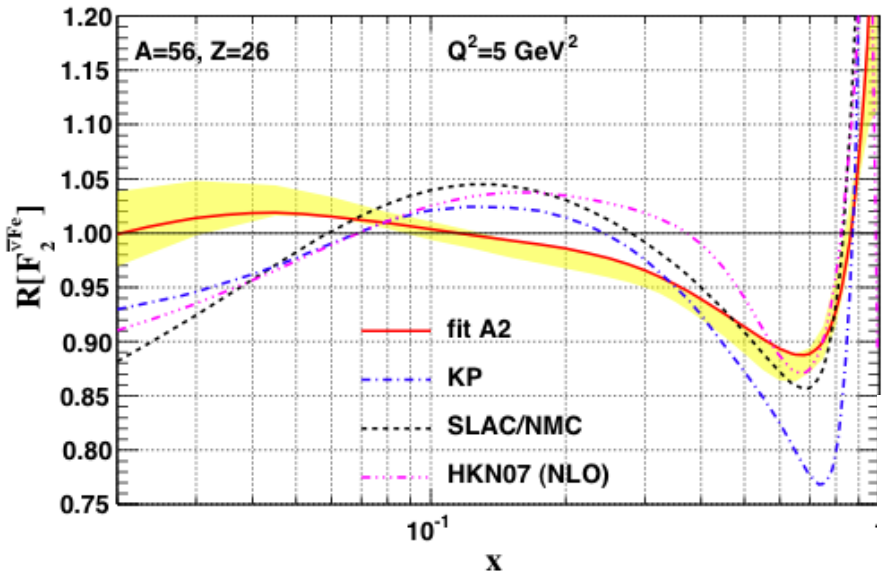
F_2 Structure Function Ratios: ν-Iron



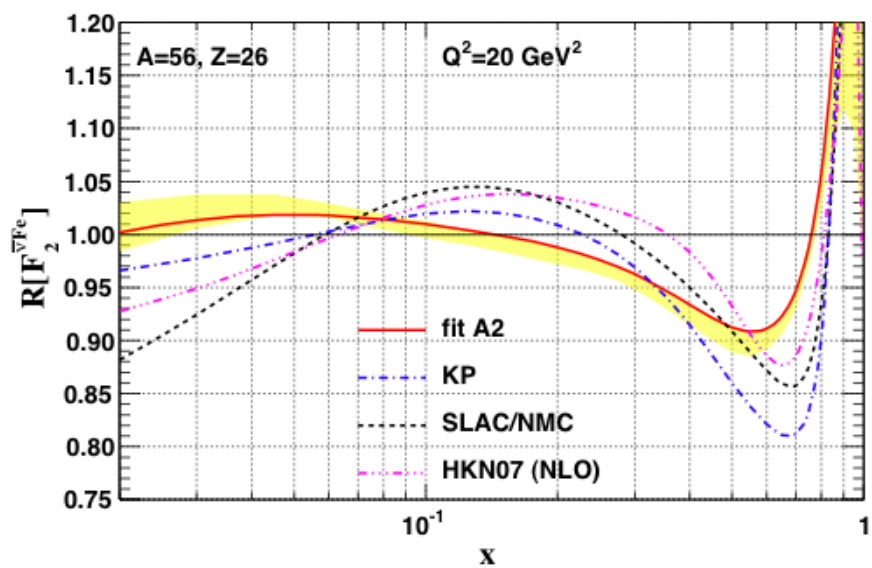
$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



F_2 Structure Function Ratios: $\bar{\nu}$-Iron

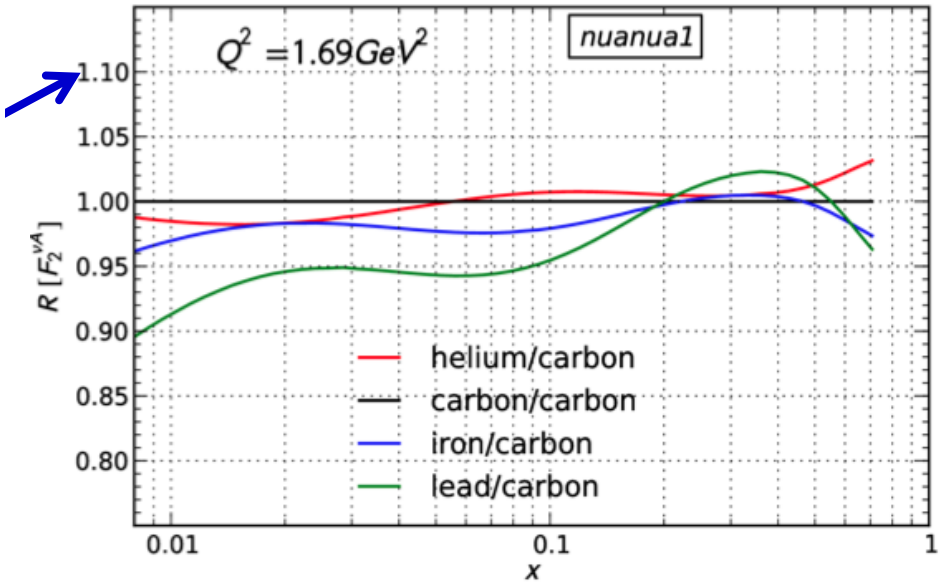


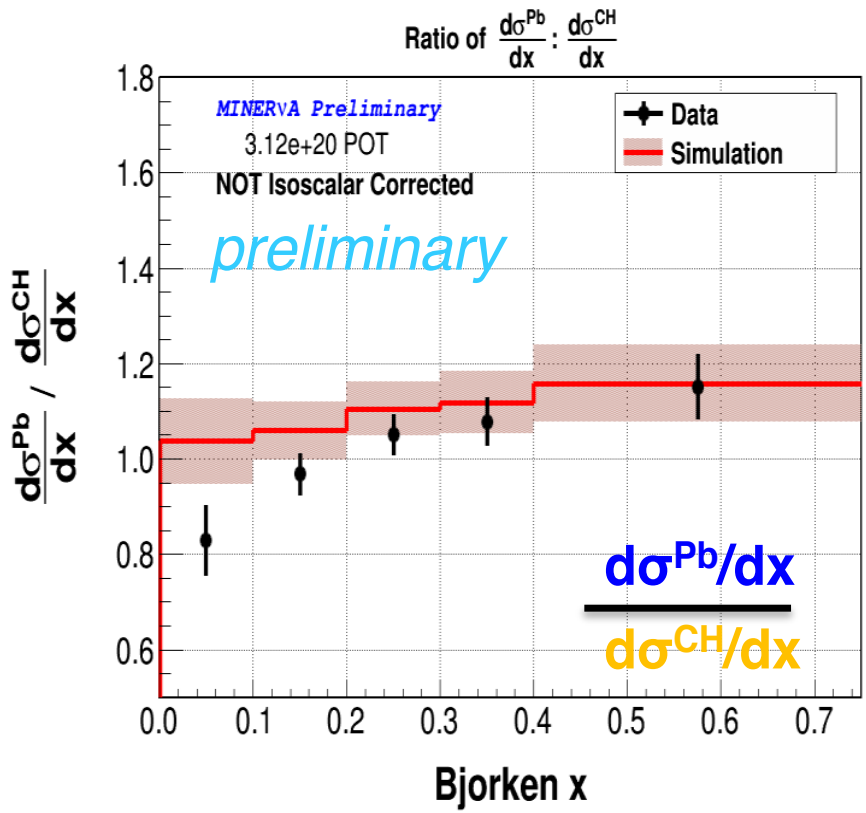
$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



MINERνA vs nCTEQ

Kovarik PRL106 (2011) 122301





- MINERνA data suggests additional nuclear shadowing in the lowest x bin ($\langle x \rangle = 0.07$, $\langle Q^2 \rangle = 2$ GeV^2)
- In this x, Q^2 bin we do NOT expect shadowing for $\ell^{\pm}$ Fe/CH scattering

Neutrino Nucleus Scattering

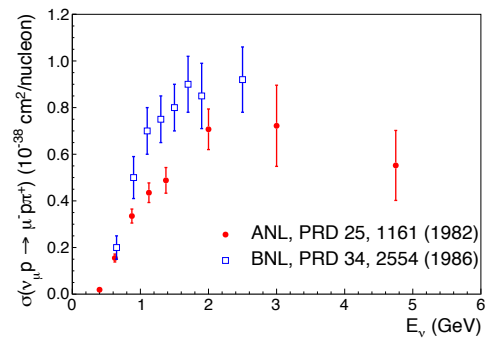
Cross Section Term: $\sigma_{c,d,e..}(E' \geq E_d)$

- The events we observe in our detectors are convolutions of:

$$Y_{c\text{-like}}(E_d) \;\alpha\; \phi_\nu(E' \geq E_d) \;\otimes\; \sigma_{c,d,e..}(E' \geq E_d) \;\otimes\; Nuc_{c,d,e..\,\boxtimes\,c}(E' \geq E_d)$$

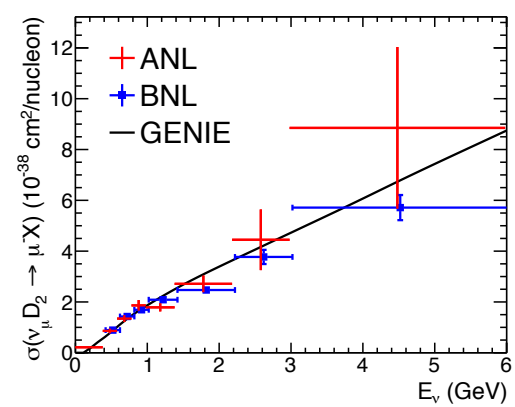
- $\sigma_{c,d,e..}(E')$ is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus.**

- **Limited statistics ANL and BNL bubble chamber data off D_2 from the 80's is what we have ie. 1 π production.**



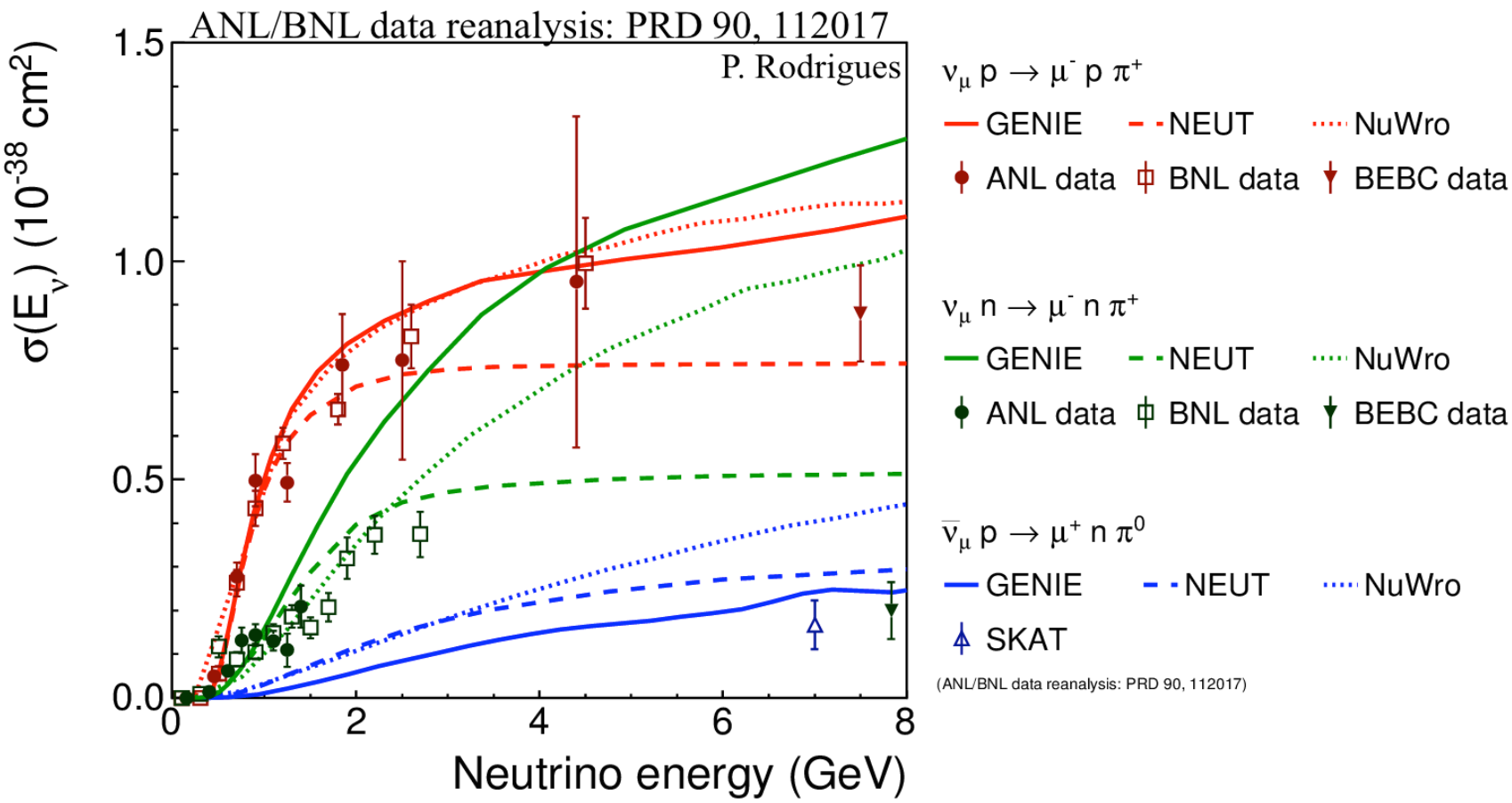
- **Recent combined analyses of ANL and BNL data using ratios of σ_{QE} to σ_{Tot} have claimed to resolve flux issues and we now could have a much improved combined fit.**

Wilkinson et al. – arXiv:1411.4482



- **However a recent study by Sato suggests that nuclear effects in deuterium have to be carefully considered.**

What About ν **Nucleon** --> π Cross Sections?



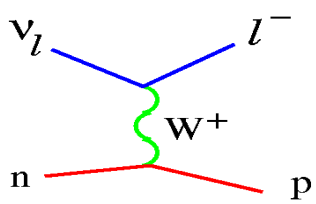
- **However a recent study by Sato suggests that nuclear effects in deuterium have to be carefully considered.**

Conclusions the multi-π zone (W < 1.8 GeV)

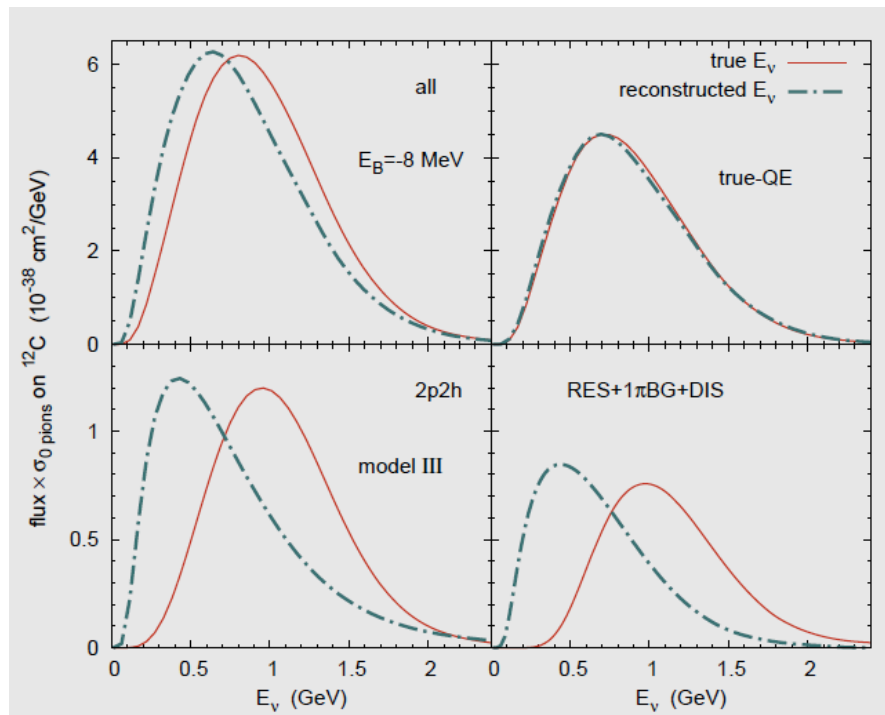
- Distributions of the muon observables (p_μ,θ_μ,E_ν,Q^2) are sensitive to nuclear structure.
- They are complementary to pion variables (T_π , θ_π), which are sensitive to FSI.
- The Q^2 spectrum provides the most detail and no single model describes both the π^+ and π^0 distributions.
- **Once again we see experimental evidence pointing toward the need of improved nuclear models!**

These Nuclear Effects Change the E_{QE} and Q_{QE}^2 Reconstruction for "QE" Events

- Using the outgoing lepton to determine E_{QE} and Q_{QE}:



$$E_{QE} = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$



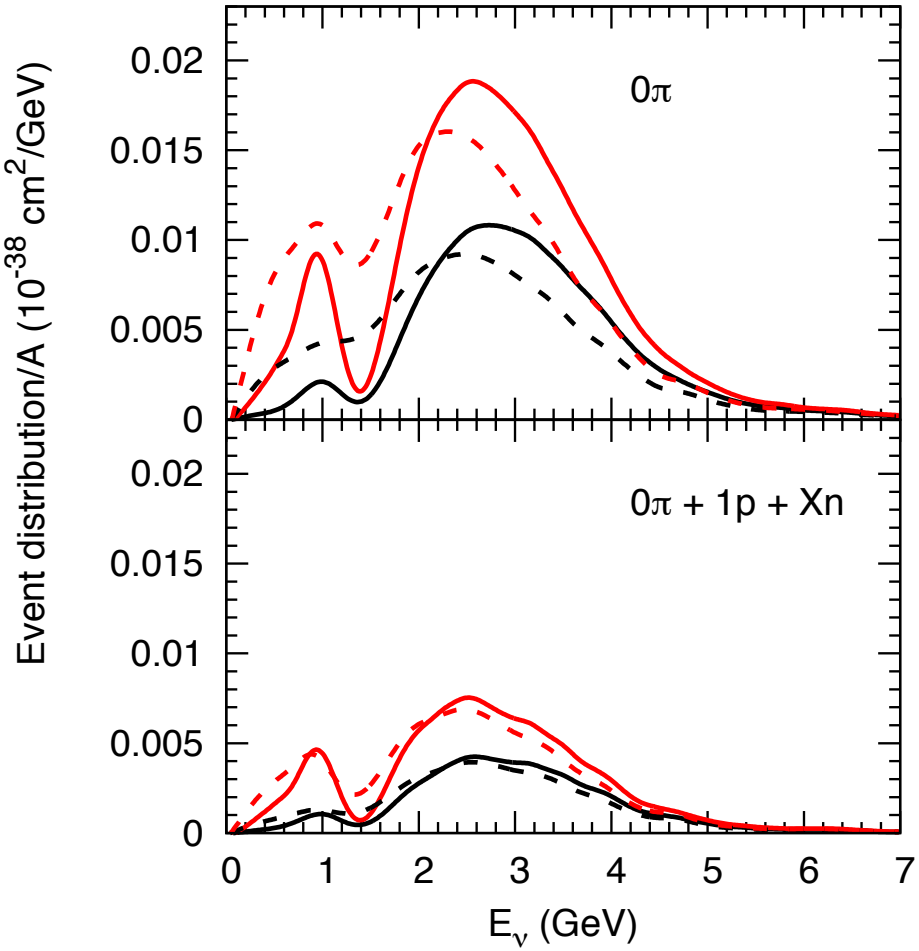
Reconstructed energy shifted to lower energies for all processes other than true QE.

Number of events experiencing these shifts depends on the nuclear model being used!

U. Mosel GiBUU

Significant Implications for Oscillation Experiments using only the Lepton Information

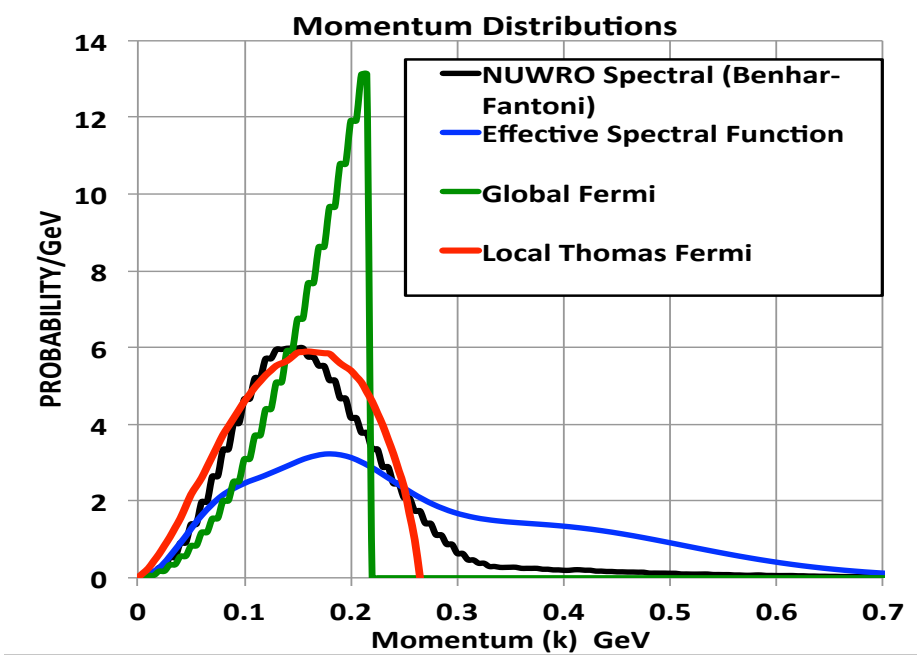
- **We need an excellent model of this convolution to be able to extract physics quantities from the far detector measurements to needed precision.**
- At right, for ν_e appearance, using a pre-DUNE E_ν spectrum looking for CP violations with $\delta_{CP} = +\pi/2$ (red) and $-\pi/2$ (black) at initial interaction (solid) and detected after nuclear effects (dashed).
- **Other generators using alternative models get different results.**



GiBUU

What is happening with our model of the nucleus?
The Nucleus: How are the nucleons moving within the nucleus?

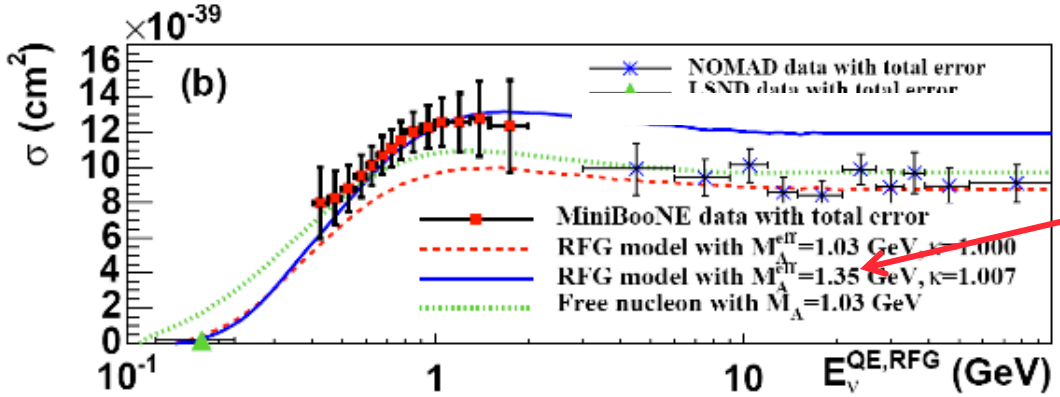
- **Fermi Gas**: Nucleons move freely within the nuclear volume in a constant binding potential.
- **Spectral Function**: The probability of removing a nucleon with momentum $\vec{p}$ and leaving residual nucleus with excitation energy E. Allows off mass shell nucleons.



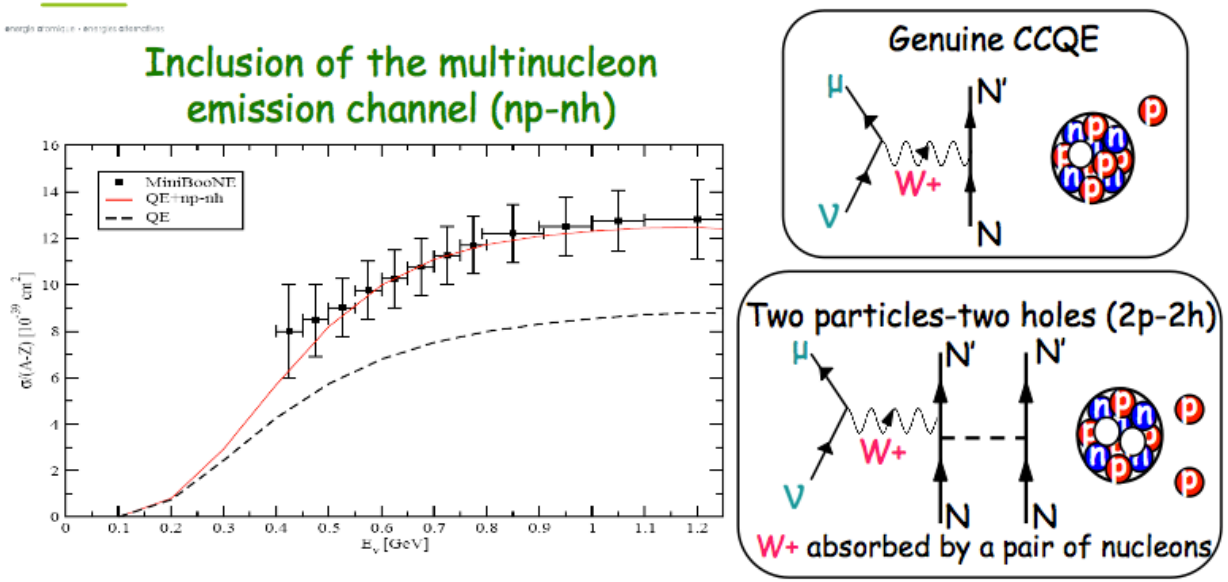
The MiniBooNE QE Analysis:

Introduction of nucleon-nucleon correlations

Meson Exchange Currents – 2p2h Effects



$M_A = 1.35$ GeV



M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

NuSTEC Workshops

- We promote the exchange of information within our community

- **Workshops**: We coordinate and organize community-wide workshops.
  - **NuInt – next one in Toronto, CA in June 2017!**
    - » organized every18 months.
    - » Comparison of experimental results and nuclear models via event generators
    - » Highlight open problems
  - Topic-specific
    - » to be held in between NuInts
    - » Workshop on Global Fits to Neutrino Scattering Data and Generator Tuning (NuTune2016), July in Liverpool
    - » NuSTEC coordinates multiple workshops to avoid date collisions and unwanted duplication

NuSTEC Schools/Training Programs

- NUSTEC organizes and runs generator and neutrino scattering physics schools/trainings

- **Training**:
  - **Long (10-day) schools – one so far, next one to be at Fermilab in 2017.**
    - » Every 3 years
    - » Broad, mainly theory with experiment highlights
    - » NuSTEC Training in Neutrino Nucleus Scattering Physics, October 2014, Fermilab with **85** participants.
  - Short (≤ week) schools – two so far
    - » More specific or practical or generator-oriented
    - » Correlated in time and space with NuInt
    - » The Liverpool NuSTEC Nu Generator School associated with NuInt14
    - » NuSTEC School in Okayama, Japan 8-14 November associated with NuInt15.

Nustec Training in Neutrino Nucleus Scattering Physics – Fermilab, October 2014

- **Electroweak interactions on the nucleon** **3 hours**
- **Strong and electroweak interactions in nuclei** **4 hours**
- **The nuclear physics of electron and neutrino scattering in nuclei in the quasielastic regime and beyond** **9 hours**
- **Pion production** **3 hours**
- **Exclusive channels and final state interactions** **3 hours**
- **Inclusive e and ν scattering in the DIS regime** **3 hours**
- **Impact of neutrino cross section uncertainties on oscillation analyses** **3 hours**
- **Selected experimental illustrations** **4 hours**

- **85 registered (paying) participants + ≈ 15-20 sitting in on the courses**

- **Financial support from DOE, NSF, Fermilab, Jlab, CERN, VaTech**

- **WE WILL REPEAT THIS LONG SCHOOL IN OCT/NOV 2017**