When Neutrinos Encounter Nuclei

MINERvA: Pion, Kaon and Inclusive Production Compared to Event Generators

NuSTEC: Improving the Nuclear Model in Event Generators

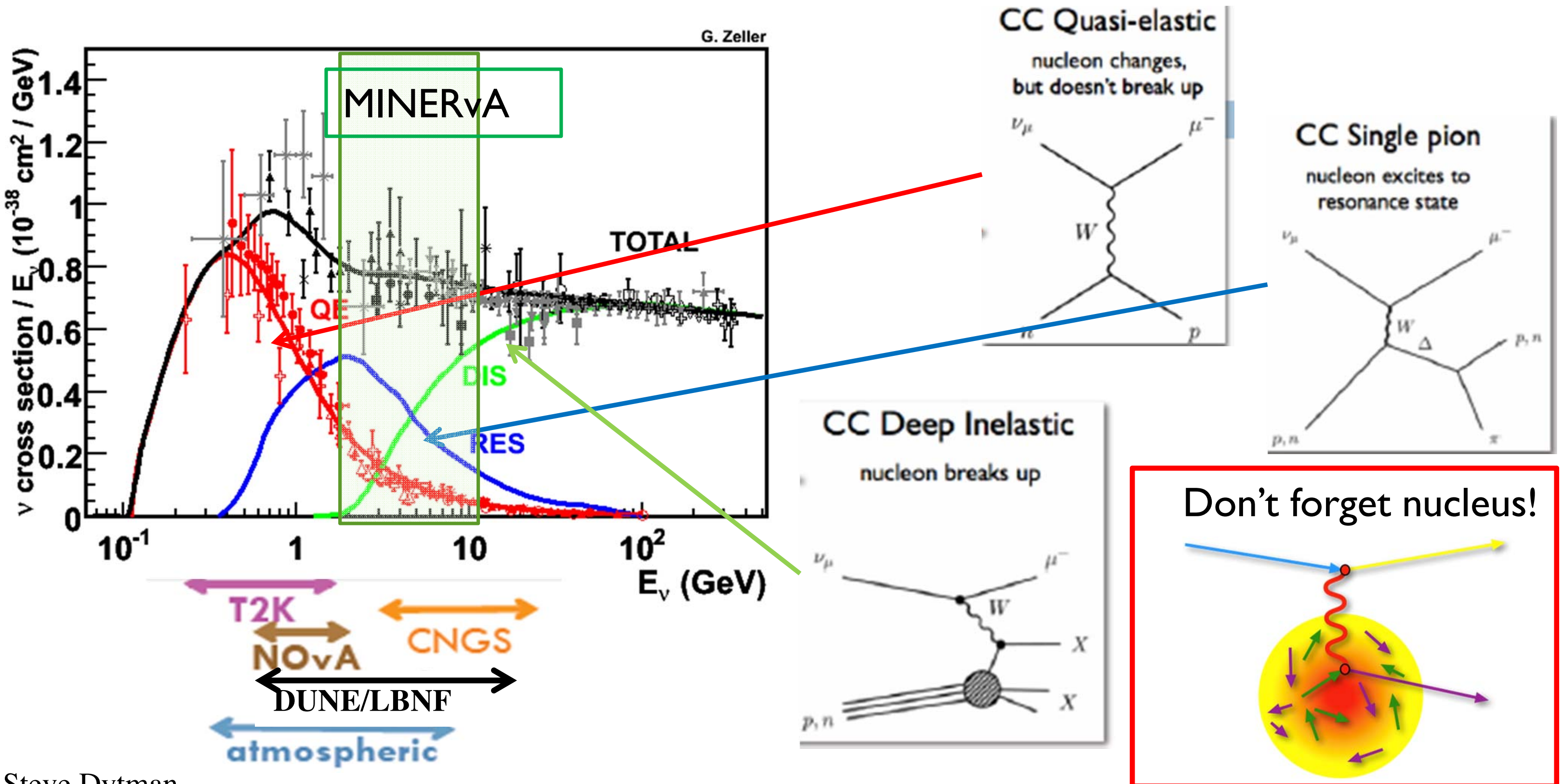
NuFact16 – Qui Nhon, Vietnam

Jorge G. Morfín
Fermilab

What are the challenges?

GeV Neutrino experiments see a mix of cross-sections

- Most nucleon data from **bubble chambers** (low statistics)
- Many ways within the nucleus to lose / gain detected exclusive production.

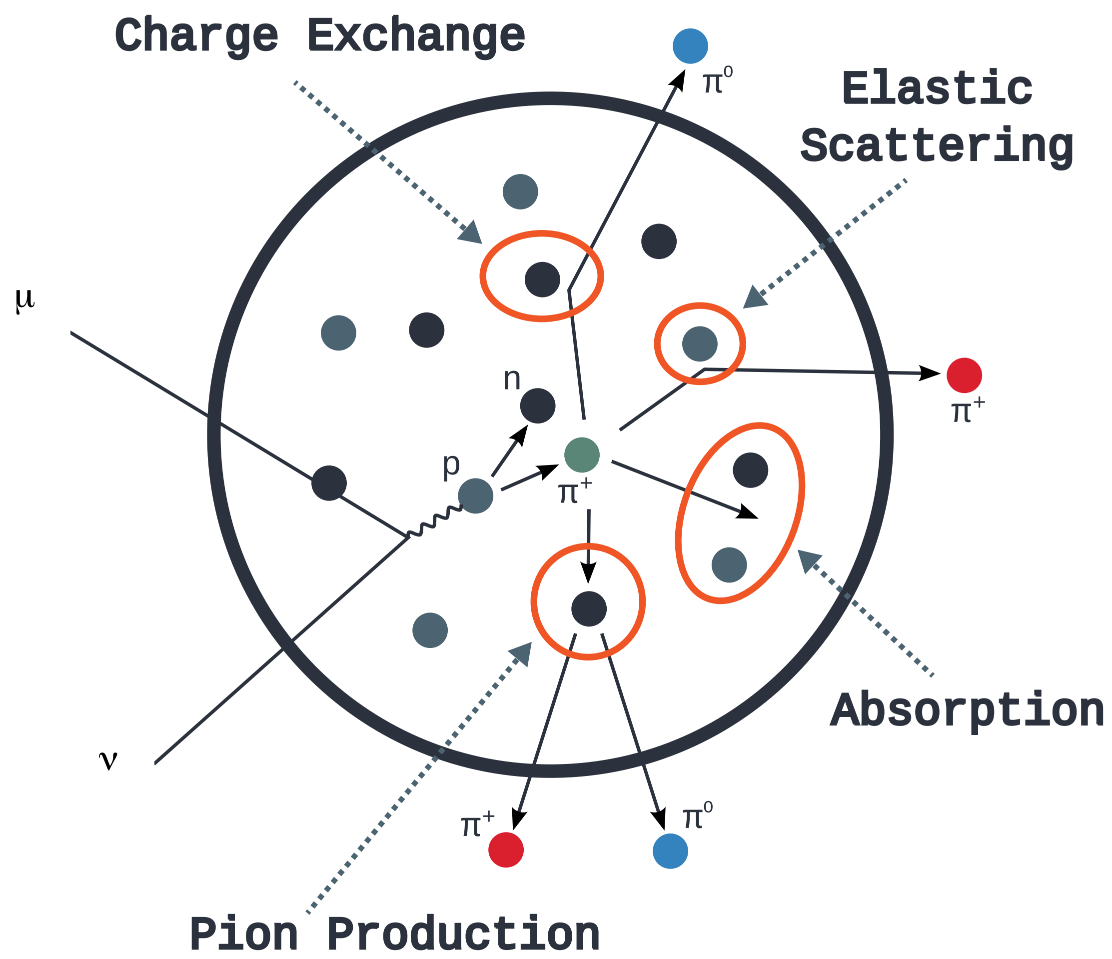


Thanks to Steve Dytman

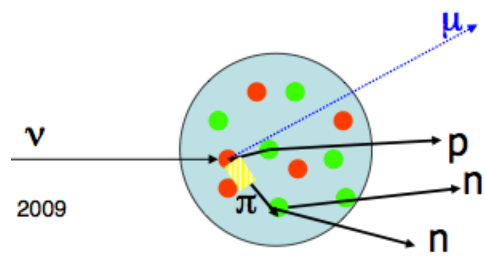
What are these Nuclear Effects in Neutrino Nucleus Interactions?

- 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 $\sigma(n\pi)$ $\otimes$ formation zone model $\otimes$ π-charge-exchange/ absorption cross sections.
- **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)



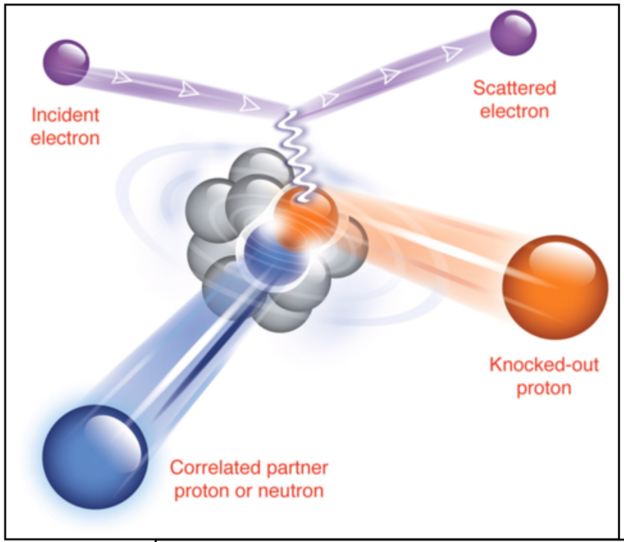
- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy. Currently using mainly **cascade models for FSI**.
- For example, an initial pion can charge exchange or be absorbed on a pair of nucleons.
- If absorbed,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

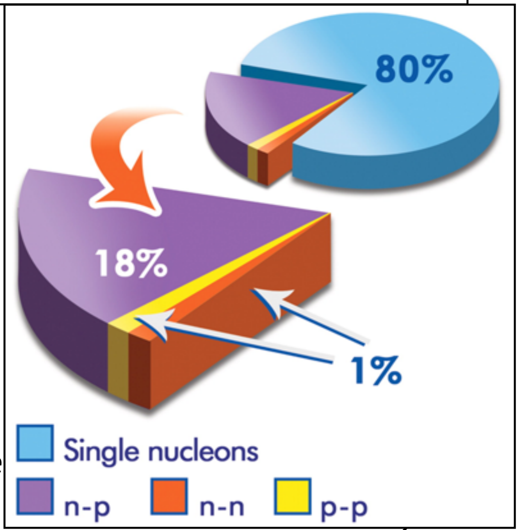
Example numbers	**Final μ p**	**Final μ p π**
Initial μ p	90%	10%
Initial μ p π	25%	75%

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

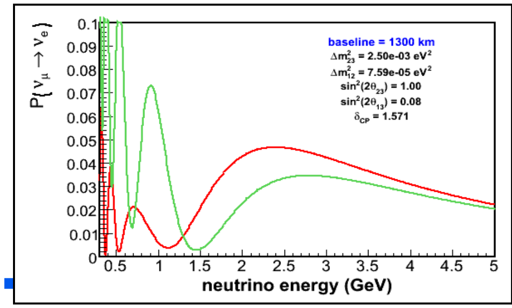
- Electron and Neutrino scattering
  - Evidence for MEC in the enhanced transverse production in e-A scattering!
  - Do not forget the **axial-vector** component!
  - **Of course, what we eventually detect can be modified by Final State Interactions when interpreting neutrino scattering data.**

- **Do not forget that pions can also be produced off correlated nucleon pairs and can be affected by RPA effects!**

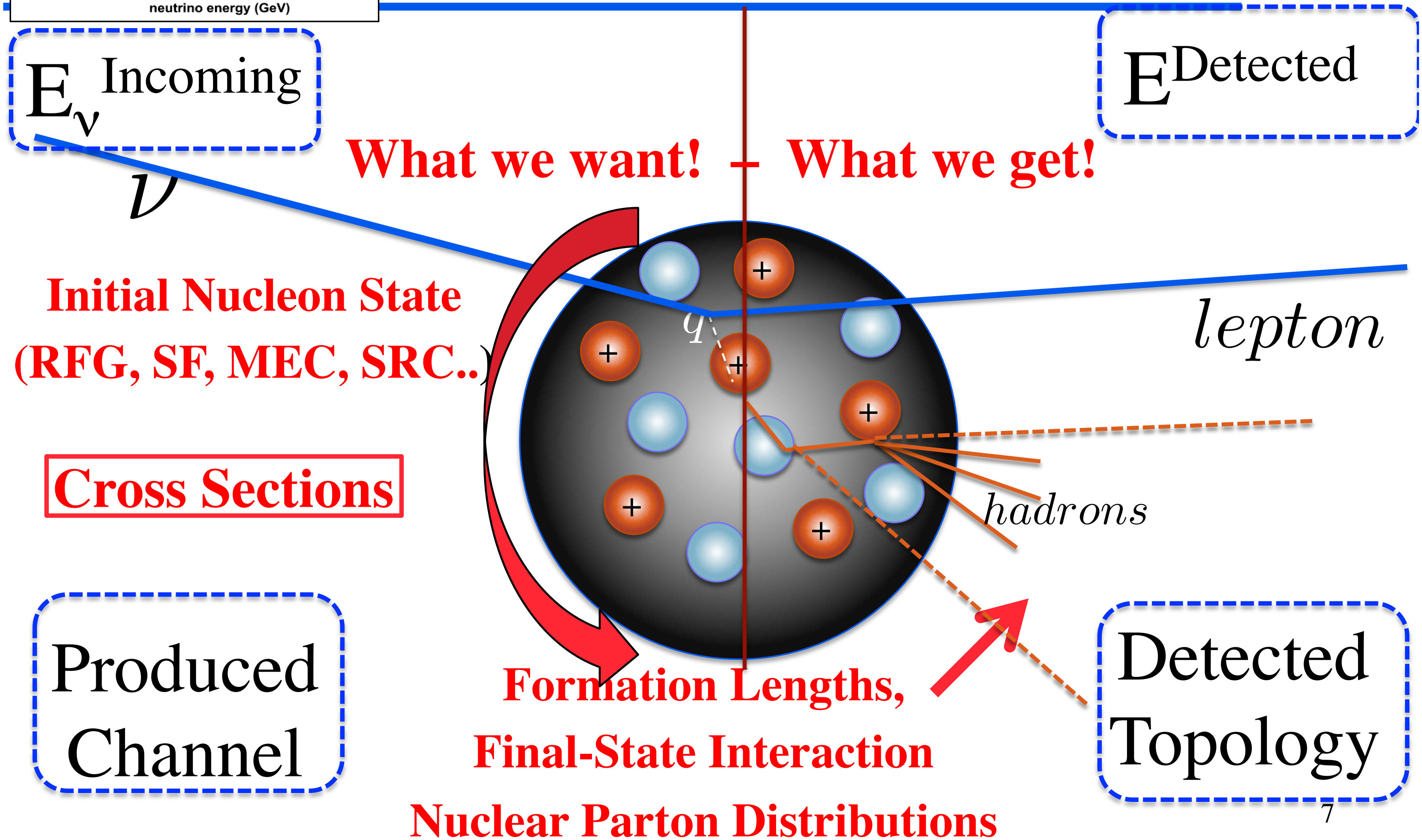




R. Subedi et al., Science 320, 1476 (2008)



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



How do we Improve our model of these nuclear effects - the Nuclear Model?

- We need many different measurements sensitive to similar nuclear effects to improve our nuclear model.
- MINERvA has taken this to heart – we continue with the MINERvA results adding to what Jeff Nelson presented on Monday.

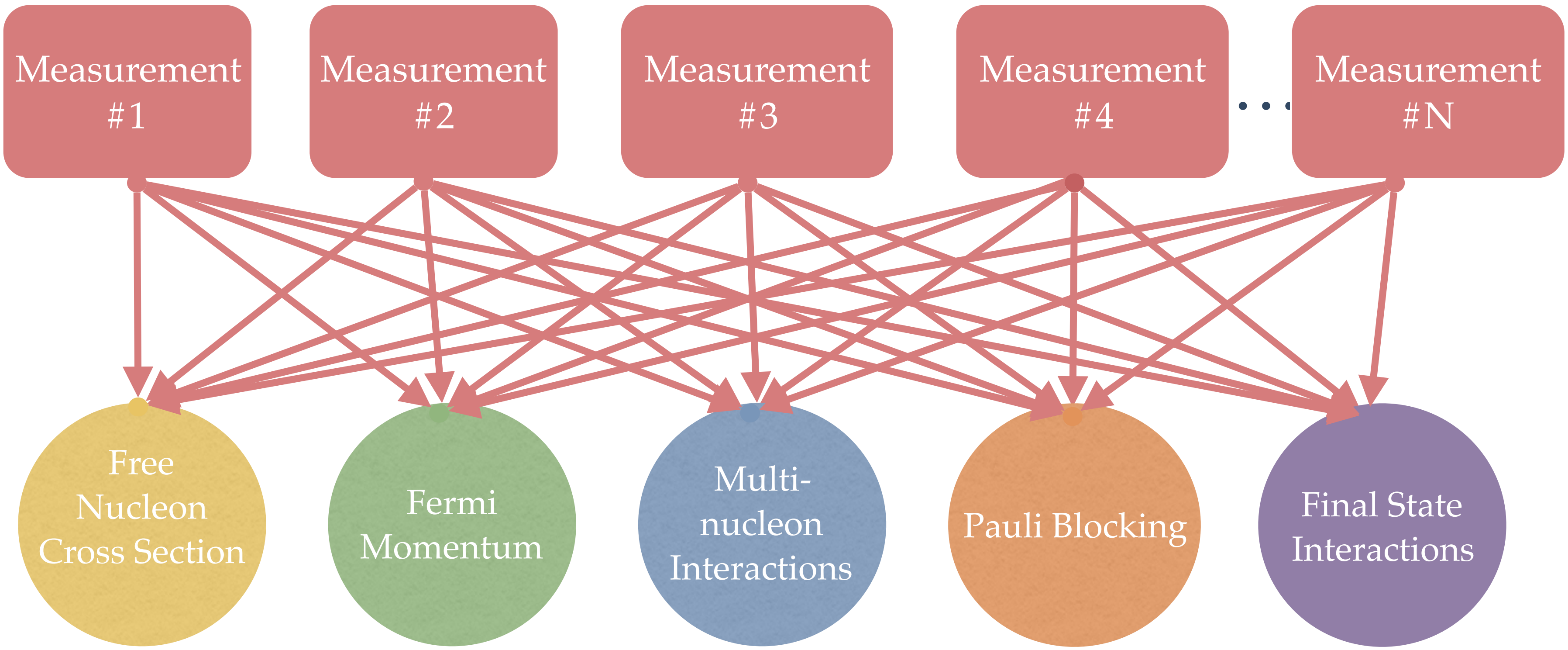


Figure from Laura Fields

Recent MINERvA Results….

1. First evidence of coherent K^+ meson production in neutrino-nucleus scattering, PRL 117, 061802 (2016)
2. Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering, PRD 93, 112007 (2016)
3. Measurement of partonic nuclear effects in deep-inelastic neutrino scattering using MINERvA, PRD 93, 071101 (2016)
4. Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer, PRL 116, 071802 (2016)
5. Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average E_ν of 3.6 GeV, PRL 116, 081802 (2016)
6. Single neutral pion production by charged-current anti-ν_μ interactions on hydrocarbon at average E_ν of 3.6 GeV, PLB 749 130 (2015)
7. Measurement of muon plus proton final states in ν_μ Interactions on Hydrocarbon at average E_ν of 4.2 GeV, PRD 91, 071301 (2015)
8. Measurement of coherent production of $\pi^\pm$ in neutrino and anti-neutrino beams on carbon from E_ν of 1.5 to 20 GeV, PRL. 113, 261802 (2014)
9. Charged pion production in ν_μ interactions on hydrocarbon at average E_ν of 4.0 GeV, PRD 92, 092008 (2015)
10. Measurement of ratios of ν_μ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2-20 GeV, PRL 112, 231801 (2014)
11. Measurement of muon neutrino quasi-elastic scattering on a hydrocarbon target at E_ν~3.5 GeV, PRL 111, 022502 (2013)
12. Measurement of muon antineutrino quasi-elastic scattering on a hydrocarbon target at E_ν~3.5 GeV, PRL 111, 022501 (2013)

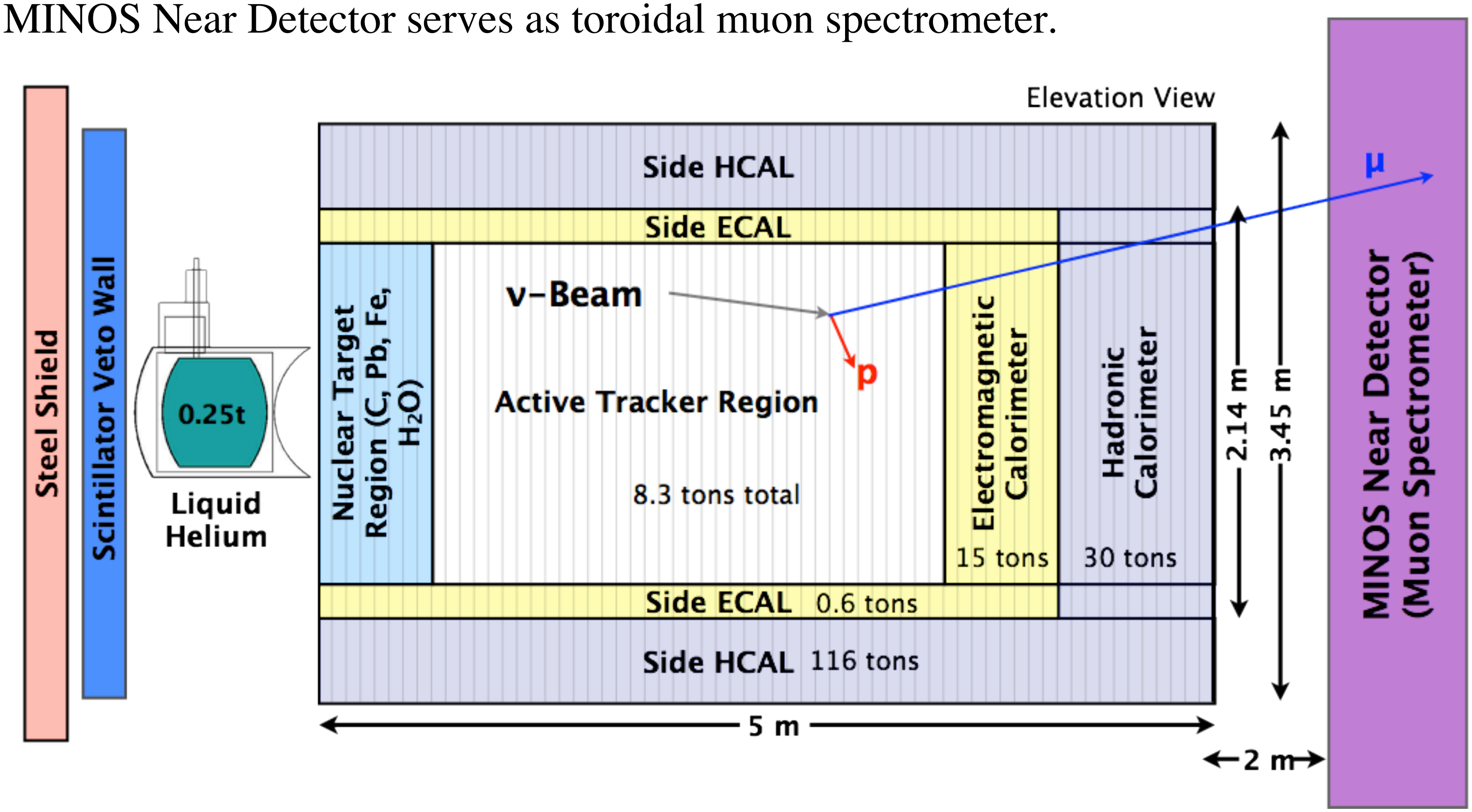
- Measurement of K^+ production in charged-current ν_μ interactions, arXiv:1604.01728
- Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon, arXiv:1604.01728
- Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few-GeV region using MINERvA, arXiv:1606.07127
- Neutrino flux predictions for the NuMI beam, arXiv:1607.00704

Several public results with in papers preparation

- Antineutrino quasielastic scattering
- Neutrino quasielastic scattering
- Charged current neutrino and antineutrino inclusive cross sections via the low-nu flux method

The MINERνA Experiment - Detector

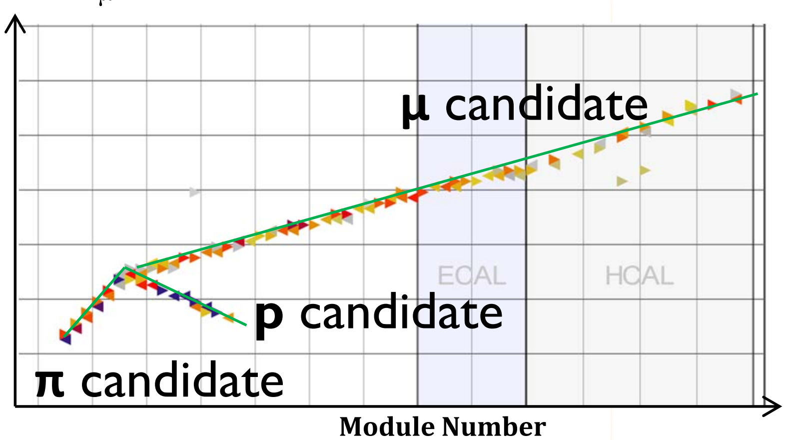
- 120 plastic scintillator modules for tracking and calorimetry (~32k readout channels).
- Construction completed Spring 2010. He and Water added in 2011.
- MINOS Near Detector serves as toroidal muon spectrometer.



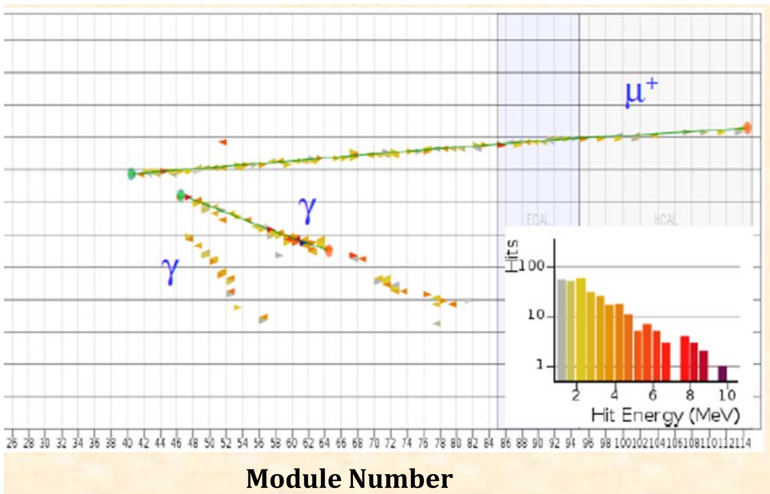
MINERvA pion production results
Comparison of π^0 and $\pi^\pm$ Models with Data
Neutrino vs. Antineutrino CC Pion Production

- Two individual analyses of the ν --> π^+ and $\bar{\nu}$ --> π^0 were published last year.
- We have submitted to the arXiv (1606.07127 hep-ex) the combined analysis which permits a more detailed comparison.

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



$\bar{\nu}_\mu$ p→$\mu^+\Delta^0$, Δ^0→nπ^0 Candidate



MINERvA: Charged and Neutral Pion Analyses

Carrie L. McGivern, Trung Le and Brandon Eberly

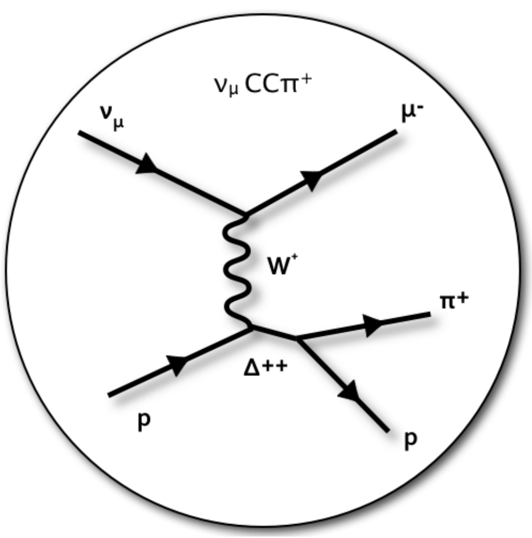
arXiv:1606.07127

Neutrino

Single charged pion production

$$\nu_\mu + CH \rightarrow \mu^-(1\pi^\pm)X$$

X can contain any number of π^0s, no charged pions

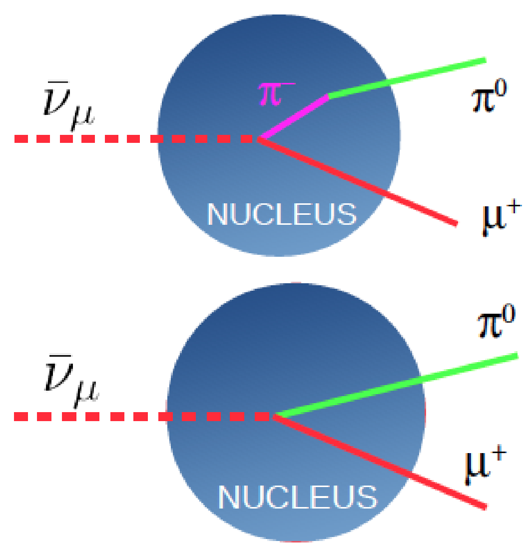


Antineutrino

Single neutral pion production

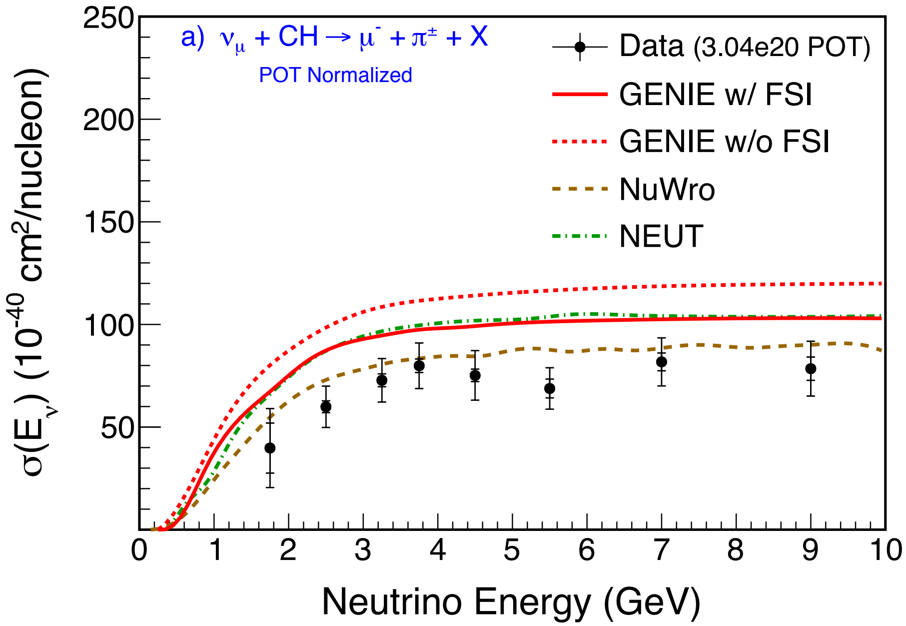
$$\bar{\nu}_\mu + CH \rightarrow \mu^+(1\pi^0)X$$

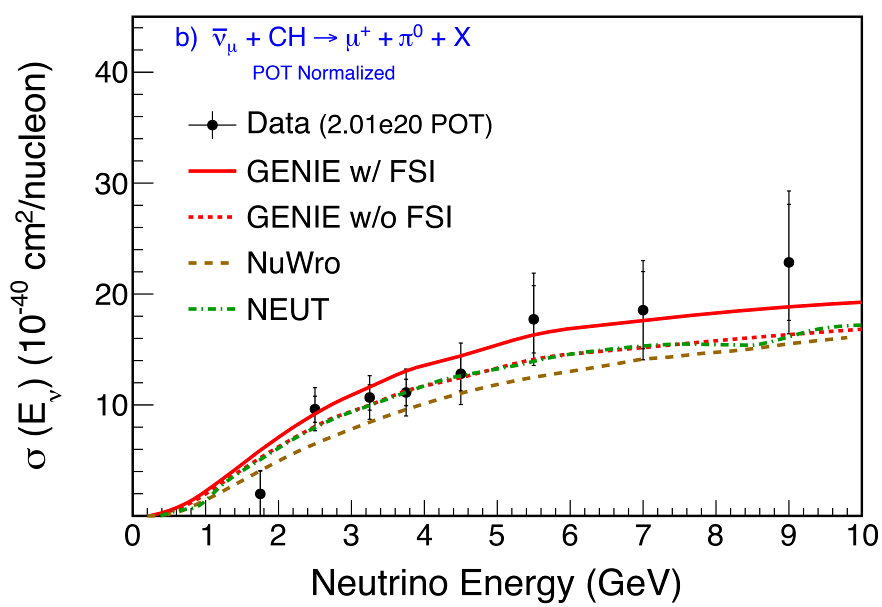
X contains no mesons



Comparison – E_ν Distribution
W (Hadronic Mass) < 1.8 GeV

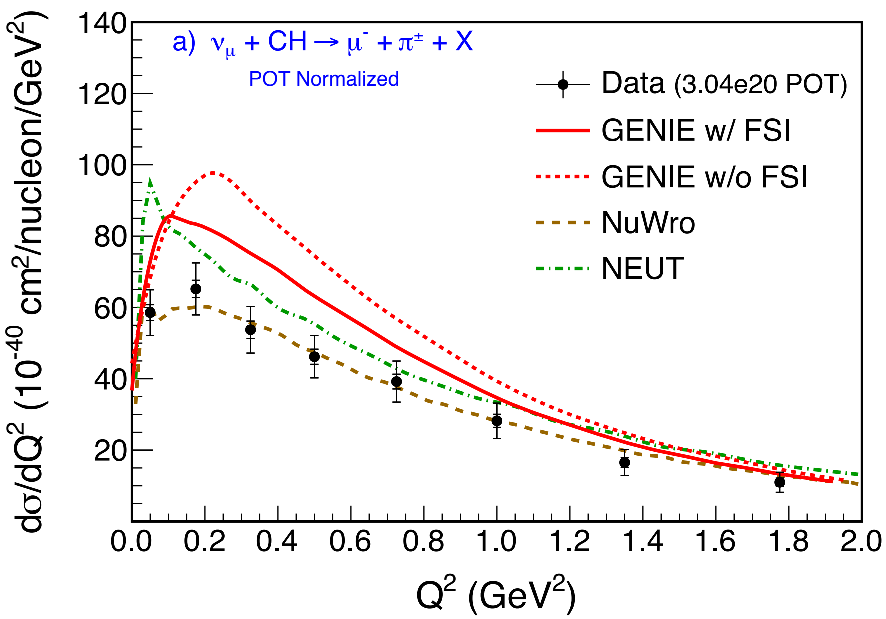
- Sum of all contributing channels up to the measured W of 1.8 GeV yielding after all cuts ≈ 5000 π^+ and 1000 π^0 events.
- Agreement on shape is very good, consistent with V-A theory.
- GENIE and NEUT overestimate the π^+ cross section.

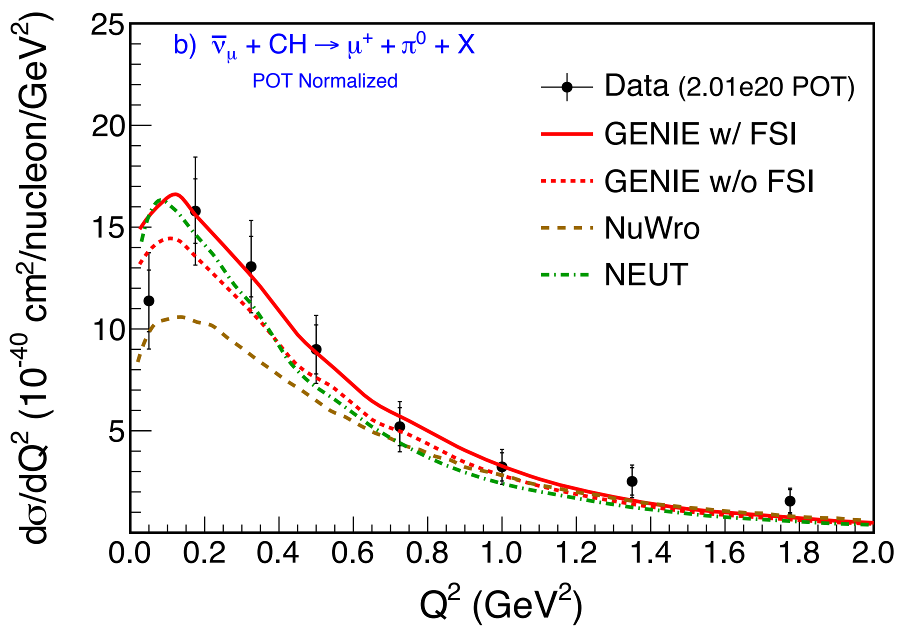




Comparison – Q^2 Distribution
W < 1.8 GeV

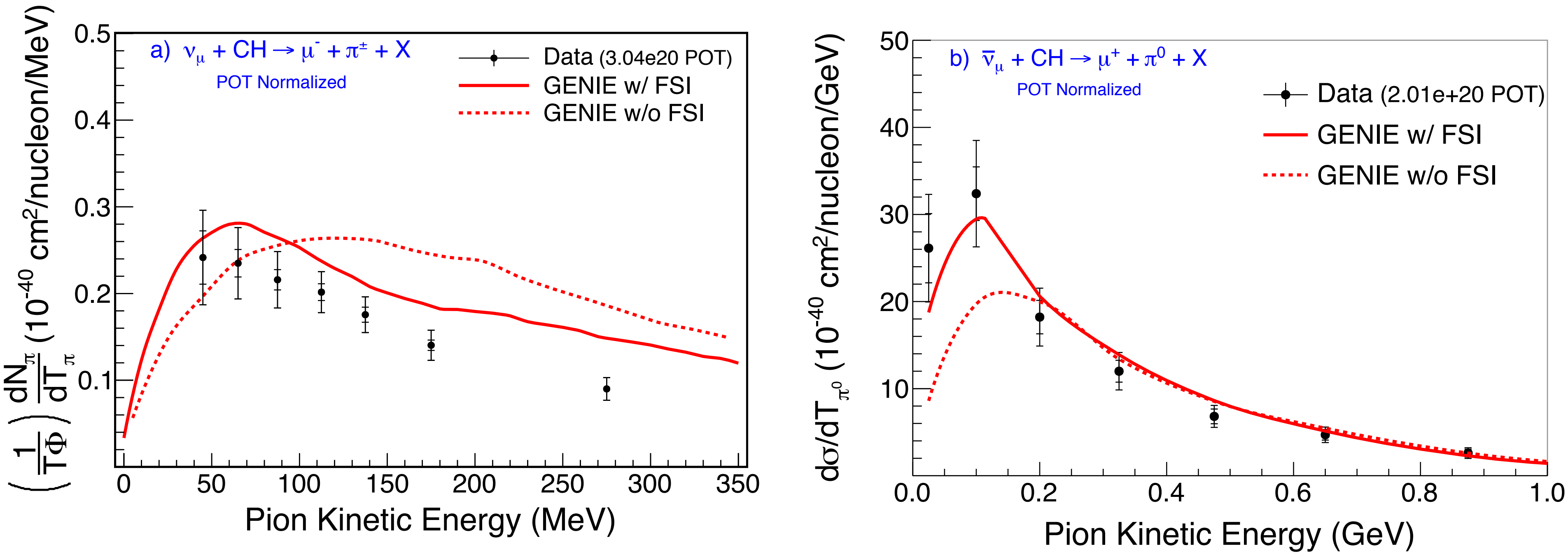
- Sensitive largely to V-A structure and nucleon-nucleon correlations as well as Pauli Blocking at low Q^2.
- NuWro (LFG), NEUT and GENIE (RFG) have good shape agreement despite differences and overall simplicity of models used.
- In charged pion both GENIE and NEUT over estimate the cross section. NuWro has normalization right for π^+ but has problems for π^0.
- Coherent contribution in (an older version?) NEUT unrealistically large.





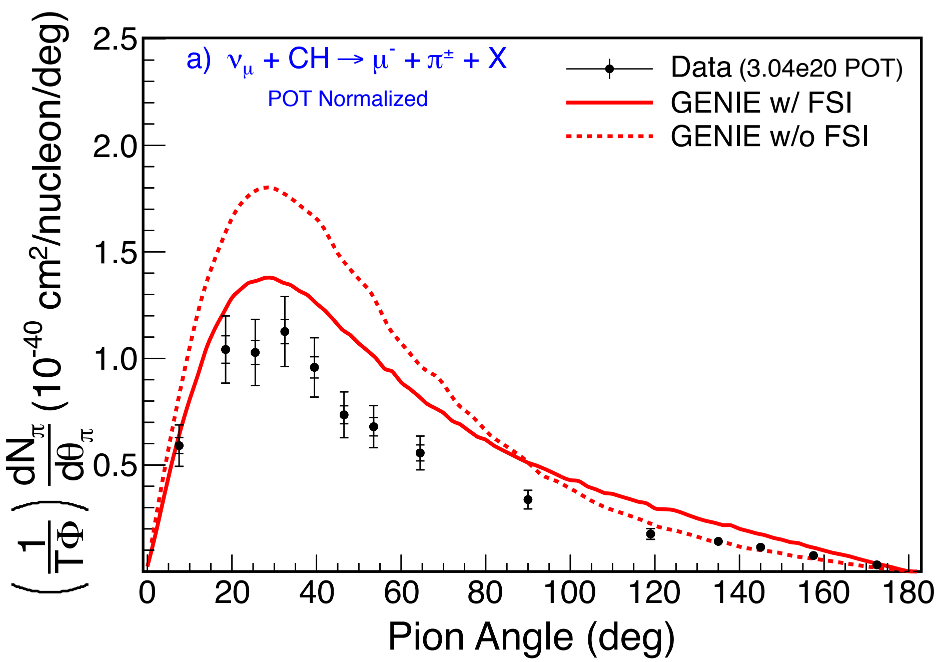
Final State Interactions (FSI) Conclusions for Pion Energy

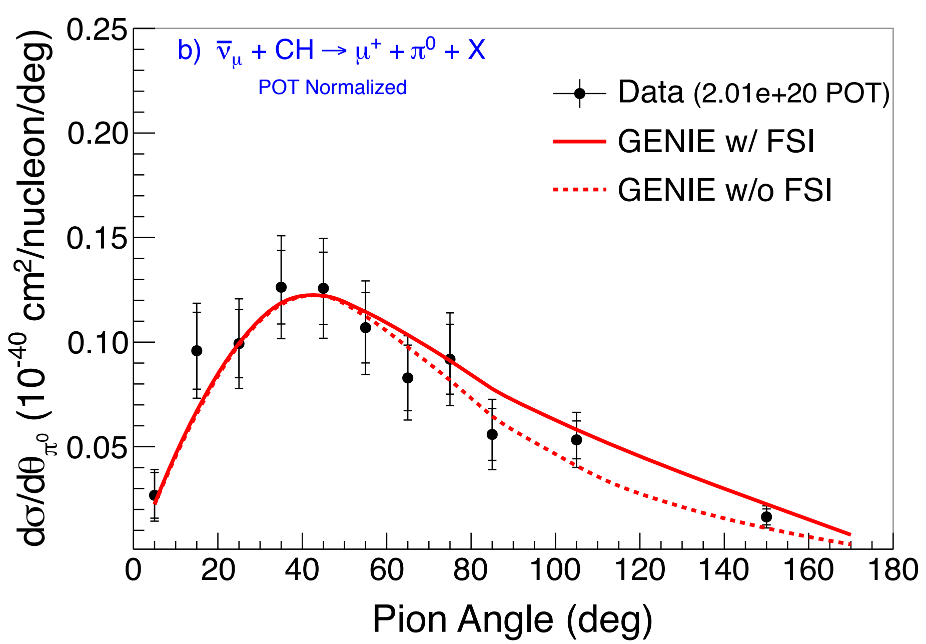
(Shape Comparisons – W < 1.8 GeV)



- Data prefer GENIE with FSI although even with FSI GENIE tends to over-predict compared to data for π^+

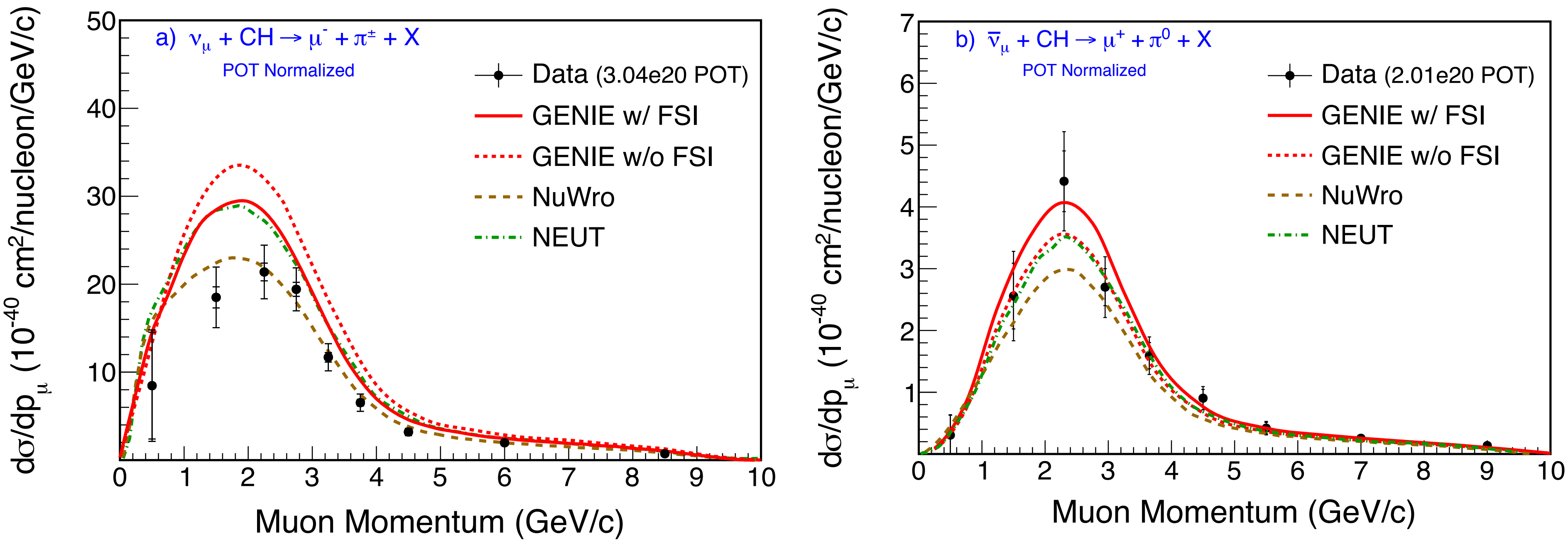
FSI Conclusions for Pion Angle Shape Comparison W < 1.8 GeV





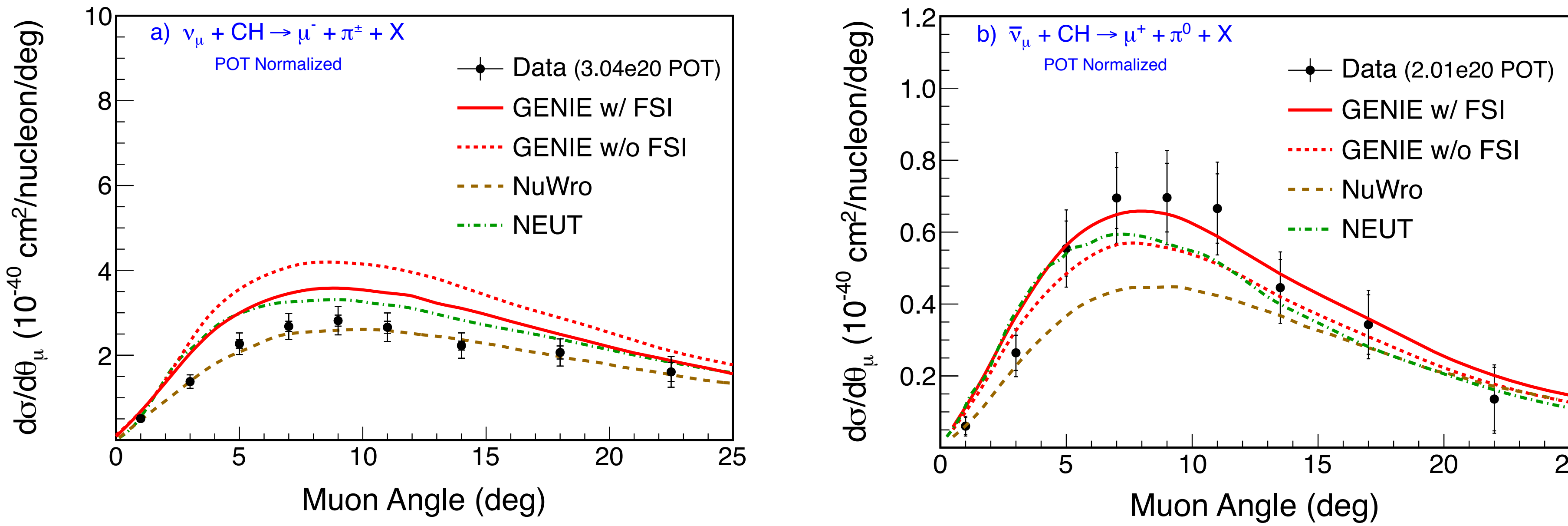
- Data prefer GENIE with FSI although. even with FSI, GENIE tends to over-predict compared to data for π^+

From the lepton side (W < 1.8 GeV)
Cross section model comparisons for μ momentum



- GENIE and NEUT predictions are similar and are higher than NuWro in both analyses.
- NuWro does well with both shape and normalization for π^+ but has problems with the π^0
- In charged pion both GENIE and NEUT overestimate the cross section

From the lepton side (W < 1.8 GeV)
Cross section model comparisons for μ angle



- The same normalization and shape behavior as with the μ mometum

Conclusions: the n($\geq$ 1)-π zone (W < 1.8 GeV)

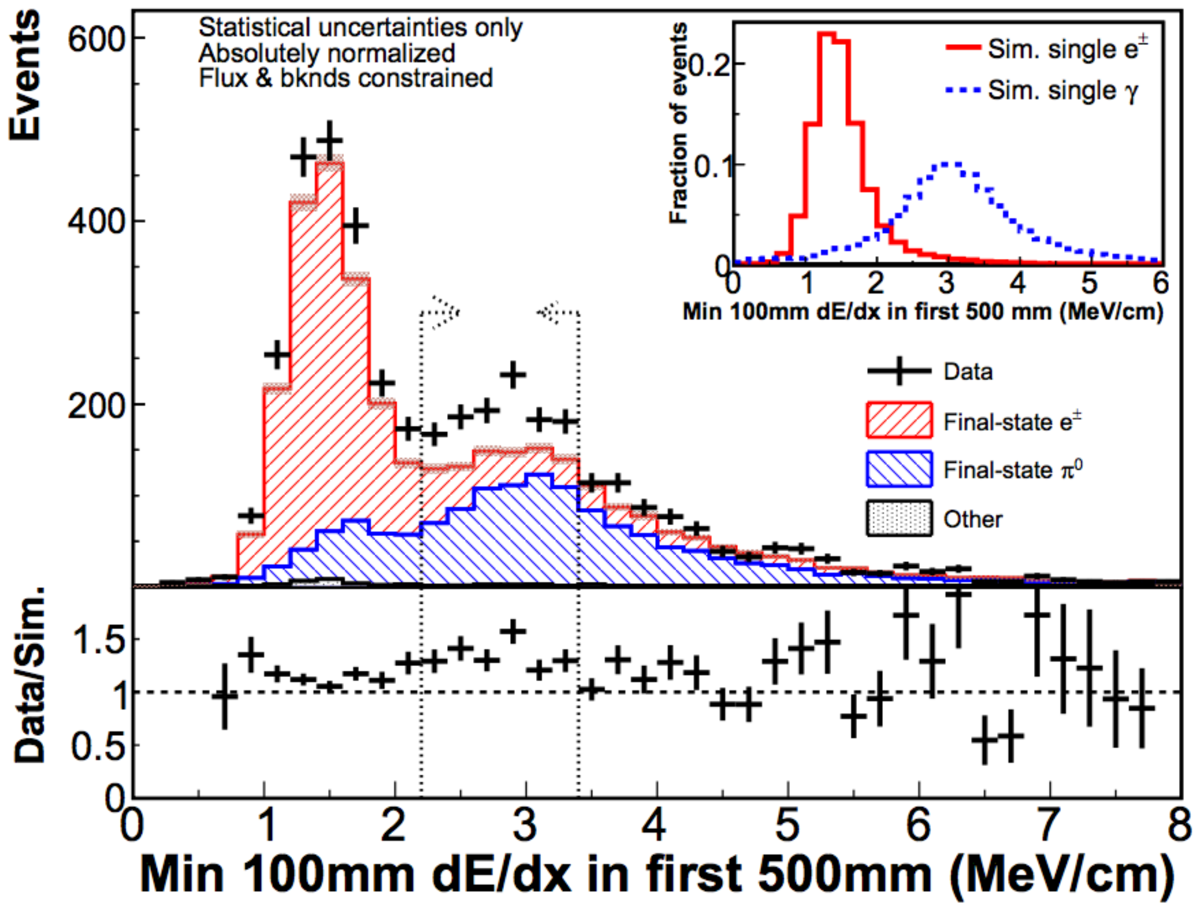
Dominated by Δ resonance that decays in the nucleus

- Distributions of the muon observables ($p_\mu, \theta_\mu, E_\nu, Q^2$) are sensitive to nuclear structure.
  - There is an indication that the GENIE normalization for π^+ production is overestimated.
  - P. Rodrigues et al reanalysis of deuterium Data arXiv:1601.01888 suggests **reduce GENIE non resonant production by ≈ 50%!**
- They are complementary to pion variables (T_π , θ_π), which are sensitive to FSI.
  - There is clear indication that the data prefers models, such as GENIE, **with** a treatment of FSI.
- The Q^2 spectrum provides the most detail and no single model describes both the π^+ and π^0 distributions.
- **We see experimental evidence suggesting models are improving. Need continued accurate experimental input to improved theoretical models to increase our understanding.**

MINERvA: Neutral Current Diffractive Pion Production

Jeremy Wolcott

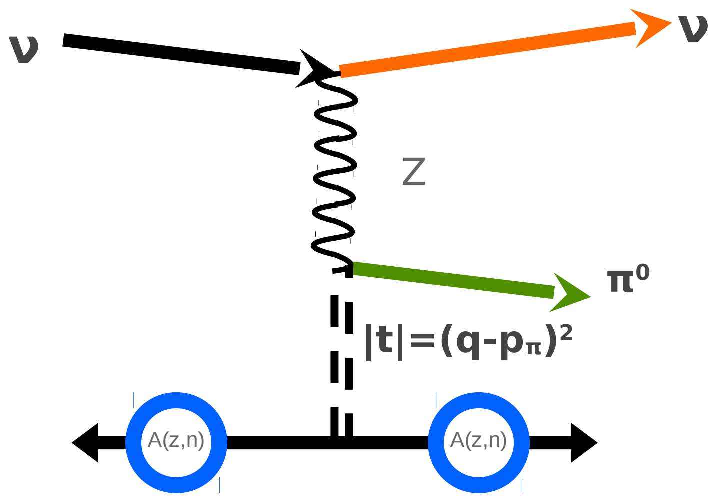
arXiv:1604.01728 accepted for PRL



arXiv:1604.01728,
Phys. Rev. Lett. 116, 081802 (2016)

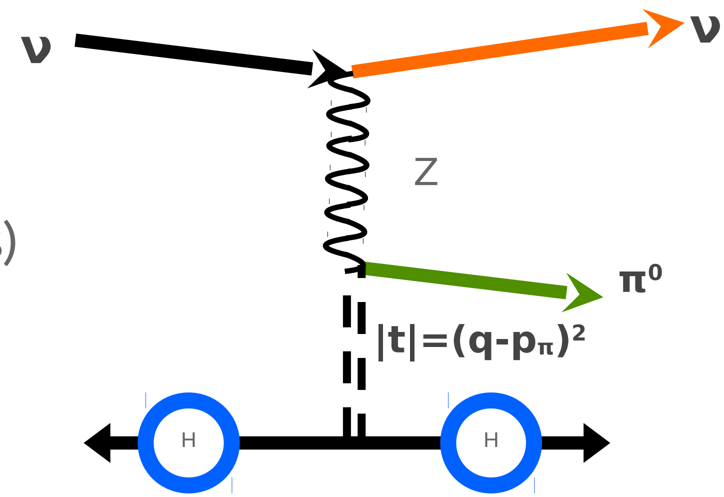
Diffractive Scattering

Called "Coherent" off a nucleus – diffractive off a nucleon

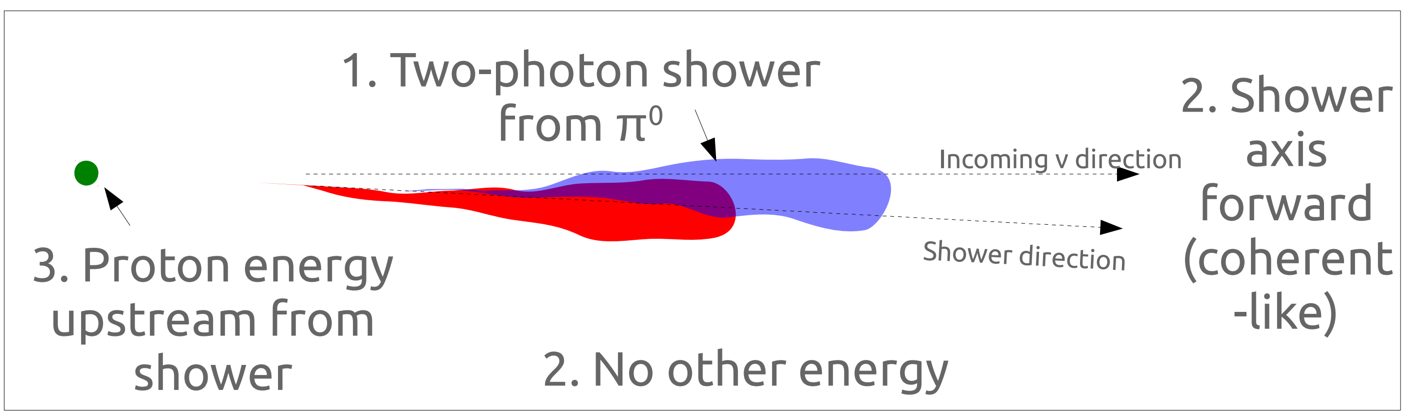


PCAC-based NC coherent production from *nuclei*

(analogous)

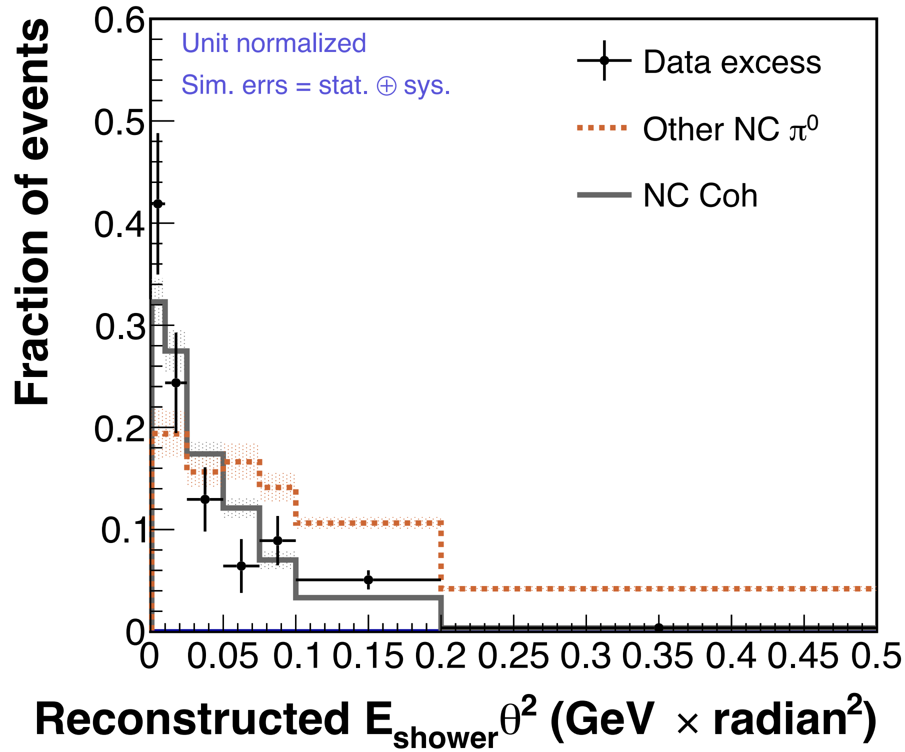


PCAC-based NC diffractive production from *H*



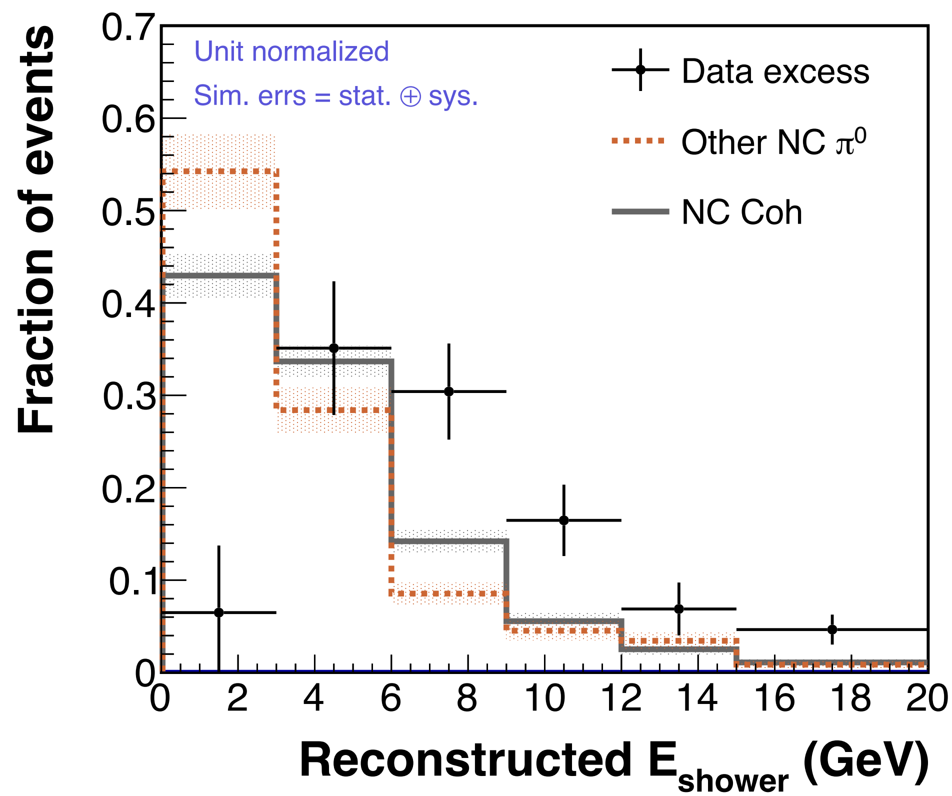
Observation compared to Predictions
$E\theta^2$ distribution

- The $E\theta^2$ distribution is the NC equivalent of the "t" distribution in CC coherent / diffractive scattering. This is a strong indication that we are observing a diffractive process.



Observation compared to Predictions
E shower distribution

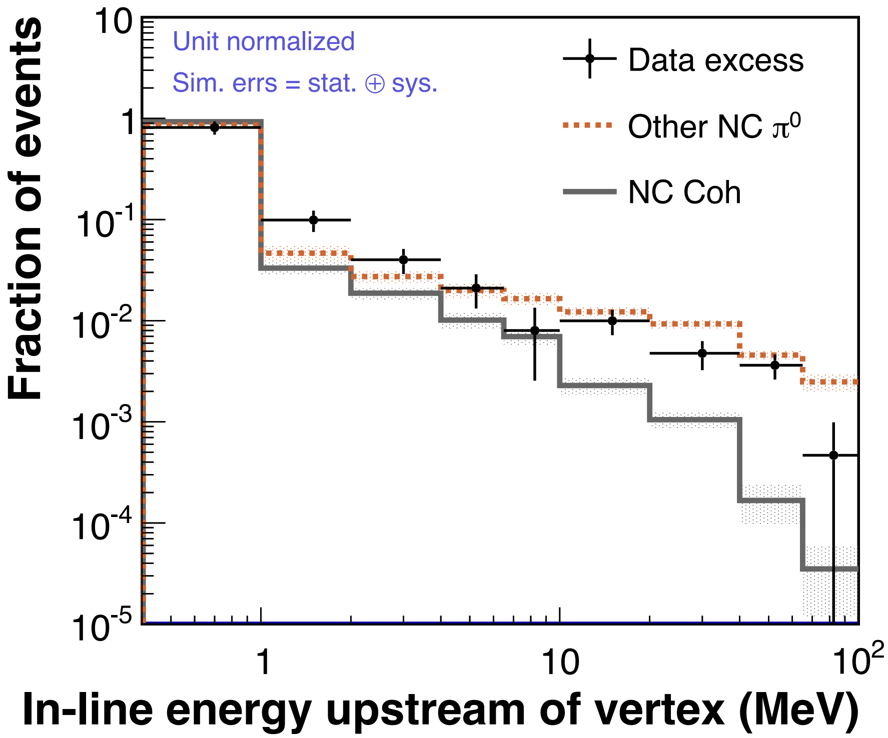
- The observed shower energy is considerably harder than expected from π^0 processes in GENIE.



Observation compared to Predictions

In-line Upstream Energy

- In line energy upstream of the shower vertex. Much more energy is observed here then expected with NC coherent – again suggesting a diffractive interaction off a light target.



MINERvA Observations compared to Predictions

With D. Rein's diffractive pion production model

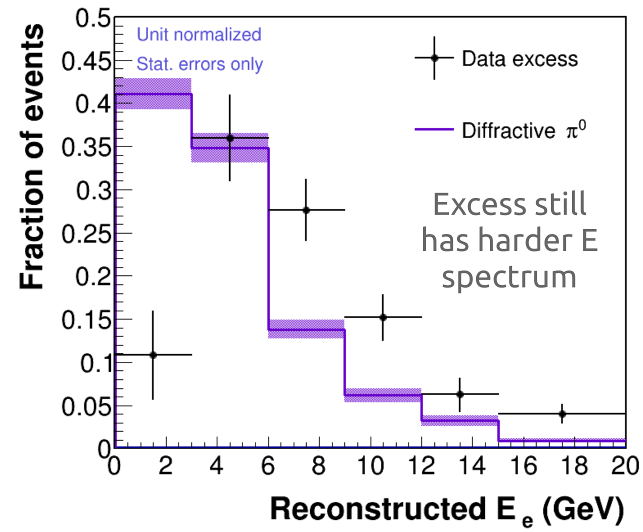
- There is one model for diffractive pion production in a beta format in GENIE. It is from Dieter Rein (NPB 278:61 1986) and is specifically for W > 2.0 GeV. It has not gone through the vetting procedure of other GENIE models.

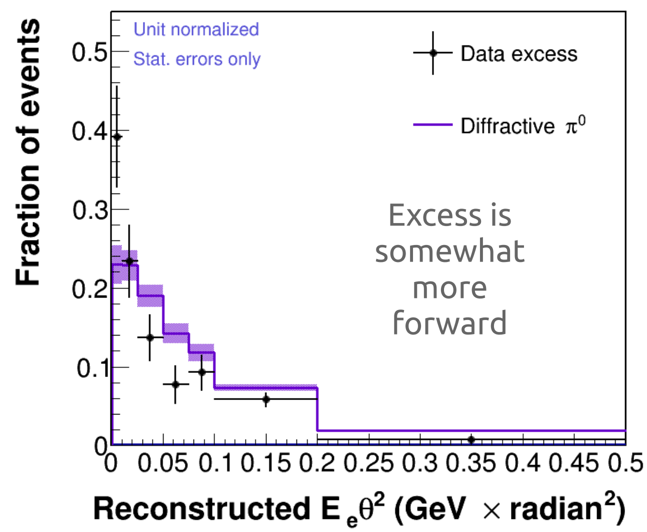
- Comparison with the candidate kinematics suggest there is still work to be done.

- Cross section: For $E_{shower} > 3$ GeV

integrated over the MINERvA flux bases on the 546 candidates:

$0.26 \pm 0.02(\text{stat}) \pm 0.08(\text{sys}) \times 10^{-39}\ \text{cm}^2/\text{CH}$



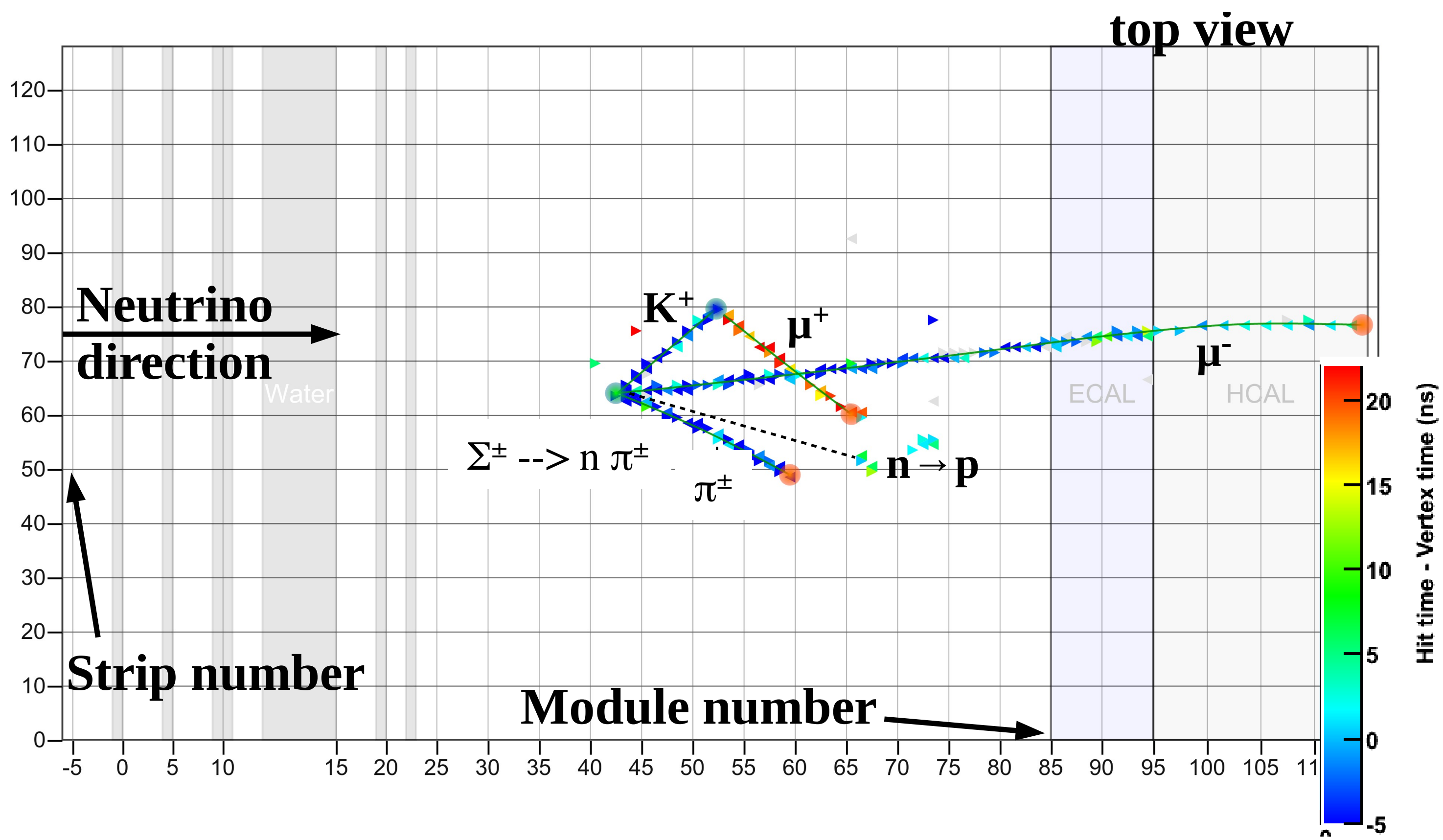


Kaon Production at MINERvA

Chris Marshall

- "Associated production", "$\Delta S = 0$": pairs of strange particles in final state
  - $\nu_\mu\, n \rightarrow \mu^- K^+ \Lambda$
  - $\nu_\mu\, n \rightarrow \mu^- K^+ K^- p$
  - $\nu_\mu\, n \rightarrow \nu_\mu K^+ \Sigma^-$
- "Single kaon production", "$\Delta S = 1$": Cabibbo-suppressed, single kaon final state
  - $\nu_\mu\, N \rightarrow \mu^- K^+ N$
- "Coherent kaon production": nucleus remains in ground state
  - $\nu_\mu\, A \rightarrow \mu^- K^+ A$

MINERvA K Production Event

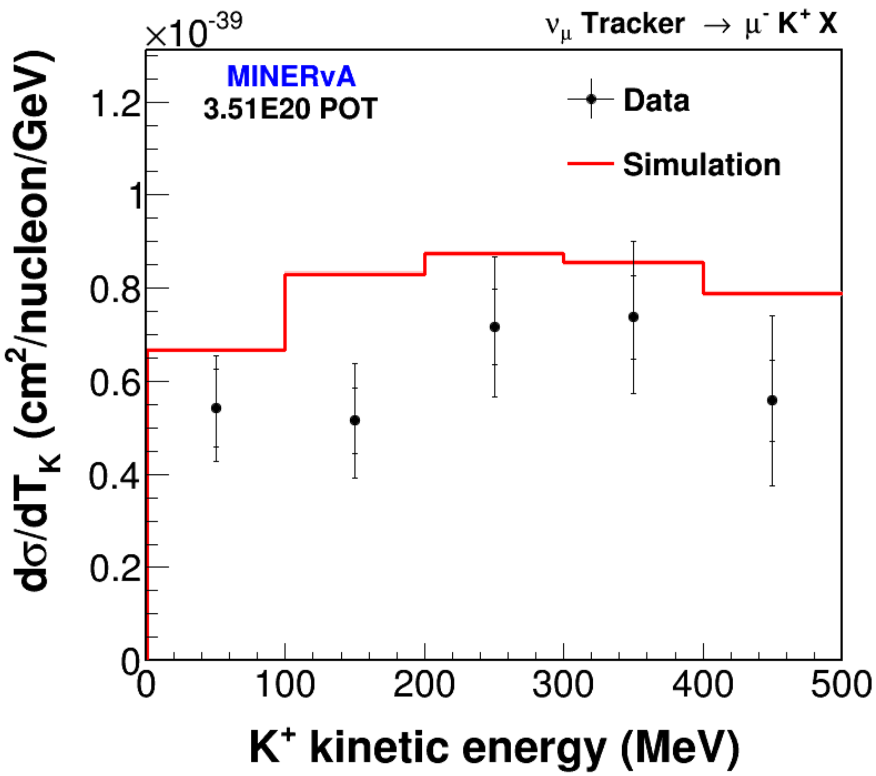


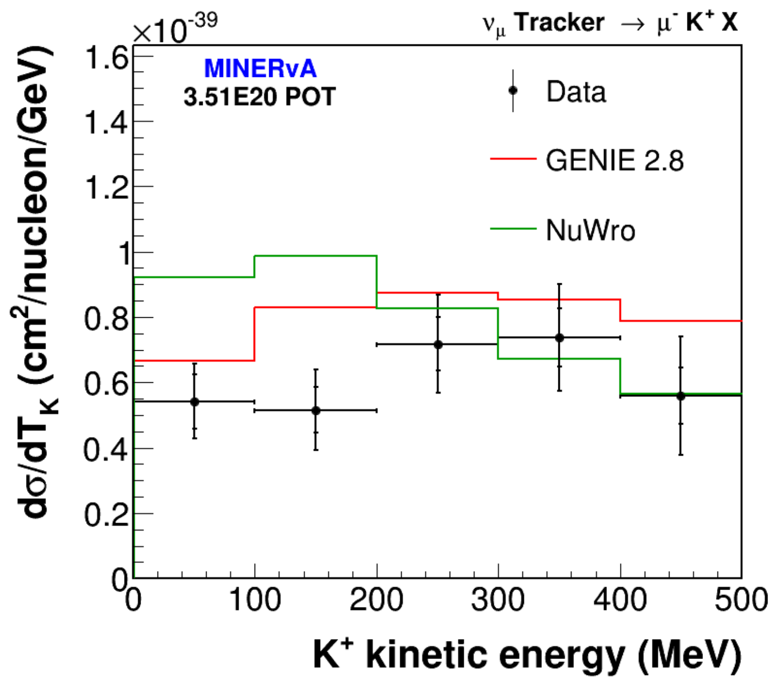
Key distinguishing feature of kaons for MINERvA: time separation of kaon and decay products.

Here, color denotes hit time

CC Cross section favors GENIE prediction

- Charged current K^+ production cross section, based on 885 events, shows reasonably good agreement with simulation.
- This measurement increased the world's sample of K^+ production events from neutrinos from dozens to hundreds!



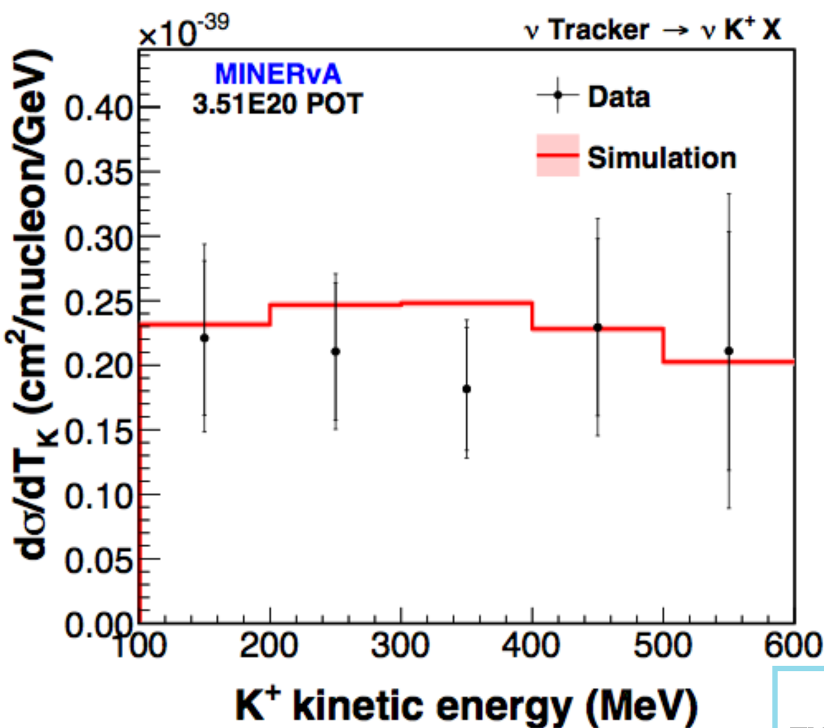


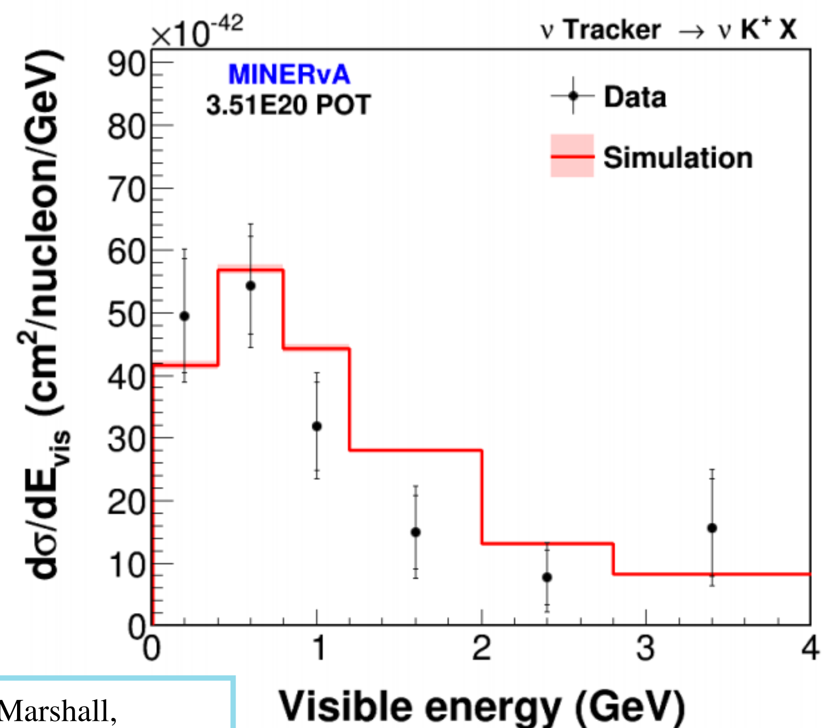
https://arxiv.org/abs/1604.03920

NC Kaon Production

Background for SUSY-preferred proton decay p → $K^+ \nu$

- Neutral current K+ production cross section, based on 200 events, shows reasonably good agreement with simulation.
- We need improvements in the interaction and FSI models, but this result supports the idea that background estimates in proton decay searches are reasonable.



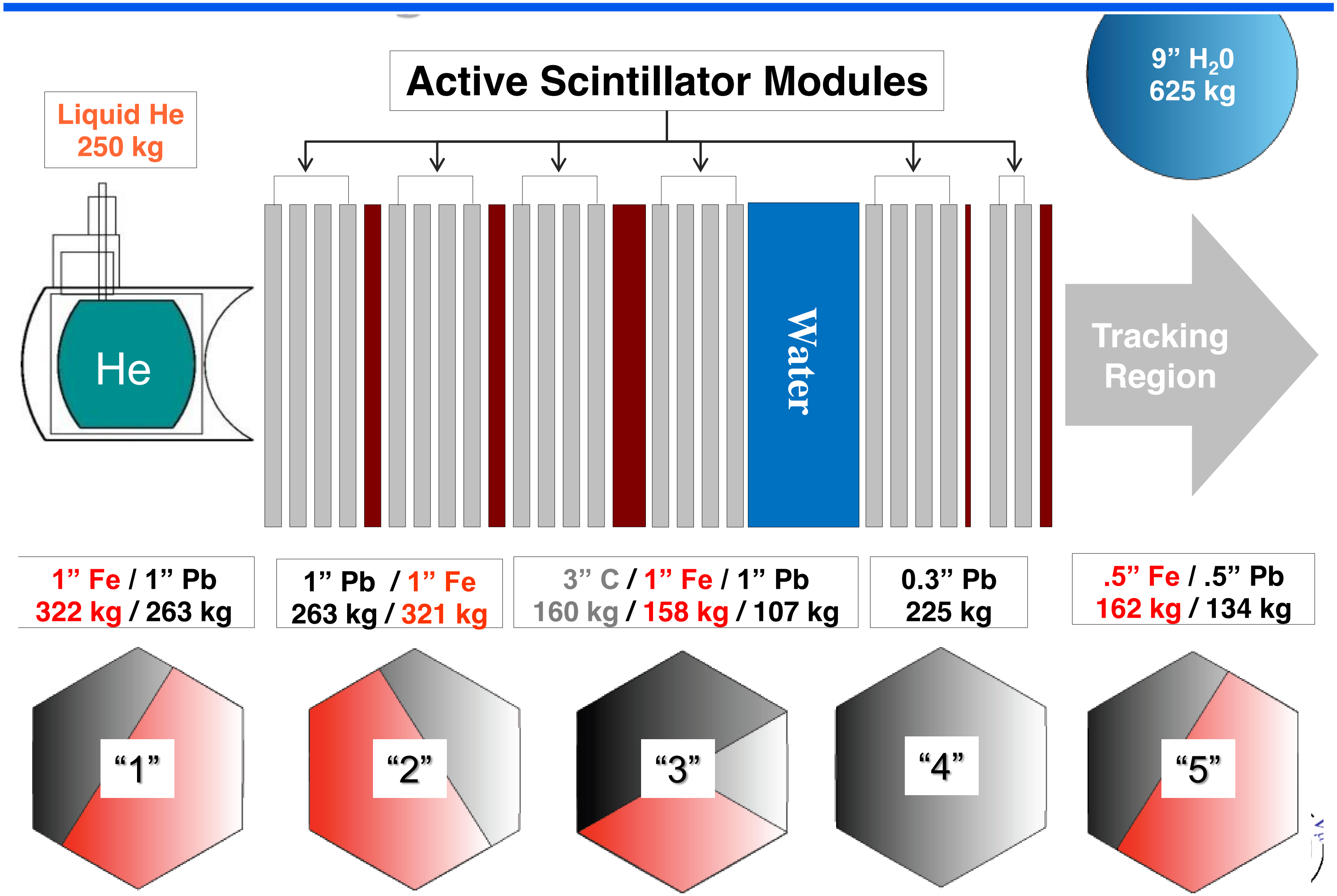


Kaon Summary

CC: Phys. Rev. D 94, 012002 (2016)
Coherent: Phys. Rev. Lett. 117, 061802 (2016)
NC paper in preparation

- MINERvA has made the best measurement to date of charged-current and neutral-current K^+ production by neutrinos
- Probed FSI by studying kaon spectrum
- Looked for "kaon plus nothing" neutral current events that could fake proton decay signal
- Observed charged-current coherent K^+ production at 3σ
- GENIE cross section + nuclear model does a good job of reproducing the data – great news for DUNE & Hyper-K nucleon decay searches

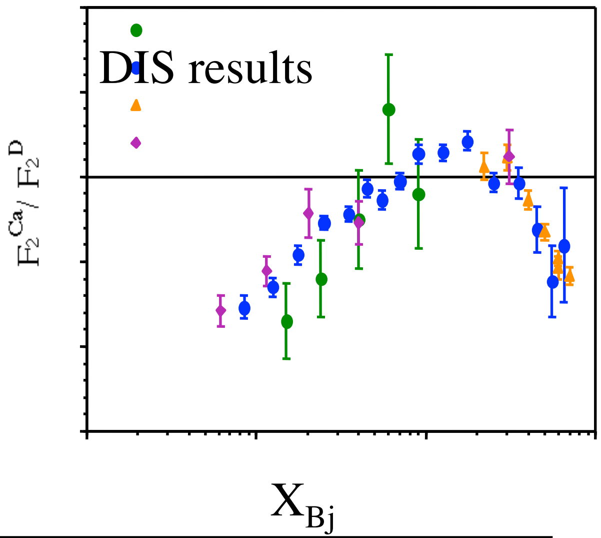
Nuclear Targets



Inclusive Nuclear Target Cross section Ratios

Minimal percentage 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 (%)	Mean Generated Q^2 (GeV^2)
0.0–0.1	11.3	42.5	5.9	19.2	0.23
0.1–0.3	13.6	36.4	16.7	9.1	0.70
0.3–0.7	32.7	32.8	11.8	1.4	1.00
0.7–0.9	55.1	25.4	4.3	0.5	0.95
0.9–1.1	62.7	21.6	2.8	0.5	0.90
1.1–1.5	69.6	18.1	1.9	0.4	0.82
> 1.5	79.1	12.8	0.6	0.3	0.86

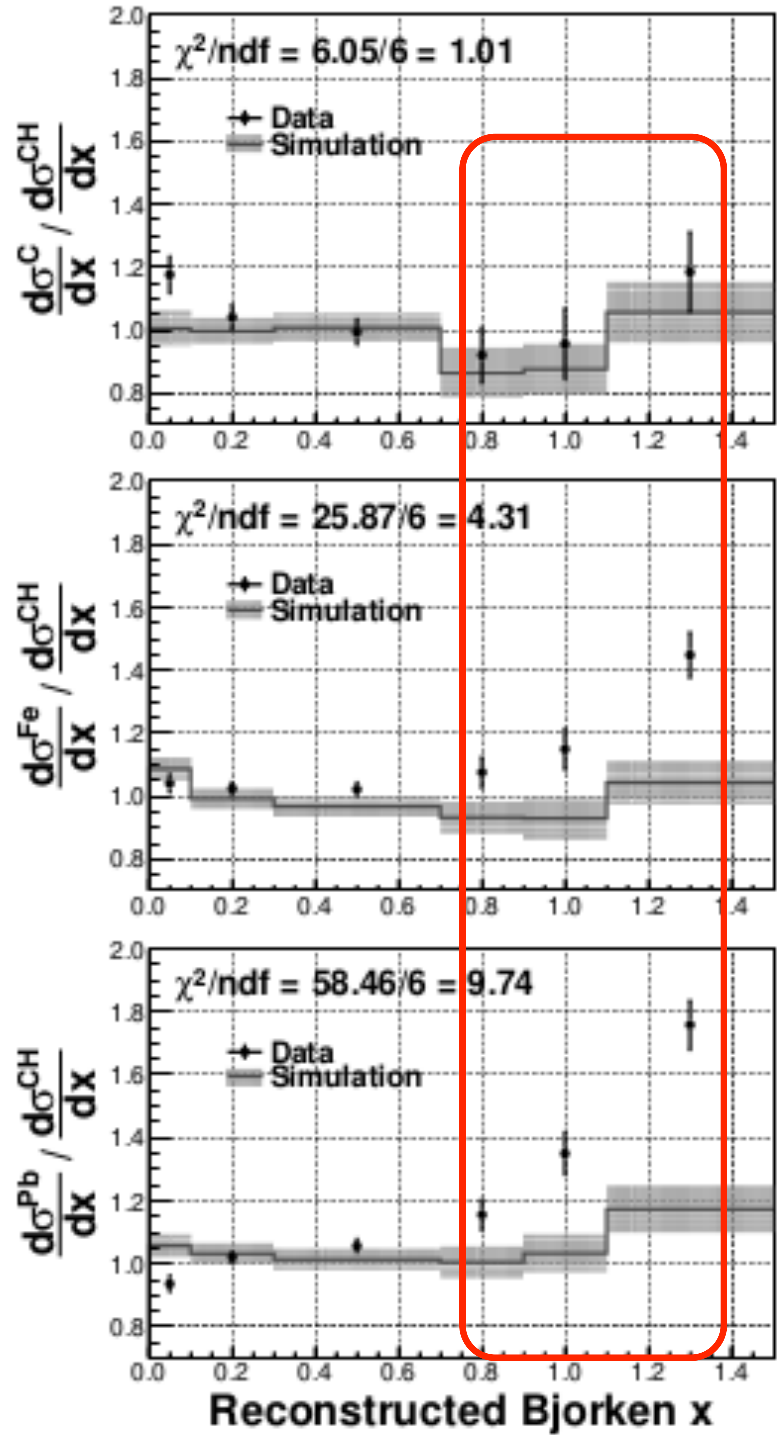
High x summary
INCLUSIVE RATIOS

Brian Tice - Phys. Rev. Lett. 112, 231801 (2014)

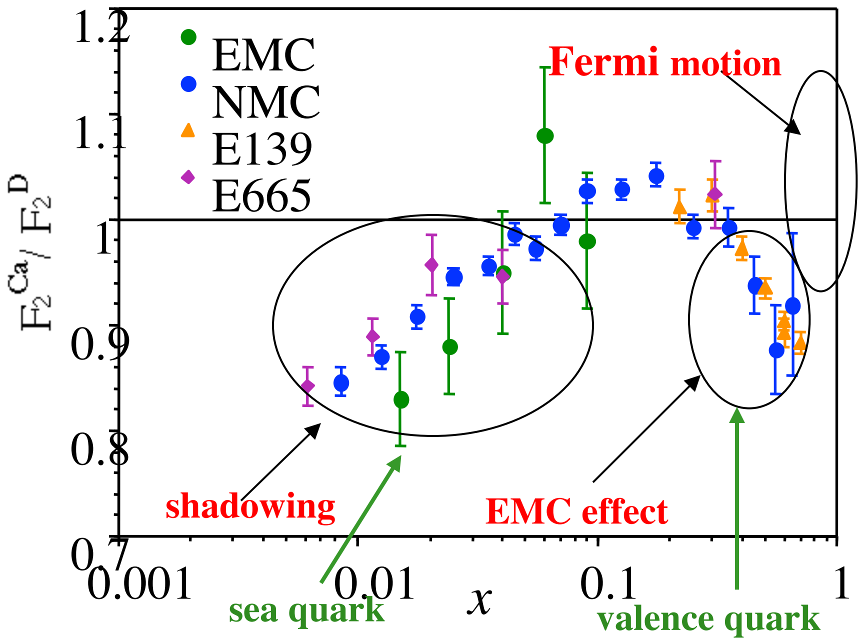
- At x = [0.7,1.1], we observe an **excess** that grows with the size of the nucleus
- This effect is not modeled in the GENIE simulation.
- **Do we not understand the A-dependence of QE and Resonance production??**

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)



Let's go to DIS where quark model is cleaner
$Q^2 > 1$ and $W > 2$

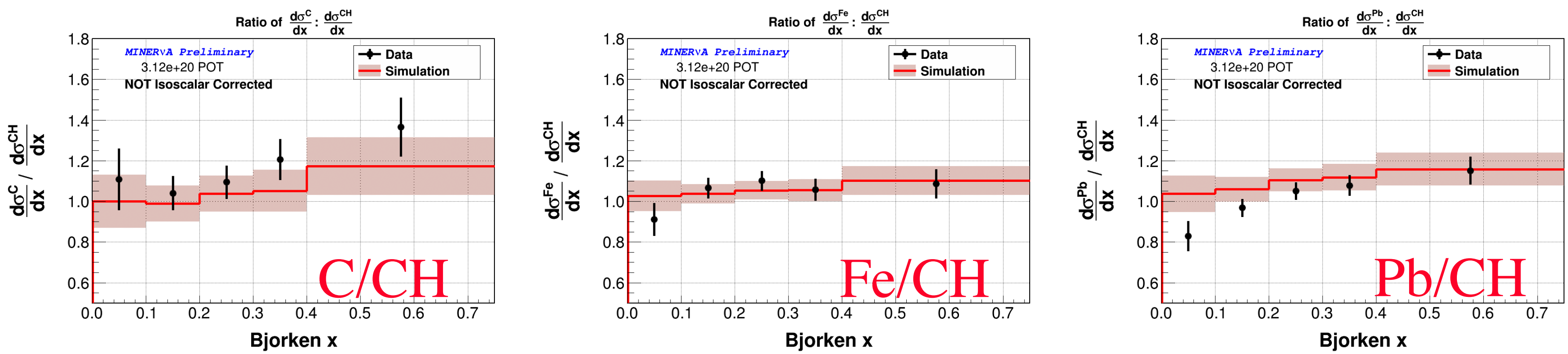


- **<u>Good reason to consider nuclear effects are DIFFERENT in ν - A</u>.**
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> for example different shadowing for xF_3 compared to F_2.**

Restrict to MINERvA DIS sample for cleaner theoretical picture

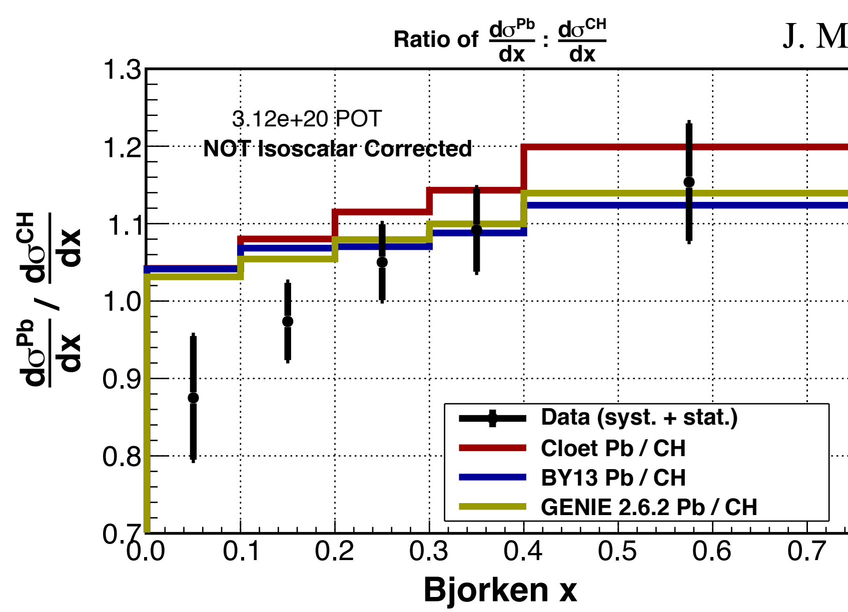
DIS Cross Section Ratios – $d\sigma/dx$

Joel Mousseau - Phys. Rev. D 93, 071101 (2016)



- The shape of the data at low x, especially with lead is consistent with additional nuclear shadowing.
- **At <x>** (0.07) **& <Q^2 >** (2 GeV^2) **negligible shadowing is expected with $l^{\pm}$.**

J. Mousseau



Shadowing

Nuclear Shadowing in Electro-Weak Interactions

B. Kopeliovich, J.G.M., I. Schmidt - Prog.Part.Nucl.Phys. 68 (2013) 314-372

- Why low x? Shadowing is multiple diffractive scatters that interfere destructively.
- The lifetime of the hadronic fluctuation has to be sufficient to allow for these multiple diffractive scatters:

$$t_c = 2E_{had} / (Q^2 + m^2)$$

- For a given Q^2 need large E_{had} to yield sufficient t_c which implies small x.
- m is larger for the vector current than the axial vector current ---> for a given Q^2 you need more E_{had} for the vector current than the axial vector current to have sufficient t_c.
- This implies you can have shadowing at higher x with neutrinos than with charged leptons

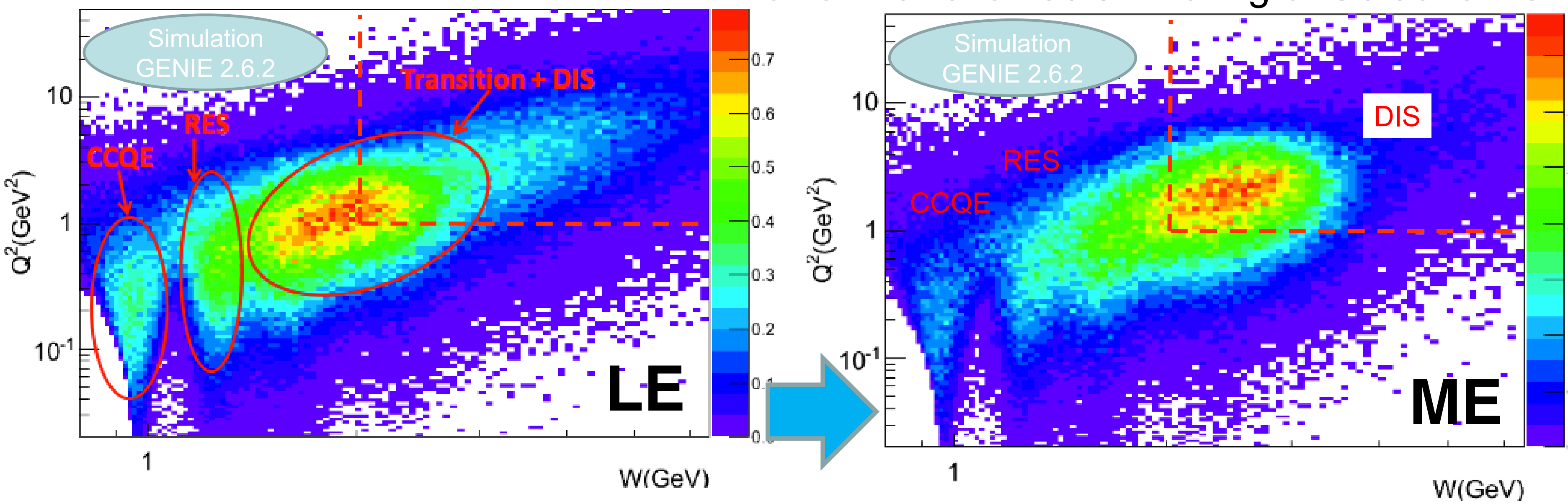
Now Taking MUCH HIGHER Statistics in the ME Beam

Already have 3 x POT in the ME as in the LE Beam

Expect a large anti-neutrino exposure starting later this year

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

Preliminary Conclusions …. Looking ahead…

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

- Comparing MINERvA results to the nuclear models in GENIE and NuWro show that considerable progress has been achieved in the last few years.
- There is clear indication from MINERvA that FSI considerations are necessary but data not yet able to discriminate between FSI models
- Need to move away from the simple IA models of the nucleus used in most event generators.
- Would help to develop a model of neutrino nucleus interactions that is not a patchwork of individual thoughts that are difficult/ challenging 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 Experiment Collaboration

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

- 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 Program

- **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 extended School to be held at Fermilab in Oct/Nov 2017.**
- **Current Project White Paper/Review Publication – State of Neutrino Nucleus Scattering Physics – what we DON"T know.**

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 with HEP Theorists

Concentrate on what we don't know.

Where should future efforts be directed.

- **Executive Summary**
- **Overview of the Current Challenges in the Theory of Neutrino Nucleon/ Nucleus Interaction Physics**
- **The Impact of Neutrino Nucleus Interaction Physics on Oscillation Physics Analyses**
- **Neutrino Event Generators**
- **e-A Scattering Input to ν-A**
- **Quasi-elastic, Quasi-elastic-like Scattering**
- **Coherent and Diffractive Meson Production**
- **Resonance Model**
- **Shallow Inelastic Scattering and Deep Inelastic Scattering**

Current NuSTEC Style Collaboration

HEP Proposal: Nuclear Theory for Neutrino-Nucleus Interactions

Introduce extended ab initio **neutrino** 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

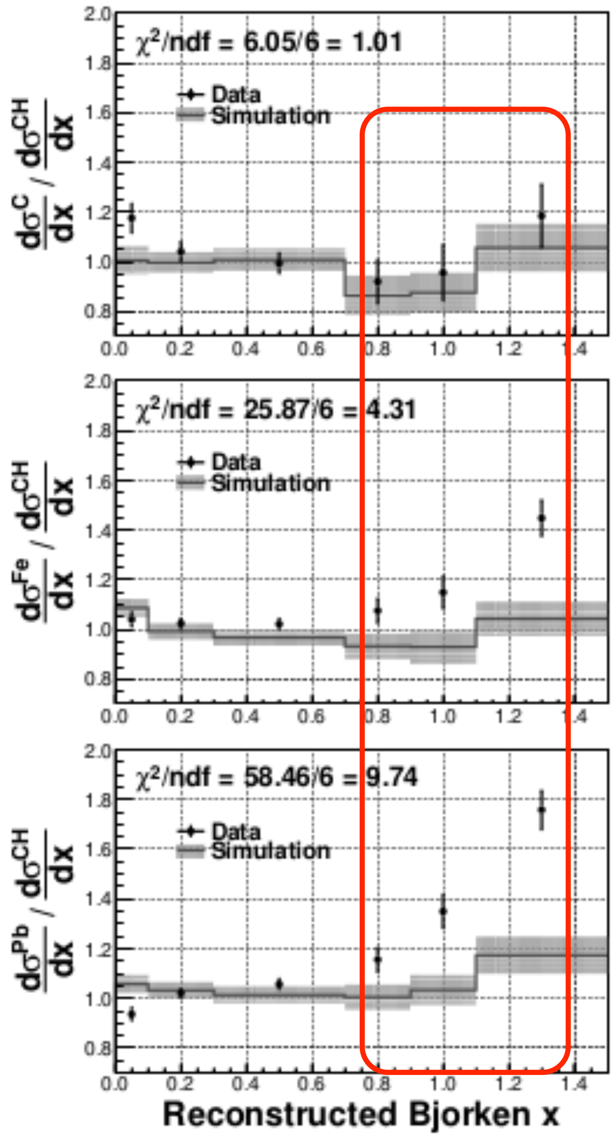
R. Schiavilla and J.W. Van Orden
Old Dominion University

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

Inclusive ratios - observed with vector current only



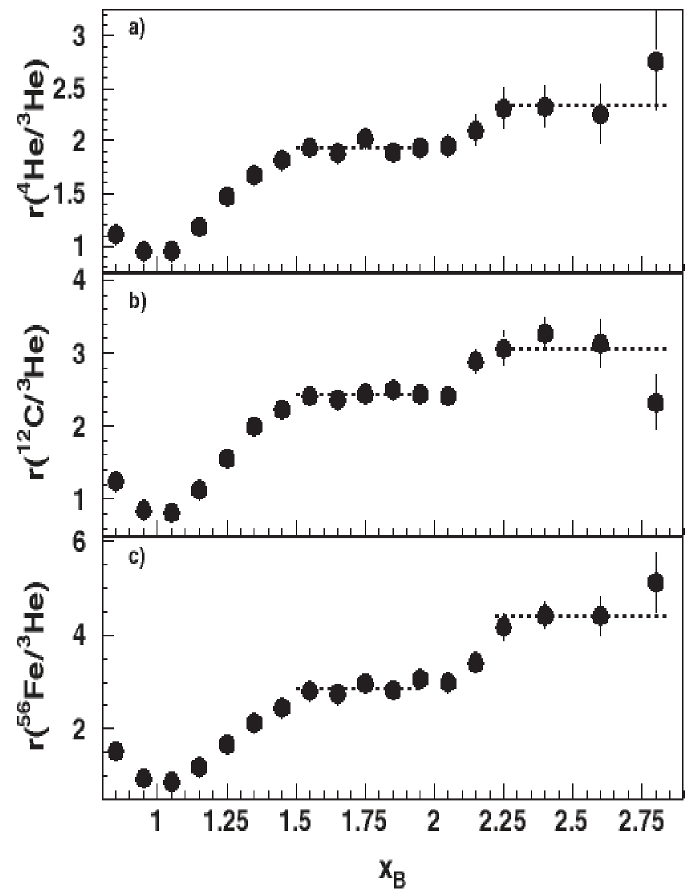


Figure 2-2: The results from a Hall B (JLab) inclusive (e, e') experiment; the cross-section ratios of ^{56}Fe, ^{12}C and ^{4}He relative to ^{3}He as a function of x_B are shown. Figure reproduced from [2].

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.

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.

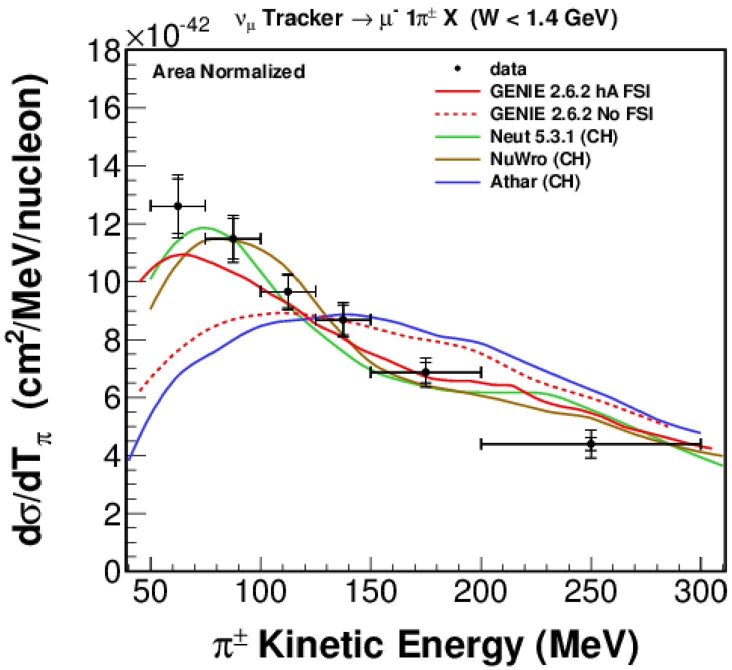
Critical dependence on the nuclear model <u>even with a near detector – SYSTEMATICS DO NOT CANCEL!</u>

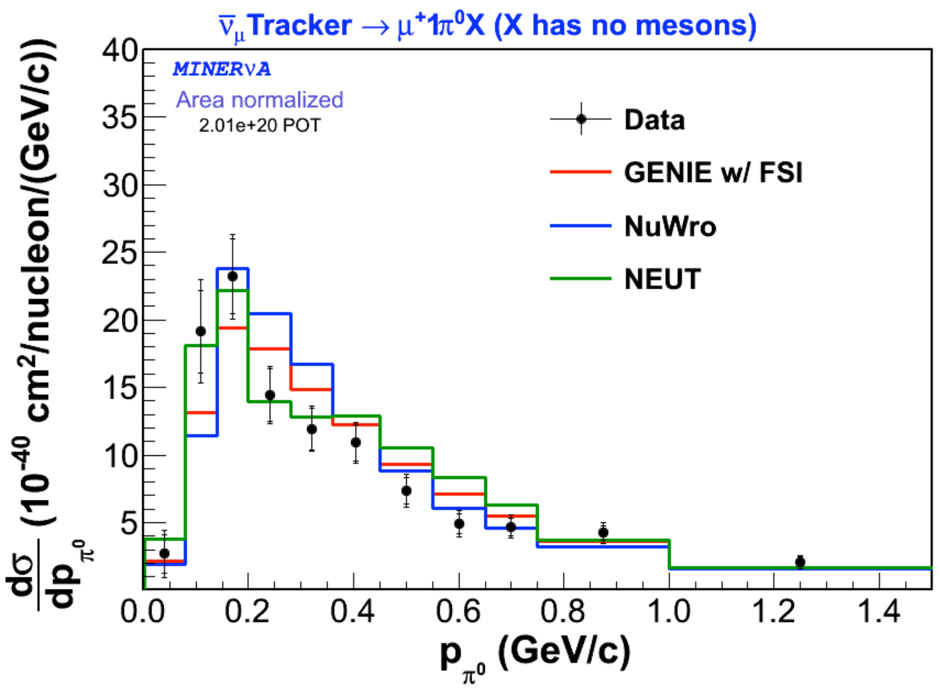
How do we improve the nuclear model?!?

FSI Conclusions for Pion Energy

(Multi model - Shape Comparisons - W < 1.4 GeV)

THIS AND NEXT THREE SLIDES PROBABLY GONE

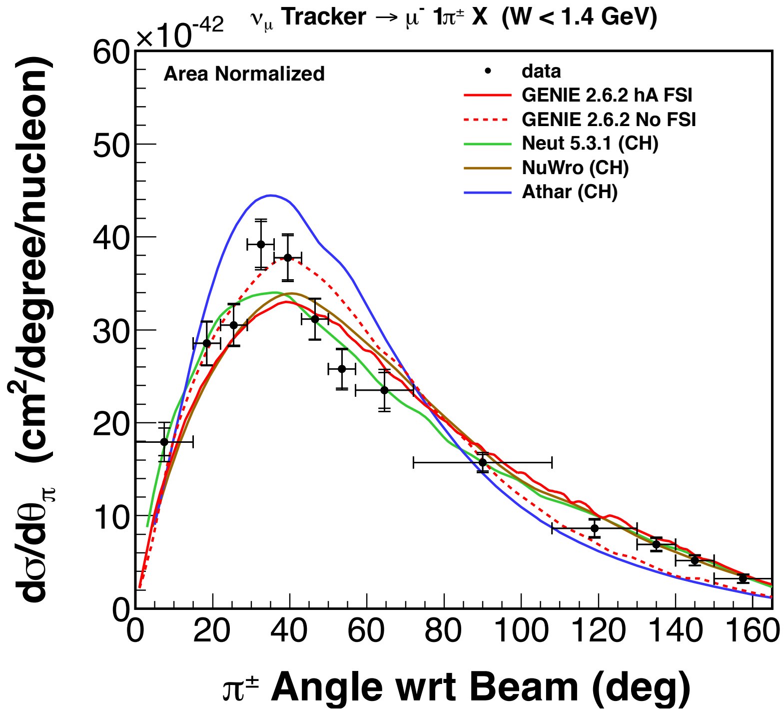


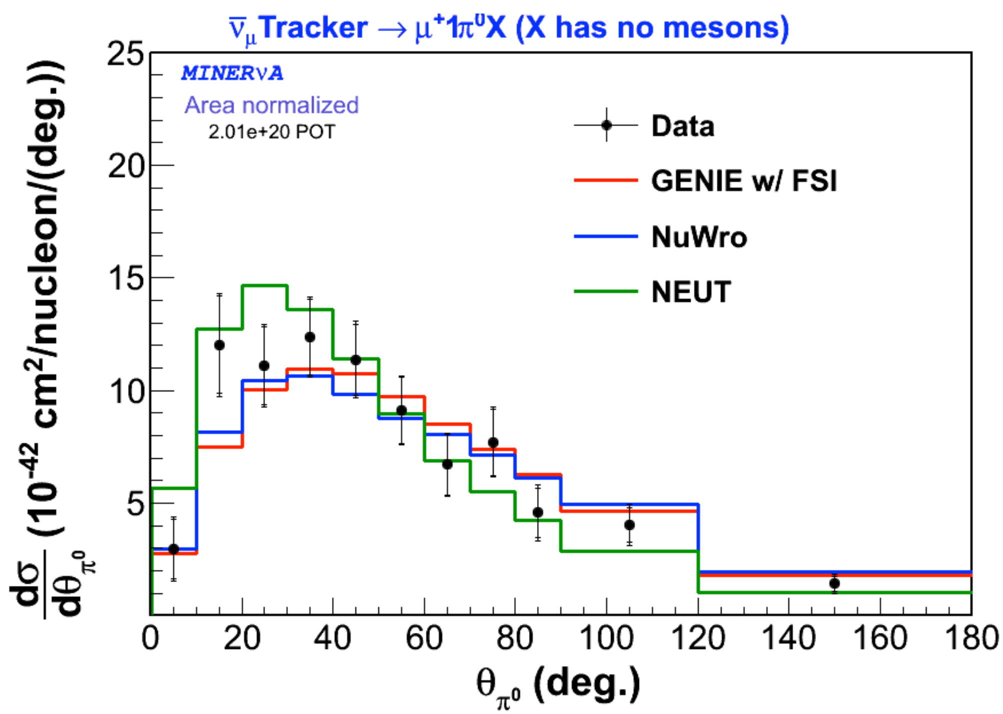


- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Data is unable to distinguish different FSI models

FSI Conclusions for Pion Angle

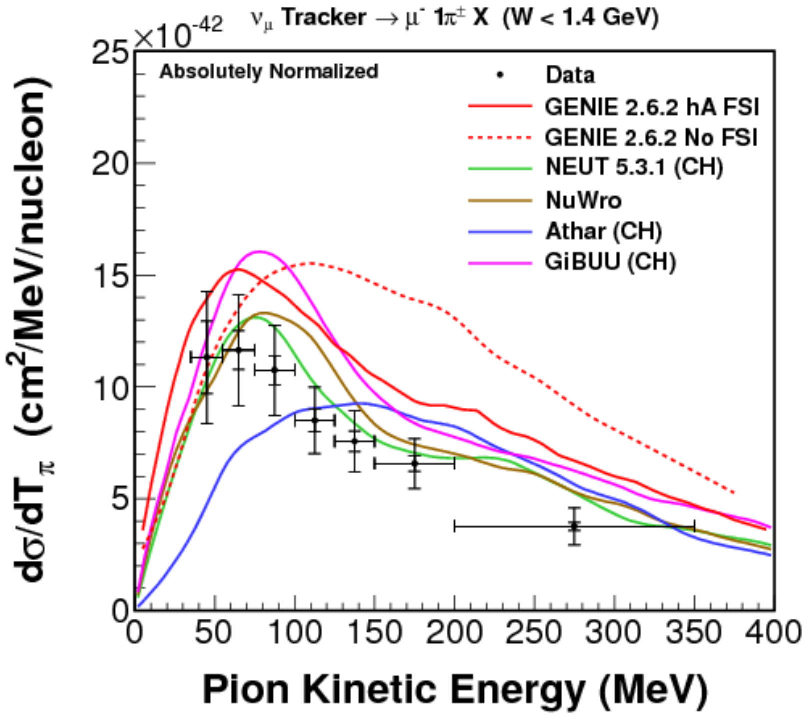
(Multi model - Shape Comparisons - W < 1.4 GeV)

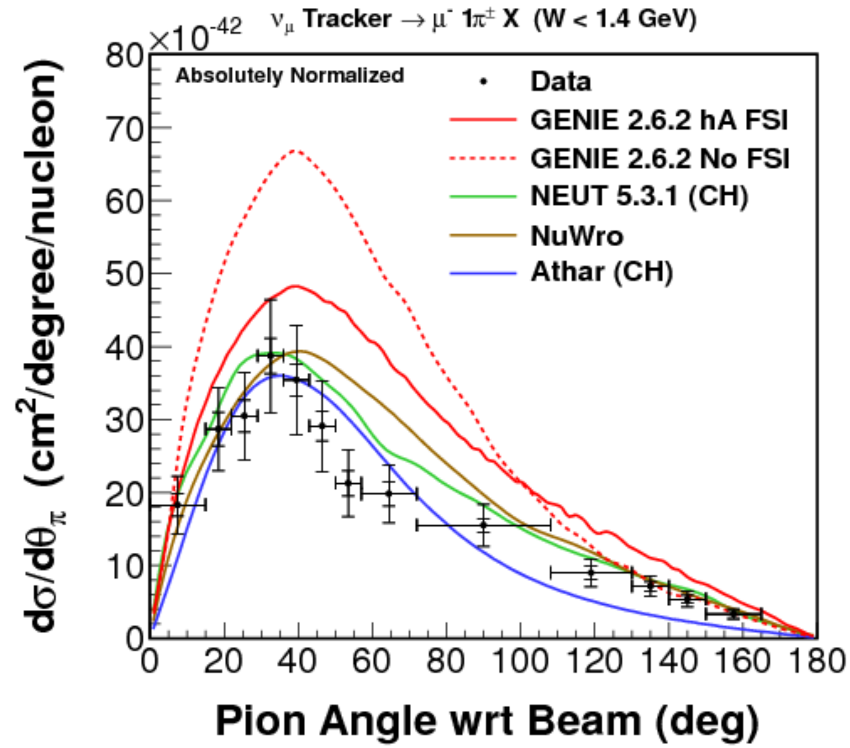




- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Again, data is unable to distinguish different FSI models

More details: charged pion (W<1.4 GeV) absolute cross section – model comparisons

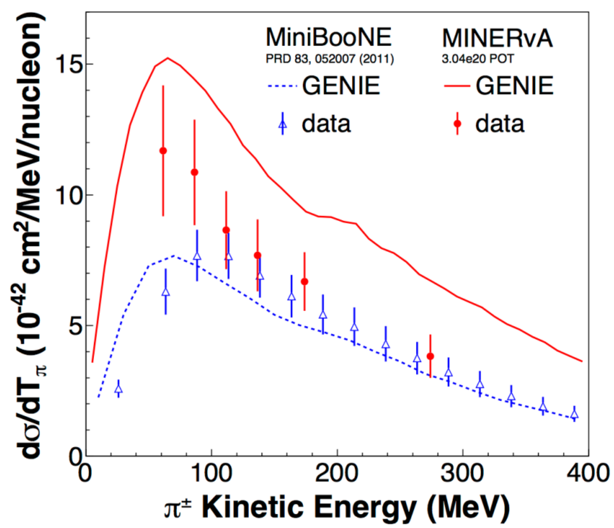




- NEUT and NuWro normalization agree the best with data.
- GiBUU, GENIE normalizations disfavored by a couple σ
- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Except for Athar, data is unable to distinguish different FSI models

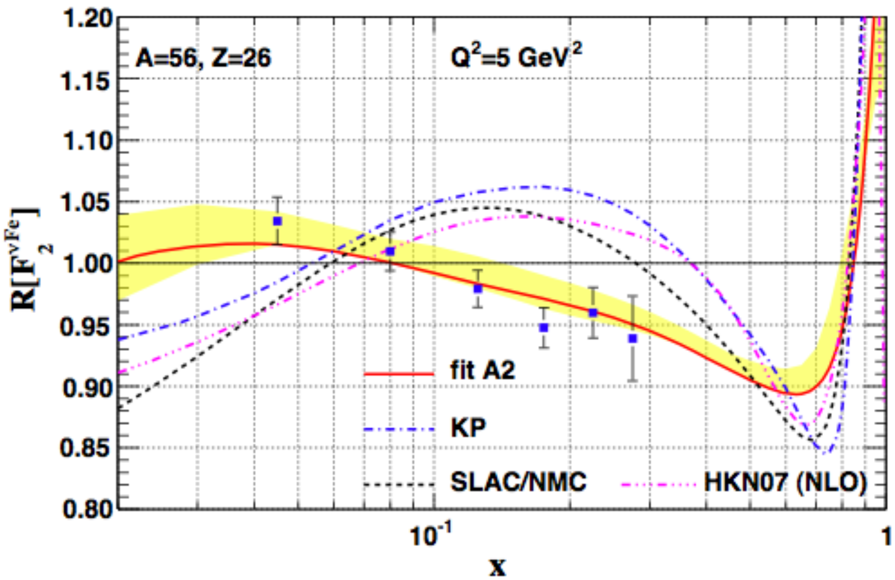
Summary for W < 1.4 GeV Analysis

- 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
  - GiBUU has shape right, but wrong magnitude

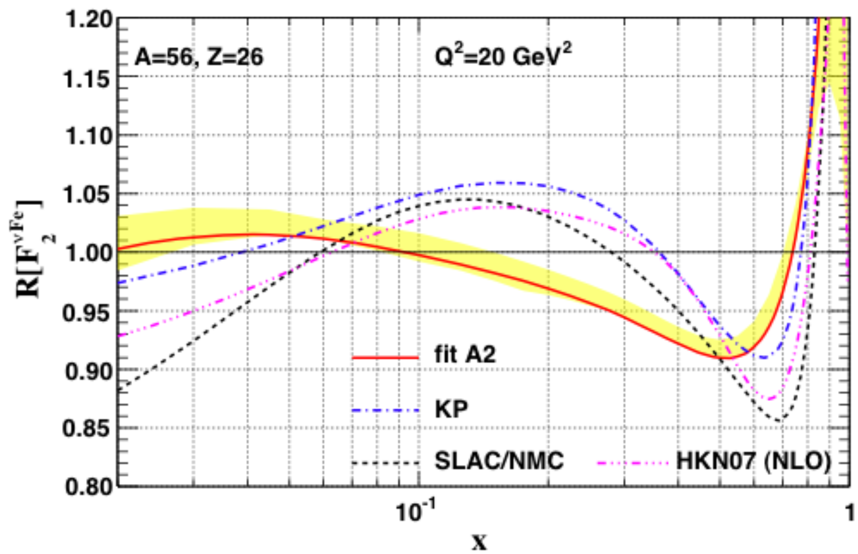


- **No models describes all data sets well!**
  - Theory based calculations have better physics (nuclear corrections), but don't describe data better than simpler event generator codes.

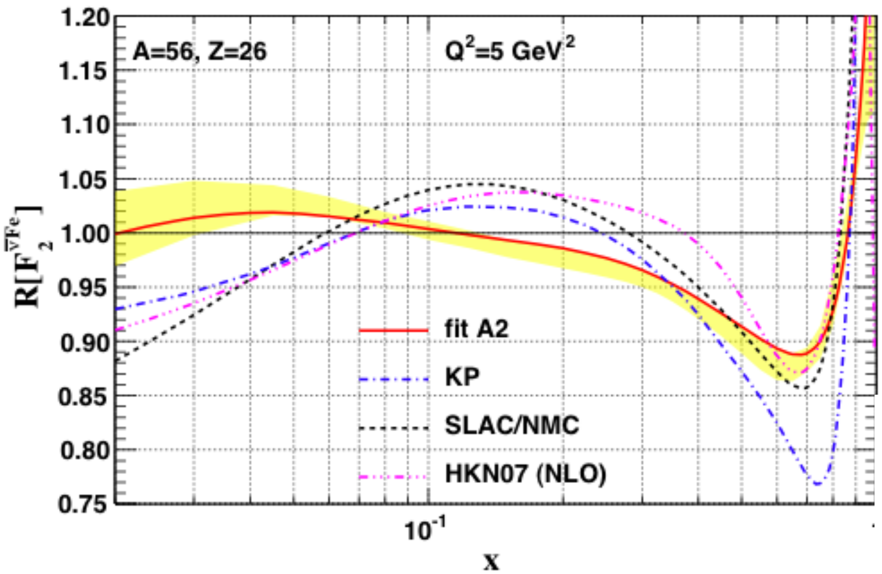
F_2 Structure Function Ratios: ν-Iron



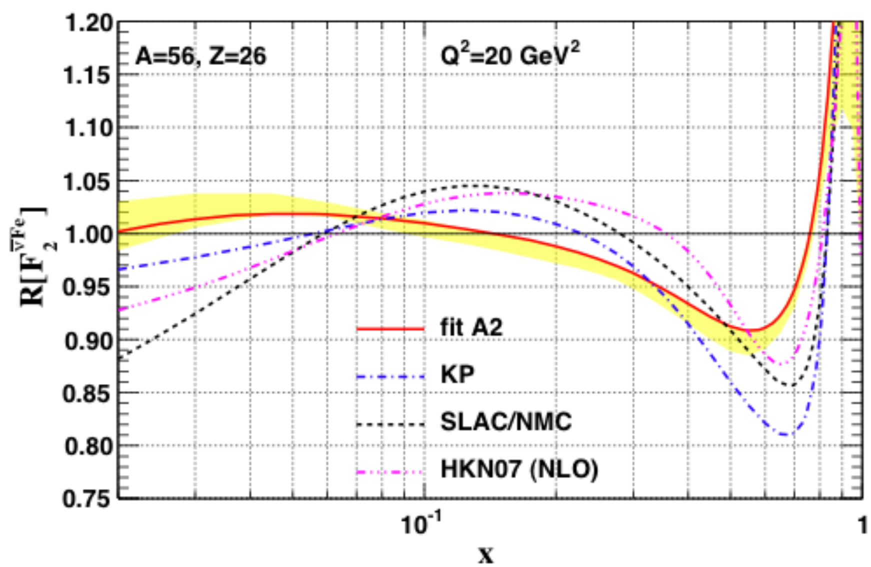
$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



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

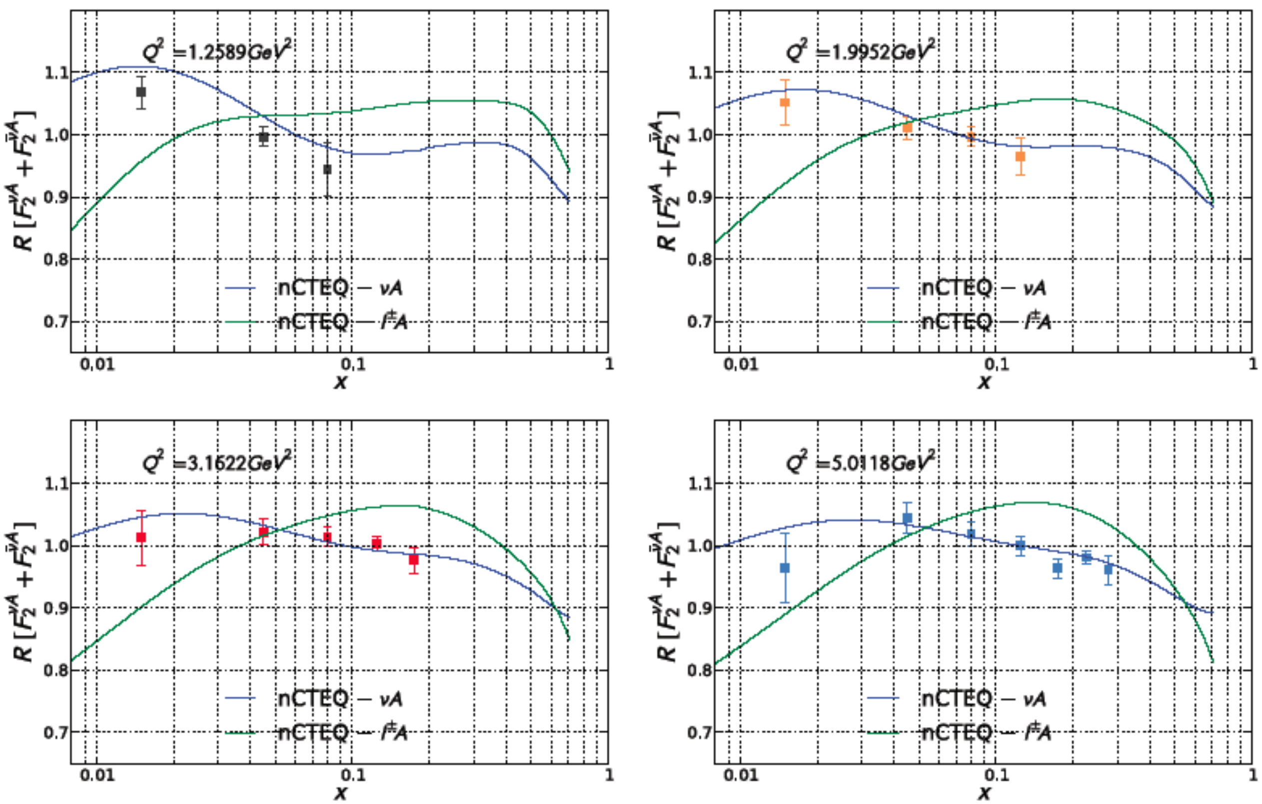


$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



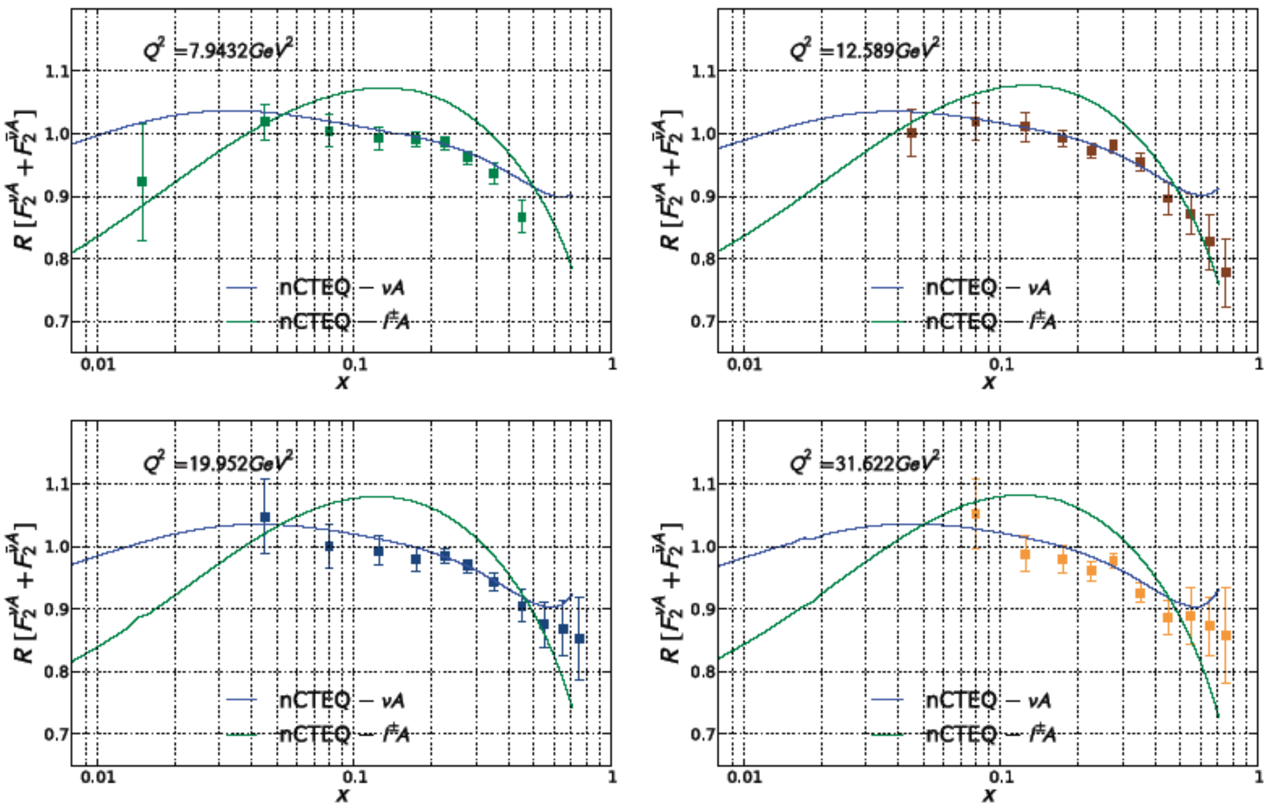
A More-Detailed Look at Differences

- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-Q^2 and low-x data cause tension with the shadowing observed in charged lepton data



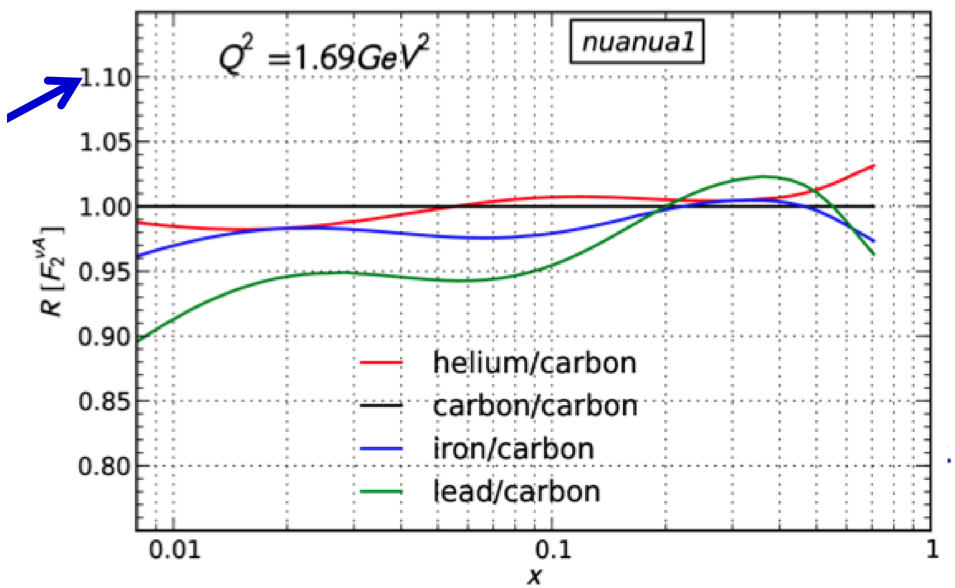
A More-Detailed Look at Differences

- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-Q^2 and low-x data cause tension with the shadowing observed in charged lepton data



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